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WiFi and Wireless Power Transfer Live Together

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***Abstract*—Power Beacons (PBs) can transfer energy wirelessly to devices in a Wireless Powered Communication Network (WPCN). When PBs are deployed in an IEEE 802.11 Wireless LAN (WLAN), the energy transfer of PBs may interfere with the WiFi stations if WiFi stations and PBs share the same frequency band. In this letter, to resolve this interference problem, we propose a new Medium Access Control (MAC) protocol for IEEE 802.11 WiFi stations to efficiently coexist with PBs. PBs contend just as WiFi stations to gain opportunity for transferring energy and determine its operation based on the average energy level of stations. It is demonstrated that the throughput of the proposed MAC protocol is superior to that of IEEE 802.11 WLAN without interference control.**

***Index Terms*—wireless power transfer, IEEE 802.11 WLAN, interference control, medium access control, energy harvesting**

I. Introduction

Recently, energy harvesting technologies have been drawing much interest to easily harvest energy and prolong the lifetime of mobile stations. In a Wireless Powered Communication Network (WPCN), stations may harvest energy from Radio Frequency (RF) signals transmitted by Power Beacons (PBs) [1]. The development of wireless PBs in industry is actively under way [2], [3]. PBs are expected to be deployed in the homes, offices, and public places, so that users conveniently charge tablet PCs and mobile phones while enjoying WiFi communications. In [4], sensors contend and request energy to RF energy harvesters based on their energy states. Then, the best spectrum to harvest energy is selected by observing the spectrum pulses of RF energy harvesters. RF energy harvesters are grouped together to avoid destructive interference of energy waves when transferring energy.

Some PBs transmit RF signals in the 5.86GHz band [5], which is also used by WiFi stations due to the shortage of wireless frequency resource. If PBs are deployed in an IEEE 802.11 WLAN, the RF energy signals from PBs can severely interfere with WiFi signals from WiFi stations or an Access Point (AP). So, without coordination or interference control of PBs, wireless powering of PBs could negatively impact WiFi data communications and possibly collapse a network. In order to prevent such a phenomenon, an appropriate interference control mechanism of PBs for WiFi stations in a WLAN is required. To our best knowledge there have not been researches on the coexistence of PBs and WiFi stations.

In this letter, we propose a novel WiFi and Wireless Power Transfer - Medium Access Control (W^{2}P-MAC) protocol to control the interference due to PBs in a WLAN. In our proposed mechanism, PBs with WiFi modules actively participate in Distributed Coordination Function (DCF) contention to transfer energy with newly defined Energy Request To Send (ERTS) and Energy Clear To Send (ECTS) frames. With this process, PBs will not interfere with data transmissions of WiFi stations. Moreover, based on the average energy level of WiFi stations, the number of operating PBs can be adaptively determined for efficient channel usage. Then, the PBs perform energy transfer when the stations need energy. We develop Markov chain models to reflect the varying number of active PBs, and evaluate the performance of the proposed W^{2}P-MAC protocol.

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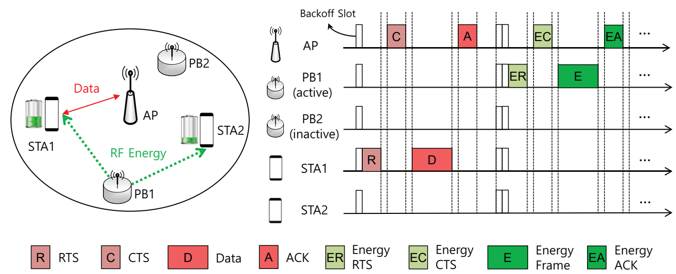

Fig. 1. The proposed W^{2}P-MAC protocol for coordinated access of PBs and WiFi stations.

II. Proposed W^{2}P-MAC Protocol

In this section, we propose a novel W^{2}P-MAC protocol for PBs to safely coexist with IEEE 802.11 WiFi stations without interference. We consider a network composed of a WiFi AP, WiFi stations, and PBs equipped with WiFi modules. WiFi stations are equipped with RF energy harvesting modules to harvest energy from PBs.

Since PBs and WiFi stations share the same channel, it is desirable for PBs to be active when they only need to do so, not to harm data communications of WiFi stations. In our W^{2}P-MAC protocol, stations can feedback the information on their energy levels to the AP by sending it in data frames. The AP can collect the information from stations and compute the average energy level to notify it to PBs, possibly in a beacon frame. PBs then utilize the average energy level to activate or inactivate themselves for RF energy transmission with the probability $p_{act,PB}$. For example, in Fig. 1, only PB1 decides to participate in the contention using the probability of $p_{act,PB}$.[1] PB2 remains silent to yield data transmission opportunities to WiFi stations. As the number of actively contending PBs can be controlled, the increase of delay of WiFi stations will be little.

