Energy-Efficient Adaptive MIMO Systems Leveraging Dynamic Spare Capacity

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***Abstract*—In this paper, we propose an adaptive technique exploiting transmission mode switching between multiple input multiple output (MIMO) and single input multiple output (SIMO) with antenna selection to conserve mobile terminals' energy. We focus on saving uplink RF transmission energy in cellular systems supporting dynamic best effort (file transfer) traffic loads. The key idea is to judiciously slow down file transfer rates when a base station is underutilized. Due to the DC power components associated with the multiplicity of transmission chains, MIMO may have higher power consumption than SIMO. Thus, considering a desired user perceived target throughput as well as energy-efficiency, we propose an algorithm for mode switching (MIMO/SIMO) and rate selection. Extensive flow-level simulations under dynamic loads and Rayleigh fading channels confirm that the proposed technique can save more than 50 % of the mobile terminals' transmission energy and enable an effective tradeoff between performance and energy conservation.**

***Index Terms*—MIMO systems, energy conservation, spare capacity**

I. Introduction

Wireless cellular systems such as WiMAX are evolving to support mobile broadband data services [1]. Though future wireless systems promise to support higher capacity, it is achieved in most cases at the expense of much higher energy consumption resulting in shorter battery lifetime for mobile terminals. Hence the study of energy saving to extend battery lifetime has been an active research area [2]–[8]. Recognizing that uplink RF transmission energy is one of the main contributors to battery consumption, *e.g.,* about 60% in time division multiple access (TDMA) phones [3], reducing the uplink RF transmission energy is of prime importance.

Fortunately, unlike voice service which requires sustained constant bit rates, data services (*e.g.,* uploading files, pictures or emails) allow mobile terminals to exploit the delay-tolerance (elastic) to save energy. Consider the *spare capacity*, in a stationary system, defined as the amount of system capacity one can reduce while remaining stable. Hence, when the base station is underutilized[1], which is likely due to dynamic user populations and traffic loads, one simple way to save energy is to leverage spare capacity – *i.e.,* slow down file transfers but keep the system stable. Indeed, even if the file transfer delay (or simply *delay* hereafter) is prolonged, the transmission power drops sharply by Shannon's theorem, and the transmission energy – the product of power and delay – is reduced [2]. We refer to this as the *energy-delay tradeoff.*

The premise on the energy-delay tradeoff, however, may not be valid if one takes into account DC power[2] in the transmission chain [4], [7], which is exacerbated in multiple input multiple output (MIMO) systems [4]; multiple transmission antennas require multiple associated circuits (mixers, synthesizers, digital-to-analog converters, filters, etc), so the DC power of MIMO transmission chains is higher than that of SIMO [4]. It is well known that MIMO is more energy-efficient than SIMO because of spatial multiplexing gains [9], but this may not be true when DC power is factored. In this regard, we claim that SIMO can be more energy-efficient than MIMO when we slow down to save energy. Thus, we propose an *adaptive* switching technique between MIMO and SIMO under dynamic user loads.

Prior work on adaptive MIMO techniques was mostly done in the physical (PHY) layer [10]–[12] and not specifically addressing energy saving. The authors in [11] proposed simple mode selection criteria to improve link level bit error rate (BER) performance. To enhance capacity, several adaptive MIMO and link adaptation techniques have been proposed [12]–[14] but they only considered the PHY layer. By contrast, our work is a cross-layer energy saving approach considering circuit power at the circuit level, multiple antennas at the physical layer and dynamic user load at the media access control (MAC) layer.

One of the challenges lies in the tradeoff between active power[3] and the DC power. Note that slowing down the transmission rate reduces active energy consumption [2], but it increases the DC energy consumption [4], [5], [7]. Thus, an energy-optimal transmission rate exits. In solving this optimization problem, the work in [5], however, is limited to physical layer modulation techniques with a single sender and receiver pair for sensor networks, and the work in [6], [7] addresses multiple users including the MAC layer but only for a *fixed* number of users in wireless local area network. Unlike previous work, we focus on dynamic user populations

[1]Utilization is defined as the average fraction of time when the system is busy.

