International Journal of Computers and Informatics (IJCI)
Vol. (5), No. (11)
IJCI
November 2026
المجلة الدولية للحاسبات والمعلوماتية
الإصدار (5)، العدد (11)

A Condition-Aware Comparative Analysis of 4G LTE, 5G, and LiFi Networks across Different Operating Conditions

Mustafa A. Feath
Director of the Department of Studies and Planning, College of Medicine,
University of Anbar, Anbar, Iraq
azeezmustafa89@uoanbar.edu.iq

Abstract

Comparisons of performance between 4G Long-Term Evolution (LTE), fifth-generation (5G) mobile wireless networking, and Light Fidelity (LiFi) in published empirical works can frequently be challenging because performance is measured is measured within varying network architectural and environment setups. The present work solved this problem by doing a secondary analysis of the published empirical results conditionally. A comparative analysis was performed regarding commercial LTE vs. 5G NSA measurements in indoor-static, outdoor-walking and outdoor-driving scenarios. In addition, an isolated testbed experiment evaluates 5G New Radio (NR), Wi-Fi 6 and LiFi in terms of throughput, one-way latency, and interruption recovery. Also, the present analysis uses a published re-analysis of the AERPAW unmanned aerial vehicle (UAV) measurements. In the source work, a total of 5,847 measurement points and 27 LTE physical-cell identity (PCI) transitions that served as handover labels are reported, with handover-prediction area under the curve (AUC) in the range of 0.934 to 0.961 for two flight traces in the source study. Mobility metrics are separated from the rest of throughput and latency measures. The summary statistics of the Rome scenarios are computed based on arithmetic mean of operator-specific subgroup medians rather than pooling the sample means in the case of Rome measurements. There is strong dominance of 5G NSA downlink, but there are no significant benefits of 5G uplink throughput or interaction scores. The results show that in controlled testbed, LiFi produces low average one-way latency, but low average throughput too as compared to 5G NR and Wi-Fi 6.

Keywords: 4G LTE. 5G NSA, 5G NR, LiFi, Empirical Measurements, Throughput, Latency, Mobility, Network Reliability, Secondary Data Analysis.

1. Introduction

The continued growth in mobile broadband, industrial connectivity, and applications that require low latency has increased the need to evaluate wireless access technology in real-world conditions. 4G LTE remains widely deployed, while 5G introduces new radio capabilities and deployment options intended to improve capacity, coverage, and service performance. LiFi, an optical wireless communication technology, provides an alternative access medium that can complement radio-frequency systems, particularly in indoor environments.

However, nominal technology capabilities do not necessarily translate into consistent user-experienced performance. Commercial mobile-network measurements show that throughput and latency depend on frequency band, coverage, device limitations, obstruction, and deployment configuration. Rochman et al. (2023), for example, compared commercial 4G and 5G deployments in Chicago and Miami and reported that optimized mid-band 4G could achieve performance comparable to some 5G deployments, while mmWave performance was sensitive to distance, body blockage, building materials, and device heating. Highway measurements by Tsoulos et al. (2024) further demonstrate that geographical and infrastructure conditions affect 4G/5G availability and performance during travel. There is a specific set of restrictions involved with LiFi. The operation is dependent on optical path conditions, receiver position, distance between transmitter and receiver, and any possible obstructions. Experiments conducted thus far have delivered impressive results as far as office-level data rates are concerned, but at the same time line-of-sight sensitivity has been identified as a key limitation (Ungolo et al., 2025). Additionally, there has been further research on channel variations due to mobility in mobile LiFi (Ma et al., 2024). The current paper analyzes the previously published results, taking into account the specific parameters of each one of them. It considers results from commercial measurements in LTE/5G NSA and testbed measurements in 5G NR /Wi-Fi /LiFi as different sets of data.

