Analyzing Delay Performance of Multi-hop Wireless Networks

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ABSTRACT

In this paper a multi-hop wireless network is considered to analyze the delay performance. We assume that there is a fixed route between a given source and destination pair. The multi-hop nature of network may cause complex correlations of the service process. In order to handle them, we propose a queue grouping technique. An interference model is assumed which is set based. With the help of interference constraints the lower bound of delay performance is obtained. To achieve this systematic methodology is used. The simple-path delay-optimal policy we designed is used for wireless networks. Empirical studies revealed that our approach is good to optimize scheduling policies and analyzing delay in multi-hop wireless networks.

Index Terms

Multi-hop wireless network, delay, flow control, wireless mesh network, optimization, queuing analysis, scheduling

1. INTRODUCTION

Wireless networks are growing at a tremendous rate and are fast becoming ubiquitous because of the low cost, ease of deployment, flexibility, accessibility, and support for mobility. The market has been flooded with wireless enabled devices such as mobile phones, laptops, PDA, sensors and so forth. It is natural to network these devices to support exchange of information and services. Such networks may be built on top of a fixed infrastructure or could be set up completely on an ad-hoc basis. It is important to understand the fundamental limits of these networks and design control policies that achieve the desired level of performance.

Multi-hop wireless networks utilize multiple wireless nodes to provide coverage to a large area by forwarding and receiving data wirelessly between the nodes. Multi-hop wireless networks can provide data access for large and unconventional spaces, but they have long faced significant limits on the amount of data they can transmit. Data can be transmitted at low power over short distances, which limits the degree of interference with other nodes. But this approach means that the data may have to be transmitted through many nodes before reaching its final destination. Or, data can be transmitted at high power, which means the data can be sent further and more quickly but the powerful transmission may interfere with transmissions from many other nodes. Multi-hop wireless is motivated by the fact that many embedded wireless devices are power-limited and cannot communicate directly with a distant base station or access point.

2. DELAY ANALYSIS IN MULTI-HOP WIRELESS NETWORK

Network delay is an important design and performance characteristic of a computer network or telecommunications network. The delay of a network specifies how long it takes for a bit of data to travel across the network from one node or endpoint to another. It is typically measured in multiples or fractions of seconds. Delay may differ slightly, depending on the location of the specific pair of communicating nodes. There is a certain minimum level of delay that will be experienced due to the time it takes to transmit a packet serially through a link. Onto this is added a more variable level of delay due to network congestion. IP network delays can range from just a few milliseconds to several hundred milliseconds. For a large class of applications such as video or voice over IP, embedded network control and for system design; metrics like delay are of prime importance. The delay performance of wireless networks, however, has largely been an open problem.
The general research on the delay analysis was progressed in the following main directions:

• **Heavy traffic regime using fluid models:**

Fluid models have typically been used to either establish the stability of the system or to study the workload process in the heavy traffic régime. The maximum-pressure policy (similar to the back-pressure policy) minimizes the workload process for a stochastic processing network in the heavy traffic regime when processor splitting is allowed.

• **Stochastic Bounds using Lyapunov drifts:**

This method is developed and is used to derive upper bounds on the average queue length for these systems. However, these results are order results and provide only a limited characterization of the delay of the system. For example, the maximal matching policies achieve O(1) delay for networks with single-hop traffic when the input load is in the reduced capacity region. This analysis however, has not been extended to the multi-hop traffic case, because of the lack of an analogous Lyapunov function for the back-pressure policy.

• Large Deviations:

Large deviation results for cellular and multi-hop systems with single hop traffic have been to estimate the decay rate of the queue-overflow probability. Similar analysis is much more difficult for the multi-hop wireless network considered here, due to the complex interactions between the arrival, service, and backlog process.

Throughput and utility of a multi-hop wireless network are important aspects of much of the research conducted on such networks. In such systems and its applications like embedded network control, system design, voice and video over IP performance metrics like delay plays a crucial role and the delay is the open problem in such systems. As there are complex interactions over wireless networks, this problem is so complex and needs lot of research. Furthermore, the interference in the wireless networks makes it worst. In this paper, we use a systematic methodology for delay analysis and also a scheduling policy in order to achieve delay performance with respect to lower bound.

