ePulsar
Control Plane for Publish-Subscribe Systems on Geo-Distributed Edge Infrastructure

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Incorporating network proximity at scale for latency-sensitive broker selection.

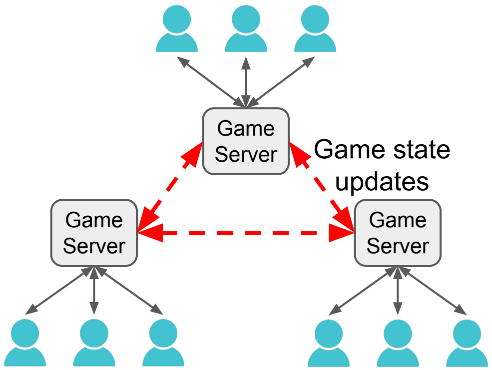
Talk Outline

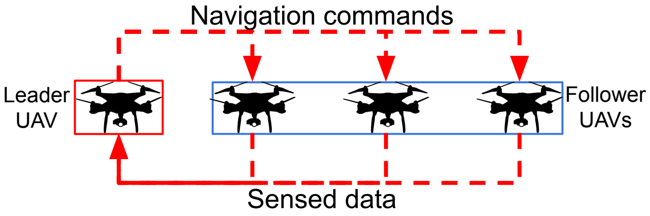
1. **Background**
2. Problem and Challenges
3. Design Principles of ePulsar
4. Architecture
   a. Network Proximity Estimation
   b. Distributed Monitoring
5. Implementation
6. Evaluations
7. Conclusion

Emerging distributed applications need publish-subscribe

- Apps with multiple distributed components
  - Massively Multiplayer Online Games (MMOG)
  - UAV Swarm coordination
  - Collaborative Perception for vehicles

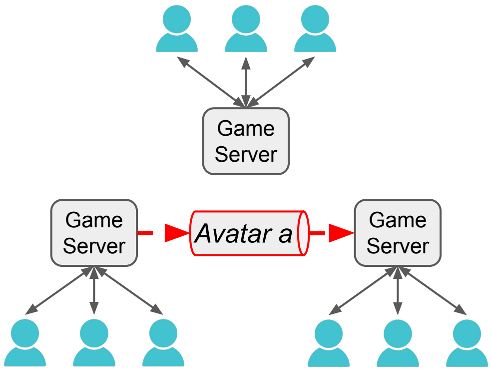
- Share sensed data, state-updates

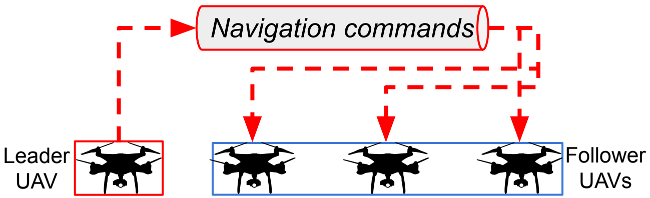




Emerging distributed applications need publish-subscribe

- Apps with multiple distributed components
- Share sensed data, state-updates
- Publish-subscribe model is a suitable abstraction
  - Decouples data ***Producers*** and ***Consumers***
  - Communication through ***Topics***





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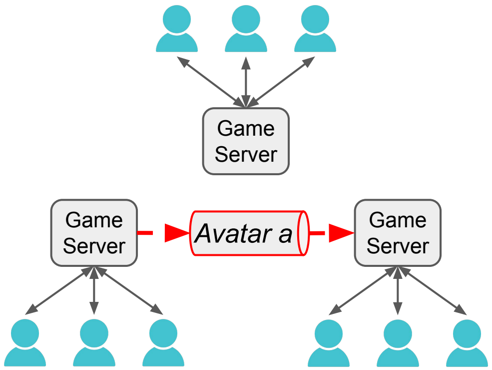
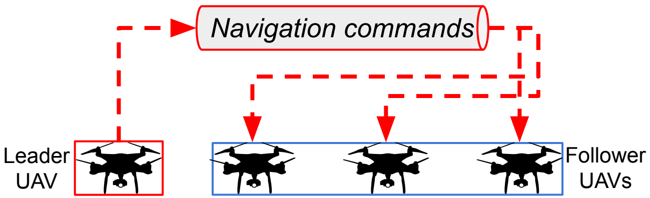
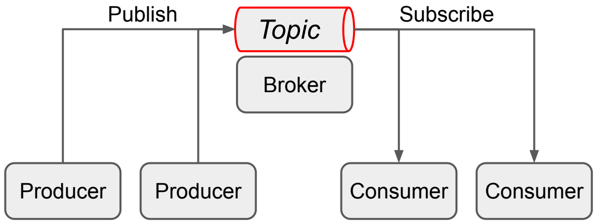
  - Decouples data ***Producers*** and ***Consumers***
  - Communication through ***Topics***
  - ***Topics*** hosted by ***Broker*** nodes



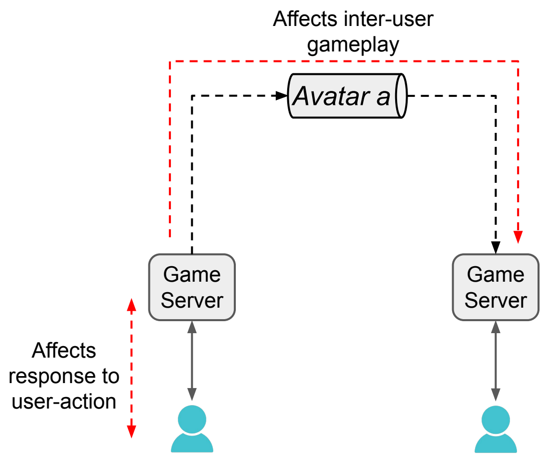




Low latency requirement

- Communication latency affects functionality

- Stringent latency requirements
    - UAV Swarm coordination: < 40 ms [1]
    - MMOG: < 100ms GS-to-GS [2]



[1]Massive MIMO for Connectivity With Drones: Case Studies and Future Directions
[2] Lag Compensation for First-Person Shooter Games in Cloud Gaming

Low latency requirement

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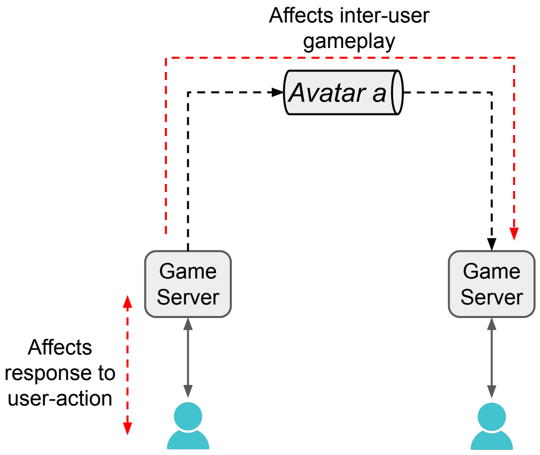
- Stringent latency requirements
  - UAV Swarm coordination: < 40 ms [1]
  - MMOG: < 100ms GS-to-GS [2]
- Cloud-based Pub-Sub systems
  - Offer strong data semantics, but
  - High end-to-end latency due to Wide Area Network



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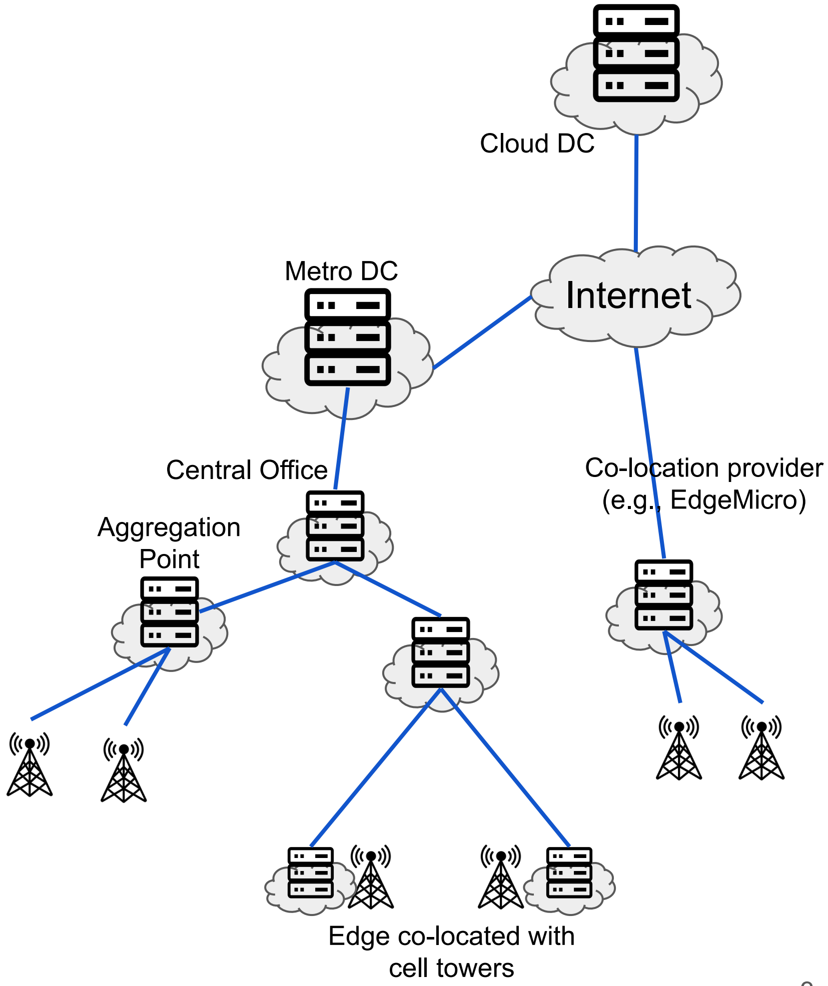
Edge infrastructure

- Edge-Cloud continuum
  - Multiple providers
  - Multi-city geographical coverage
  - Inter-edge network latency



