Throughput Analysis of TCP Cubic over 5G mmWave Networks

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Research seminar

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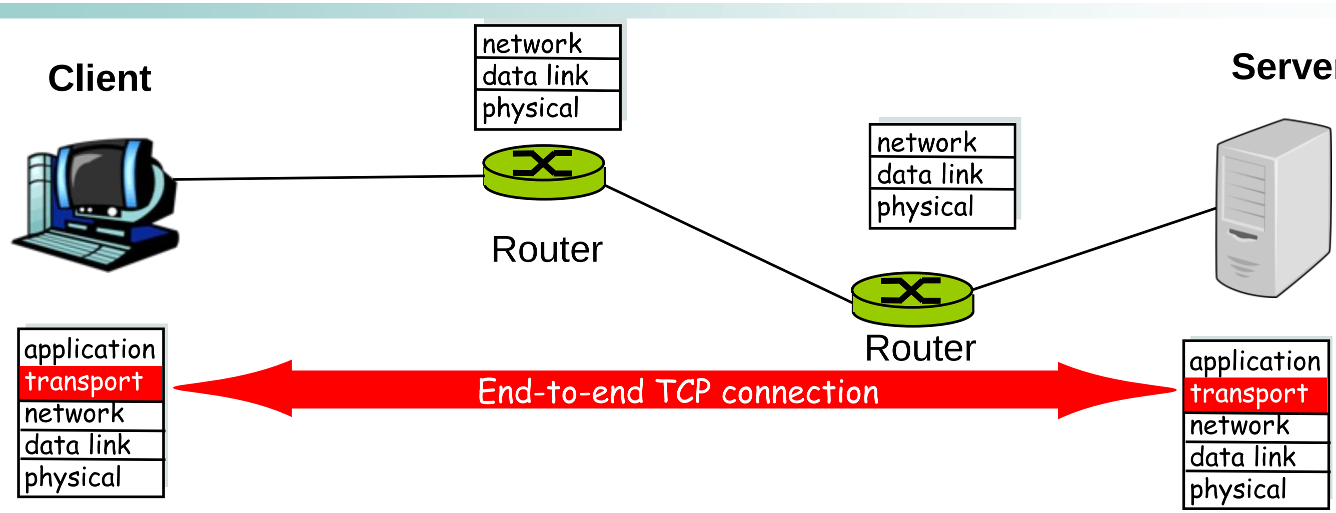
Outline

- TCP Review
  - Congestion control
  - TCP Cubic
- TCP in 5G mmWave networks
  - Challenging issues
  - Recent works
- My study
  - Proposals

Part I - TCP: Transmission Control Protocol



- TCP offers *end-to-end reliable data delivery* through network

No errors or losses, and all are delivered in order that they were sent

- TCP is the most popular protocol for many Internet applications, e.g., email, telnet, file transfer, …

Some Services of TCP

Source: Computer Networking: A top-down approach

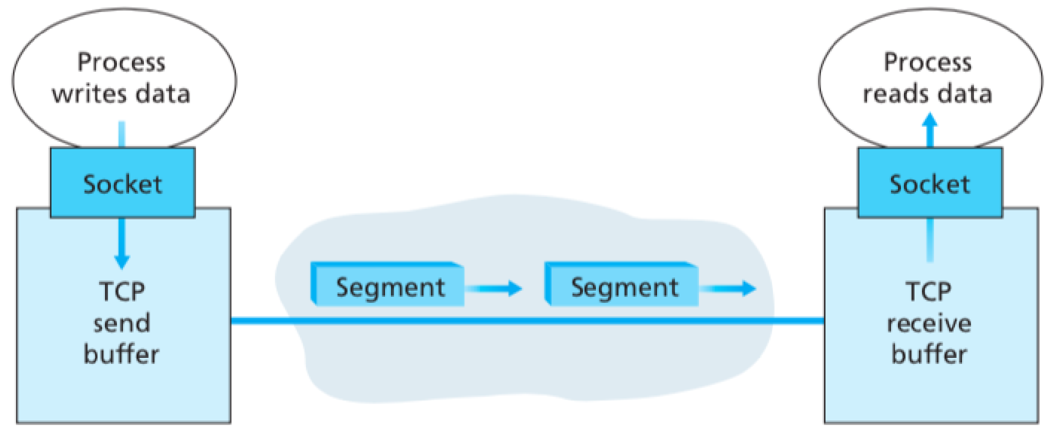


Fig. 1. TCP send and receive buffers

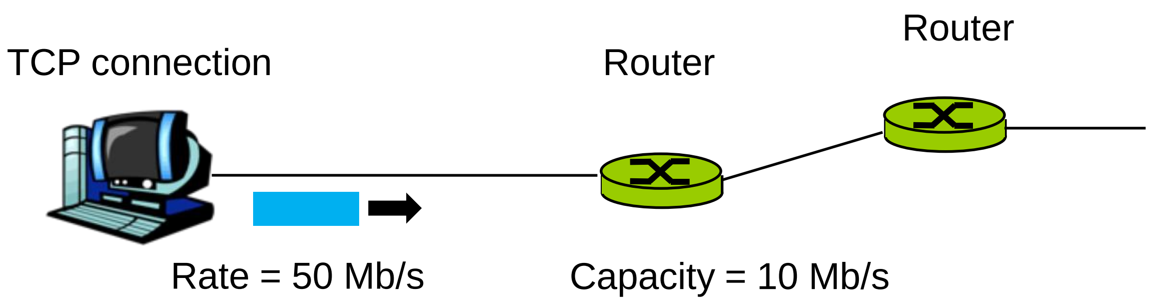
- Some services of TCP:
  - Connection management: three-way handshake
  - Reliable (retransmission), in-order delivery
  - Flow control: controls the traffic between sender and receiver
  - **Congestion Control**: control the traffic entering the networks

main focus

Congestion

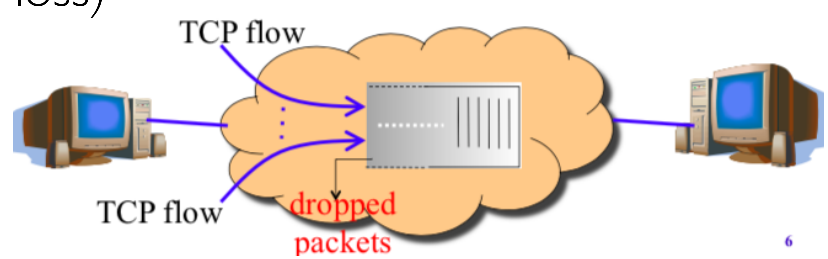
What is the congestion?

