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Energy-efficient Training-assisted Transmission Strategies for Closed-loop MISO Systems

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***Abstract*—This paper studies energy-efficient transmission strategies for a closed-loop downlink multi-input single-output (MISO) system, where a communication period consists of three phases for uplink training, downlink data sending and base station (BS) idling. For both delay-tolerant and delay-sensitive services, the durations of the three phases are optimized aimed at maximizing the energy efficiency (EE) of the system. To this end, we derive the approximate average net spectrum efficiency (SE) and outage probability with imperfect uplink channel estimation, which are used to characterize the quality of service (QoS) requirements for the two kinds of services, respectively. The impact of QoS requirement, signal-to-noise ratio and circuit power consumption on the optimal transmission durations is analyzed. For delay-tolerant services, analytical results show that the EE-oriented design leads to a longer training duration than the SE-oriented design in general. For delay-sensitive services, it is shown that introducing BS idling is crucial to improve the EE. The challenges and opportunities of applying the proposed transmission strategies in current and future cellular systems are discussed, and the transmission strategies are extended from single-user single-service to multi-user mixed-service scenarios. Simulation results demonstrate the significant EE gain of the EE-oriented design over the SE-oriented design in both single-user and multi-user scenarios.**

***Index Terms*—Energy efficiency, training design, base station idling, quality of service.**

I. Introduction

Energy efficient communications are becoming more and more desirable for future wireless networks to reduce the associated energy consumption, carbon emission, and operational cost [1]. To improve the energy efficiency (EE) while ensuring the quality of service (QoS) requirements of users, traffic and QoS-aware design is an important principle, based on which some energy efficient transmission strategies have been proposed. For example, traffic-aware power sharing policies considering spatial traffic load difference were studied in [2], base station (BS) sleeping control and power matching schemes were studied in [3] to achieve a good tradeoff between energy saving and traffic delay, and opportunistic transmission scheduling schemes and advanced relay transmission schemes exploiting the delay tolerance of services were investigated in [4] and [5], respectively. In [6] and [7], a typical QoS-aware strategy, BS idling, was investigated in time domain and frequency-time domain respectively, which provides on-demand services to users according to their QoS requirements and is commonly recognized as a promising approach to reduce energy consumption. In [8], a QoS-based antenna switching off technique was proposed, where the BS idling is in spatial domain.

The application of BS idling requires the knowledge of channel state information (CSI) at the BS, based on which the BS can transmit all data during a part of the time slots with adaptive rate, while remaining in idle mode during other time slots to save energy. In [6] and [7], perfect CSI is assumed at the BS for the optimization of BS idling, which leads to optimistic EE performance since the impact of channel estimation errors and the resource usage as well as energy consumption for channel acquisition are not taken into account.

In time division duplex (TDD) systems, the BS can obtain the downlink CSI by estimating the uplink CSI from the received uplink training signals based on the channel reciprocity. In the literature, training design for the maximization of system spectral efficiency (SE) has been well studied. In [9], the length of training signals for a multi-input multi-output (MIMO) system was optimized to maximize the lower bound of the channel capacity. It is shown that the optimal training length equals to the number of transmit antennas when the transmit powers of training and data are jointly optimized. The optimal training length that maximizes the net uplink SE and downlink SE in multi-user MIMO systems was respectively investigated in [10] and [11].

However, the training designed for high SE does not necessarily lead to high EE when taking into account the circuit power consumption and signaling overhead. The training design aimed at EE maximization was first studied in [12] for a single-input single-output (SISO) system, where the length and transmit power of training signals are optimized. In [13], energy-efficient power allocation between training and data symbols was investigated for a training-based downlink MIMO system. Both the works in [12] and [13] considered the optimization of downlink training, either without or with the circuit power consumptions. The EE-oriented design of uplink training for closed-loop systems was studied in our preliminary work [14], where only delay-tolerant services are considered and BS idling is not taken into account.

In this paper, we study the energy efficient transmission

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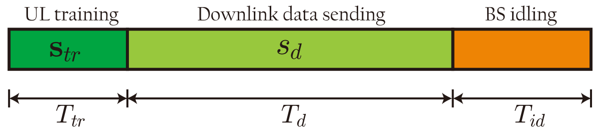

Fig. 1. A communication period of the considered TDD systems consisting of uplink training, downlink data sending, and idling, where $T_{tr}+T_d+T_{id}=T$.

strategies for a training-assisted downlink closed-loop system, where a communication period is divided into three phases for uplink training, downlink data sending, and BS idling. We first consider a single-user multi-input single-output (MISO) system, which can act as a good start for continuing the design of energy efficient closed-loop strategies for general multi-user MIMO systems. Noting that maximizing EE should not sacrifice the user experience and different traffics impose different QoS provisions, we consider both delay-tolerant and delay-sensitive services in the analysis. For each kind of services, the durations of the three phases are jointly optimized aimed at maximizing EE, and the impact of QoS requirement, signal-to-noise ratio (SNR) and circuit power on the optimal durations and system EE is analyzed. We then discuss the challenges and opportunities of applying the proposed transmission strategies in current and future cellular systems, and provide one way to extend the transmission strategy designs from single-user single-service to multi-user mixed-service scenarios. Simulation results validate our analytical analysis, and demonstrate the EE gain of the EE-oriented design over the SE-oriented design.

Notations: $\mathbf{I}$ denotes the identity matrix, $|\cdot|$ and $\|\cdot\|$ represent the magnitude and Euclidian norm, respectively, $(\cdot)^H$ denotes conjugate transpose, and $\otimes$ is the Kronecker product. $\mathbb{N}^+$ and $\mathbb{N}$ denote the set of positive integers and non-negative integers, respectively.

II. System, Power Consumption and Service Models

A. System Model

Consider a TDD MISO system where the BS is equipped with M antennas and the user has a single antenna. We assume block fading channels, which remain constant during each communication period but are independent between different periods. As shown in Fig. 1, the communication period has the duration of T symbols, which is divided into three phases including uplink training, downlink data sending, and BS idling with the durations of T_{tr}, T_d and T_{id} symbols, respectively. In the uplink training phase, the user sends uplink training signals to the BS. Then in the downlink data sending phase, the BS estimates the uplink CSI and obtains the downlink CSI based on channel reciprocity, with which the downlink precoder is computed for data transmission. In the BS idling phase, the BS switches into idle mode to save energy if the QoS requirement of the user has been satisfied. In the paper, we consider the BS idling that can operate in the symbol level. To realize the fast deactivation and reactivation of the hardware, some components of the BS may not be completely turned off but they can operate with low power consumption. For example, the millisecond-level BS idling has been considered in [15]. Compared with the long-term BS idling, which can be only used during the traffic off-peak hours, the employed BS idling is a whole-day strategy and is recognized as an important approach for energy saving [7].

During the uplink training phase, the training signals $\mathbf{s}_{tr}$ are sending from the user over the T_{tr} symbols, where $\mathbf{s}_{tr}\in\mathbb{C}^{T_{tr}\times 1}$ and $\mathbf{s}_{tr}^H\mathbf{s}_{tr}=P_uT_{tr}$ with P_u denoting the transmit power of the user. Then the received signal at the BS can be expressed as

$$\mathbf{y}_u=\mathbf{S}_{tr}\mathbf{h}+\mathbf{n}_u, \tag{1}$$

where $\mathbf{S}_{tr}=\mathbf{I}\otimes\mathbf{s}_{tr}$ is a $MT_{tr}\times M$ training matrix, $\mathbf{h}\sim\mathcal{CN}(\mathbf{0},\sigma_h^2\mathbf{I})$ is a $M\times 1$ channel vector whose elements are independent and identically distributed (i.i.d) complex Gaussian random variables with zero mean and variance σ_h^2, and $\mathbf{n}_u\sim\mathcal{CN}(\mathbf{0},\sigma_u^2\mathbf{I})$ is additive white Gaussian noise (AWGN) at the BS.

We consider minimum mean square error (MMSE) channel estimator. Then, the relationship between the true value of channel vector $\mathbf{h}$ and its MMSE estimate $\hat{\mathbf{h}}$ can be modeled as

$$\mathbf{h}=\hat{\mathbf{h}}+\mathbf{e}. \tag{2}$$

where $\hat{\mathbf{h}}\sim\mathcal{CN}(\mathbf{0},\sigma_{\hat{h}}^2\mathbf{I})$, $\mathbf{e}\sim\mathcal{CN}(\mathbf{0},\sigma_e^2\mathbf{I})$ is the estimation error vector, and $\hat{\mathbf{h}}$ and $\mathbf{e}$ are uncorrelated [16]. It is not hard to show that $\sigma_{\hat{h}}^2=\frac{\sigma_h^2\gamma_uT_{tr}}{1+\gamma_uT_{tr}}$ and $\sigma_e^2=\frac{\sigma_h^2}{1+\gamma_uT_{tr}}$, where $\gamma_u\triangleq\frac{P_u\sigma_h^2}{\sigma_u^2}$ is the average uplink SNR.

During the downlink data sending phase, maximum ratio transmission (MRT) precoder is employed [17], which can be expressed as $\mathbf{w}=\sqrt{P_d}\frac{\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}$, where P_d is the transmit power of the BS. The received signal at the user is

$$y_d=\mathbf{h}^H\mathbf{w}s_d+n_d, \tag{3}$$

where s_d is the downlink data symbol, and $n_d\sim\mathcal{CN}(0,\sigma_d^2)$ is the AWGN at the user.

By assuming perfect estimation of the downlink equivalent channel $\mathbf{h}^H\mathbf{w}$, the downlink instantaneous SNR can be obtained from (2) and (3) as

$$\mathrm{SNR}=\frac{P_d}{\sigma_d^2}\left|\frac{\mathbf{h}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\right|^2=\frac{P_d}{\sigma_d^2}\left|\|\hat{\mathbf{h}}\|+\frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\right|^2, \tag{4}$$

and the instantaneous net SE of the system during the whole period is

$$SE^{in}=\frac{T_d}{T}\log_2(1+\mathrm{SNR})=\frac{T_d}{T}\log_2(1+\frac{P_d}{\sigma_d^2}\left|\|\hat{\mathbf{h}}\|+\frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\right|^2). \tag{5}$$

B. Power Consumption Model

Considering the fact that the overall power consumption at the user is far less than that at the BS, we only consider the power consumed by the BS.

During the uplink training phase, the BS operates in receiving mode. The power consumption can be modeled as [1]

$$P_{bu}=\frac{M\cdot(P_{RF}^{RX}+P_{BB}^{RX})}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})}\triangleq M\cdot P_c^{RX}, \tag{6}$$

where P_{RF}^{RX} and P_{BB}^{RX} are the powers consumed by radio frequency (RF) links and baseband (BB) signal processing

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such as synchronization and channel estimation, σ_{DC}, σ_{MS} and σ_{cool} are the loss factors used to reflect the powers incurred by DC-DC power supply, mains supply and active cooling, respectively, and $P_c^{RX} \triangleq \frac{P_{RF}^{RX}+P_{BB}^{RX}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})}$ is the circuit power per antenna when the BS operates in receiving mode.

