An Article Title That Spans Multiple Lines to Show Line Wrapping

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Abstract

We address a network design optimization problem in which the optimal bandwidth allocation must accommodate multiple oblivious traffic flows with known statistical properties. We propose a practical traffic management mechanism that ensures the allocated bandwidth meets optimal performance guarantees. Specifically, our approach maintains a packet loss rate below a given threshold , provided that each flow adheres to a predefined mean μ and an interval $[\mu - \sigma, \mu + \sigma]$. Each traffic flow is guaranteed a minimum bandwidth allocation and operates independently, unaffected by other flows.

I. Introduction

Ensuring optimal bandwidth allocation for uncertain traffic while minimizing packet loss is a critical challenge in modern network design. Specifically, when multiple uncertain traffic flows with known statistical properties coexist, each flow requires a guaranteed bandwidth allocation to ensure that packet loss remains below a predefined threshold ε while ensuring that the network resources allocated to each flow remain isolated from interference by others.

The task consists of two parts: (1) calculating the minimal bandwidth required to ensure that packet loss remains below a predefined threshold ε and (2) designing a system that classifies traffic flows and dynamically controls the allocated bandwidth for each flow.

For traffic flows that strictly fall within the interval $[\mu - \sigma, \mu + \sigma]$ with a mean traffic rate of μ, the system guarantees that packet loss remains below the predefined threshold. However, if a traffic flow deviates from this rule—either by exceeding $\mu + \sigma$ or having a mean rate higher than μ the system ensures only the guaranteed bandwidth while discarding excess traffic. In this case, the packet loss of the flow may exceed the predefined threshold ε.

This article presents a practical traffic management mechanism that ensures a minimal guaranteed bandwidth for each flow while maintaining low packet loss, even under uncertain and bursty traffic conditions.

A key requirement for such a system is to ensure that each flow receives a minimum guaranteed bandwidth that is isolated from interference caused by other bursty traffic. Additionally, regular traffic flows—those that adhere to the rule by remaining within the interval $[\mu - \sigma, \mu + +\sigma]$ with a mean traffic rate of μ should have packet loss kept below the predefined threshold ε.This ensures that network resources are fully utilized, especially in environments where traffic volumes cannot be accurately predicted but exhibit long-term statistical properties.

Research Background and Motivation

In the field of optimization-based traffic engineering, a longstanding challenge is defining and managing network traffic uncertainty. Traditionally, traffic volumes are predicted, and network resources are allocated based on these estimations. However, in reality, network traffic often deviates from predictions, making precise allocation challenging. To address this uncertainty, conventional approaches rely on strict bandwidth metering to keep traffic within predefined limits. While this method prevents overflow, it reduces flexibility and hinders efficient resource allocation, leading to suboptimal network utilization.

In optimization problems, calculating the minimum bandwidth for uncertain traffic is not straightforward. Unlike fixed traffic flows, this process must consider the statistical properties of the traffic. In the paper[**Paper1**], we discuss a method for determining the minimum bandwidth required when multiple uncertain traffic flows with known statistical properties coexist.

Even though the problem has been theoretically solved, many challenges remain in practical implementation. This paper aims to address these issues and propose a mechanism that can be effectively implemented to solve them.

Problems to be solved

Using robust optimization[**Robust Optimization**], we analyze the utilization of the most congested link for traffic flows that fall within the interval$[\mu - \sigma, \mu + \sigma]$ with a mean of μ. Based on this research, we

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Table 1: *Symbols and Their Descriptions Used in the Robust Optimization Model*

Constant	
Symbol	Description
L	The set of physical network links.
W	The set of Origin-Destination (OD) pairs.
g_w	guaranteed bandwidth of OD pair w.
u_w	upper limit bandwidth for OD pair $w(u_w > g_w)$.
ρ_w	$\frac{u_w - g_w}{u_w + g_w}$
wl	bandwidth required on link l for OD pair w.
ε	The maximum tolerable packet loss.

derive a formula to determine the minimal bandwidth required for flows that adhere to a specified rule (referred to as "the rule" in this paper, meaning traffic within $[\mu - \sigma, \mu + \sigma]$ with a mean of μ). This approach effectively addresses the first problem.

The second question is how to ensure that traffic flows adhere to the specified rules. This involves two key aspects: preventing traffic from exceeding $[\mu - \sigma, \mu + \sigma]$ and ensuring that the mean remains at μ.

The third question addresses handling traffic flows that do not comply with the rules (referred to as "naughty flows" in this paper). A naughty flow is defined as one that exceeds $\mu + \sigma$, has a mean rate greater than μ, or both. In contrast, flows that adhere to the rules are called "regular flows." The challenge is determining how to penalize naughty flows to prevent them from negatively impacting regular flows.

The fourth and final question is how to ensure that traffic flows remain isolated from one another, preventing interference between flows.

