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Delay-Constrained Data Transmission for Energy Harvesting Transmitter

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***Abstract*—A point-to-point communication scenario is considered, where the transmitter is an energy harvesting node. During the transmission, energy packets and data packets of different sizes arrive at the transmitter. Specially, each data packet is associated with an individual deadline. The delay requirements for different data packets are generally considered to be different. Firstly, we investigate a delay-constrained throughput maximization problem. Two cases will be further distinguished, i.e., the case where incompletely transmitted data packets are useless and the case where the transmitted part of a data packet is still useful. Secondly, we additionally consider a delay-constrained energy minimization problem, e.g., when all the data packets can be completely transmitted in time. In this framework, we focus on modelling the considered scenario and optimization problems. In particular, the considered optimization problems can be formulated as convex and mixed-integer programs, respectively. The optimal transmission policies can be found by solving the corresponding optimization problems.**

I. Introduction

Energy harvesting (EH) is a promising technology to extend the life time of battery-operated communication devices, e.g., wireless sensors and mobile phones. An EH communication device is able to collect ambient energy from the environment, such as solar energy and radio frequency waves, to recharge its battery. The harvested energy can then be used for data transmission. A central concern in EH communications is how to efficiently use the harvested energy.

In this paper, we consider the transmit power adaptation in a point-to-point EH communication scenario. Thus only the transmitter is assumed to be an EH node. In many applications, not all the data that needs to be transmitted is available at the transmitter in advance. For instance, a wireless sensor may continually acquire measurements while operating. Therefore, we consider that data packets[1] of different sizes arrive at the transmitter during the transmission, in addition to the energy arrivals. Furthermore, in systems with delay requirements, e.g., feed-back control systems and emergency response systems, the data must be transmitted within a certain time interval after being acquired by the transmitter. Based on this, we also assume that each data packet is associated with an individual deadline. The delay requirements for different data packets are considered to be different in general. From the communication theory point of view, we will employ the offline approach, i.e., the energy and the data arrivals are assumed to be non-causally known at the transmitter in advance.

[1] This term shall not be confused with the "packet" in computer networking, which is a data unit at the network layer.

Firstly, we investigate a delay-constrained throughput maximization problem. For this problem, we further distinguish the following two cases depending on whether the data packets which cannot be completely transmitted before their deadlines are still useful to the receiver or not:

Case 1: If the incompletely transmitted data packets are useless, those data packets shall be entirely discarded by the transmitter when they arrive, and not be transmitted at all.

Case 2: If the transmitted part of a data packet is still useful, e.g., the low resolution version of a high resolution image, only the data that cannot be transmitted before the deadline shall be discarded by the transmitter.

In both of the two cases introduced above, the delay-constrained throughput represents the amount of data that can be transmitted before the deadlines of the data packets. However, if the harvested energy is sufficient to completely transmit all the data packets, or to completely transmit the data packets that are not discarded, the throughput maximization problem does not yield a unique optimal transmission policy. Therefore, we will consider a delay-constrained energy minimization problem in addition. The goal of this framework is to model the considered EH data transmission scenario and to find the optimal transmission policy maximizing the delay-constrained throughput or minimizing the consumed energy.

The optimization problems associated with EH communications have attracted a lot of attention recently. A review on this topic is given in [1]. The offline approach is a commonly used approach for finding the performance bounds in different scenarios. In [2], the throughput maximization problem is considered along with an EH process and a battery of finite capacity. The solution is graphically illustrated by the feasible energy tunnel, and the optimal transmission policy is represented by the shortest string connecting the beginning and the end of the feasible tunnel. In [3] and [4], the data arrivals are considered in addition to the energy arrivals. The harvested energy is assumed to be sufficient to transmit all the data packets. Finding the optimal transmission policy is considered as a scheduling problem and the goal is to minimize the transmission completion time. The EH data transmission over a fading channel is considered in [5], where a directional water-filling algorithm is employed to solve the throughput maximization problem and the transmission completion time minimization problem.