- Load on the network is greater than the capacity of network
- E.g.



What do Routers do?

- Drop the packets (clarify the packet loss)



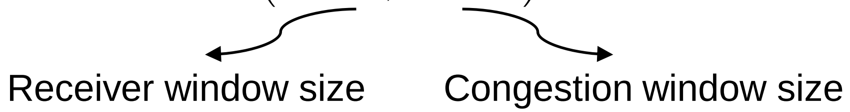
Consequence?

- Waste bandwidth for retransmission, delay

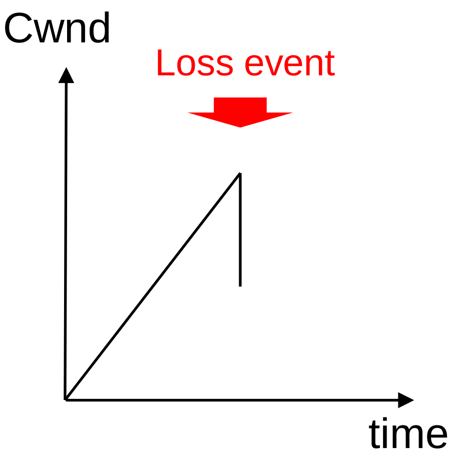
➡ Need a congestion control mechanism

TCP Congestion Control

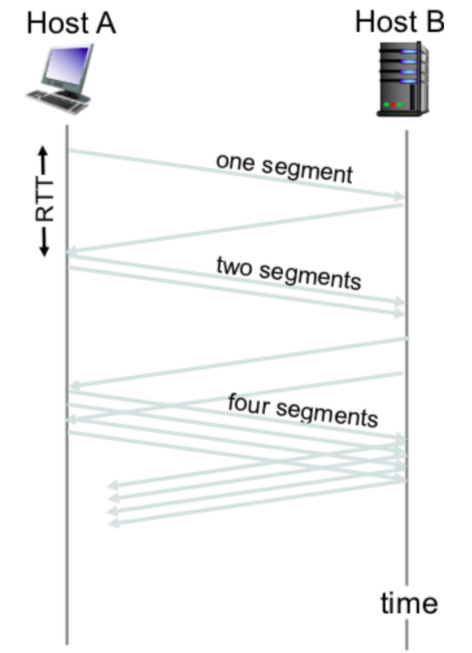
- Purpose of congestion control?
  - Keep senders from overloading the network (keep the load below the capacity)
- Congestion window size
  - Maximum data (segments) can be transmitted
  - Actual window size = min(rwnd, cwnd)



- How it works?
  - Adjust the congestion window size
  - Increase the window size upon not detecting congestion
  - Decrease the window size if detecting the congestion



Phases of Congestion Control



- *Slow start phase* (start a transmission):
  - Exponential increase
  - Initially cwnd = 1 MSS (maximum segment size)
  - Double cwnd every RTT (round-trip-time)

➡ Happen at a very short time duration

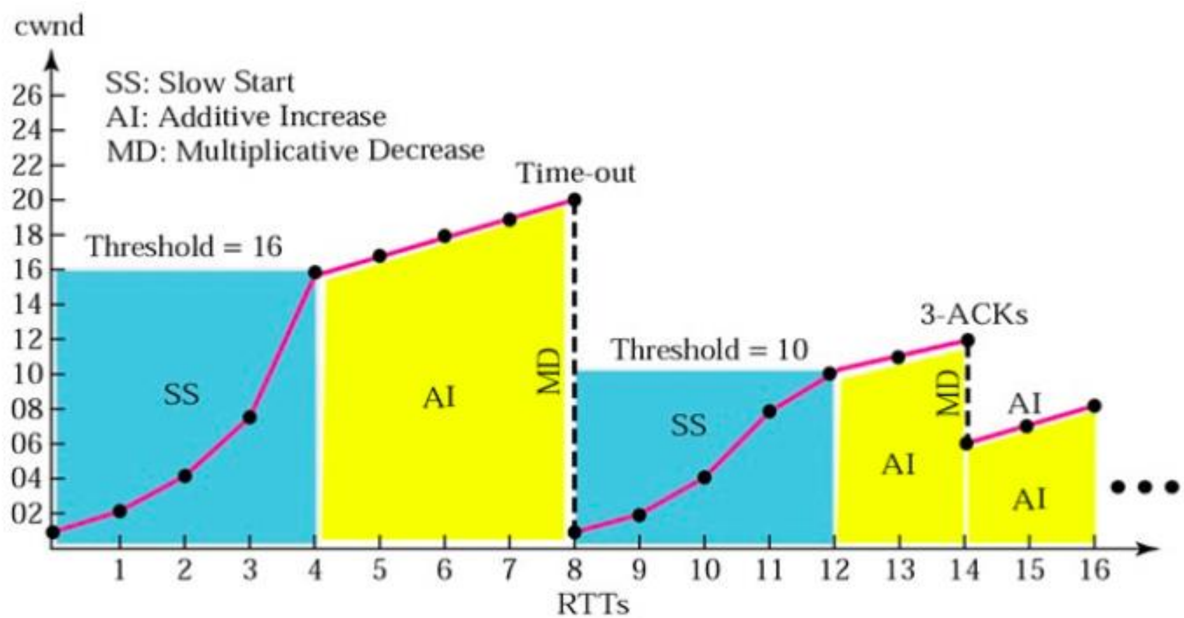
- *Congestion avoidance phase*: cwnd > threshold
- *Congestion detection and recovery phase: congestion happens*
  - Indicated by either time-out or triple duplicate ACK
  - Reduce cwnd

➡ Traditional TCP variants such as Tahoe, Reno, use the AIMD (additive increase – multiplicative decrease) algorithm

