Lifetime-Throughput Tradeoff for Elastic Traffic in Multi-Hop Hotspot Networks[†]

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***Abstract*— Multi-hop hotspot networks consist typically of one or few wireless access nodes (ANs) and many self-organizing, self-coordinating, and battery-powered portable nodes (PNs). Nodes maintain cooperative connectivity among each other without any need for wired infrastructure. On one hand, because PNs are power-limited, efficient use of their available energy resources is crucial to their lifetimes. On the other hand, because higher rates of elastic flows provide higher QoS, it is desirable to maximize the throughput. Unfortunately, increasing lifetime and maximizing throughput are two conflicting objectives which cannot be optimized simultaneously. In this paper, we propose an extension of our early-presented scheme [1] to support elastic traffic routing in multi-hop hotspot networks. The proposed routing scheme strikes a balance between the need to keep the nodes operational with sufficient energy resources and the desire to allocate higher throughput to elastic flows. The proposed scheme also deals systematically with both objectives of maximizing the network lifetime and minimizing the total consumed energy.**

***Key words*—Network lifetime, throughput, elastic traffic, rate feasibility, multi-hop hotspot networks.**

I. INTRODUCTION

Hotspot networks have been emerging rapidly over the last few years. They are open-to-public wireless networks that provide data and Internet services in dense locations such as hotels and airports. Typically, these networks consist of one or few access nodes (known as access points) and many self-organizing and self-coordinating portable nodes (e.g., laptops). Nodes cooperatively maintain connectivity without any need for wired infrastructure. If a portable node (PN) is within a transmission range of an access node (AN), the PN communicates with the AN in a single-hop transmission. Otherwise, it communicates in a multi-hop transmission by relying on intermediate nodes to forward its traffic. Because these portable nodes are battery-powered, efficient use of their available energy is crucial to their lifetimes. As a result, energy aware routing protocols for such networks have been the focus of many studies [2–8]. One class of routing schemes is based on finding routes that minimize the total consumed energy [2, 5, 7]. Another class of schemes focuses on maximizing the lifetime of the network by avoiding routes with nodes having the least amount of available energy [8]. Some schemes formulate the routing problem as an optimization problem where the objective function is to optimize energy consumption either by minimizing the total used energy or maximizing the time until the first node runs out of energy resources [3, 4].

Even though these reported approaches reduce energy consumption, they all do not consider elastic flows. Since they consider only inelastic flows which are characterized by their required and stringent rates, routing solutions must satisfy such rates. However, not all traffic is inelastic. Unlike inelastic traffic, the QoS of elastic traffic such as web browsing and file transfer does not require such rate rigidity to meet quality of service needs. In fact, the QoS of elastic flows degrades gracefully when the achieved throughput is less than that desired, while higher throughput provides proportionally higher QoS. Therefore, from a throughput perspective, it is desirable to maximize the rates of elastic flows. Unfortunately, maximizing throughput and increasing lifetime are two conflicting objectives that cannot be achieved simultaneously.

In this paper, we propose an extension of our early-presented routing [1][1] approach to support elastic traffic in multi-hop hotspot networks. The proposed scheme strikes to balance between the need to prolong the network lifetime and the desire to allocate higher throughput to elastic flows. In addition, the proposed routing scheme deals systematically with both objectives of maximizing the minimum available energy—i.e., increasing the lifetime of the network—and minimizing the total energy consumption. Some of the existing solutions, however, deal with both objectives in an ad hoc fashion (e.g., [8]) based on a parameter that the designer must choose in advance.

This paper is organized as follows. In Section II, we present the network model. We propose the routing solution in Section III. In Section IV, we illustrate the proposed routing scheme by an example. Section V illustrates the features of the proposed scheme as opposed to those reported in the literature. Finally, we conclude the paper in Section VI.

II. MODEL

We model the hotspot network as a directed graph $G = (\mathcal{N}, \mathcal{F})$ of a finite nonempty set $\mathcal{N}$ of nodes and a set $\mathcal{F}$ of flows. Each flow f corresponds to an ordered pair of distinct nodes (n, m) such that m is within n's transmission range and n needs to transmit to m. The set $\mathcal{N}$ consists of one access node

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[1] The early-presented scheme is designed for inelastic traffic routing in sensor networks.

