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Energy-efficient opportunistic scheduling schemes in wireless networks

Sung-Guk Yoon [a], Changhee Joo [b,*], Saewoong Bahk [a]

[a] INMC, School of EECS, Seoul National University, Seoul, Republic of Korea
[b] Department of EECE, Korea University of Technology and Education, Cheonan, Chungnam, Republic of Korea

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ABSTRACT

Exploiting the multiuser diversity in wireless networks has a fundamental tradeoff between throughput and energy saving. To balance the tradeoff, we reconsider the opportunistic scheduling in the aspect of energy saving, and propose a new energy-efficient opportunistic (EEFO) scheduling. Our goal is to maximize the performance of bits per energy unit under the constraint of fair resource allocation, and EEFO scheduling achieves it by controlling the number of users participating in the channel feedback. Through simulations, we show that EEFO scheduling is able to transmit significantly more amount of traffic compared to the competitive schemes under the given energy constraint.

1. Introduction

In recent decades, wireless communication technology has advanced rapidly and become popular in civil life. Ubiquitous connectivity is promising in support of mobility and multimedia services with small hand-hold devices. However, as mobile users are battery limited, energy efficient communications become of importance and attract attention for the next generation networking. Conventional approaches for energy saving have been independently applied to Physical (PHY) and Media Access Control (MAC) layers. In the PHY layer, minimum power allocation has been used under quality of service (QoS) constraints [12], and in the MAC layer, sleep/awake scheduling has been used to switch transceivers on and off according to the traffic [9,16]. In this paper, we focus on the MAC layer solution and incorporate it accordingly with opportunistic scheduling schemes to improve performance in terms of bits per energy unit.

Because of the time varying characteristic of wireless channel, opportunistic scheduling properly uses the channel status information to increase the throughput performance by exploiting the multiuser diversity [1,10,11]. However, there is a fundamental tradeoff between performance gain and energy efficiency according to the channel feedback. With the number of users participating in the channel feedback, it is more likely for the base station (BS) to transmit at a higher rate. This means that the throughput performance improves, but the total energy consumption increases too. This problem becomes more challenging when it comes to multi-channel environments with multiple-input and multiple-output (MIMO) or orthogonal frequency-division multiplexing (OFDM) technique, since these communication technologies incur significantly more amount of channel feedback [4].

There have been several works that address this problem [4,14,6]. Svedman et al. [14] proposed a scheme that limits each user to feed back the best n sub-channels only. In [6], each user sends its channel status to the BS only when the channel condition is better than a certain threshold. However, these schemes do not consider energy consumption of each user for the channel feedback, and hence, their effectiveness on the energy efficiency still remains questionable. It has been shown that a wireless transceiver consumes a substantial amount of energy in sensing the channel and transmitting the channel status to the BS [5].

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[*] Corresponding author. Tel.: +82 415601402; fax: +82 415643261.
E-mail addresses: sgyoon@netlab.snu.ac.kr (S.-G. Yoon), cjoo@kut.ac.kr (C. Joo), sbahk@snu.ac.kr (S. Bahk).

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In this paper, we develop a new scheduling scheme that achieves high energy efficiency while exploiting the benefit of opportunistic scheduling. By controlling the number of users that participate in the channel feedback, we improve energy efficiency and achieve fair resource allocation among users. We start with a simple network scenario, where all users are assumed to have the same channel statistics, and extend the basic idea to more general cases.

The rest of the paper is organized as follows. We first describe our system model in Section 2. Then, we propose new scheduling schemes with two heuristic algorithms in Section 3. After evaluating the proposed schemes in Section 4, we conclude our paper in Section 5.

2. System model

We consider a time-slotted system with a single frequency downlink channel. For uplink channel, or if there are multiple available channels, our solution can be applied to each channel. There are N mobile users and a single BS. We assume that users have low mobility and thus the number of users in the system is relatively static. We assume that the length of a time slot is appropriately chosen such that the channel state does not change within a single time slot. To exploit multiuser diversity, we basically employ an opportunistic scheduler. We assume that users have low mobility, and thus the number of users in the system is relatively static.

Fig. 1 illustrates the frame structure of the system[1] and user activities during a single time slot. At the beginning of each time slot, the BS transmits a pilot signal, and then n out of N users inform the BS of their received signal-to-noise ratios (SNRs).[2] We denote the users who report their channel status as *non-sleeping*, and the others as *sleeping*. Using the channel feedback information, the BS chooses a single user according to the opportunistic scheduler and reserves the time slot for that user. We denote the chosen user as *active*, and the other non-sleeping users as *idle*. The active user transmits and/or receives data packets from the BS, while $n-1$ idle users deactivate their transceivers and save energy. The $N-n$ sleeping users turn their wireless transceivers off at the beginning of time slot and do not participate in the channel feedback, thereby saving energy further. We assume that each user can switch between active and idle modes instantly but needs some time to switch to and from the sleeping mode.

