Delay-Constrained Energy-Efficient Scheduling over a Multihop Link

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***Abstract*— This paper focuses on delay-constrained energy-efficient packet transmission over a static multihop link. Optimal offline scheduling (vis-à-vis total transmission energy), assuming information of all packet arrivals before scheduling, is derived. The optimal offline schedule relies on a simple delay budget allocation scheme, which allocates the delay budget to the first hop (from source to the first relaying node) as much as possible. All the relaying nodes simply perform buffer-clearing during any transmission opportunities. The total transmission energy and average packet delay are analyzed and characterized. It is demonstrated that energy savings via multihopping are possible, but depend heavily on factors such as multihop resource orthogonalization mode, delay constraints, and SNR operating regimes.**

I. Introduction

Relay assisted wireless transmission, proposed as early as in the seventies [12] [5], has recently emerged as a promising technique for cellular, ad-hoc, wireless local area network, and hybrid networks. Relaying improves coverage, capacity, robustness against channel variations, flexibility and adaptability to dynamic deployment scenarios and traffic needs, and power efficiency [6] [10].

For many *ad hoc* and commercial networks, power and/or energy efficiency is of high importance as it can impact network lifetime. Optimal power allocation for different relaying schemes has been considered in [9] [7] [13]. These prior relaying results assume immediate availability of data for transmission, and the impact of traffic variations has not been considered.

Energy efficient scheduling utilizing traffic variations and the associated delay constraint requirements for the traditional 'single-hop' transmission (or, direct transmission) has been a popular research topic (see [14] and references therein). The optimal energy-efficient scheduling algorithm for minimizing the total transmission energy of packets subject to *a single transmission deadline* over a static channel was investigated in [11]. The optimal *offline* algorithm assumed knowledge of the total number of packets and the inter-arrival times of these packets before packet scheduling. Scheduling for packets subject to *individual packet delay constraints* was considered in [8][14][4]. In [4], the optimal offline schedule was shown to yield a symmetry property in the optimal packet transmission durations from which a simple and exact solution of the average packet delay (including queuing and transmission delays) can be obtained.

In this paper, we focus on energy-efficient packet transmission over a *multihop link*, subject to the above two delay constraint models. We consider static channels. This can be viewed as an extension of the work in [11][14][2][4] over the *single-hop* link. We want to address the following questions: given a set of randomly arriving packets, how do we schedule these packets for maximum energy efficiency over a multihop link subject to the underlying delay constraints? How are the achieved energy and delay related? We begin by deriving the optimal offline scheduling over multihop transmissions. The optimal offline schedule relies on a simple delay budget allocation scheme, which allocates the delay budget to the first hop (from source to the first relaying node) as much as possible. All the relaying nodes simply perform buffer-clearing during any transmission opportunities. This optimal allocation is independent of traffic characteristics (*e.g.*, number of packets, packet sizes, burstiness, *etc.*) and channel characteristics (*e.g.*, path loss exponents, inter-distance between nodes, *etc.*). The total transmission energy and average packet delay are analyzed and characterized. It is demonstrated that energy savings via multihopping are possible, but heavily depend on factors such as multihop resource orthogonalization mode, delay constraints, and SNR operating regimes.

This paper is organized as follows. In Section II, the system model is described. The optimal offline scheduling over a multihopping channel is presented in Section III, while its performance is analyzed in Section IV. Numerical results are given in Section V.