TCP-based AIMD

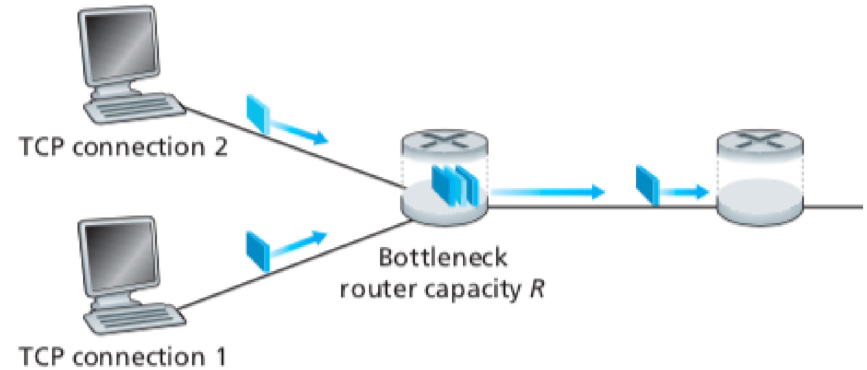
- Congestion avoidance phase: additive increase
  - Increase the rate linearly: $cwnd_{current} = cwnd_{previous} + 1$
  - Until reach the maximum cwnd
- Congestion detection phase: multiplicative decrease
  - Decrease the current cwnd by a half: $cwnd_{current} = 0.5 \times cwnd_{previous}$

Example



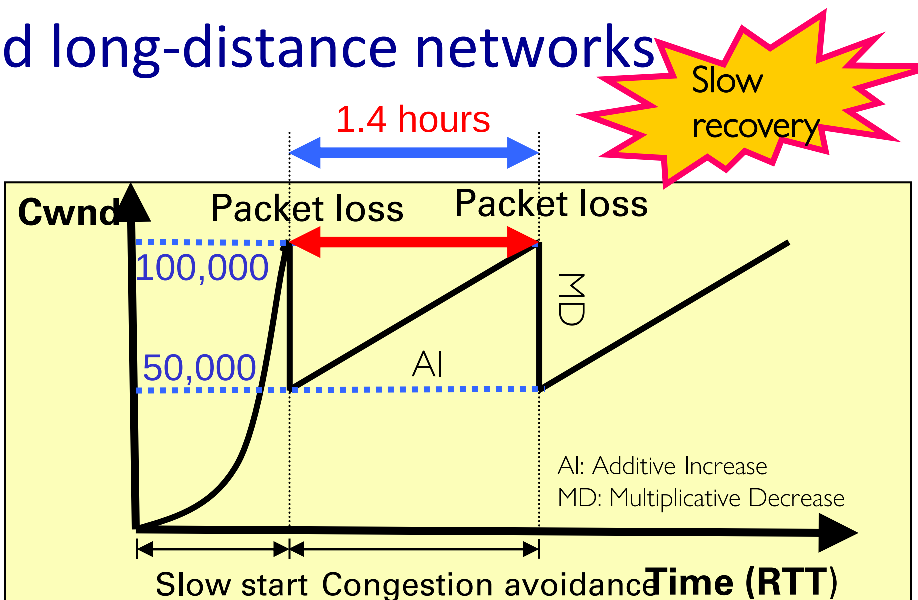
Drawback of AIMD

- (1) Fairness issues
  - RTT of flow 1 > RTT of flow 2
  - Flow 2 receives ACKs faster
  - cwnd of flow 2 grows faster



➡ Unfairness between TCP flows

- (2) Inefficiency in high-speed and long-distance networks
  - BW = 10 Gbps
  - RTT = 100 ms
  - Packet size = 1250 bytes
  - BDP of path = 100,000 packets
  - Full-utilized = 100,000 packets
  - Half-utilized = 50,000 packets



TCP Cubic

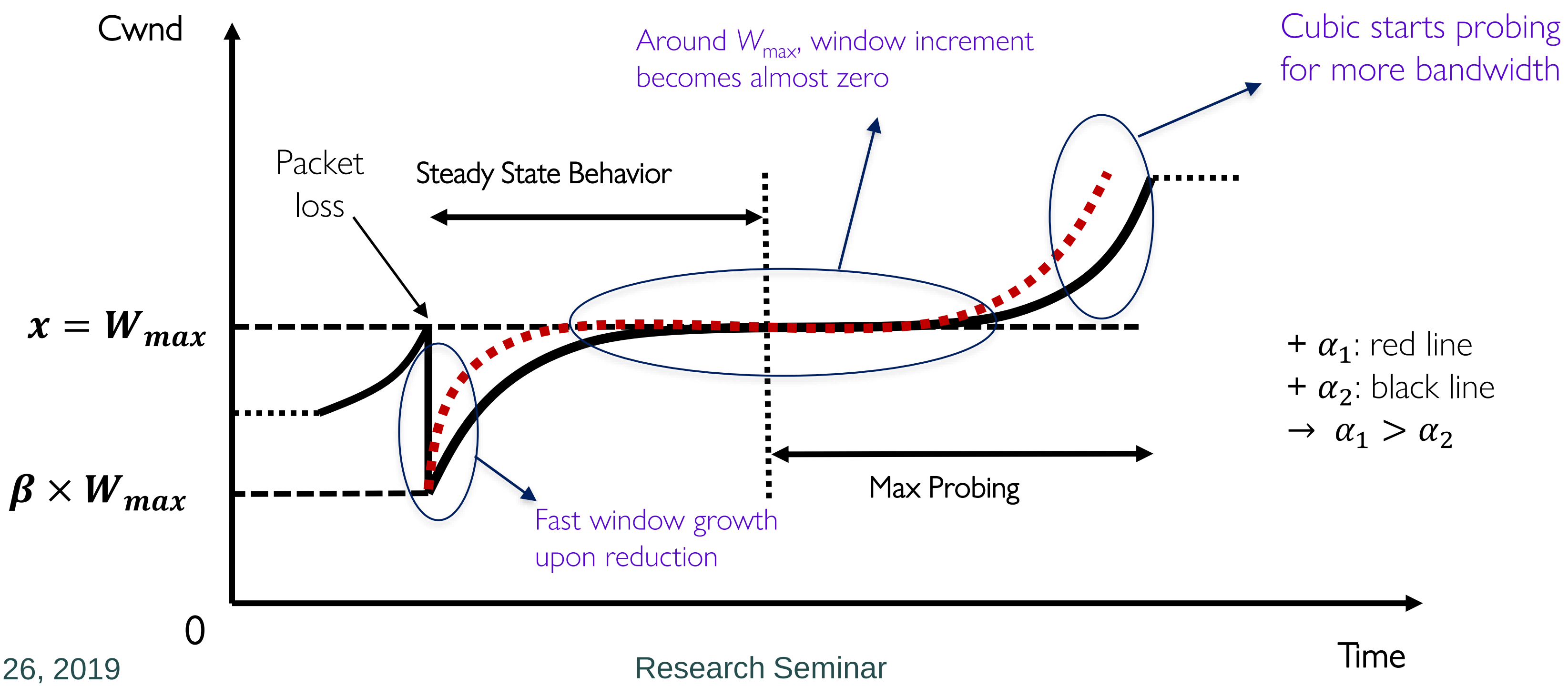
- Cubic is specifically designed for high-bandwidth and long-distance networks
- Default TCP in Linux (kernels 2.6.19 and above)
- The congestion window control is a Cubic function defined in real-time since the last congestion event
  - Independent with RTT: fairness between TCP flows (TCP friendliness)
  - Cubic increases its cwnd aggressively when it is far from the previous saturation point (last loss event) and more slowly when it is close
    - Stable and scalable

