Rate Adaptation, Power Adaptation and Mutual Exclusion in Variable Rate Wireless Networks

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***Abstract*— We consider the joint design of rate adaptation, power adaptation and mutual exclusion for the MAC layer of a multi-hop, ad-hoc wireless network. We assume the physical layer supports a variable bit-rate. Most of the existing MACs analyze impacts of only one of these elements, and the jointly optimal strategy is not known. We assume that successive decoding is not implemented, i.e. one receiver decodes only one source at a time. Using a theoretical model that neglects protocol overhead, we numerically find the optimal combination of the three basic elements. Our results suggest that the optimal strategy has the following properties: (1) When a node transmits it should always transmit with the maximum power and no power adaptation is necessary. (2) There is an optimal exclusion region around a destination. While a destination is receiving, nodes inside the exclusion region should stay silent. Nodes outside of the exclusion region should transmit in parallel. The size of the exclusion region does not depend on link sizes, nor on position of nodes, but only on maximum transmitted power. (3) A sender should adapt the transmission rate to the amount of interference generated by nodes outside of the exclusion region of a receiver. We present the results in detail for the 802.11a/g physical layer (but our conclusions hold for other rate functions as well). We show by simulations that the optimal protocol outperforms the existing 802.11 rate adaptation protocols; the exclusion region of 802.11a/g is too large and the spatial reuse is too low, in other words, the efficiency of 802.11 could be improved by allowing more interference.**

I. INTRODUCTION

A. Problem Definition

Design of a wireless MAC protocol, unlike designs of wired counterparts, has several degrees of freedom. In addition to medium access control, a wireless MAC protocol has to adapt rate and power in order to maximize performance. We focus on multi-hop wireless networks with variable link rates. We are interested in maximizing flow rates, and our design objective is to achieve proportional fairness [1]. We also assume that a rate is an arbitrary function of the signal-to-noise ratio at a receiver.

We are interested in finding the optimal MAC protocol, or in other words, to jointly optimize power adaptation, rate adaptation and medium access (i.e mutual exclusion of transmitting nodes). Our goal is to understand the fundamental design choices of a hypothetical optimal MAC. We also compare the existing MAC protocol designs with the optimal one in order to assess their efficiency.

B. Physical Layer and Rate Adaptation

The physical layer of a wireless link defines communication parameters such as bandwidth, modulation and coding that can be used to establish communication with some level of bit or packet errors. One of the most important parameters of the physical layer is signal-to-interference-and-noise ratio (SINR) at the receiver. The higher the SINR is, the higher communication rates can be attained, and one of the goals of networking design is to efficiently track and adapt SINRs and/or rates on links.

We assume that receivers do not perform multi-user detection and successive decoding, a strategy known to achieve the multi-access channel capacity. Indeed, we consider the ad-hoc framework, where we assume that a node can decode only one user at a time. There are more complex transmitter or receiver designs that can overcome these limitations but they are not used in most of the contemporary multi-hop networks.

Some of the existing wireless systems use fixed communication rates, like cellular systems or 802.11. In contrast, most of the recently proposed wireless physical layers allow rates to vary with SINR. Typical examples are 802.11a/b/g [2], CDMA/HDR [3], TH-UWB [4]. Those physical layers use adaptive modulation [5], [2] and/or adaptive coding [4], [2] to adjust the rate to the SINR at the receiver while maintaining a constant, guaranteed bit-error rate. The function that maps a given SINR to the maximum achievable rate is called *rate function*.

C. Wireless MAC Design

The first wireless MAC protocols for multi-hop networks were designed to control only mutual exclusion.

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A typical example is the original 802.11 network (while the latter incarnations 802.11a/b/g offered variable link rates, the original 802.11 offered communications only at 1Mbps). It always uses maximum power for transmitting a packet, and aims to establish communication on a predefined link rate. Medium access contention is resolved by CSMA and RTS/CTS packets. The combination of RTS/CTS packets and carrier sensing can be seen as a mean to enforce **exclusion regions** around sources and destinations: nodes that hear and decode RTS/CTS packets (thus in the exclusion regions) will be excluded from transmitting in parallel, while nodes that do not hear RTS/CTS (thus outside of the exclusion regions) may proceed with transmitting.

