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무선전력 통신네트워크를 위한 Backscatter 통신

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Backscatter Communication for Wireless-Powered Communication Networks

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요 약

본 논문에서는 무선 센서 네트워크 환경에서 전력의 제약이 있는 센서들의 장거리통신을 가능케 하는 backscatter 통신에 대해 소개하고, 이를 접목해 무선전력 통신네트워크(wireless-powered communication networks, WPCN)의 doubly near-far 문제를 해결하는 방안을 논의한다. Backscatter에 기반한 WPCN에서 유저들은 하이브리드 엑세스 지점으로부터 전송되는 신호와 반송파 송신기로부터 전송되는 반송파 신호로부터 에너지를 수집한 후, 주파수 편이 변조를 이용한 반송파 신호의 반사를 통해 정보를 전송하게 된다. 위의 통신환경에서 energy-free 조건과 신호대 잡음비 outage 영역을 정의한다. 또한 본 논문에서는 에너지 수집과 정보 전송을 위한 최적의 시간 할당 방법을 제안하고, 이를 통해 시스템 전체의 정보전송 효율을 최대화할 수 있는 backscatter 기반의 수집 후 전송 프로토콜을 설계한다. 실험결과를 통해 제안한 backscatter 기법이 종래의 WPCN에 비해 광범위한 서비스 영역과 축소된 신호대 잡음비 outage 영역을 갖는 것을 보였고, 정보전송 효율을 최대화할 수 있음을 보였다.

Key Words : Backscatter communication, wireless-powered communication networks, energy harvesting, energy-free, SNR outage zone, backscatter based harvest-then-transmit.

ABSTRACT

In this paper, we introduce backscatter communication for power-limited sensors to enable long-range transmission in wireless sensor networks, and envision a way to avoid doubly near-far problem in wireless-powered communication network (WPCN) with this technology. In backscatter based WPCN, users harvest energy from both the signal broadcasted by the hybrid access point and the carrier signal transmitted by the carrier emitter in the downlink, and then transmit their own information in a passive way via the reflection of the carrier signal using frequency-shift keying modulation in the uplink. We characterize the energy-free condition and the signal-to-noise ratio (SNR) outage zone in backscatter based WPCN. Further, we propose backscatter based harvest-then-transmit protocol to maximize the sum-throughput of the backscatter based WPCN by optimally allocating time for energy harvesting and information transmission. Numerical results demonstrate that the backscatter based WPCN increases significantly the transmission range and diminishes greatly the SNR outage zone

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Ⅰ. INTRODUCTION

With the evolution of large-scale wireless sensor networks, energy replenishment of energy-constrained wireless devices has been a challenging issue. Although replacing or recharging batteries can extend lifetime of sensors, it causes high cost, inconvenience and is sometimes hazardous or impossible. To circumvent this problem, radio frequency (RF) based energy harvesting has recently emerged to prolong the lifetime [1]. Sensors equipped with RF energy harvesting capability can scavenge energy from dedicated or ambient RF signals.

Wireless-powered communication networks (WPCNs), where wireless devices replenish energy from dedicated or ambient RF signals, have recently gained an upsurge of research interests. In [2], a multi-user WPCN model with harvest-then-transmit protocol was proposed, in which one hybrid access point (H-AP) transfers energy to multiple users in the downlink (DL) and the users with no other energy sources transmit their own information to the H-AP in the uplink (UL) using the harvested energy only. In this WPCN, however, with wireless energy transfer (WET) in the DL and wireless information transmission (WIT) in the UL, we face doubly near-far problem that near users from the H-AP can gain more energy than far users and use this harvested energy for the sake of their information transmission advantageously. But far users suffer from less amount of the harvested energy and degradation of the UL throughput than near users due to the distance-dependent (i.e., round-trip) double attenuation.

In order to overcome this doubly near-far problem, common-throughput maximization scheme was proposed in [2] but it causes severe degradation of overall network performance for fairness. Also, authors in [3] presented user cooperation to alleviate the doubly-near far problem. It has been shown that a near user first helps relay information of a far user to the H-AP and then uses the remaining time as well as energy to transmit its own information for more balanced throughput with desired fairness. However, the only two-user case has been analyzed in [3] and the proposed cooperation protocol with undue complexity may not be feasible for large-scale wireless sensor networks.

Backscatter communication is suitable for the WPCNs suffering doubly near-far problem because it enables a long-range communication with low power in a passive way via the reflection of the carrier signal rather than active radio transmission. As backscatter communication fits well into low-rate, low-power and large-scale wireless sensor networks with RF energy harvesting, it can be an alternative approach to break through the challenges ahead. Backscatter communication for WPCNs can help to increase the coverage of such network and diminish the signal-to-noise ratio (SNR) outage zone, compared to the active radio based WPCNs [2,3].

