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RESEARCH ARTICLE

# Markov-Chain Based Performance Analysis and Evaluation of Harvest-Then-Access Scheduling for Wireless Powered Communication Network

**ATSUHIRO IWAKI, (Member, IEEE), KOSUKE SANADA, (Member, IEEE), HIROYUKI HATANO, (Member, IEEE), AND KAZUO MORI, (Member, IEEE)**

Department of Electrical and Electronic Engineering, Mie University, Tsu, Mie 514-8507, Japan

Corresponding author: Kosuke Sanada (k.sanada@elec.mie-u.ac.jp)

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**ABSTRACT** Wireless powered communication network (WPCN) is a novel structure of the network that integrates wireless information communication (WIT) and wireless energy transfer(WET). The scheduling design is a key factor for performance improvement for WPCN. As an effective scheduling design approach, ‘‘Harvest-then-Access’’ has been proposed. This approach requires optimizing control parameters in the scheduling. Therefore, some approaches, such as machine learning or simulation, have been used. This paper proposes a Markov-chain model-based analytical model of Harvest-then-Access scheduling for WPCN. We propose a new Markov-chain model, which includes the essential operation in WPCN with Harvest-then-Access. From the analytical model, we derive the optimal time interval of WET in the network with Harvest-then-Access, which simultaneously provides throughput improvement and fairness among devices. The validity of the proposed analytical model is demonstrated by comparing the analytical and simulation result. Then, we evaluate the performance of Harvest-then-Access scheduling through comparison to the other scheduling.

**INDEX TERMS** Wireless powered communication network (WPCN), wireless energy transfer (WET), queuing theory, Markov-chain model, energy queuing model.

## I. INTRODUCTION

Wireless energy transfer (WET) technology, in which wireless devices harvest power energy from radio frequency (RF) signal, has attracted attention because this technique contributes to prolonging network life time [1], [2]. The wireless powered communication network(WPCN) is a novel network structure where wireless information transmission (WIT) and wireless energy transfer (WET) are integrated [3]. In WPCN, a hybrid access point (HAP) supplies the energy to STAs through WET, and STAs harvest this energy to transmit a packet to the HAP. Achieving better performance in WPCN requires the appropriate protocol design that considers WET and WIT operations in the network. The resource allocation for WET and WIT is one of the critical factors in the protocol design of WPCN. Considering WET and WIT operate under a time division duplex (TDD) manner, the excess time allocation to WET leads to throughput degradation due to the lack of opportunities for WIT, and vice versa. From the above explanation, this paper focuses on the scheduling methods in WPCN.

The scheduling methods for WPCN are mainly classified into centralized and decentralized approaches. In the centralized approach, the HAP manages all of the WET and WIT opportunities in the network. This means that the HAP controls time resources for not only energy-supplying opportunities but also information communication ones. Although this approach provides better performance, significant communication overhead between HAP and STAs is required, especially for a network with massive STAs. In the distributed approach, on the other hand, each STA achieves its WET and WIT opportunities following a random access (RA)

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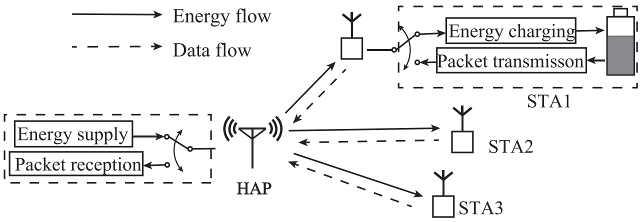


**FIGURE 1.** An example of a WPCN.

policy. Although this approach does not require communication overhead, it may cause ineffective energy-supplying efficiency in the network [4]. Taking into account the above characteristics in both approaches, a hybrid approach named "Harvest-then-Access" scheduling has been proposed in [5], [6], and [7]. The Harvest-then-Access employs a frame structure in which a HAP supplies energy to STAs at the begging of the frame, then STAs access the channel for WIT under RA policy until the end of the frame. This means WET in Harvest-then-Access is performed with a constant time interval. An appropriate time interval of WET in Harvest-then-Access provides effective WET opportunities, leading the network-throughput improvement. Harvest-then-Access is expected to provide high performance because this method supports the demerits for each approach. However, it is challenging to derive the optimal time interval for WPCN with Harvest-then-Access.

One of the solutions for the above problem is to establish an analytical model for WPCN with Harvest-then-Access, then derive the optimal parameter from the model. An effective analytical model of WPCN with distributed scheduling has been proposed, named as "energy queuing model [8]." The model uses queuing theory to represent the recharging/consuming operation of the residual energy in STA's battery. This enables us to mathematically consider the transition of battery residual which is an essential behavior of WPCN. However, the energy queuing model cannot be applied to the performance analysis of WPCN with Harvest-then-Access. Because the energy queuing model is based on M/M/1 queueing model, the model cannot consider a HAP-initiated WET in the frame structure of Harvest-then-Access, which does not follow the Poisson-arrival process. For establishing the analytical model, a novel energy-queueing model that considers the characteristic operation in Harvest-then-Access is required.