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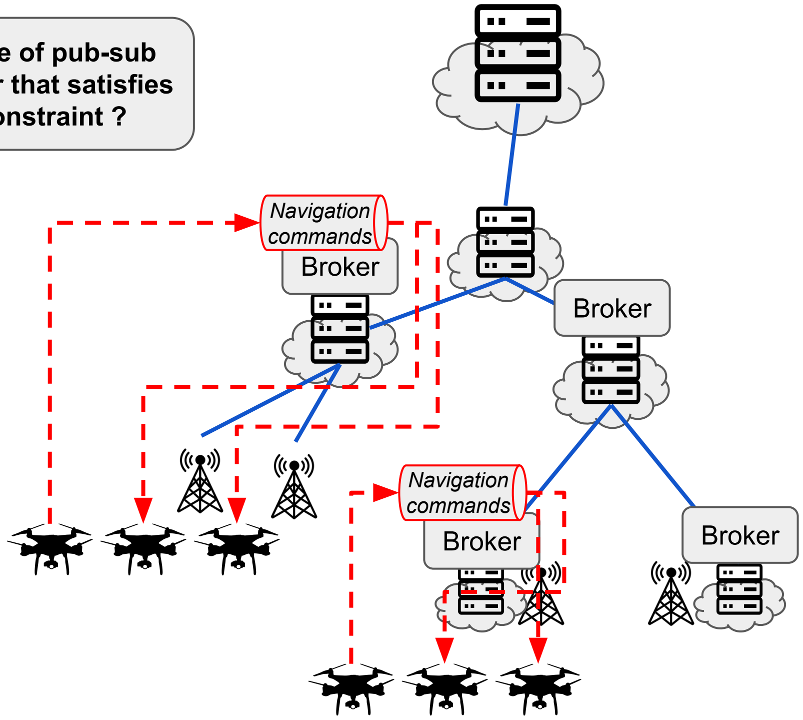
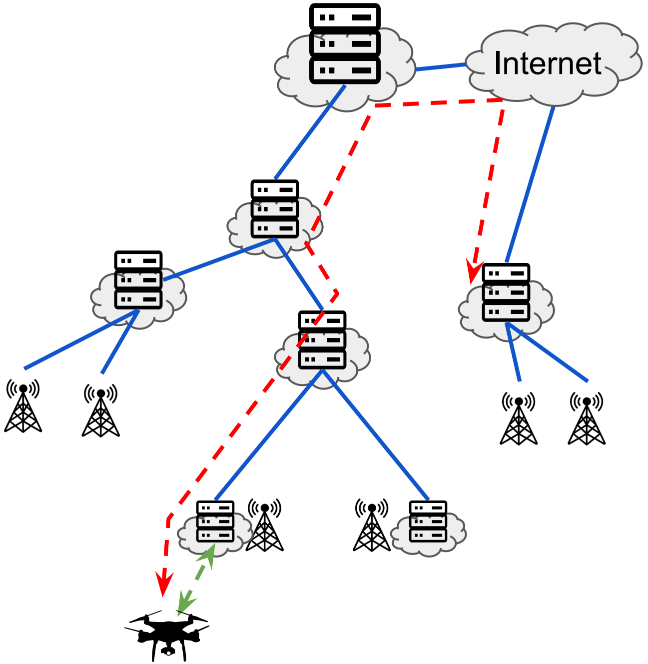
Problem: Serving pub-sub latency requirement of apps

How to aid control-plane of pub-sub system to select a broker that satisfies end-to-end latency constraint ?



Challenges in operating a geo-distributed pub-sub system

- Topology awareness
  - Edge network topology is highly heterogeneous
  - Latency variation
  - Dense geo-distribution



Challenges in operating a geo-distributed pub-sub system

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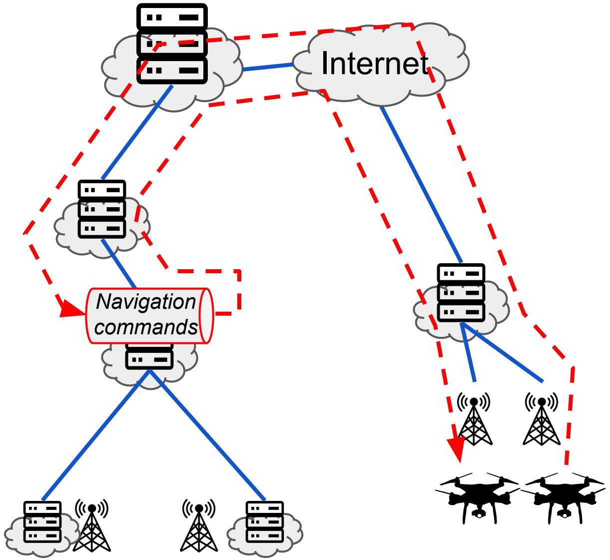
- Client mobility
  - Publish-subscribe latency violation



Using cloud-based pub-sub systems on the Edge

- E.g., Apache Pulsar, Apache Kafka

- Control-plane designed for datacenter workloads
    - Focus on even workload distribution, not end-to-end latency
    - Don’t consider high client-edge communication latencies

- Need to provide latency-awareness to broker selection

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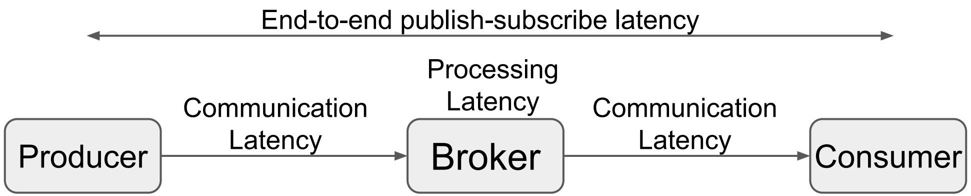
Design principles of ePulsar’s edge-ready control-plane



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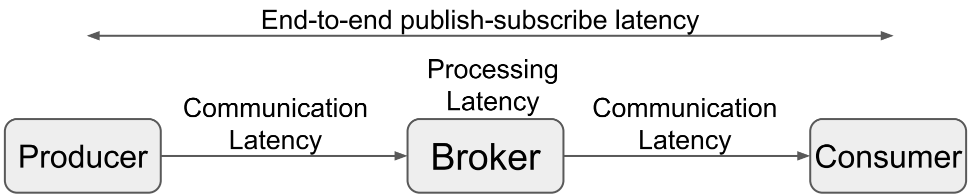

- Scalable Network Proximity Estimation → communication latency

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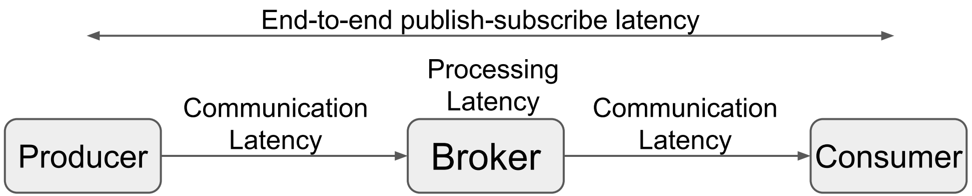

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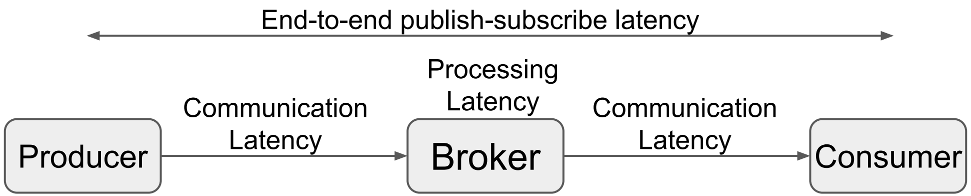

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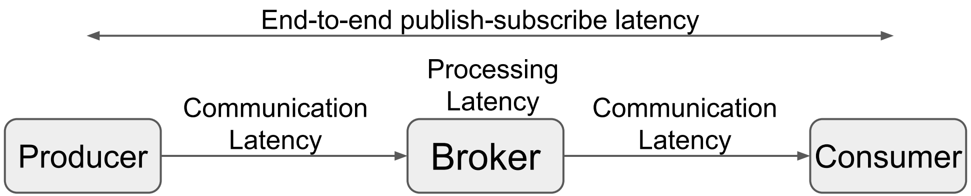

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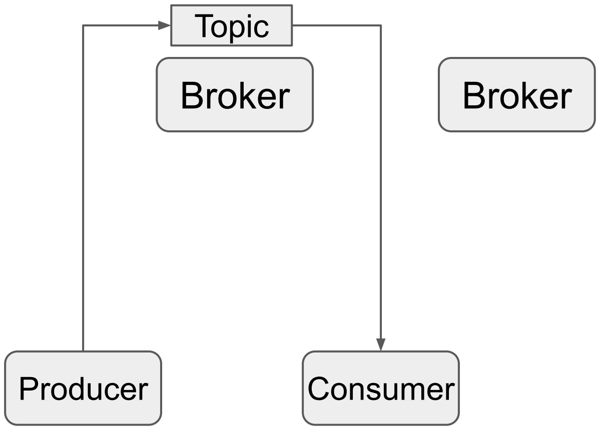
High-level architecture of ePulsar

- Geo-distributed Broker nodes
  - Host Topics
- Producers and Consumers share data through topics



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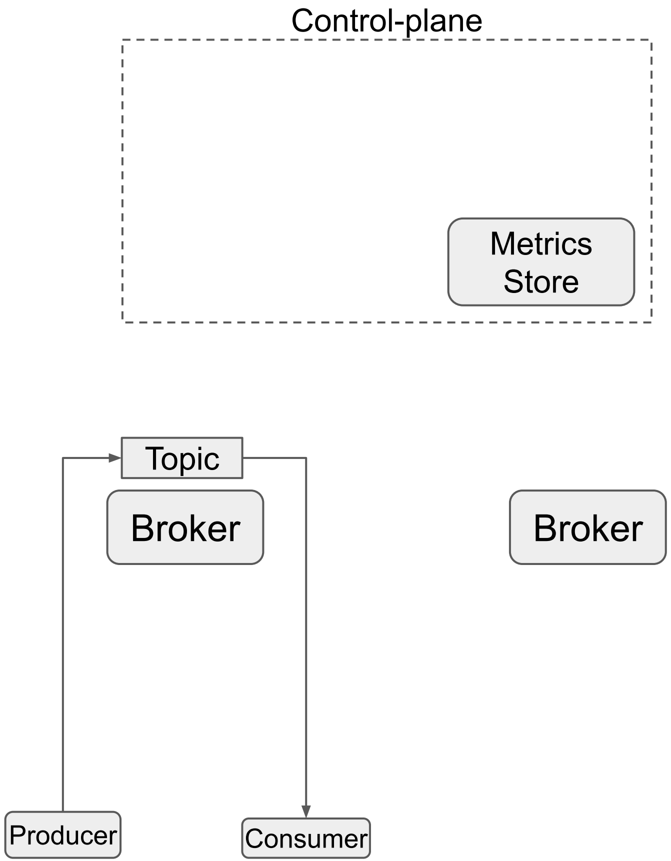
- Components of control-plane
  - **Metrics Store** for storing monitoring data