Delay requirements are investigated in a few recent works. In [6], data arrivals with individual deadlines are considered. The authors model the arrived data as continuous valued

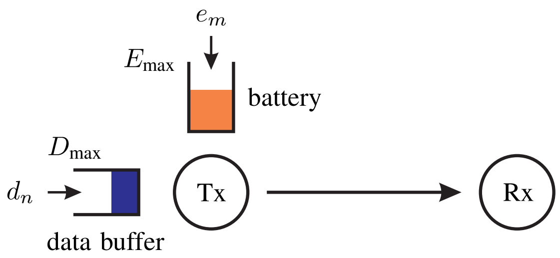


Fig. 1. A point-to-point communication scenario where an EH transmitter, which is equipped with a battery and a data buffer, transmits to a receiver

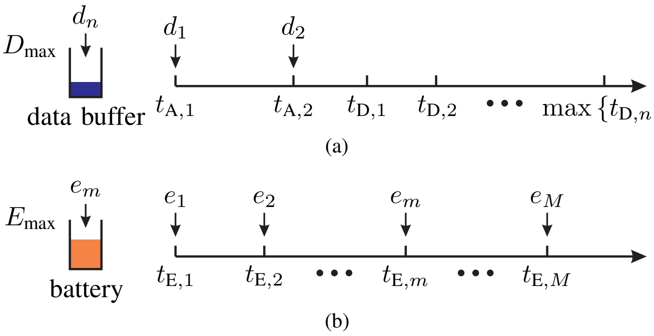


Fig. 2. The considered (a) data arrival process and (b) EH process

samples rather than data packets of finite sizes. The goal is to minimize the distortion resulting from compression, which leads to a source channel coding problem. The optimization problem is convex and can be solved using standard convex solvers. During the preparation of the current paper, an independent work taking delay requirements into consideration is published in [7]. The modelling of [7] is similar to our work, despite the different meanings of data packets. However, all the data packets are assumed to have the same delay requirement in [7], which significantly simplifies the resulting optimization problem.

The remaining part of this paper is organized as follows. In Section II, the considered scenario is modelled. The delay-constrained throughput maximization problem and the delay-constrained energy minimization problem are considered in Section III and IV, respectively. Numerical simulations are shown in Section V, and are followed by the conclusions.

II. System Model

The considered point-to-point communication scenario is shown in Fig. 1. The transmitter is assumed to be an EH node being able to harvest ambient energy from the environment. The harvested energy will be only used for data transmission, i.e., the energy consumption in circuits and for signal processing will be neglected. A data arrival process and an EH process are considered at the transmitter.

We assume that the data obtained by the transmitter within a certain time interval can only be transmitted afterwards. Therefore, the data arrival process is modeled as a discrete time process, i.e., data packets arrive at discrete time instants, as shown in Fig. 2(a). Each data packet contains the data obtained since the last data arrival and has a finite size. The sizes of the data packets are assumed to be different in general. Once a data packet arrives, it will be first stored in a data buffer of size $D_{\max}$ equipped at the transmitter, and is then ready to be transmitted. Furthermore, each data packet is associated with an individual deadline. Let d_n denote the size of the data packet whose arrival time and deadline are $t_{\mathrm{A},n}$ and $t_{\mathrm{D},n}$, respectively. In other words, the allowed transmission interval of the data packet d_n is $[t_{\mathrm{A},n}, t_{\mathrm{D},n}]$. The total time interval that needs to be considered depends on the number of data packets as well as their arrival times and deadlines. Assume a total number of N data packets which differ from each other by at least one of the arrival time or the deadline. That is to say, two data packets with both common arrival time and common deadline will be considered as a single one. Without loss of generality, we consider $t_{\mathrm{A},1}$ to be the initial time, i.e., $t_{\mathrm{A},1} = \min\{t_{\mathrm{A},n}\} = 0$ is assumed. Furthermore, define $T = \max\{t_{\mathrm{D},n}\}$. The total time interval that needs to be considered is therefore $[0, T]$. The data arrival process, including the sizes of the data packets, their arrival times, and their deadlines, is assumed to be known at the transmitter in advance.

