Energy-Efficient Scheduling with Individual Packet Delay Constraints and Non-Ideal Circuit Power

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Abstract: **Exploiting the energy-delay tradeoff for energy saving is critical for developing green wireless communication systems. In this paper, we investigate the delay-constrained energy-efficient packet transmission. We aim to minimize the energy consumption of multiple randomly arrived packets in an additive white Gaussian noise channel subject to individual packet delay constraints, by taking into account the practical on-off circuit power consumption at the transmitter. First, we consider the offline case, by assuming that the full packet arrival information is known *a priori* at the transmitter, and formulate the energy minimization problem as a non-convex optimization problem. By exploiting the specific problem structure, we propose an efficient scheduling algorithm to obtain the globally optimal solution. It is shown that the optimal solution consists of two types of scheduling intervals, namely "selected-off" and "always-on" intervals, which correspond to bits-per-joule energy efficiency maximization and "lazy scheduling" rate allocation, respectively. Next, we consider the practical online case where only causal packet arrival information is available. Inspired by the optimal offline solution, we propose a new online scheme. It is shown by simulations that the proposed online scheme has a comparable performance with the optimal offline one and outperforms the design without considering on-off circuit power as well as the other heuristically designed online schemes.**

Index Terms: **Energy efficiency, individual packet delay constraints, on-off circuit power, scheduling.**

I. INTRODUCTION

Due to the explosive growth of wireless devices and applications, the energy consumption of wireless networks has dramatically increased. To reduce energy consumption as well as to decrease the resulting carbon dioxide emission, green wireless communication has attracted much interest recently, and many innovative green techniques among different protocol layers have been proposed [1]. The authors of [2] pointed out four fundamental tradeoffs for green wireless networks, among which exploiting the energy-delay tradeoff for energy saving is significantly important. On the other hand, the emerging data applications in recent wireless networks always have heterogeneous delay requirements, which must be guaranteed to ensure the service experience [3]. As a result, the design of energy-efficient resource allocation schemes to reduce the energy consumption subject to delay constraints has become an essential issue for green wireless communication systems.

There have been some works in the literature discussing the energy efficient scheduling under delay constraints [4]–[9]. In [4], the authors considered the energy minimization problem in an additive white Gaussian noise (AWGN) channel under dynamic packet arrivals, where an optimal "lazy scheduling" rule was proposed to conserve energy subject to a single packet delay constraint (deadline). The idea of "lazy scheduling" was extended to the case under individual packet delay constraints in [5] and [6]. In [7] and [8], the authors considered the energy-efficient scheduling over fading channels, and designed opportunistic transmission schedulers by exploiting the stochastic characteristics of wireless channels. However, all the above-mentioned works considered transmit power as the only energy budget. In this case, the consumed energy for data transmission over a wireless link can always be reduced by prolonging the transmission time, i.e., longer delay will result in less transmission energy. Nevertheless, for a practical transmitter, besides the transmit power, the transmission independent non-ideal circuit power also accounts for a significant portion of the total energy consumption. In particular, when the transmitter is *on*, i.e., the transmit power is larger than zero, the circuits such as the alternating current/direct current (AC/DC) converters, mixers, and filters consume significant power which is comparable with the transmit power; whereas when the transmitter is *off* with zero transmit power, the circuits can be turned off to save energy. Because of the on-off feature, the circuit power has a significantly impact on the energy-delay tradeoff and thus will fundamentally change the energy efficient scheduling principles. Specifically, it is observed in [2] that transmitting at infinitely small data rates with extremely long delay is always optimal when considering only the transmit power, however, it is not optimal any more if the on-off circuit power is taken into account. This is due to the fact that slowing down the transmission rates reduces the transmission energy [4] but in turn increases the circuit energy [10]. As a result, there exists a tradeoff between transmit power and circuit power consumption. Motivated by this phenomenon, the energy-efficient scheduling rules should be redesigned. It is worth remarking that energy-efficient power allocation to maximize the bits-per-joule energy efficiency (EE) by considering the non-ideal circuit power has been extensively studied in the literature (please see [10]–[12] and the references therein), where the EE is generally defined as the achievable throughput divided

Manuscript received February 4, 2013; approved for publication by Lee, Jungwoo, Division II Editor, November 30,2013.

This work is supported in part by the National Basic Research Program of China (973 Program) under Grant No. 2012CB316004, and Specialized Research Fund for the Doctoral Program of Higher Education under Grant No. 20133402110061.

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Digital object identifier 10.1109/JCN.2014.000007

by the total energy consumption during transmission. However, these works only considered constant circuit power but did not capture its on-off feature; meanwhile, they only considered static systems without considering the effect of traffic dynamics such as random data arrivals and departures.

In this paper, we investigate the energy-efficient scheduling problem in an AWGN channel with multiple randomly arrived packets, where each packet is subject to an individual delay constraint. We also consider a practical on-off circuit power at the transmitter. We aim to optimize the transmission duration (or rates) of packets to minimize the total energy consumption while ensuring the individual delay constraint of each packet. First, we consider the offline optimization by assuming that the data arrival information is known prior to the transmission. In this case, the energy minimization problem is formulated as a non-convex problem owning to the on-off circuit power. By exploiting the specific problem structure, we propose an efficient algorithm to achieve the globally optimal solution to the formulated problem. The optimal solution is shown to consist of two types of scheduling intervals, namely "selected off" and "always on" intervals, where for the former "selected off" intervals, the transmitter switches between *on* and *off*, and EE-maximization rate allocation is employed during the *on* state; whereas for the latter "always on" intervals, the transmitter is always *on*, and the "lazy scheduling" rate allocation rule is utilized. As a result, the EE-maximization and "lazy scheduling" are combined in the optimal solution of our interest. Next, we consider the online case where only causal knowledge of the packet arrival information is available at the transmitter. Inspired by the optimal offline solution, we propose a new online policy. It is shown by simulations that the proposed online policy achieves a comparable performance with the optimal offline scheme and outperforms the design without considering the non-ideal circuit power as well as the other heuristically designed online schemes.

The rest of this paper is organized as follows. Section II introduces the system model and presents the problem formulation. Section III presents the optimal offline scheduler and Section IV proposes the online schedulers. Section V provides the numerical results. Finally, Section VI concludes this paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a point-to-point single-antenna link where the transmitter sends M packets to the receiver, $M \geq 1$. It is assumed that each packet i randomly arrives at time t_i, $i = 1, \cdots, M$, where t_i's are generally modeled as a random process following a continuous probability distribution. For convenience, we set $t_1 = 0$ and denote the inter-arrival time as d_i, i.e., $d_i = t_{i+1} - t_i, i = 1, \cdots, M-1$. The packet size of the ith packet is denoted as B_i (bits), where $B_i \geq 0$, $i = 1, \cdots, M$. We also assume that each packet i has an individual delay constraint represented by T_i, i.e., the packet must be delivered before the deadline $t_i + T_i, i = 1, \cdots, M$. For the last packet M, we denote $d_M = T_M$ as its inter-arrival time for convenience.