AN and many portable nodes PNs. The AN is connected to the external information infrastructure through a separate wired or wireless network. We assume that PNs interact with the external infrastructure only through the AN. If the AN is not within direct communication range of a PN, then the PN relies on other PNs to send its information to the AN. We only consider connected networks; that is, for each portable node PN there exists at least one path (a set of nodes) through which PN can communicate with the AN. We further assume that the traffic generated by the PNs is *elastic* and destined to the AN only, and no traffic is generated by the AN to the PNs. Let Q_i denote the desired rate[2] of the elastic traffic generated by portable node i.

III. ROUTING FOR ELASTIC TRAFFIC

Let $B_i(t)$ denote the energy resources available at node i for network communications at a given time instant t. Also, let ϵ_{ij} denote the energy required to transmit a bit from node i to node j. Let x_{ij} denote the number of bits per second forwarded by node i to a neighboring node j. Given the desired rate vector $Q = [Q_i]_{1 \leq i \leq |\mathcal{N}|}$, we aim at finding a routing solution that strikes a balance between the desire to allocate higher throughput to elastic flows and the need to keep the network operational for longer time. In the remainder of this section, we describe our routing approach.

A. Routing Constraints

Independent of the routing objectives, given the desired rate vector $Q = [Q_i]_{1 \leq i \leq |\mathcal{N}|}$ for elastic flows, the following set of constraints must be satisfied.

- FLOW BALANCE CONSTRAINTS:
  At each portable node, the total outgoing traffic rate must equal the sum of the incoming traffic rate and the traffic generated at the PN. For the AN, the total incoming traffic rate must equal the total traffic generated by all PNs. That is, for each node $i \in \mathcal{N}$,

$$\sum_{j \in \mathcal{N}} x_{ji} + \mu Q_i = \sum_{j \in \mathcal{N}} x_{ij} \quad i \neq AN \tag{1}$$

$$\sum_{j \in \mathcal{N}} x_{ji} = \sum_{j \in \mathcal{N}} \mu Q_j \quad i = AN \tag{2}$$

$$x_{ij} \geq 0 \quad j \in \mathcal{N} \tag{3}$$

$$\mu \geq 0, \tag{4}$$

  where the variable μ represents the fraction of the desired rate Q_i allocated to the elastic flow of node i. For example, when $\mu = 0.2$, the elastic flow of node i is allocated a rate of 20% of its desired rate Q_i. This variable also imposes fairness constraints by allocating throughputs to elastic flows in proportion to their desired rates Q_is. Without such fairness requirement, elastic flows from nodes closer to the AN will get greater share of the throughput at the expense of elastic flows from farther nodes. From a throughput perspective, the objective is then to maximize μ. However, larger values of μ imply greater energy consumption. One then has to carefully choose μ so that it balances between the desire to allocate higher rates to elastic flows and the need to maintain longer lifetimes of the nodes.
- ENERGY CONSUMPTION CONSTRAINTS:
  If node i has $B_i(t_0)$ amount of energy at a particular time t_0, then the remaining energy at any future time $t \geq t_0$ must be greater than or equal to zero. That is, for each portable node i,

$$B_i(t_0) \geq (t - t_0) \sum_{j \in \mathcal{N}} \epsilon_{ij} x_{ij}. \tag{5}$$

  We assume that the AN has an infinite amount of energy.
- MEDIUM CONTENTION CONSTRAINTS:
  The contention constraints on sharing the medium depend on the medium access control (MAC) protocol. For instance, in an IEEE 802.11 MAC protocol [9] based network, if node i is in communication with node j, then all nodes within the same transmission range of i or j cannot communicate. Let Ψ_{ij} denote the set of all ordered pairs of nodes that cannot communicate with each other as long as node i is transmitting to node j. Then, the rate vector $[x_{ij}]_{1 \leq i,j \leq |\mathcal{N}|}$ is feasible—it satisfies the medium access constraints—if for each ordered pair (i, j) of nodes the following medium contention constraints hold [10].

$$x_{ij} + \sum_{(p,q) \in \Psi_{ij}} x_{pq} \leq C. \tag{6}$$

  C is the maximum rate supported by the wireless medium.