Scatter radio communication is attracting considerable attention recently. The most remarkable and commercial application of this technology is radio frequency identification (RFID). However, as this RFID has a certain disadvantage of short transmission range due to round-trip path loss, bistatic scatter radio communication, which dislocates the carrier signal generator from the reader, thereby increasing the transmission range, has emerged as a promising technique for low-rate, low-power and large-scale wireless sensor networks.

Bistatic scatter radio architecture has been introduced in [4-6], in which a carrier emitter generates the carrier wave and illuminates a tag/sensor. The tag/sensor does not transmit information like classical radio but reflects the incident carrier signal and modulates the signal using on-off keying (OOK) or frequency-shift keying (FSK) by switching the antenna load with different levels or rates. Then, software-defined radio (SDR) reader decodes the superposition of the carrier signal transmitted directly from the carrier emitter and the backscattered signal from the tag/sensor. In [7], a tag/sensor is assumed to be semi-passive (energy-assisted) with extra energy source, and coherent binary FSK modulation is employed for bistatic scatter communication.

Further, an increased range is offered with short block-length cyclic channel codes suitable for tag/sensors.

With low-cost and low-power principle of a system (by detaching the energy transmitter, i.e., carrier emitter from the reader, unlike conventional RFID), bistatic scatter radio communication can be utilized for ubiquitous and large-scale wireless sensor networks (WSNs) in a distributed area. The promising application is environmental monitoring where numerous sensors are deployed to measure and monitor environmental conditions [4]. Backscatter communication can be a potential key-enabler for deployment of future batteryless WSNs.

In this paper, we propose backscatter based WPCN as an alternative approach to deal with the doubly near-far problem in active radio based WPCNs. To this end, the users, which have no other energy sources but resort only to the harvested energy for transmission, first harvest energy from the RF signal broadcasted by the H-AP and also the carrier signal generated by the carrier emitter in the DL. Then they transmit their own information by reflecting the carrier wave via FSK modulation in the UL. As the carrier emitter can be utilized as another energy source for RF energy harvesting, it can render far users to mitigate severe range discrimination caused by doubly near-far problem. The latter is due to the fact that the carrier emitter can be deployed close by the tag/sensor, and the energy source can be dislocated from the H-AP. Also, backscatter communication relying on passive transmission rather than active one can increase a communication range with low power. With this new approach, we aim to achieve a long-range coverage and diminish the SNR outage zone, compared with the active radio based WPCNs.

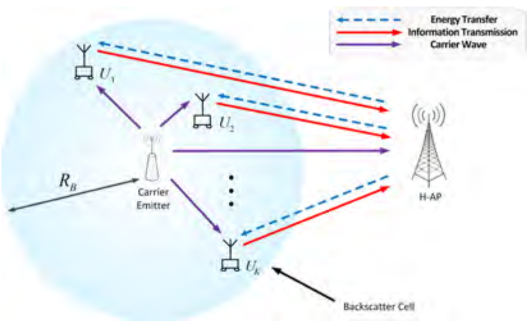

Fig. 1. Backscatter based wireless-powered communication network (WPCN).

Considering the coverage and SNR outage zone in the backscatter based WPCN, we maximize the sum-throughput of multiple tags in the backscatter based WPCN by optimally allocating time for WET in the DL and WIT in the UL with backscatter based harvest-then-transmit protocol, subject to a given time constraint. With this optimal time allocation, the achievable maximum sum-throughput of all tags in the backscatter based WPCN is evaluated.

The rest of this paper is organized as follows. Section II introduces the system model with backscatter based harvest-then-transmit in backscatter based WPCN. Section III characterizes both the energy-free condition and the SNR outage zone. Section IV formulates the sum-throughput maximization problem in the backscatter based WPCN. Section V presents simulation results to show the increased coverage and the diminished SNR outage zone in the backscatter based WPCN over the active radio based WPCNs, and simulation results on the achievable maximum sum-throughput in the backscatter based WPCN. Finally, conclusion is drawn in Section VI.

Ⅱ. SYSTEM MODEL

As shown in Fig. 1, this paper considers backscatter communication based WPCN which consists of one H-AP and a backscatter cell that comprises a carrier emitter and users (e.g., tags/sensors) denoted by U_i, $i=1,\cdots,K$ with WET in the DL and WIT in the UL. The carrier emitter is deployed in the center of a backscatter cell and illuminates the tags within backscatter cell boundary R_B with a carrier signal at the ultra high frequency (UHF) band. The passive tags that have no other energy sources need to harvest energy from both the signal broadcasted by the H-AP and the carrier signal generated by the carrier emitter in the DL, and reflect the incident RF signal while performing binary FSK modulation by switching their own antenna load with different rates F_j for corresponding bits $j \in \{0,1\}$ in the UL. It is assumed that the H-AP, carrier emitter and tags are equipped with one single antenna each and operate by time-division multiple access (TDMA) over the same frequency band.