Several improvements to the initial approach have been proposed. According to the type of improvement, the MAC protocols can be divided globally in three groups.

Power adaptation protocols: One group of protocols [6], [7], [8], [9] considers power adaptation while keeping the rates fixed. These protocols try to minimize the power necessary for each link to achieve the desired, predefined and fixed, rate. The mutual exclusion further ensures that a newly arrived packet does not destroy an ongoing transmission. The major drawback of these protocols is that the rate is fixed and cannot be adapted to network conditions. We are not aware of any power adaptation protocol that adapts rates as well.

Rate adaptation protocols: The second group of protocols [10], [11], [12], [13], [14] is focused on rate adaptation: the transmission power is still kept fixed, but the rate is adapted to the actual channel conditions and the amount of interference. The medium access control is kept the same as in the initial 802.11 MAC: RTS/CTS packets are sent at the beginning of each transmission and they are encoded with the lowest available rate (the most error-prone coding and modulation). All the nodes that receive an RTS/CTS packet stay silent, and since the lowest rate is heard on a large surface, most of the interference is eliminated. Each source then adapts the transmission rate to the channel conditions on a link. The aim of this rate adaptation is thus to adapt to mobility and channel fading, and not to adapt to possible concurrent, interfering transmissions (which is already eliminated by mutual exclusion). These principles are also applied in 802.11a/b/g design.

The major drawback of these protocols is that mutual exclusion and power are not adapted to network conditions. In all of the rate-adaptation based protocols mutual exclusion is implemented through RTS/CTS packets where RTS/CTS are assumed to be sent at the lowest rate possible. This way, the total interference at a receiver is small, and the link rate is high. At the same time many nodes are excluded and the spatial reuse might be low. To illustrate the problem we turn to [15], where a similar problem is discussed within the framework of HDR cellular networks. The authors concluded that there exists an optimal exclusion region around a destination (base-station). The optimal strategy is to have nearby nodes with strong signals transmitting alone in a given slot, whereas distant nodes with weaker signals should be grouped and transmit during the same time slot. Given these conclusions, it is not clear if the existing mutual exclusion strategies are indeed optimal. Furthermore, packets are always sent with the full power, which also decreases a potential spatial reuse, and the optimality of this decision is also not clear.

Both rate and power adaptation: The third group of protocols tries to adapt both rate and power [16], [5], [17], [18], [19], [20]. In [16], the authors present a methodology that finds the jointly optimal MAC protocol for wireless network with an arbitrary physical layer. Due to the numerical complexity it is applicable only to networks with less than 6-7 nodes, and cannot be used to draw general conclusions. In [5], the authors analyze the joint rate and power adaptation problem for cellular networks. They do not consider mutual exclusion but assume all nodes constantly access the medium.

The joint rate adaptation, power adaptation and mutual exclusion protocols for a networks with linear rate functions (UWB and low-gain CDMA physical layers) is studied in [17], [18], [19]. It is found in [21] that, in this case, the optimal power allocation is always $0/P^{\max}$.

D. Goal and Organization of this Paper

We consider a multi-hop wireless network based on physical layers with arbitrary rate functions, where link rates, transmission powers and mutual exclusions can be varied. Our goal is to characterize the jointly optimal rate control, power control and mutual exclusion. We do this numerically for networks with 40 nodes. Since the size of analyzed networks is considerably larger then in previous works (less than 10 nodes), we are able to demonstrate some general properties of the jointly optimal solution that have not been not shown before. Furthermore, we analyze what this tells us for the special case of 802.11 physical layer. The next section describes system assumptions and the model. In Section III we present the methodology and numerical results.

II. ASSUMPTIONS AND MODELING

A. Notations

The model of a wireless network is very similar to the one in [19]. We model the wireless network as a set of I flows, L links, O nodes and N time-slots. Flows are unicast or multicast. We give here a list of notations used in this section to describe the model. The precise definitions are given in subsequent subsections.