II. System Model

A. Traffic Model and Time-Slotted Channel

We consider a time-slotted channel, in which packets arrive only at slot boundaries, and can be served immediately ($i.e.$, the minimum possible queuing delay is 0). Without loss of generality, the random aggregate arrived packet sizes at each slot are denoted by $B_i > 0, i \in [1, \cdots, M]$, and $B_i = 0$ for $i \in [M+1, M+D-1]$, where M is the total number of packets, and D is a delay constraint to be detailed later. This is illustrated in Fig. 1. The total number of slots is fixed to be $(M + D - 1)$, and the slot duration is denoted as τ_s. A fluid packet departure model is assumed. That is, a transmitted

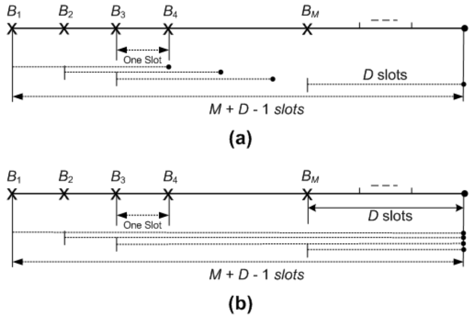


Fig. 1. The slotted system model (a): equal individual delay constraints; (b): single deadline.

packet is not necessarily an integer number of arrived packets, but may be assembled using fragmented packets up to an arbitrary precision.

For the *individual delay constraint model* (Fig. 1(a)), each packet is subject to an end-to-end delay constraint. In this paper, we will focus on the case when all packets have the same delay constraint of an integer multiple of slots, denoted as D (slots). In one special realization of unequal individual delay constraints, all packets have to be delivered by the single common deadline $(M+D-1)\tau_s$ (Fig. 1(b)). This model will be briefly treated in the sequel as a special case.

The set of packets are transmitted through an L-hop channel, instead of the conventional single-hop channel as discussed in [11][2][4][3]. Throughout the paper, we use the superscripts (l), $l \in [1, \cdots, L]$, to denote the l-th hop in an L-hop transmission, and, $l = 0$ to denote the conventional single-hop transmission for the purpose of performance comparison.

We will focus on static channels in which the channel gains are fixed at each hop. However, the channel gains, denoted by $g^{(l)}$, $l \in [0, \cdots, L]$, may be different for different hops.

B. Design Goals and Assumptions

Each packet transmission consumes some energy. The energy-rate functions, denoted by $w^{(l)}(r)$ for a transmission rate r over different hops $l \in [0, \cdots, L]$, are *not* necessarily the same. As in [11][14][2], it is assumed that $w^{(l)}(r)$, $\forall l$, is strictly convex and monotonically increasing in r.

The goal of the optimal offline schedule is to choose the optimal transmission rate $r_i^{(l)}$, $0 \leq l \leq L$, for each slot i and hop l, such that the total transmission energy of these M packets is minimized while the underlying delay constraints are satisfied.

The *offline* schedule assumes perfect knowledge of packet sizes for the entire duration $[0, \cdots, M+D-1]$ before scheduling. As in [11][4][3], all schedulers are assumed to follow the first-in-first-out (FIFO) service rule, the causality constraint, and the non-idling scheduling constraint.

Without loss of generality, the processing delays at each node are ignored such that a packet received at the end of a slot m by a node is available for transmission immediately at the next slot $m+1$. It is also assumed that scheduling is only

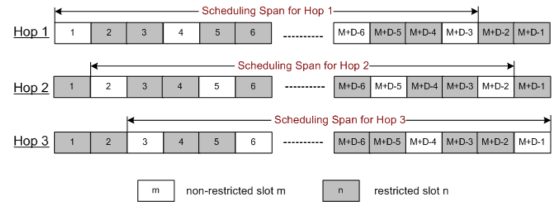


Fig. 2. TDM Mode for Multihop Transmission ($L = 3$).

performed at slot boundaries. Thus, there is a minimum one-slot delay per hop in the first $L-1$ slots, and subsequently, the end-to-end delay is larger than $L-1$ slots. To ensure feasibility, we need $D \geq L$.

