Bandwidth Estimation Metrics and Terminology

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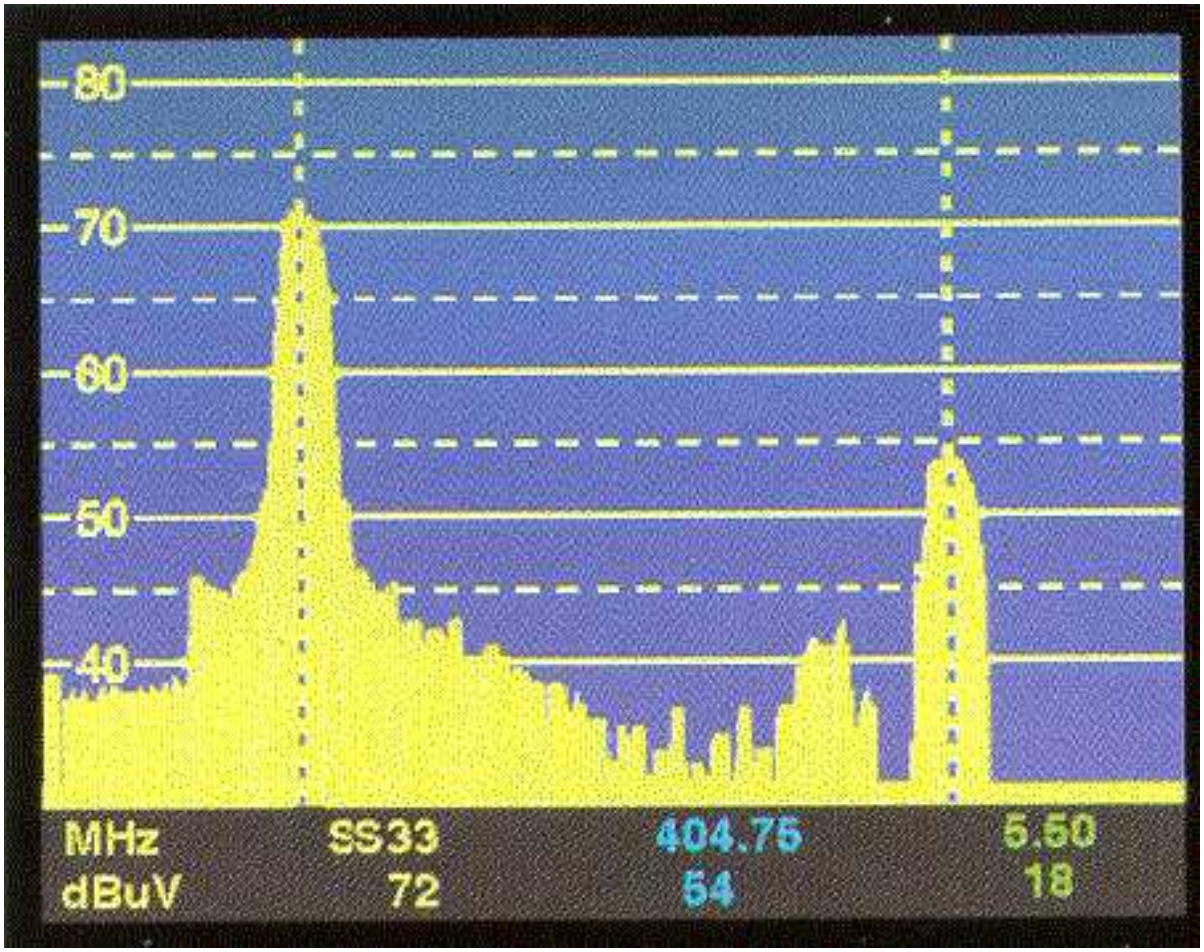
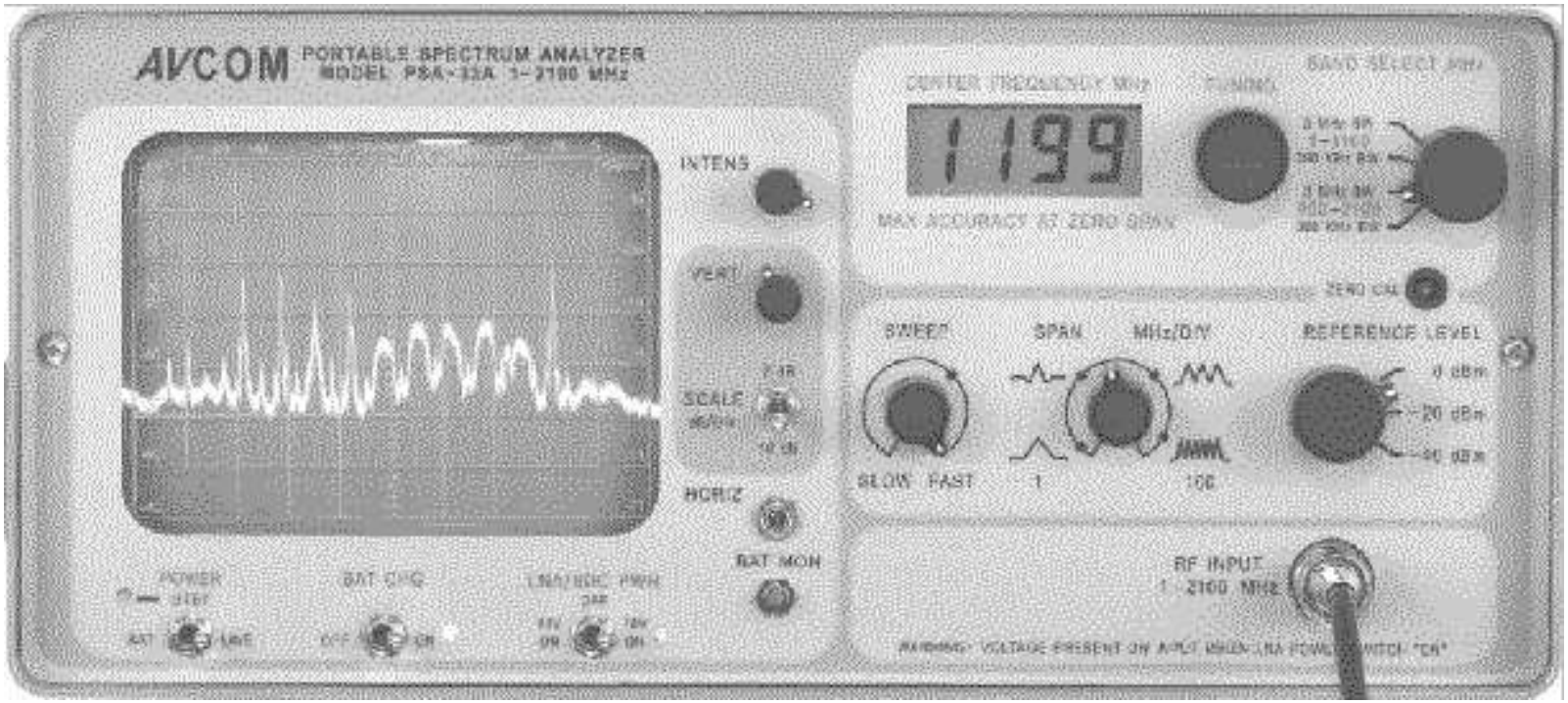
Bandwidth (Hz) versus Bandwidth (bps)

