Comparison on Uplink Transmission Protocols for Two-User Wireless Powered Communication Network

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Abstract: Limited battery lifetime is a major consideration of wireless communication network systems. Wireless power transfer (WPT) is the emerging solution for the limited battery lifetime problem. Wireless powered communication network (WPCN) is one application of the WPT technology where devices are powered wirelessly by hybrid access point (H-AP) and transmit information to H-AP. In this paper, we adopt discrete time switching (DTS) protocol for two-user WPCN system. We propose two different uplink transmission protocols and present the performance comparisons of them.

Keywords—**WPCN, DTS, uplink protocol**

1. Introduction

In conventional wireless communication network systems, devices were usually powered by battery which has limited lifetime. These devices have to recharge or replace their battery to maintain the communication. It may be inconvenient (for distributed sensor network of large area), dangerous (in toxic environment) or even impossible (for body implanted sensors) [1]. Wireless power transfer (WPT) is the emerging technology which can solve the battery lifetime problem with reliable and stable energy support to devices.

Radio frequency (RF) signal which was considered as an information container in conventional wireless communication systems, contains energy since it is a wave. WPT technology exploits this natural and obvious characteristic. In other words, RF signal can be considered as information container or energy container at the same time. Wireless powered communication network (WPCN) is one application of the WPT technology composed of hybrid access point (H-AP) and users. In WPCN the H-AP transfers energy to users through downlink channel and users transmit information to the H-AP through uplink channel [2]. There are many research issues for WPCN including time allocation and power control [2–6], beamforming [7, 8], scheduling [9], etc..

In this paper, we focus on time allocation protocol for downlink and uplink. We adopt discrete time switching (DTS) protocol which is proposed in [10]. In [10] there is only one user in the system model. We consider the WPCN with DTS protocol which has two users rather than single user. When DTS protocol meets multi-user environment couple of things are changed from [10]. The most important change is the uplink transmission protocol. Since [10] has single user, the system considers only one user's condition (e.g. battery state, receive filter) for uplink transmission. However, in multi-user system, action of one user affects the other. So the modification on uplink transmission protocol is required. In this paper we propose two uplink transmission protocols and compare each other and compare to single-user system.

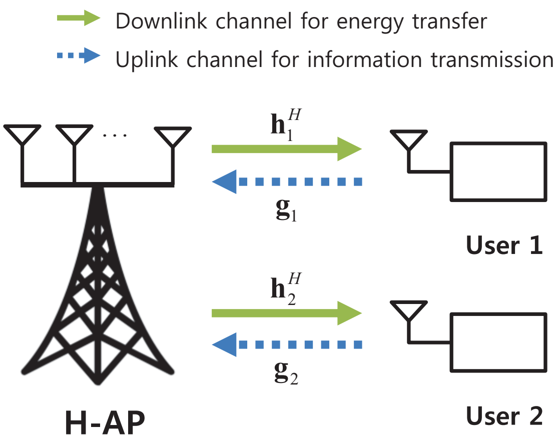


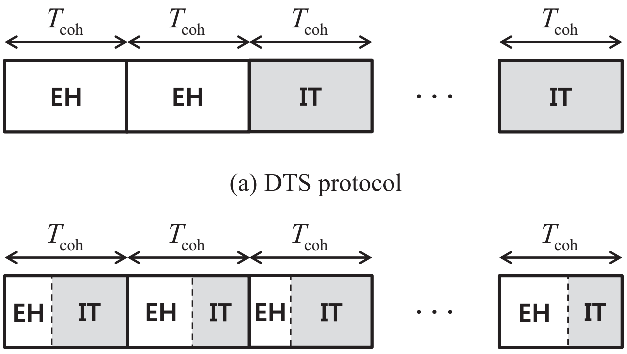
Figure 1. WPCN system model with two users.

Details of a system model is presented in Section 2 and proposed protocols for two-user WPCN are described in Section 3. After introducing the system model and proposed protocols we present simulation results for proposed protocols in Section 4. Future works are described in Section 5 and Section 6 concludes the paper.

2. System Model

In this paper, we consider a WPCN system with one H-AP and two users. Fig. 1 depicts the system model of paper. H-AP has $N > 1$ antennas and is connected to a power supply. Each user is equipped with single antenna and has a battery with finite capacity C. Both H-AP and user operate in half duplex. In WPCN system H-AP transfers energy to users, users harvest and store the transferred energy and transmit information using only harvested energy.

