Low-Complexity Energy-Efficient Scheduling for Uplink OFDMA*

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Abstract

Energy efficient transmission in wireless communications is very important as mobile devices are battery-constrained. For mobile devices in a cellular system, uplink power consumption dominates the wireless power budget, due to the RF power requirements for reliable communications over long distances. Our previous work in this area demonstrated significant energy savings in uplink cellular OFDMA transmissions, with iterative approaches maximizing the instantaneous bits-per-Joule energy efficiency. In this paper, we use a time-averaged bits-per-Joule metric to develop low-complexity schemes. Specifically, we obtain closed-form solutions for energy-efficient link adaptation in frequency-selective channels. We also derive closed-form approaches for the maximum arithmetic and geometric mean energy-efficient schedulers. Simulation results show that the proposed schemes not only have low complexity but also perform close to the globally optimum solutions obtained through exhaustive search.

Index Terms– energy efficiency, OFDMA, bits per Joule, link adaptation, resource allocation

* This work was supported by Intel Corp. and the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-20-0011.

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I. Introduction

While standards are designing higher capacity wireless links to meet increasing demand from multimedia applications, device power consumption is also increasing. Slow improvement of battery technologies [1] has lead to an exponentially increasing gap between the demand for energy and the battery capacity offered [2]. Besides, shrinking device sizes further impose an ergonomic limit on battery capacity. Hence, power efficiency is becoming increasingly important for wireless system design.

Energy consumption is affected by all layers of system design and needs to be tackled across all layers [2]–[11]. Additionally, *orthogonal frequency division multiple access* (OFDMA) has emerged as one of the prime multiple access schemes for next generation wireless networks [12], [13]. While extensive research has been done to improve throughput [14], [15], limited has been conducted for energy-efficient communications in OFDMA systems. Our previous work in [16]–[19] studied uplink energy-efficient communications in OFDMA systems to improve utilization of mobile energy. Specifically, we focused on optimizing a "bits-per-Joule" metric to target energy-efficiency instead of throughput or peak rates. Circuit power consumption, in addition to transmit power was also included in our optimization. Significant energy savings were demonstrated with energy optimal link adaptation and resource allocation schemes for uplink flat fading channels in [16]. We show that for energy-efficient transmission, both modulation order and energy efficiency increase with channel gain. Furthermore, the modulation order on each subchannel should decrease with the number of subchannels assigned while the energy efficiency increases. In [17], [18], we further address energy-efficient link adaptation for frequency-selective fading channels. We derived the necessary and sufficient conditions for a unique globally optimal link adaptation solution to exist and developed iterative methods to obtain this solution. In contrast to the existing water-filling power allocation schemes that maximize throughput under overall transmit power constraint [14], [15], our scheme adjusts both overall transmit power and its allocation according to the states of all subchannels and circuit power consumption to optimize energy efficiency. While increasing bandwidth allocation for a user always improves energy efficiency, all subchannels can not be allocated exclusively to one user in a multi-user system due to fairness issues. Hence, a system approach is critical in determining the overall network energy efficiency. We investigated resource allocation techniques both with and without fairness constraint for uplink OFDMA systems assuming flat-fading channels in [16] and developed globally optimal subchannel assignment policies that maximize the overall network energy efficiency. In [19], we further develop energy-efficient power optimization schemes for interference-limited communications. Both cooperative and noncooperative energy-efficient power optimization approaches are designed. For the noncooperative approach, we show that the equilibrium always exists. Furthermore, when there is only one subchannel or the channel experiences flat fading, there will be a unique equilibrium. However, in frequency-selective channels, this is not true in general. We give a sufficient condition that assures the uniqueness. Simulation results show that the proposed scheme improves not only energy efficiency but also spectral efficiency uniformly for all users due to the conservative nature of energy-efficient power allocation, which reduces other-cell interference to improve the overall network throughput.

This paper develops schemes to reduce the complexity associated with the iterative search techniques developed in [16]–[19]. Both low-complexity energy-efficient link adaptation and resource allocation schemes are designed. We use a time-averaged "bits-per-Joule" energy efficiency metric to obtain closed-form link adaptation and resource allocation schemes for uplink OFDMA systems in frequency-selective channels.

