Distributed Cooperative Rate Adaptation for Energy Efficiency in IEEE 802.11-Based Multihop Networks

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***Abstract*—In this paper, we study the problem of using the rate adaptation technique to achieve energy efficiency in an IEEE 802.11-based multihop network. Specifically, we formulate it as an optimization problem, i.e., minimizing the total transmission power over transmission data rates, subject to the traffic requirements of all the nodes in a multihop network. Interestingly, we can show that this problem is actually a well-known multiple-choice knapsack problem, which is proven to be an NP-hard problem. Therefore, instead of finding an optimal solution, which is NP-hard, we seek a suboptimal solution. Our key technique to attack this problem is distributed cooperative rate adaptation (CRA). Here, we promote node cooperation due to our observation that the inequality in noncooperative channel contention among nodes caused by hidden terminal phenomenon in a multihop network tends to result in energy inefficiency. Under this design philosophy, we propose a distributed CRA scheme and prove that it converges. Simulation results show that our CRA scheme can reduce power consumption up to 86% as compared to the existing (noncooperative) algorithm.**

***Index Terms*—Cooperation, energy efficiency, IEEE 802.11, rate adaptation, wireless multihop network.**

I. Introduction

ENERGY efficiency is one of the key issues in wireless multihop networks since most mobile devices are battery-operated. An effective way to achieve energy efficiency is to reduce the transmission power whenever possible. However, in a multirate-enabled network, reducing transmission power may result in reduced transmission rate [assuming that the bit error rate (BER) has to be below than a certain threshold]. Hence, power control and rate adaptation need to be jointly considered. The joint design of power control and rate adaptation to achieve energy efficiency while maintaining the required throughput is especially challenging in an IEEE 802.11-based multihop network. This is because the inequality of channel access in multihop networks can result in severe overall energy inefficiency. More specifically, in an IEEE 802.11-based multihop network, the hidden terminal phenomenon will cause some node may have smaller contention probability than another node (say, node in the hidden position), and hence, different nodes will have different probabilities to win the channel access (we call this phenomenon as inequality of channel access). It can be shown that this inequality of channel access can result in severe overall energy inefficiency (see Section IV). Here, we choose IEEE 802.11 [1]–[4] for the physical layer (PHY) and the medium access control (MAC) since it is the de facto standard for both wireless local area network (WLAN) and multihop networks. Multirate is supported in IEEE 802.11. For example, IEEE 802.11a [2] supports eight PHY channel rates ranged from 6 to 54 Mb/s based on different modulation schemes and coding rates.

To address this energy inefficiency problem in an IEEE 802.11-based multihop network, we seek to use power control and rate adaptation to optimize the energy efficiency while satisfying the throughput requirements. Since the transmission power can be uniquely determined by the transmission rate, given the required BER, interference level, the modulation scheme, and the distance between the transmitter and the receiver, in this paper, we will focus on rate adaptation only. Then, the problem can be formulated as an optimization problem, i.e., minimizing the total transmission energy over transmission data rates, subject to the traffic requirements of all the nodes in a multihop network.

Interestingly, we can show that the aforementioned power minimization problem is actually a well-known multiple-choice knapsack problem [5], which has already been proven as an NP-hard problem. Therefore, instead of finding an optimal solution, which is NP-hard, we seek a suboptimal solution for the power minimization problem; specifically, our key technique to attack this problem is distributed cooperative rate adaptation (CRA). Here, "distributed" means that a node makes rate adaptation decisions locally instead of globally as in a centralized scheme.

In addition, we promote node cooperation in rate adaptation, due to our observation that the inequality in noncooperative channel contention among nodes caused by hidden terminals in a multihop network tends to result in severe overall energy inefficiency (see Section IV). Under this design philosophy, we propose a distributed CRA scheme to achieve energy efficiency in IEEE 802.11-based multihop networks. The CRA scheme consists of three modules: information exchange algorithm,

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rate selection algorithm, and node cooperation algorithm. With the information exchange algorithm, each node can obtain the information of all links in its maximum interference range; the information includes the required channel time for satisfying the traffic requirements and corresponding energy consumption under all possible PHY rates on the link. Given the link information, each node uses the rate selection algorithm to calculate the most energy-efficient setting of PHY rates for all links in its maximum interference range. After obtaining the new PHY rates, a node uses the node cooperation algorithm to consult the neighboring nodes about the feasibility of the new PHY rates; if the PHY rates are feasible, they become valid. Then, a node uses the rate selection algorithm and node cooperation algorithm again to obtain new PHY rates that are feasible and reduce the total energy consumption. This procedure is repeated until it converges. Although the rate selection only bases upon local knowledge, each step of rate adaptation can guarantee the reduction of the total energy consumption and the total energy consumption is lower bounded, our CRA scheme must converge. Once the CRA converges, the resulting PHY rates and the corresponding transmission power can be used for rate adaptation and power control of each node.

To evaluate the performance of our CRA scheme, we conduct simulations. The results show that our CRA scheme can reduce power consumption up to 86%, as compared to the existing (noncooperative) algorithm.

The reminder of this paper is organized as follows. In Section II, we review related works. In Section III, we formulate the problem and prove its NP-hardness. In Section IV, we discuss why node cooperation can help improve overall energy efficiency. In Section V, we present our distributed CRA scheme for energy efficiency in 802.11-based multihop networks. Section VI shows the simulation results that demonstrate the effectiveness of our CRA scheme. Finally, Section VII concludes this paper.

II. Related Work

Today, three different PHYs for the IEEE 802.11 wireless network are available (802.11a/b/g); they all provide multirate capabilities. To achieve a high performance under varying conditions, these 802.11-enabled devices need to adapt their transmission rate dynamically, which has motivate the research on how to adjust the rate in an efficient way recently.