During the downlink data sending phase, the BS consumes both transmit and circuit powers. The power consumption can be modeled as

$$P_{bd} = \frac{\frac{P_d}{\eta} + M \cdot (P_{RF}^{TX} + P_{BB}^{TX})}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \triangleq \mu \cdot P_d + M \cdot P_c^{TX}, \quad (7)$$

where P_{RF}^{TX} and P_{BB}^{TX} are the powers consumed by RF links and BB signal processing such as precoding, modulation and coding, η is the efficiency of power amplifier (PA), $\mu \triangleq \frac{1}{\eta(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})}$ is a parameter that reflects the loss of transmit power, and $P_c^{TX} \triangleq \frac{P_{RF}^{TX}+P_{BB}^{TX}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})}$ is the circuit power per antenna when the BS operates in transmitting mode. Obviously, the power consumption of the BS during the downlink data sending phase is larger than that during the uplink training phase, i.e., $P_{bd} > P_{bu}$.

When the BS operates in idling mode, its power consumption P_{id} is far less than P_{bu} and P_{bd}. Therefore, we assume $P_{id} = 0$ in the analytical analysis, which does not change the conclusions we obtained.

Then, the total power consumption during a communication period can be expressed as

$$P_{tot} = \frac{P_{bu}T_{tr} + P_{bd}T_d}{T}. \quad (8)$$

C. Service Model

As mentioned before, the basic principle of energy-efficient design is to maximize the EE of the system meanwhile guarantee the QoS for each user. Different services impose different QoS constraints and have different traffic models, which lead to different optimization problems and EE gains. In this paper, we consider two classes of services with the following models to illustrate the EE gains of the systems with "on-demand" transmission strategies, which have very different QoS requirements.

- For *delay-tolerant services*, the traffic model provided by [18] is used, which reflects the services such as best efforts. It is assumed that there is always a sufficiently large backlog of data in the buffer for transmission. Since the data arrival process may be discontinuous in time and the amount of data arrived may be variable, the transmit strategy needs to ensure that the average transmission rate is no smaller than the average arrival rate.
- For *delay-sensitive services*, the traffic model provided by [19] is used. It models the delay-sensitive services such as VoIP, where packets arrive regularly and each must be transmitted within a given delay bound with a given outage probability.

III. Delay-tolerant Services

To achieve high EE for the system whereas guarantee QoS for the user with delay-tolerant services, we optimize the durations for uplink training, downlink data sending and BS idling, where the average net SE is used to characterize the user's rate requirement and to compute the EE of the system.

A. Average Net SE and Problem Formulation

From (5), the average net SE is

$$SE = \mathbb{E}\left[\frac{T_d}{T}\log_2(1 + \frac{P_d}{\sigma_d^2}\left|\|\hat{\mathbf{h}}\| + \frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\right|^2)\right], \quad (9)$$

where the expectation is taken over both channel estimate $\hat{\mathbf{h}}$ and estimation error $\mathbf{e}$, whose closed-form expression is difficult to obtain.

Considering that an explicit expression of the average net SE is crucial for formulating and solving the EE-optimization problem, in the sequel we seek its approximate expression. It is easy to show that $\|\hat{\mathbf{h}}\|$ is the square root of the sum of squares of M independent complex Gaussian random variables with zero mean and variance $\sigma_{\hat{h}}^2$, and $\frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}$ is a complex Gaussian variable with zero mean and σ_e^2. Moreover, it is obvious that $\sigma_{\hat{h}}^2$ is a monotonically increasing function of the average uplink SNR γ_u, while σ_e^2 is a monotonically decreasing function of γ_u. This suggests that when M is large and γ_u is high, the term $\frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}$ in (2) is far less than the term $\|\hat{\mathbf{h}}\|$ in a high probability, and the instantaneous downlink SNR can be approximated as

$$\text{SNR} = \frac{P_d}{\sigma_d^2}\left|\|\hat{\mathbf{h}}\| + \frac{\mathbf{e}^H\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}\right|^2 \approx \frac{P_d}{\sigma_d^2}\|\hat{\mathbf{h}}\|^2 \triangleq \widetilde{\text{SNR}}, \quad (10)$$

where $\widetilde{\text{SNR}} \sim \Gamma(k,\theta)$ is subject to Gamma distribution with shape k and scale θ, $k = M$, $\theta = \frac{\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}$, and $\gamma_d \triangleq \frac{P_d\sigma_{\hat{h}}^2}{\sigma_d^2}$ is the average downlink SNR.

Based on the moment matching method in [20], if a random variable $X \sim \Gamma(k,\theta)$, then $Y = X + c$ can be approximated as a Gamma distributed variable satisfying $\Gamma(k_y,\theta_y)$, where $c \geq 0$ is a constant, $k_y = \frac{(k\theta+c)^2}{k\theta^2}$ and $\theta_y = \frac{k\theta^2}{k\theta+c}$. The approximation is accurate when k is large enough. Then from (10), $1+\widetilde{\text{SNR}}$ is an approximate Gamma distributed variable satisfying $\Gamma(k_1,\theta_1)$, where

$$k_1 = \frac{(k\theta+1)^2}{k\theta^2} = M + \frac{1}{M\theta^2} + \frac{2}{\theta}, \quad \theta_1 = \frac{k\theta^2}{k\theta+1} = \frac{M\theta^2}{M\theta+1}. \quad (11)$$

For the variable $Y \sim \Gamma(k_y,\theta_y)$, $\mathbb{E}[\ln(Y)] = \psi(k_y)+\ln(\theta_y)$, where $\psi(k_y)$ is the Digamma function [20]. With this property the average net SE can be approximated as

$$SE \approx \frac{T_d}{T}\frac{1}{\ln 2}\mathbb{E}[\ln(1+\widetilde{\text{SNR}})] \approx \frac{T_d}{T}\frac{1}{\ln 2}(\psi(k_1) + \ln(\theta_1)). \quad (12)$$

When the value of M is large, k_1 will be large and $\psi(k_1) = \ln(k_1) + \mathcal{O}(\frac{1}{k_1}) \approx \ln(k_1)$ [20]. Then the average net SE can be further approximated as

$$SE \approx \frac{T_d}{T}\log_2(k_1\theta_1) = \frac{T_d}{T}\log_2(1 + \frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}) \triangleq \widetilde{SE}(T_{tr}, T_d, T_{id}), \quad (13)$$

which is accurate when the number of antennas M is large and the average uplink SNR is high. We will show the accuracy of the approximation via simulations later.

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Then the SE-oriented transmission strategy optimization problem, aimed at maximizing the average net SE, can be formulated as

$$\max_{T_{tr},T_d,T_{id}} \widetilde{SE}(T_{tr},T_d,T_{id}) \quad (14a)$$
$$s.t.\ T_{tr}+T_d+T_{id}=T \quad (14b)$$
$$T_{tr}\in\mathbb{N}^+,\quad T_d,T_{id}\in\mathbb{N}, \quad (14c)$$

where $T_{tr}\geq 1$ is considered for the closed-loop system.

We use SE_{max} to denote the optimal value of the objective function of problem (14), which is the maximum achievable average net SE of the system.

To maximize the EE of the considered system supporting delay-tolerant services, the objective function is defined as the ratio of the average net SE to the total power consumed at the BS during a communication period, which is

$$\widetilde{EE}(T_{tr},T_d,T_{id}) = \frac{\widetilde{SE}(T_{tr},T_d,T_{id})}{P_{tot}} = \frac{T_d}{P_{bu}T_{tr}+P_{bd}T_d}\log_2(1+\frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}). \quad (15)$$

The problem to optimize the durations for uplink training, downlink data sending and BS idling, aimed at maximizing the EE of the system, can be formulated as

$$\max_{T_{tr},T_d,T_{id}} \widetilde{EE}(T_{tr},T_d,T_{id}) \quad (16a)$$
$$s.t.\ \widetilde{SE}(T_{tr},T_d,T_{id})\geq SE_{min} \quad (16b)$$
$$T_{tr}+T_d+T_{id}=T \quad (16c)$$
$$T_{tr}\in\mathbb{N}^+,\quad T_d,T_{id}\in\mathbb{N}, \quad (16d)$$

where SE_{min} is the minimum average net SE requirement for the user to support delay-tolerant services.

B. Solution of Optimal Durations

Proposition 1: The optimal solutions of problems (14) and (16) are achieved when $T_{tr}+T_d=T$.

Proof: See Appendix A. ∎

It suggests that the BS never operates in idling mode when supporting delay-tolerant services. This is because with a minimal average rate constraint, the EE can be always improved by transmitting more data with higher rate in a longer duration. Based on Proposition 1, we have $T_d=T-T_{tr}$, then (13) and (15) can be expressed as

$$\widetilde{SE}(T_{tr})=\frac{T-T_{tr}}{T}\log_2(1+\frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}), \quad (17)$$
$$\widetilde{EE}(T_{tr})=\frac{T-T_{tr}}{P_{bu}T_{tr}+P_{bd}(T-T_{tr})}\log_2(1+\frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}). \quad (18)$$

Then problem (16) can be simplified as

$$\max_{T_{tr}} \widetilde{EE}(T_{tr}) \quad (19a)$$
$$s.t.\ \widetilde{SE}(T_{tr})\geq SE_{min} \quad (19b)$$
$$1\leq T_{tr}\leq T \quad (19c)$$
$$T_{tr}\in\mathbb{N}^+. \quad (19d)$$

To solve problem (19), we first remove constraint (19d) by regarding T_{tr} as a continuous variable within $[1,T]$, and then round the optimal solution to the nearest integer. The same approach can be used to solve the SE-oriented problem (14). The following proposition shows that such a relaxed version of the problem is convex.

Proposition 2: Both $\widetilde{EE}(T_{tr})$ in (19a) and $\widetilde{SE}(T_{tr})$ in (19b) are concave functions of T_{tr}, and their first-order derivatives, $\widetilde{EE}'(T_{tr})$ and $\widetilde{SE}'(T_{tr})$, are monotonically decreasing functions of T_{tr}.

Proof: See Appendix B. ∎

Therefore, the solutions to the relaxed versions of the SE-oriented and EE-oriented optimization problems can be numerically found with efficient algorithms [21]. Though we cannot find their closed-form solutions, we are able to compare the difference in the optimal training durations towards maximizing the EE and towards maximizing the SE.

C. Difference in Training Duration Optimized Towards EE and SE

Define T^*_{trSE} and T^*_{trEE} as the optimal uplink training durations of the relaxed versions of the SE-oriented optimization and the EE-oriented optimization, respectively. Denote $\Delta T^*_{tr}=T^*_{trEE}-T^*_{trSE}$ as the difference in the optimal training durations under the two criteria.

1) Impact of QoS requirement: The following proposition reflects the impact of the QoS requirement on the difference.

Proposition 3: $\Delta T^*_{tr}\geq 0$ always holds, the value of ΔT^*_{tr} remains constant first and then decreases with the increase of the minimum SE requirement, SE_{min}, and the equality holds when $SE_{min}=SE_{max}$.