Similar to the data arrival process, we model the EH process as a discrete time process as well, i.e., energy packets arrive at discrete time instances as shown in Fig. 2(b). A battery of capacity $E_{\max}$ is equipped at the transmitter to store the harvested energy. Resulting from this model, only the energy packets arriving before T can be used to transmit the considered N data packets. We assume M energy packets arriving within the right-open time interval $[0, T)$. Let e_m denote the energy packet which arrives at time instant $t_{\mathrm{E},m}$. Specially, we assume that e_1 is the initial energy in the battery with $t_{\mathrm{E},1} = t_{\mathrm{A},1} = 0$, and e_M is the last energy packet arriving before T with $t_{\mathrm{E},M} < T$. The EH process, including the energy contained in the energy packets and the arrival times, is also assumed to be known in advance.

In this paper, the communication channel between the transmitter and the receiver is assumed to remain constant in the considered time interval $[0, T]$ and to be known by the transmitter. The channel is generally characterized by a rate-power function $r(t) = \mathrm{f}(p(t))$, where $r(t)$ and $p(t)$ are the transmission rate for a given outage error probability and the transmit power, respectively. The rate-power function $\mathrm{f}(\cdot)$ is assumed to be non-negative, strictly increasing, and strictly concave [2]. It shall be mentioned that our work is not restricted to these assumptions. With little modification, it can also be extended to block fading channels and channels where the rate-power function is non-concave, e.g., multiple-input-multiple-output channels. However, these extensions are out of the scope of the present paper.

III. Delay-Constrained Throughput Maximization

A. Objective Function

Consider a time interval which does not include any energy arrival, any data arrival, or the deadline of any data packet. Then a constant transmit power throughout this time interval is optimal in terms of the throughput, since the considered rate-power function is concave [2], [4]. Based on this, let the considered time interval $[0, T]$ be slotted. Specifically, we consider I time slots defined by the time instants $t_1 = 0$, t_2, ..., and $t_{I+1} = T$, with the beginning and the end of the i-th time slot being t_i and t_{i+1}, respectively. The time instant t_i

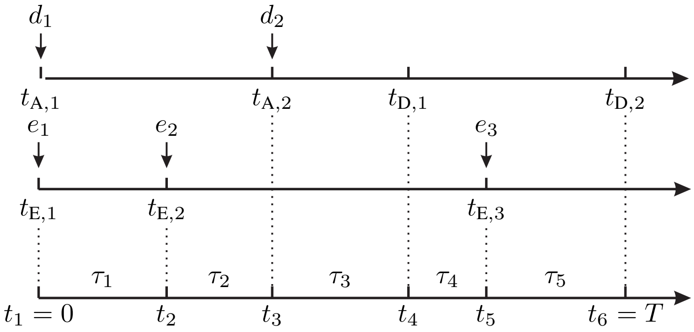


Fig. 3. An example illustrates the time interval $[0, T]$ being divided into 5 time slots of unequal durations

corresponds to either the arrival time $t_{\mathrm{E},m}$ of an energy packet, the arrival time $t_{\mathrm{A},n}$ of a data packet, or the deadline $t_{\mathrm{D},n}$ of a data packet. Furthermore, the duration of the i-th time slot is denoted by $\tau_i = t_{i+1} - t_i$, for $i = 1, 2, \ldots, I$. An example of the time slots resulting from two data arrivals and three energy arrivals is shown in Fig. 3.

Define p_i and r_i to be the average transmit power and the average throughput in the i-th time slot, respectively. Thus the throughput in the considered time interval $[0, T]$ can be formulated as

$$R = \frac{1}{T} \sum_{i=1}^{I} r_i \tau_i, \tag{1}$$

where r_i shall be given by

$$r_i = \mathrm{f}(p_i)\,., \quad \forall i = 1, 2, \ldots, I. \tag{2}$$

Equation (1) is also the objective function of the considered delay-constrained throughput maximization problem.