Rate adaptation in IEEE 802.11-based networks has been addressed in [6]–[16]. In [6], an automatic-rate-fallback (ARF) algorithm was proposed to maximize the throughput by adapting the PHY rate based on the channel conditions. In ARF, the PHY rate is increased after consecutive transmission successes, and decreased when failures occur. In [7], a rate adaptive MAC protocol named receiver-based auto rate (RBAR) was proposed. By RBAR, the rate adaptation is controlled by the receiver instead of the sender, and request to send/clear to send (RTS/CTS) frames are used to probe the channel condition and adapt rate. In [9], an opportunistic-auto-rate (OAR) protocol was proposed. The main idea of OAR is opportunistically sending multiple back-to-back packets whenever the channel quality is good. Theoretical analysis of the goodput under the rate adaptation for 802.11a-based WLANs were presented in [8] and [10]. However, all the aforementioned works [6]–[16] are targeted at maximizing the throughput [6]–[15] or optimizing both throughput and delay performance [16]. These works do not address the energy-efficiency issue, which is of our interest.

Energy efficiency of rate adaptation in 802.11-based WLANs were addressed in [17]–[20]. In [17], the authors considered point coordination function (PCF)-based WLANs and proposed energy-efficient PCF operations for transmission power control (TPC) and rate adaptation. DCF-based WLANs were considered in [20] and its preliminary work [18] and proposed an energy efficient scheme for joint TPC and rate adaptation, using a table that contains offline-computed optimal rate-power values. In addition, [20] also proposed to transmit the CTS frames at a higher power level in order to combat the TPC-induced interference. The problem of maximizing the goodput while minimizing energy consumption by joint TPC and rate adaptation in WLANs were considered in [21]–[24]. However, the key difference between multihop networks and WLANs is that multihop networks tend to exhibit inequality of channel access for different nodes caused by hidden terminal while WLANs do not. Therefore, the methods suitable for WLANs may not be applicable to multihop networks. In this paper, we address the inequality of channel access, which is unique for multihop networks, and propose a CRA scheme to achieve energy efficiency while maintaining the required throughput.

III. Problem Formulation

In this section, we first specify a power minimization problem that we want to solve, and then mathematically formulate the problem, based on analytical models for path loss, transmission, and contention. Finally, we prove the NP-hardness of the power minimization problem by mapping it to the multiple-choice knapsack problem.

A. Problem Statement

Given a wireless multihop network, and the traffic requirements on each link, determine the PHY rate and the corresponding transmission power for each link to minimize the total energy consumption while satisfying the traffic requirements of all links.

B. Analytical Models

In this section, we describe our network model, signal attenuation model (path loss model), the relationship between the transmission power and the PHY rate, the relationship between the energy consumption and the PHY rate, the relationship between the channel (access) time and the PHY rate, and the link conflict model. Based on these models, we formulate the power minimization problem mathematically.

1) Network Model: A wireless multihop network is modeled as a graph $G = (V, E)$, in which V is the node set, and E is the directed-link set. The link from source s to destination d is denoted by a tuple (s, d) and $\mathrm{dist}(s, d)$ denotes the geographical distance between s and d. The minimum traffic

TABLE I
RECEIVING POWER REQUIREMENTS OF IEEE 802.11a

Mode	PHY Rate (Mb/s)	Receiving Power Threshold $P_r(PHYrate)$ (dBm)
1	6	-82
2	9	-81
3	12	-79
4	18	-77
5	24	-74
6	36	-70
7	48	-66
8	54	-65

requirement on link (s,d) is represented by $\lambda(s,d)$, and current PHY rate on link (s,d) is represented by $R(s,d)$ (both in bits per second).

2) Signal Attenuation Model: The signal attenuation model defines the mapping from the transmission power $P_{\rm t}$ of source to the receiving power $P_{\rm r}$ of destination. In this paper, we adopt the path-loss model [25] as the signal attenuation model

$$P_{\rm r} = c \cdot \frac{P_{\rm t}}{d^k} \tag{1}$$

where d is the geographical distance between source and destination, and both c and k are constants, which are determined by environments.

3) Relationship Between Transmission Power and PHY Rate: In wireless communication, typically the BER is required to be less than a certain threshold; otherwise, the packet retransmission rate may be intolerably high. This implies that different PHY rates (or different constellation size in modulation) have different minimum SINR requirements. Generally, speaking, the higher the PHY rate, the more vulnerable to channel errors, resulting in a higher minimum SINR requirement and hence a higher transmission power.

Taking IEEE 802.11a [2] as an example, we use Table I to characterize the required receiving signal power as a function of the PHY transmission rate.

Using the aforementioned signal attenuation model, we can relate the transmission power of a source to the PHY rate as follows:

$$P_{\rm t}\left(R(s,d)\right) = \frac{P_{\rm r}\left(R(s,d)\right) \cdot {\rm dist}(s,d)^k}{c}. \tag{2}$$

4) Relationship Between Energy Consumption and PHY Rate: Now, we characterize the energy consumption as a function of PHY rate $R(s,d)$, given the traffic requirement $\lambda(s,d)$.

Taking IEEE 802.11a under RTS/CTS handshake mode as an example, RTS frames, CTS frames, and ACK frames in IEEE 802.11a are all transmitted at the basic rate, i.e., 6 Mb/s, while DATA frames are transmitted at the PHY rate selected by the source.

Here, we define average power consumption as the average energy consumption per second, which is averaged out over the whole time horizon and hence is different from instantaneous transmission power. In the rest of this paper, for simplicity, we use "power consumption" instead of "average power consumption." By simple derivation, the (average) power consumption ${\rm En}_{(s,d)}(R)$ on link (s,d) with the traffic requirement $\lambda(s,d)$ and the PHY rate $R(s,d)$ is given by

$$\begin{aligned}{\rm En}_{(s,d)}\left(R(s,d)\right) = \frac{\lambda(s,d)}{\text{packet\_size}}\,&[P_{\rm t}(\text{basic\_rate}) \\ \cdot\left(t_{\rm RTS}+t_{\rm CTS}+t_{\rm ACK}\right) &+ P_{\rm t}\left(R(s,d)\right)\cdot t_{\rm DATA}\left(R(s,d)\right)]\end{aligned} \tag{3}$$

where packet_size is the length of a payload packet in each DATA frame, $t_{\rm RTS}, t_{\rm CTS}$, and $t_{\rm ACK}$ are the transmission duration of an RTS frame, a CTS frame, and an ACK frame, respectively, and $t_{\rm DATA}(R(s,d))$ is the transmission duration of a DATA frame at the PHY rate $R(s,d)$, which is given by

$$t_{\rm DATA}\left(R(s,d)\right) = t_{\rm PLCP} + \frac{\text{packet\_size} + \text{overhead\_size}}{R(s,d)} \tag{4}$$

where $t_{\rm PLCP}$ is the transmission duration of the PHY header of a DATA frame, and overhead_size is the length of the overhead of a DATA frame.