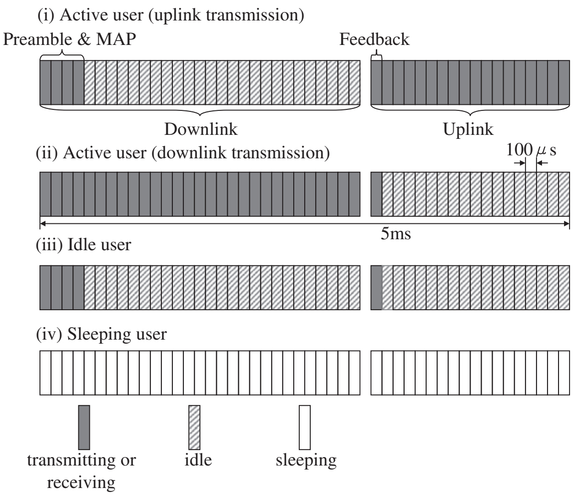

Fig. 1. Frame structure of the system for a time slot. Each small box indicates a symbol. The time slot is divided into two periods for downlink and uplink transmissions. The BS transmits the pilot signal during the preamble in the downlink period and gets the feedback at the first symbol in the uplink period. MAP has been used to indicate which users are chosen for communication during the time slot. Based on the status of wireless transceiver (i.e., communicating, idle, and sleeping), users are classified as active (either for uplink or for downlink), idle, and sleeping users.

Let $s_k(t)$ denote an indicator that has 0 when user k is sleeping at time slot t, and 1 when non-sleeping, and $\vec{s}(t)$ denote its vector. Similarly $I_k(t)$ equals 1 when user k is active at time slot t and 0 when inactive (i.e., idle or sleeping). Let $r(\vec{s}(t))$ and $e(\vec{s}(t))$ denote the expected throughput and energy consumption for a given $\vec{s}(t)$, respectively. Further, let $U(\vec{s}(t))$ denote the energy efficiency in bits per energy unit, i.e., $U(\vec{s}(t)) := r(\vec{s}(t))/e(\vec{s}(t))$. In our model, our objective is to maximize the average efficiency under the constraint of fair resource allocation. Then, the problem can be formulated as follows.

$$(\mathbf{P})\quad \max_{\{\vec{s}(t)\}} \qquad \frac{1}{T}\sum_{t=1}^{T} U(\vec{s}(t))$$

$$\text{subject to}\ \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T} I_k(t) = \frac{1}{N},\quad \text{for all } k,$$

$$I_k(t) = \begin{cases} 1 & \text{if } k = \arg\max_{l\in E} \Gamma_l \cdot s_l(t), \\ 0 & \text{otherwise,} \end{cases}$$

where Γ_l is a random variable for the preference metric of user l, e.g., the ratio of the instantaneous rate to the average rate of user l, and E is the set of all users.

The problem ($\mathbf{P}$) is a generic form of our problem. To solve the problem analytically, we use the proportional fair (PF) scheduling's preference metric. Using the techniques in [3], we can estimate the expected throughput $r(\vec{s}(t))$. The wireless channel between the BS and a user is assumed a stationary and ergodic i.i.d. process following the Rayleigh fading model. Let Z_k and z_k denote a random variable for the received SNR of user k and its mean, respectively. Let R_k denote a random variable for the transmission rate of user k and $\widetilde{R}_k$ denote its average. Also let $\Gamma_k = R_k/\widetilde{R}_k$ denote a random variable for the preference metric of user k. From the Shannon formula with bandwidth W, we can write the distribution of Γ_k as

$$\begin{aligned} F_k(z) &:= P\{\Gamma_k \leqslant z\} = P\{R_k \leqslant \widetilde{R}_k \cdot z\} \\ &= P\Big\{W\log(1+Z_k) \leqslant \widetilde{R}_k \cdot z\Big\} \\ &= 1 - \exp\left(-\frac{1}{z_k}\left(e^{\frac{\widetilde{R_k \cdot z}}{W}} - 1\right)\right). \end{aligned} \tag{1}$$

---

[1] We have used the frame structure of the Mobile WiMAX system as an example. However, our proposed scheme is not limited to a particular communication system, and can be applied to different communication systems.

[2] In a plain opportunistic scheduling, all the N users feed their channel status back to the BS.

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Let $\mathit{\Gamma} := \text{argmax}_{l \in E} \mathit{\Gamma}_l \cdot s_l(t)$, and $F(z, \vec{s}(t))$ denote its distribution. Assuming the channels are independent of each other, we have

$$F(z,\vec{s}(t)) = P\{\mathit{\Gamma}_1 \cdot s_1(t), \ldots, \mathit{\Gamma}_N \cdot s_N(t) \leqslant z\} = \prod_{k=1}^{N} \left(1 - \exp\left(-\frac{1}{z_k}\left(e^{\frac{\widetilde{R_k \cdot z}}{W}} - 1\right)\right)\right)^{s_k(t)}. \tag{2}$$

Let $R(\vec{s}(t))$ denote a random variable for the system throughput. Then, it can be written as

$$R(\vec{s}(t)) = \sum_{k=1}^{N} \widetilde{R}_k s_k(t) \mathit{\Gamma}_k I_k. \tag{3}$$

For the expected throughput at time t, we have

$$r(\vec{s}(t)) = \mathbb{E}[R(\vec{s}(t))] = \sum_{k=1}^{N} \widetilde{R}_k s_k(t) \mathbb{E}[\mathit{\Gamma}_k I_k]. \tag{4}$$