The rest of the paper is organized as follows. In Section II, we describe the system model and design objectives. Then we develop energy-efficient link adaptation in Section III and resource allocation schemes in Section IV. Simulation results are provided in Section V. Finally, we conclude the paper in Section VI.

II. System Description

We focus on the uplink OFDMA system shown in Figure 1, as the *radio frequency* (RF) transmit power for a user dominates the limited power budget of a battery-constrained mobile device. The *base station* (BS) assigns subchannels for each user to optimize the overall network energy efficiency. Channels are assumed to be frequency-selective and with block fading, i.e. the channel state is constant within each frame [20]. Accurate channel state information is available to both BS and mobile users to optimize energy-efficient communications. The link adaptation and resource allocation settings are allowed to vary from one frame to another according to the channel state information.

Consider a network with N users and K subchannels. Denote the index set of all subchannels as $\mathcal{K} = \{1, 2, \cdots, K\}$. Denote the index set of subchannels assigned to User n at Frame t to be $\mathcal{C}_n[t]$. Each subchannel is only assigned to one user during a frame. Then,

$$\begin{aligned} &\mathcal{C}_i[t] \bigcap \mathcal{C}_j[t] = \emptyset, \forall i \neq j \\ &\bigcup_i \mathcal{C}_i[t] \subseteq \mathcal{K}, \end{aligned} \tag{1}$$

where $\emptyset$ is an empty set. The data rate of User n is

$$r_n[t] = \sum_{k \in \mathcal{C}_n[t]} r_{nk}[t], \tag{2}$$

where $r_{nk}[t]$ is the data rate of User n at subchannel k. The average throughput of User n at Frame t, $T_n[t]$, is obtained using an exponentially weighted low-pass filter,

$$T_n[t] = (1 - \frac{1}{w})T_n[t-1] + \frac{1}{w}r_n[t], \tag{3}$$

where $w \gg 1$.

Denote the *signal-to-noise ratio* (SNR) for reliable reception of $r_{nk}[t]$ to be

$$\eta_{nk} = S(r_{nk}[t]). \tag{4}$$

Similar to the argument in [16], function $S(r)$ is assumed to be strictly convex in r and $S(0) = 0$. Denote the signal power attenuation of User n at Subchannel k at Frame t to be $g_{nk}[t]$, then required power to transmit at a rate of $r_{nk}[t]$ will be

$$p_{nk}[t] = \frac{\eta_{nk}\sigma^2}{g_{nk}[t]} = \frac{S(r_{nk}[t])\sigma^2}{g_{nk}[t]}, \tag{5}$$

where σ^2 is the noise power on each subchannel.

The overall transmit power of User n is

$$p_n[t] = \sum_{k \in \mathcal{C}_n[t]} p_{nk}[t]. \tag{6}$$

As indicated in [16], [17], circuit power, p_c, in addition to the transmit power, also plays an important role in energy-efficient communications. While transmit power is used for reliable data transmission, circuit power represents energy consumption of device electronics. The overall average power consumption, $P_n[t]$, is also obtained using an exponentially weighted moving average low-pass filter, that is,

$$P_n[t] = (1 - \frac{1}{w})P_n[t-1] + \frac{1}{w}(p_n[t] + p_{cn}[t]). \tag{7}$$

The circuit power, $p_{cn}[t]$, is user and time dependent. $p_{cn}[t]$ is measured at Frame t by each mobile.

For energy-efficient communications, users want to send as much data as possible with a given amount of energy. Hence, with energy $\triangle e$ consumed in a duration $\triangle t$, User n wants to send a maximum amount of data by choosing $r_{nk}[t], k \in \mathcal{C}_n[t]$, to maximize

$$\frac{T_n[t] \triangle t}{\triangle e}, \tag{8}$$

which is equivalent to maximize

$$u_n[t] = \frac{T_n[t]}{\triangle e / \triangle t} = \frac{T_n[t]}{P_n[t]}. \tag{9}$$

u_n is called average energy efficiency of User n. Adapting transmission rate and power to optimize equation (9) is referred to as energy-efficient link adaptation.

