Delay Efficient Control Policies for Wireless Networks

[Extended Abstract]

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1. INTRODUCTION

Scheduling algorithms for multi-hop wireless networks and high-speed switches have been widely studied for the purpose of maximizing the throughput performance of the system, beginning with the seminal work of [7]. Various studies have subsequently focused on the design of simpler scheduling algorithms with provable performance guarantees on the throughput. Our studies [3] as well as recent results in the community, point to deficiencies when focusing the design of these scheduling systems primarily based on throughput. Moreover, the development of analytical techniques to study the delay performance is crucial to provide guarantees on the quality of service, network design (choice of buffer sizes, capacity of links) etc. Analyzing the delay performance of throughput optimal (queue-length based) scheduling policies in such systems is extremely difficult due to complex correlations that arise between the arrival, service, and the queue length processes. In this thesis, we develop novel techniques for performance analysis of wireless networks and also design novel scheduling policies that are delay-efficient.

2. DELAY ANALYSIS

We consider a multi-hop wireless network with multiple flows. Each flow traverses a fixed path (for example see Fig 1). We consider a general combinatorial interference model and ensure that whenever a link is scheduled, none of the links in its interference set is scheduled simultaneously. We generalize the typical notion of a bottleneck. In our terminology, a (K, X)-bottleneck is defined to be a set of links X such that no more than K of them can be scheduled simultaneously. For example, Fig 1 shows (1, X)-bottlenecks in the system under node-exclusive interference model. We also develop a novel queue grouping technique which allows us to handle the correlations in the service processes of links along the path of a multi-hop flow. We lower bound the expected queueing delay of the flows crossing a bottleneck by analyzing a reduced single-server system fed with appropriate arrival processes. In [4], we develop a systematic methodology to derive a fundamental lower bound on the system-wide expected delay under any scheduling policy. By defining the bottlenecks appropriately, we can also analyze the networks with heterogeneous and time-varying links.

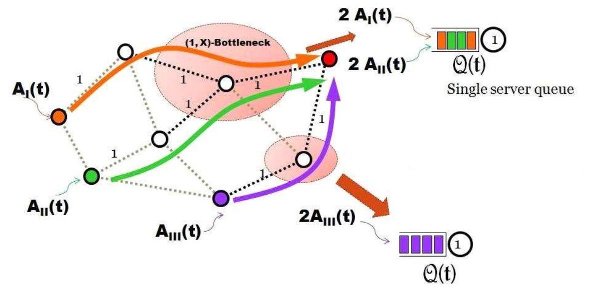

Figure 1: Reduction technique to derive a fundamental lower bound on the expected delay of a wireless-network

2.1 Insights Gained

Our lower bound can be achieved by a *fictitious scheduler* that schedules a packet in every bottleneck. However, such a schedule may not be feasible due to interference constraints. Instead, we focus on designing control policies that keep the bottleneck busy most of the times and hence are delay-efficient. We also derive an upper bound on the performance of the MWM class of policies for single-hop traffic in [2, 5] that is tighter than [8]. We analyze a policy that balances the expected drift at each queue by using the knowledge of the arrival rates and thus minimizes the upper bound. Our studies indicate that balancing the load in a network with single-hop flows improves the delay performance.

For networks with single-hop traffic, our simulation studies in [5] suggest that the average delay of certain control policies such as the celebrated Max Weighted matching (MWM) can be made close to the lower bound for even though the policy itself does not explicitly compute these bottlenecks. For example, consider the tree topology shown in Fig. 2. The link capacity and load (Poisson arrivals) is chosen randomly from $\{1, 2, 3, 4\}$ and $\{0, \lambda, 2\lambda\}$ respectively. Assume that the channel states are i.i.d. Bernoulli with the ON probability, p for each link. We consider $p = 0.8$ and $p = 0.9$. As shown in Fig. 3, the performance of MWM policy is close to the lower bound. Furthermore, by reducing *idling*, delay performance can be improved. However, it is impossible to avoid idling. We find in Fig. 3, that the delay of the MWM policy increases only slightly by a decrease in