[2]DC power refers to the collection of circuit power that is constant irrespective of the transmission rate.

[3]Active power refers to the power consumption of RF power amplifier that is roughly captured by Shannon's capacity theorem and thus an exponential function of the transmission rate.

in a *cellular* system capturing a realistic environment where new file transfers are initiated at random and leave the system after being served.

In this paper, we have two primary questions to answer. The first one concerns *mode switching*; how to change the transmission mode between MIMO and SIMO to save energy when a system serves a dynamic load. The second concerns *rate selection*; how to determine the transmission rate considering DC and idle power consumption to save energy while satisfying the target throughput of each user. The effect of idle power will be explained in Section III in detail.

Contributions

1) We propose an adaptive mode switching technique between MIMO and SIMO exploiting the fact that SIMO can be more energy-efficient than MIMO when the DC power is included. In a two transmit and two receive antenna (2×2) MIMO system, which is a practical set-up for real environments, we demonstrate for example that mode switching can save uplink transmission energy significantly by more than 50 % as compared to MIMO only without substantially change user-perceived performance. Switching benefits are more significant when the target throughput is low. Interestingly, if MIMO uses the zero forcing receiver, mode switching saves energy even if DC and idle power are neglected. This is because ill-conditioned channels degrade the performance of zero forcing receivers.

2) This work is the first to leverage *dynamic spare capacity* to realize energy savings in MIMO systems. Dynamic spare capacity is available when the system is underutilized, occasionally, due to dynamic user population and/or bursty traffic loads. Energy is saved by slowing down transmission rates when the system is underutilized. DC and idle power, however, deteriorate the energy saving benefit and total energy consumption may increase if the user target throughput is too low. The proposed algorithm effectively avoids this problem by exploiting an energy-optimal transmission rate.

Discussion on the assumptions

1) Are wireless base stations really underutilized? One might argue that wireless networks are not usually underutilized. In fact, underutilization is common in networks; e.g., Internet service providers' networks see a low utilization as low as 20% [15]. Broadband cellular systems have much higher time and spatial variability in traffic loads and system capacity [16]. Thus, bursty, uncertain traffic loads and fluctuating capacity necessitate conservative design, so base stations are likely to be underutilized.

2) Are slow downs acceptable for energy savings? One might argue that users may prefer file transfers be realized as quickly as possible rather than conserve energy. This may be true if saving energy compromises user-perceived performance. Specifically, for the downlink, fast transmission is important for user satisfaction with say web browsing or file download applications. However, for the uplink, which is the main concern in this paper, uploading of files, e.g., pictures or emails, may be quite delay-tolerant and could be carried out as *background* process after users click the 'send button'.

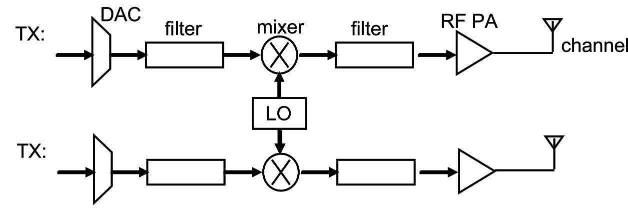


Fig. 1. Transmission chain for a MIMO system with two antennas.

