On the Capacity Requirement for Arbitrary End-to-End Deadline and Reliability Guarantees in Multi-hop Networks

Han Deng
Texas A&M University
College Station, Texas 77840
hdeng@tamu.edu

I-Hong Hou
Texas A&M University
College Station, Texas 77840
ihou@tamu.edu

ABSTRACT

It has been shown that it is impossible to achieve both stringent end-to-end deadline and reliability guarantees in a large network without having complete information of all future packet arrivals. In order to maintain desirable performance in the presence of uncertainty of future packet arrivals, common practice is to add redundancy by increasing link capacities. This paper studies the amount of capacity needed to provide stringent performance guarantees and propose a low-complexity online algorithm. Without adding redundancy, we further propose a low-complexity order-optimal online policy for the network.

CCS CONCEPTS

•**Networks** → **Packet scheduling;**

KEYWORDS

Multi-hop Network; Online Scheduling; CompetitiveRatio; Capacity Performance Trade-off

ACM Reference format:
Han Deng and I-Hong Hou. 2017. On the Capacity Requirement for Arbitrary End-to-End Deadline and Reliability Guarantees in Multi-hop Networks. In *Proceedings of SIGMETRICS '17, June 5–9, 2017, Urbana-Champaign, IL, USA, ,* 2 pages.
DOI: http://dx.doi.org/10.1145/3078505.3078540

1 INTRODUCTION

Many emerging safety-critical applications, such as Internet of Things (IoT) and Cyber-Physical Systems (CPS), require communication protocols that support strict end-to-end delay and reliability guarantees for all packets. In a typical scenario, when sensors detect unusual events that can cause system instability, they send out this information to actuators or control centers. This information needs to be delivered within a strict deadline for actuators or control centers to resolve the unusual events. The system can suffer from a critical fault when a small portion of packets fail to be delivered on time.

In the multi-hop network system, packet arrivals are time-varying and unpredictable. It is obvious that one cannot design the optimal network policies without obtaining complete knowledge of future packet arrivals and incurring high computation complexity. Therefore, practical solutions need to rely on online suboptimal policies. In order to maintain desirable performance using online suboptimal policies, current practice is to add redundancy into the system. During system deployment, the capacities of communication links are chosen to be larger than necessary. Such redundancy alleviates the negative impacts of suboptimal decisions by online policies. Using this approach, a critical question is to determine the amount of redundancy needed to provide the desirable performance guarantees. This paper aims to answer this question.

We formulate the problem as a linear programming problem and propose an online policy that achieves good performance in terms of competitive ratio using the primal-dual [1] method. We show that when there is no redundancy added to the system, the performance of our online policy is asymptotically better than that of the recent work by Mao et al. [2] when the size of the network increases. Next, we establish a theoretical lower bound of competitive ratio for all online policies. In addition, we propose an online policy that achieves order-optimal with fixed link capacity.

2 SYSTEM MODEL

We consider a network with multihop transmissions. The network is represented by a directed graph where each node represents a router and an edge from one node to another represents a link between the corresponding routers. Different links in the network may have different link capacities. Packets arrive at their respective source nodes following some unknown sequence. When a packet arrives at its source node, it specifies its destination and a deadline. At the beginning of each time slot, each node decides which packets to transmit over its links. The packet requests to be delivered to its destination before its specified deadline. Packets that are not delivered on time do not have any value, and can be dropped from the network. We aim to deliver as many packets on time as possible.

This material is based upon work supported in part by the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF-15-1-0279 and NPRP Grant 8-1531-2-651 of Qatar National Research Fund (a member of Qatar Foundation).
Full paper can be found: https://arxiv.org/pdf/1704.04857.pdf.

SIGMETRICS '17, June 5–9, 2017, Urbana-Champaign, IL, USA
 ACM ISBN 978-1-4503-5032-7/17/06.
DOI: http://dx.doi.org/10.1145/3078505.3078540

It is obvious that designing the optimal routing and scheduling policy requires complete knowledge of all packet arrivals in advance. In fact, a recent work has shown that, when the longest path between a source node and a destination node is L, no online policy can guarantee to deliver more than $\frac{1}{log_2 L}$ as many packets as the optimal solution. Such performance guarantee is usually unacceptable for practical applications, especially when the size of the network is large.

In order to achieve good performance for online policies in the presence of unknown future arrivals, we consider the scenario where service providers can increase link capacities by, for example, upgrading network infrastructures. We assume the link capacities are all increased by R times.

