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# Joint Optimization of Link Scheduling, Power Control, and Routing in Ad Hoc Wireless Networks

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**Abstract**: Cross-layer design is an extensive research area in ad hoc wireless networks and is particularly important under energy constraints. The physical layer, link layer, and network layer are known to have great impact on network performance as well as on energy consumption; hence, the interactions between these layers should be studied. In this paper, we formulate an optimal link scheduling and power control policy that supports a particular data rate on each link in the network while satisfying the Signal to Interference plus Noise Ratio (SINR) and the maximum transmission power constraints at each node. We present an optimization problem considering both the energy consumed of each node in the routing path and the delay associated on each link as the link cost metrics. The problem is to find an optimal link scheduling, power control and routing policy that minimizes the end-to-end delay as well as the energy link cost subject to certain constraints. We provide numerical examples for our schemes and relationships between the parameters i.e. the higher the required data rate and the higher the SINR requirement; the system will become less energy-efficient since a high transmission power is needed. This paper is a preliminary step towards our distributed joint scheduling, power control and routing algorithm for ad hoc networks using cross layer approach.

**Keywords:** Ad hoc networks, scheduling, power control, routing, cross layer, optimization.

## 1. INTRODUCTION

Recently, researchers realize that in wireless networking there is strong coupling among the traditional layers of the OSI architecture and these layer interactions cannot be ignored. Hence, they present cross layer design ideas by exploiting the dependence between protocol layers to obtain performance gains. According to [1], there are three main reasons why wireless links in the network motivate designers to violate the layered architecture. The three main reasons are the unique problems created by wireless links, the possibility of opportunistic communication on wireless links, and the new modalities of communication offered by the wireless medium.

Many research works in routing in the literature assume a fixed underlying protocol for access control and most of the research on multiple access control assume fixed routes and flow requirements. According to [2], the choice of MAC layer protocol does, in fact, affect the relative performance of the routing protocols. Hence, a cross layer design should be implemented between the network and the MAC layer since the functionalities of the two layers interact. Likewise, coupling between power control in the physical layer and scheduling in the MAC layer should be investigated further.

One of our objectives in this study is to minimize the overall transmission power of the network. The interdependencies between these three layers are being studied since they take part for the energy expenditure of the whole system. The MAC layer controls the interference level at any time instance which may lead to transmit power adaptation in physical layer. The physical layer, on the other hand, classifies the node's local neighborhood and thus defines the context in which access, routing, and other higher-layer protocols operate. The exchange of routing information between nodes also entails energy cost. Thus, the joint scheduling, power control, and routing protocol in an ad hoc wireless networks is a significant design challenge, especially under energy constraints where the exchange of data consumes precious energy resources.

## 2. RELATED WORKS

The inherent characteristics of ad hoc networks such as lack of centralized control, limited node capability, and variability of the links and network topology pose different problems and design challenges to researchers nowadays. The inflexibility and sub-optimality of layered architecture design usually result in poor performance of a network, especially when energy is a constraint or the application has high bandwidth needs, and/or stringent delay constraints [6]. According to Goldsmith et al. a cross-layer protocol design that supports adaptivity and optimization across multiple layers of the protocol stack is needed.

Kozat et al. [3] developed a framework for cross-layer design towards energy-efficient communication. They addressed the joint problem of power control and scheduling with the objective of minimizing the total transmit power subject to the end-to-end QoS guarantees for sessions in terms of bandwidth and bit error rate guarantees. However, their algorithms are centralized and routing issues were not incorporated. Cruz and Santhaman [4] on the other hand, developed an integrated routing, link scheduling and

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power allocation policy for a general multihop network that minimizes the total average power consumption to support minimum average rate requirements per link. Their results showed that finding optimum allocations do not necessarily route traffic over minimum energy paths and non-minimum energy paths can be exploited to increase throughput. Hence, we could see from their study that there is a tradeoff between energy and throughput. In addition, authors in [5] provide a centralized algorithm of joint power control, scheduling, and routing in TDMA-based wireless ad-hoc networks. In their simulations, they showed that there is a trade-off between the energy consumption and the network performance such as throughput and delay.

