# Modeling and Analysis of Networks with High-speed TCP Connections

Sudheer Poojary Vinod Sharma

Department of ECE, Indian Institute of Science, Bangalore

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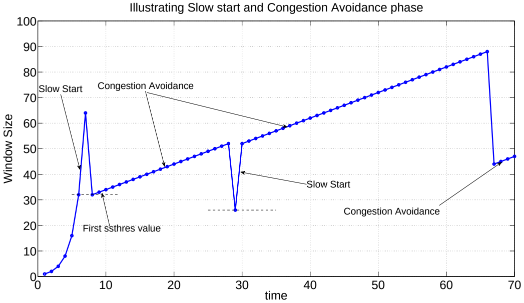
# Introduction

TCP is a dominant transport protocol which provides

- reliable, in-order, end-to-end data transfer,
- congestion and flow control,
- fair allocation of resources.

TCP congestion control has two phases:

- **Slow start**, $W_n < ssthres$
- **Congestion avoidance**, $W_n \geq ssthres$



# High Speed TCP variants

AIMD TCP prevents congestion and is 'fair'. However, $\cdots$

- TCP does not distinguish between non-congestion losses and congestion losses.
    - **poor performance in wireless environment**.
- For high speed networks, AIMD TCP is too slow.
    - **inefficient link usage in large BDP networks**.

High speed TCP variants use adaptive window increments

- efficiently use links,
- take lesser time to recover from losses.

We consider two widely used TCP variants: TCP CUBIC and TCP Compound.

## TCP CUBIC

**Default Linux TCP** algorithm since 2006.

TCP CUBIC Window Evolution:

$$W_{cubic}(W_0, t) = \mathcal{C}(t - \sqrt[3]{(W_0\beta/\mathcal{C})})^3 + W_0. \tag{1}$$

- $W_0$: window size at the last loss epoch
- $t$: time since last loss; $\beta$: the multiplicative drop factor
- If loss, the window size is reduced by a factor of $(1 - \beta)$.

Also uses

$$W_{reno}(W_0, t) = W_0(1 - \beta) + 3\frac{\beta}{2 - \beta}\frac{t}{R}. \tag{2}$$

# TCP Compound

## TCP Compound

- It is used by Windows servers.
- $W_n$ : Window size at end of $n^{th}$ RTT.
- The TCP Compound window size is given by

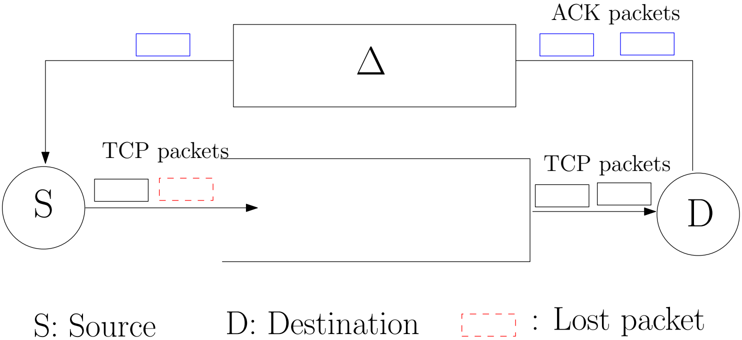
$$W_{n+1} = \begin{cases} W_n + \alpha W_n^k, & \text{if no loss} \\ \frac{W_n}{2}, & \text{if loss is detected;} \end{cases} \tag{3}$$

## Our Contribution

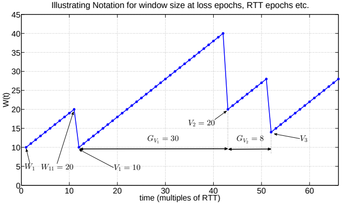
- TCP throughput has been evaluated using Markov models and deterministic **periodic loss-based models**.
- The Markov models typically assume **random i.i.d. packet losses**.
- The assumption of random losses is reasonable in wireless networks.
- The Markov models in previous literature are **more exact** than deterministic periodic loss-based models.
- However the Markov models are only **numerically evaluated**.
- We derive a **closed-form** approximation for TCP throughput under random losses for TCP CUBIC and TCP Compound.