We consider an AWGN channel in this study. Let us suppose that the transmit power over time is $p(t), t \geq 0$. By employing the adaptive modulation and coding, the achievable rate $c(t)$ at time $t \geq 0$ is denoted as [13]

$$c(t) = w\log_2\left(1 + \frac{g}{\sigma^2\Gamma}p(t)\right) \tag{1}$$

where w is the bandwidth, g is the channel gain, $\Gamma \geq 1$ accounts for the gap from the channel capacity owning to the practical modulation and coding scheme used, and $\sigma^2 = N_0 w$ denotes the noise power at the receiver with N_0 being the noise power spectral density. For notational convenience, we denote $\gamma = g/\sigma^2\Gamma$ as the channel gain to noise ratio. Thus, we have

$$p(t) = \frac{2^{\frac{c(t)}{w}} - 1}{\gamma}. \tag{2}$$

We consider a practical power model by taking into account the on-off circuit power. In particular, if the transmitter is *on* with $c(t) > 0$, then the circuits such as the AC/DC converters, mixers, and filters consume a significant amount of energy, which is specified by the non-ideal circuit power. On the other hand, if the transmitter is *off* with $c(t) = 0$, the transmitter can switch off these circuit components to save energy during which only the idling power given by $\beta \geq 0$ is consumed. Hence, a practical power consumption model is given by [14]

$$f\left(c\left(t\right)\right) = \begin{cases} \frac{2^{\frac{c(t)}{w}} - 1}{\eta\gamma} + \alpha, & c\left(t\right) > 0, \\ \beta, & c\left(t\right) = 0 \end{cases} \tag{3}$$

where $0 < \eta \leq 1$ is the drain efficiency of the power amplifier. In practice, β is much smaller than α and thus can be ignored without loss of generality, i.e., we set $\beta = 0$ in the sequel. Furthermore, since η is only a scaling constant, we also assume $\eta = 1$ in the rest of this study. The results in this study can be readily extended to the case where $\beta > 0$ and $0 < \eta < 1$.

Suppose that the transmission duration of packet i is denoted as τ_i with $0 < \tau_i \leq T_i, i = 1, \cdots, M$, during which the transmitter is *on*, and denote $\boldsymbol{\tau} = [\tau_1, \tau_2, \cdots, \tau_M]$ as a vector consisting of the transmission duration of the M packets. Because $f\left(c\left(t\right)\right)$ can be shown to be strictly convex in $c\left(t\right)$ when $c\left(t\right) > 0$, we can easily verify that the optimal policy is to set the transmission rate as a constant B_i/τ_i, $i = 1, \cdots, M$ during the transmission duration [6]. We let $E\left(\tau_i\right)$ denote the total energy required to deliver the ith packet with transmission duration τ_i, then it follows that

$$E\left(\tau_i\right) = \left(\frac{2^{\frac{B_i}{\tau_i w}} - 1}{\gamma} + \alpha\right)\tau_i, \quad i = 1, \cdots, M. \tag{4}$$

On the other hand, the first-in-first-out service rule [4] is applied to model the packet transmission in the present study, where the packets are delivered on the order of their arrival. Note that if $d_i \geq T_i$, an idling period, $t \in (t_i + T_i, t_{i+1}]$, during which no transmission can occur, becomes inevitable due to the fact that there is no packet to be delivered during this period. To remove the idling periods, we use inter-arrival vector $\widehat{\mathbf{d}} = [\widehat{d}_1, \widehat{d}_2, \cdots, \widehat{d}_M]$ to replace the original vector $\mathbf{d} = [d_1, d_2, \cdots, d_M]$, where $\widehat{d}_i = \min(d_i, T_i)$. Accordingly, we redefine the arrival instant of the ith packet as $t_{i,\mathrm{arr}}$, where

$t_{i,\mathrm{arr}} = \sum_{h=1}^{i-1} \widehat{d}_h$. After this reformulation, it is optimal to set $\sum_{i=1}^{M} \tau_i \geq \sum_{i=1}^{M} \widehat{d}_i$ in the ideal circuit power ($\alpha = 0$) case as shown in [5], which corresponds to the case when the transmitter is always in the *on* mode. We refer to this case as "always on". Nevertheless, in the non-ideal circuit power ($\alpha > 0$) case, "always on" cannot be optimal any longer. We thus introduce an off-period for packet i, which is denoted by $\tau_{i,\mathrm{off}}$.[1] According to the newly introduced off-period, the scheduler may completely deliver the ith packet before the packet $i+1$ arrives, and the transmitter will be *off* with $c(t) = 0$ during this off-period. Suppose that $t_{i,\mathrm{over}}$ is the instant of the ith packet being completely delivered at $t_{i,\mathrm{over}} = \sum_{h=1}^{i} \tau_h + \sum_{h=1}^{i-1} \tau_{h,\mathrm{off}}$. Then, the off-period of the ith packet may correspond to the interval $(t_{i,\mathrm{over}}, t_{i+1,\mathrm{arr}})$. It is worth noting that if packet $i+1$ arrives before the transmission of packet i is finished, then $\tau_{i,\mathrm{off}}$ will be equal to zero. Thus, we can calculate the off-period $\tau_{i,\mathrm{off}}$ recursively as

$$\tau_{i,\mathrm{off}} = \left[\sum_{h=1}^{i} \widehat{d}_h - \left(\sum_{h=1}^{i} \tau_h + \sum_{h=1}^{i-1} \tau_{h,\mathrm{off}} \right) \right]^+ \quad (5)$$

where $[x]^+ \triangleq \max(0, x)$. Moreover, we have the following two constraints for the packets:

$$\sum_{h=1}^{i} (\tau_h + \tau_{h,\mathrm{off}}) \geq \sum_{h=1}^{i} \widehat{d}_h, \forall i, \quad (6)$$

$$\tau_i + \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\mathrm{off}}) - \sum_{h=1}^{i-1} \widehat{d}_h \leq T_i, \forall i \quad (7)$$

where (6) denotes the packet causality constraints, i.e., each packet transmission cannot begin before the packet arrives, and (7) denotes the delay constraints, i.e., packet i must be completely delivered before the deadline $t_i + T_i$.