Cubic Congestion Control

- The window growth function of TCP Cubic

$$w(x,\tau) = \alpha\left(\tau - \sqrt[3]{(1-\beta)x/\alpha}\right)^3 + x,$$

Where α: Cubic factor, τ: elapsed time from the last window reduction, β: multiplicative decrease factor, and x: window size just before the last window reduction.



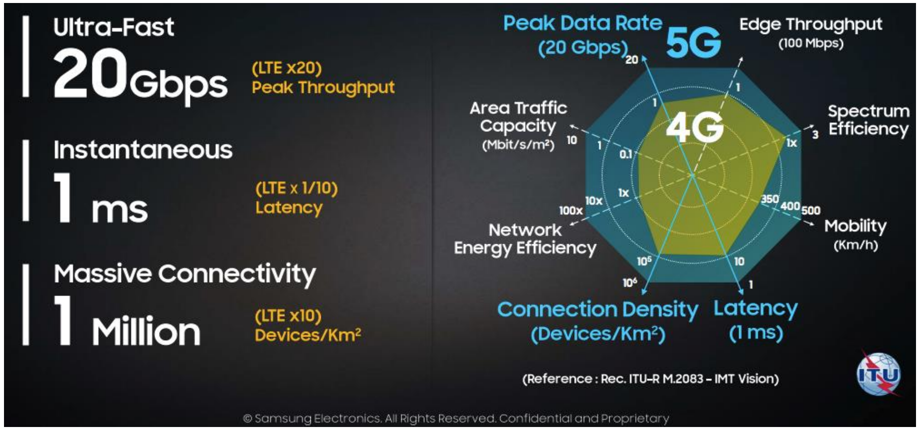
Pros and Cons

- **Pros:**
  - Fairness between TCP flows: independent of RTT
  - Scalability and stability: Cubic increases cwnd to last window reduction quickly, keep it there longer, and then grow quickly to find more BW
  - High utilization in high-speed and long-distance networks
- **Cons:**
  - Speed of react: it can be sluggish to find new saturation point if this point is far beyond the last one
  - Window growth rate is slower than TCP-based AIMD when RTT is short

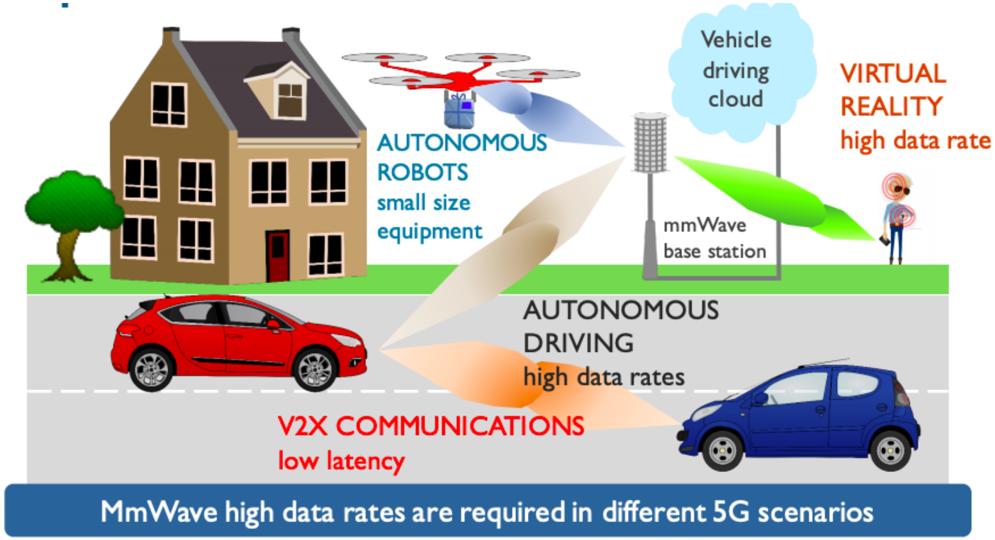
Part II - 5G mmWave Networks

- Key future of 5G

Source: Qualcomm

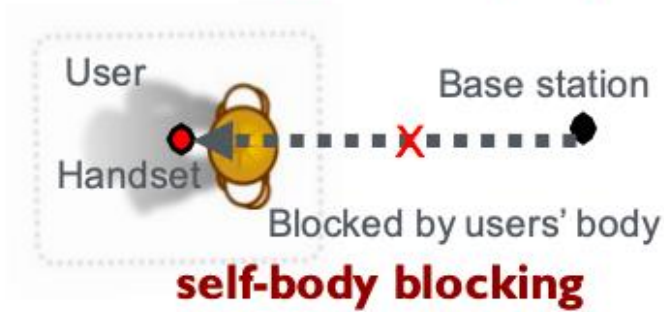


- mmWave
  - Short range service
  - High data rate



Major Channel Impairment

- Blockage is the main challenging issue of mmWave



Pose various challenges in system design

TCP over 5G mmWave Networks

- Most of works on 5G mmWave has focused on the physical and link layers, not so many studies on the performance of transport protocols over this kind of links

Source: www.mmwave.dei.unipd.it

- The performance of TCP is degraded by the fading mmWave channels (bandwidth fluctuation in LOS/NLOS transition)
  - As the transmission errors occur due to wireless link, the TCP may reduce its sending rate even if there is no actual congestion: *decrease throughput*
  - Long time to recover full throughput after an outage
  - TCP algorithm and parameters, that are proper for one environment, are not always suitable for other environments

→ Need to investigate the performance of TCP in 5G mmWave Networks

Tools and Techniques

- How to investigate the performance of TCP?