Let $n(t)$ denote the number of non-sleeping users at time t, i.e., $n(t) := \sum_k s_k(t)$. Since each non-sleeping user can be chosen equally under the i.i.d. channel assumption [7], we have[3]

$$\mathbb{E}[\mathit{\Gamma}_k I_k] = \mathbb{E}[\mathit{\Gamma}]/n(t). \tag{5}$$

As a result, we obtain

$$r(\vec{s}(t)) = \mathbb{E}[\mathit{\Gamma}] \frac{\sum_{k=1}^{N} \widetilde{R}_k s_k(t)}{n(t)} = \frac{\sum_{k=1}^{N} \widetilde{R}_k s_k(t)}{n(t)} \int_0^\infty (1 - F(z, \vec{s}(t))) dz. \tag{6}$$

We also assume that at each time slot, each user consumes a fixed amount of energy according to its activity. An active user consumes α units of energy for transmitting and/or receiving packets, an idle user β units for the channel feedback, and a sleeping user γ units for the duration of a time slot. Simply $\alpha \geqslant \beta \geqslant \gamma > 0$ and we can express the total energy consumption $e(\vec{s}(t))$ as2

$$e(\vec{s}(t)) = \alpha + \beta(n(t) - 1) + \gamma(N - n(t)). \tag{7}$$

3. Energy-efficient opportunistic scheduling

In this section, we propose a new opportunistic scheduling scheme that balances energy efficiency and system throughput. Then, we name it energy-efficient opportunistic (EEFO) scheduling. We describe the EEFO scheduling with a simple network scenario first and extend it to cover more general cases.

3.1. EEFO scheduling for users with an identical mean SNR

We first consider a special case where each user has an identical mean SNR z_0 and the $r(\vec{s}(t))$ has been analyzed in [2] under the identical mean SNR assumption. We can simplify (2) as

$$F(x, \vec{s}(t)) = F_0(x, n(t)) = \left(1 - \exp\left(-\frac{1}{z_0}\left(e^{\frac{x}{W}} - 1\right)\right)\right)^{n(t)}. \tag{8}$$

Also, we have

$$\widetilde{R}_k = \widetilde{R}_0 = \int_0^\infty \exp\left(-\frac{1}{z_0}\left(e^{\frac{z}{W}} - 1\right)\right) dz \tag{9}$$

for each non-sleeping user k. Then it is clear that the efficiency $U(\vec{s}(t))$ can be expressed as $U(n(t))$ according to (6)–(9).

Suppose that at time slot t, we know an optimal number of non-sleeping users $n^*(t)$ that maximizes the efficiency $U(n(t))$. Then, we can meet the constraint of fair resource allocation by choosing a user among the non-sleeping ones at random or in a round robin manner. Hence, the problem (**P**) simply becomes finding an optimal $n^*(t)$. In addition, from the assumption of a stationary and ergodic i.i.d. channel, the optimal $n^*(t)$ will not change across time. Then, we can simplify our problem as

$$(\mathbf{S}) \quad \max_{n(t)} \quad U(n) := \frac{r(n)}{e(n)}$$
$$\text{subject to} \quad 1 \leqslant n \leqslant N.$$

where $r(n) = \widetilde{R}_0 \int_0^\infty (1 - F_0(x, n)) dx$ and $e(n) = \alpha + \beta(n - 1) + \gamma(N - n)$. Problem (**S**) is still a non-convex integer optimization problem. We can show that this is a quasi-convex integer problem and can be solved by relaxing the integer constraint on n.

Let $r_c(x)$ and $e_c(x)$ denote the continuous versions of $r(n)$ and $e(n)$, respectively, which are obtained by relaxing integer n to real number x. $r_c(x)$ is a strictly concave function because

$$r''_c(x) := -\widetilde{R}_0 \int_0^\infty (\ln G_0(z))^2 (G_0(z))^x dz < 0,$$

where $G_0(z) = 1 - \exp\left(-\frac{1}{z_0}\left(e^{\frac{z}{W}} - 1\right)\right)$. Let $U_c(x) := r_c(x)/e_c(x)$. Then we have the following lemma.

Lemma 1. *There exists a unique point x_0 that maximizes $U_c(x)$ when $U'_c(x_0) = 0$.*

Proof. Since $U_c(x)$ is a continuous and second-order differentiable function, we have

$$U'_c(x) = \frac{r'_c(x) e_c(x) - r_c(x) e'_c(x)}{e_c^2(x)}. \tag{10}$$

Let $f(x) := r'_c(x) e_c(x) - r_c(x) e'_c(x)$. By differentiating $f(x)$, we obtain

$$f'(x) = r''_c(x) e_c(x) < 0, \tag{11}$$

because $e''_c(x) = 0$ and $r''_c(t) < 0$. Let x^* denote a maximizer of $U_c(x)$. Since $f(x^*) = 0$, we have $U'_c(x) > 0$ for $x < x^*$ and $U'_c(x) < 0$ for $x > x^*$. From the continuity of $U'_c(x)$, we have $U'_c(x^*) = 0$. The point x^* is unique because $f(x)$ monotonically decreases. Then we have $x_0 = x^*$. □

According to Lemma 1, we can find n^* by differentiating $U_c(x)$. This motivates us to develop our EEFO scheduling scheme. The overall operation of EEFO is described as

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[3] Obviously, $P\{I_k = 1, \mathit{\Gamma}_k < z | \mathit{\Gamma} < z\} = 1/n(t)$. From $P\{I_k = 1, \mathit{\Gamma}_k < z\} = P\{I_k = 1, \mathit{\Gamma}_k < z | \mathit{\Gamma} < z\} P\{\mathit{\Gamma} < z\} = P\{\mathit{\Gamma} < z\}/n(t)$, the result follows.