C. Multihop Access Mode

We consider two types of orthogonal division multiplexing schemes. The first one is TDM, in which case at any point of time at most one node is transmitting and all nodes (source and relaying) have equal share of partial transmissions following a round-robin pattern, as illustrated in Fig. 2 for a 3-hop scenario, where slots are labeled with different colors indicating whether a slot is restricted for transmission or not. The length of the scheduling span (SS) ($i.e.$, the duration from the start of the first non-restricted slot till the end of the last non-restricted slot) is the same for any hop $l \in [1, \cdots, L]$. That is:

$$SS_{TDM}^{(l)} = \{l, \cdots, L(\lfloor (M+D-1)/L \rfloor - 1) + l\}. \quad (1)$$

where $\lfloor . \rfloor$ denotes the $floor(.)$ operation. Each hop is allowed to transmit during slots $[1, L+1, 2L+1, \cdots]$ *within its scheduling span* $SS_{TDM}^{(l)}$, $l = 1, \cdots, L$ (see Fig. 2). In other words, the transmission opportunities are hop-independent conditioned on $SS_{TDM}^{(l)}$. To characterize this conditional independence, we introduce an indicator vector $\vec{I}_{TDM}$ to indicate whether a slot is available for transmission (1) or not (0), $i.e.$,

$$\vec{I}_{TDM} = [1, \underbrace{0, \cdots, 0}_{L-1}, 1, \underbrace{0, \cdots, 0}_{L-1}, \cdots, 1, \underbrace{0, \cdots, 0}_{L-1}, 1], \quad (2)$$

It is easy to verify that the indicator vector $\vec{I}_{TDM}$ is symmetric, $i.e.$, $I_{TDM,i} = I_{TDM, L(\lfloor (M+D-1)/L \rfloor - 1)+2-i}$, $\forall i$. The combination of $SS_{TDM}^{(l)}$ and $\vec{I}_{TDM}$ completely characterizes the TDM access mode for all hops.

The second type of multiplexing is assumed to be FDM, in which resource orthogonality is achieved in the frequency domain. All nodes are allowed to transmit at any time. After incorporating the minimum one-slot per-hop delay, we have

$$SS_{FDM}^{(l)} = \{l, \cdots, M+D-1-L+l\}, \quad (3)$$

and

$$\vec{I}_{FDM} = [\underbrace{1, \cdots, 1}_{M+D-L}]. \quad (4)$$

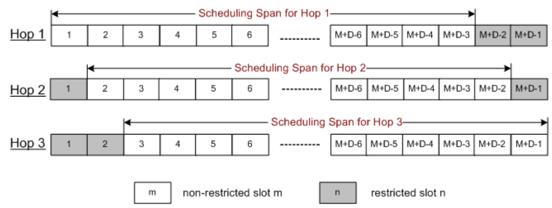


Fig. 3. FDM Mode for Multihop Transmission ($L = 3$).

III. Optimal Multihop Offline Scheduling

In this section, we start by presenting two key scheduling properties, which lead to the optimal offline schedule over a multihop link. Detailed proofs of some of the results can be found in [1].

A. Optimal Offline Schedule vs. Delay Constraints

Although we assume the same *end-to-end* individual packet delay constraint, the *per-hop* packet delay constraints in the L-hop link may not necessarily be the same. Also, due to the fluid packet departure model, the number of packets of distinct delay constraints may be different at different hops. Consider a general packet size vector $\vec{\tilde{B}}$ of an arbitrary length $\tilde{M} \geq 1$, associated with any delay constraint vector $\vec{\tilde{D}}$ of the same length $\tilde{M}$. It is intuitive that as the delay constraint $\vec{\tilde{D}}$ increases, the resulting optimal rate vector $\vec{r}(\vec{\tilde{B}}, \vec{\tilde{D}})$ should become no less energy-efficient. That is,

Claim 1: Given the same sets of packet arrivals $\vec{\tilde{B}}$ and transmission opportunities $\vec{I}$, the resulting optimal offline rate vector is no less energy-efficient when the delay constraints $\vec{\tilde{D}}$ increase :

$$e(\vec{\tilde{B}}, \vec{\tilde{D}} + \Delta\vec{\tilde{D}}) \leq e(\vec{\tilde{B}}, \vec{\tilde{D}}).$$

where $e(\vec{\tilde{B}}, \vec{\tilde{D}})$ denotes the total transmission energy associated with the rate vector $\vec{r}$ derived based on $\vec{\tilde{B}}$ and $\vec{\tilde{D}}$, and $\Delta\vec{\tilde{D}} \triangleq [\Delta\tilde{D}_1, \cdots, \Delta\tilde{D}_{\tilde{M}}]$, with $\Delta\tilde{D}_m \geq 0$, $\forall m$.