[1]To determine whether a PB is active or not, it only needs to draw a random number and compare it with $p_{act,PB}$ obtained from the AP. So, the complexity of PB operation will not be high, causing little overhead.

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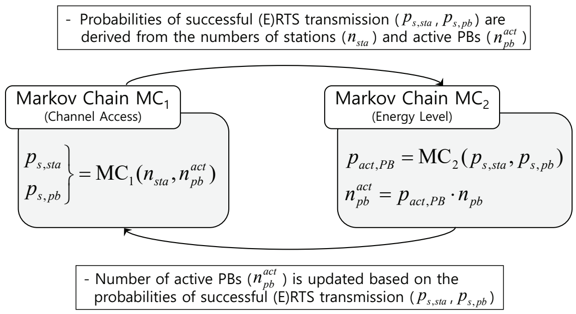

Fig. 2. The proposed conjugated Markov chains to model the WLAN with varying number of active PBs.

Algorithm 1 Operation of PBs in W^{2}P-MAC Protocol

Obtain $p_{act,PB}$ from AP
Draw random value r in $(0, 1)$
if $r < p_{act,PB}$ **then**
  Become active and select a backoff counter
  Decrement backoff counter when channel is idle until backoff counter = 0
  Send ERTS frame to AP
  if ECTS frame received from AP **then**
    Transfer energy to stations
  else
    Increase CW and retry ERTS/ECTS process until the maximum retry limit
  end if
else
  Become inactive
end if

An active PB selects a random backoff counter value in the range from 0 to w_i for the transmission of RF energy signal, where w_i is the size of the Contention Window (CW) at the i-th backoff stage. Whenever a slot is sensed idle, it decrements the value of the backoff counter. When the backoff counter value of a PB becomes zero, it transmits ERTS to the AP to reserve the channel for RF energy transmission. All the stations with energy harvesting capability listening to ERTS change the mode from the data reception mode to the energy reception mode.

Following the Short Interframe Space (SIFS), the AP receiving ERTS from a PB broadcasts ECTS to the PB and to the other stations. Then the PB now transmits the RF energy signal to the stations by broadcasting wireless RF energy to the stations, or possibly to some specific stations by beamforming. The AP then broadcasts the Energy Acknowledgment (EACK) frame to inform the end of the RF energy signal transmission of the PB. All the stations in the network can know the interval of wireless RF energy transfer of the PB through the Network Allocation Vector (NAV) in the ERTS and the ECTS frames. Since the proposed ERTS/ECTS handshake mechanism of PBs stems from the the IEEE 802.11 DCF, the complexity will not be high.

In Fig. 1, PB1 wins and transmits ERTS. Following ECTS allows PB1 transfers RF signal to the WiFi stations 1 and 2. The process ends with the EACK frame of the AP. The operation of PBs in W^{2}P-MAC is indicated in Algorithm 1.

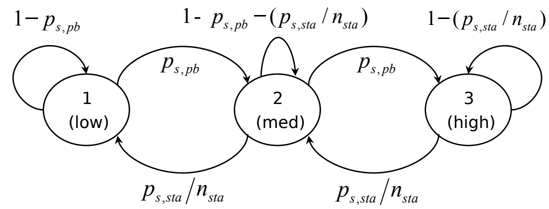

Fig. 3. The proposed Markov chain to model the energy level of stations and determine the number of active PBs.

III. Performance Analysis

In this section, we present the analysis of the proposed W^{2}P-MAC protocol. The network consists of an AP, n_{sta} WiFi stations, and n_{pb} PBs. The overall analysis model is indicated in Fig. 2 as *conjugated* Markov chains, i.e., Markov chain 1 (MC$_1$) and Markov chain 2 (MC$_2$). The channel activities of WiFi stations and PBs are modeled in MC$_1$ for numbers of stations and active PBs. Then, using the result of MC$_1$, the energy level transition of a station is modeled in MC$_2$. In MC$_2$, the probabilities of energy levels are determined and the active probability of PBs ($p_{act,PB}$) is calculated. Using the active probability, the number of active PBs (n_{pb}^{act}) is evaluated as in Fig. 2.