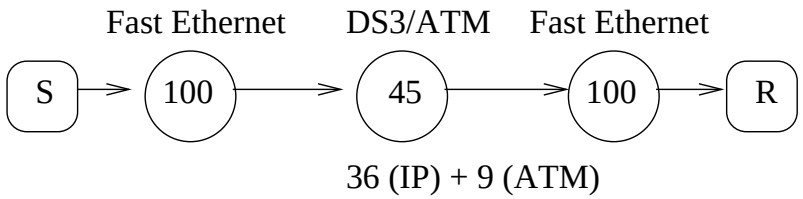


Bandwidth estimation in the physical layer

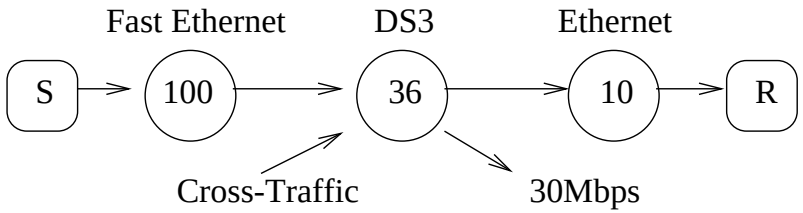


Major bandwidth metrics

- **Capacity**



- **Available bandwidth**



- **Bulk-Transfer Capacity (BTC)**

Definition of capacity

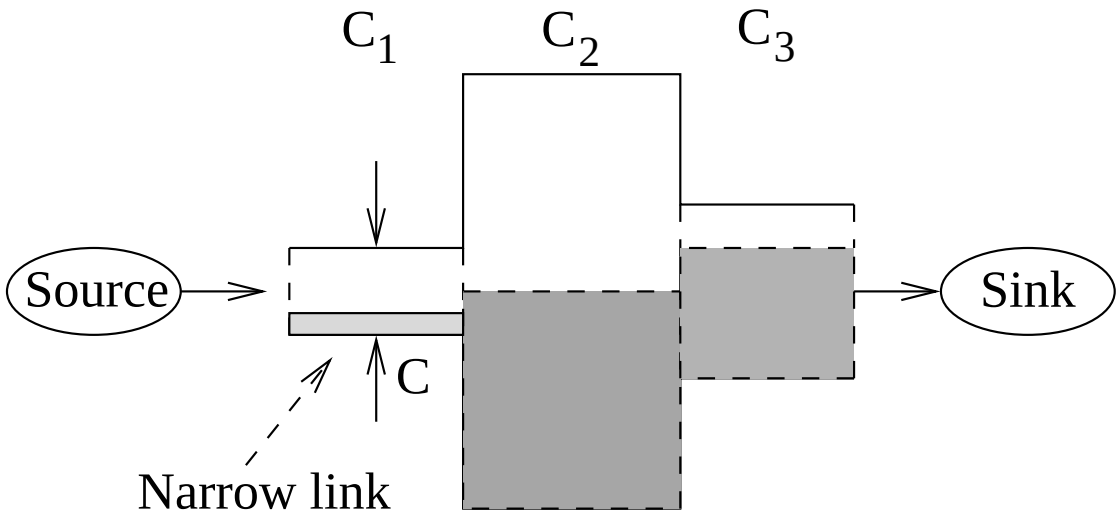
- Link capacity: C_i for link i (bps)

  typically constant at layer-2, related to transmission clock

- Path capacity:

$$C = \min_{i=0...H} \{C_i\} = C_n$$

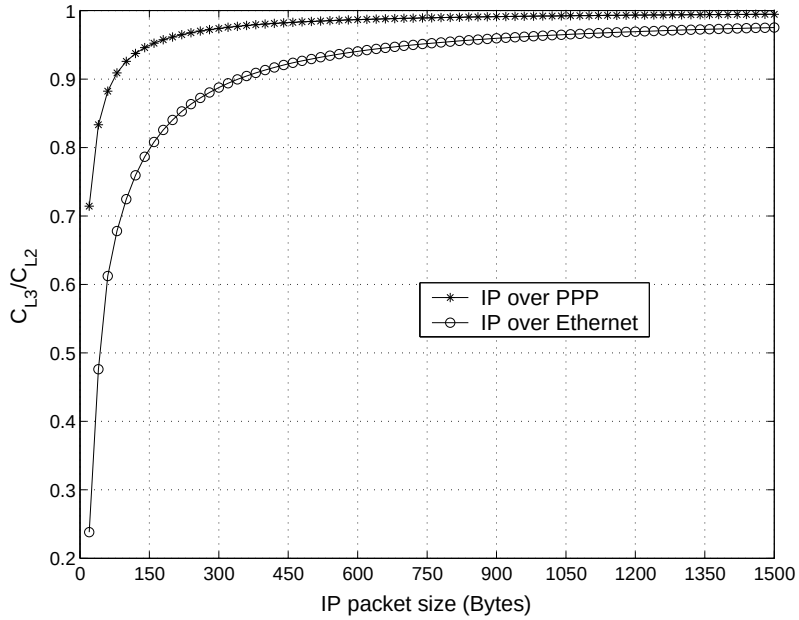
- Path capacity is limited by *narrow link* n:



Capacity at IP-layer

- Capacity C_{L3} at IP-layer as function of C_{L2} at layer-2:

$$C_{L3} = \frac{L_{L3}}{\Delta_{L3}} = C_{L2} \frac{1}{1 + \frac{H_{L2}}{L_{L3}}}$$