In all current protocols, the MAC and routing protocols really need improvement in order to reduce the energy consumption and increase the life of the nodes [10]. There exist MAC protocols such as SMAC, PAMAS, and etc. which deal on the energy conservation at the MAC layer by powering OFF the nodes when they are doing no useful work [10]. For routing, most papers consider only the minimum energy path irregardless of the delay associated with transporting a data while some papers deal only with end-to-end delay which leads to finding the shortest-hop path (see [10] and references herein.). In this way, one or more nodes on the shortest-hop path are heavily loaded and nodes will tend to have widely differing energy consumption which results in an early death of some nodes. Hence, in this paper, we take into account both the delay and energy consumption of each link in the network. Section 3.2 dwells on this matter in more detail.

## 3. SYSTEM MODEL

We consider a general wireless ad hoc network, where all nodes need not be in the transmission range of each other. At this time, we just assume that there is good global time known to all users and each node has one omni-directional antenna which cannot receive and transmit simultaneously. We assume a symmetric hearing matrix, that is, node $i$ can receive signal from node $j$ if and only if node $j$ can receive signal from node $i$. We define a link $(i,j)$ to represent an active direct communication pair and $l(i,j) \in L$ (see Fig. 1). Likewise, we define that the channel gain between two nodes is approximately the same in both directions.

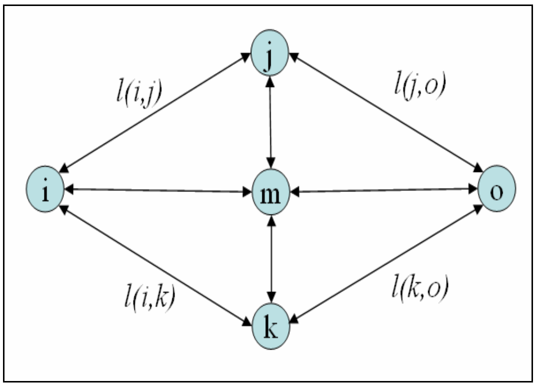

Fig. 1. System Model

We let $G_{ij}$ as the link gain between the transmitter $j$ and its intended receiver $i$ and we also let $G_{ji}$ as the link gain of the transmitter $i$ to a receiver $j$. On the other hand, $G_{ik}$ is the link gain of the receiver $i$ and a transmitter $k$ - an interfering node. We let $\Gamma_i(\mathbf{P})$ be the SINR at node $i$ and $\gamma_i$ is its target SINR. The interference caused by simultaneous transmissions is treated as noise. We let node $j$ denote the node transmitting a packet to node $i$, and node $i$ receives a transmission from node $j$ successfully if the corresponding SINR at node $i$ is greater than or equal to a given threshold $\gamma_i$.

$$\Gamma_{ij}(\mathbf{P}) = \frac{P_{ij}G_{ij}}{\sum_{j \neq k} G_{ik}P_{ik} + N_i} \geq \gamma_i \qquad (1)$$

Assuming presence of Gaussian noise and interference, the Shannon capacity of a link over a frequency bandwidth W is given by

$$R_i(P) = W \log_2(1 + \Gamma_i(P)) \qquad (2)$$

It is the capacity in bits per second and the theoretical maximum that can be achieved. We presume a system of ad hoc network consisting of M nodes. We let $\mathbf{P} = (P_1, P_2, ..., P_M)^T$ as a power vector where $P_i$ is the transmit power of a node $i$. We let $N_j$ as the thermal noise at the receiver node $i$, where $N_i = \eta_O B_T$ and $\eta_O$ is the noise density with bandwidth $B_T$. Furthermore, we define a noise power vector $\mathbf{N} = (N_1, N_2, ..., N_M)$, for every node $i$.

### 3.1 Optimal Link Scheduling and Power control Policy

The problem aims to find an optimal link scheduling and power control policy that minimizes the total transmission power subject to minimum data rate, maximum transmission power constraint, and SINR constraint. Here, we focus on next neighbor transmissions, that is, the node is sending packets to the specified neighbors while meeting the constraints at the intended receivers. The optimization problem is a linear programming (LP) problem where the objective function (3) could be stated as

$$\text{Minimize} \quad H(\mathbf{P}) = \sum_{i=1}^{M} \alpha_i P_i \qquad i = 1, 2, .., \text{M} \qquad (3)$$

$$\text{subject to} \quad 0 \leq P_i \leq P_i \max \qquad (4)$$

$$\Gamma_i(\mathbf{P}) \geq \gamma_i \qquad (5)$$

$$R_i(\mathbf{P}) \geq X_i \qquad (6)$$

where $\alpha$ is the cost or weight assigned for each transmission power where $\sum_{i=1}^{M} \alpha_i = 1$, and $X_i$ is the minimum data rate. The constraints (4), (5) and (6) denote the node's maximum transmission power, SINR constraint, and the minimum data rate constraint, respectively. From (1) and (2) you can see that constraints (5) and (6) are not linear. However, (5) can be written in the form of $A\mathbf{P} \ge b$, where A is a receiver by transmitter matrix.

