Energy-Aware Routing for Delay-Sensitive Applications Over Wireless Multihop Mesh Networks

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***Abstract*—In this paper, a cross-layer algorithm that aims at minimizing the end-to-end transmission energy subject to a packet delay deadline constraint is proposed. The optimal transmission energy and rates, and the optimal route are computed to minimize the end-to-end total transmission energy in a delay constraint wireless mesh network. A cross-layer optimization framework is proposed under a constraint that all successfully received packets must have their end-to-end delay smaller than their corresponding delay deadline. In addition to the optimal solution, a suboptimum solution is also proposed. This solution has close-to-optimal performance with lower complexity. The simulation results show that, for the same delay constraint and bit error rate (BER), the optimum proposed algorithm has less energy consumption than routing algorithms that consider delay constraint only.**

***Index Terms*—Wireless mesh networks, delay sensitive applications, convex optimization, cross layer optimization.**

I. Introduction

Multihop wireless mesh networks provide a low-cost and flexible infrastructure that can be utilized by multiple users for simultaneous transmission of their data streams. Different multihop routing algorithms have been proposed in the literature to address the different QoS requirements for different applications. Routing algorithms targeting the minimization of the transmission energy has a great importance in energy limited devices [1] and [2].

This paper considers cross-layer design to optimize the performance of delay-sensitive applications by jointly considering multiple protocol layers. Cross-layer design for throughput maximization has received increased attention over the past few years [3]. The design challenges and the importance of cross-layer design for meeting application requirements in energy constrained networks were described in [4]. Cross-layer design with more focus on modeling of circuit and transmission energy was described in [5].

To our knowledge, there are no cross-layer algorithms that target total transmission energy minimization and, at the same time, ensure the timely reception of the packets in delay-constrained applications. For example, the authors in [6], [7] and [8] focus on achieving a QoS for delay-constrained applications while ignoring the energy constraint by using a constant transmission energy. In [9], both energy consumption and delay constraints are considered, but only for a single link. In [10] and [11], the authors target maximizing the network lifetime while conserving the total flow through different nodes. Conservation of flow does not guarantee that explicit packet-based delay constraints are met for delay-sensitive applications.

The goal of this paper is to minimize the total transmission energy for delay-constrained applications in a multihop wireless mesh network. To achieve this goal, different control parameters are optimized across the protocol layers (network and physical layers). An optimum algorithm to determine the best physical layer parameters is first proposed for a string topology. The optimum algorithm is then extended to the case of mesh networks. The algorithm is proposed to determine the optimal parameters under a predetermined delay deadline for each packet. It is considered as an exhaustive search algorithm for the determination of the optimized-mesh network parameters. These parameters are the path selection in the network layer, the modulation and the transmission energy in the physical layer.

A less complex, suboptimum algorithm is also proposed. Based on this algorithm, the network graph is divided to small subnetworks. For every subnetwork, all the cross-layer parameters and the optimum route are calculated for each path and the search through all the possible paths is required in order to find the optimum path for this subnetwork. Consequently, this optimization has lower complexity because it considers smaller subnetworks instead of the large one. These algorithms are proposed for a single user; however they can be extended to the case of multiple users.

The rest of the paper is organized as follows. Section II describes the system model and introduces the optimization problem and constraints. Section III introduces the proposed optimum and suboptimum energy-aware routing algorithms that determine the transmission parameters. Section IV presents the simulation environment and results. Finally, Section V concludes the paper.

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II. Problem Definition

A. System Model

In this paper, multihop wireless mesh networks with a single transmit/receive pair are considered. It should be noted that the methods in this paper can be extended to the case of multiple users. In the considered model, there is one source node, one sink node and many limited-energy intermediate nodes. We assume that each node can change its transmission power and modulation scheme. The link schedule in the proposed algorithm is an interference-free Time Division Multiple Access (TDMA) schedule. Link-layer retransmissions are not considered in this paper, mainly for two reasons. The first is that retransmissions introduce additional delay in data delivery, which is not controllable. Therefore, delayed packets could be received too late and become unusable. The second reason is that a single packet retransmission would double power consumption, while a lower increase in the transmission power could bring more benefits in terms of probability of correct reception.