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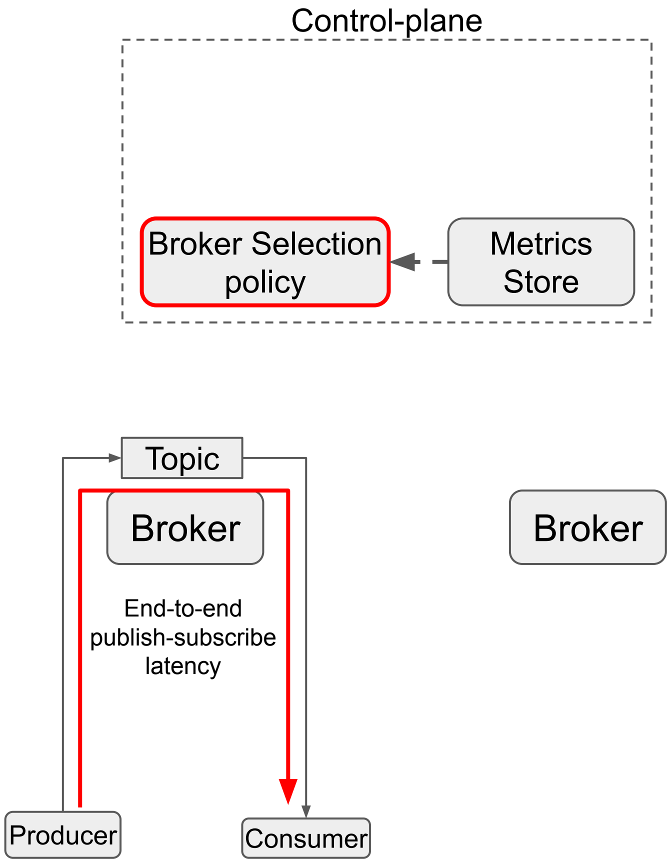
    Latency-aware Topic → Broker mapping



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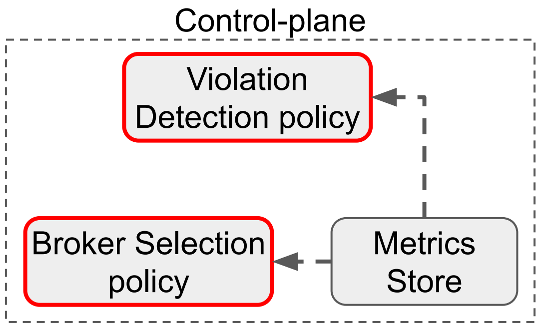

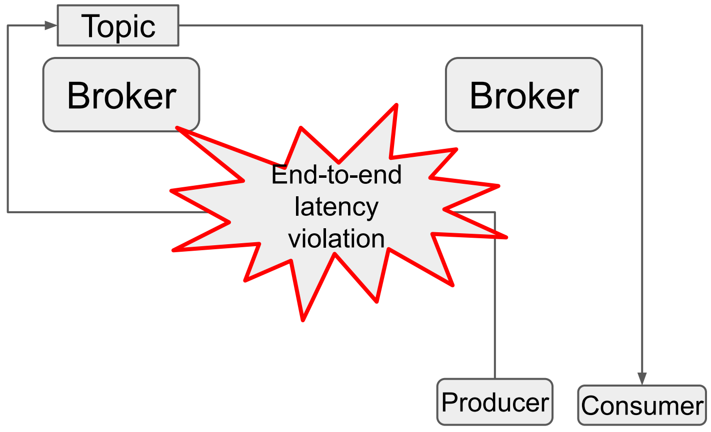

High-level architecture of ePulsar

- Geo-distributed Broker nodes
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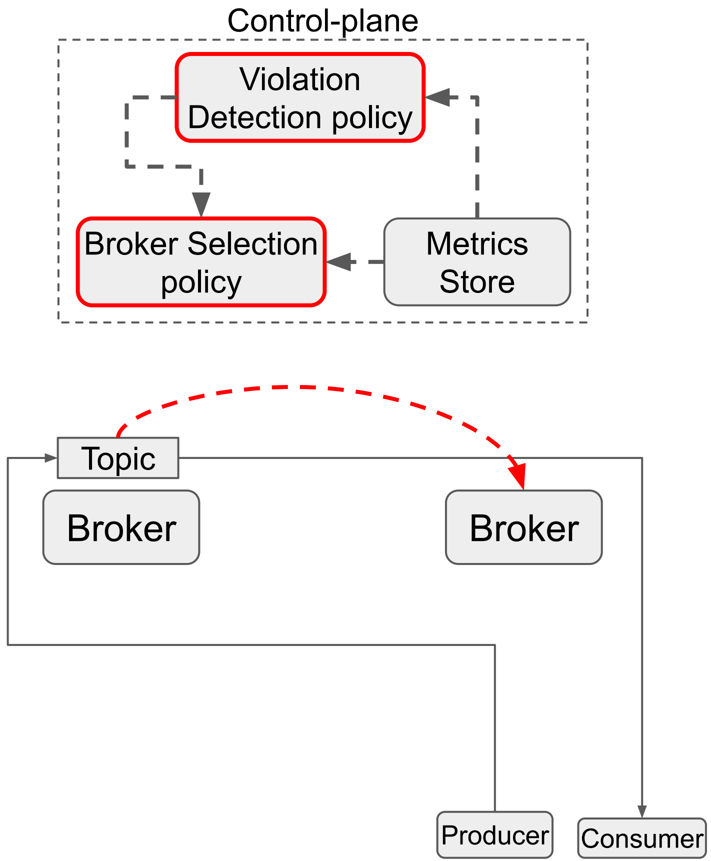
- Producers and Consumers share data through topics

- Centralized control-plane
  - **Metrics Store** for storing monitoring data
  - **Broker Selection Policy**
    Latency-aware Topic → Broker mapping
  - **Violation Detection Policy**
    → Triggers topic migration



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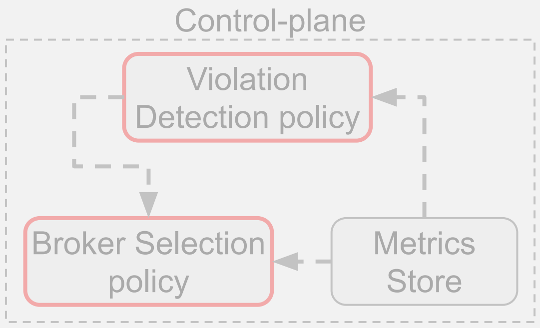

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End-to-end latency estimation is at the core of control-plane policies.

  - **Broker Selection Policy**
    Latency-aware Topic → Broker mapping
  - **Violation Detection Policy**
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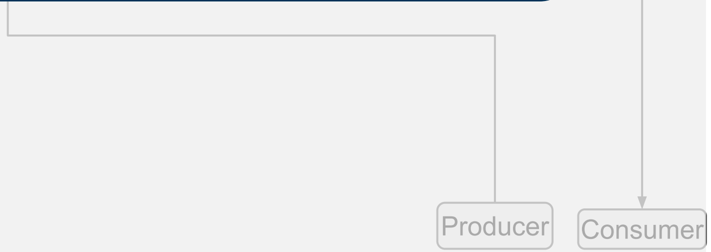
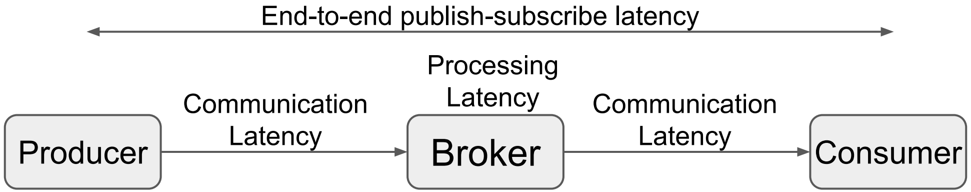


Estimating end-to-end publish-subscribe latency



- Network Proximity estimations for communication latency

- Message rate + offline profiling for processing latency
    - Khare et al. (SEC 2018)

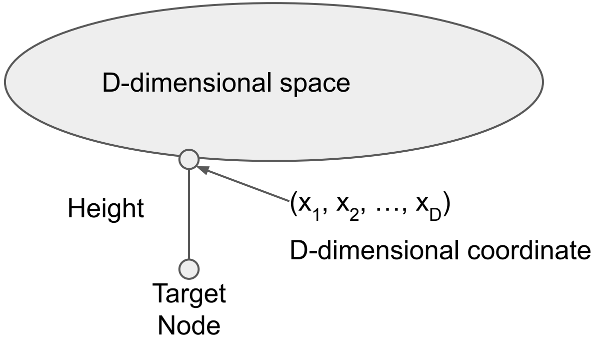
Khare, Shweta, et al. "Scalable edge computing for low latency data dissemination in topic-based publish/subscribe." *2018 IEEE/ACM Symposium on Edge Computing (SEC)*. IEEE, 2018.