Note that for simplicity, we only consider the power consumption in transmission, since the power consumption in reception and in the idle mode are much smaller than that in transmission [26].

5) Relationship Between Channel Time and PHY Rate: Next, we characterize the desired channel (access) time for satisfying the traffic requirements as a function of the PHY rate. By channel time, we mean the fraction of a second used by a successful RTS/CTS/DATA/ACK exchange between a source and a destination. According to IEEE 802.11 standard, the channel time used by link (s,d) can be derived as follows:

$$\begin{aligned}&\text{Channel Time}_{(s,d)}\left(R(s,d)\right) = \frac{\lambda(s,d)}{\text{packet\_size}} \\ &\cdot\left(t_{\rm DIFS}+t_{\rm RTS}+2\cdot t_{\rm SIFS}+t_{\rm CTS}+t_{\rm DATA}\left(R(s,d)\right)+t_{\rm ACK}\right).\end{aligned} \tag{5}$$

6) Link Conflict Model: We assume a single channel is used in a multihop network since currently commercial available 802.11 devices can only be allowed to configure in one common channel within one multihop network.[1] Then, the receiving data of a node (say, node A) can be corrupted if another unintended node is transmitting in the interference range of node A. IEEE 802.11 MAC is a CSMA/CA protocol; each node in an 802.11-based network has a sensing range in which the signals can be detected. The sensing range of a node is determined by the clear-channel-assessment (CCA) sensitivity, which is the minimal detectable signal strength. We assume that the CCA sensitivity is also the minimal interfering signal strength that

[1] Note that it is easy to extend single-channel conflict model to multichannel conflict model by combining multiple single-channel confliction model among all orthogonal channels, since the signals do not conflict among different (orthogonal) channels.

can corrupt an intended transmission. Then, the interference range $R_I(s)$ of node s with transmission power P_s is

$$R_I(s) = \sqrt[k]{c \cdot \frac{P_s}{\text{CCA}}} \tag{6}$$

where both c and k are constants given by the signal attenuation model.

Since bidirectional handshakes are required in IEEE 802.11, then two links, say (s, d) and (u, v), conflict with each other when any of the following conditions holds:

$$\begin{aligned} &\langle 1\rangle\ \text{dist}(s,u) \le \max\left(R_I(s), R_I(u)\right) \\ &\langle 2\rangle\ \text{dist}(s,v) \le \max\left(R_I(s), R_I(v)\right) \\ &\langle 3\rangle\ \text{dist}(d,u) \le \max\left(R_I(d), R_I(u)\right) \\ &\langle 4\rangle\ \text{dist}(d,v) \le \max\left(R_I(d), R_I(v)\right). \end{aligned} \tag{7}$$

We then derive the channel time constraints according to the conflict graph proposed in [27]. Each vertex in the conflict graph represents a wireless link in the multihop network, and there is an edge between two vertexes if and only if the links represented by the vertexes conflict. A clique in the conflict graph represents a set of links that cannot transmit concurrently, and hence have to access the channel exclusively. Therefore, the total channel time utilized by all the links that form a clique in the conflict graph must be less than or equal to 1, i.e.,

$$\sum_{(i,j)\in S} \text{Channel Time}_{(i,j)}\left(R(i,j)\right) \le 1$$
$$S \in \{\text{all max cliques in the conflict graph}\}. \tag{8}$$

7) Problem Formulation: Finally, the problem stated in Section III-A can be formulated as the following optimization problem:

$$\min_{R(i,j)} \left(\sum_{(i,j)\in E} \text{En}_{(i,j)}\left(R(i,j)\right) \right)$$
$$\text{s.t.}$$
$$\langle 1\rangle\ R(i,j) \in \{\text{all possible PHY rates}\}$$
$$\langle 2\rangle\ \sum_{(i,j)\in S} \text{Channel Time}_{(i,j)}\left(R(i,j)\right) \le 1.$$
$$S \in \{\text{all max cliques in the conflict graph}\}. \tag{9}$$

Hence, the energy-efficiency problem is formulated as selecting a PHY rate for each link from its possible rate set to minimize the total power consumption while satisfying all channel time constraints, which are modeled by the conflict graph.

C. Proof of NP-Hardness

Now, we prove the aforementioned power minimization problem is NP-hard. The proof is based on our observation that the power minimization problem is actually a multiple-choice knapsack problem, which was proven to be NP-hard [5].

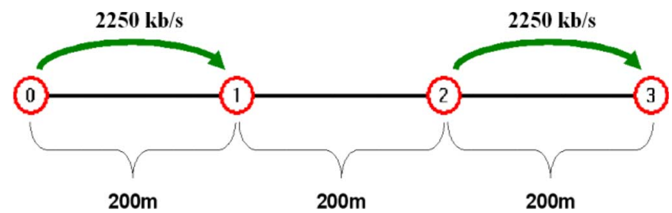

Fig. 1. Chain topology and traffic patterns.

Let us explain how to map the power minimization problem to a multiple-choice knapsack problem. Assume there are K links in a multihop network; for each link k $(k \in \{1, \ldots, K\})$, there are N_k PHY rates to be used for transmission; denote the set of these N_k PHY rates by Γ_k. Each PHY rate $j \in \Gamma_k$ is associated with channel time w_{kj} and power consumption v_{kj}. Now, if we regard a PHY rate as an item, a link as a class, a channel time as a weight, and power consumption as a cost (or a negative value), the power minimization problem is exactly a multiple-choice knapsack problem, i.e., the problem is to choose exactly one item (PHY rate) from each class (link) such that the sum of the values (negative energy consumption) of the chosen items is maximized, while the sum of the weights (channel time) of the chosen items cannot exceed a given capacity c. Here, the capacity c is equal to 1.