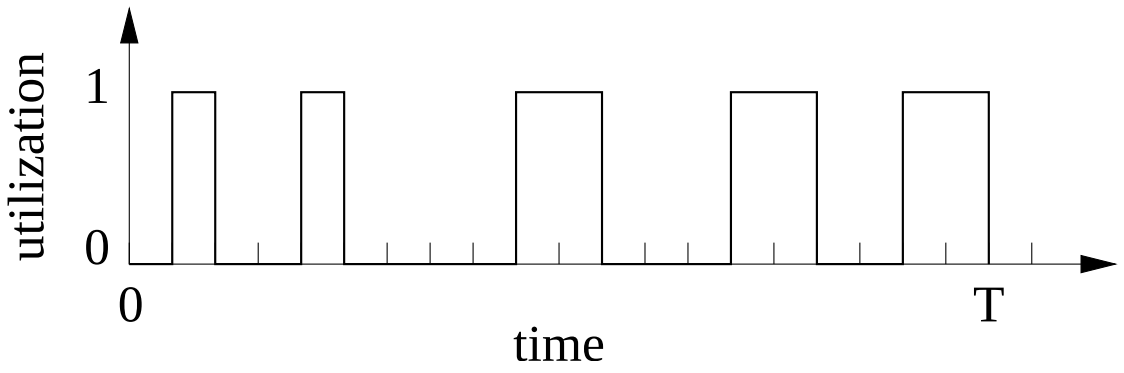


- Beware of: traffic shapers, wireless links, time-varying capacity

Definition of average link utilization

- Instantaneous link utilization $u(x) \in \{0, 1\}$
- Average utilization $\bar{u}_\tau(t)$ in timescale τ:

$$\bar{u}_\tau(t) = \frac{1}{\tau} \int_{t-\tau}^{t} u(x)dx$$

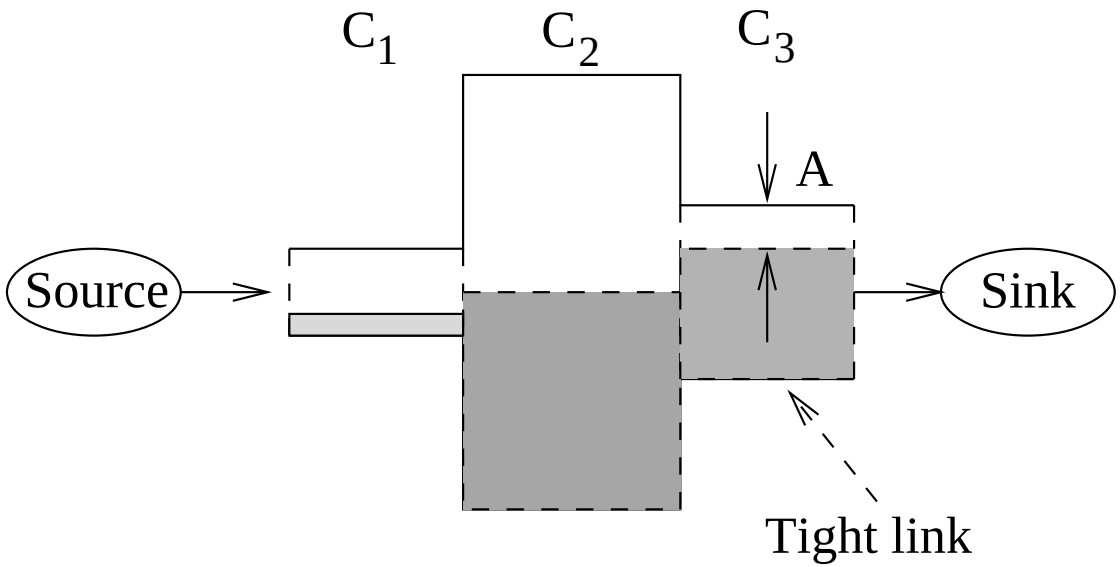


- Note: variance of random process $\bar{u}_\tau$ decreases with τ

Definition of available bandwidth

- $u_{i,\tau}$: Average utilization of link i in time interval of length τ $(0 \leq u_{i,\tau} \leq 1)$
- Avail-bw of link i: $A_{i,\tau} = C_i \left(1 - u_{i,\tau}\right)$

  End-to-end avail-bw: $A_\tau = \min_{i=0\ldots H} A_{i,\tau} = \min_{i=0\ldots H} C_i \left(1 - u_{i,\tau}\right)$



- Available bandwidth is limited by *tight link*

Bulk-Transfer Capacity definition

- Bulk-Transfer Capacity (BTC): long-term average TCP throughput
- Congestion-limited transfer, i.e., sufficiently large receiver window
- BTC depends on:
  - Exact TCP implementation at sender & receiver
  - Available bandwidth
  - Link buffer sizes
  - Cross traffic responsiveness (elasticity)

Bulk-Transfer Capacity estimation

- BTC can be derived mathematically
  - Simplest model:

$$\text{Throughput} = \frac{c\,\text{MSS}}{\text{RTT}\sqrt{\text{lossrate}}}$$

  - Note: such models cannot be used to predict BTC, because RTT and lossrate may be increased due to new TCP connection