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(K, X)-Bottleneck in the System For Multi-Hop Wireless Networks

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Abstract:

In multi-hop wireless networks performance is very important. Analyzing delay performance can help in when the network has fixed routes for data transfer between source and destination. Many complex correlations may result in the multihop network. Handling such correlations is to be given paramount important in order to minimize packet delay using efficient scheduling policies. Recently a queue grouping technique was introduced by Gupta et al. in order to analyze delay performance in multi-hop wireless networks. They also used a set based interference model to minimize packet delay. In this paper we implement those concepts practically. We build a prototype application, a custom simulator, in Java platform to demonstrate the proof of concept. The empirical results revealed that the prototype is useful and can be used to build real time applications.

Index Terms:

Multi-hop wireless network, wireless mesh network, delay analysis, optimal scheduling.

INTRODUCTION:

In wireless networks it is important to get maximum throughput and utility of the network. There has been much research on it. There are many applications in the real world that use multi-hop wireless networks. They include voice over IP, system design and network control. In all applications delay has its impact on the communications. In fact the delay problem in wireless networks is the open problem to be addressed. In such wireless applications multiple and complex interactions take place. The delay in packets has adverse effect on the performance of the applications that run in multi-hop wireless networks.

The delay has to be resolved in order to maximize the performance of such networks. There is interference common in wireless networks. It makes the situation worse. A systematic methodology is required in order to overcome this problem. An efficient scheduling policy should be in place and it has to be analyzed for delay performance with respect lower bound. For the purpose of the research a multi-hop wireless network with many pairs of source and destinations for routing traffic are considered.We consider the lower bound analysis as an important first step towards a complete delay analysis of multi-hop wireless systems. For a network with node exclusive interference, our lower bound is tight in the sense that it goes to infinity whenever the delay of any throughput optimal policy is unbounded. For a tandem queueing network, the average delay of a delay optimal policy proposed by [31] numerically coincides with the lower bound provided in this paper. A clique network is a special graph where at most one link can be scheduled at any given time. Using existing results on work conserving queues, we design a delay optimal policy for a clique network and compare it to the lower bound.

EXISTING SYSTEM:

A large number of studies on multi-hop wireless networks have been devoted to system stability while maximizing metrics like throughput or utility. These metrics measure the performance of a system over a long time-scale. 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. This problem is notoriously difficult even in the context of wireline networks, primarily because of the complex interactions in the network (e.g., superposition, routing, departure, etc.)

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that make its analysis amenable only in very special cases like the product form networks. The problem is further exacerbated by the mutual interference inherent in wireless networks which, complicates both the scheduling mechanisms and their analysis. Some novel analytical techniques to compute useful lower bound and delay estimates for wireless networks with single-hop traffic were developed in. However, the analysis is not directly applicable to multi-hop wireless network with multihop flows, due to the difficulty in characterizing the departure process at intermediate links.

The metric of interest in this paper is the system-wide average delay of a packet from the source to its corresponding destination. We present a new, systematic methodology to obtain a fundamental lower bound on the average packet delay in the system under any scheduling policy. Furthermore, we re-engineer well known scheduling policies to achieve good delay performance viz-a-viz the lower bound.

PROPOSED SYSTEM :

We analyze a multi-hop wireless network with multiple source-destination pairs, given routing and traffic information. Each source injects packets in the network, which traverses through the network until it reaches the destination. For example, a multi-hop wireless network with three flows is shown in Fig. 1. The exogenous arrival processes AI (t), AII (t) and AIII (t) correspond to the number of packets injected in the system at time t. A packet is queued at each node in its path where it waits for an opportunity to be transmitted. Since the transmission medium is shared, concurrent transmissions can interfere with each others' transmissions.

The set of links that do not cause interference with each other can be scheduled simultaneously, and we call them activation vectors (matchings). We do not impose any a priori restriction on the set of allowed activation vectors, i.e., they can characterize any combinatorial interference model.

For example, in a K-hop interference model, the links scheduled simultaneously are separated by at least K hops. In the example show in Fig. 1, each link has unit capacity; i.e., at most one packet can be transmitted in a slot. For the above example, we assume a 1-hop interference model.

The delay performance of any scheduling policy is primarily limited by the interference, which causes many bottlenecks to be formed in the network. We demonstrated the use of exclusive sets for the purpose of deriving lower bounds on delay for a wireless network with single hop traffic. We further generalize the typical notion of a bottleneck. In our terminology, we define a (K, X)-bottleneck to be a set of links X such that no more than K of them can simultaneously transmit. Figure 1 shows (1, X) bottlenecks for a network under the 1-hop interference model. In this paper, we develop new analytical techniques that focus on the queuing due to the (K, X)-bottlenecks. One of the techniques, which we call the "reduction technique", simplifies the analysis of the queuing upstream of a (K, X)-bottleneck to the study of a single queue system with K servers as indicated in the figure.

