Implementation of Bistatic Backscatter Wireless Communication System Using Ambient Wi-Fi Signals

Young-Han Kim[1], Hyun-Seok Ahn[1], Changseok Yoon[1], Yongseok Lim[1], Seung-ok Lim[1], and Myung-Hyun Yoon[1]
[1] Smart Network Research Center, KETI (Korea Electronics Technology Institute)
Seoul, South Korea
[e-mail: ekmyph@keti.re.kr, hsahn@keti.re.kr, dbscod@gmail.com, busytom@keti.re.kr, solim@keti.re.kr, mhyoon@keti.re.kr]
*Corresponding author: Young-Han Kim

Received September 12, 2016; revised February 5, 2016; accepted February 27, 2017; published February 28, 2017

Abstract

This paper presents the architecture design, implement, experimental validation of a bistatic backscatter wireless communication system in Wi-Fi network. The operating principle is to communicate a tag's data by detecting the power level of the power modulated Wi-Fi packets to be reflected or absorbed by backscatter tag, in interconnecting with Wi-Fi device and Wi-Fi AP. This system is able to provide the identification and sensor data of tag on the internet connectivity without requiring extra device for reading data, because this uses an existing Wi-Fi AP infrastructure. The backscatter tag consists of Wi-Fi energy harvesting part and a backscatter transmitter/a power-detecting receiver part. This tag can operate by harvesting and generating energy from Wi-Fi signal power. Wi-Fi device decodes information of the tag data by recognizing the power level of the backscattered Wi-Fi packets. Wi-Fi device receives the backscattered Wi-Fi packets and generates the tag's data pattern in the time-series of channel state information (CSI) values. We believe that this system can be achieved wireless connectivity for ultra- low-power IoT and wearable device.

Keywords: Backscatter communication, Wi-Fi, sensor tag, ambient RF, Channel State Information (CSI)

This work was supported by Institute for Information & communications Technology Promotion(IITP) grant funded by the Korea government(MSIP) (No.B0126-15-1076, "Development of non-powered technology combined with ambient RF energy harvesting and Backscatter data transfer").

https://doi.org/10.3837/tiis.2017.02.036 **ISSN : 1976-7277**

1. Introduction

The internet of things (IoT) will rapidly change our life through smart wireless connectivity and create opportunities for innovation and economic growth. By connecting our world and monitoring our surrounding environment, this will bring many practical advancements in our life, improving our health, safety and comfort. The IoT is not a choice for better humanity but necessary for apparatuses to maintain relevance and control over our world. For effective realization of these IoT applications and services, the IoT device should improve sensing, actuating, processing, power supplying and wireless communicating capabilities [1]. Above all, the requirements for perpetual operation and ultra low power wireless communication become more and more important for developing various new IoT services. Various types of low power wireless communication and network technologies are applied to devices to send data to each to the internet and to each other without cable [2]-[4]. The communication method is decided by selection of appropriate wireless connectivity technology considering network situation of various IoT applications. Key aspects for selection of optimal network connectivity includes the operating range, data rate, power consumption, carrier frequency, cost-effectiveness, and so on. However, it's hard to select the optimal wireless connectivity because of their tradeoffs. For example, Wi-Fi is quite apparent choice for supporting fast data transfer and high quantities of data in indoor environment. However, it requires expansive infrastructure and considerable power. The wireless connectivity technologies for sensor devices are Bluetooth, Zigbee, Z-wave, and RFID [5]-[8]. These have to be operated low-power and made inexpensive. The conventional wireless communications for sensor devices exist the limitations of power life time and needs an additional infrastructure [9]. We suggest method for ulta-low-power wireless connectivity using Wi-Fi without needing the additional wireless communication infrastructure [10].

The organization of the paper is as follows. In Section 2, we analyze the advantages using the backscatter communication compared to using conventional methods of wireless communication and review the backscatter theory. Section 3 addresses the bistatic backscatter wireless communication system using Wi-Fi signal. We describes the design of the wireless power transmission system as well as the bistatic backscatter wireless communication architecture. Section 4 presents the implementation and experimentation. Finally, conclusions are drawn in Section 5.

2. Related Work

2.1 Backscatter wireless communication system

The backscatter wireless communication is the modulation method for ultra-low-power. It is operated that the energy of the incident RF signal is reflected back to a source. This method is to transfer data by the measurement of changing a radar cross section (RCS) of the antenna. The bakscatter device sends data during periods of transmitting the RF signal by switching its input impedance at its frequency, changing its RCS and modulating the field [11].

The backscatter devices consists of an antenna, a switching transistor and a load capacitance. The state of the antenna is changed by switching the load capacitive, causing the RCS to be modulated [12]. The reflected RF signal incident on the antenna is modulating the binary backscatter data by altering amplitude and phase.

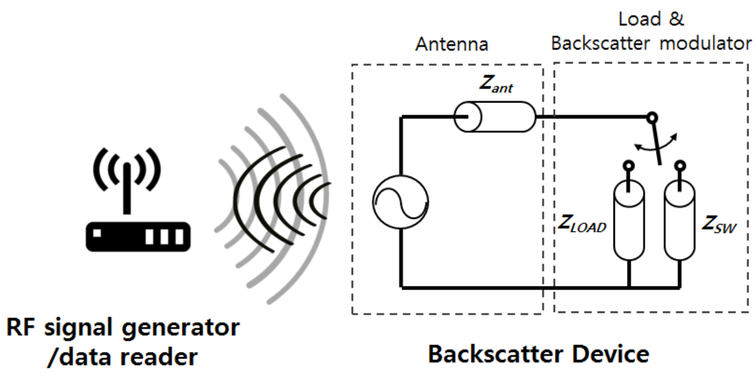

Fig. 1. Equivalent circuit of backscatter system

The system model for backscattering can be found from the equivalent Thevenin circuit [13] of the antenna and the modulator, as shown in **Fig. 1**, where $Z_{ant} = R_{ant} + jX_{ant}$ is the antenna impedance, Z_{LOAD} is the load impedance and Z_{SW} is the switching impedance for the backscatter modulation. The RCS is given by [14]:

$$\sigma = \frac{\lambda^2 G^2 R_{ant}^2}{\pi \left| Z_{ant} + Z_{LOAD,SW} \right|^2} \tag{1}$$

where λ is the wavelength and G is the device antenna gain. The reradiated power by the antenna can indicate the differential backscattered power $P_{diff.bs}$ as:

$$P_{diff.bs} = \frac{1}{2} \left| I_{LOAD} - I_{SW} \right|^2 R_{ant} G \tag{2}$$

where I_{LOAD} and I_{SW} are the currents in different switched the impedance states Z_{LOAD} and Z_{SW}, and show that:

$$P_{diff.bs} = S \frac{\lambda^2 G^2}{4\pi} \left| \Gamma_{LOAD} - \Gamma_{SW} \right|^2 \tag{3}$$

$$\Gamma_{LOAD} = \frac{Z_{LOAD} - Z_{ant}^*}{Z_{LOAD} - Z_{ant}}, \quad \Gamma_{SW} = \frac{Z_{SW} - Z_{ant}^*}{Z_{SW} - Z_{ant}} \tag{4}$$

where Γ_{LOAD} and Γ_{SW} are the reflection coefficients and S is the power density S of an incoming RF signal. By substituting (1), (2) and (3), the magnitude of vector differential RCS $\Delta\sigma$ is expressed [15]:

$$\Delta\sigma = \frac{P_{diff.bs}}{S} = \frac{\lambda^2 G^2}{4\pi} \left| \Gamma_{LOAD} - \Gamma_{SW} \right|^2 \tag{5}$$

2.2 Wireless energy harvesting system

In wireless energy harvesting, the amount of the harvested energy can be decided by the radiation power, the antenna gain, wavelength of the RF signals and the operational range of the harvesting device.

The theoretical operating power of a tag according to Friis equation is [16]:

$$P_{Backscatter\ tag} = EIRP \bullet G_{Tag\ antenna} \bullet \eta_{rec} \bullet \left(\frac{\lambda}{4\pi d}\right)^2 \tag{6}$$

Where, $P_{Backscatter\ tag}$ is the received power, $EIRP$ is the effective isotropic radiation power, $G_{Tag\ antenna}$ is tag antenna gain, η_{rec} is the RF to DC power conversion efficiency of the rectifier, λ is the wavelength of the RF signal, and d is the operational range of tag, as shown in **Fig. 2**. From this equation, it is concluded that the improvement on the efficiency of the rectifier and the antenna gain of the tag are the high priority in terms of expanding the harvesting range.

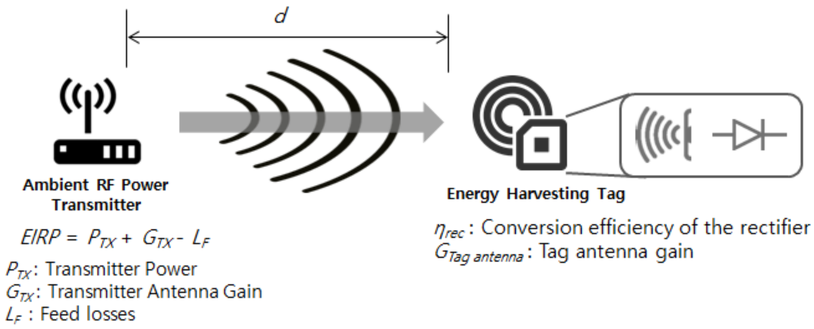

Fig. 2. Operating power of RF energy harvesting system

3. Communication System Architecture

3.1 Bistatic backscatter wireless communication system overview

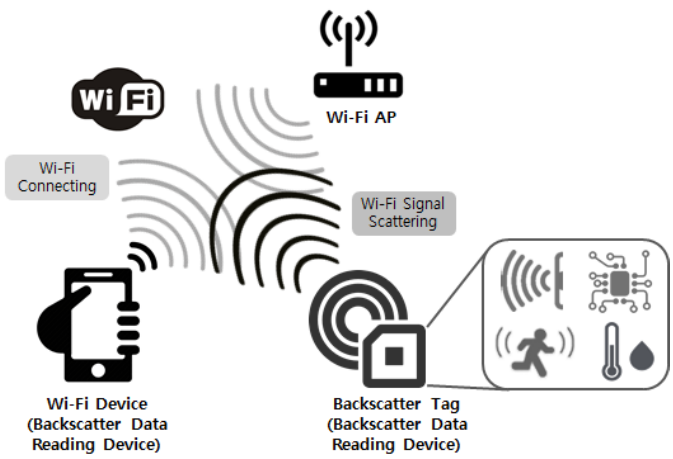

Fig. 3. Architecture of the bistatic backscatter communication system using Wi-Fi signal

The bistatic backscatter wireless communication system is composed of Wi-Fi AP and Wi-Fi device for Wi-Fi connection and a backscatter tag as seen in **Fig. 3**. The backscatter tag transfers the data by reflecting or absorbing the Wi-Fi packets while communicating between Wi-Fi AP and Wi-Fi device [17]. At first, Wi-Fi AP connects with Wi-Fi device to Wi-Fi network. Via the modulated Wi-Fi packet from Wi-Fi AP or Wi-Fi device, the backscatter tag is received the power for system operation and a request command. And the backscatter tag transmits the identification and data of tag to Wi-Fi device by modulating Wi-Fi channel.

