Smart Distributed Sensing in Adaptive Wireless Networks

Disputation

Jonas Höchst | October 11, 2022

1

Introduction

Trends in Technology

Ubiquity of Sensor Data

Machine Learning

Reconfigurability of Adaptive Networks

Problem Statement

Improve quality of algorithms, protocols, and applications using different kinds of sensor data and sources.

Sensing

Adaptive Networks

Transitions

Structure

1. Introduction
2. Fundamentals
3. Categorizing Smart Systems
4. Smart Environmental Monitoring
5. Smart Adaptive Disruption-tolerant Networking
6. Smart Transitional Wireless Networking
7. Conclusion

2

Fundamentals

Smart Distributed Sensing

Smart distributed sensing is the combination of a number of autonomously operating devices and sensors that perform a sensing task in a coordinated manner.

[Thesis]

Adaptive Wireless Networks

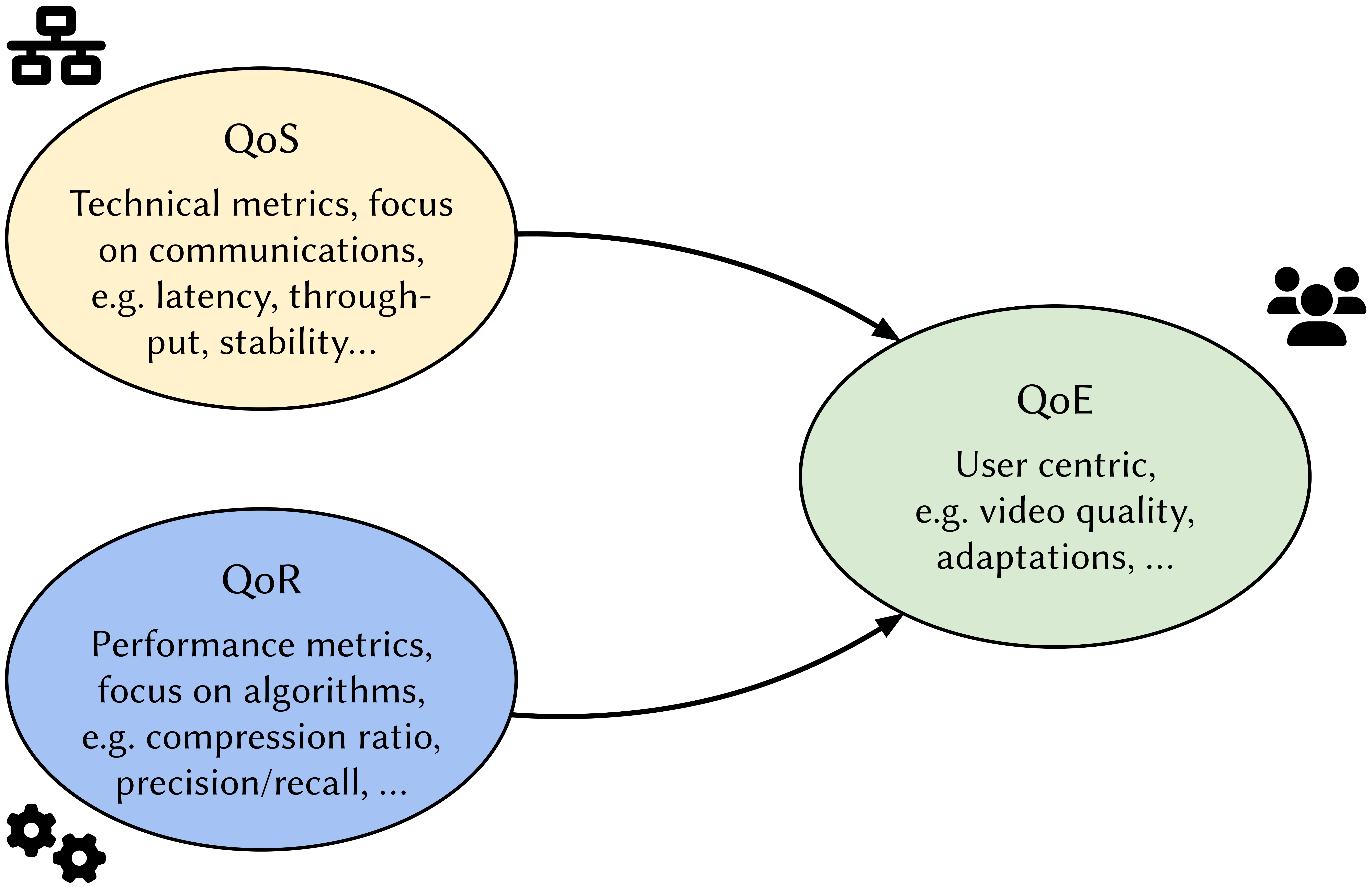
Adaptive wireless networks describes networks that adapt by means of conventional adaptation within specific mechanisms or protocols or by means of mechanism transitions.

[Thesis]

3

Categorizing Smart Systems

Quality of Service / Result / Experience



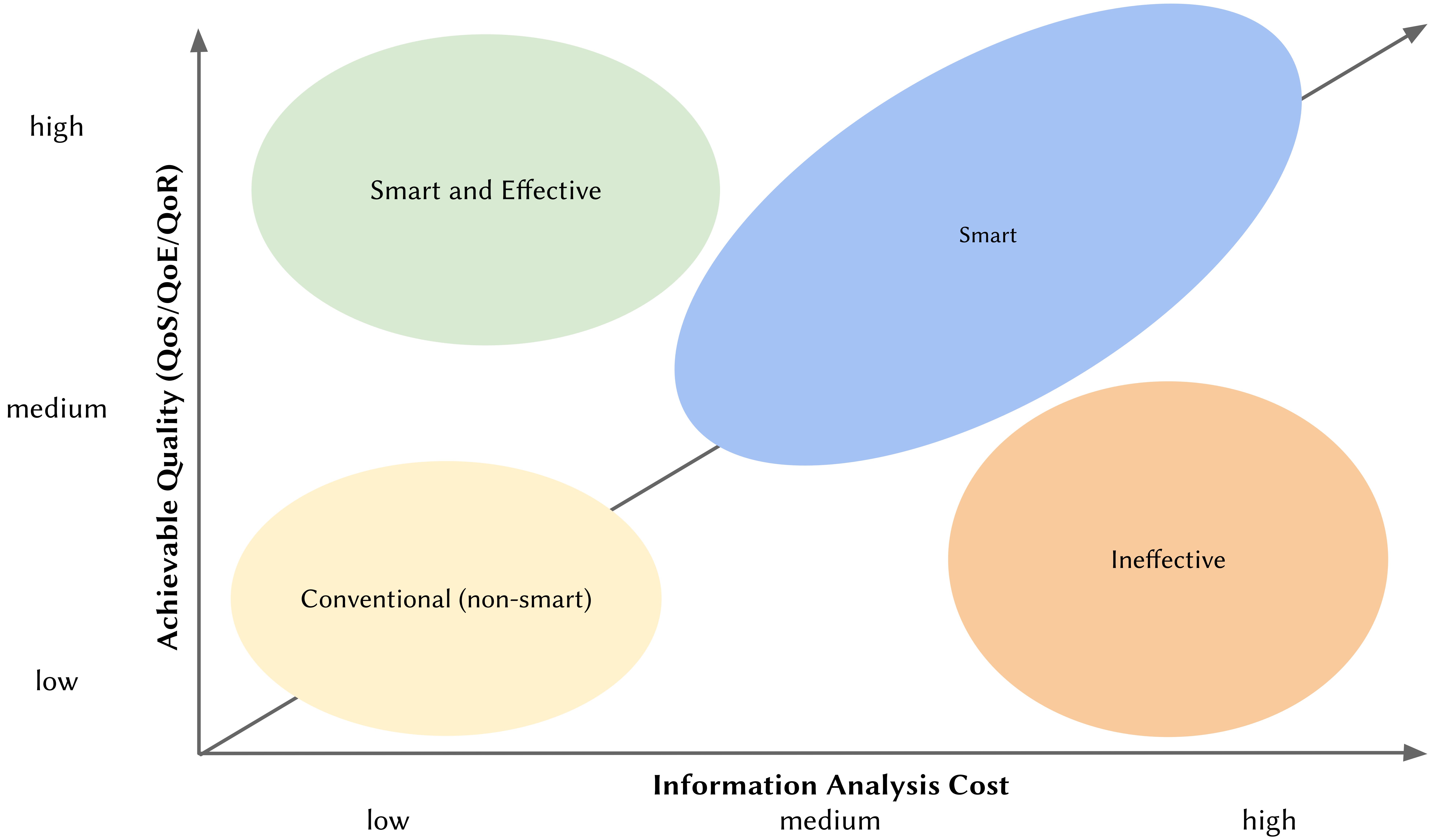
Information Analysis Cost

Computation

Storage

Communication

Categorizing Smart Systems



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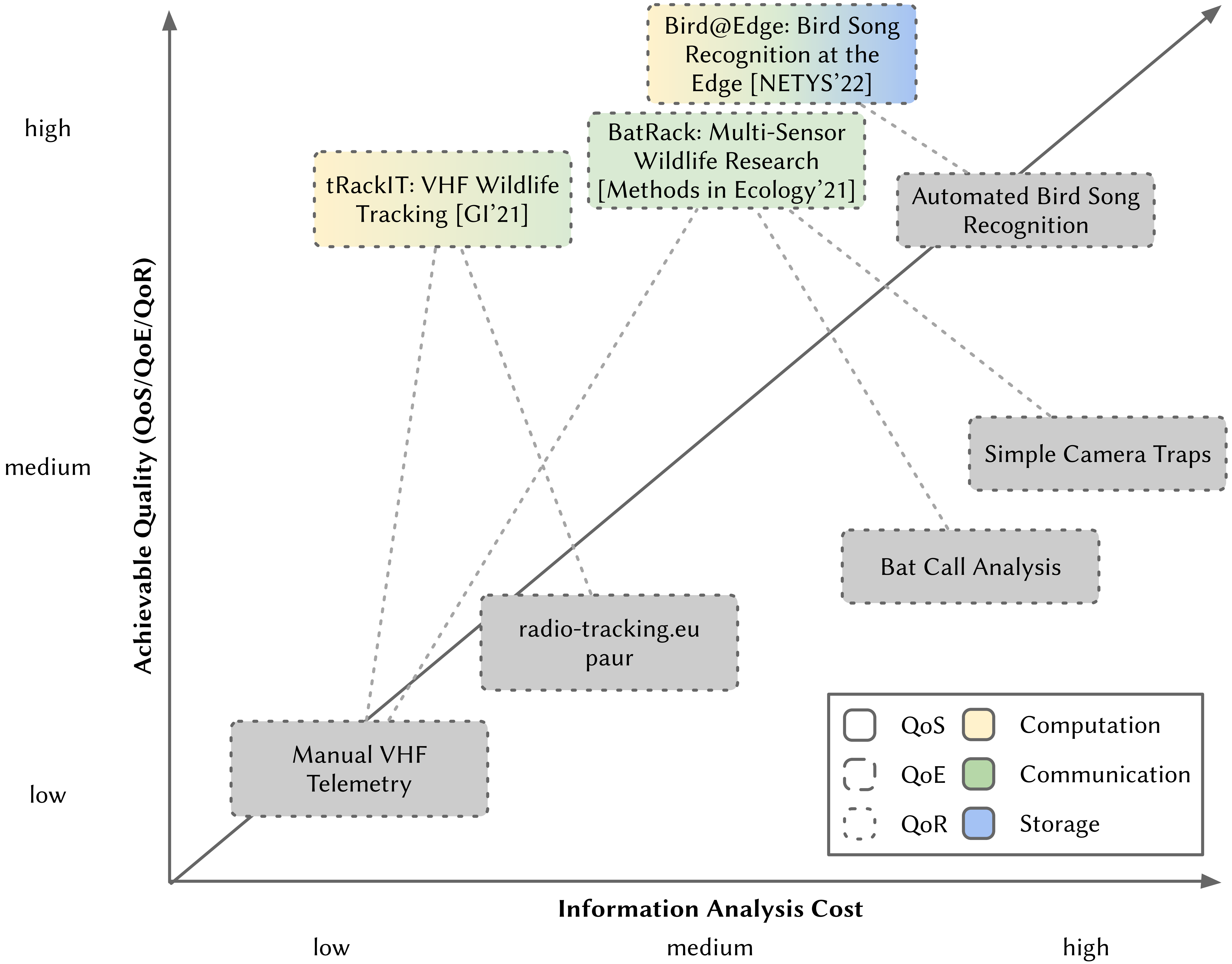
Smart Environmental Monitoring

Environmental Monitoring: Cost / Quality

Goal: Improve methodology, i.e., Quality of Result using smart distributed sensing:

- BatRack: VHF, ultrasonic audio, and video for direct observation
- Bird@Edge: Real-time biodiversity monitoring in soundscapes
- **tRackIT OS: Fine-grained VHF localization of small animals**



GI Informatik 2021

tRackIT OS

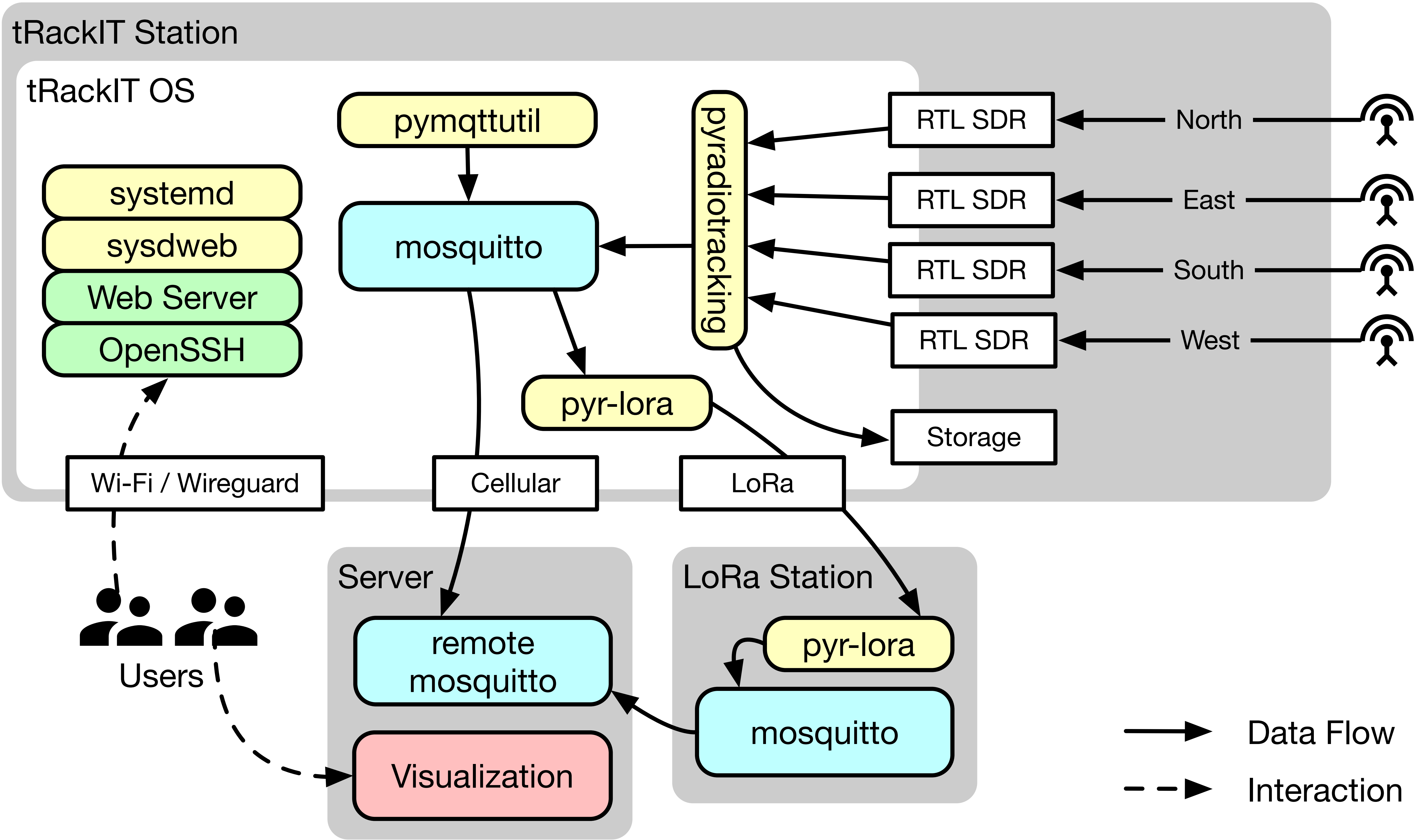
Open-source Software for Reliable VHF Wildlife Tracking

- Motivation: Scientific analysis of the consequences of human-wildlife interaction
- Goal: Spatial observation of small animals, in particular bats
- Alternatives:
  - GPS tags: Not suitable for small animals
  - Manual radio telemetry: Est. in 1970s, labour intensive
  - Specialized installations: Expensive, bad availability
- Requirements:

Low Entry Barrier **High Reliability** **Fast Data Availability**

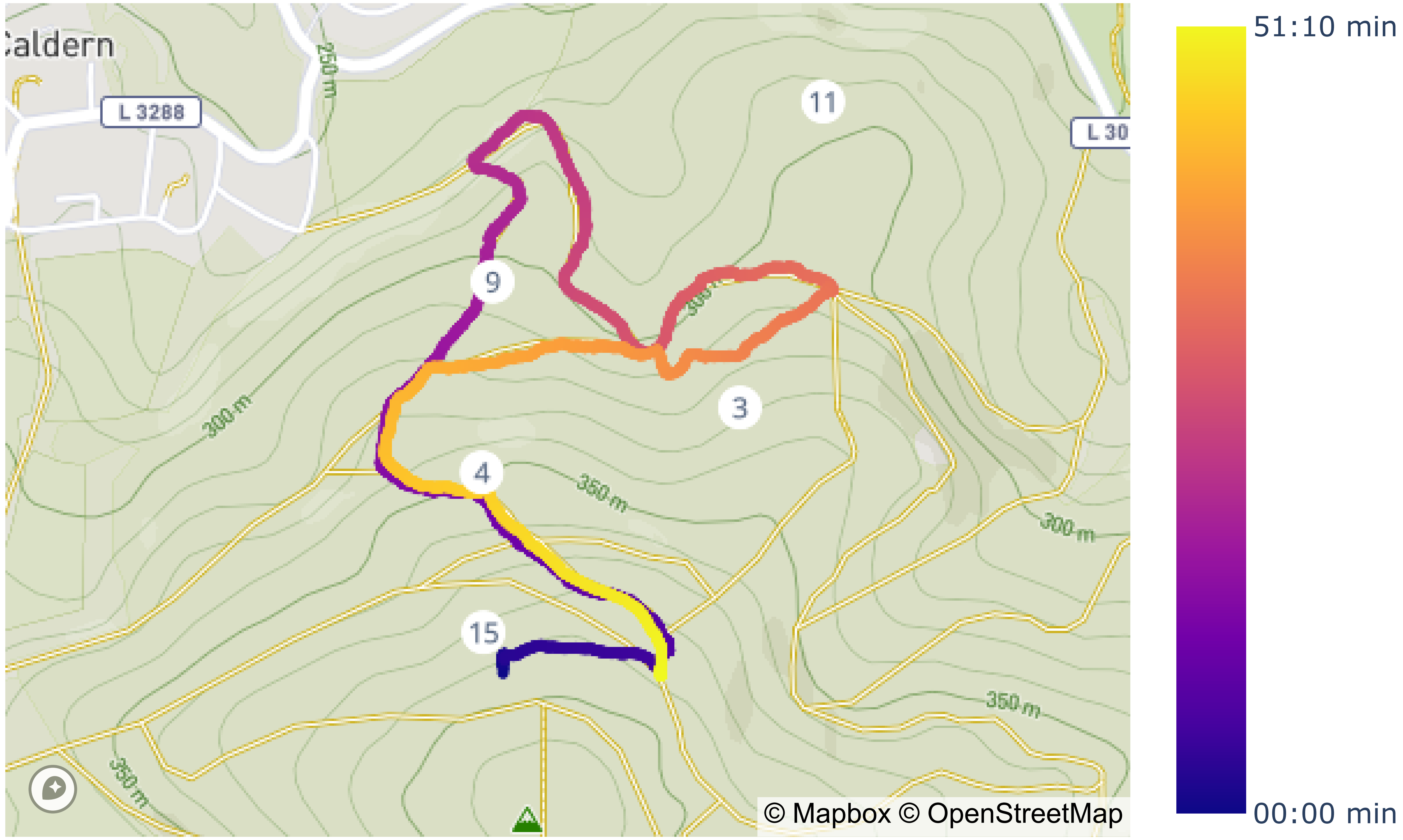
tRackIT OS
Proposed Software Solution

- Open source components where possible
- Custom developments when required, i.e. *pyradiotracking*
- Web-based configuration and monitoring
- Data processing on device
- Self monitoring to cope with harsh conditions



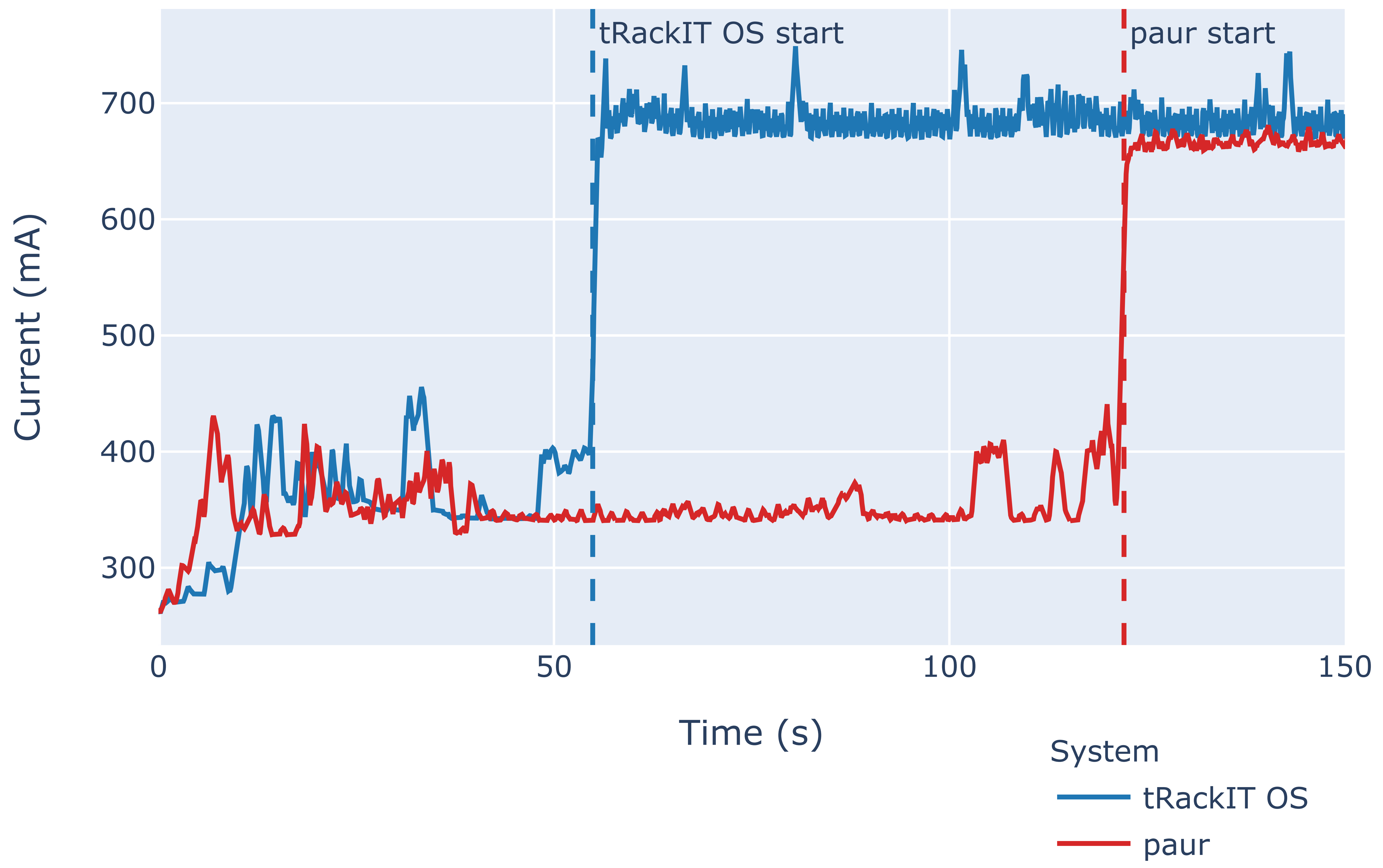
tRackIT OS
Quality of Result

- 51 minute track with 600µW test tag on 5 stations carried out with
  a) *tRackIT OS* 0.7.0
  b) *paur* 4.2 (radio-tracking.eu)
- No delay in signal reception; elimination of manual filtering
- 1,525 signals detected per station on average; **+103.3%**
- Reduction in bearing error from 38.9° *(paur)* to 23.7°; **-39.1%**



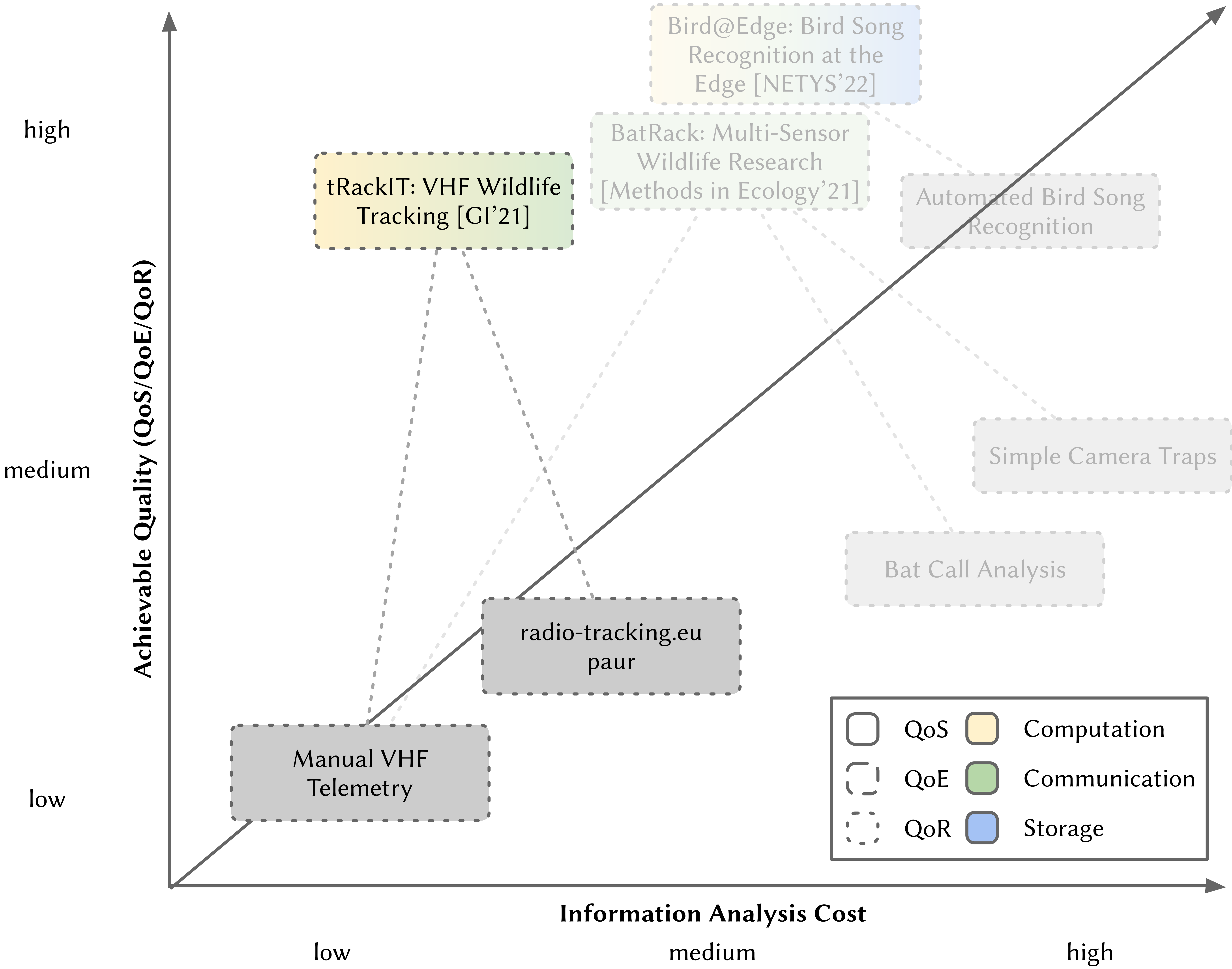
tRackIT OS
Information Analysis Cost

- Additional power overhead
  paur: 8.03 W
  tRackIT OS: 8.23 W + 2.55%
- Runtime of 5.5 days on 12 V batteries of 120 Ah, usage of 300 watts solar panel
- Additional cost: Filtering of falsely detected signals in *paur*



tRackIT OS
Cost / Quality

- Manual VHF telemetry: High manual effort, low(er) information analysis cost
- *paur:* High information analysis cost in latter signal filtering; less detected signals with higher mean error.
- *tRackIT OS:* Low information analysis cost; high QoR. -> Smart solution



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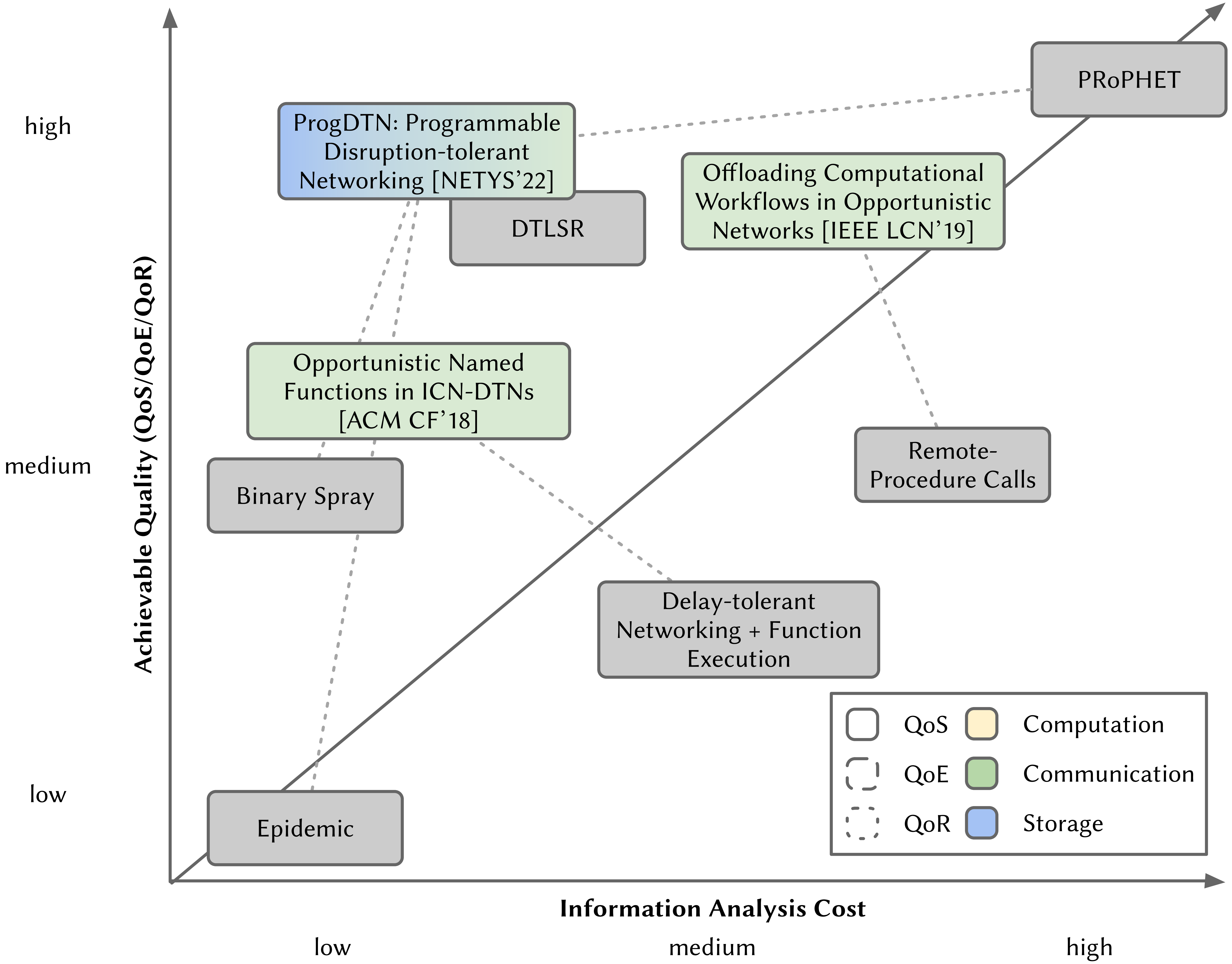
Smart Adaptive Disruption-tolerant Networking

Smart Adaptive Disruption-tolerant Networking: Cost / Quality

Goal: Improve Quality of Service, i.e., delay, bandwidth, …:

- ONF in ICN-DTNs: Opportunistic execution of functions based on interests
- OPPLOAD: Offloading workflows to network nodes based on capabilities
- **ProgDTN: Programmable DTN router using shared context information**