B. Routing Formulation

Let t_0 be the initial time, and T be a time horizon over which the routing optimization is performed. The routing problem is to determine the values of x_{ij} subject to constraints (1)-(6) with the following conflicting objectives: (i) maximize the rate allocation to elastic flows, (ii) maximize the minimum available energy among all nodes at time $t_0 + T$, and (iii) minimize the total consumed energy by all the nodes over the period T. The first objective tries to achieve higher rate allocation. The second objective tends to increase the lifetime of the network[3] since the objective avoids finding routes with nodes having the least amount of available energy. The third objective, on the other hand, tends to conserve the overall energy.

We propose to divide the multiple objective routing problem into two optimization problems (OPs). In the first OP (OP-I), the objective function aims at balancing between higher rate allocation and lifetime maximization, and can be achieved by maximizing a utility function $\mathcal{U}$ of both the throughput and the

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[2] Hereafter, the terms rate and throughput—which both have the same meaning—will be used interchangeably.

[3] As defined in [3, 8], the lifetime of the network under rate vector x is the amount of time that runs out the first battery.

lifetime subject to constraints (1)-(6). In the second OP (OP-II), the objective function is to minimize the total consumed energy by all the nodes subject not only to constraints (1)-(6) but also to maintaining the maximum value of the objective function achieved by solving OP-I. Thus, the optimal solution to OP-II is also an optimal solution to OP-I. The idea here is that there are often multiple optimal solutions to OP-I which each corresponds to a data rate vector. If this is the case, OP-II chooses then from among these multiple rate vectors the one that optimizes the objective function of OP-II.

We introduce a fictitious variable, denoted λ, and add a new set of constraints that ensure that the energy available at each node after the network is operational for T seconds is at least λ. We call these constraints LIFETIME CONSTRAINTS. Formally, the LIFETIME CONSTRAINTS can be written as follows. For every portable node i,

$$\lambda \leq B_i(t_0) - T \sum_{j \in \mathcal{N}} \epsilon_{ij} x_{ij}. \tag{7}$$

Maximizing λ subject to constraints (1)-(7) can be shown [11] to be equivalent to maximizing the minimum available energy among all nodes at time $t = t_0 + T$ subject to constraints (1)-(6). We choose the utility function of OP-I to be[4]

$$\mathcal{U}(\lambda, \mu) = (1 - \alpha)\lambda + \alpha\, log(1 + \mu),$$

where the tunable parameter α, $0 \leq \alpha \leq 1$, characterizes the linear combination between longer lifetime utility and higher rate utility. For instance, if $\alpha = 0$, then OP-I maximizes the lifetime of the network, whereas if $\alpha = 1$, then OP-I maximizes the rates for the elastic traffic.

Therefore, OP-I can be expressed as:

Maximize $\mathcal{U}(\lambda, \mu)$
Subject to:
FLOW BALANCE CONSTRAINTS
ENERGY CONSUMPTION CONSTRAINTS
MEDIUM CONTENTION CONSTRAINTS
LIFETIME CONSTRAINTS

Let λ^* and μ^* be the maximal values respectively of λ and μ obtained from solving OP-I defined above. Then, OP-II can be stated as:

Maximize $\sum_{j \in \mathcal{N}, j \neq AN} B_j(t_0 + T)$
Subject to:
FLOW BALANCE CONSTRAINTS*
ENERGY CONSUMPTION CONSTRAINTS
MEDIUM CONTENTION CONSTRAINTS
LIFETIME CONSTRAINTS*

where FLOW BALANCE CONSTRAINTS* and LIFETIME CONSTRAINTS* are those used in OP-I, except the value of λ and μ are replaced by λ^* and μ^*, respectively. Note that the first set of constraints in OP-II enforces that the portion of desired rates of all nodes is above the optimal value μ^*; whereas the fourth set of constraints enforces that the available energy at all nodes at time $t = t_0 + T$ is above the optimal energy value λ^*. Hence, in the proposed two-level OP formulation, OP-I tries to balance lifetime maximization and higher rate allocation to the elastic traffic, whereas OP-II tries to minimize the overall energy consumption.