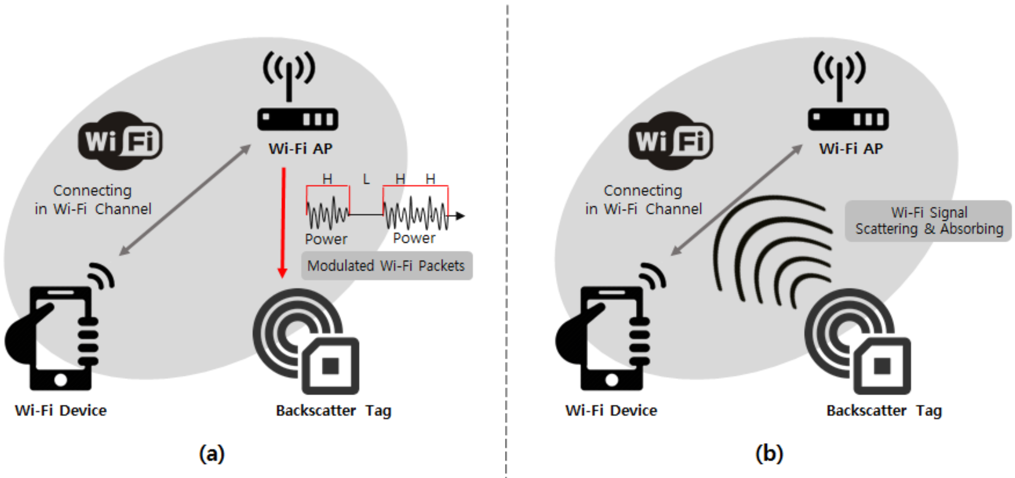

Fig. 4. Operation method of data link (a) data downlink(from Wi-Fi AP/device to the backscatter tag), (b) data uplink (from the backscatter tag to the Wi-Fi device)

On the data downlink from Wi-Fi device to the tag, the Wi-Fi device transfers the modulated request command and wireless power, as shown in **Fig. 4 (a)**. The request command is modulated an encoding data by adjusting length of preamble, header, payload, and short inter-frame space (SIFS) in Wi-Fi packets. As shown in **Fig. 4 (b)**, on the uplink from the tag to Wi-Fi device, the backscatter tag transmits the data by scattering the existing Wi-Fi packets between Wi-Fi device and Wi-Fi AP. It operates to change the reflection coefficient of antenna by switching the load impedance. The changed reflection coefficient affects the phase and magnitude of the Wi-Fi signal. The data of the backscatter tag is demodulated and decoded by extracting the CSI and RSSI values of the modulated Wi-Fi packet.

The backscatter tag is operating in a battery-less as well as a battery-assisted mode. It is possible to efficiently harvest a tiny amount of energy from Wi-Fi AP and Wi-Fi Device transmitting at a power level of 50 to 100 mW. This tag is designed to minimize power consumption because of the physical limitation of Wi-Fi energy harvesting quantity.

3.2 Backscatter tag system

A block diagram of the implemented the backscatter tag system is shown **Fig. 5**. This consists of the parts for the backscatter communication, Wi-Fi signal energy harvester, and a sensor interface. The backscatter communication part includes the RF front-end block for detecting the Wi-Fi packet power envelope and backscattering the Wi-Fi signal and the digital baseband block for decoding/encoding the data and controlling the system. The wake-up signal generator turns on the whole system by providing initial boot up level of power supply. The wake-up system operates by making a preamble sequence which triggers the wake up event. The Wi-Fi power envelope detector extracts a data from the envelope of Wi-Fi packet signal and conveys demodulated signal to the data decoder. It is comprised of a Wi-Fi power envelope detector with a filter, a reference voltage generator, and a data silcer. It converts the modulated Wi-Fi packet signal to the coded digital data. The backscatter load modulator sends the backscatter modulated data to the Wi-Fi device by switching of load impedance. The backscatter load modulator modulates the power level of Wi-Fi signal to reflect the Wi-Fi packet back to the Wi-Fi device. This is configured to a single switch and capacitors for load modulation.

The Wi-Fi signal energy harvesting part generates energy from Wi-Fi signal and provides required power to entire tag system. This block consists of a Wi-Fi signal-DC converter and a power management circuit. The Wi-Fi signal-DC converter converts from the ambient Wi-Fi signals to a DC voltage. This block uses the active components supporting low power threshold for the improvement of the conversion efficiency. The output power of the Wi-Fi signal-DC converter is unstable voltage level due to complex modulated Wi-Fi signal field. Because the whole system requires a constant DC voltage, the purpose of the power management circuit is to provide the stable DC voltage that is independent of the source variation. The tag antenna implements a Wi-Fi band directional antenna that is able to absorb and reflect Wi-Fi packet. The tag antenna of impedance matching is required to ensure the maximum energy of the input Wi-Fi signal for transferring from source to the system load. The input impedance of the Wi-Fi signal-DC converter is generally much higher than the input Wi-Fi signal impedance.

The sensor interface part is designed to allow connection between the sensor output and the data analyzer. It is configured to support the digital and analog outputs of the connected sensor. The clock generator and controller supplies the system clock to operating the digital baseband, the sensor interface, and the memory.