Proof: See Appendix C. ∎

Note that the required minimum average SE by the user does not necessarily equals to SE_{max}. It implies that in general the EE-oriented optimization leads to a longer training duration for delay-tolerant services. This is because the power consumption of the BS in receiving mode is smaller than that in transmitting mode so that a longer uplink training duration will reduce the total power consumption of the BS.

2) Impact of uplink SNR: To show the impact of uplink S-NR on the difference in optimal training duration, we examine (17) and (18) in the extreme case where $\gamma_u\to\infty$.

For $T_{tr}\geq 1$, we have $\widetilde{SE}(T_{tr})\to(1-\frac{T_{tr}}{T})\log_2(1+M\gamma_d)$ from (17) and $\widetilde{EE}(T_{tr})\to\frac{T-T_{tr}}{P_{bu}T_{tr}+P_{bd}(T-T_{tr})}\log_2(1+M\gamma_d)$ from (18). The asymptotic expressions of both $\widetilde{SE}(T_{tr})$ and $\widetilde{EE}(T_{tr})$ are monotonically decreasing functions of T_{tr}. Therefore, $T^*_{trEE}=T^*_{trSE}=1$ when $\gamma_u\to\infty$.

This implies that at high uplink SNR, both criteria lead to the same short training duration.

3) Impact of circuit power consumption: To simplify the notations, we set $P_c^{TX}=\lambda P_c^{RX}$, where $\lambda>1$ means that the circuit power consumed at the BS in transmitting mode is larger than that in receiving mode. Then, the ratio of P_{bd} and P_{bu} can be expressed as

$$\frac{P_{bd}}{P_{bu}}=\frac{\lambda MP_c^{RX}+\mu P_d}{MP_c^{RX}}=\lambda+\frac{\mu P_d}{MP_c^{RX}}. \quad (20)$$

Substituting (20) into (C.6) in Appendix C, we have

$$\widetilde{SE}'(T^o_{trEE})=-\frac{\widetilde{SE}(T^o_{trEE})}{\frac{T}{\frac{\mu P_d}{MP_c^{RX}}+\lambda-1}+T-T^o_{trEE}}, \quad (21)$$

whereT^o_{trEE} is the training duration that maximizes $\widetilde{EE}$ without the minimum average SE constraint, as defined in Appendix C.

It is shown from (21) that $\widetilde{SE}'(T^o_{trEE})$ will increase with P_c^{RX} but is always less than zero. Since $\widetilde{SE}'(T_{tr})$ is monotonically decreasing and $\widetilde{SE}'(T^*_{trSE}) = 0$ where T^*_{trSE} is the training duration that maximizes the average SE, T^o_{trEE} will decrease with the increase of P_c^{RX} but is always larger than T^*_{trSE}. According to the analysis of the relationship among T^o_{trEE}, T^*_{trEE} and T^*_{trSE} in Appendix C, T^*_{trEE} will decrease with the increase of P_c^{RX} but always exceed T^*_{trSE}. Therefore, the difference in optimal training duration under the two criterion, ΔT^*_{tr}, will decrease with the increase of the circuit power.

If $\lambda = 1$, i.e. $P_c^{TX} = P_c^{RX}$, $\widetilde{SE}'(T^o_{trEE})$ will approaches zero when P_c^{RX} approach infinity, i.e., the optimal training duration T^o_{trEE} maximizing EE also maximizes $\widetilde{SE}$. Therefore, ΔT^*_{tr} will approach zero in this case.

In summary, $T^*_{trEE} = T^*_{trSE} = 1$ in high uplink SNR regime, and ΔT^*_{tr} approaches zero when the minimum SE requirement approaches the maximum achievable SE or when the circuit power is very large and $P_c^{TX} = P_c^{RX}$. In general scenarios, $T^*_{trEE} > T^*_{trSE}$, and ΔT^*_{tr} decreases with the increase of circuit power.

IV. Delay-sensitive Services

To achieve high EE and guarantee the QoS of delay-sensitive services, again we optimize the durations for uplink training, downlink data sending and BS idling, where the QoS requirement can be characterized by the outage probability for transmitting a given number of bits over the communication period as shown in Fig. 1.

A. Outage Probability and Problem Formulation

To model the QoS requirement, where a given number of bits (say B bits) should be transmitted within the duration T over the bandwidth W with the assistance of T_{tr} training symbols, we define a required net SE, $SE_r \triangleq \frac{B}{WT}$. Due to channel fluctuation and channel estimate errors, the required number of bits may not be transmitted reliably in the communication period even when the BS and the user employ their maximal transmit powers. The outage probability is defined as the probability that the instantaneous net SE, SE^{in}, is not larger than the required value of SE_r, i.e.,

$$\begin{aligned}P_{out}(T_{tr}, T_d, T_{id}|SE_r) =& Pr(SE^{in} \le SE_r)\\ =& Pr(\frac{T_d}{T}\log_2(1+\frac{P_d}{\sigma_d^2}\left|\|\hat{\mathbf{h}}\| + \frac{\mathbf{e}\hat{\mathbf{h}}^H}{\|\hat{\mathbf{h}}\|}\right|^2) \le SE_r). \end{aligned} \tag{22}$$

For notational simplicity, we define $\Psi \triangleq \left|\|\hat{\mathbf{h}}\| + \frac{\mathbf{e}\hat{\mathbf{h}}^H}{\|\hat{\mathbf{h}}\|}\right|^2$. Noting that $\frac{\mathbf{e}\hat{\mathbf{h}}^H}{\|\hat{\mathbf{h}}\|} \sim \mathcal{CN}(0, \sigma_e^2)$, then for a given $\|\hat{\mathbf{h}}\|$, Ψ is a noncentral chi-squared distributed random variable with two degrees of freedom and non-centrality parameter $\frac{\|\hat{\mathbf{h}}\|^2}{\sigma_e^2}$, whose cumulative distribution function (CDF) is denoted by $F_{(nc-\chi^2,2)}(\cdot)$. Therefore, the outage probability for a given $\|\hat{\mathbf{h}}\|$ can be expressed as

$$\begin{aligned}P_{out}(T_{tr}, T_d, T_{id}|SE_r, \|\hat{\mathbf{h}}\|) =& Pr(\Psi \le \frac{2^{SE_rT/T_d}-1}{P_d/\sigma_d^2})\\ =& F_{(nc-\chi^2,2)}(\frac{2^{SE_rT/T_d}-1}{P_d/\sigma_d^2}). \end{aligned} \tag{23}$$

Further considering that $\|\hat{\mathbf{h}}\|$ is a central chi-distributed random variable with $2M$ degrees of freedom, from the proof in the Appendix of [22] we can obtain the outage probability as

$$P_{out}(T_{tr}, T_d, T_{id}|SE_r) = \frac{\sum_{i=0}^{M-1}\binom{M-1}{i}(\gamma_u T_{tr})^i \Gamma_{i+1}(\frac{2^{\frac{SE_rT}{T_d}}-1}{\gamma_d})}{(1+\gamma_u T_{tr})^{M-1}}, \tag{24}$$

where$\binom{M-1}{i}$ is the number of combinations, and $\Gamma_M(x) = \frac{1}{(M-1)!}\int_0^x t^{M-1}e^{-t}dt$ is the incomplete Gamma function.

To maximize the EE of the considered system supporting delay-sensitive services, the objective function is defined as $\frac{SE_r}{P_{tot}}$. Denoting ϵ as the maximum acceptable outage probability, then the optimization problem can be formulated as

$$\max_{T_{tr},T_d,T_{id}} \quad \frac{SE_r}{P_{bu}T_{tr} + P_{bd}T_d} \tag{25a}$$
$$s.t.\ P_{out}(T_{tr}, T_d, T_{id}|SE_r) \le \epsilon \tag{25b}$$
$$T_{tr} + T_d + T_{id} = T \tag{25c}$$
$$T_{tr} \in \mathbb{N}^+,\ T_d, T_{id} \in \mathbb{N}. \tag{25d}$$

Since SE_r is a pre-determined value, problem (25) is equivalent to the following problem

$$\min_{T_{tr},T_d,T_{id}} \quad P_{bu}T_{tr} + P_{bd}T_d \tag{26a}$$
$$s.t.\ P_{out}(T_{tr}, T_d, T_{id}|SE_r) \le \epsilon \tag{26b}$$
$$T_{tr} + T_d + T_{id} = T \tag{26c}$$
$$T_{tr} \in \mathbb{N}^+,\ T_d, T_{id} \in \mathbb{N}. \tag{26d}$$

B. Solution of Optimal Durations

The optimization problem (26) is hard to solve, because the expression of the outage probability in (24) is rather involved. To circumvent this problem, we approximate the outage probability by using the approximate SNR in (10), which can be rewritten as

$$\widetilde{\mathrm{SNR}} = \frac{P_d}{\sigma_d^2}\|\hat{\mathbf{h}}\|^2 = \frac{\gamma_d\gamma_u T_{tr}}{2(1+\gamma_u T_{tr})}\cdot\nu, \tag{27}$$

where $\nu \triangleq \frac{2\|\hat{\mathbf{h}}\|^2}{\sigma_{\hat{h}}^2}$ is a chi-squared distributed variable with $2M$ degrees of freedom. Then from (22) the outage probability can be approximated as

$$\begin{aligned}\widetilde{P_{out}}(T_{tr}, T_d, T_{id}|SE_r) =& Pr(\frac{T_d}{T}\log_2(1+\widetilde{\mathrm{SNR}}) \le SE_r)\\ =& Pr(\nu \le \frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_rT}{T_d}}-1))\\ =& F_{(\chi^2,2M)}(\frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_rT}{T_d}}-1)), \end{aligned} \tag{28}$$

where $F_{(\chi^2,2M)}(\cdot)$ is the CDF of a chi-square random variable with $2M$ degrees of freedom.

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Further considering the monotonicity of $F_{(\chi^2,2M)}(\cdot)$, problem (26) can be reformulated as

$$\min_{T_{tr},T_d,T_{id}} \quad P_{bu}T_{tr}+P_{bd}T_d \tag{29a}$$
$$s.t. \ \frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_rT}{T_d}}-1)\le \nu_c \tag{29b}$$
$$T_{tr}+T_d+T_{id}=T \tag{29c}$$
$$T_{tr}\in\mathbb{N}^+,\ T_d,T_{id}\in\mathbb{N}, \tag{29d}$$

where $\nu_c \triangleq F^{-1}_{(\chi^2,2M)}(\epsilon)$ is a constant determined by ϵ, and $F^{-1}_{(\chi^2,2M)}(\cdot)$ represents the inverse function of $F_{(\chi^2,2M)}(\cdot)$.

To solve problem (29), we first replace T_{id} by $T_{id} = T - T_{tr} - T_d$ from (29c), then relax T_d as a continuous variable within $[0,T]$ and T_{tr} as a continuous variable within $[\varsigma, T]$ with ς denoting a very small positive number near zero, because we consider $T_{tr}\ge 1$ for the closed-form system. After solving the relaxed problem, we round the optimal solution of T_{tr} to the nearest positive integer, and find the minimal integer around the optimal solution of T_d to ensure the QoS constraint (29b) satisfied. In the sequel, we show that the relaxed version of problem (29) is convex.