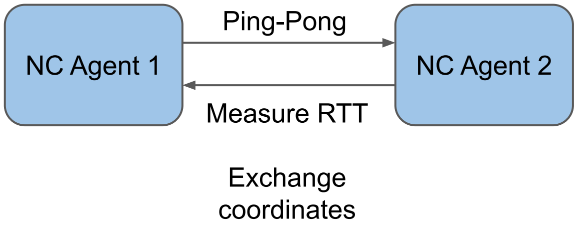
Network Proximity Estimation in ePulsar

- **Network Coordinates (NC)**
  - Arrange nodes in a Euclidean space
  - Euclidean distance b/w nodes equals RTT

- Network Coordinate (NC) Agents

- Decentralized P2P protocol [1]

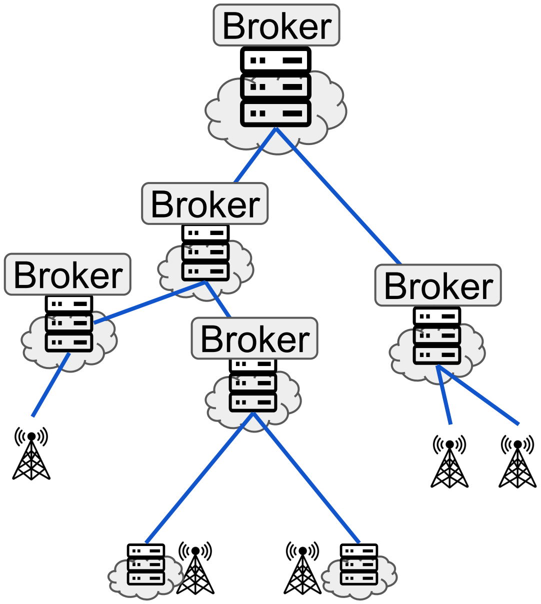




If $|\, d(NC_1, NC_2) - measured\_rtt \,| > error$
Update NC_1

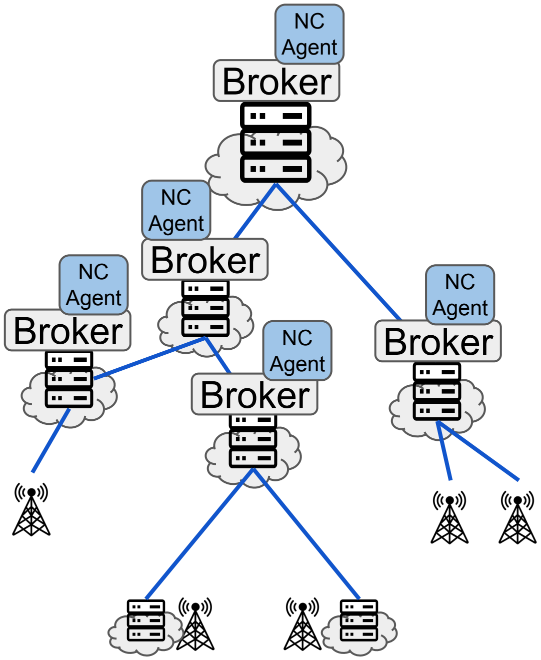
[1] Dabek, Frank, et al. "Vivaldi: A decentralized network coordinate system." ACM SIGCOMM Computer Communication Review 34.4 (2004): 15-26.
[2] Ledlie, Jonathan, Paul Gardner, and Margo I. Seltzer. "Network Coordinates in the Wild." NSDI. Vol. 7. 2007.
[3] Lee, Sanghwan, et al. "On suitability of euclidean embedding for host-based network coordinate systems." IEEE/ACM Transactions on Networking 18.1 (2009): 27-40.

Deployment of Network Coordinate Agents



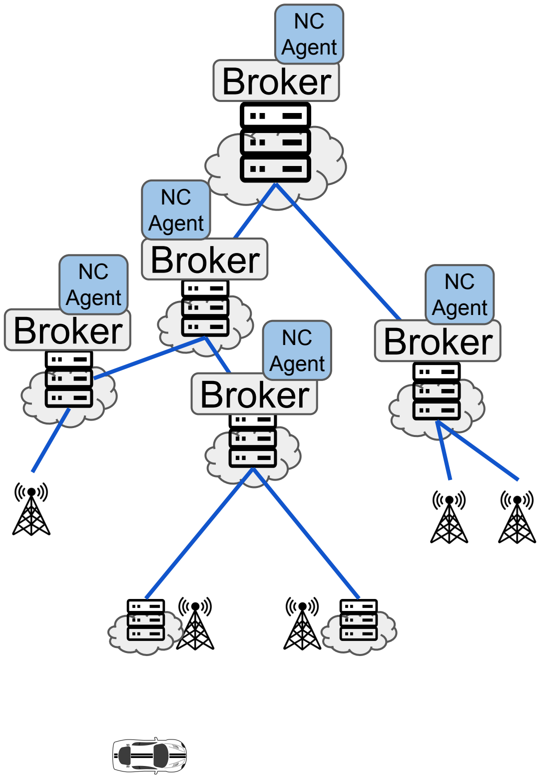
Deployment of Network Coordinate Agents

- NC Agent deployed with Broker



Deployment of Network Coordinate Agents

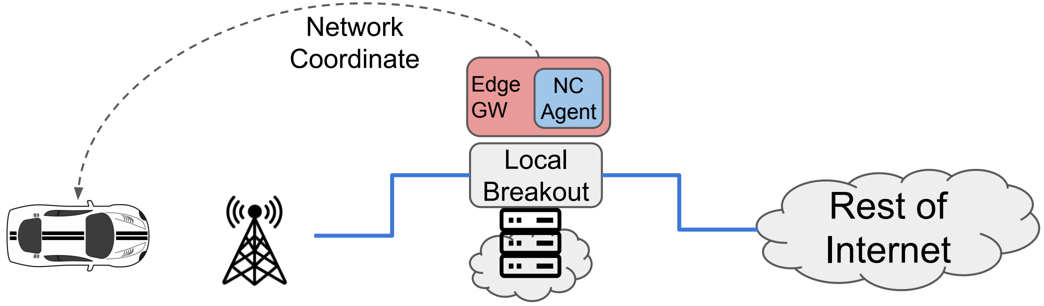
- NC Agent deployed with Broker
- Handling mobile clients

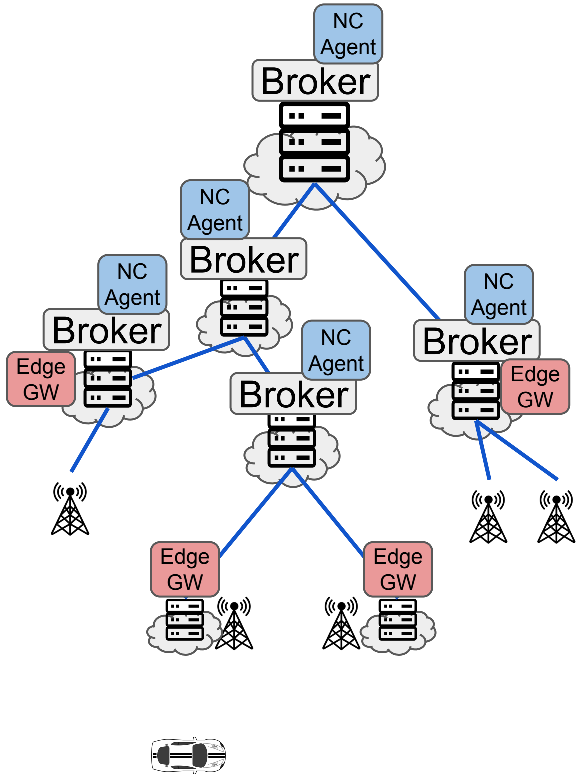


Deployment of Network Coordinate Agents

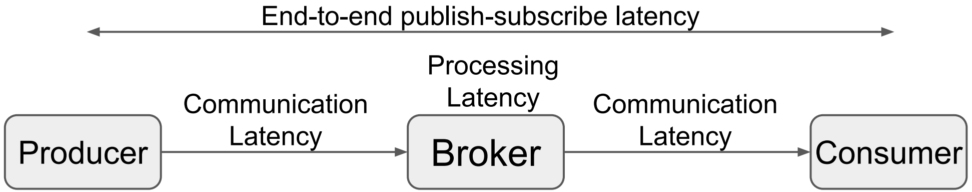
- NC Agent deployed with Broker

- Handling mobile clients
  - Additional Edge Gateway component
  - Located at gateway of access point
  - Adjust for Client-Edge GW RTT





Network proximity for end-to-end latency calculation



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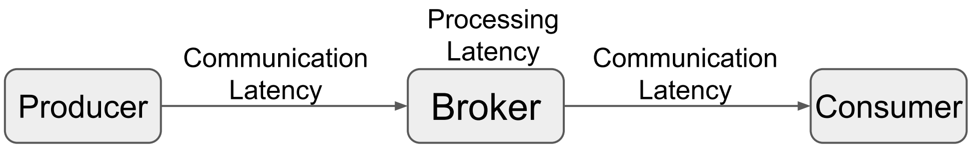
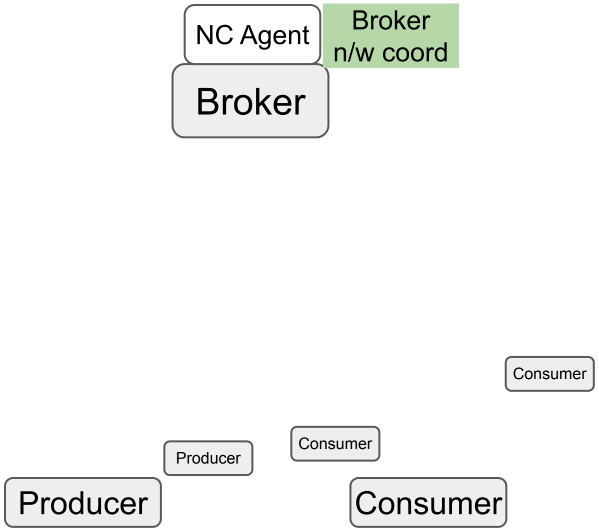


- Network Coordinate (NC) Agents
  - On Brokers



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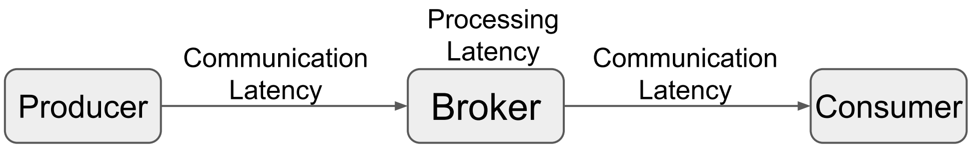
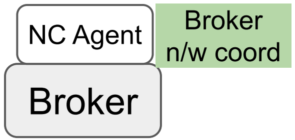
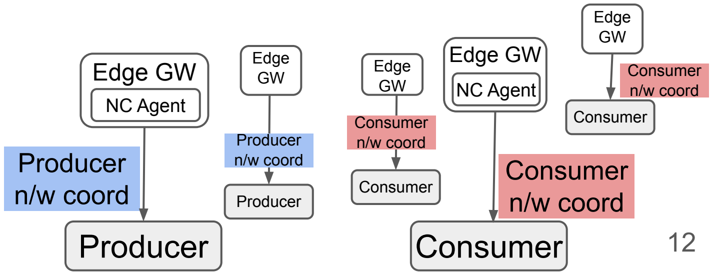