If we fix the overall transmit power, the objective of Equation (9) is equivalent to maximizing the overall throughput and existing water-filling power allocation approaches [14], [21] can be used. However, besides adapting the power distributions on all subchannels, the overall transmit power can also be adapted according to the states of all subchannels and the history of data transmission and power consumption to maximize the average energy efficiency. Hence, the solution to Equation (9) is different from existing power allocation schemes that maximize throughput with power constraints.

The BS determines subchannel assignment to optimize the overall network performance. We consider two multi-user performance metrics, arithmetic and geometric means. The resource management is optimized to maximize the arithmetic or geometric average of the performances of all users with arithmetic- or geometric-mean metric. Considering these performance metrics in the context of spectral efficiency, we note that the arithmetic-mean metric leads to power allocation for sum throughput maximization, which assures no fairness since some users may have zero throughput. However, the geometric-mean metric leads to a solution for throughput product maximization and assures proportional fairness among all users [22], [23]. Analogously, we call energy efficiency optimization schemes using geometric- or arithmetic-mean metrics to be energy-efficient schedulers with or without fairness.

When using the arithmetic-mean metric, the subchannels are allocated to maximize the arithmetic average of the energy efficiency of all users, i.e. to maximize

$$U[t] = \sum_{n=1}^{N} u_n[t]. \tag{10}$$

When using the geometric-mean metric, the subchannels are allocated to maximize the geometric average of the energy efficiency of all users, i.e. to maximize

$$V[t] = \sum_{n=1}^{N} \log(u_n[t]). \tag{11}$$

For the above optimization, consider a special case that the circuit power dominates the power consumption, i.e.

$$p_{cn}[t] \gg p_n[t], \qquad \forall t. \tag{12}$$

This is usually true for short-range communications as low transmit power is needed to compensate for path loss. In this case, maximizing energy efficiency (9) is equivalent to maximizing throughput $T_n[t]$ as $P_n[t]$ is almost independent of power allocation and rate adaptation. Correspondingly, (10) is equivalent to maximizing the sum of throughput weighted by the inverse of circuit power and (11) equals maximizing the product of throughput. The dependence of the optimization on circuit power will be further demonstrated later.

In the following, we develop link adaptation and resource allocation strategies in closed-forms, based on optimizing the energy efficient metrics discussed in this section.

III. Energy-Efficient Link Adaptation

In this section, we investigate energy-efficient link adaptation for a user with a given channel assignment. Therefore, user index n is dropped in the subsequent discussion in this section.

We need to determine the data rates at all subchannels to maximize

$$\begin{aligned} u[t] =& \frac{T[t]}{P[t]} \\ =& \frac{(1-\frac{1}{w})T[t-1] + \frac{1}{w}\sum_k r_k[t]}{(1-\frac{1}{w})P[t-1] + \frac{1}{w}(\sum_k p_k[t] + p_c[t])}, \end{aligned} \tag{13}$$

where $p_k[t+1]$ is given by (5).

Denote $c = |\mathcal{C}[t]|$, which is the number of elements in $\mathcal{C}[t]$ and $\mathcal{C}[t] = \{k_i | k_1 < k_2 < \cdots < k_c\} \subseteq \mathcal{K}$. Denote the data rate vector to be $\mathbf{r}[t] = [r_{k_1}[t], r_{k_2}[t], \cdots, r_{k_c}[t]]$. Then $u[t]$ is a function of $\mathbf{r}_k[t]$. It is easy to see that the sublevel sets

$$S_\alpha = \{\mathbf{r}[t] \big| u[t] \geq \alpha\} \qquad \text{for any real } \alpha, \tag{14}$$

are strictly convex. Hence, $u[t]$ is a strictly quasi-concave function optimized on a convex set $\mathbf{r}[t]$ [24] and a unique globally optimal rate vector, $\mathbf{r}^*[t]$, exists and every element in $\mathbf{r}^*[t]$ satisfies

$$\frac{\partial u[t]}{\partial r_k[t]} = 0 \tag{15}$$

if $r_k[t] > 0$. Solving (15) yields the following optimal rate condition

$$\frac{\partial p_k[t]}{\partial r_k[t]} = \frac{P[t]}{T[t]} = \frac{1}{u[t]}, \forall k. \tag{16}$$