Proposition 4: The optimal solution of the relaxed version of problem (29) makes the constraint (29b) hold with equality.

Proof: See Appendix D. ■

According to proposition 4, the duration for downlink data sending can be expressed as

$$T_d=\frac{SE_rT}{\log_2(1+\frac{\gamma_d\gamma_u\nu_c}{2}\frac{T_{tr}}{1+\gamma_uT_{tr}})}, \tag{30}$$

then problem (29) can be relaxed by omitting the constraints in (29d) as

$$\min_{T_{tr}} \ P_{bu}T_{tr}+P_{bd}\frac{SE_rT}{\log_2(1+\frac{\gamma_d\gamma_u\nu_c}{2}\frac{T_{tr}}{1+\gamma_uT_{tr}})} \tag{31a}$$
$$s.t. \ T_{tr}+\frac{SE_rT}{\log_2(1+\frac{\gamma_d\gamma_u\nu_c}{2}\frac{T_{tr}}{1+\gamma_uT_{tr}})}\le T \tag{31b}$$
$$\varsigma\le T_{tr}\le T, \tag{31c}$$

where (30) is used to transform the equality constraint (29c) into the inequality constraint (31b).

For the sake of notational simplicity, we denote (31a) and the left hand side of the inequality constraint (31b) as

$$h(T_{tr})\triangleq P_{bu}T_{tr}+P_{bd}\frac{SE_rT}{\log_2(1+\frac{\gamma_d\gamma_u\nu_c}{2}\frac{T_{tr}}{1+\gamma_uT_{tr}})} = a_1T_{tr}+\frac{a_2}{\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})}, \tag{32}$$

$$c(T_{tr})\triangleq T_{tr}+\frac{SE_rT}{\log_2(1+\frac{\gamma_d\nu_c}{2}\frac{\gamma_uT_{tr}}{1+\gamma_uT_{tr}})}, \tag{33}$$

where a_1, a_2, b_1 and b_2 denote P_{bu}, $P_{bd}SE_rT$, $\frac{\gamma_d\gamma_u\nu_c}{2}$ and γ_u, respectively. In the following proposition, we show that problem (31) is convex.

Proposition 5: Both $h(T_{tr})$ in (32) and $c(T_{tr})$ in (33) are convex functions of T_{tr}.

Proof: See Appendix E. ■

It follows that the relaxed problem (31) can be numerically solved with efficient convex optimization algorithms [21].

C. Impact of QoS Requirement, SNR and Circuit Power on the Optimal Solution

We first examine the properties of the objective function, $h(T_{tr})$, and the left hand side of the inequality constraint (31b), $c(T_{tr})$, as follows.

When $T_{tr}\to 0$, the term $\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})$ in (E.1) given in Appendix E approaches zero, and hence the first order derivative $h'(T_{tr})\to-\infty$ as shown in (E.1). When $T_{tr}\to T$, T_d will approach zero considering the constraint (29c). Further noting from (30) that $T_d=\frac{SE_rT}{\log_2(1+\frac{\gamma_d\gamma_u\nu_c}{2}\frac{T_{tr}}{1+\gamma_uT_{tr}})}=\frac{SE_rT}{\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})}$, we know that $\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})$ will approach infinity when $T_{tr}\to T$. Substituting it into (E.1), we know that $h'(T_{tr})$ will approach a_1, which is a positive number. Since $h''(T_{tr})>0$ always holds as shown in (E.2), it is not hard to find that $h(T_{tr})$ first decreases and then increases within the duration $(0,T)$. Similarly, we can prove that $c(T_{tr})$ also decreases at first and then increases within the duration $(0,T)$.

Denote $[T^{low}_{tr},T^{up}_{tr}]$ as the feasible set of T_{tr} for problem (31), which is the intersection of the sets defined by its two constraints (30b) and (30c). Let $[z^{low},z^{up}]$ denote the set defined by the constraint (30c), i.e., $\{T_{tr}|c(T_{tr})\le T\}$. Since we have shown that $c(T_{tr})$ is convex and decreases at first and then increases within the duration $(0,T)$, further noting that $c(\varsigma)>T$ and $c(T)>T$, we can obtain that z^{low} and z^{up} are the two solutions to the equation $c(T_{tr})=T$, and $\varsigma<z^{low}\le z^{up}<T$, i.e., $[z^{low},z^{up}]$ is a subset of $[\varsigma,T]$ defined by (30b). Therefore, we obtain that $T^{low}_{tr}=z^{low}$ and $T^{up}_{tr}=z^{up}$.

Denote T^v_{tr} as the duration for uplink training that minimizes $h(T_{tr})$ without the constraint (31b), and T^c_{tr} as the duration for uplink training that minimizes $c(T_{tr})$, respectively. Since both $h(T_{tr})$ and $c(T_{tr})$ are convex functions and they first decrease and then increase within the duration $(0,T)$, we have $h'(T^v_{tr})=0$ and $c'(T^c_{tr})=0$. It's easy to see that $T^c_{tr}\in[T^{low}_{tr},T^{up}_{tr}]$ since T^c_{tr} minimizes $c(T_{tr})$ so that the inequality constraint in (31b) is satisfied.

Let $T^*_{trEEout}$, T^*_{dEEout} and $T^*_{idEEout}$ denote the optimal solutions of the relaxed problem (31). We have the following proposition.

Proposition 6:

- $T^v_{tr}\ge T^c_{tr}$ always holds, and the equality holds if and only if $SE_r=0$.
- Denote SE^o_r as the SE_r with which $T^v_{tr}=T^{up}_{tr}$ holds. Then when $SE_r\le SE^o_r$, $T^*_{trEEout}=T^v_{tr}$ that increases with SE_r; when $SE_r>SE^o_r$, $T^*_{trEEout}=T^{up}_{tr}$ that decreases with SE_r.
- When $P^{TX}_c=P^{RX}_c$ and both of them are sufficiently large, we have $T^v_{tr}\le T^{up}_{tr}$, and $T^*_{trEEout}=T^v_{tr}$ that increases with SE_r and decreases with circuit power.

Proof: See Appendix F. ■

Due to the difficulty of finding a closed-form solution of $T^*_{trEEout}$, it is not easy to analyze the impact of general average uplink SNR on $T^*_{trEEout}$. However, we can gain some insight from the results at high average uplink SNR. When $\gamma_u\to\infty$, from (30) the optimal duration for downlink data sending becomes $T^*_{dEEout}=\frac{SE_rT}{\log_2(1+\frac{\gamma_d\nu_c}{2})}$, which increases with the SE requirement linearly and decreases with

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the increase of average downlink SNR. Since T^*_{dEEout} is independent of $T^*_{trEEout}$ in this case, by substituting it into the optimization problem (31), we can obtain that $T^*_{trEEout} = \varsigma$. It suggests that the energy efficient strategy for delay-sensitive services reduces the resources for uplink training in order to increase the opportunity of BS idling, which is different from the strategy for delay-tolerant services that keeps the BS active all the time.

Remark 1: The different behaviors for BS idling under the two kinds of services can be explained as follows. For delay-tolerant services, the user has only a minimal average rate constraint. Then for any given duration for uplink training, the BS can always improve the system EE by transmitting more data in a longer duration (i.e., the EE is an increasing function of T_d for any given T_{tr} as shown by (15)), which can reduce the impact of the circuit power consumed for receiving uplink training signals at the BS. Therefore, BS idling is not needed in this case. For delay-sensitive services, the amount of data to be transmitted is fixed in the given duration, therefore the BS can switch into the idle mode to reduce the power consumption when all the data has been transmitted.

Remark 2: The proposed transmission strategy for delay-sensitive services cannot be directly applied to the real-time video service with time-varying data rate. A simple way to handle this problem is to consider the worst-case design. For example, we can optimize the duration for uplink training before the packets arrive based on the highest possible data rate of real-time video services. Then given the uplink training, one can determine the durations for downlink data sending and idling for each arrived packet.

V. Discussions and Extensions

In the previous sections, we have designed transmission strategies for two kinds of services in single-user scenario. In this section, we analyze the challenges and opportunities of applying the proposed strategies to current and future cellular systems, and provide one way to extend the single-user single-service designs to the multi-user scenario with mixed services.

A. Challenges and Opportunities

The designed transmission strategies in previous sections can not be applied to existing cellular systems, e.g., the Long Term Evolution (LTE) system, due to the following reasons. First, the proposed method optimizes the duration for uplink training, which may exceed the maximal uplink training duration of the LTE system. Second, a macro or micro BS in the LTE system often serves multiple users with mixed traffics. With the proposed single-user designs, the optimized durations for uplink training, downlink data sending, and BS idling may be non-identical for different users, which will lead to the echo interference at the BS caused by transmitting to and receiving from different users simultaneously. Third, the proposed method considers the symbol-level BS idling, and different users may require different BS idling durations. This requires the BS to operate in idle mode for one user and in active mode for another user simultaneously.

Nevertheless, these challenges can be overcome with the emerging advanced technologies for future cellular systems. First, the ultra dense networks lead to very small coverage of each BS, where the number of users in every small cell will be very limited and the user-specific system parameter configuration will become possible [23]. Second, effective echo interference cancelation techniques enable the BS to transmit and receive simultaneously in a full-duplex mode [24]. Third, the fast hardware deactivating/reactivating technology supports the symbol-level BS idling, and the bandwidth adaptation technology enables BS idling in frequency domain, which allows multiple users to have different BS idling durations in time domain [15].

B. Extension to Multiple Users with Mixed Services

In the following we provide one way to extend the proposed strategies to the multi-user scenario with mixed services, which takes into account the constraint on the maximal uplink training duration and does not need the echo interference cancelation techniques.

Assume that the BS can be idle in both frequency and time domain. BS idling in frequency domain is also known as bandwidth adaptation, which can reduce the maximum RF output power of the BS by adaptively adjusting the occupied bandwidth according to the QoS requirement when given the power spectral density of the signals. Then the operating point of the PA can be adapted to the required output power for saving energy [25]. BS idling in time domain saves energy by deactivating power-consuming hardware components when there are no data to transmit. Although BS idling schemes in frequency and time domain are based on different principles, they perform similarly in energy saving in practice as analyzed in [25].