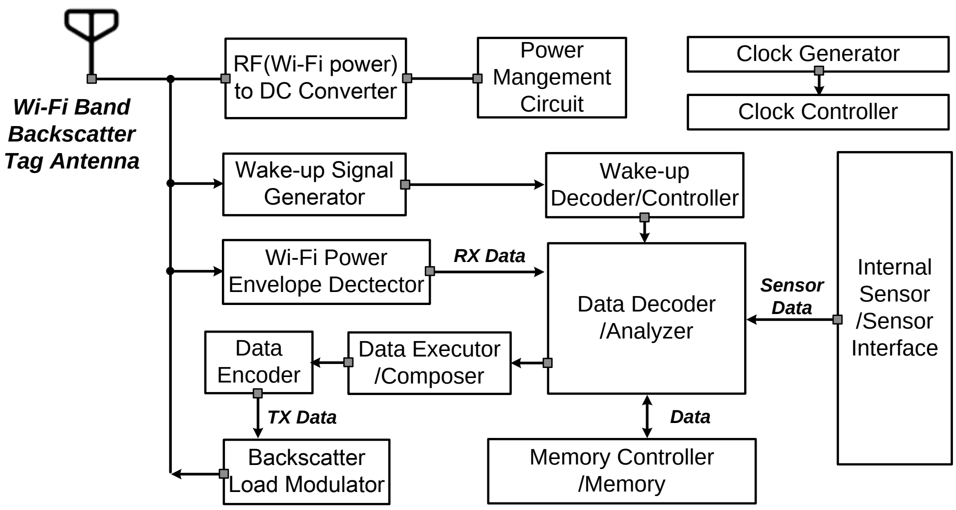

Fig. 5. System architecture of the backscatter tag

3.3 Communication sequence

Fig. 6 shows the communication sequence of the bistatic backscatter data transfer system. It starts from what is the backsactter reading mode of Wi-Fi device. The backsactter reading mode can be controlled by mobile software of Wi-Fi device. After that, Wi-Fi device discovers the surrounding Wi-Fi AP by listening for beacon frames being broadcast regularly. Then again, Wi-Fi device sends probe requests to recognize Wi-Fi networks nearby. Probe requests advertise Wi-Fi device supported capabilities such as IEEE 802.11n. If Wi-Fi AP has compatible data rates, it sent a probe response advertising the wireless network name (SSID) and its IEEE 802.11n capabilities [18]. During discovering the Wi-Fi network by scanning all possible channels and listening to beacons, the backscatter tag near Wi-Fi device is waken by supplying power form Wi-Fi signal. Next, Wi-Fi device sends a Wi-Fi authentication frame to Wi-Fi AP setting the authentication to open. Wi-Fi AP receives the authentication frame and responds to Wi-Fi device with authentication frame set to open. Once Wi-Fi device decides which Wi-Fi AP would like to associate, it sends an association request to that Wi-Fi AP. Wi-Fi AP creates an association identification for the Wi-Fi device of the backscatter reading mode and respond with an association response. Next, the four-way handshake process for using to derive the encryption keys is operated between Wi-Fi AP and Wi-Fi device, as shown in Fig. 6. Finally, they transmit and receive the parameter sets for the backscatter communication mode. That's all it is the association step for the backscatter communication mode.

After operating the association step, Wi-Fi AP or Wi-Fi device sends a query command to the backscatter tag. It responds to the query command with a RN16 command response. Subsequently, the tag replies the identification, sensor data, and the other data with a backscatter data packet by the acknowledgement and read commands. This way, it is run the data transfer process between Wi-Fi AP/Device and the backscatter tag.

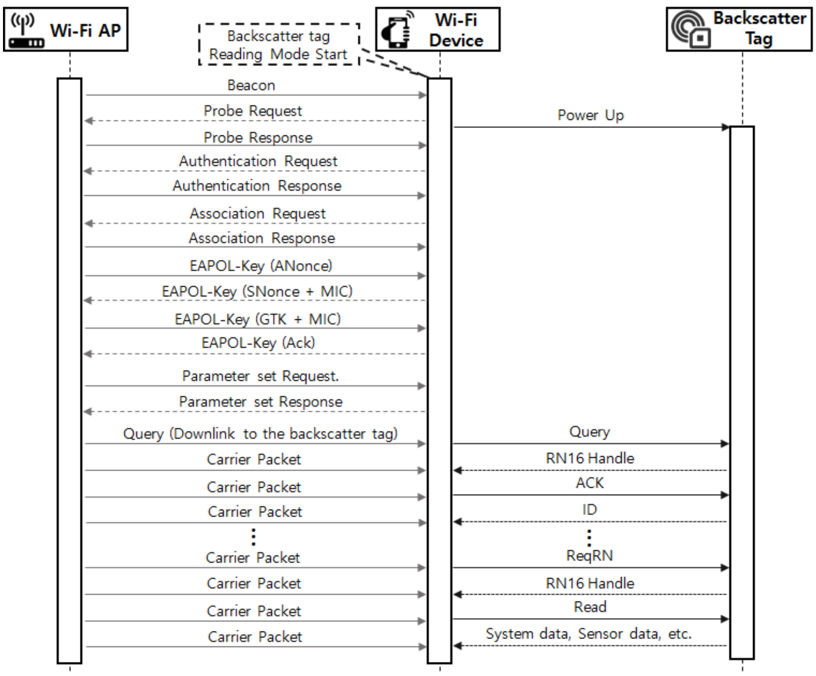

Fig. 6. Communication protocol sequence for data transfer process between Wi-Fi AP/Device and the backscatter tag

We define the encoding and modulating methods of the data downlink and uplink for communication sequence. In data downlink sequence, we design that the packet generator of Wi-Fi AP encode data using length and existence of Wi-Fi packets. As shown in **Fig. 7**, the encoding mechanism at the Wi-Fi AP uses pulse interval encoding (PIE) [19]. This is the encoding method based on time duration of data symbols '0' and '1'. These symbols can be sent to control the length of data payload in the packet generator of Wi-Fi AP. It encodes a ‘1’ bit with increasing data payload length of a Wi-Fi packet and a ‘0’ bit with no data. The division between the bits depends on short interframe space (SIFS). The backscatter tag is designed to detect the envelope of the Wi-Fi packet and SIFS. It decodes data by tracing energy and voltage level of Wi-Fi packets encoded PIE.

In data uplink sequence, the proposed system transfers data of the tag by backscatter modulating the Wi-Fi packets from interconnected Wi-Fi AP, as shown in **Fig. 8**. For improving the performance of backscatter modulating, FM0 and miller encoding methods are used to maximize the number of the transitions in the data. While transmitting the Wi-Fi packets of the constant power and length from Wi-Fi AP, Wi-Fi device extracts the backscatter data of the modulated Wi-Fi packets through analyzing phase and amplitude information of the received channel state information (CSI). For increasing the data rate of the uplink communication, the designed tag can use the multi-level load modulation method.

