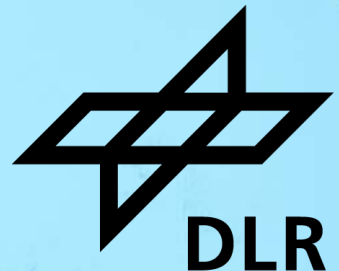


ADVANCING REMOTE CONTROL CAPABILITIES FOR MARITIME AUTONOMOUS SURFACE SHIPS

Insights and Lessons from Trials

8th International Conference On Maritime Autonomous Surface Ships (ICMASS)

Authors: Arne Bokern, Janusz Piotrowski and Dr.-Ing. Matthias Steidel



Motivation

- Rapid advancement of remote control (RC) technologies for MASS → ROC playing central role
 - Companies like Seafar, Kongsberg, Massterly drive technological advancement
- Emergence of guidelines from classification societies like ABS, DNV and BV [1-3]
 - Still, regulatory frameworks lag behind
 - Formal IMO MASS code still under development [4]



[5]

→ Technology is ahead of regulation and while uncertainty about regulations persist

- Means of connectivity
 - Often cellular networks = primary channel, satellite communication = fallback [6-8]
 - 5G → most promising solution for inland and coast

- Harbor environments present unique challenges

- Metal structures (Cranes, dry docks etc.)
- Dynamic vessel movement
- Radio-based communication systems
- High user density in urban areas

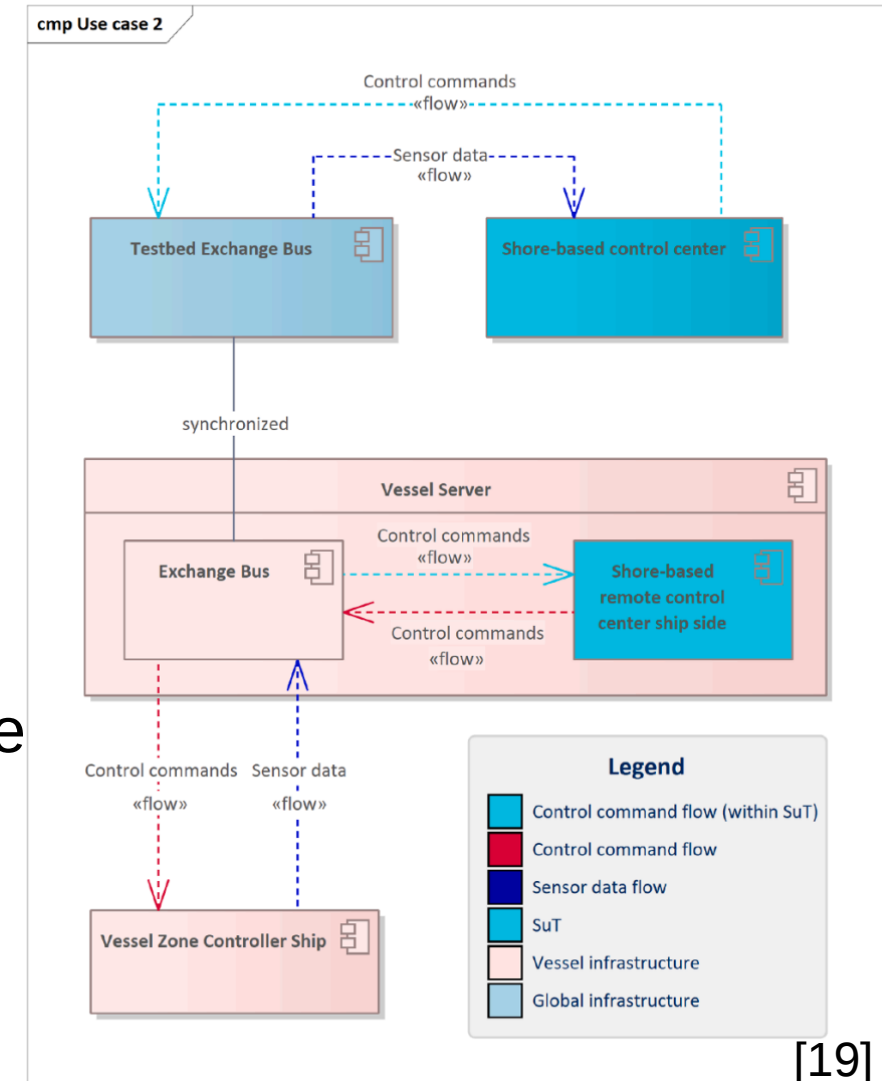


→ Related work: Lack of real-world trial data regarding remote operations using 5G/LTE in harbors and effect on connectivity

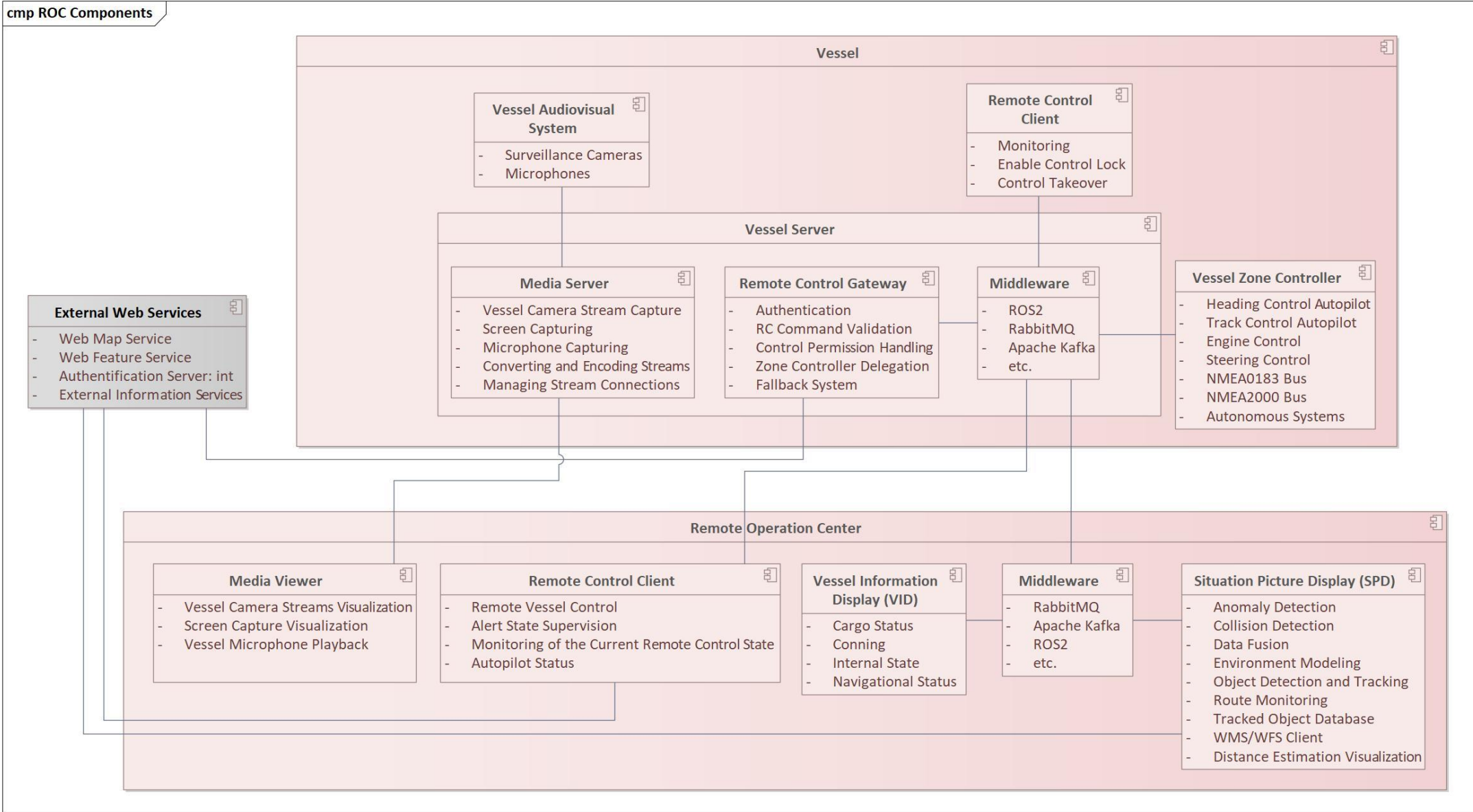
[9]

System Architecture for Evaluation

- Requirement for gathering trial data: ROC setup reflecting systems used in practice
- Based on requirements by classification societies
 - ABS (Autonomous and Remote Control Functions) [1]
 - DNV (DNV-CG-0264) [3]
 - BV (NI 641 DT R01 E) [2]
- Builds upon the concept introduced in [18] and incorporates the Open Testbed Vessel Architecture [19]



Remote Operation Center Architecture



Test Setup and used Technologies

■ Components

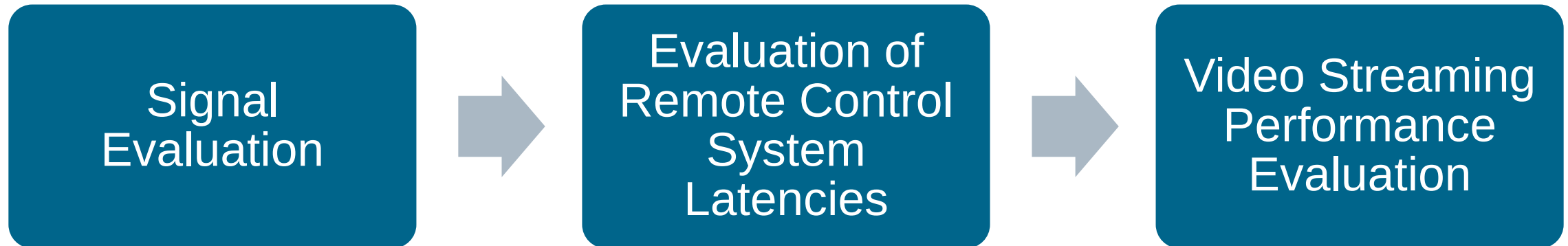
- Test Carrier Sally
 - 4 Cameras mounted on board
 - Open Testbed Vessel Architecture
- Remote Operation Center
 - RC-Application
 - eMaritime Prototype Display with ENCs provided by a Web Map Service
 - Conning
 - Distance Estimation Assistance System

■ Technologies

- Exchange Middleware → RabbitMQ
- Message Format → Protocol Buffers (Protobuf)
- Video Streaming → WebRTC with H.265 using MediaMTX



Evaluation Process



Signal Evaluation – Antenna Locations

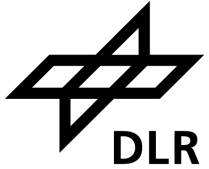


○ = Telekom

○ = Vodafone

[20]

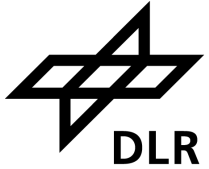
Signal Evaluation – Metrics [21]



	RSRQ (dB)	SINR (dB)	RSSI (dBm)	RSRP (dBm)
Excellent	> -10	> 15	> -65	> -80
Good	-10 to -15	10 to 15	-65 to -75	-80 to -90
Fair	-15 to -20	5 to 10	-75 to -85	-90 to -100
Poor	< -20	< 5	≤ -85	≤ -100
Telekom (Mean, 5G)	-11.512	9.4	-48.6	-81.7
Vodafone (Mean, LTE)	-11.49	7.04	-55.69	-88.17

→ Certain packet loss and unreliability expected especially when using Vodafone's LTE network

