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Backscatter Radio Communication for Wireless Powered Communication Networks

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***Abstract*—Backscatter radio communication has become a newly emerging technique for low-rate, low-power and large-scale wireless sensor networks. As this promising technology enables a long-range communication for sensors with low power in a distributed area, it is desirable to support wireless powered communication networks (WPCNs) that experience doubly near-far problem. In a backscatter radio based WPCN, users harvest energy from both the signal broadcast by the hybrid access point and the carrier signal transmitted by the carrier emitter in the downlink and 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 a backscatter radio based WPCN. Numerical results demonstrate that the backscatter radio based WPCN achieves an increased long-range coverage and a diminished SNR outage zone compared to the active radio based WPCNs.**

***Index Terms*—Backscatter radio communication, large-scale wireless sensor networks, energy harvesting, wireless powered communication networks, energy-free, SNR outage zone.**

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 costs, 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 encounter *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 doubly distance-dependent signal attenuation.

In order to overcome this doubly near-far problem, authors in [2] proposed common-throughput maximization scheme 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 radio 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 transmission. As backscatter radio 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 radio 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].

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 sources, 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 low-cost and low-power tag/sensor.

In this paper, we propose a backscatter radio based WPCN as an alternative approach to deal with the doubly near-far problem in the active radio based WPCNs. To this end, the

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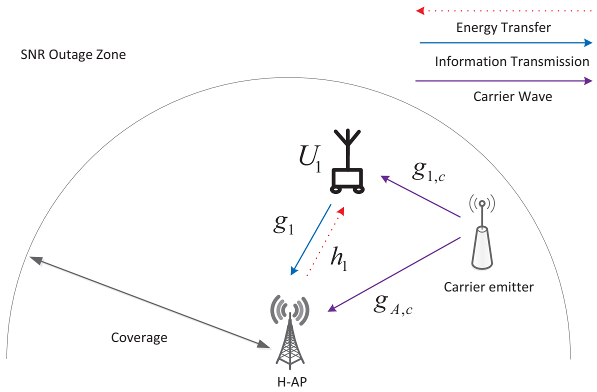

Fig. 1. A backscatter radio based wireless powered communication network (WPCN).

users, which have no other energy sources but depend only on the harvested energy for transmission, first harvest energy from the RF signal broadcast 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 radio 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.

The rest of this paper is organized as follows. Section II introduces the system model in a backscatter based WPCN. Section III characterizes both the energy-free condition and the SNR outage zone. Section IV 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. Finally, conclusion is drawn in Section V.

II. System Model

As shown in Fig.1, this paper considers a backscatter radio based WPCN which consists of one H-AP, a carrier emitter and a user (e.g., tag/sensor) denoted by U_1 with WET in the DL and WIT in the UL. The carrier emitter is deployed around the tag and transmits a carrier signal at the ultra high frequency (UHF) band. The passive tag that has no other energy sources needs to harvest energy from both the signal broadcast by the H-AP and the carrier signal generated by the carrier emitter in the DL, reflects the incident RF signal while performing binary FSK modulation by switching its antenna load with different rates F_i corresponding to information bits $i \in \{0, 1\}$ in the UL. It is assumed that the H-AP, the carrier emitter and the tag 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_1 is denoted by a complex random variable $\tilde{h}_1$ with channel power gain $h_1 = |\tilde{h}_1|^2$. The UL channel from U_1 to the H-AP, the channel from the carrier emitter to U_1 and the channel from the carrier emitter to the H-AP are denoted by $\tilde{g}_1$, $\tilde{g}_{1,c}$ and $\tilde{g}_{A,c}$ with channel power gain $g_1 = |\tilde{g}_1|^2$, $g_{1,c} = |\tilde{g}_{1,c}|^2$ and $g_{A,c} = |\tilde{g}_{A,c}|^2$, respectively. In the above channels, we assume that channel reciprocity holds for the DL and UL when time-division duplexing (TDD) is adopted, 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 radio transmission (i.e., narrowband), and the channel power gains remain constant during one block transmission time, denoted by T, but appear independent from block to block.

We define a transmission protocol operating within T that consists of $\tau_0 T$ and $\tau_1 T$. 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_1 is assigned to the UL for the tag to transmit information in the passive way. The carrier signal, transmitted from the carrier emitter operating continuously during one block time, can be used for RF energy harvesting over τ_0 and for information transmission over τ_1 by the tag.

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

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

where ΔF represents the frequency offset between the carrier emitter and the H-AP and P_c denotes the carrier transmission power.