Since the multiple-choice knapsack problem is proven to be NP-hard [5], our power minimization problem is also NP-hard. Due to the NP-hardness of the power minimization problem, we seek a suboptimal solution to the problem instead of an optimal solution. Our suboptimal solution is based on cooperation among nodes. We argue that node cooperation is necessary to achieve global energy efficiency, and the reasoning is presented in the next section.

IV. Why Do We Need Node Cooperation?

In this section, we illustrate how the inequality in channel competition among nodes due to topologies and traffic patterns can result in unfair channel access and energy inefficiency and argue that to achieve global energy efficiency from the viewpoint of a network, node cooperation is necessary.

Consider a multihop network with a chain topology as shown in Fig. 1. The geographical distance between any two adjacent nodes is 200 m. There exist two flows with the same traffic rate requirement of 2250 kb/s: one is from node 0 to node 1, and the other is from node 2 to node 3. Each node uses IEEE 802.11a protocol.

In node 1, the transmission from node 2 to node 3 can corrupt the concurrent signals received by node 1 from node 0, but cannot be sensed by node 0; thus, node 2 is a "hidden terminal" of node 0. Since node 3 is out of the interference range of both node 0 and node 1, the transmission on (2, 3) cannot be corrupted by the transmission on (0, 1).

In IEEE 802.11, data transmission is initiated by the sender when the channel is sensed as idle. In Fig. 1, the channel sensed idle by node 2 is also free for node 3 to receive data. However, the channel sensed idle by node 0 may be actually busy due to the hidden terminal effect. Therefore, node 2 gains an advantage over node 0 in channel contention.

TABLE II
PHY RATES AND ENERGY CONSUMPTION COMPARISONS

	PHY Rate on (0,1)	PHY Rate on(2,3)	Total Power Consumption(mW)
Non-Cooperative Solution	48Mb/s	9Mb/s	6.704
Optimal Solution	18Mb/s	18Mb/s	2.352

If each node in this network takes into account only its own energy efficiency in rate adaptation, i.e., achieves energy efficiency in a noncooperative manner, then node 2 will use the most energy efficient (and usually lower) power level, i.e., choose the most energy efficient PHY rate (9 Mb/s in this case), as long as its own traffic requirement can be satisfied. As a result, node 2 will use the channel with more channel time and hence node 0 will have less channel time. To accommodate the less available channel time, node 0 has to adopt a higher PHY rate with higher transmission power. In this case, although node 2 can save some energy with a low PHY rate, node 0 has to consume more energy than that saved by node 2, resulting in higher total (average) power consumption as shown in Table II. This could result in global energy inefficiency.

Table II shows the PHY rates and total power consumption of two links for the noncooperative solution and the optimal solution to the power minimization problem, respectively. The noncooperative solution is that (2, 3) uses a very low PHY rate (i.e., 9 Mb/s), while (0, 1) uses a very high one (i.e., 48 Mb/s), and while the optimal solution is that both (0, 1) and (2, 3) use 18 Mb/s. It can be seen that the power consumption of the noncooperative solution is much higher than that of the optimal one.

Let us look at what happens for the noncooperative and cooperative case, respectively. If there is no cooperation among the nodes shown in Fig. 1, when node 2 uses a low PHY rate to achieve its own energy efficiency, it is not aware of the disadvantaged situation of link (0, 1) and link (0, 1) cannot change the situation by itself. Therefore, a cooperation mechanism is needed for global energy efficiency; for example, node 0 and 1 can actively inform node 2 of the situation, and call for its help.

From the example discussed above, we see the following.

1) In a multihop network, the inequality in channel contention among nodes due to topologies and traffic patterns could result in unfair channel time allocation among links.
2) If each node only takes its own energy efficiency into consideration, the above unfair channel time allocation could result in global energy inefficiency.

Therefore, to achieve global optimality in energy consumption, information exchange, and node cooperation among nodes are needed. Next, we present such a mechanism called CRA algorithm.

V. Distributed CRA Algorithm

In this section, we first explain the general ideas and main framework of CRA in Section V-A. Then, we introduce the detailed procedures of CRA in Section V-B. Finally, we prove the convergence of CRA in Section V-C.

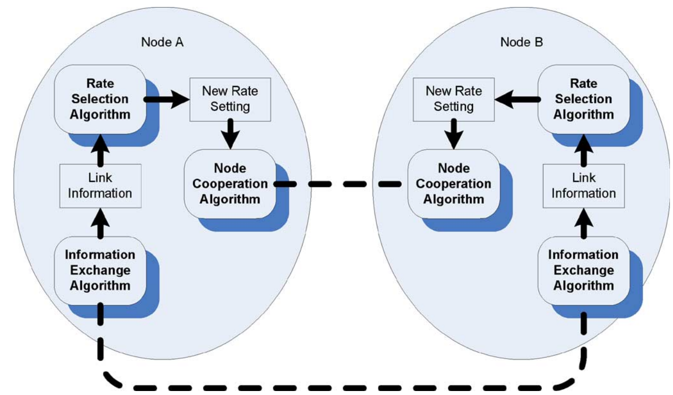

Fig. 2. Architecture of CRA.

A. General Ideas and Framework of CRA

Due to the decentralized characteristic of wireless multihop networks, we seek a practical distributed solution for the problem at hand. Moreover, the key findings in Section IV demand cooperation among node.

Under the design philosophy of node cooperation, we construct our CRA algorithm as follows. CRA consists of three modules: information exchange algorithm, rate selection algorithm, and node cooperation algorithm. The "information exchange algorithm" is to help each node obtain relevant information of all the links in its maximum interference range, which includes the needed channel time for satisfying the traffic requirements and corresponding power consumption under all possible PHY rates on the link. With this link information, each node uses the "rate selection algorithm" to calculate and obtain the most energy efficient setting of PHY rates for all the links in its maximum interference range. Then, each node requests its neighboring nodes to check the feasibility of this new rate setting through the "node cooperation algorithm." The node cooperation algorithm accepts rate change when the new rate is feasible and can reduce the energy consumption. Fig. 2 illustrates the components of CRA. Among the three modules, the rate selection algorithm is the kernel. The information exchange algorithm provides it with the input for calculation (the link information), while the node cooperation algorithm processes its output (checks its feasibility and carries it out).

