On the Energy Efficiency of Wireless Random Access Networks with Multi-packet Reception

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***Abstract*—In this paper, we consider wireless random access networks (RANs) with both single packet reception (SPR) and multi-packet reception (MPR) techniques in fading channels, and compare their performance in terms of sum rate and energy efficiency. We adopt a simple power consumption model including transmission power and idle power. With MPR techniques, the transmission rate selection at each user is very important for achieving higher throughput in the uplink of RANs, but the optimal transmission rate at each user may not be feasible in a distributed manner. Thus, we propose a suboptimal rate selection technique in which each user chooses an appropriate transmission rate and, thus, it operates in a distributed manner for practical RANs. It is shown that the MPR yields higher sum rate than the SPR through extensive computer simulations. As for the energy efficiency, the MPR also significantly outperforms the SPR especially when the transmission power is comparable with the idle power.**

***Index Terms*—Energy efficiency, random access network, multi-packet reception, fading channels, transmission data rate**

I. INTRODUCTION

Random access protocols such as ALOHA, slotted ALOHA, and carrier-sense multiple access (CSMA) have received much attention due to their simplicity in the past years. In random access networks (RANs), a number of users simultaneously communicate with a base station (BS) in a distributed manner. The random access protocols have been known as cost-effective methods for supporting the traffic with low activity like machine-type communication services [1]. However, the RANs tend to yield low throughput due to packet collision among users as the number of users in the network increases [2]. Thanks to the recent advanced signal processing techniques at physical layer, the BS can detect all or part of the simultaneously transmitted packets in wireless communications, which is called multi-packet reception (MPR) [3], [4], [5]. Especially, the multiple antenna technique is being considered as a representative method of MPR [6], [7], [8].

Energy problems have recently received much attention due to limitation of fossil fuel and environment issues such as CO_2 emissions. According to a report, information and communication technology (ICT) industry contributes approximately 2% of the total human carbon footprint. Recently, there have been many activities for improving energy efficiency (EE) in wireless communication systems, including Green Radio [9], Energy Aware Radio and Network Technologies (EARTH) [10], and Green Touch [11]. Energy efficiency is expected to become more important when designing future wireless communication systems.

In principle, there exists a trade-off relationship between spectral efficiency (SE) and EE. One of the most popular metrics for EE in communications is *bits/Joule* [12], [13]. From the information theoretic viewpoint on point-to-point communications, it has been shown that higher EE is achieved in the lower rate regime [14]. In RANs, however, *packet collisions* among users simultaneously transmitting data may happen and the effect of the packet collisions should be also considered when investigating the EE of RANs. Furthermore, in fading channels, the availability of channel state information (CSI) also plays a very important role in both EE and SE due to the time-varying nature of fading channels. We need to investigate the effect of each user's knowledge of CSI on the EE in wireless RANs.

In this paper, we investigate the effect of the MPR technique on the EE in wireless RANs and compare the performance of the MPR-based RAN and the SPR-based RAN in terms of sum rate and EE. Especially, we focus on the relationship among transmission rate, transmission probability of each user, and EE in RANs for a given ratio between transmission power and idle power[1]. We exploit each user's knowledge of CSI for further enhancing the performance of the conventional RANs. As related work, Zhao and Tong [15] proposed the opportunistic CSMA protocol with the back-off strategy with *local CSI*[2] for improving the EE in a sensor network. They assumed that each user transmits data with the optimally chosen data rate which depends on not only its own CSI but also CSIs of users simultaneously transmitting data. However, it requires an additional signaling overhead before data transmission for implementation in practice. In this paper, therefore, we consider the slotted ALOHA as a basic MAC protocol, which does not require the carrier sensing and assume that each user transmits data with fixed rate operating with local CSI and independent from the CSIs of other users.

The rest of this paper is organized as follows. Section II describes the RAN that we consider in this paper, including a mathematical model for power consumption. In Section III and Section IV, we analyze the sum rate and the EE of RANs with SPR and MPR, respectively. In Section V, we show numerical results. Finally, we draw a conclusion in Section VI.

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[1] Idle power indicates the consumed power when the user does not transmit packets. In general, it is modeled as a constant, which is independent of data transmission rate.

[2] It is defined as the CSI that can be obtained without any coordination or explicit signaling from other nodes.