We assume that a "link" exits when the received power at a receiving node, for maximum power transmitted from the source node, is greater than a predefined threshold. By introducing a reasonable threshold, links that are very weak will not be considered [10]. If the threshold chosen is very low, the network considered will be fully connected. This increases the complexity of the network model used for cross-layer optimization. It is also assumed that at any given time, any node can either transmit to, or receive from, at most one other node in the network.

B. Optimization Problem

In this paper, the optimization problem is initially formulated for a string topology, before being generalized for a multihop mesh network. The string topology consists of one source and one sink, connected by intermediate nodes that are arranged linearly as shown in Fig. 1. It is assumed that each pair of neighboring nodes are separated by the same distance d, and connected by a direct link. The network carries information generated by the source to the sink. For a single link i with bandwidth w, the data rate that can be transmitted is

$$r_i = w \log_2(1 + k\gamma) \tag{1}$$

where $k = -1.5/(\log(5\text{BER}))$ as in [12] and γ is the signal to noise ratio at the receiver side and is defined as

$$\gamma = \frac{P_r}{N_0 \cdot w} \tag{2}$$

where N_0 is the noise spectral density and P_r is the received power. We allow r_i to take all values in $\mathbb{R}_+$. From (1) we get

$$\gamma = \frac{(2^{r_i/w} - 1)}{k} \tag{3}$$

From (2) and (3) we get

$$P_r = \frac{N_0 \cdot w}{k}(2^{r_i/w} - 1) \tag{4}$$

A deterministic path loss model as in [13] is used, where

$$P_r = P_t \, \frac{g_t \cdot g_r \cdot \lambda^2}{(4\pi d)^2} = P_t \cdot \alpha \tag{5}$$

where P_t is the transmitted power, g_t is the transmit antenna gain, g_r is the receive antenna gain, λ is the wavelength and α is the overall path loss. We define the link cost x_i as

$$x_i = \frac{k \cdot \alpha}{N_0 \cdot w} \, |h_i| \tag{6}$$

where $|h_i|$ is the fading channel magnitude for link i. In our model, it is assumed that there is only one link active at a time. There are no queues in the network except small buffers at different nodes to receive and forward the packets. A central scheduler will schedule the node that currently hosts the packet to transmit for a period of time $T_i = l/r_i$. The required transmission energy over link i to send a packet of length l with rate r_i is

$$e_i = \frac{P_i \cdot l}{r_i} = \frac{l}{r_i \cdot x_i}(2^{r_i/w} - 1) \tag{7}$$

where P_i is the transmitted power over link i. The objective of the optimization problem is to minimize the total transmission energy $\left(\sum_{i=1}^{i=N} e_i\right)$ over all links from the source to the sink under a constraint that each packet must be received at the sink before its delay exceeds the packet delay deadline D_l. Therefore, the problem of minimizing the total transmission energy can be written as

$$\begin{gathered} \min \left(\sum_{i=1}^{i=N} \frac{l}{r_i \cdot x_i}(2^{r_i/w} - 1) \right) \\ \text{such that} \\ \sum_{i=1}^{i=N} \frac{l}{r_i} \leq D_l \end{gathered} \tag{8}$$

where N is the total number of hops in the network. To solve this optimization problem, the (-1) term is neglected with respect to $2^{r_i/w}$ to have a convex problem, which can be solved using the interior-point methods (for more details, see [14]). The optimization problem in (8) is a function of the link cost x_i, the link bandwidth w, the packet length l and the packet delay deadline D_l. The last two variables are imposed by the higher layers. Consequently, the unknowns in this problem are the transmission rates r_i. By knowing the rates, the required transmission energy from different nodes can then be obtained from (7).