A. Markov Chain for Data/Energy Contention (MC$_1$)

We utilize a Markov chain to model the backoff counter value and the backoff stage in a slot time [6] of a station or a PB. Let $b_{k,l}$ be the steady state distribution of the backoff stage k and the backoff counter value l. The probability that a station or an active PB transmits a data frame or an energy signal (frame) at a time slot can be calculated by

$$p_t = \sum_{k=0}^{R} b_{k,0}, \tag{1}$$

where R is the retransmission limit. The probability that a channel is sensed busy in a slot is given by

$$p_{busy} = 1 - (1 - p_t)^n, \tag{2}$$

where $n = n_{sta} + n_{pb}^{act}$.

The probabilities of successful ERTS/RTS transmission of a WiFi station or an active PB are calculated as

$$p_{s,sta} = n_{sta} p_t (1 - p_t)^{n-1}, \tag{3}$$
$$p_{s,pb} = n_{pb}^{act} p_t (1 - p_t)^{n-1}. \tag{4}$$

The probability of collision in a slot by at least two WiFi stations/active PBs is written as,

$$p_{coll} = 1 - (1 - p_t)^n - n p_t (1 - p_t)^{n-1}. \tag{5}$$

B. Markov chain for energy level distribution (MC_2)

To appropriately control the activity of PBs, the energy level distribution of stations can be modeled. In order to derive the energy level distribution of WiFi stations, we design a new discrete-time Markov chain (see Fig. 3). The state of a Markov chain denotes the energy level (1 (low), 2 (medium) or 3 (high)) of a station after the successful transmission of a station or a PB. We use the success probability $p_{s,sta}$ of WiFi stations and the success probability $p_{s,pb}$ of PBs to derive the steady state energy level distribution π_1, π_2, and π_3 of stations.

It is assumed that if a PB succeeds in contention, RF energy is transfered to the stations so that the energy level of a station increases by one level, e.g., low→med or med→high. If a station succeeds in contention, energy is consumed for data transmission so that the energy level of a station decreases by one level. Then the state transition probability $P_{j,k}$ from level j to level k $(j, k \in \{1\,(\text{low}), 2\,(\text{medium}), 3\,(\text{high})\})$ can be derived as

$$P_{1,1} = 1 - p_{s,pb}, \tag{6}$$

$$P_{1,2} = P_{2,3} = p_{s,pb}, \tag{7}$$

$$P_{2,2} = 1 - p_{s,pb} - \frac{p_{s,sta}}{n_{sta}}, \tag{8}$$

$$P_{2,1} = P_{3,2} \frac{p_{s,sta}}{n_{sta}}, \tag{9}$$

$$P_{3,3} = 1 - \frac{p_{s,sta}}{n_{sta}}. \tag{10}$$

The steady state energy level distribution $\vec{\pi} = [\pi_1\ \pi_2\ \pi_3]$ of WiFi stations can be derived from balance equations and $\vec{\pi}\mathbf{P} = \vec{\pi}$, $\mathbf{P} = [P_{j,k}]$.

$$\pi_l = \frac{c_l}{\left(1 + n_{sta}\frac{p_{s,pb}}{p_{s,sta}} + \left(n_{sta}\frac{p_{s,pb}}{p_{s,sta}}\right)^2\right)}, \quad l = 1, 2, 3 \tag{11}$$

where $c_1 = 1$, $c_2 = n_{sta}\frac{p_{s,pb}}{p_{s,sta}}$, and $c_3 = \left(n_{sta}\frac{p_{s,pb}}{p_{s,sta}}\right)^2$. If PBs become active when the average energy level of stations is low or medium, the number of active PBs now becomes

$$n_{pb}^{act} = n_{pb} \cdot p_{act,PB} = n_{pb} \cdot (\pi_1 + \pi_2). \tag{12}$$

With the number of active PBs in Eq. (12), the contention probabilities $p_{s,sta}$, $p_{s,pb}$, and p_{coll} are newly computed by Eqs. (3), (4), and (5). Then new $\vec{\pi}$ is computed by Eqs. (6)-(11) to update n_{pb}^{act} again. This process repeats until they converge as described in Fig. 2.

