A Latency Analysis of IEEE 802.11-based Tactile Wireless Multi-Hop Networks

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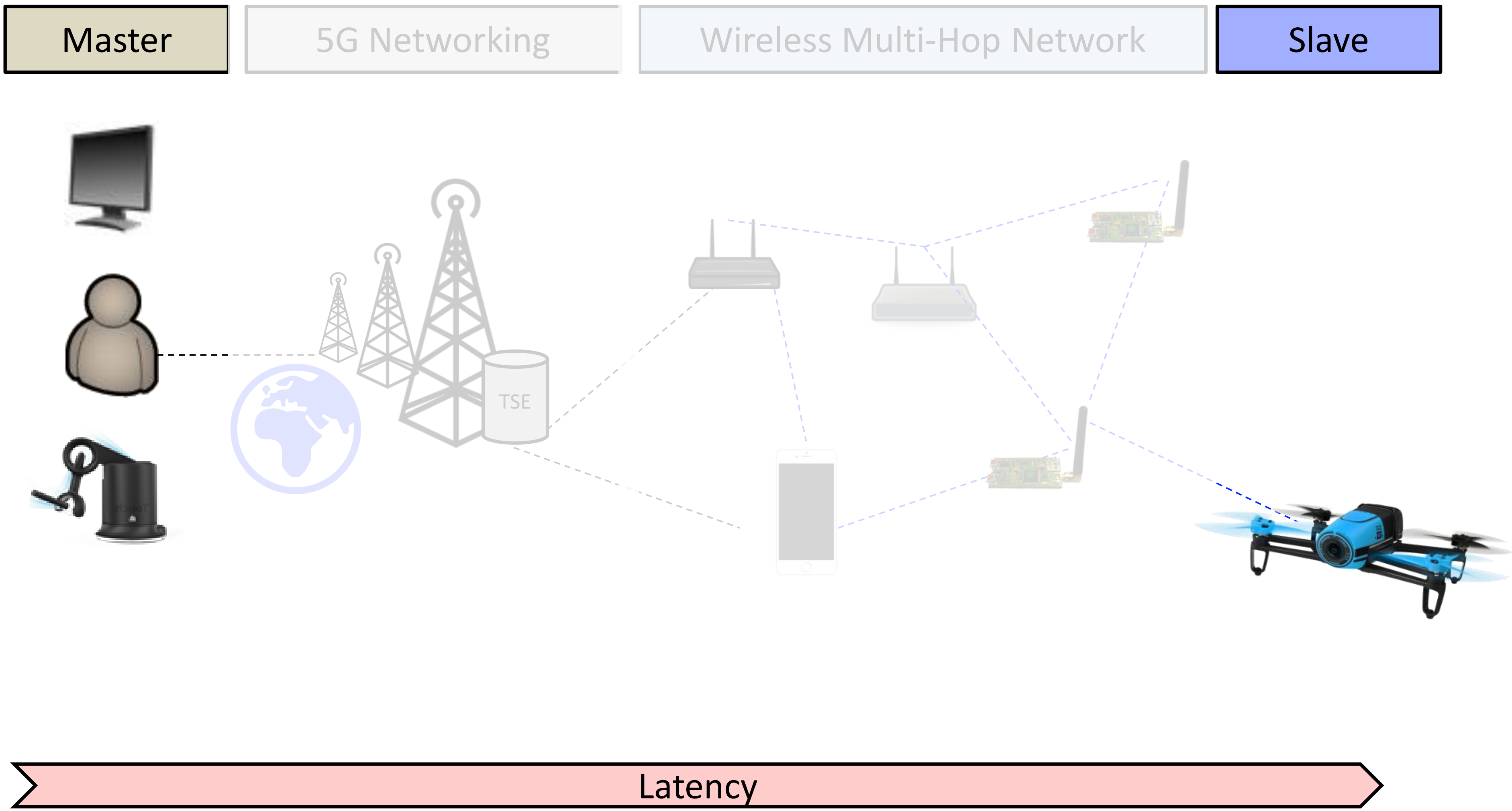
Tactile Wireless Multi-Hop Networks