B. Energy Constraints

The energy constraints result from both the EH process and the finite capacity of the battery. In order to unify the notations, we introduce an empty energy packet $e_{M+1} = 0$ which arrives at time instant $t_{\mathrm{E},M+1} = T$.

On the one hand, the energy being stored in the battery must always be non-negative. Let the energy being stored in the battery before and after the m-th energy arrival be denoted by E_m and E'_m, respectively. Thus,

$$E_{m+1} = E'_m - \sum_{i \in \mathbb{E}_m} p_i \tau_i \geq 0 \tag{3}$$

must hold for all the energy packets, where

$$\mathbb{E}_m = \{i : i \in \{0, 1, \ldots, I\}, t_{\mathrm{E},m} \leq t_i < t_{\mathrm{E},m+1}\} \tag{4}$$

is the index set of the time slots in between of the m-th and the $(m+1)$-th energy arrivals. For instance in Fig. 3, three time slots are in between of the 2nd and the 3rd energy arrivals, and $\mathbb{E}_2 = \{2, 3, 4\}$ therefore holds. This also means the energy consumed in the time interval between two consecutive energy arrivals shall not exceed the available energy in the battery after the earlier energy arrival of the two. On the other hand, the energy being stored in the battery is limited by the battery capacity $E_{\max}$. That is to say, if an energy packet causes a battery overflow, the battery will be fully charged and the remaining energy is wasted. Taking battery overflows into consideration,

$$E'_m = \min\{E_m + e_m, E_{\max}\} \tag{5}$$

follows. Substituting (5) into (3) yields a recursive formulation of the energy constraints, i.e.,

$$E_{m+1} = \min\{E_m + e_m, E_{\max}\} - \sum_{i \in \mathbb{E}_m} p_i \tau_i \geq 0 \tag{6}$$

must hold for $m = 1, 2, \ldots, M$. The non-recursive formulation of the energy causality constraints is made up of a set of m inequality constraints for the m-th energy packet, which can be written as

$$\sum_{i \in \mathbb{E}_m} p_i \tau_i \leq E_{\max}, \tag{7}$$

$$\sum_{i \in \mathbb{E}_m \cup \mathbb{E}_{m-1}} p_i \tau_i \leq e_m + E_{\max}, \tag{8}$$

$$\vdots$$

$$\sum_{i \in \bigcup_{\mu=1}^{m} \mathbb{E}_\mu} p_i \tau_i \leq \sum_{\mu=1}^{m} e_\mu. \tag{9}$$

In plain words, the available energy for a time slot only depends on the latest battery overflow and the energy arrivals afterwards.

Sometimes, for instance when throughput maximization without data arrivals is considered [2], the time intervals before and after a battery overflow can be considered separately without loss of optimality. Then the energy constraints can be simplified to a single inequality constraint of (9) for each energy arrival, which are commonly referred to as the energy causality constraints. However in our scenario, battery overflow may occur in between of the arrival and the deadline of a data packet. Therefore, separately considering the time intervals before and after the battery overflow is suboptimal.

C. Auxiliary Variables

Before discussing the data constraints, we first introduce an auxiliary variable α_n for each data packet such that $\alpha_n d_n$ represents the transmitted data of the n-th data packet within its transmission interval $[t_{\mathrm{A},n}, t_{\mathrm{D},n}]$. The auxiliary variables α_n reveal the connection and the difference between the two cases introduced in Section I. If case 1 is considered, where the incompletely transmitted data packets are useless, α_n must be binary, which equals to one if the data packet is completely transmitted, and zero if the data packet is discarded. If case 2 is considered, where the successfully transmitted parts of the data packets are still of some use, we assume that α_n can take any value in between zero and one. In both cases, an equality constraint

$$\sum_{n=1}^{N} \alpha_n d_n = \sum_{i=1}^{I} r_i \tau_i \quad \begin{cases} \alpha_n \in \{0, 1\} & \text{for case 1} \\ 0 \leq \alpha_n \leq 1 & \text{for case 2} \end{cases} \tag{10}$$

follows, since both sides of (10) represent the total transferred data in the considered time interval $[0, T]$.