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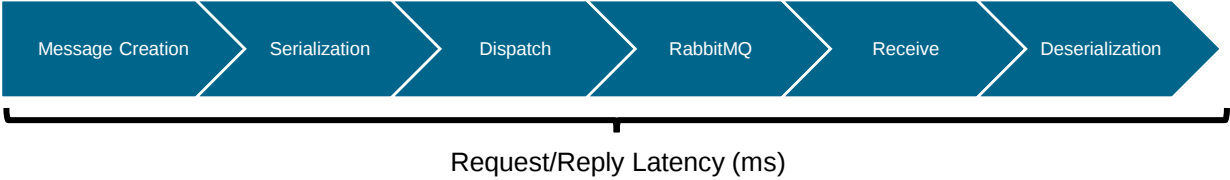
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Signal Evaluation – Spatial Analysis

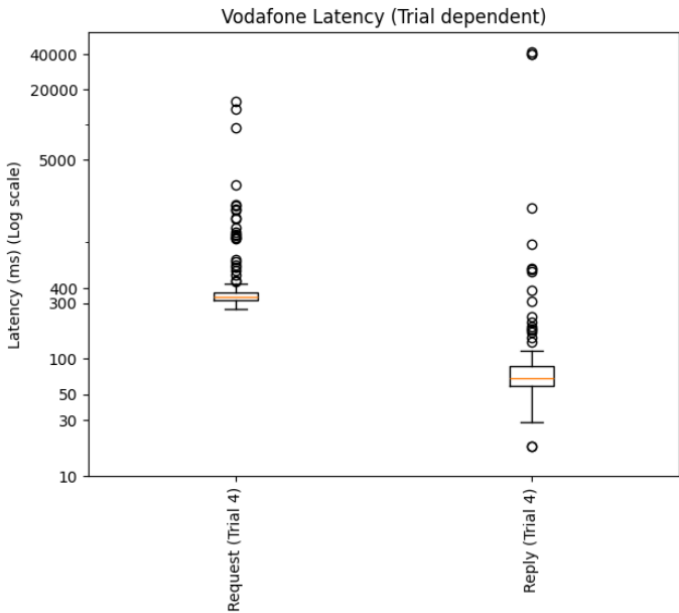
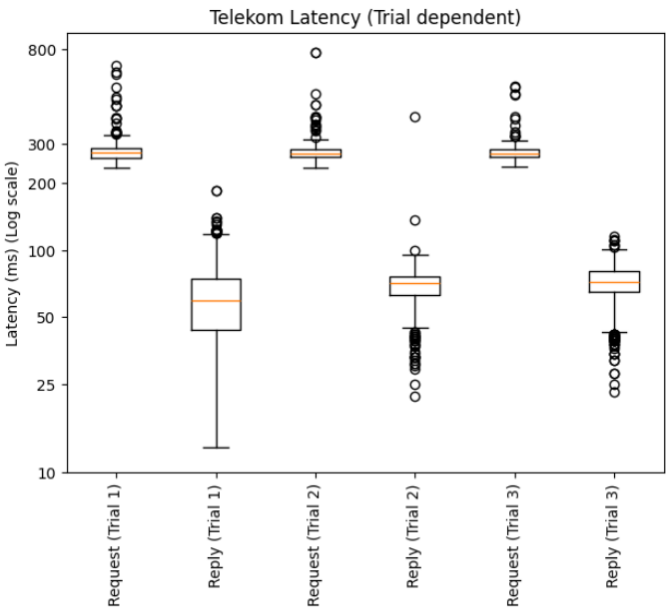
RSRP (dBm) for Telekom 5G (Left) and Vodafone LTE (Right)



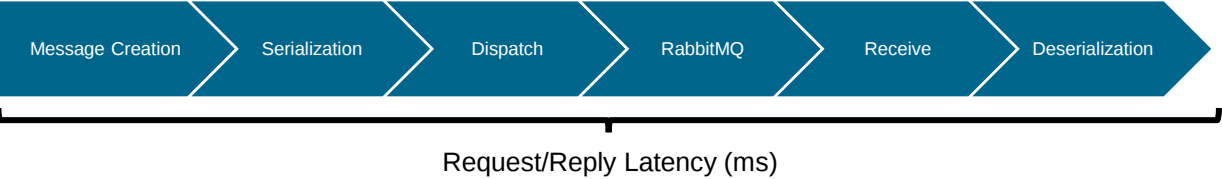
Remote Control Latency Evaluation



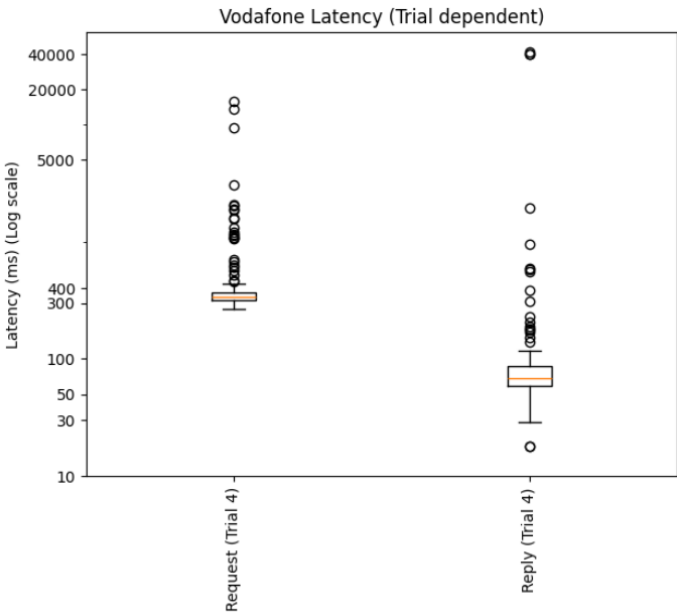
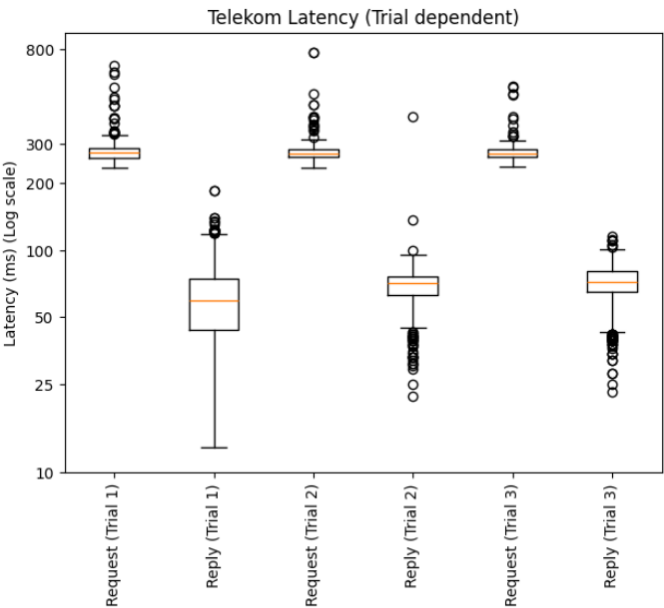
Trial	1	2	3	4	5
Provider	Telekom 5G	Telekom 5G	Telekom 5G	Vodafone LTE	Vodafone LTE
Connection	OpenVPN	Direct	OpenVPN	OpenVPN	OpenVPN
ROC Clients	1	1	2	1	2
Mean request latency (ms)	282.97	282.69	276.8	625.07	Connection loss
Mean reply latency (ms)	51.07	54.54	56.09	53.91	Connection loss



Remote Control Latency Evaluation

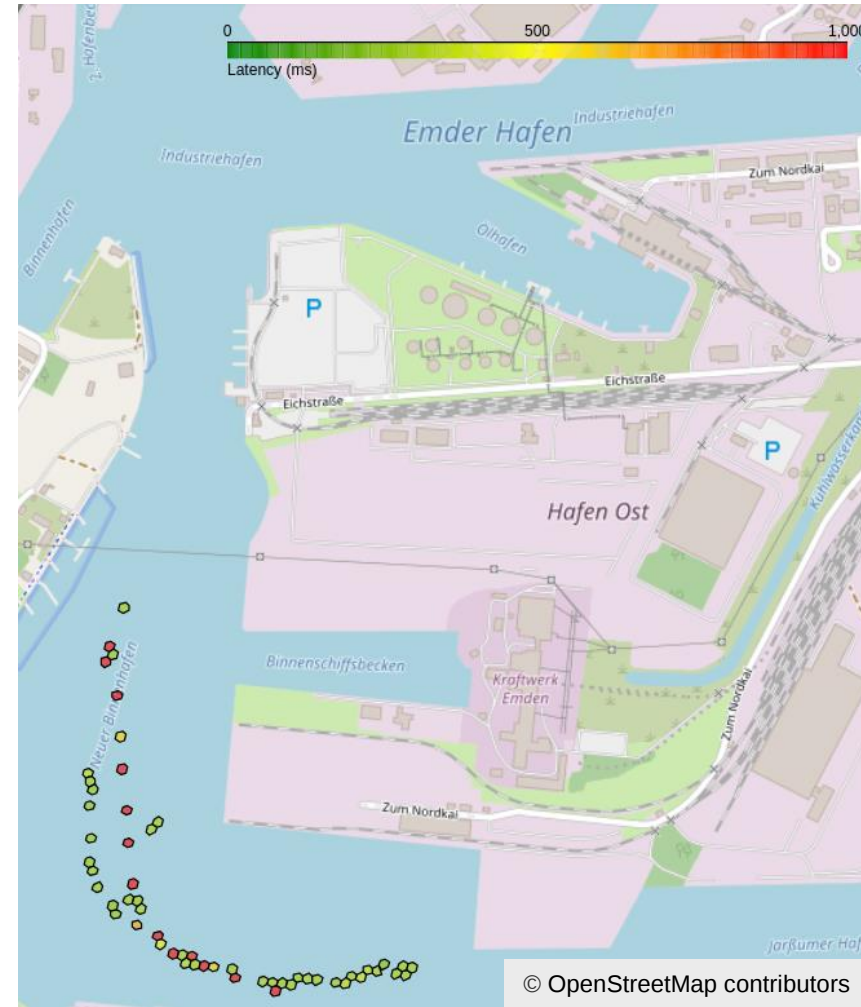


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Remote Control Latency Evaluation