We consider the orthogonal frequency division multiple access (OFDMA) based multiuser transmission, which is a widely used technique for broadband cellular systems. Suppose that the BS serves K users with mixed services, where the users occupy orthogonal subcarriers. Let T_{UL} and T_{DL} denote the durations of uplink and downlink sub-frames of the system, and $T^k_{UL} < T_{UL}$ denote the duration that can be used to transmit uplink training for user k. The remaining uplink duration, $T_{UL} - T^k_{UL}$, is used by user k to transmit its uplink data. Define $T^k = T^k_{UL} + T_{DL}$ as the total communication period of user k, and T^k_{tr}, T^k_d and T^k_{id} as the durations for uplink training, downlink data sending and BS idling of user k. It should be noted that BS idling can occur not only in the downlink sub-frame but also in the uplink sub-frame when $T^k_{tr} < T^k_{UL}$. Then the transmission strategy optimization problem for user k can be formulated as follows.

$$\max_{T^k_{tr}, T^k_d, T^k_{id}} \; EE_k \tag{34a}$$

$$s.t. \; \text{QoS requirement of user } k \tag{34b}$$

$$T^k_{tr} + T^k_d + T^k_{id} = T^k \tag{34c}$$

$$T^k_{tr} \in \mathbb{N}^+, \; T^k_d, T^k_{id} \in \mathbb{N} \tag{34d}$$

$$T^k_{tr} \leq T^k_{UL} \tag{34e}$$

$$T^k_d \leq T_{DL}, \tag{34f}$$

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where the objective function (34a) and the QoS constraint (34b) are determined by the service type of user k, which are given by (16) for delay-tolerant services and by (25) for delay-sensitive services.

Compared with the optimization problems (16) and (25) for the single-user scenario, we add two new constraints (34e) and (34f). Since both the constraints are convex, we can use the same approaches for problem (16) and (25) to solve problem (34).

In the transmission mechanism, we limit the uplink training duration of all users not to exceed the common duration of uplink sub-frame T_{UL}, and the downlink data sending duration of all users not to exceed the common downlink sub-frame T_{DL}. In this manner, echo interference at the BS can be avoided, and the transmission strategies of multiple users can be optimized separately.

Remark 3: In the paper we suppose that the transmit powers of the BS and the user are both constant. The power consumption of the user is not taken into account in the EE of the downlink system. When the transmit power of a user can be adjusted, it is not hard to find that the EE is maximized when the user transmits with its maximal power. This implies that the transmit power of the user will be constant regardless of the QoS requirement or SNR. Therefore, transmit power control at the user side will not affect the results we obtained. On the other hand, transmit power control at the BS side provides more freedom to balance the transmit and circuit powers, and hence will improve the EE. Yet the joint optimization of the transmit power at each time slot and the durations for uplink training, downlink data sending and BS idling is non-convex and difficult to solve. This makes the analysis of the impact of transmit power control at the BS on the performance of the proposed transmission strategies very complicated. We will leave this interesting problem for future work.

VI. Simulation Results

In this section, we use simulations to validate the analytical analysis and evaluate the maximum EE for different services. Unless otherwise specified, in the simulations we assume that the BS has $M = 4$ antennas with the transmit power of 46 dBm, the users transmit with 23 dBm, the communication period T is set to 140 symbols corresponding to the duration of one LTE frame, and the maximum outage probability for delay-sensitive services is 5%. The power consumption parameters are configured as in [1] for a macro BS, where the per-antenna circuit powers of the BS in transmitting and receiving modes are set to the same as 47.1 W, and the parameter reflecting transmit power loss, μ, is set as 4.24. The path-loss model is set as $35.3 + 37.6\log_{10}(d)$, where d is the distance between the BS and the user in meters [26]. Since the average downlink SNR is usually higher than the average uplink SNR, we set $\gamma_d = \gamma_u + 10$ dB.

In the following, we first evaluate the accuracy of the approximations, validate the analysis for the optimal durations, and show the EE gain by simulating the single-user scenario under the two kinds of services, where each BS serves only one user. After that, we show the EE gain for the multi-user scenario by simulating a case where each BS serves two users with mixed services. Following the previous definitions, we use SE_{min} and SE_r to denote the data rate requirements of a user with delay-tolerant and delay-sensitive services, respectively. Herein, both SE_{min} and SE_r are normalized by the bandwidth occupied by the user, or in other words, unit bandwidth per user is supposed in the simulations. For the two kinds of services, different packet schedulers are assumed based on the QoS requirements as described in Section II-C, with which the BS periodically removes some of the data from the buffer of a user and transmits to the user according to the optimized transmission strategies.

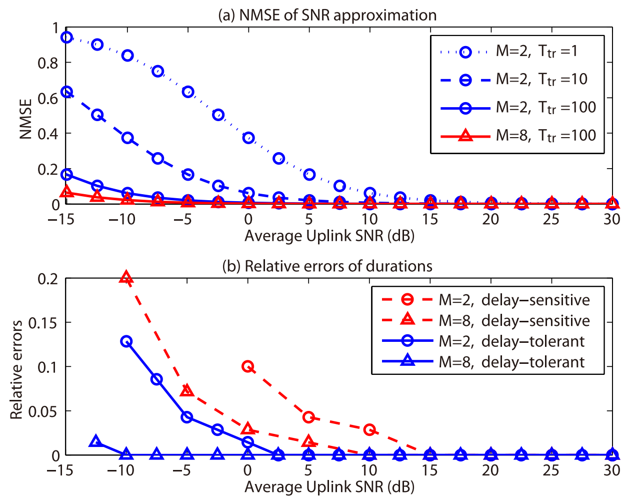

Fig. 2. NMSE of the approximate SNR and relative errors of the designed durations, where $SE_{min} = SE_r = 1$ bps/Hz is considered in Fig. 2(b).

A. Accuracy of the Approximations

We first examine the accuracy of the SNR approximation given in (10), which are used in the optimizations for both delay-tolerant and delay-sensitive services. In Fig. 2(a), the normalized mean square error (NMSE) of the SNR approximation, defined by $\frac{\mathbb{E}\{|\mathrm{SNR}-\widehat{\mathrm{SNR}}|^2\}}{\mathbb{E}\{|\mathrm{SNR}|^2\}}$, is plotted, where different uplink SNRs γ_u, number of antennas M, and uplink training durations T_{tr} are considered. It is shown that the accuracy of the SNR approximation is poor when γ_u and M are small and improves with the growth of γ_u and M. Moreover, we find that the NMSE decreases with the increase of T_{tr}, because increasing uplink training duration improves the quality of channel estimation. Note that in our work the value of T_{tr} is not fixed, which adapts to the SNR and QoS requirements. A low SNR generally leads to a large T_{tr}, which can compensate the accuracy degradation of the SNR approximation to a certain extent in low SNR regime. To see this effect, we then plot the relative errors between the designed durations and the optimal durations, defined by $\frac{|T_{tr}^{opt}-T_{tr}|+|T_{d}^{opt}-T_{d}|+|T_{id}^{opt}-T_{id}|}{T}$, in Fig. 2(b), where T_{tr}, T_d and T_{id} denote the designed durations based on both the SNR approximation and the moment matching for Gamma distribution, and T_{tr}^{opt}, T_d^{opt} and T_{id}^{opt} are the optimal durations that are obtained by exhaustive searching over all possible combinations of the durations for uplink training, downlink

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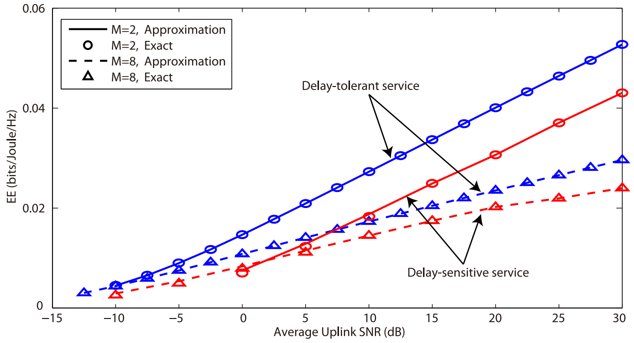


Fig. 3. Exact and approximate maximum EE versus the average uplink SNR with $SE_{min} = SE_r = 1$ bps/Hz.

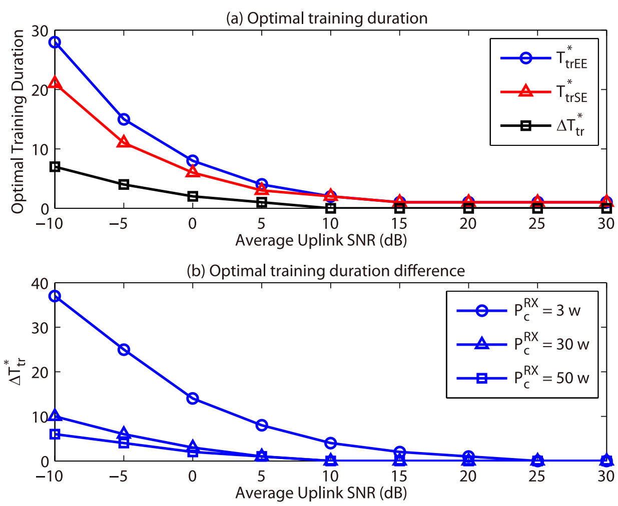
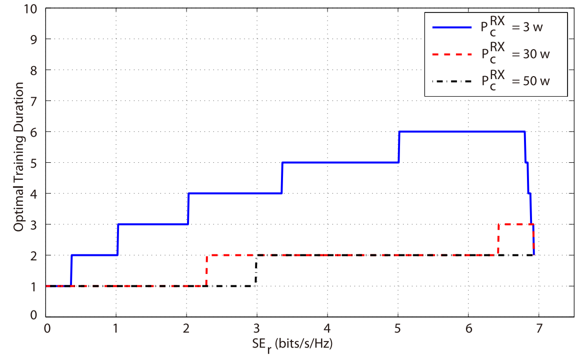


Fig. 4. Optimal training duration and optimal training duration difference for delay-tolerant services with $SE_{min} = 1$ bps/Hz.

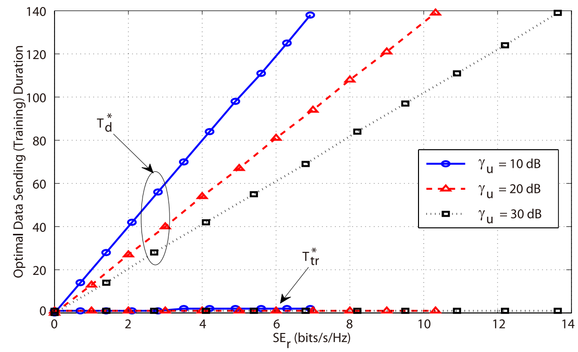
data sending and BS idling. During the exhaustive searching, for each combination we obtain the average net SE by Monte-Carlo methods and compute the outage probability based on the exact expression (24), therefore the optimal durations are not based on any approximations. It is shown that the errors caused by the approximations are small (less than 0.2) even for small γ_u and M. We can also see that the relative errors for delay-sensitive services are larger than those for delay-tolerant services, because the delay-sensitive services usually have a shorter uplink training duration in order to increase BS idling duration, while BS idling never occurs for delay-tolerant services. The impact of the duration errors on the system EE is evaluated in Fig. 3, where the EEs corresponding to the designed durations and the optimal durations are plotted. We can see that the small duration errors have a negligible impact on the EE for delay-tolerant services, and only very small gap can be observed for delay-sensitive services under small γ_u and M.

B. Validation on the Analysis of Optimal Transmission Durations

In this subsection, we validate the analytical analysis of the impact of QoS requirement, SNR and circuit power on the



(a) Optimal training duration with $\gamma_u = 10$ dB



(b) Optimal data sending duration

Fig. 5. Optimal durations for uplink training and downlink data sending versus net SE requirement for delay-sensitive services.

optimal transmission durations for delay-tolerant and delay-sensitive services, respectively.

