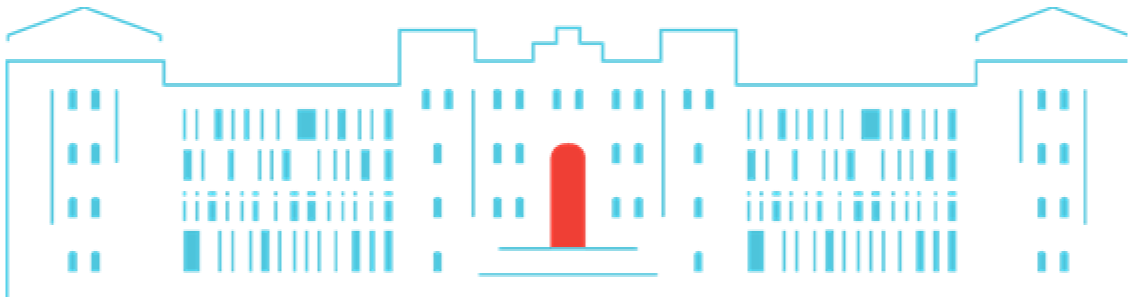
Introduction to IEEE 802.15.4

ComNets
TUHH
Institute of Communication Networks



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14th of April – 17th of April 2025

Course Contents

Online lectures

- ~~Lecture 1 - Introduction~~
- ~~Lecture 2 – IEEE 802.15.4~~
- ~~Lecture 3 – IETF 6TiSCH~~

Physical Meeting 13th to 17th of April

- Lecture 4 – Theoretical Analysis
- Cooja Simulations and Experiments
- Industrial visit and a talk
- Team Presentations on self learned material
- Lecture 5 – Research Project Results

More details on our padlet,
https://tuhh.padlet.org/c00zll01/enabling-industry-4-0-j88rkh1i3j7rzmv3

Performance Evaluation of 6TiSCH

These slides were prepared using the following reference.

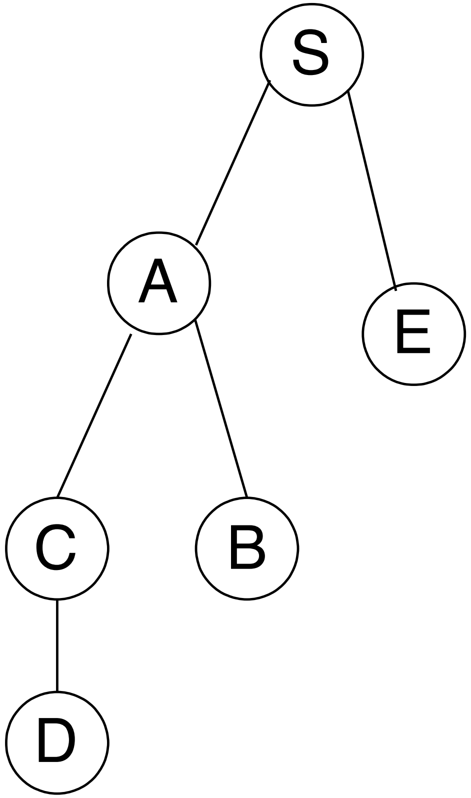
[1] Shudrenko, Yevhenii, and Andreas Timm-Giel. "Modeling end-to-end delays in TSCH wireless sensor networks using queuing theory and combinatorics." Computing (2024): 1-25.

ComNets

End-to-End Delay

Discuss the following:

- **What kind of delays are involved when A sends data to S?**
- **When C sends data to S?**
- **What is definition of end-to-end delay?**



End-to-End Delay contd.