This paper proposes a Markov chain based analytical model of Harvest-then-Access scheduling for WPCN. To consider transitions of STA-residual energy in the battery in Harvest-then-Access, we propose a new Markov-chain model, which includes the energy queuing and the HAP-initiated WET with a fixed time interval. We derive the appropriate time interval for WET in the network with Harvest-then-Access, which provides performance improvement of the network. The validity of the proposed analytical model is demonstrated through the comparison with the simulation results. Then, we evaluate the performance of Harvest-then-Access scheduling through the comparison to distributed scheduling.

## II. RELATED WORKS

### A. WIRELESS POWERED COMMUNICATION NETWORKS (WPCN)

Figure 1 shows a simple example of WPCN. As shown in Figure 1, WPCN consists of a HAP and several STAs. The HAP supplies the energy to the STAs through WET, and the STAs harvest this energy to transmit information. WET and WIT are desired to operate in the same frequency band to achieve higher spectrum efficiency and cost-effectiveness. Following this policy, the conventional works regarding the protocol design in WPCN often assume that HAP and STAs operate by switching the WET and WIT under TDD manner [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. Therefore, the protocol for WPCN should be designed under the consideration of both WIT and WET operations.

As another essential concern on the design of WPCN, we explain the "double-near-far problem" [7], [9], [10]. The STAs far from the HAP can harvest less energy than the STAs nearby the HAP due to distance-dependent signal attenuation of RF signal. In addition, the STAs far from the HAP need to consume more energy than the STAs nearby HAP in order to transmit information with the same data rate as near-STAs. Namely, the STAs far from HAP harvest poor energy from HAP; nevertheless, they need more energy for information transmission. This causes unfair throughput among STAs in WPCN. A straightforward solution to this problem is frequently supplying energy with high power to avoid the battery depletion of the STAs far from HAP. However, this may cause excess WET, leading to degradation of WIT performance due to the TDD manner in WPCN. In this sense, the scheduling design, which affects not only throughput but also fairness performance among network nodes, is a critical factor for WPCN.

### B. THE SCHEDULING FOR WPCNs

Various scheduling methods have been proposed [8], [9], [10], [11], [12], [13], [14]. These are classified into two types: centralized scheduling and distributed scheduling. In the centralized approach, the HAP manages all of the WET and WIT opportunities in the network. This means that the HAP controls time resources for not only energy-supplying opportunities but also information communication ones. Reference [9] has proposed "Harvest-then-transmit" scheduling in which a round-robin-based frame structure consists of the duration for WET prior to the duration for WIT. HAP allocates WET and WIT for STAs to each time resource in a frame by referencing channel state information(CSI) between HAP and each STA. Moreover, [9] has proposed time allocation methods to obtain maximum throughput while taking into account the fairness among STAs. By extending the method in [9], [11] has proposed the scheduling for WPCN with beamforming WET technology. Reference [12] has proposed the scheduling for WPCN with harvesting from WET and other ambient energy sources. As a common operation of these methods, a round-robin-based frame structure is considered for centralized scheduling since the time allocation of each STA contributes to throughput improvement. To achieve high throughput based on such scheduling methods, it is necessary for a HAP to control the time allocation optimally according to STAs-communication requirements. For that, the communication overhead to get CSI and time synchronization between HAP and STAs is required. Considering the network with massive STAs, such overheads may cause system performance degradation.

On the other hand, [8], [14], [15], [16], [17], [18] have proposed the scheduling methods based on the distributed approach. In distributed scheduling, WIT and WET operate following a RA policy such as CSMA and ALOHA. The HAP performs WET by responding to a request from STAs [8], [14], [15], [16]. In [15], the radio frequency medium access control (RF-MAC) has been proposed as a distributed scheduling for WPCN. This paper is the first one which provides the distributed scheduling approach concept. As a common operation of distributed scheduling, STAs send a request signal or frame to trigger to serve the WET to HAP. Reference [8] has proposed a distributed scheduling-based protocol integrating WET and WIT following *p*-persistent CSMA. In this scheduling, STAs whose battery becomes empty send an energy request buzz (ERB) signal to recharge the battery. The WET operation is performed in response to the ERB signal. This means that the triggering of WET in the network depends on the residual power energy of the STAs. Reference [14] has proposed two distributed MAC access protocols that are similar to [8]. The distributed scheduling methods are robust to residual power depletion. On the other hand, to achieve fair throughput performance among network nodes, HAP attempts to supply enough energy to the STAs far from the HAP. This causes excess WET in networks because such WET is unnecessary for the STAs near the HAP.

Distribute scheduling without WET requests has been proposed in [17], named the Harvest-or-Access protocol. This method applies the slotted ALOHA access protocol for WIT. The HAP judges that the current RA slot is idle if no incoming signal is detected for a predetermined time from the beginning of each access slot. If the current access slot is recognized as idle, the HAP immediately performs WET during the remainder of the idle slot. Because all of the idle slots are used for WET, it reduces time-resource waste. However, this method may result in inefficient use of power in the network.

