Evaluation of Methods for Prediction and Computation of Delay Violation Probability in Industrial URLLC Applications

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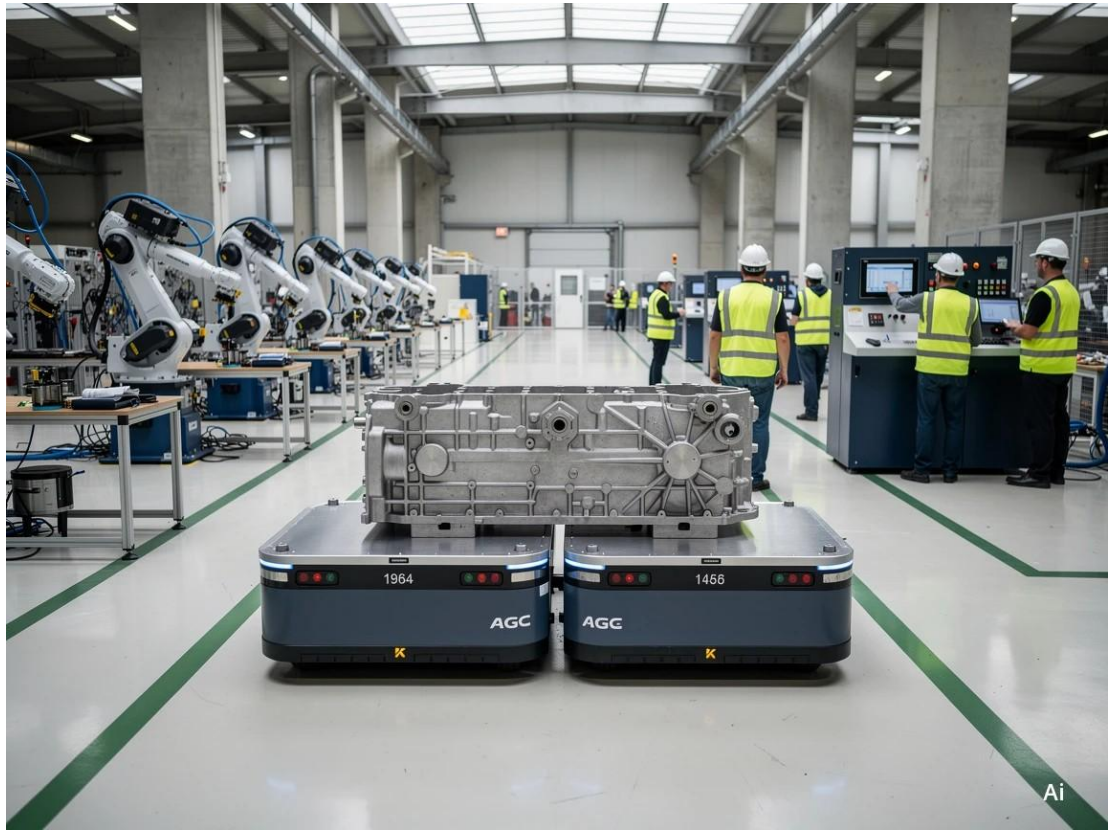
Motivation

- **Reliable low-latency communication** is a key requirement in industrial automation applications, e.g., in the domain of cyber-physical systems, cooperative robotics and smart manufacturing.
- Average delay vs. delay violation probability
- Packet delay is influenced by **multiple interacting factors**, such as queuing, encoding/decoding, and retransmissions.
- As a result, **delay violation events** are difficult to anticipate using end-to-end delay measurements alone.
- Accurate delay violation probability analysis requires **delay decomposition**, **theoretical analysis**, and **prediction methods.**



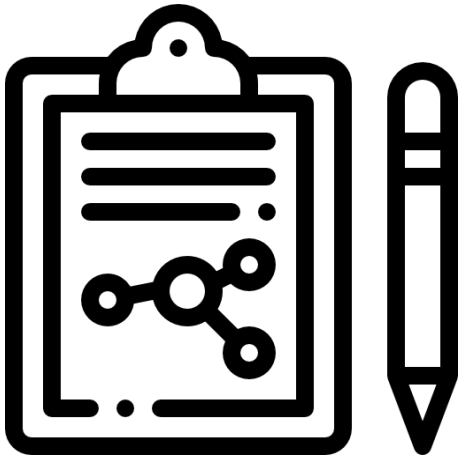
Delay Violation Probability: Definition and Analysis Approaches

Probability that total delay exceeds target threshold

$$\mathrm{DVP} = \mathrm{P}\left(\tau_{\sum} > d\right),$$

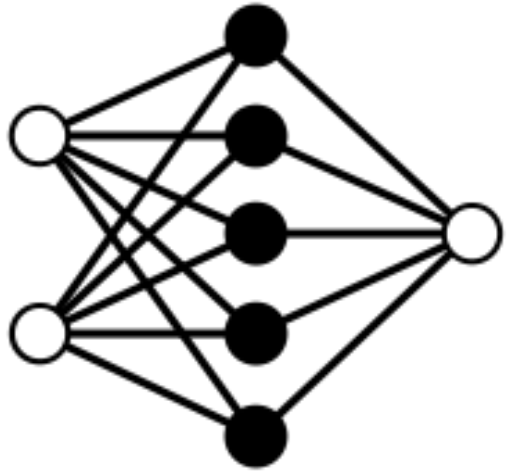
d: $target\ delay\ threshold$

$\tau_{\sum}$: $total\ packet\ delay$



Theoretical Analysis

Experimental Measurement
End-to-end Delay Analytics Framework
(USRP B210+OAI)



Learning-Based Prediction
(LSTM/Transformer)

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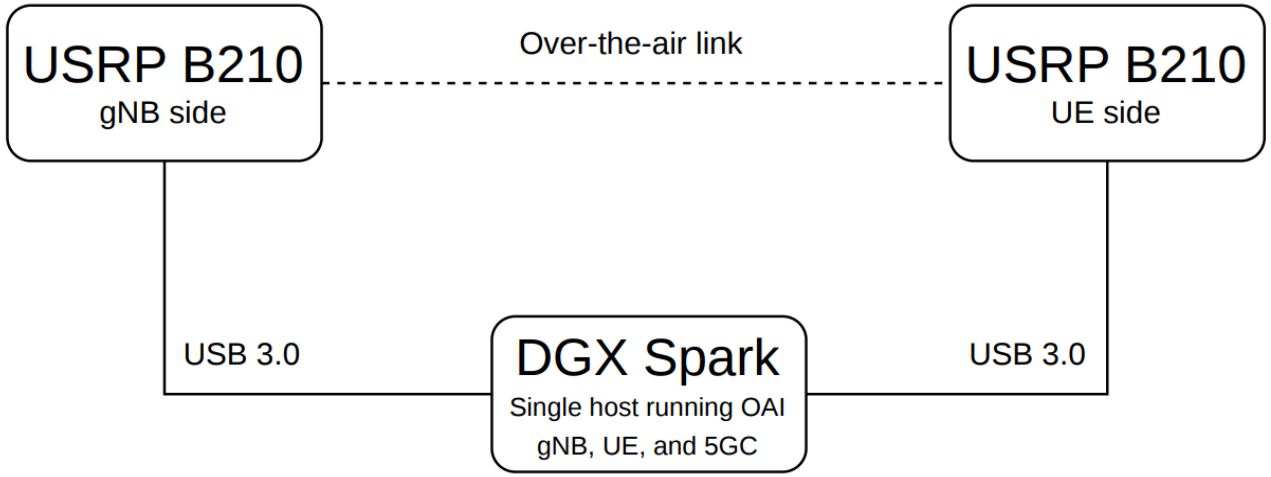
Experimental Setup & EDAF Decomposition: OAI on DGX Spark with USRP B210

- OpenAirInterface (OAI) provides a flexible and open 5G research platform.
- The testbed uses OAI on DGX Spark with two USRP B210 devices.
- The setup is analyzed using EDAF delay decomposition.

DGX Spark

Our setup



Based on Cammerer et al., 2025.
DGX Spark image source: NVIDIA.