ProgDTN

Programmable Disruption-tolerant Networking

- Motivation: Use benefits of softwarization in DTNs
- Goal: Improve QoS while reducing overheads using scenario-specific routing
- Alternatives:
  - Generic DTN routing algorithms,
    i.e., Epidemic Routing, Spray-and-Wait, DTLSR, …
  - Routing algorithms designed for specific scenarios,
    i.e., PRoPHET, Context-Aware Adaptive Routing (CAR), Sensor CAR (SCAR), Context-Aware Community Based Routing (CACBR), …

ProgDTN
Design & Implementation

- System Requirements:

Operator-configurable Routing Algorithm

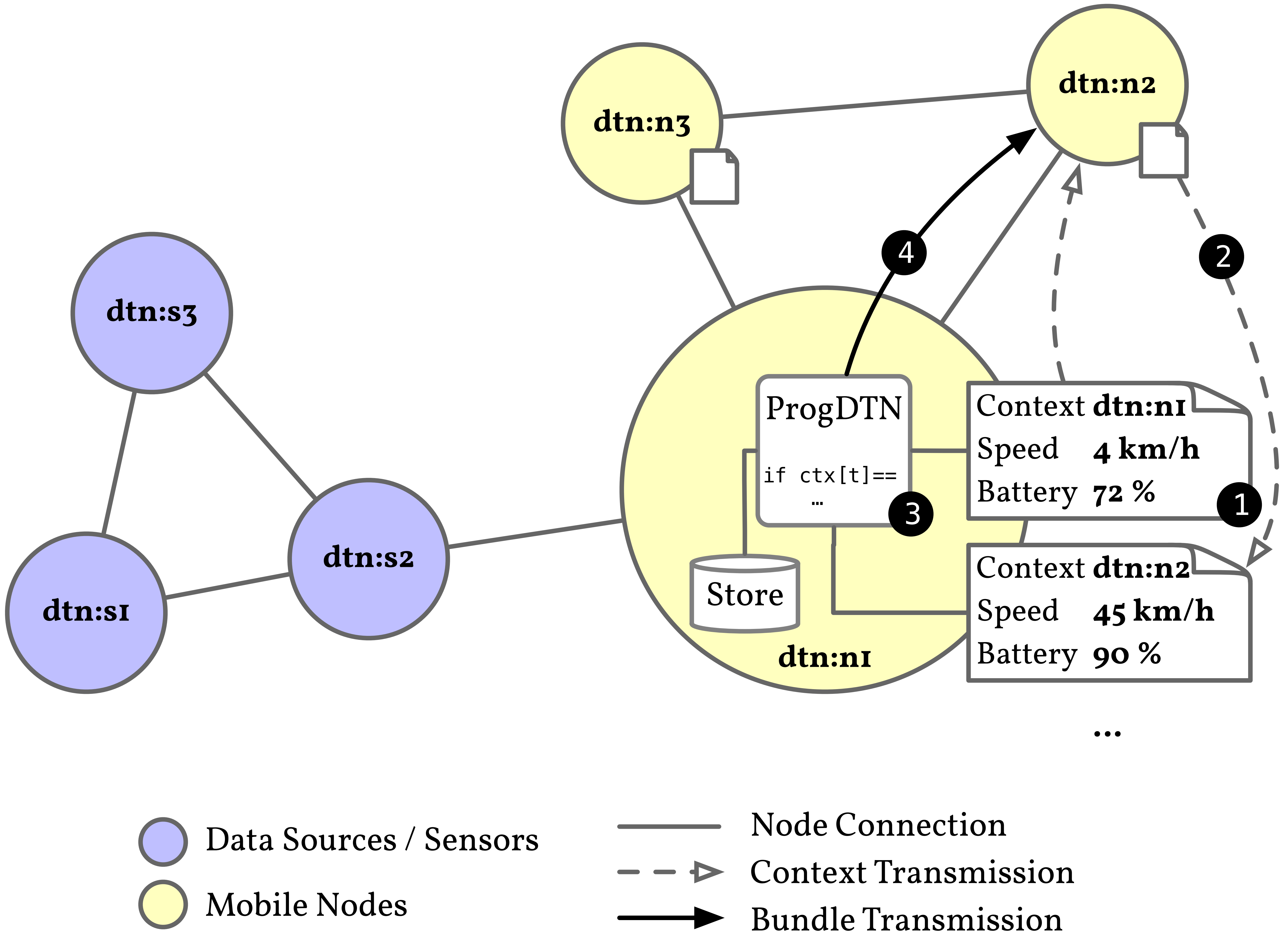
Use Arbitrary Context Information

No modification of DTN Software

- Implementation decisions: *dtn7-go*, *JavaScript* routing algorithms, *JSON* context
- Context information per *Node* and per *Bundle*

ProgDTN
Context Routing Processing

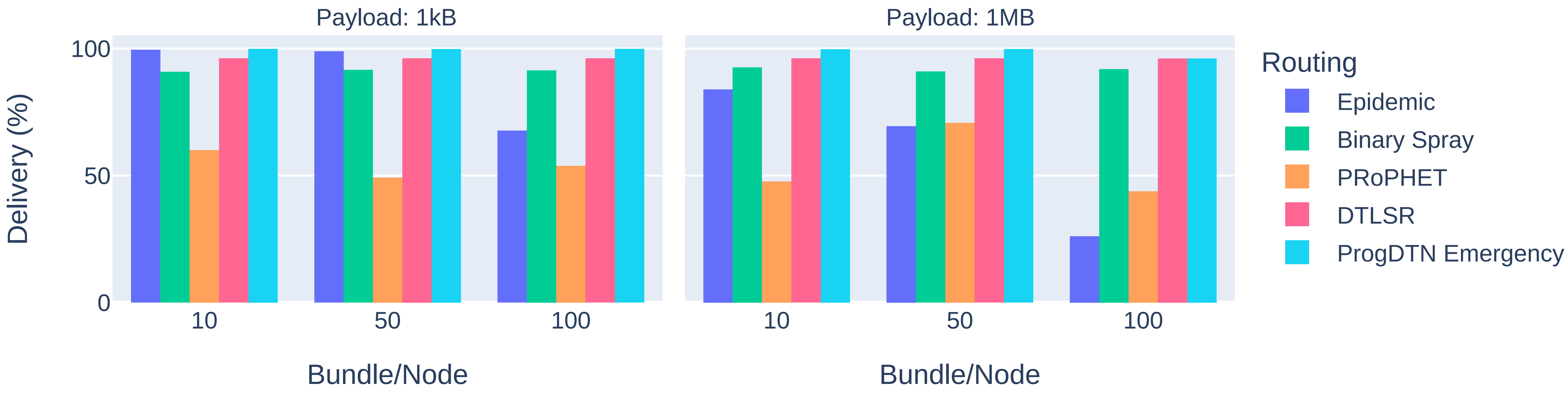
1. Local node context generation
2. Remote node contexts
3. Routing script execution
4. List of selected peers



ProgDTN
Evaluation Setup

- Common Open Research Emulator (CORE)
- Disaster scenario with 31 nodes of 3 types (civilian, responder, coordinator)
- Custom routing algorithm matching the scenario
- Five routing approaches
  - Epidemic
  - Binary Spray
  - PRoPHET
  - DTLSR
  - ProgDTN Emergency
- 210 experimental configurations each running 1 hour

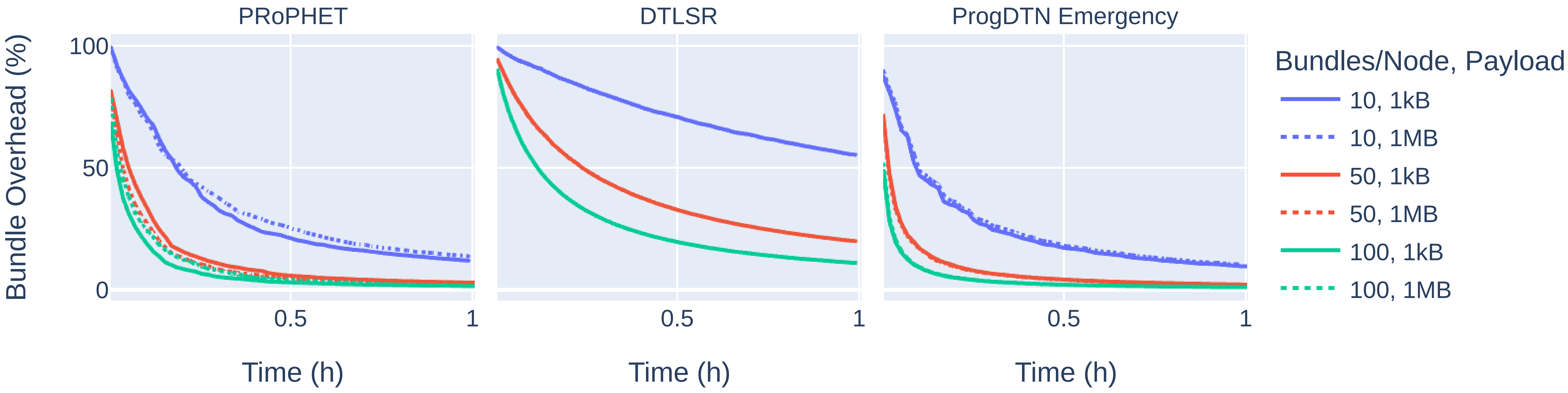
ProgDTN
Quality of Service: Delivery Ratio



- ProgDTN Emergency is equal or better compared to other routing approaches.
- Delivery ratio of 99.8% in all scenarios

ProgDTN

Information Analysis Cost: Bundle Overhead



- Comparatively high overhead in DTLSR, ~15 - 50% after full experiment runtime
- Rapid decay in PRoPHET and ProgDTN Emergency

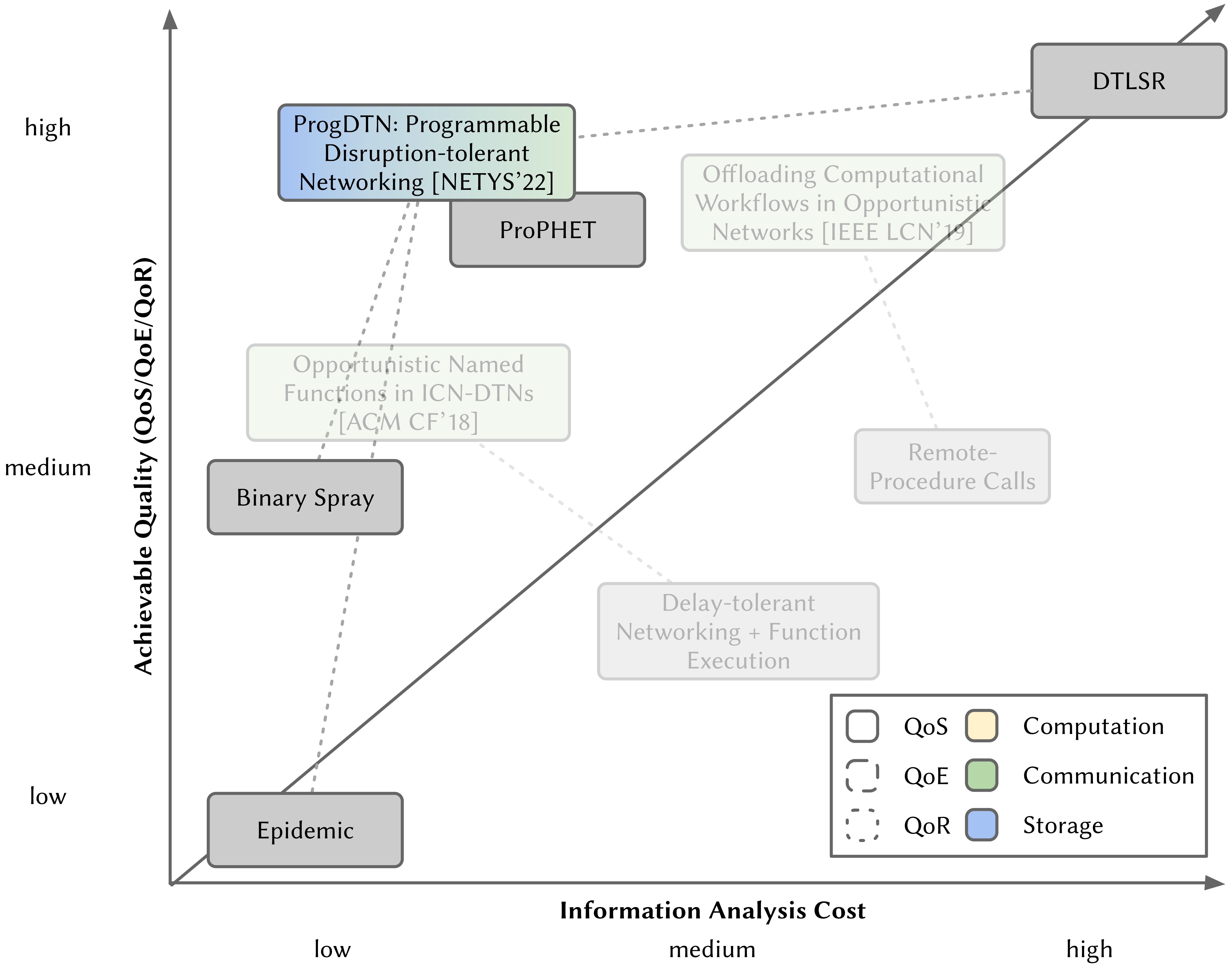
ProgDTN
Quality Improvement vs. Information Analysis Cost

	Delivery Rate	QoS Delivery Rate	Median Delivery Time (ms)	QoS Delivery Times	Overall QoS	Bundle Overhead
Epidemic	69.46 %	1.00	3.18	1.00	1.00	0
Binary Spray	90.98 %	1.31	1.30	2.45	1.88	0
PRoPHET	70.77 %	1.02	0.72	4.42	2.72	2.35
DTLSR	96.15 %	1.38	0.62	5.13	3.26	19.94
ProgDTN	99.8 %	1.44	0.75	4.24	2.84	2.11

- ProgDTN Emergency is able to reach best delivery rates in good delivery times introducing only small overheads.
- Improvements achieved by using context information and scenario specific routing.

ProgDTN
Cost / Quality

- Epidemic Routing: Baseline
- Binary Spray: Higher delivery rate, no additional cost
- PRoPHET: Higher bundle overheads, lower QoS
- DTLSR: Highest QoS due to minimal delivery time, heavy overhead
- ProgDTN: Smart and efficient solution due usage of context.



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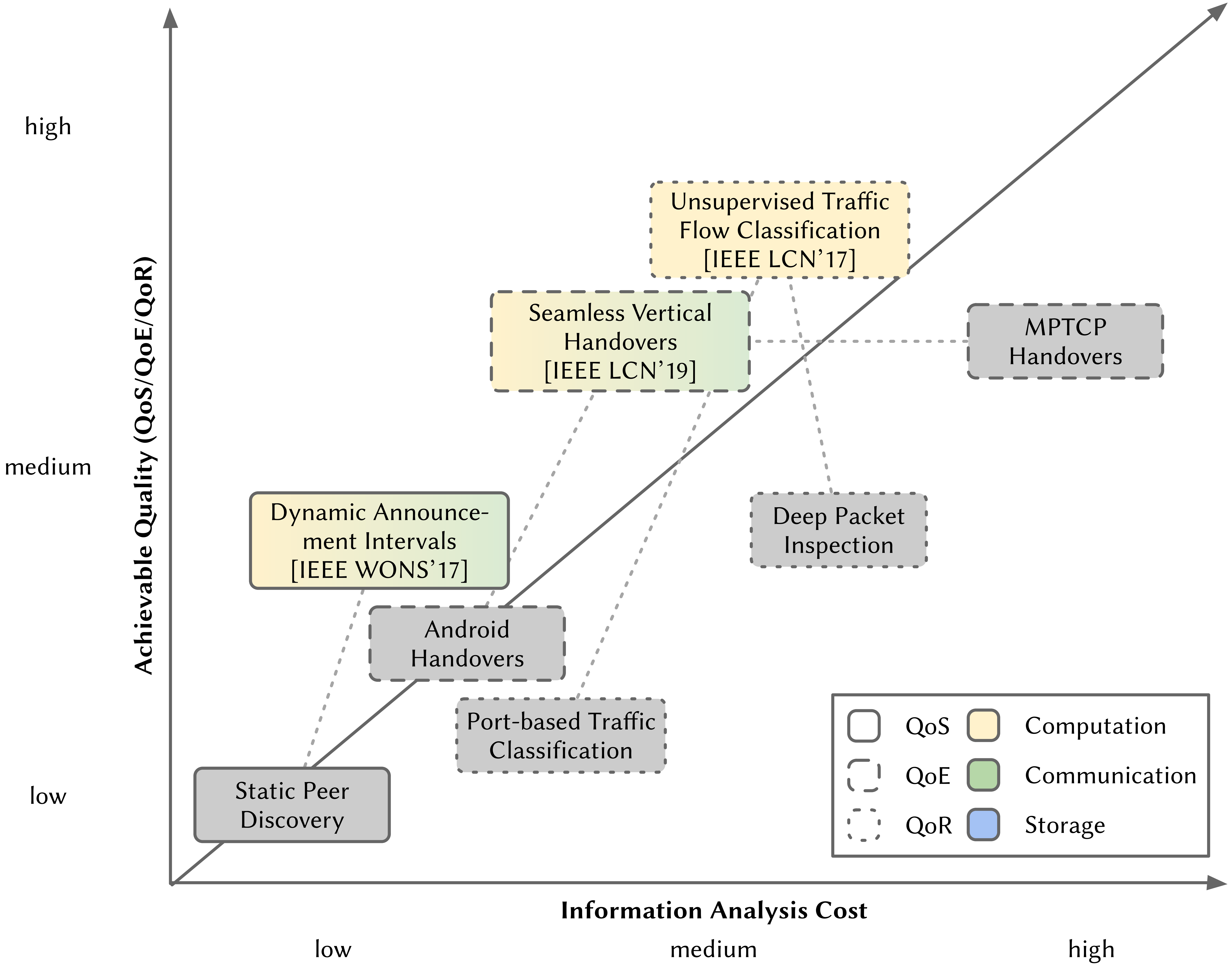
Smart Transitional Wireless Networking

