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# Impact of Channel State Information on Energy Efficient Transmission in Interference Channels

Gam D. Nguyen[1], Sastry Kompella[1], Clement Kam[1], Jeffrey E. Wieselthier[2], and Anthony Ephremides[3]

[1]Information Technology Division, Naval Research Laboratory, Washington, DC
[2]Wieselthier Research, Silver Spring, MD
[3]Electrical and Computer Engineering Department, University of Maryland, College Park

**Abstract.** We study the energy-efficient transmission problem for a time-varying interference channel. Assume that each source transmits in each time slot according to a transmission probability, which is a continuous value between 0 and 1. Our goal is to determine the values of the transmission probabilities and the transmission power levels so that the network energy efficiency is maximized. We show that the energy efficiency is maximized when the transmission probabilities are either 0 or 1. We also show that simultaneous transmissions reduce energy efficiency. We then address the impact of the accuracy and timeliness of channel state information (CSI) on energy efficiency. The following cases are considered: perfect CSI, erroneous CSI, delayed CSI, and unknown CSI.

## 1 Introduction

The improvement of energy efficiency is an important objective for modern system and network design, due to the growing concerns about the cost and environmental impacts of energy production and consumption, as well as the proliferation of sensor systems whose lifetime is limited by the constraints of finite battery energy. Many research activities (such as publications, workshops, conferences, and projects) are dedicated to green communication and networking [2, 4, 5, 7, 9, 11]. This paper addresses energy efficiency achievable by transmission methods that exploit channel state information (CSI) in a time-varying interference channel.

A $K$-user *interference channel* (IC) consists of $K$ sources $S_1, S_2, \ldots, S_K$ that wish to send their separate information to $K$ destinations $D_1, D_2, \ldots, D_K$ via a common channel. Transmissions are affected by receiver noise, channel fading, and other-user interference. The IC consists of $K$ direct links and $K(K-1)$ interference links. The case of $K = 2$ is shown in Fig. 1.

In this paper we focus on the IC [1, 3, 6], which is fundamental and pervasive in the wireless environment (other forms of communication networking are reserved for future studies). While research on the IC typically addresses the capacity rate regions, we aim to address the energy-efficiency criterion. Knowledge of CSI can be exploited for improving system performance in a time-varying channel. For example, when CSI (such as a measured/estimated channel fading level) is known for some period of time, an appropriate subset of users can be scheduled for transmission during that time period. The optimal scheduling problem for maximizing the network *rate* under various forms of CSI is studied in [8] for the case of $K = 2$. In this paper, instead of rate-maximization, we are more concerned with energy efficiency, which is related to the number of successfully transmitted bits per unit energy and is an important performance criterion in communication systems and networks.

The contributions and organization of our paper are summarized as follows. First, we formulate the joint optimization problem of transmission control and power control for optimal energy efficiency in a time-varying $K$-user IC. Assume that source $S_i$ transmits with probability $p_i$, which is a continuous value between 0 and 1, and can vary with time, based on channel conditions. Our goal is to determine the vector $(p_1, p_2, \ldots, p_K)$ and the corresponding transmission power vector $(P_1, P_2, \ldots, P_K)$ so that the network energy efficiency is maximized. In this paper, we show that the maximum energy efficiency is achieved if the transmission probabilities $p_i$ are either 0 or 1 (see Theorem 1 of Section 2). This result, which holds for *any* form of fading and receiver noise, implies that the search space for the optimal probabilities is reduced from an infinite and continuous space to a finite set of points. Thus, our problem is equivalent to that of determining a subset of transmission nodes and transmission power levels to maximize energy efficiency.

Next, we consider an IC consisting of link states that vary according to Markov chains (as in [8]). For each time slot, given the channel state in that slot, the goal is to specify which sources and the power levels used for transmission to maximize energy efficiency. We show that, as long as the energy-efficiency maximization is the main concern, simultaneous transmissions should be avoided (see Theorem 2 of Section 2). This observation is useful for scheduling energy-efficient transmissions. In particular, we shows that the optimal set of transmission sources can be found with linear complexity $\mathrm{O}(K)$, which is significantly lower than the exponential complexity $\mathrm{O}(2^K)$ required by exhaustive search.

We then address the exploitation of CSI for energy-efficient transmissions (Section 3). Ideally, CSI is known exactly without any errors (perfect CSI). More realistically, the knowledge is not exact due to measurement/estimation errors (erroneous CSI) or delays (delayed CSI). We also consider the case of unknown CSI. We then show the impact of the accuracy and timeliness of CSI on energy efficiency. The issue of fairness in energy-efficient transmission is also considered (Section 4).

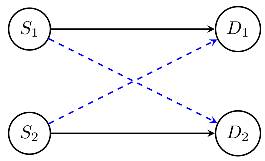


Fig. 1 A two-user interference channel: $(S_i, D_i)$ is a direct link, $(S_i, D_j)$, $i \neq j$, is an interference link.

## 2 System Model and Energy-Efficient Transmission

We study the energy-efficient transmission for a time-varying IC, subject to the following assumptions. The nodes are equipped with omnidirectional antennas. Each source can communicate directly with its destination (i.e., routing is not needed). Each source always has traffic to transmit, i.e., its transmission queue is never empty. Time is divided into slots. The traffic is expressed in terms of fixed-size packets such that the duration of each packet equals one time slot. The users share the same channel (i.e., simultaneous transmissions interfere with each other). Transmissions are also affected by channel fading and receiver noise. Our main performance measure is energy efficiency, which is related to the average number of successful bits transmitted per unit energy. We do not address issues such as time delays or stability analysis in this paper. Our goal is to study energy-efficient networking under heavy traffic conditions via a model that can be evaluated from elementary parameters such as receiver noise and power levels. Thus, the discussions of details such as the structure of the receiver detectors, modulation schemes, error-control coding, synchronization, message format, and implementation issues are beyond the scope of this paper.