We aim to optimize the transmission vector $\boldsymbol{\tau}$ to minimize the total energy consumption of the M packets denoted by $E(\boldsymbol{\tau}) = \sum_{i=1}^{M} E(\tau_i)$ subject to delay constraints. More precisely, the optimization problem can be formulated as

$$(\mathrm{P1}): \min_{\boldsymbol{\tau}} \sum_{i=1}^{M} \left(\frac{2^{\frac{B_i}{\tau_i w}} - 1}{\gamma} + \alpha \right) \tau_i \quad (8a)$$

$$\text{s.t. } \tau_i + \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\mathrm{off}}) - \sum_{h=1}^{i-1} \widehat{d}_h \leq T_i, \forall i, \quad (8b)$$

$$\sum_{h=1}^{i} (\tau_h + \tau_{h,\mathrm{off}}) \geq \sum_{h=1}^{i} \widehat{d}_h, \forall i, \quad (8c)$$

$$\tau_{i,\mathrm{off}} = \left[\sum_{h=1}^{i} \widehat{d}_h - \left(\sum_{h=1}^{i} \tau_h + \sum_{h=1}^{i-1} \tau_{h,\mathrm{off}} \right) \right]^+, \forall i. \quad (8d)$$

[1] Note that the off-period here is different from the idling period described previously. The previous idling period due to $d_i - T_i > 0$ has been removed via introducing $\widehat{d}_i$. The off-period here denotes the *off* status in the duration $(t_{i,\mathrm{arr}}, t_{i+1,\mathrm{arr}})$ because of the non-ideal circuit power. Moreover, the existence of $\tau_{i,\mathrm{off}}$ will be verified in the next section.

It can be shown that problem (P1) is generally non-convex since the equality constraints in (8d) are generally not affine when $\tau_{i,\mathrm{off}} > 0$ for any $i \in \{1, \cdots, M\}$ [16]. Thus, it is difficult to find the globally optimal solution to (P1). Fortunately, through investigating the specific structure of this problem, we propose an efficient algorithm to obtain the optimal solution as we will show next.

Remark 1: To provide further insight, it is interesting to point out one special case of the ideal circuit power ($\alpha = 0$). In this case, it can be shown that the total energy consumption in (8a) is monotonically decreasing with respect to the transmission duration τ_i's. As a result, τ_i's should be as large as possible. This result implies that the "always on" rule should be optimal, and accordingly it follows that the off-period should be zero at the optimal solution, i.e., $\tau_{i,\mathrm{off}} = 0, \forall i$. By substituting $\tau_{i,\mathrm{off}} = 0, \forall i$, into (P1), we can show that (P1) will be reduced to the energy minimization problem in [5], which is efficiently solved by the lazy scheduling algorithm (please see Section III-B for more details). Hence, problem (P1) generalizes the case of the ideal circuit power in [5].

III. OPTIMAL OFFLINE SCHEDULER

In this section, we consider the offline scheduler for the energy minimization (P1), assuming that all the data arrival information is known prior to the transmission. To obtain some insights, we first consider two special cases, i.e., the single-packet case with non-ideal circuit power ($M = 1, \alpha \geq 0$) and the multi-packet case with ideal circuit power ($M \geq 1, \alpha = 0$), and then extend the solution to the general case of $M \geq 1, \alpha \geq 0$. In this section, unless explicitly specified, we assume that the individual delay constraints and the packet sizes of all packets are the same, i.e., $T_1 = \cdots = T_M = T$ and $B_1 = \cdots = B_M = B$. The results herein can be simply extended to the scenarios with unequal delay constraints and packet sizes.

A. Single-Packet Case with Non-Ideal Circuit Power

Suppose that there is only a single packet to be delivered, i.e., $M = 1, \alpha \geq 0$. In this case, by using $c_i = B_i/\tau_i$, the original (P1) can be rewritten as

$$(\mathrm{P2}): \min_{c_1} \frac{B \cdot \left(\frac{2^{\frac{c_1}{w}} - 1}{\gamma} + \alpha \right)}{c_1} \quad (9a)$$

$$\text{s.t. } c_1 \geq \frac{B}{T}. \quad (9b)$$

We can observe that the objective of (P2) is a fractional function with a convex differentiable numerator and an affine differentiable denominator, and the constraint in (9b) is affine. Thus, we be easily verify that (P2) is a pseudo-convex optimization problem [12], which can be solved efficiently by applying standard convex optimization techniques. To obtain a well-structured solution, we relax the constraint in (9b), and reduce (P2) as

$$\max_{c_1} \frac{c_1}{\frac{2^{\frac{c_1}{w}} - 1}{\gamma} + \alpha}. \quad (10)$$

Problem (10) can be solved by setting the first derivative of the objective function as zero in which the solution is given by

$$c_{\mathrm{ee}} = \frac{\left(W\left(\frac{\alpha\gamma-1}{e}\right)+1\right)w}{\ln 2} \tag{11}$$

where $W(\cdot)$ is the Lambert W function [15], which is defined as

$$W(y)\exp(W(y)) = y. \tag{12}$$

After obtaining c_{ee} in (11), we can easily verify that the objective function in (9a) is monotonically decreasing as a function of c_1 if $0 \le c_1 \le c_{\mathrm{ee}}$, and is monotonically increasing if $c_1 > c_{\mathrm{ee}}$. Thus, the solution of problem (P2) can be obtained as

$$c_1^* = \max\left(c_{\mathrm{ee}}, \frac{B}{T}\right). \tag{13}$$

Denote the corresponding optimal transmission duration by $\tau_1^* = B/c_1^*$, it follows that

$$\tau_1^* = \min(\tau_{\mathrm{ee}}, T) \tag{14}$$

in which

$$\tau_{\mathrm{ee}} = \frac{B\cdot\ln 2}{\left(W\left(\frac{\alpha\gamma-1}{e}\right)+1\right)w}. \tag{15}$$

Remark 2: From the optimal solution in (14), we obtain the following observations. If $\tau_{\mathrm{ee}} \ge T$, then we have $\tau_1^* = T$; consequently, $\tau_{1,\mathrm{off}}^* = 0$, which corresponds to an "always-on" transmission. However, if $\tau_{\mathrm{ee}} < T$, then we have $\tau_1^* = \tau_{\mathrm{ee}}$; consequently, $\tau_{1,\mathrm{off}}^* = T - \tau_{\mathrm{ee}} > 0$, which corresponds to a "selected-off" transmission. Moreover, for the case of "selected-off" transmission, it is interesting to observe that problem (10) is identical to the EE maximization in [12]. This phenomenon implies that the transmission rate in the "selected off" transmission corresponds to the EE-maximization rate allocation. Also note that if $\alpha = 0$, then it follows that $\tau_{\mathrm{ee}} \to \infty$, and as a result $\tau_1^* = T$ always holds, which corresponds to the "always on" transmission.

B. Multi-Packet Case with Ideal Circuit Power

Next, we consider the multi-packet case with ideal circuit power, i.e., $M \ge 1, \alpha = 0$. In this case, the consumed energy in (4) is re-expressed as $\widetilde{E}(\tau_i) = \tau_i(2^{B_i/\tau_i w} - 1)/\gamma$. We can easily verify that $\widetilde{E}(\tau_i)$ is monotonically decreasing as a function of τ_i, and thus we can show that $\tau_{i,\mathrm{off}}^* = 0, \forall i$. Therefore, (P1) is reformulated as

$$\text{(P3)}: \min_{\boldsymbol{\tau}} \sum_{i=1}^{M} \tau_i\left(\frac{2^{\frac{B_i}{\tau_i w}}-1}{\gamma}\right) \tag{16a}$$

$$\text{s.t.} \quad \sum_{h=1}^{i}\tau_h - \sum_{h=1}^{i-1}\widehat{d}_h \le T, \forall i, \tag{16b}$$

$$\sum_{h=1}^{i}\tau_h \ge \sum_{h=1}^{i}\widehat{d}_h, \forall i. \tag{16c}$$

Table 1. OOSI algorithm.