Smart Transitional Wireless Networking: Cost / Quality

Goal: Quality Improvements, i.e., delay, bandwidth, …:

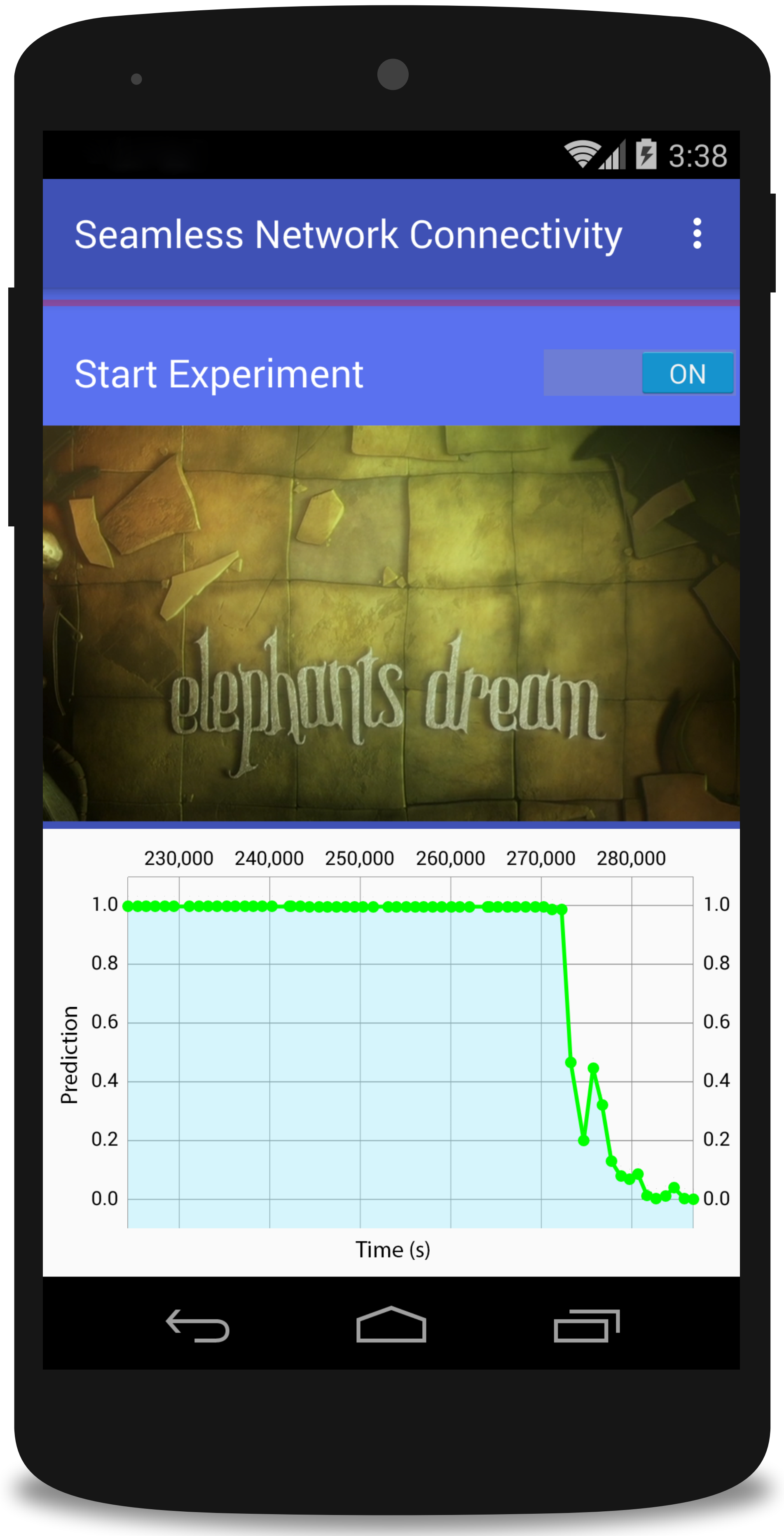
- Traffic flow classification: Data-driven decision basis
- Dynamic announcements: Efficient service discovery for adaptive networks
- **Seamless vertical handovers: Learn and predict WiFi connection loss from heterogeneous sensor data**



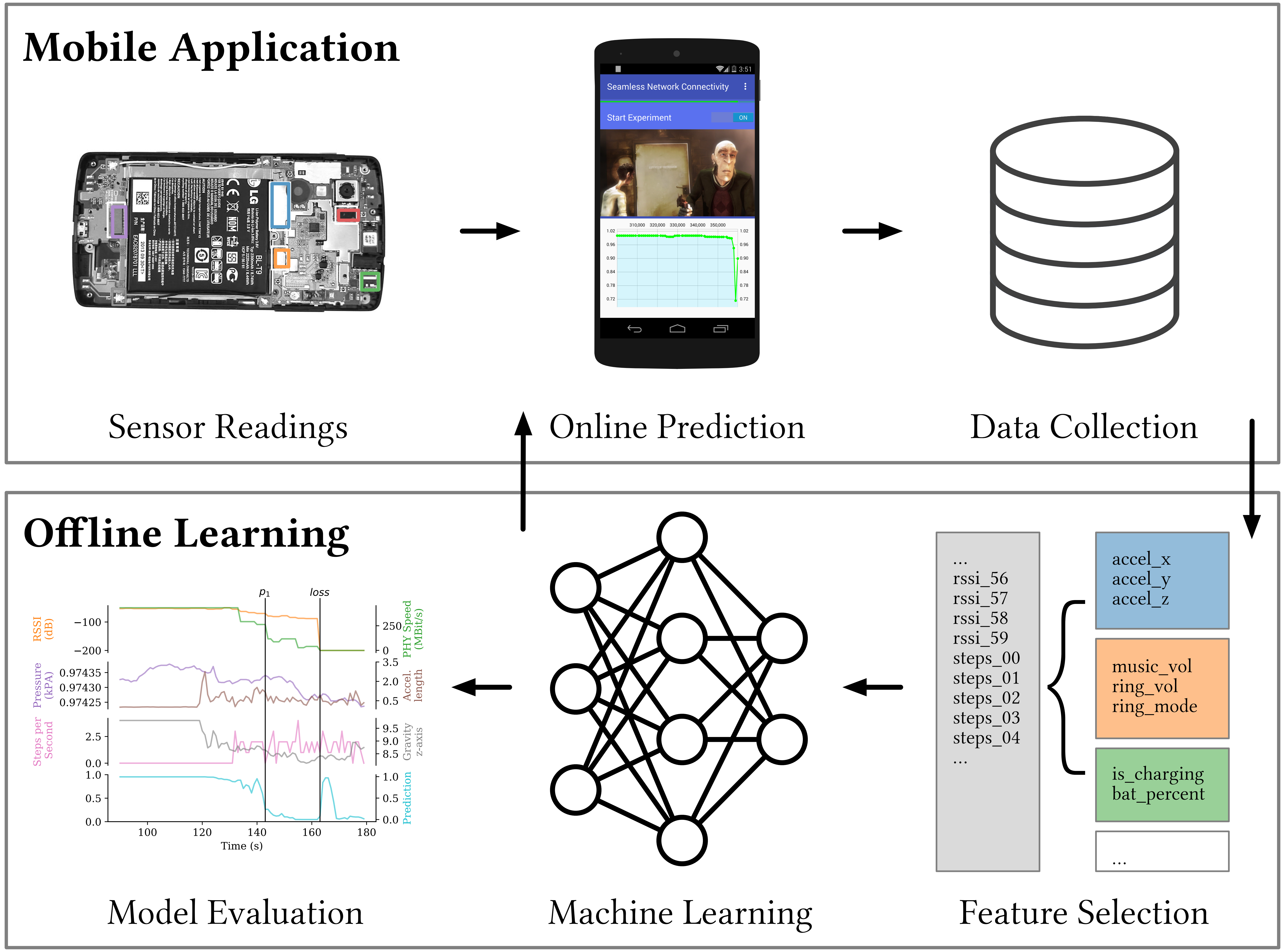
IEEE LCN 2019
Best Paper

Seamless Vertical Handovers
Learning Wi-Fi Connection Loss Predictions

- Motivation: Use of heterogeneous sensor data available on smartphones
- Goal: Improve QoS / QoE while reducing overheads introduced by MPTCP
- Alternatives:
    - Reactive handovers based on connection losses; applications deals with connection loss
    - Plain MultiPath-TCP, no connection loss prediction; higher energy and data plan usage



Seamless Vertical Handovers
Conceptual Overview



Seamless Vertical Handovers
Machine Learning

- Feature Vectors:
  a) Full: 25 sensors x 60 s = 1500 features
  b) Reduced: 8 sensors x 60 s = 480 features
- Ground Truth: Wi-Fi RSSI > -70 dBm, shifted
- Machine learning methods:
  a) Random forest, down-sampling, 10 trees
  b) Neural networks with 1, 3 and 5 hidden layers

Metric	Forest	*NN 1*	*NN 2*	*NN 3*
Loss Prec.	0.89	0.95	0.97	0.97
Loss Recall	0.98	0.94	0.95	0.95
F_1-score	0.93	0.94	0.96	0.96

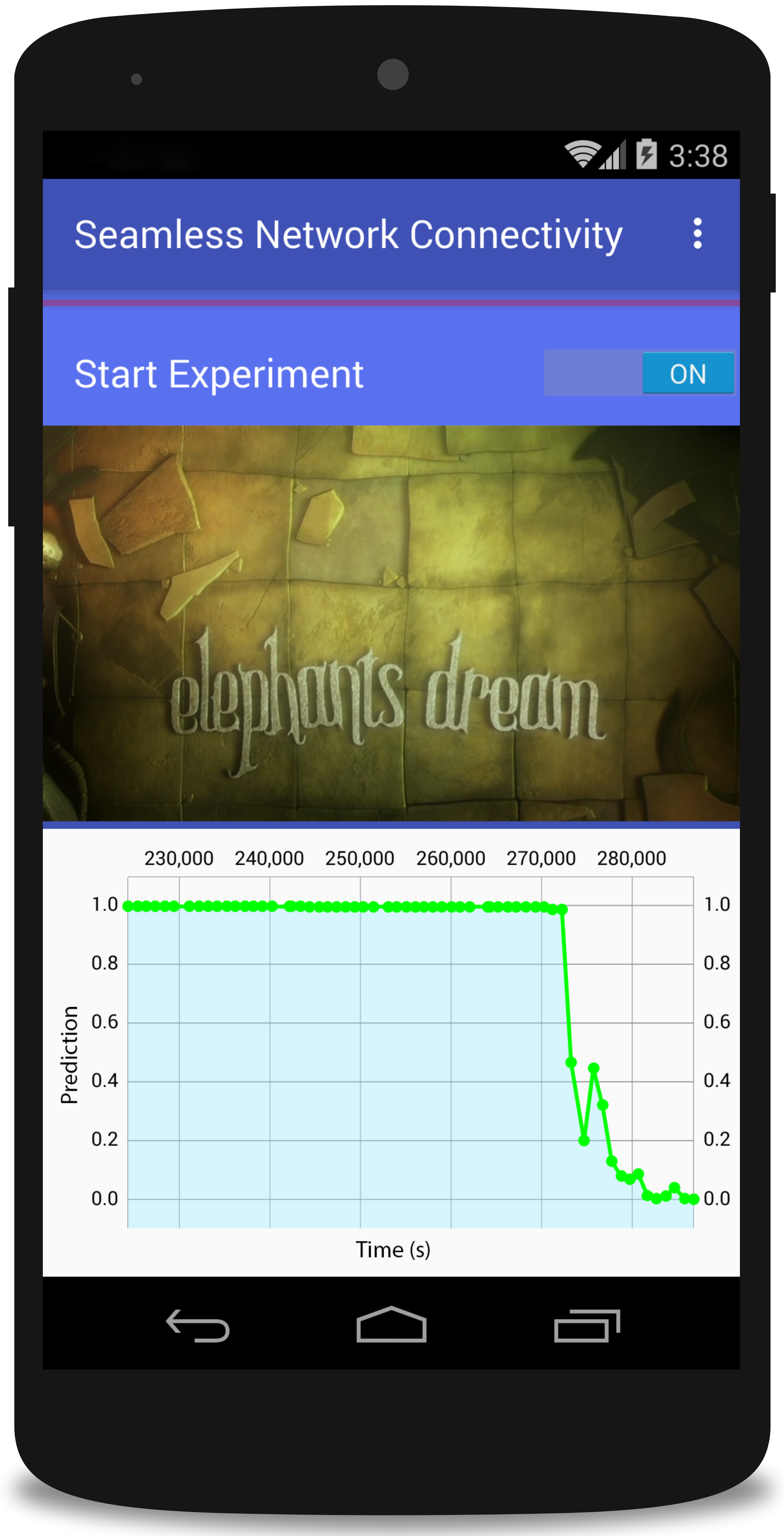
Table: Reduced Feature Vector, Random Data Split