1.1. Research Problem:

The published performance data for LTE, 5G, and LiFi come from different network architectures, operating scenarios, traffic loads, and measurement processes. Thus, trying to rank the technologies based on the performance data alone will lead to a wrong understanding of the situation. The question at hand is how to analyze the available data and maintain the distinctions made above.

1.2. Research Objectives:

1. To measure the documented differences in throughput performance of downlink and uplink operations in commercial 4G LTE and 5G NSA in three operational scenarios.
2. To analyze scenario-based changes in the documented interaction score of LTE and 5G NSA.
3. To analyze testbed measurements of 5G NR, Wi-Fi 6, and LiFi in terms of throughput and one-way delay.
4. To compile empirical findings on mobility, blockage, interruption and recovery, and UAV handover.
5. To develop a condition-aware framework for interpreting cross-technology performance data.

1.3. Research Questions:

- RQ1: How do the measured downlink and uplink throughputs for 4G LTE and 5G NSA vary in indoor-static, outdoor-walking, and outdoor-driving conditions?

- RQ2: For the studied operational scenarios, is the reported interaction score indicative of a bias toward 5G NSA?
- RQ3: What throughputs and latencies have been observed for LiFi and 5G NR in a laboratory multi-access testbed?
- RQ4: How do the factors of mobility, optical obstructions, network structure, and handover affect the interpretation of the reported results?
- RQ5: What research precautions are needed for making comparison of empirical results taken from various studies possible?

2. Related Work

2.1. Measurement-Based Comparison of 4G and 5G:

Rochman et al. (2023) carried out a measurement-based comparison of 4G and 5G deployment in Chicago and Miami. This work involved the use of low-, mid-, and high-frequency bands to assess coverage, throughput, and latency in outdoor, outdoor-to-indoor, and high-temperature scenarios. The authors stated that optimized mid-band 4G can be made to match certain 5G deployments in terms of throughput and latency. Further, they showed that mmWave throughput depends on distance, human-body blockage, low-emissivity glass, obstruction, and heating of devices. Altogether, these results imply that the generation designation is not enough for predictions.

Kousias et al. (2024) studied commercial 5G non-standalone (NSA) deployment through measurements carried out in Rome, Italy, from two mobile network operators. This campaign considered indoor static, outdoor walking, and outdoor driving scenarios as well as the performance of enhanced mobile broadband and low-latency services. The authors found increased 5G NSA downlink throughput and decreased latency compared to 4G in their measurements, as well as the influences of radio propagation, system configurations, and handovers. Subgroup medians reported in this study represent the primary source for the LTE /5G NSA comparison in the current work.

Rojas-Mora et al. (2026) have compared 4G and 5G based on the performance of these technologies using municipal level data obtained from crowdsourcing by the telecom regulator in Colombia. Their primary analysis matched 1,461 municipality–operator–reporting-period observations across 634 municipalities and assessed download speed, upload speed, latency, jitter, and packet loss. Under equal-municipality weighting, the reported 5G/4G geometric-mean ratios were 1.94 for download, 1.19 for upload, 0.90 for latency, 0.78 for jitter, and 0.68 for packet loss. This paper reveals that contrast estimates are dependent on sample selection and weighting schemes and improvements in the five parameters are not consistent. The paper provides up-to-date, geographically extensive evidence that complements field measures by operators. Its Colombian regulatory aggregates and first-half-2026 reporting windows differ from the measurement scenarios examined in the present study; its numerical results are therefore used for contextual comparison only and are not pooled with

the datasets analyzed here.

In their study on commercial 5G NSA network development, Caso et al. (2024) looked at evolution of the technology with measurement campaigns held in 2021 and 2023 and including six operators in Italy and Sweden. They found that higher deployments and more spectrum do not always lead to higher downlink throughput; coverage and connectivity could limit the performance. This study also addresses the issue of real-time gaming, augmented and virtual reality, roaming, and positioning.