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Experimental Measurements

- Measure UDP packets transmission under various:
  - Physical Distance (0.5m/1m/1.5m)
  - Physical Resource Blocks (51/106)
  - Packet Inter-arrival Time (2ms/5ms/10ms/20ms)
  - Packet Size (50B/100B)

- Introduce End-to-end Delay Analysis Framework (EDAF) into our setup:
  - Decompose a packet's journey into different components
  - Inserting timestamps into the OAI code for log output
  - Use the format: t dir src--dest prop:globalId:localId

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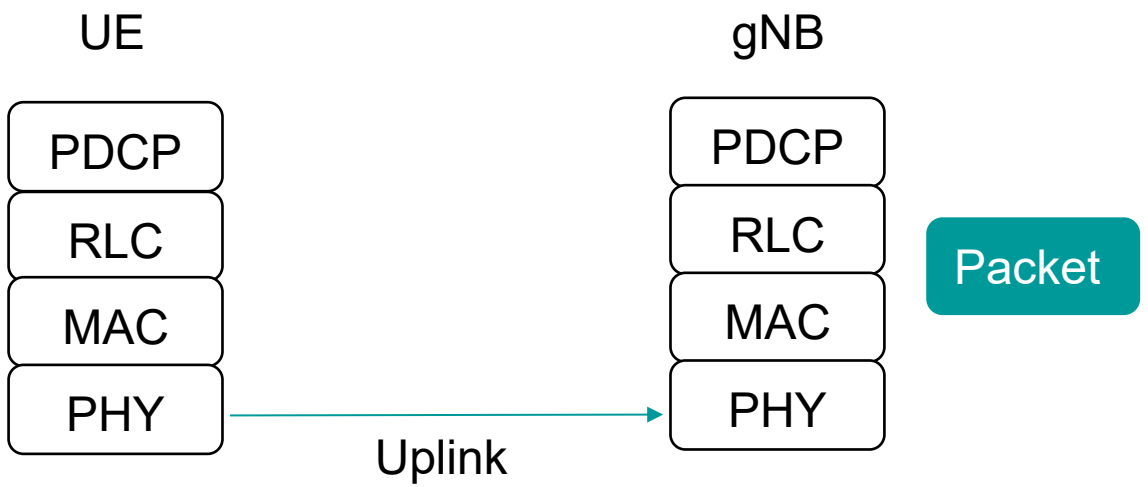
EDAF – A graphical example

- We want to know the time of a packet stays in RLC layer.
  1. Packet MAC --> RLC



Based on Mostafavi et al., 2025; Moothedath et al., 2025

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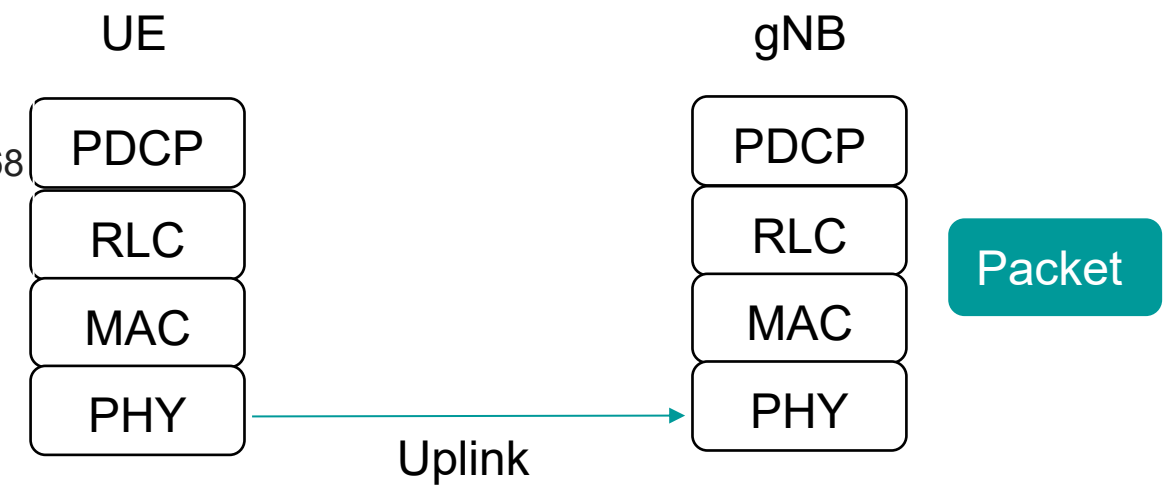
  1. Packet MAC --> RLC
  2. Starts a thread to write the string into the ring buffer

Thread 1

14183704354389 U mac.demuxed--rlc.decoded len109::fm467.sl8.lcid4.hqpid1.Hbuf221047680.MRbuf221047683.rnti7f22



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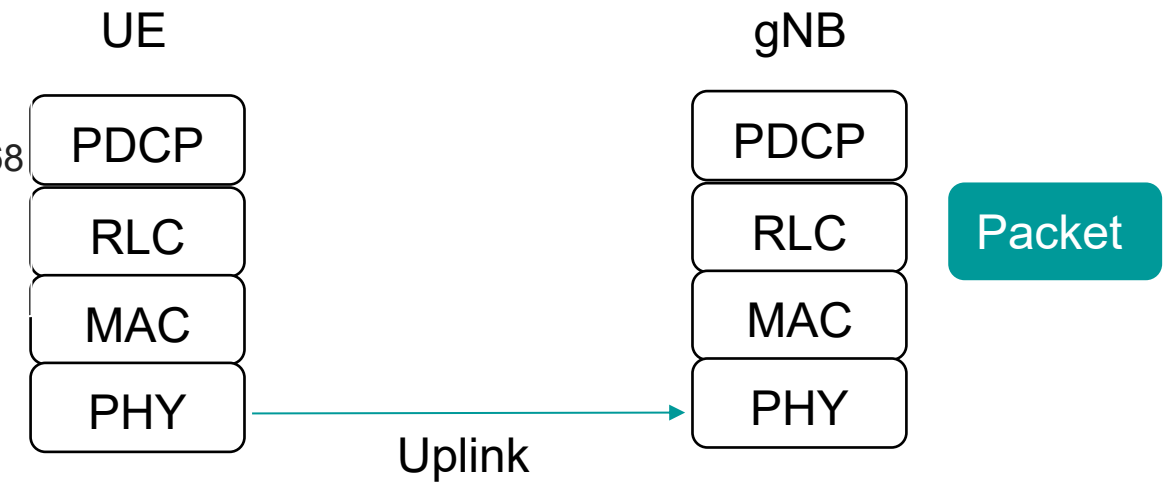

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  3. Starts a thread in RLC layer
  4. Packet RLC --> PDCP

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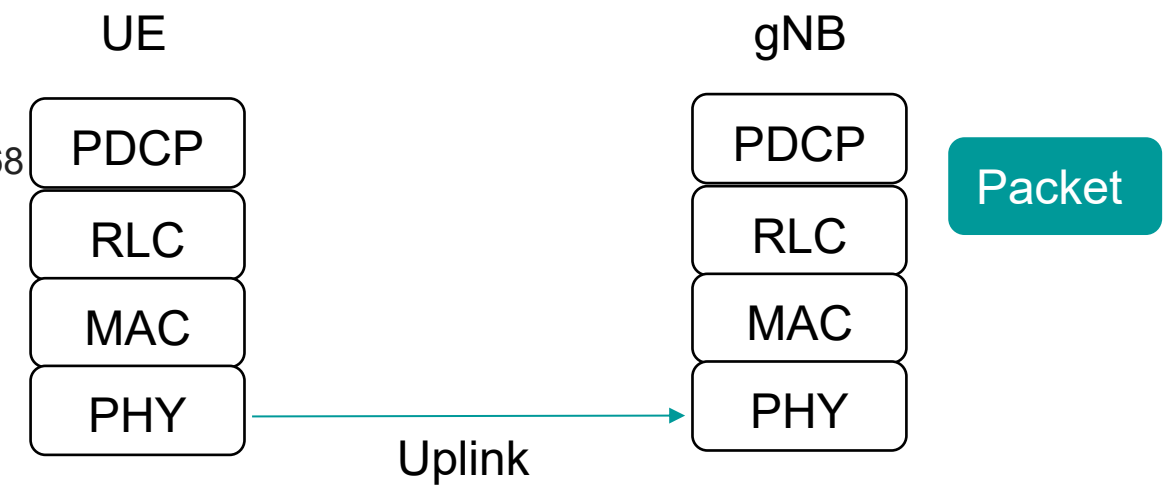
Thread 2

14183704358463 U rlc.decoded--rlc.reassembled len104::MRbuf221047683.p0.si2.sn6.so427

Thread 3

14183704362612 U rlc.reassembled--pdcp.ind len531::sn6.PIBuf3749066208



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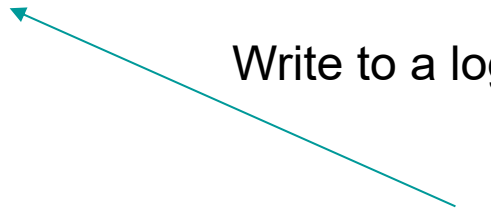

Write to a log file

Data Collector Thread
(Round Robin)