Seamless Vertical Handovers
Evaluation: Online Prediction

On-device model execution

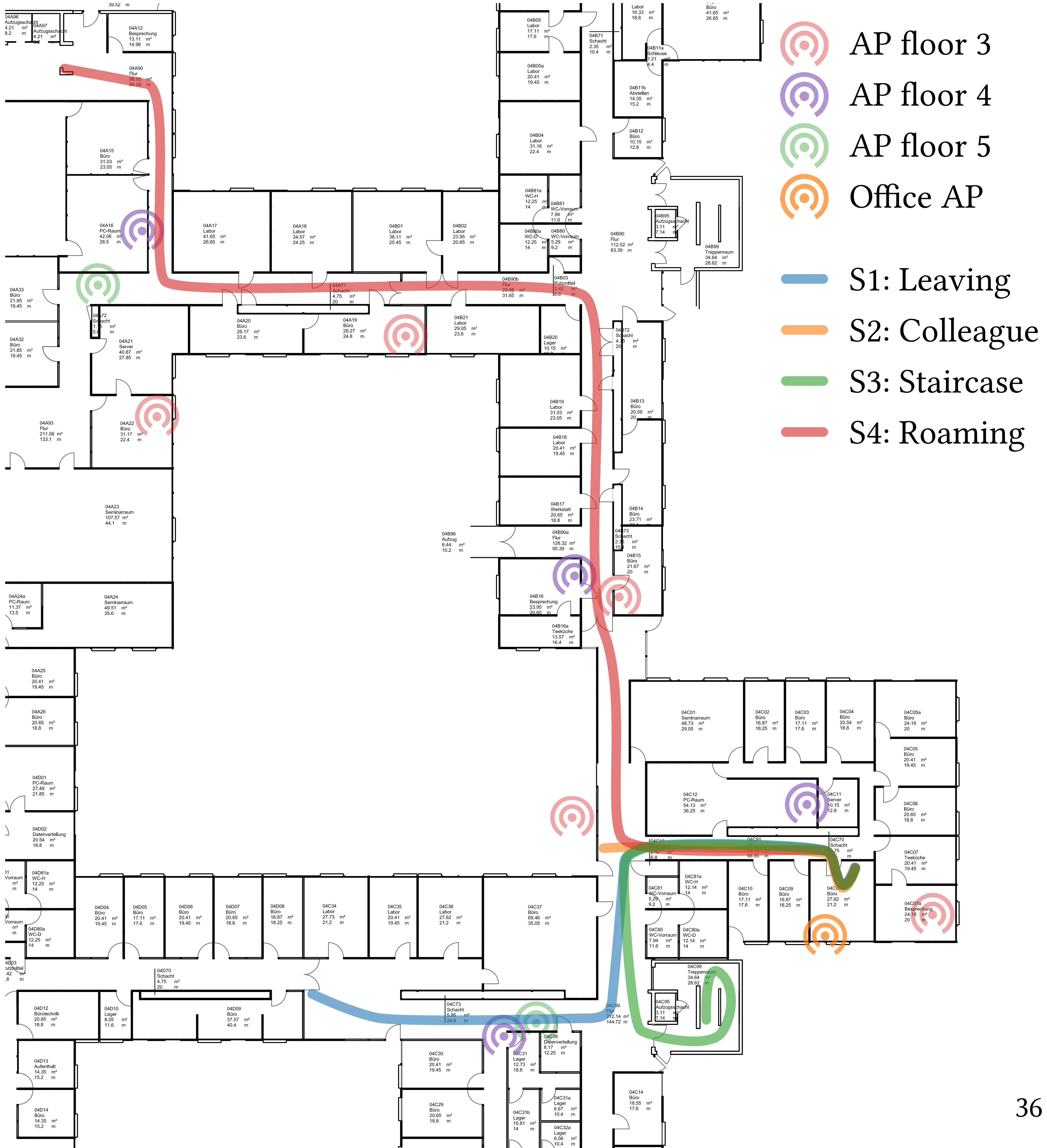
DASH.js video playback

MPTCP handovers



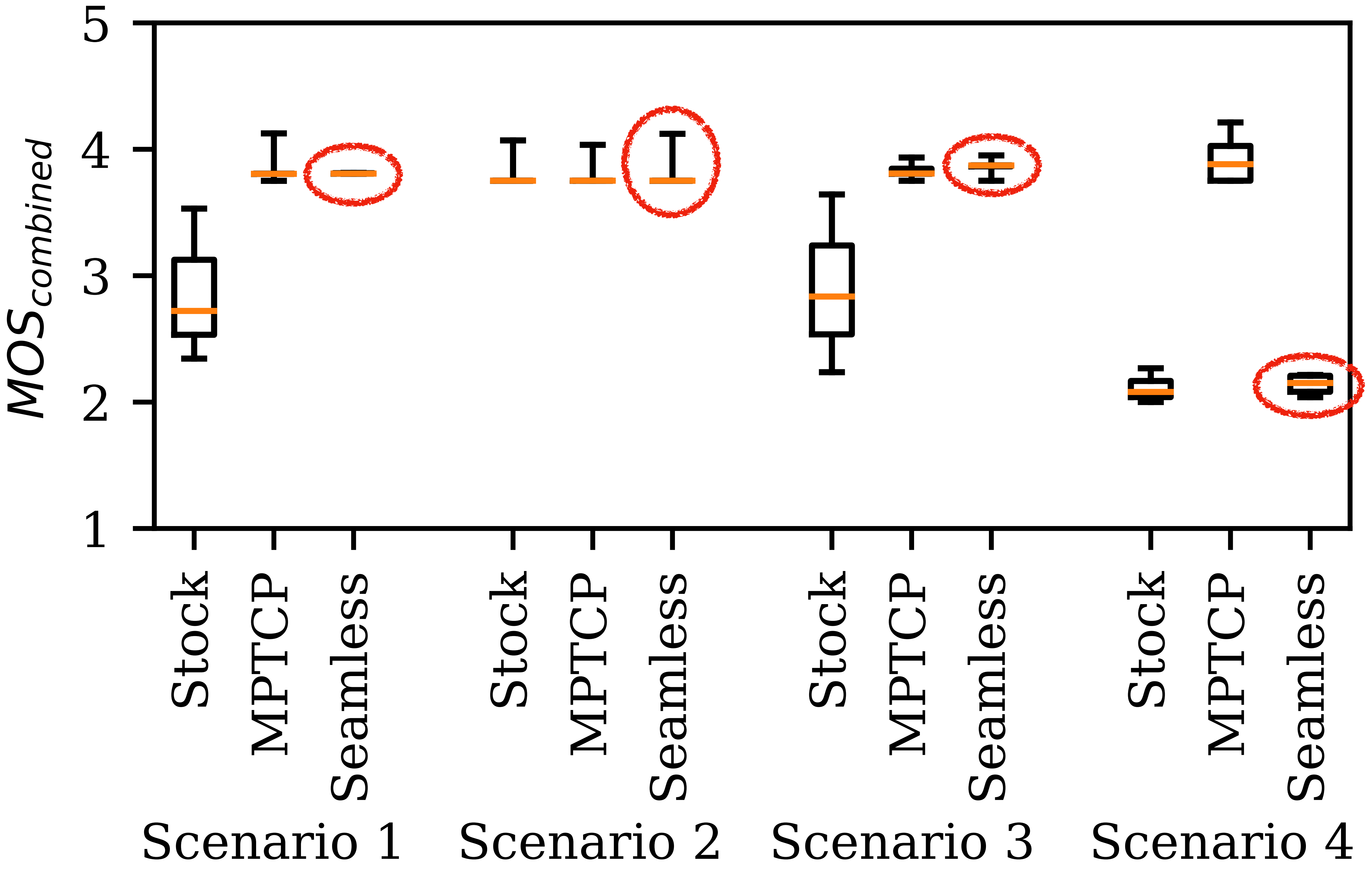
Seamless Vertical Handovers
Experimental Evaluation: Scenarios

- Four scenarios:
  - Leaving the office (1)
  - Visiting a colleague (2)
  - Using the staircase (3)
  - Wi-Fi roaming support (4)
- Three connectivity modes:
  - Android, MPTCP, Seamless



Seamless Vertical Handovers
Experimental Evaluation: Quality of Experience

- Mean Opinion Score: Empirically determined scores of subjectively perceived quality
- $MOS_{combined}$: Video quality and stalling
- Scenarios 1 - 3:
  Performance as good as MPTCP
  reduced cellular data usage
- Scenario 4:
  WiFi roaming: connection unstable
  cellular connection are established and terminated frequently



Seamless Vertical Handovers
Experimental Evaluation: Quality vs. Cost

(a) Scenario 1: Leaving

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	3	1.46 s	23	87 %	21.75 MB
MPTCP	0	0 s	20	89 %	41.32 MB
Seaml.	0	0 s	27	88 %	36.11 MB

(b) Scenario 2: Colleague

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	0	0 s	10	92 %	0 MB
MPTCP	0	0 s	10	91 %	9.98 MB
Seaml.	0	0 s	17	92 %	9.59 MB

(c) Scenario 3: Staircase

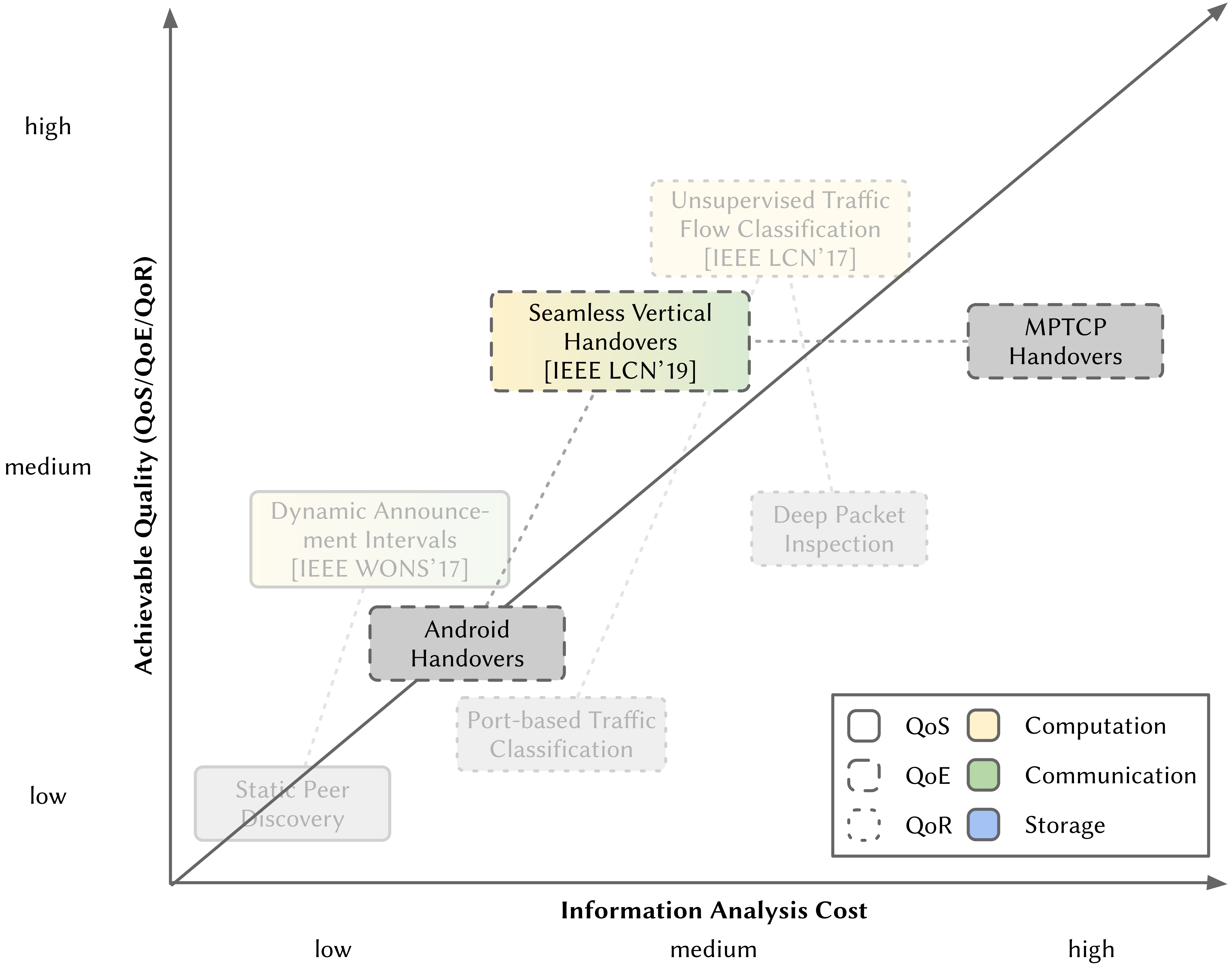
Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	3	2.06 s	49	80 %	0 MB
MPTCP	0	0 s	32	87 %	33.92 MB
Seaml.	0	0 s	28	85 %	16.81 MB

(d) Scenario 4: Wi-Fi Roaming

Mode	# St.	∅ St.	# A.	HQ	∅ TD
Stock	18	14.98 s	42	53 %	0.89 MB
MPTCP	0	0 s	38	86 %	71.99 MB
Seaml.	15	5.47 s	23	84 %	15.50 MB

Seamless Vertical Handovers
Cost / Quality

- Achievable quality better than stock Android handovers, on par with MPTCP handovers
- Increased cost in terms of computation compared to MPTCP / Stock Android
- Lower cost due to reduced cellular bandwidth usage



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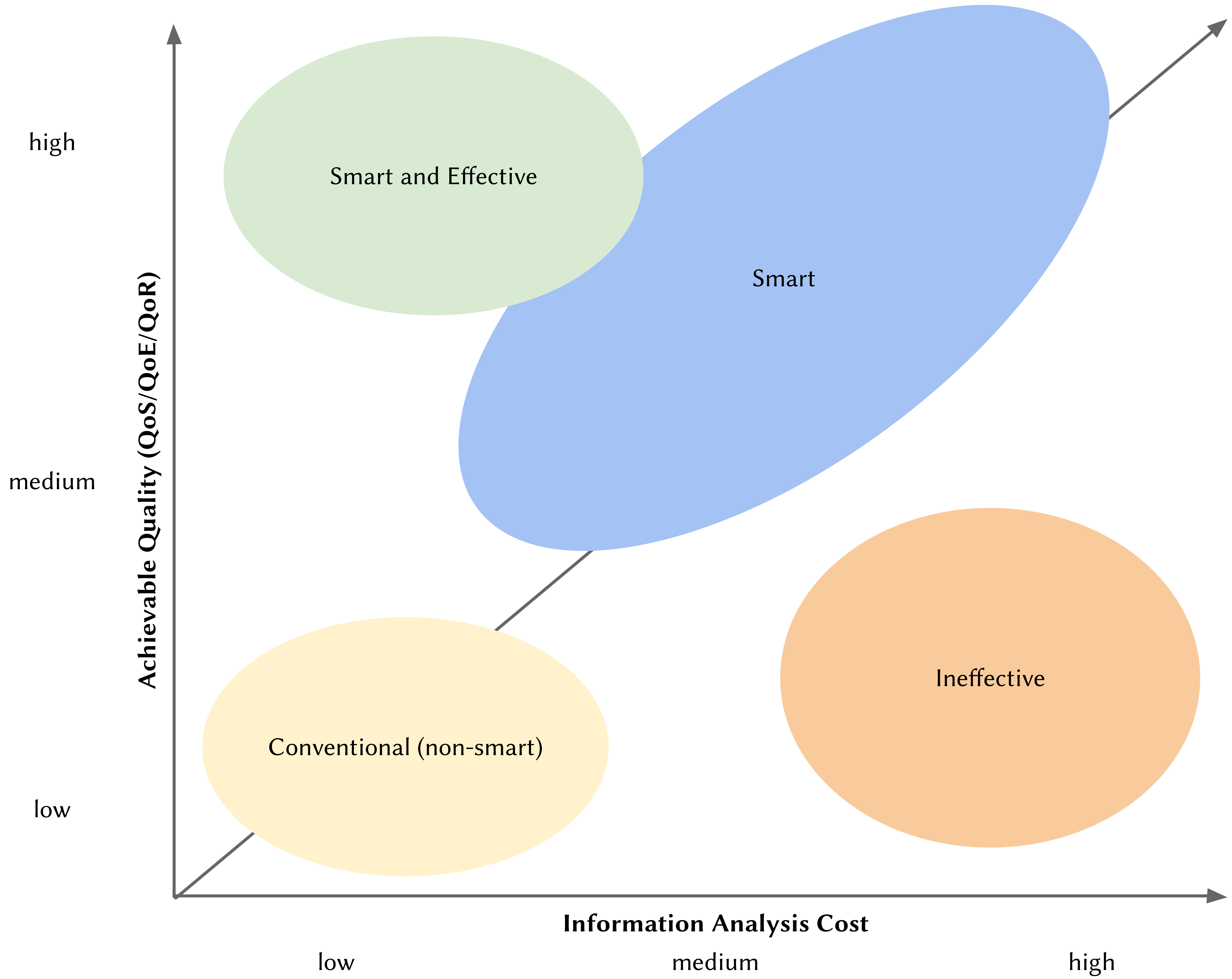
Conclusion

Summary

Smart Systems in three areas:

- Environmental monitoring
- Adaptive disruption-tolerant networking
- Transitional wireless networking

Overarching categorization to evaluate smart systems based on Achievable Quality and Information Analysis Cost.