Since $w \gg 1$, $P[t] \approx P[t-1]$, and $T[t] \approx T[t-1]$,

$$\frac{\partial p_k[t]}{\partial r_k[t]} = \frac{P[t-1]}{T[t-1]} = \frac{1}{u[t-1]}, \forall k. \tag{17}$$

Together with (5), we have

$$S^{'}(r_k[t]) = \frac{1}{u[t-1]} \frac{g_k[t]}{\sigma^2}, \forall k. \tag{18}$$

where $S^{'}(\cdot)$ is the first-order derivative of the function $S(\cdot)$. Consequently, the optimal data rate follows immediately,

$$r_k^*[t] = \max\left(S^{'-1}(\frac{1}{u[t-1]} \frac{g_k[t]}{\sigma^2}), 0\right) \forall k \in \mathcal{C}[t]. \tag{19}$$

where $S^{'-1}()$ is the inverse function of $S^{'}$. The corresponding optimal power allocation is

$$p_k^*[t] = \frac{S(r_k^*[t])\sigma^2}{g_k[t]}, \forall k \in \mathcal{C}[t]. \tag{20}$$

If the Shannon capacity [21] is achieved on each subchannel, $S(r) = 2^{\frac{r}{B}} - 1$, where B is the subchannel bandwidth. The optimal data rate is

$$r_k^*[t] = \max\left(B \log_2 \left(\frac{B g_k[t]}{u[t-1]\sigma^2 \log 2}\right), 0\right) \forall k \in \mathcal{C}[t]. \tag{21}$$

The corresponding optimal power allocation is

$$p_k^*[t] = \max\left(\frac{B}{u[t-1] \log 2} - \frac{\sigma^2}{g_k[t]}, 0\right) \forall k \in \mathcal{C}[t], \tag{22}$$

which is a water-filling power allocation with a water level of $\frac{B}{u[t-1]\log 2}$. We can see that the energy-efficient link adaptation in (19), (20), (21), and (22) is determined by $u[t-1]$ and $g_k[t]$, and is expressed in closed form. This significantly reduces the complexity associated with the iterative solutions developed earlier in [16]. The low-complexity energy-efficient water-filling power allocation in (22) can be illustrated in Figure 2, in which every shadowed part corresponds to the power allocated on each subchannel.

IV. Energy-Efficient Resource Allocation

In this section we will consider low-complexity energy-efficient resource allocation. We will be using the index n to refer to a particular user in this multi-user case. Schedulers based on both the arithmetic and the geometric mean will be considered.

A. Max Arithmetic Mean Energy-Efficient Scheduler

In this section, the subchannels are assigned such that the sum energy efficiency $U[t]$ is maximized. Since $U[t-1]$ is fixed, it is equivalent to maximize

$$\begin{aligned}\triangle U &= U[t] - U[t-1] \\ &= \sum_{n=1}^{N} u_n[t] - \sum_{n=1}^{N} u_n[t-1] \\ &= \sum_{n=1}^{N} (u_n[t] - u_n[t-1]).\end{aligned} \tag{23}$$

We can see that

$$\begin{aligned}u_n[t] - u_n[t-1] &= \frac{T_n[t]}{P_n[t]} - \frac{T_n[t-1]}{P_n[t-1]} \\ &= \frac{T_n[t]P_n[t-1] - P_n[t]T_n[t-1]}{P_n[t]P_n[t-1]}.\end{aligned} \tag{24}$$

Substituting Equations (3) and (7) into (24), we have

$$
\begin{aligned}
& u_n[t] - u_n[t-1] \\
&= \left(P_n[t-1] \sum_{k \in \mathcal{C}_n[t]} r_{nk}[t] - T_n[t-1] (\sum_{k \in \mathcal{C}_n[t]} p_{nk}[t] + p_{cn}[t]) \right) / (w P_n[t] P_n[t-1]) \\
&= \sum_{k \in \mathcal{C}_n[t]} \frac{P_n[t-1] r_{nk}[t] - T_n[t-1] p_{nk}[t]}{w P_n[t] P_n[t-1]} - \frac{T_n[t-1] p_{cn}[t]}{w P_n[t] P_n[t-1]} \\
&= \sum_{k=1}^{K} I_k(\mathcal{C}_n[t]) \frac{P_n[t] r_{nk}[t] - T_n[t-1] p_{nk}[t]}{w P_n[t] P_n[t-1]} - \frac{T_n[t-1] p_{cn}[t]}{w P_n[t] P_n[t-1]},
\end{aligned}
$$

where indicator function $I_k(\mathcal{C}_n)$ is defined as

$$
I_k(\mathcal{C}_n) = \begin{cases} 1 & k \in \mathcal{C}_n, \\ 0 & \text{otherwise.} \end{cases} \tag{25}
$$

