Impact of Lossy Links on Performance of Multihop Wireless Networks

Yuxi Li Janelle Harms Robert Holte
Department of Computing Science, University of Alberta, Edmonton, AB, Canada T6G 2E8
{yuxi, harms, holte}@cs.ualberta.ca

***Abstract*— Multihop wireless networks have unique features such as lossy links and interference. Both interference and lossy links affect the maximum achievable throughput of a network. Some wireless networks have energy constraints. Lossy links also affect energy efficiency due to retransmissions and broadcasting. We investigate the impact of lossy links on maximum achievable throughput and minimax energy utilization. These can be modeled as linear programming optimization problems. We give optimal solutions for both flow-based and destination-based routing. Experiments show that lossy links do have significant impact on the maximum achievable throughput. There are cases where a network can only achieve half of the throughput of the corresponding lossless network. The results show less significant impact of loss on energy efficiency. In some cases, the loss may be advantageous for energy efficiency, since the energy consumption may be reduced due to the loss of broadcasting messages. Experiments also show the significant impact of overhearing on energy efficiency.**

I. INTRODUCTION

Research in multihop wireless networks, such as wireless ad hoc networks, wireless sensor networks and wireless community mesh networks, has drawn much attention recently. A critical problem is to characterize the achievable throughput. When the energy source is costly or there are energy constraints, energy efficiency is a paramount issue.

The seminal paper by Gupta and Kumar [8] gives asymptotic bounds on the throughput of multihop wireless networks. Recently researchers have investigated the achievable throughput in given wireless networks. Kodialam and Nandagopal [12] study the achievable throughput for the “free of secondary interference” model [3], where a node can transmit to or receive from at most one node. Necessary and sufficient conditions are derived. Jain et al. [10] use a conflict graph to model the interference relationship between links and investigate lower and upper bounds of achievable network flow.

Previous work on energy efficiency has made great progress. Singh et al. [16] propose several routing metrics and study their performance through simulation. The problem of maximizing the lifetime of a wireless ad hoc network with energy constraints is studied in [4], [13], where the lifetime is defined as the length of the time until the first node drains out its energy. It assumes every node is important. Kar et al. [11] investigate how to route the maximal number of messages in wireless ad hoc networks with energy constraints. Lin et al. [15] study power-aware routing with renewable energy sources. Ephremides gives an overview on energy concerns in [7].

With knowledge of the traffic pattern, the problem of maximum achievable throughput or maximum lifetime can be modeled as an optimization problem using network flow [2]. The traffic pattern of a wireless network may be known a priori in some applications, such as in a wireless sensor network in which sensors periodically report weather information.

There is previous work, such as [5] and [6], that propose heuristic link metrics to attempt to accommodate loss. However, in the previous work to optimize either achievable throughput or energy efficiency, little has been done to consider lossy links. In this paper, we investigate the impact of lossy links on achievable throughput and energy efficiency in multihop wireless networks. We give LP formulations to compute respectively the maximum achievable throughput and the minimax energy utilization. Energy utilization of a node is the energy consumption divided by the initial energy level. Empirical results show that loss has significant impact on the achievable throughput. The loss affects the energy efficiency. In several studied cases, the lifetime can be longer when loss is considered. Briefly, the energy consumption saved for overhearing the broadcast messages may be greater than the energy waste for retransmissions in a lossy network.

The LP models are general enough for several radio transmission models, such as omni-directional and directional antennas and a radio equipped with various possible granularities of transmission power levels. It can also work with a multi-channel and/or multi-radio wireless system.

We present illustrative examples in Section II. In Section III, we give an LP model that maximizes achievable throughput, which is a straightforward extension of the LP model in a wired network. In Sections III-A and III-B, we present how to express concerns about lossy links and interference as linear constraints. We give the LP to compute the maximum achievable throughput in Section III-C. In Section III-D, we present how to express linear energy constraints. Then we give the LP to optimize energy efficiency in Section III-E. In Section III-F, we give the LP formulation for destination-based routing. We study the impact of loss empirically in Section IV. Then we draw conclusions.