Based on Mostafavi et al., 2025; Moothedath et al., 2025

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Thread 2

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Time Conversion

- Runtime: Low-overhead delay tagging
  1. Record the virtual timer count from system register
  2. Once per second, record the Unix time and virtual timer count as follows (“S logs”)
     - 3530958760381 S rdtsc—gettimeofday 1778358211.798450864

- Timeline reconstruction for post-processing
  Calculate linear interpolations between every two "S logs"

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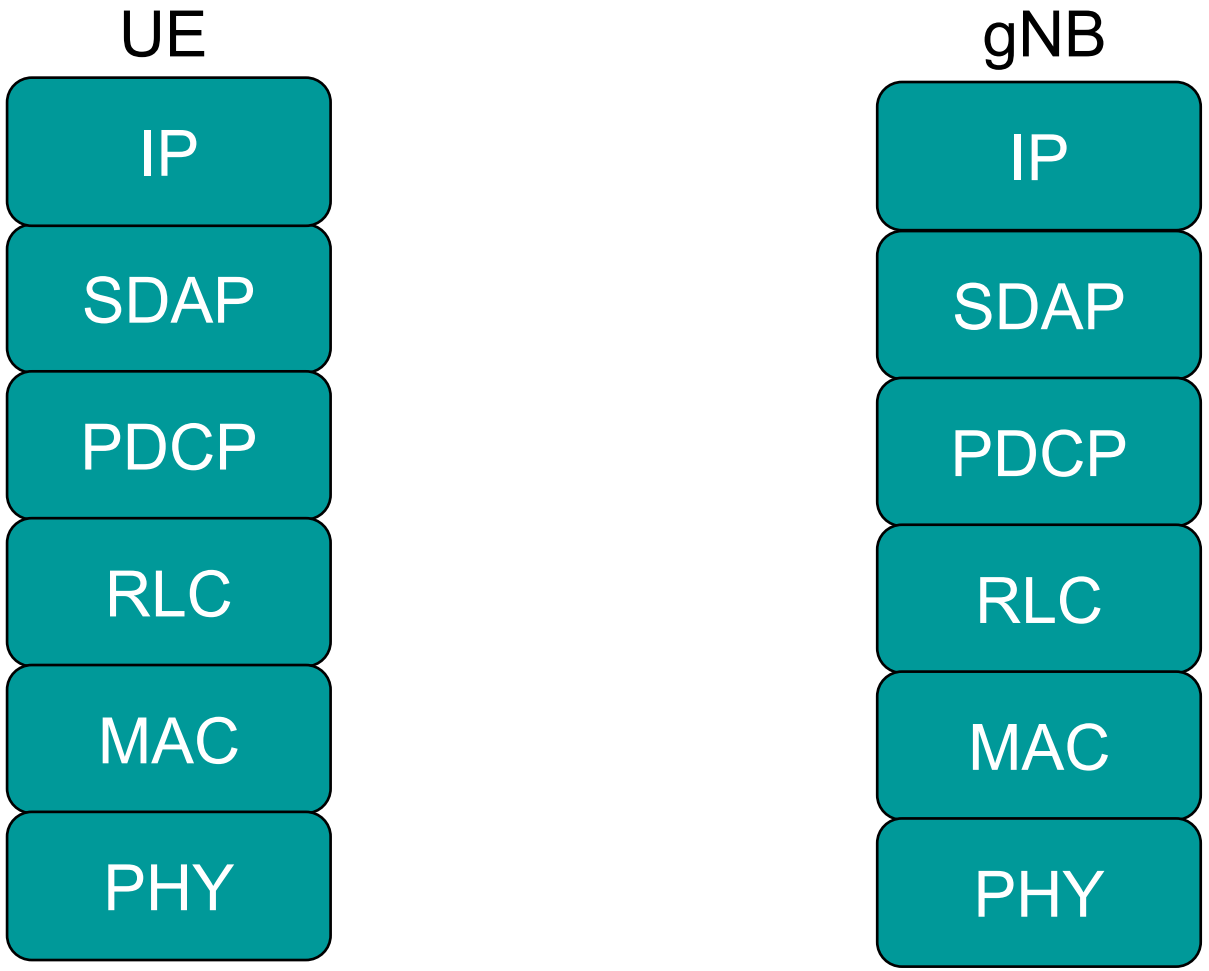
A complete End-to-end Delay Decomposition - Uplink



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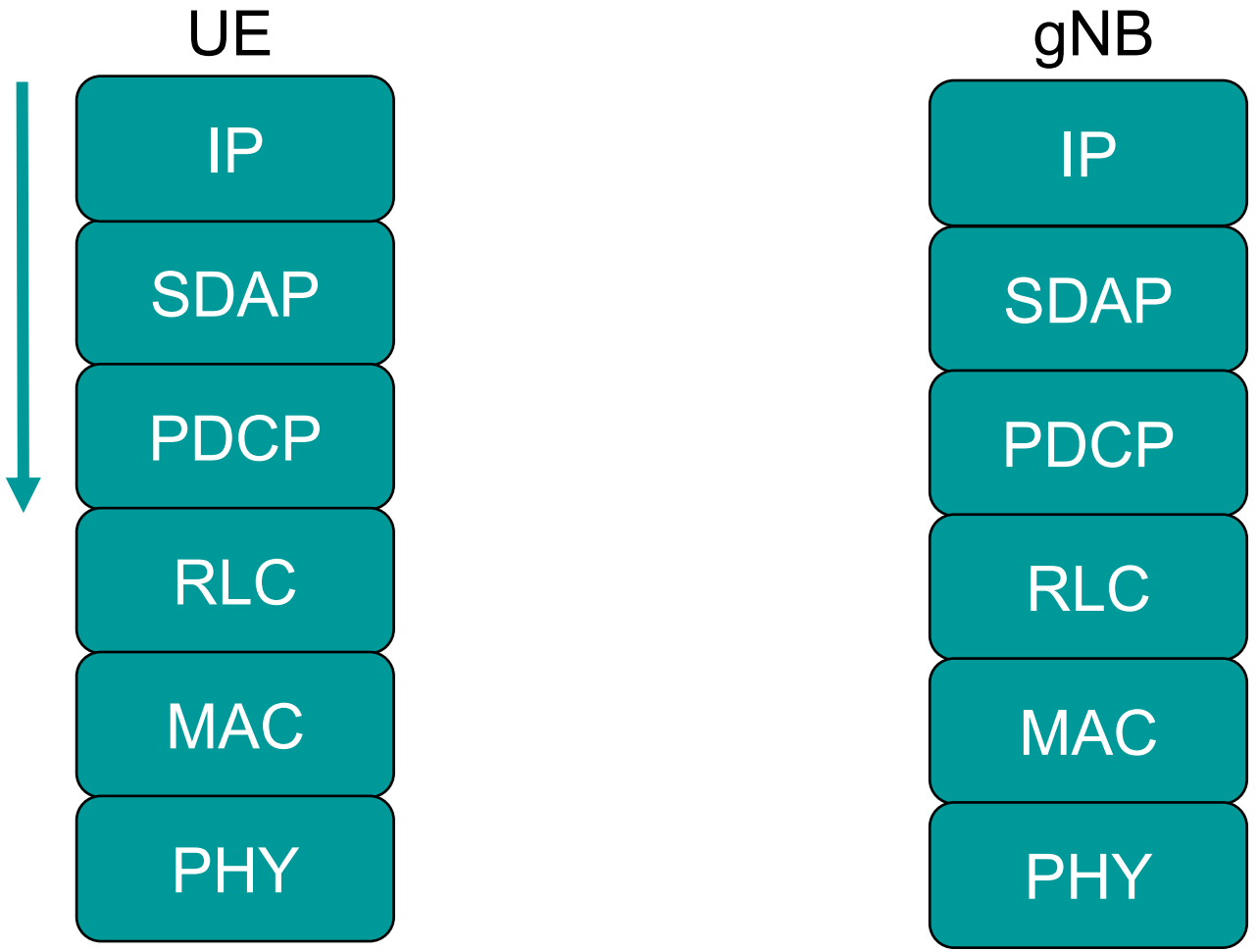
A complete End-to-end Delay Decomposition - Uplink

ip2rlc delay
(From IP to RLC queue)