B. Maximum Possible Per-Hop and Total Energy-Efficiency

Recall that each of the first $L-1$ hops introduces at least a one-slot packet delay. Given an end-to-end delay constraint of D slots, any packet in any hop has a maximum delay constraint of $(D-L+1)$ slots, regardless of the scheduling algorithms in any of the other $L-1$ hops. In other words,

$$\vec{D}^{(l)} \leq (D-L+1)\vec{1}, \forall l,$$

where $\vec{1}$ is an all-ones vector of length $M^{(l)}$. From Claim 1, we have the following claim to characterize the maximum possible energy-efficiency at any hop and over all hops:

Claim 2: The total transmission energy expended by any hop l (denoted by $e^{(l)}(\vec{B}^{(l)}, \vec{D}^{(l)})$) is no less than the total energy expended by scheduling using the original packet arrival process $\vec{B}$ with an equal packet delay constraint of $(D-L+1)$ slots (denoted by $e^{(l)}(\vec{B}, (D-L+1)\vec{1})$), $i.e.$,

$$e^{(l)}(\vec{B}^{(l)}, \vec{D}^{(l)}) \geq e^{(l)}(\vec{B}, (D-L+1)\vec{1}), \forall l.$$

The total energy over all hops is thus always lower-bounded by $\sum_{l=1}^{L} e^{(l)}(\vec{B}, (D-L+1)\vec{1})$.

C. Optimal Offline Schedule for Individual Delay Constraints

Now consider a simple delay budget allocation scheme given by

$$[D-L+1, \underbrace{1, \cdots, 1}_{L-1}].$$

That is, scheduling is *only* done at the source node, while all the relaying nodes simply perform a buffer-clearing of all pending packets at each transmission opportunity. Obviously, the resulting optimal offline transmission rate vectors over all hops are the same, except for the deterministic right-shifts, $i.e.$,

$$\vec{r}^{(1)}(SS^{(1)}) = \vec{r}^{(2)}(SS^{(2)}) = \cdots = \vec{r}^{(L)}(SS^{(L)}). \quad (5)$$

where $SS^{(1)}$ is given by (1) or (3). We have:

Theorem 1: In an L hop link where all hops have the same time-shifted transmission opportunities, characterized by (1) and (2) for the TDM mode, and by (3) and (4) for the FDM mode, respectively, the optimal offline schedule under the individual delay constraint model is to perform the scheduling only at the source node, assuming an equal delay constraint of $D-L+1$ slots for all packets, while all the relaying nodes simply perform a buffer-clearing at each transmission opportunity.

Proof: Here we provide a sketch of the proof. For any single queue, the optimal offline transmission rate vector is independent of the energy function $w(r)$ (as long as it is strictly convex and monotonically increasing in r) [14][4]. On the other hand, from (5), under the simple delay budget allocation scheme, all hops have the same set of optimal transmission rates, which achieve the minimum per-hop energy expenditure and hence the the minimum possible total energy expenditure of $\sum_{l=1}^{L} e^{(l)}(\vec{B}, (D-L+1)\vec{1})$ (see Claim 2). ■

It is worth emphasizing that, similar to the single queue case [14][4], the optimality of the simple delay budget allocation scheme holds for any arrival processes. More importantly, the optimality of the above delay budget allocation for the multihop link is independent of $w^{(l)}(r)$, $\forall l$. In other words, the simple budget allocation scheme is optimal for any channel characteristics (*e.g.*, distances between the nodes, path loss exponents, *etc.*) associated with the multihop link.