Under the distributed design philosophy, we decompose the global power minimization problem into subproblems for each node that only involves the neighbors within the maximum interference range of each node. In CRA, each node independently calculates the most energy efficient setting of PHY rates for all the links in its maximum interference range based upon the information obtained within the maximum interference range. Then, the new PHY rate setting is distributed to all the other nodes in the maximum interference range. Later in Section V-C, we prove that CRA converges even though each node only has local knowledge.

TABLE III
LINK INFORMATION OF FIG. 1

Information of link (0, 1)			
Rate Index	PHY Rate(Mb/s)	Channel Time(s)	Power Consumption(mW)
0	54	0.374	6.643
1	48	0.380	5.776
2	36	0.397	2.961
3	24	0.432	1.727
4	18	0.467	1.176
5	12	0.537	1.087
6	9	0.607	0.928
7	6	0.747	1.053
Information of link (2, 3)			
0	54	0.374	6.643
1	48	0.380	5.776
2	36	0.397	2.961
3	24	0.432	1.727
4	18	0.467	1.176
5	12	0.537	1.087
6	9	0.607	0.928
7	6	0.747	1.053

B. Detailed Procedures of CRA

In this section, we describe the three modules of CRA in detail.

1) Information Exchange Algorithm: The main function of the information exchange algorithm is to provide each node with the link information needed in the calculation of the new rate setting. The information on a link includes the needed channel time for satisfying the traffic requirements and the corresponding power consumption under all possible PHY rates. As an example, Table III shows all the link information for the scenario in Fig. 1. A node should broadcast the information of its outgoing and incoming links in its maximum interference range.

A node also needs to broadcast the information about the cliques in the conflict graph with maximum power level, which represent the channel time constraints. A node can derive whether one of its neighborhood links could conflict with it on lower power level by (6) and (7). In this paper, we assume the topology of the network is fixed or changes very slowly; thus, the clique information can be updated in a slow time scale and will not incur too much signaling overhead. Note that the change of traffic requirements could incur extra signaling overhead, we may need to balance the frequency of changing the traffic requirement on each wireless link and the signaling overhead to propagate the changed traffic requirements.

2) Rate Selection Algorithm: Although we decompose the problem into subproblems for each node, a subproblem at each node is in essence still a multichoice knapsack problem, which is NP hard. Therefore, we seek a suboptimal solution and design the rate selection algorithm shown in Fig. 3, where we assume node A uses the rate selection algorithm to calculate the most energy efficient setting of PHY rates for all the links in its maximum interference range.

Now, we explain the rate selection algorithm. Suppose there are K available PHY rates, and we index them from 0 to $K-1$ in the descending order, i.e., rate 0 corresponds to the highest rate while rate $K-1$ corresponds to the lowest rate. If link l switches its rate from i to j, we define the benefit (power consumption reduced over channel time increased) of such switching as "benefit ratio" of replacing rate i with j on link l, which is defined by

$$\text{benefit\_ratio}(l,i,j) = \begin{cases} \frac{\text{power\_consumption}(l,i) - \text{power\_consumption}(l,j)}{\text{channel\_time}(l,j) - \text{channel\_time}(l,i)}, & i \neq j \\ 0, & i = j \end{cases} \tag{10}$$

where channel_time(l,i) is the needed channel time for satisfying the traffic requirements on l under rate i, which can be obtained by (5), and power_consumption(l,i) is the power consumption on l under rate i, which can be obtained by (3).

To illustrate the physical meaning of the benefit ratio, we plot Fig. 4 for link l. In Fig. 4, the channel time and power consumption of each PHY rate on link l corresponds to a point on the plane. benefit_ratio(l,i,j) is the absolute value of the slope of the line between the point for rate i and the point for rate j. It is the ratio of the power consumption reduction to the increased channel time when replacing rate i with rate j on link l.

Next, we use the scenario in Fig. 1 to show how the rate selection algorithm works. Suppose that it is node 0 that invokes the rate adaptation algorithm. Before executing the rate adaptation algorithm, the information exchange algorithm has already provided the information of all the links in node 0's maximum interference range, namely, link (0, 1) and (2, 3). The information is shown in Table III. Note that the information for link (0, 1) and link (2, 3) is the same since the two links have the same transmitter–receiver separation distance. Table III shows channel time versus power consumption for link (0, 1) and link (2, 3), respectively.

Node 0 executes the rate selection algorithm by the following steps.

- Step 1) The initial PHY rates of both (0, 1) and (2, 3) are set to 54 Mb/s. For each link, calculate the benefit ratio of each remaining PHY rate, with respect to the initial PHY rate.
- Step 2) For each link l, find the rate $R^*(l)$ with the largest benefit ratio among the remaining PHY rate. Then, choose the link with a larger benefit ratio among the two links; if the largest benefit ratio is the same for the two links, randomly choose one of the links. The corresponding $R^*(l)$ is the new rate.
- Step 3) Check the feasibility of the new rate $R^*(l)$. If it is feasible, select the new rate setting; otherwise, reset to the previous setting. Repeat Steps 2) and 3) until all rates are parsed.

The results of the rate setting are as follows: 54 Mb/s for (0, 1), 54 Mb/s for (2, 3), 36 Mb/s for (0, 1), 36 Mb/s for (2, 3), 24 Mb/s for (0, 1), 24 Mb/s for (2, 3), 18 Mb/s for (0, 1), and

Step 1: Set the PHY rate for each link in A's maximum interference range to the highest value as the initial setting.

Step 2: For each link within A's maximum interference range, select a PHY rate that has the largest $\Delta E/\Delta T$, where ΔE denotes energy reduction and ΔT denotes the channel time increase, as compared to the current setting. Then, choose the link that has the largest $\Delta E/\Delta T$ among all the links within A's maximum interference range (The power/rate of all other links is not changed). Note that ΔE should be greater than 0. If we can not find a setting that could result in ΔE>0, the algorithm ends.

Step 3: Check whether the new PHY rate of the link is feasible by (8). If it is feasible, select the new rate setting; otherwise, reset to the previous setting.

Step 4: Go to Step 2.

Fig. 3. Rate selection algorithm.