Initialization: $n=0$; $\mu_i^{(0)} \ge 0$; $\xi_i^{(0)} \ge 0$.
a) Calculate $\tau_i^{(n)}$ using (21) subject to $\mu_i^{(n)} \ge 0$ and $\xi_i^{(n)} \ge 0$.
b) Update $\mu_i^{(n+1)}$ and $\xi_i^{(n+1)}$ using (23) and (24), respectively. Set $n = n+1$.
c) Repeat Step a) and Step b) until $\tau_i^{(n)}, i = 1, \cdots, M$ is optimal.

This problem is identical to the energy minimization problem in [5], which shows that the "lazy scheduling" rule can be applied to optimally solve it. To facilitate the latter description, we give an alternative solution on the basis of convex optimization.

We can easily show that (P3) is convex, because the objective function is the sum of the perspective functions and the constraints are all affine [16]. Thus, we can use the Lagrange dual method to solve it. Let $\boldsymbol{\mu} = [\mu_1, \mu_2, \cdots, \mu_M] \succeq \mathbf{0}$ and $\boldsymbol{\xi} = [\xi_1, \xi_2, \cdots, \xi_M] \succeq \mathbf{0}$ be the vectors consisting of the Lagrange multipliers associated with the constraints in (16b) and (16c), respectively, where "$\succeq$" represents the component-wise inequality. Then, the Lagrangian function is given as

$$\begin{aligned} &L(\boldsymbol{\tau}, \boldsymbol{\mu}, \boldsymbol{\xi}) \\ &= \sum_{i=1}^{M}\tau_i\left(\frac{2^{\frac{B_i}{\tau_i w}}-1}{\gamma}\right) + \sum_{i=1}^{M}\mu_i\left(\sum_{h=1}^{i}\tau_h - \sum_{h=1}^{i-1}\widehat{d}_h - T\right) \\ &- \sum_{i=1}^{M}\xi_i\left(\sum_{h=1}^{i}\tau_h - \sum_{h=1}^{i}\widehat{d}_h\right). \end{aligned} \tag{17}$$

Accordingly, the dual function is defined as

$$D(\boldsymbol{\mu}, \boldsymbol{\xi}) = \min_{\boldsymbol{\tau}} L(\boldsymbol{\tau}, \boldsymbol{\mu}, \boldsymbol{\xi}). \tag{18}$$

As a result, the dual problem is expressed as

$$\text{(P3D)}: \max_{\boldsymbol{\mu}\succeq\mathbf{0}, \boldsymbol{\xi}\succeq\mathbf{0}} D(\boldsymbol{\mu}, \boldsymbol{\xi}). \tag{19}$$

Since (P3) is convex and satisfies the Slater's condition, strong duality holds between (P3) and (P3D) [16]. Therefore, (P3) can be equivalently solved by solving (P3D). Given $\boldsymbol{\mu}$ and $\boldsymbol{\xi}$, the minimization problem (18) can be re-expressed as follows by discarding the irrelevant constant terms.

$$\min_{\boldsymbol{\tau}} \sum_{i=1}^{M}\tau_i\left(\frac{2^{\frac{B_i}{\tau_i w}}-1}{\gamma}\right) + \sum_{i=1}^{M}\mu_i\sum_{h=1}^{i}\tau_h - \sum_{i=1}^{M}\xi_i\sum_{h=1}^{i}\tau_h. \tag{20}$$

Then, we can obtain its optimal transmission duration τ_i^* for (20) with the given $\boldsymbol{\mu}$ and $\boldsymbol{\xi}$ by applying the Karush-Kuhn-Tucker optimality conditions as

$$\tau_i^* = \frac{B\ln 2}{\left(W\left(\frac{\left(\sum_{h=i}^{M}\mu_h - \sum_{h=i}^{M}\xi_h\right)\gamma - 1}{e}\right)+1\right)w}. \tag{21}$$

With τ_i^* available, we can solve (18) to obtain $D(\boldsymbol{\mu}, \boldsymbol{\xi})$ for any given $\boldsymbol{\mu}$ and $\boldsymbol{\xi}$. To find the optimum values of $\boldsymbol{\mu}$ and $\boldsymbol{\xi}$ to maximize $D(\boldsymbol{\mu}, \boldsymbol{\xi})$, we re-express (P3D) as

$$\max_{\boldsymbol{\mu},\boldsymbol{\xi}\succeq 0} \sum_{i=1}^{M} \mu_i \left(\sum_{h=1}^{i} \tau_h^* - \sum_{h=1}^{i-1} \widehat{d}_h - T \right) - \sum_{i=1}^{M} \xi_i \left(\sum_{h=1}^{i} \tau_h^* - \sum_{h=1}^{i} \widehat{d}_h \right). \quad (22)$$

Then, the sub-gradient method [17] can be applied to obtain the optimum values of $\boldsymbol{\mu}$ and $\boldsymbol{\xi}$, which can be described as

$$\mu_i^{(n+1)} = \left[\mu_i^{(n)} + \delta \left(\sum_{h=1}^{i} \tau_h^* - \sum_{h=1}^{i-1} \widehat{d}_h - T \right) \right]^+, \quad (23)$$

$$\xi_i^{(n+1)} = \left[\xi_i^{(n)} + \delta \left(\sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i} \tau_h^* \right) \right]^+ \quad (24)$$

where n is the iteration index and δ is the step size. The convergence can be verified for δ being sufficiently small. Then we can obtain the optimal μ_i^* and ξ_i^* for (P3D). Accordingly, the corresponding τ_i^* in (21) becomes the optimal solution for (P3). As a result, the optimal offline scheduling with ideal circuit power (OOSI) can be summarized in Table 1.

C. General Multi-Packet Case with Non-Ideal Circuit Power

Inspired by the solution of the above two special cases, we are now ready to investigate the optimal solution to the general multi-packet case with non-ideal circuit power, i.e., $M \geq 1, \alpha \geq 0$. The following propositions are initially provided.

Proposition 1: For any packet $i = 1, \cdots, M$, if $\sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}}) \leq \tau_{\text{ee}}$, then $\tau_i^* \geq \sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}})$ and $\tau_{i,\text{off}}^* = 0$.

Proof: Suppose that the transmission of packet $i, i = 1, \cdots, M$ starts from the time instant $\sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}})$ with the deadline $\sum_{h=1}^{i} \widehat{d}_h$. Thus, the transmission can be viewed as a signal-packet transmission with delay constraint $\sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}})$. If $\sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}}) \leq \tau_{\text{ee}}$, then it follows from Section III-A that the optimal solution of τ_i^* is given by $\tau_i^* \geq \sum_{h=1}^{i} \widehat{d}_h - \sum_{h=1}^{i-1} (\tau_h + \tau_{h,\text{off}})$. Accordingly, it follows $\tau_{i,\text{off}}^* = 0$ from (5). Thus, the proposition is proven. □

Proposition 2: If $\tau_{i,\text{off}} = 0, \forall i$, the OOSI is optimal for the case with non-ideal circuit power.