Future Work

Smart Environmental Monitoring

- **Incorporate topology, vegetation, weather factors in VHF tracking**
- Explore federated learning at the edge
- Consolidation and integration of diverse data sources

Smart Adaptive Disruption-tolerant Networking

- **Design and smart usage of additional convergency layers for modern RATs in DTNs**
- Exploration of incentive mechanisms in opportunistic networks
- Online re-configuration of DTN programmable routing algorithm

Smart Transitional Networking

- Additional domain-specific non-device sensors, e.g., Wi-Fi load
- Specialize model for user/access point combination
- **Wi-Fi regain prediction to cope with roaming issues**

Publications (1)

1. **Jonas Höchst,** Lars Baumgärtner, Franz Kuntke, Alvar Penning, Artur Sterz, Markus Sommer, and Bernd Freisleben. “Mobile Device-to-Device Communication for Crisis Scenarios Using Low-cost LoRa Modems.” in: *Disaster Management and Information Technology: Professional Response and Recovery Management in the Age of Disasters (accepted for publication).* ed. by Hans Jochen Scholl, Eric E. Holdeman, and F. Kees Boersma. Springer Nature, 2022 [Höc+22a]
2. Patrick Lampe, Markus Sommer, Artur Sterz, **Jonas Höchst**, Christian Uhl, and Bernd Freisleben. “Unobtrusive Mechanism Interception: Teaching an Old Dog New Tricks.” in: *2022 IEEE 47th Conference on Local Computer Networks (LCN 2022).* Edmonton, Canada, Sept. 2022 [Lam+22b]
3. Patrick Lampe, Markus Sommer, Artur Sterz, **Jonas Höchst**, Christian Uhl, and Bernd Freisleben. “ForestEdge: Unobtrusive Mechanism Interception in Environmental Monitoring.” in: *2022 IEEE 47th Conference on Local Computer Networks (LCN 2022).* Edmonton, Canada, Sept. 2022 [Lam+22a]
4. **Jonas Höchst**, Hicham Bellafkir, Patrick Lampe, Markus Vogelbacher, Markus Mühling, Daniel Schneider, Kim Lindner, Sascha Rösner, Dana G. Schabo, Nina Farwig, and Bernd Freisleben. “Bird@Edge: Bird Species Recognition at the Edge.” in: *International Conference on Networked Systems (NETYS).* Springer. May 2022 [Höc+22b]
5. Markus Sommer, **Jonas Höchst**, Artur Sterz, Alvar Penning, and Bernd Freisleben. “ProgDTN: Programmable Disruption-tolerant Networking.” in: *International Conference on Networked Systems (NETYS).* Springer. May 2022 [Som+22]
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7. Julian Zobel, Paul Frommelt, Patrick Lieser, Jonas Höchst, Patrick Lampe, Bernd Freisleben, and Ralf Steinmetz. “Energy-efficient Mobile Sensor Data Offloading via WiFi using LoRa-based Connectivity Estimations.” in: *51. Jahrestagung der Gesellschaft für Informatik, INFORMATIK 2021*, Berlin, Germany. LNI. GI, Sept. 2021 [Zob+21]
8. Jannis Gottwald, Patrick Lampe, **Jonas Höchst**, Nicolas Friess, Julia Maier, Lea Leister, Betty Neumann, Tobias Richter, Bernd Freisleben, and Thomas Nauss. “BatRack: An Open-source Multi-sensor Device for Wildlife Research.” in: *Methods in Ecology and Evolution* (July 2021). [Got+21]
9. Johnny Nguyen, Karl Kesper, Gunter Kräling, Christian Birk, Peter Mross, Nico Hofeditz, **Jonas Höchst**, Patrick Lampe, Alvar Penning, Bastian Leutenecker-Twelsiek, Carsten Schindler, Helwig Buchenauer, David Geisel, Caroline Sommer, Ronald Henning, Pascal Wallot, Thomas Wiesmann, Björn Beutel, Gunter Schneider, Enrique Castro-Camus, and Martin Koch. “Repurposing CPAP Machines as Stripped-down Ventilators.” in: *Scientific Reports 11.1* (June 2021), pp. 1–9. [Ngu+21]
10. Lars Baumgärtner, Alexandra Dmitrienko, Bernd Freisleben, Alexander Gruler, **Jonas Höchst**, Joshua Kühlberg, Mira Mezini, Richard Mitev, Markus Miettinen, Anel Muhamedagic, Thien Duc Nguyen, Alvar Penning, Dermot Pustelnik, Filipp Roos, Ahmad-Reza Sadeghi, Michael Schwarz, and Christian Uhl. “Mind the GAP: Security & Privacy Risks of Contact Tracing Apps.” in: *2020 IEEE 19th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom).* vol. 1. IEEE. Dec. 2020, pp. 458–467. [Bau+20]
11. **Jonas Höchst**, Alvar Penning, Patrick Lampe, and Bernd Freisleben. “PIMOD: A Tool for Configuring Single-Board Computer Operating System Images.” in: *2020 IEEE Global Humanitarian Technology Conference (GHTC 2020).* Seattle, USA, Oct. 2020, pp. 1–8. [Höc+20b]

Publications (2)

12. **Jonas Höchst**, Lars Baumgärtner, Franz Kuntke, Alvar Penning, Artur Sterz, and Bernd Freisleben. “LoRa-based Device-to-Device Smartphone Communication for Crisis Scenarios.” in: *17th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2020)*. Blacksburg, Virginia, USA, May 2020 [Höc+20a]
13. Lars Baumgärtner, **Jonas Höchst**, and Tobias Meuser. “B-DTN7: Browser-based Disruption-tolerant Networking via Bundle Protocol 7.” in: *2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM’19)*. Paris, France, Dec. 2019. [BHM19]
14. Alvar Penning, Lars Baumgärtner, **Jonas Höchst**, Artur Sterz, Mira Mezini, and Bernd Freisleben. “DTN7: An Open-Source Disruption-tolerant Networking Implementation of Bundle Protocol 7.” in: *18th International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW 2019)*. Esch-sur-Alzette, Luxemburg, Oct. 2019. [Pen+19]
15. **Jonas Höchst**, Artur Sterz, Alexander Frömmgen, Denny Stohr, Ralf Steinmetz, and Bernd Freisleben. “Learning Wi-Fi Connection Loss Predictions for Seamless Vertical Handovers Using Multipath TCP.” in: *2019 IEEE 44th Conference on Local Computer Networks (LCN 2019)*. **Best Paper Award**. Osnabrück, Germany, Oct. 2019. [Höc+19]
16. Artur Sterz, Lars Baumgärtner, **Jonas Höchst**, Patrick Lampe, and Bernd Freisleben. “OPPLOAD: Offloading Computational Workflows in Opportunistic Networks.” in: *2019 IEEE 44th Conference on Local Computer Networks (LCN 2019)*. Osnabrück, Germany, Oct. 2019. [Ste+19]
17. Lars Baumgärtner, Patrick Lampe, **Jonas Höchst**, Ragnar Mogk, Artur Sterz, Pascal Weisenburger, Mira Mezini, and Bernd Freisleben. “Smart Street Lights and Mobile Citizen Apps for Resilient Communication in a Digital City.” in: *2019 IEEE Global Humanitarian Technology Conference (GHTC 2019)*. Seattle, USA, Oct. 2019. [Bau+19]
18. Manisha Luthra, Boris Koldehofe, **Jonas Höchst**, Patrick Lampe, Ali Haider Rizvi, and Bernd Freisleben. “INetCEP: In-Network Complex Event Processing for Information-Centric Networking.” in: *15th ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS 2019)*. Cambridge, UK, Sept. 2019. [Lut+19]
19. Pablo Graubner, Patrick Lampe, **Jonas Höchst**, Lars Baumgärtner, Mira Mezini, and Bernd Freisleben. “Opportunistic Named Functions in Disruption-tolerant Emergency Networks.” in: *ACM International Conference on Computing Frontiers 2018 (ACM CF 2018)*. Ischia, Italy: ACM, May 2018. [Gra+18a]
20. Jonas Höchst, Lars Baumgärtner, Matthias Hollick, and Bernd Freisleben. “Unsupervised Traffic Flow Classification Using a Neural Autoencoder.” in: *42nd Annual IEEE Conference on Local Computer Networks (LCN 2017)*. Singapore, Oct. 2017. [Höc+17]
21. Lars Baumgärtner, Pablo Graubner, **Jonas Höchst**, Anja Klein, and Bernd Freisleben. “Speak Less, Hear Enough: On Dynamic Announcement Intervals in Wireless On-demand Networks.” in: *13th Conference on Wireless On-demand Network Systems and Services (WONS 2017)*. Jackson Hole, USA, Feb. 2017. [Bau+17]
22. Lars Baumgärtner, Paul Gardner-Stephen, Pablo Graubner, Jeremy Lakeman, **Jonas Höchst**, Patrick Lampe, Nils Schmidt, Stefan Schulz, Artur Sterz, and Bernd Freisleben. “An Experimental Evaluation of Delay-Tolerant Networking with Serval.” in: *2016 IEEE Global Humanitarian Technology Conference (GHTC)*. Seattle, USA, Oct. 2016. [Bau+16]
23. Lars Baumgärtner, **Jonas Höchst**, Matthias Leinweber, and Bernd Freisleben. “How to Misuse SMTP over TLS: A Study of the (In) Security of Email Server Communication.” in: *Trustcom/BigDataSE/ISPA, 2015 IEEE. vol. 1.* IEEE. 2015, pp. 287–294. [Bau+15]

Presented publication; presented in thesis; additional publication.

EOF

Time for questions

Additional Slides

Smart Systems

A ‘smart’ service system is a system capable of learning, dynamic adaptation, and decision making based upon data received, transmitted, and/or processed to improve its response to a future situation.

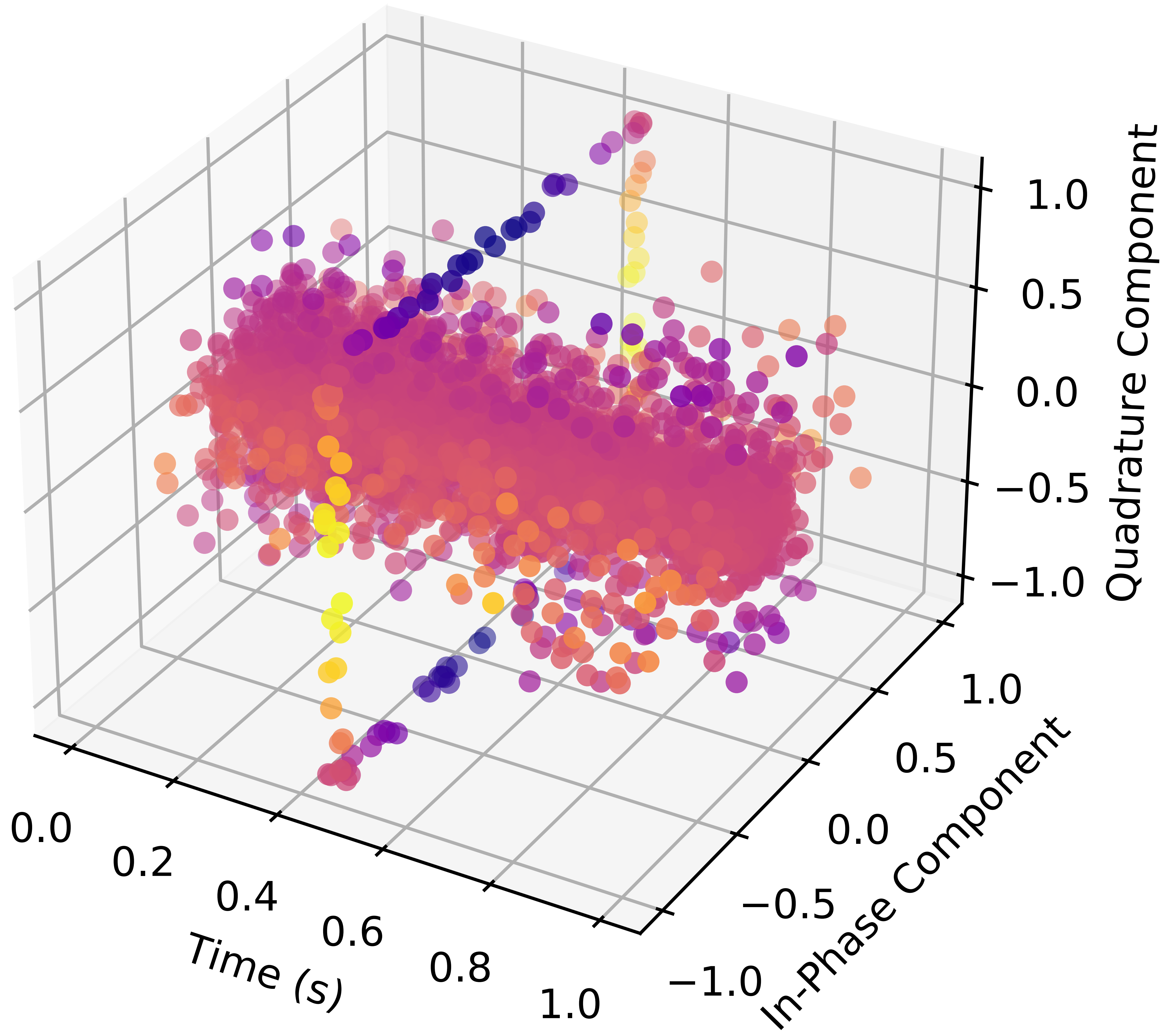
Medina-Borja, NSF [Med15]

Distributed System

A distributed system is a collection of independent computers that appears to its users as a single coherent system.

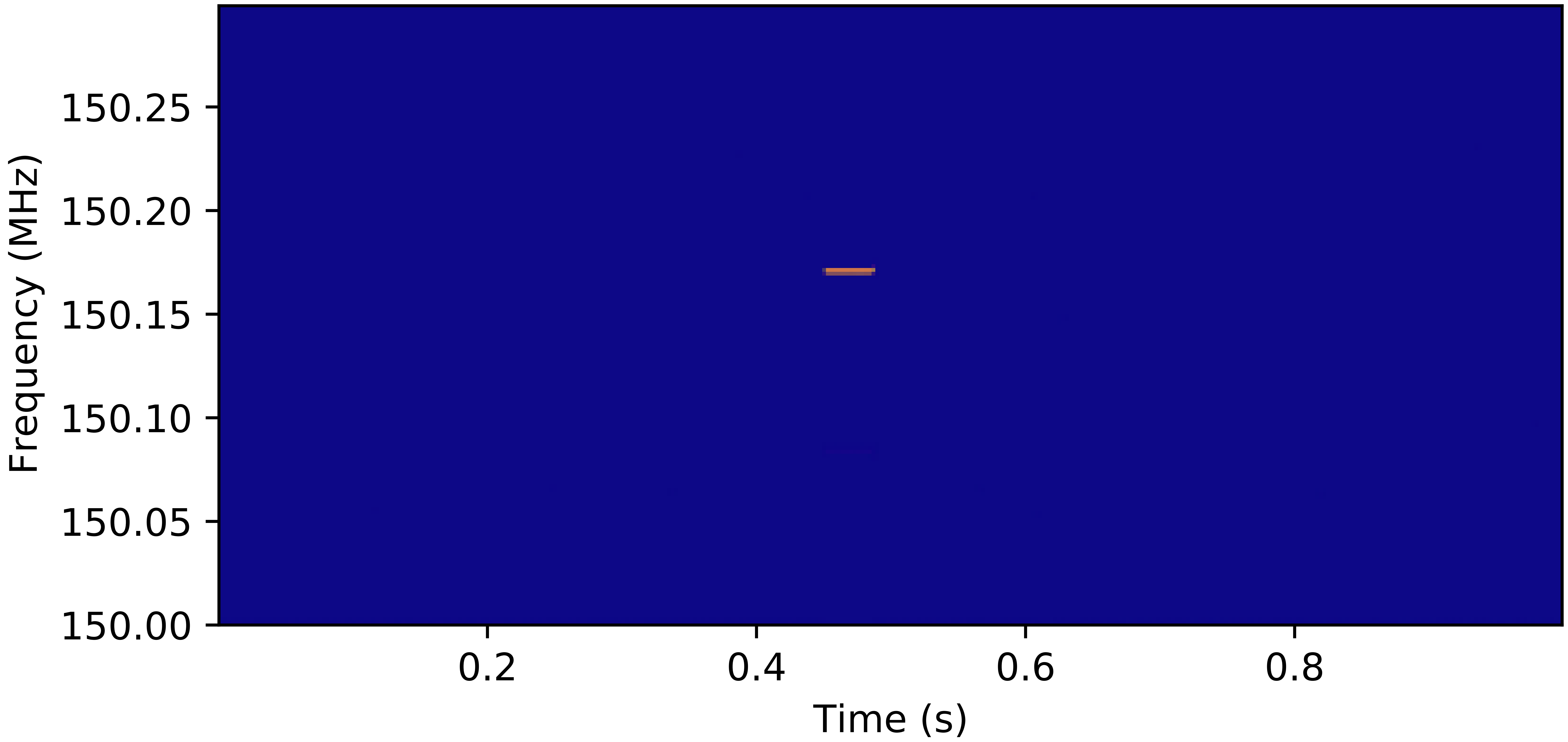
[Tanenbaum]