II. SYSTEM MODEL

We consider a random access model where N users communicate with a single receiver over a common channel. We assume that all users and the single receiver have a single antenna. Time is slotted into time slots with a duration of T and the time slot has a discrete index $m = 0, 1, \ldots$. We consider T is set to 1 for simplicity. All users are synchronized with a common time reference. The transmitted packets are received at the receiver through independent and identical Rayleigh block fading channels. The fading channel gain between user i and the single receiver during time slot m is denoted by $h_i(m)$, which follows an exponential cumulative distribution $F(h_i)$ with mean H_{mean}. The received signal of the receiver from n users at time slot m is expressed as

$$y(t) = \sum_{i=1}^{n} \sqrt{h_i(m)}\sqrt{P_i}s_i(t) + n(t) \quad t \in [mT, (m+1)T), \tag{1}$$

where P_i is the transmitted power from user i, $s_i(t)$ is the transmitted packet of user i and $n(t)$ is an independent, circularly symmetric, complex Gaussian random variable with variance N_0. Without loss of generality, we assume N_0 is set to 1.

We assume that each user knows its own channel information at the start of every slotted time, without knowing others' channel information. The knowledge of the channel gain to each user allows to exploit multiuser diversity in random access networks [16], which increases the throughput performance. Like the paper, we assume each user transmits a packet when its channel gain is larger than a threshold. Under this assumption, the transmission probability of user i depends on a threshold value $h_{T,i}$ and is expressed as $p_i(h_{T,i}) = 1 - F(h_{T,i})$. We assume that the receiver knows the channel state information of transmitted users.

We define a reception model based on the multiuser uplink capacity approach given by [17], which allows the reception of multiple packets simultaneously with taking into account the rates, transmit powers, and channel states of transmitting users. The reception model is given by a set of N functions. The kth function assigns success (1) or failure (0) of reception of k packets when users $\{1, 2, \ldots, k\}$ simultaneously transmit their packets with rates $\mathbf{R}_k = (R_1, \ldots, R_k)$ and transmit powers $\mathbf{P}_k = (P_1, \ldots, P_k)$ at their channel states $\mathbf{h}_k = (h_1, \cdots, h_k)$. That is,

$$\begin{aligned}&\theta_k(\mathbf{R}_k, \mathbf{P}_k, \mathbf{h}_k)\\ &= \{a \in \{0,1\} | k \text{ users transmit with } \mathbf{R}_k \text{ and } \mathbf{P}_k \text{ at } \mathbf{h}_k\}.\end{aligned} \tag{2}$$

Based on the multiuser uplink capacity approach, we assign the kth function, $\theta_k(\mathbf{R}_k, \mathbf{P}_k, \mathbf{h}_k)$, to 1 (success) if the following conditions are satisfied.

$$\sum_{k \in S} R_k < \log_2(1 + \frac{\sum_{k \in S} h_k P_k}{N_0}) \text{ for all } S \subset \{1, \cdots, k\}. \tag{3}$$

Otherwise, we assign the kth function to 0 (failure).

In the case of SPR, there is no possibility that more than one transmitted packet are successfully received, that is, $\theta_k(\mathbf{R}_k, \mathbf{P}_k, \mathbf{h}_k) = 0$ for $k = 2, \ldots, N$. If only a single user transmits a packet with rate R and power P at fading gain h, the transmission is successful if the following condition is satisfied

$$R < \log_2(1 + \frac{hP}{N_0}). \tag{4}$$

In [16], authors have used Eq. (4) to define the maximum rate at which a single user can reliably transmit.

A. Power Consumption Model

We assume that user i has a maximum power constraint as follows:

$$P_i(h) \le \check{P} \qquad \forall h \ge h_{T,i}. \tag{5}$$

Note that since each user knows its own channel gain at each time slot and transmits a packet when the channel gain is larger than h_T, we can consider a power constraint over a channel gain instead of time index.