C. Throughput Analysis of the Proposed W^{2}P-MAC

Now we compute the throughput of WiFi stations. In the case of the (E)RTS/(E)CTS access method, the channel occupation time of a WiFi station and that of a PB when the transmission is successful can be computed as

$$\begin{aligned} T_{s,sta}^{R/C} &= T_{RTS} + 3 \cdot T_{SIFS} + 4 \cdot T_{PROP} + T_{CTS} \\ &\quad + T_H + T_{DATA} + T_{ACK} + T_{DIFS}, \\ T_{s,pb}^{ER/EC} &= T_{ERTS} + 3 \cdot T_{SIFS} + 4 \cdot T_{PROP} + T_{ECTS} \\ &\quad + T_{EH} + T_{ENERGY} + T_{EACK} + T_{DIFS}, \end{aligned} \tag{13}$$

TABLE I
PARAMETERS FOR SIMULATION

Parameter	Value	Parameter	Value
Frame payload	8184 bits	Data rate	1 Mbps
(E)RTS frame	288 bits	SIFS (T_{SIFS})	28 μs
(E)CTS frame	240 bits	DIFS (T_{DIFS})	128 μs
(E)ACK frame	240 bits	Timeout (T_{OUT})	300 μs
Slot time (σ)	50 μs	Minimum CW (w_0)	31
Propagation delay	1 μs	Max. backoff stage (m)	3

where T_{RTS}, T_{CTS}, T_H, T_{DATA}, and T_{ACK} are the transmission times of the RTS, CTS, data frame header, data frame, and ACK frame exchanged between a station and the AP. T_{SIFS}, T_{PROP}, and T_{DIFS} are the time intervals of SIFS, DCF Interframe Space (DIFS), and the propagation delay, respectively. T_{ERTS}, T_{ECTS}, T_{EH}, T_{ENERGY}, and T_{EACK} are the transmission times of the ERTS, ECTS, energy frame header, energy frame, and EACK frame for the RF energy transfer of PBs. In the case of collision, the average channel occupation time of stations or PBs

$$T_c^{(E)R/(E)C} = T_{(E)RTS} + T_{PROP} + T_{OUT} + T_{DIFS}, \tag{14}$$

where T_{OUT} is the timeout duration. In the W^{2}P-MAC protocol, the sizes and the frame formats of (E)RTS are the same, so the channel occupation times are equal when a collision of stations or PBs occur.

In the case of the basic access method, the overall channel occupation times

$$\begin{aligned} T_{s,sta}^B &= T_H + T_{DATA} + T_{SIFS} + T_{PROP} + T_{ACK} \\ &\quad + T_{PROP} + T_{DIFS}, \\ T_{s,pb}^B &= T_{EH} + T_{ENERGY} + T_{SIFS} + T_{PROP} + T_{EACK} \\ &\quad + T_{PROP} + T_{DIFS}, \\ T_c^B &= T_{(E)H} + T_{DATA/ENERGY} + T_{PROP} \\ &\quad + T_{OUT} + T_{DIFS}. \end{aligned} \tag{15}$$

The network throughput S_{prop} with the W^{2}P-MAC protocol is given in Eq. (16), where σ, D are the slot interval, and the size of the payload, respectively.

$$S_{prop} = \frac{p_{s,sta}D}{(1 - p_{busy})\sigma + p_{s,sta}T_{s,sta} + p_{s,pb}T_{s,pb} + p_{coll}T_c}. \tag{16}$$

D. Throughput Analysis of the IEEE 802.11

We present an analysis model for the case without interference control of PBs to compare performance of the proposed W^{2}P-MAC protocol with that of the IEEE 802.11 without interference control. In the IEEE 802.11, PBs randomly transmit RF energy signals without coordinating with WiFi data communications. Thus, data frames transmitted by stations may collide with randomly transmitted RF energy signals by PBs. Thus, overall network performance is likely to deteriorate by the irregular and uncontrolled energy transfer of PBs.

It is assumed that PBs transmit energy signals by a Poisson process with the rate of λ. Then, if PBs transmit energy signals during T_s ($T_s = T_{s,sta}^{R/C}$ or $T_s = T_{s,sta}^B$ by the type of access), the data transmission of a station fails by interference. Then, the throughput S_{conv} without interference control of PBs can be derived as follows.

$$S_{conv} = \frac{p_{s,sta} f_0 D}{(1-p_{busy})\sigma + p_{s,sta}T_s + p_{coll}T_c}, \quad (17)$$

where $p_{s,sta}$ and p_{coll} are given in Eqs. (3) and (5) in which $n_{pb} = 0$. And f_0 is the probability that PBs do not transmit energy signals during the data transmission time T_s, where

$$f_k = \frac{(\lambda T_s)^k e^{-\lambda T_s}}{k!}. \quad (18)$$

IV. Performance Evaluation

In this section, we verify the analysis of the proposed W^{2}P-MAC protocol by simulations. We assume that the stations are randomly deployed in a network within the coverage of the AP and the PBs. It is assumed that there are always data frames to send in the stations. We consider an initial contention window size w_0 of 31 and the maximum backoff stage m of 3. In the scheme without interference control of PBs, λ=50 arrivals/sec for both the RTS/CTS and the basic access methods. The simulation parameters are represented in Table I. We compare the throughput of the proposed MAC protocol with that of the IEEE 802.11, which lacks interference control of PBs.