We first consider the case of the two-user IC (i.e., $K = 2$, as shown in Fig. 1) to ease the understanding of the basic idea. The channel states may vary from one time slot to the next (see Section 2.3). Consider a time slot and assume that the channel stays in some state during this time slot. Note that, due to interference and channel conditions, a transmission may or may not be successful. We define the *throughput* of a source for this time slot to be the average number of packets it *successfully* transmits during this time slot. Assume that source $S_i$ transmits with probability $p_i \in [0, 1]$ in the time slot, $i \in \{1, 2\}$. For $i, j \in \{1, 2\}$ and $i \neq j$, the throughput of source $S_i$ is then

$$T_i = p_i(1 - p_j)T_{i|i} + p_i p_j T_{i|i,j} \tag{1}$$

where $T_{i|i}$ is the throughput of $S_i$ given that $S_i$ transmits alone in the time slot with power $P_{i|i}$, and $T_{i|i,j}$ is the throughput of $S_i$ given that both $S_i$ and $S_j$ simultaneously transmit in the same time slot with power $P_{i|i,j}$ and $P_{j|i,j}$, respectively. Let $P_i$ be the average transmission power from source $S_i$, i.e.,

$$P_i = p_i(1 - p_j)P_{i|i} + p_i p_j P_{i|i,j} \tag{2}$$

Note that $p_i$, $P_i$, $P_{i|i}$, $P_{i|i,j}$, $T_i$, $T_{i|i}$, and $T_{i|i,j}$ in (1) and (2) depend on the channel states and can vary from one time slot to the next time slot. We now define the transmission *energy efficiency* in some particular time slot as

$$e_t = \frac{T_1 + T_2}{P_1 + P_2} \tag{3}$$

Let $b$ be the average number of successful bits in the time slot. Then $b = (T_1 + T_2)L$, where $L$ is the number of bits per packet. Let $w$ be the transmission energy during the time slot. Then $w = (P_1 + P_2)d$, where $d$ is the slot duration. From (3), we then have $e_t = \frac{d}{L}\frac{b}{w}$, which is directly proportional to the average number of successful bits per unit energy $b/w$.

In this paper we focus on the transmission energy efficiency for each time slot (3). Other forms of energy efficiency are reserved for future studies (e.g., the energy efficiency over all time slots).

For a given channel condition at each time slot, the goal is to find the value of transmission probability $p_i$ and the transmission power for each source for maximizing the energy efficiency $e_t$. Let $e_{i|i} = T_{i|i}/P_{i|i}$ and

$$e_{1,2|1,2} = \frac{T_{1|1,2} + T_{2|1,2}}{P_{1|1,2} + P_{2|1,2}}$$

Next, let $e^*_{i|i} = \max_{P_{i|i}}(e_{i|i})$ be the maximum value of $e_{i|i}$ that is obtained by optimizing the power level $P_{i|i}$, and $e^*_{1,2|1,2} = \max_{P_{1|1,2},P_{2|1,2}}(e_{1,2|1,2})$ be the maximum value of $e_{1,2|1,2}$ that is obtained by jointly optimizing the power levels $P_{1|1,2}$ and $P_{2|1,2}$.

Theorem 1 below shows that the maximum energy efficiency is given by $e^*_t = \max(e^*_{1|1}, e^*_{2|2}, e^*_{1,2|1,2})$, which is achieved when the transmission probability for each source is either 0 or 1, i.e., $p_1, p_2 \in \{0, 1\}$.

We now consider the general case of $K \geq 2$. Recall that we have a time-varying $K$-user IC, which consists of $K$ independent sources $S_1, S_2, \ldots, S_K$ that wish to send their separate information to $K$ different destinations $D_1, D_2, \ldots, D_K$ via a common channel. Assume that source $S_i$ transmits with probability $p_i$, which is a continuous value between 0 and 1, and can vary from slot to slot, based on channel conditions. Our goal is to determine the vector $(p_1, p_2, \ldots, p_K)$ and the corresponding transmission power vector $(P_1, P_2, \ldots, P_K)$ so that the network energy efficiency is maximized.

Consider an arbitrary time slot. For $1 \leq i \leq K$, let $H_i$ be a transmission set that contains source $S_i$, i.e., $S_i \in H_i$. Let $P_{i|H_i}$ be the power level used by source $S_i$ for transmission, given that all the sources in $H_i$ simultaneously transmit in the time slot. Let $T_{i|H_i}$ be the resulting throughput of source $S_i$, given that all the sources in $H_i$ simultaneously transmit in the time slot. As generalization of (1) and (2), the throughput $T_i$ and the corresponding transmission power $P_i$ of source $S_i$ for the time slot are given as follows.

$$\begin{aligned} T_i = &\sum_{H_i \neq \{S_1, S_2, \ldots, S_K\}} \prod_{S_j \in H_i} p_j \prod_{S_j \notin H_i} (1 - p_j) T_{i|H_i} \\ &+ \prod_{k=1}^{K} p_k T_{i|\{S_1, S_2, \ldots, S_K\}} \\ = &\sum_{H_i} \prod_{S_j \in H_i} p_j \prod_{S_j \notin H_i} (1 - p_j) T_{i|H_i} \end{aligned}$$

where we define $\prod_{S_j \notin \{S_1, S_2, \ldots, S_K\}} (1 - p_j) = \prod_{S_j \in \emptyset} (1 - p_j) = 1$ merely for notational convenience. Similarly, we have

$$P_i = \sum_{H_i} \prod_{S_j \in H_i} p_j \prod_{S_j \notin H_i} (1 - p_j) P_{i|H_i}$$

As generalization of (3), the transmission *energy efficiency* in the time slot is defined as

$$e_t = \frac{\sum_{i=1}^{K} T_i}{\sum_{i=1}^{K} P_i}$$

**Theorem 1.** The energy efficiency $e_t$ is maximized when the transmission probability for each source is either 0 or 1, i.e., $p_i \in \{0, 1\}$, $1 \le i \le K$. In particular, the maximum energy efficiency $e_t^*$ is achieved by letting $p_i = 1$ if $S_i \in H^*$ and $p_i = 0$ if $S_i \notin H^*$, for some nonempty subset $H^* \subseteq \{S_1, S_2, \ldots, S_K\}$.

**Proof.** We have

$$\sum_{i=1}^{K} T_i = \sum_{i=1}^{K} \sum_{H_i} \prod_{S_j \in H_i} p_j \prod_{S_j \notin H_i} (1 - p_j) T_{i|H_i}$$

After rearranging and combining terms, it can be shown that

$$\sum_{i=1}^{K} T_i = \sum_{H \neq \emptyset} \prod_{S_j \in H} p_j \prod_{S_j \notin H} (1 - p_j) \sum_{S_i \in H} T_{i|H}$$

Similarly, we also have

$$\sum_{i=1}^{K} P_i = \sum_{H \neq \emptyset} \prod_{S_j \in H} p_j \prod_{S_j \notin H} (1 - p_j) \sum_{S_i \in H} P_{i|H}$$