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follows. At the beginning of each slot, EEFO allows n^* non-sleeping users to report their channel feedback to the BS, and allocates the current slot to a user with the best channel status. The chosen active user communicates with the BS while the other non-sleeping users remain idle. During this slot, the $N - n^*$ sleeping users turn off their transceivers and sleep to save energy. Our proposed EEFO scheduling is explained as an algorithmic form in Algorithm 1, and it assumed that n^* is known at the BS by solving (**S**).

Algorithm 1: EEFO scheduling algorithm with n^*

```
1: At each time slot $t$
2: BS chooses $n^*$ non-sleeping users in a round-robin
   manner
3: Each non-sleeping user feeds channel information
   back to BS
4: BS allocates slot $t$ to the user with the best
   preference metric
```

The remaining problem is to determine which n^* users report their channel information to the BS or sleep (Algorithm 1.2). In order to satisfy the fairness constraints, EEFO determines non-sleeping users in a round robin manner as shown in Fig. 2. Numbering users from 1 to N, EEFO schedules user k for non-sleeping for $k = ((t-1) \bmod N) + 1, \ldots, ((t-n^*) \bmod N) + 1$. Fig. 2 illustrates a scheduling example under EEFO when $N = 10$ and $n^* = 4$. At each time slot, active and idle users are marked by black and white circles, respectively, and sleeping users are not marked. There are four non-sleeping users and six sleeping users, and according to their channel status, one of the non-sleeping users is selected and becomes active.

Non-sleeping users are scheduled in a round robin manner to minimize the number of switchings between sleeping and non-sleeping modes. Alternatively, we may choose n^* users at random at each slot and still satisfy the fairness constraints. However, in practice, there involves time and energy cost when a user switches between sleeping and non-sleeping mode, which is assumed to be larger than the cost incurred by the change between active and idle mode. While we do not quantify these costs in this paper, we intend to reduce the switching cost by scheduling non-sleeping users in a round robin manner.

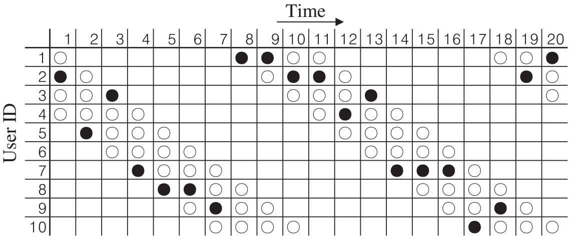

Fig. 2. Resource allocation example of EEFO scheduling with $n^* = 4$ and $N = 10$. Active, idle, and sleeping users are marked by black circles, white circles, and empty boxes, respectively. Non-sleeping users are chosen in a round robin manner to ensure fair resource allocation and to minimize the switching cost.

3.2. EEFO scheduling for users with different mean SNRs

In this section, we consider a more general network for the practical use of EEFO. Since users have different locations in reality, they could have different channel statistics, i.e., different mean SNRs. Let Z_k denote the mean SNR of user k.

Due to different mean SNRs for different users, the throughput $r(\vec{s}(t))$ depends on which users are non-sleeping, so (**P**) cannot be simply reduced to (**S**). Since it is hard to obtain an optimal solution to (**P**) because of complexity, we develop two heuristic approaches to approximate the considered problem: averaging and grouping approaches.

Averaging Approach: Let $\tilde{z}_0 := \frac{1}{N}\sum_k z_k$. Applying $\tilde{z}_0$ for all the users instead of individual z_k, we can approximate (**P**) as the following.

$$(\mathbf{A}) \quad \max_n \qquad \widetilde{U}(n) := \frac{\tilde{r}(n)}{e(n)}$$
$$\text{subject to} \quad 1 \leqslant n \leqslant N,$$

where $\tilde{r}(n) = \widetilde{R}_0 \int_0^\infty \left(1 - \left\{1 - \exp\left(-\frac{1}{\tilde{z}_0}\left(e^{\frac{y}{W}} - 1\right)\right)\right\}^n\right) dy$ and $\widetilde{R}_0$ is estimated using $\tilde{z}_0$. Problem (**A**) is an approximation to (**P**) in the form of (**S**) using the average mean SNR $\tilde{z}_0$. Therefore, using Lemma 1, we can find an optimal number n^*, and schedule these n^* users as non-sleeping to maximize the throughput per energy unit. Users are chosen in a round robin manner to ensure the fairness. We denote this approach by EEFO with Averaging (or simply EEFO-A). The detailed procedure of EEFO-A is the same with EEFO shown in Algorithm 1.