- $\mathbf{f} \in \mathbb{R}^I$ is the vector of average rates achieved by flows.
- $\bar{\mathbf{x}} \in \mathbb{R}^L$ is the vector of average rates achieved on links.
- for every $n \in \{1, \cdots, N\}$, $\mathbf{x}^n \in \mathbb{R}^L$ is the vector of rates achieved on links in time slot n.
- for every $n \in \{1, \cdots, N\}$, $\mathbf{p}^n \in \mathbb{R}^L$ is the vector of transmitted power of links in time slot n.
- $\mathbf{P}^{MAX} \in \mathbb{R}^L$ is the vector of maximum allowed transmission powers on links, which are assumed constant in time (every link may have a different maximum power).
- $\eta \in \mathbb{R}$ is the white noise at a receiver, and is assumed constant for all links in time.
- for every $n \in \{1, \cdots, N\}$, $\mathbf{SINR}^n \in \mathbb{R}^L$ is the vector of signal-to-noise ratios at the links' receivers in time slot n.
- $r(\mathbf{SINR})$ represents the maximum achievable rate given SINR at a receiver
- for every $n \in \{1, \cdots, N\}$, $\alpha^n \in [0, 1]$ is the relative frequency of time slot n in the schedule.
- R (routing matrix) is such that $R_{l,i} = 1$ if flow i uses link l. We have $R\mathbf{f} \leq \bar{\mathbf{x}}$. The matrix R is defined by the routing algorithm.
- $h_{l_1 l_2}$ is the attenuation of a signal from the source of link l_1 to the destination of link l_2.

B. Physical Network Model

All physical links are point-to-point, this means each link has a single source and a single destination. A node can either send to one next hop or receive from one at a time.

We assume that the transmitted signals are Gaussian, which is the case in most of the physical models, including 802.11 and CDMA. Then the SINR at the receiver of link l in slot n will be

$$\mathbf{SINR}_l(\mathbf{p}^n) = \frac{\mathbf{p}_l^n h_{ll}}{\eta + \sum_{k \neq l} \mathbf{p}_k^n h_{kl}}.$$

Attenuation h_{ll} is assumed to decay as a power function of distance from the sender. If the link length is d_l then we have that the attenuation is $h_{ll} = K_a d_l^{-\gamma}$, where K_a and γ are constants.

The achievable rate is a function $r(\mathbf{SINR})$ of the SINR at the receiver. We use the 802.11a/b rate function given in [2]. This function is a stair function which can achieve a certain fixed number of rates, with different given modulation and coding scheme. With a more fine-grained coding the number of achievable rates can be increased, and we interpolate the function between these points to obtain a smooth rate function.

We have chosen the rate function from [2] to illustrate our results on a realistic system. However, similar conclusions hold for a large variety of concave rate functions.

We also assume the power of transmitted signal is upper-bounded by some P^{MAX}. In 802.11 networks, this power typically varies between 1mW and 100mW.

C. MAC Layer

The MAC layer of a network defines power control and scheduling policies. We assume that time is divided into time slots of arbitrary lengths. In each time slot each node can choose to transmit with an arbitrary power that is constant throughout the slot and constrained by the link's power limitations, or it can choose to remain silent. A node cannot send and receive within the same slot, nor can it send or receive from two nodes at a time. A schedule defines in which slot a node transmits, to whom, and with what power. Although a schedule can have any number of slots, we show in Section II-G that it is sufficient to consider only schedules with a bounded number of slots. Each slot n is characterized by its power allocation $\mathbf{p}^n$ and its relative frequency α^n, which represents what fraction of the overall schedule is occupied by that slot. We do not need to specify the time-scale of a schedule, but we assume it is sufficiently larger than the symbol duration. A slot can be scheduled with different durations in arbitrary time intervals, as long as it relative frequency remains unchanged.

D. Routing

Let us consider a network with a fixed MAC protocol that achieves a long term link rates $\bar{\mathbf{x}}$. Then any routing can be represented with an inequality $R\mathbf{f} \leq \bar{\mathbf{x}}$, where $\mathbf{f}$ are long-term end-to-end flow rates and R is the routing matrix.

We use a simple routing approach: given the maximum hop length, the routing algorithm activates only links that are shorter than this maximum, and for each flow it chooses a route with the smallest number of links (similar to AODV or DSR). By varying the maximum hop length we get different routing matrices. We use this algorithm as an approximate parametrization of the set of possible routes. If we choose a small maximum hop lengths, we get paths with a large number of hops, and by increasing the hop length we decrease the lengths of routes. If the hop length is sufficiently high we end up by having no routing and sending directly do destinations.