- Network Coordinate (NC) Agents
  - On Brokers
  - On Edge Gateways





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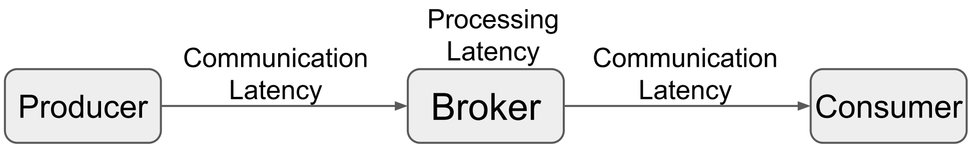
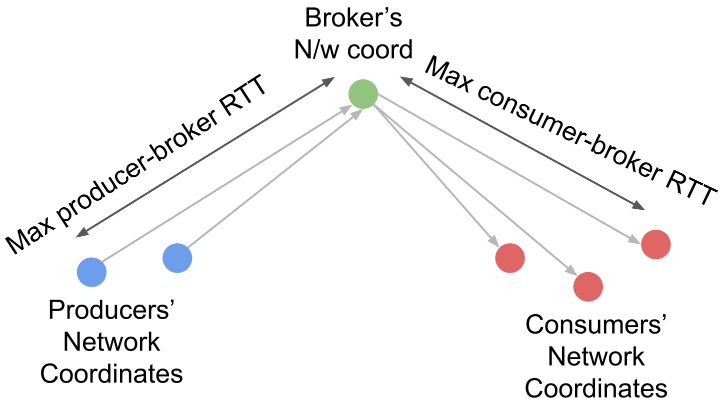


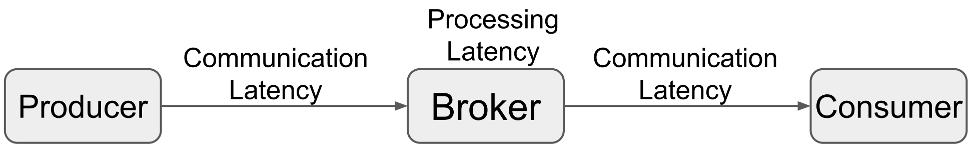
System entities for topic T



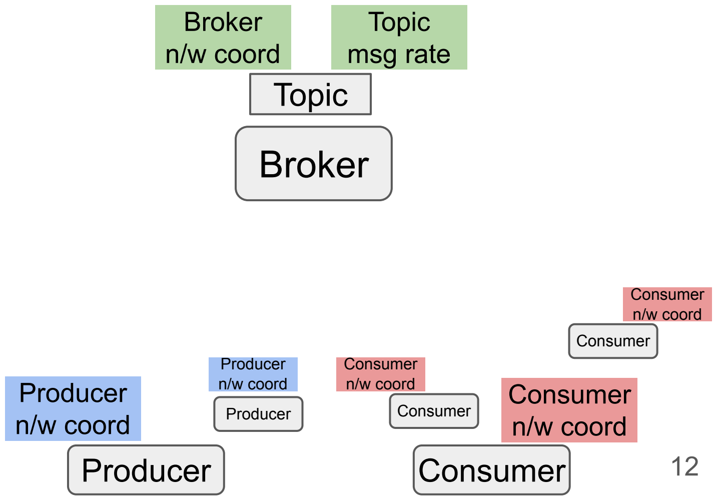
- Network Coordinate (NC) Agents

- Worst-case communication latency for topic
    - Using network coordinates

Network proximity for end-to-end latency calculation

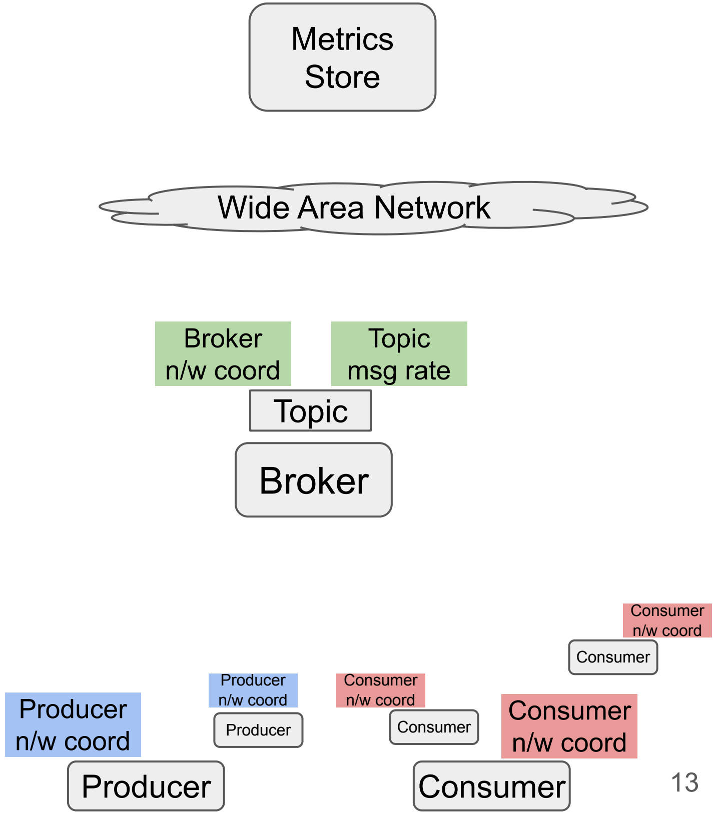


- Network Coordinate (NC) Agents
- Worst-case communication latency for topic
- End-to-end Pub-sub latency estimate
    - Violation Detection policy
    - Broker Selection policy



Distributed Monitoring in ePulsar

- Need all topics' metrics at Metrics Store
  - High monitoring traffic through WAN



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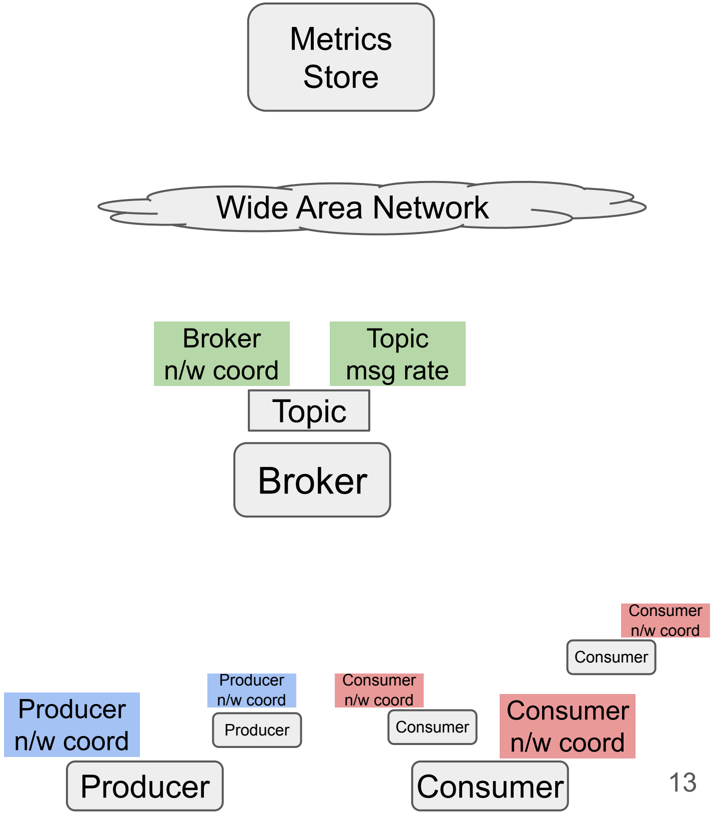
- Need all topics' metrics at Metrics Store
  - High monitoring traffic through WAN
- Distributed metric aggregation
  - Independently per topic



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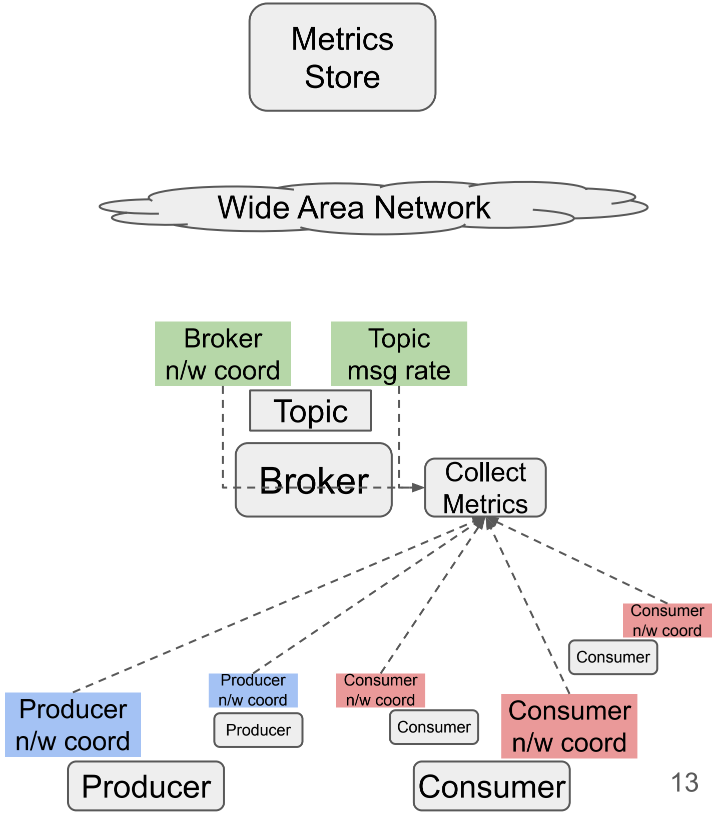

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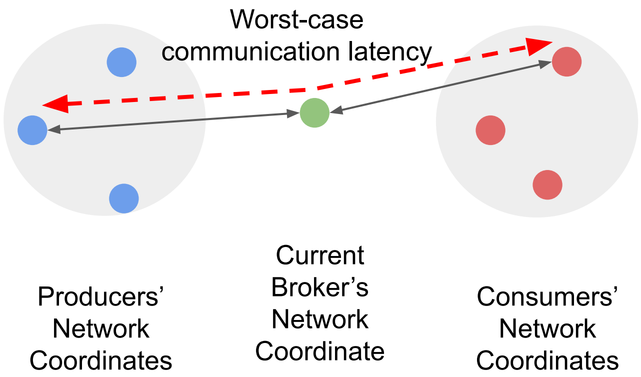