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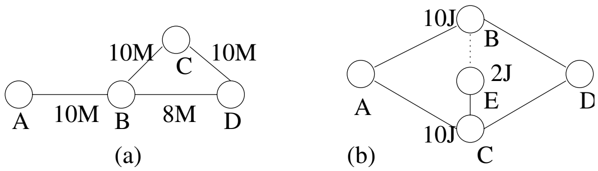

Fig. 1. Toy Examples

II. Illustrative Examples

We present two simple examples to illustrate the impact of lossy links. Suppose the network operates on a single channel. Consider the free of secondary interference model, where a node can transmit to or receive from at most one node.

In Figure 1(a), a maximum throughput of $5Mbps$ is achievable from A to D on path $ABCD$, by simultaneously activating edges (A, B) and (C, D). Consider that edge (B, C) has loss rate 50%. In this case, path $ABCD$ can only achieve a throughput of $2.5Mbps$. Path ABD is preferable now, which can achieve a throughput of $4Mbps$. Because edges (B, C), (C, D) and (B, D) can't be active at the same time, routing on both paths $ABCD$ and ABD won't increase the throughput. This simple example shows that lossy links may affect both the maximum achievable throughput and the routing.

On the topology in Figure 1(b), we are to transmit $3Mbps$ data between A and D. Every link has $10Mbps$ bandwidth. Nodes B, C, E have initial energy of $10J$, $10J$ and $2J$, respectively. Suppose one unit of transmission, reception and overhearing at nodes B and C consumes one unit of energy, and nodes A and D have infinite amount of energy. First assume links are lossless. Edge set $\{(A, B), (C, D)\}$ and edge set $\{(A, C), (B, D)\}$ can be active simultaneously. Because of the overhearing at node E from both B and C, any routing of $3Mbps$ on paths ABD and ACD achieves the minimax energy utilization, resulting in a lifetime[1] of $\frac{2}{3}$. Now suppose edge (B, E) has 100% loss rate and the other edges are lossless. An optimal routing to minimax energy utilization (thus to maximize lifetime) is to assign $2Mbps$ to path ABD and $1Mbps$ to ACD. This yields a lifetime of 2, which is longer than $\frac{2}{3}$. This simple example shows the impact of lossy links on energy efficiency and routing. The lifetime can be longer in a lossy network, where some broadcast packets are lost. Longer lifetimes are also achieved in several cases in the experiments as will be shown in Section IV.

III. Optimal Routing With Lossy Links

We first discuss the network model used in this paper. A stationary multihop wireless network can be abstracted as a digraph $G = (V, E)$, where V is the set of wireless nodes and E is the set of "edges". There is an edge (u, v) if node u can reach node v. We assume the digraph is strongly connected. An edge has a bandwidth $c(s, t)$, i.e., the data rate it can support. We assume stationary channel conditions, e.g. an additive white Gaussian noise (AWGN) channel with constant noise power. We assume a transmitting node uses a fixed modulation scheme. We denote the set of neighbors of a node u as $nbr(u)$, i.e., $nbr(u) = \{v|(u, v) \in E\}$. For a neighbor v of u, we define $nbr(v, -u) = \{w|w \in nbr(v), w \neq u\}$. That is, $nbr(v, -u)$ denotes the set of neighbors of node v, a neighbor of node u, excluding node u.

In this paper, we keep the notation *traffic matrix* (TM) as in the literature of the Internet traffic engineering. Denoting the number of nodes as n, a traffic matrix is an $n \times n$ nonnegative matrix where the diagonal entries are 0. A traffic matrix provides the amount of traffic between each Origin-Destination (OD) pair over a certain time interval, with an entry d_{ij} for OD pair $i \to j$. It characterizes the traffic pattern in an average sense.

