Multi-User Cross-Layer Optimization for Delay-Sensitive Applications Over Wireless Multihop Mesh Networks

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***Abstract*—In this paper, the energy-limited wireless multihop mesh networks are considered. Minimizing the total transmission energy in the network, while satisfying the applications' delay constraints, is the target of our optimization problem. To achieve this goal, energy-efficient design should be supported across all layers of the protocol stack through a cross-layer design. This paper proposes energy-efficient joint routing, scheduling, and link adaptation strategies that minimize the total transmission energy in the network. The proposed cross-layer energy-aware algorithms allocate resources, dynamically according to channel quality and traffic load so as to minimize the overall transmission energy, while satisfying the given packets delay and bit error rate (BER) constraints. The resources considered are the transmitted power and modulation in the physical layer, scheduling in the link layer and routing in the network layer. In addition to the proposed optimal solution, suboptimum solutions are presented as well. The simulation results show that, under the same conditions, the proposed optimum algorithm has less energy consumption than routing algorithms that consider delay constraints only. Moreover, simulations show that the suboptimum algorithms have performance near to the optimum algorithm with a huge reduction in the complexity.**

***Index Terms*—Energy efficiency, Wireless mesh networks, Link adaptation, Cross-Layer Optimization.**

I. INTRODUCTION

Multihop wireless mesh networks provide a low-cost and flexible infrastructure that can be utilized by multiple users for transmission of their data streams. This paper considers a cross-layer design to minimize the energy consumption in mesh networks for delay sensitive applications. Cross-layer design is used to improve the overall system's performance by jointly considering multiple protocol layers.

Cross-layer design for throughput maximization has received much attention over the past few years [1]. This paper proposes dynamic cross-layer radio resource allocation algorithms. The framework proposed determines parameters in different layers to optimally allocate the wireless network resources among all users. We assume that all users in the system are delay sensitive users. Therefore, the maximum end-to-end transmission delay for each packet must be controlled to meet a given deadline to support the required QoS. Since all layers of the protocol stack affect the energy consumption and delay for the end-to-end transmission of each packet, an efficient system requires a dynamic design across all these layers to meet the delay constraints and minimize the total transmission energy. Dynamic allocation algorithms achieve higher throughput and lower power consumption than static methods due to their adaptive nature [2].

A. Prior Work

To our knowledge, there are no cross-layer algorithms that target total transmission energy minimization and, at the same time, ensures the timely reception of the packets in multi-user delay-constrained networks. For example, the authors in [3] focused on achieving a QoS for delay-constrained applications while not considered energy consumption by assuming constant transmission energy. In [4], the authors presented a general framework for optimizing the quality of video streaming in wireless networks having multiple wireless stations. They minimized the overall distortion for all wireless stations given wireless medium capacity constraint only. In [5], the problem was formulated as a distortion-delay optimization problem. Cross-layer design was used to minimize the expected video distortion under given packet delay constraint. The transmission power was assumed to be uniformly distributed among all users.

The objective in [6] was to maximize the throughput and spectral efficiency under the heterogeneous delay constraints only. In [7], the authors proposed an algorithm that minimized the overall average packet delay and took into account queuing delay, modulation, and coding scheme supported by each user and ignored energy constraint. Energy efficient power control and scheduling, with no rate adaptation on links, for QoS provisioning were considered in [8]. The first framework that targets energy minimization and delay constraint, in wireless mesh network, was proposed in [9]. However, the solution proposed in [9] considered only the single-user case.

B. Outline

The proposed cross-layer architecture is shown in Figure 1. In this architecture, different parameters are captured from different layers and passed to the cross layer server to produce

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the optimal system parameters for each user. The cross layer server receives from each transmitter the required delay constraints from the application layer and the available transmitted power that can be supported by the physical layer. At the same time, it receives the channel conditions from the receivers. The cross layer server determines the scheduled user at the data-link layer. For each scheduled user, the optimal route at the network layer is determined in addition to the modulation and the transmitted power at the physical layer.

Our goal is to minimize the overall energy consumed by all nodes that cooperate to transfer a known number of packets from the source nodes to their destinations. Therefore, the proposed cross-layer optimization problem can be formulated as an energy-delay optimization problem, where the design objective is to minimize the total transmission energy under the given packets delay constraints. We use Time Division Multiple Access (TDMA), which eliminates interference, as a multiple access scheme.