We analyze a multi-hop wireless network with many source and destination pairs provided traffic and routing information. The packet flow is as described here. A source node sends packets into network. In turn the packets move through network and finally reach the destination. Fig. 1 shows three flows pertaining to wireless multi-hop network.

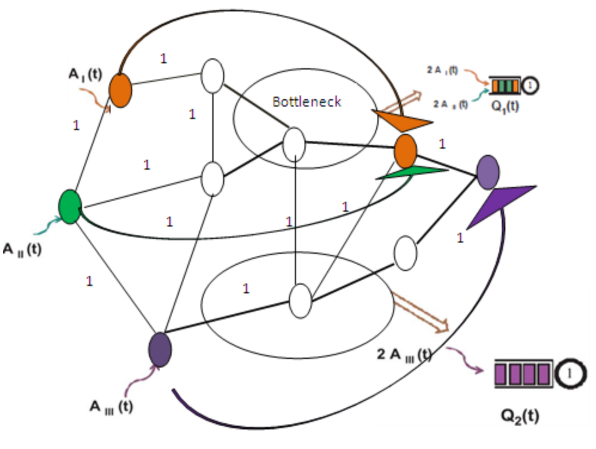

Fig. 1 Multi-hop wireless network with flows and bottlenecks

As the transmission medium is shared, at each node a packet is queued in its path and waits for an opportunity for it to be transmitted. Scheduling can be done on two links that do not cause interference with each other. Such links are known as activation vectors. The unit capacity of each link is one packet in a slot. Delay performance of any scheduling policy is influenced by interference. In [5] the use of exclusive set of links is used to demonstrate the single hop traffic. In this paper we define bottleneck as a set of links such that no more than one of them can simultaneously transmit. In [5] sharper upper bounds could be used. However, in this paper our focus is to derive fundamental bound on performance of any policy. As per our consideration the lower bound analysis is an important step. In this regard [16] is similar to this paper. We also reengineer a back – pressure scheduling policy whose delay performance is close to the lower bound. Our contributions in this paper are a new queue grouping technique; new technique to reduce the analysis of queuing upstream of a bottleneck; derivation of a fundamental lower bound on the system wide average queuing delay of packet in multi-hop wireless network; extensive discussion and numeral studies.

3. PROPOSED SYSTEM MODEL

This section describes system model. We consider a wireless network which is represented as G = (V, L) where set of nodes in the network is represented by V and L denotes the set of links. Unit capacity is associated with each link. We consider N number of flows. Each flow contains source and destination pairs (si, di). We assume a fixed route between source and destination nodes. Exogenous arrival stream of each flow is computed as.

$$\{A_i(t)\}_{t=1}^{\infty}$$

The service time of a packet is considered a single unit. Another assumption is that the exogenous arrival stream of each flow is independent. Set of links where mutual interference is not caused and thus can be scheduled simultaneously are known as activations. Two hop interference model is used in the simulation studies as it can model the behavior of large class of MAC protocols. It is because it supports virtual carrier sensing which makes use of CTS/RTS message.

FINDING AVERAGE DELAY LOWER BOUNDS

For a given multi-hop wireless network, the methodology used to derive lower bounds on the system wide average packet delay. The network flows are partitioned into many groups and each group passes through a bottleneck. In the process the queuing of each is individually analyzed. The intention behind grouping is to maximize the delay system wide. When a flow is passing a bottleneck, the sum of queues is lower bound both upstream and downstream. By using statistics of the exogenous arrival processes, the computation of lower bound on the system-wide average delay is performed. The reduction of a bottleneck to a single – queue system is justified by our analysis. A greedy algorithm has been implemented that takes a system with flows and bottlenecks as input and generate a lower bound on the system-wide average packet delay.

Greedy Partitioning Algorithm

This algorithm is meant for dividing the whole wireless network into many single – queue systems and get bound on expected delay.