	Scopes
Measurement	- Have a real measurement - Real results
Network simulation	- Provides a convenient way to predict the performance when the proposed network is not available for measurement. - Can incorporate more details than analytical modeling; results can be produced that are closer to the real ones
Analytical modeling	- Provide a good approximation of network performance with various channel conditions in a relatively quick fashion - Convenience methods for design and optimization protocols

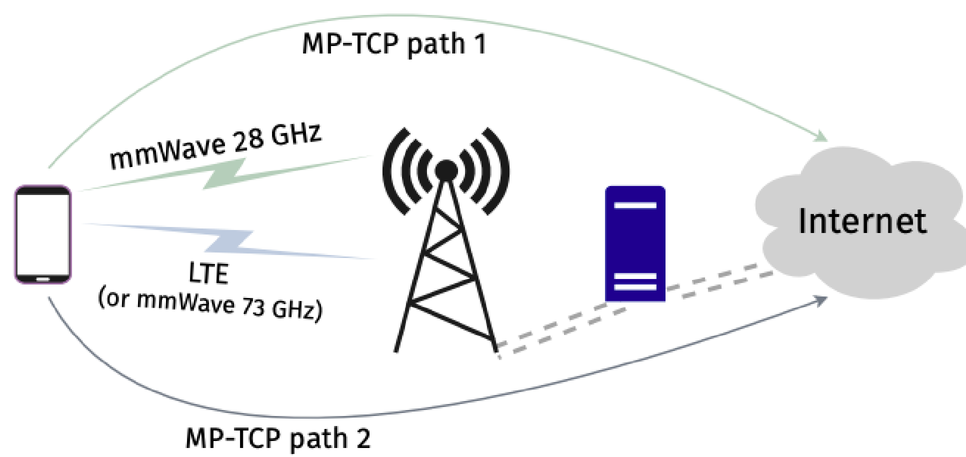
Source: M. Hassan and R. Jain. High Performance TCP/IP Networking: Concepts, Issues, and Solutions. Book 2003.

Some Recent Works (1)

- Most of studies on TCP using network simulation (NS-3)
  - [1]. 2019. Will TCP Work in mmWave 5G Cellular Network
- Some papers are interested in Multipath TCP (MP-TCP)
  - [2] 2019. Optimal multipath TCP Offloading Over 5G NR and LTE Networks
  - Modern devices have multiple network interfaces
  - They use MP-TCP to provide *path diversity* in LTE + mmWave cellular networks

Design goals

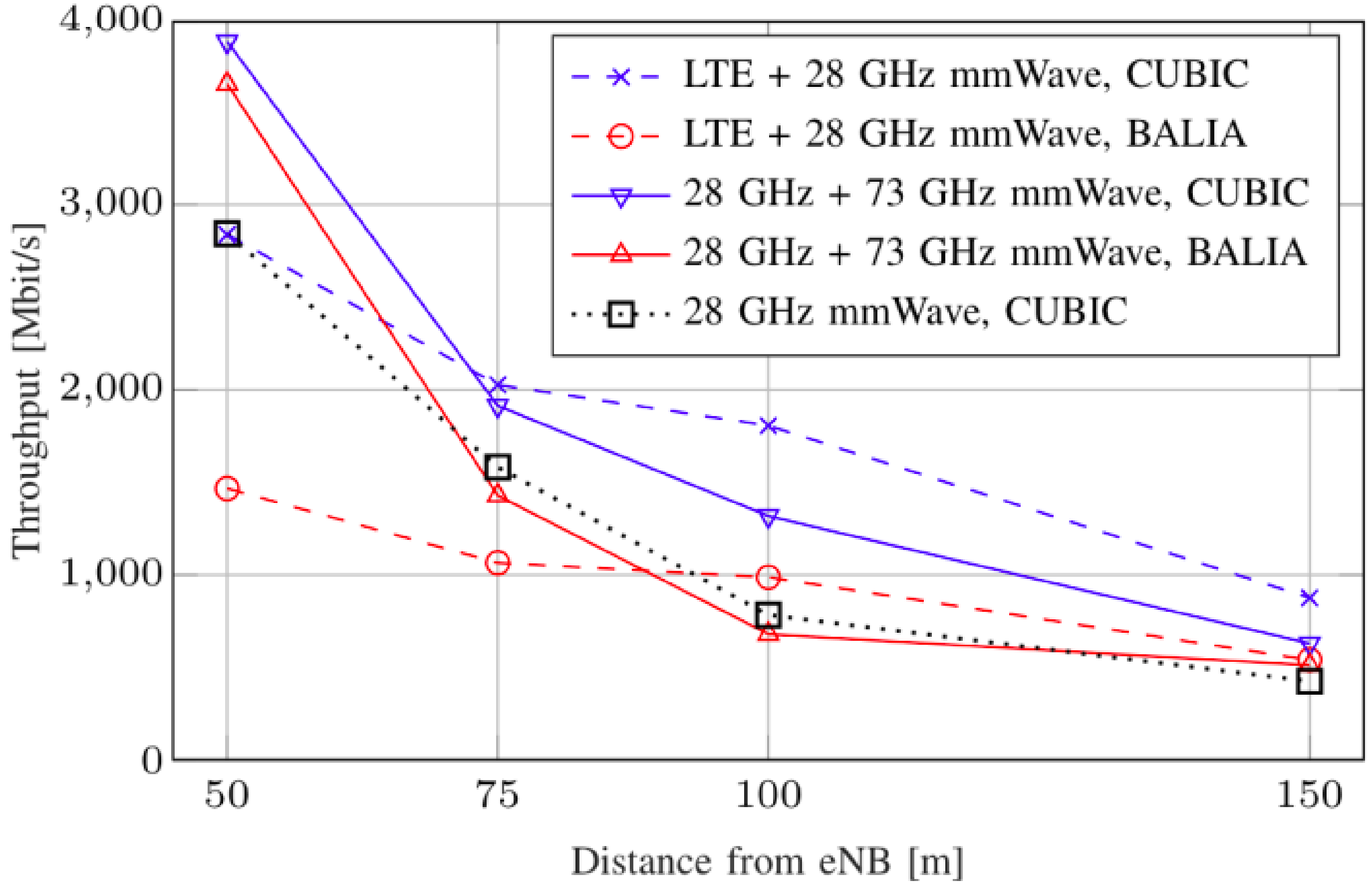
- **Improve throughput**: perform at least better than single path TCP
- **Avoid congestion**: prefer less congested paths among the available ones