Note that, under the optimal offline schedule, there is no need to propagate the time stamp information of any packets to any relaying nodes, which leads to a very simple design at the relaying nodes. The optimality of the simple delay budget allocation for the L-hop link is not surprising. The optimal offine schedule can be viewed as an equalization process [14][4]. Maximum possible equalization of traffic variations is achieved by the simple delay budget allocation.

D. Optimal Offline Scheduling for Single Transmission Deadline

The same derivation is also applicable to the single deadline model:

Theorem 2: In an L hop link where all hops have the same time-shifted transmission opportunities, the optimal offline schedule under the single transmission deadline model is to perform the scheduling only at the source node, assuming a common deadline of $(M+D-L)$ slots for all packets, while all the relaying nodes simply perform a buffer-clearing at each transmission opportunity.

E. Per-hop Optimal Offline Schedule

Under the optimal offline schedule over an L-hop link, all the hops have the same time-shifted optimal transmission rate vector, which are derived based on a delay constraint of $D^I \triangleq D-L+1$ slots and the indicator vector $\vec{I}$. The derivation similarly follows the procedure in [2][4][3] for the single-hop transmission, but differs by the potential existence of restricted slots not seen in the single hop case. The optimal transmission rate at slot m, $1 \le m \le M+D-1$, can be shown as

$$r_m^I = \begin{cases} \min_{m \le i \le M+D^I-1} r_{1[i]}^I & \text{if } I_m = 1, \\ 0 & \text{if } I_m = 0, \end{cases} \tag{6}$$

where $r_{1[i]}^I, i \in [m, \cdots, M+D^I-1]$ is given by

$$r_{1[i]}^I \tau_s = \max \left\{ \frac{U_m^I + \sum_{l=m}^{i} B_l}{\sum_{j=m}^{i} I_j}, U_{m,D^I-1}, \frac{U_{m,D^I-2}+U_{m,D^I-1}}{\sum_{j=m}^{\overline{(m+1)}} I_j}, \right.$$
$$\left. \cdots, \frac{\sum_{l=1}^{D^I-1} U_{m,l}}{\sum_{j=m}^{\overline{(m+D-2)}} I_j}, \frac{U_m^I + B_m}{\sum_{j=m}^{\overline{(m+D-1)}} I_j}, \cdots, \frac{U_m^I + \sum_{l=m}^{i-1} B_l}{\sum_{j=m}^{\overline{(i+D-2)}} I_j} \right\}, \tag{7}$$

where $\overline{x} \triangleq \min\{x, M+D^I-1\}$, $U_m^I \triangleq U_{m,1} + U_{m,2} + \cdots + U_{m,D^I-1}$ is the total buffer size before slot m, and $U_{m,i}$ denotes the number of buffered bits that arrived at slot $m-i$, which have a delay constraint of $D-i$, $1 \le i \le D-1$.

In the case of the *single transmission deadline model*, the optimal transmission rate at slot m can be simplified to

$$r_{single,m}^I \tau_s = \begin{cases} \min_{m \le i \le M} \frac{U_m^I + \sum_{l=m}^{i} B_l}{\sum_{j=m}^{i} I_j} & \text{if } I_m = 1, \\ 0 & \text{if } I_m = 0. \end{cases} \tag{8}$$

IV. Performance Analysis

In this section, we analyze the energy and delay performance of the optimal offline scheduler over the L-hop link.

A. Energy Saving Upper Bound

Herein we additionally assume the energy-rate function $w^{(l)}(r)$ for any hop $l \in [0, \cdots, L]$, is inversely proportional to the received SNR, $\gamma^{(l)}$. Also, conditioned on the same $\gamma^{(l)}$, we assume the energy-functions are the same for all hops as a function of r. Obviously, the minimum total transmission energy over all hops is achieved by a linear network with equi-distant nodes, in which $\gamma^{(1)} = \cdots = \gamma^{(L)} = L^\alpha$, where α is the path loss exponent.