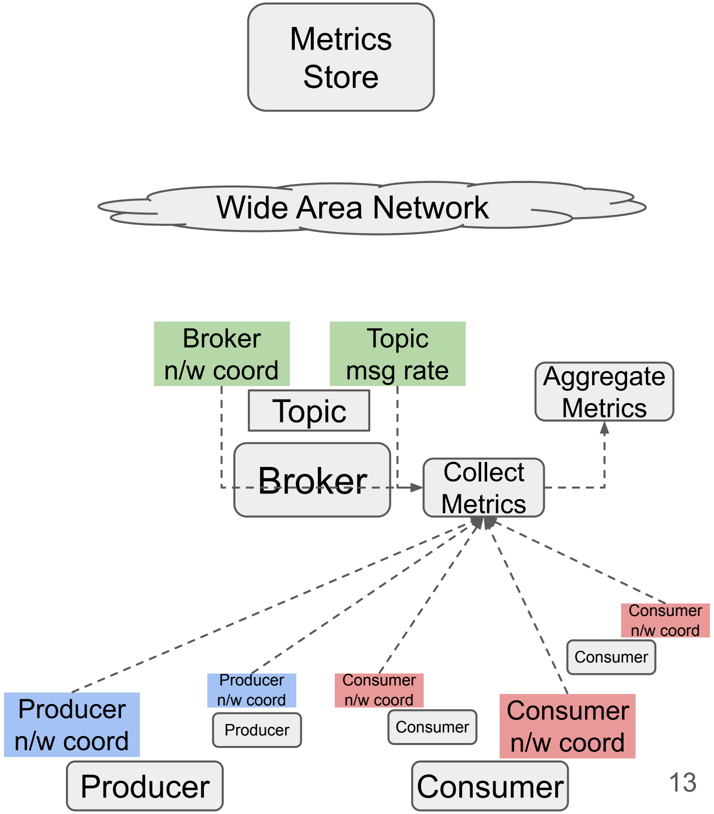

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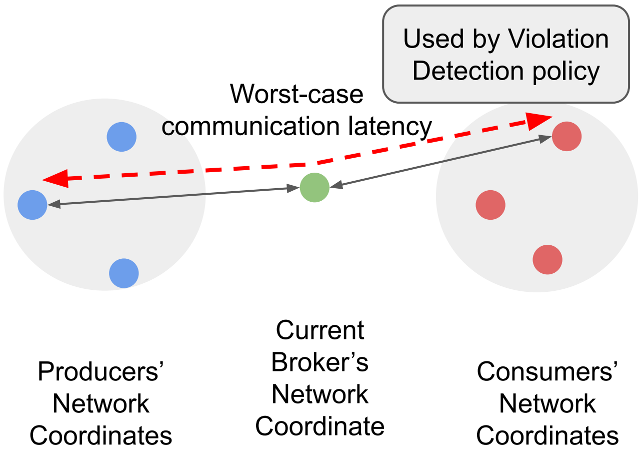

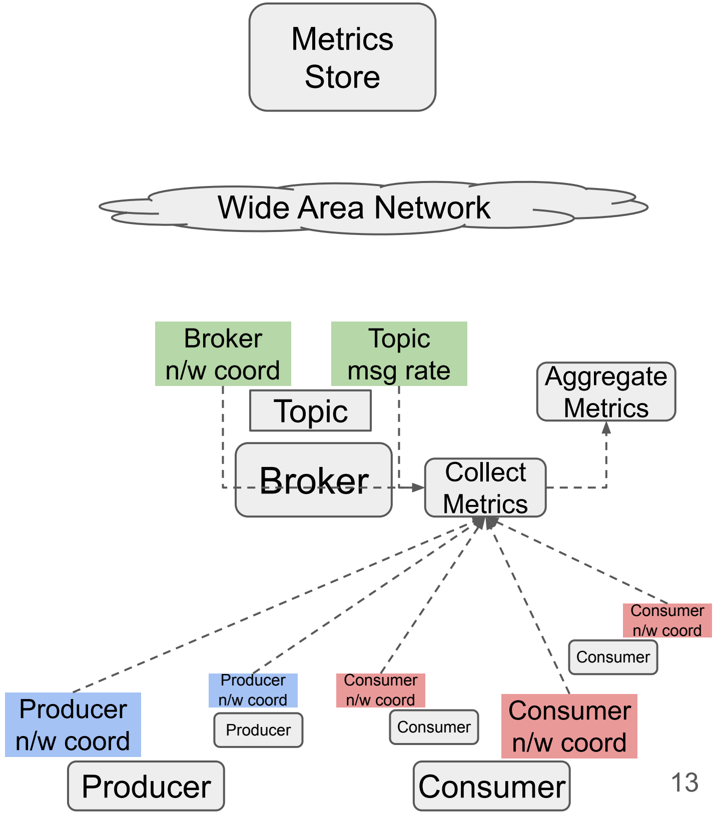

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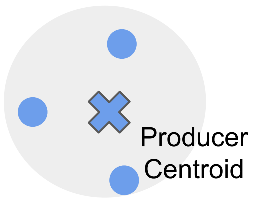
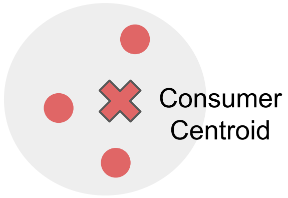
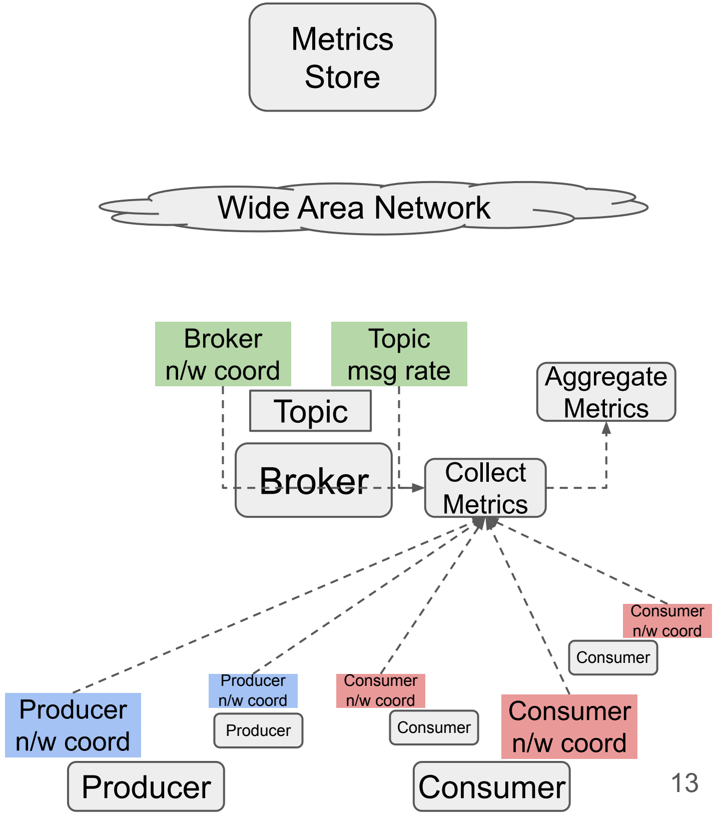
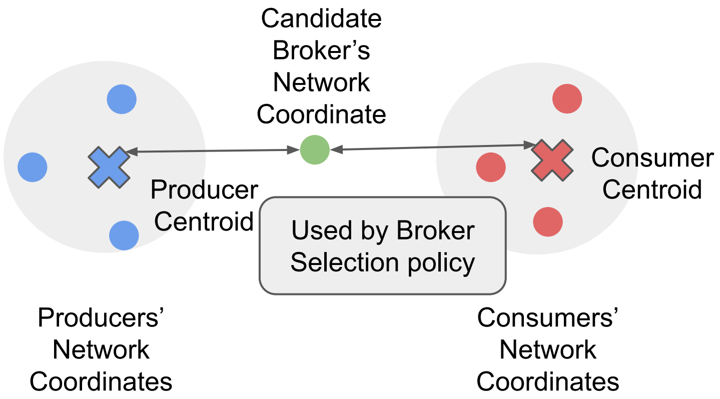
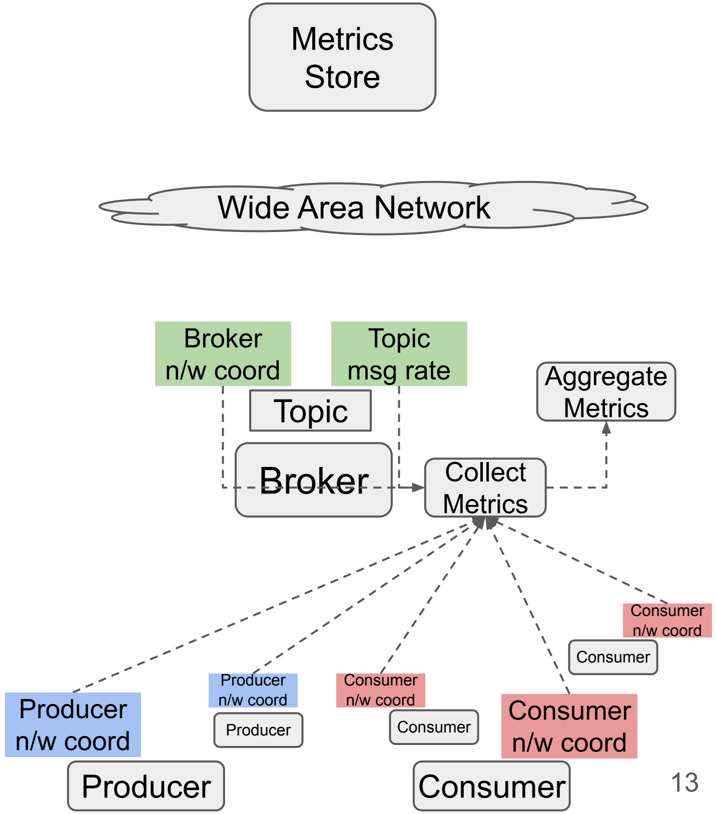