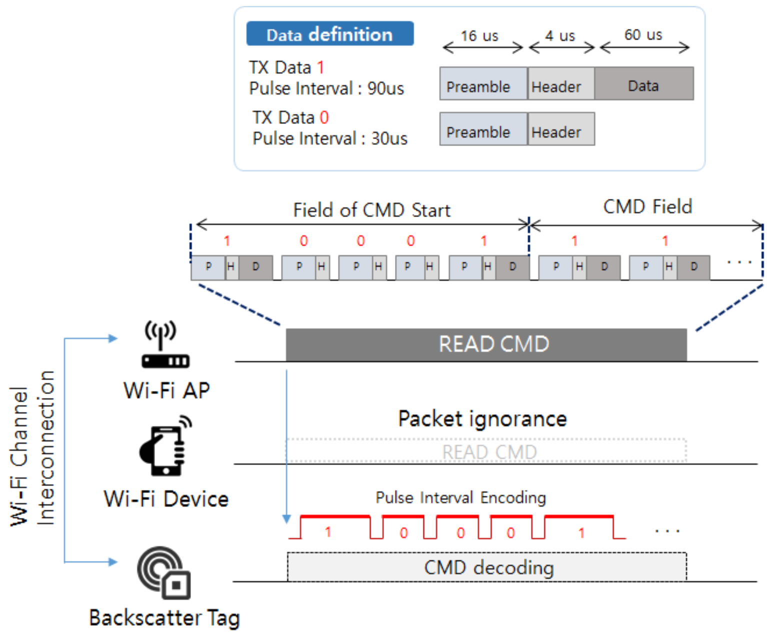

Fig. 7. Data downlink sequence (Wi-Fi AP to the tag)

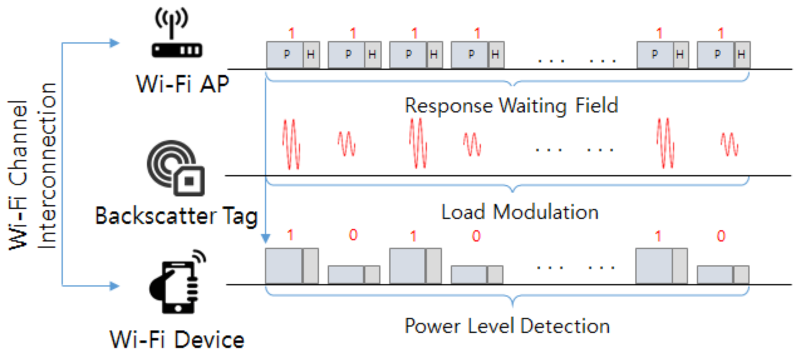

Fig. 8. Data uplink sequence (Tag to the Wi-Fi AP)

4. Implementation and Test

4.1 Implementation

We implement the backscatter tag and Wi-Fi device for reading the backscatter data. The proposed backscatter tag system comprises the components for the communicating and harvesting Wi-Fi energy, as shown in **Fig. 9 (a)**. The data communicating block includes the Wi-Fi packet power envelope detector of Wi-Fi packet and the backscatter load modulator. The power envelope detector removes the 2.4 GHz carrier frequency, and extracts a data from the envelope of Wi-Fi packet and SIFS. It is made up of a filter, a voltage doubler and ultra-low-power comparator. We design the voltage doubler to use Schottkey diode with high rectification efficiency at low RF power levels. The TS881 [20] ultra-low-power comparator from STMicroelectronics is selected for its low power operation. The backscatter load modulator generates the modulation index of backscatter signal via capacitor load array. For switching at 2.4 GHz band, the ADG901/902 [21] RF switch components from Analog Devices are selected.

The Wi-Fi signal energy harvesting part obtains power from Wi-Fi signal and supplies the power of the whole tag. This block is composed of an RF energy to DC converter and a power management. The RF energy to DC converter transforms from the ambient Wi-Fi signals to a DC voltage. It consists of Schottky diodes and capacitors based on voltage multiplier structure [22]. The output voltage level is nominally the twice the peak input voltage and increases to be multiplied by the number of stages, and is correlated with the frequency of the incident Wi-Fi power, the output load resistance and the threshold voltage of Schottky diodes [23].

The backscatter tag antenna is designed a micro-strip patches, which resonates at 2.4 GHz that can absorb and reflect Wi-Fi signal, as shown in **Fig. 9 (b)**. The input impedance of the tag antenna is approximately designed by the RL circuit required for bandwidth optimization and conjugate matching at 2.4 GHz. **Fig. 9 (c)** shows the simulation result of the tag antenna. The power reflection coefficient of the designed tag antenna is depicted in the left of **Fig. 9 (c)**. This result is less than -10 dB at 2.4 ~ 2.65 GHz, which satisfies the bandwidth need of the backscatter modulation in Wi-Fi bands. The far-field 3-dimensional radiation patterns and the calculated gain of the designed tag antenna at 2.4 GHz are plotted in the right of **Fig. 9 (c)**. It can be noted that the main radiation direction of the designed antenna tends to the orientation that is perpendicular to the antenna surface. The antenna gain is more than 6 dBi when the operating frequency ranges from 2.4 to 2.65 GHz.

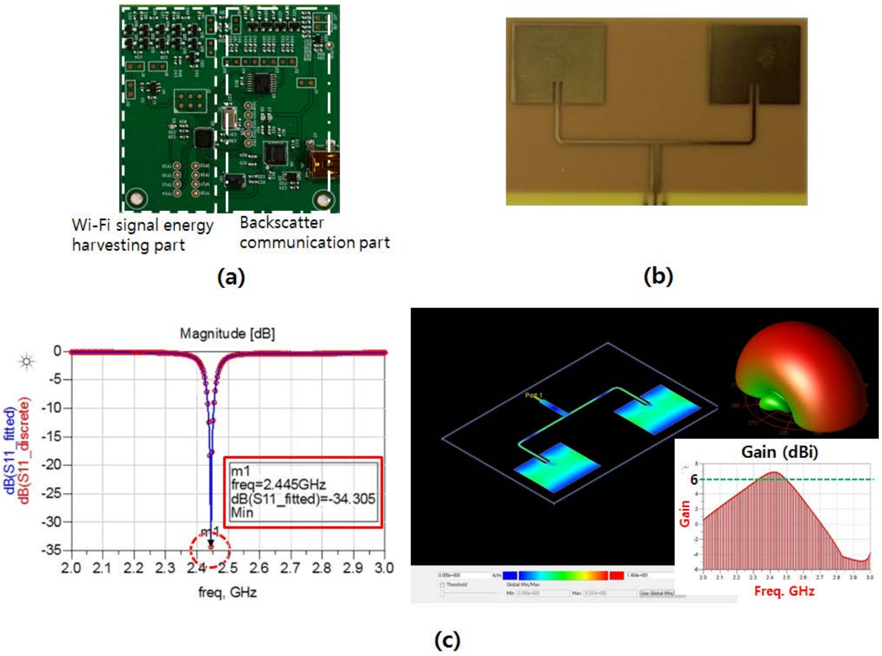

Fig. 9. Implementation of the backscatter tag prototype (a) system board of the backscatter tag, (b) the designed backscatter tag antenna, (c) simulation result of the backscatter tag antenna