tRackIT OS
Signal Analysis (1): IQ Samples



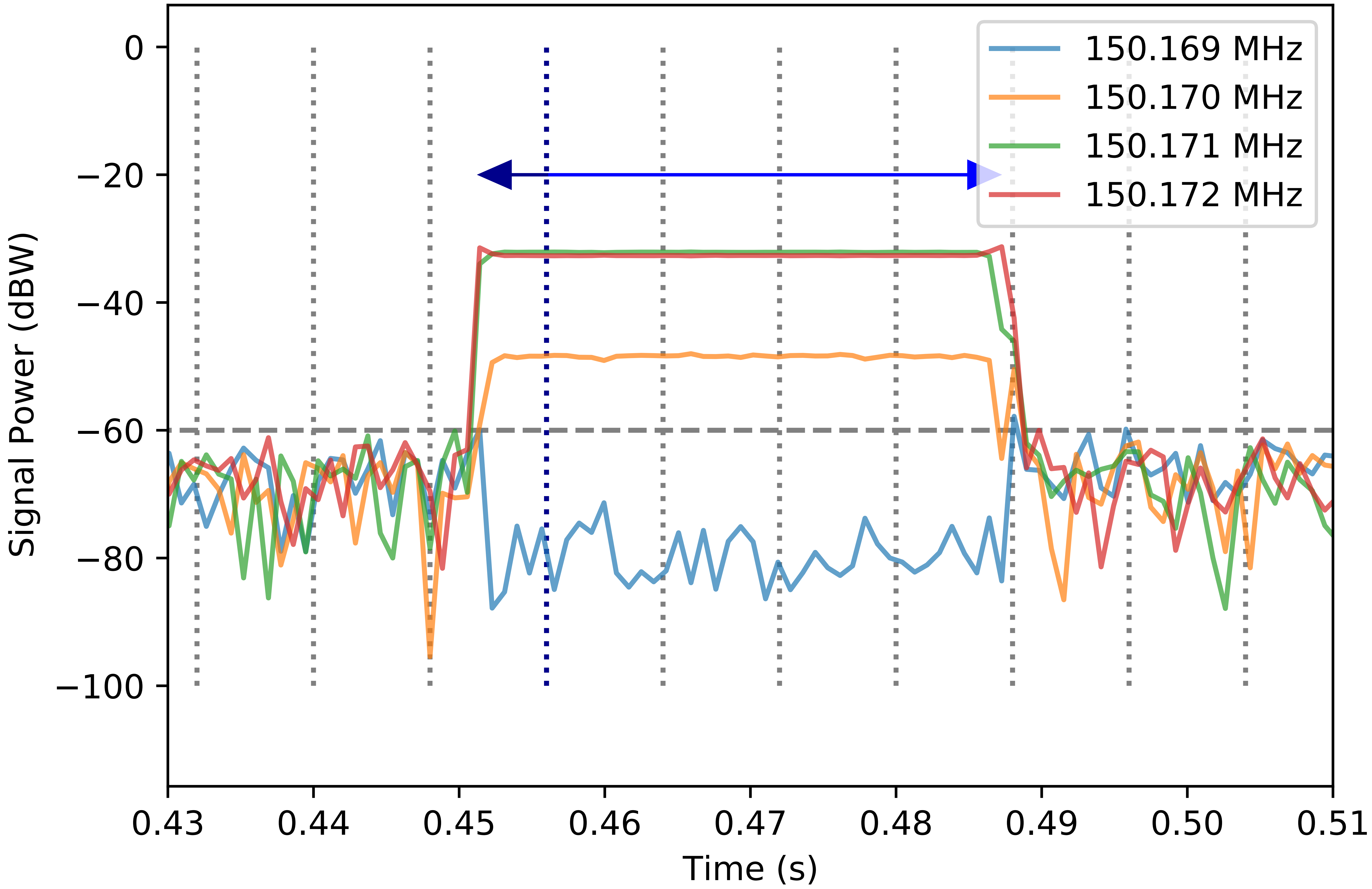
tRackIT OS

Signal Analysis (2): Power Spectrum



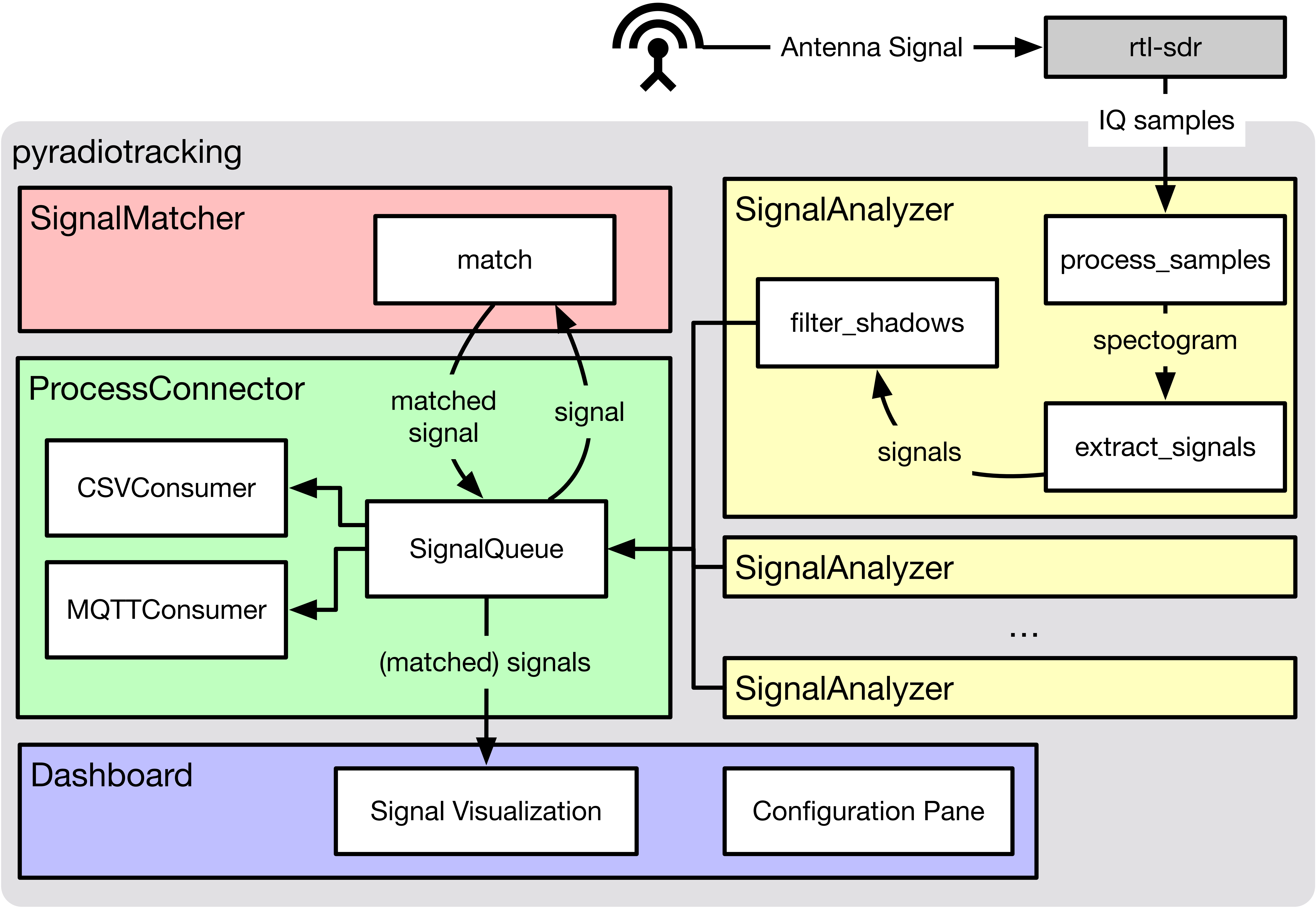
tRackIT OS

Signal Analysis (3): Signal Search



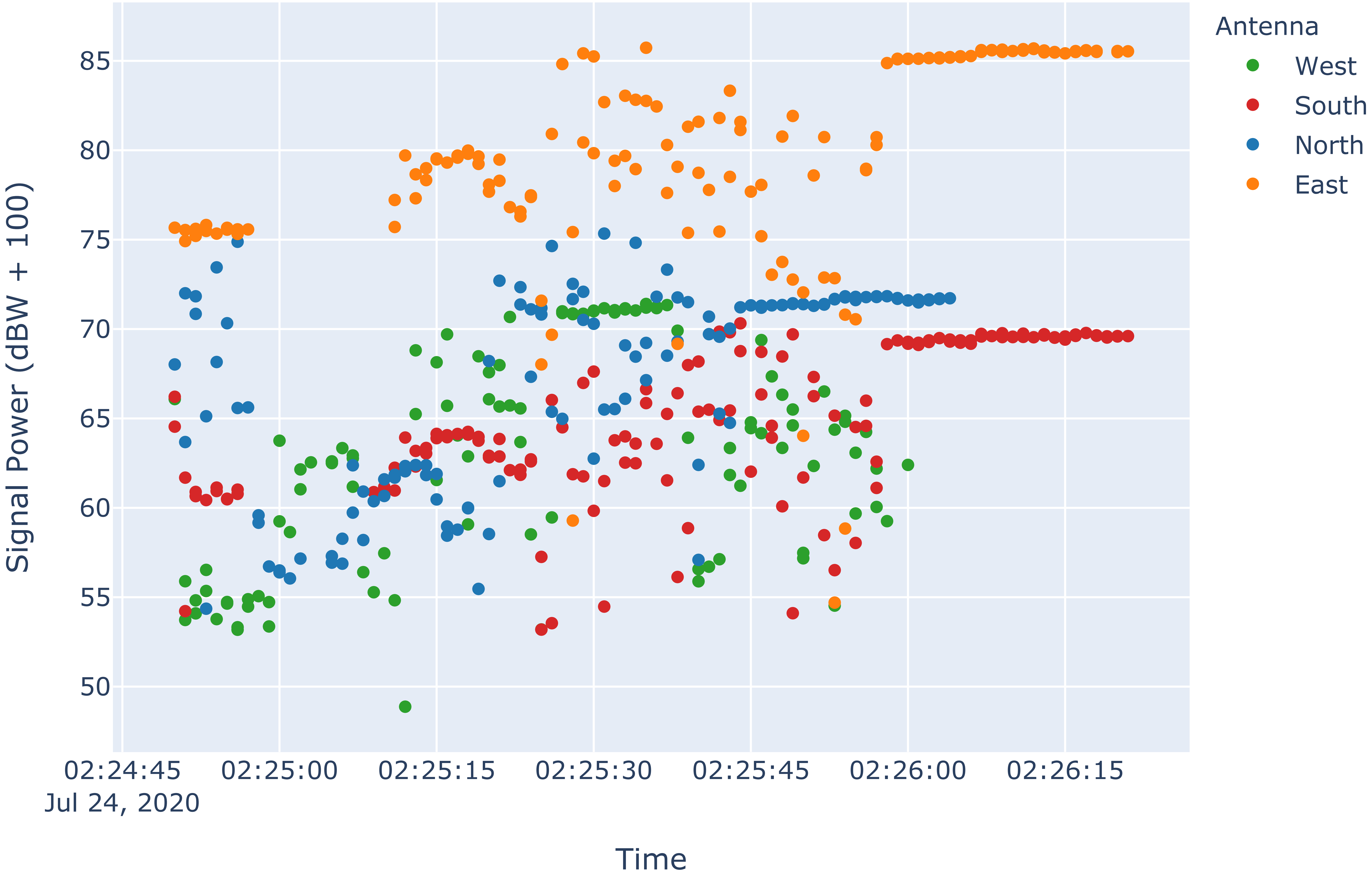
tRackIT OS

pyradiotracking Architecture



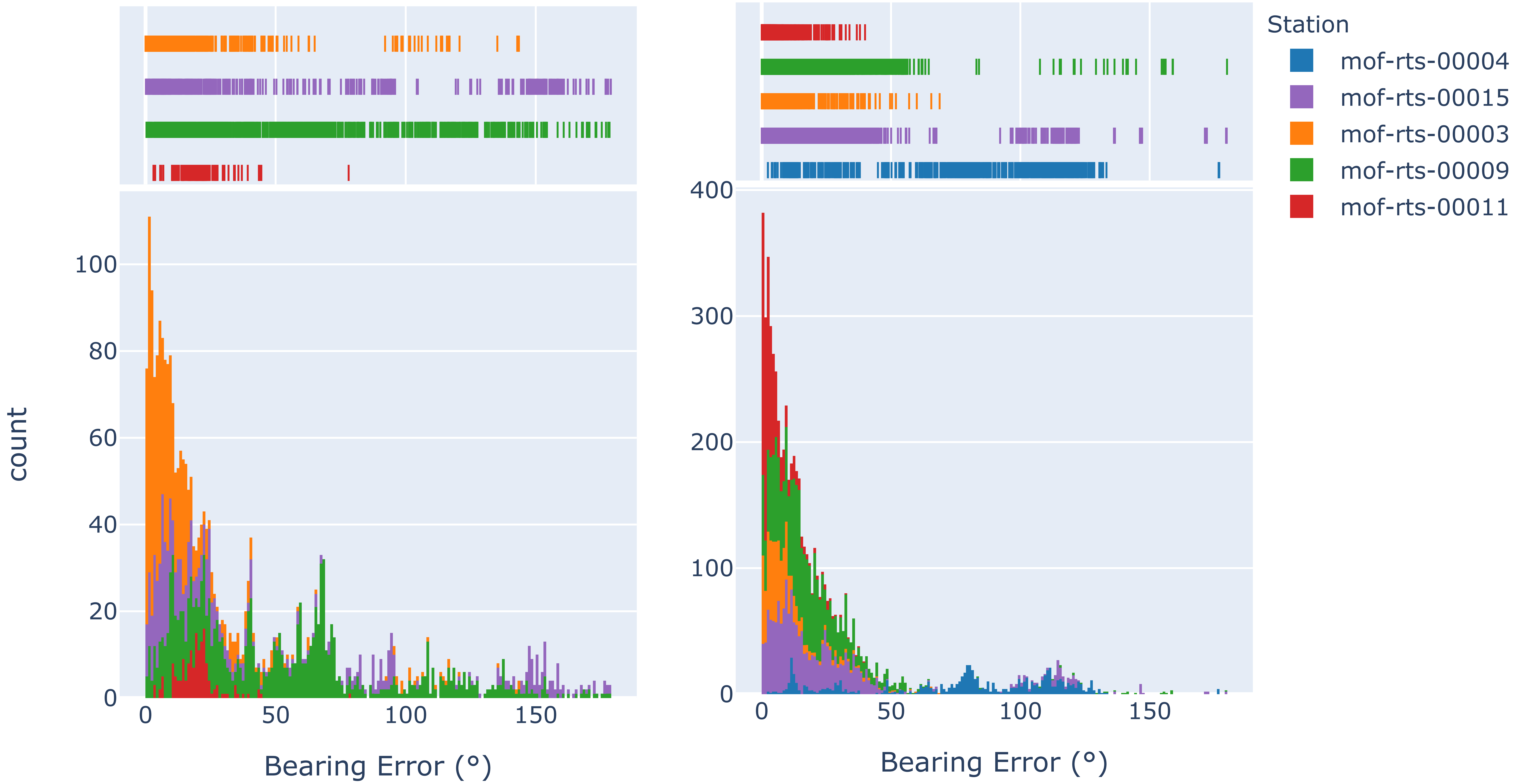
tRackIT OS

paur Time Drift

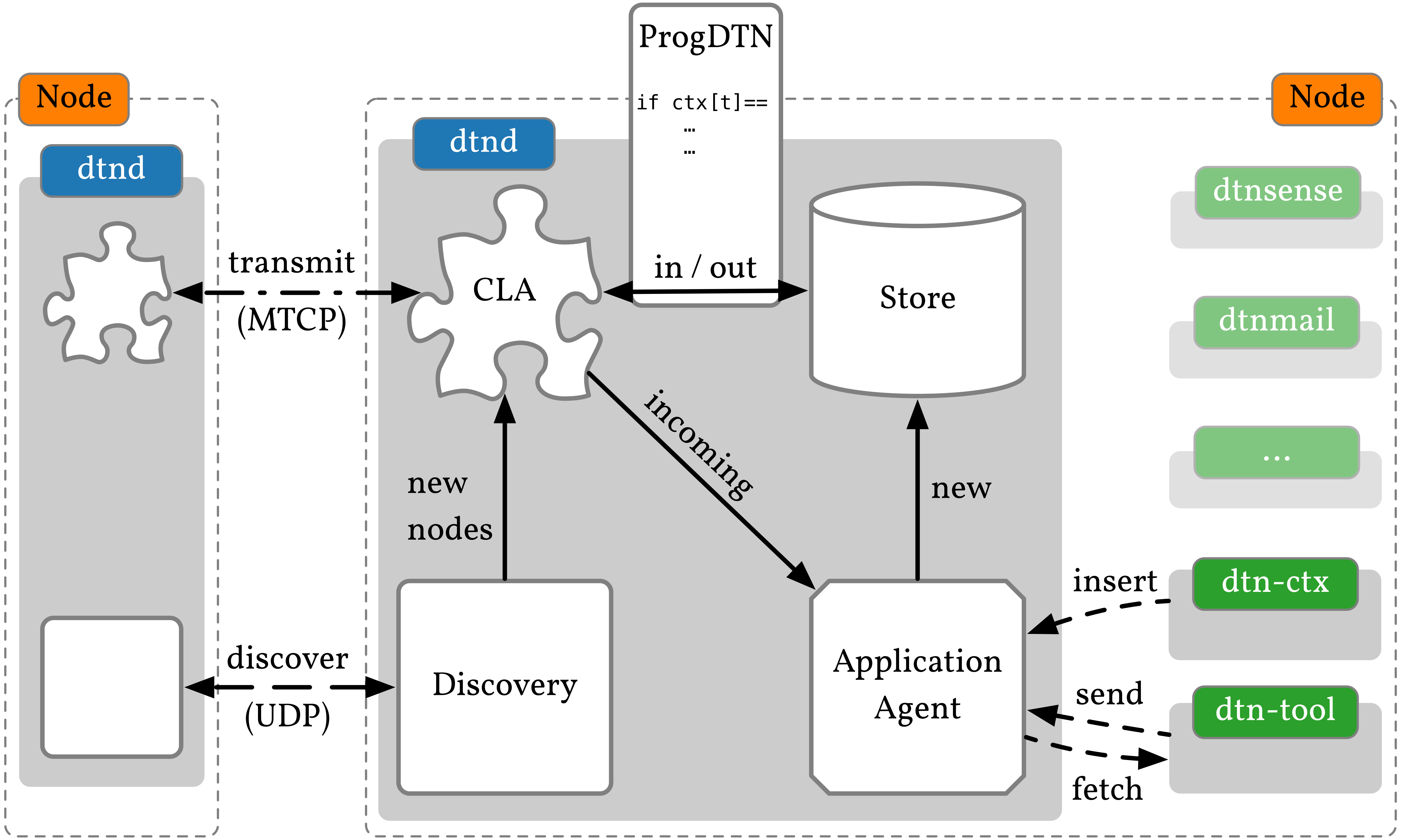


tRackIT OS

Bearing Error: paur vs. tRackIT OS

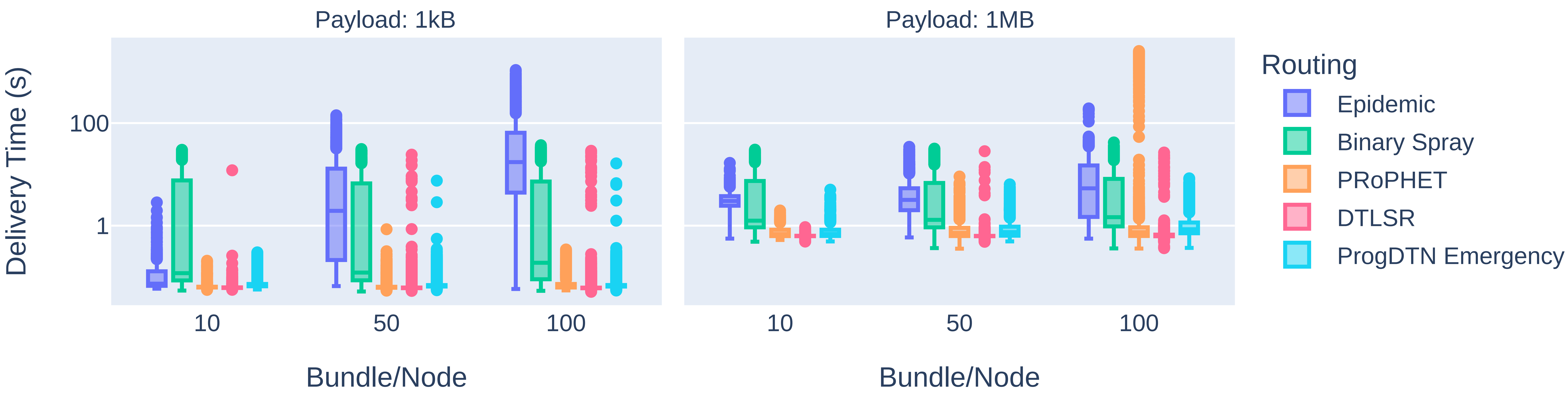


ProgDTN
Application Architecture



ProgDTN

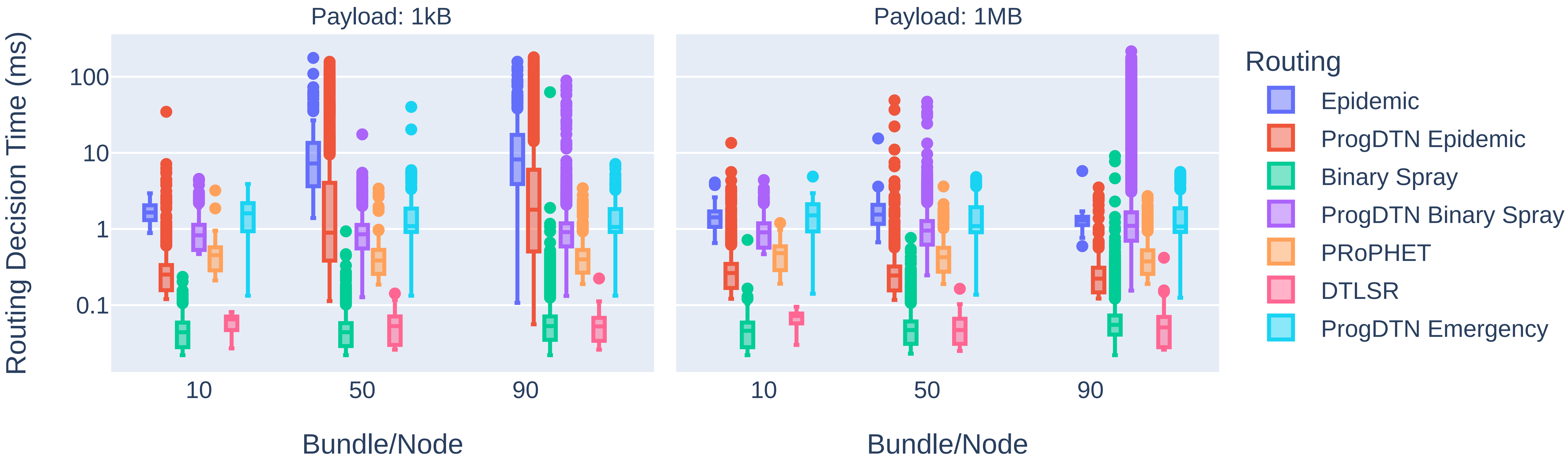
Quality of Service: Delivery Times



- ProgDTN Emergency on par with other algorithms, except outliers
- Epidemic, Binary Spray: Large number of transmissions lead to long delivery times

ProgDTN

Information Analysis Cost: Routing Decision

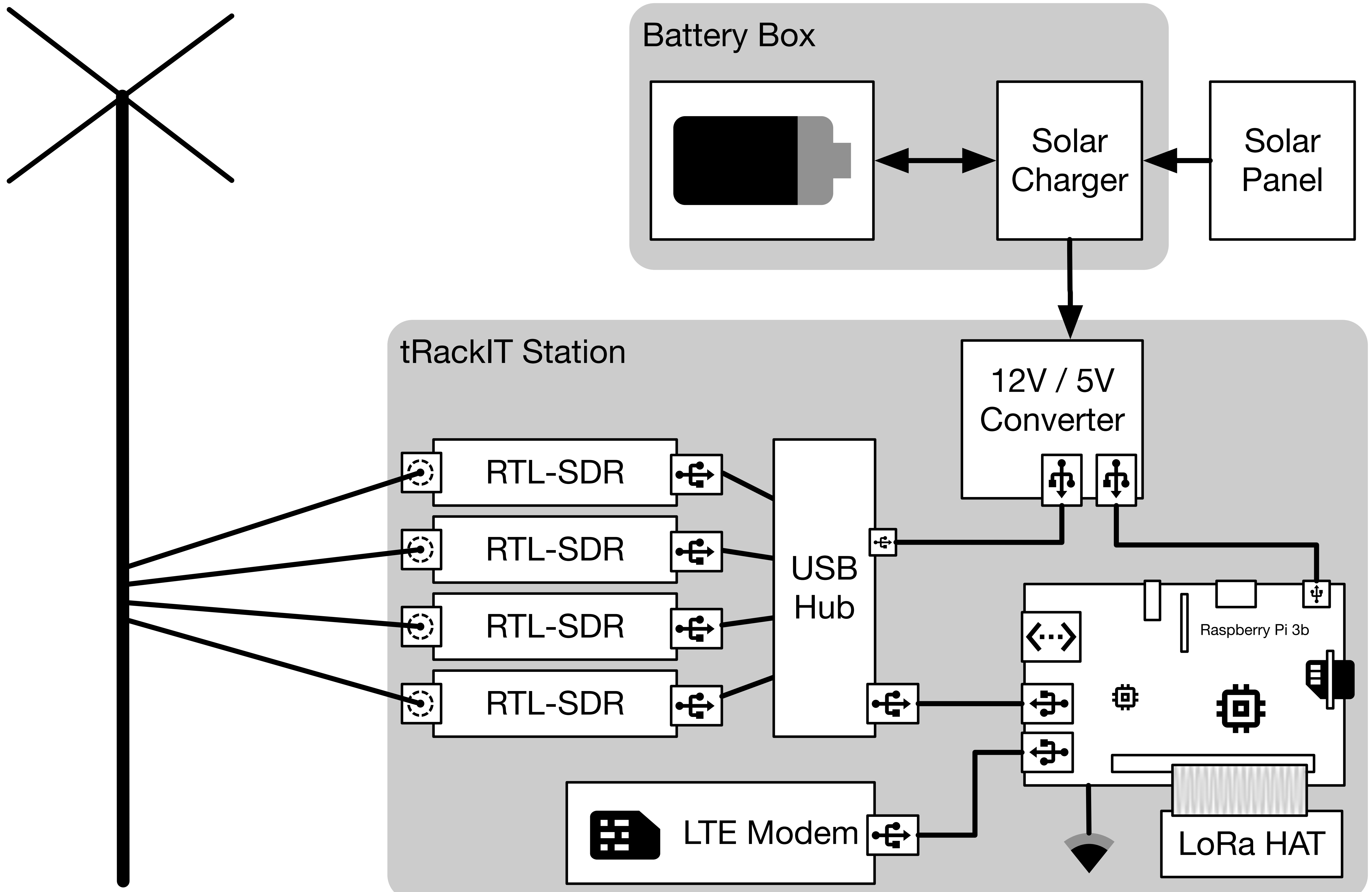


- Overheads introduced through JavaScript VM in ProgDTN variants
- ProgDTN 75%-quantile below 50 ms; in ProgDTN Emergency even below 3 ms

tRackIT OS
Proposed Hardware Solution

Multiple autonomously sensing tRackIT Stations:

- Software-defined radios (SDR), single-board computer, LTE modem / LoRa modem, solar power supply