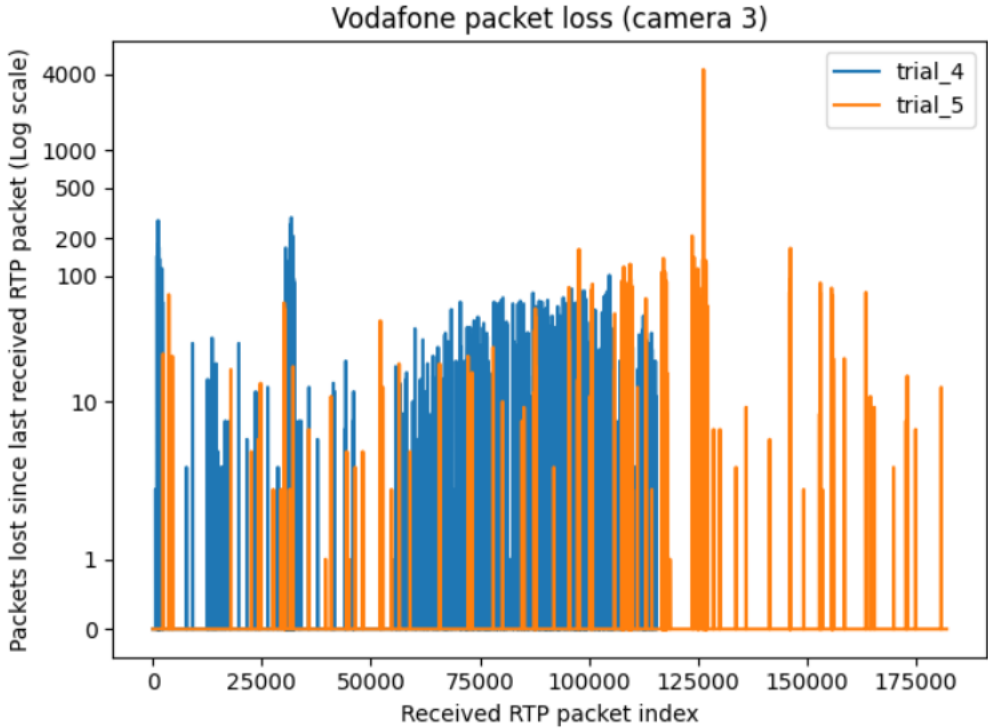
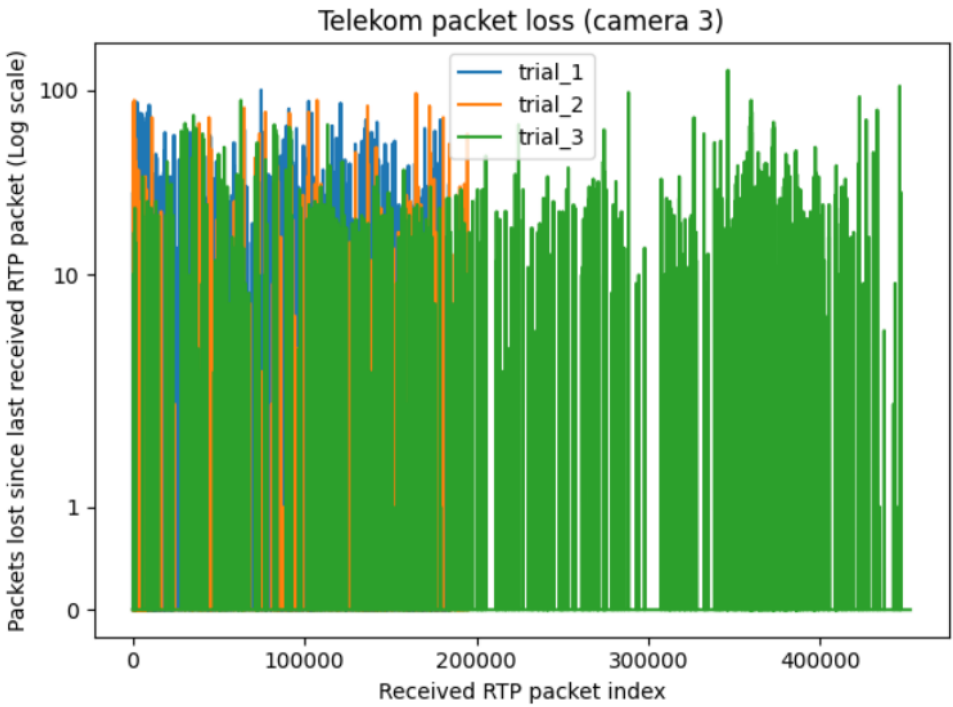
Latency (ms) for Telekom 5G (Left) and Vodafone LTE (Right)



Video Streaming Performance Evaluation



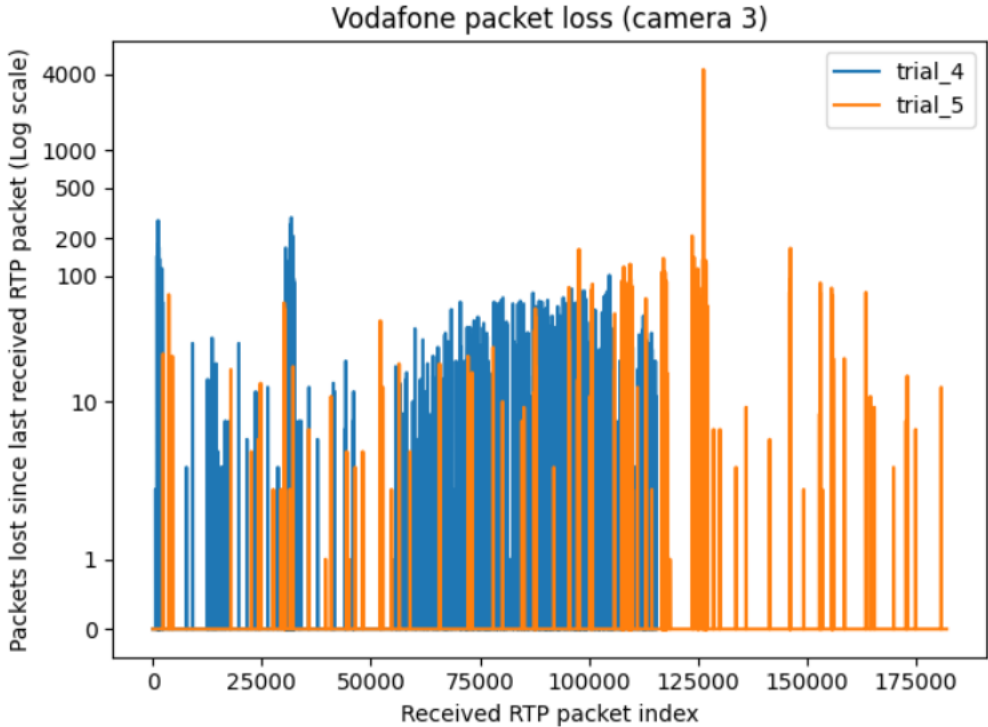
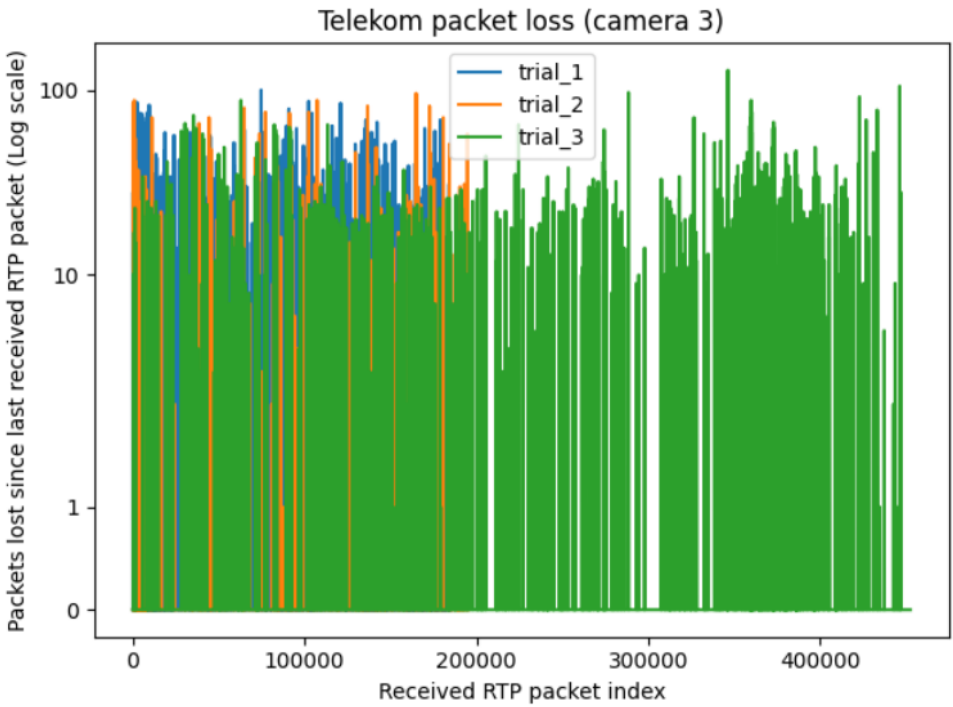
	Resolution	Compression	Mean latency (Telekom, ms)	Mean latency (Vodafone, ms)	Mean percentual packet loss (Telekom)	Mean percentual packet loss (Vodafone)
Camera 1	720p	45	68.29	90.39	3.74	22.22
Camera 2	720p	45	85.73	130.96	2.97	23.96
Camera 3	1080p	60	63.21	98.26	5.3	15.29
Camera 4	720p	60	69.96	84.6	3.83	23.4



Video Streaming Performance Evaluation



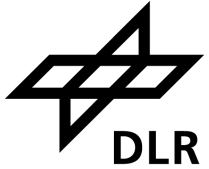
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Camera 3	1080p	60	63.21	98.26	5.3	15.29
Camera 4	720p	60	69.96	84.6	3.83	23.4



- Signal quality drops near dry docks and cranes
- Telekom 5G: latency < 2500ms for video streaming and < 1000ms RC [2]
- Vodafone LTE performance worse
 - Latencies generally in bounds but high packet loss → stream issues & connection loss
 - Confirms prior 4G vs. 5G findings [14, 22]
 - Using two ROC instances → Network load increases unreliability
 - Highlights need for message prioritization
 - Part of guidelines but not yet implemented in test setup

- Remote Operations in harbor environments using cellular networks generally within requirements of the guidelines
 - But highly depend on the used provider and technology
 - Connection metrics are varying in the harbor → Signal degradation near dry docks and cranes for both 5G and LTE
 - Still, Telekom 5G offered stable performance while Vodafone LTE resulted in high packet loss, especially under increased network load
- RC of vessels via cellular networks in harbors is feasible, stable and within requirements, provided that qualified network infrastructure is available

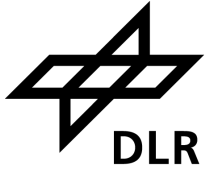
References



- [1] American Bureau of Shipping. Requirements for Autonomous and Remote Control Functions. Spring, USA: American Bureau of Shipping; 2022 2022.
- [2] Bureau Veritas. Guidelines for Autonomous Shipping: Guidance Note NI 641 DT R01 E. La Defense Cedex, France: Bureau Veritas; 2019 2019.
- [3] DNV. Autonomous and remotely operated vessels. DNV; 2024 2024.
- [4] International Maritime Organization. Autonomous shipping; 2024 [cited 2025 June 18] Available from: URL: <https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx>.
- [5] Massterly. Remote Operations Centre opened; 2024. Available from: URL: <https://www.massterly.com/archives/blog-post-title-three-mrmsx>.
- [6] Reach Subsea. Reach Remote: A major milestone for uncrewed over-the-horizon maritime operations 2024.
- [7] Kongsberg. Remote and autonomous vessels | Engineering and support: Remote & Autonomous Ship Technology; 2025 [cited 2025 June 18] Available from: URL: <https://www.kongsberg.com/maritime/shiptypes/autonomous-ships/>.
- [8] Kia G. European Space Agency - Project: SeaNext-Port of Future: Remote monitoring and control of semiautonomous vessels 2024.
- [9] Jaspersen, C. Traditionswerft Nordseewerke in Emden ist wieder insolvent; 2019 [cited 2025 September 10]. Available from: URL: <https://www.abendblatt.de/region/niedersachsen/article216227817/Traditionswerft-Nordseewerke-in-Emden-ist-wieder-insolvent.html>.
- [10] Stateczny A, Burdziakowski P. Universal Autonomous Control and Management System for Multipurpose Unmanned Surface Vessel. Polish Maritime Research 2019; 26(1): 30–9 [https://doi.org/10.2478/pomr-2019-0004]
- [11] Bertin D, Cesana P, Lucci M. U-Ranger - An Unmanned Surface Vehicle for Surface and Underwater Missions. In: Association for Unmanned Vehicle Systems International, editor. U-Ranger - An Unmanned Surface Vehicle for Surface and Underwater Missions; 2009. Red Hook, NY: Curran.