Furthermore, our analysis needs only the exogenous inputs to the system and thereby avoids the need to characterize departure processes on intermediate links in the network. For a large class of input traffic, the lower bound on the expected delay can be computed using only the statistics of the exogenous arrival processes and not their sample paths. To obtain a lower bound on the system wide average queuing delay, we analyze queuing in multiple bottlenecks by relaxing the interference constraints in the system. Our relaxation approach is novel and leads to nontrivial lower bounds.We now summarize our main contributions in this paper:

• Development of a new queue grouping technique to handle the complex correlations of the service process resulting from the multi-hop nature of the flows. We also introduce a novel concept of (K, X)-bottlenecks in thenetwork.

• Development of a new technique to reduce the analysis of queueing upstream of a bottleneck to studying simplesingle queue systems. We derive sample path bounds on a group of queues upstream of a bottleneck.

• Derivation of a fundamental lower bound on the system wide average queuing delay of a packet in multihopwireless network, regardless of the scheduling policy used, by analyzing the single queue systems obtained above.

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• Extensive numerical studies and discussion on useful insights into the design of optimal or nearly optimal scheduling policies gained by the lower bound analysis.

Theorem:

For a (K,X)-bottleneck in the system, at any time T ≥ 0, the sum of the queue lengths SX in X, under any scheduling policy is no smaller than that of the reduced system, i.e., QX(T) ≤ SX(T). Proof: We prove the above theorem using the principle of mathematical induction. Base Case: The theorem holds true for T = 0, since the system is initially empty. Induction hypothesis: Assume that the theorem holds at a time T = t, i.e., QX(t) ≤ SX(t). Induction Step: The following two cases arise.
Case 1: QX(t) ≥ K
QX(t + 1) = QX(t) – K + AX(t)
≤ SX(t) – K + AX(t)
≤ SX(t) – IX(t) + AX(t)
= SX(t + 1).
Case 2: QX(t) < K.
Using Eq. (III.11), we have the following,
QX(t + 1) = AX(t)
≤ SX(t) – IX(t) + AX(t)
= SX(t + 1).
Hence, the theorem is holds for T = t + 1.
Thus by the principle of mathematical induction, the theorem holds for all T.

IMPLEMENTATION:

Characterizing Bottlenecks in the system:

We also discuss type of bottleneck in the case of a cycle graph with 5 nodes, where no more than two links can be scheduled simultaneously. Some of the important exclusive sets for the wireless grid example under the 2-hop interference model are highlighted in Fig. 9.We use the indicator function 11{i2X} to indicate whether the flow i passes through the (K, X)-bottleneck, i.e.,

$$\mathbf{1}_{\{i\in X\}} = \begin{cases} 1 & \text{if } i \in X \\ 0 & \text{otherwise.} \end{cases}$$

The total flow rate _X crossing the bottleneck X is given by:

$$\Lambda_X = \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}}(\lambda_i).$$

Let the flow i enter the (K, X)-bottleneck at the node vki I and leave it at the node vli i . Hence, (li–ki) equals the number of links in the (K, X)-bottleneck that are used by flow i. We define _X and AX(t) as follows:

$$\lambda_X = \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}}(l_i - k_i)(\lambda_i).$$

$$A_X(t) = \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}}(l_i - k_i)(A_i(t)).$$

The reduction technique:

In this section, we describe our methodology to derive lower bounds on the average size of the queues corresponding to the flows that pass through a (K, X)-bottleneck. By definition, the number of links/packets scheduled in the bottleneck, IX(t) is no more than K, i.e.,

$$\sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}} \sum_{j=k_i}^{l_i-1} I_i^j(t) = I_X(t) \le K.$$

A flow i may pass through multiple links in X. Among all the flows that pass through X, let FX denote the maximum number of links in the (K, X)-bottleneck that are used by any single flow, i.e.,

$$F_X = \max_{i=1}^{N} \mathbf{1}_{\{i\in X\}}(l_i - k_i).$$

Let Sk i (t) denote the sum of queue lengths of the first k queues of flow i at time t, i.e.,

$$S_i^k(t) = \sum_{j=0}^{k} Q_i^j(t)$$

Summing Eq. (II.2) from j = 0 to k, we have

$$S_i^k(t+1) = S_i^k(t) + A_i(t) - I_i^k(t).$$

The sum of queues upstream of each link in X at time t is given by SX(t) and satisfies the following property.

$$S_X(t) = \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}} \sum_{j=k_i}^{l_i-1} S_i^j(t) \ge \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}} \sum_{j=k_i}^{l_i-1} Q_i^j(t)$$
$$\ge \sum_{i=1}^{N} \mathbf{1}_{\{i\in X\}} \sum_{j=k_i}^{l_i-1} I_i^j(t) = I_X(t).$$

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Now we consider the evolution of the queues SX under an arbitrary scheduling policy which is given by the following equation.

$$\mathcal{S}_X(t+1) = \mathcal{S}_X(t) - I_X(t) + A_X(t).$$

Reduced System:

Consider a system with a single server and AX(t) as the input. The server serves at most K packets from the queue. Let QX(t) be the queue length of this system at time t. The queue evolution of the reduced system is given by the following equation.