The DL channel from the H-AP to U_i is denoted by a complex random variable $\widetilde{h_i}$ with channel power gain $h_i = |\widetilde{h_i}|^2$. The UL channel from U_i to the H-AP, the channel from the carrier emitter to U_i and the channel from the carrier emitter to the H-AP are denoted by $\widetilde{g_i}$, $\widetilde{g_{i,c}}$, and $\widetilde{g_{A,c}}$ with channel power gain $g_i = |\widetilde{g_i}|^2$, $g_{i,c} = |\widetilde{g_{i,c}}|^2$ and $g_{A,c} = |\widetilde{g_{A,c}}|^2$, respectively. In the above channels, we assume that channel reciprocity holds for the DL and UL, and 30dB average signal power attenuation is at the reference distance of 1m with Rayleigh short-term fading. It is also assumed that the channels are quasi-static flat fading because of low-rate backscatter transmission (i.e., narrowband), and the channel power gains remain constant during one block transmission time, denoted by T, but appear independent in each block.

As shown in Fig. 2, we define a transmission protocol, backscatter based harvest-then-transmit, operating within T that consists of $\tau_i T$, $i = 0, 1, \cdots, K$. For convenience, we assume each block time $T = 1$ without loss of generality. The amount of time τ_0 is assigned to the DL for the H-AP to transfer wireless energy and the remaining time τ_i is assigned to the UL for each tag U_i to transmit independent information in a passive way. The carrier signal, transmitted from the carrier emitter operating continuously during one block time, can be used for RF energy harvesting and information transmission by the tags. Not only can U_i harvest energy from both the signal broadcasted by the H-AP and the carrier signal generated by the carrier emitter over τ_0, but also it can keep harvesting energy from the carrier wave

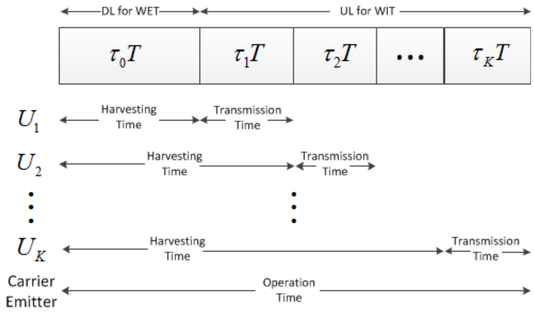

Fig. 2. Backscatter based harvest-then-transmit protocol.

continuously while other tags transmit information over $\tau_1, \tau_2, \cdots, \tau_{i-1}$ before its own transmission time τ_i. Also, the tags can reuse the same pair of sub-frequencies for FSK modulation to transmit information because the transmission protocol operates in dynamic TDMA.

In the backscatter based harvest-then-transmit protocol, it is assumed that the tags do not harvest energy after finishing their own information transmission. This is because our proposed backscatter protocol is based on the principle of the harvest-then-transmit one proposed in [2]. So, energy harvesting and information transmission for all tags are designed to start and end within one block time. We may attempt to harvest energy even after transmission, which is worth of further study to optimize the resource allocation.

Following the system model in [4], [7], the carrier emitter continuously sends a carrier wave of frequency F_{car} whose complex baseband is of the form

$$c(t) = \sqrt{2P_c}\, e^{-j(2\pi \triangle F t)} \tag{1}$$

where $\triangle F$ represents the frequency offset between the carrier emitter and the H-AP, and P_c denotes the carrier transmission power.

The tags perform the binary FSK modulation by switching their own antenna load between two distinct values, corresponding to reflection coefficients Γ_j with different rates F_j for bits $j \in \{0,1\}$. The baseband backscattered FSK waveform at U_i can be written as

$$b_{i,j}(t)=(A_s-\frac{\Gamma_0+\Gamma_1}{2})+\frac{\Gamma_0-\Gamma_1}{2}\frac{4}{\pi}cos(2\pi F_j t+\Phi_j) \quad (2)$$

where A_s represents a complex-valued term related to the antenna structural mode [8], [9], frequency and random initial phase are F_j and $\Phi_j \in [0,2\pi)$ for bits $j\in\{0,1\}$ [7]. Thus, $b_{i,j}(t)$ represents the fundamental frequency component of a 50% duty cycle waveform of amplitude 1.

The attenuated, modulated and reflected signal waveform is additionally attenuated by a scaling term $s(t)$ depending on the inherent scattering efficiency. The scattering efficiency is usually time varying owing to the use of rectifiers on the passive sensors, but for low-rate transmission (e.g., a block of a few bits) or the energy-assisted case, it can be considered constant [4]. Thus, $s(t)$ can be simplified to a constant value s, and the baseband scattered waveform at U_i can be expressed as

$$x_{B,i}(t)=s\,b_{i,j}(t)\sqrt{g_{i,c}}c(t),\ \ j\in\{0,1\}. \quad (3)$$

The H-AP receives the superposition of the carrier signal directly from the carrier emitter and the backscattered signal from U_i, and hence the received waveform is of the form

$$y_{B,i}(t)=\sqrt{g_{A,c}}c(t)+\sqrt{g_i}x_{B,i}(t)+n_{B,i}(t) \quad (4)$$

where $n_{B,i}(t)$ is a circularly symmetric complex Gaussian noise with mean 0 and variance σ_i^2.