Distributed Monitoring in ePulsar





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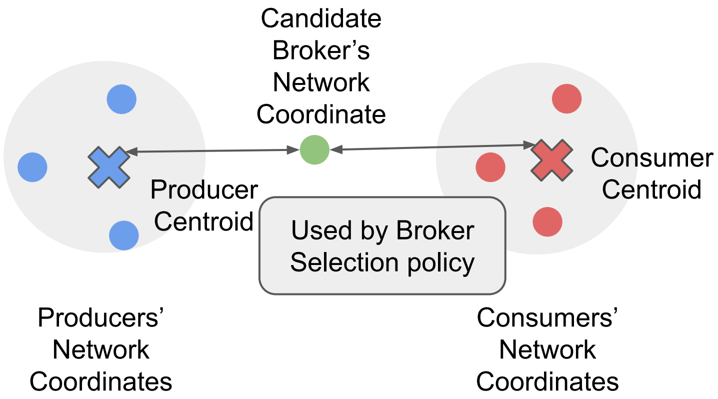
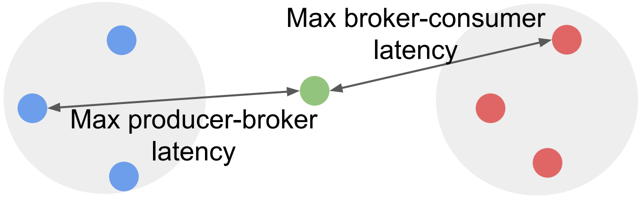
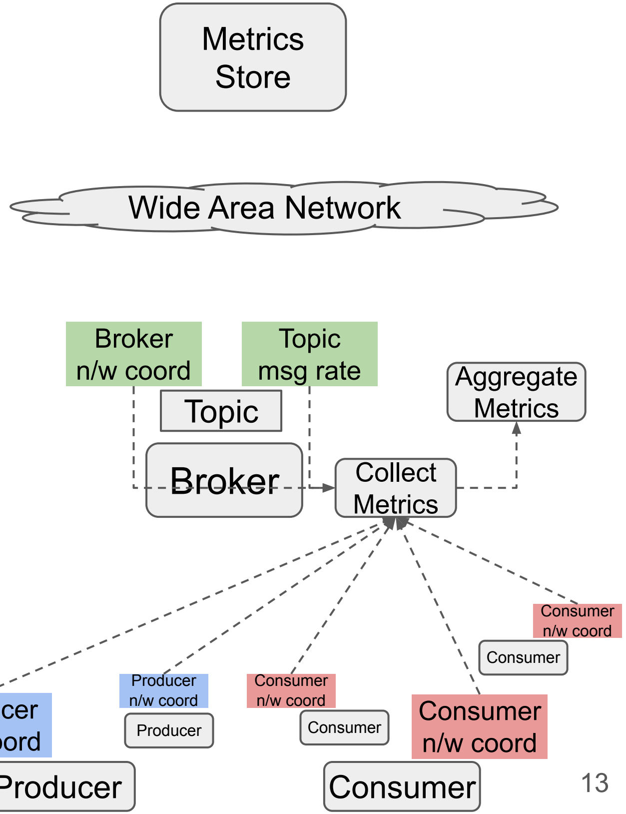


AllPairs Broker Selection policy





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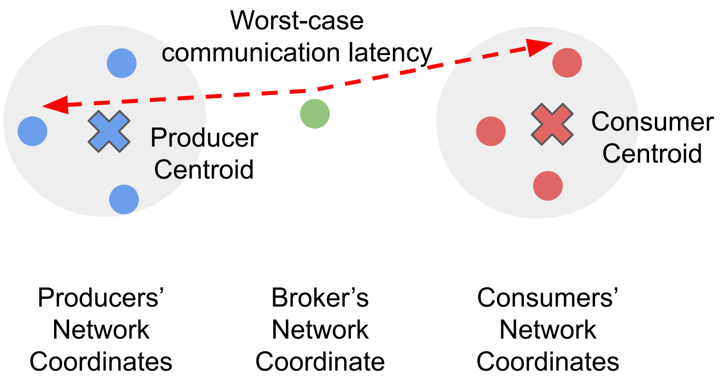
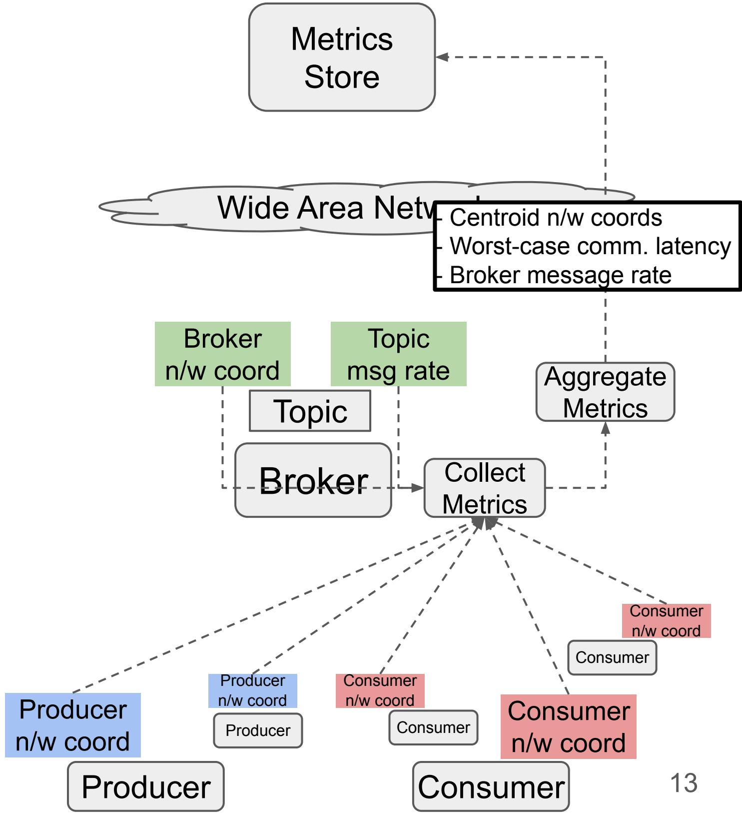
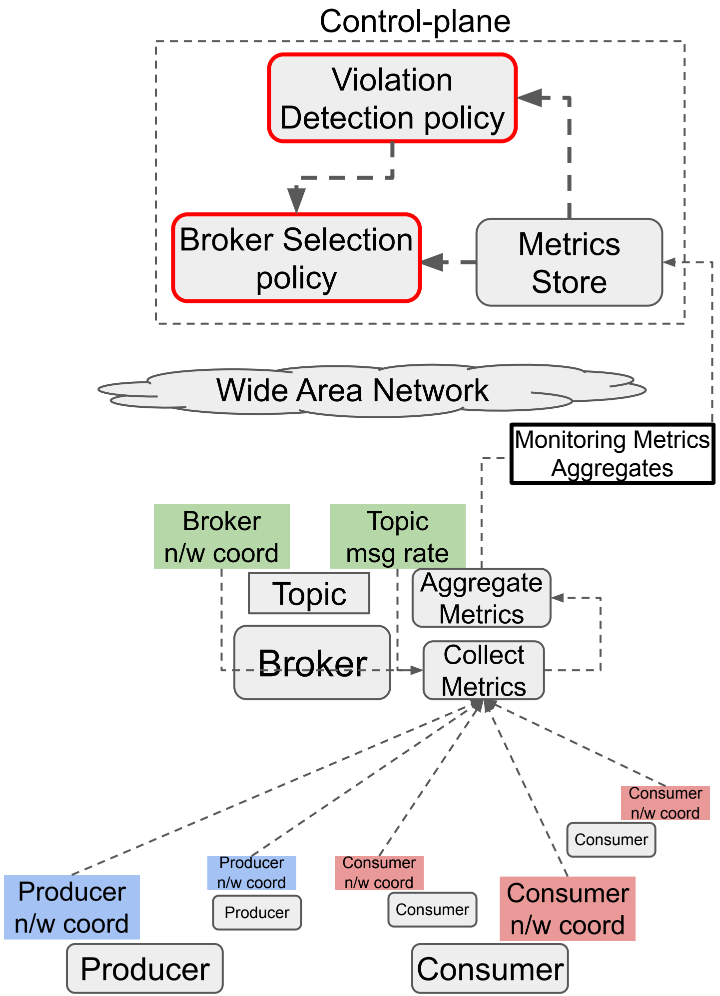




Putting it all together



Talk Outline

1. Background
2. Problem and Challenges
3. Design Principles of ePulsar
4. Architecture
    a. Network Proximity Estimation
    b. Distributed Monitoring
5. **Implementation**
6. Evaluations
7. Conclusion

Implementation of enhanced control-plane

- Apache Pulsar PULSAR
    - Edge-aware Load Manager module
        - Broker Selection Policy
        - Violation Detection Policy
    - Per-topic monitoring and placement → no bundling of topics
    - ZooKeeper as Metrics Store (as in vanilla Pulsar)

Image source: https://dev.to/alvsanand/life-beyond-kafka-with-apache-pulsar-3mcg

Implementation of enhanced control-plane

- Apache Pulsar
- Serf as Network Coordinate Agent

Image source: https://www.serf.io/

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Evaluations

Hypotheses being evaluated

1. Network Coordinates protocol has low error and resource overheads.

2. ePulsar’s Broker Selection satisfies end-to-end latency constraint.

3. ePulsar’s Distributed Monitoring reduces monitoring overhead with increasing scale.

4. ePulsar is able to dynamically detect and mitigate latency violations.

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- Emulated clients and edge topology
  - Containernet (Open vSwitch + Docker)
  - Linux Traffic Control (*tc*) for synthetic latency

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- Workload
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    - Massively Multiplayer Online Gaming

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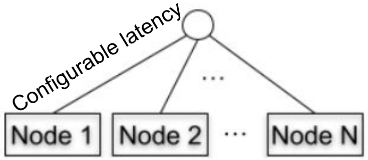
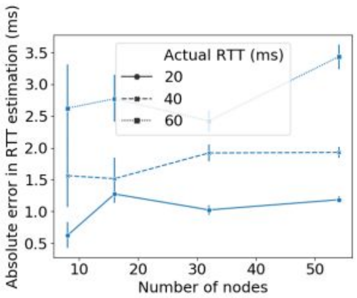
Evaluation of network coordinates for measuring proximity

- Low error in RTT estimation < 3.5ms
- Low CPU and memory overhead
  - < 1% CPU util on AMD EPYC 7501
  - < 15 MB memory usage



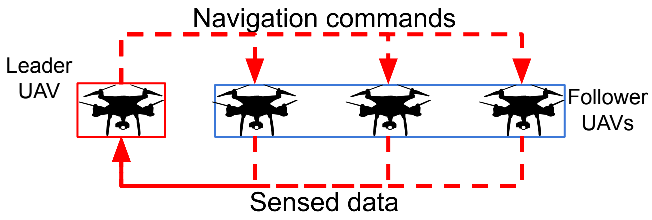
(a) NC Cluster Topology.