$$\mathcal{Q}_X(t+1) = (\mathcal{Q}_X(t) - K)^+ + A_X(t)$$

$$\text{where} \qquad (x)^+ = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases}$$

The reduction procedure is illustrated in Fig. 2 where we have reduced one of the bottlenecks in the grid example shown in Fig. 9. Flows II, IV and VI pass through an exclusive set using two, three and two hops of the exclusive set respectively. The corresponding G/D/1 system is fed by the exogenous arrival streams 2AII (t), 3AIV (t) and 2AV I (t). Without loss of generality we can assume that both systems are initially empty, i.e., QX(0) = SX(0) = 0. We now establish that at all times t ≥ 0, QX(t) is smaller than SX(t).

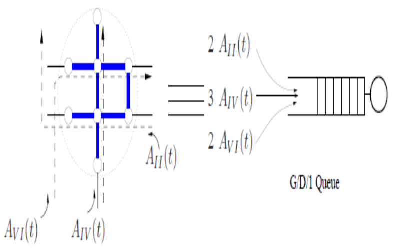

Fig. 2. Reducing a bottleneck exclusive set in Fig. 9 to a G/D/1 queue. Note that $A_{VI}(t)$, $A_{IV}(t)$, $A_{II}(t)$ are external arrivals to the original system, so the arrivals to the reduced G/D/1 system are all external.

Bound on Expected Delay :

We now present a lower bound on the expected delay of the flows passing through the bottleneck as a simple function of the expected delay of the reduced system. In the analysis, we use above Theorem to bound the queueing upstream of the bottleneck and a simple bound on the queueing downstream of the bottleneck. Applying Little's law on the complete system, we derive a lower bound on the expected delay of the flows passing through the bottleneck.

Design Of Delay Efficient Policies:

A scheduler must satisfy the following properties.

• Ensure high throughput: This is important because if the scheduling policy does not guarantee high throughput then the delay may become infinite under heavy loading.

• Allocate resources equitably: The network resources must be shared among the flows so as not to starve some of the flows. Also, non-interfering links in the network have to be scheduled such that certain links are not starved for service. Starvation leads to an increase in the average delay in the system.

The above properties are difficult to achieve; given the dynamics of the network and the lack of apriori information of the packet arrival process. In the light of the previous work we choose to investigate the back-pressure policy with fixed routing . The back-pressure policy has been widely used to develop solutions for a variety of problems in the context of wireless networks and the importance of studying the trade-offs in stability, delay, and complexity of these solutions is now being realized by the research community.

This policy tries to maintain the queues corresponding to each flow in decreasing order of size from the source to the destination. This is achieved by using the value of differential backlog (difference of backlogs at the two ends of a link) as the weight for the link and scheduling the matching with the highest weight. As a result, the policy is throughput optimal. Henceforth, we shall refer to this policy as only the back-pressure policy. We first study the delay optimal policy for a clique network.

Flow Scheduling
For each link $e \in L$, find the flow with the maximum differential backlog

$$f_e^*(t) = \underset{i}{\text{argmax}}\, \nabla Q_i^e \qquad \text{(IV.28)}$$

Assign weights to every link

$$w_e = \max(\nabla Q_{f_e^*}^e, 0) \qquad \text{(IV.29)}$$

Link Scheduling
Schedule the maximum weighted matching

$$I(t) = \underset{J \in \mathcal{J}}{\operatorname{argmax}} \langle w, J \rangle \qquad \text{(IV.30)}$$

where for two vectors x and y, $\langle x, y \rangle = \sum_l x_l y_l$ denotes the inner product.

RELATED WORK:

Much of the analysis for multi-hop wireless networks has been limited to establishing the stability of thesystem. Whenever there exists a scheme that can stabilize the system for a given load, the back-pressure policy is also guaranteed to keep the system stable. Hence, it is referred to as a throughput-optimal policy. It also has the advantage of beinga myopic policy in that it does not require knowledge of the arrival process. In this paper, we have taken an important step towards the expected delay analysis of these systems. The general research on the delay analysis of scheduling policies has 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 regime. It has been shown in [5] that 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 in [8], [19], [23], [24] 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, it has been shown in [24] that 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, hasnot 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 obtained in [32], [35] 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.

CONCLUSION:

In this paper we focused on the delay analysis of a multi-hop wireless network. Analyzing delay and proposing optimal scheduling policies is very important to solve the open problem of delay performance. In this paper we implement the concepts provided by Gupta et al. [1]. The focus here is lower bound analysis in order to identity and reduces bottlenecks present in wireless network with multiple hops. We implemented scheduling policies that can improve performance of the network by reducing bottlenecks. We made a general analysis that can be used for various classes of arrival processes. Our work also has support for channel variations. Near optimal policies could be made by identifying bottlenecks accurately. We built a prototype application in Java platform which simulates the concept effectively. The empirical results reveal that the applic ation is effective and can be used in the real world.

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