- **Tactile Internet (TI) requires ultra reliable, ultra low-latency networks**
- **WMHN are more flexible than single-hop networks**
- **5G will introduce multi-hop characteristics through Device-2-Device, but question of performance is open**
- **V2X, Teleoperation, Telesurgery, …**

Tactile Wireless Multi-Hop Networks



Aijaz, A. et al., Realizing the tactile internet: Haptic communications over next generation 5g cellular networks, IEEE Wireless Communications 2017

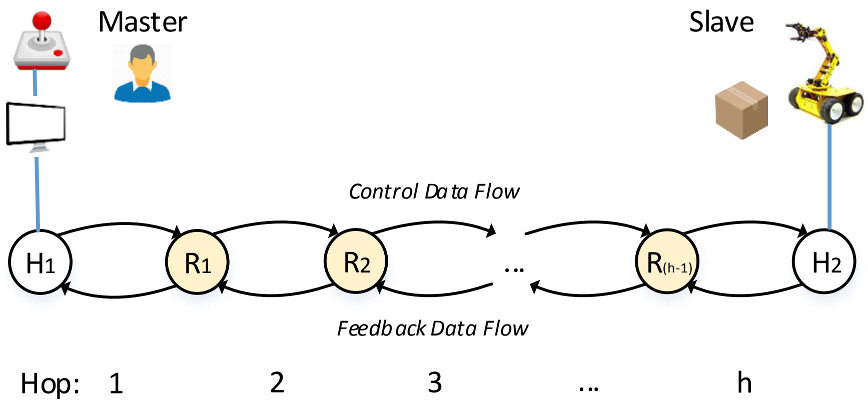
Single-Flow Latency Model

A *haptic flow consists of*

- *a sub-flow Master→Slave*
- *another sub-flow Slave→Master*

Both sub-flows have the properties

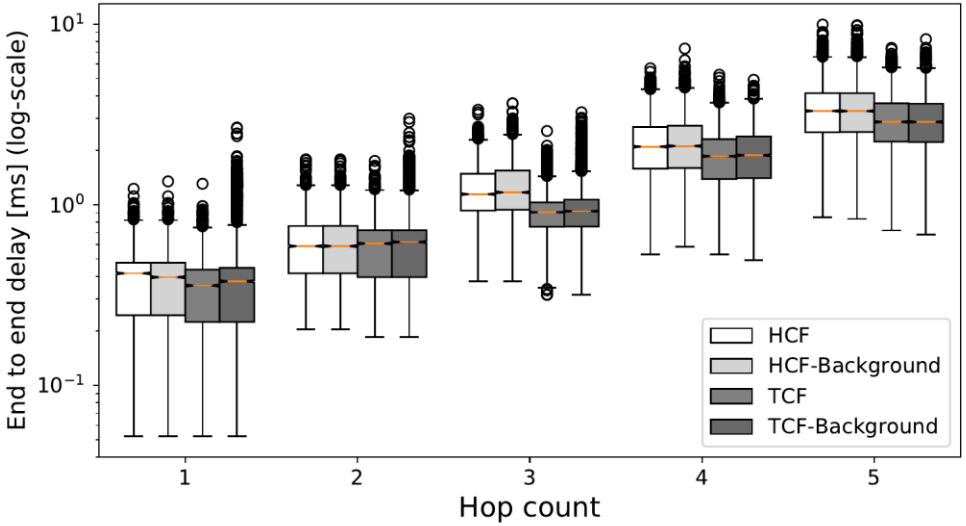
- 1 kHz packet rate
- <100 Bytes per packet (e.g. 6*sizeof(float), a 6 DoF vector)
- requires 1 ms latency bound