D. Data Causality and Data Buffer Constraints

The discussion of the data causality constraints and the constraints due to the finite data buffer size follows the same line as the energy constraints. To unify the notations, we also introduce an empty data packet $d_{N+1} = 0$ which arrives at time instant $t_{\mathrm{D},N+1} = T$.

Let the data being stored in the data buffer before and after the n-th data arrival be D_n and D'_n, respectively. Thus,

$$D_{n+1} = D'_n - \sum_{i \in \mathbb{D}_n} r_i \tau_i \geq 0 \tag{11}$$

must hold for all the data packets, where

$$\mathbb{D}_n = \{i : i \in \{0, 1, \dots, I\}, t_{\mathrm{D},n} \leq t_i < t_{\mathrm{D},n+1}\} \tag{12}$$

is the index set of the time slots in between of the (n)-th and the $(n+1)$-th data arrivals. Furthermore, the data being stored in the data buffer is limited by the data buffer size $D_{\max}$. That is to say, a data buffer overflow may occur when a data packet arrives. However, the effect of a data buffer overflow can be subsumed in the auxiliary variables α_n, such that only part of a data packet $\alpha_n d_n$ is stored in the data buffer. In other words, all the data being stored in the data buffer will be and can be transmitted to the receiver in time. The remaining part of a data packet $(1 - \alpha_n) d_n$ is discarded by the transmitter when the data packet arrives. Based on this,

$$D'_n = D_n + \alpha_n d_n \leq D_{\max} \tag{13}$$

follows, where $\alpha_n \in \{0, 1\}$ if case 1 is considered and $0 \leq \alpha_n \leq 1$ if case 2 is considered. In other words, data buffer management is implicitly considered by using the auxiliary variables. Combining (11) and (13) yields the data causality constraints

$$\sum_{i \in \bigcup_{\nu=1}^{n} \mathbb{D}_\nu} r_i \tau_i \leq \sum_{\nu=1}^{n} \alpha_n d_n, \tag{14}$$

and the constraints due to finite data buffer size

$$\sum_{i \in \bigcup_{\nu=1}^{n} \mathbb{D}_\nu} r_i \tau_i \geq \sum_{\nu=2}^{n+1} \alpha_n d_n - D_{\max}, \tag{15}$$

for $n = 1, 2, \dots, N$.

E. Individual Delay Constraints

We first examine three examples: 1) a data packet d_n whose transmission interval $[t_{\mathrm{A},n}, t_{\mathrm{D},n}]$ does not overlap with that of any other data packet, 2) two data packets whose transmission intervals partially overlap, as shown in Fig. 4(a), and 3) two data packets with the transmission interval of one of them being a subinterval of the other, as shown in Fig. 4(b). For the first example, the delay constraint for the data packet is

$$\sum_{i \in \mathbb{S}_{n,n}} r_i \tau_i \geq \alpha_n d_n, \tag{16}$$

where

$$\mathbb{S}_{n_1,n_2} = \{i : i \in \{0, 1, \dots, I\}, t_{\mathrm{A},n_1} \leq t_i < t_{\mathrm{D},n_2}\}, \tag{17}$$

is defined to be the index set of the time slots between the arrival time of the n_1-th data packet and the deadline of the

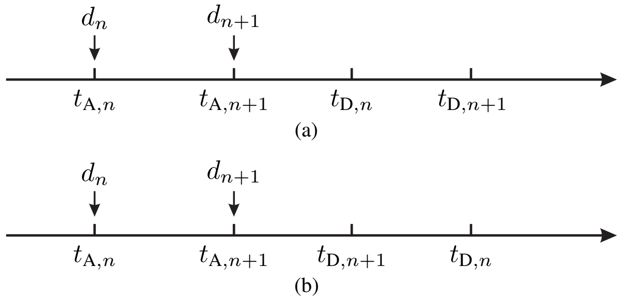


Fig. 4. Data packets with overlapped transmission intervals

n_2-th data packet. For the second example, the resulting delay constraints for the two data packets are