1) Delay-tolerant Services: Fig. 4(a) shows the impact of SNR on the uplink training durations optimized towards SE and EE. We can see that when the SNR exceeds 15 dB, $T^*_{trEE} = T^*_{trSE} = 1$ and $\Delta T^*_{tr} = 0$. In general cases, the EE-oriented optimization requires more training symbols than the SE-oriented optimization. In Fig. 4(b), we show the impact of circuit power on ΔT^*_{tr}. It is shown that when the circuit power is small, there is an obvious difference in training duration between the EE-oriented and the SE-oriented optimization, and the difference decreases with the increase of the circuit power. When $P_c^{TX} = P_c^{RX}$ and the circuit power is very large, $\Delta T^*_{tr} \to 0$. These results agree well with our analytical analysis.

2) Delay-sensitive Services: Fig. 5(a) shows the optimal duration for uplink training versus the QoS requirement with different values of circuit power. We can see that when circuit power is very large (say $P_c^{RX} = 50$ W), the optimal training duration increases with SE_r. In general, when SE_r is small, the optimal training duration increases with the increase of SE_r and the decrease of P_c^{RX}. When SE_r is large, the optimal training duration decreases with the increase of SE requirement. Fig. 5(b) shows the optimal duration for downlink data sending and uplink training versus the QoS requirement with different values of SNR. It shows that when the SNR is very high, e.g., 20 and 30 dB, one training symbol is optimal. The optimal transmit duration increases with SE_r linearly, and decreases with the increase of SNR. These results agree well

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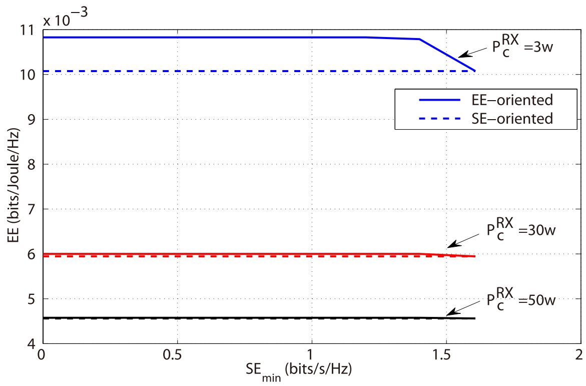
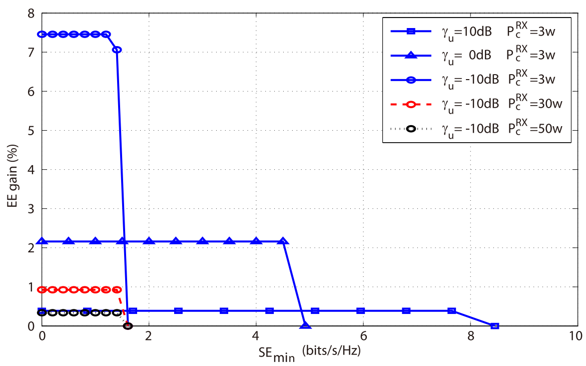
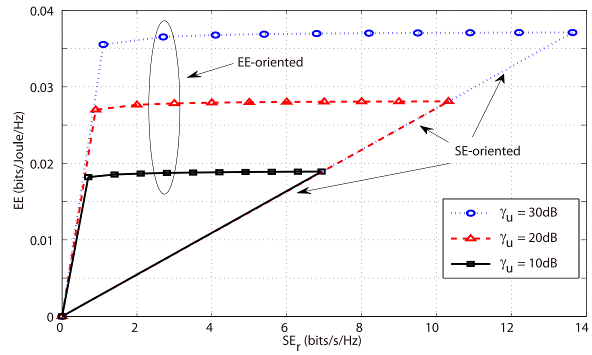


(a) Maximum EE with $\gamma_u = -10$ dB

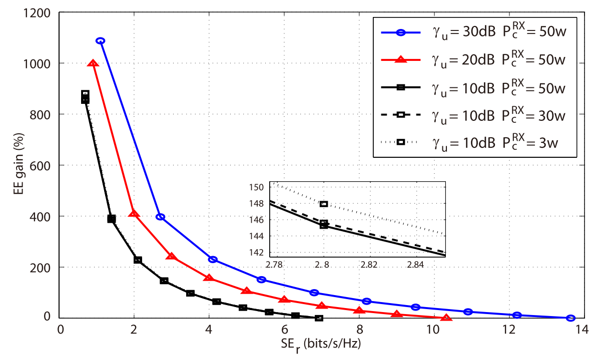


(b) EE gain

Fig. 6. Maximum EE achieved by the EE-oriented and SE-oriented optimization and EE gain of the EE-oriented optimization over the SE-oriented optimization for delay-tolerant services.



(a) Maximum EE with $P_c^{RX} = 50$ W



(b) EE gain

Fig. 7. Maximum EE achieved by the EE-oriented and SE-oriented optimization and EE gain of the EE-oriented optimization over the SE-oriented optimization for delay-sensitive services.

with the analysis in Section IV.

C. Maximum EE and EE Gain v.s. QoS Requirement

1) Delay-tolerant services: In Fig. 6(a), we compare the EE achieved by the EE-oriented optimization (16) and the SE-oriented optimization that maximizes the SE in (14). Since the optimal training duration maximizing the SE is independent of SE_{min}, the corresponding EE is a constant. When the circuit power is small, we can see that the EE achieved by the EE-oriented optimization first remains constant and then decreases to the EE achieved by SE-oriented optimization when $SE_{min} = SE_{max}$, as indicated by Proposition 3. Fig. 6(b) shows the EE gain of the EE-oriented optimization over the SE-oriented optimization, which is defined as $(EE(T_{trEE}^*) - EE(T_{trSE}^*))/EE(T_{trSE}^*)$, where $EE(T_{trEE}^*)$ and $EE(T_{trSE}^*)$ are respectively the EE achieved by the EE-oriented and the SE-oriented optimization following the definitions in Section III. It is shown that the EE gain first remains constant and then decreases to zero with the increase of the minimum net SE requirement. Besides, the EE gain decreases with the growth of circuit power, because the optimal training duration difference under the two criteria decreases with the increase of circuit power as shown in Fig. 4(b). The EE gain decreases with the increase of SNR, and approaches zero when the SNR is sufficiently high, i.e. the EE-oriented optimization reduces to the SE-oriented optimization in this case, which agrees with our previous analysis.

2) Delay-sensitive services: In Fig. 7(a), we compare the EE achieved by the EE-oriented optimization (25) and by the SE-oriented optimization. Again, because the optimal training and data sending durations maximizing the SE do not depend on the QoS requirement, the power consumption is fixed and the achieved EE increases with the QoS requirement linearly. We can see that the EE achieved by the EE-oriented optimization is always higher than that by the SE-oriented optimization, unless the SE requirement equals to zero or equals to the maximum achievable SE. In Fig. 7(b), we evaluate the EE gain of the EE-oriented optimization over the SE-oriented optimization. It is shown that the EE gain is remarkable at low SE requirements. The EE gain improves with the increase of SNR. This is because the system can satisfy the SE requirement with fewer downlink data sending symbols for high SNR and low QoS requirement. It is also shown that higher EE gain can be achieved with lower circuit power, but the impact is relative little. This is because the impact of circuit power mainly comes from uplink training phase, however the optimal training duration is short when SNR is high.

D. EE Gain for Multiple Users and Mixed Services

In this subsection, we evaluate the EE gain of the proposed EE-oriented optimization over the SE-oriented optimization in the scenarios with multiple users and mixed services. Specifically, we consider that the BS serves $K = 2$ users that occupy orthogonal subcarriers, where user 1 is with

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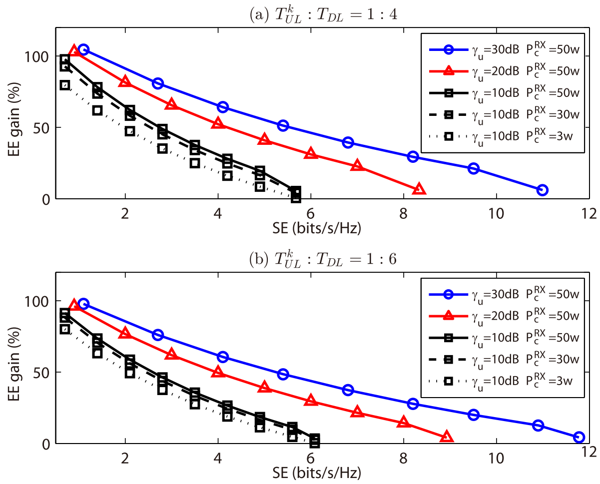

Fig. 8. EE gain of the EE-oriented optimization over the SE-oriented optimization for $K = 2$ users and mixed services, where $SE_{min} = SE_r$ are given in the x-axis, and $T_{UL}^k : T_{DL} = 1 : 4$ and $1 : 6$ are considered in Fig. 8(a) and Fig. 8(b), respectively.

the delay-tolerant service, user 2 is with the delay-sensitive service, and $SE_{min} = SE_r$ is assumed for the two kinds of services. The total communication periods of the two users are set as $T^1 = T^2 = 140$, within which the maximal uplink training durations for the two users are set to the same, i.e., $T_{UL}^1 = T_{UL}^2$. To reflect different configurations of uplink-downlink sub-frame durations, we consider $\frac{T_{UL}^k}{T_{DL}} = \frac{1}{4}$ an $\frac{1}{6}$ in Fig. 8(a) and 8(b), respectively.[1] We can see that under both configurations the EE gain is evident especially for small SE requirements. Moreover, given the SE requirement, the EE gain increases with the SNR. The result coincides with the analysis in Fig. 7(b) for the pure delay-sensitive services, but contradicts to the result in Fig. 6(b) for the pure delay-tolerant services, where the EE gain decreases with the SNR. The difference comes from the new constraint introduced for the multi-user case that downlink data sending cannot use the time slots in uplink sub-frame. This leads to the result that even for the delay-tolerant services, BS idling may occur in some uplink time slots in order to reduce the receiving power consumption, while we have proved that this will not happen in the single-user case. A higher SNR will reduce the uplink training duration, which leads to the increase of the BS idling duration in the uplink sub-frame and hence achieves a larger EE gain. Similarly, the BS idling duration in the uplink sub-frame will increase with the growth of circuit power in order to save more powers, which leads to the improvement of the EE gain as shown in the figures. In addition, by comparing Fig. 8(a) and 8(b), we can find that a longer downlink sub-frame can support a higher SE requirement.