$$\mathbf{A} = \begin{bmatrix} 1 & \frac{-\gamma_1 G_{12}}{G_{11}} & \cdots & -\frac{\gamma_1 G_{1M}}{G_{11}} \\ \frac{-\gamma_2 G_{21}}{G_{22}} & 1 & \cdots & \frac{-\gamma_2 G_{2M}}{G_{22}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-\gamma_M G_{M1}}{G_{MM}} & \frac{-\gamma_M G_{M2}}{G_{MM}} & \cdots & 1 \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} \frac{\gamma_1 N_1}{G_{11}} \\ \frac{\gamma_2 N_2}{G_{22}} \\ \vdots \\ \frac{\gamma_M N_M}{G_{MM}} \end{bmatrix}$$

Likewise, the constraint (6) can be written in the form of $C\mathbf{P} \ge d$.

$$R_i(\mathbf{P}) = W \log_2(1 + \Gamma_i(P)) \ge X_i$$

$$\left( \frac{P_{ij} G_{ij}}{\sum_{j \ne k} G_{ik} P_{ik} + N_i} \right) \ge 2^{\frac{X_i}{W}} - 1 \tag{7}$$

If we let $\varphi_i = 2^{\frac{X_i}{W}} - 1$ then we have equation (7) of the form $C\mathbf{P} \ge d$ where

$$\mathbf{C} = \begin{bmatrix} 1 & \frac{-\varphi_1 G_{12}}{G_{11}} & \cdots & -\frac{\varphi_1 G_{1M}}{G_{11}} \\ \frac{-\varphi_2 G_{21}}{G_{22}} & 1 & \cdots & \frac{-\varphi_2 G_{2M}}{G_{22}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-\varphi_M G_{M1}}{G_{MM}} & \frac{-\varphi_M G_{M2}}{G_{MM}} & \cdots & 1 \end{bmatrix} \quad \mathbf{d} = \begin{bmatrix} \frac{\varphi_1 N_1}{G_{11}} \\ \frac{\varphi_2 N_2}{G_{22}} \\ \vdots \\ \frac{\varphi_M N_M}{G_{MM}} \end{bmatrix}$$

The optimization problem, which is our main problem, can be formally written as

$$\underset{P \in [0, P\max]}{\text{minimize}} \quad H(\mathbf{P}) = \alpha^T \mathbf{P} \tag{8}$$

$$\text{subject to} \quad -A\mathbf{P} \le -b \tag{9}$$

$$-C\mathbf{P} \le -d \tag{10}$$

The first objective of the joint scheduling and power control problem is to find an optimal transmission power satisfying the SINR requirement as well as the required data rate of all nodes. There may or may not exist a network power vector **P** that satisfies the given constraints. If there is a solution, the objective function converges to a minimum power vector. The SINR requirement may not be satisfied when some elements in the converged minimum power vector are larger than $P_{max}$ or there is really no solution. If a solution to the minimization problem (8) exists, this provides an optimal transmission power vector such that the total power expenditure of the system is minimized.

Since the Shannon formula for a band-limited channel is (2), there is a one-to-one correspondence between the instantaneously achievable data rates and the required link SINR [7]. An optimal solution to the problem in (8) exists if and only if there is a solution to the constraints given by equations (9) to (10) i.e. there is at least one set of transmission powers which ensures the successful reception at all receiver nodes which at the same time satisfies maximum node's transmission power, SINR, and data rate constraints respectively.

The minimization problem in (8) is now a linear programming (LP) problem. Observe that, the transmit power is bounded by $0 \le P_i \le P_{i\max}$ for all nodes; hence, an optimal solution exists by virtue of Theorem 3.4 in [9]. The optimal solution or minimizer $\mathbf{P}^*$ can be solved using simplex method or any other simple means.