$$\sum_{i \in \mathbb{S}_{n,n}} r_i \tau_i \geq \alpha_n d_n, \tag{18}$$

$$\sum_{i \in \mathbb{S}_{n+1,n+1}} r_i \tau_i \geq \alpha_{n+1} d_{n+1}, \tag{19}$$

$$\sum_{i \in \mathbb{S}_{n,n+1}} r_i \tau_i \geq \alpha_n d_n + \alpha_{n+1} d_{n+1}, \tag{20}$$

where (20) is a redundant constraint in this case and can be omitted. For the third case, the resulting delay constraints for the two data packets are

$$\sum_{i \in \mathbb{S}_{n,n}} r_i \tau_i \geq \alpha_n d_n, \tag{21}$$

$$\sum_{i \in \mathbb{S}_{n+1,n+1}} r_i \tau_i \geq \alpha_{n+1} d_{n+1}, \tag{22}$$

$$\sum_{i \in \mathbb{S}_{n+1,n+1}} r_i \tau_i \geq \alpha_n d_n + \alpha_{n+1} d_{n+1}, \tag{23}$$

where (22) is a redundant constraint in this case and can be omitted.

Due to the existence of data packets whose transmission intervals overlap, the delay constraints shall be formulated as follows in general. For any time interval $[t_{\mathrm{A},n_1}, t_{\mathrm{D},n_2}]$ between the arrival time of the n_1-th data packet and the deadline of the n_2-th data packet, the delay constraint

$$\sum_{i \in \mathbb{S}_{n_1,n_2}} r_i \tau_i \geq \sum_{n \in \mathbb{N}_{n_1,n_2}} \alpha_n d_n \tag{24}$$

must hold, where

$$\mathbb{N}_{n_1,n_2} = \{n : n \in \{1, 2, \dots, N\}, [t_{\mathrm{A},n}, t_{\mathrm{D},n}] \subseteq [t_{\mathrm{A},n_1}, t_{\mathrm{D},n_2}]\} \tag{25}$$

is the index set of the data packets whose transmission intervals are subintervals of $[t_{\mathrm{A},n_1}, t_{\mathrm{D},n_2}]$, and $\alpha_n \in \{0, 1\}$ if case 1 is considered and $0 \leq \alpha_n \leq 1$ if case 2 is considered. Note that depending on the data arrival process, some constraints of (24) may be redundant constraints and can be omitted.

F. Solutions

To summarize, the delay-constrained throughput maximization problem in the considered scenario is

$$\text{maximize} \quad \sum_{i=1}^{I} r_i \tau_i, \tag{26}$$

subject to the energy constraints given in the recursive form of (6), the equality constraint of (10) due to the auxiliary variables, the data constraints (14) and (15), and the individual delay constraints (24). The inverse rate-power function $p_i = \mathrm{f}^{-1}(r_i)$ can be substituted in the constraints to eliminate the transmit powers p_i. The energy causality constraints are convex constraints in the transmission rates r_i, and the other constraints are linear constraints in r_i and the auxiliary variables α_n. Therefore, the considered delay-constrained throughput maximization problem is a convex optimization problem for case 2. However for case 1, since the auxiliary variables α_n are binary valued, it is a mixed-integer problem. Then case 2 can also be considered as a linear relaxation of case 1. Despite the computational complexity, standard algorithms for convex programming and integer programming [8], [9] can be employed to solve the delay-constrained throughput maximization problems and the global optimum transmission policy, although it may not be unique, can be found. For space reasons, we do not further discuss the details of these solvers.

For the special case where all the data packets have a common delay requirement, the delay constraints (24) can be greatly simplified. Consequently, the considered delay-constrained throughput maximization problems can be efficiently solved using the directional water filling algorithm. This special case is discussed in [7].

IV. Delay-Constrained Energy Minimization

The delay-constrained energy minimization problem can be considered in the following two cases. First, the harvested energy is sufficient to completely transmit all the N data packets before their deadlines. Second, the harvested energy is insufficient, and the throughput is maximized considering case 1, i.e., some data packets are discarded and the remaining data packets can be completely transmitted in time.