For each nonempty subset $H \subseteq \{S_1, S_2, \ldots, S_K\}$, let

$$e_{H|H} = \frac{\sum_{S_i \in H} T_{i|H}}{\sum_{S_i \in H} P_{i|H}}$$

be the energy efficiency obtained by letting $p_i = 1$ if $S_i \in H$ and $p_i = 0$ if $S_i \notin H$. Further, let $e_{H|H}^* = \max_{P_{i|H, S_i \in H}} e_{H|H}$ that is obtained by choosing the optimal power levels for all the sources in $H$. We then have

$$\begin{aligned} e_t &= \frac{\sum_{i=1}^{K} T_i}{\sum_{i=1}^{K} P_i} \\ &= \frac{\sum_{H \neq \emptyset} \prod_{S_j \in H} p_j \prod_{S_j \notin H} (1 - p_j) \sum_{S_i \in H} T_{i|H}}{\sum_{H \neq \emptyset} \prod_{S_j \in H} p_j \prod_{S_j \notin H} (1 - p_j) \sum_{S_i \in H} P_{i|H}} \\ &\le \max_{H \neq \emptyset} \left( \frac{\sum_{S_i \in H} T_{i|H}}{\sum_{S_i \in H} P_{i|H}} \right) \\ &= \max_{H \neq \emptyset} (e_{H|H}) \\ &\le \max_{H \neq \emptyset} (e_{H|H}^*) \end{aligned}$$

which implies that $e_t^* = \max_{H \neq \emptyset} (e_{H|H}^*)$. By letting $H^* = \arg\max_{H \neq \emptyset} (e_{H|H}^*)$, we have $e_t^* = e_{H^*|H^*}^*$. That is, the energy efficiency is maximized by letting $p_i = 1$ if $S_i \in H^*$ and $p_i = 0$ if $S_i \notin H^*$. □

Theorem 1 is general in the sense that it is applicable to *any* form of channel fading, noise, and transmission power. Recall that we define the *throughput* of a source for a time slot to be the average number of packets it successfully transmits during this time slot. So far, to keep the model general, we do not explicitly define the meaning of successful transmission yet (see Section 2.1). Note that the throughput $T$ of source $S$ depends on its transmission power $P$, i.e., $T = T(P)$. We now assume that the throughput $T_{i|i}$ of source $S_i$ satisfies the following condition:

$$T_{i|i}(P) \ge T_{i|H_i}(P) \tag{4}$$

for all subsets $H_i$ of transmitting sources that include $S_i$ (i.e., $S_i \in H_i$), where $P$ is the transmission power of $S_i$. Note that $H_i \setminus \{S_i\}$ is the set of sources that interfere with $S_i$'s transmission. Thus, condition (4) simply states that the throughput of $S_i$ obtained when it transmits alone is not lower than that obtained when other sources transmit simultaneously with $S_i$ (here, the same power $P$ is used by $S_i$ whether or not the other sources are introduced into the time slot).

According to Theorem 1, an optimal subset of sources (for maximizing energy efficiency) is scheduled to transmit at each time slot. Solving the $K$-user problem by exhaustive search (i.e., by testing all the $2^K - 1$ non-empty candidate subsets) is expensive for large $K$. By using (4), we have Theorem 2, which shows that, as long as the energy-efficiency maximization is the main concern, the number of candidate subsets can be reduced to the $K$ singleton sets. That is, Theorem 2 shows that the optimal set of transmission sources can be found with linear complexity $O(K)$, which is significantly lower than the exponential complexity $O(2^K)$ required by exhaustive search.

**Theorem 2.** For $1 \le i \le K$, let $e_{i|i}^* = \max_{P_{i|i}} (e_{i|i})$ be the maximum of $e_{i|i}$ obtained by optimizing the power level $P_{i|i}$. Let $k = \arg\max_{1 \le i \le K} (e_{i|i}^*)$. Then the energy efficiency $e_t$ is maximized by letting source $S_k$ transmit alone in the time slot. The maximum energy efficiency is $e_t^* = e_{k|k}^*$.

**Proof.** Using (4) , we have

$$\frac{T_{i|H_i}}{P_{i|H_i}} \le \frac{T_{i|i}}{P_{i|H_i}} \le e_{i|i}^* \tag{5}$$

From the proof of Theorem 1, we have

$$\begin{aligned} e_t &\le \max_{H \neq \emptyset} \left( \frac{\sum_{S_i \in H} T_{i|H}}{\sum_{S_i \in H} P_{i|H}} \right) \\ &\overset{(a)}{=} \frac{\sum_{S_i \in H^*} T_{i|H^*}}{\sum_{S_i \in H^*} P_{i|H^*}} \\ &\le \max_{S_i \in H^*} \frac{T_{i|H^*}}{P_{i|H^*}} \\ &\overset{(b)}{=} \frac{T_{k|H^*}}{P_{k|H^*}} \\ &\overset{(c)}{\le} e_{k|k}^* \end{aligned}$$

where $H^*$ in (a) denotes the optimal subset of transmitting sources, $k$ in (b) denotes the index of the optimal source $S_k$, and (c) follows from (5). Thus, the maximum energy efficiency is then given by $e_t^* = e_{k|k}^*$ for some source $S_k$. □

### 2.1 SINR-Based Criterion for Successful Transmission

We now address the criterion for successful transmission. We assume that a packet is successfully received, even in the presence of interference and noise, as long as its signal-to-interference-plus-noise ratio (SINR) exceeds a given threshold. More precisely, suppose that we are given a set $H$ of sources that simultaneously transmit in the same time slot, and $S \in H$. Let $P_{\rm rx}(S,D)$ be the signal power received from node $S$ at node $D$, and let $\text{SINR}_{SD|H}$ be the SINR at node $D$ for the transmission from node $S$, i.e.,

$$\text{SINR}_{SD|H} = \frac{P_{\rm rx}(S,D)}{P_{\rm noise}(D) + \sum_{U \in H \setminus \{S\}} P_{\rm rx}(U,D)} \tag{6}$$

where $P_{\rm noise}(D)$ is the receiver noise power at node $D$. We assume that a transmission from $S$ is successfully received by $D$ if

$$\text{SINR}_{SD|H} > \beta$$

where $\beta \geq 0$ is an SINR threshold, which is determined by application requirements (such as data rates and BER). Let $C_{SD|H}$ be the probability that a transmission from source $S \in H$ is successfully received by destination $D$, given that all the sources in $H$ simultaneously transmit, i.e.,

$$C_{SD|H} = \Pr\{\text{SINR}_{SD|H} > \beta\} \tag{7}$$

Note that $1 - C_{SD|H} = \Pr\{\text{SINR}_{SD|H} \leq \beta\}$ is the familiar outage probability [10]. From (6) and (7), for any $H$ that includes $S$ (i.e., $S \in H$), we have

$$C_{SD|\{S\}} \geq C_{SD|H} \tag{8}$$

Recall that the throughput of a source is the average number of packets it successfully transmits per time slot. Thus, the successful transmission probability $C_{SD|\{S\}}$ is the throughput of source $S$ when it transmits alone in a time slot. Similarly, $C_{SD|H}$ is the throughput of source $S$ when all the sources in $H$ simultaneously transmit in the same time slot. Relation (8) implies that condition (4) is satisfied, i.e., Theorem 2 holds when the throughput is defined via the SINR-based criterion for successful transmission.