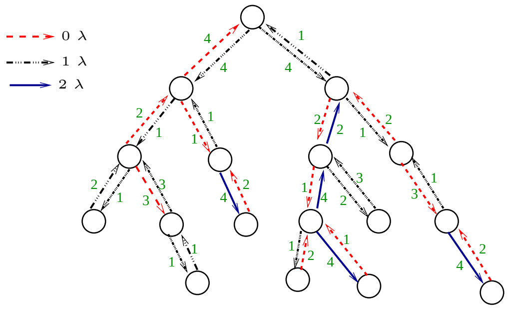

Figure 2: Tree with heterogeneous link capacities (indicated by the number) and non-uniform load (indicated by the type of arrow)

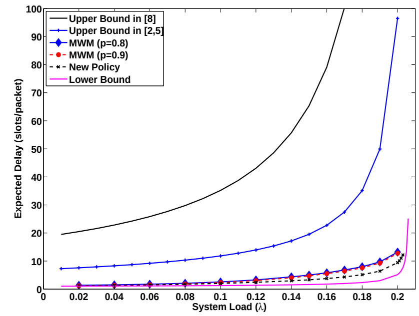

Figure 3: Simulation results for Tree Topology

the value of p. Interestingly, the upper bounds (also lower bounds) for both these values of p coincides numerically because the underlying capacity region is almost unchanged. This indicates that our analysis captures the effect of fading, multiplexing and interference in wireless networks.

3. DELAY-EFFICIENT SCHEDULERS

For the purpose of scheduling, a $N_1 \times N_2$ switch with crossbar constraints is equivalent to a wireless network with a bipartite graph and node exclusive interference. We schedule heavy bottlenecks (nodes) in the switch as opposed to the traditional approach of scheduling heavy links in the system. These schedulers are likely to be delay-efficient since they closely mimic the *fictitious scheduler* which achieves the lower bound. Interestingly, we are able to show [1] that these schedulers drain the packets in minimum possible time for any given initial configuration, provided there are no further arrivals. We show that if a policy ensures the scheduling of a large enough set of heavy ports in the system, it is enough to achieve the maximum throughput. We call this new class of policies "LHPF (Lazy-Heaviest Port First) policies" because they may not even be work-conserving.

We develop a novel Lyapunov function (weight of the heaviest node) and a non-standard technique to prove throughput-optimality. Our technique captures the behavior of a scheduling algorithm over a large number of slots. The LHPF class of policies has lower worst-case complexity and is potentially simpler to implement than the MWM type policies. We then show that a particular scheduler in this class, MVM (maximum vertex weighted matching policy), minimizes the idling for any given configuration by scheduling the heaviest matching. Since MVM is also a maximum size matching, this is the first proof that a maximum size matching is throughput optimal. Simulation results show that this policy is nearly delay-optimal.

The wireless networks with general interference model pose a serious challenge to the design of delay-efficient schedulers; both because of complexity of computation and communication. Our analysis shows that the delay performance of some recently proposed CSMA based asynchronous, distributed schedulers [6] is poor because of scheduling links with empty queues. We are currently working on the development of novel techniques to analyze and design CSMA based schedulers that do not schedule empty queues and yet are provably throughput optimal.

3.1 Improving Back-pressure

The back-pressure policy has been widely used to develop solutions for a variety of problems in the context of multi-hop wireless networks. The policy tries to decrease the differential backlog (difference in the backlogs) across each link, by scheduling flows with high differential backlogs. In [4], we show that the back-pressure policy can be modified to perform close to the lower bound for certain representative topologies. However, for we have also identified situations in which the delay performance of the back-pressure policy is quite poor. For example, for a tandem network with heterogeneous links, the back-pressure policy causes some links to be heavily back-logged. We are working on improving the delay performance of the back-pressure policy.

4. REFERENCES

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