We design the backscatter data reading system by using CSI data. The CSI values essentially characterize the channel frequency response for each subcarrier between Wi-Fi device and Wi-Fi AP. Because the changed power of Wi-Fi packet is captured in the CSI values for all subcarriers, it can extract more accurate backsactter data. For demodulating the backscatter data, the backscatter data reading system of Wi-Fi device consists of Wi-Fi band multi-antenna, Wi-Fi communication module, CSI tool driver, CSI data extrcter, and CSI data preprocessor, as shown in **Fig. 10**. We design the system using Wi-Fi Intel link 5300 card that can collect the CSI data. CSI tool driver and CSI data extrcter extract the subspecialized CSI information. CSI data preprocessor is composed of a diversity combiner, a resampler, decimation filter, a DC rejecter, and a band-pass filter.

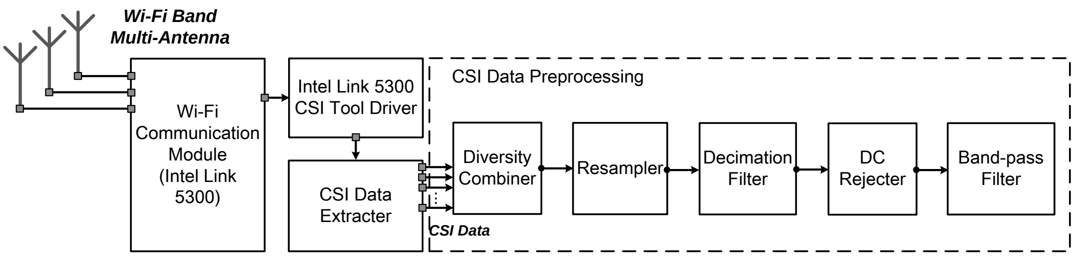

Fig. 10. The backscatter data reading system of Wi-Fi device for demodulating the backscatter data

The designed CSI data reading system is operated as follows. The CSI data refers to the signal distortion during the signal propagation process from transmitter to receiver through the air interface. In Wi-Fi standard (IEEE 802.11), the signal included in legacy long training field (L-LTF) of frame header is used for getting CSI data. Each CSI data is affected by the combined effect of the general channel properties and the tag state changes. The CSI data streams from the received frames can be presented as

$$s_i(t) = \sum_{n=-\infty}^{\infty} h_i(t_n)\delta(t - t_n) \tag{7}$$

where t_n denote each frame receiving time, $h_i(t)$ denotes CSI data affected by the combined channel properties.

The CSI data for OFDM based Wi-Fi standard frame can be obtained for each subcarriers and diveristy path. These signals can be combined to get a single high SNR signal. The signals having high SNR are selected and combined as

$$s_{\Sigma}(t) = \sum_{i=M} \alpha_i s_i(t) \tag{8}$$

where $s_i(t)$ denotes i^{th} selected signal and α_i is linked weight factor. The combined CSI data has variable sampling rates because of transmitter transfer frame at irregular time due to CSMA/CA multiple access protocol. Through this process, the irregular sampling time is recovered and converted to constant for the succeeding signal processing steps.

$$s[n] = \sum_{-\infty}^{\infty} \hat{s}(nT_s)\delta(t - nT_s) \tag{9}$$

where $\hat{s}(t)$ denotes the estimated signal, T_s denotes sampling periods.

The recovered signal need to be filtered out for removing high frequency bands and reduce the number of samples for lessening the processing . The polyphase decimation filter is used for this purpose.

$$s_{deci}[n] = \sum_{k=0}^{K-1} s_{rs}[nM - k] \bullet h_{lpf}[k] \tag{10}$$

where M denotes decimation facator, $h_{lpf}[k]$ denotes lowpass filter coefficients. The CSI data inherently has DC value on it because it also includes the general channel properties as well as the tag signal. For estimating DC value, basically IIR filter is used because It typically uses less memory than FIR and is more efficient. The narrow bandwidth lessen the effect of nolinear phase distortion.

$$s_{dcrej}[n] = s_{deci}[n] - DC(s_{deci}[n]) \tag{11}$$

where $DC(\cdot)$ denotes DC value estimate IIR filter. DC offset estimated from this result is excluded by DC rejecter for improving signal-to-noise-ratio (SNR) in decoding process.

The tag signal is designed for seperating from the general fading effects (i.e. FM0, miller-subcarrier, manchester). Therefore the signal has particular band incluing tag signal. The bandpass FIR filter is used for selecting the data of the backscatter tag signal.

$$y[n] = \sum_{k=0}^{N} x[k] \bullet h_{bpf}[k] \tag{12}$$

Where $h_{bpf}[k]$ denotes bandpass filter coefficient related to tag encoding scheme.

4.2 Test

We implement a prototype of the tag and Wi-Fi device, and test a bistatic backscatter communication system using a commercial Wi-Fi AP. **Fig. 11** shows the test environment. Wi-Fi device can decode information on the date uplink at distances of up to 1 m. This is achieved at data rates to 1 kbps.