From the above discussions, appropriate WET controlling under distributed scheduling may improve system performance. Thus, the system integrating centralized WET with distributed WIT has been proposed [4], [5], [6], [7], which are called as "Harvest-then-Access." Harvest-then-Access has a frame structure consisting of WET prior to the RA of WIT.

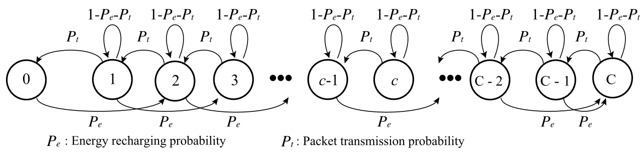


**FIGURE 2. The energy queuing model in [8].**

The HAP controls the WET by adjusting frame size or the ratio of WET duration in one frame. Reference [5] has proposed the Harvest-then-Access scheduling in which a RA duration with a fixed-size slot based on slotted ALOHA is preceded by the WET duration. In [5], the appropriate frame size is obtained from a machine-learning approach. Reference [4] applies the enhanced distributed coordination function (EDCF) MAC protocol to a Harvest-then-Access-based protocol. Reference [6] has proposed controlling the ratio of WET duration to fixed length frame and channel access probability of each STA to obtain high fairness throughput in the network with Harvest-then-Access. Reference [7] has proposed controlling the number of packets transmitted by STAs in one frame for achieving a higher throughput in the entire network under Harvest-then-Access scheduling. From the latest research on WPCN scheduling, the Harvest-then-access-based approach is expected to improve network performance effectively. However, the Harvest-then-access-based approach requires the optimal control of WET duration in a frame for achieving performance improvement.

### C. ANALYTICAL MODELS FOR WPCN: ENERGY QUEUING MODEL

Several models for the performance analysis of WPCN have been proposed [4], [17], [18], [19]. In [9], [11], and [12], for centralized scheduling, the throughput of each STAs is formulated as a function of time for WET and WIT of each STA. The analytical expression derives optimal parameter settings which provide maximum throughput and fairness. References [9], [11], and [12] analyzes the throughput by the ratio of time for WET and WIT of each STA under the assumption that the energy supplied by HAP is consumed certainly in allocated WIT time. Because it is assumed that the STA exhausts the energy harvested at the beginning of the frame within this frame, this model cannot consider the detailed residual energy states.

Considering surplus energy in the battery at each STA, [8] has proposed the analytical model named "Energy queuing model." Figure 2 shows an example of an energy queuing model. In the energy queuing model, the residual energy is considered discretely. In Figure 2, state $c$ represents the STA having $c$ units of energy in its battery. The leftward transition represents the energy consumption due to WIT, and the rightward transition represents the energy recharging due to WET. In the case of Figure 2, STAs recharge 2 units of energy in probability

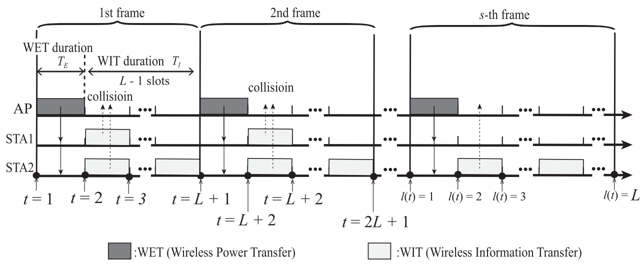


**FIGURE 3.** Frame structure of the Harvest-then-Access scheduling with the channel access example.

$P_e$ and STAs consume 1 unit of energy in probability $P_t$. Because queueing model enables consideration of state transition due to consumption/recharging, the energy queuing model effectively considers the essential behavior of STAs in WPCN.

### D. PERFORMANCE ANALYSIS FOR WPCN WITH HARVEST-THEN-ACCESS

Several mathematical analysis methods for WPCN with Harvest-then-Access have been proposed in [6] and [7]. Reference [6] derives the WET duration, which provides enough WET and high throughput, under the assumption that the battery capacity of STAs is infinite. On the other hand, [7] assumes that the STAs store only energy for one packet transmission. However, [6], [7] don't consider the recharging/consumption operation of residual energy due to WET and WIT in distributed WIT as [8] and [20].

As mentioned above, the conventional works of performance analysis for WPCN with Harvest-then-Access cannot handle energy-state transition due to consumption/recharging. For the detailed evaluation and optimization of Harvest-then-Access, it is necessary to establish an analytical model which enables handling the energy-state transition due to consumption/recharging under the operation of Harvest-then-Access in WPCN.

## III. SYSTEM MODEL AND ASSUMPTIONS

### A. NETWORK MODEL

As Figure 1, this paper considers a single-cell WPCN consisting of 1 HAP and $N$ STAs.

### B. FRAME STRUCTURE AND CHANNEL ACCESS MODEL: HARVEST-THEN-ACCESS

WET and WIT are performed over the same frequency band, so STAs perform energy harvesting and information communication in a TDD manner.