II. System model

A. Assumptions

We consider a centralized wireless communication system with one base station (BS) serving multiple mobile terminals (MT). Target systems could be, but are not limited to, WiMAX or 3GPP-LTE. We assume that the system is based on MIMO and shared by time division multiple access (TDMA). Since energy savings are more important at the mobile terminals than at the base station, we focus on uplink transmissions.[4] Our work is, however, also applicable in saving downlink energy at the base station. We consider MIMO systems where the transmitter does not have the channel state information (CSI), *i.e.,* no channel feedback. Nevertheless, we assume that the BS informs each MT of the appropriate transmission mode, either MIMO or SIMO, which requires 1 bit of feedback. In addition, in the case of SIMO, the BS informs the MT of the antenna index with higher channel gain, which requires an additional 1 bit of feedback. We assume that the channels experience flat fading[5] and the dimension of channel matrix $\mathbf{H}$ is $N_r \times N_t$ where N_r is the number of receive antennas at the BS and N_t is the number of transmit antennas at the MT. For simplicity, we focus on the case of $N_t = 2$ and $N_r = 2$. The assumption of two transmit antennas at mobile terminals is in accordance with the antenna configurations listed in the IEEE802.16m [17] and 3GPP LTE [18]. Our focus is on delivering delay-tolerant (best effort) traffic.

B. Problem definition

As mentioned in the introduction, the key questions are 1) how to change transmission mode between MIMO and SIMO to save energy in a system supporting dynamic user population (*mode switching*), and 2) how to determine the appropriate transmission rate considering DC and idle power consumption as well as the average target throughput of each user (*rate selection*). Because MIMO is more energy-efficient at high transmission rate, it is desirable to use MIMO if the base station is congested (and fast transmission is required). However, when the system is underutilized, mobile terminals can slow down to save energy. Then, it is not clear which mode – MIMO or SIMO – is more energy-efficient.

[4]Note that we do not consider the power consumption of receiving blocks of mobile terminals because it is not much affected by the download rate.

[5]Flat fading can be obtained in practice using multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM).

C. Transmission power models

Fig. 1 (redrawn from [4]) shows the transmission chain for MIMO. A key element of our work is to have a reasonable transmission power model.

1) MIMO power model: Since the mobile terminals do not know the CSI, we use equal power allocation to each antenna.[6] Let λ_1 and λ_2 be the eigenvalues of $\mathbf{H}^*\mathbf{H}$ where $\mathbf{H}^*$ is a complex conjugate of $\mathbf{H}$. Then, the achievable spectral efficiency of MIMO given $\mathbf{H}$ can be expressed by [9]

$$C = \sum_{i=1}^{N_t} \log\left(1 + \frac{P}{N_0 N_t}\lambda_i\right) \tag{1}$$

where $N_t = 2$ and P is the transmission power, and N_0 is the noise power. Based on (1) and assuming that the power consumed by the power amplifiers is linearly dependent on the output power [4], we have the following transmission power equation $f_m(r)$ for MIMO at transmission rate r with spectral bandwidth w and DC power consumption $p_{\text{dc},m}$:

$$f_m(r) = \frac{1}{\eta}\frac{2}{\lambda_1\lambda_2}N_0 \times \left(\sqrt{\left(\frac{\lambda_1+\lambda_2}{2}\right)^2 + \lambda_1\lambda_2(2^{r/w}-1)} - \frac{\lambda_1+\lambda_2}{2}\right) + p_{\text{dc},m} \tag{2}$$

where the subscript m stands for MIMO and η is the drain efficiency, which is defined as the ratio of the output power and the power consumed in the power amplifier. For simplicity, we assume that the transmission rate is continuous.[7]

Note that (1) and (2) are based on an ideal MIMO receiver. As an example of a practical linear receiver, we here consider a zero forcing receiver which gives us the analytical tractability. Then, (1) is modified to [19]

$$C = \sum_{i=1}^{N_t} \log\left(1 + \frac{P}{N_0 N_t}\frac{1}{[(\mathbf{H}^*\mathbf{H})^{-1}]_{i,i}}\right) \tag{3}$$