On the other hand, regardless of the multihop access mode, due to a smaller delay constraint, the optimal offline transmission rate vector at any hop can not be more energy-efficient than that of the single-hop. In addition, regardless of the access mode, there are at least $L-1$ slots restricted from transmissions for any hop in the L-hop link. Thus, we can obtain the following energy-saving lower bound:

Theorem 3: Under the optimal offline scheduling, the total transmission energy consumed by all nodes in an L hop link is more than $L^{-\alpha+1}$ times of that for a single-hop transmission.

This lower bound holds for both delay constraint models.

B. Average Packet Delay Performance Comparison for the Individual Delay Constraint Model

A simple and exact closed form solution of the average packet delay performance was derived in [4][3] for the single-hop transmission, utilizing a symmetry property of the optimal offline transmission rate vector [1]. That is,

$$\bar{q}(M) = \tau_s \left[1 + \frac{M+1}{2M}(D-1) \right]. \tag{9}$$

where $\bar{q}(M) \triangleq E\{\frac{1}{M}\sum_{m=1}^{M} q_m\}$, and q_m is the delay (including queuing delay and transmission delay) experienced by packet m under the optimal offline schedule.

Under a symmetric $\vec{I}$, the symmetry property of the optimal transmission rate vector still holds [1]. However, due to the potential existence of restricted slots, the above symmetry property leads to lower and upper bounds of the average packet delay performance (proof omitted):

Theorem 4: For any $M \ge 1$ and $D^I \ge 1$, when the vector of packet sizes $[B_1, \cdots, B_M]$ has a joint probability distribution that is identical to that of $[B_M, \cdots, B_1]$, and when the indicator vector $\vec{I}$ is symmetric, under the optimal offline scheduling, the average packet delay $\bar{q}^I(M)$ is in the interval

$$\left[\tau_s \left(1 + \frac{M+1}{2M}(D^I-1) \right) - \delta, \tau_s \left(1 + \frac{M+1}{2M}(D^I-1) \right) \right], \tag{10}$$

where $\delta \triangleq \tau_s c_0/(2M)$ and c_0 is the total number of restricted slots. When $M \to \infty$, $\tau_s(D^I+1)/2 - \delta \le \bar{q}^I(\infty) \le \tau_s(D^I+1)/2$.
Note that when there are no restricted slots, *i.e.*, $c_0 = 0$, the lower bound and the upper bound are tight.

Therefore, under the FDM mode, the total end-to-end average packet delay for a L-hop link is:

$$\bar{q}^{FDM}(M) = \tau_s \left[1 + \frac{M+1}{2M}(D-L) \right] + \tau_s(L-1). \tag{11}$$

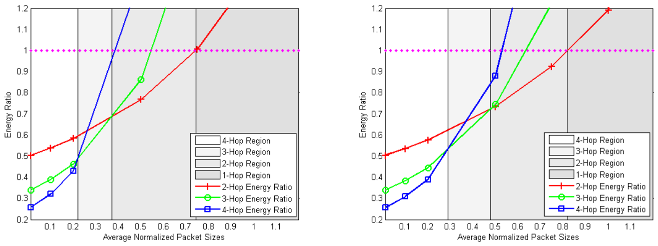
When $M \to \infty$, $\bar{q}^{FDM}(\infty) = \tau_s(D+L)/2$. Comparing with the single hop transmission (see (9)), we have $\Delta\bar{q}^{FDM}(M) \triangleq \bar{q}^{FDM}(M) - \bar{q}(M) = \tau_s(L-1)(M-1)/(2M) \ge 0$. In particular, $\Delta\bar{q}^{FDM}(\infty) = \tau_s\left(\frac{L-1}{2}\right)$.