Proof: Because $\tau_{i,\text{off}} = 0, \forall i$, the total transmission duration for packets 1 to M is $D = \sum_{i=1}^{M} \widehat{d}_i$. Therefore, the energy minimization problem for the M packets can be reformulated as

$$(\text{P4}): \min_{\boldsymbol{\tau}} \sum_{i=1}^{M} \left(\frac{2^{\frac{B}{\tau_i w}} - 1}{\gamma} \right) \tau_i + \alpha D \quad (25a)$$

$$\text{s.t.} \sum_{h=1}^{i} \tau_h - \sum_{h=1}^{i-1} \widehat{d}_h \leq T, \forall i, \quad (25b)$$

$$\sum_{h=1}^{i} \tau_h \geq \sum_{h=1}^{i} \widehat{d}_h, \forall i. \quad (25c)$$

It is observed that αD in (25a) is a constant term. Therefore, (P4) has the same optimal solution problem (P3). As a result, the OOSI in Section III-B is optimal for (P3) and thus optimal for (P4), which completes the proof of Proposition 2. □

On the basis of the two propositions, we are ready to present the optimal solution for (P1). To assist us in the description, we set $m_0 = k_0 = s_0 = 0$ and define

$$k_1 = \min_{k=1,\cdots,M} \left\{ k : \sum_{i=1}^{k} \tau_{\text{ee}} < \sum_{i=1}^{k} \widehat{d}_i \right\}, \quad (26)$$

$$s_1 = \min_{s=1,\cdots,M} \left\{ s : \sum_{i=1}^{s} \tau_{\text{ee}} \geq \sum_{i=1}^{s-1} \widehat{d}_i + T \right\} \quad (27)$$

and set $m_1 = \min(k_1, s_1)$. For $j \geq 1$, let

$$k_{j+1} = m_j + \min_{k=1,\cdots,M-m_j} \left\{ k : q_{m_j+1} + \sum_{i=1}^{k} \tau_{\text{ee}} < \sum_{i=1}^{k} \widehat{d}_{m_j+i} \right\}, \quad (28)$$

$$s_{j+1} = m_j + \min_{s=1,\cdots,M-m_j} \left\{ s : q_{m_j+1} + \sum_{i=1}^{s} \tau_{\text{ee}} \geq \sum_{i=1}^{s-1} \widehat{d}_{m_j+i} + T \right\} \quad (29)$$

where $m_j = \min(k_j, s_j)$, and the buffering delay $q_{m_j+1} = \left[T - \widehat{d}_{m_j} \right]^+ 1_{\{m_j = s_j\}}$. The indicator $1_{\{\cdot\}}$ is defined as $1_{\{m_j = s_j\}} \triangleq 1$ if $m_j = s_j$ and 0 otherwise. We proceed above until $m_j = M$ and set $J = \{j : m_j = M\}$. Then, we present the following proposition.

Proposition 3: The optimal solution of (P1) has the following structure. If $m_j = k_j$ holds for some $j \in [1, s, J]$, the optimal transmission duration for packets $m_{j-1} + 1$ to m_j is

$$\tau_i^* = \tau_{\text{ee}}, i = m_{j-1} + 1, \cdots, m_j. \quad (30)$$

If $1 < l \leq J - j$ exists, where $m_j = k_j$, $m_{j+l} = k_{j+l}$, and $m_{j+l'} = s_{j+l'}, l' = 1, \cdots, l-1$, it follows that

$$\tau_{i,\text{off}}^* = 0, i = m_j + 1, \cdots, m_{j+l-1} \quad (31)$$

and then, the corresponding optimal transmission duration can be derived using the OOSI by treating $m_j + 1$ and m_{j+l-1} as the first and the last packets, respectively.

Proof: Please see Appendix. □

From Proposition 3, it follows that the proposed policy divides the scheduling intervals into two different types of decoupled scheduling intervals, namely "selected-off" and "always-on" intervals, which can be separately optimized. On one hand, if $m_j = k_j$ for some $j \in [1, \cdots, J]$, packets $i \in \{m_{j-1} + 1, \cdots, m_j\}$ can all be transmitted with optimal duration τ_{ee}.

Table 2. OOSNI algorithm.

Initialization:
a) Calculate τ_{ee} according to (15).
b) Find k_j and s_j according to (28) and (29), respectively.
  Set $m_j = \min\{k_j, s_j\}$.
c) Repeat b) until $m_j = M$. Set $J = \min\{j : m_j = M\}$
  and $l = 1$.
Function: find the optimal transmission durations.
1) **For** $j = 1 : J$
2)   **If** $m_j = k_j$
3)   Set $\tau_i^* = \tau_{\text{ee}}, i = m_{j-1}+1, \cdots, m_j$.
4)   **If** $l > 1$
5)   Set $\widehat{d}_{m_{j-1}} = T$.
6)   Apply OOSI to get the solutions τ_i^*,
        $i = m_{j-l}+1, \cdots, m_{j-1}$.
7)   Reset $l = 1$.
8)   **End If**
9)   **Else If** $m_j = s_j$
10)   Set $l = l + 1$.
11)   **End If**
12) **End For**
13) **If** $m_J = s_J$
14)   Apply OOSI to get the solutions $\tau_i^*, i = m_{J-l}+1, \cdots, M$.
15) **End If**

Moreover, the m_jth packet is completely delivered before the (m_j+1)th packet arrives, i.e., $\tau_{m_j,\text{off}} > 0$. As a result, this interval is referred to as "selected-off" scheduling interval. On the other hand, for intervals where there exists $1 < l \leq J - j$ that $m_j = k_j$, $m_{j+l} = k_{j+l}$, and $m_{j+l'} = s_{j+l'}, l' = 1, \cdots, l-1$, it is optimal to directly apply the OOSI algorithm by setting $\tau_{i,\text{off}} = 0, i = m_j+1, \cdots, m_{j+l-1}$. As a result, these intervals are referred to as "always on" scheduling intervals. Additionally, if $s_J = M$, by setting $j' = \max\{j | m_j = k_j\}$, we can obtain the optimal solutions for packets $m_{j'}+1$ to M by applying the OOSI. To sum up, the optimal offline scheduling with non-ideal circuit power (OOSNI) is listed in Table 2.