The considered time interval $[0, T]$ can be slotted as discussed in Sec. III-A, and keeping a constant transmit power in each time slot is also optimal in terms of energy. Therefore, the delay-constrained energy minimization problem is

$$\text{minimize} \quad \sum_{i=1}^{I} p_i \tau_i, \tag{27}$$

subject to the energy constraints given in the recursive form of (6), the equality constraint of (10) due to the auxiliary variables, the data constraints (14) and (15), and the individual delay constraints (24). The rate-power function (2) can be substituted in the constraints to eliminate the transmission rates r_i. Since the data packets that shall be transmitted are known, α_n is a given parameter, and the optimization variables are the transmit powers p_i in each time slot. The delay-constrained energy minimization problem is also a convex problem and can be readily solved using standard algorithms for convex optimization [8].

V. Simulation Results

In the following simulations, a constant additive white Gaussian noise channel is considered, where the rate-power function is given by $r_i = \log_2(1 + p_i)$. All the parameters are normalized and the units are simply omitted.

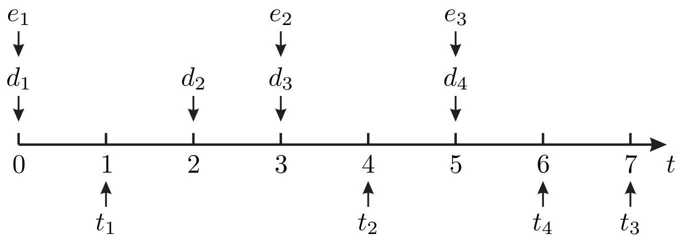
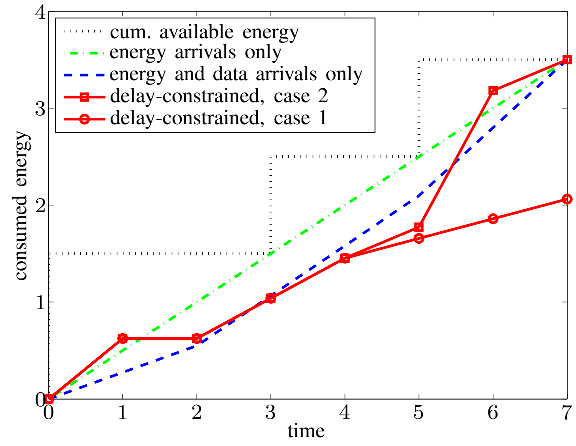


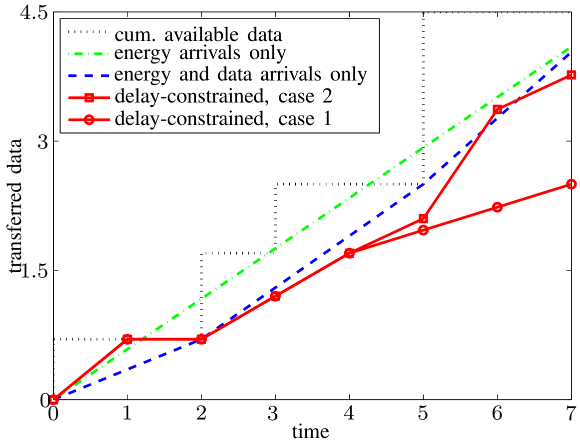
Fig. 5. The EH process, data arrival process, and the deadlines of the data packets of the numerical example