Hence, the subchannel assignment is to maximize

$$
\begin{aligned}
\triangle U = & \sum_{n=1}^{N} (u_n[t] - u_n[t-1]) \\
= & \sum_{n=1}^{N} \sum_{k=1}^{K} I_k(\mathcal{C}_n[t]) \frac{P_n[t-1] r_{nk}[t] - T_n[t-1] p_{nk}[t]}{w P_n[t] P_n[t-1]} \\
& - \sum_{n=1}^{N} \frac{T_n[t-1] p_{cn}[t]}{w P_n[t] P_n[t-1]} \\
= & \sum_{k=1}^{K} \sum_{n=1}^{N} I_k(\mathcal{C}_n[t]) \frac{P_n[t-1] r_{nk}[t] - T_n[t-1] p_{nk}[t]}{w P_n[t] P_n[t-1]} \\
& - \sum_{n=1}^{N} \frac{T_n[t-1] p_{cn}[t]}{w P_n[t] P_n[t-1]}.
\end{aligned}
$$

Denote the allocation metric to be

$$\begin{aligned} J(n,k) &= \frac{P_n[t-1]r_{nk}[t] - T_n[t-1]p_{nk}[t]}{P_n[t]P_n[t-1]} \\ &\approx \frac{P_n[t-1]r_{nk}[t] - T_n[t-1]p_{nk}[t]}{P_n^2[t-1]} \\ &= \frac{r_{nk}[t]}{P_n[t-1]} - u_n[t-1]\frac{p_{nk}[t]}{P_n[t-1]}, \end{aligned} \tag{26}$$

where $r_{nk}[t]$ is given by (19) and $p_{nk}[t]$ (20).

It is easy to see that $\triangle U$ is maximized by assigning subchannel k to the user with the highest allocation metric $J(n,k)$ on that subchannel, that is, the optimal subchannel assignment is

$$\mathcal{C}_n^* = \{k | J(n,k) > J(m,k), \forall m \neq n\}, \forall n. \tag{27}$$

When the circuit power dominates the power consumption, the allocation metric is

$$J_t(n,k) \approx \frac{r_{nk}[t]}{P_n[t-1]}. \tag{28}$$

Assume all users consume the same circuit power and $P_n[t-1]$ is the same for all users. Since the user with the maximum $r_{nk}[t]$ is the same as the one with the maximum SINR on that subchannel, the energy-efficient scheduler is equivalent to applying the traditional max-SINR scheduler on each subchannel to achieve the highest spectral efficiency [25], which is,

$$\mathcal{C}_n^* = \{k | r_{n,k} > r_{m,k}, \forall m \neq n\}, \forall n. \tag{29}$$

B. Max Geometric Mean Energy-Efficient Scheduler

In order to maximize the geometric mean of the energy efficiency of all users, the subchannels are assigned to maximize

$$V[t] = \sum_{n=1}^{N} \log(u_n[t]), \tag{30}$$

which is equivalent to maximize

$$\begin{aligned} \triangle V &= V[t] - V[t-1] \\ &= \sum_{n=1}^{N} \log(u_n[t]) - \sum_{n=1}^{N} \log(u_n[t-1]) \\ &= \sum_{n=1}^{N} \left(\log\left(\frac{T_n[t]}{T_n[t-1]}\right) - \log\left(\frac{P_n[t]}{P_n[t-1]}\right)\right). \end{aligned} \tag{31}$$