# System Model

We have a single long-lived TCP flow with **constant RTT, $R$**.
Each packet of the flow is dropped w.p. $p$ independently of the other packets.



# Stationarity of the Window Size Process




- $W_n(p)$ : Window size at the end of $n^{th}$ RTT.
- $V_k(p)$ : Window size at the end of $k^{th}$ loss epoch.
- $G^p_{V_k(p)}$ : Time between the $k^{th}$ and the $(k+1)^{st}$ loss epochs.

## Stationarity of $\{W_n(p)\}$ process

We show that for packet loss rate, $p \in (0, 1)$, the window size process, $\{W_n(p)\}$ has a **unique stationary distribution** and has **finite mean under stationarity** for TCP CUBIC and TCP Compound.

# Asymptotic Approximations

As $p \to 0$, $W_n(p) \to \infty$. However, if we consider an appropriately scaled version of $\{W_n(p)\}$, we can derive some useful results. For the time between losses, we have

- TCP Comp.: For $x \geq 1$, $p^{\frac{1-k}{2-k}} G^p_{\lfloor \frac{x}{p^{\frac{1}{2-k}}} \rfloor} \xrightarrow{w} \overline{G}_x$, as $p \to 0$, with $\mathbb{P}(\overline{G}_x \geq y) = f_{ctcp}(\alpha, k, x, y)$.
- TCP CUBIC: For $x \geq 1$, $p^{\frac{1}{4}} G^p_{\lfloor \frac{x}{p^{\frac{3}{4}}} \rfloor} \xrightarrow{w} \overline{G}_x$, as $p \to 0$, where $\mathbb{P}(\overline{G}_x \geq y) = f_{cubic}(C, R, x, y)$.

For the $\{V_k(p)\}$ process, (with $\{\overline{V}_k\}$, a Markov process with transitions dependent on $\overline{G}_{\overline{V}_{k-1}}$), as $p \to 0$,

- TCP Comp.: If $\lim_{p \to 0} p^{\frac{1}{2-k}} V_0(p) \xrightarrow{w} \overline{V}_0$, $\{p^{\frac{1}{2-k}} V_n(p)\} \xrightarrow{w} \{\overline{V}_n\}$.
- TCP CUBIC: If $\lim_{p \to 0} p^{\frac{3}{4}} V_0(p) \xrightarrow{w} \overline{V}_0$, $\{p^{\frac{3}{4}} V_n(p)\} \xrightarrow{w} \{\overline{V}_n\}$.

# Throughput Approximation

Now, $\mathbb{E}[W(p)] = \frac{\frac{1}{p}}{\mathbb{E}[G^{p}_{V(p)}]}$

- TCP Compound: By simulations we get, $\frac{1}{\mathbb{E}[\overline{G}_{\overline{V}_\infty}]} = 0.257$.

  Therefore for small $p$,

$$\mathbb{E}[W(p)] \approx 0.257 p^{-\frac{1}{2-k}}, \quad (4)$$

- TCP CUBIC: By simulations, we get $\frac{1}{\mathbb{E}[\overline{G}_{\overline{V}_\infty}]} = 1.3004$, for $R = 1$,

  Hence,

$$\mathbb{E}[W(p)] \approx \max\left\{1.3004\left(\frac{R}{p}\right)^{\frac{3}{4}}, \frac{1.31}{\sqrt{p}}\right\}. \quad (5)$$

# Summary

- We derive **throughput approximations** for TCP CUBIC and TCP Compound under **random losses** via analytical models.
- Our model approximations have been validated by ns2 simulations.
- Our model results are as accurate as the more exact (compared to fluid models) Markov models.
- For TCP Compound, all model results are close to simulation results.
- Our model for TCP CUBIC (in the cubic mode of operation) is more accurate than the fluid approximation.

Visit poster for simulation results and other details. **Thank you**.