Ⅲ. CHARACTERIZATION OF SNR OUTAGE ZONE

Due to the doubly near-far problem based on distance-dependent double attenuation in both the UL and DL in the active radio based WPCNs, near users to the H-AP can harvest more energy in the DL and use less energy to satisfy a target received signal power P_0 at the H-AP. On the other hand, far users harvest less energy in the DL but have to spend more energy to achieve the same P_0 at the H-AP.

As a result, the SNR outage zone where the received signal power at the H-AP is below a desired target level P_0 largely expands in the active radio based WPCNs. To get the SNR outage zone shrink, we propose a backscatter based WPCN where the tags can harvest energy not only from the signal broadcasted by the H-AP but also the carrier signal from the carrier emitter deployed close by the tag. The latter helps effectively overcome the double (round-trip) attenuation by detaching the energy source (i.e., carrier emitter) from the distant H-AP. After harvesting a sufficient energy, they can transmit information farther in a long range because of the low-power passive tag transmission based on reflection. To characterize the SNR outage zone, we define the coverage beyond which all tags experience the SNR outage for successful transmission. For the sake of clear comparison of coverage, we consider a single user/tag U_1 (i.e., $K=1$) in both the active radio and backscatter based WPCN.

3.1 Active radio based WPCNs

In the active radio based WPCNs introduced in [2], the H-AP transfers wireless energy to multiple users in the DL while the users with no other energy sources perform active transmission to the H-AP in the UL, using the harvested energy only. During the DL phase, the H-AP transmits a random signal x_A with transmit power $E[|x_A|^2]=P_A$. The signal received at U_1 can be represented as

$$y_1=\sqrt{h_1}x_A+n_1 \quad (5)$$

where y_1 and n_1 denote the received signal and noise at U_1, respectively. We assume that P_A is sufficiently large enough to ignore noise n_1 at U_1. Hence, the amount of energy harvested by U_1 in the DL can be represented as

$$E_1=\eta P_A h_1 \tau_0 \quad (6)$$

where η denotes the energy harvesting efficiency at U_1.

After harvesting energy in the DL, the user transmits its own information to the H-AP with the total harvested energy during the amount of time τ_1 in the UL. The average transmitted power from U_1 can be represented as

$$P_t = \frac{E_1}{\tau_1}. \quad (7)$$

The received signal from U_1 can be expressed as

$$y_{A,1} = \sqrt{g_1}\, x_1 + n_{A,1} \quad (8)$$

where x_1, $y_{A,1}$ and $n_{A,1}$ denote the transmitted signal from U_1, the received signal and noise at the H-AP, respectively. As the channel reciprocity is assumed for the DL and UL considering the TDD mode, the average received signal power at the H-AP is given by

$$P_{A,1} = \frac{\eta P_A h_1 g_1 \tau_0}{\tau_1} = \frac{\eta P_A \left(10^{-3}\rho_1^2\right)^2 \tau_0}{\tau_1} \times R_1^{-2\alpha} \quad (9)$$

where R_1 and ρ_1 denote the distance and Rayleigh short-term fading between the H-AP and U_1, respectively, α represents the path-loss exponent and 10^{-3} represents 30dB average signal power attenuation at the reference distance of 1m.

To characterize the SNR outage zone, the condition $P_{A,1} \geq P_0$ should be satisfied. The coverage, beyond which all users experience the SNR outage, determines the SNR outage zone. Hence, by equating $P_{A,1} = P_0$, the coverage R_o can be evaluated as

$$R_o = \left[\frac{\eta P_A \left(10^{-3}\rho_1^2\right)^2 \tau_0}{\tau_1 P_0}\right]^{\frac{1}{2\alpha}}. \quad (10)$$

3.2 Backscatter based WPCN

In the active radio based WPCNs, users can replenish energy from the RF signal in the DL and upload information via active transmission in the UL with the harvested energy. To the contrary, backscatter based WPCN is the passive network, in which tags can take advantage of the dislocated (i.e., avoiding the round-trip attenuation) carrier signal for information transmission on the principle of reflection. Although the tags in the backscatter based WPCN do not utilize the harvested energy for active transmission, they need sufficient energy enough to operate and maintain a low-power passive circuit (a single RF transistor switch [4]) for the reflection transmission. In particular, they can harvest energy from both the RF signal broadcasted by the H-AP and the carrier signal generated by the carrier emitter.