C. Routing Implementation

The data forwarding approach presented in this section is identical to that proposed in our early work [1], and provided here for completeness. We assume that the AN has an unlimited amount of energy, which is reasonable since typically the AN is connected to an accessible power-supplied infrastructure. Provided that the AN has a reliable power supply, it is responsible for most of the intensive computational processing such as solving OP-I and OP-II.

The AN first solves OP-I and OP-II. The optimal rate solution $\mathbf{x}$ obtained by solving OP-II is then sent to the portable nodes. Once a node i receives the rates from the AN, it forwards every packet to its neighbor j with a *packet forwarding probability*, p_{ij}, computed as

$$p_{ij} = \frac{x_{ij}}{\sum_{k \in \mathcal{A}_i} x_{ik}}$$

where $\mathcal{A}_i$ is the set of i's neighbors. This routing process is repeated every T seconds; that is, periodically, the AN solves the routing problem and sends the rates to all the nodes. Nodes use the rate solution to forward packets for the next T seconds. At the end of each optimization horizon T, each node sends its battery level information and its neighbor list to the AN which uses to determine the optimal rates for the next horizon.

There are two points worth noting. First, our routing approach assures that the rates provided by the optimal solution are met on the average. The instantaneous rates, however, may deviate considerably from the optimal rates. If T is sufficiently large, then the rates averaged over this horizon are likely to be close to the optimal rates. Second, since all the traffic is going to the AN, packets are forwarded to a given neighbor based only on the forwarding probability and not on the origin of the packets. This works perfectly so long as there is no packet looping during the routing process of the traffic. Packet looping occurs if packets could return to where they came from during the routing process, and results in packets never reaching the AN. The proposition below shows that the solution resulting out of OP-II is cycle-free[5], and thus the above forwarding scheme ensures that all the packets will reach the AN.

Proposition *1:* If $\mathbf{x}$ is an optimal solution to OP-II, then $\mathbf{x}$ is cycle-free [1].

IV. ILLUSTRATION OF THE ROUTING APPROACH

In this section, we illustrate the lifetime-throughput tradeoff of the proposed routing solution and the importance of the two-level optimization in the formulation. Hereafter, we assume that

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[4] Note that λ—the minimum remaining energy among all nodes—characterizes lifetime and μ—portion of the allocated rate—characterizes throughput.

[5] We use the traditional definition of cycles; i.e., x has a cycle if there exists a sequence $(n_1 n_2 \ldots n_k)$ of nodes in $\mathcal{N}$ such that $x_{k1} > 0$ and $x_{ii+1} > 0$ for $1 \leq i < k$.

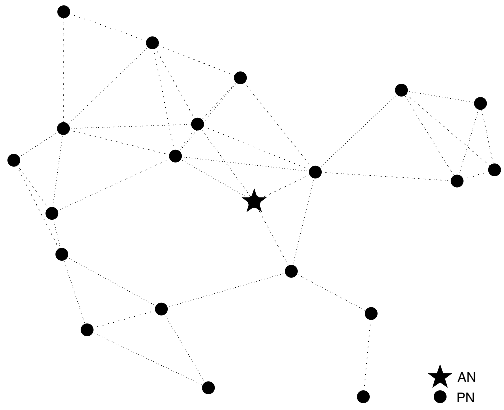


Fig. 1. Hotspot network.

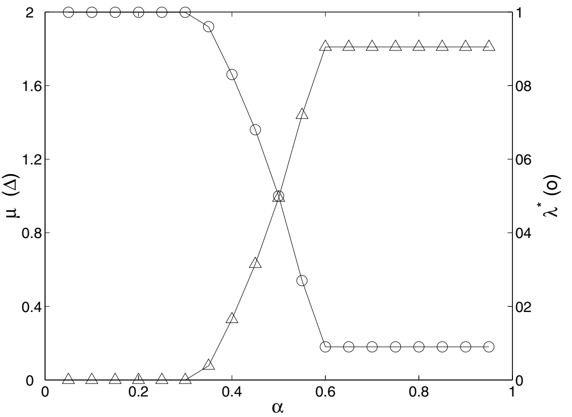


Fig. 2. Lifetime-throughput tradeoff.