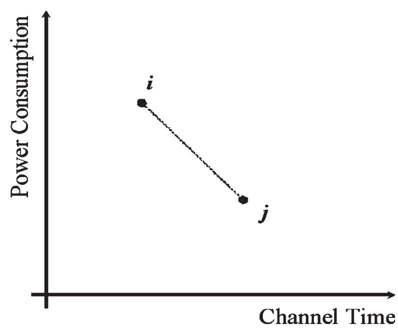

Fig. 4. Physical meaning of benefit ratio.

18 Mb/s for (2, 3). Finally, the algorithm produces 18 Mb/s for (0, 1), and 18 Mb/s for (2, 3) as the output.

3) Node Cooperation Algorithm: Node cooperation algorithm serves two purposes. First, it helps a node determine the feasibility of a new rate setting determined by the rate selection algorithm of its neighboring node. Second, the algorithm carries out the new setting when it is feasible. It works by the following steps[2]:

a) HELP: After obtaining a new rate setting, a node finds out all the links that need rate adaptation and sends each of them a HELP message. The HELP message contains the new rate of all involved links.

b) ACK and REJECT: Upon receiving a HELP message, a node should check whether the new rate setting is feasible in its maximum interference range. Note that it is possible that the new rate setting is not feasible for this node that receives the HELP message, since the interference range of this node may be different from that of the seeking-help node.

If the node receiving HELP message justify the feasibility of the new rate setting, it will reply with an ACK message to the seeking-help node to notify acceptance of the new setting. Otherwise, it will reply with a REJECT message to that node to notify declination of the new setting.

c) APPLY: Once the seeking-help node gets a REJECT message, it cancels the current candidate solution, and recalculates a new solution by excluding the nonfeasible one. If the seeking-help node gets ACK messages from all the helpers (i.e., the nodes that receive a HELP message), it then adjusts its PHY rate according to the current solution and sends an APPLY message with the new rates to all the helpers. A helper also adjusts its PHY rate upon receiving the APPLY message.

[2]We assume the rate adaptation of CRA is asynchronous among nodes, which means each node claims its rate setting proposal in turn. We rely on existing technologies to achieve this [28].

C. Convergence of CRA

The convergence is critical to the performance of CRA, because if CRA could not converge, the rate adaptation and the corresponding message exchanges will not stop, resulting in a large number of broadcast messages.

Now, we prove the convergence of CRA. Suppose that node i calculates a new rate setting by the rate selection algorithm. By the node cooperation algorithm, if feasible, the new rate setting can result in less power consumption than the previous rate setting for all the nodes within node i's maximum interference range. For the links outside node i's maximum interference range, their PHY rate does not change. Therefore, their total power consumption is also unchanged [according to (3)]. Therefore, the scheme guarantees that the total power consumption of the whole network is reduced after rate adaptation.

Since each rate adaptation under CRA results in a (monotonic) decrease in total power consumption and the total power consumption is lower bounded by zero, hence, CRA must converge.

VI. Performance Evaluation

A. Simulation Setup

We developed a simulator using C++ to evaluate and compare the performance of CRA with that of the noncooperative heuristic under various topologies and traffic patterns. We adopt IEEE 802.11a in all simulations. The CCA sensitivity of IEEE 802.11a is set at −82 dBm according to the standard [2]. We use $P_{\mathrm{r}} = 5.0625 \cdot (P_{\mathrm{t}}/d^4)$ as the path loss model. The traffic is generated at a constant bit rate (CBR) with a fixed packet size of 512 B. We assume nodes are immobile and hence the routing paths (chosen by certain routing protocol) are assumed to be fixed. Other parameters are listed in Table IV.

TABLE IV
SIMULATION PARAMETERS

$t_{DIFS} = 50\mu s$	$t_{RTS} = 58.67\mu s$
$t_{SIFS} = 10\mu s$	$t_{CTS} = 50.67\mu s$
$t_{PLCP} = 32\mu s$	$t_{ACK} = 50.67\mu s$
$packet\_size = 512bytes$	$overhead\_size = 48bytes$

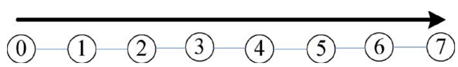

Fig. 5. Traffic pattern in chain topology.

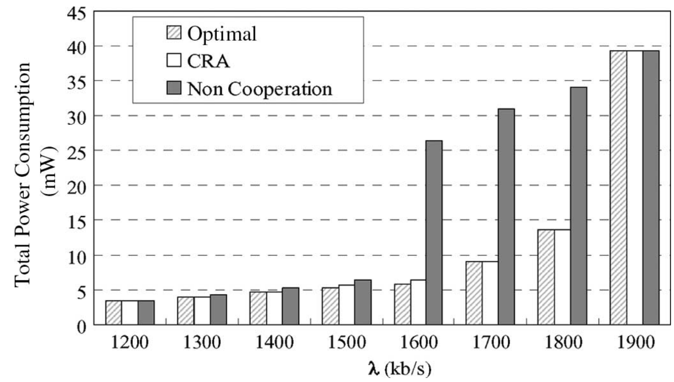

Fig. 6. Power consumption comparison in chain topology.

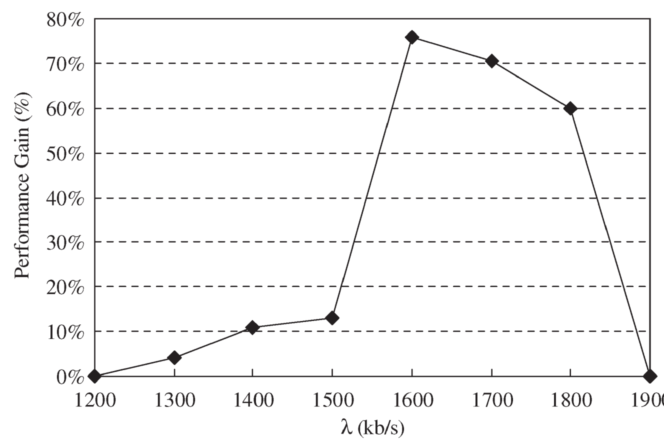

Fig. 7. Performance gain of CRA over noncooperative heuristic in chain topology.