The remainder of this paper is organized as follows. Section II describes the system model, the optimization problem and the proposed optimum cross-layer algorithm. Section III proposes suboptimum energy-aware routing algorithms. Section IV introduces the complexity analysis of the different proposed algorithms. Section V presents the simulation environment and results. Finally, section VII concludes the paper.

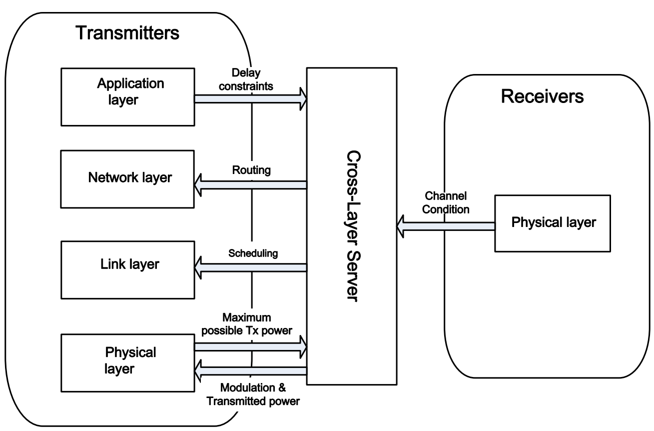

Fig. 1. Cross-layer architecture.

II. Energy-Optimal Cross-Layer Design

A. System Model

In this paper, a multiuser multihop wireless mesh network with multiple transmit/receive pairs is considered. There are K source-destination pairs that send their delay sensitive packets through N hops. At the h-th hop $(1 \leq h \leq N-1)$, m_h limited energy intermediate nodes act as relays to forward the transmitted data from the sources to their destinations. It is assumed that each pair of neighbor nodes is separated by the same distance d, and connected by a direct link. The corresponding scenario is illustrated in Figure 2. We assume that each user, j, generates a packet of data with length l_j bits. The delay deadline of user's j packet is D_j. The parameters used in this paper are listed in Table I. Variable-length TDMA scheme is used, where the slots' lengths are optimally assigned to the users according to the routing requirement while minimizing the energy consumption across the network. In our model, it is assumed that there is only one active link at a time, for a period of time $t_{ij} = l_j/r_{ij}$, to transmit the data of user j over link i.

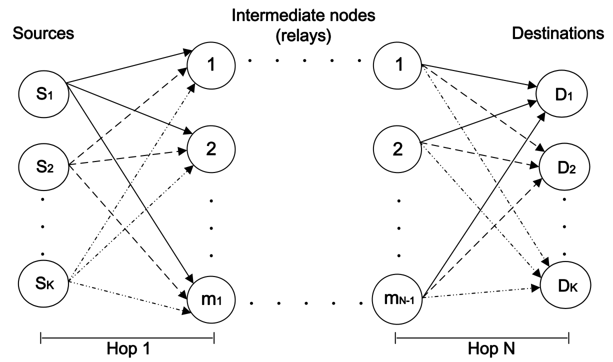

Fig. 2. The multihop overlay network model with K users and N hops.

It is assumed that the network is static or changing very slowly, thus, the optimization can be done in a central node. The optimal slots assignment and scheduling information is then broadcasted to the network. Since the optimal slot lengths are given in continuous real values, they can be quantized according to a reference slot length Δ to make it easily implemented in a TDMA scheme. The whole TDMA frame is slotted into T/Δ slots, and then the number of slots for each user j on link i is assigned by rounding t_{ij}/Δ. As long as the reference slot length Δ is sufficiently small, the performance deviation due to rounding is negligible. Thus, in this paper, we will focus on getting the optimal t_{ij}'s by finding the optimal r_{ij}'s on all links from the sources to their destinations. For scheduling, we use round robin to schedule the users in time (to achieve fairness between users).