In the scenario of wired networks, given a traffic matrix, the optimal routing to determine the fraction of traffic α that is achievable is solvable as a LP multi-commodity flow problem [2]. We use $g_{ij}(u, v)$ to denote the flow for OD pair $i \to j$ on edge (u, v). In network flow, we have flow conservation constraints (1), link capacity constraints (2) and flow non-negative constraints (3). In (1), α is the maximum throughput fraction. It characterizes the achievable flow rates, as will be clear in LP (4).

$$\begin{cases} \forall \text{ pairs } i \to j, k \neq i, j: \\ \quad \sum_{(k,u) \in out(k)} g_{ij}(k, u) - \sum_{(v,k) \in in(k)} g_{ij}(v, k) = 0 \\ \forall \text{ pairs } i \to j: \\ \quad \sum_{(i,t) \in out(i)} g_{ij}(i, t) = \alpha d_{ij} \end{cases} \tag{1}$$

$$\forall \text{ edges } (u, v): \quad \sum_{i,j} g_{ij}(u, v) \leq c(u, v) \tag{2}$$

$$\forall \text{ pairs } i \to j, \forall \text{ edges } (u, v): \quad g_{ij}(u, v) \geq 0 \tag{3}$$

In the above, $in(k)$ and $out(k)$ denote the sets of edges "into" and "out of" node k respectively.

The LP to maximize the achievable fraction is:

$$\begin{array}{l} \max \alpha \\ \text{Subject to: Constraints (1), (2) and (3).} \end{array} \tag{4}$$

This is a concurrent multicommodity flow problem. It computes the maximum "fraction" of the traffic demand matrix that can be accommodated by the network.

LP (4) obtains the maximum throughput given the desired traffic demand d_{ij}'s. Network throughput can also be defined as the sum of the traffic of all OD pairs. In this case, d_{ij}'s are variables to be determined. This approach tends to favor OD pairs of which the origin and the destination are close to each other. Thus, this may pose a fairness issue, as it may be preferable to transmit the same proportion of data for all OD pairs. Thus in the following we focus on LP models based on LP (4), which implicitly considers this fairness issue.

Wireless networks have unique features, such as lossy links, interference and energy constraints. In the following, we present how to express concerns about lossy links and interference as linear constraints. Then we discuss how to maximize achievable throughput and to optimize energy efficiency with these constraints.

[1] We use the definition of lifetime as until the first node dies. Its validity, as shown in this example where a node not on a transmission path dies first, is an interesting question. Redefinition of lifetime is worth further investigation.

A. Lossy Links

Most previous work based on a LP model, e.g., [4], [13] implicitly assumes the wireless links are lossless. Loss may be ignored in wired networks when formulating a LP network flow model. This may not be the case in wireless networks. A wireless link is usually lossy and some applications need reliable transmission. As a consequence, a packet may require several transmissions. Thus modifications need to be made to the usual flow conservation constraints, by considering some link loss factor, which measures the average number of transmissions needed to successfully transmit a packet on the link. We assume there is a link loss factor $\gamma_{ij} \geq 1$ for each edge (i, j). This link loss factor characterizes the quality of the transmission channel. The loss may result from multi-path fading, attenuation, etc. We will assume a synchronized slotted system in an interference-limited environment, as will be clear in Section III-B. Interference is thus not a factor for the loss. We assume a loss happens in the transmission medium. That is, after the sender transmits a packet, it may get lost or not. If the packet is lost, the receiver and the neighboring nodes can not hear it at all. With the link loss factor, we have linear flow conservation constraints:

$$\begin{cases} \forall \text{ pairs } i \to j: \\ \quad \sum_{(i,t)\in out(i)} \frac{g_{ij}(i,t)}{\gamma_{it}} = \alpha d_{ij} \\ \forall \text{ pairs } i \to j, k \neq i, j: \\ \quad \sum_{(k,u)\in out(k)} \frac{g_{ij}(k,u)}{\gamma_{ku}} - \sum_{(v,k)\in in(k)} \frac{g_{ij}(v,k)}{\gamma_{vk}} = 0 \end{cases} \tag{5}$$

As before, $g_{ij}(u, v)$ denotes the actual flow for OD pair $i \to j$ on edge (u, v); while $\frac{g_{ij}(u,v)}{\gamma_{uv}}$ denotes the effective flow.