Fig. 4 shows the throughputs of the IEEE 802.11 without interference control and the proposed W^{2}P-MAC protocol with fixed n_{pb} (1 or 5) and without energy level information of stations. The simulation and analysis results are shown to be well matched for both the proposed W^{2}P-MAC protocol and the IEEE 802.11 with no interference control. The throughputs of the W^{2}P-MAC protocol are superior to those of the case without interference control of PBs. By coordinating PBs to participate in the DCF contention with the WiFi stations, the interference induced by energy transfer is reduced. The throughput of the W^{2}P-MAC protocol with a single PB ($n_{pb} = 1$) is larger than that of the W^{2}P-MAC protocol with multiple PBs ($n_{pb} = 5$) due to different total numbers of stations and PBs participating in the DCF contention. Without the energy level information of stations, the PBs may occupy channel even when the WiFi stations do not need energy.

Fig. 5 represents the throughputs of the proposed W^{2}P-MAC protocol with and without energy level information of stations. The throughput of the proposed W^{2}P-MAC protocol with energy level information of stations is superior to that without energy level information. Since the frequency of channel access of PBs is controlled by adjusting the number of active PBs, the throughput degradation is minimized. In case without energy level information, all the PBs participate in the DCF contention for transmission of RF energy signals. Thus, the throughput of the protocol is reduced compared with the W^{2}P-MAC with energy level information.

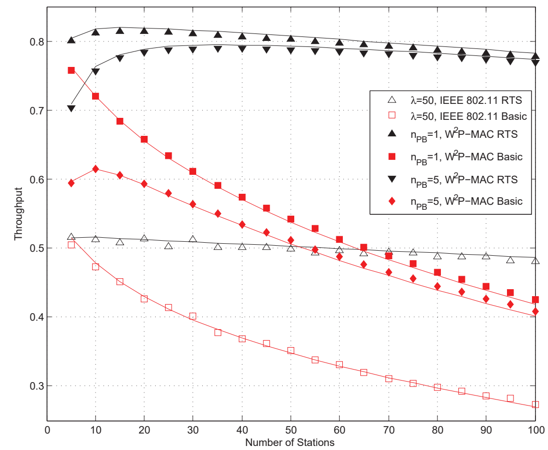

Fig. 4. Throughputs of the proposed W^{2}P-MAC protocol and the IEEE 802.11 with no interference control for varying number of stations (solid line: analysis).

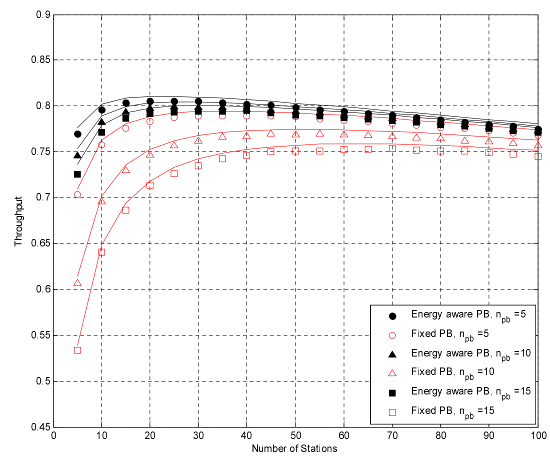

Fig. 5. Throughputs of the proposed W^{2}P-MAC protocol with and without energy level information of WiFi stations (solid line: analysis).

V. Conclusion

In this letter, we have proposed a new W^{2}P-MAC protocol to prevent the interference of RF energy transfer to IEEE 802.11 WiFi stations. The proposed MAC protocol enables coordinated use of PBs for wireless RF energy transfer and the existing WiFi stations for data exchange in the same frequency band. We have presented an analytical model on the throughput performance using Markov chains. We verify that the performance of the W^{2}P-MAC protocol with controlled PBs is superior to that of the IEEE 802.11 WiFi protocol with PBs without interference control.

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