### 3.2. Joint Scheduling, Power control and Routing Policy

In this paper, the routing algorithm is guided by the computation of the minimum power associated with optimal scheduling and power control for supporting the data rate on each link. The optimization problem for routing packets from a source to a destination considers both the energy consumed of each node in the routing path and the delay associated on each link as the link cost metrics.

#### 3.2.1 Minimize Energy Link Cost Problem

One of our goals is to maximize the life of all nodes in the network, i.e. to minimize the power cost of sending a packet from a source to a destination via intermediate nodes. The path to be selected must consider the energy reserves of the nodes such that nodes with depleted energy reserves do not lie on many paths. In Fig. 1, if node *m* will be selected as a route for packets going to node *o* from node *i*, node *m* will used up its battery at a faster rate compared to other nodes, hence, will die first than the other nodes in the network. Thus, this metric is important in order to extend the network life of the nodes.

According to [10], the discharge curve for some batteries is almost linear and we can associate a linear node cost function such as $\mathrm{f_i(z_i)} = \delta_i \mathrm{z_i}$ with each node where $z_i$ denotes the measured voltage that gives a good indication of the energy used so far. We define the total cost of sending a packet along some path $p_i$ as the sum of the weights of all nodes that lie along that path $p_i$. The cost of sending a packet from $n_i$ to $n_k$, [10] via intermediate nodes $n_2$, $n_3$, $n_{k-1}$ is given by

$$F_{pi}(z_i) = \sum_{i=1}^{k-1} f_i(z_i) \tag{11}$$

The goal is to minimize $F_{pi}$ for all packets sent from a source node to a destination node in a routing path.

#### 3.2.2 Minimize End-to-End Delay

We let $\Lambda = \sum f_{ij}(\lambda)$ as the aggregate rate of flow on link *(i,j)* or a local rate traffic from node *i* to *j*. We let $R_j$ as the transmission capacity, which according to Shannon $R_i(\mathbf{P}) = W\log_2(1+\Gamma_i(\mathbf{P}))$.

The cost of the link *(i,j)* considering delay on each link in an M/M/1 queue is dependent on the service rate and the arrival of packets on each link. Here, we use $R_i(\mathbf{P})$ and $R_{ij}(\mathbf{P})$ interchangeably, since it both denotes the transmission capacity of the link for every source-destination pair. Hence, the delay for a given link *(i,j)* in an M/M/1 queue can be computed by

$$D_{ij}(\Lambda_{ij}, R_{ij}) = \frac{\Lambda_{ij}}{R_{ij} - \Lambda_{ij}} \text{ or } \frac{1}{R_{ij} - \Lambda_{ij}} \qquad (12)$$

The end-to-end delay from source to destination of a specific path $p_i$ is given by

$$D(\Lambda, R) = \sum_{(i,j)\in L} D(\Lambda_{ij}, R_{ij}) \quad \forall l \in pi \qquad (13)$$

The minimization problem becomes

$$\text{Minimize } D(\Lambda, R) = \sum_{(i,j)\in L} D(\Lambda_{ij}, R_{ij}) \quad \forall l \in pi \qquad (14)$$

$$\text{subject to } \Lambda = \sum f_{ij}(\lambda) \quad \forall l \in L \qquad (15)$$

$$R_i(P) = W\log_2(1+\Gamma_i(\mathbf{P}))$$

$$0 \le P_i \le P_i \max$$

The goal is to minimize the end-to-end delay $D(\Lambda, R_{ij})$ for all packets sent from a source node to a destination node in a routing path $p_i$.

### 3.2.3 Optimal Link Scheduling, Power Control and Routing Policy.

Our goal is to find an optimal policy $\rho = (D(\Lambda_{ij}, R_{ij}), F_{pi}(z_i))$ as a function of delay and energy consumed of transmission links of a specific routing path, $p_i$. The problem is to find an optimal link scheduling, power control and routing policy that minimizes the end-to-end delay (14) as well as the energy link cost (11) subject to certain constraints. The problem can be stated as

$$\underset{0\le P_i \le P_i \max}{\text{Minimize}} \ \rho = (D(\Lambda_{ij}, R_{ij}), F_{pi}(z_i)) \qquad (16)$$