- [12] Brushane F, Ja msa K, Lafond S, Lilius J. A Experimental Research Platform for Maritime Automation and Autonomous Surface Ship Applications. IFAC-PapersOnLine 2021; 54(16): 390–4 [<https://doi.org/10.1016/j.ifacol.2021.10.121>]
- [13] Lin N, Yan X, Liu J, Li C, Li S. Research on Cyber-Physical Fusion Test and Verification for Remote-Controlled Ship. In: Research on Cyber-Physical Fusion Test and Verification for Remote-Controlled Ship; 2023. IEEE; 317–23.
- [14] Slamnik-Krijes torac N, Vandenberghe W, Masoudi-Dione N, et al. On Assessing the Potential of 5G and beyond for Enhancing Automated Barge Control. In: On Assessing the Potential of 5G and beyond for Enhancing Automated Barge Control; 2023. IEEE; 693–8.
- [15] Slamnik-Krijes torac N, Vandenberghe W, Limani X, et al. 5G-enhanced Teleoperation in Real-Life Port Environments: Lessons Learned from the 5G-Blueprint Project. In: 5G-enhanced Teleoperation in Real-Life Port Environments: Lessons Learned from the 5G-Blueprint Project; 2024. IEEE; 973–8.
- [16] Lindenbergs A, Muehleisen M, Payaro M, et al. Seamless 5G Multi-Hop Connectivity Architecture and Trials for Maritime Applications. Sensors (Basel) 2023; 23(9) [<https://doi.org/10.3390/s23094203>][PMID: 37177407]
- [17] Coccolo E, Delea C, Steinmetz F, et al. System Architecture and Communication Infrastructure for the RoboVaaS project 2022 [<https://doi.org/10.48550/arXiv.2206.11082>].
- [18] Lamm A, Piotrowski J, Hahn A. Shore based Control Center Architecture for Teleoperation of Highly Automated Inland Waterway Vessels in Urban Environments. In: Shore based Control Center Architecture for Teleoperation of Highly Automated Inland Waterway Vessels in Urban Environments; 2022. SCITEPRESS - Science and Technology Publications; 17–28
- [19] Piotrowski JA, Steger C, Hahn A. Open testbed vessel—Reusable and generic test carrier architecture for maritime testbeds. Ocean Engineering 2025; 325: 120747 [<https://doi.org/10.1016/j.oceaneng.2025.120747>]
- [20] Bundesnetzagentur. Funkanalagen und elektromagentische Felder; 2025 [cited 2025 June 13] Available from: URL: <https://www.bundesnetzagentur.de/DE/Vportal/TK/Funktechnik/EMF/start.html?p=haFjggNsYXTLQEggZOufw7yjbG5ny0AmdtwAAAABoXoPoW2oRU1GS2FydGWhbJarU3RPQkFubGFnZW6qQUZ1QW5sYWdlbqhBTVNha3RpdqhNZXNzb3J0ZbVOaWVvZXJmcmVxdWVvUEkFubGFnZW6wU21hbGxDZWxsQW5sYWdlbqFkg6FswKFpwKFz wg>.

References



- [21] Teltonika. Teltonika Networks Wiki: Mobile Signal Strength Recommendations; 2025 [cited 2025 August 8] Available from: URL: https://wiki.teltonika-networks.com/view/Mobile_Signal_Strength_Recommendations.
- [22] Tsoulos G, Athanasiadou G, Zarbouti D, Nikitopoulos G, Tsoulos V, Christopoulos N. 5G and 4G in the Field: Performance Assessment through Trials. In: 5G and 4G in the Field: Performance Assessment through Trials; 2024. IEEE; 1–4.
- [23] Magnum X. Edredon – Magnum-x [cited 2025 September 10] Available from: URL: <https://www.magnum-x.pl/artykul/edredon>.
- [24] Roland, A. TERCOFIN 2 [cited 2025 September 10] Available from: URL: [TERCOFIN 2 Cargo ship, IMO , MMSI 205251290, Call Sign PG2298 under the flag of Belgium by Maritime Database](#).

Thank you for your attention!

Contact: arne.bokern@dlr.de

Related Work

- Remote control often part of autonomous operations in trials
- Differentiation between ASV/USV and Full scale inland vessels

Unmanned Surface Vehicles (USV) or Autonomous Surface Vehicles (ASV)

- Equipped with minimal systems and sensors and generally do not consider MASS regulations
- Trials using radio communication [10, 11] and 4G technology [12] → No latency evaluation
- Detailed latency evaluation in [13] using 5G CPE → Avg latency: 27ms, use of one camera, reliability 93.1%



[23]

Full Scale Inland Vessels

- Evaluation of RC Systems using 4G and 5G connectivity in [14, 15] on Scheldt river (Antwerp) and Zelzate
 - Avg end-to-end latency: 27ms (Antwerp), 38ms (Zelzate)



[24]

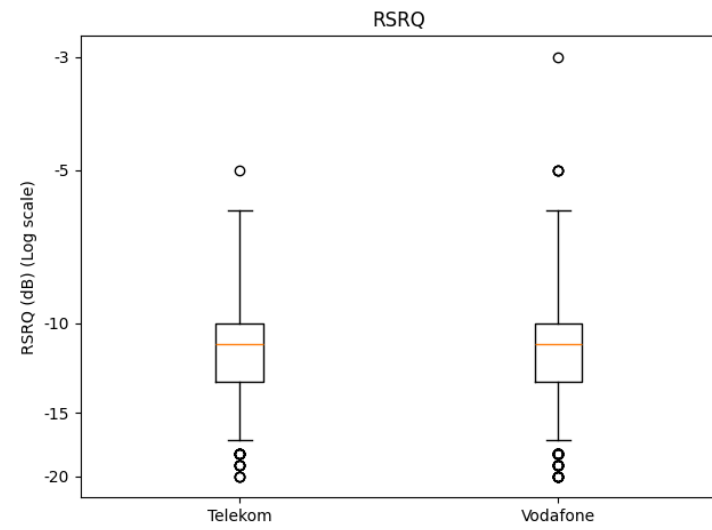
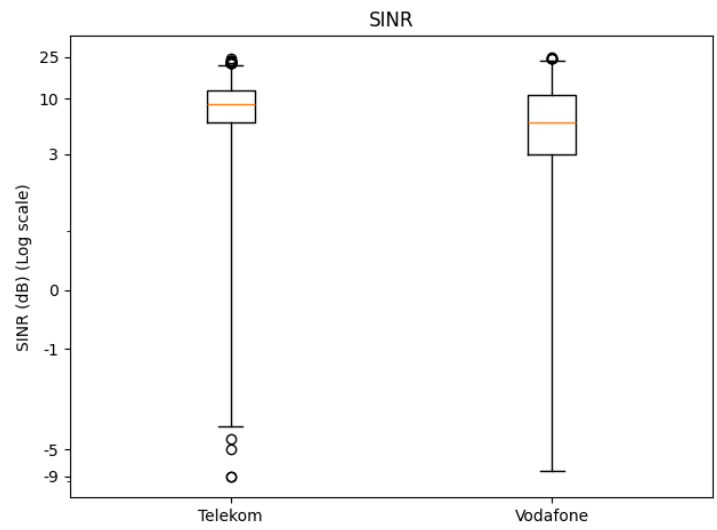
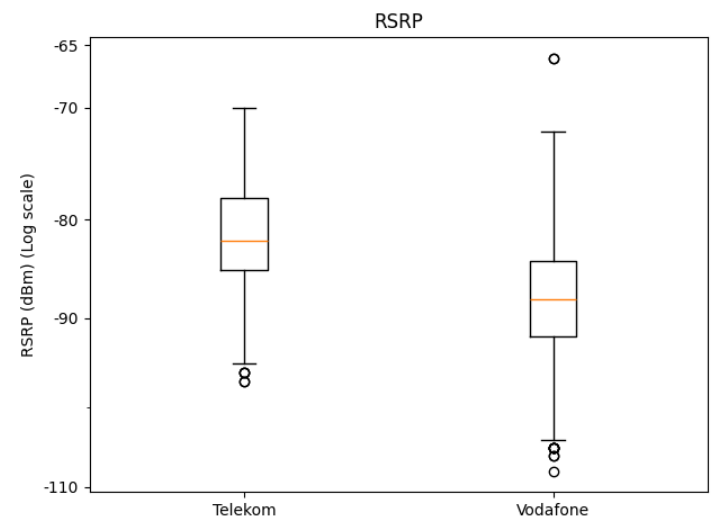
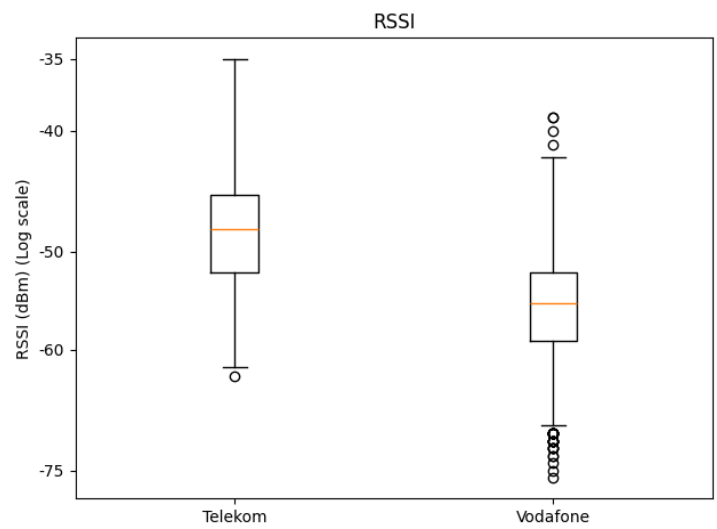
→ Generally, trials were conducted at sea, lakes or inland waterways [15, 16, 17], not in harbor environments – [14] conducted trials in Antwerp Harbor → No video evaluation or serialization latency