In general, the wireless channel is affected by fading, i.e., the received power $P_{\rm rx}(S,D)$ is a random variable. Our algorithms and performance evaluation rely on the knowledge of elementary parameters and statistics such as the SINR threshold $\beta$ and the receiver noise power $P_{\rm noise}$, which are assumed to be known or can be estimated.

### 2.2 Rayleigh Channel Fading

For our analysis and numerical evaluation, we assume that the channel is affected by flat Rayleigh fading. It would be possible to extend our analyses and performance evaluation to other types of fading as well.

Recall that $C_{SD|H}$ denotes the probability that a transmission from $S$ is successfully received by $D$, given that all sources in $H$ simultaneously transmit in the same time slot. For the case of Rayleigh fading, we have [10]:

$$C_{SD|\{S\}} = \exp\left(-\frac{\beta P_{\rm noise}(D)}{E[P_{\rm rx}(S,D)]}\right)$$

The received power is related to the transmitted power $P_{\rm tx}(S)$ by

$$E[P_{\rm rx}(S,D)] = h_{SD} P_{\rm tx}(S)$$

where $h_{SD}$ is the channel gain that reflects the attenuation and fading for link $(S,D)$. Higher $h_{SD}$ indicates better channel condition. As discussed later, we consider a two-state channel: higher (lower) $h_{SD}$ corresponds to the "good" ("bad") state.

As discussed in Section 2.1, $C_{SD|\{S\}}$ is also the throughput of source $S$ when it transmits alone in a time slot. Consider link $(S_i, D_i)$ for the case of Rayleigh fading, and by simplifying the notation, we have

$$T_{i|i} = \exp\left(-\frac{\beta_i P_{n_i}}{h_{ii} P_{i|i}}\right) \tag{9}$$

where $P_{i|i}$ is the power used by $S_i$ when it transmits alone, $\beta_i$ is the SINR threshold required by destination $D_i$ for successful packet decoding, $P_{n_i}$ is the receiver noise power at destination $D_i$, and $h_{ii}$ is the channel gain for link $(S_i, D_i)$.

**Remark 1.** Using Theorem 2 for the case of Rayleigh fading and $K = 2$, we have the following. Let $e_{i|i}^* = \max_{P_{i|i}}(e_{i|i})$ be the maximum of $e_{i|i}$ obtained by optimizing the power $P_{i|i}$, $i = 1, 2$. Let $S_k$ be the source such that $e_{k|k}^* = \max(e_{1|1}^*, e_{2|2}^*)$. Then the energy efficiency $e_t$ is maximized by letting source $S_k$ transmit alone in the time slot. The maximum energy efficiency is $e_t^* = e_{k|k}^*$.

### 2.3 Channel States

The channel conditions may vary from one time slot to the next time slot. In particular, the time-varying channel is modeled as a set of two-state Markov chains: state 0 is for the bad channel condition (e.g., severe fading) and state 1 is for the good channel condition (e.g., mild fading). For $i, j \in \{1, 2\}$, the Markov chain for link $(S_i, D_j)$ is described by the probability transition matrix

$$\mathbf{P_{ij}} = \begin{array}{c} \\ 0 \\ 1 \end{array}\begin{array}{c} \begin{array}{cc} 0 & 1 \end{array} \\ \begin{pmatrix} q_{ij}^{0|0} & q_{ij}^{1|0} \\ q_{ij}^{0|1} & q_{ij}^{1|1} \end{pmatrix} \end{array}$$

where $q_{ij}^{b|a} = q_{ij}(b|a)$ denotes the probability of transitioning from state $a$ to state $b$, with $a, b \in \{0, 1\}$. Let $\pi_{ij}^{(a)}$ be the stationary probability that link $(S_i, D_j)$ is in state $a \in \{0, 1\}$, which is given by [13] $\pi_{ij}^{(0)} = q_{ij}^{0|1}/(q_{ij}^{0|1} + q_{ij}^{1|0})$ and $\pi_{ij}^{(1)} = q_{ij}^{1|0}/(q_{ij}^{0|1} + q_{ij}^{1|0})$.

The notation $T_{i|i}^{(a)}$ denotes the throughput of source $S_i$ when it transmits alone on link $(S_i, D_i)$, given that the link is in state $a$. Similarly, $T_{i|i,j}^{(a,b)}$, $i \neq j$, denotes the throughput of source $S_i$ when $S_i$ and $S_j$ simultaneously transmit in the same time slot, given that link $(S_i, D_i)$ is in state $a$ and link $(S_j, D_i)$ is in state $b$. Also, $h_{ij}^{(a)}$ denotes the channel gain for link $(S_i, D_j)$, given that it is in state $a$. Because the channel states $a$ and $b$ are random, $T_{i|i}^{(a)}$, $T_{i|i,j}^{(a,b)}$, and $h_{ij}^{(a)}$ are also random.

## 3 Effects of CSI on Energy-Efficient Transmission

We now address the improvement in energy efficiency that can be achieved by exploiting the knowledge of CSI. We first consider the case of unknown CSI, which is used as a benchmark for comparison. The case of erroneous CSI is considered next, for which the CSI may contain errors, e.g., due to imperfect measurement/estimation. We then consider the case of perfect CSI, i.e., the CSI is known exactly without any errors. Finally, we consider the case for which the CSI at the current time slot is not known, but the CSI of some previous time slots is known at the current time slot (i.e., delayed CSI). As shown below, as expected, better CSI can be exploited to improve energy efficiency.