We assume in our networks that hop lengths for all the nodes are the same. Given a network and a traffic demand, we vary the hop length and we obtain a number of different routing matrices R. We run our optimization for each of these routing matrices and we choose the one that gives the best performance. The characteristics of the optimal routing are out of scope of this paper.

E. Traffic Demand and Flow Control

We assume all flows have infinite amounts of data to send. Since lower protocol layers will define in a unique way the available rate for each flow, we assume our flow control layer is able to completely use this available rate.

F. Performance Comparison

In this analysis we focus on rate-maximization objectives. There are several rate-maximization performance metrics, like maximizing sum of rates, max-min fairness and proportional fairness [1]. It has been shown in [22] that proportional fairness, which maximized the sum of log utilities of flow rates, provides a good trade-off between efficiency and fairness. Log utility of flow rate allocation vector $\mathbf{f}$ is defined as $\sum \log(f_i)$ and our performance objective is maximize the log utility over the set of achievable flow rates.

G. Optimization Problem

We assume that a schedule consists of time slots $n = 1...N$ of frequency α_n. We normalize these lengths such that $\sum_{n=1}^{N} \alpha_n = 1$. Let us call $\mathbf{p}^n$ the vector of transmission powers assigned to links in slot n, and let $\mathbf{SINR}^n$ be the vector of signal-to-noise ratios at receivers of the links, induced by $\mathbf{p}^n$. The rate achievable on link l in slot n is $\mathbf{x}_l^n = r(\mathbf{SINR}_l^n)$. The vector of average rates on the links is thus $\bar{\mathbf{x}} = \sum_{n=1}^{N} \alpha_n \mathbf{x}^n$. Since $\mathbf{x}^n$ has dimension L (where L is a number of links), by virtue of Carathéodory theorem, it is enough to consider $N \leq L+1$ time slots of arbitrary lengths $\boldsymbol{\alpha}$ in order to achieve any point in the convex closure of points $\mathbf{x}^n$.

We next describe set $\mathcal{F}(R)$ of feasible average flow rates under a given routing matrix R. It is the set of $\mathbf{f} \in \mathbb{R}^I$ such that there exist a schedule $\boldsymbol{\alpha}$, a set of power allocations $\mathbf{p}^n$ and a corresponding set of rate allocations $\mathbf{x}^n$ for all $n = 1 \cdots N$, and average rates $\bar{\mathbf{x}}$, such that the following set of equalities and inequalities are satisfied for all $n = 1 \cdots N, i = 1 \cdots I, l = 1 \cdots L, o = 1 \cdots O$:

$$\begin{array}{rcl}
R\mathbf{f} & \leq & \bar{\mathbf{x}} \\
\bar{\mathbf{x}} & = & \sum_{n=1}^{L+1} \alpha_n \mathbf{x}^n \\
\mathbf{x}_l^n & = & r(\mathbf{SINR}_l(\mathbf{p}^n)) \\
\mathbf{SINR}_l(\mathbf{p}^n) & = & \frac{\mathbf{p}_l^n h_{ll}}{N+\sum_{k\neq l} \mathbf{p}_k^n h_{kl}} \\
1 & = & \sum_{n=1}^{L+1} \alpha_n \\
1 & \geq & \sum_{l\,:\,l.\text{src}=o} 1_{\{p_l^n>0\}} + \sum_{l\,:\,l.\text{dst}=o} 1_{\{p_l^n>0\}} \\
\mathbf{p}_l^n & \leq & P_l^{MAX}
\end{array} \qquad (1)$$

where $l.\text{src} = o$ and $l.\text{dst} = o$ are true if node o is the source or the destination of link l, respectively.

The goal of the problem is to maximize log-utility over all feasible flow rate allocations. This is equivalent to the following optimization problem:

$$U = \max_{R\in\mathcal{R},\mathbf{f}\in\mathcal{F}(R)} \sum_{i=1}^{I} \log(f_i) \qquad (2)$$

where $\mathcal{R}$ is the set of possible routing algorithms defined by Section II-D. It is easy to verify that the set of rates is convex and the objective function is concave hence a solution exists. The optimization problem (2) has as free variables routing matrix R, time slots' frequencies α_n, and vectors of transmission powers assigned to links in slot n, $\mathbf{p}^n$. The values of these variables that solve (2) define the optimal routing, scheduling and power control in the given network.