The tag performs the binary FSK modulation by switching its antenna load between two distinct values, corresponding to reflection coefficients Γ_i with different rates F_i for bits $i \in \{0, 1\}$. The baseband backscattered FSK waveform at U_1 can be written as

$$b_i(t) = (A_s - \frac{\Gamma_0 + \Gamma_1}{2}) + \frac{\Gamma_0 - \Gamma_1}{2}\frac{4}{\pi}\cos(2\pi F_i t + \Phi_i) \tag{2}$$

where A_s represents a complex-valued term related to the antenna strucural mode [8], [9], frequency and random initial phase are F_i and $\Phi_i \in [0, 2\pi)$ for bits $i \in \{0, 1\}$ [7] repectively. Thus, $b_i(t)$ 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 can be expressed as

$$x_B(t) = sb_i(t)\sqrt{g_{1,c}}\,c(t),\ \ i \in \{0,1\}. \tag{3}$$

The H-AP receives the superposition of the carrier signal directly from the carrier emitter and the backscattered signal from U_1, and hence the received waveform is given by

$$y_B(t) = \sqrt{g_{A,c}}\,c(t) + \sqrt{g_1}\,x_B(t) + n_B(t) \tag{4}$$

where $n_B(t)$ a circularly symmetric complex Gaussian noise.

III. Characterization of SNR Outage Zone

Due to the doubly near-far problem based on distance-dependent signal 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 make the SNR outage zone shrink, we propose a backscatter radio based WPCN where the tags can harvest energy not only from the signal broadcast by the H-AP but also the carrier signal from the carrier emitter deployed close by the tag. The latter helps effectively overcome the doubly (round-trip) attenuation by dislocating 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 100% SNR outage for successful transmission.

A. 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 $\mathbb{E}[|x_A|^2] = P_A$. The signal received by U_1 can be represented as

$$y_1 = \sqrt{h_1}\,x_A + n_1 \tag{5}$$

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

$$E_1 = \eta P_A h_1 \tau_0 \tag{6}$$

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

$$P_t = \frac{E_1}{\tau_1}. \tag{7}$$

The received signal from U_1 can be expressed as

$$y_{A,1} = \sqrt{g_1}\,x_1 + n_{A,1} \tag{8}$$

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

$$\begin{aligned} P_{A,1} &= \frac{\eta P_A h_1 g_1 \tau_0}{\tau_1} \\ &= \frac{\eta P_A (10^{-3}{\rho_1}^2)^2 \tau_0}{\tau_1} \times {R_1}^{-2\alpha} \end{aligned} \tag{9}$$

where R_1 and ρ_1 denote the distance and Rayleigh short-term fading between the H-AP and U_1, respectively, and α represents the path-loss exponent.

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 represented as [10]

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

B. Backscatter radio 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 a backscatter radio based WPCN is the passive network, in which tags can take advantage of the *dislocated* (i.e., avoiding the doubly round-trip attenuation) carrier signal for information transmission on the principle of reflection. Although the tags in the backscatter radio 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 broadcast 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 radio based WPCN is required to have enough 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 radio communication with RF energy harvesting by the tag.

The harvested energy E_H from the RF signal broadcast by the H-AP and the carrier wave from the carrier emitter over τ_0 by U_1 is given by

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

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

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

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 radio based WPCN, we need to derive the received signal waveform at the H-AP. By substituting (1) - (3) in (4), the received baseband signal waveform at the H-AP during a single bit $i \in \{0, 1\}$ can be represented as

$$\begin{aligned} y_B(t) &= \sqrt{g_{A,c}}\, c(t) + \sqrt{g_1}\sqrt{g_{1,c}}\, s b_i(t) c(t) + n_B(t) \\ &= \Bigg[\underbrace{\sqrt{2P_c}\left\{ \sqrt{g_{A,c}} + \sqrt{g_1}\sqrt{g_{1,c}}\, s (A_s - \frac{\Gamma_0 + \Gamma_1}{2}) \right\}}_{DCvalue} \\ &\quad + \sqrt{2P_c}\left\{ \sqrt{g_1}\sqrt{g_{1,c}}\, s \frac{\Gamma_0 - \Gamma_1}{2} \frac{4}{\pi} \cos(2\pi F_i t + \Phi_i) \right\} \Bigg] \\ &\quad \times e^{-j2\pi \Delta F t} + n_B(t). \end{aligned} \quad (13)$$