B. Interference Concerns

In an interference-limited wireless network, it is necessary to consider schedulability of a routing.

The free of secondary interference model [3] receives considerable attention. Kodialam and Nandagopal [12] give necessary and sufficient conditions of schedulability. These conditions are expressed as linear constraints over the flows and data rate on neighboring edges of a node. The necessary and sufficient conditions can be expressed as follows for each node s when β takes the values of 1 and $\frac{2}{3}$ respectively:

$$\sum_{t\in nbr(s)} \{ \frac{\sum_{i,j} g_{ij}(s,t)}{c(s,t)} + \frac{\sum_{i,j} g_{ij}(t,s)}{c(t,s)} \} \leq \beta. \tag{6}$$

Here $c(s, t)$ denotes the data rate the edge (s, t) can support. Because of their linearity, we can add the set of constraints for the necessary or sufficient condition in our LP models. We can guarantee the schedulability of the routing by stipulating the sufficient condition. Then the scheduling problem can be solved as a graph-coloring problem [12].

Jain et al. [10] use a conflict graph to model interference relationship between links. In the conflict graph, a vertex represents a link in the connectivity graph. There is an edge between two vertices in the conflict graph, if the two corresponding links in the connectivity graph interfere with each other. They consider two interference models. In the protocol interference model, a transmission is successful if the receiver is within the transmission range of the transmitter and any node within its interference range does not transmit. In the physical interference model, a transmission is successful if the signal-to-noise ratio (SNR) at the receiver exceeds a threshold, where SNR is determined by the ambient noise of the receiving node and the interference due to other ongoing transmissions. They study the lower and upper bounds on the achievable throughput. For the lower bound, independent sets (in which there is no edge for any two vertices) in the conflict graph are used to add constraints to the space of the feasible network flows so that the resulting flow is schedulable. Although it is hard to obtain all the independent sets to make the lower bound tight, the bound gets tighter with more independent sets [10]. More recently, Wu et. al. [18] use elementary capacity graphs to characterize achievable throughput.

We demonstrate how to express linear schedulability constraints for the protocol interference model based on the derivation of lower bound of the throughput in Jain et al. [10]. Linear schedulability constraints for the physical interference model can be developed similarly. We first find K maximum independent sets, $I_i, 1 \leq i \leq K$. Let λ_i denote the fraction of time allocated to independent set I_i.

$$\begin{array}{l} \sum_{i=1}^{K} \lambda_i \leq 1 \\ \sum_{i,j} g_{ij}(s,t) \leq \sum_{(s,t)\in I_i} \lambda_i c(s,t) \end{array} \tag{7}$$

Here $c(s, t)$ denotes the data rate the edge (s, t) can support. The first constraint requires that only one independent set can be active at a time. The second requires that the flow can not exceed the convex combination of edge capacities in the independent sets. Once we solve the LP, we obtain the λ_i's. A scheduling can be constructed on the K independent sets according to their fractions λ_i's of activation. Thus we achieve a schedulable routing.

The 802.11 protocol uses Request to Send (RTS) and Clear to Send (CTS) to establish interference-free, reliable connection between two nodes. For this interference model, the above discussion based on Jain et al. [10] is still applicable.

C. Maximum Achievable Throughput

In the above, we discuss issues about lossy links and interference in wireless networks. In a lossy environment, we use (5) to reflect the impact of loss. In an interference-limited scenario, we add linear constraints (6) or (7) to guarantee schedulability of the routing. Thus the LP to optimize an achievable throughput with the presence of lossy links and interference in multihop wireless networks is:

$$\begin{array}{l} \max \alpha \\ \text{Subject to: Constraints (5), (2), (6 or 7) and (3).} \end{array} \tag{8}$$

The LP model can handle any combination of the presence of lossy links and interference. With the assumption of a lossless network, we set $\gamma_{uv} = 1, \forall \text{edge } (u, v)$, in (5). When interference is not a (severe) problem, we remove the set of constraints (6 or 7).