Next, we describe a power consumption model. In each time slot, all users consume power for transmission or idle modes. Let P_{tx} and P_{idle} denote the total average power consumed in transmission and idle state over all users, respectively. We derive P_{tx} and P_{idle} as follows:

$$P_{tx} = \sum_{i=1}^{N} \int_{h_{T,i}}^{\infty} P_i(h)\, dF(h), \tag{6}$$

$$P_{idle} = \sum_{i=1}^{N} \int_{0}^{h_{T,i}} P_i^{idle} f(h)\, dF(h), \tag{7}$$

where P_i^{idle} and P_i are the idle and transmit power of user i, respectively. We assume that all users have the same idle power consumption at all time slots, that is, $P^{idle} = P_i^{idle}$ for all $i = 1, \ldots, N$.

We define the energy efficiency metric as follows:

$$\eta = \frac{S}{P_{tx} + P_{idle}}, \tag{8}$$

where S is the sum rate which we will address in the following sections.

III. ENERGY EFFICIENCY OF RANDOM ACCESS WITH A SINGLE PACKET RECEPTION

In this section, we describe the sum rate and energy efficiency of random access with SPR. In this paper, we consider a symmetric case where all users transmit packets with the same transmission probability p under a maximum power constraint.

When each user knows its own channel gain in a random access system with SPR, Qin and Berry [16] have addressed fixed- and variable-rate algorithms. They have focused on the sum rate performance, not on the energy efficiency. Thus, we investigate the energy efficiency of random access with SPR.

We summarize the sum rate of random access with SPR as follows:

- Fixed-Rate Algorithm
  Since each user transmits a packet when its own channel gain is larger than h_T and the transmission power satisfies

the maximum power constraint, the fixed rate is chosen to $\log_2(1+\check{P}h_T)$. The sum rate of the fixed rate algorithm with a maximum power constraint is expressed as [16]

$$\check{S}^{SPR,f}(N,p) = Np(1-p)^{N-1}\log_2(1+\check{P}h_T). \quad (9)$$

- Variable-Rate Algorithm
  Since each user knows its own channel gain, he use a maximum power $\check{P}$ to adapt a rate $\log_2(1+\check{P}h)$. The sum rate of the variable rate algorithm with a maximum power constraint is expressed as [16]

$$\check{S}^{SPR,v}(N,p) = N(1-p)^{N-1}\int_{h_T}^{\infty}\log_2(1+\check{P}h)\,dF(h). \quad (10)$$

To compare the energy efficiency of SPR-capable random access with that of MPR-capable random access, we derive the total average power consumption and energy efficiency. Since the maximum power constraint implies the power consumption at a time slot, the total power consumption is expressed as

$$P_{tot} = N(\check{P}p + P^{idle}(1-p)). \quad (11)$$

The energy efficiencies for the fixed- and variable-rate cases are expressed, respectively, as

$$\check{\eta}^{SPR,f}(N,p) = \frac{\check{S}^{SPR,f}(N,p)}{N(\check{P}p + P^{idle}(1-p))}. \quad (12)$$

$$\check{\eta}^{SPR,v}(N,p) = \frac{\check{S}^{SPR,v}(N,p)}{N(\check{P}p + P^{idle}(1-p))}. \quad (13)$$

IV. ENERGY EFFICIENCY OF RANDOM ACCESS WITH A MULTI PACKET RECEPTION

In this section, we first derive the sum rate and energy efficiency of random access with MPR under a maximum power constraint. We propose a suboptimal rate selection scheme for reducing computational burden. We consider a symmetric case where all users have the same maximum power constraint $\check{P}$, fixed rate $R = R_1 = \cdots = R_N$, and transmission probability p. We use a simple notation such as $\theta_k(R,\check{P},\mathbf{h}_k)$ instead of $\theta_k(\mathbf{R}_k,\mathbf{P}_k,\mathbf{h}_k)$.

A. Analysis of Sum Rate and Energy Efficiency

In our model, each user transmits a packet when its own channel gain is larger than h_T. If a user transmits a packet, the distribution of its channel gain has to be conditioned in the reception model. Thus, we consider a cumulative distribution $F_{|h_T}(h)$. $F_{|h_T}(h)$ is expressed as

$$F_{|h_T}(h) = \begin{cases} \frac{F(h)-F(h_T)}{1-F(h_T)}, & \text{if } h \geq h_T \\ 0, & \text{otherwsie.} \end{cases} \quad (14)$$

The sum rate under a maximum power constraint, denoted by $S^{MPR}(R,p)$, is expressed as

$$\begin{aligned} S^{MPR}&(R,p) \\ &= \sum_{k=1}^{N} kR\binom{N}{k}(p)^k(1-p)^{N-k} \\ &\times \int\cdots\int_{H^k_{|h_T}} \theta_k(R,\check{P},\mathbf{h}_k)\prod_{i=1}^{k} dF_{|h_T}(h_i), \end{aligned} \quad (15)$$

where $H^k_{|h_T} = \{(h_1,\ldots,h_k)|h_1,\ldots,h_k \geq h_T\}$ and $p = \int_{h_T}^{\infty} dF(h)$.