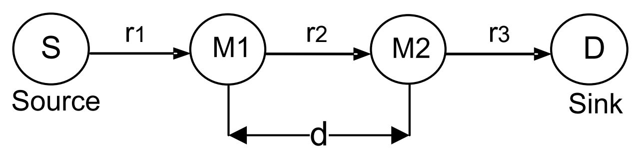

Fig. 1. String Topology.

III. Energy-Aware Routing Algorithms

In the previous section, the optimization problem was solved for a single path multihop network comprised of cascaded links. In this section, routing over wireless multihop mesh network is considered. First, the optimum algorithm that chooses the optimum route from the source to the sink and the transmission parameters corresponding to the total minimum energy consumption under the delay constraint is derived. Then, a suboptimum algorithm with lower complexity than the optimum algorithm is porposed.

A. Optimum Algorithm (Exhaustive Search)

This algorithm is considered optimum because we take into consideration all possible paths from the source to the sink and choose the minimum energy path that satisfies the delay requirement. The steps of the algorithm are as follows:

1) Convey information on the conditions of each link and calculate links cost x_i.
2) Determine all possible paths from the source to the sink.
3) For each path, solve the optimization problem in (8) and get the optimum rates for it.
4) Calculate the total transmission energy for each path.
5) Choose the path with minimum transmission energy, it will be the optimum energy route from the source to the sink.

The main step of this algorithm involves the solution of the convex optimization problem in (8) multiple times, equal to the number of paths from the source to the sink. This number, in large networks, is prohibitively large making the optimum algorithm too complex to implement.

B. Suboptimum Algorithm

In this subsection, a suboptimum algorithm that has a lower complexity than the exhaustive search algorithm is proposed. This algorithm tradeoffs between the complexity reduction and the resulting increase in energy consumption. The main steps of this algorithm are as follows:

1) Convey information on the conditions of each link and calculate links cost x_i.
2) Divide the large network into smaller subnetworks as shown in Fig. 2.
3) Determine the delay deadline for each subnetwork to be used in finding the optimum route in this subnetwork (i.e. distribute the end-to-end delay deadline D_l between the subnetworks, as explained later).
4) In each subnetwork, solve the optimization problem in (8) for all possible subnetwork source-destination pairs.
5) Choose the paths with minimum energy from the source(s) to destination(s) of every subnetwork, one path for every source/destination pair. For example, in Fig. 2, there are 2 paths in subnetwork 1 (S→M4 and S→M5) and 2 paths in subnetwork 2 (M4→D and M5→D) with minimum energies e_{S4}, e_{S5}, e_{4D} and e_{5D}.
6) Concatenate subnetworks as shown in Fig. 3 using the energies obtained in the previous step.
7) In the simplified network in Fig. 3, calculate the total transmission energy in each possible end-to-end path.
8) Choose the path with the minimum transmission energy.

It should be noted that there is complexity/energy-consumption tradeoff in deciding the number of subnetworks in step 2. As the number of subnetworks increases, the algorithm complexity decreases. However, the total energy consumption will increase compared to the optimum algorithm.

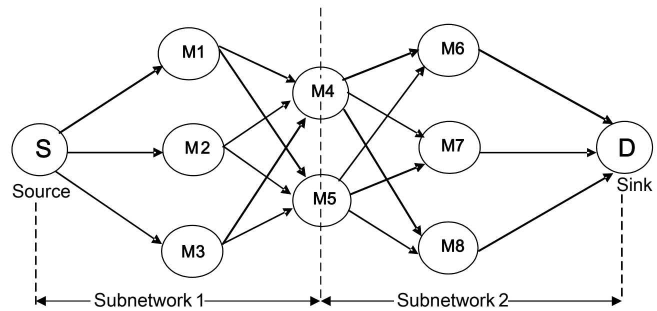

Fig. 2. Overlay Network Topology.

The challenging task in this algorithm is the distribution of the end-to-end delay deadline D_l between different subnetworks. As shown later, a small error in the delay distribution compared to the exhaustive search algorithm, will lead to a large increase in the total transmission energy compared to the optimum algorithm. Two methods are suggested to distribute the end-to-end delay deadline on the subnetworks.