To evaluate the performance of online policies, we define a competitive ratio that incorporates the increase in capacities:

Definition 2.1. Given a sequence of packet arrivals, let Γ_{opt} be the optimal number of delivered packets with original link capacity, and $\Gamma_\eta(R)$ be the number of packets that are delivered under an online policy η when the link capacities are increased by R times. The online policy η is said to be (R, ρ)-*competitive* if $\Gamma_{opt}/\Gamma_\eta(R) \leq \rho$, for any sequence of packet arrivals.

3 RESULT

We have three main results in the paper.

3.1 An Online Algorithm and Its Competitive Ratio

We propose an low-complexity online algorihtm based on primal-dual method. It suggests a route for an arriving packet by considering all link usage on any possible route. When a route is chosen for the packet, all links along the path will update the link usages according to the method we propose in the algorithm. We have the following theorem for its competitive ratio.

THEOREM 3.1. *Let C_{min} be the minimum link capacity, $d_{min} := (1 + 1/C_{min})^{RC_{min}}$, and L be the longest path between a source node and a destination node. Our algorithm is $(R, 1+\frac{L}{d_{min}-1})$-competitive, which converges to $(R, 1+\frac{L}{e^R-1})$-competitive, as $C_{min} \to \infty$.*

3.2 A Theoretical Lower Bound for Competitive Ratio

We derive a lower bound on the performance of all online algorithms.

THEOREM 3.2. *Any online algorithm cannot be better than $(R, 1 + \frac{L-2e^R}{(L+1)e^R-L})$-competitive.*

Therefore, to guarantee to deliver at least $1 - \frac{1}{\theta}$ as many packets as the optimal solution, the capacity requirement of our policy is at most $\ln(L + 2\theta - 1)$ away from the lower bound. Suppose we fix the ratio between L and θ, and let them both go to infinity, then we have $(\ln L + \ln \theta)/(\ln L + \ln \theta - \ln(L+2\theta-1)) \to 2$. Therefore, when both L and θ are large, our policy at most requires twice as much capacity as the theoretical lower bound.

3.3 An Order-Optimal Online Policy with Original Capacity

We propose an optimal online algorithm which is $(1, O(\log L))$-competitive when the link capacity cannot be increased. The online algorithm uses a similar process to choose routes but it updates link usages with a different method. Comparing the updating process with the previous online algorithm, we find it to increase much slower when the link is lightly loaded and increase much faster when the link is heavy loaded. Such mechanism ensures that more packets with long routes can be accepted, especially when the network is lightly loaded.

4 A HEURISTIC FOR DISTRIBUTED IMPLEMENTATION

The two algorithms that we have proposed so far are both centralized algorithms. Specifically, when a packet arrives at a node, the node needs to have complete knowledge of all link usages at different time to find a route. Such information is usually infeasible to obtain. Thus we propose a distributed heuristics based on the design of our centralized algorithm.

Our distributed heuristic is composed of two parts: First, when a packet arrives at a node, the node determines a suggested schedule based on statistics of past system history. This suggested schedule consists of the route for forwarding the packet, as well as a local deadline for each link. After determining the suggested schedule, the node simply forwards it to the first link of the route. On the other hand, when a link receives a packet along with a suggested schedule, the link tries to forward the packet to the next link in the suggested schedule before its local deadline. The link drops the packet when it cannot forward the packet on time.

5 CONCLUSIONS

In this paper, we study the multi-hop network scheduling problem with end-to-end deadline and hard transmission rate requirement. Given the capacity of each link in the network, we aim to find out how much capacity we need to increase to guarantee the required ratio of packets can be successfully transmitted to its destination before its deadline without knowing the packet arrival sequences in advance. We propose two centralized online algorithms which both have better performance than that presented in [2]. We also propose a heuristic for distributed implementation based on the first online algorithm.

REFERENCES

[1] Niv Buchbinder and Joseph (Seffi) Naor. 2009. The Design of Competitive Online Algorithms via a Primal: Dual Approach. *Found. Trends Theor. Comput. Sci.* 3, 2–3 (Feb. 2009), 93–263. DOI:https://doi.org/10.1561/0400000024
[2] Z. Mao, C. E. Koksal, and N. B. Shroff. 2016. Optimal Online Scheduling With Arbitrary Hard Deadlines in Multihop Communication Networks. *IEEE/ACM Transactions on Networking* 24, 1 (Feb 2016), 177–189. DOI: https://doi.org/10.1109/TNET.2014.2363136