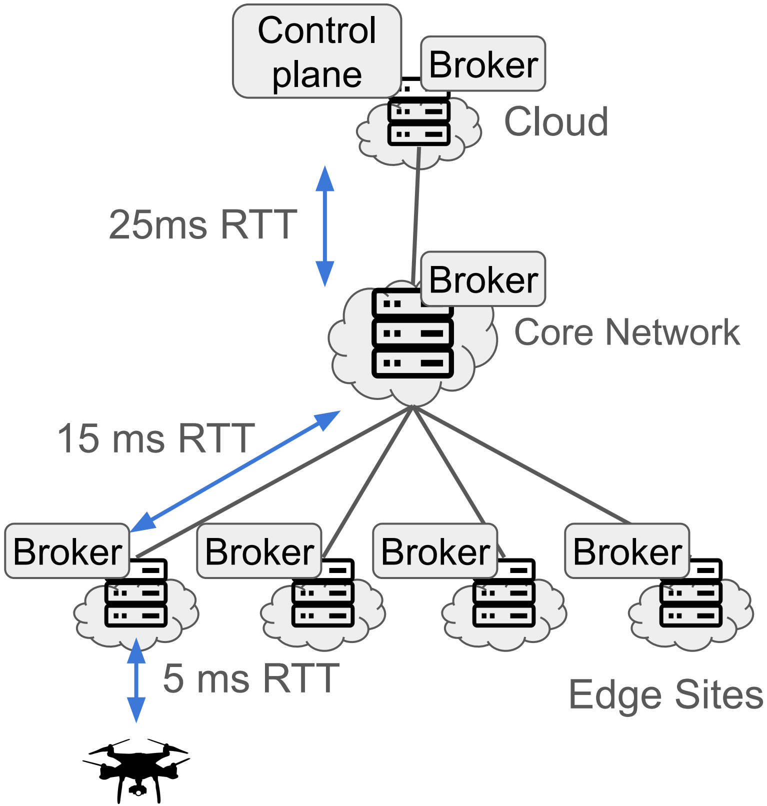


(b) RTT estimation error.

Evaluation of UAV Swarm scenario

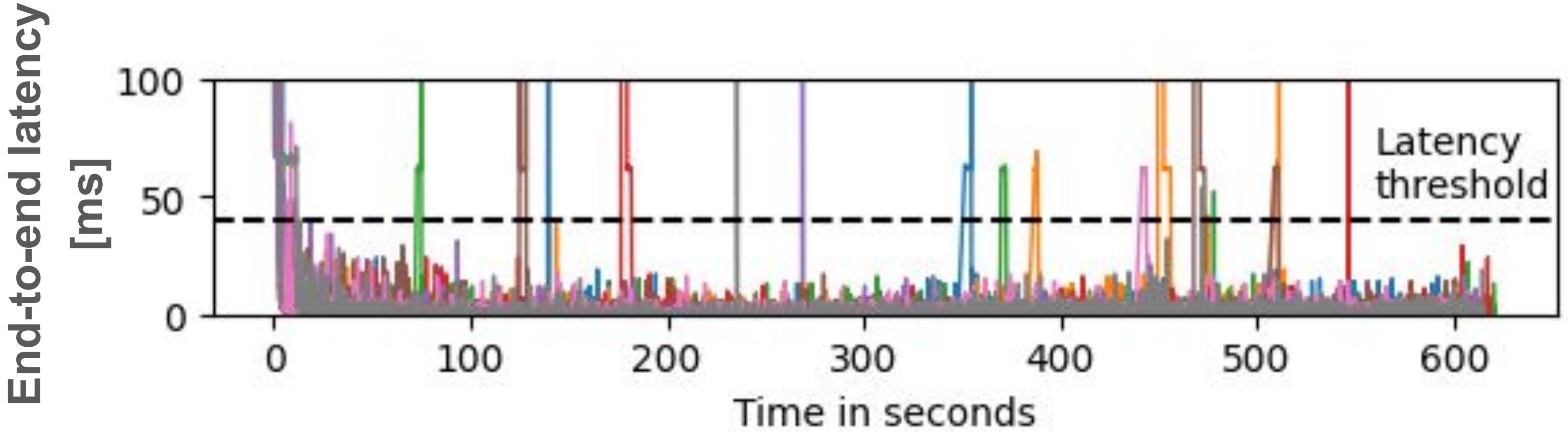
UAV Swarm Coordination application





Dynamic violation detection and topic migration

- 16 drone swarms - each with 8 drones
- Random Waypoint mobility model in a city with 8 edge sites



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Conclusion

- Control-plane architecture for geo-distributed publish-subscribe system
- Ensures end-to-end publish-subscribe latency
- Latency-aware broker selection and topic migration
- Network Proximity Estimation
- Distributed Monitoring

Conclusion

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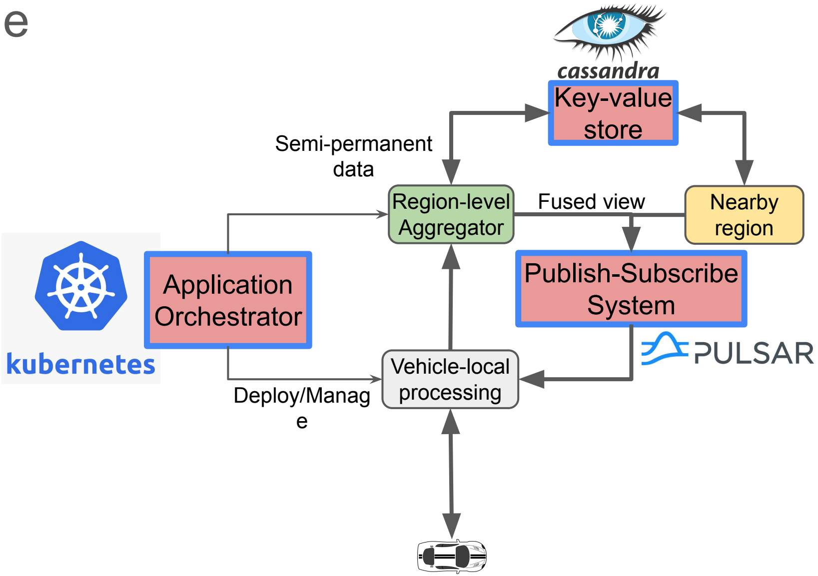
Check out the paper for

- Optimizations for agile reconfigurations
- Support for persistent topics
- Evaluation of MMOG application scenario

Future Work

- Decentralize publish-subscribe control-plane (Desousis et al. ICDCS 2018)
- Enable other edge-ready platform services
  - Network Proximity Estimation and Distributed Monitoring as independent services



Dedousis, Dimitris, Nikos Zacheilas, and Vana Kalogeraki. "On the fly load balancing to address hot topics in topic-based pub/sub systems." 2018 IEEE 38th International Conference on Distributed Computing Systems (ICDCS). IEEE, 2018.

Thank you!

ePulsar

- Control-plane architecture for geo-distributed publish-subscribe system
- Ensures end-to-end publish-subscribe latency
- Latency-aware broker selection and topic migration
- Network Proximity Estimation
- Distributed Monitoring

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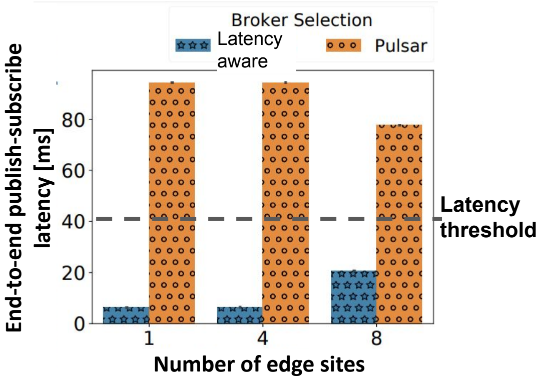
Backup Slides

Limitations of state-of-the-art in geo-distributed pub-subs

- Off-the-shelf Cloud-based pub-subs on the Edge
  - E.g., Apache Pulsar, Apache Kafka
  - Focus on even workload distribution, not end-to-end latency
  - Don’t consider high client-edge communication latencies



Comparing end-to-end publish-subscribe latency of off-the-shelf Apache Pulsar running on the Edge vs. a topology-aware approach.

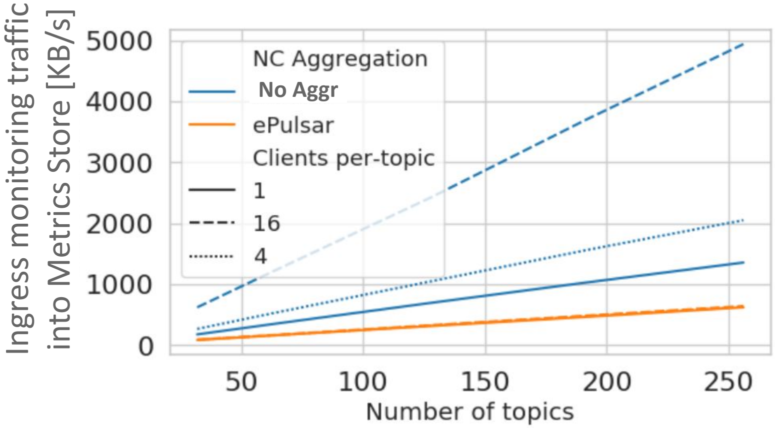
- Pub-subs designed for the Edge
  - E.g., EMMA [1], MultiPub [2]
  - Active measurements for topology awareness [1]
    ⇒ High monitoring overhead
  - Require latency between each client-broker pair [2]
    ⇒ Scales poorly

[1] Rausch, Thomas, Stefan Nastic, and Schahram Dustdar. "Emma: Distributed qos-aware mqtt middleware for edge computing applications." 2018 IEEE International Conference on Cloud Engineering (IC2E). IEEE, 2018.
[2] Gascon-Samson, Julien, Jörg Kienzle, and Bettina Kemme. "Multipub: Latency and cost-aware global-scale cloud publish/subscribe." 2017 IEEE 37th International Conference on Distributed Computing Systems (ICDCS). IEEE, 2017.

Distributed Monitoring: monitoring traffic analysis

- **ePulsar** vs. **NoAggr**

- ePulsar: Lower monitoring overhead
  - With increasing scale of workload



Broker selection policy with network proximity awareness

- Systems compared
  - **Pulsar**: No network proximity awareness
  - **NoAggr**: Same as ePulsar (w/o network coord. aggr.)
- Metric: per-topic worst-case publish-subscribe latency
  - Across producer-consumer pairs
- 16 UAV swarms
  - Each with 8 drones
- Drones in a swarm move together
  - Randomized swarm locations