TABLE I
Table of Notations

v	Packet length
λ	Wave length
D_l	Delay deadline
T	Frame duration
K	Number of users
N	Number of hops
w	Available bandwidth
N_0	Noise spectral density
α	Overall path loss in each link
$\lvert h_{ij}\rvert$	Fading channel magnitude
x_{ij}	Link cost of link i for user j
m_h	Number of relay nodes in h-th hop
P_{max}	Maximum transmitted power at all nodes
b_{ij}	Constellation size used for user j in i-th hop
N_{comb}	Number of all paths between all transmit-receive pairs
t_{ij}	The transmitted time for user j in link i
r_{ij}	The transmitted rate for user j in link i
d_m	Transmission time at node m if it sends with power P_{max}
d_{ij}	Transmission time on link i to forward a packet of user j
M_p	Number of all possible paths from the source to destination

B. Optimization Problem

In this section, we review our previous work in [9] and extend it for multi-users mesh network. All related parameters in the model are defined in the same way as in [9]. In the rest of the paper, we will assume that all user's packet's delay deadlines are the same and equals to D_l. We consider the problem of computing a minimum-energy joint routing, scheduling, and link adaptation strategy to transfer all users' data packets with a delay deadline D_l. Because we use TDMA scheduling, the delay deadline D_l can be satisfied if $\sum_{j=1}^{K}\sum_{i=1}^{N} t_{ij} \leq D_l$. This constraint ensures that the last transmitted packet will arrive to its destination before D_l. 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 $k = -1.5/\log(5 \cdot \mathrm{BER})$ as in [10] and γ is the signal to noise ratio at the receiver side. By using the same analysis as in [9], we can formulate the optimization problem. The objective of the optimization problem is to minimize the total transmission energy to send all users' packets over all links between all sources-destinations pairs, under a constraint that each packet must be received at its destination before its delay exceeds the delay deadline D_l. Therefore, the problem of minimizing the total transmission energy can be written as

$$\begin{aligned} &\min\left(\sum_{j=1}^{K}\sum_{i=1}^{N}\frac{l_j}{r_{ij}x_{ij}}(2^{r_{ij}/w}-1)\right)\\ &\text{such that} \\ &\sum_{j=1}^{K}\sum_{i=1}^{N}\frac{l_j}{r_{ij}} \leq D_l \end{aligned} \tag{2}$$

where x_{ij} is the link cost of link i for user j, defined as [9]

$$x_{ij} = \frac{k\cdot\alpha}{N_0\cdot w}\ |h_{ij}| \tag{3}$$

We assume that the links' costs are constant during the packets transmission from the sources to destinations. This optimization problem can be approximated by a convex problem as in [9] and can be efficiently solved using known techniques [11]. The optimization problem can be converted to integer form by assuming that uncoded M-QAM is used and the constellation size assigned to link i, to transmit packet of user j, is denoted as $b_{ij} = log_2 M_{ij}$ as in [12]. To determine the modulation order, substitute r_{ij} with $w \cdot b_{ij}$ in the optimization problem and solve it to find the constellation size b_{ij}.

C. Optimum Algorithm (Exhaustive Search)

In this Section, routing over wireless multihop mesh networks is considered. The optimum algorithm that chooses the optimum routes from sources to destinations and the transmission parameters corresponding to the total minimum energy consumption under the delay constraints is derived. For each user, there are many possible paths to send packets to the destination. To illustrate the idea of this algorithm, we assume a two-hop network in Figure 3. As shown, there are three possible paths for the source S1 to send its data to the destination D1 (L11, L12, L13), and another three possible paths for S2 to send its data to D2 (L21, L22 and L23). Each path consists of two links (e.g L11 consists of L11a, L11b). To transfer the data from S1 and S2 to their destinations D1 and D2, there are many combinations of paths that can be used. These combinations are (L11- L21, L11- L22, L11- L23, L12- L21, L12- L22, L12- L23, L13- L21, L13- L22, L13- L23). In general, if the number of possible paths, for each user, is M_p (where $M_p = \prod_{h=1}^{N-1} m_h$) and the total number of users is K, then the total number of all possible combinations will be $N_{comb} = M_p^K$.

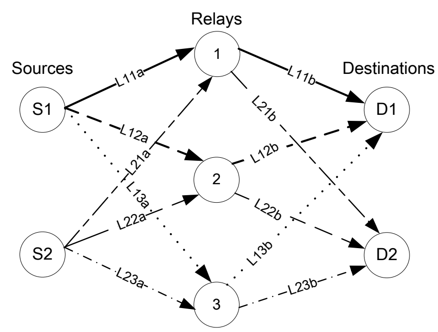

Fig. 3. An example for two-hop network.

This algorithm is considered optimum because it takes into consideration all possible combinations of paths from the sources to the destinations and chooses, for each user, the minimum energy path that satisfies the delay requirements. The main steps of this algorithm are as follows:

1) Convey information on the conditions of each link and calculate links cost x_{ij}.
2) Solve the optimization problem in (2) for all combinations of paths N_{comb}. From solving the optimization problem, we get the rates and the required transmission time for each user on each link.
3) Choose the combination with minimum transmission energy (in this step, we get the route for each user).