where $[(\mathbf{H}^*\mathbf{H})^{-1}]_{i,i}$ denotes ith diagonal element of $(\mathbf{H}^*\mathbf{H})^{-1}$. Thus, if λ_i is replaced by $1/[(\mathbf{H}^*\mathbf{H})^{-1}]_{i,i}$ in (2), we get the transmission power model of a MIMO with zero forcing receiver. In computing the DC power, we assume that MIMO requires N_t number of each transmission block, but the frequency synthesizer, *i.e.,* local oscillator (LO), is shared by multiple antennas [1], [4] as can be seen in Fig. 1. Then, the total DC power consumption of MIMO is given by

$$p_{\text{dc},m} = N_t(p_{\text{dac}} + p_{\text{mix}} + p_{\text{filt}}) + p_{\text{syn}} \tag{4}$$

where p_{dac}, p_{mix}, p_{filt}, p_{syn} stand for the power consumption from a digital-to-analog converter, a mixer, a filter, and a frequency synthesizer, respectively.

[6] Our work is also applicable to closed loop MIMO, but it may be hard to get the closed form expression of the transmission power as a function of the rate.

[7] For the discrete transmission rate, *i.e.,* finite modulation order with BER constraint, see [4].

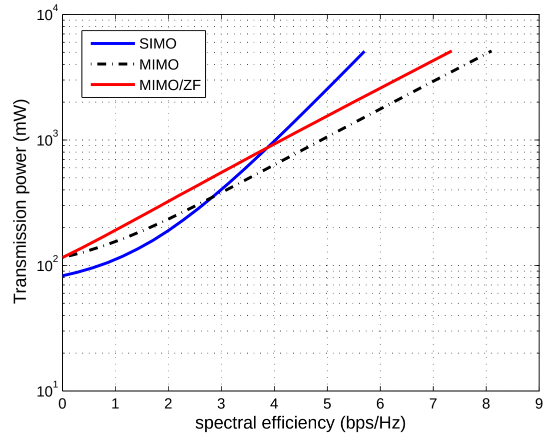


Fig. 2. Transmission power consumption of mobile terminals including DC power.

2) SIMO power model: The transmission power of SIMO $f_s(r)$ where the subscript s stands for SIMO, is given by

$$f_s(r) = \frac{1}{\eta}\frac{2^{r/w}-1}{|h_1|^2+|h_2|^2}N_0 + p_{\text{dc},s} \tag{5}$$

where h_1 and h_2 are channel coefficients and the DC power for SIMO is $p_{\text{dc},s} = p_{\text{dac}} + p_{\text{mix}} + p_{\text{filt}} + p_{\text{syn}}$. In the case of SIMO, the antenna with higher gain is selected using 1 bit antenna selection feedback.

D. Motivation for mode switching

Fig. 2 exhibits the transmission powers for both of MIMO and SIMO for Rayleigh fading channels. Note the crossover around $r/w = 3$ bps/Hz below which SIMO is more energy-efficient than MIMO. (This figure is an example of one realization of the channel $\mathbf{H}$ – different realizations will give different results.) In addition, as an example of MIMO with linear receiver, we plot the transmission power of MIMO with zero forcing receiver and note that the crossover point is higher than that for the ideal receiver, *i.e.,* $r/w = 3.9$ bps/Hz. The crossover points show the necessity of the good switching policy between MIMO and SIMO considering the transmission rate, user-perceived throughput and energy-efficiency.

III. Energy-efficient Adaptive MIMO in dynamic user population

A. Simple mode switching

If SIMO and MIMO use the same transmission rate r, it is straightforward to choose the transmission mode; we pick up the transmission mode that consumes least power at rate r, and the selected mode $\hat{z}$ at rate r is

$$\hat{z}(r) = \arg\min_{z\in\{m,s\}} f_z(r). \tag{6}$$

Let us call this *simple mode switching*.