Channels between H-AP and user are assumed to be block fading channels, which has a constant channel gain during each coherence time block with length of T and changes independently from one block to the other time block. In this paper, we adopt discrete time switching (DTS) protocol instead of harvest-then-transmit (HTT) protocol. Fig. 2 shows the DTS protocol and the HTT protocol [10]. In the DTS, signals are transmitted to only one way, downlink or uplink, in each coherence time block. On the other hand in the HTT protocol, energy transfer through downlink and information



(a) DTS protocol

(b) HTT protocol

Figure 2. Time slot allocation of (a) DTS protocol and (b) HTT protocol, EH: energy harvesting, IT: information transmission.

transmission through uplink occur within one coherence time block. Especially we consider users have target throughput R, so users store energy until stored energy in battery is sufficient to achieve target throughput. Channel state information (CSI) for downlink and uplink channel are assumed to be known to both H-AP and user. And users do not know each other's channel state information.

As described in Fig. 1, $\mathbf{H}^H \in \mathbb{C}^{N\times 2}$ denotes downlink channel and $\mathbf{G} \in \mathbb{C}^{N\times 2}$ denotes uplink channel. Here, $(\cdot)^H$ represents a Hermitian, or conjugate transpose. The elements of downlink channel $\mathbf{H} = [\mathbf{h}_1^H \ \mathbf{h}_2^H]^H$ are assumed to be independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variable with zero-mean and variance of γ where $\mathbf{h}_k^H \in \mathbb{C}^{N\times 1}$ is a downlink channel between H-AP and user k. The elements of uplink channel $\mathbf{G} = [\mathbf{g}_1 \ \mathbf{g}_2]$ have same distribution to the downlink channel where $\mathbf{g}_k \in \mathbb{C}^{N\times 1}$ is a uplink channel between H-AP and user k. P denotes transmit power of the H-AP and the variance of additive white Gaussian (AWGN) noise is denoted by N_0.

On downlink channel H-AP transfers energy to users and dominant eigenmode transmission is known to be the optimal strategy for maximizing the sum harvested energy [11]. The harvested energy of user k can be described as

$$\begin{aligned} E_{\mathrm{H},k} &= \eta|y_k|^2 \\ &= \eta|\sqrt{P}\mathbf{h}_k\mathbf{w}s + n_k|^2, \end{aligned} \tag{1}$$

where η $(0 \leq \eta \leq 1)$ denotes radio frequency (RF) to direct current (DC) conversion efficiency, n_k is a AWGN and $\mathbf{w}$ is a beamforming vector of the H-AP. As we mentioned above, dominant eigenmode transmission is the optimal beamforming, so beamforming vector $\mathbf{w} = \mathbf{v}_1$ can be obtained from singular value decomposition (SVD) of the channel $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$ where $\mathbf{V} = [\mathbf{v}_1 \ \cdots \ \mathbf{v}_N]$, $\mathbf{v}_k = \in \mathbb{C}^{N\times 1}$.

Meanwhile in uplink channel users transmit information to the H-AP with stored energy. Users have target throughput R and users transmit information when the amount of stored energy is judged to be sufficient to achieve R. In this paper we compare two different uplink transmission protocols. Two protocols will be described in next section.

3. Uplink Transmission Protocols for DTS-WPCN

In WPCN users transmit information using the harvested energy. Users have target throughput R, they calculate the amount of energy required to achieve R at each time slot. If the amount of stored energy is larger than the amount of required energy, user is said to be *ready* for transmission. Since users do not have information about each other's channel, they calculate the required energy by using own channel state information. The required energy for user k $E_{\mathrm{T},k}$ is derived from

$$\log_2\left(1 + \frac{E_{\mathrm{T},k}||\mathbf{g}_k||^2}{N_0}\right) = R, \tag{2}$$

which can be manipulated into

$$E_{\mathrm{T},k} = \frac{(2^R - 1)N_0}{||\mathbf{g}_k||^2}. \tag{3}$$

Since the H-AP transfers energy to users using dominant eigenmode transmission, the amount of received energy of users are different. And the required energy $E_{\mathrm{T},k}$ differs according to each user's uplink channel gain. Because of these reasons, users may not be *ready* at the same time for every time slot. So the simple protocol that user transmit information when the battery state is *ready*, should be reconsidered. Followings are candidates for uplink transmission protocol.