The main step of this algorithm involves the solution of the convex optimization problem in (2) N_{comb} times. This number, in large networks, is prohibitively large making the optimum algorithm hard to implement in practical life. For this reason, we propose suboptimum algorithms with lower complexities, as outlined in the next section.

III. Energy-Aware Suboptimum Routing Algorithms

A. Equal Delay Algorithm

In this algorithm, instead of solving the optimization problem for all users, each user will choose the best route and the transmission parameters independent of the other users. This will reduce the number of times the optimization problem in (2) is solved. The main steps of this algorithm are as follows:

1) Divide the total end-to-end delay deadline D_l among all users equally and get the delay deadline for each user.
2) Convey information on the conditions of each link and calculate links' costs x_{ij}.
3) For each user j, solve the optimization problem

$$\min \left(\sum_{i=1}^{i=N} \frac{l_j}{r_{ij} x_{ij}} (2^{r_{ij}/w} - 1) \right)$$
$$\text{such that} \quad (4)$$
$$\sum_{i=1}^{i=N} \frac{l_j}{r_{ij}} \leq \frac{D_l}{K}$$

for all paths of this user. For example, in Figure 3, solve the optimization problem three times for each user.
4) By solving the optimization problem, find the rate on each link and the total transmission energy for each path.
5) By comparing the paths' energies in step 4, choose the path with the minimum energy for each user with the rates found in step 4.

B. Minimum Delay Algorithm

In this algorithm, instead of solving the optimization problem for all paths, for each user, to find the optimum route, we will choose the best route first, according to a certain criteria, then solve the optimization problem for this route only to get the transmission parameters. The main steps of this algorithm are as follows:

1) For each user j, from the source to the destination, calculate the transmission time at each link if we send with power P_{max} on it, according to the following equation

$$d_{ij} = \frac{l_j}{w \log_2(1 + k \frac{P_{max}\alpha}{N_0 w})} \quad (5)$$

2) Calculate, for each path, the end-to-end delay in all links $\sum_{i=1}^{N} d_{ij}$.
3) Choose, for each user, the path with minimum delay.
4) From feedback information, calculate links' costs x_{ij}.
5) Solve the optimization problem in (2) on the chosen paths to get the rates on all links for all users.

C. Delay Estimate Algorithm

This proposed algorithm has the lowest complexity among the algorithm considered in this paper. The main step that increases the complexity of the other algorithms is solving the convex optimization problem in (2). In this algorithm, we define a relationship between the link cost and the corresponding delay deadline per link. Instead of solving the convex optimization problem to get the rates, we use this relation to calculate the rates. To illustrate that, we summarize this algorithm in the following steps:

1) For each user, from source to destination, calculate the transmission time at each link if we send with power P_{max} as in (5).
2) Calculate, for each path of user j, the end-to-end delay in all links $\sum_{i=1}^{N} d_{ij}$ and then choose the path with minimum delay for each user.
3) From feedback information, calculate links' costs x_{ij}.
4) To optimize the transmitted energy at each node, the delay required at each node to transmit its data to the next hop should be proportional with the link cost. So for link i and user j the delay required $d_{ij} = c/x_{ij}$, where

$$c = \frac{D_l}{\sum_{j=1}^{K} \sum_{i=1}^{N} 1/x_{ij}} \quad (6)$$

Note that the total end-to-end delay deadline for all users is still satisfied because $\sum_{j=1}^{K} \sum_{i=1}^{N} d_{ij} = D_l$.
5) By using the calculated delays from the previous step, the node will transmit with rate $r_{ij} = l_j/d_{ij}$ the packet of user j, on the link i that was chosen from step (2).

The performance of these suboptimum algorithms is compared with the optimum algorithm in Section V.

IV. Complexity Analysis Of The Different Proposed Algorithms

Each proposed algorithm determines the optimal parameters in a different way and also requires a varying amount of feedback on the conditions of all the various links in the multihop mesh network. This results in varying computational and communication requirements for these algorithms. In this section, we will compare the complexity of the proposed algorithms.