Using the Taylor series expansion and the fact that $w \gg 1$, we can express

$$\begin{aligned} \log\left(\frac{T_n[t]}{T_n[t-1]}\right) &= \log\left(1 - \frac{1}{w} + \frac{\frac{1}{w}\sum_{k\in\mathcal{C}_n} r_{nk}[t]}{T_n[t-1]}\right) \\ &\approx \log(1-\frac{1}{w}) + \frac{\sum_{k\in\mathcal{C}_n} r_{nk}[t]}{T_n[t-1](w-1)}. \end{aligned} \tag{32}$$

Similarly, we have

$$\begin{aligned} &\log\left(\frac{P_n[t]}{P_n[t-1]}\right) \\ &\approx \log(1-\frac{1}{w}) + \frac{\sum_{k\in\mathcal{C}_n} p_{nk}[t] + p_{cn}[t]}{P_n[t-1](w-1)}. \end{aligned} \tag{33}$$

Hence, $\triangle V$ can be expressed by

$$\begin{aligned} \triangle V = \sum_{n=1}^{N} \Bigg(&\frac{\sum_{k\in\mathcal{C}_n[t]} r_{nk}[t]}{T_n[t-1](w-1)} \\ &- \frac{\sum_{k\in\mathcal{C}_n[t]} p_{nk}[t] + p_{cn}[t]}{P_n[t-1](w-1)}\Bigg) \end{aligned}$$

$$
\begin{aligned}
&= \sum_{n=1}^{N}\sum_{k=1}^{K}\Big(I_k(\mathcal{C}_n[t])\big(\frac{r_{nk}[t]}{T_n[t-1](w-1)} \\
&-\frac{p_{nk}[t]}{P_n[t-1](w-1)}\big)\Big) - \sum_{n=1}^{N}\frac{p_{cn}[t]}{P_n[t-1](w-1)} \\
&= \sum_{k=1}^{K}\sum_{n=1}^{N}\Big(I_k(\mathcal{C}_n[t])\big(\frac{r_{nk}[t]}{T_n[t-1]} \\
&-\frac{p_{nk}[t]}{P_n[t-1]}\big)/(w-1)\Big) - \sum_{n=1}^{N}\frac{p_{cn}[t]}{P_n[t-1](w-1)}.
\end{aligned}
$$

Denote the allocation metric to be

$$
J_f(n,k) = \frac{r_{nk}[t]}{T_n[t-1]} - \frac{p_{nk}[t]}{P_n[t-1]}, \tag{34}
$$

where $r_{nk}[t]$ is given by (19) and $p_{nk}[t]$ (20).

$\triangle V$ is maximized by assigning subchannel k to the user with the highest allocation metric $J_f(n,k)$ on that subchannel, that is, the optimal subchannel assignment achieving proportional fairness is

$$
\mathcal{C}_n^* = \{k | J_f(n,k) > J_f(m,k), \forall m \neq n\}, \forall n. \tag{35}
$$

When the circuit power dominates the power consumption, the allocation metric is

$$
J_{tf}(n,k) \approx \frac{r_{nk}[t]}{T_n[t-1]}, \tag{36}
$$

and the energy-efficient scheduler is equivalent to applying the traditional proportional-fair scheduler [22], [23] on each subchannel, that is,

$$
\mathcal{C}_n^* = \{k | J_{tf}(n,k) > J_{tf}(m,k), \forall m \neq n\}, \forall n. \tag{37}
$$

V. Simulation Results

In the previous sections, we have obtained closed-form and approximate expressions for energy efficient link adaptation and resource allocations, using the average energy efficiency metric. In this section, we compare the proposed schemes with the global optima to evaluate the suboptimality gap. The global optima are obtained by exhaustive search. Since the weight of the exponentially weighted low-pass filter determines approximation accuracy, we focus on its impact on the system performance.

We consider a system with 8 subchannels to reduce complexity of exhaustive search. The subchannels are experiencing independent and identically-distributed Rayleigh fading with unit average power gain. Capacity approaching coding is assumed. Figure 3 shows the suboptimality gap of energy-efficient link adaptation. The energy efficiency of the proposed link adaptation is normalized by the energy efficiency of the global optimal solution. We show the normalized energy efficiency when different weights, ws, are used. We also change the average transmit power to circuit power ratio, ϵ, by varying the circuit power. We can observe that the proposed link adaptation performs closely to the global optimum, with a performance loss of less than 2% when $w > 10$. Similarly, we show the normalized energy efficiency of different schedulers in Figure 4 when there are three users in the system. The performance loss is within 5% when $w > 20$ for the proposed schedulers.