Backup: Connectivity Setup

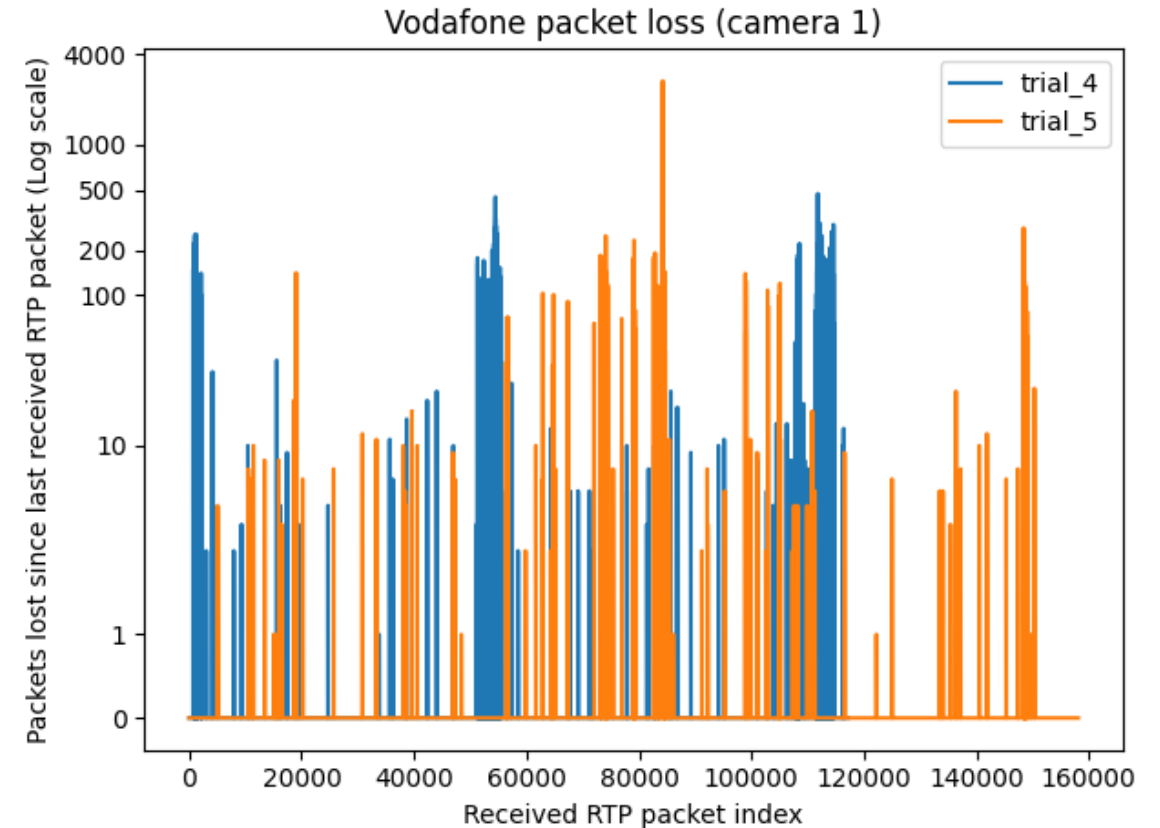
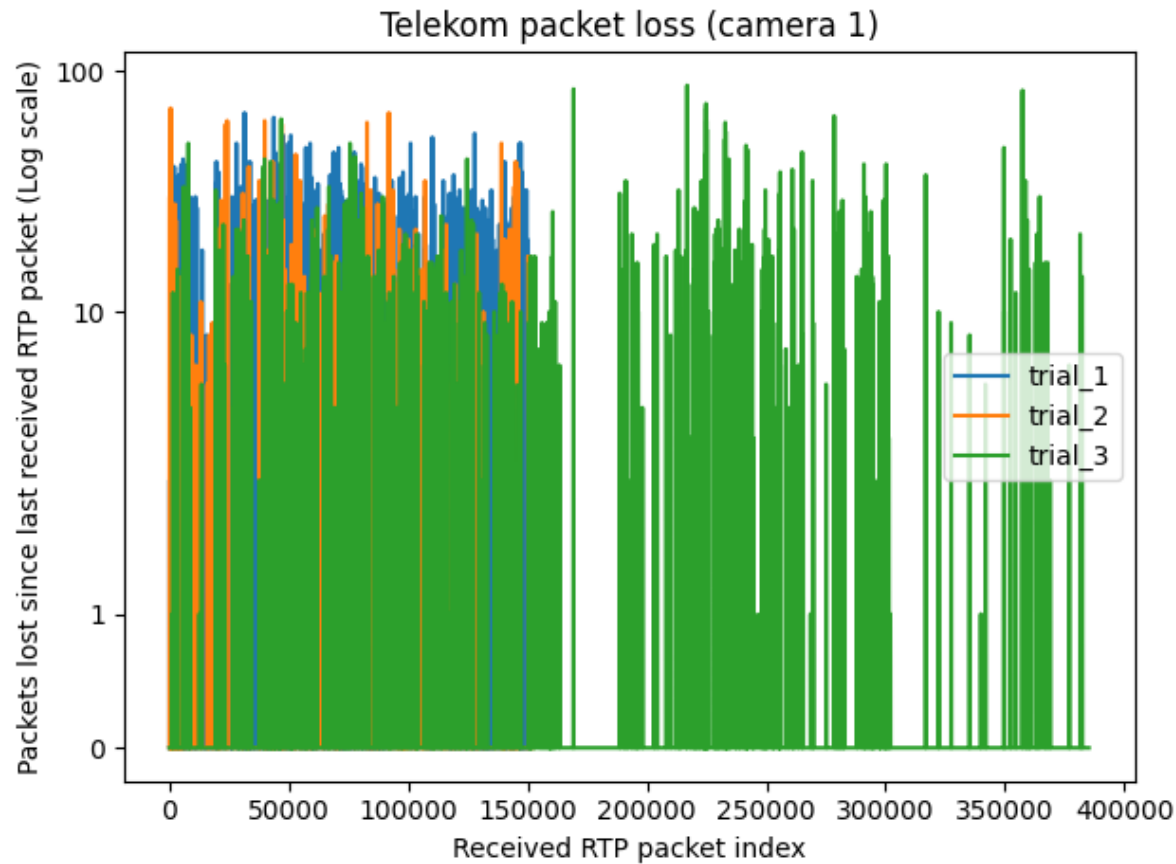
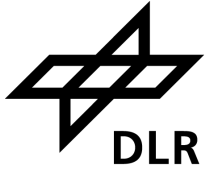
- 2x Teltonika RUTX50
- 2x Poynting XPLO-1-5G omnidirectional antenna
- Network configuration
 - Telekom 5G Network
 - Vodafone LTE Network



Backup: Metrics

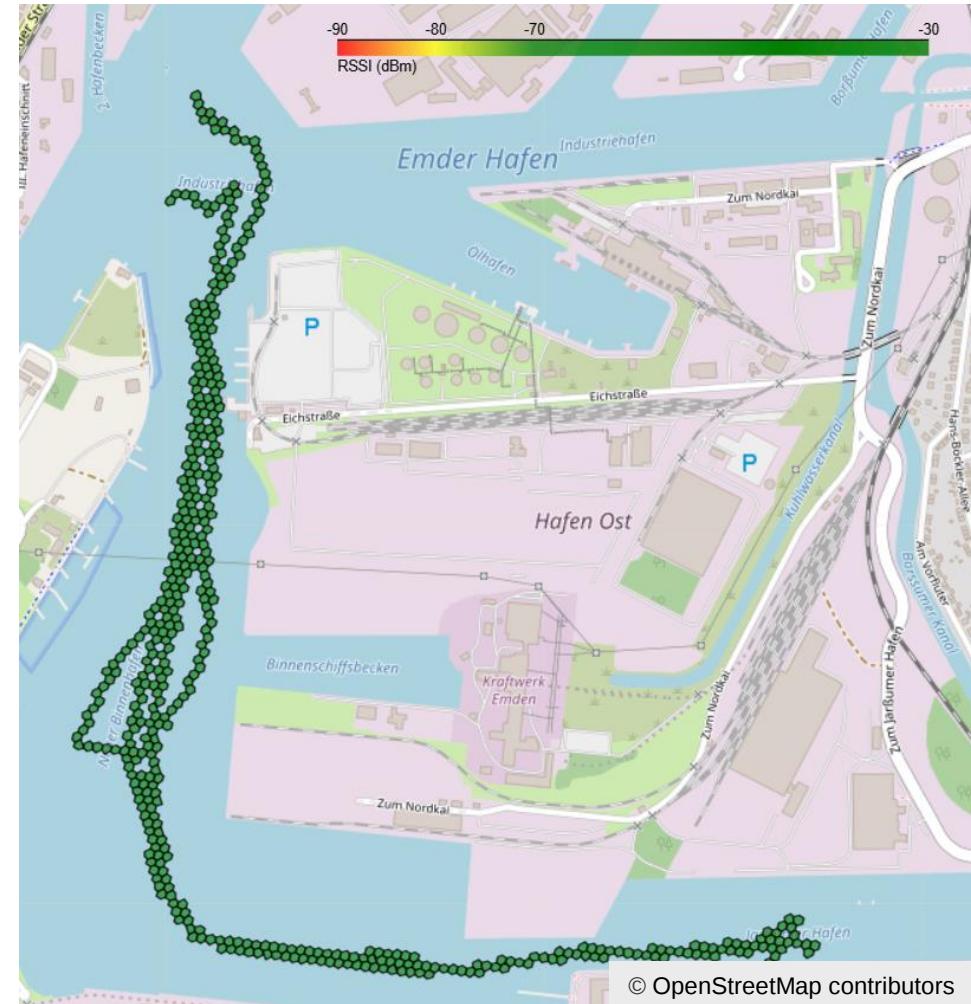
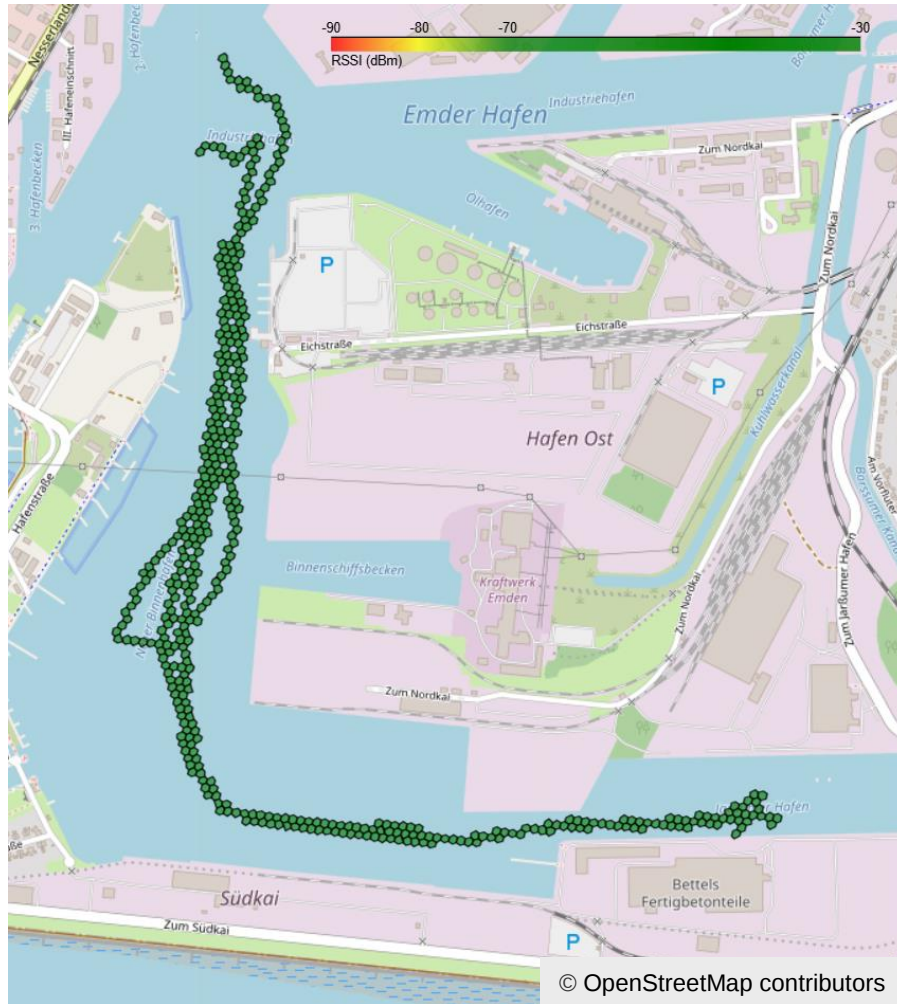