Here we assume that the carrier frequency offset ΔF 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 $\mathbb{E}\{y_B(t)\}$ without loss of generality. Thus, the received signal at the H-AP can be rewritten as

$$\begin{aligned} y_B(t) = &\sqrt{2P_c}\left\{ \sqrt{g_1}\sqrt{g_{1,c}}\, s (\frac{\Gamma_0 - \Gamma_1}{2}) \frac{4}{\pi} \cos(2\pi F_i t + \Phi_i) \right\} \\ &+ n_B(t). \end{aligned} \quad (14)$$

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

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

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

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

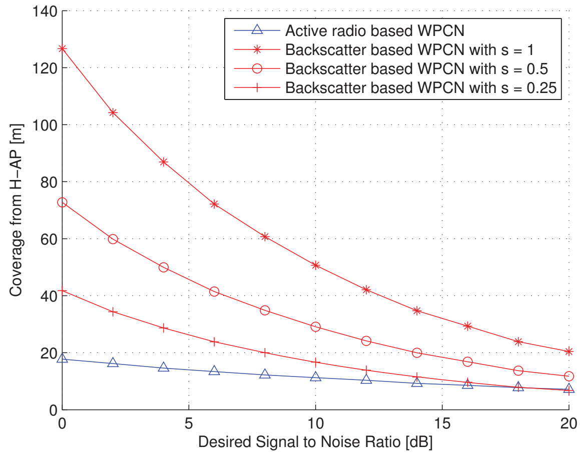

Fig. 2. Coverage versus desired SNR with different scattering efficiency.

IV. Results

In this section, we compare the coverage which determines the SNR outage zone in the backscatter radio based WPCN versus in the active radio based WPCN. 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 = 13dBm. The sub-frequencies F_i corresponding to bits $i \in \{0, 1\}$ for FSK modulation are 125KHz and 250KHz, repectively. 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, path-loss exponent and the ratio τ_0 to τ_1 are set to η = 0.5, α = 2.5 and $\frac{\tau_0}{\tau_1}$ = 2, respectivly. Without loss of generality, the reflection coefficients Γ_0 = 1 and Γ_1 = -1 are chosen from [4], and the antenna structural value A_s = 0.6047 + j0.5042 (realistic antenna value) is chosen from [8].

Fig. 2 shows the coverage of the backscatter radio based WPCN for the desired SNR (dB) according to the different scattering efficiency s values when the distance between the tag and the carrier emitter is 1m. It is observed that the coverage of the backscatter radio 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 radio based WPCN, however, decreases sharply 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

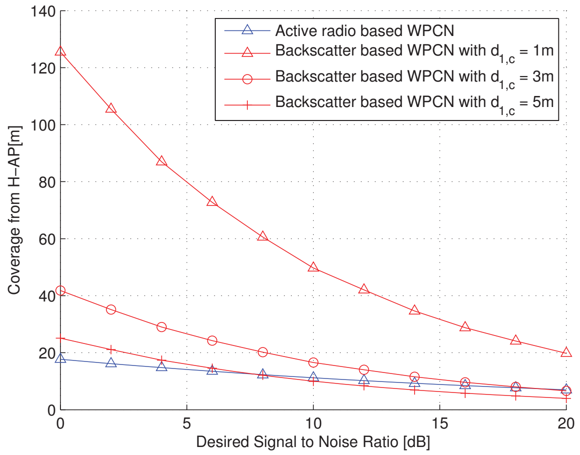

Fig. 3. Coverage versus desired SNR with different distance between the tag and the carrier emitter.

outage zone of the backscatter radio based WPCN. With this prominent effect of the scattering efficiency, it is the prerequisite for implementation of the backscatter radio based WPCN to maximize the scattering efficiency.

Fig. 3 shows the coverage comparison for the desired SNR (dB) with different distance values between the tag and the carrier emitter in the backscatter radio based WPCN and the active radio based WPCN when the scattering efficiency is fixed to be 1. The coverage is observed to decrease rapidly with increased distance between the tag and the 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.

In Fig. 3, 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 the 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. It is worth noticing that the significance of the deployment plan of the carrier emitter at optimal location becomes more prominent. In the future work, we will consider the deployment plan of the carrier emitter which is a crucial factor for implementation of the backscatter radio based WPCN.

V. Conclusion

We have presented the backscatter radio based WPCN in which a tag first harvests energy from both the RF signal broadcast 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 through TDMA. The distance coverage which determines the SNR outage zone has been derived by analysis.

Results demonstrated that the proposed backscatter radio based WPCN can achieve a long-range coverage, compared to the active radio based WPCN with a short-range coverage due to the doubly 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 radio communication can be an effective alternative solution for WPCNs to resolve the problem of short 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 radio 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. Future work will focus on a multi-cell structure backscatter radio 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).

Acknowledgment

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