1) Delay distribution using number of hops: In this method, the delay deadline for each subnetwork is determined by using the number of hops in this subnetwork. The delay deadline of the subnetwork s_i is calculated as

$$D_{s_i} = \frac{D_l \cdot N_{si}}{N} \tag{9}$$

where N_{si} is the number of hops in subnetwork s_i.

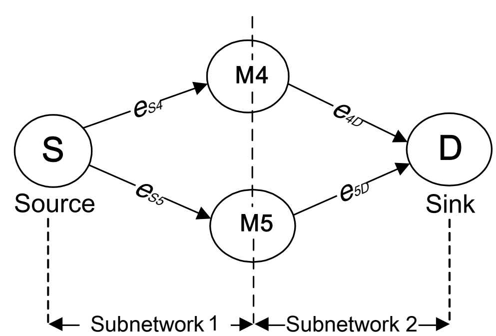

Fig. 3. Simplified Network Topology.

2) Delay distribution using exhaustive search: In this method the optimum algorithm is executed once and the optimum route is found. Then, the packet delays over the hops of the optimum path are used to get the delay deadlines in the different subnetworks. Specifically, the delay deadline in subnetwork s_i equals to the time required for the packet to travel over the hops in the optimum route that belongs to subnetwork s_i.

$$D_{s_i} = \sum_{j=1}^{m} \frac{l}{r_j} \tag{10}$$

where m is a number of hops that belongs to the optimum route in subnetwork s_i. The performance of this method depends on the channel states of the different links. If the channels vary significantly with time, the delay distribution will change completely. In this case, the optimum algorithm is executed frequently to update the delay distribution.

IV. Simulation Results

The simulation results were generated using the overlay network topology shown in Fig. 2. Note that, any multihop network that can be modeled as a directed acyclic graph can be modified to fit into this overlay structure by simply adding virtual nodes [15]. The simulation parameters used are given in Table I.

TABLE I
Simulation Parameters

Parameter	Value
N_0	-174 dBm
λ	0.12
w	5 kHz
d	10 m
l	1000 bit
g_r	1
g_t	1
D_l	0.1 sec
BER	10^{-4}
Sampling time	0.1 sec

In the mesh network considered, all the connected nodes are assumed to be separated by the same distance d. To model small scale channel variations, flat Rayleigh fading is used for each link.

In the proposed optimum algorithm, the path with the total minimum transmission energy is chosen. In each link on this path the optimum transmission energy is chosen to satisfy the overall delay constraint. In Fig. 4, the performance improvement gained by optimizing the transmission energy for each link is assessed. In this figure, the total transmit energy is plotted versus the channel realizations with Doppler frequancy 0.1 Hz and the sampling rate given in Table I.

Optimizing the transmission energy for each link was not considered in the previously proposed algorithms dealing with satisfying a delay constraint [6][7]. We define the "delay routing" algorithm which uses the minimum transmission energy path chosen in the proposed optimum algorithm. In all links on this path, we send with a constant transmission energy E_{max}, which is the maximum transmission energy used in any link in the optimum algorithm. Note that, both algorithms satisfy the delay constraint and give the same bit error rate. As shown in Fig. 4, with changing the channels in all links, the proposed optimum algorithm has less energy consumption than the delay routing algorithm, which is targeting the delay constraint only. In order to assess the performance of the proposed simplified suboptimum algorithm compared to the proposed optimum algorithm, define the performance deviation (PD) as

$$PD = \frac{E_{sub} - E_{opt}}{E_{opt}} \tag{11}$$

where E_{sub} is the total transmission energy in the suboptimum algorithm and E_{opt} is the total transmission energy in the optimum algorithm.

