Transmission Rate, Transmission Delay, Propagation Delay, and Queuing Delay

Introduction

When a packet travels through a computer network, it experiences multiple types of delays before reaching its destination. These delays depend on:

- Packet size and link bandwidth
- Physical distance between sender and receiver
- Router load and congestion

The four key performance measures are:

Transmission Rate, Transmission Delay, Propagation Delay, Queuing Delay.

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Transmission Rate (Bandwidth)

Definition

The **Transmission Rate** R is the speed at which bits are transmitted over a link, measured in **bits per second (bps)**.

$$R = \frac{\text{Number of bits transmitted}}{\text{Time (s)}}$$

Example

If $R = 100\,\text{Mbps}$, the link can transmit 100×10^6 bits every second.

Analogy

Think of a water pipe. The **width of the pipe** corresponds to the **transmission rate**. A wider pipe allows more water (bits) per second.

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Transmission Delay

Definition

The time required to *push all the bits of a packet* into the link:

$$D_{\text{trans}} = \frac{L}{R}$$

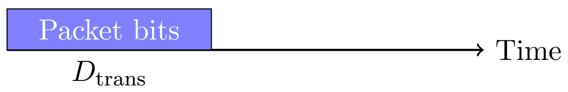
Example

If packet size $L = 8 \times 10^6$ bits and $R = 10\,\text{Mbps}$:

$$D_{\text{trans}} = \frac{8 \times 10^6}{10 \times 10^6} = 0.8\,\text{s}$$

Analogy

Filling a water tank with a pump. The time taken to push *all the water* into the pipe is like transmission delay.



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Propagation Delay

Definition

The time for a bit to physically travel across the medium:

$$D_{\text{prop}} = \frac{d}{s}$$

Example

If $d = 3000\,\text{km}$ and $s = 2 \times 10^8\,\text{m/s}$:

$$D_{\text{prop}} = \frac{3 \times 10^6}{2 \times 10^8} = 0.015\,\text{s}$$

Analogy

The time taken for the **first drop of water** to travel through a long pipe is like propagation delay.

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Queuing Delay

Definition

The time a packet spends waiting in a router's buffer before transmission.

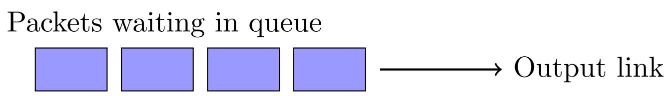
Example

If 4 packets are ahead, each needing 0.8 seconds to transmit:

$$D_{\text{queue}} = 4 \times 0.8 = 3.2\,\text{s}$$

Analogy

Cars waiting at a toll booth. Each car must wait until the cars ahead pass. This waiting time is the queuing delay.



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Packet Delay: Four Sources

The total delay experienced by a packet at a node (**nodal delay**) is:

$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$

1. Nodal Processing Delay (d_{proc})

Time for a router to examine the packet header, check for bit errors, and determine the appropriate output link. Typically very small: < 1 microsecond.

2. Queuing Delay (d_{queue})

Time a packet spends waiting in the router's queue before being transmitted. Depends on the congestion level of the router and the number of packets ahead.

3. Transmission Delay (d_{trans})

Time to push all packet bits onto the link:

$$d_{\text{trans}} = \frac{L}{R}$$

where L = packet length (bits) and R = link transmission rate (bps).

Example: If $L = 8 \times 10^6$ bits and $R = 10$ Mbps, then $d_{\text{trans}} = 0.8$ s.

4. Propagation Delay (d_{prop})

Time for a bit to travel from sender to receiver over the physical link:

$$d_{\text{prop}} = \frac{d}{s}$$

where d = length of physical link and s = propagation speed ($\sim 2 \times 10^8$ m/s).

Example: If $d = 3000$ km, then $d_{\text{prop}} = 0.015$ s.

Key Point

d_{trans} and d_{prop} are fundamentally different:

- Transmission delay depends on packet size and link bandwidth.
- Propagation delay depends on physical distance and medium speed.

Packet Queueing and Throughput

Queueing Delay Analysis

Let:

- λ = average packet arrival rate (packets/sec)
- L = packet length (bits)
- R = link bandwidth (bits/sec)

$$\text{Traffic intensity} = \frac{\lambda L}{R}$$

Queueing Delay Insights

- $\lambda L/R \approx 0$: Average queueing delay is small.
- $\lambda L/R \to 1$: Average queueing delay becomes large.
- $\lambda L/R > 1$: More work is arriving than can be serviced; the average delay grows without bound.

Throughput

- **Throughput**: Rate at which bits are successfully sent from sender to receiver.
- **Instantaneous throughput**: Rate at a specific moment in time.
- **Average throughput**: Rate measured over a longer period.

Pipe Analogy

Think of the server sending bits like fluid into a pipe:

- R_s = sending rate (bits/sec)
- R_c = pipe capacity (bits/sec)

Scenarios:

- $R_s < R_c$: All bits flow through; pipe never congested.
- $R_s > R_c$: Pipe is a bottleneck; queue builds up, reducing throughput.

End-to-End Throughput in a Network

- Throughput along a path is constrained by the **bottleneck link** (smallest R along the path).
- For multiple connections sharing a link of capacity R:

$$\text{per-connection throughput} \approx \min(R_c, R_s, R/10)$$

- In practice, either the sender or receiver link often forms the bottleneck.

Summary Table

Concept	Formula	Analogy
Transmission Rate	R (bps)	Pipe width
Transmission Delay	$D_{\text{trans}} = L/R$	Filling a tank
Propagation Delay	$D_{\text{prop}} = d/s$	First drop in pipe
Queuing Delay	Depends on traffic	Cars at toll booth