VI. Conclusion

We have considered uplink energy-efficient communications in OFDMA systems since mobile stations are battery powered. Time-varying circuit power is accounted for system design. Based on optimizing a time averaged energy efficiency metric, we first obtain a closed-form link adaptation scheme for frequency-selective channels. Furthermore, as a system approach is critical in determining the overall network performance, we also design maximum-energy-efficiency and proportional fair energy-efficient schedulers, both in closed forms. Our simulation results show that the proposed low-complexity schemes perform close to the optimum that is obtained by exhaustive search.

ACKNOWLEDGMENT

The authors would like to thank Dave Bormann, Changho Suh, Hongseok Kim, and Ozgur Oyman for helpful discussions.

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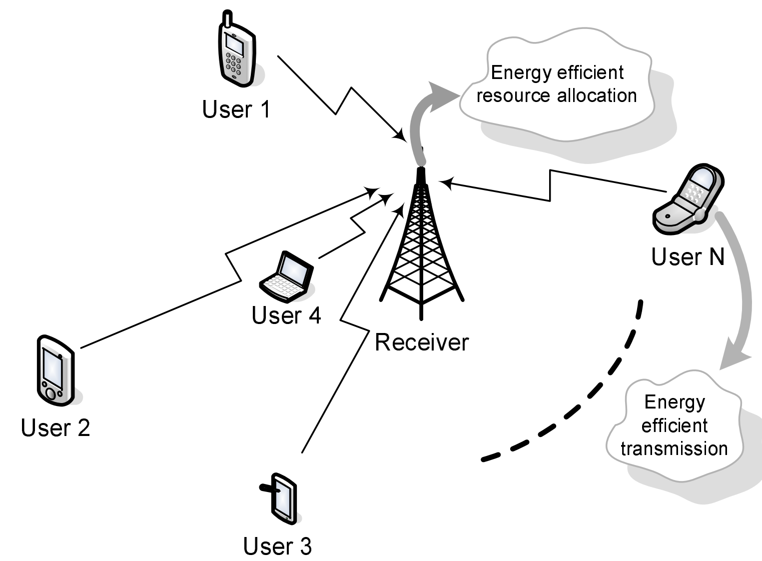