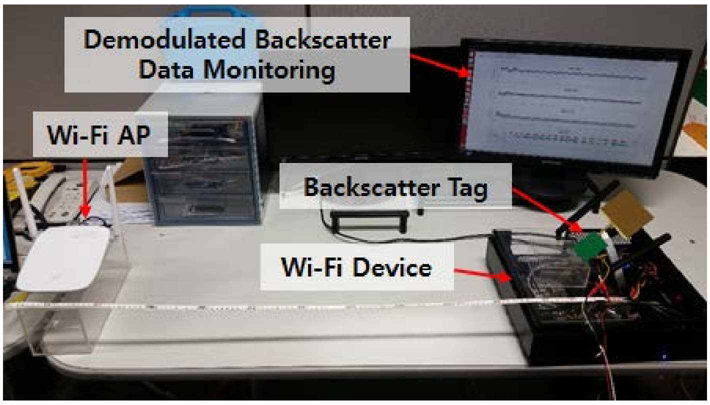

Fig. 11. Test environment

Fig. 12 shows the result of restoring the backscatter data using CSI data. The backscatter tag data, encoded FM0, is transmitted by backscatter modulation to Wi-Fi device. CSI level data are extracted from the incident backscatter modulated Wi-Fi packets and preprocessed, as shown in **Fig. 12 (a)**. And CSI data are restored the backscatter data through a low-pass decimation filtering and generating a threshold value, as shown in **Fig. 12 (b)**.

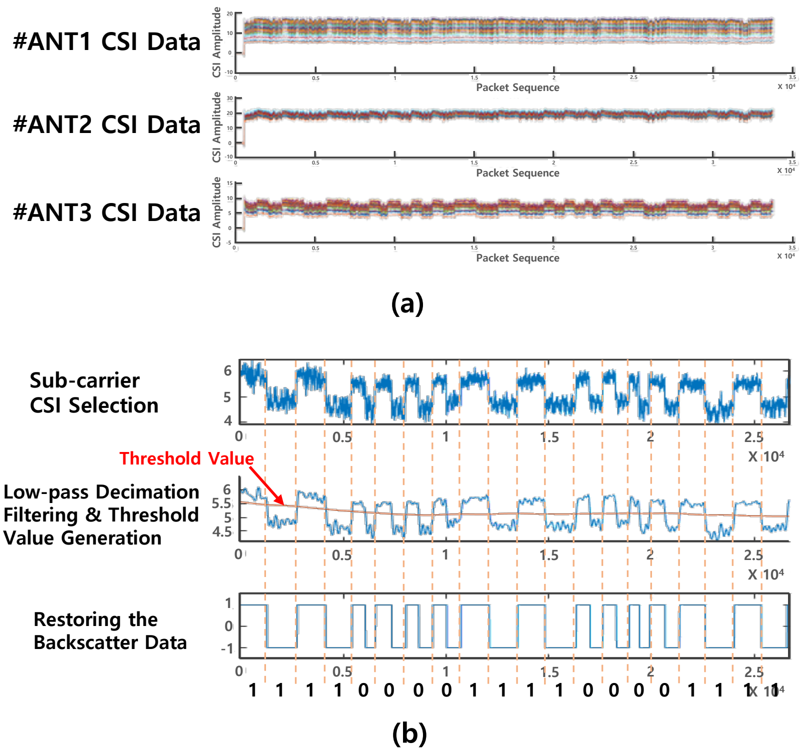

Fig. 12. Result of restoring the backscatter data using CSI data (a) preprocessing of CSI data (b) post-processing of CSI data

5. Conclusion

This paper has presented the backscatter communication system using Wi-Fi signals. We propose the backscatter tag system and the downlink/uplink sequence between the backscatter tag and Wi-Fi device. And we implement a prototype of the backscatter tag and Wi-Fi device for reading the backscatter data, and test the bistatic communication system. This work will be expanded in the future with the implementation of the system-on-a chip (SoC) that includes the backscatter communication part and Wi-Fi signal energy harvesting part. We will make the tag size of the credit card.

References

[1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari and M. Ayyash, "Internet of Things: a survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347-2376, June 2015. Article (CrossRef Link)
[2] Sanjay Kumar, *Wireless Communications Fundamental & Advanced Concepts*, River Publisher, 2015.
[3] J. Wu and G. Zhou, "A New Ultra-Low Power Wireless Sensor Network with Integrated Energy Harvesting, Data Sensing, and Wireless Communication," in *Proc. of IEEE International Conference on Communications (ICC)*, June 5-9, 2011. Article (CrossRef Link)
[4] A. Schoofs, G.M.P. O'Hare and A.G. Ruzzelli, "Debugging Low-Power and Lossy Wireless Networks: A Survey" *IEEE Communications Surveys & Tutorials*, vol. 14, no. 2, pp. 311-321, March, 2011. Article (CrossRef Link)
[5] R. Buyya, and A. V. Dastjerdi, *Internet of Things: Principles and Paradigms*, Morgan Kaufmann, 2016.
[6] J. Lee, Y. Su and C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi", *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, pp. 46-51, November, 2007. Article (CrossRef Link)
[7] Zensys, Inc. *Z-Wave Protocol Overview*, March, 2007.
[8] EPC Global Inc., *EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz–960 MHz Version 1.0.9*, January, 2005. [Online]. Available:http://www.gs1.org/gsmp/kc/epcglobal/uhfc1g2/uhfc1g2_1_0_9-standard-20050126.pdf
[9] M. P. Praveen and N. B. Mehta, "Trade-offs in analog sensing and communication in RF energy harvesting wireless sensor networks," in *IEEE International Conference on Communications (ICC)*, May 22-27, 2016. Article (CrossRef Link)
[10] D. D. Donno, L. Catarinucci and L. Tarricone, "A Battery-Assisted Sensor-Enhanced RFID Tag Enabling Heterogeneous Wireless Sensor Networks," *IEEE Sensors Journal*, vol. 14, no. 4, pp. 1048-1055, April, 2014. Article (CrossRef Link)
[11] R. B. Green, "*The general theory of antenna scattering*," Ph.D. dissertation, Dept. Elect. Comput. Eng., Ohio State Univ, Columbus, OH, 1963.
[12] P. V. Nikitin and K. V. S. Rao, "Theory and measurement of backscattering from RFID tags," *IEEE Antennas and Propagation Magazine*, vol. 48, no. 6, pp. 212–218, December, 2006. Article (CrossRef Link)
[13] D.D. King, "The measurement and interpretation of antenna scattering," *Proceedings of the IRE*, pp. 250-257, vol. 37, no. 7, pp. 770–777, July, 1949. Article (CrossRef Link)
[14] R. K. Schneider, "A re-look at antenna in-band RCSR via load mismatching," in *Antennas and Propagation Society International Symposium*, pp. 1398–1401, June, 1996. Article (CrossRef Link)
[15] P. V. Nikitin, K. V. S. Rao and R. D. Martinez, "Differential RCS of RFID tag," *Electronics Letters*, vol. 43, no. 8, pp. 431–432, April, 2007. Article (CrossRef Link)
[16] K. Kotani and T. Ito, "High efficiency CMOS rectifier circuit with self-Vth-cancellation and