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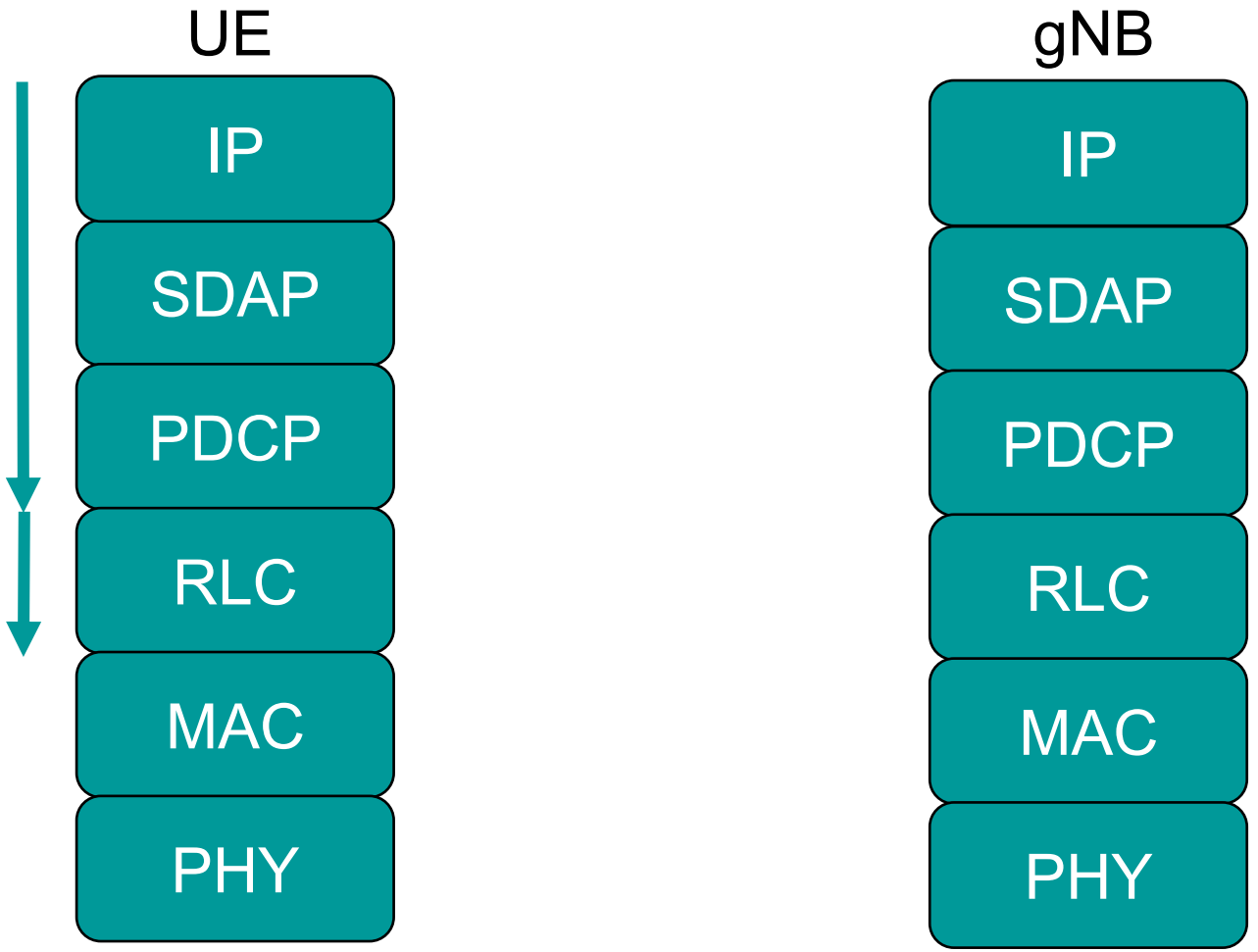
rlc_queuing_delay
(From RLC queue to RLC pdu)



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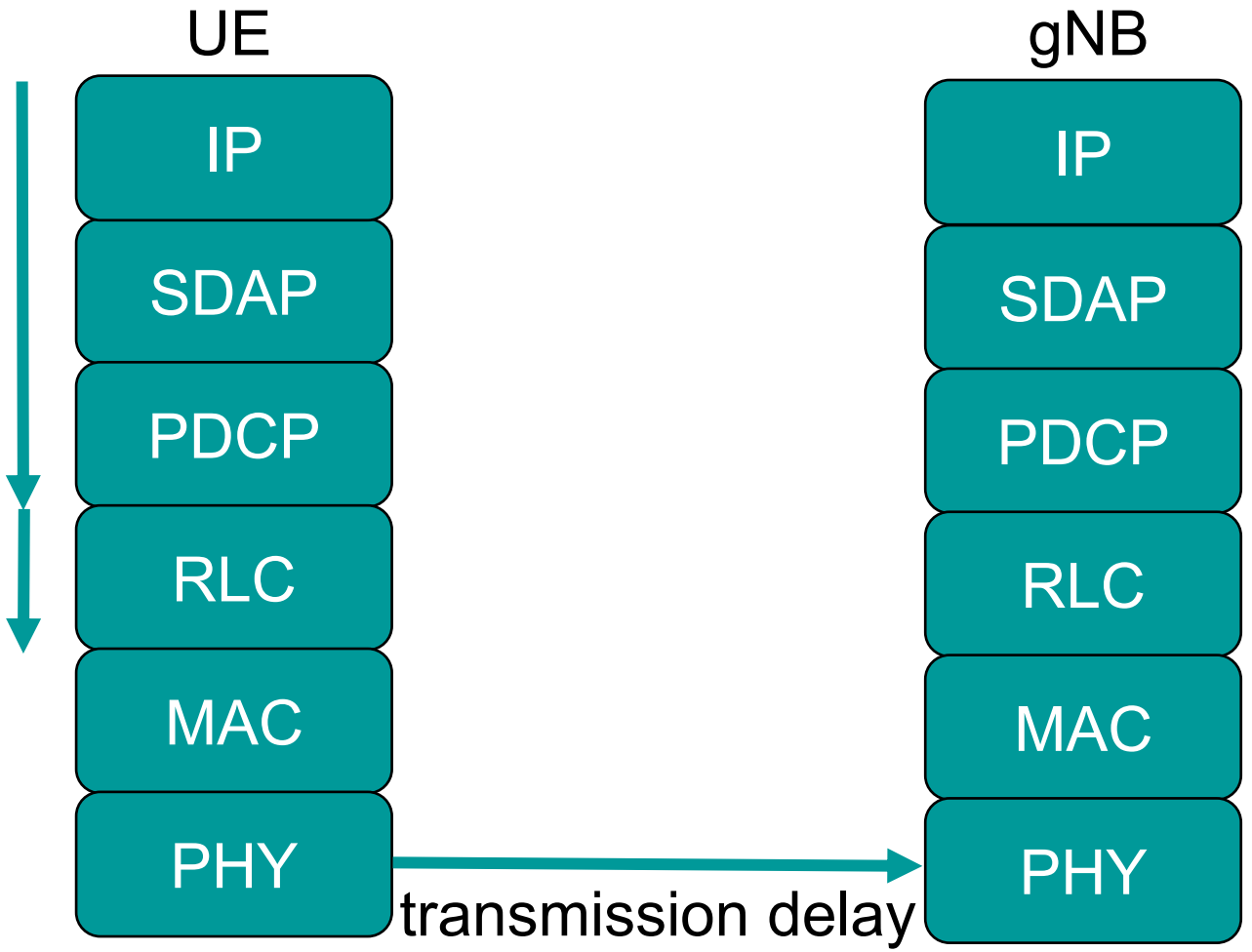