VII. Conclusions

In this paper, we investigated the energy-efficient transmission strategies for downlink TDD closed-loop MISO systems, where the three-phase communication is considered consisting of uplink training, downlink data sending and BS idling. To optimize the durations of the three phases aimed at maximizing the downlink EE while guarantee the user's QoS, we first derived the closed-form expressions of the approximate average net SE and outage probability, which are employed to characterize the QoS of delay-tolerant and delay-sensitive services, respectively. Then we proposed methods to find the optimal durations of the three phases, and analyzed the impact of QoS requirement, SNR and circuit power on the optimal durations for each kind of services. For delay-tolerant services, we showed that the EE-oriented design requires a longer uplink training than the SE-oriented design in general, and they will coincide for high uplink SNR and large circuit power, or when the minimal SE requirement equals to the maximum achievable SE. Moreover, we found that the BS will not operate in idle mode with the optimal strategy for supporting delay-tolerant services. For delay-sensitive services, we showed that the optimal duration for uplink training first increases and then decreases with the increase of QoS requirement in general. In high average uplink SNR regime, one training duration is optimal, and the optimal duration for downlink data sending increases with the QoS requirement linearly and decreases with SNR. Moreover, we found that BS idling plays an important role in reducing circuit power consumption when supporting delay-sensitive services. We also provided a simple way to apply the obtained transmission strategies for the scenarios with multiple users and mixed services. Simulation results validated our analytical analysis, and demonstrated a significant EE gain of the EE-oriented design over the SE-oriented design in both single-user single-service and multi-user mixed-service scenarios.

[1]The values of $\frac{T_{UL}^k}{T_{DL}}$ are smaller than the configurations of uplink-downlink sub-frame durations because $T_{UL}^k < T_{UL}$ is only the uplink training duration.

Appendix A
Proof of Proposition 1

For the SE-oriented problem (14), it is easy to see that $\widetilde{SE}(T_{tr}, T_d, T_{id})$ is maximized when $T_{id} = 0$, since $\widetilde{SE}(T_{tr}, T_d, T_{id})$ is an increasing function of T_d for any given T_{tr} according to (13).

For the EE-oriented problem (16), we can prove by contradiction that the maximum EE of (16) is obtained when $T_{tr} + T_d = T$ as follows.

First, we assume that the maximum EE is obtained when $T_{tr} + T_d < T$, which satisfies the constraint (16c). Denote T_{tr1} and T_{d1} as the optimal uplink training duration and optimal downlink data sending duration, respectively. Then the maximum EE can be denoted as $\widetilde{EE}(T_{tr1}, T_{d1})$, and the corresponding SE, $\widetilde{SE}(T_{tr1}, T_{d1}) \geq SE_{min}$ satisfying the constraint (16b).

We can find another downlink data sending duration T_{d2}, which is larger than T_{d1} but satisfies (16c). From (13) and (15), we can find that both $\widetilde{EE}(T_{tr}, T_d)$ and $\widetilde{SE}(T_{tr}, T_d)$ are the monotonically increasing functions of T_d. Therefore, there will be $\widetilde{SE}(T_{tr1}, T_{d2}) > \widetilde{SE}(T_{tr1}, T_{d1}) \geq SE_{min}$ which means the constraint (16b) is satisfied, and $\widetilde{EE}(T_{tr1}, T_{d2}) > \widetilde{EE}(T_{tr1}, T_{d1})$. Obviously, it is contradictory with the assumption that $\widetilde{EE}(T_{tr1}, T_{d1})$ is the maximum EE. It follows that the initial assumption that the maximum EE is obtained when

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$T_{tr} + T_d < T$ must be false. Further considering constraint (16c), the maximum EE is obtained when $T_{tr} + T_d = T$, proving the proposition.

Appendix B
Proof of Proposition 2

To simplify the notation, we rewrite (18) as

$$\begin{aligned}\widetilde{EE}(T_{tr}) &= \frac{T - T_{tr}}{P_{bu}T_{tr} + P_{bd}(T - T_{tr})}\log_2(1 + \frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}) \\ &\triangleq g_1(T_{tr}) \cdot g_2(T_{tr}),\end{aligned} \tag{B.1}$$

where $g_1(T_{tr}) = \frac{T-T_{tr}}{P_{bu}T_{tr}+P_{bd}(T-T_{tr})} \geq 0$ and $g_2(T_{tr}) = \log_2(1 + \frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}) \geq 0$.

Considering that $P_{bd} > P_{bu}$, it is easy to show that

$$\begin{aligned}g_1'(T_{tr}) &= -\frac{P_{bu}T}{[P_{bu}T_{tr} + P_{bd}(T - T_{tr})]^2} < 0, \\ g_1''(T_{tr}) &= \frac{-2P_{bu}T(P_{bd} - P_{bu})}{[P_{bd}T - (P_{bd} - P_{bu})T_{tr}]^3} < 0, \\ g_2'(T_{tr}) &= \frac{1}{\ln 2}\frac{M\gamma_d\gamma_u}{(1+\gamma_u T_{tr} + M\gamma_d\gamma_u T_{tr})(1+\gamma_u T_{tr})} > 0, \\ g_2''(T_{tr}) &= -\frac{M\gamma_d\gamma_u}{\ln 2}\frac{2(\gamma_u + \gamma_u^2 T_{tr} + M\gamma_d\gamma_u^2 T_{tr}) + M\gamma_d\gamma_u}{[(1+\gamma_u T_{tr} + M\gamma_d\gamma_u T_{tr})(1+\gamma_u T_{tr})]^2} < 0.\end{aligned}$$

Then, we can obtain the derivatives of $\widetilde{EE}(T_{tr})$ as

$$\begin{aligned}\widetilde{EE}'(T_{tr}) &= g_1'(T_{tr})g_2(T_{tr}) + g_1(T_{tr})g_2'(T_{tr}), \qquad \text{(B.2)} \\ \widetilde{EE}''(T_{tr}) &= g_1''(T_{tr})g_2(T_{tr}) + 2g_1'(T_{tr})g_2'(T_{tr}) + g_1(T_{tr})g_2''(T_{tr}).\end{aligned}$$

We can see that $\widetilde{EE}''(T_{tr}) < 0$ always holds. Therefore, $\widetilde{EE}(T_{tr})$ is a concave function of T_{tr}, and $\widetilde{EE}'(T_{tr})$ is a monotonically decreasing function of T_{tr}.

Similarly, we rewrite (17) as

$$\widetilde{SE}(T_{tr}) = \frac{T - T_{tr}}{T}\log_2(1 + \frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}) = f_1(T_{tr}) \cdot f_2(T_{tr}),$$

where $f_1(T_{tr}) = \frac{T-T_{tr}}{T} \geq 0$ and $f_2(T_{tr}) = \log_2(1 + \frac{M\gamma_d\gamma_u T_{tr}}{1+\gamma_u T_{tr}}) \geq 0$, whose derivatives are $f_1'(T_{tr}) = -\frac{1}{T} < 0$, $f_1''(T_{tr}) = 0$, $f_2'(T_{tr}) = \frac{1}{\ln 2}\frac{M\gamma_d\gamma_u}{(1+\gamma_u T_{tr}+M\gamma_d\gamma_u T_{tr})(1+\gamma_u T_{tr})} > 0$, and $f_2''(T_{tr}) = g_2''(T_{tr}) < 0$. Then we have

$$\begin{aligned}\widetilde{SE}'(T_{tr}) &= f_1'(T_{tr})f_2(T_{tr}) + f_1(T_{tr})f_2'(T_{tr}), \qquad \text{(B.3)} \\ \widetilde{SE}''(T_{tr}) &= f_1''(T_{tr})f_2(T_{tr}) + 2f_1'(T_{tr})f_2'(T_{tr}) + f_1(T_{tr})f_2''(T_{tr}).\end{aligned}$$

Since $\widetilde{SE}''(T_{tr}) < 0$ always holds, $\widetilde{SE}(T_{tr})$ is a concave function of T_{tr}, and $\widetilde{SE}'(T_{tr})$ is monotonically decreasing.

Appendix C
Proof of Proposition 3

We begin with providing the derivatives of EE and SE, $\widetilde{EE}'(T_{tr})$ and $\widetilde{SE}'(T_{tr})$, at two extreme cases of the training duration with $T_{tr} = \xi$ and $T_{tr} = T$, where ξ is a very small positive value that approaches zero.

From (B.2) and (B.3) in Appendix B, we have

$$\widetilde{EE}'(\xi) \approx \frac{1}{\ln 2}\frac{M\gamma_d\gamma_u}{P_{bd}} > 0, \tag{C.1}$$

$$\widetilde{EE}'(T) = -\frac{1}{P_{bu}T}\log_2(1 + \frac{M\gamma_d\gamma_u T}{1+\gamma_u T}) < 0, \tag{C.2}$$

$$\widetilde{SE}'(\xi) \approx \frac{M\gamma_d\gamma_u}{\ln 2} > 0, \tag{C.3}$$

$$\widetilde{SE}'(T) = -\frac{1}{T}\log_2(1 + \frac{M\gamma_d\gamma_u T}{1+\gamma_u T}) < 0. \tag{C.4}$$

Considering $\widetilde{EE}'(\xi) > 0$ and $\widetilde{EE}'(T) < 0$ from (C.1) and (C.2), as well as the fact that $\widetilde{EE}'(T_{tr})$ is monotonically decreasing from Proposition 2, it follows that $\widetilde{EE}(T_{tr})$ first increases and then decreases. Let T_{trEE}^o denote the training duration that maximizes $\widetilde{EE}$ without the constraint (19b) on the minimum SE. Since $\widetilde{EE}(T_{tr})$ is a concave function, we know that $\widetilde{EE}'(T_{trEE}^o) = 0$.

Since $\widetilde{SE}'(T_{tr})$ is monotonically decreasing, and $\widetilde{SE}'(0) > 0, \widetilde{SE}'(T) < 0$ from (C.3) and (C.4), $\widetilde{SE}(T_{tr})$ first increases and then decreases with T_{tr}. Considering that $\widetilde{SE}(T_{tr})$ is concave, T_{trSE}^* can be found from $\widetilde{SE}'(T_{trSE}^*) = 0$.

From (17) and (18), we can obtain the relationship between the approximations of the EE and the SE as

$$\widetilde{EE}(T_{tr}) = \frac{\widetilde{SE}(T_{tr})T}{P_{bu}(T + (\frac{P_{bd}}{P_{bu}} - 1)(T - T_{tr}))}. \tag{C.5}$$

By taking the derivative with respect to T_{tr} respectively to the left and right hand sides of (C.5) and considering that $\widetilde{EE}'(T_{trEE}^o) = 0$, we can obtain

$$\widetilde{SE}'(T_{trEE}^o) = -\frac{\widetilde{SE}(T_{trEE}^o)}{\frac{T}{\frac{P_{bd}}{P_{bu}}-1} + T - T_{trEE}^o}. \tag{C.6}$$

Obviously, $\widetilde{SE}'(T_{trEE}^o) < 0$. Further considering that $\widetilde{SE}'(T_{trSE}^*) = 0$ and $\widetilde{SE}'(T_{tr})$ is monotonically decreasing, we have $T_{trEE}^o > T_{trSE}^*$.

If T_{trEE}^o satisfies constraint (19b), we know that $T_{trEE}^* = T_{trEE}^o > T_{trSE}^*$.