Under the TDM mode, the lower bound of the average packet delay $\bar{q}^{TDM,LB}(M)$ can be obtained as

$$\tau_s \left[1 + \tfrac{M+1}{2M}(D-L) \right] + \tau_s(L-1) - \tau_s \tfrac{(M+D-L-1)(L-1)}{2LM}. \tag{12}$$

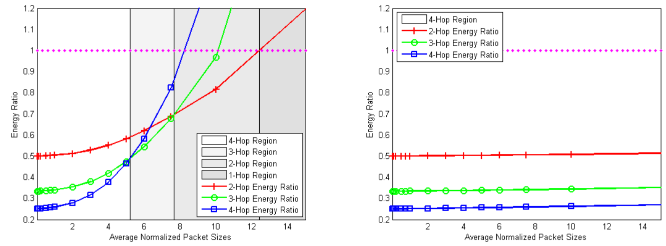
Similarly, we have $\Delta\bar{q}^{TDM,LB}(M) \triangleq \bar{q}^{TDM,LB}(M) - \bar{q}(M) = \tau_s \frac{(L-1)(LM-M-D+1)}{2LM} \ge 0$, which converges to $\tau_s(L-$

[1] That is, the optimal transmission rates r_m and r_{M+D-m} are identically distributed, when the vector of packet sizes $[B_1, \cdots, B_M]$ has a joint probability distribution that is identical to that of its reversed vector $[B_M, \cdots, B_1]$.



(a) D=9 (b) D=45

Fig. 4. Ratios of the total transmission energy of TDM multihop transmissions over the single-hop transmission.



(a) D=9 (b) D=45

Fig. 5. Ratios of total transmission energy of FDM multihop transmissions over the single-hop transmission.

$1)^2/(2L)$, when $M \to \infty$. The upper bound is simply $\bar{q}^{TDM,UB}(M) = \bar{q}^{FDM}(M)$.

Note that both the FDM and TDM modes result in an average end-to-end delay slightly larger than the single-hop link. When M is sufficiently large, the average delay increase is roughly by a ratio of $(L-1)/(D+1)$.

V. Numerical Results

The energy-rate function is assumed to be $w(r) = (2^{2r} - 1)L^{-\alpha}$, resulting from Shannon capacity, where $\alpha = 2$ and a linear network with equi-distant nodes is assumed. The packet sizes are normalized based on frequency bandwidth and slot duration and can be interpreted as the number of bits per channel use (or bandwidth efficiency), and are assumed to be random and follow an exponential distribution. The number of packets is fixed at $M = 1000$. We focus on the individual delay constraint model.

A. TDM Mode

Fig. 4 shows the ratios of the total transmission energy between TDM multihop transmissions (up to 4 hops) and the single-hop transmission as a function of the average normalized packet size, with $D = 9$ and $D = 45$. From Theorem 3, the lower bounds on the energy ratios are simply $L^{-\alpha+1} = 1/L$, where $\alpha = 2$, as can be observed. As the normalized packet size increases, it becomes preferable to use fewer hops. The regions corresponding to the optimal numbers of hops (vis-à-vis minimum total transmission energy) are also shown. Note that hopping-advantageous regions, regardless of D, are rather limited. This is due to the TDM operation, in which packets are forced to accumulate during restricted slots, which necessitates higher transmission rates during subsequent non-restricted slots.

B. FDM Mode

Fig. 5 shows the energy ratios for the FDM mode. In this case, even with a stringent delay constraint (D=9), multihop transmissions still provide energy savings over the single-hop transmission in reasonably large regions. In fact, when D is large (D=45), the 4-hop transmission always yields the least transmission energy even when the normalized packet size is as large as 15 (number of bits/channel use). Thus, from the traffic variation and energy-efficient scheduling perspective, it is preferable to not orthogonalize multihopping resources in the time domain, but rather in other domains such as frequency.

Acknowledgments

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