For the optimum algorithm (Section II-C), the overall complexity for scheduling all users' packets is:

$$C_{opt} = \left(\prod_{i=1}^{N-1} m_i \right)^K C_{convex} \quad (7)$$

where C_{convex} represents the complexity of solving the optimization problem in (2). The complexity of this algorithm dependents on the number of users and the number of intermediate relay nodes. Note that, as the number of users increases the complexity of this algorithm will increase exponentially.

For the equal delay algorithm (Section III-A), the overall complexity is:

$$C_{sub1} = K \left(\prod_{i=1}^{N-1} m_i \right) C_{convex} \quad (8)$$

The complexity of this algorithm dependents on the number of users and the number of intermediate relay nodes. Note that, as the number of users increases, the complexity of this algorithm increases linearly.

For the minimum delay algorithm (Section III-B), the overall complexity is:

$$C_{sub2} = K \left(\prod_{i=1}^{N-1} m_i \right) C_{delay} + C_{convex} \quad (9)$$

where C_{delay} represents the complexity of transmission time estimates in (5). In this algorithm, the complexity consists of two part, one for estimating the delay in all paths, and the other for the optimization problem to calculate the rates. Hence, the main advantage of this algorithm is that the optimization problem is solved only once, independent of the number of users.

For the delay estimate algorithm (Section III-C), the overall complexity is:

$$C_{sub3} = K\left(\prod_{i=1}^{N-1} m_i\right)\left(C_{rate} + C_{delay}\right) \quad (10)$$

where C_{rate} represents the complexity of estimating the delay deadline for each link and calculating the transmission rates, as in step 4 and 5. It is the simplest proposed algorithm because it does not solve the complex optimization problem. There is another advantage in this algorithm, that each node determines the next relay node and the transmission rate independent of the other nodes. The feedback information requirements for each algorithm can be expressed in terms of the number of links as in [13]. As the network size becomes larger, the complexity of these algorithms will increase. Therefore, for large networks, we can divide the large network into smaller subnetworks as in [9], and apply the same proposed algorithms on these subnetworks.

V. Simulation Results

In this section, the performance and the complexity are compared for the optimum and the suboptimum algorithms. The simulation results were generated using the overlay network topology shown in Figure 4. 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 [14]. The simulation parameters used are given in Table II. It is assumed that all users' packets have the same length l. To model small scale channel variations, flat Rayleigh fading is used for each link.

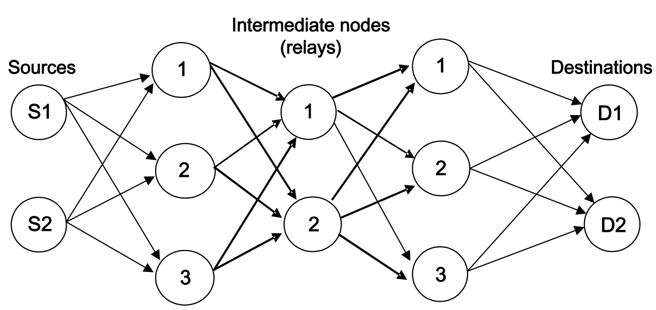

Fig. 4. Simulated network model.

TABLE II
Simulation Parameters

Parameter	Value	Parameter	Value
N_0	-174 dBm	λ	0.12 m
w	50 kHz	d	10 m
l	1000 bit	BER	10^{-4}
D_l	0.1 sec	Doppler frequancy	0.1 Hz

In the proposed optimum algorithm, for each link, the optimum transmission energy is chosen to satisfy the overall delay constraint. In Figure 5, we assess the performance improvement gained by optimizing the transmission energy for each link. In this figure, the total transmitted energy to transmit all users' packets is plotted versus the number of users in the system. Optimizing the transmission energy for each link was not considered in the previously proposed algorithms dealing with satisfying a delay constraint ([3] and [13]). We define the "constant energy" algorithm which uses the minimum transmission energy path chosen in the proposed optimum algorithm. In all links on this path, it sends with a constant transmission energy E_{max}, which is the maximum transmission energy used in any link on the path chosen by the optimum algorithm. Note that, both algorithms satisfy the delay constraint and give the same bit error rate. As shown in Figure 5, with increasing the number of users in the system, the difference between the energy consumed by the proposed optimum algorithm and the constant energy algorithm increases.