3.1 Wait until all charged (WUAC) protocol

The first protocol we suggest is wait-until-all-charged (WUAC) protocol. In the WUAC protocol two users transmit information simultaneously when all users are sufficiently charged. If one of the users has insufficient energy, all users do not transmit information and continue harvesting energy until all users are *ready* to transmit information. When all users are *ready*, users transmit information simultaneously and the H-AP receives transmitted signals using zero-forcing (ZF) receiver to ensure inter-user interference (IUI) free transmission. Since users calculate required energy $E_{T,k}$ assuming that the H-AP uses MRC, so the target throughput R can be achieved when the H-AP uses MRC. But in WAUC the H-AP uses ZF receiver so the throughput of user k R_k would be

$$R_k = \log_2\left(1 + \frac{E_{\mathrm{T},k}}{N_0||\mathbf{g}_k^{\mathrm{inv}}||^2}\right), \tag{4}$$

where $\mathbf{G}^\dagger = [\mathbf{g}_1^{\mathrm{inv}} \ \mathbf{g}_2^{\mathrm{inv}}]^T$, $\mathbf{g}_k^{\mathrm{inv}} \in \mathbb{C}^{N\times 1}$ is the pseudo-inverse of the uplink channel G. The superscript T represents the transpose. (4) shows that uplink throughput may differ from R when the ZF receiver is used.

3.2 First charged first transmit (FCFT) protocol

The second protocol we propose is first-charged-first-transmit (FCFT) protocol. In the FCFT protocol user concerns only

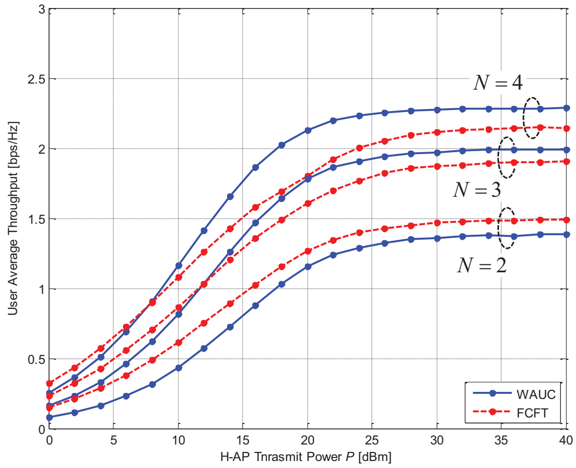


Figure 3. User average throughput of two proposed protocols versus H-AP transmit power for number of H-AP antennas $N = [2, 3, 4]$ with target throughput $R = 3$.

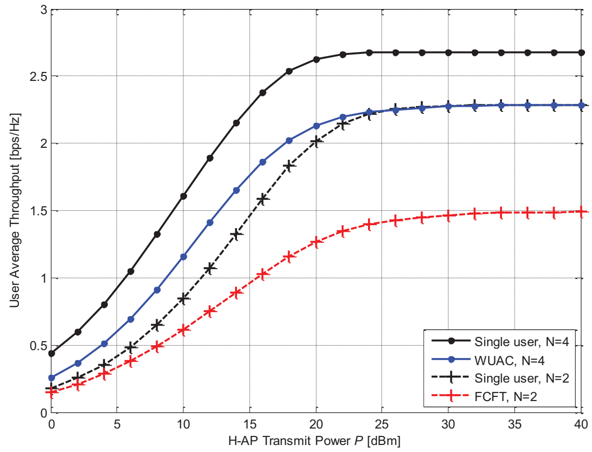


Figure 4. User average throughput of proposed protocols for two-user WPCN and single-user WPCN versus H-AP transmit power for number of H-AP antennas $N = [2, 4]$ with target throughput $R = 3$.

its own battery state. Once one's stored energy is sufficient, the user transmits information immediately instead of waiting another one's battery being charged. If all users are sufficiently charged, all users transmit information simultaneously like the WUAC protocol. Since the H-AP and users operate in half duplex, one user cannot neither harvests energy nor transmits information while the other user transmits information. In other words, the FCFT protocol has empty time slots for one user in certain case. In the FCFT protocol user's throughput would be R when only one user transmit information and would be (4) same to the WUAC when two users transmit information simultaneously.