B. Simulation Results

In this section, we compare the performance of CRA and the noncooperative heuristic in terms of total power consumption of the whole network and performance gain defined by

$$\text{performance\_gain} = 1 - \frac{\text{CRA Energy Consumption}}{\text{Noncooperative Heuristic Energy Consumption}}. \quad (11)$$

We conduct simulations under three types of topologies: chain, grid, and random topologies. For the chain topology, we compare the performance of CRA, the noncooperative heuristic, and the optimal solution to (9), under various traffic settings; the optimal solution to (9) is obtained by exhaustive search. For the grid and random topologies, which are much more complicated than the chain topology, the optimal solution to (9) is too expensive to calculate (due to its NP-hardness) and hence we compare CRA with the noncooperative heuristic.

1) Results in Chain Topology: The chain topology and its traffic pattern are shown in Fig. 5. The geographical distance between any two adjacent nodes is 200 m. There is only one flow in the chain topology, i.e., the flow from node 0 to node 7, which has a traffic requirement of CBR λ kb/s. We perform a series of simulations by varying λ from 1200 to 1900 kb/s. The reason of setting 1200 kb/s as the lower bound of the data rate is that when the data rate is less than 1200 kb/s, each link on the chain can satisfy its traffic requirement by using the most energy efficient PHY rate of its own, making the optimization problem (9) trivial. The reason of setting 1900 kb/s as the upper bound of the data rate is that when the data rate is greater than 1900 kb/s, each link on the chain is unable to meet its traffic requirement even if it uses the highest PHY rate. The traffic rate requirements ranged from 1200 to 1900 kb/s are the possible space where a cooperative energy efficient rate adaptation algorithm could have performance gain over the nonoperative scheme.

Fig. 6 shows power consumption of the three schemes. It can be seen that the solutions calculated by CRA are very close to the optimal solutions in all the cases and are even equal to the optimal solutions in some cases. This demonstrates that for simple topologies such as chain topologies, the rate selection algorithm in CRA can produce a very good solution, which is near the optimal solution. On the other hand, the noncooperative heuristic performs poorly for λ from 1600 to 1800 kb/s, as compared to CRA and the optimal scheme. This clearly shows the advantage of node cooperation.

Fig. 7 shows the performance gain of CRA over the noncooperative heuristic. We have the following observations.

1) The performance gain increases as the data rate increases from 1200 kb/s.
2) The performance gain reaches the maximal value when the data rate equal to 1600 kb/s.
3) The performance gain reduces as the data rate increases from 1600 kb/s.

This phenomenon is due to three reasons. First, when the data rate is 1200 kb/s, each link on the chain can satisfy its traffic requirement by using the most energy efficient PHY rate of its own; so there is no need to do optimization, i.e., the noncooperative heuristic achieves the same performance as that of CRA. Second, when the data rate is 1900 kb/s, each link on the chain has to use the highest PHY rate to meet its traffic requirement; hence, there is no room to do optimization, i.e., the noncooperative heuristic achieves the same performance as that of CRA. Third, when the data rate is greater than 1200 kb/s and less than 1900 kb/s, CRA can achieve better performance than the noncooperative heuristic since CRA is able to appropriately allocate the channel time among advantaged nodes and disadvantaged nodes to attain energy efficiency, as discussed in Sections IV and V.

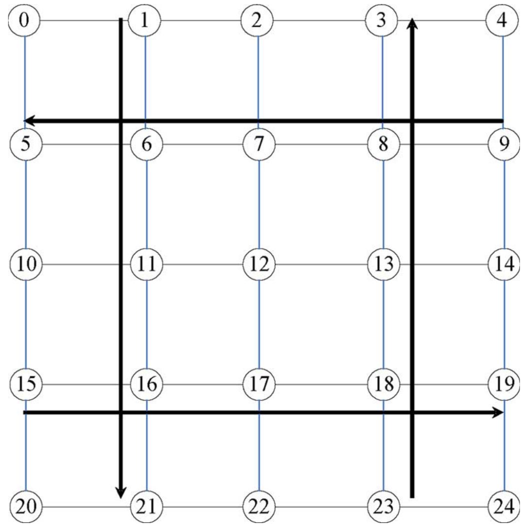

Fig. 8. Traffic pattern in grid topology.

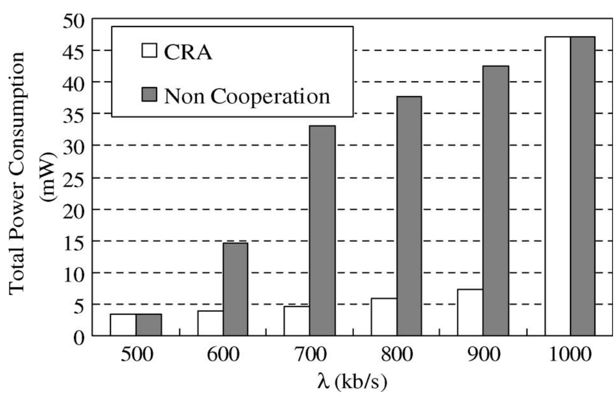

Fig. 9. Power consumption comparison in grid topology.

2) Results in Grid Topology: The grid topology and its traffic patterns are shown in Fig. 8. The geographical distance between any two adjacent nodes is also set to 200 m. There are four flows in the network: one from node 9 to node 5, one from node 15 to node 19, one from node 1 to node 21, and one from 23 to 3. All flows have the same traffic requirement of CBR λ kb/s. A series of simulations are performed by varying λ from 500 to 1000 kb/s. Similar to the chain topology, both the lower bound and the upper bound of the data rate are determined by the achievable range for the possible PHY rates in 802.11a.

Figs. 9 and 10 show power consumption comparison and performance gain of CRA, respectively. The results show that for a grid topology, CRA also achieves quite high performance gain over the noncooperative heuristic. Especially when the data rate is 700 kb/s, CRA achieves the highest performance gain of 86% over the noncooperative heuristic. Since both the interference and traffic patterns of the grid topology are more complicated than those of the chain topology, the simulation results demonstrate that CRA can also achieve high power efficiency under complicated interference and traffic patterns. As shown in Fig. 10, the performance gain under the grid topology exhibits similar behavior to that under the chain topology. The reason is the same as mentioned in Section VI-B1.