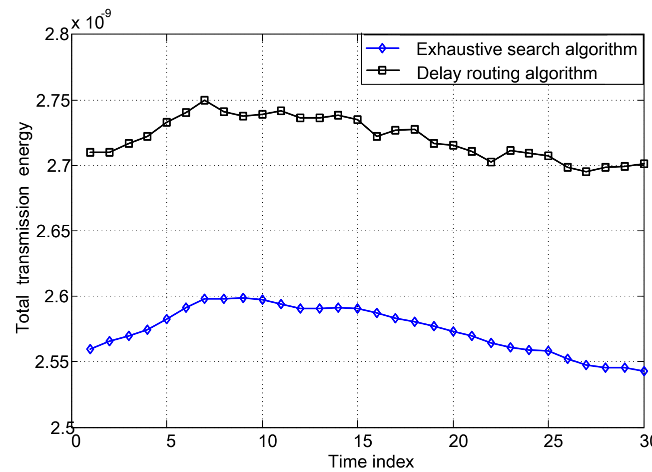

Fig. 4. A comparison between the total transmission energy using the optimum proposed algorithm and the delay routing algorithm.

Fig. 5 shows the importance of the delay distribution in the suboptimum algorithm. If there is only 20% error in the delay distribution of the suboptimum algorithm compared to the delay distribution of the optimum algorithm, the performance deviation is 84%.

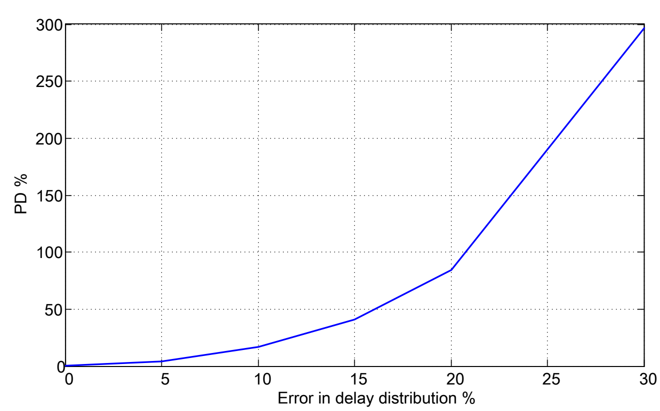

Fig. 5. The performance deviation of the proposed suboptimum algorithm, in the presence of error in the delay distribution.

In the suboptimum algorithm, two methods to distribute the delay were proposed. Fig. 6 illustrates the performance deviation for the suboptimum algorithm using the two proposed delay distribution methods. The performance deviation of the delay distribution using the number of hops, which does not depend on the channel state, is almost constant with the channel variation. In the delay distribution using exhaustive search method, the performance deviation depends on the channel state on each link as described earlier. As a result, the performance of this method is highly dependent on the channel state as shown in Fig. 6. In this figure, the PD is plotted with varying the channel in each link with Doppler frequancy 0.1 Hz and sampling time 0.1 sec.

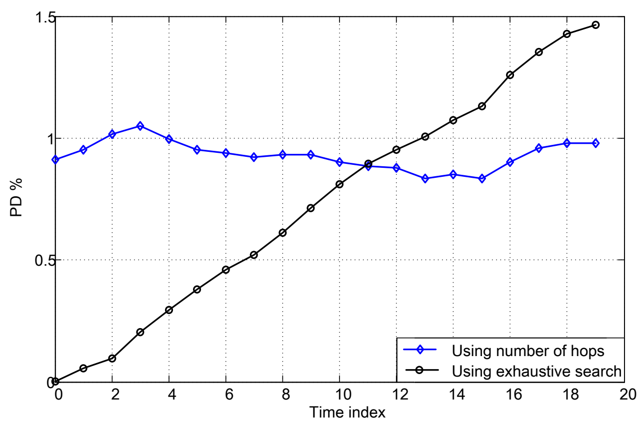

Fig. 6. The performance deviation of the suboptimum algorithm while the channel varies due to the Doppler spread.

The network shown in Fig. 7 is used to assess the effect of increasing the number of subnetworks. Fig. 8 shows the performance of this network. The Doppler frequency used in this case is 0.7 Hz. It is clear from the figure that increasing the number of subnetworks will result in increasing the PD for the suboptimum algorithm. On the other hand the complexity decreases with respect to the optimum algorithm.