4. Simulation Results

In this section we present simulation results for two proposed protocols WUAC and FCFT. And we also illustrate the performance comparison between two-user WPCN and single-user WPCN. Throughout simulations we adopt a path loss model of $\gamma = 10^{-3}d^{-\alpha}$ where d is the distance between the H-AP and users, and α is the path loss exponent [10]. We assume distances from the H-AP to all users are same as $d = 10$m, the path loss exponent $\alpha = 2$, RF to DC inefficiency $\eta = 0.5$, the noise power $N_0 = -90$dBm, coherence time $T = 1$ and the battery capacity $C = 2 \times 10^{-6}$.

At first, we compare the WUAC protocol and the FCFT protocol. Fig. 3 shows the user average throughput of two proposed protocols versus H-AP transmit power for three different number of H-AP antennas. Result shows that the user average throughput of the FCFT protocol outperforms the WUAC protocol when $N = 2$ for all P interval and $N > 2$ for low P interval. This can be explained in two reasons. First, the number of chances to transmit information. At small N condition, required energy E_{T} is relatively high. (3) shows that small number of H-AP antennas makes channel norm smaller and makes E_{T} higher. Combined with limited battery capacity this leads to the conclusion that small N condition has less chances of information transmission. Users need energy harvesting more frequently because battery runs out fast with high E_{T} so the number of chances to transmit information decrease. And at low P condition, in other words small $E_{\mathrm{H},k}$ condition, battery state is not always sufficient so the number of chances to transmit is dominant for the same reason in small N condition (frequent energy harvesting requirement). The second reason is the average throughput of the users in one time slot. When only one user transmit information in the FCFT protocol, transmitting user achieves R and the other's throughput is 0, so the average throughput of time slot is $R/2$. On the other hand, average throughput of ZF receiver becomes larger than $R/2$ when N grows larger. Note that in Fig. 3 the average throughput of the WUAC is higher than $R/2 = 1.5$ when $N = [3, 4]$. If N is large or P is high, equivalent to infrequent energy harvesting requirement, the second reason becomes dominant for user average throughput.

Secondly we compare the average throughput of two-user WPCN and single-user WPCN with DTS protocol. For comparison we take the superior protocol for two-user WPCN according to the number of H-AP antennas N. As we mentioned and can be seen from Figure 3, we take the FCFT protocol for $N = 2$ and take the WUAC protocol for $N = 4$. Note that the average throughput of two-user WPCN system is double of the user average throughput since there are two users in system. It is clear that Fig. 4 shows the user average throughput degrades in two-user WPCN compared to one-user WPCN. This degradation is natural since the presence of other user prevents transmission (WUAC's waiting principle) or makes inter-user interference (simultaneous transmission) or makes empty time slots (FCFT's empty time slot). However, the sum throughput of users or the system throughput of two-user WPCN is much higher than single-user WPCN. Because sum harvested energy of users increases as the number of users increases while H-AP radiates same power to its cover area.

5. Future Works

Future works for this research are various. At first, mathematical analysis on the system should be done. In this paper we present the numerical result and analysis of the system. Studies for sophisticated mathematical analysis is required. Secondly, expansion into multi-user WPCN (i.e. $K > 2$ users) is required. We observed that just adding one more user to single-user WPCN causes additional protocol and change in performance. This motivates us to expand the system model into multi-user WPCN system. Thirdly, adoption of full-duplex communication may cause whole different system and lots of analysis points.

6. Conclusion

In two-user WPCN with DTS protocol, user uplink transmission should be well organized. Average of two users' instantaneous throughput and the number of chances to transmit are two main factors that determine the performance. If one user transmits information in the FCFT, average of two users throughput always be $R/2$. Simultaneous transmission with ZF receiver has higher average throughput than $R/2$ when N gets larger. Average throughput of one transmission time slot is dominant factor when battery is sufficient. However when battery is insufficient, the number of chances to transmit becomes dominant. Fig. 3 shows the performance of the FCFT outperforms the WUAC when P is high or N is small. Mathematical analysis and expansion into multi-user WPCN should be studied further.

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