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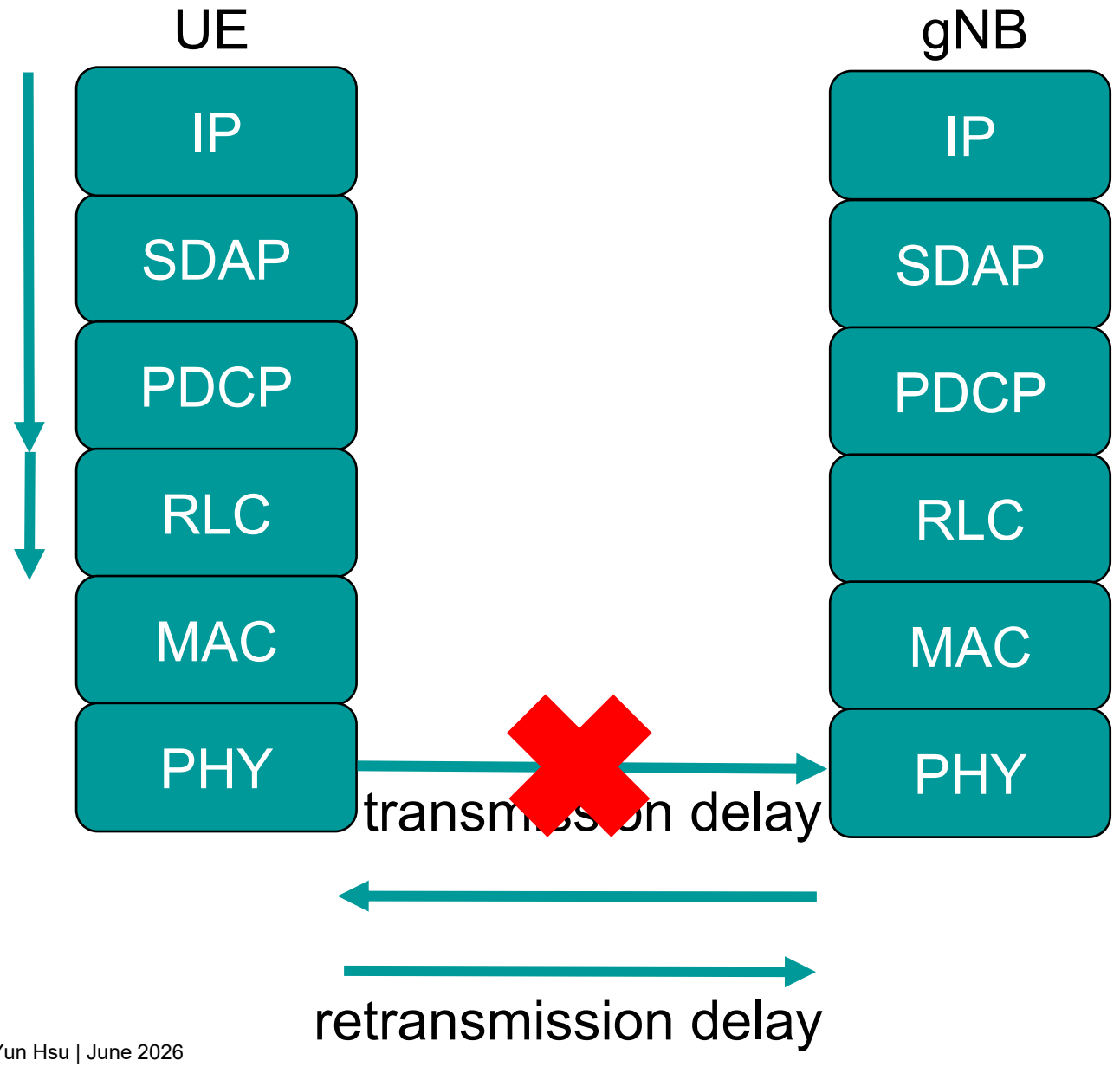

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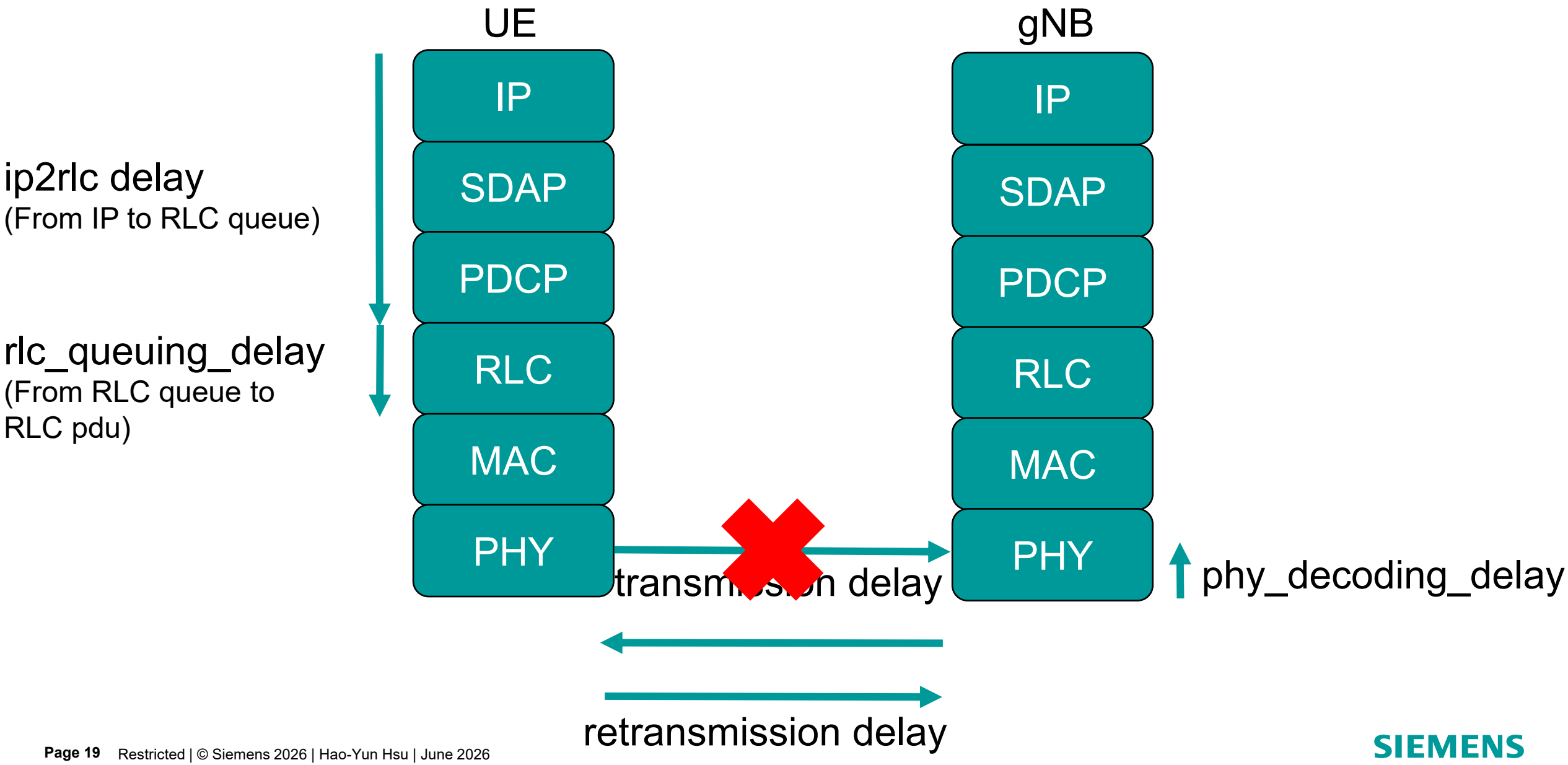

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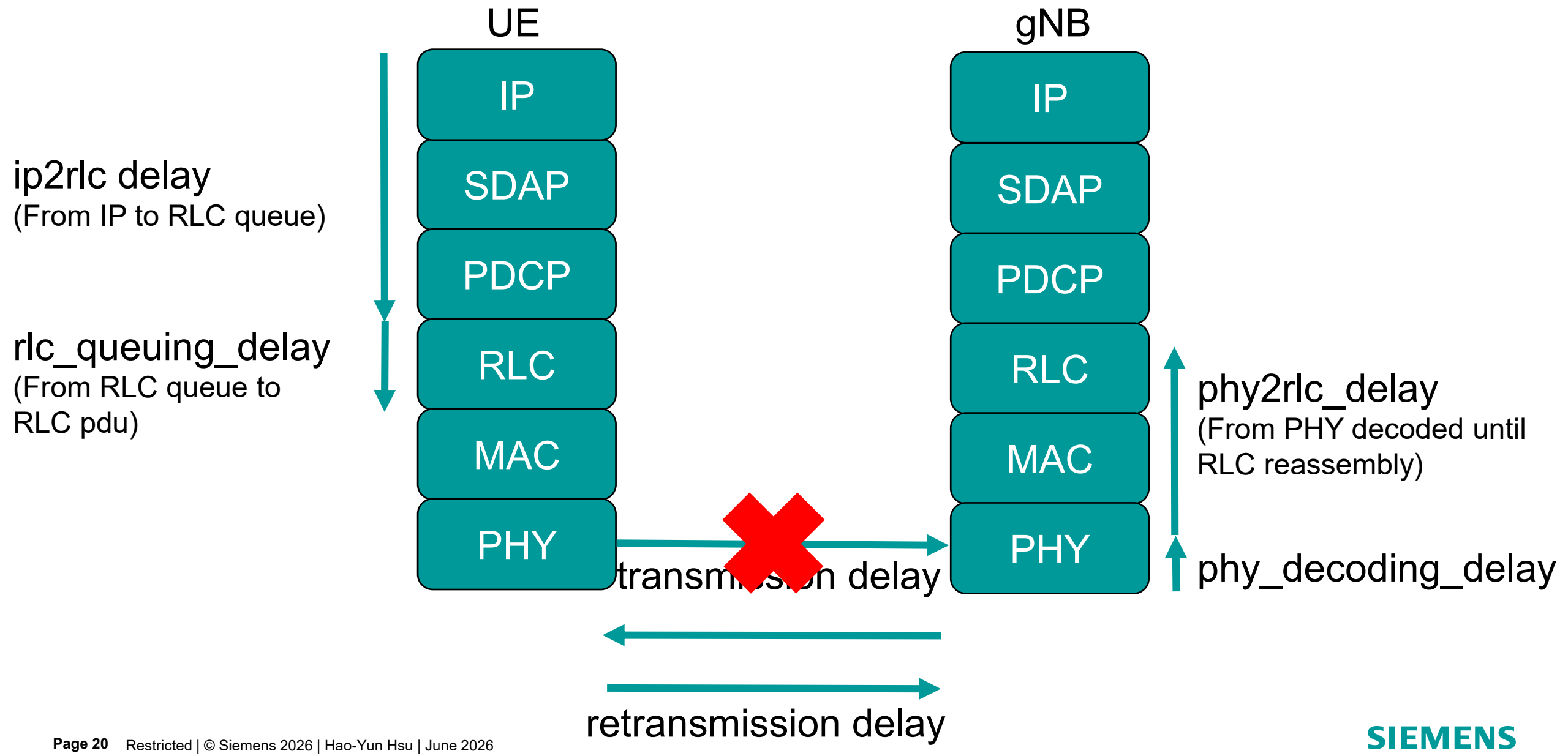