Backup: Video Streaming Performance – Packet loss Camera 1



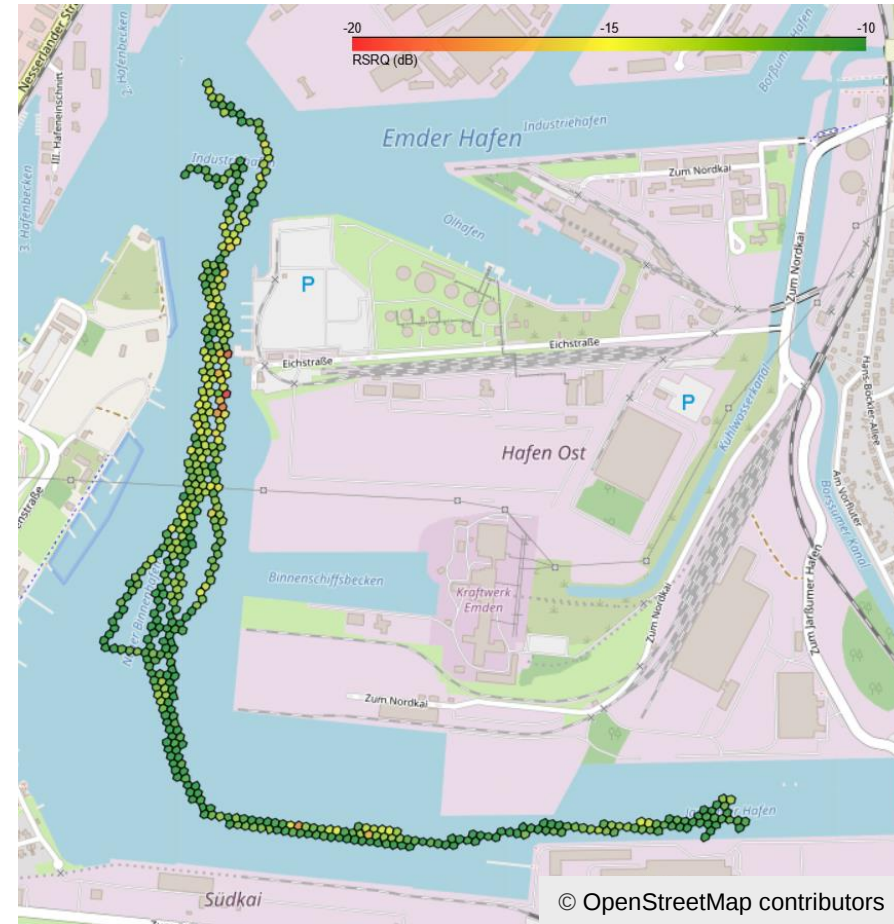
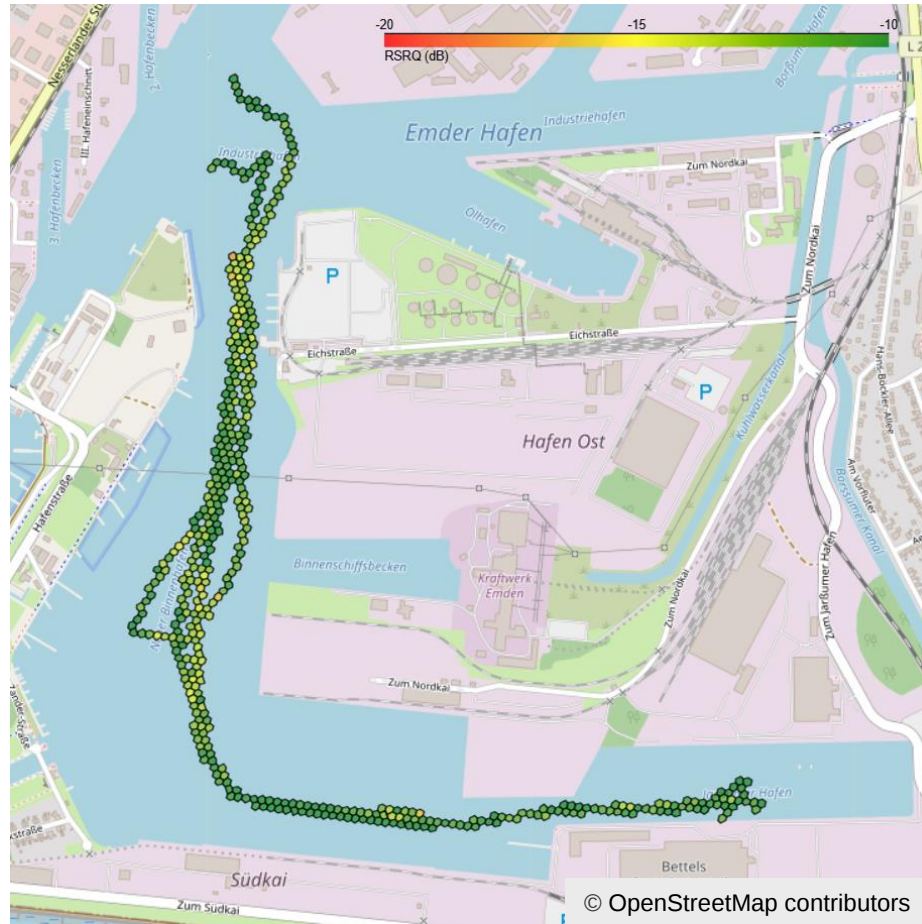
Backup: RSSI

RSSI (dBm) for Telekom 5G (Left) and Vodafone LTE (Right)



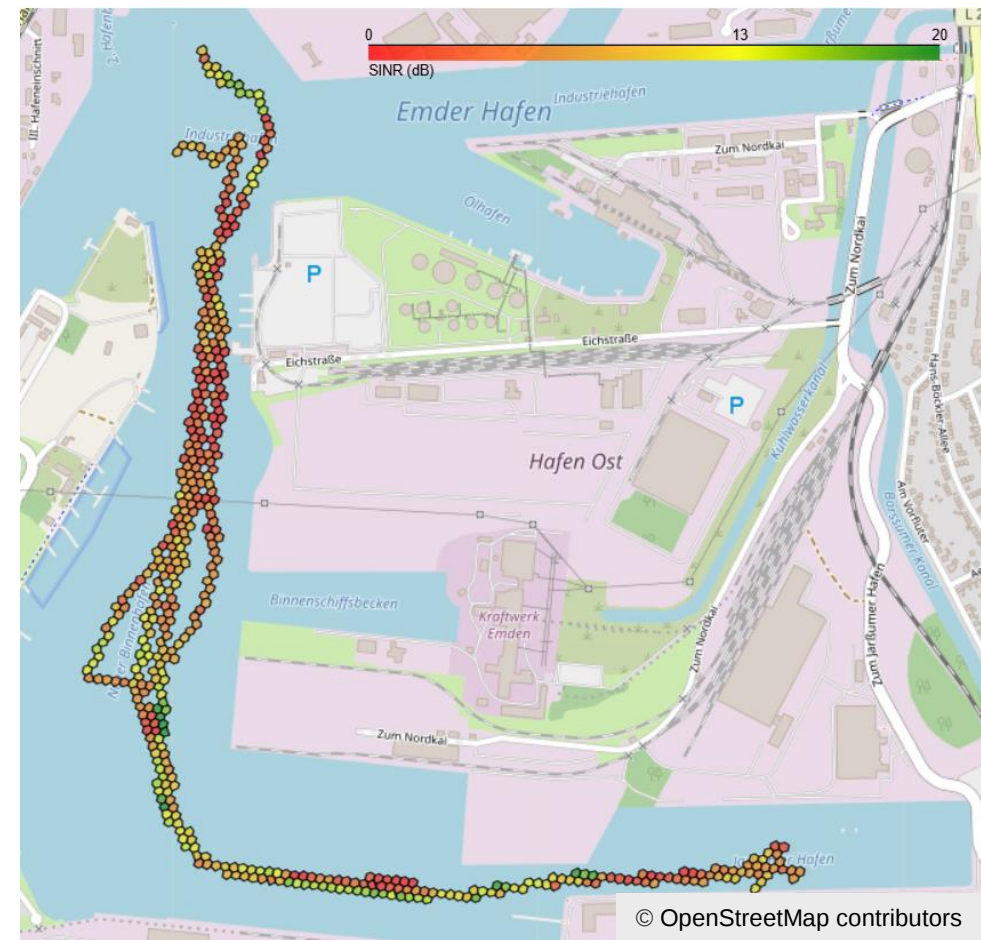
Backup: RSRQ

RSRQ (dB) for Telekom 5G (Left) and Vodafone LTE (Right)