Some Recent Works (2)

- MP-TCP with single path TCP (TCP Cubic)

2017. TCP in 5G mmWave Networks: Link Level Retransmissions and MP-TCP



Note: BALIA – the state of art CC algorithm for MP-TCP, but based on the design of AIMD

Some Recent Works (3)

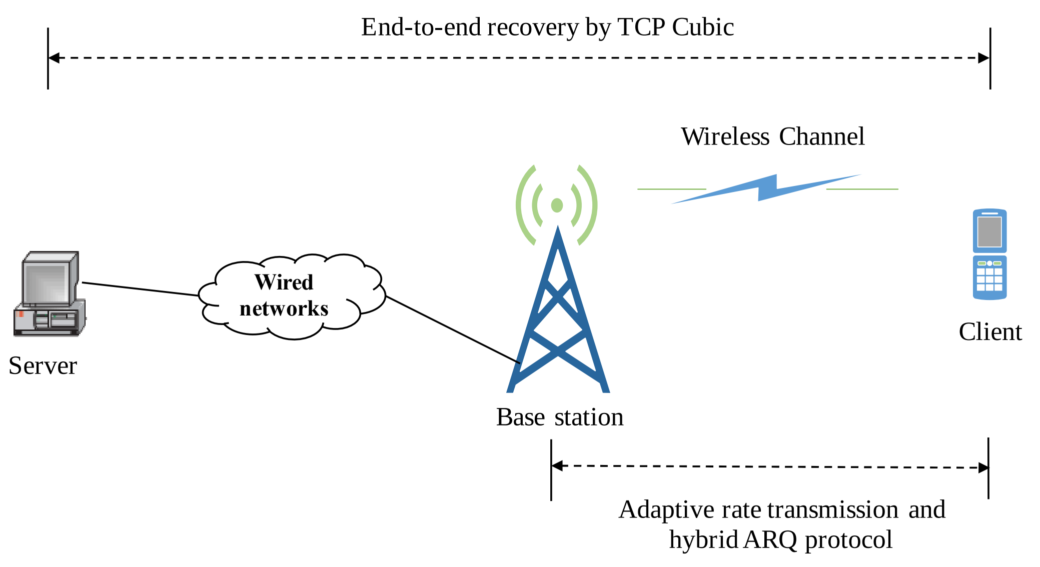
- The current available CC algorithm do not respect MP-TCP design goals
  - [3]. 2017. TCP in 5G mmWave Networks: Link Level Retransmissions and MP-TCP
- The performance of TCP Cubic is highlighted in term of throughput
  - [4]. 2019. Analysis of TCP Performance in 5G mm-wave Mobile Network

TCP Cubic is one of a candidate for 5G mmWave Networks

Lack of the analytical modeling of TCP Cubic

Part III - My study

- We want to provide an analytical modeling of TCP Cubic over 5G mmWave networks (Throughput analysis)
- Consider the improvement taking the physical and link layer designs
  - Physical layer: adaptive rate transmission
  - Link layer: hybrid ARQ (simplest type)