The LP model is general enough for a wireless system with multi-channel and multi-radio. In this case there will be multiple edges between a pair of nodes in a graph representation.

The LP models still work on this multigraph. The channels operated by a radio usually interfere with each other. But there is no interference among channels operated by multiple radios orthogonal with each other. The work to handle interference in Kodialam and Nandagopal [12] and Jain et al. [10] are applicable here. The LP models are thus extensible to a multi-input multi-output (MIMO) system.

D. Energy Concerns

In some scenarios, energy constraints may be an issue. When some nodes run out of energy, a previous achievable throughput may not still be achievable. It is necessary to balance load and energy consumption. We first discuss the energy consumption model. Now each node u has an initial energy level $pow(u)$.

Energy Consumption Model. The energy consumption to transmit a unit amount of data from node u to node v is $tx(u,v)$. Usually $tx(u,v)$ depends on the distance between u and v. The amount of energy consumption in transmission is proportional to the amount of data to be transmitted. This linear model is used in previous work on energy efficiency, e.g. [4], [9], [11], [13].

We use $r(u)$ and $h(u)$ to model the energy consumption of node u to receive and to overhear a unit of data respectively. Overhearing means a node receives a packet not addressed to it. We separate reception and overhearing since they may consume different amounts of energy. For instance, a node may overhear the whole data packet or only the preamble before discarding it. In the former case, overhearing consumes a comparable amount of energy to reception; while in the latter overhearing may consume much less energy. The energy consumption for processing data may be a component of the transmission model and the reception model, thus we do not model it explicitly. The overhearing may be avoided in a slotted system, by switching to idle mode. However, switching between idle and active modes consumes energy. We take a simplistic approach to model the overhearing energy consumption as $h(u)$, which can be 0 if there is no overhearing.

The energy consumption of node s for d_{ij} is,

$$\begin{aligned}\text{energy}_s(i,j) &= \textstyle\sum_{t\in nbr(s)}\{g_{ij}(s,t)tx(s,t)\}\\ &+ \textstyle\sum_{t\in nbr(s)}\{g_{ij}(t,s)r(s)\}\\ &+ \textstyle\sum_{t\in nbr(s)}\sum_{k\in nbr(t,-s)}\{I_{(t,s)}^{(t,k)}g_{ij}(t,k)h(s)\}\end{aligned}$$

$I_{(t,s)}^{(t,k)}$ is an indicator function defined as,

$$I_{(t,s)}^{(t,k)} = \begin{cases} 1 & \text{if } s \text{ can overhear transmission from } t \text{ to } k;\\ 0 & \text{otherwise.}\end{cases}$$

The first term in $\text{energy}_s(i)$ is the energy consumption for transmission, the second for reception and the third for overhearing. We use $I_{(t,s)}^{(t,k)}$ to indicate that if node s is within the transmission range of the transmission from t to k, s can overhear the transmission and consumes energy for the overhearing. The total energy consumption for node s is,

$$\textbf{energy}_s = \sum_{i,j}\text{energy}_s(i,j).$$

Lossy links. The energy consumption model needs to change in a lossy environment. $g_{ij}(u,v)$ denotes the actual flow originating for OD pair $i \to j$ on edge (u,v). Thus there is no change for the term for transmission. For reception, node s receives one copy out of γ_{ts} transmissions from t to s. For overhearing, node s receives one copy out of γ_{ts} transmissions from t to k. Thus, with lossy links, the energy consumption of node s for d_{ij} is,

$$\begin{aligned}\text{energy}_s(i,j) &= \textstyle\sum_{t\in nbr(s)}\{g_{ij}(s,t)tx(s,t)\}\\ &+ \textstyle\sum_{t\in nbr(s)}\{\frac{g_{ij}(t,s)}{\gamma_{ts}}r(s)\}\\ &+ \textstyle\sum_{t\in nbr(s)}\sum_{k\in nbr(t,-s)}\{I_{(t,s)}^{(t,k)}\frac{g_{ij}(t,k)}{\gamma_{ts}}h(s)\}\end{aligned}$$

Generalization. The energy model is general enough to take into account several issues in radio transmission. By properly defining the indicator function, we can handle the case in which a node can vary its transmission range with arbitrary precision, at several discrete levels, or with a fixed transmission range. Note a node may transmit on different links with different power; but the power on a link is constant.