Figure 3 shows the frame structure of the Harvest-then-Access scheduling considered in this paper. In Fig. 3, the frame structure consists of $L$ slots. We define the 1st slot in each frame as "WET duration" and from the 2nd slot to $L$-th slot in each frame as "WIT duration." At the 1st slot, HAP supplies energy to all STAs during $T_E$ sec. In the remaining $L-1$ slots, the STAs access the channel to transmit a data packet following slotted ALOHA. Therefore, the HAP performs WET every constant time interval of $T_E+(L-1)\sigma$, where $\sigma$ is a duration of a system slot.

### C. TRAFFIC MODEL

The STAs generate packets following a Poisson arrival process with the packet-arrival probability of an arbitrary slot, which is denoted as $\lambda$. Only uplink traffic flows are considered; thus the destination of the generated packets is the HAP. The transmission duration for sending a packet is the same as the duration of a slot.

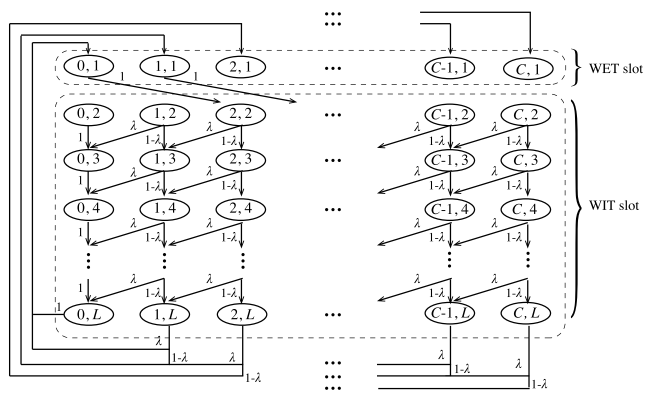


**FIGURE 4.** Two-dimensional discrete Markov-chain model for Harvet-then-Access.

### D. BATTERY MODEL

Similar to [8], each STA has its own battery in which its battery residual is expressed as a discrete number. It is defined that the battery capacity is the natural number $C$, and 1 unit of energy is $1/C$ of the battery capacity.

### E. CHANNEL MODEL

Channel condition is ideal for evaluating MAC-layer performance for the proposed scheduling. Therefore, transmission failure due to PHY-layer is not considered. That is, only transmission failures due to signal collision occur.

## IV. MARKOV-CHAIN BASED PERFORMANCE ANALYSIS FOR HARVEST-THEN-ACCESS

This section proposes a mathematical analysis model for WPCN with Harvest-then-Access scheduling. As shown in Figure 3, the HAP supplies energy at every constant time interval. This means the battery recovery operation for each STA definitely occurs every constant time interval. In WIT duration, on the other hand, each STA transmits a packet probabilistically at each slot. Because the HAP does not supply energy in WIT duration, each node never recovers energy. This means each STA consumes its energy following the Poisson process in the WIT duration. Considering the above characteristics of the Harvest-then-Access protocol, this paper proposes the two-dimensional discrete Markov-chain model with energy queueing.

### A. MARKOV-CHAIN MODEL WITH ENERGY QUEUEING IN THE HARVEST-THEN-ACCESS

Figure 4 shows the Markov-chain model with energy queueing in the Harvest-then-Access. In the following explanation, time $t$ is defined as the beginning of the $t$-th slot, including WET duration as Figure 3. $t = sL + 1$, $(s \geq 0, s \in \mathbb{Z})$ means the begging of the WET slot, and $t = sL + 2$ means the begging of the first WIT slot for each frame. Each state in Figure 4 is defined as $(c, l)$, where $c \in \{0, \cdots, C\}$ is a stochastic process which represents $c$ units of energy stored STA's battery, and $l \in \{1, \cdots, L\}$ is a stochastic process which represents that $l$ slots have passed from the begging of a frame. As shown in Figure 4, state $(c, 1)$ for $0 \leq c \leq C$ means the state where the HAP supplies energy at the WET slot. In addition, state $(c, l)$ for $0 \leq c \leq C$ and $2 \leq l \leq L$ means the state where arbitrary slots of WIT slots in a frame. In the Markov-chain model, the one-step transition probability is denoted as $p_{(i_1,j_1),(i_0,j_0)} = \Pr\{c(t+1) = i_1, l(t+1) = j_1) \,|\, (c(t) = i_0, l(t) = j_0)\}$. The transition matrix in the Markov-chain model is characterized as $(C+1)L \times (C+1)L$ sized matrix as follows:

$$\mathbf{P} = \begin{pmatrix} p_{(0,0),(0,0)} & \cdots & p_{(0,0),(C,L)} \\ p_{(1,0),(0,0)} & \cdots & p_{(1,0),(C,L)} \\ \vdots & \ddots & \vdots \\ p_{(C,L),(0,0)} & \cdots & p_{(C,L),(C,L)} \end{pmatrix}. \tag{1}$$

When $l = 1$, HAP supplies $\alpha$ units of energy to the STAs. Therefore, the one-step transition probability regarding WET operation is defined as

$$\begin{aligned} p_{(c,1),(c+\alpha,2)} &= \Pr\{(c+\alpha, 2) \,|\, (c, 1)\} = 1, \\ &\quad \text{for } 0 \leq c < C - \alpha, \\ p_{(c,1),(C,2)} &= \Pr\{(C, 2) \,|\, (c, 1)\} = 1, \\ &\quad \text{for } C - \alpha \leq c \leq C. \end{aligned} \tag{2}$$