Now we consider the case when T_{trEE}^o does not satisfy (19b). Denote $[T_{tr}^{min}, T_{tr}^{max}]$ as the feasible set of T_{tr} defined by the constraint in (19b). It is easy to see that $T_{trSE}^* \in [T_{tr}^{min}, T_{tr}^{max}]$ since T_{trSE}^* maximizes the SE so that the constraint in (19b) is satisfied. Further considering the fact $T_{trEE}^o > T_{trSE}^*$, if T_{trEE}^o is outside of the feasible set, there must be $T_{trEE}^o > T_{tr}^{max}$. As we have analyzed, $\widetilde{EE}(T_{tr})$ first increases and then decreases with T_{tr}, and the transition point is at T_{trEE}^o. Therefore, we have $\widetilde{EE}(T_{tr}^{min}) \leq \widetilde{EE}(T_{trSE}^*) \leq \widetilde{EE}(T_{tr}^{max}) < \widetilde{EE}(T_{trEE}^o)$. Consequently, $T_{trEE}^* = T_{tr}^{max} \geq T_{trSE}^*$ in this case. The equality $T_{trEE}^* = T_{trSE}^*$ holds if $T_{tr}^{max} = T_{trSE}^*$, i.e., if SE_{min} equals to the maximum achievable net SE, SE_{max}.

Based on the above results, the impact of SE_{min} on ΔT_{tr}^* can be observed as follows. For small SE_{min} that satisfies $SE_{min} \leq \widetilde{SE}(T_{trEE}^o)$, we have $T_{trEE}^* = T_{trEE}^o > T_{trSE}^*$, and thus ΔT_{tr}^* remains constant. With the increase of SE_{min} so that $SE_{min} > \widetilde{SE}(T_{trEE}^o)$, we have $T_{trEE}^* = T_{tr}^{max} \geq$

T^*_{trSE}. It is easy to see that T^{max}_{tr} is a monotonically decreasing function of SE_{min}, which means that ΔT^*_{tr} decreases with the increase of SE_{min} in this case and $\Delta T^*_{tr} = 0$ when $SE_{min} = SE_{max}$.

APPENDIX D
PROOF OF PROPOSITION 4

First, we assume that the minimum energy consumption is obtained when $\frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_r T}{T_d}}-1) < \nu_c$, which satisfies constraint (29b). Denote T_{tr3} and T_{d3} as the optimal durations for uplink training and downlink data sending, respectively. Then the minimum energy consumption can be denoted as $P_{bu}T_{tr3}+P_{bd}T_{d3}$, and $T_{tr3}+T_{d3} \le T$ satisfying the constraint in (29c).

From (29b), we can find that $\frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_r T}{T_d}}-1)$ is a monotonically decreasing function of T_d. Therefore, we can find another downlink data sending duration T_{d4} which is smaller than T_{d3}, but still satisfies (29b) and (29c). Then there will be $P_{bu}T_{tr3} + P_{bd}T_{d4} < P_{bu}T_{tr3} + P_{bd}T_{d3}$, which is contradictory with the assumption that $P_{bu}T_{tr3}+P_{bd}T_{d3}$ is the minimum energy consumption. It follows that the initial assumption that the minimum energy consumption is obtained when $\frac{2}{\gamma_d}(1+\frac{1}{\gamma_u T_{tr}})(2^{\frac{SE_r T}{T_d}}-1) < \nu_c$ must be false, i.e., the constraint (29b) should hold with equality.

APPENDIX E
PROOF OF PROPOSITION 5

From (32), we can obtain the derivatives of $h(T_{tr})$ as

$$h'(T_{tr}) = a_1 - \frac{a_2 b_1}{\ln 2}\frac{1}{(1+b_1T_{tr}+b_2T_{tr})(1+b_2T_{tr})\left[\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})\right]^2}, \quad \text{(E.1)}$$

$$h''(T_{tr}) = \frac{a_2 b_1}{\ln 2}\frac{\left[b_1+2b_2(1+b_1T_{tr}+b_2T_{tr})\right]\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})+\frac{2b_1}{\ln 2}}{\left[(1+b_1T_{tr}+b_2T_{tr})(1+b_2T_{tr})\right]^2\left[\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})\right]^3}. \quad \text{(E.2)}$$

We can see that $h''(T_{tr}) > 0$ always holds. Therefore, $h(T_{tr})$ is a convex function of T_{tr}.

Similarly, we can prove that $c''(T_{tr}) > 0$ always holds by replacing P_{bu} and P_{bd} in (32) with 1, hence $c(T_{tr})$ in (33) is also a convex function of T_{tr}.

APPENDIX F
PROOF OF PROPOSITION 6

Considering $h'(T^v_{tr}) = 0$ and $c'(T^c_{tr}) = 0$, we have from (E.1) that

$$j(T^v_{tr}) = (1+b_1T^v_{tr}+b_2T^v_{tr})(1+b_2T^v_{tr})\left[\log_2(1+\frac{b_1T^v_{tr}}{1+b_2T^v_{tr}})\right]^2 = \frac{b_1}{\ln 2}SE_rT\frac{P_{bd}}{P_{bu}}, \quad \text{(F.1)}$$

$$j(T^c_{tr}) = (1+b_1T^c_{tr}+b_2T^c_{tr})(1+b_2T^c_{tr})\left[\log_2(1+\frac{b_1T^c_{tr}}{1+b_2T^c_{tr}})\right]^2 = \frac{b_1}{\ln 2}SE_rT, \quad \text{(F.2)}$$

where $j(T_{tr}) = (1+b_1T_{tr}+b_2T_{tr})(1+b_2T_{tr})\left[\log_2(1+\frac{b_1T_{tr}}{1+b_2T_{tr}})\right]^2$ is a monotonically increasing function of T_{tr}.

Since $b_1 > 0$ and $\frac{P_{bd}}{P_{bu}} > 1$ always hold, we have $j(T^v_{tr}) \ge j(T^c_{tr})$, and the equality holds if and only if $SE_r = 0$. Since $j(T_{tr})$ is monotonically increasing, we have that $T^v_{tr} \ge T^c_{tr}$ always holds and the equality holds if and only if $SE_r = 0$.

In the following, we consider two cases.

1) T^v_{tr} satisfies the inequality constraint in (31b): In this case, $T^v_{tr} \le T^{up}_{tr}$ and thus $T^*_{trEEout} = T^v_{tr}$. From (F.1), we have that $j(T^v_{tr})$ increases with the increase of SE requirement, SE_r. Since $j(T^v_{tr})$ is a monotonically increasing function of T^v_{tr}, hence the optimal training duration $T^*_{trEEout} = T^v_{tr}$ increases with the increase of SE requirement in this case.

2) T^v_{tr} does not satisfy the inequality constraint in (31b): Noting that $T^v_{tr} \ge T^c_{tr}$, if T^v_{tr} is out of the feasible set $[T^{low}_{tr}, T^{up}_{tr}]$, there must be $T^v_{tr} > T^{up}_{tr}$. As we have analyzed, $h(T_{tr})$ first decreases and then increases with T_{tr}, and the transition point is at T^v_{tr}. Therefore, we have $h(T^{low}_{tr}) \ge h(T^c_{tr}) \ge h(T^{up}_{tr}) > h(T^v_{tr})$. Consequently, $T^*_{trEEout} = T^{up}_{tr}$ when $T^v_{tr} > T^{up}_{tr}$.

As we have analyzed, $c(T_{tr})$ first decreases and then increases with T_{tr}, and the transition point is at T^c_{tr}. Hence, the upper bound of the feasible set of training duration, T^{up}_{tr}, must belong to the increasing interval of $c(T_{tr})$, i.e., $c(T^{up}_{tr})$ is a increasing function of T^{up}_{tr}. The value of T^{up}_{tr} can be obtained when the constraint in (31b) hold with the equality $c(T^{up}_{tr}) = T$, i.e.,

$$c(T^{up}_{tr}) = T^{up}_{tr} + \frac{SE_rT}{\log_2(1+\frac{\gamma_d\nu_0}{2}\frac{\gamma_uT^{up}_{tr}}{1+\gamma_uT^{up}_{tr}})} = T. \quad \text{(F.3)}$$

Obviously, $c(T^{up}_{tr})$ increases linearly with the increase of SE_r. Therefore, to ensure $c(T^{up}_{tr}) = T$ holds, the value of T^{up}_{tr} must decrease when SE_r increases. It follows that $T^*_{trEEout} = T^{up}_{tr}$ decreases with the increase of SE requirement in this case.

The above two cases will be respectively active for different values of SE_r. For small SE_r, we have from (F.1) and (F.2) that $j(T^v_{tr}) \approx j(T^c_{tr})$ and then $T^v_{tr} \approx T^c_{tr}$. Since $T^c_{tr} \le T^{up}_{tr}$ always holds, we have $T^v_{tr} \le T^{up}_{tr}$, which belongs to Case one. With the increase of SE_r, there will be a value of SE_r, under which both T^{up}_{tr} and T^{low}_{tr} will approach T^c_{tr}, i.e., the feasible set is a point. We have shown that $T^v_{tr} > T^c_{tr}$ when $SE_r \ne 0$, therefore we have $T^v_{tr} > T^{up}_{tr}$ when SE_r is sufficiently large, which belongs to Case two.

Considering that T^v_{tr} increases with SE_r while T^{up}_{tr} decreases with SE_r, we can always find a SE_r (denoted by SE^o_r) with which $T^v_{tr} = T^{up}_{tr}$ holds. When $SE_r \le SE^o_r$, we have $T^v_{tr} \le T^{up}_{tr}$, and $T^*_{trEEout} = T^v_{tr}$ which increases with SE_r; when $SE_r > SE^o_r$, we have $T^v_{tr} > T^{up}_{tr}$, and $T^*_{trEEout} = T^{up}_{tr}$ which decreases with SE_r.

To analyze the impact of circuit power, we substitute (20) into (F.1) and have that

$$j(T^v_{tr}) = \frac{b_1}{\ln 2}SE_rT(\lambda + \frac{\mu P_d}{MP^{RX}_c}). \quad \text{(F.4)}$$

When P^{RX}_c is large and $\lambda = 1$, i.e., $P^{TX}_c = P^{RX}_c$, we have that $j(T^v_{tr}) \approx j(T^c_{tr})$, and hence $T^v_{tr} \approx T^c_{tr}$. Since $T^c_{tr} \le T^{up}_{tr}$ always holds, we have $T^v_{tr} \le T^{up}_{tr}$ in this scenario,

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which belongs to Case one, regardless of the value of SE_r. Therefore, we have $T^*_{trEEout} = T^v_{tr}$ which increases with SE_r. Moreover, it can be observed from (F.4) that $j(T^v_{tr})$ decreases with the increase of circuit power, P^{RX}_c. Since $j(T^v_{tr})$ is a monotonically increasing function of T^v_{tr}, we have $T^*_{trEEout} = T^v_{tr}$ which decreases with circuit power.

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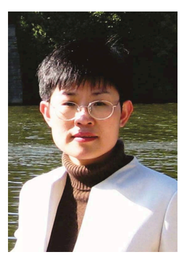

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