For ease of notation and understanding, we now focus on the case of $K = 2$ and Rayleigh fading. The general case of arbitrary $K$ can be similarly studied with more cumbersome notation. In the following analysis, we rely on Remark 1, which states for the case of Rayleigh fading that the energy efficiency $e_t$ is maximized by letting the source with higher maximized energy efficiency transmit alone in the time slot. The maximum energy efficiency is $e_t^* = \max(e_{1|1}^*, e_{2|2}^*)$, where $e_{i|i}^*$ is the optimal value of $e_{i|i} = T_i/P_{i|i}$, i.e., $e_{i|i}^* = \max_{P_i}(e_{i|i})$. We assume that $\beta_i$, $P_{n_i}$, and $q_{ii}^{a|b}$ are known, $i = 1, 2$, and that $\beta_1 P_{n_1} = \beta_2 P_{n_2}$. As seen in Section 2.3, $q_{ii}^{a|b}$ can be used to compute $\pi_{ii}^{(a)}$, the stationary probability that link $(S_i, D_i)$ is in state $a \in \{0, 1\}$. Depending on the cases to be considered, the channel states may or may not be known, i.e., the users may or may not know that the channel gain is $h_{ii}^{(0)}$ or $h_{ii}^{(1)}$ at each time slot, $i = 1, 2$. Note that the energy efficiency $e_t$ in (3) depends on the channel states, which are random variables. Thus, in the following we are interested in the mean energy efficiency $E[e_t]$, which is averaged over the states.

### 3.1 Unknown CSI

For the case of Rayleigh fading, unknown CSI implies that the users do not know which member of $\{h_{ii}^{(0)}, h_{ii}^{(1)}\}$ is the true channel gain value at each time slot. Thus, the transmission power $P$ used by each source is independent of the channel states. The transmission power for source $S_i$ is chosen to maximize its average energy efficiency $E[e_{i|i}]$. For $i \in \{1, 2\}$, let $E[e_{i|i}^*] = \max_{P_i}(E[e_{i|i}])$, where

$$E[e_{i|i}] = \sum_{a \in \{0,1\}} \frac{1}{P_i} \exp\left(-\frac{\beta_i P_{n_i}}{h_{ii}^{(a)} P_i}\right) \pi_{ii}^{(a)}$$

Let $E[e_{k|k}^*] = \max(E[e_{1|1}^*], E[e_{2|2}^*])$. Then $S_k$ transmits alone with power $P_k^*$ in every time slot, where $P_k^* = \arg\max_{P_k}(E[e_{k|k}^*])$. When the CSI is unknown, the same schedule is used for all time slots, i.e., the transmission scheduling is static, and does not vary from one time slot to the next. The same schedule being used for all time slots can raise the issue of fairness, which is discussed later in Section 4.

### 3.2 Erroneous CSI

We now assume that only an estimated version of the true states is available to the users, i.e., only the estimated state $\hat{a}$ of the true state $a$ is known, $a = 0, 1$. The accuracy of the estimate is given by the probabilities $u_{0|1} = \Pr(\hat{a} = 0|a = 1)$ and $u_{1|0} = \Pr(\hat{a} = 1|a = 0)$. We have $u_{1|1} = 1 - u_{0|1}$ and $u_{0|0} = 1 - u_{1|0}$. For $\hat{a} \neq a$, $u_{\hat{a}|a}$ is the state-estimate error probability (e.g., due to imperfect channel estimation/measurement).

Let $P_i^{(\hat{a})}$ be the transmission power of source $S_i$ when the estimated state of link $(i, i)$ is $\hat{a}$. The value of $P_i^{(\hat{a})}$ is chosen to maximize the (average) energy efficiency

$$E[e_t] = \sum_{a,b,\hat{a},\hat{b} \in \{0,1\}} e_{(\hat{a},\hat{b})}^{(a,b)} \pi_{11}^{(a)} \pi_{22}^{(b)} u_{\hat{a}|a} u_{\hat{b}|b} \tag{10}$$

where $e_{(\hat{a},\hat{b})}^{(a,b)}$ is the energy efficiency when (i) the true and estimated state of link $(1, 1)$ is $a$ and $\hat{a}$, respectively, and (ii) the true and estimated state of link $(2, 2)$ is $b$ and $\hat{b}$, respectively.

The network operates based only on the *estimated* states $(\hat{a}, \hat{b})$, without knowing the true states $(a, b)$. In particular, the source having better estimated link state will transmit alone in the time slot, and either one of the sources can transmit alone when both sources have the same estimated link states (here we simply let source $S_1$ transmit in this case), i.e., the following rule is used:

- If $(\hat{a}, \hat{b}) = (0, 0)$, then only $S_1$ transmits with power $P_1^{(0)}$.
- If $(\hat{a}, \hat{b}) = (0, 1)$, then only $S_2$ transmits with power $P_2^{(1)}$.
- If $(\hat{a}, \hat{b}) = (1, 0)$, then only $S_1$ transmits with power $P_1^{(1)}$.
- If $(\hat{a}, \hat{b}) = (1, 1)$, then only $S_1$ transmits with power $P_1^{(1)}$.

The action at each time slot is also described formally as

$$(S_{\text{tx}}, P_{\text{tx}}) = \begin{cases} (S_1, P_1^{(\hat{a})}) & \text{if } \hat{a} \geq \hat{b} \\ (S_2, P_2^{(\hat{b})}) & \text{if } \hat{a} < \hat{b} \end{cases} \tag{11}$$

where $P_{\text{tx}}$ denotes the power transmitted by source $S_{\text{tx}}$ in the time slot.

Under Rayleigh fading, the term $e_{(\hat{a},\hat{b})}^{(a,b)}$ in (10), which can be computed from (9) and (11), is given by

$$e_{(0,0)}^{(0,0)} = e_{(0,0)}^{(0,1)} = \frac{1}{P_1^{(0)}} \exp\left(-\frac{\beta_1 P_{n_1}}{h_{11}^{(0)} P_1^{(0)}}\right)$$

$$e_{(0,1)}^{(0,0)} = e_{(0,1)}^{(1,0)} = \frac{1}{P_2^{(1)}} \exp\left(-\frac{\beta_2 P_{n_2}}{h_{22}^{(0)} P_2^{(1)}}\right)$$

$$e_{(1,0)}^{(0,0)} = e_{(1,1)}^{(0,0)} = e_{(1,0)}^{(0,1)} = e_{(1,1)}^{(0,1)} = \frac{1}{P_1^{(1)}} \exp\left(-\frac{\beta_1 P_{n_1}}{h_{11}^{(0)} P_1^{(1)}}\right)$$

$$e_{(0,1)}^{(0,1)} = e_{(0,1)}^{(1,1)} = \frac{1}{P_2^{(1)}} \exp\left(-\frac{\beta_2 P_{n_2}}{h_{22}^{(1)} P_2^{(1)}}\right)$$

$$e_{(0,0)}^{(1,0)} = e_{(0,0)}^{(1,1)} = \frac{1}{P_1^{(0)}} \exp\left(-\frac{\beta_1 P_{n_1}}{h_{11}^{(1)} P_1^{(0)}}\right)$$

$$e_{(1,0)}^{(1,0)} = e_{(1,1)}^{(1,0)} = e_{(1,0)}^{(1,1)} = e_{(1,1)}^{(1,1)} = \frac{1}{P_1^{(1)}} \exp\left(-\frac{\beta_1 P_{n_1}}{h_{11}^{(1)} P_1^{(1)}}\right)$$

### 3.3 Perfect CSI

Here we assume that the true channel state is known at each time slot. For the case of Rayleigh fading, the users know which member of $\{h_{ii}^{(0)}, h_{ii}^{(1)}\}$ is the true channel gain value at each time slot.