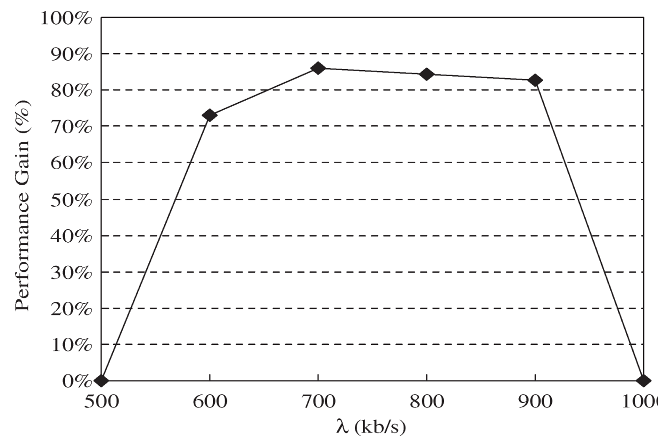

Fig. 10. Performance gain of CRA over noncooperation heuristic in grid topology.

3) Results in Random Topologies: The geographical area for random topology generation is a square of 1000×1000 m. For each generation of random topology, 50 nodes are randomly placed in the square area, and 15 traffic requests are randomly created. The traffic rate of each request is uniformly distributed from 0 to a predetermined maximal load. We perform a series of simulations by varying the maximal load. The principle of setting the lower bound and the upper bound of the maximal load is similar to that under the chain topology. For each setting of the maximal load, the performance gain of CRA is obtained by averaging the simulation results performed under 50 randomly generated network topologies and 15 traffic requests.

Fig. 11 illustrates the performance gain of CRA under different maximal loads. The results show that in most cases, CRA achieves high average performance gain (up to 72%) over the noncooperative heuristic. Again, the behavior of the performance gain under varying maximal load is similar to that under the chain and grid topologies.

VII. Conclusion

Energy efficiency is a key issue in wireless multihop networks. It is known that energy efficiency and throughput are two conflicting design objectives. Hence, power control (used to achieve energy efficiency) and rate adaptation (used to improve throughput) need to be jointly considered. The joint design of power control and rate adaptation to achieve energy efficiency while maintaining the required throughput is particularly challenging in an IEEE 802.11-based multihop network. This is due to the inequality of channel access for different nodes.

To address the energy inefficiency problem caused by the inequality of channel access, we sought to use power control and rate adaptation and formulated an optimization problem, i.e., minimizing the total (average) power consumption over transmission data rates, subject to the traffic requirements of all the nodes in a multihop network. Here, the tuning parameters are PHY transmission data rates only, since the transmission power can be uniquely determined by the transmission rate, given the required BER, interference level, the modulation scheme, and the distance between the transmitter and the receiver.

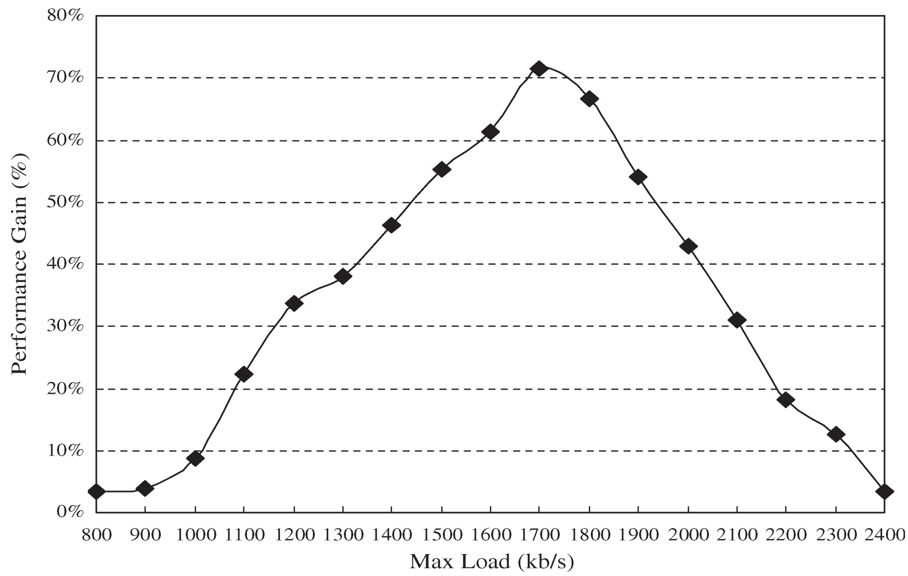

Fig. 11. Performance gain of CRA over noncooperative heuristic in random topologies.

Interestingly, we showed that the aforementioned optimization problem is actually a well-known multiple-choice knapsack problem, which is proven to be an NP-hard problem. Therefore, instead of finding an optimal solution, which is NP-hard, we sought a suboptimal solution; specifically, our key technique to attack this problem is distributed CRA. Here, we promote node cooperation in rate adaptation, due to our observation that the inequality in noncooperative channel contention among nodes in a multihop network tends to result in severe overall energy inefficiency. Under this design philosophy, we proposed a distributed CRA scheme to achieve energy efficiency in IEEE 802.11-based multihop networks. The CRA scheme consists of three modules, namely information exchange algorithm, rate selection algorithm, and node cooperation algorithm. We proved the convergence of the CRA scheme. Another nice feature of our CRA scheme is that a node only needs to make rate adaptation decisions locally instead of globally, as in a centralized scheme.

To evaluate the performance of our CRA scheme, we conduct simulations. The results show that our CRA scheme can reduce the power consumption up to 86% as compared to the existing (noncooperative) algorithm.

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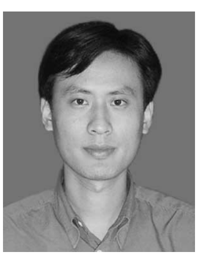

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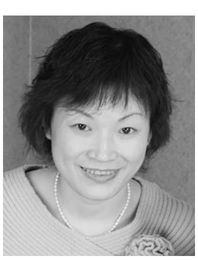

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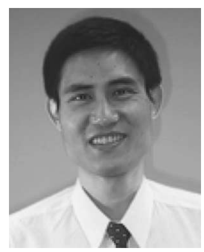

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