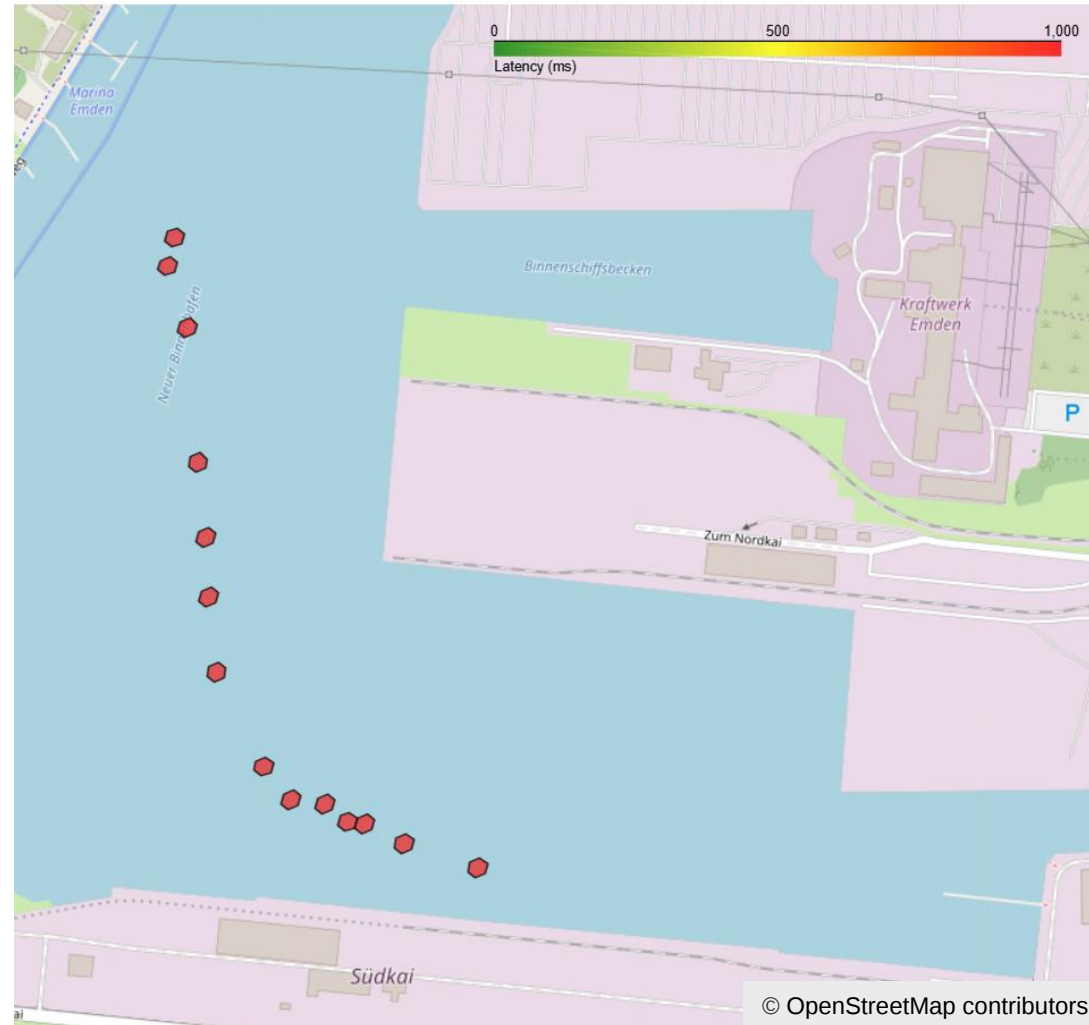


Backup: SINR

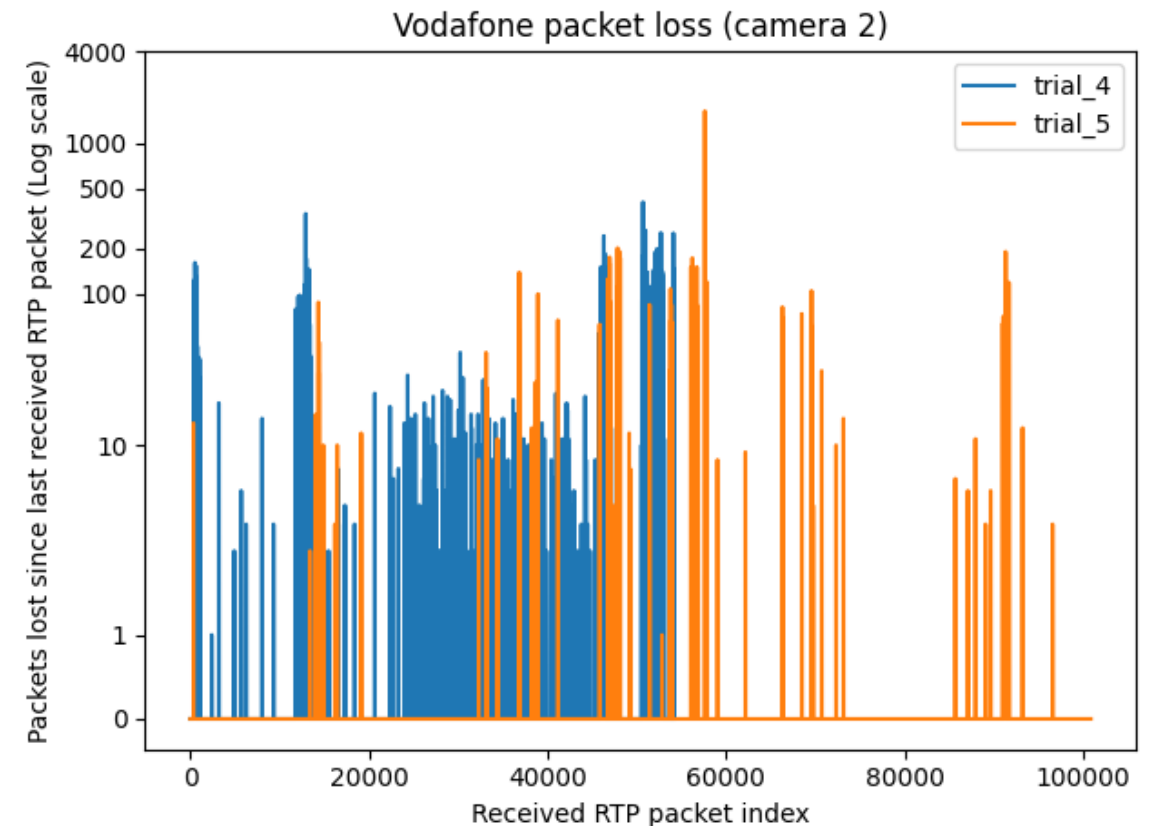
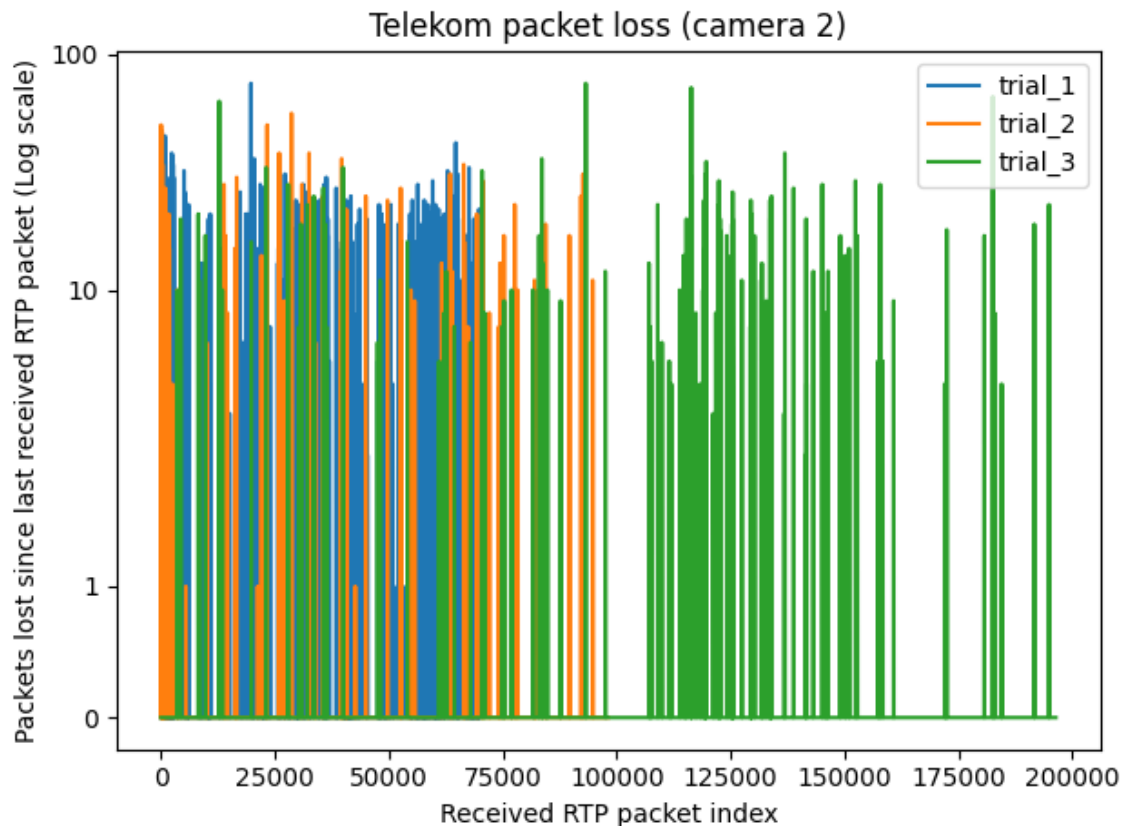
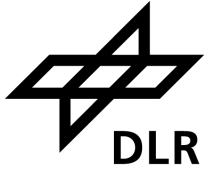
SINR (dB) for Telekom 5G (Left) and Vodafone LTE (Right)



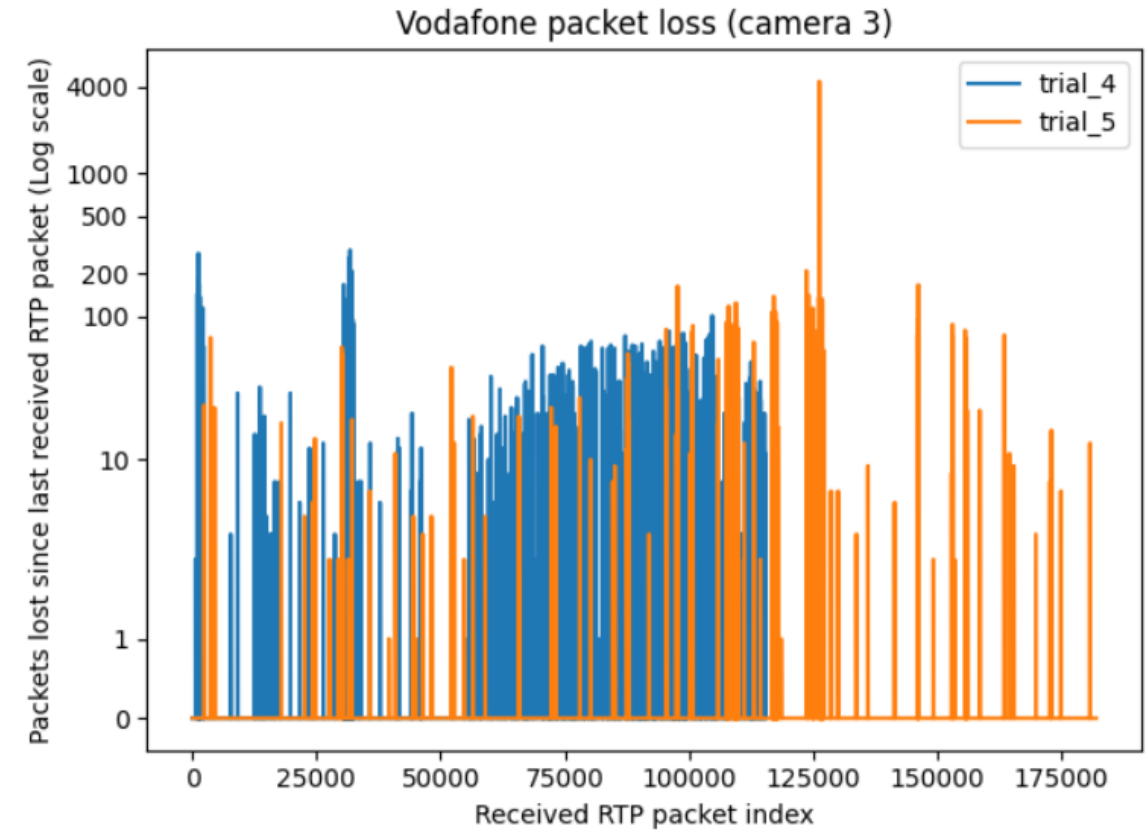
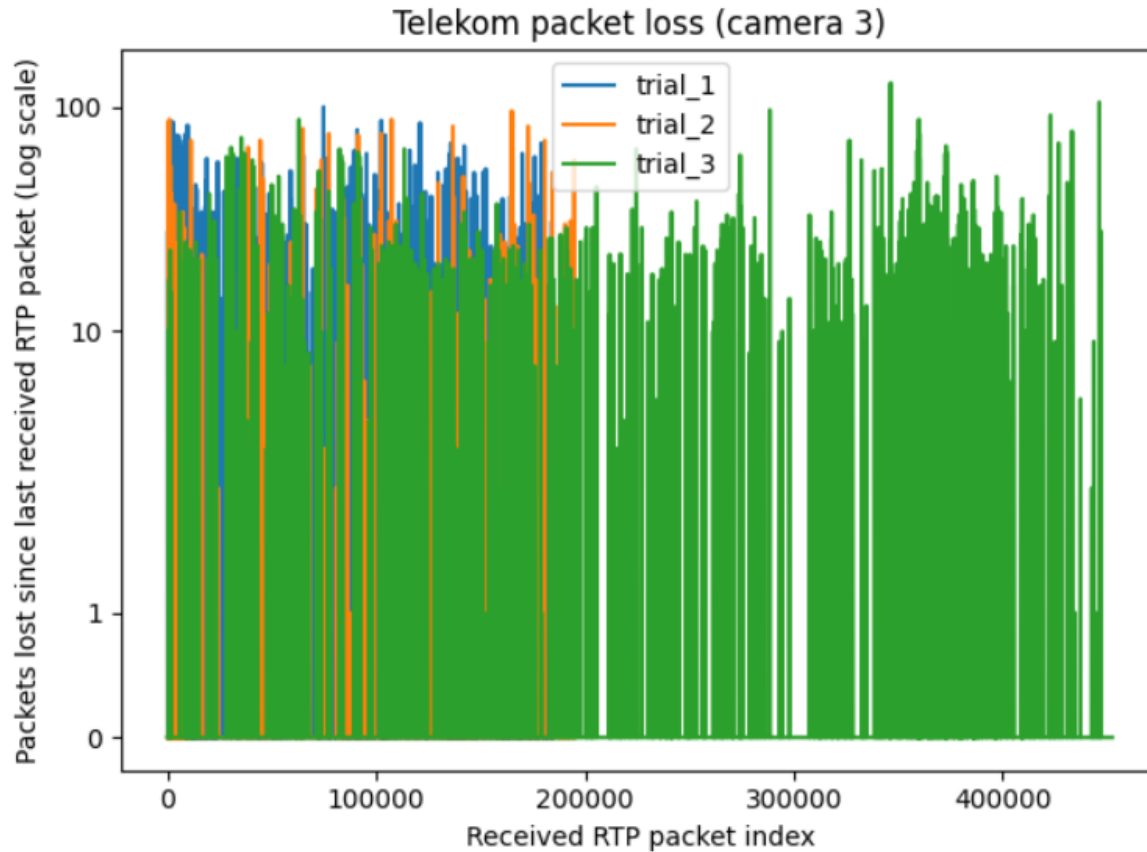
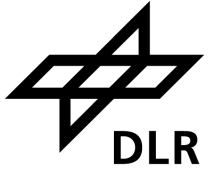
Backup: Vodafone Outliers