From [11], a batteryless backscatter sensor node can work continuously with RF energy harvesting for power density 0.1103$\mu W/cm^2$ or equivalently input power -18dBm at frequency 868MHz without using any boost converter. We can characterize an energy-free condition that a tag in the backscatter based WPCN has sufficient energy to work continuously during transmission time. For this, the total harvested energy should be greater than or equal to the energy required for the backscatter communication with RF energy harvesting by the tag. The harvested energy $E_{H,1}$ from the RF signal broadcasted by the H-AP and the carrier wave from the carrier emitter over τ_0 at U_1 is given by

$$E_{H,1} = \eta P_A h_1 \tau_0 + \eta P_c g_{1,c} \tau_0. \quad (11)$$

Thus, the energy-free condition for U_1 can be represented as

$$\begin{aligned} E_{H,1} &= \eta P_A h_1 \tau_0 + \eta P_c g_{1,c} \tau_0 \\ &= \eta P_A \left(10^{-3}\rho_1^2 R_1^{-\alpha}\right)\tau_0 + \eta P_c \left(10^{-3}\rho_{1,c}^2 d_{1,c}^{-\alpha}\right)\tau_0 \\ &\geq P_{th}\tau_1 \end{aligned} \quad (12)$$

where P_{th} is the required input power (for example, -18dBm), $\rho_{1,c}$ denotes Rayleigh short-term fading between U_1 and the carrier emitter, and $d_{1,c}$ represents the distance between U_1 and the carrier emitter. As shown in (12), both the distance between the carrier emitter and the tag and between the H-AP and the tag play an important role in determining the amount of harvested energy and the resulting energy-free feasibility. Thus, the energy-free condition can be fulfilled by properly deploying the carrier emitter near the tag as a key factor for RF energy harvesting. From now on, it is assumed that the energy-free condition can be satisfied.

To characterize the SNR outage zone in the backscatter based WPCN as depicted in Fig. 3, we need to derive the received signal waveform at the H-AP. By substituting (1) - (3) into (4), the received baseband signal waveform at the H-AP during a single bit $j \in \{0,1\}$ for U_1 can be represented as

$$\begin{aligned} y_{B1}(t) &= \sqrt{g_{A,c}}\,c(t) + \sqrt{g_1}\sqrt{g_{1,c}}\,s b_{1,j}(t) c(t) + n_{B1}(t) \\ &= \Bigg[\underbrace{\sqrt{2P_c}\left\{\sqrt{g_{A,c}} + \sqrt{g_1}\sqrt{g_{1,c}}\,s\left(A_s - \frac{\Gamma_0+\Gamma_1}{2}\right)\right\}}_{DC\,value} \\ &\quad + \sqrt{2P_c}\left\{\sqrt{g_1}\sqrt{g_{1,c}}\,s\frac{\Gamma_0-\Gamma_1}{2}\frac{4}{\pi}cos(2\pi F_j t+\Phi_j)\right\}\Bigg] \\ &\quad \times e^{-j2\pi\triangle Ft} + n_{B1}(t). \end{aligned} \quad (13)$$

Here we assume that the carrier frequency offset $\triangle F$ can be compensated at the H-AP sufficiently and the DC value, which does not convey any information on the bit, can be removed by estimation and elimination of the received signal's mean value $E\{y_{B,1}(t)\}$. Thus, the received signal at the H-AP can be represented as

$$\begin{aligned} y_{B,1}(t) = &\sqrt{2P_c}\left\{\sqrt{g_1}\sqrt{g_{1,c}}\,s\left(\frac{\Gamma_0-\Gamma_1}{2}\right)\frac{4}{\pi}cos(2\pi F_j t+\Phi_j)\right\} \\ &+ n_{B,1}(t). \end{aligned} \quad (14)$$

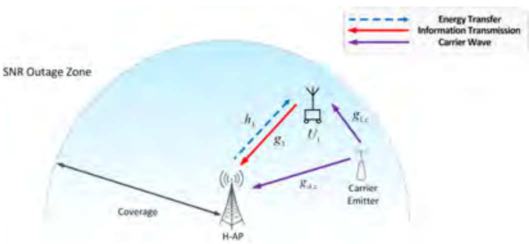

Fig. 3. SNR outage zone in a backscatter based wireless-powered communication network (WPCN).

The average received signal power at the H-AP can be derived as

$$\begin{aligned} P_{B,1} &= P_c g_1 g_{1,c} s^2 (\Gamma_0-\Gamma_1)^2 \left(\frac{2}{\pi}\right)^2 \\ &= P_c (10^{-3})^2 \rho_1^2 \rho_{1,c}^2 R_1^{-\alpha} d_{1,c}^{-\alpha} s^2 (\Gamma_0-\Gamma_1)^2 \left(\frac{2}{\pi}\right)^2. \end{aligned} \quad (15)$$

Since the condition $P_{B,1} \geq P_0$ is satisfied within the coverage, the coverage of the backscatter based WPCN can be determined from the SNR outage zone by equating $P_{B,1} = P_0$, for which the coverage R_o can be evaluated as

$$R_o = \left[\frac{P_c (10^{-3})^2 \rho_1^2 \rho_{1,c}^2 d_{1,c}^{-\alpha} s^2 (\Gamma_0-\Gamma_1)^2 \left(\frac{2}{\pi}\right)^2}{P_0}\right]^{\frac{1}{\alpha}}. \quad (16)$$