B. Challenges in mode switching and rate selection

In each mode z, however, we need to be careful to choose the transmission rate r considering the tradeoff between active and DC power consumption. If there is no DC power consumption, the transmission energy is a monotonically decreasing function of the transmission time [2]. By contrast, when the DC power exists, the DC energy consumption grows linearly with the transmission time, and the total energy consumption becomes a convex function of the transmission time. Thus there exists an energy-optimal rate. As can be seen in (2) and (5), MIMO and SIMO have different active and DC powers, and thus different energy-optimal transmission rates.

A dynamic user population makes realizing such energy-delay tradeoffs more challenging. Let us consider a TDMA system. In every timeslot, the scheduled user uploads data while other users, called *idle users*, wait. Ideally, idle users should be able to turn off all the transmission circuits to minimize energy expenditures. In a real system, however, it may not be possible due to leakage currents or practical implementation issues. Thus, idle users consume a small amount of power called *idle power*.[8] Recall that we address dynamic systems where each user arrives with a file, sojourns in the system and leaves after completing file transfer. Then, if the file transfer rate is reduced to take advantage of energy-delay tradeoffs, the number of users may accumulate, and each user becomes idle longer which makes idle power consumption grow. Consequently, we need to judiciously select the transmission rate to avoid excessive idle power consumption.

C. Proposed algorithm: CUTE

Now, we describe our proposed rate selection and mode switching algorithm in multi-user scenario in time varying MIMO channels. This algorithm is named CUTE, which stands for *Conserving User Terminals' Energy*. The CUTE algorithm resolves two objectives: saving energy and achieving (or exceeding) a target user-perceived throughput. The underlying principle is to switch between SIMO and MIMO adaptively in accordance to the number of users, throughput history and channel fluctuations. In a TDMA system, we assume that time is divided into equal-sized *frames*. A frame is defined as the time period during which all users are scheduled an equal fraction of time, *i.e.,* temporally fair scheduling. Round robin scheduling falls into this category. Let t denote the frame index.

Rate selection: Suppose that $n(t)$ users share the uplink channel for an equal fraction of time. Let $r_{i,z}(t)$ be the transmission rate of user i using transmission mode $z \in \{m, s\}$. We specify the maximum possible transmission rate as $c_{i,z}(t)$, which is determined by the time varying MIMO channel matrix $\mathbf{H}$ and the maximum output power p_{out}. Since we assume that users share the channel in a temporally fair way, each user is only allocated a fraction $1/n(t)$ of the time frame, and the maximum achievable rate of user i should be $c_{i,z}(t)/n(t)$. Let $q_i(t)$ denote the target rate of user i. Note that the target rate is specified so as to satisfy the user's throughput requirement and it should be independent of z. So, we do not have a subscript z in $q_i(t)$. Finally, we define an energy-optimal transmission rate as $e_{i,z}(t)$, which captures the DC and idle power consumption. Then, the transmission rate $r_{i,z}(t)$ is given by

$$r_{i,z}(t) \quad = \quad \min\left(\max\left(e_{i,z}(t), q_i(t)\right), \frac{c_{i,z}(t)}{n(t)} \right), \qquad (7)$$

which means that we pick up the maximum of the energy-optimal rate and the target rate (if feasible). The specification of $e_{i,z}(t)$ and $q_i(t)$ are given later.

Mode switching: Suppose that $r_{i,z}(t)$ is given. Since each user uses $1/n(t)$ fraction of time frame, the instantaneous rate should be $n(t)r_{i,z}(t)$ to achieve $r_{i,z}(t)$, and the corresponding transmission power is $f_{i,z}\big(n(t)r_{i,z}(t)\big)$. So, the energy per bit is given by $f_{i,z}\big(n(t)r_{i,z}(t)\big)/n(t)r_{i,z}(t)$, and the transmission mode of user i is selected as that with least energy per bit, *i.e.,*

$$\hat{z}_i \quad = \quad \arg\min_{z\in\{m,s\}} \frac{f_{i,z}\big(n(t)r_{i,z}(t)\big)}{r_{i,z}(t)}. \qquad (8)$$

Note that $r_{i,z}(t)$ might be different for MIMO and SIMO because of different $e_{i,z}(t)$ or $c_{i,z}(t)$. If $r_{i,m}(t) = r_{i,s}(t)$, then the above rule is identical to simple mode switching in (6). After we determine the mode, the service rate of user i is

$$r_i(t) = r_{i,\hat{z}_i}(t). \qquad (9)$$

Fig. 3 shows the overall operation of the proposed algorithm.