It is worth pointing out that the "selected off" and "always on" scheduling intervals are significantly impacted by the parameters such as the packet arrival rate, delay constraint T, packet size B, and non-ideal circuit power α. Specifically, if the packet arrival rate is small and/or the delay constraint T is large, then $\sum_{i=1}^{k} \hat{d}_{m_j+i}$ in (28) becomes large; meanwhile, with small packet size B and/or large non-ideal circuit power α, it can be shown that τ_{ee} in (15) is small. In these scenarios, (28) is more likely to hold for most scheduling intervals. In other words, more intervals will belong to the type of "selected-off". This result is intuitive, since non-ideal circuit power consumption dominates the transmit power in this case, and thus "selected-off" is preferred to save the non-ideal circuit power consumption. On the other hand, if the packet arrival rate is large, the delay constraint T is small, the packet size B is large and/or the circuit power α is small, then the opposite result holds. In other words, more scheduling intervals are likely to belong to the type of "always on" [cf. (29)], which is due to the fact that in this case the transmit power becomes more dominant. It is also worth pointing out one special case of ideal circuit power with $\alpha = 0$. In this case, since $\tau_{\text{ee}} \to \infty$ always holds [cf. (15)], all intervals should belong to the type of "always on". As a result, (P1) is reduced to (P4); consequently, the OOSNI algorithm is reduced to the OOSI algorithm.

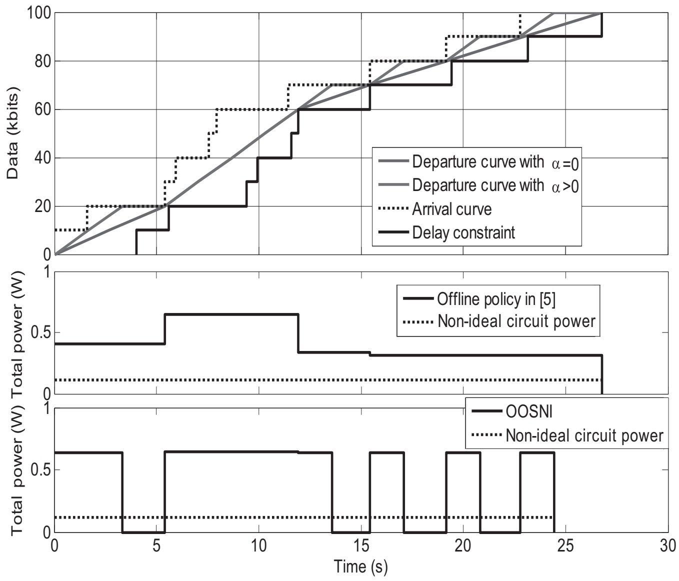

Fig. 1. Transmission duration and power allocation by OOSNI and the offline policy in [5].

Example: To illustrate the two types of scheduling intervals, we compare the OOSNI with the offline policy in [5] shown in Fig. 1 with $M = 10$, $T = 4$ s, $\Gamma = 1$, and $\gamma = 1$. Suppose that the packet size is $B = 10$ kbits, the bandwidth is $w = 10$ kHz and $\alpha = 115.9$ mW.[2] The inter-arrival time follows an exponential distribution with the mean parameter $\lambda = 3$ s. Note that the offline policy in [5] obtains the optimal solution of (P1) under the special case with $\alpha = 0$, which is considered here for comparison as a suboptimal algorithm with $\alpha > 0$ by assuming that the transmitter is always *on*. It is observed the proposed optimal policy has two types of scheduling intervals, i.e., packets 3 to 6 correspond to the "always-on" scheduling intervals, and the other packets correspond to the "selected-off" scheduling intervals. In contrast, only the "always-on" scheduling is applied by the offline policy in [5]. It is calculated that the total energy consumption is calculated as 10.42 and 11.29 mJ for the OOSNI algorithm and the offline policy in [5], respectively.

IV. ONLINE SCHEDULERS

After obtaining the optimal offline scheduler, we are interested in developing online schedulers by assuming causal packet arrival information known at the transmitter. Specifically, we assume that only the information of the current queue backlog is available. It is worth noting that the optimal online scheduler can be obtained based on the dynamic programming. However, this

[2]We consider the non-ideal circuit power of a mobile terminal here, which is modeled as the sum of the energy consumption from a digital-to-analog converter (i.e., 15.6 mW), a mixer (i.e., 30.3 mW), a filter (i.e., 20.0 mW), and a frequency synthesizer (i.e., 50.0 mW) [14].

approach is complex and impractical due to the *curse of dimensionality* of dynamic programming. In this section, we propose a new online algorithm inspired by the optimal offline scheduler.

A. Proposed Online Scheduler

We present the new online policy in this subsection. Suppose that there are N packets in the buffer at a certain time instant t, with residual packet sizes of $B_1, \cdots, B_N$. The residual individual delay constraint of each packet is denoted as $T_n, n = 1, \cdots, N$, where it is assumed that $T_1 \le T_2 \le \cdots \le T_N$. Because no future information of the packet-arrival process is available, the online scheduler is designed by minimizing the total energy consumption of the currently backlogged N packets. We first present the following proposition.

Proposition 4: To minimize the total power consumption of the currently backlogged N packets, the optimal transmission duration of the first packet is given by

$$\tau_{\mathrm{f}}^* = \min\left(\tau_{\mathrm{f}}, \tau_{\mathrm{f,ee}}\right) \tag{32}$$

and

$$\tau_{\mathrm{f}} = B_1 \min_{1\le n\le N} \frac{T_n}{\sum_{i=1}^{n} B_i} \tag{33}$$

where $\tau_{\mathrm{f,ee}} = B_1 \ln 2 / \left(W\left(\frac{\alpha\gamma-1}{e}\right)+1\right) w$ according to (15).

Proof: We prove this proposition by considering the following two cases. First, we investigate the case where $T_n > \sum_{i=1}^{n} \tau_{i,\mathrm{ee}}, \forall n \in [1, \cdots, N]$, which implies that the optimal transmission duration is equivalent to $\tau_{\mathrm{f,ee}}$ according to (28) and (30). In this case, we have

$$\begin{aligned} B_1 \min_{1\le n\le N} \frac{T_n}{\sum_{i=1}^{n} B_i} &> B_1 \min_{1\le n\le N} \frac{\sum_{i=1}^{n} \tau_{i,\mathrm{ee}}}{\sum_{i=1}^{n} B_i} \\ &\overset{(a)}{=} B_1 \min_{1\le n\le N} \frac{\sum_{i=1}^{n} B_i}{c_{\mathrm{ee}} \sum_{i=1}^{n} B_i} = \tau_{\mathrm{f,ee}} \end{aligned} \tag{34}$$

where equality (a) is due to (11) and (15). Thus, (32) holds from (34).