Ⅳ. SUM-THROUGHPUT MAXIMIZATION

In this section, we perform the sum-throughput maximization of multiple tags in the backscatter based WPCN, which consists of one H-AP and a backscatter cell that comprises a carrier emitter and multiple tags, with backscatter based harvest-then-transmit protocol. From (13) and (14), the received signal waveform without DC value, removed by the estimation and elimination of the received signal's mean value $E\{y_{B,i}(t)\}$ for U_i, can be represented as

$$\begin{aligned} y_{Bi}(t) = &\sqrt{2P_c}\left\{\sqrt{g_i}\sqrt{g_{i,c}}\,s\left(\frac{\Gamma_0-\Gamma_1}{2}\right)\frac{4}{\pi}cos(2\pi F_j t+\Phi_j)\right\} \\ &+ n_{Bi}(t). \end{aligned} \quad (17)$$

Thus, the achievable UL throughput of U_i at the H-AP can be evaluated as

$$\begin{aligned} R_{B,i} &= \tau_i \log_2\left(1 + \frac{P_c g_i g_{i,c} s^2 (\Gamma_0-\Gamma_1)^2 \left(\frac{2}{\pi}\right)^2}{\sigma_i^2}\right), \\ &= \tau_i \log_2\left(1 + \frac{P_{B,i}}{\sigma_i^2}\right), \\ &= w_i \tau_i. \end{aligned} \quad (18)$$

As shown in (18), the average received signal power $P_{B,i}$ at the H-AP is independent for both energy harvesting and information transmission time assigned to U_i, since the tag transmits its own information in a passive way via the reflection of the carrier signal, not in an active way. Accordingly, the term $\log_2(1+\frac{P_{B,i}}{\sigma_i^2})$, can be transformed simply to w_i which is the non-negative throughput weight for U_i.

From (18), the sum-throughput of all tags in the backscatter cell can be expressed by $R_{sum}(\tau)=\sum_{i=1}^{K} R_{B,i}(\tau)$. To perform an optimal time allocation for dynamic TDMA through the sum-throughput maximization, we solve the following optimization problem:

$$
\begin{aligned}
&\text{(P1)} \ \max_{\tau} \ R_{sum}(\tau) \\
&\text{s.t. Energy}-\text{free condition for } U_i,\ i=1,\cdots,K, \\
&\quad \textstyle\sum_{i=0}^{K} \tau_i \le 1, \\
&\quad \tau_i \ge 0,\ i=0,1,\cdots,K.
\end{aligned}
$$

Here, energy-free conditions ensure for all batteryless backscatter sensor nodes to work continuously with RF energy harvesting for power density 0.1103$\mu W/cm^2$ or equivalently input power -18dBm at frequency 868MHz without using any boost converter [11]. In other words, all tags in the backscatter based WPCN are required to have enough energy to work continuously during transmission time, which means that the total harvested energy should be greater than or equal to the energy required for the backscatter communication with RF energy harvesting by each individual tag. Thus, the energy-free condition for U_i can be represented as

$$
\begin{aligned}
E_{H,i} =& (\eta P_A h_i + \eta P_c g_{i,c})\tau_0 + (\eta P_c g_{i,c})\tau_1 + (\eta P_c g_{i,c})\tau_2 \\
&+ \cdots + (\eta P_c g_{i,c})\tau_{i-2} + (\eta P_c g_{i,c})\tau_{i-1} \\
&\ge P_{th}\tau_i.
\end{aligned}
\tag{19}
$$

As shown in (18), U_i can obtain sufficient energy to meet the energy-free condition by harvesting the required energy during $\tau_0, \tau_1, \cdots, \tau_{i-1}$, continuously, and then transmit its own information during τ_i using the backscatter based harvest-then-transmit protocol. With this optimal time allocation for all tags, their energy-free conditions can be fulfilled to achieve the maximum sum-throughput.

Accordingly, (P1) can equivalently be reformulated as

$$
\begin{aligned}
&\text{(P2)} \ \min_{\tau} -\sum_{i=i}^{K} w_i \tau_i \\
&\text{s.t.} -(\eta P_A h_1 + \eta P_c g_{1,c})\tau_0 + P_{th}\tau_1 \le 0, \\
&\quad -(\eta P_A h_2 + \eta P_c g_{2,c})\tau_0 - (\eta P_c g_{2,c})\tau_1 + P_{th}\tau_2 \le 0, \\
&\quad \vdots \\
&\quad -(\eta P_A h_K + \eta P_c g_{K,c})\tau_0 - (\eta P_c g_{K,c})\tau_1 - (\eta P_c g_{K,c})\tau_2 - \\
&\quad \cdots - (\eta P_c g_{K,c})\tau_{K-2} - (\eta P_c g_{K,c})\tau_{K-1} + P_{th}\tau_K \le 0, \\
&\quad \textstyle\sum_{i=0}^{K} \tau_i \le 1, \\
&\quad \tau_i \ge 0,\ i=0,1,\cdots,K.
\end{aligned}
$$

The optimal solution for (P2) can be derived without difficulty via Linear Programming [12].