$$\text{subject to } \mathrm{D}_{pi} \le \mathrm{D}_T \qquad (17)$$

$$f_i z_i \ge E_T \qquad (18)$$

As you can see, the minimization problem in (16) is multi-objective. $D_T$ is the tolerable delay or delay threshold for sending packets from a source node to the destination/sink and $E_T$ is the energy threshold e.g. of a node or specifically, the voltage threshold of node's battery. From the discharge model of a Lithium-ion battery in [10], if the voltage is 2.8V, the battery is already dead since all of its capacity has been consumed. Here we could take $E_T$=3.6V where 80% of battery's capacity has been consumed.

Our planned routing algorithm is summarized in Fig. 2. Considering the joint scheduling and power control policy, the minimum energy path $p_i$ from all paths available for transmitting packets from source to destination, will be used. For every hop, the remaining energy of each node will be computed such that it should be greater or equal to the energy/voltage threshold, $E_T$ of node's battery. If a specific node's energy in path $p_i$ falls below the threshold, the intermediate node will search for other available node on the next hop for transmission. This will form a new path $p_i$ and the process continues. The delay for each link and the end-to-end delay of that specific path will be computed too. It should be less than or equal to the tolerable delay or delay threshold, else, that specific path $p_i$ will be eliminated for the next transmission. This means that another minimum energy path $p_i$ will be utilized if it is available.

## 4. NUMERICAL EXAMPLES

To test our joint scheduling and power control policy, we consider an asymmetric diamond topology [4] as shown in Fig. 3. Nodes in this topology are equipped with omni directional antennas i.e. they are not able to transmit and receive data at the same time. Node 1 is the source node and node 4 is the sink node. The path loss between each node is given by $G_{ij}=1/d_{ij}^4$ and we assume that the peak transmission power of each node is 1Watt. We use a channel frequency of 916MHz, a thermal noise n=–104dBm, and a SINR threshold of 6dB.

We consider our scheduling algorithm where all links share a common bandwidth and we have a per-node peak power constraint. We split the path into {1→2→4} and {1→3→4}. Since a node is not able to transmit and receive packets at the same time, we only allowed transmissions {1→2, 3→4} and {1→3, 2→4}) alternately, also to avoid interference.

We solved our optimization problem in (8) i.e. there exists a power vector that minimizes the total transmission power of transmitting nodes, using MATLab. We first consider the link's transmission {1→2, 3→4} where we plot the total minimum power with increasing required data rate demands as shown in Fig. 4. Same target SINR is assumed for all users. As the data rate increases, the network tends to become less energy-efficient. We vary the data rate from 1Mbps to 8Mbps with $\sum_{i=1}^{M} \alpha_i = 1$. The joint scheduling and power control algorithm uses more power for larger rate. As observed in the figure, the optimal transmission power required to achieve a data rate beyond 5Mbps increases with a greater slope. Hence, high data rate demands also require high transmission power. In addition, more power is needed to overcome the interference and satisfy the SIR requirement.