- Live data transmission for monitoring and further data analysis

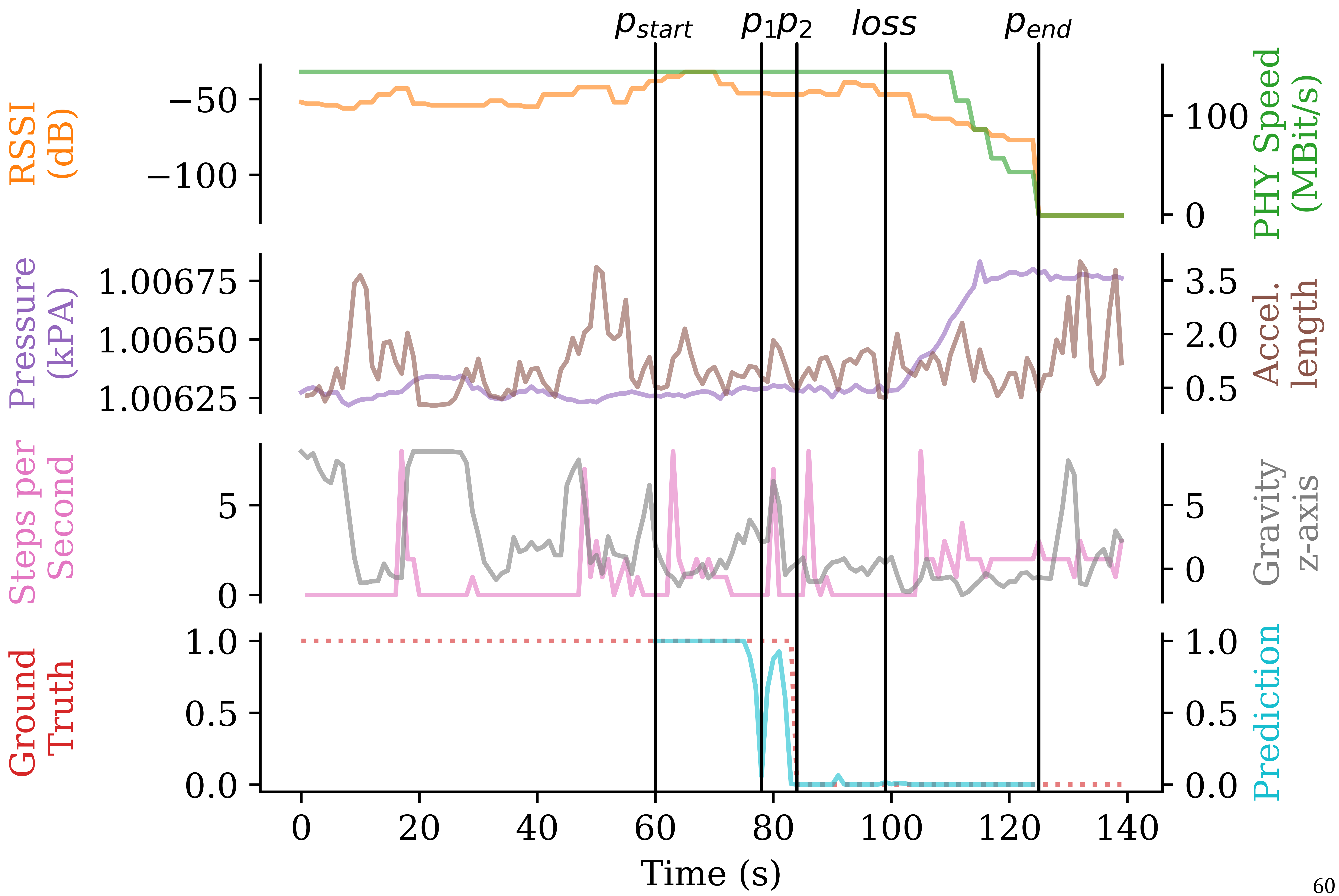


Seamless Vertical Handovers
Design & Implementation

- Novel data-driven, proactive approach for seamless vertical Wi-Fi/ cellular handovers
- Multiple heterogeneous smartphone sensors to predict Wi-Fi connection loss
- Multipath-TCP based seamless connection handover
- Experimental evaluation based on Quality of Experience
- Open demo implementation and experimental artifacts

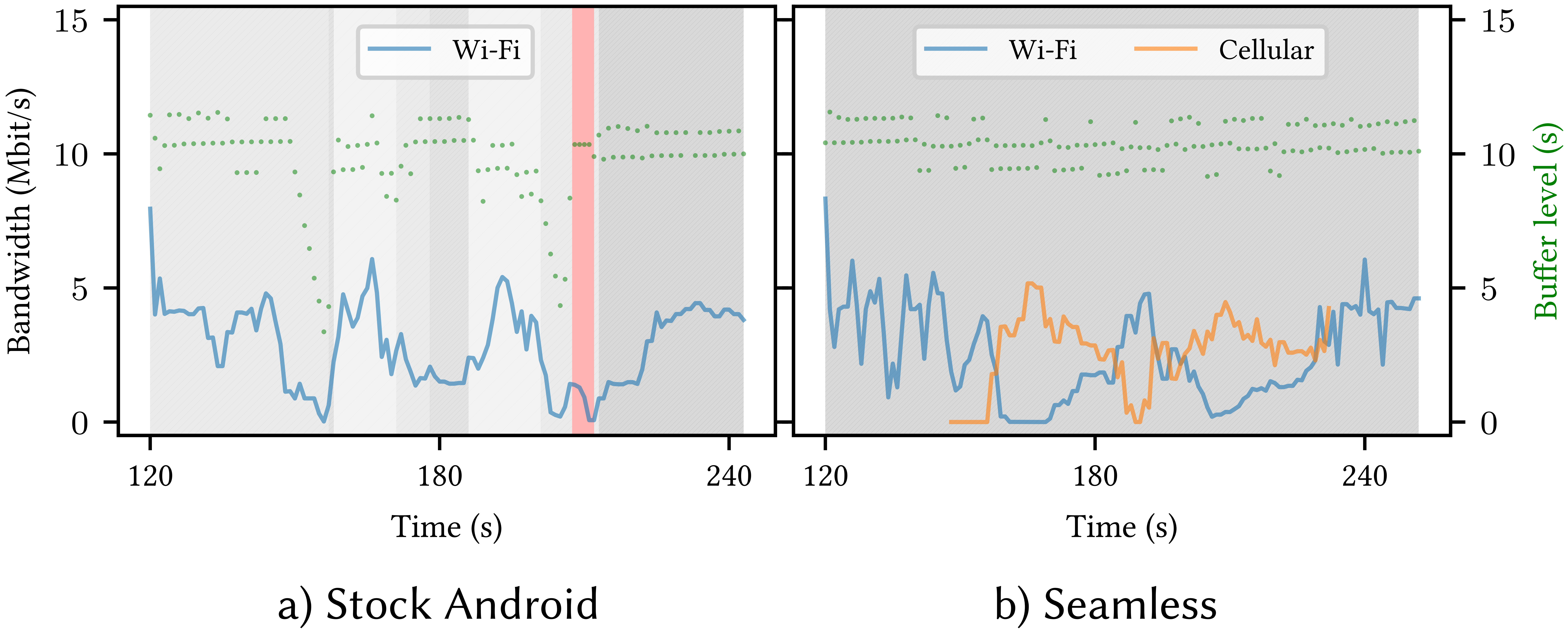
Seamless Vertical Handovers
Sensor Data Example

- Sensor data from 6 sensors visualized
- Connection loss at t = 100s, ground truth 15s beforehand
- Connection loss prediction after 60s of filling data
- p_1: early prediction
- p_2: intended prediction



Seamless Vertical Handovers

Sensor Data Example: Scenario 3



Bandwidth, buffer levels and video quality in scenario 3


11:28
Seamless Network Connectivity
Start Experiment
AN
0 300 600 900 1.200 1.500 1.800
0,9990
0,9985
0,9980
0,9965
Disabling MPTCP suggested, but transitions are disabled.
Stock Android
11:49
Seamless Network Connectivity
Start Experiment
AN
No chart data available.
Seamless Connectivity