As well, we can handle the radio irregularity problem studied recently, e.g. in [17], that a radio has different maximum transmission ranges in different directions. This affects the neighborhood relationship. The energy model can be used for wireless communications using either an omni-directional antenna or a directional antenna.

E. Maximum Lifetime

We introduce a performance metric, *maximum energy utilization*, $\max_s \frac{\textbf{energy}_s}{pow(s)}$, where $pow(s)$ is the initial energy level of node s. The lifetime of a wireless network is inversely proportional to the energy consumption rate of the node that consumes energy the fastest. When we minimize the maximum energy utilization, we maximize the lifetime of the wireless network.

We have flow conservation constraints, without α in contrast to (5):

$$\begin{cases}\forall \text{ pairs } i\to j:\\ \quad \sum_{(i,t)\in out(i)}\frac{g_{ij}(i,t)}{\gamma_{it}} = d_{ij}\\ \forall \text{ pairs } i\to j, k\neq i,j:\\ \quad \sum_{(k,u)\in out(k)}\frac{g_{ij}(k,u)}{\gamma_{ku}} - \sum_{(v,k)\in in(k)}\frac{g_{ij}(v,k)}{\gamma_{vk}} = 0\end{cases} \tag{9}$$

For a given traffic matrix (assume it is achievable, otherwise we can compute the achievable traffic demand using LP(8)), the following LP gives an optimal routing that minimizes the maximum energy utilization:

$$\begin{aligned}&\min u\\ &\forall \text{nodes } s: \frac{\sum_{i,j}\text{energy}_s(i,j)}{pow(s)} \le u\\ &\text{Constraints (9), (2), (6 or 7) and (3).}\end{aligned} \tag{10}$$

F. Destination-based Routing

The previous LP models are flow based, i.e., a routing decision considers both the origin and the destination. In some applications, it is preferable to use destination-based routing, where a routing decision considers only the destination. Compared with the flow-based routing, the complexity of the LP and the size of the routing table are both reduced by n-fold, where n is the number of nodes. We give the LP formulation for maximizing achievable throughput directly as follows. Destination-based routing for the problem of maximum lifetime can be formulated similarly.

$$
\begin{array}{l}
\max\ \alpha \\
\forall \text{ pairs } i \to j, \text{nodes } k: \\
\quad \sum_{(k,u)\in out(k)} \frac{g_j(k,u)}{\gamma_{ku}} - \sum_{(v,k)\in in(k)} \frac{g_j(v,k)}{\gamma_{ku}} - \alpha d_{kj} = 0 \\
\forall \text{ edges } (u,v): \\
\quad \sum_j g_j(u,v) \leq c(u,v) \\
\forall \text{nodes } s: \\
\quad \sum_{t\in nbr(s)} \{ \frac{\sum_j g_j(s,t)}{c(s,t)} + \frac{\sum_j g_j(t,s)}{c(t,s)} \} \leq \beta \\
\forall \text{ pairs } i \to j, \forall \text{ edges } (u,v): \\
\quad g_j(u,v) \geq 0
\end{array}
\qquad (11)
$$

In LP (11), $g_j(u,v)$ denotes the flow for destination j on edge (u,v). It is an aggregate flow of all OD pairs destined to j. The first set of constraints are flow conservation constraints and the second set are link capacity constraints. The third set of constraints express the necessary or sufficient conditions (by taking β as 1 or $\frac{2}{3}$ respectively) for schedulability of the routing, based on the work in Kodialam and Nandagopal [12].