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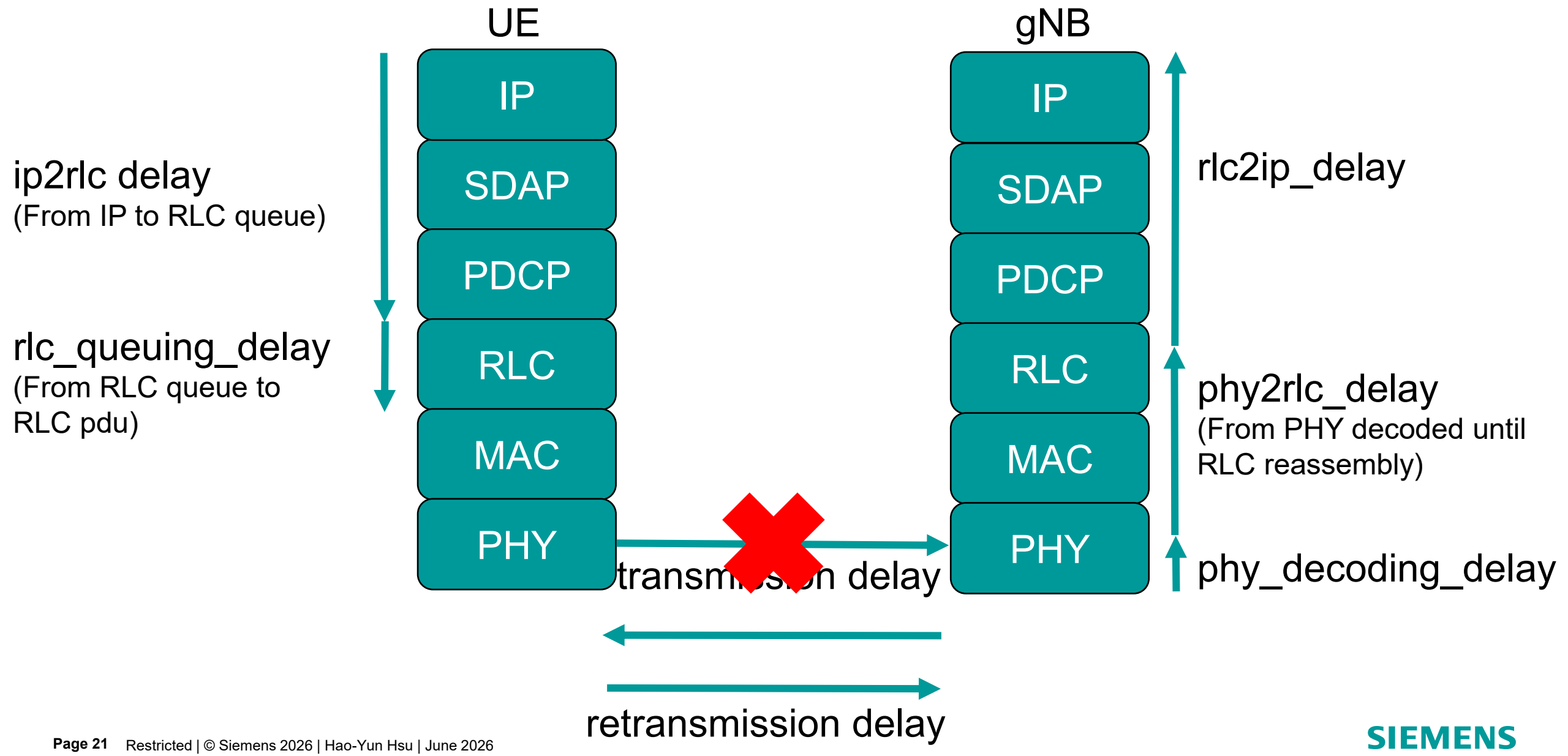

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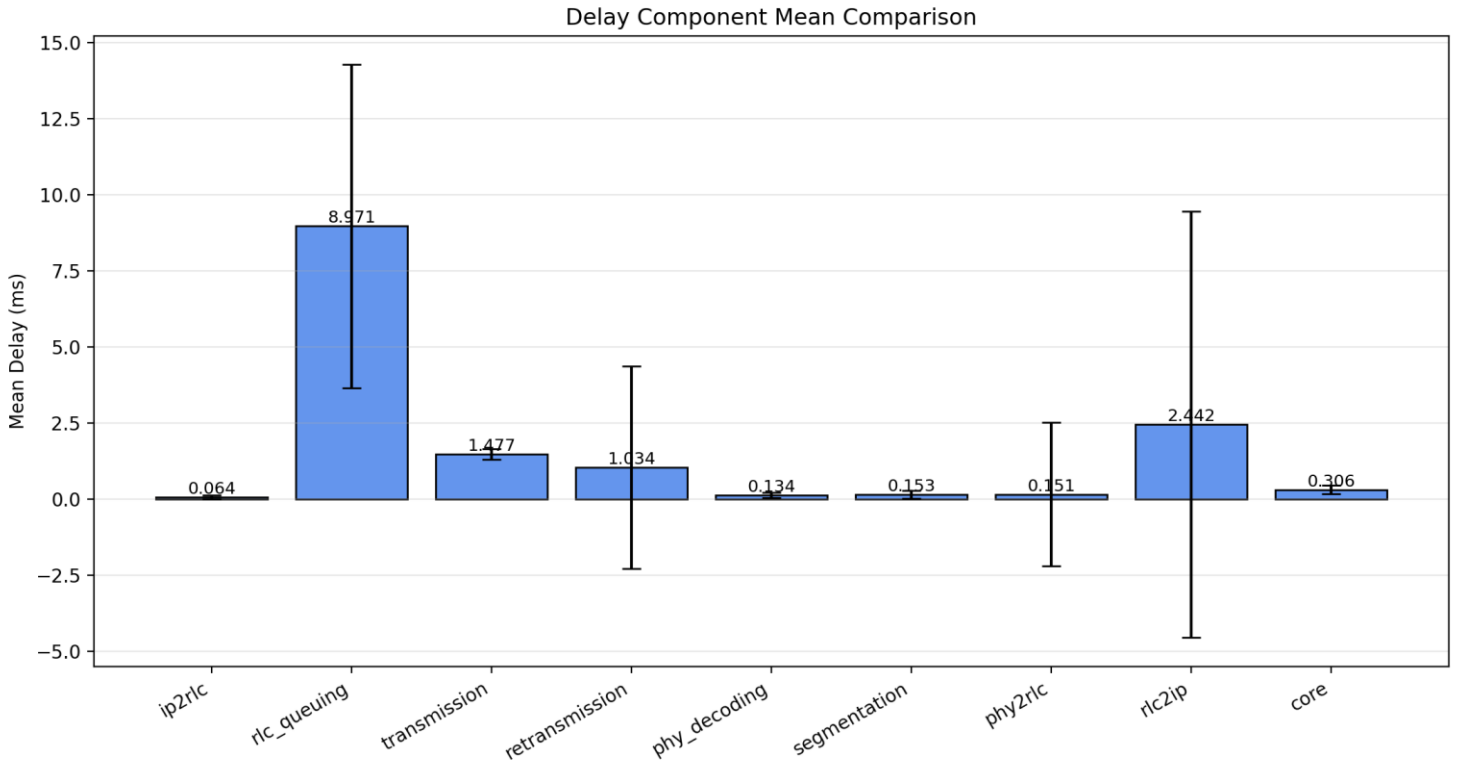
Delay decomposition reveals the dominant component of uplink delay

- End-to-end delay is not evenly distributed across protocol layers.
- In this setup, RLC queuing dominates the mean uplink delay.
- Transmission contributes less than queuing, while the remaining components are relatively small.