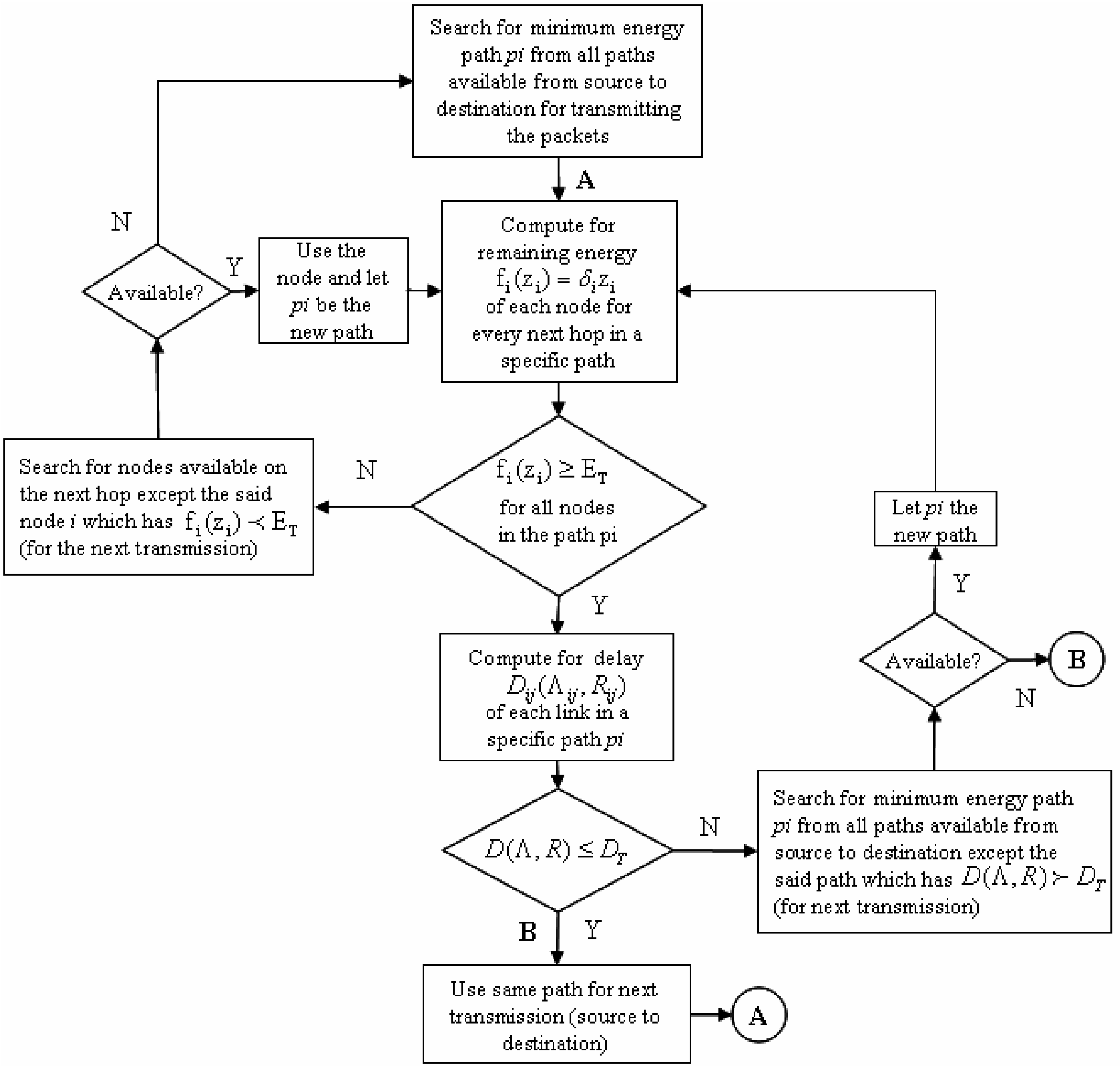


Fig. 2. A flowchart summarizing the intended routing algorithm.

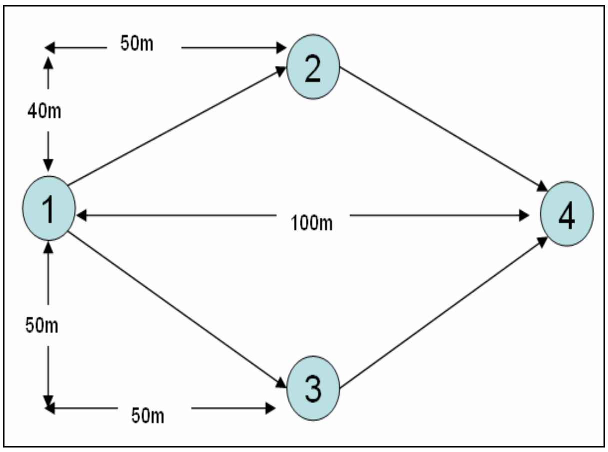


Fig. 3. Diamond Topology: node 1 is the source node and node 4 is the sink node.

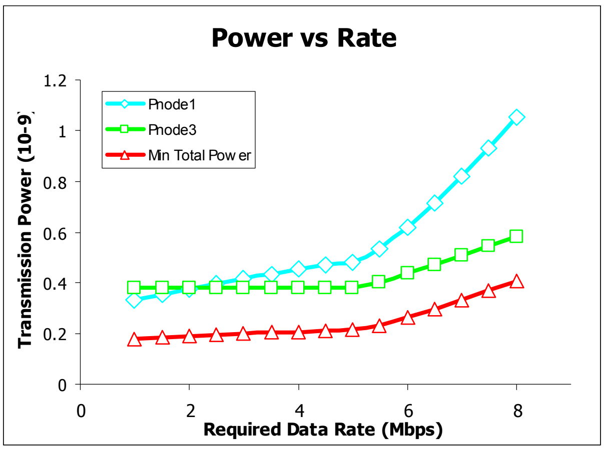


Fig. 4. Optimal transmission power versus the increasing required data rate demands in {1→2, 3→4} transmission.