EEFO-A achieves the optimal performance when each user has the same mean SNR, but it cannot achieve the optimal performance in general. Clearly, as the variation $\sum_k |z_k - \tilde{z}_0|$ increases, the performance gap will be enlarged. The error occurs because the mean SNR z_k of user k is different from the system parameter $\tilde{z}_0$ of EEFO-A. This notion motivates us to develop another heuristic algorithm that compensates this difference.

Grouping Approach: The idea is to classify users into several groups according to similar mean SNRs and to serve each group in a round robin manner (or at random) with a different number of non-sleeping users. When each user has the same mean SNR z_0, n^* is a function of z_0 and N. Hence, it will be beneficial to group users according to similar mean SNRs and serve each group differently.

We group N users as follows. For each user k, we first assume that all N users have the same mean SNR z_k and estimate an optimal number of non-sleeping users by solving (**S**). Let n_k^* denote the estimated value for user k. Two users k and m belong to the same group if $n_k^* = n_m^*$. Let $K(j) := \{k | n_k^* = j\}$ denote a group with the estimated value of j and $|K(j)|$ denote the number of users that belong to this group.

For each user k, the estimation n_k^* depends on the mean SNR z_k and the number of users N in the system. Fig. 3 shows the estimated n_k^* of user k from its mean SNR z_k when $N = 10$, 100, and 200. Users with the same n_k^* form group $K(n_k^*)$, and each number in parenthesis indicates

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the average number of users belonging to the group (i.e., $|K(n_k^*)|$) assuming that users are distributed uniformly within the cell. The average number of users in each group is obtained from the group's relative size of area multiplied by the number of users N in the system. When a user has a higher mean SNR, it is directed to belong to the group with a smaller estimation. For instance, when $N = 100$, a user i with the mean SNR of -5 dB belongs to the group with the number of non-sleeping users $n_i^* = 6$. However, a user j with its mean SNR of 15 dB belongs to a group with $n_j^* = 3$. Since each user's rate is a logarithm function of received SNR, the regions in small mean SNR has steeper slope than that in high mean SNR. It means that more number of non-sleeping users is advantageous to exploit the multiuser diversity more in the small mean SNR region. Another interesting observation is that the estimated number of non-sleeping users increases with N. It implies that increasing the number of non-sleeping users is beneficial to exploit the diversity further.

In the grouping approach, we conduct two levels of scheduling. At the higher level, a 'group' is selected first either at random or in a round robin manner (Algorithm 2.5). For simplicity, we use the round-robin method because it has the benefits of guaranteeing a fixed delay and short-term fairness. If group $K(j)$ is scheduled, it will be served for $c \cdot |K(j)|$ time slots where c is a positive integer. For $c \cdot |K(j)|$ slots, the users in the other groups turn off their transceivers and enter the sleeping mode. At the lower level, the 'users' in the selected group $K(j)$ are scheduled by EEFO scheduling for $c \cdot |K(j)|$ slots. During the scheduled slots, j non-sleeping users among $|K(j)|$ users are chosen in a round robin manner for fair resource allocation and report their channel status to the BS. Then one of the j non-sleeping users will be selected for actual transmission according to the channel state. If the optimal number of non-sleeping users in group $K(j)$ is larger than $|K(j)|$, the number of non-sleeping users is set at $|K(j)|$. In this case, all the users in group $K(j)$ feedback their channel status during $c \cdot |K(j)|$ slots which is the same as a plain opportunistic scheduling. We denote this approach by EEFO with Grouping (or simply EEFO-G). Algorithm 2 depicts the detailed procedure of EEFO-G.

Algorithm 2: EEFO-G scheduling algorithm

```
1: /*Initialization: Grouping */
2: Each user measures its mean SNR and reports it to
   BS
3: BS classifies each user into groups according to the
   SNR levels
4:
5: /*Group Scheduling */
6: Choose a group $K(j)$ in a round-robin manner
7:
8: /*Scheduling */
9: Execute Algorithm 1 with $n^* = j$ for $c \cdot |K(j)|$ slots
10:
11: After serving the group for $c \cdot |K(j)|$ slots go to Line 6
```

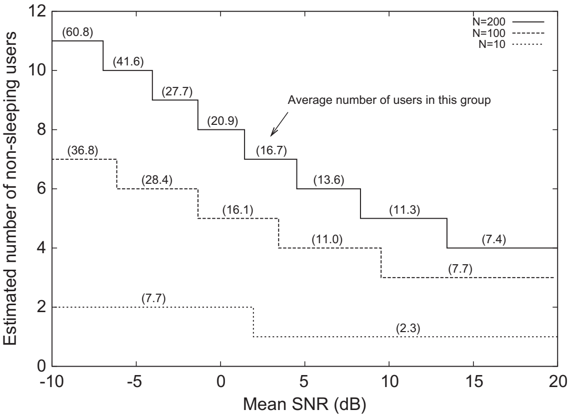

Fig. 3. Estimated number of non-sleeping users under EEFO-G. We assume that users are distributed uniformly within the cell. The distant user and the closet user has mean SNR 20 dB and -10 dB, respectively. For $N = 10$, 100, and 200, y-axis shows the estimation of n_k^* for user k when its mean SNR is given. The average number of users belonging to each group (i.e., $|K(n_k^*)|$) is also shown in the parenthesis.