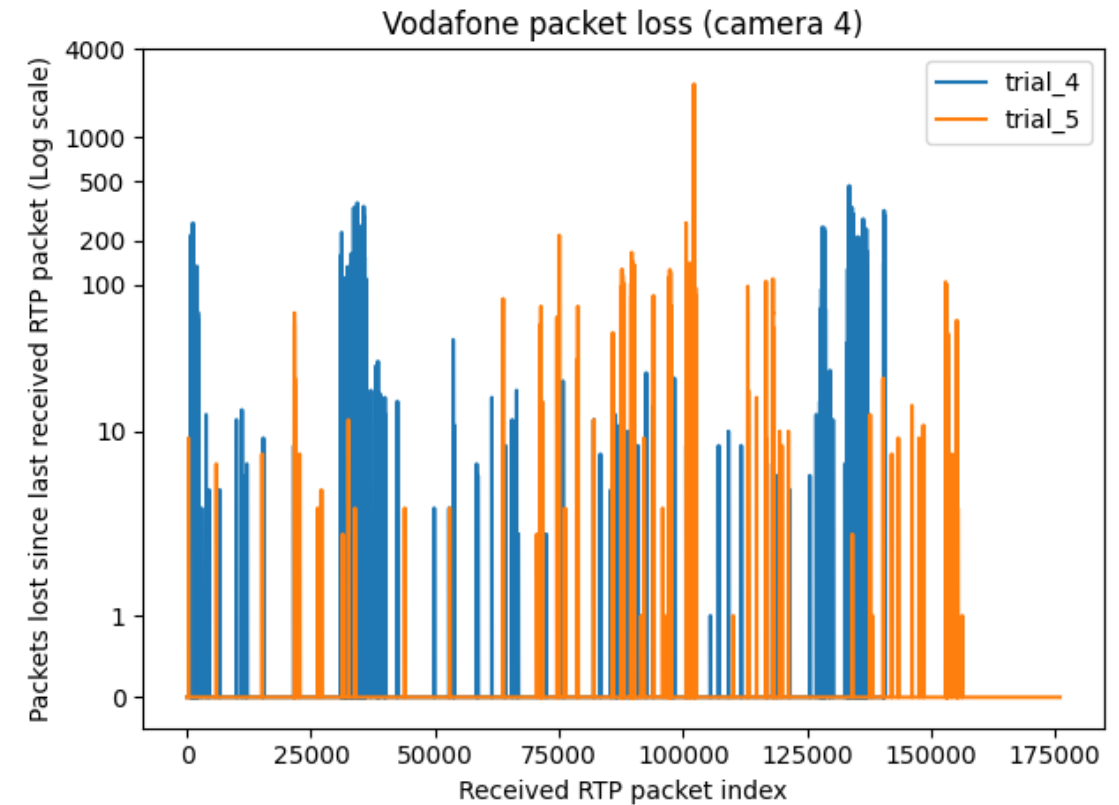
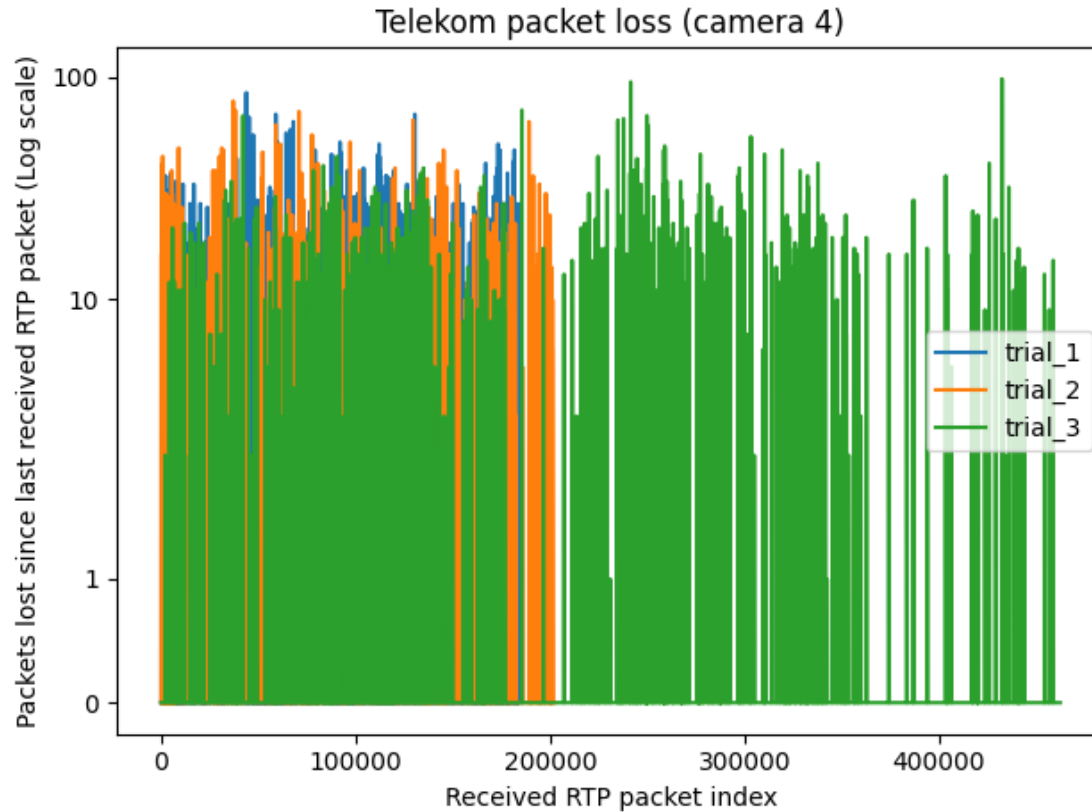
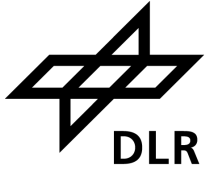
Backup: Video Streaming Performance – Packet loss Camera 2



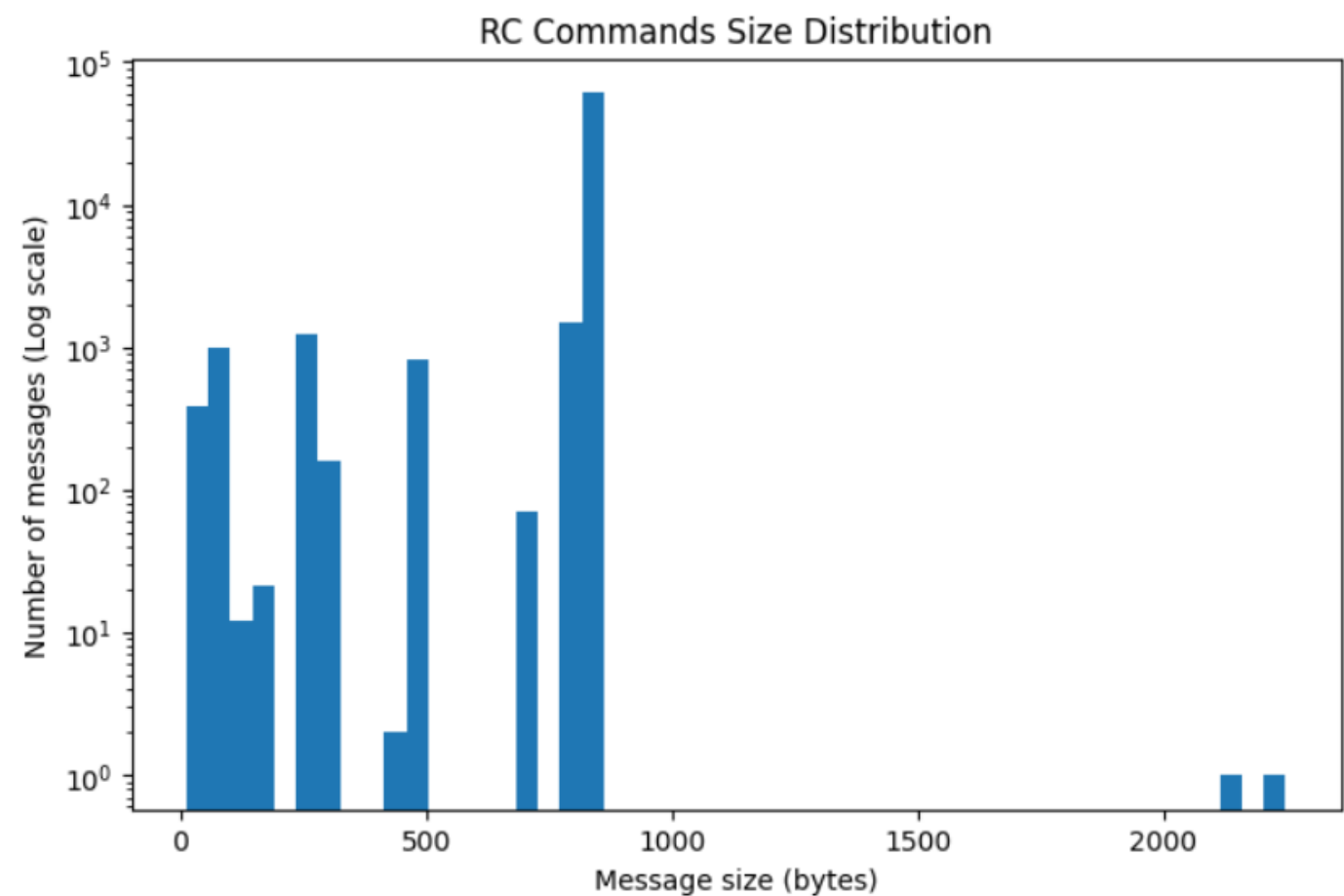
Backup: Video Streaming Performance – Packet loss Camera 3



Backup: Video Streaming Performance – Packet loss Camera 4



Backup: Message Distribution



Topic: **Advancing Remote Control Capabilities for Maritime Autonomous Surface Ships**
Insights and Lessons from Trials

Date: 2025-10-09

Author: Arne Bokern, Janusz Piotrowski, Dr.-Ing. Matthias Steidel

Institute: Systems Engineering for Future Mobility

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