When the STA has more than $\beta$ units of energy in its battery during the WIT slots in $2 \leq l \leq L - 1$, the STA transmits a packet with the probability $\lambda$. After the packet transmission, the STA consumes $\beta$ units of energy. When the battery energy is less than $\beta$ units, the STAs unable to transmit a packet. About the $l$, a STA transits from $l$ to $l + 1$. Therefore, the one-step transition probability regarding WIT operation in $2 \leq l(t) \leq L - 1$ is defined as

$$\begin{aligned} p_{(c,l),(c-\beta,l+1)} &= \Pr\{(c-\beta, l+1) \,|\, (c, l)\} = \lambda, \\ &\quad \text{for } \beta \leq c \leq C, 2 \leq l \leq L-1 \\ \text{for } p_{(c,l),(c,l+1)} &= \Pr\{(c, l+1) \,|\, (c, l)\} = 1 - \lambda, \\ &\quad \text{for } \beta \leq c \leq C, 2 \leq l \leq L-1 \\ p_{(c,l),(c,l+1)} &= \Pr\{(c, l+1) \,|\, (c, l)\} = 1, \\ &\quad \text{for } 0 \leq c < \beta, 2 \leq l \leq L-1. \end{aligned} \tag{3}$$

After the end of all WIT slots, which means state $(c, L)$, the state returns to WET slots. Therefore, the one-step transition probability from the end of the WIT slot to WET is defined as

$$\begin{aligned} P_{(c,L),(c-\beta,1)} &= \Pr\{(c-\beta, 1) \,|\, (c, L)\} = \lambda, \\ &\quad \text{for } \beta \leq c \leq C, \\ P_{(c,L),(c,1)} &= \Pr\{(c, 1) \,|\, (c, L)\} = 1 - \lambda, \\ &\quad \text{for } \beta \leq c \leq C, \\ P_{(c,L),(c,1)} &= \Pr\{(c, 1) \,|\, (c, L)\} = 1, \\ &\quad \text{for } 0 \leq c < \beta. \end{aligned} \tag{4}$$

The value of other transition probabilities from the above is zero.

Here, we denote the steady-state probability of state $(c, l)$ as $\pi_{(c,l)}$. Then, we denote the vector whose components are the steady-state probabilities in the Markov-chain model as $\boldsymbol{\pi} = [\pi_{(0,1)}, \cdots, \pi_{(C,L)}]^\top$, where $[*]^\top$ is transposition symbol. To obtain the values for all the steady-state probabilities, we calculate the eigenvector for the matrix $\mathbf{P}$ corresponding to eigenvalue 1. Namely, we calculate $\boldsymbol{\pi} = \mathbf{P}\boldsymbol{\pi}$.

### B. DERIVATIONS OF TRANSMISSION PROBABILITY

When a STA has more than $\beta$ units of energy at each WIT slot in the frame, the STA transmits a packet in probability $\lambda$. Therefore, STA-transmission probability at the $l$-th WIT slot in the frame is expressed as follows:

$$\tau^{(l)} = \lambda \frac{\sum_{c=\beta}^{C} \pi_{(c,l)}}{\sum_{c=0}^{C} \pi_{(c,l)}}, \quad \text{for } 2 \leq l \leq L. \tag{5}$$

In the following discussion, we apply the superscript STA $n$ for transmission probability to consider the energy consumption with respect to each STA in the network. Namely, $\tau_n^{(l)}$ means transmission probability for STA $n$ at the $l$-th slots in the frame.

### C. SYSTEM THROUGHPUT

The success probability of information transmission at $l$-th slot in the frame can be represented as

$$s^{(l)} = \sum_{n=1}^{N} \tau_n^{(l)} \prod_{m=1, m\neq n}^{N} \left(1 - \tau_m^{(l)}\right), \quad \text{for } 2 \leq l \leq L. \tag{6}$$

By calculating all of the throughputs for WIT slots in a frame for the duration of one frame in the steady state, the system throughput is obtained as follows:

$$S = \frac{\sum_{l=2}^{L} s^{(l)}}{\frac{T_E}{\sigma} + L}. \tag{7}$$

**TABLE 1. Units for magnetic properties.**

| Parameters | Value |
|---|---|
| The battery capacity ($C$) | 5 units |
| $\alpha_{near}$ | 2 units |
| $\alpha_{far}$ | 1 units |
| $\beta_{near}$ | 1 units |
| $\beta_{far}$ | 2 units |
| Slot time ($\sigma$) | 1 sec |
| WET duration time ($T_E$) | 10 sec |

### D. ENERGY SHORTAGE PROBABILITY

This paper defines the probability that STA cannot transmit a packet due to the shortage of residual energy as "energy shortage probability." When the residual energy is less than $\beta$ units of energy in its battery, STA cannot transmit any packets. Therefore, the energy shortage probability in WIT duration is expressed as

$$\Psi = \frac{\sum_{l=2}^{L}\sum_{c=0}^{\beta-1}\pi_{(c,l)}}{L-1}. \tag{8}$$

## V. SIMULATION VERIFICATION AND PERFORMANCE EVALUATION

This section verifies the proposed analytical model through the comparison with simulation results. Then, we evaluate the performance of Harvest-then-Access scheduling through the analytical results. We develop the original network simulator, including Harvest-then-Access, in C language.