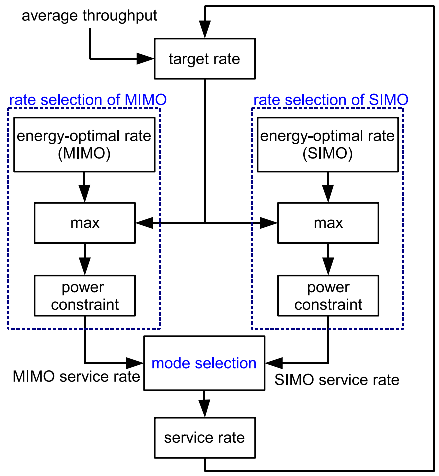
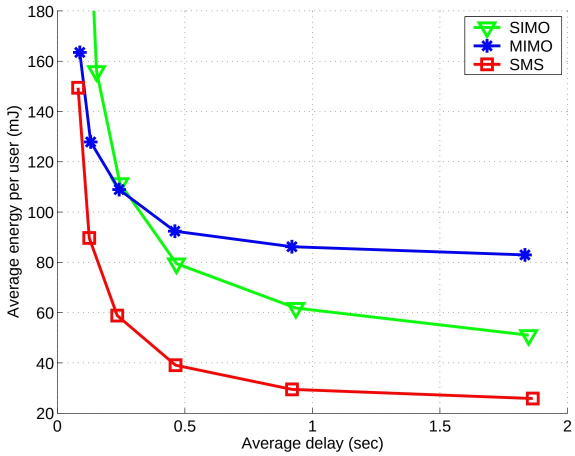


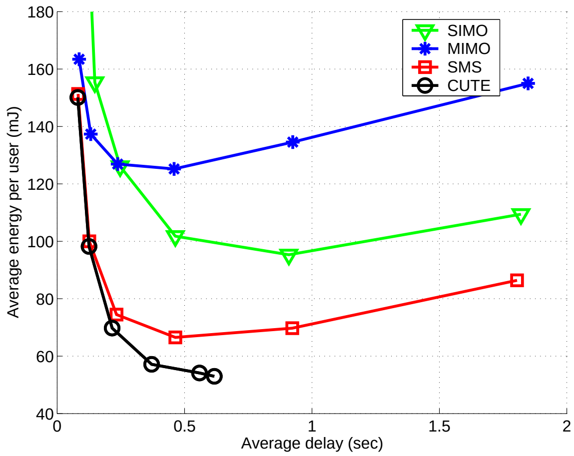
Fig. 3. Flow chart of the proposed algorithm.

Target rate $q_i(t)$: Suppose that each user wants to achieve a throughput q_i. Since we focus on best effort traffic, which is assumed to be tolerant to transmission rate variation, we do not need to achieve q_i instantaneously. Instead, we consider achieving q_i on average. Based on an exponential averaging of

[8]For example, in idle timeslots, RF PA goes to standby mode to save energy, but still 1 $\sim$ 10 mA of idle current can conduct at 2.5V, *i.e.,* 2.5 $\sim$ 25 mW of idle power consumption [20]. In fact, the idle power value depends on the specific system implementation.