Fig. 4 illustrates an example of EEFO-G scheduling in a network, where users are classified into two groups of $K(3)$ and $K(5)$. At each time slot, active and idle users are marked by black and white circles, respectively, and all the unmarked users are sleeping. We also shade users if they belong to the group that is not served. In this example, we set c at 1, so groups $K(3)$ and $K(5)$ take turns being scheduled for 6 slots and 10 slots, respectively. At time slots of [1,6], three users among the members of group $K(3)$ are alternatively chosen to be non-sleeping in a round robin manner, and report their channel information to the BS. The other users in group $K(3)$ and all the users in group $K(5)$ are sleeping. After serving group $K(3)$, all the users in group $K(3)$ go to sleep and five users among the members of group $K(5)$ are alternatively chosen for the next 10 time slots, and so on.

Note that as the objective of the original problem (**P**) is to maximize average throughput performance per energy unit with equal time resource allocation, EEFO-G provides equal share of resource allocation when all users have a sufficient large battery. However, when users have a finite energy buffer, some user may deplete their battery earlier than the others. For instance, users in $K(5)$ will exhaust its energy quicker than those in $K(3)$ due to a large amount of channel feedback. As a result, EEFO-G does not provide a strict fairness as EEFO and EEFO-A and shows slight performance decrease in terms of fairness, which can be observed in Fig. 8.

4. Simulations

In this section, we compare the performance of EEFO with other competitive scheduling algorithms in terms of throughput, energy consumption, and total transferred traffic during the network lifetime.

4.1. Simulation settings

We consider a wireless network with a BS and N mobile users. The wireless channel between the BS and user k is

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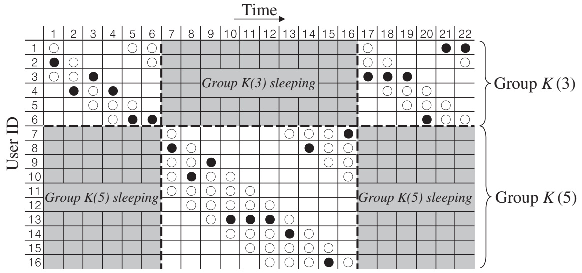

Fig. 4. Resource allocation example of EEFO-G with two groups of $K(3)$ with six users and $K(5)$ with 10 users ($c = 1$). Active, idle, and sleeping users are marked by black circles, white circles, and empty boxes, respectively. Users in the out-of-service group are shaded. When a group $K(j)$ is in service for $|K(j)|$ time slots, j users within the group are chosen to be non-sleeping in a round robin manner to ensure fair resource allocation.

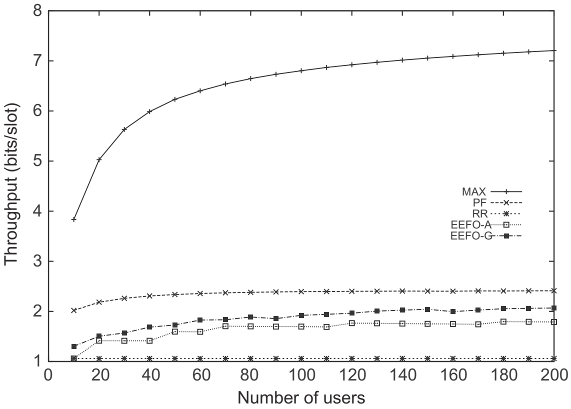

Fig. 5. Throughput performance according to the number of users. MAX outperforms the others because it always chooses a user with the best channel, and PF, EEFO-G, and EEFO-A follow next in order.

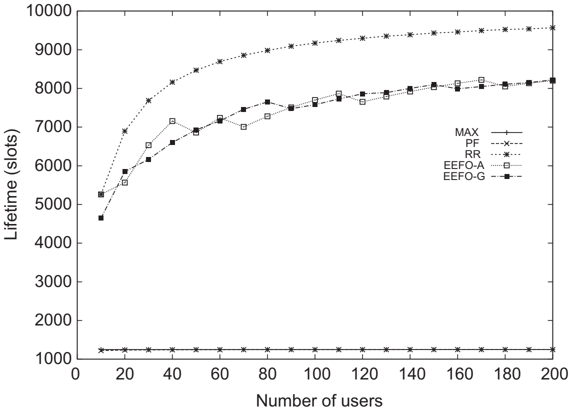

Fig. 6. Network lifetime performance according to the number of users. In contrast to the throughput performance, RR achieves the longest lifetime, and MAX and PF the shortest. The performance difference comes from the number of non-sleeping users at each time slot. The initial energy of each user is 1000α, where α is the amount of energy consumption of an active user for a single time slot.

modeled as a stationary and ergodic i.i.d. process following the Rayleigh fading model with mean SNR z_k. Each user has a limited battery which activation time is up to 1000 time slots. That is, the total energy of a battery is 1000α, where α is the amount of energy consumption of an active user for a single time slot. We set the bandwidth W in the Shannon formula to one.