Algorithm 1: Greedy Partitioning Algorithm

```
Z ← {1, 2 ... N}
BOUND ← 0
repeat
  Find the (K, X)-bottleneck which maximizes E[D_X]
  BOUND ← BOUND + Λ_X E[D_X]
  Z ← Z \ i : i ∈ X
until Z = Φ
return BOUND / Σ_{i=1}^{N} λ_i
```

TABLE 1: shows greedy partitioning algorithm

A dynamic program can be used for optimal partition. However, this approach is computationally expensive. For this reason in this paper the greedy algorithm presented in table1 was developed in order to find average delay of a wireless network which contains bottlenecks.

4. DESIGN OF DELAY-EFFICIENT POLICIES

Delay efficient scheduler designing is an important question in multi-hop wireless networks. Delay efficient policies can improve performance of multi-hop wireless networks. It is extremely complex to derive delay optimal policies for general purpose although it is easy for specific networks such as tandem and clique. The delay efficient scheduler that works for all networks must satisfy the criteria given below.

- It has to ensure high throughput. This is important for any scheduling policy to maintain delay under control. If not the delay may become infinite when loading is heavy.
- When there are multiple flows running in the network, these flows must be allocated resources equally. Therefore no flow is starved from sufficient resources. The non interference links are to be managed in such a way that no links are starved from resources and service as starvation leads to an increase in the average delay of the system.

As the network is dynamic and has complex interactions, it is not easy to achieve the criteria or properties mentioned above. This is due to lack of prior knowledge about flows and complex interactions in a multi-hop wireless network. As learned from the work of [9], and [11], we opted to use back-pressure policy with fixed routing. In the context of wireless networks, the back-pressure policy has been widely used to solve problems of multi-hop wireless networks [4], [11]. The research community has realized the significance of studying such policy in terms of delay, network stability and complexity of interactions for different flows. The proposed policy is meant for managing queues pertaining to flows in the decreasing order of size. This is considered from the source node to destination node. By using a value known as differential backlog this has been achieved. The differential backlog is used as the weight for the link and scheduling. The scheduling that is matching highest weight is considered. This is the reason this policy is referred to as back-pressure policy. This policy has been studied and applied to various networks of multi-hop nature such as tandem, clique and so on.

Back-Pressure Policy

The policy known as back-pressure can lead to large delays. This is because from the destination the backlogs are gradually larger. The flow of packets is from larger queue to a shorter queue. Moreover the it is possible that some of the links may remain idle. The result of this is that there will be larger delays at bottlenecks. Experiments with this policy were done with various network topologies such as tandem queue, dumbbell, tree and cycle. As per the results it likely that upstream queues of a bottleneck grow long resulting in larger delays. Observation for clique and tandem network is that increase in priority of packets close to destination results in reduction of the delay. The same thing is known as LBFS rule in wired networks [12]. This policy is similar to the policy in [16].

5. ILLUSTRATIVE EXAMPLE

The methodology we proposed and tested on various topologies mentioned in the previous section is described here. We analyze the back-pressure policy and the lower bounds. The lower bounds can also help to understand back-pressure policy well. Maximal policy [1], [18] and back pressure policies are compared. For a given interference model, we computed set of graphs exclusively. We also implemented greedy algorithm. The arrival stream at each source is a collection of active and idle periods. The lower bounds are obtained using algorithm 1. For expected single queue system we use analysis proposed in [3].