Ⅴ. RESULTS

We first compare the coverage which determines the SNR outage zone in the backscatter based WPCN and demonstrate an effectiveness of the backscatter communication as an alternative way to overcome doubly near-far problem. We then determine the maximum sum-throughput in problem (P1) for backscatter based WPCN with harvest-then-transmit protocol.

For the evaluation we have assumed the following values of system parameters. The bandwidth is set to 1MHz. The average transmit power P_A at the H-AP is 25dBm. A carrier emitter is set to transmit a carrier signal of frequency 868MHz with $P_c = 13$ dBm. The sub-frequencies F_j corresponding to bits $j \in \{0,1\}$ for FSK modulation are 125KHz and 250KHz, respectively. The additive white Gaussian noise (AWGN) at both the H-AP and the tag receiver is assumed to have the one-sided power spectral density of -160dBm/Hz. The harvesting efficiency and path-loss exponent are set to $\eta = 0.5$ and $\alpha = 2.5$, respectively. The ratio τ_0

to τ_1 for the active radio based WPCN is assumed to be $\tau_0/\tau_1 = 2$. Without loss of generality, the reflection coefficients $\Gamma_0 = 1$ and $\Gamma_1 = -1$ are chosen from [4], and the antenna structural value A_s = 0.6047 + j0.5042 (realistic antenna value) is chosen from [8].

5.1 Coverage

Fig. 4 shows the coverage of the backscatter based WPCN for the desired SNR (dB) according to the different scattering efficiency s values when the distance between the tag and carrier emitter is 1m. It is observed that the coverage of the backscatter based WPCN is longer than that of the active radio based WPCN, which indicates that the SNR outage zone shrinks in the backscatter one compared to the active one. The coverage of the backscatter based WPCN, however, decreases drastically as the scattering efficiency decreases, due to the fact that the received signal power at the H-AP is considerably affected by the scattered signal power at the tag. It is worth noting that the scattering efficiency s is a critical key factor to determine the coverage and SNR outage zone of the backscatter based WPCN. With this prominent effect of the scattering efficiency, it is the prerequisite for implementation of the backscatter based WPCN to maximize the scattering efficiency.

Fig. 5 shows the coverage comparison for the desired SNR (dB) with different distance values

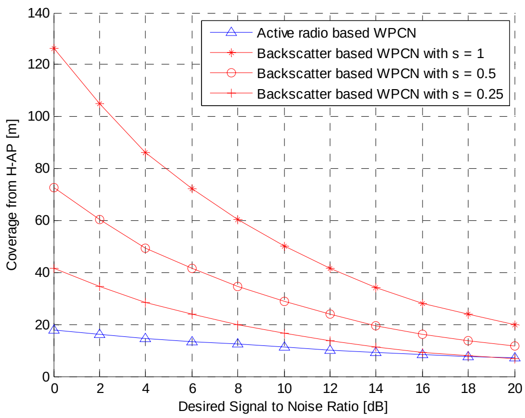

Fig. 4. Coverage versus desired SNR with different scattering efficiency.

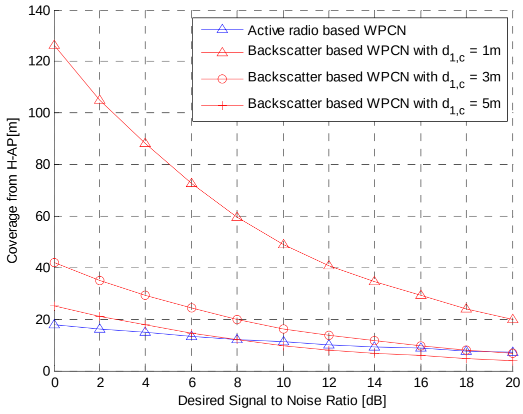

Fig. 5. Coverage versus desired SNR with different distance between the tag and carrier emitter.

between the tag and carrier emitter in the backscatter and active radio based WPCNs when the scattering efficiency is fixed to be 1. The coverage is observed to decrease rapidly with increased distance between the tag and carrier emitter. This is because as $d_{1,c}$ increases, the channel attenuation based on the path loss becomes larger, the carrier signal power reflected by the tag becomes smaller. Consequently the received signal power at the H-AP drops drastically.

We further observe that as the desired SNR (dB) increases, the coverage of the backscatter one becomes smaller than that of the active one at some point where $d_{1,c}$ is 5m. This is because the large distance-dependent path loss between the carrier emitter and tag results in serious degradation of the coverage of the backscatter one. As the tag in the backscatter one transmits its own information by the reflection of the carrier signal in a passive way, it is inevitable to get seriously influenced by the distance between the tag and the carrier emitter. Therefore, the significance of the deployment plan of the carrier emitter at an optimal location becomes more prominent. In future work, we will consider a deployment plan of the carrier emitter which is a crucial issue for implementation of the backscatter based WPCN.