We obtain the parameter values of α, β, and γ of (7) from the IEEE 802.11a system. In [13], it has been shown that a user consumes $C_s = 132$ mW in sleeping, $C_i = 990$ mW in idle, $C_r = 1320$ mW in receiving, and $C_t = 1820$ mW in transmitting, respectively. We apply these settings to Mobile WiMAX. The frame structure has been simply presented in Fig. 1. In the Mobile WiMAX system, each frame consists of 47 symbols. We can divide the frame into 29 symbols of downlink period and 18 symbols of uplink period. In the downlink period, the first six symbols are reserved for synchronization and resource allocation. In the uplink period, the first symbol is used for the channel feedback. All the other symbols are used for downlink and uplink data transmissions [15]. Let α_{tx} and α_{rx} denote the energy consumption for downlink and uplink transmissions for a frame, respectively. We can estimate each amount of the energy consumption as follows:

$$\alpha_{tx} = 6C_r + 23C_i + 18C_t = 63{,}450\ \text{mW/slot},$$
$$\alpha_{rx} = 29C_r + 1C_t + 17C_i = 56{,}930\ \text{mW/slot},$$
$$\beta = 6C_r + 23C_i + 1C_t + 17C_i = 49{,}340\ \text{mW/slot},$$
$$\gamma = 47C_s = 6{,}204\ \text{mW/slot}.$$

Throughout the simulations, we estimate the total energy consumption of the system with n non-sleeping users for a time slot as

$$e(n) = 1 + \beta'(n-1) + \gamma'(N-n), \tag{12}$$

where β' and γ' are normalized parameters of β and γ, respectively, and configured as $\beta' := \frac{\beta}{\alpha_{tx}} \approx \frac{\beta}{\alpha_{rx}} \approx 0.8$, and $\gamma' := \frac{\gamma}{\alpha_{tx}} \approx \frac{\gamma}{\alpha_{rx}} \approx 0.1$.

4.2. Evaluation of EEFO

We first consider a scenario of 100 users that each user has an identical mean SNR of 10 dB. The throughput denotes the average number of bits transferred in one time slot, and the network lifetime is the number of total time slots when all the users exhaust their energy, and the total transferred traffic is the number of delivered bits during the network lifetime.

We compare the performance of EEFO with those of proportional fair (PF) and round robin (RR) schedulers. For EEFO, we have $n^* = 3$ by solving (**S**). Therefore, there are three non-sleeping users who report their channel status to the BS, one user with the best channel status will be chosen for transmission, and the other 97 users sleep at each time slot. For PF, all the 100 users are non-sleeping and send their channel status to the BS, and for RR, one active user is chosen for transmission in a round robin manner regardless of its channel status while all the others are sleeping.

The simulation results are shown in Table 1. Owing to the multiuser diversity, the throughput of PF is 1.94 times

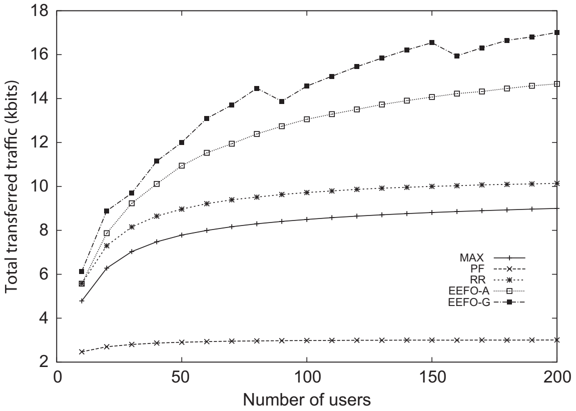

Fig. 7. Total transferred traffic according to the number of users with initial energy of 1000α. EEFO-G and EEFO-A significantly outperform MAX, PF, and RR in terms of bits per energy unit.

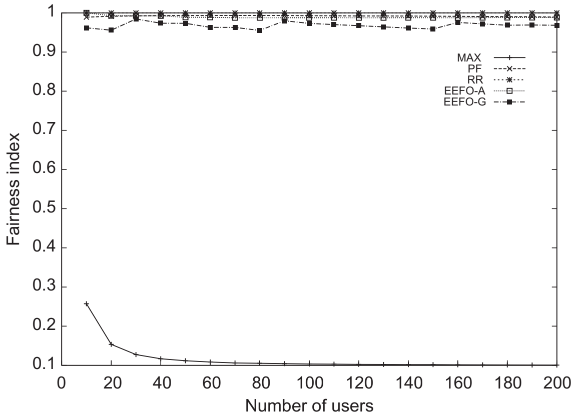

Fig. 8. Fairness index of scheduling policies according to the different number of users N. A reasonably fair resource allocation has been achieved for most scheduling policies except MAX, under which resources are more likely allocated to the user with the higher mean SNR.

greater than that of RR while its energy consumption is also 7.36 times higher than that of RR. Therefore, the total transferred traffic of RR is 3.79 times larger compared to that of PF. EEFO achieves better throughput than RR and consumes much less energy than PF. As a result, it achieves the best performance in terms of total transferred traffic.