**Theorem 3.** With perfect CSI, the energy efficiency is maximized by, at each time slot, letting the source having the larger maximum energy efficiency transmit alone in the time slot. For the case of Rayleigh fading, suppose that link $(1,1)$ is in state $a$ and link $(2,2)$ is in state $b$ in a time slot. Let $P_1^{(a)} = \beta_1 P_{n_1}/h_{11}^{(a)}$ and $P_2^{(b)} = \beta_2 P_{n_2}/h_{22}^{(b)}$. Then source $S_1$ transmits alone with power $P_1^{(a)}$ if $P_1^{(a)} \le P_2^{(b)}$, and source $S_2$ transmits alone with power $P_2^{(b)}$ if $P_1^{(a)} > P_2^{(b)}$. The maximum energy efficiency is given by

$$E[e_t^*] = \pi_{11}^{(0)}\pi_{22}^{(0)}\frac{h_{11}^{(0)}}{e\beta_1 P_{n_1}} + \pi_{11}^{(0)}\pi_{22}^{(1)}\frac{h_{22}^{(1)}}{e\beta_2 P_{n_2}} + \left[\pi_{11}^{(1)}\pi_{22}^{(0)} + \pi_{11}^{(1)}\pi_{22}^{(1)}\right]\frac{h_{11}^{(1)}}{e\beta_1 P_{n_1}}$$

When the maximum energy efficiency is achieved, the corresponding network throughput is $1/e$ for every time slot.

**Proof.** This case can be derived from the case of erroneous CSI (considered in Section 3.2), by letting $u_{\hat{a}|a} = 0$ for $\hat{a} \neq a$, which implies that $(\hat{a}, \hat{b}) = (a, b)$. Then (10) becomes

$$E[e_t] = \sum_{a,b\in\{0,1\}} e_{(a,b)}^{(a,b)}\pi_{11}^{(a)}\pi_{22}^{(b)} \qquad (12)$$

which is maximized by choosing the power level that maximizes each $e_{(a,b)}^{(a,b)}$. For the case of Rayleigh fading, using the fact that $xe^{-x} \le e^{-1}$, we have

$$e_{(0,0)}^{(0,0)} = \frac{1}{P_1^{(0)}}\exp\left(-\frac{\beta_1 P_{n_1}}{h_{11}^{(0)}P_1^{(0)}}\right) \le \frac{h_{11}^{(0)}}{e\beta_1 P_{n_1}}$$

and the upper bound is achieved by choosing $P_1^{(0)} = \frac{\beta_1 P_{n_1}}{h_{11}^{(0)}}$, i.e., $e_{(0,0)}^{(0,0)} = \frac{h_{11}^{(0)}}{e\beta_1 P_{n_1}}$. Similarly, it can be shown that $e_{(0,1)}^{(0,1)} = \frac{h_{22}^{(1)}}{e\beta_2 P_{n_2}}$ and $e_{(1,0)}^{(1,0)} = e_{(1,1)}^{(1,1)} = \frac{h_{11}^{(1)}}{e\beta_1 P_{n_1}}$. The maximum energy efficiency $e_t^*$ is obtained by using these maximum values of $e_{(a,b)}^{(a,b)}$ in (12).

Consider a time slot that is in state $a \in \{0,1\}$. Suppose that source $S_k$ transmits in this time slot with the optimal power $P_k^{(a)} = \beta_k P_{n_k}/h_{kk}^{(a)}$. The resulting throughput for this time slot is then

$$T_{k|k}^{(a)} = \exp\left(-\frac{\beta_k P_{n_k}}{h_{kk}^{(a)}P_k^{(a)}}\right) = \frac{1}{e} \qquad \square$$

For the special case of $\pi_{11}^{(a)} = \pi_{22}^{(a)}$, $h_{11}^{(a)} = h_{22}^{(a)}$ and $\beta_1 P_{n_1} = \beta_2 P_{n_2} = \beta P_n$, Theorem 3 implies

$$E[e_t^*] = \frac{h_{11}^{(0)}\left[\pi_{11}^{(0)}\right]^2 + h_{11}^{(1)}\left(2\pi_{11}^{(0)}\pi_{11}^{(1)} + \left[\pi_{11}^{(1)}\right]^2\right)}{e\beta P_n} \qquad (13)$$

### 3.4 Delayed CSI

We now assume that, although the current CSI is unknown, some past CSI is known at the current time slot. This is the case, for example, when the source receives (from the destination) the feedback for the CSI of the previous time slot.

Here we consider the case in which the CSI of $k$ time slots ago is available at the current time slot. Consider a link, and let $a \in \{0,1\}$ be the current state of this link, and $a_k \in \{0,1\}$ be the state at $k$ time slots ago for this link. Assume that $a$ is unknown and $a_k$ is known. Let $q^{a|b}$ and $\pi^{(a)}$ be the transition probability and stationary distribution, respectively, for this link. In Section 3.2, we assume that the exact CSI of the current time slot is unknown in general, but must be estimated by some method, which results in the state-estimate error probability $u_{\hat{a}|a}$, $\hat{a} \neq a$. The estimate can be obtained via a decision function $d(a_k) = \hat{a} \in \{0,1\}$, where $\hat{a}$ is the estimate of $a$, given that $a_k$ is observed. There are 4 possible decision functions: $d_1(a_k) = a_k$, $d_2(a_k) = 1-a_k$, $d_3(a_k) = 0$, and $d_4(a_k) = 1$, $a_k \in \{0,1\}$. Our goal is to find a decision function that maximizes the energy efficiency $E[e_t]$ in (10).