II. Problem Formulation and Solution

Minimal Bandwidth Calculation

We refered the paper "Design of Bandwidth Guaranteed OpenFlow Virtual Networks Using Robust Optimization"[**Paper1**]. The meanings of the constants are defined in Table 1.

$$\sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{\sum_{w\in W}(\rho_w y_{wl})^2} \leq \alpha C_l - \sum_{w\in W} y_{wl} \forall l \in L \tag{1}$$

According to Table. 1.α represent the utilization of the most congested link, and let C_l denote the physical capacity of link l. Since our research focuses on a single link, we replace αC_l with c, representing the effective capacity, and change the inequality $\leq$ to an equality $=$. Throughout the discussion, we use c as the capacity to simplify the formulation.

$$\sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{\sum_{w\in W}(\rho_w y_{wl})^2} = c - \sum_{w\in W} y_{wl} \forall l \in L \tag{2}$$

This is the first step in simplifying the problem, as we are analyzing a single link with multiple oblivious flows that share the same statistical properties. Therefore, we replace g_w and $u_w$with $\mu - \sigma$ and $\mu + \sigma$, respectively, to redefine the representation of ρ_w. To further simplify the scenario, we assume that all OD pairs have the same g_w and u_w. With this assumption, we modify the formula as follows:

$$\sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{\sum_{w\in W}(\frac{\sigma}{\mu} y_w)^2} = c - \sum_{w\in W} y_w \tag{3}$$

As mentioned earlier, our assumption includes multiple oblivious flows that share the same statistical properties. Therefore, we replace any variable with a subscript w by expressing it as a constant multiplied by the number of flows n, and we modify the equation as follows:

$$\sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{n(\frac{\sigma}{\mu} y)^2} = c - ny \tag{4}$$

We expect the allocated bandwidth for each flow to be μ. Thus, we replace μ as follows:

$$\sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{n\sigma^2} = c - n\mu \tag{5}$$

With this equation, we can determine the required bandwidth for our research problem.

$$c = \sqrt{2\ln\frac{1}{\varepsilon}} \times \sqrt{n\sigma^2} + n\mu \tag{6}$$

Queue to drop the exceed traffic

For implementation we need a mechanism to ensure that the traffic volume will not exceed the uppler limit $\mu + \sigma$. So we use queue to adjust the traffic like figure 1.

No matter what rate the traffic input, the queue dequeue with same rate. In our researched problem, the rate is the upper limit $\mu + \sigma$. That means the traffic after the first queue would not exceed this upper limit.

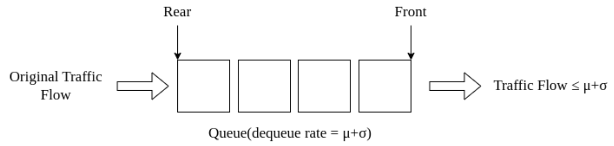

Figure 1: *Schematic diagram expressing how queue drop exceeded traffic flow*

GCRA

Piority Queue to QoS

$$\cos^3\theta = \frac{1}{4}\cos\theta + \frac{3}{4}\cos 3\theta \tag{7}$$

We refered the paper "Design of Bandwidth Guaranteed OpenFlow Virtual Networks Using Robust Optimization". It has

Minimal Bandwidth Calculation

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Robust Optimization

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Queue, GCRA and Priority Queues

Assume that the traffic usage patterns of each tenant follow a Gaussian distribution. We can then represent the problem using the model outlined in Equation 8. The constant values used in this formulation are provided in Table 2.

$$\begin{aligned}
&\min\ \alpha \\
&\quad \text{subject to} \\
&\quad P\Big(\sum_{s,t\in N, s\neq t} d_{st} f_{st}(e) \leq c_e\Big) \geq \eta && \forall e \in E \\
&\quad \sum_{s,t\in N, s\neq t} f_{st}(e) \leq \alpha c_e && \forall e \in E \\
&\quad \sum_{e\in E_n^{OUT}} f_{st}(e) - \sum_{e\in E_n^{IN}} f_{st}(e) = \begin{cases} \mu_{st} & \text{if } n = s \\ 0 & \text{if } n \neq s, n \neq t \\ -\mu_{st} & \text{if } n = t \end{cases} \\
&\quad \forall n, s, t \in N\ s \neq t \\
&\quad f_{st}(e) \geq 0 && \forall s, t \in N\ s \neq t\ , e \in E
\end{aligned} \tag{8}$$

The first constraint stipulates that **the probability that the traffic on link e does not exceed its capacity must be greater than the constant η**. In our experiments, we set $\eta = 0.9$. The second constraint ensures that link utilization does not exceed the maximum allowable utilization. If this constraint were omitted, α would be unconstrained. The third constraint enforces **flow conservation**. Since d_{st} is a random variable, the demand is replaced by its mean, μ_{st}. The final constraint addresses the **non-negativity** of the decision variables, ensuring that $f_{st}(e) \geq 0$.

Queue

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[1] Example footnote text.