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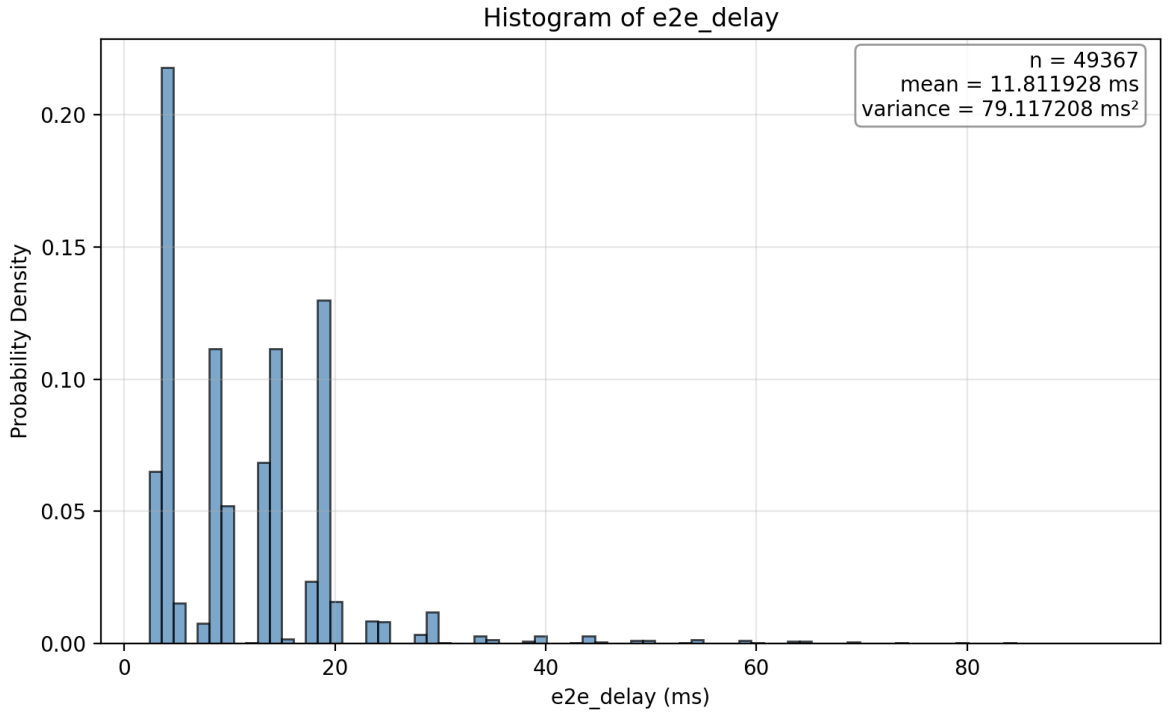
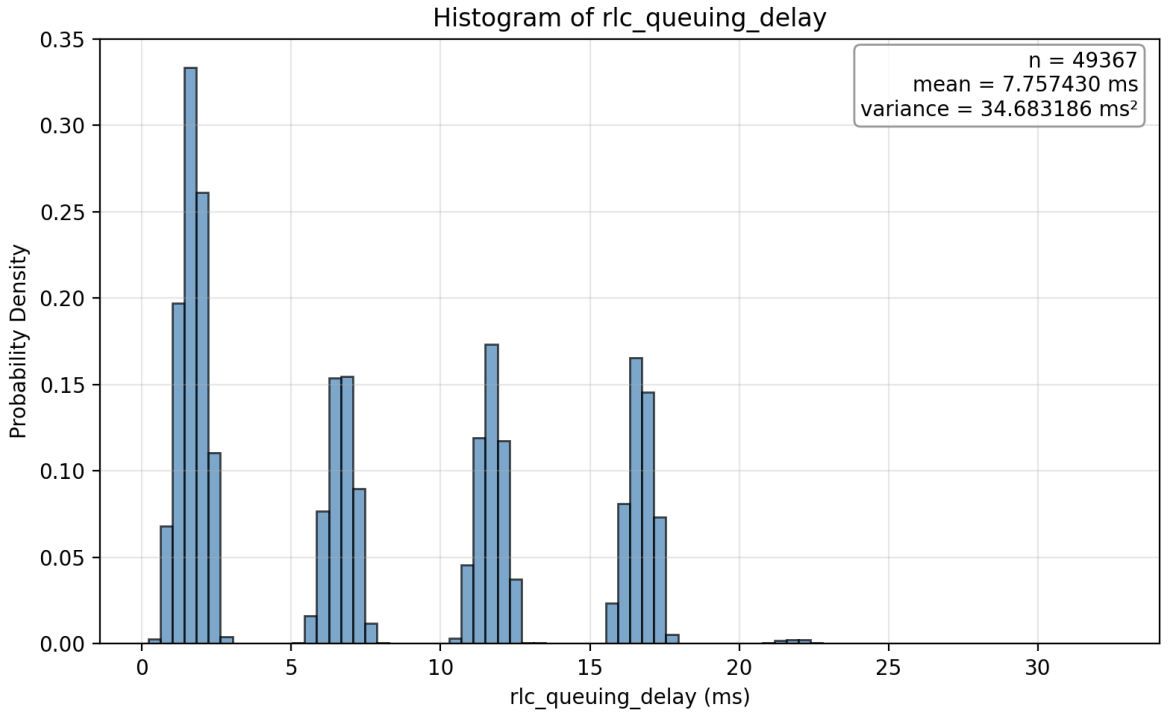
End-to-end delay closely follows RLC queuing

- The histogram of end-to-end delay closely resembles that of RLC queuing delay.
- This similarity is visible in the overall distribution shape.
- Hence, the variability of end-to-end delay is largely inherited from the queuing process.
- This makes RLC queuing a key component for explaining DVP.





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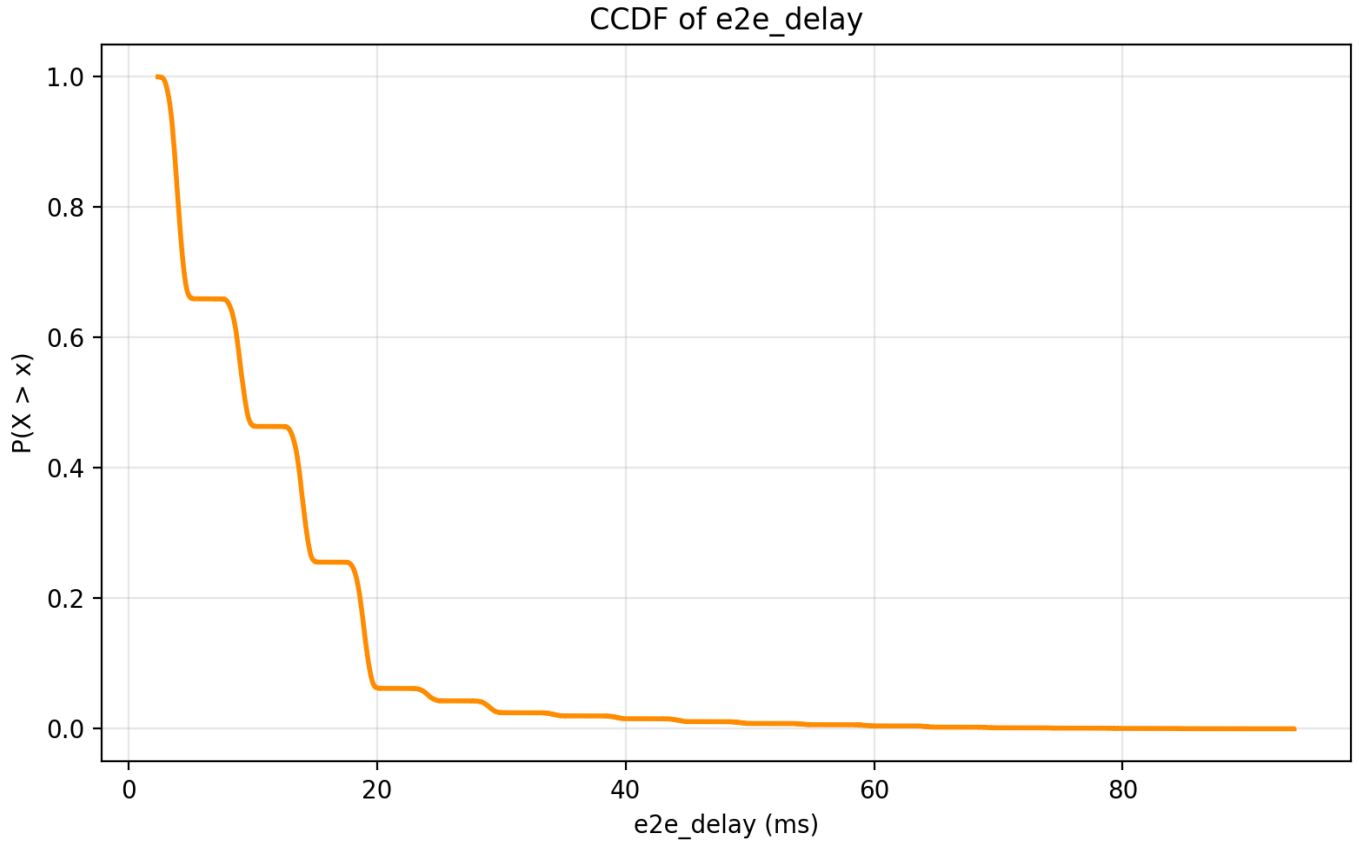
Deriving DVP from end-to-end delay