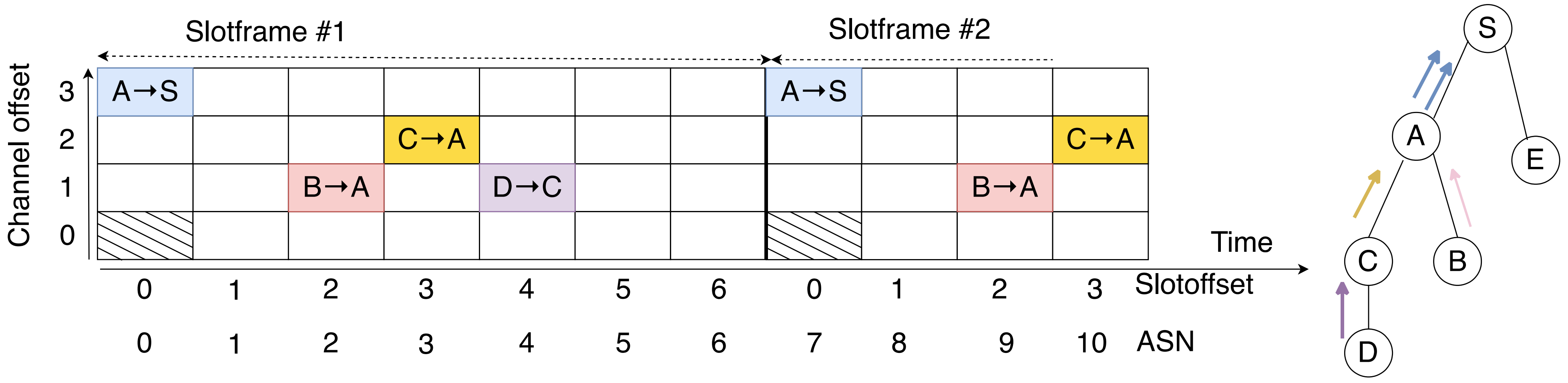
$$D(h) = \sum_{i=1}^{h} D_i = \sum_{i=1}^{h} \left(D_p + D_s + D_t + T_i\right),$$

- D_p is the propagation delay
- D_s is the processing delay
- D_t is the transmission delay
- T_i is the queuing delay (sojourn time)
    - consists of the service time W and queuing time Q

Any delays to be ignored?

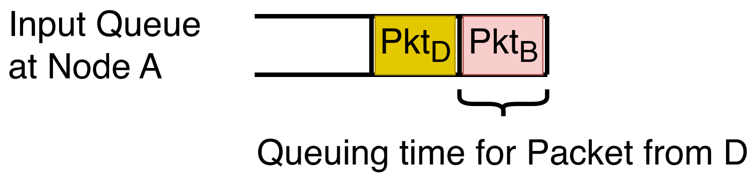
Service Time

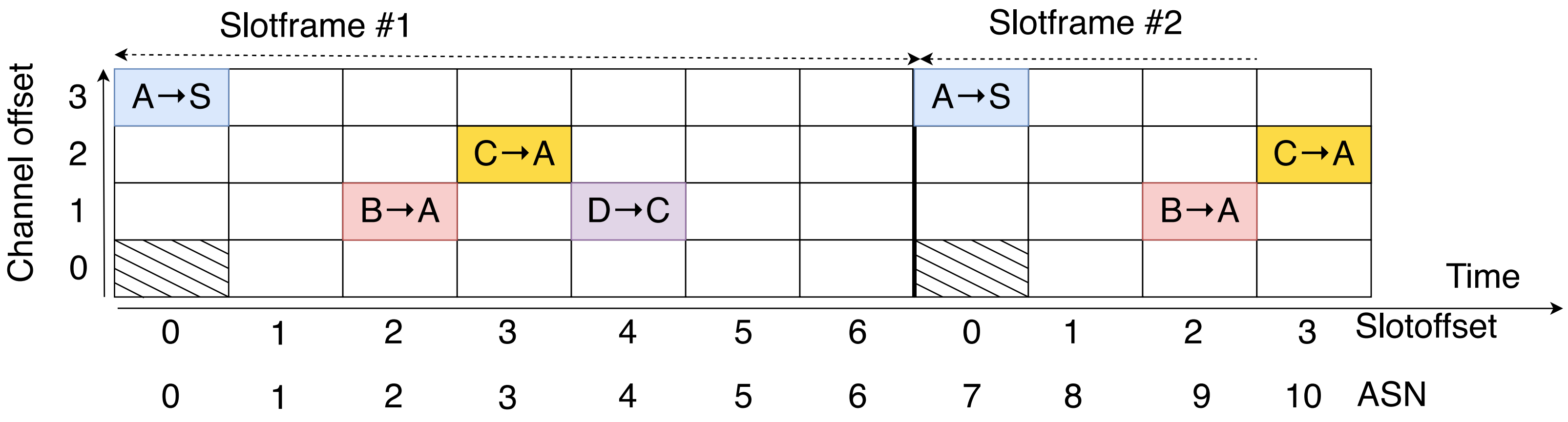
- D transmits a packet at ASN = 4.
  - How many slots does this packet wait at C?
  - How many slots does this packet wait at A?