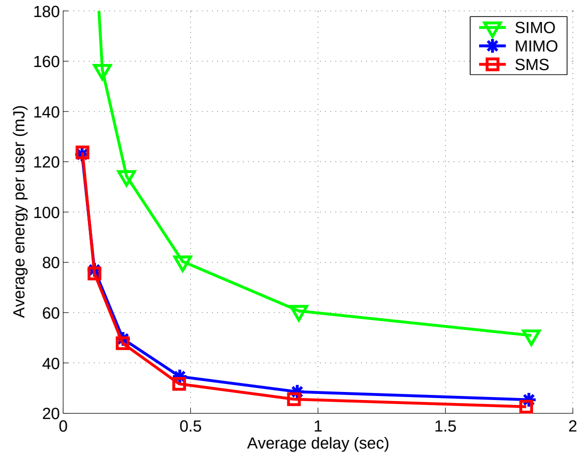


(a) Without DC or idle power.

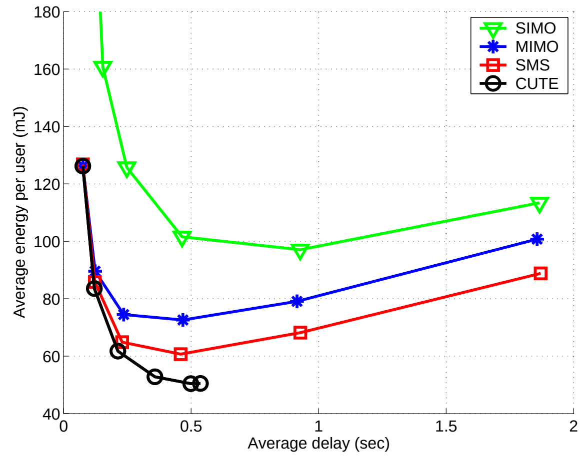


(b) With DC and idle power.

Fig. 4. Average energy consumption per file transfer versus average file transfer delay (MIMO with zero forcing receiver).



(a) Without DC or idle power.



(b) With DC and idle power.

Fig. 5. Average energy consumption per file transfer versus average file transfer delay (ideal MIMO receiver).

$r_i(t)$, let us define the *average* rate $\bar{r}_i(t)$ seen by user i up to time frame t as $\bar{r}_i(t) = \bar{r}_i(t-1)\nu + r_i(t)(1-\nu)$ where $0 < \nu < 1$ corresponds to averaging weight on the past. We define a *relaxed target rate* $q_i(t)$ to satisfy $q_i = \bar{r}_i(t-1)\nu + q_i(t)(1-\nu)$ so $q_i(t)$ is given by

$$q_i(t) = \frac{q_i - \bar{r}_i(t-1)\nu}{1-\nu}, \tag{10}$$

which relaxes the time scale over which the performance target should be met. It is shown in [8] that the relaxed target rate enables additional energy savings.

Energy-optimal rate *$e_{i,z}(t)$:* Given $f_z(r)$ and the idle power consumption p_{idle}, we define the energy-optimal transmission rate $e_{i,z}(t)$ as that which minimizes the energy per bit during a time frame such as

$$e_{i,z}(t) = \arg\min_r \left(\frac{1}{n(t)} f_{i,z}(n(t)r) + \frac{n(t)-1}{n(t)} p_{\text{idle}} \right) \frac{1}{r}, \tag{11}$$

which means that a typical user consumes $f_{i,z}(n(t)r)$ power for $\frac{1}{n(t)}$ fraction of time and p_{idle} for $\frac{n(t)-1}{n(t)}$ fraction of time. Note that p_{idle} is independent of z. The proposed algorithm converges *exponentially fast* to an equilibrium rate given a fixed $n(t)$ and channel gains – the proof is given in [8].