IV. Performance Study

We study the impact of lossy links on the maximum achievable throughput and the maximum lifetime on random topologies. We put nodes on a $k \times k$ grid, each cell of which represents a $10m \times 10m$ area. In each cell of the grid, we put a node at a random position. The bandwidth of each edge is set randomly, uniformly within $[10, 20]Mbps$. Suppose omni-directional antennas are used. For brevity, we use a disk model for radio transmission. That is, suppose the maximum transmission range of node u is R_{max}, there is an edge (u,v) if $R_{max} \geq dist(u,v)$, where $dist(u,v)$ denotes the distance between u and v. In the simulations, every node has the same maximum transmission range. To consider interference, we use linear constraints (6), and set $\beta = 1.0$. The traffic demand for an OD pair is set randomly, uniformly within $[1, 2]Mbps$. Note that all of the performance metrics as discussed later are invariant with the scaling of bandwidth and traffic demand. We use CPLEX [1] to solve the LP programs.

Usually different links have different loss ratios. We conduct experiments on networks of various sizes, with loss ratio of each edge uniformly set within $[0\%, 50\%]$. For each size of the network, we study two maximum transmission ranges, 15m and 20m. First we study the achievable throughput when interference and lossy links are present, without the energy constraint. We compare the maximum throughput fraction α when loss is considered or not. We use the measure $\frac{\alpha_1}{\alpha_0} \times 100\%$ to show the degree of impact of loss on the maximum achievable throughput, where α_0 is the maximum throughput fraction when only interference is considered, while α_1 is the fraction when both interference and loss are considered. In Table I, we report the min, median, mean and max of the measure for 9 runs of the experiments. The results show that with lossy links, a network can not achieve the same throughput as when links are lossless. However, in some cases, a network may achieve similar throughput. This suggests that the good performance of a routing designed without considering loss on these topologies may be misleading: for topologies with low $\frac{\alpha_1}{\alpha_0} \times 100\%$ values, the maximum throughput computed without considering loss will be far from achievable. In contrast, LP (8) can compute the maximum achievable throughput and its optimal routing.

N	R_{max}	min	median	mean	max
25	15m	53.511	75.652	73.275	84.301
25	20m	70.351	74.012	74.323	76.835
36	15m	65.163	75.507	77.598	98.363
36	20m	68.633	74.120	76.041	89.840
49	15m	43.310	68.593	68.244	94.461
49	20m	62.588	74.608	73.679	80.387

TABLE I
Impact of Loss on Maximum Throughput (%)

Next we study the impact of lossy links on maximum lifetime. We compare the maximum lifetime t, which is the inverse of the objective u of LP (10), when loss is considered or not. We use the measure $\frac{t_1}{t_0} \times 100\%$ to show the degree of the impact, where t_0 is the maximum lifetime when only interference is considered, while t_1 is the lifetime when both interference and loss are considered. We use the energy model in [9], i.e., we set $tx(u,v) = E_{elec} + \epsilon_{amp} \times dist^2(u,v)$ and $r(u) = E_{elec}$, where E_{elec} represents the energy consumption for running the transmitter or the receiver circuitry, ϵ_{amp} represents the energy consumption for running the transmitter amplifier to achieve an acceptable signal-noise ratio. As in [9], we set $E_{elec} = 50nJ/bit$ and $\epsilon_{amp} = 100pJ/bit/m^2$. We set $h(u) = r(u)$, i.e., we assume that overhearing consumes the same amount of energy per unit of message as reception. The initial energy level of each node is set randomly, uniformly within $[20, 30]J$ (note $\frac{t_l}{t_0}$ is invariant with the scaling of the initial energy level).

In Table II, we report the min, median, mean and max of the impact measure for 9 runs of the experiments. The mean of 9 runs has more than 86% of the maximum lifetime for the corresponding lossless networks. In most cases (except 3 out of 54), $\frac{t_1}{t_0}$ is greater than 0.75, while the mean loss ratio is 0.25. There are even cases where a lossy network has longer lifetime than the lossless counterpart. This might be counter-intuitive, since in a lossy environment, retransmissions are required thus energy is wasted. Taking a closer look at the broadcast nature of wireless communication, we see the results reveal that, due to loss, the saving in energy consumption for overhearing may compensate for the energy waste for retransmission. It is even possible to take advantage of the loss and design routing to improve energy efficiency, e.g. in the cases where $\frac{t_1}{t_0} > 1$ (there are 4 cases). LP (10) can compute such a routing.