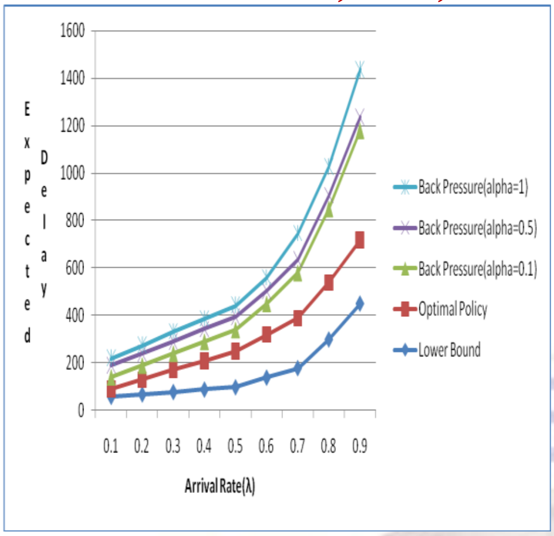

Fig. 2 Simulation results for Tandem Queue

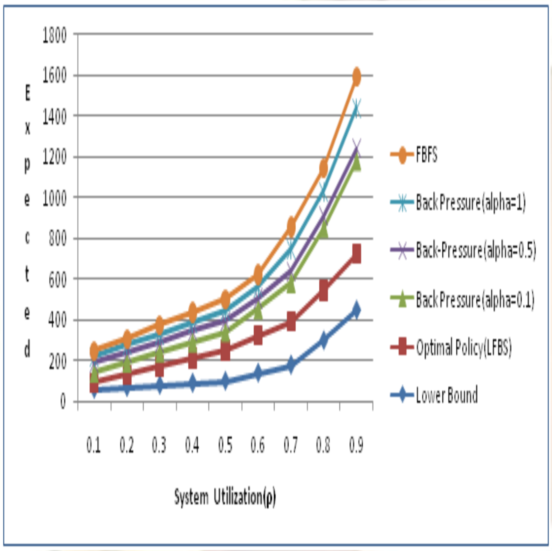

Fig. 3 Shows simulation results for clique

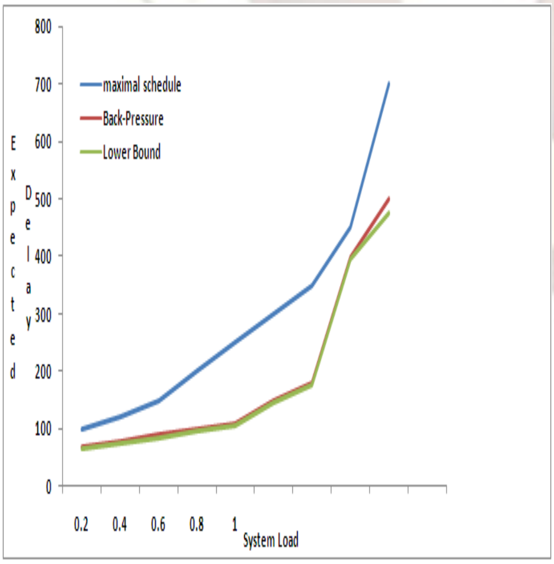

Fig. 4 shows simulation results for dumbbell topology

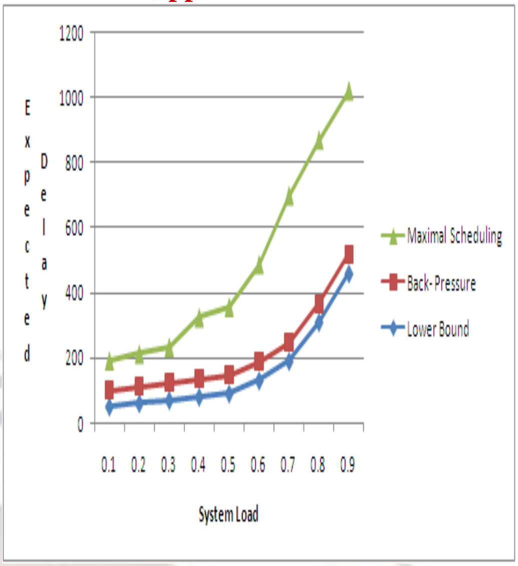

Fig. 5 shows simulation results for tree topology

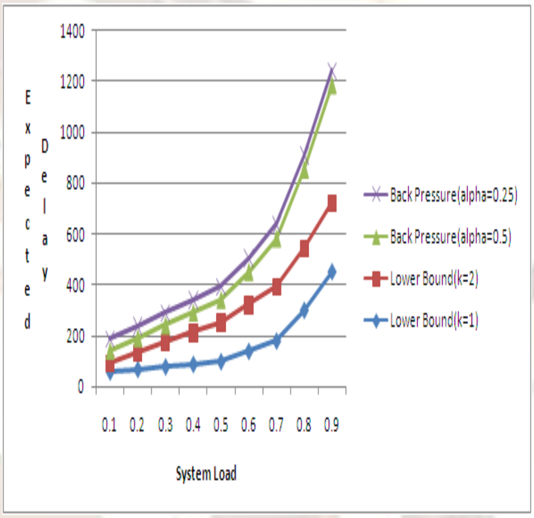

Fig. 6 Shows simulation results for cycle topology

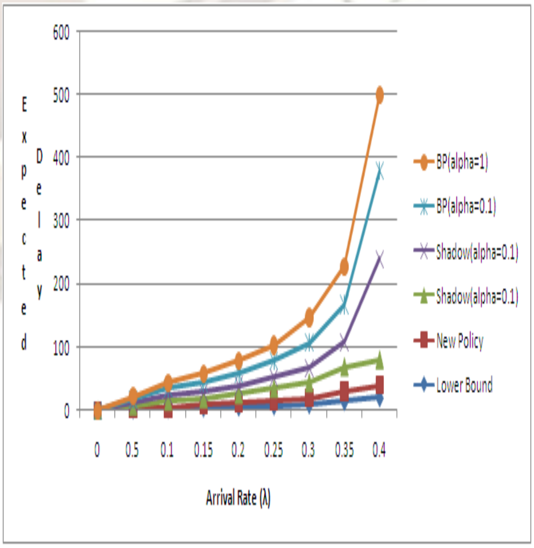

Fig. 7 Simulation results for linear network

6. DISCUSSION AND RELATED WORK

Research that has been done so far on wireless networks [1], [4], and [11] focused on stability of the system. The schemes developed for stability the back – pressure policy has been used. It is also known as throughput-optimal policy. Expected delay analysis of these systems is focused in this paper.

In order to test the stability of increase it or study workload, fluid models are used. It is described in [2] that maximum pressure policy can reduce workload process for heavy traffic networks. In [4], [10], [13], and [14] stochastic bounds using Lyapunoy drifts method is used to derive upper bounds. This has not been extended to multi-hop traffic. In order to calculate large deviation results for cellular systems large deviation results are used in [17] and [20]. This kind of analysis for multi-hop wireless network is not easy as there are complex interactions. For this reason our approach is different and used to reduce the wireless network into singe queuing systems and then analyzed for obtaining lower bound. This technique along with back pressure policy captures essential features of wireless networks. Very important advantage of lower bound is that it supports analysis of large class of arrival processes as described in [3]. In addition to this our approach also depends on the ability to compute the bottlenecks in the system. The characterization of bottlenecks in wireless networks is very difficult to achieve. Instead of that characterizing exclusive set [7] is good for delay analysis. Even though it is good approach, it is not sufficient to obtain tight lower bounds. Developing a delay optimal policy that can achieve least average delay is very challenging. Such schemes were described in [19].