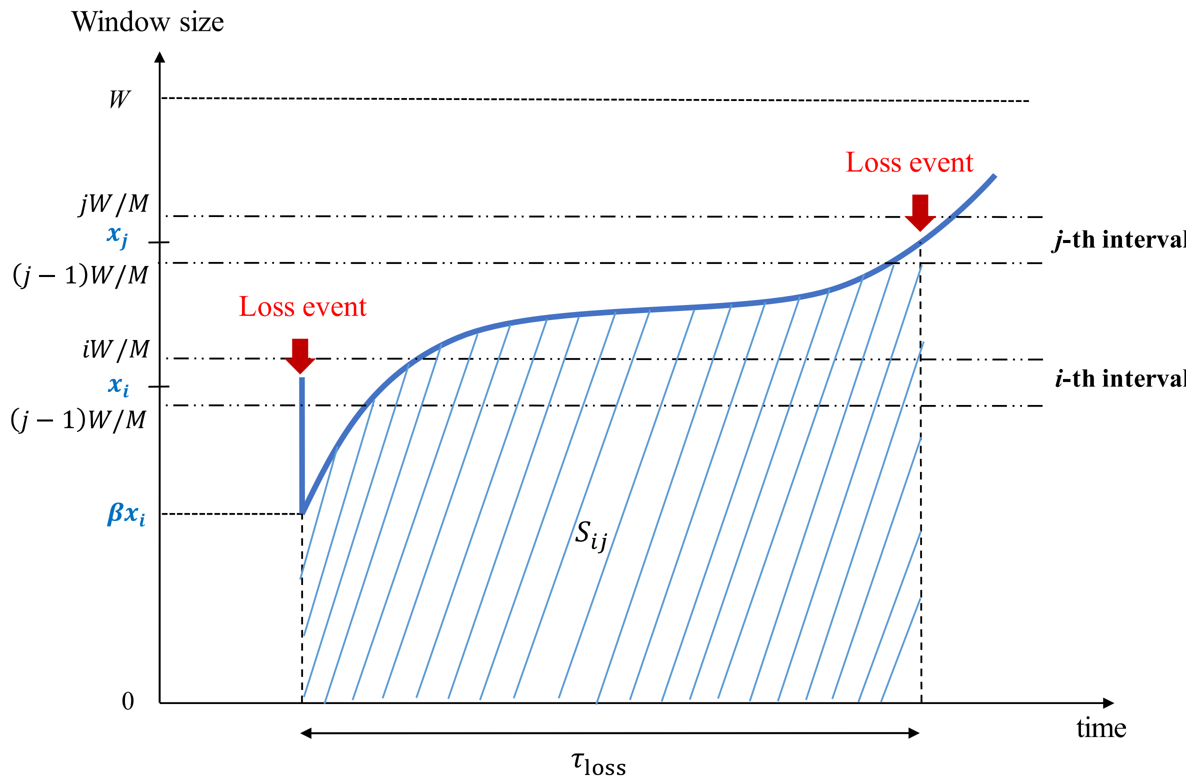
Data Structure

- TCP: Segment
- Link-layer: Frame including CRC, FEC code
- Physical-layer: Burst including adaptive multiple frames depending on AR transmission

How to Model the TCP Throughput?

- Study the congestion window evolution in terms of cycles
- Cycles: period between two consecutive loss events

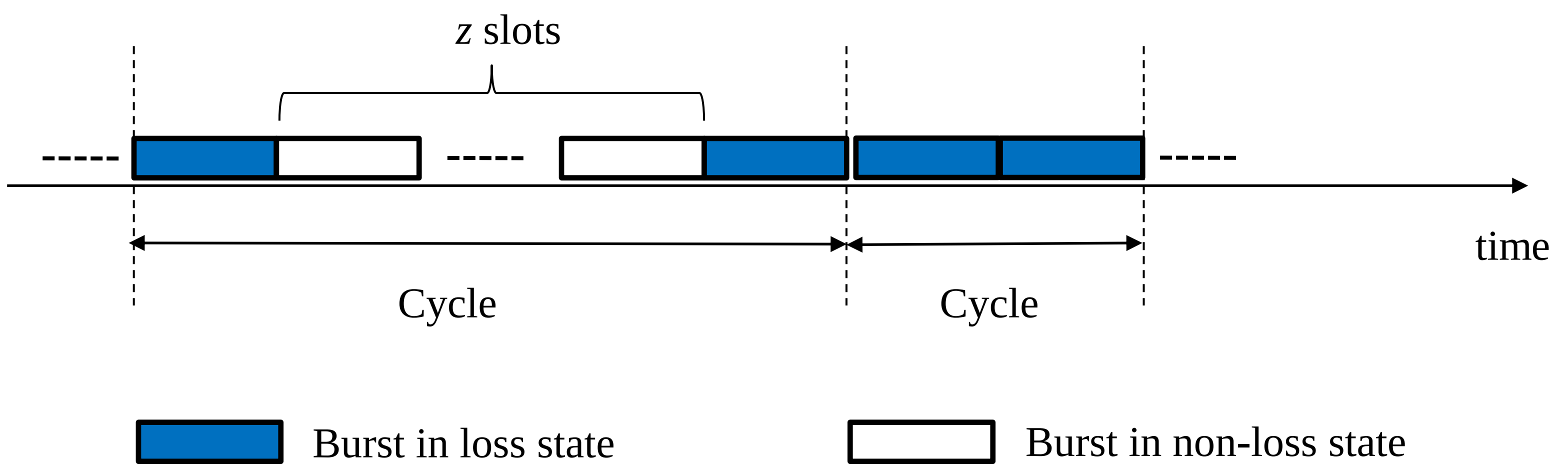
The range of possible cwnd [0,*W*] is partitioned into *M* intervals



Need to investigate the loss rate

Loss rate

- To find the loss rate, we consider the burst transmission cycles

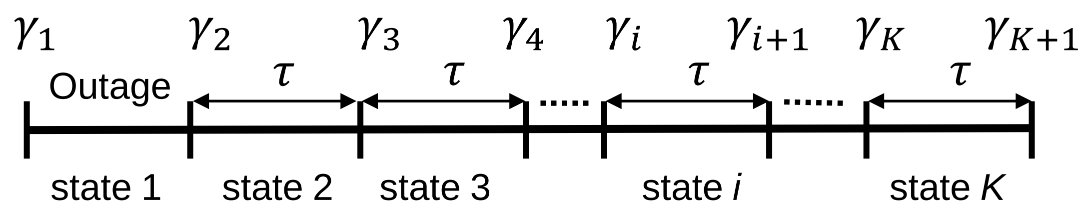


Build the burst loss model

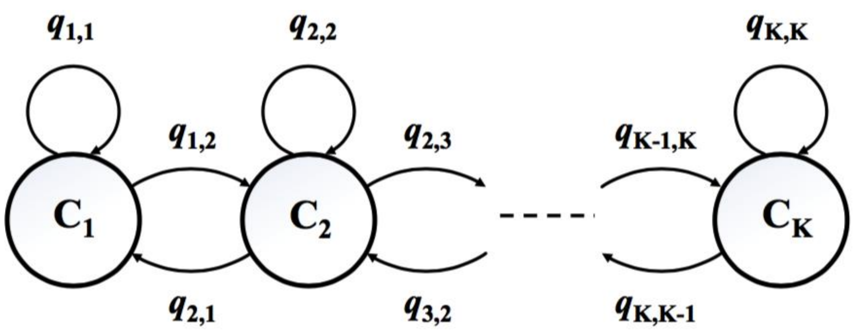
Consider the time-varying behavior of fading and channel modeling for burst transmission (Nakagami-*m* is assumed)