4.3. Evaluation of EEFO-A and EEFO-G

In this section, we evaluate the performances of the considered scheduling policies in practical network settings where users have different mean SNRs. We vary N between 10 and 200 that are uniformly distributed within the cell. We assume that the mean SNR of each user depends only on the distance from the BS. The most distant and closest users have the mean SNR of −10 dB and 20 dB, respectively. We evaluate PF, RR, EEFO-A, EEFO-G, and maximum-throughput[4] (MAX) scheduling.

Table 1
Performance comparison of EEFO, PF, and RR for users with the same mean SNR.

Scheduling policies	Throughput (bits/slot)	Network lifetime (slots)	Total transferred traffic (kbits)
PF	5.6844	1248	7.094
RR	2.9301	9171	26.872
EEFO	3.8889	8163	31.745

Fig. 5 shows the system throughput performances per slot according to N. MAX achieves the highest throughput, and PF, EEFO-G, and EEFO-A follow next in order. Since RR does not exploit the multiuser diversity, it achieves the lowest throughput. In terms of network lifetime, Fig. 6 shows that the order of network lifetime has been reversed to that of system throughput. RR has the longest lifetime, and MAX and PF the shortest. EEFO-A and EEFO-G achieve about 80% of the life time in RR.

The total amount of traffic transferred during the lifetime has been depicted in Fig. 7. EEFO-G and EEFO-A significantly outperform the other scheduling policies of MAX, PF, and RR. This confirms that EEFO-G and EEFO-A improve the performance in terms of bits per energy unit. EEFO-G performs better than EEFO-A since it exploits each user's channel condition very well. PF delivers the least amount of traffic per energy unit, which implies that the energy consumption for the channel feedback is substantial.

Finally, we compare the fairness of the scheduling policies. The fairness index I_F^* introduced by Jain et al. [8] is given as

$$I_F^* = \frac{\left(\sum_{k=1}^{N} X_k\right)^2}{N\sum_{k=1}^{N} X_k^2},$$

where X_k denotes the number of time slots allocated to user k. The fairness index has a value in $\left[\frac{1}{N}, 1\right]$. As I_F^* is close to one, time slots are allocated in a fair manner and vice versa. Perfect fairness ($I_F^* = 1$) can be achieved by allocating the same number of time slots to each user. The fairness results are shown in Fig. 8. It shows that all the scheduling schemes except MAX allocate resources to users in a reasonably fair manner. Under MAX, time slots are more likely allocated to the user with the higher mean SNR.

5. Conclusion

Opportunistic scheduling is a key MAC layer technology for enhancing throughput performance by exploiting the multiuser diversity. However, when it comes to energy consumption, e.g., network lifetime, the performance of opportunistic scheduling is significantly poorer even than that of the conventional round robin (RR) scheduling. There is a fundamental tradeoff between the performance gain from the multiuser diversity and the energy consumption for the channel feedback.

In this paper, we proposed energy-efficient opportunistic scheduling (EEFO) that combines opportunistic scheduling with energy-efficient sleep/awake scheduling. EEFO controls the number of non-sleeping users that feedback

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[4] All the users feedback their channel status to the BS, and the user with the highest channel rate is scheduled.

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their channel conditions to the BS. We considered two heuristic algorithms to select an optimal set of non-sleeping users; EEFO with averaging (EEFO-A) and EEFO with grouping (EEFO-G). These schemes improve energy efficiency while exploiting multiuser diversity to increase system throughput. As a result, EEFO schemes enable the network lifetime to be prolonged significantly at the cost of a slight degradation in the system throughput compared to PF scheme, and accordingly transfers a largest amount of traffic under a given battery energy constraint.

In future work, we need to develop more advanced grouping method to enhance throughput performance. Also we need to work on an on-line grouping algorithm, considering each group dynamically changes in size by joining or leaving of users.

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Sung-Guk Yoon is currently a Ph.D. candidate in the School of Electrical Engineering and Computer Science, Seoul National University. He received his B.S. degree from Seoul National University, in 2006. His research interests include fourth-generation wireless networks, cross-layer optimization, resource management, and power line communication.

Changhee Joo received his Ph.D. degree from Seoul National University, Korea, 2005. In 2005, he worked at the Center of Wireless Systems and Applications, Purdue University, as an associated researcher. In July 2007, he moved in The Ohio State University, Columbus, Ohio, USA. In March 2010, he joined Korea University of Technology and Education, Korea. His research interests include multi-hop wireless networks, cross-layer optimization, data aggregation, congestion control and active queue management. He is a member of IEEE, and a recipient of the IEEE INFOCOM 2008 best paper award.

Saewoong Bahk received B.S. and M.S. degrees in Electrical Engineering from Seoul National University in 1984 and 1986, respectively, and the Ph.D. degree from the University of Pennsylvania in 1991. From 1991 through 1994 he was with AT&T Bell Laboratories as a member of technical staff where he worked for AT&T network management. In 1994, he joined the school of electrical engineering at Seoul National University and currently serves as a professor. He has been serving as TPC members for various conferences including ICC, GLOBECOM, INFOCOM, PIMRC, WCNC, etc. He is on the editorial board of Journal of Communications and Networks (JCN). His areas of interests include performance analysis of communication networks and network security. He is an IEEE senior member and a member of Who's Who Professional in Science and Engineering.

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