A policy was proposed in [6] that demonstrate the delay for given flows less than the constant factor. The experiments were conducted for quasi reversible networks. In [6] a scheme named "poissonation scheme" was proposed and this was causing the delay to be increasing. To overcome these drawbacks, the lower bound analysis is described and implemented in this paper which works under general interference constraints for general class of arrival processes. For switches the algorithm given in [8] has been studied. The simulations in that paper suggest a fact that the delay reduced with the alpha value. This is also used to analyze heavy traffic [15]. The drawback in these researches is that they did not focus on multi-hop wireless networks. The fact such as MWM-policy for switched networks can be observed with back-pressure policy of multi-hop wireless network is not known. The process that works for single hop may not work intuitively for multi-hop wireless networks.

7. CONCLUSION

In wireless networks delay analysis is an open problem which is very challenging. This problem is further intensified with the interference in wireless network. For this reason, new approaches are essential to overcome this problem in multi-hop wireless network. We focused on lower bound analysis in order to reduce the bottlenecks in multi-hop wireless systems. For specific wireless network we could a sample-path delay-optimal scheduling policy could be obtained. The analysis we did is general and works for a large class of arrival processes. It also supports channel variations. Identifying bottlenecks in the system is the main problem and the lower bound helps in finding near-optimal policies.

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