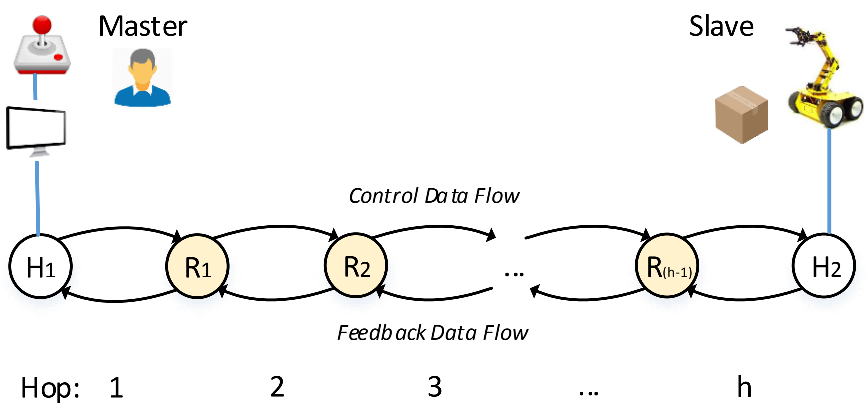


Single-Flow Latency Model

- **End-to-End latency**
  $$d_{e2e} \sim h$$
  $$= k \cdot h$$

→ Upper bound for h to reach latency requirement