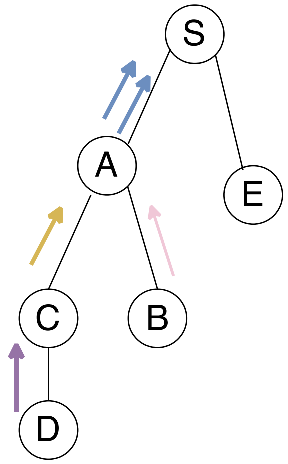


Queuing Time

- Assume the case where B transmits at ASN = 2 and D transmits at ASN = 4

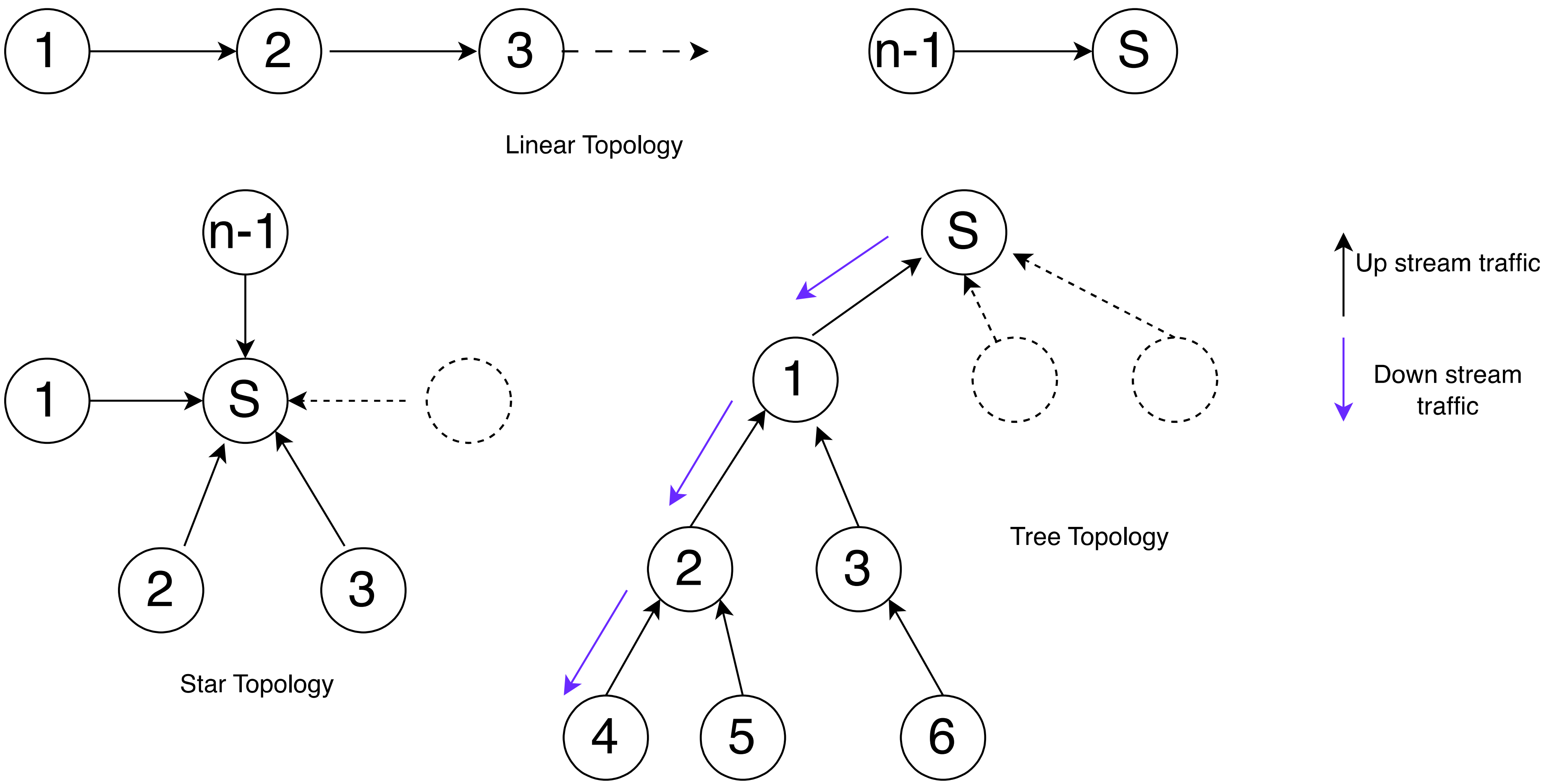






Network Topologies

ComNets



Theoretical Analysis

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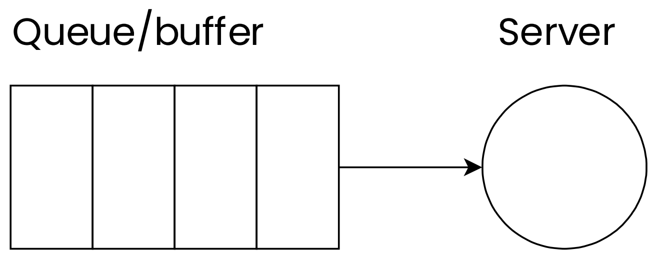
- Why do we need theoretical analysis?
- Assumptions!