Fig. 1: Network Architecture

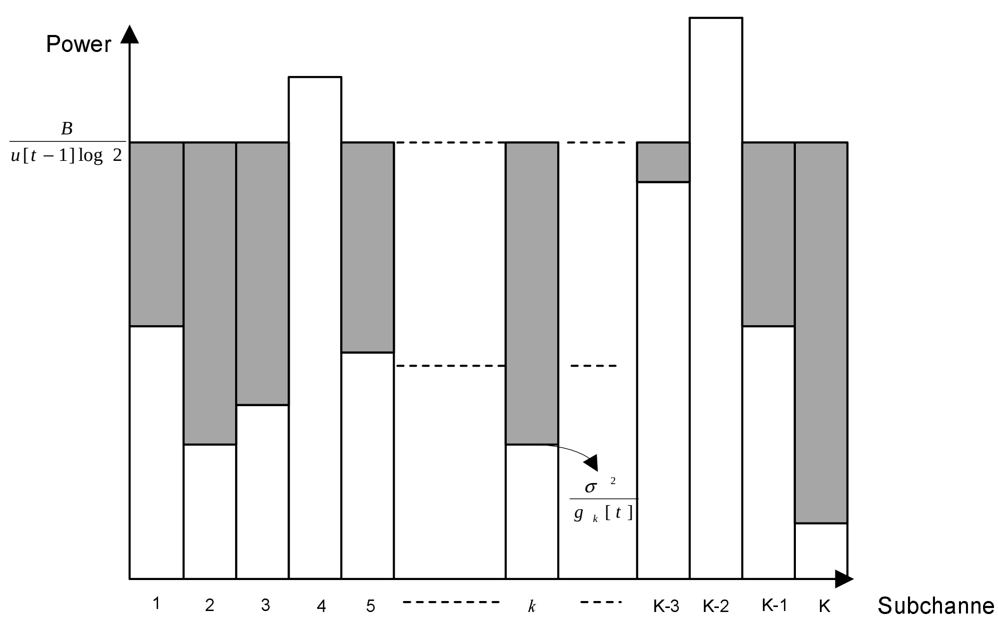

Fig. 2: Low-complexity energy-efficient water-filling power allocation

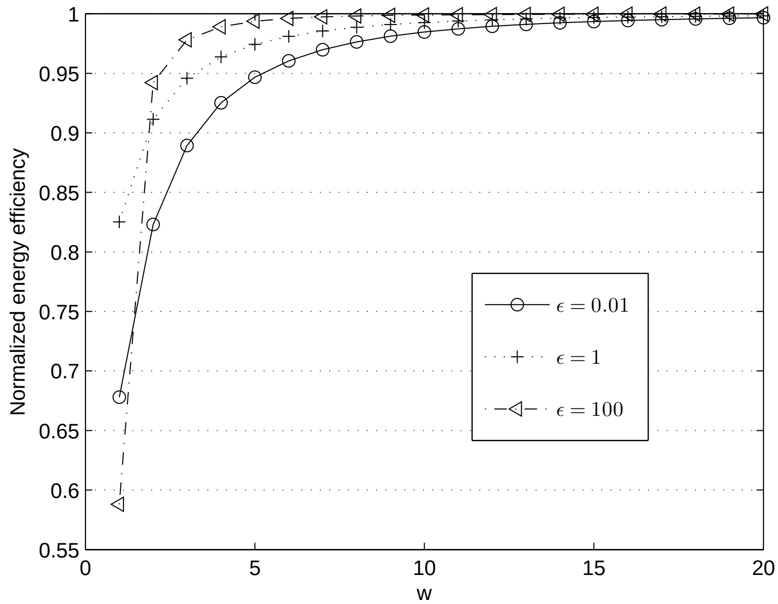

Fig. 3: Normalized energy efficiency of one link

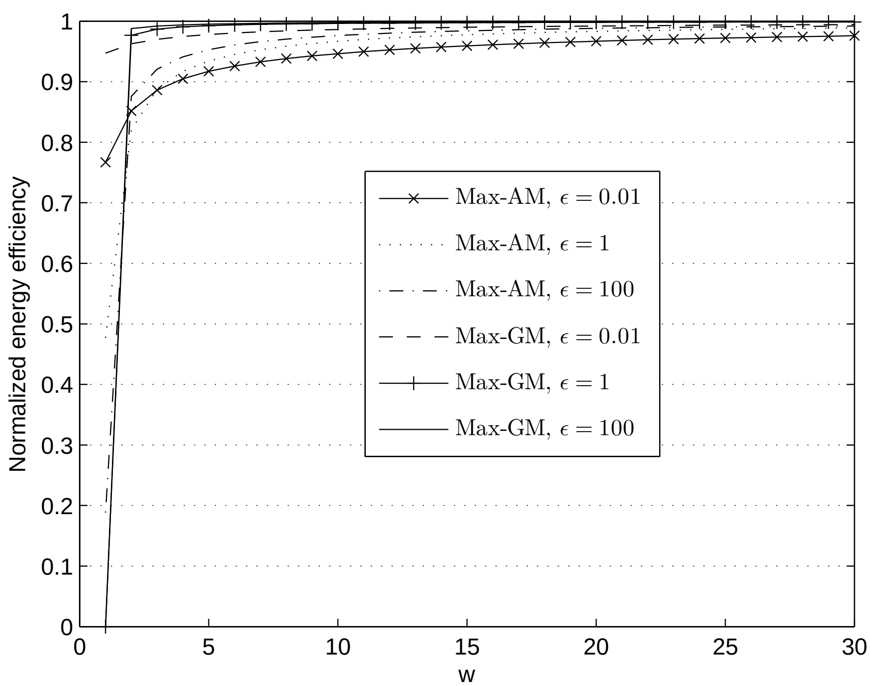

Fig. 4: Normalized average energy efficiency of a three-user network