The energy consumption model affects the impact of loss on the maximum lifetime. It is expected that with much lower energy consumption for overhearing, the gain in the loss of broadcasting will be less significant. Thus, we won't be able to enjoy a close or longer lifetime as shown in Table II. The

N	R_{max}	min	median	mean	max
25	15m	76.841	90.891	93.024	114.089
25	20m	87.193	92.489	92.149	95.877
36	15m	83.552	89.047	93.396	118.050
36	20m	91.807	95.097	94.775	97.346
49	15m	67.519	88.493	86.719	94.825
49	20m	91.597	93.587	93.601	96.730

TABLE II

IMPACT OF LOSS ON MAXIMUM LIFETIME (%)

previous study shows that different network sizes have similar results. Here we study networks of size 25. The first and second rows in Table III for $h(u) = r(u)/10$ confirm our expectation. The extreme case is when overhearing does not consume energy. The third and fourth rows show the results.

N	R_{max}	$h(u)$	min	median	mean	max
25	15m	$r(u)/10$	59.173	79.277	77.187	86.101
25	20m	$r(u)/10$	77.482	82.381	82.661	85.651
25	15m	0	57.562	77.601	75.799	85.089
25	20m	0	76.673	81.225	80.872	84.013

TABLE III

IMPACT OF LOSS ON MAXIMUM LIFETIME (%) WHEN OVERHEARING CONSUMES DIFFERENT AMOUNTS OF ENERGY

We also investigate the impact of overhearing on energy efficiency. Both interference and loss are considered. We use the measure $\frac{t_1^o}{t_0^o} \times 100\%$ to show the degree of the impact, where t_0^o is the maximum lifetime when overhearing is not considered, while t_1^o is the lifetime when overhearing is considered. We study networks of size 25. In Table IV, we report the min, median, mean and max of the impact measure for 9 runs of the experiments. The first and third rows show the results when links have loss ratio uniformly in $[0\%, 50\%]$; while the second and fourth rows for lossless networks. We see overhearing has a hugh impact on energy efficiency, esp. for denser networks ($R_{max} = 20m$). On average, only 60% or much less (32%) lifetime can be achieved. The results suggest that, with omni-directional antennas, overhearing is an important factor to consider for energy efficiency.

N	R_{max}	loss ratio	min	median	mean	max
25	15m	$U[0, 0.5]$	49.628	58.757	59.347	76.011
25	15m	0	39.613	45.227	48.655	60.131
25	20m	$U[0, 0.5]$	32.817	35.325	36.548	45.063
25	20m	0	28.883	31.726	32.048	40.175

TABLE IV

IMPACT OF OVERHEARING ON LIFETIME (%)

V. CONCLUSIONS

Multihop wireless networks have unique features such as lossy links and interference. Besides interference, lossy links affect the maximum achievable throughput. Some wireless networks have energy constraints. Lossy links also affect energy efficiency. We investigate the impact and model the problems of maximum achievable throughput and minimax energy utilization as LP optimization problems. We give optimal solutions for both flow-based and destination-based routing. The experiments show that lossy links do have significant impact on the maximum achievable throughput. There are cases where a lossy network can only achieve half of the throughput when links are lossless. The results show less significant impact of loss on energy efficiency. In some cases, the loss may be advantageous for energy efficiency, i.e., the lifetime can be longer when loss is considered. Experiments also show the significance of overhearing on energy efficiency.

In [14], we design a simple method to improve the quality of routing with respect to the number of paths and how far the paths are from the shortest paths, with only little degradation of the major objective of minimax link utilization. This will be useful to improve the quality of routings in this paper.

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