- Delay Violation Probability (DVP) is defined as the probability that packet delay exceeds a target threshold.
- Therefore, the CCDF of end-to-end delay directly provides the empirical DVP curve.
- Since the delay distribution is strongly influenced by RLC queuing, the DVP is also expected to depend heavily on queue dynamics.



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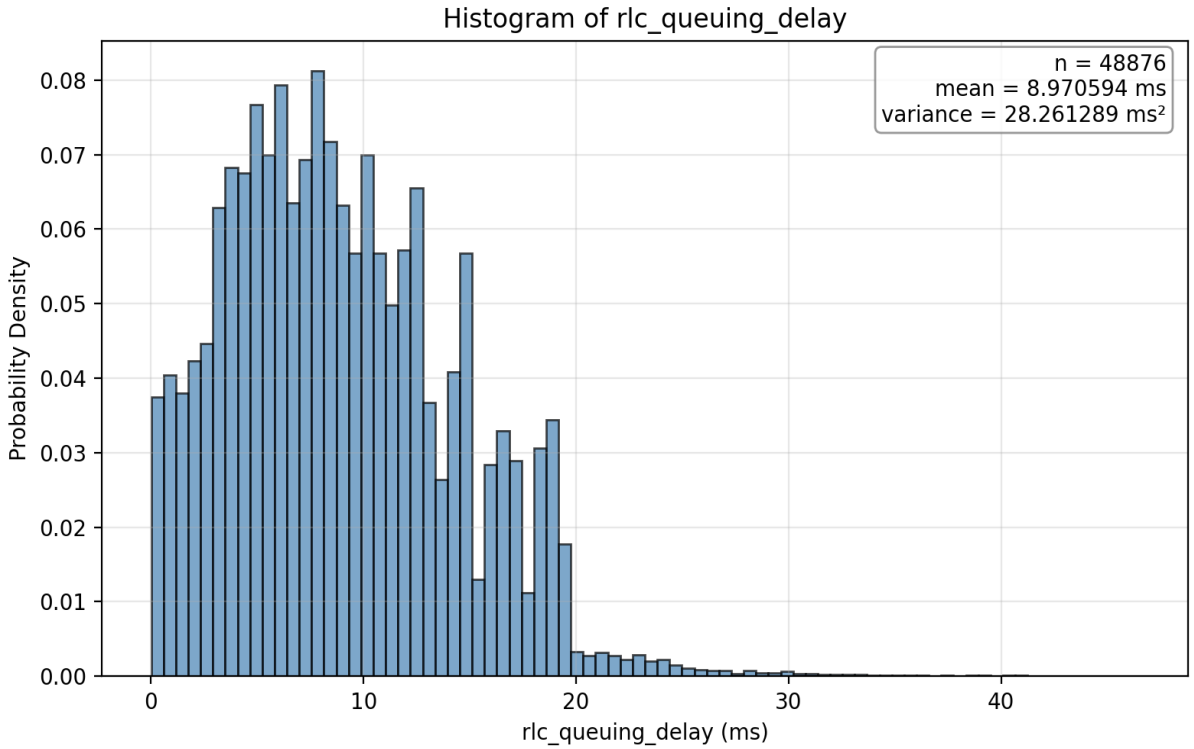
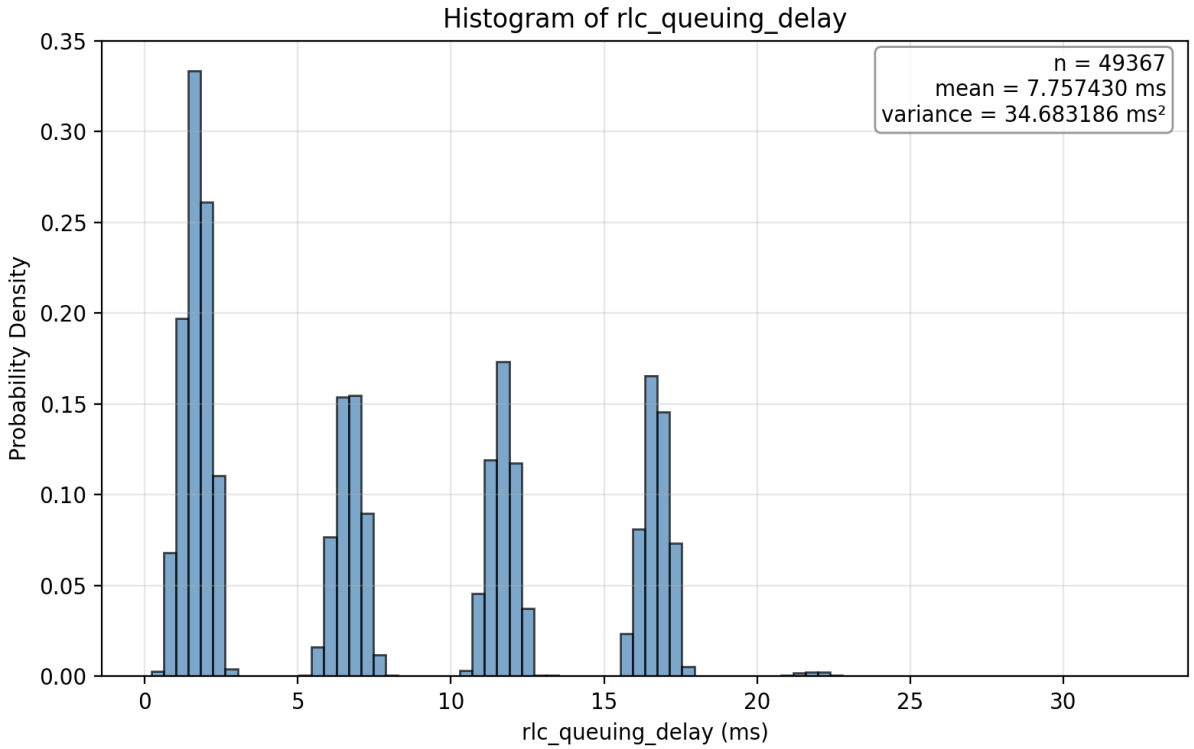
Different RLC queuing delay patterns under different packet inter-arrival times

Queuing Delay at inter-arrival time 2ms



Queuing Delay at inter-arrival time 5ms



- The RLC queuing delay distribution changes significantly with packet inter-arrival time.
- At 5 ms, the histogram shows structured / multi-modal peaks, indicating phase-dependent waiting times.
- At 2 ms, the distribution becomes smoother, suggesting a more persistently backlogged queue.
- Traffic periodicity affects not only the average delay, but also the underlying queueing mechanism.

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Conclusion

- Delay decomposition matters — aggregate e2e delay alone hides the dominant mechanism.
- RLC queuing dominates the measured uplink delay in our setup.
- DVP is therefore tightly linked to queue dynamics rather than only transmission time.
- Traffic periodicity shapes delay behavior:
  - Sparse arrivals can create discrete delay modes.
  - Persistent arrivals can sustain backlog and long tails.

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Next Step: Probabilistic DVP Prediction

- Goal
  - Use LSTM and Transformer to predict the violation probability of the future delay.
  - Move from delay analysis to proactive delay prediction.
  - Evaluate how well the prediction works on our testbed.

- Key Questions
  - How much training data is needed?
  - Which model performs better?
  - Which features (e.g., MCS, retransmission) contribute the most?
  - Can the model generalize to unseen scenarios?

Inspired by prior work: Mostafavi et al., Probabilistic Delay Forecasting in 5G Using Recurrent and Attention-Based Architectures.

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