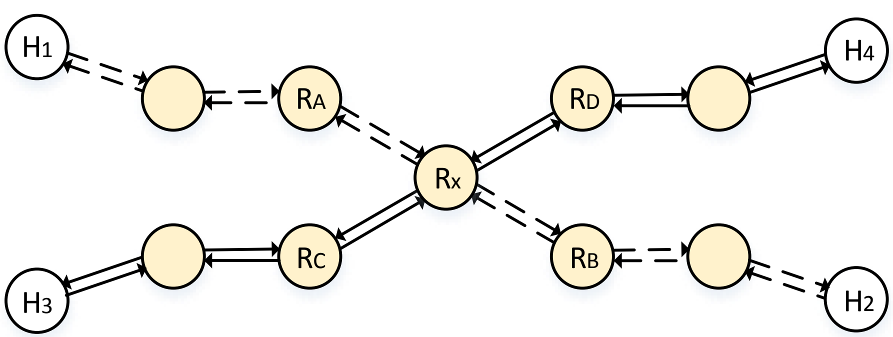


Multi-Flow Latency Model

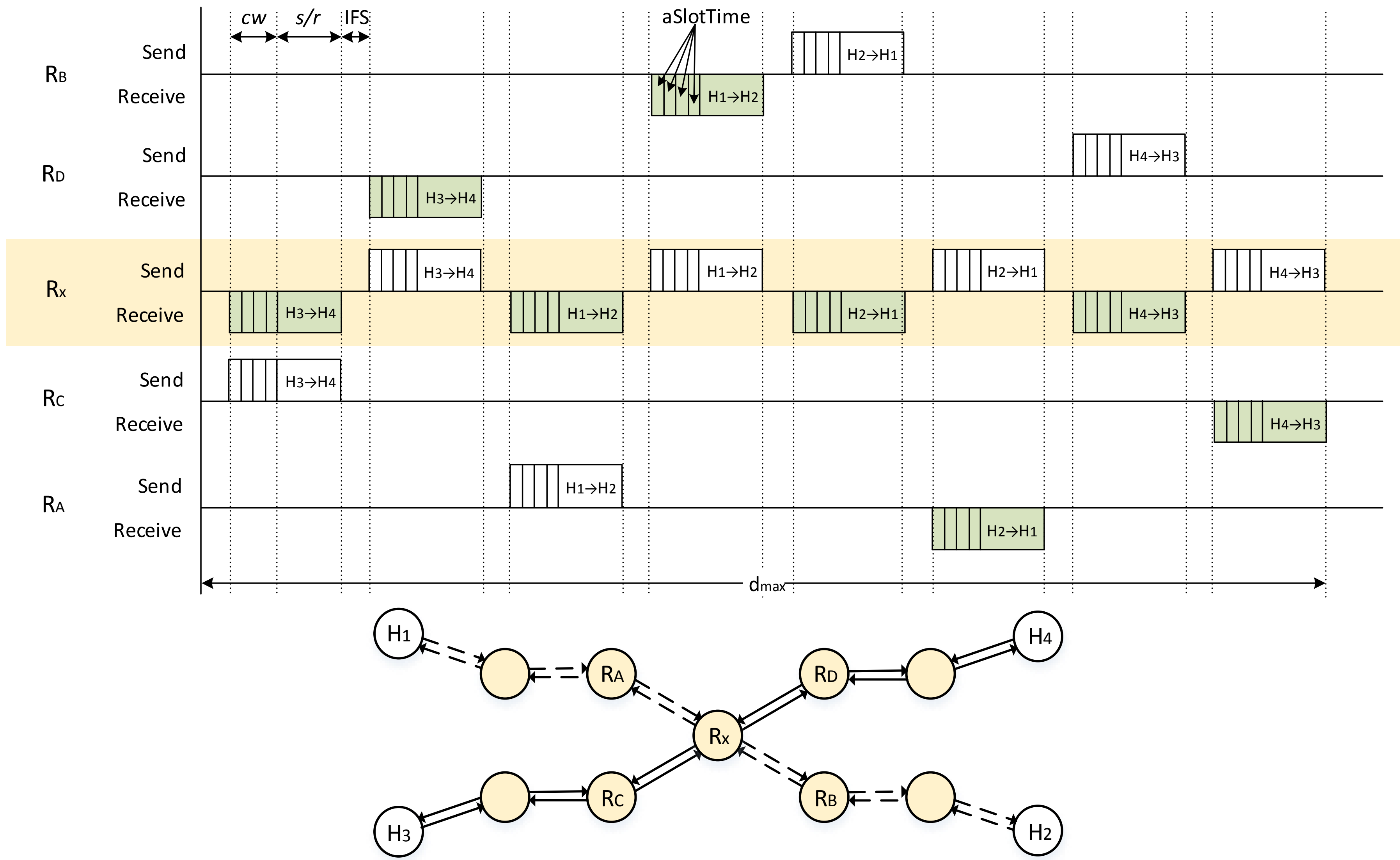
- Multiple flows may cross at one or more routers