5.2 Sum-Throughput Maximization

Fig. 6 shows the average throughput in the backscatter based WPCN versus distance between the H-AP and carrier emitter located in the center of the backscatter cell with different values of backscatter cell boundary R_B. The number of tags, scattering efficiency, and path-loss exponent are fixed to be $K=5$, $s=1$, and $\alpha=2.5$, respectively. It is observed that the maximum sum-throughput normalized by the number of tags, i.e., $R_{sum}(\tau)/K$, decreases as the distance between the H-AP and carrier emitter increases. This is because as the distance increases, the distance-dependent path loss becomes larger and the signal power received by the H-AP becomes smaller. Also, as shown in Fig. 6, the normalized sum-throughput is shown to decrease with increasing R_B, since the carrier signal power, reflected by the tags far from the carrier emitter, reduces and the received signal power at the H-AP can be smaller as a result.

Fig. 7 shows the average throughput comparison versus different values of the path-loss exponent α in the backscatter based WPCN for the distance between the carrier emitter and the H-AP, denoted by $d_{A,c}$. The number of tags, scattering efficiency, and backscatter cell boundary are set to be $K=5$, $s=1$, and $R_B=1$ m, respectively. We observe that the average sum-throughput decreases rapidly as α or $d_{A,c}$ increases. This is because as α or $d_{A,c}$ increases, the signal attenuation depending on the path loss becomes larger and the received signal power at the H-AP drops sharply.

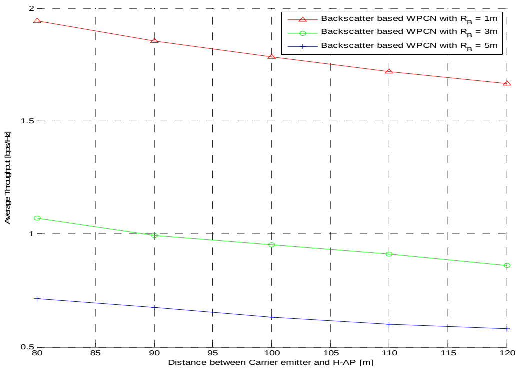

Fig. 6. Average throughput versus distance between the carrier emitter and H-AP with different backscatter cell boundary.

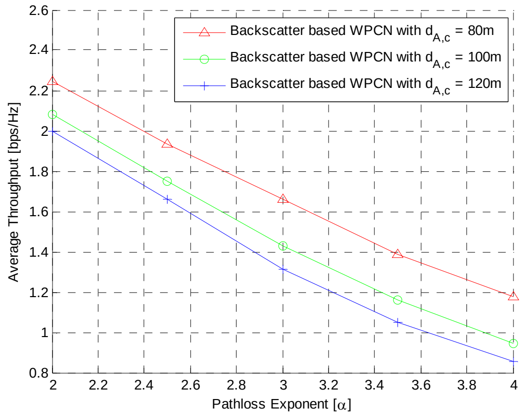

Fig. 7. Average throughput versus path-loss exponent with different distance between the carrier emitter and H-AP.

Ⅵ. CONCLUSION

We have presented the backscatter based WPCN in which a tag first harvests energy from both the RF signal broadcasted by the H-AP and the carrier signal transmitted by the carrier emitter in the DL, and then transmits its own information in a passive way by reflecting the carrier signal while performing binary FSK modulation in the UL. The distance coverage which determines the SNR outage zone has been derived by analysis.

Results demonstrated that the proposed backscatter based WPCN can achieve a long-range coverage, compared to the active radio based WPCN with short-range coverage due to the round-trip attenuation. This indicates that the SNR outage zone in the backscatter one becomes smaller than that in the active one. In other words, backscatter communication can be an effective alternative solution for WPCNs to resolve the problem of small coverage and wide SNR outage zone, seriously caused by the doubly near-far problem (also observed in conventional RFID).

Results also revealed the significance of the scattering efficiency that largely affects the scattered power at the tag and the deployment plan of the carrier emitter that can be utilized for both RF energy harvesting and information transmission. As a result, backscatter communication can be regarded as an important key design factor to pave the way for a promising low-cost, large-scale and dense ubiquitous WPCN in the near future.

Further, we have proposed a backscatter based harvest-then-transmit protocol for backscatter based WPCNs to maximize the sum-throughput. The proposed protocol fulfills energy-free condition for all tags through an optimum time allocation via dynamic TDMA. Consequently the achievable maximum sum-throughput for backscatter based WPCNs has been achieved by the backscatter based harvest-then-transmit protocol.

Future work will focus on a multi-cell structure backscatter based WPCN where a number of clusters locally separated, each containing a subset of tags/sensors around a carrier emitter, are being served by a single H-AP/reader (i.e., gateway). Multi-cell structure backscatter based WPCN can be implemented based on two fundamental principles, namely frequency division multiplexing (FDM) and time division multiplexing (TDM). Comparing the two types of multi-cell structure backscatter based WPCNs, i.e., FDM within backscatter cell and TDM across backscatter cells versus TDM within backscatter cell and FDM across backscatter cells, we will investigate which one yields a better performance.

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