The third line in Eq. (15) represents the probability of successful reception of k packets, which is denoted as $P_k^{succ,MPR}(R,\check{P},h_T)$, when k users who have a larger fading channel gain than h_T transmit with rate R and transmit power $\check{P}$. To obtain the probability $P_k^{succ,MPR}(R,\check{P},h_T)$, a set $D_{k|h_T}$ of channel states which satisfy Eq. (3) given a rate of R and a transmit power of $\check{P}$. The set $D_{k|h_T}$ is expressed as

$$\begin{aligned} D_{k|h_T} =& \{(h_1,h_2,\ldots,h_k)|\sum_{i\in S} h_i > \frac{(2^{|S|R}-1)N_0}{\check{P}} \\ & \text{for all } S \subset \{1,\cdots,k\} \text{ and } h_1,\ldots,h_k > h_T\}. \end{aligned} \quad (16)$$

Then, we obtain the probability $P_k^{succ,MPR}(R,\check{P},h_T)$ as an integration over the region $D_{k|h_T}$ as follows:

$$\begin{aligned} P_k^{succ,MPR}&(R,\check{P},h_T) \\ &= \int\cdots\int_{D_{k|h_T}} 1\,dF_{|h_T}(h_1)\cdots dF_{|h_T}(h_k). \end{aligned} \quad (17)$$

It is also hard to represent $P_k^{succ,MPR}(R,\check{P},h_T)$ as a closed form. Thus, we obtain $P_k^{succ,MPR}(R,\check{P},h_T)$ through simulation.

The energy efficiency of random access with MPR under a maximum power constraint is derived as

$$\check{\eta}^{MPR}(R,p) = \frac{S^{MPR}(R,p)}{N(\check{P}p + P^{idle}(1-p))}. \quad (18)$$

B. Suboptimal Rate Selection

In the previous subsection, we describe the sum rate and energy efficiency of random access with MPR. It is hard to derive $P_k^{succ,MPR}(R,\check{P},h_T)$ as a closed form. We have to rely on simulation to obtain the $P_k^{succ,MPR}(R,\check{P},h_T)$. A high computation burden is expected to select the optimal sum rate or energy efficiency. To mitigate this computation burden, we propose a suboptimal rate selection scheme.

Given N users and the transmission probability p, the average number of transmitting users is Np. As a suboptimal scheme, it makes sense that a maximum rate is selected subject that the successful transmission probability of Np users is one. From Eq. (16) and Eq. (17), the rate is obtained as

$$R_{subopt} = \frac{\log_2(1+\frac{\lceil Np\rceil h_T\check{P}}{N_0})}{\lceil Np\rceil}, \quad (19)$$

where $\lceil x\rceil$ represents a minimum integer which is larger than x. Note that when the number of transmitting users who select a rate with Eq. (19) is less than Np, the successful transmission probability is always 1.

The sum rate and energy efficiency of the suboptimal rate selection are expressed as

$$
\begin{aligned}
&S^{MPR,subopt}(R,p) = \\
&= \sum_{k=1}^{\lceil Np \rceil} kR_{subopt} \binom{N}{k} (p)^k (1-p)^{N-k} \\
&+ \sum_{k=\lceil Np \rceil+1}^{N} kR_{subopt} \binom{N}{k} (p)^k (1-p)^{N-k} \\
&\times \int \cdots \int_{H^k_{|h_T}} \theta_k(R_{subopt}, \check{P}, \mathbf{h}_k) \prod_{i=1}^{k} dF_{|h_T}(h_i) \qquad (20)
\end{aligned}
$$

$$
\check{\eta}^{MPR,subopt}(R,p) = \frac{S^{MPR,subopt}(R,p)}{N(\check{P}p + P^{idle}(1-p))} \qquad (21)
$$

V. PERFORMANCE EVALUATION

In this section, we compare the sum rate and energy efficiency of the fixed and variable rate selections under SPR and the optimal and suboptimal rate selections under MPR for varying transmission probabilities.