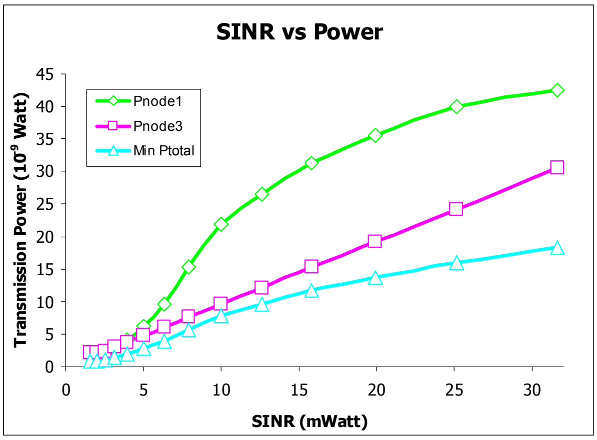


Fig. 5. Optimal transmission power versus the increasing required SINR demands in {1→2, 3→4} transmission.

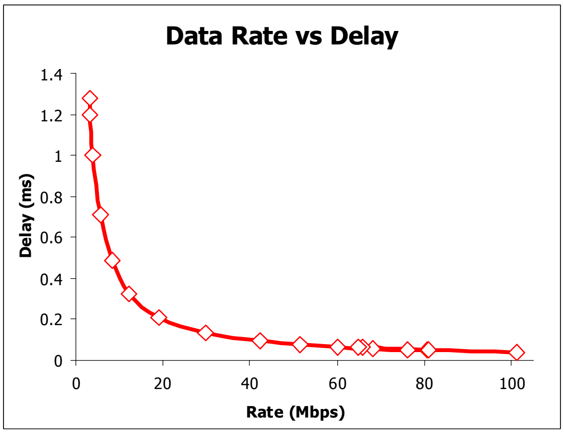


Fig. 6. The end-to-end delay in {1→2→4} transmission with increasing data rate.

Still considering the transmissions {1→2} and {3→4}, we plot the total minimum power with increasing required SINR (Fig. 5). We assumed a required data rate of 3MHz for all nodes. The transmission power of the nodes increases for larger SINR requirement.

Using the transmission power of node 1 from Fig. 5, we have plotted the end-to-end delay of {1→2→4} transmission as shown in Fig. 6. We used equation (12) in computing the delay on each link transmission where we set $\lambda = 2000s$. As you can see in Fig. 6, we find that as data rate increases, delay decreases. Note that we have not consider yet our optimal routing policy since we have not consider the aggregate flow if there is too much traffic or nodes transmitting to only one node. In such a case, the queues will keep on growing and delay will increase significantly as the rate increases.

The relationships between the parameters obtained are applicable when each user has a respective target SINR and users will access different services with different transmission rates. This presents the idea that the higher the required data rate and the higher the SINR requirement, the system will become less energy-efficient since a high transmission power is needed. Moreover, the faster the service or transmission capacity on each link, the lesser will be the end-to-end delay of the network. Further studies will be done to investigate the effects of these parameters on our routing algorithm. Also, the solution for the multi-objective problem in (16) will be provided in the future.

## 4. CONCLUSION

We have formulated an energy-constrained optimization problem for the link scheduling, power control and routing in ad hoc wireless networks. We have provided numerical examples for our scheme and relationships between the parameters i.e. the higher the required data rate and the higher the SINR requirement; the system will become less energy-efficient since a high transmission power is needed.

At this time, our approach considers quasi-stationary or fully stationary wireless ad hoc networks. This is just a preliminary step towards our distributed joint scheduling, power control and routing algorithm for ad hoc networks using cross layer approach. For our future work, we will provide the joint scheduling, power control and routing algorithm where we could relate our optimal policy and be able to investigate it.

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