In the evaluation scenario, considering the double-near-far problem in WPCN, STA $n \in \{1, 2, \cdots, \lfloor N/3 \rfloor\}$ is deployed near the HAP, and we denote the set of those STAs as "near-STAs." Similarly, STA $n \in \{\lfloor N/3 \rfloor + 1, \lfloor N/3 \rfloor + 2, \cdots, N\}$ is deployed far from the HAP, and we denote the set of those as "far-STAs." In addition, the amount of recharging energy in a WET duration for near-STAs (far-STAs) is denoted as $\alpha_{near}$ ($\alpha_{far}$). Similarly, the amount of consuming energy in a packet transmission for near-STAs (far-STAs) is denoted as $\beta_{near}$ ($\beta_{far}$). The detail of simulation parameters is shown in Table 1.

### A. THE VALIDITY OF THE ANALYTICAL MODEL

Figure 5 shows the system throughput for $N = 30$ as a function of $L$ for fixed packet arrival rate $\lambda$. In Fig. 5, $\lambda = 1/20$, $1/30$, and $1/40$ are considered. In the figure, the lines and the plots show analytical results and simulation ones, respectively. It is seen from Fig. 5 that the analytical results agree with the simulation results quantitatively for each packet arrival rate. This result shows the validity of the analytical model proposed in this paper.

In the case of $\lambda = 1/20$, it is confirmed that the maximal throughput is obtained when $L = 37$. For $L \leq 37$, the energy-supplying interval is so short that the HAP performs WET more than necessary for the network, providing few opportunities for information transmission of STAs in the entire network. As a result, the throughput degrades for $L \leq 37$. For $L \geq 37$, on the other hand, the energy-supplying interval is so long that the HAP cannot perform the WET operation for the demands of STAs in the network. As a result, this energy-supplying interval causes frequent battery depletions at STAs in the network, leading to performance degradation. The above mentions correspond to the essential characteristic of WPCN. Additionally, it is confirmed that our proposed analytical model presents the above characteristic in Harvest-then-Access scheduling completely.

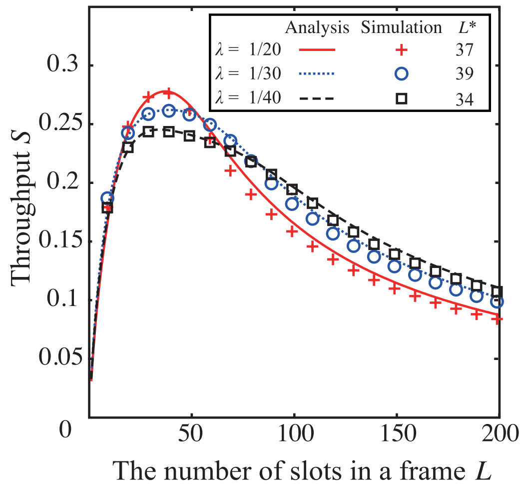


**FIGURE 5.** The system throughput for $N = 30$ as a function of the number of slots in WIT duration $L$.

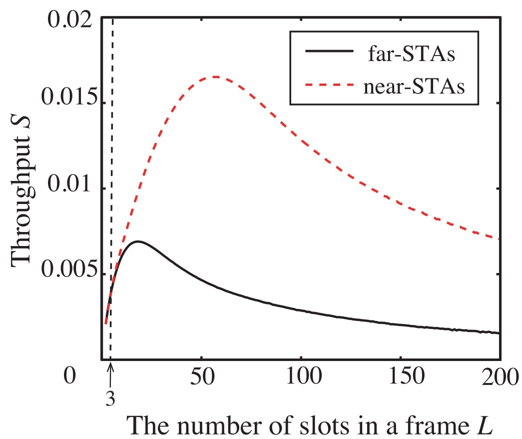


**FIGURE 6.** The average throughput of far-STAs and near-STAs as a function of the number of slots in a frame $L$.

From the results of our proposed analytical model, the optimal value of $L$, which provides the maximal throughput, can be derived quickly. In the following discussion, we denote the optimal value of $L$ as $L^*$.