A. Sum Rate

We compare the sum rate of the fixed- and variable-rate selections under SPR and the optimal and suboptimal rate selections under MPR when $N = 25$, $\check{P} = 0dB$, and $H_{mean} = 0dB$ for varying transmission probabilities. In the case of the optimal rate selection, we choose the optimal sum rate over rates at each transmission probability. Fig. 1 shows the sum rate of the rate selections under SPR and MPR for varying transmission probabilities. The optimal sum rate of SPR is obtained at the value, which is close to the optimal transmission probability $(1/N)$ of a backlogged slotted ALOHA system with the classic collision channel. However, the optimal sum rate of MPR is achieved at a high transmission probability. In the case of the suboptimal rate selection, the sum rate is almost similar to that of the fixed rate under SPR when the average number of transmitting users is less than 1. The sum rate of the proposed suboptimal rate selection follows that of optimal rate when the transmission probability is less than 0.4.

As the transmission probability increases, h_T decreases and the rate at which a single user can reliably transmit, $\log_2(1 + h_T\check{P}/N_0)$, also decreases. In MPR, a selected rate lower than the rate can increase the sum rate due to successful MPR unlike SPR. Fig. 2 shows the fixed rate, optimal rate, and suboptimal rate for varying transmission probabilities. At a low transmission probability region with $p \leq 0.04$, for both the fixed and suboptimal schemes, the same rate is selected and the same sum rate is achieved. At a transmission probability region with $0.04 \leq p \leq 0.85$, the optimal rate which is lower than the fixed rate is selected. At a high transmission probability region with $p \geq 0.85$, the optimal rate follows the fixed rate scheme. This implies that the receiver with MPR can obtain much higher sum rate than the receiver with SPR at a high transmission probability region.

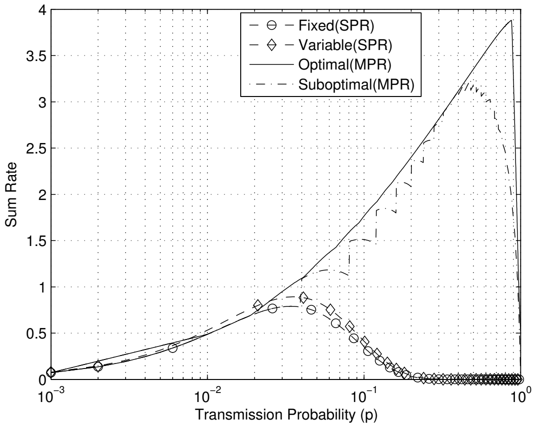

Fig. 1. Comparison of the sum rate between SPR and MPR

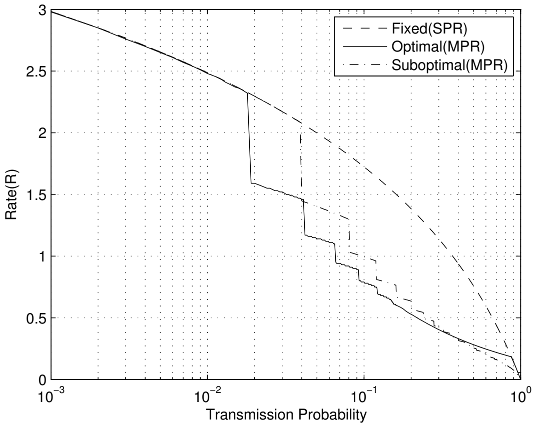

Fig. 2. Comparison of fixed rate under SPR with the optimal and suboptimal rate under MPR for varying transmission probability

B. Energy Efficiency

In the previous subsection, we show that the MPR yields higher sum rates than the SPR. The optimal transmission probability of MPR is also higher than that of SPR. A higher transmission probability may cause lager power consumption. Therefore, we consider the effect of MPR on the energy efficiency of random access.