III. RESULTS

A. General Findings

The optimization problem (2) remains highly complex, and is difficult to solve in the general case, even using advanced optimization methods such as in [23]. A discussion for arbitrary networks with up to 6 nodes is given in [24]. It is impossible to draw general conclusions about network design from such small networks.

We first consider power adaptation. In our previous results [21] we theoretically proved that power control is not needed when the rate function is linear. In other words, when a node sends data, it should always send with the full power. The rate function of 802.11 physical layer [2] is not linear and the finding does not hold in general. However, we tested this finding numerically on a large number of examples and we found that it is always optimal or nearly optimal. Due to space limitation we do not present the numerical results here. We thus use this power allocation strategy in the rest of the analysis.

We next consider a random, two-dimensional network, with 40 nodes. The heuristics we use to solve the optimization problem is to define a number of alternative strategies for scheduling, and analyze the performance of each of them; we use the same heuristics as we did in [19] for the special case of UWB and low gain CDMA. Some of the strategies have variable exclusion region size, and others have fixed. We find that it is always optimal for a node, when transmitting, to transmit with maximum power. Otherwise, it should remain silent. There should be an exclusion region around each destination receiving a packet. During packet reception, all nodes within this exclusion region should remain silent. Nodes outside of the exclusion region should transmit in parallel (to maximize spatial reuse). Finally, it is easy to demonstrate that, within this framework, a sender should adapt the rate (that is, the modulation and coding) to the SINR experienced at the receiver. The size of the optimal exclusion region does not depend on the size of a link, nor on the position of other nodes but only on the maximum transmitting power.

B. Application to 802.11

For the physical layer described in [2] and channel described in [25], we found that the optimal strategy is to exclude link k, when link l is receiving, if $P_k^{MAX} h_{kl}/N > 17dB$, regardless of link sizes, positions of other nodes and transmitted power. This is in sharp contrast to the existing rate adaptation protocols [11], [12], [13], [14] that send RTS/CTS packets with the lowest available rate (around 0dB), hence they induce larger, suboptimal exclusion regions.

In order to illustrate this result, we give in detail the comparison of the optimal strategy to three other common strategies. One strategy is to let all nodes transmit all the time (interference is always allowed). The other is to have only one node at a time (this is, in our framework, equivalent to time division multiple access, TDMA). Finally, we emulate the 802.11 MAC. Standard RTS/CTS packet in 802.11 are sent with the lowest possible code and modulation rate so it can be decoded by a large number of nodes. The actual threshold varies with the deployed hardware and we set the required SNR of the RTS/CTS to 0dB. All the nodes that receive RTS/CTS with SNR higher than 0dB thus remain silent, and the others transmit in parallel. We do not simulate RTS/CTS packet but we require inequality $P_k^{MAX} h_{kl}/N < 0dB$ to be satisfied for concurrently transmitting nodes.

Given a network and a traffic demand, we first choose the scheduling strategy. We then fix the maximum hop length for the routing algorithm, and obtain the routing matrix R. For each link we construct a list of links that cannot be active at the same time (due to exclusions). We repeat the same procedure for each node and each flow, and construct a schedule in a greedy manner. Then, we optimize slot frequencies in order to maximize the system utility. We repeat the same for each routing matrix and we choose the routing that maximizes the performance.

We numerically analyze the performance of these strategies on a set of networks with 40 nodes, where nodes are randomly distributed on 200m x 200m square. We take the [25] NLOS path loss model. We consider uniform and non-uniform network topologies, both in the sense of node positioning, power constraints and traffic demands. The results of the numerical comparisons are presented on Figure 1.

We first consider a network of uniformly distributed nodes on a unit square, where half of the nodes are sources talking to a randomly chosen destinations from the other half of the nodes. The results are given on the left of Figure 1. We see that in most of the cases the 17 dB strategy is the optimal one. The only exception is in case of 1mW transmitted power where the optimal exclusion region should be even slightly smaller. We see that the utility of the optimal strategy is by 5 to 10 higher than the utility of 802.11 exclusion region. For a network with 40 nodes (20 flows) this means that we have approximately from 30% to 60% of rate improvement per flow. We also consider heterogeneous scenarios in the center and on the right of Figure 1, and we see that the same conclusions hold in those cases as well.