Next, we consider the case where $T_{n'} \le \sum_{i=1}^{n'} \tau_{i,\mathrm{ee}}$ for some $n' \in [1, \cdots, N]$. Thus, we have

$$\begin{aligned} B_1 \min_{1\le n\le N} \frac{T_n}{\sum_{i=1}^{n} B_i} &\le B_1 \frac{T_{n'}}{\sum_{i=1}^{n'} B_i} \\ &\le B_1 \frac{\sum_{i=1}^{n'} B_i}{c_{\mathrm{ee}} \sum_{i=1}^{n'} B_i} = \tau_{\mathrm{f,ee}}. \end{aligned} \tag{35}$$

In this case, the first packet belongs to the "always-on" scheduling interval according to (29) and (31), and the optimal transmission duration is [6]

$$\tau_{\mathrm{f}}^* = B_1 \min_{1\le n\le N} \frac{T_n}{\sum_{i=1}^{n} B_i}. \tag{36}$$

By combining the two cases, Proposition 4 is proven. □

From Proposition 4, we can obtain the online transmission policy as

$$r_H^*(t) = \max\left(\max_{1\le n\le N} \frac{\sum_{i=1}^{n} B_i}{T_n}, \frac{W\left(\frac{\alpha\gamma-1}{e}\right)+1}{\ln 2} w\right). \tag{37}$$

The policy in (37) provides a convenient way of implementing the packet transmission, as explained as follows. The transmitter simply keeps the information on the backlogged packets, and computes the optimal transmission rate at instant t as given in (37). When the first packet is completely delivered, the second packet becomes the new first packet, and the optimal transmission rate for the new first packet can be obtained by repeating the above procedure. It is worth emphasizing that this scheduler is optimal when there is no future packet arrival. If a new packet arrives before the first packet delivered, a new term will be added to the right-hand side of (33), i.e., $N \leftarrow N+1$, and τ_{f} may decrease. In this case, the transmission rate of the first packet can be accordingly recalculated by (37).

B. Heuristically Designed Online Scheduler

For comparison, we also consider a heuristically designed online policy which simply extends the rate allocation of the single packet case in (13). Suppose that there are N packets in the buffer at a certain time instant t, the scheduler simply set the transmission rate as

$$r_I^*(t) = \max\left(c_{\mathrm{ee}}, \frac{NB}{T}\right). \tag{38}$$

Note that the transmission rate is always no smaller than $NB/T, N \ge 1$, and thus the delay constraints can always be guaranteed. Also note that if a packet in the buffer is completely delivered or a new packet arrives, then the transmission rate should be changed as $\max\left(c_{\mathrm{ee}}, (N-1)B/T\right)$ and $\max\left(c_{\mathrm{ee}}, (N+1)B/T\right)$, respectively.

V. NUMERICAL RESULTS

In this section, we compare the energy expended by the proposed online scheduler with the optimal offline scheduler which gives the upper bound performance, the policy without considering a non-ideal circuit power [5], and the heuristically designed online policy. A total number of 1,000 packets are considered, and the inter-arrival times follow an exponential distribution with mean parameter λ.

Fig. 2 shows the average energy consumed by each packet versus deadline T (with $\lambda = 1.5$ s and $\alpha = 115.9$ mW). It is observed that the proposed online policy performs close to the optimal offline policy and outperforms the other two policies. It

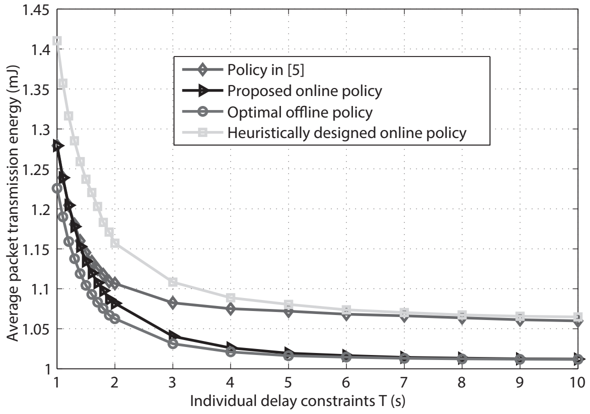

Fig. 2. Average packet energy versus T at $\alpha = 115.9$ mW, and $\lambda = 1.5$ s.

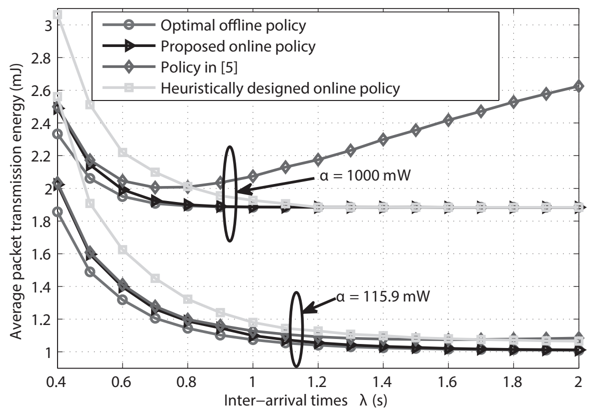

Fig. 3. Average packet energy versus λ at $T = 4$ s.

is also observed that for both the proposed online and the optimal offline policies, the energy consumption first decreases and then remains constant as T increase, because that when T is sufficiently large, inequality (29) can not be satisfied and $\tau_{\rm f,ee}$ will be smaller than $\tau_{\rm f}$. In this case, both the proposed online and the optimal offline policies transmit packets with rate $c_{\rm ee}$.

Fig. 3 shows the average energy consumed by each packet versus λ at $T = 4$ s and the different values of the non-ideal circuit power. In both case for α, the proposed online policy performs better than the policy in [5] as well as the heuristically designed online policy, and close to the optimal offline policy. If λ and α are small, the policy in [5] can yield a performance similar to the proposed online policy because in this case, $\tau_{\rm f}$ is always smaller than $\tau_{\rm f,ee}$; thus the proposed online policy degenerates to the policy in [5]. Further, with a large α value, i.e., $\alpha = 1,000$ mW, the energy consumption increases as λ increases when $\lambda \geq 0.7$ s for the policy in [5]. This is because that the non-ideal circuit power dominates the power consumption in this case, assuming that a low transmit power is needed when the transmission duration is large, and the energy consumption of the circuit is proportional to the transmission duration. Interestingly, with large α and λ values (i.e., $\alpha = 1,000$ mW and $\lambda \geq 1.2$ s), the energy consumption of the heuristically designed online policy will converge to the same value as that of the optimal offline policy, because the number of packets in buffer N is sufficiently small and $c_{\rm ee}$ is large in this case; thus, both policies deliver packets with rate $c_{\rm ee}$.

VI. CONCLUDING REMARKS

We have studied the energy-efficient scheduling problem in an AWGN channel with a non-ideal circuit power subject to individual packet delay constraints. Although the formulated problem is non-convex, we initially propose an optimal offline scheduler by employing a specified problem structure, which corresponds to either the "selected-off" or "always-on" scheduling intervals, where the "lazy scheduling" and EE-maximization are integrated. Inspired by the optimal offline scheduler, we propose a new online policy. In the simulations, we show that the proposed online scheme performs close to the optimal offline policy and outperforms the scheme that does not consider the non-ideal circuit power as well as the heuristically designed online scheme.

In this paper, we have only considered the case with an AWGN channel due to page limit. Considering the extension of this study into fading channels would be interesting for future works. Nevertheless, due to the coupling of channel variations and traffic dynamics, the optimal delay-constrained scheduling in fading channels with non-ideal circuit power will be very challenging and thus worth pursuing.