Next, we show the performance difference between near-STAs and far-STAs. Figures 6 and 7 show the throughput of near-STAs and that of far-STAs as a function of $L$, and $N = 30$ and $\lambda = 1/30$. In $L > 3$, it is seen from Figs. 6 and 7 that near-STAs obtain obviously the higher throughput than

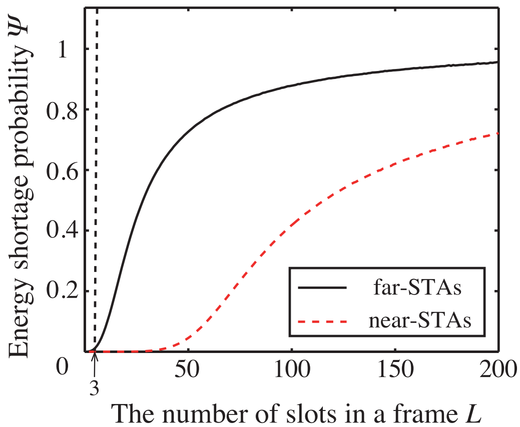


**FIGURE 7. The battery shortage probability of far-STAs and near-STAs as a function of the number of slots in a frame *L*.**

far-STAs. In addition, the battery of far-STAs becomes empty with a higher probability than near-STAs. This result shows the STAs communicate with the HAP under unfair communication, especially for $L > 3$. On the other hand, in $L < 3$, it is shown from Figs. 6 and 7 that the throughput of near-STAs is the same as that of far-STAs, and no depletion occurs in the network. These results show that the excess WET in the network degrades the throughput to achieve fair communication between near-STAs and far-STAs. It is confirmed from the results that the proposed analytical expressions support such a trade-off relationship between throughput and fairness in the WPCN.

### *B. PERFORMANCE COMPARISON WITH DISTRIBUTED SCHEDULING*

In this section, we compare the performance of the Harvest-then-Access protocol and the distributed scheduling from [8]. For a fair comparison, we apply some simplifications to the operation in the method of [8]. In [8], STAs perform channel access following slotted $p$-persisted CSMA, and saturated traffic condition is considered. Each slot prepares a special duration for transmitting the ERB signal, which is used to request the HAP to supply the WET. As the assumptions related to the operations in [8], we assume that STAs in the network perform channel access following slotted ALOHA with packet arrival probability $\lambda$. This is the same meaning as $p$-persisted CSMA in which the value of $p$ is replaced as $\lambda$. Furthermore, the special duration for transmitting the ERB signal is also idealized as 0 [sec]. About the WET, when the STAs exhaust power energy in their battery in each slot, HAP supplies power energy to all STAs by consuming $T_E$[sec] at the next slot. The packet arrival rate $\lambda$ is assumed as $1/N$, which provides the maximal throughput in the network with the slotted ALOHA. We also implemented distributed scheduling with the above simplification into our network simulator. We have confirmed that the network simulator's results completely agree with the analytical model of [8].

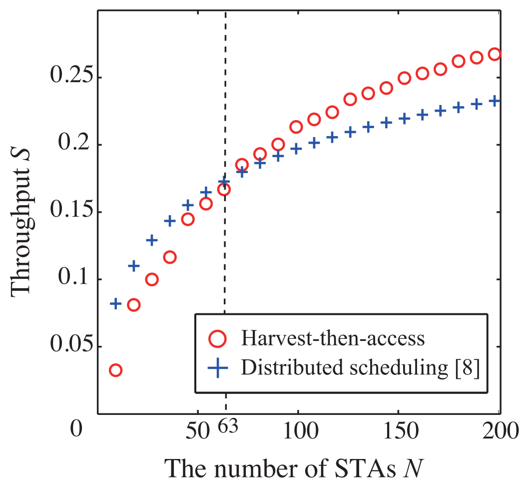


**FIGURE 8. The comparison of throughput *S* as a function of the number of STAs *N*.**

In distributed scheduling, HAP supplies energy depending on the request from STAs. Therefore, because far-STAs also harvest energy as soon as their battery is depleted, the unfairness communication appears. Thus, we compare the performance between the distributed scheduling and Harvest-then-Access under the condition that fair communication for each scheduling method is obtained.

Specifically, we define $\Gamma$ as the ratio of the throughput of near-STAs to the difference in the mean value of near-STAs throughput and far-STAs one as the index for the evaluation of fairness as follows:

$$\Gamma = \frac{\left|\dfrac{S_{near}}{N_{near}} - \dfrac{S_{far}}{N_{far}}\right|}{\dfrac{S_{near}}{N_{near}}}, \tag{9}$$

where $S_{near}(S_{far})$ is near-STAs(far-STAs) throughput, and $N_{near}(N_{far})$ is the number of near-STAs(far-STAs). We assume that fairness communication is performed in $\Gamma \leq 0.01$, and in Harvest-then-Access scheduling, that $L$ is set so as to obtain maximum throughput under the $\Gamma \leq 0.01$ for the fair comparison with the distributed scheduling.