In the following we analyze the case of $k = 1$ (one-time-slot delayed CSI), i.e., the CSI of the previous time slot is available at the current time slot. Recall that $u_{\hat{a}|a}$ is the state-estimate error probability, $\hat{a} \neq a$. It can be shown that

$$u_{1|0} = \Pr(\hat{a} = 1|a = 0, a_1 = 0)q^{0|0} + \Pr(\hat{a} = 1|a = 0, a_1 = 1)q^{0|1}\pi^{(1)}/\pi^{(0)} \qquad (14)$$

$$u_{0|1} = \Pr(\hat{a} = 0|a = 1, a_1 = 0)q^{1|0}\pi^{(0)}/\pi^{(1)} + \Pr(\hat{a} = 0|a = 1, a_1 = 1)q^{1|1} \qquad (15)$$

By applying the decision function $d_1(a_1) = a_1$ to (14), we have $\Pr(\hat{a} = 1|a = 0, a_1 = 0) = 0$ and $\Pr(\hat{a} = 1|a = 0, a_1 = 1) = 1$. Thus, the state-estimate error probability $u_{1|0}$ under $d_1$ becomes $u_{1|0}(d_1) = q^{0|1}\pi^{(1)}/\pi^{(0)}$. Using (15), we have $u_{0|1}(d_1) = q^{1|0}\pi^{(0)}/\pi^{(1)}$. Similarly, it can be shown that the error probabilities under the other decision functions are: $u_{1|0}(d_2) = q^{0|0}$, $u_{0|1}(d_2) = q^{1|1}$, $u_{1|0}(d_3) = 0$, $u_{0|1}(d_3) = q^{1|0}\pi^{(0)}/\pi^{(1)} + q^{1|1}$, $u_{1|0}(d_4) = q^{0|0} + q^{0|1}\pi^{(1)}/\pi^{(0)}$, and $u_{0|1}(d_4) = 0$.

Note that the energy efficiency $E[e_t]$ in (10) is a function of the state-estimate error probability $(u_{1|0}, u_{0|1})$. Because $(u_{1|0}, u_{0|1})$ depends on a decision function $d$, we have $E[e_t] = E[e_t(d)]$. An optimal decision function $d^*$ is the one that maximizes the energy efficiency $E[e_t(d)]$, i.e., $d^* = \arg\max_d E[e_t(d)]$.

The operation for the case of delayed CSI can be summarized as follows. Suppose that the states $a_1$ and $b_1$ (from the previous-time-slot CSI) are observed at the current time slot for links $(1,1)$ and $(2,2)$, respectively. We then compute the estimates $\hat{a} = d^*(a_1)$ and $\hat{b} = d^*(b_1)$, where $d^*$ is the optimal decision function. Then the action specified by (11) is used for the current time slot.

### 3.5 Numerical Evaluation

Recall that, in this section, we study the energy-efficient transmission for a two-user IC (as shown in Fig. 1). The

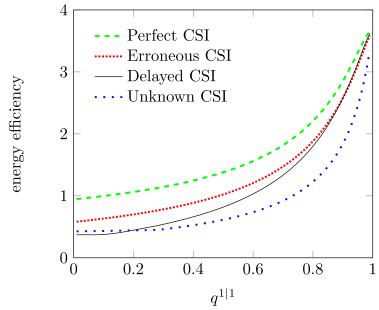


Fig. 2 Energy Efficiency ($q^{1|0} = 0.1$).

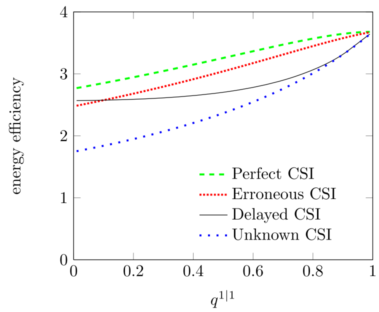


Fig. 3 Energy Efficiency ($q^{1|0} = 0.9$).

channel states of link $(i, i)$ vary according to an independent two-state Markov chain, with transition probability matrix $\mathbf{P_{ii}}$, $i = 1, 2$. The channel link $(i, i)$ is affected by Rayleigh fading, i.e., $T_{i|i}$ is given by (9), with two possible channel gain values: $h_{ii}^{(0)}$ and $h_{ii}^{(1)}$. In the following numerical evaluation, we assume that $\mathbf{P_{11}} = \mathbf{P_{22}}$, $\beta_1 = \beta_2 = 10$, $P_{n_1} = P_{n_2} = 0.001$, $h_{ii}^{(0)} = 0.01$ and $h_{ii}^{(1)} = 0.1$.

The energy efficiency $E[e_t^*]$ vs. $q^{1|1}$ is shown in Fig. 2 ($q^{1|0} = 0.1$) and in Fig. 3 ($q^{1|0} = 0.9$), where $q^{1|i} = q_{11}^{1|i}$ denotes the probability of transitioning from state $i$ to state 1 for link $(1, 1)$ between source $S_1$ and destination $D_1$. The curves for Delayed CSI correspond to a delay of one time slot. The curves for Erroneous CSI correspond to the case of $u_{1|0} = u_{0|1} = 0.1$. Increasing the delay or error probability would result in decreased energy efficiency.

Because $\pi^{(1)} = q^{1|0}/(1 - q^{1|1} + q^{1|0})$, larger $q^{1|1}$ and $q^{1|0}$ imply larger $\pi^{(1)}$ (i.e., the probability of being in the good state increases), resulting in increased energy efficiency.

Note that the results for the case of Perfect CSI can be obtained from those for Erroneous CSI by letting $u_{1|0} = u_{0|1} = 0$. As expected, the Perfect CSI case provides the best energy efficiency. The results show that the Delayed CSI case is better than the Unknown CSI case for most values of system parameters that are studied. The energy efficiency under perfect CSI can be significantly higher than that under unknown CSI, especially when $q^{1|1}$ and $q^{1|0}$ are not close to 1 (i.e., when the channel is not in the good state most of the time). The results show that it is desirable to gain more knowledge of CSI, because it can be used to significantly improve energy efficiency.

## 4 Fairness Considerations

The model in Section 3 is basic in the sense that the sole goal is, for a given level of CSI, to maximize energy efficiency, without considering other issues such as fairness and some guaranteed minimum throughput for each user. In the basic model, for the case of Rayleigh fading, the energy efficiency $e_t$ is maximized by letting the source with higher maximized energy efficiency transmit alone in the time slot, i.e., interference-free transmission is more energy efficient. The model favors the source with higher energy-efficiency transmission by allowing it to transmit more frequently, without regard to fairness, priorities or other requirements.

A simple way for incorporating fairness into the basic model is to use a TDMA-based approach in which each source takes turn to transmit so that an interference-free transmission is achieved. The TDMA slot assignment can be static or dynamic, evenly or unevenly allocated, depending on system requirements such as traffic levels and priorities.