- Jupyter Notebook
  - linear topology
  - model end-to-end delay with
    - service, queuing times
    - periodic packet arrivals

Queue Model

- Single server
- Unlimited buffer
- Arrival rate λ in packets per slotframe (pkt/sf)
  - Periodic arrivals
- Service rate μ in cells per slotframe



Are these scenarios valid?

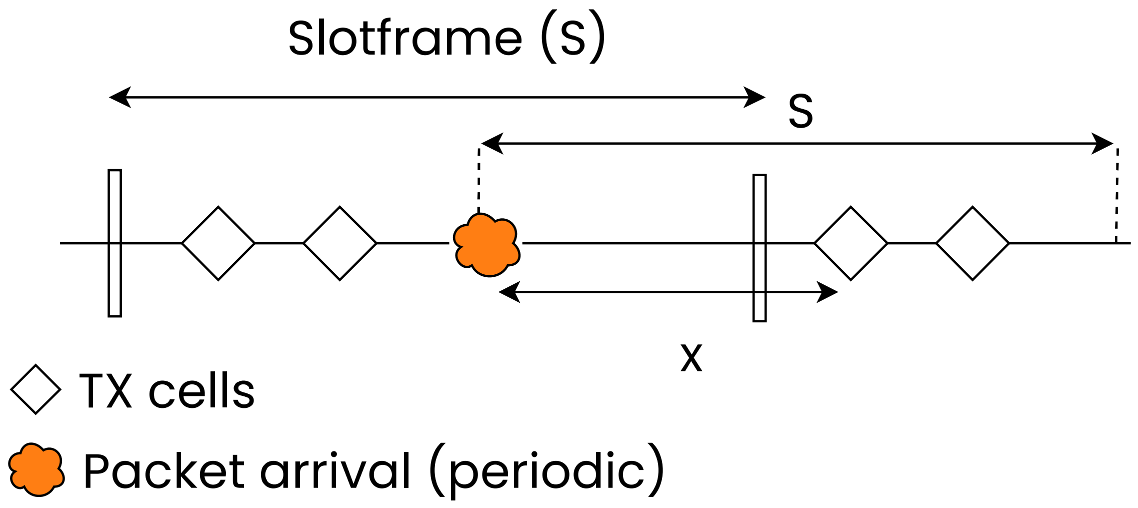
- $\boldsymbol{\lambda = 1.3, \mu = 2}$
- $\boldsymbol{\lambda = 2.3, \mu = 2}$
- $\boldsymbol{\lambda = 1.3, \mu = 1.6}$

Service Time Modeling

- Packet arrives in an empty queue
- The Cumulative Distribution Function (CDF) of the service time is

$$F_W = (W < x) = 1 - \left(1 - \frac{x}{S}\right)^{\mu},$$

- S is the slotframe length in time slots
- $0 < W < S$



Run cell A1 of the Jupyter Notebook

Service Time Modeling contd.

- Given the CDF, the probability density function is (by definition):

$$f_W(x) = \frac{d}{dx} F_W(x) = \frac{\mu}{S}\left(1 - \frac{x}{S}\right)^{\mu-1}$$

- And the mean value:

$$E[W] = \int_0^S x f_W(x) dx = \cdots = \frac{1}{\mu + 1}$$

Run cell A2 of the Jupyter Notebook

Service Rate in MSF

- Adapted based on cell utilization
  - Upper threshold u_h

$$\mu = \left\lceil \frac{\lambda}{u_h} \right\rceil$$

What is the impact of a high/low u_h?

Sojourn Time

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- The total time T spent by a packet in the queue
  - Its own service time W (head of the queue)
  - But might also wait for previous packets to be served (queuing time Q)

$$T = W + Q$$

- Over n hops,

Run cells B and C of the Jupyter Notebook

$$T^{(n)} = \sum_{i=1}^{n} T_i$$

Impact of Traffic Patterns on the Sojourn Time

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- Periodic
  - Deterministic, no queuing (almost, check cell D of the Jupyter Notebook for more details)
- Event driven
  - Poisson arrivals, queuing delays due to exponentially distributed interarrival times

$$T_p = W + Q_p = \frac{1}{\mu + 1} + \frac{\rho}{2\mu(1-\rho)},$$

Run cells D & E of the Jupyter Notebook

Q_p is the queuing time with Poisson traffic,

$\rho = \frac{\lambda}{\mu}$ is the system utilization.