Channel modeling

- We model the channel into states whose average duration = burst time



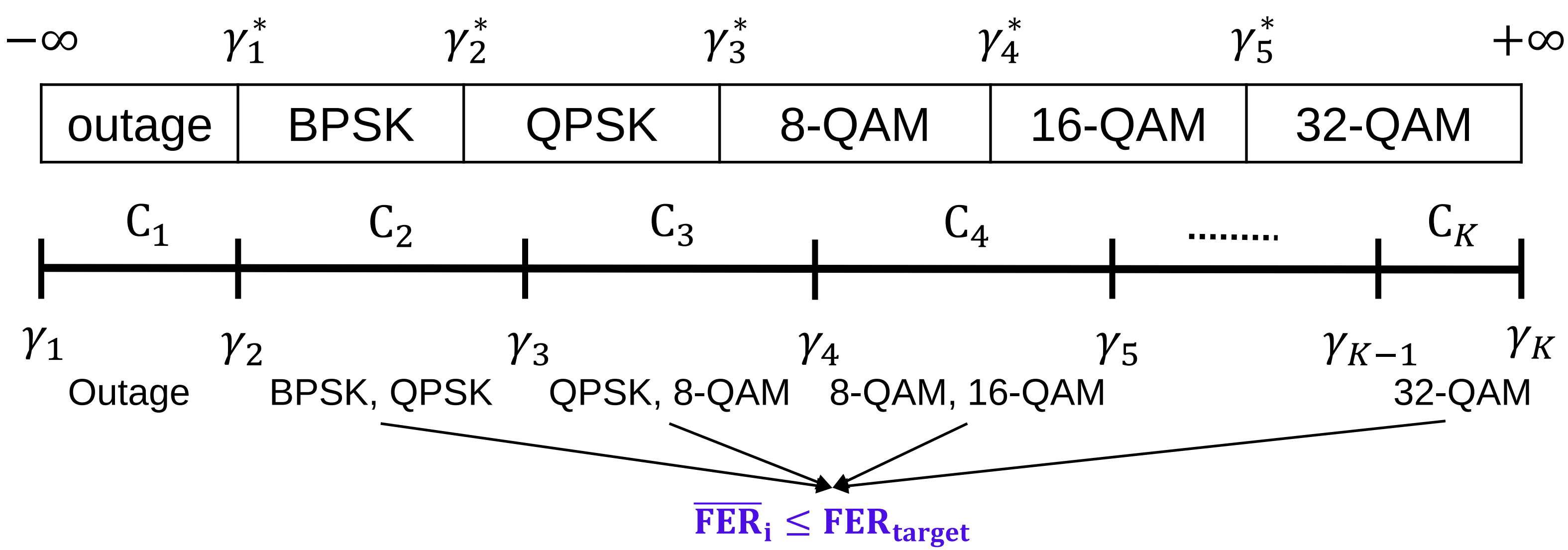
Finite-state Markov chain to model the behavior of channel



Use the channel model to develop the loss model

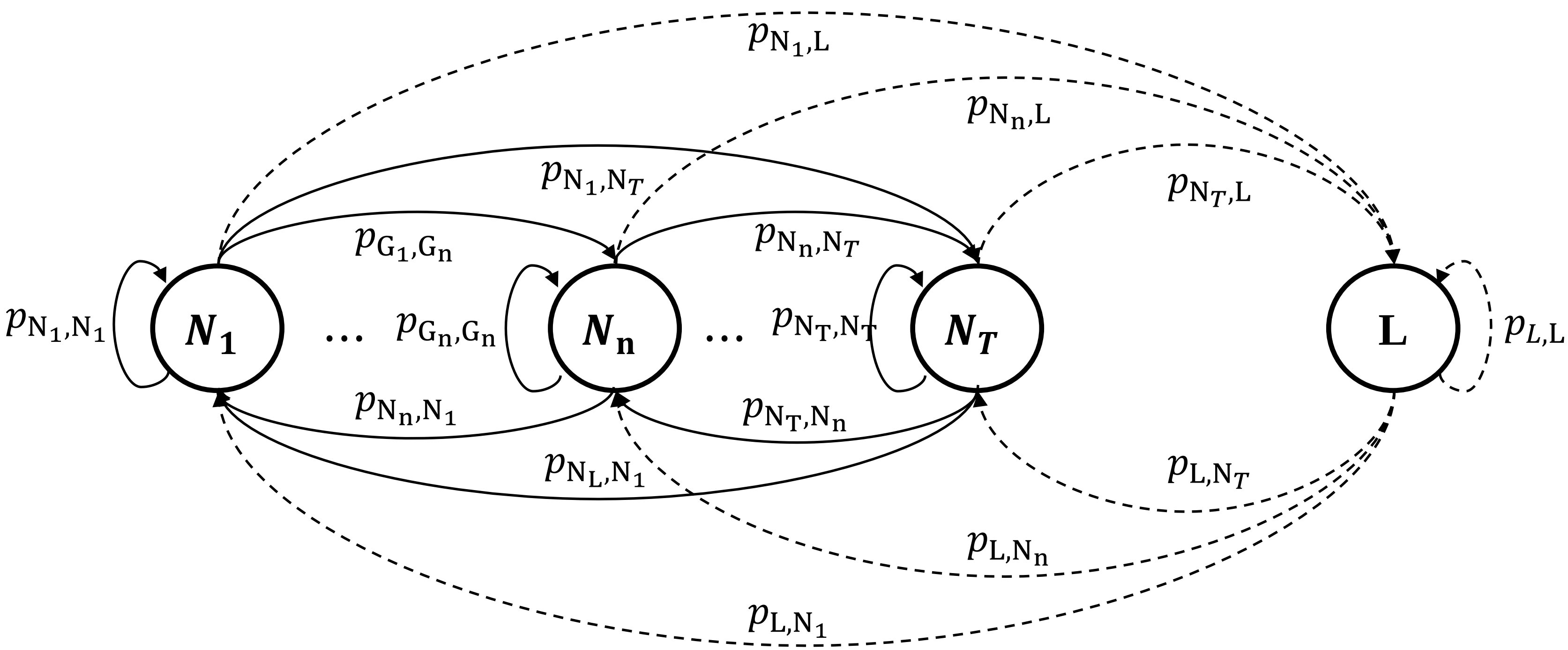
Transmission modes for channel-state

- How to decide transmission mode for each channel-state
  - The number of transmission modes
  - Decision rule
- Each state will be assigned a specific transmission mode
  - (1) highest data rate
  - (2) satisfy a pre-defined frame error rate ($\mathbf{FER_{target}}$)



Burst Loss Model

- Burst loss
  - Loss state (L): one of frame in burst is lost (reach a maximum number of retransmission of truncated HARQ)
  - Non-loss state (N): none of frame in burst is lost



Thank you for your attention!

(Q&A)