Figure 8 shows the network throughput $S$ as a function of STAs $N$. Figure 9 shows the WET duration ratio, which is the time ratio of all the WET duration to simulation time, as a function of the number of STAs $N$. We obtain the WET duration ratio from the simulations. When $N \geq 63$, it is seen from Fig. 8 that the throughput of Harvest-then-Access is higher than in the distributed scheduling. On the other hand, it is seen from Fig. 9 that the WET duration ratio of Harvest-then-Access is lower than in distributed scheduling. These results show Harvest-then-Access scheduling can obtain higher throughput than distributed scheduling by reducing time resource for WET. In distributed scheduling, due to frequent battery depletion, far-STAs frequently

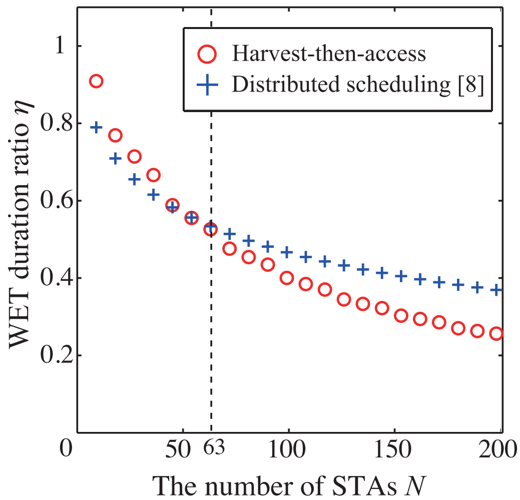


**FIGURE 9.** The comparison of WET duration ratio as a function of the number of STAs $N$.

request WET. Demanding all the requests leads to the degradation of throughput. As a result, the throughput of distributed scheduling decreases as increasing the number of far-STAs. On the other hand, it is seen from Fig. 8 that the throughput in Harvest-then-Access is lower than in distributed scheduling when $N \leq 63$. It is seen from Fig. 9 that the WET duration ratio in Harvest-then-Access is higher than in distributed scheduling. This is because that Harvest-then-Access requires the HAP to supply energy frequently in order to maintain fairness in the network with the small number of STAs. In a network with a small number of STAs, battery depletion of a STA significantly affects the entire network's fairness. Therefore, in Harvest-then-Access, the HAP needs to frequently supply energy not to deplete the battery of all STAs. Therefore, distributed scheduling provides higher throughput than Harvest-then-Access when the number of STAs in the network is small.

## VI. CONCLUSION

This paper proposed a Markov-chain model-based analytical model of Harvest-then-Access scheduling for WPCN. We derived the appropriate time interval for WET in the network with Harvest-then-Access, which simultaneously provides throughput improvement and fairness among STAs. The validity of the proposed analytical model was demonstrated through the comparison with the simulation results. Then, we evaluated the performance of Harvest-then-Access scheduling through the comparison to distributed scheduling. The effectiveness of Harvest-then-access scheduling was confirmed mathematically, especially in the network with a large number of STAs. We believe this novel knowledge is expected to contribute to the design of the protocol for WPCN.

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**ATSUHIRO IWAKI** (Member, IEEE) received the B.E. and M.E. degrees from Mie University, Mie, Japan, in 2021 and 2023, respectively. He is currently with SINFONIA TECHNOLOGY Corporation. His research interests include theoretical analysis and protocol design for wireless-powered communication networks. He received the International Conference on CCNC Best Student Paper Award, in 2023.

**KOSUKE SANADA** (Member, IEEE) received the B.E., M.E., and Ph.D. degrees from Chiba University, Japan, in 2011, 2012, and 2015, respectively. From October 2015 to February 2016, he was a Postdoctoral Researcher with Chiba University. Since March 2016, he has been with Mie University, where he is currently an Assistant Professor. He is a member of IEICE. His research interests include theoretical analysis, simulation, and experiments for IEEE 802.11 in wireless multi-hop networks.

**HIROYUKI HATANO** (Member, IEEE) received the B.E., M.E., and Dr. Eng. degrees from Nagoya University, Aichi, Japan, in 2003, 2005, and 2008, respectively. From 2008 to 2013, he was with Shizuoka University, Shizuoka, Japan. From 2014 to 2019, he was with Utsunomiya University, Tochigi, Japan. Since April 2019, he has been with Mie University, Mie, Japan, where he is currently an Associate Professor. Since April 2019, he has been a Visiting Associate Professor with Nagoya University. His current research interests include global positioning systems (GPS), radar/sensor networks, intelligent transport systems (ITS), and mobile communication systems. He is a member of IEICE, IPSJ, and JSAE. He is also a member of the IEICE ITS Research Group. He received the International Conference on ITST Best Paper Award, in 2012, the IPSJ ITS Research Group Best Paper Award, in 2014, and the International Workshop on Informatics Best Paper Award, in 2014.

**KAZUO MORI** (Member, IEEE) received the B.E. degree in computer engineering from the Nagoya Institute of Technology, Japan, in 1986, and the Ph.D. degree in information electronics engineering from Nagoya University, Japan, in 2000. In 1986, he joined the Hyper-Media Research Center, SANYO Electric Company Ltd., and he was engaged in research and development on telecommunication systems. From 1995 to 2000, he was a Research Engineer with YRP Mobile Telecommunications Key Technology Research Laboratories Company Ltd., where he was engaged in research on mobile communication systems. Since August 2000, he has been with Mie University, Japan, where he is currently a Professor with the Division of Electrical and Electronic Engineering, Graduate School of Engineering. From 2005 to 2006, he was a Visiting Research Fellow with King's College London, U.K. His research interests include mobile communication systems, wireless sensor networks, radio resource management, and teletraffic evaluation. He received the Excellent Paper Award from IEICE, Japan, in 2002.