power regulation functions for UHF RFIDs," in *Proc. of IEEE Asian Solid-State Circuits Conference (ASSCC)*, IEEE Asian, pp. 119–122, November 12-14, 2007. Article (CrossRef Link)

[17] B. Kellogg, A. Parks, S. Gollakota, J. R. Smith and D. Wetherall, "Wi-Fi Backscatter: Internet Connectivity for RF-Powered Devices," in *ACM Special Interest Group on Data Communication (SIGCOMM)*, August 17-22, 2014. Article (CrossRef Link)

[18] "*Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Standard 802.11*", 2012.

[19] X. Wang, S. Zhang, L. Mao, K. Xu and H. Zhang, "A novel low-power digital baseband controller for passive UHF RFID tag," in *Proc. of 8th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM)*, September 21-23, 2012. Article (CrossRef Link)

[20] TS881, *Rail-to-rail 0.9 V nanopower comparator*, STMicroelectronics. [Online]. http://www.st.com/content/ccc/resource/technical/document/datasheet/a2/60/3e/5d/b2/c1/4a/e9/DM00057901.pdf/files/DM00057901.pdf/jcr:content/translations/en.DM00057901.pdf

[21] ADG901/902, *Absorptive/Reflective Switches*, Analog Devices. [Online]. http://www.analog.com/en/products/switches-multiplexers/analog-switches-multiplexers/adg901.html

[22] Y. Kim, T. Ki, C. Chung, Y. Moon, Y. Lim and S. Lim, "Implementation of a low-cost and low-power batteryless transceiver SoC for UHF RFID and wireless power transfer system," in *Proc. of IEEE 42nd European Microwave Conference (EuMC)*, October 29-November 1, 2012.

[23] U. Karthaus and M. Fischer, "Fully integrated passive UHF RFID transponder IC with 16.7-/spl mu/W minimum RF input power," *IEEE J. Solid-State Circuits*, vol. 38, no. 10, pp. 1602-1608, October, 2003. Article (CrossRef Link)

Young-Han Kim was born in Gyeonggi-do, Korea, in 1981. He received the B.S. degree in electrical engineering from Inha University, Incheon, Korea, in 2007, and the M.S. degree in electrical & information/ communication engineering at the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2010. From 2010 to 2012, he was with LS Industrial Systems (LSIS Co., Ltd.) where he was an associate research engineer and worked on the design of RF/analog circuits in wireless communication system (UHF RFID). He is currently a senior researcher with Smart Network Research Center, Korea Electronics Technology Institute (KETI), Seoul, Korea, from 2012 to now.

His professional experience includes RF/analog integrated circuit design, wireless communication systems, electronics design, and RFID/IoT systems. His current research interests include ultra-low power sub-threshold circuit design, wireless power transfer (WPT), ultra-low power wireless communication, and RFID/IoT systems.

Hyun-Seok Ahn received the B.S. degree in electrical engineering from Korea University. Seoul, Korea, in 2005 and the M.S degree in electrical and computer science from Seoul National University, Seoul, Korea, in 2007. From 2007 to 2012, he was with GCT Semiconductor where he was a member of technical staff and worked on the design of Analog/RF circuits in wireless communication system. He joined the Smart Network Research Center of the Korea Electronics Technology Institute (KETI) in 2013. His main research interests include Analog and RF circuit design for wireless power transfer (WPT) and wireless communication system.

Changseok Yoon received the B.S. degree in media communication engineering, the M.S. degree in electronics and communication engineering from Hanyang University, Seoul, Korea, in 2006 and 2008, respectively. He is currently a researcher at the Smart Network Research Center of the Korea Electronics Technology Institute (KETI). His current research interests include wireless power transfer (WPT) using RF and magnetic field and ultra-low power wireless communication.

Yongseok Lim received the B.S., M.S. and Ph.D. degrees in electronics engineering from Korea University, Seoul, Korea in 2001, 2003 and 2017, respectively. He was with the ASIC Lab, Central Research Institute, Samsung Electro-Mechanics Inc., from 2003 to 2005. He is currently a managerial researcher with Smart Network Research Center, Korea Electronics Technology Institute (KETI), Seoul, Korea. His research interests include magnetic resonance coupled wireless power transfer (WPT) and embedded system.

Seung-ok Lim respectively received a B.S., M.S., and Ph.D. degree in Electrical Engineering from KonKuK University, Seoul, Korea, in 1997, 1999, and 2005. He is now a director at the Smart Network Research Center in Korea Electronics Technology Institute (KETI), Seoul, Korea. His research interests include wireless communication systems for harsh environments such as underground and underwater environments, and wireless power transfer (WPT) systems based on magnetic coupling mechanism.

Myung-Hyun Yoon received the B.S. degree in electronics engineering from Kyungpook National University, Daegu, Korea, in 1982, the M.S. degree in nuclear engineering at the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1984, and the Ph.D. degree in electrical engineering from the Iowa State University, Ames, IA, in 1994.

He was a director at the u-Embedded Research Center in Korea Electronics Technology Institute (KETI), from 2001 to 2009. He worked as a project director (PD) of Home Network/Information Appliances in Korea Evaluation Institute of Industrial Technology (KEIT), from 2009 to 2012. He is currently a vice president with Communications & Media Research Division in KETI, Seoul, Korea, from 2013 to now.