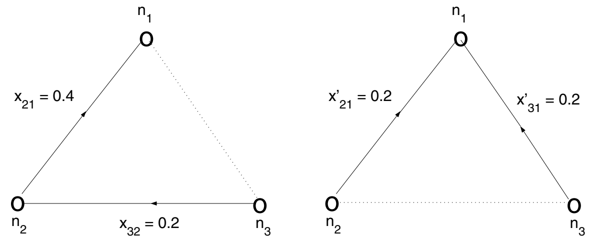
the capacity of the medium $C = 1$, $\epsilon_{ij} = 0.05$ Joules per bit for all i and j, and the optimization horizon $T = 100$ seconds.

A. Illustration of the Lifetime-Throughput Tradeoff

Consider the hotspot network shown in Fig. 1 consisting of one AN and 20 PNs. Let us assume that all PNs have elastic flow rates of 0.05 ($Q_i = 0.05 \forall i$) and battery levels of 1 ($B_i(0) = B = 1 \forall i$). To illustrate the lifetime-throughput tradeoff, we solve the proposed routing problem and collect λ^* and μ^* for different values of α. Fig. 2 shows λ^* (lifetime) and μ^* (throughput) as a function of α. First, note that when α is small, the optimal value of the utility function results in zero throughput and no energy consumption during which battery levels remain unchanged ($B = 1$). This is as expected since small values of α imply that rates are of no interest. Conversely, for large values of α (i.e., rates weigh more than battery), the reciprocal behavior is observed. In fact, the increase of μ^* and the decrease of λ^* occur rapidly as α increases from 0.4 to 0.6. It worth noting that the rates (or μ^*) increase sharply until they reach a threshold (around $\alpha = 0.6$) after which they remain the same. This observed upper bound results from the medium access constraints. In fact, it is not possible for the rates to be higher than that threshold because by doing so, they would violate the MEDIUM CONTENTION CONSTRAINTS. Now, since the rates are kept the same when α reaches 0.6, the battery levels remain unchanged as well. In summary, one can observe that lifetime and throughput are very sensitive to each other, and tradeoffs between them must be chosen carefully.

B. Illustration of the Two-level Routing Optimization

To illustrate the importance of two-level OP formulation, we consider a network of one access node n_1 and two portable nodes n_2 and n_3, as shown in Fig. 3, where all the nodes are neighbors of each other. Assume that the elastic flow rates Q_2 and Q_3 of n_2 and n_3 are both equal to 0.2, and the battery values of n_2 and n_3 are respectively equal to $B_2 = 2$ and $B_3 = 1$. For simplicity of illustration, consider $\alpha = 1$ (the analysis is also valid for $\alpha \neq 1$). The rate vector $\mathbf{x}$, shown in Fig. 3(a), where $x_{32} = 0.2$, $x_{21} = 0.4$, and $x_{ij} = 0$ otherwise is a solution to OP-I (with $\lambda^* = 0$ and $\mu^* = 1$). The rate solution $\mathbf{x}'$ of OP-II is shown in Fig. 3(b) and such that $x'_{21} = x'_{31} = 0.2$, and $x_{ij} = 0$ otherwise. Note that both $\mathbf{x}$ and $\mathbf{x}'$ are optimal solutions to OP-I since they both achieve the same optimal values of $\lambda^* = 0$ and $\mu^* = 1$, and both result in a network lifetime of 100 seconds and a throughput of 0.2 for each node. However, observe that $\mathbf{x}'$ consumes less total energy ($= (0.2 + 0.2) \times 100 \times 0.05 = 2$ Joules) than that consumed by $\mathbf{x}$ ($= (0.4 + 0.2) \times 100 \times 0.05 = 3$ Joules). In fact, if we route the traffic using the rate vector $\mathbf{x}$, all nodes die simultaneously after 100 seconds. Alternatively, routing with $\mathbf{x}'$ also takes 100 seconds for the first node, n_3, to die, but node n_2 will be left with a battery of 1 Joule worth of energy which keeps it alive for another 100 seconds. Thus, the proposed two-level OP formulation yields to an optimal solution that minimizes the total consumed energy while achieving an optimal lifetime-throughput tradeoff.



(a) Solution to OP-I. (b) Solution to OP-II.

Fig. 3. Rate solutions for the illustrative example.