Table 2: *Symbols and Their Descriptions Used in the Robust Optimization Model*

	Constant
Symbol	Description
E	The set of physical network links.
N	The set of physical network nodes.
E_n^{OUT}	The set of links emanating from node n.
E_n^{IN}	The set of links terminating at node n.
d_{st}	A Gaussian random variable representing the traffic demand between origin-destination pair st, where $d_{st} \sim \mathcal{N}(\mu_{st}, \sigma_{st}^2)$.
μ_{st}	The mean of the Gaussian random variable d_{st}, indicating the average traffic demand for the pair st.
σ_{st}^2	The variance of the Gaussian random variable d_{st}, reflecting the uncertainty in the traffic demand for the pair st.
c_e	The capacity of link e, which represents the maximum allowable traffic flow on the link.
η	The probability threshold ensuring that the traffic does not exceed the link capacity, serving as a reliability measure.
	Decision Variables
Symbol	Description
α	The maximum allowable link utilization, where $\alpha \geq 0$.
$f_{st}(e)$	The traffic flow from node s to node t through link e.

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GCRA

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Priority Queues

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Machanism

Simulation Architecture

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Grid Based Packets and Configuration

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Table 3: *Example single column table.*

Location		
East Distance	West Distance	Count
100km	200km	422
350km	1000km	1833
600km	1200km	890

Modules

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Figure 2: *Anther of thale cress (Arabidopsis thaliana), fluorescence micrograph. Source: Heiti Paves, https://commons.wikimedia.org/wiki/File:Tolmukapea.jpg.*

Referencing a figure using its label: Figure 2.

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Table 4: *Example two column table with fixed-width columns.*

Location		
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100km	200km	422
350km	1000km	1833
600km	1200km	890

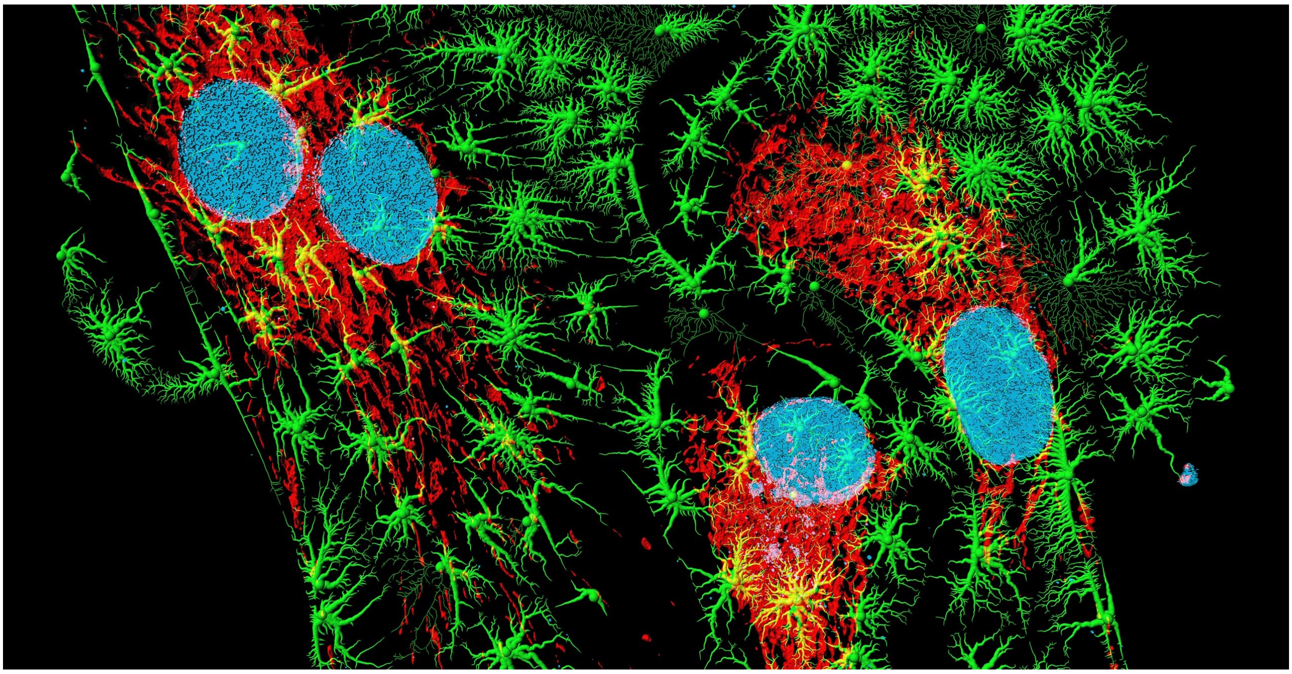

Figure 3: *Bovine pulmonary artery endothelial cells in culture. Blue: nuclei; red: mitochondria; green: microfilaments. Computer generated image from a 3D model based on a confocal laser scanning microscopy using fluorescent marker dyes. Source: Heiti Paves, https://commons.wikimedia.org/wiki/File:Fibroblastid.jpg.*

International Support

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Experiment

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Conclusions

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References

[1] J. M. Smith and A. B. Jones. *Book Title*. 7th. Publisher, 2023.

[2] A. B. Jones and J. M. Smith. "Article Title". In: *Journal title* 13.52 (Mar. 2024), pp. 123–456. DOI: `10.1038/s41586-021-03616-x`.

References

[1] Thomas, L. & Ari, R. d. *Biological Feedback* (CRC Press, USA, 1990).

[2] Thomas, L. & Ari, R. d. *Biological Feedback* (CRC Press, USA, 1990).