In conclusion, we find that the optimal MAC is similar to the existing 802.11 rate adaptation protocol. However, these protocols do not control the size of the exclusion region. They send RTS/CTS packets with the lowest possible rate, thus making the exclusion regions too large, and reduce the spatial reuse. We find that, for the rate function of [2] and channel model of [25], the optimal RTS/CTS packets should be coded for SNR at the receiver of 17 dB instead of 0dB. Similar analysis can be performed for different rate functions. In, general, the existing 802.11 could be improved by reducing the exclusion region, i.e., allowing more concurrent transmissions (and thus more interference).

C. Other Examples

We applied our model to the cellular setting by letting all receivers concentrate in one point, representing a base station. We obtained the same conclusion as [15]: near-by nodes should send separately (they are in the exclusion region of the base-station so they have to time-share), while distant nodes should send together (since they are outside of the exclusion region). Rates are also adapted to the channel condition and the transmitted power is always maximum. Our findings thus confirm the results from [15].

Finally, we also compared the optimal MAC with CA/CDMA [9], the state-of-art power adaptation protocol for fixed rate networks. We implement a simplified version that does not account for protocol overhead but only reflects the fundamental principles of the protocol. We found that CA/CDMA performs far worse than the optimal version; it cannot benefit from power adaptation. We omit the numerical results for these two cases due to lack of space.

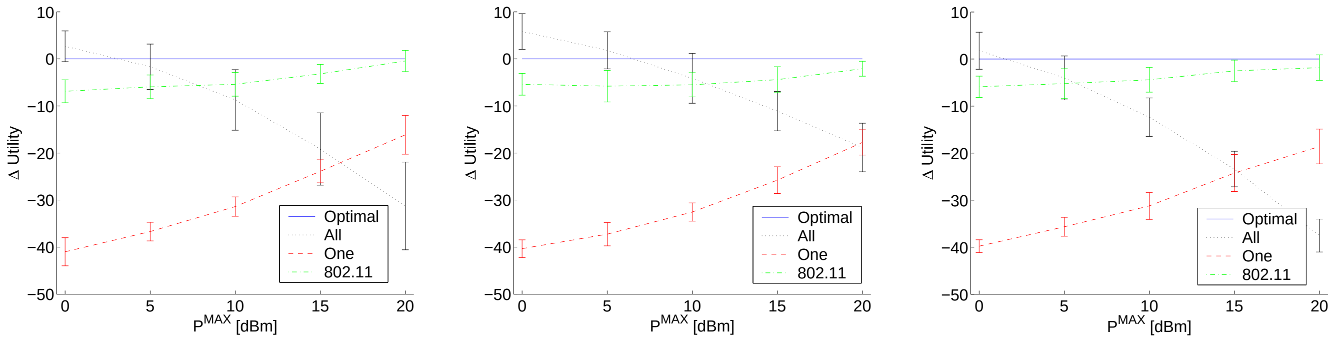

Fig. 1. Performance comparison of different MAC protocols on random networks with 40 nodes on 200m x 200m square. On the x axis: we plot the maximum transmitted power constraint. On the y axis we plot the difference between the log-utility achieved by the optimal protocol and those achieved by different other protocols. On the left, we consider topologies where nodes are distributed uniformly random on the square, and sources and destinations of flows are randomly chosen among them. In the center, we assume 1/4 of nodes is distributed on the left half of the square and 3/4 on the right half. Sources and destinations of flows are again randomly chosen among them. Finally, on the right, nodes, sources and destinations are uniformly distributed, but the power constraints of nodes are not uniform and vary randomly between 50% and 150% of the constraint given on the x axis.

IV. CONCLUSION

Our results are heuristics based on numerical explorations. Nonetheless, even in this current form, they do show interesting conclusions for improving existing MAC protocols. We hope our findings will trigger further analysis to provide theoretical confirmation, as is already available in some special cases [17], [15], [21].

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