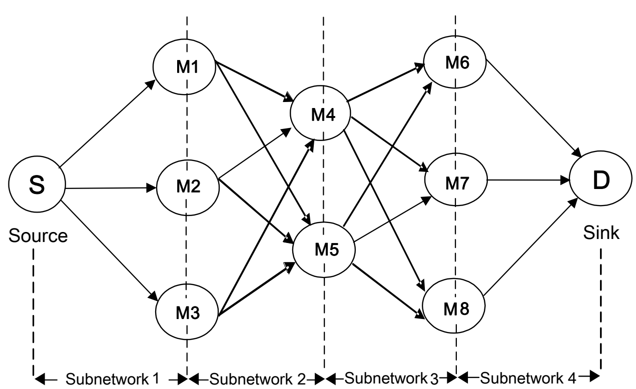

Fig. 7. Overlay Network Topology after increasing the number of subnetworks.

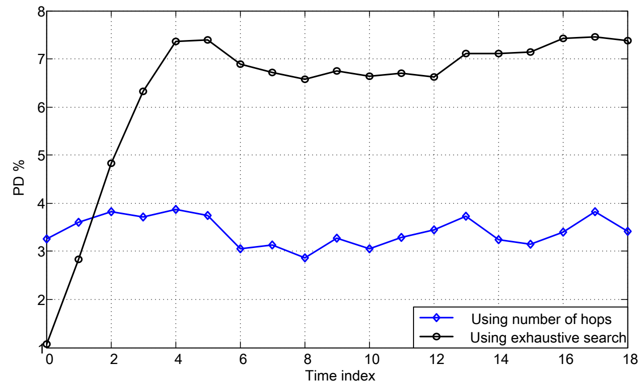

Fig. 8. The performance deviation of the suboptimum algorithm while varying the channel and increasing the number of subnetworks for the network shown in Figure 7.

For simplicity, another suboptimum algorithm, "constant path" routing, is suggested. The main steps of this algorithm are as follows:

1) The optimum algorithm is executed.
2) The optimum path is identified and is used for a certain period of time.
3) In this period, as channels vary, solve the optimization problem in (8) for the identified path only to find the new data rates.
4) After the end of this period, run the optimum algorithm again to find the new optimum path.

The disadvantage of this algorithm is that as the channels change, the performance deviation between the already chosen path and the optimum path will increase as shown in Fig. 9. Doppler frequency of 0.7Hz is used in this figure.

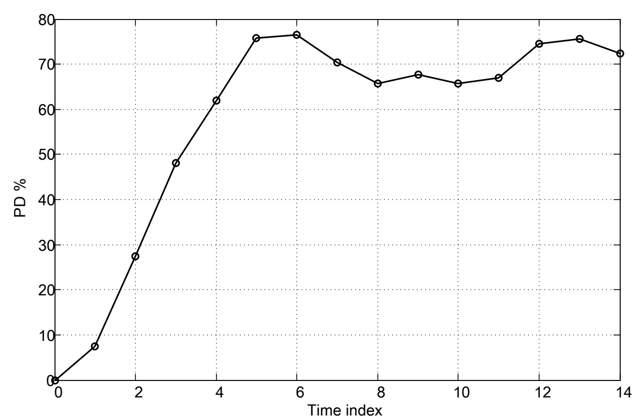

Fig. 9. The performance deviation of the constant path routing algorithm in the varying channel.

V. Conclusion

In this paper, a cross-layer optimization framework is proposed. This framework jointly minimizes the total transmission energy, determines the optimal modulation scheme, and identifies the optimal route to the destination. The minimization is performed under the constraint that all successfully received packets must have their end-to-end delay smaller than their corresponding delay deadline. Beside the optimum algorithm, a suboptimum algorithm is proposed that has less complexity than the optimum algorithm. The proposed suboptimum algorithm makes a tradeoff between the complexity reduction and the energy consumption. The simulation results show that, for the same delay constraint and BER, the optimum proposed algorithm has less energy consumption than the delay routing algorithm that considers the delay constraint only.

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