APPENDIX

To prove Proposition 3, we divide the M intervals in (P1) into two types of scheduling intervals according to (28) and (29), e.g., packets m_{j-1} to m_j construct a type I scheduling interval and packet packets m_j+1 to m_{j+l-1} construct a type II scheduling interval (setting $\widehat{d}_{m_{j+l-1}} = T$). We can verify that the M intervals can be either a type I interval or type II interval. We first prove that the solution given in Proposition 3 is optimal for both types I and II scheduling intervals, and then prove that the optimal solution for types I and II scheduling intervals are optimal for (P1).

The discussion in Section III-A clearly shows that $\tau_i = \tau_{\rm ee}$ is optimal for the ith packet whenever it is feasible. If $m_j = k_j$, we can feasibly set $\tau_i = \tau_{\rm ee}, i = m_{j-1}, \cdots, m_j$ according to (28) and (29), i.e., the causality and delay constraint are satisfied. Thus, the optimality of the solution given in (30) for the type I scheduling intervals is verified.

Then, we prove the second part when there exists $1 < l \leq J-j$ that $m_j = k_j$, $m_{j+l} = k_{j+l}$, and $m_{j+l'} = s_{j+l'}, l' = 1, \cdots, l-1$. First, we show that $\tau^*_{i,\rm off} = 0, i = m_j + 1, \cdots, m_{j+l-1}$ by contradiction. Suppose that the optimal solution contains an off-period, i.e., $\tau^*_{i,\rm off} > 0$, with $(t_{\rm off}, t_{\rm off} + \Delta t_{\rm off}) \subset \left(\sum_{h=1}^{m_j} \widehat{d}_h, \sum_{h=1}^{m_{j+l-1}-1} \widehat{d}_h + T\right)$. From (29), there must exist $n \in [m_j+1, \cdots, m_{j+l-1}]$ such that $\tau_n < \tau_{\rm ee}$. Then we construct a new transmission policy with $\tau'_n = \tau_n + \delta$, where δ is sufficiently small such that $\delta < \Delta t_{\rm off}$ and $\tau'_n < \tau_{\rm ee}$. We can easily verify that the new policy is feasible and satisfies the delay constraint. Because the consumed energy of packet n is monotonously decreasing with τ_n when $\tau_n < \tau_{\text{ee}}$ due to the pseudo-convex property discussed in Section III-A, it follows that the new policy consumes less energy. This condition results in a contradiction, and thus $\tau^*_{i,\text{off}} = 0, i = m_j+1, \cdots, m_{j+l-1}$ is verified. Then, from Proposition 2, OOSI is optimal for the type II scheduling intervals, where the exploitation of the individual delay constraint is maximized.

Finally, we need to prove that the two types of scheduling intervals are decoupled and the optimal solutions of the types I and II scheduling intervals are optimal for (P1). In type I scheduling intervals, there must exits at least one certain data packet $i \in \{m_{j-1}, \cdots, m_j\}$ satisfies $\tau_{i,\text{off}} > 0$ according to (5) and (28). Note that the optimal off-period $\tau_{i,\text{off}}$ may not be unique since the order between τ_i and $\tau_{i,\text{off}}$ does not affect the optimality. Without loss of generality, we assume that the transmitter is chosen to be *on* if the residual data packets in the buffer are not delivered completely. Hence, only the last packet m_j has a non-zero *off* period for the "selected-off" scheduling interval, i.e., $\tau^*_{m_j,\text{off}} > 0$ and $\tau^*_{i,\text{off}} = 0, i = m_{j-1}, \cdots, m_j - 1$. This condition implies that the m_jth packet is completely delivered before the $(m_j + 1)$th packet arrives because $\tau^*_{m_j,\text{off}} > 0$ according to (28) and (30). Therefore, the scheduling of packets before and after the m_jth can be decoupled. In the second case, according to (28), we find that the optimal schedule is not affected by starting the transmission of $(m_{j+l-1} + 1)$th packet when the m_{j+l-1}th packet is completely delivered at the instant $\sum_{h=1}^{m_{j+l-1}-1} \widehat{d}_h + T$, where the exploitation of the individual delay constraint is maximized. Thus, the scheduling of the packets before and after the m_{j+l-1}th interval can also be decoupled. From the above discussion, (P1) can be divided into decoupled types I and II scheduling intervals, which can be optimized separately. Thus, Proposition 3 is proven.

REFERENCES

[1] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green cellular networks: A survey, some research issues, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 524–540, 2011.

[2] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, June 2011.

[3] P. Tsiaflakis, Y. Yi, M. Chiang, and M. Moonen, "Throughput and delay performance of DSL broadband access with cross-layer dynamic spectrum management", *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2700–2711, Sept. 2012.

[4] E. Uysal-Biyikoglu, B. Prabhakar, and A. El Gamal, "Energy-efficient packet transmission over a wireless link," *IEEE/ACM Trans. Netw.*, vol. 10, pp. 487–499, Aug. 2002.

[5] W. Chen, M. J. Neely, and U. Mitra, "Energy-efficient transmissions with individual packet delay constraints," *IEEE Trans. Inf. Theory.*, vol. 54, no. 5, pp. 2090–2109, May 2008.

[6] M. A. Zafer and E. Modiano, "A calculus approach to energy-efficient data transmission with quality-of-service constraints," *IEEE/ACM Trans. Netw.*, vol. 17, pp. 898–911, June 2009.

[7] J. Lee and N. Jindal, "Energy-efficient scheduling of delay constrained traffic over fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1866–1875, Apr. 2009.

[8] M. I. Poulakis, A. D. Panagopoulos, and P. Constantinou, "Channel-aware opportunistic transmission scheduling for energy-efficient wireless links," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 192–204, Jan. 2013.

[9] D. J. Dechene and A. Shami, "QoS, channel and energy-aware packet scheduling over multiple channels," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1058–1062, Apr. 2011.

[10] J. Xu and L. Qiu, "Energy efficiency optimization for MIMO broadcast channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 690–701, Feb. 2013.

[11] G. Miao, N. Himayat, G. Y. Li, and S. Talwar, "Low-complexity energy-efficient scheduling for uplink OFDMA," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 112–120, Jan. 2012.

[12] C. Isheden, Z. Chong, E. Jorswieck, and G. Fettweis, "Framework for link-level energy efficiency optimization with informed transmitter," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2946–2957, Aug. 2012.

[13] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2004.

[14] H. Kim and G. Veciana, "Leveraging dynamic spare capacity in wireless systems to conserve mobile terminals energy," *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 802–815, June 2010.

[15] R. M. Corless, G. H. Gonnet, D. E. G. Hare, D. J. Jeffrey, and D. E. Knuth, "On the Lambert W function,“ *Adv. Comput. Math.*, vol. 5, pp. 329–359, 1996.

[16] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[17] S. Boyd, *Convex Optimization II* [Online]. Available: http://www.stanford.edu/class/ee364b/lectures.html

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