V. FEATURES OF THE PROPOSED ROUTING FORMULATION

The proposed routing scheme has four distinguishing features. First, the proposed scheme considers elastic flows. In our formulation, by maximizing a utility function of λ and μ, we can achieve a balance between higher data rates for elastic traffic and longer lifetime of the network while maintaining the overall energy consumption as low as possible. The proposed routing approach as described in Section III focuses on dealing with elastic traffic. Depending on α, optimal rate solutions could be zero or close to zero (as illustrated in the example in Subsection IV-A). To prevent this from happening, one could impose a nonnegative lower bound on μ by means of Equation 4 that guarantees that rate solutions are above certain thresholds. In fact, these thresholds could be thought of as inelastic traffic, and thus the scheme could be easily extended to mixed traffic: inelastic and elastic.

Second, the proposed formulation incorporates multiple access constraints whereas those reported in the literature (e.g., [3, 4]) do not consider them. If one does not account for the multiple access nature of the wireless medium, the resulting solution may not be feasible [10]. That is, the medium will likely not be able to support the net data rate needed to deal with all the traffic flows routed through some spatial neighborhoods. When this happens, the packet queues at the corresponding nodes will grow and there will be either larger delays or packet losses, both of which result in violation of QoS requirements.

Third, the proposed formulation consistently deals with both objectives of maximizing the minimum available energy (lifetime) and minimizing the total consumed energy. It is well known in literature that there is need for dealing with both of these objectives. However, the existing solutions deal with these two objectives in an ad hoc fashion. For example, the solution provided in [8] switches between these two objectives based on a parameter that a designer must choose a priori. Our solution does not require such a design parameter, thus alleviating the problem of a priori choice.

Fourth, our packet forwarding scheme makes the proposed scheme suitable and more practical for networks where nodes must transition between Active, Idle, and Sleep modes to save energy. It is shown [12, 13] that Idle nodes (nodes which neither transmit nor receive) consume a significant amount of energy; in fact, the amount of consumed energy is almost as high as that consumed by nodes in Receive (Active) mode. As a result, to conserve energy, it is important to put nodes in Sleep mode rather than in Idle mode whenever they are neither transmitting nor receiving. Therefore, power aware routing schemes should be suitable and efficient for such Active-Idle-Sleep networks. If nodes are allowed to sleep as in these networks, then the reported routing schemes require a coordination mechanism by which they are able to discriminate between nodes that are in Sleep mode and those that are not. Such mechanism adds complexity and restriction to the routing algorithm. For example, if a node of a given path transitions to Sleep mode, most of the reported routing approaches (e.g., [8]) need to rerun their algorithms to find new paths. Our approach does not require such extra re-computation, and is not concerned with the extra complexity added by the sleep-awareness mechanism. To satisfy the rate solution, nodes often need to forward their traffic to more than one neighbor with different packet forwarding probabilities. Therefore, nodes can manage locally to send more data (higher rate) to one neighbor while the other neighbor is sleeping. When the sleeping node transitions back to Active mode, then the sending node can transmit at higher rate to that recently awakened node. This is managed so that the overall average rates are equal to the optimal rates. Hence, the proposed scheme requires only local coordination between nodes and their direct neighbors. Note that, as we show in Proposition 1, the proposed energy aware routing solution is cycle-free. This guarantees that all traffic eventually will reach the access point without looping. Our proposed solution does not require any cooperation between the sleep-aware mechanism and the routing algorithm. In addition, there is no need to recompute the routing solution (e.g., paths) when one or more nodes transition to Sleep mode. This feature becomes significantly important in dense networks where the Active-Idle-Sleep power saving technique is essential to consider since putting some nodes asleep can be achieved without loosing connectivity.

VI. CONCLUSION

In this paper, we propose a routing approach for elastic traffic in multi-hop hotspot networks. The proposed routing scheme strikes a balance between the need to prolong network lifetime and the desire to allocate higher throughput to elastic flows. The proposed scheme also deals systematically with both objectives of maximizing the network lifetime and minimizing the total consumed energy. By an illustrative example, we show the sensitivity of lifetime-throughput tradeoffs and demonstrate the importance of the two-level formulation on energy savings.

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