IV. Simulation Results

To validate the proposed algorithm, we compute the average energy consumption per file transfer and the average delay using flow-level event-driven simulations [21]. In each frame, users arrive according to a Poisson process with rate $5.2/sec$. One user arrives with one file having identical and independently distributed (*i.i.d.*) exponential distribution with mean 60 kbytes [21]. Users are assumed to experience *i.i.d.* 2×2 Rayleigh fading channels. Simulation parameters are as follows: the drain efficiency $\eta = 0.2$, $\nu = 0.95$, $w = 1$ MHz, $p_{\text{mix}} = 30.3$ mW, $p_{\text{syn}} = 50.0$ mW, $p_{\text{filt}} = 20.0$ mW, $p_{\text{idle}} = 25$ mW, $p_{\text{dc}} = 15.6$ mW [1], [4], [20].[9] The average received

[9]Since the value of p_{filt} in [5] is too low for cellular systems, we adjust it from 2.5 to 20 mW, but the simulation results are almost the same.

SNR at the base station when the mobile terminal transmits at its maximum power $p_{\text{out}} = 27.5$ dBm is 17.5 dB. When the mobile terminals reduce the target throughput, the average received SNR decreases. The duration of a time frame is 5 ms, and the number of time frames for the simulation is 1,000,000. We plot the curves by varying q_i from 8.35 Mbps to 260 kbps to exhibit how slowing down the target performance impacts the tradeoff between delay and energy.

In Fig. 4 we show the simulation results for MIMO with zero forcing receivers. Fig. 4(a) plots the pair of average delay and average energy per file transfer when the DC or the idle power does not exist. Three curves correspond to SIMO with antenna selection, MIMO with zero forcing receivers, and simple mode switching (SMS). Interestingly, we see significant energy savings with SMS even though DC or idle power is not factored in. This is because ill conditioned channels degrade the energy-efficiency of MIMO.

Fig. 4(b) shows the energy-delay curves when the DC and idle power are factored. As can be seen, we still have significant energy savings using SMS versus MIMO. One interesting observation is that three energy curves of SIMO, MIMO and SMS grow up again if the delays are larger than some thresholds. This is because the effect of DC and the idle energy emerges when the file transfer delay is long. Hence, we cannot exploit energy-delay tradeoff. By contrast, the proposed algorithm CUTE effectively removes the undesirable points, (*i.e.,* long delay and large energy consumption) by incorporating the energy-optimal transmission rate. Even though the user specifies an excessively low target throughput (and large delay), the proposed algorithm automatically sends faster than the user's requirement to save energy. We see that energy savings by CUTE against MIMO is significant, *e.g.,* more than 50 % at 0.4 second delay.

Fig. 5 illustrates the results for MIMO with ideal receivers. Comparing Fig. 4 and Fig. 5 shows that the energy-delay performance of MIMO is better than that of MIMO with zero forcing receivers. Nevertheless, the performance of SMS and CUTE are almost the same as before, which implies that SIMO mainly contributes to saving energy at low transmission rates. In Fig. 5(a), we see that SMS performs better than MIMO even without DC or idle power. This gain comes from SIMO antenna selection. In Fig. 5(b), we also see that CUTE removes the undesirable pair of delay and energy successfully. We conjecture that, in the future work, if more sophisticated MIMO receivers, such as minimum mean square error (MMSE) or successive interference cancelation (SIC), are considered, the energy-delay performance will be between the case of MIMO and MIMO with zero forcing receivers.

V. Conclusion

In this paper, we showed that significant energy-saving is achieved by transmission mode switching between MIMO and SIMO under dynamic loads and channels realization. Even though MIMO is more energy-efficient than SIMO thanks to multiplexing gains, it may not be true when DC power consumption is included. This is because DC power can be dominant at low transmission rates. Mode switching contributes to saving energy even more for the case of MIMO with zero forcing receiver, which occasionally suffers from ill-conditioned channels. Allowing 1 bit feedback for SIMO antenna selection also makes the mode switching simple and feasible. To capture the dynamic user population, we performed flow-level simulations under Rayleigh fading channels. In doing this, we considered the effect of idle power consumption, which led us to investigate the energy-optimal transmission rates, and solved the mode switching problem combined with rate selection. The proposed algorithm CUTE not only saved energy significantly but also eliminated the undesirable pair of excessive delay and energy consumption.

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