We now consider one of the most basic forms of fairness, by requiring that two sources have equal chance of transmission. This is accomplished by using a static TDMA scheme in which source $S_1$ transmits in odd-numbered time slots and source $S_2$ transmits in even-numbered time slots. For $i \in \{0, 1\}$, let $(X_{i,n}, n = 1, 2, 3, 4, \ldots)$ be the channel states for link $(S_i, D_i)$, where $X_{i,n}$ is the state at time slot $n$. Because $(X_{i,n}, n = 1, 2, 3, 4, \ldots)$ is Markov, it can be shown that the odd-numbered subsequence $(X_{i,n}, n = 1, 3, \ldots)$ and the even-numbered subsequence $(X_{i,n}, n = 2, 4, \ldots)$ are also Markov. Further, their state stationary probabilities are the same as $\pi_{ii}^{(a)}$ of the original sequence $(X_{i,n}, n = 1, 2, 3, 4, \ldots)$. For $i = 1, 2$, the (average) energy efficiency for source $S_i$ is then given by

$$E[e_{i|i}] = \sum_{a \in \{0,1\}} \frac{1}{P_i^{(\hat{a})}} \exp\left(-\frac{\beta_i P_{n_i}}{h_{ii}^{(a)} P_i^{(\hat{a})}}\right) \pi_{ii}^{(a)} \qquad (16)$$

where $P_i^{(\hat{a})}$ is transmission power by source $S_i$, given $\hat{a}$ being the estimated state of the true state $a$.

First, consider the case of perfect CSI, i.e., $\hat{a} = a$. As seen previously, $E[e_{i|i}]$ is then maximized by choosing $P_i^{(\hat{a})} = \beta_i P_{n_i}/h_{ii}^{(a)}$. By using the optimizing power in (16), the resulting maximum energy efficiency is then given by

$$E[e_{i|i}^*] = \frac{h_{ii}^{(0)} \pi_{ii}^{(0)} + h_{ii}^{(1)} \pi_{ii}^{(1)}}{e \beta_i P_{n_i}} \qquad (17)$$

Next, consider the case of unknown CSI, i.e., the transmission power is chosen without knowing CSI (e.g., no channel state measurement or estimation). Thus, the transmission power $P_i$ is independent of the channel (true or estimate) state, i.e., $P_i^{(\hat{a})} = P_i$, for $a, \hat{a} \in \{0, 1\}$. Then (16) becomes

$$E[e_{i|i}] = \frac{1}{P_i} \sum_{a \in \{0,1\}} \exp\left(-\frac{\beta_i P_{n_i}}{h_{ii}^{(a)} P_i}\right) \pi_{ii}^{(a)} \qquad (18)$$

The chosen transmission power $P_i^*$ is the one that maximizes (18), i.e., $P_i^* = \arg\max_{P_i} E[e_{i|i}]$, and the resulting optimal energy efficiency is

$$E[e_{i|i}^*] = \frac{1}{P_i^*} \sum_{a \in \{0,1\}} \exp\left(-\frac{\beta_i P_{n_i}}{h_{ii}^{(a)} P_i^*}\right) \pi_{ii}^{(a)} \qquad (19)$$

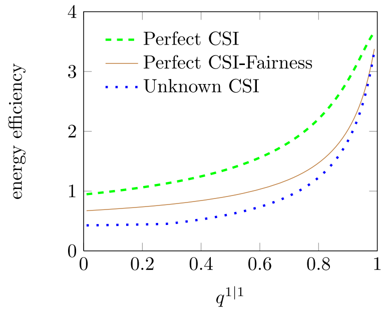


Fig. 4 Energy Efficiency ($q^{1|0} = 0.1$).

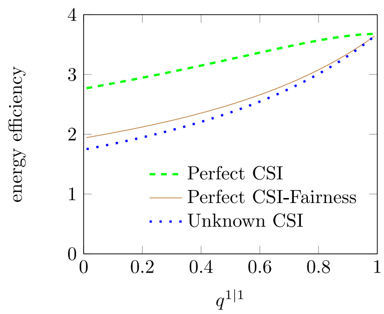


Fig. 5 Energy Efficiency ($q^{1|0} = 0.9$).

The following numerical performance evaluation and comparison use the same assumptions as in Section 3.5. In particular, assume that the channel states of links $(1,1)$ and $(2,2)$ vary according to independent two-state Markov chains that have identical transition probability matrices, i.e., $\mathbf{P_{11}} = \mathbf{P_{22}}$. Further, $\beta_1 = \beta_2$ and $P_{n_1} = P_{n_2}$. From these assumptions, it can be shown that $E[e^*_{1|1}] = E[e^*_{2|2}]$ for both the case of perfect CSI (17) and the case of unknown CSI (19). Further, regarding to the case of unknown CSI, the energy efficiency under the TDMA-based fairness is the same as that under the criterion of sole maximum energy efficiency considered previously in Section 3.5.

The energy efficiency results under the fairness constraint (Perfect CSI-Fairness and Unknown CSI) are shown in Figs. 4 (for $q^{1|0} = 0.1$) and 5 (for $q^{1|0} = 0.9$). As noted above, the results under fairness for the case of unknown CSI are the same as those in Figs. 2 and 3. For the purpose of comparison, we also include the energy efficiency results without the fairness constraint (Perfect CSI) of Section 3.5. As expected, the energy efficiency under the fairness constraint can be significantly lower than that without the fairness constraint. These results again illustrate the well-known tradeoff between performance efficiency and fairness [12].

## 5 Conclusion

While throughput maximization remains an important goal, energy efficiency improvement is a growing important objective in the design of modern communication systems and networks, due to the high cost of energy use and production as well as the resulting environment impacts. Our goal of this paper is to focus exclusively on the transmission energy efficiency, without other additional constraints. For this baseline model, we show that energy efficiency is maximized by the choice of an appropriate transmission set, rather than via a randomized approach in which the sources transmit with some probability. This reduces the optimization problem from a continuous one to a finite one. Further, simultaneous transmissions should be avoided if the energy-efficiency maximization is the main concern. As discussed in the paper, CSI can be exploited to improve energy efficiency, as expected. Our basic model can be extended to address the issue of fairness. Other extensions are possible for future studies. For example, additional constraints can be imposed to the basic model, such as a deadline or a delay constraint [14]. However, energy efficiency will be reduced when such constraints are incorporated into the model. In addition to the transmission energy efficiency, the energy required for hardware and electronic circuitry can be considered. The more refined model should also include the cost of obtaining the CSI.


## Acknowledgment

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