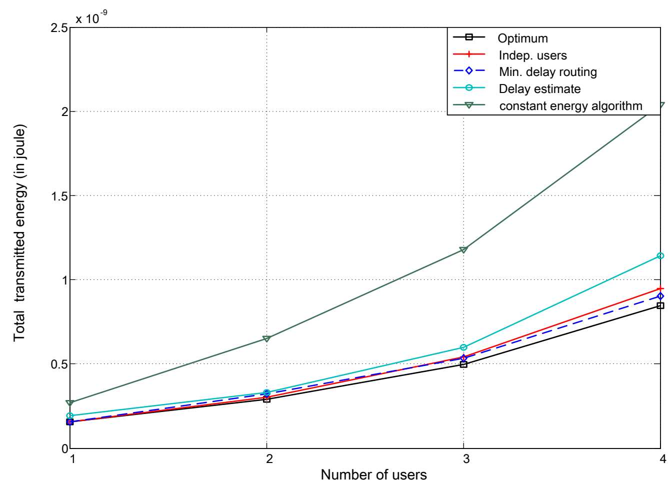

Fig. 5. Comparison of total transmitted energy for different proposed algorithms.

Figure 5 illustrates also a comparison between the required transmission energy for the four proposed algorithms with changing the number of users in the network. In order to assess the performance of the proposed simplified suboptimum algorithm compared to the proposed optimum algorithm, define the performance deviation (PD) as

$$PD = \frac{E_{sub} - E_{opt}}{E_{opt}} \quad (11)$$

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

For a small number of users, there are no significant differences among the four proposed algorithms. For example, for two users scenario, the PD is about 3% for the equal delay algorithm, 10% for the minimum delay algorithm, and 13% for the delay estimate algorithm. As the number of users increases, the difference between these algorithms increases, as shown in Figure 5.

The equal delay algorithm depends on the number of users in the system, therefore, as number of users increases, the performance deviation between the equal delay algorithm and the optimum algorithm increases. For example, for the two users scenario the PD is about 3%, while it is about 12% for the four users scenario. This limitation is because the algorithm distributes the total end-to-end delay deadline equally among users. Therefore, it will not be possible for any user having a bad channel to be assigned a larger transmission time than the other users, and so this user will have to transmit using very high energy to satisfy the delay constraint.

The minimum delay algorithm has less complexity than the optimum algorithm with acceptable performance deviation (for four users scenario the PD is about 7%).

Lastly, the delay estimate algorithm is the simplest proposed algorithm, because it does not require solving the convex optimization problem in (2), as the other algorithms. For a small number of users, the performance deviation between the delay estimate algorithm and the optimum algorithm is small. On the negative side, as the number of users increases the performance deviation increases (for two users scenario the PD about 13%, and for four users scenario about 35%).

To illustrate the complexity analysis of the proposed algorithms, we compare between them experimentally as shown in Table III.

TABLE III
COMPARISON OF SIMULATION TIMES FOR DIFFERENT PROPOSED ALGORITHMS EXECUTED ON THE SAME PLATFORM.

Number of users	Optimum	Equal delay	Minimum delay	Delay estimate
1	21.562 s	21.562 s	2.594 s	0.0026 s
2	9.656 min	45.503 s	2.988 s	0.0048 s
3	2.744 h	1.142 min	3.738 s	0.0068 s
4	2.187 d	1.526 min	4.127 s	0.014 s

Table III shows enormous complexity reductions for the suboptimum algorithms in case of four-users. An exhaustive search would require 2.187 days of simulation time. The equal delay algorithm would require 1.526 minutes whereas the minimum delay algorithm requires 4.127 seconds and the delay estimate algorithm requires 0.014 seconds only.

VI. CONCLUSION

In this paper, multihop wireless networks with multiple transmit/receive pairs are considered. In the proposed approach, transmitted energy, application QoS constraints, and scheduling are jointly integrated into a cross-layer design framework. This framework is used to dynamically perform radio resource allocation for multiple users, and to effectively choose the optimal system parameters to adapt to the varying channel conditions. The proposed cross-layer algorithms determine the modulation type, the transmitted energy and the route for each user in a way to minimize the overall transmission energy while taking into account the given packets delay constraints and BER.

As expected, the more complex the mesh topology is , the higher the rate of increase of complexity for the optimum proposed algorithm. Therefore, in addition to the optimal proposed solution, suboptimum solutions are presented to reduce the complexity significantly with minimal performance degradation, as shown in the simulation results. The simulation results show also that, under the same conditions, the optimum proposed algorithm has less energy consumption than the constant-energy routing algorithms that consider the delay constraints only.

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