We first consider a numerical example to demonstrate the influence of individual delay constraints to the optimal transmission policy. The EH process, the data arrival process, and the deadlines of the data packets are shown in Fig. 5. The duration of all time slots is chosen to be one. The energy contained in the three energy packets is 1.5, 1, and 1, respectively. The sizes of the four data packets are 0.7, 1, 0.8, and 2, respectively. For now, we first ignore the influence of the finite battery capacity and data buffer size, and assume $E_{\max}$ and $D_{\max}$ to be infinitely large. For comparison, two reference scenario are considered. In the first reference scenario, only the energy arrivals are considered and all the data packets are assumed to be available at the transmitter in advance. In the second reference scenario, both the energy arrivals and the data arrivals are considered. In both reference scenarios, the individual deadlines of the data packets are ignored, but only a single transmission deadline of $t = 7$ is considered. The cumulative consumed energy and transferred data of the optimal transmission policies in the two reference scenarios and for the two cases in our scenario are shown in Fig. 6(a) and 6(b), respectively. If case 2 is considered in our scenario, the first three data packets can be completely transmitted before their deadlines. However, only 63.4% of the fourth data packet can be transmitted in time due to the relatively large size and short delay requirement. The results are illustrated by the solid lines marked by squares. If case 1 is considered, discarding the fourth data packet is optimal in terms of throughput. Afterwards, the delay-constrained energy minimization problem is considered to efficiently and completely transmit the previous three data packets. The results are illustrated by the solid lines marked by circles. As compared to these, the optimal transmission policies in the reference scenarios can reduce the variation of the power due to having less constraints, and therefore achieve higher throughput.

Next we consider the stochastic EH process and data arrival process. Assume 5 data packets whose arrival times are independently and uniformly distributed in the time interval $[0, 10]$. The size of each data packet is uniformly distributed following $\mathcal{U}(0, D_{\text{max}})$, where the data buffer size D_{max} is assumed to be 10. The delay requirements are assumed to follow the uniform distribution $\mathcal{U}(0, 2\Delta t)$. We further assume 5 energy packets whose arrival times are independently and uniformly distributed in the considered time interval. The energy contained in each energy packet is uniformly distributed following $\mathcal{U}(0, 2\bar{e})$. The battery capacity is assumed to be 10. The delay-constrained throughput maximization problem for case 2 is considered. The achieved throughput averaged over a large number of realizations is shown in Fig. 7. The influence of the average harvested energy $\bar{e}$ and the influence of the



(a)



(b)

Fig. 6. A numerical example: (a) energy consumption and (b) transferred data of the optimal transmission policies

average delay Δt are investigated. When the data packets have low delay requirements, harvesting more energy from each energy arrival has a very limited effect on the achievable throughput. The reason is that the transmit power has to be very large within the short transmission intervals of the data packets, which results in an inefficient usage of the harvested energy. However, as the delay requirements become larger, the throughput also increases faster with the harvested energy, because the harvested energy can be used more efficiently by maintaining a relatively low transmit power within the transmission intervals of the data packets.

VI. Conclusion

In this paper, we consider data transmission in an EH point-to-point scenario with individual deadlines. A delay-constraint throughput maximization problem and a delay-constrained energy minimization problem are considered. For the former problem, we further distinguish two cases, i.e., the case where a data packet shall either be completely transmitted or entirely discarded, and the case where only the data that cannot be transmitted before the deadline shall be discarded. For

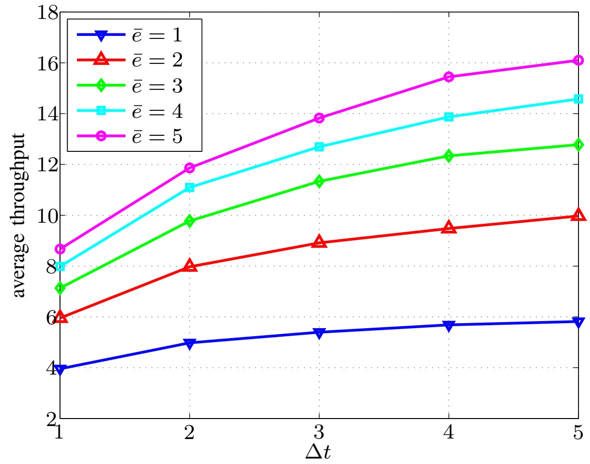


Fig. 7. Average throughput as a function of the average delay Δt

the two cases, the delay-constrained throughput maximization problem is formulated as a convex optimization problem and a mixed-integer optimization problem, respectively. For all the considered problems, the optimal transmission policy can be found.

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