→ $d_{e2e} \sim h$ is no longer true

- E.g, a simple example with two flows crossing at router Rx



Multi-Flow Latency Model

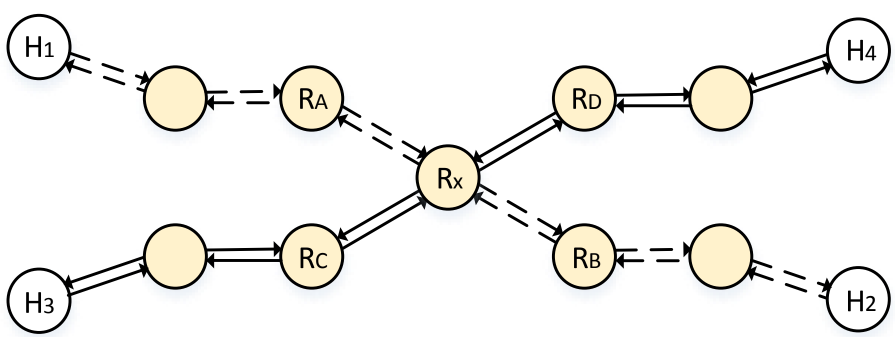


Multi-Flow Latency Model

- Multiple flows may cross at one or more routers

→ $d_{e2e} = k \cdot h + 8 \cdot d_{Pkt,max}$ for this example

→ $d_{e2e} = k \cdot h + 4 \cdot n \cdot d_{Pkt,max}$ for n intersecting flows



Evaluation of Queueing Delay relative to n

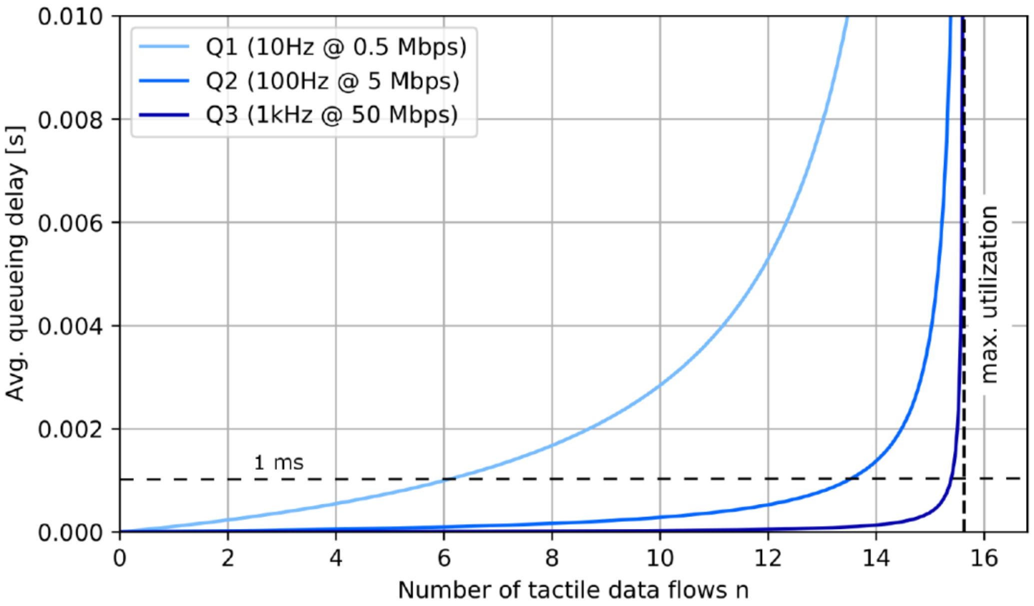
- **We model an M/M/1 Queue for the sender of Rx**
  - Unscheduled WiFi traffic, which has non-deterministic behavior
- **Average delay $d_{avg} = \frac{\lambda}{\lambda(\mu - \lambda)}$ with arrival rate λ and service rate μ**
  - $\mu = r/s$ with transmission bit rate r, packet size s
  - $\lambda = 4 \cdot n \cdot \lambda_{Flow}$, with the packet rate per flow $\lambda_{Flow} = 1kHz$
- $d_{avg}(n) = \frac{4 \cdot s \cdot n \cdot \lambda_{Flow}}{r^2 - 4 \cdot r \cdot n \cdot \lambda_{Flow}}$

Evaluation

- **We consider three constellations: Q1, Q2, Q3**

	Q1	Q2	Q3
Arrival rate (per flow) λ_{Flow} $[s^{-1}]$	10	100	1000
Bit rate r [Mbit/s]	0.5	5	50
Packet size s [bit]	800	800	800
Service rate μ $[s^{-1}]$	625	6250	62500

- $d_{avg}(n) = \frac{4 \cdot s \cdot n \cdot \lambda_{Flow}}{r^2 - 4 \cdot r \cdot n \cdot \lambda_{Flow}}$
  - Linearization is possible, e.g. for n<14 for Q3!



Concluding Remarks

- **Linearization could lead to a simple linear model for the entire network:**

  $$d_{Flow,avg}(n,h) = k_1 \cdot h + k_2 \cdot n_{Flow},$$

  with n_{Flow}=number of concurrent flows intersecting the current flow

- **Model calibration based on simulation and also on real-hardware testbeds is ongoing work**