We compare the energy efficiency of the fixed- and variable-rate selections under SPR and the optimal and suboptimal rate selections under MPR for varying transmission probabilities when $N = 25$, $\check{P} = 0dB$, $H_{mean} = 0dB$, and $P^{idle}/\check{P} = 0.5$ and 0.01.

In Fig. 3, we compare the energy efficiency of the fixed- and variable-rate selections under SPR and the optimal and suboptimal rate selections under MPR when $P^{idle}/\check{P} = 0.5$. For SPR, the transmission probability achieving the optimal energy efficiency is close to that achieving the optimal sum rate. In other words, the maximum energy efficiency yields the maximum sum rate. For MPR, the transmission probability achieving the optimal energy efficiency is different from that achieving the optimal sum rate because a higher transmission probability causes higher total power consumption. Nonetheless, the MPR yields much higher energy efficiency than the SPR. The proposed suboptimal scheme achieves the optimal

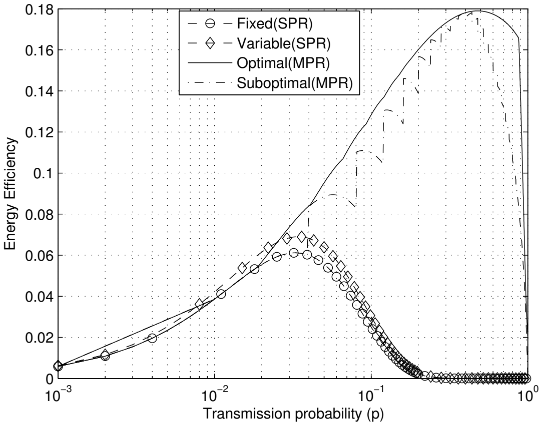

Fig. 3. Comparison of the energy efficiency of the fixed- and variable-rates under SPR and the optimal and suboptimal rate selections under MPR when $P^{idle}/\check{P} = 0.5$

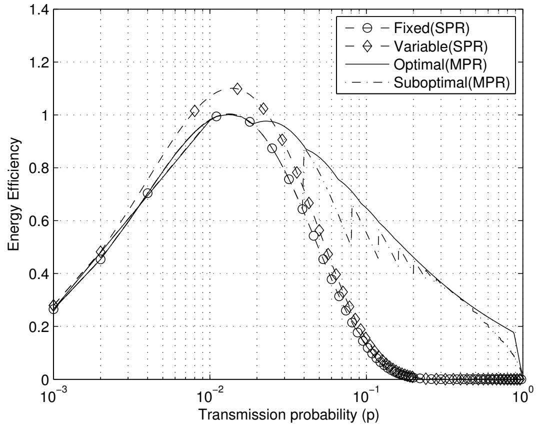

Fig. 4. Comparison of the energy efficiency of the fixed- and variable-rates under SPR and the optimal and suboptimal rate selections under MPR when $P^{idle}/\check{P} = 0.01$

energy efficiency.

In Fig. 4, we compare the energy efficiency of the fixed- and variable-rate selections under SPR and the optimal and suboptimal rate selections under MPR when $P^{idle}/\check{P} = 0.01$. For the SPR and MPR, the transmission probability achieving the optimal energy efficiency is different from that achieving the optimal sum rate. Since each user consumes much less power for idle mode than that for transmission mode, waiting is much more efficient than the MPR to avoid collisions. In the case of MPR, a high sum rate is achieved at a high transmission probability, which causes much larger transmission power consumption than idle power consumption. Thus, MPR is not energy-efficient when the idle power is much lower than the transmission power.

From the above results, we conclude that when we design an energy-efficient random access network, we need to decide whether MPR or SPR is implemented depending on the ratio of the transmission energy consumption to the idle energy consumption.

VI. CONCLUSION

In this paper, we investigated the energy efficiency (EE) of random access networks (RANs) where a multi-packet reception (MPR) technique is utilized. We compared the performance of MPR-based RANs with SPR-based RANs in terms of sum rate and EE. Simulation results show the MPR significantly improves both the sum rate and EE in RANs. However, the transmission rate of each user in MPR-based RANs should be carefully selected for achieving better performance. We also proposed a simple but effective suboptimal transmission rate selection algorithm for MPR-based RANs, which can be applied to practical RANs.

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