2.2. Experimental Evaluation of LiFi:

An experimental study carried out by Ungolo et al. (2025) on a LiFi network involved a testbed in an office room. This research sought to establish the effects of distance, orientation of receiver and obstacles on the bit rate of a user. The maximum bit rate recorded during this experiment was 250 Mbps while sensitivity to line-of-sight and obstructions was highlighted as some major limitations of this technology. It should be noted that this bit rate is the maximum one and hence cannot be used in a comparison with average bit rates of other testbeds.

A research conducted by Ma et al. (2024) on the feasibility of mobile LiFi involved use of experimental measurements such as device rotation and movement data. The analysis carried out covered channel characteristics which vary with time, channel coherence and channel tracking schemes. The researchers found out that mobile LiFi communication could be made feasible using several photodiodes oriented at different angles. With a MIMO configuration, they were able to report a rate of 36 Mbit/s. This study is significant for the reason that it considers mobility of devices.

Alshaer and Haas (2023) proposed an experimental platform based on software-defined networking that integrates LiFi and Wi-Fi. This platform was designed to handle mobility management, traffic engineering and remote experiments.

2.3. Integrated 5G, Wi-Fi, and LiFi Testbeds:

Navarro-Ortiz et al. (2024) presented a real-equipment multi-connectivity testbed incorporating 5G NR in Standalone (SA) mode, Wi-Fi 6, and LiFi. The study used Multipath TCP (MPTCP) and developed a weighted round-robin scheduler to control traffic distribution among the wireless access technologies. In the static testbed, average downlink throughput was 342 Mbps for the high-throughput 5G configuration, 116 Mbps for the low-latency 5G configuration, 1.19 Gbps for Wi-Fi, and 12.1 Mbps for LiFi. The reported average one-way latency was 10.1 ms for 5G, 5.6 ms for low-latency 5G, 1.28 ms for Wi-Fi, and 1.08 ms for LiFi. The authors also reported MPTCP interruption recovery in the approximate range of 400–500 ms. These values are specific to the reported testbed and should not be interpreted as universal technology characteristics.

2.4. Research Gap:

The reviewed studies document commercial LTE/5G performance and experimental LiFi behavior, but they do so in different settings. Municipal scale recent research conducted by Rojas-Mora et al.

(2026) gives a broad comparison between 4G and 5G in terms of different quality of service metrics in the case of Colombian municipalities. However, this research does not compare LiFi or does not include any of the mentioned control mechanisms in the tests performed. Celluar research usually takes into account operator networks or radio coverage, while LiFi usually uses optical testbed indoors. Even if these studies provide the same metrics in different papers, their configuration might be different. In this case, mixing the information to create a ranking might lead to an invalid comparison.

This research tries to cover the gaps through a condition-aware secondary analysis which means that commercial 5G NSA and 5G NR /Wi-Fi /LiFi testbed subgroup results are analyzed separately, the descriptive scenario-level summaries are created when appropriate in the source paper, and the criteria of valid cross-study comparison are presented. It is worth noting that this research cannot replace a new experimentally verified field study.

2.5. Additional Empirical Evidence on Commercial 5G:

The following measurement campaigns extend the empirical basis from the Rome dataset. Narayanan et al. (2021) looked at commercial 5G deployments both in NSA and SA modes, in sub-6 GHz and mmWave frequency ranges, in stationary, walking, and driving mobility scenarios and compared 5G to LTE. Their findings stress the impact of the deployment mode, handovers, radio state transitions, and energy consumption of the devices on users' experience. Rischke et al. (2021) performed 5G campus network measurements of one-way packet delay and packet loss in both SA and NSA modes and made their measurement traces publicly available. Mohamed et al. (2021) carried out indoor field trials measuring 5G SA and NSA and found them to have similar latency and NSA being slightly ahead in the uplink rate among the configurations considered. All of these papers explain why it is important to separate NSA and SA.

Additional field data comes from the study by Milde and Pilinsky Zentner (2022), which compares the quality-of-experience measures of 4G and 5G NR NSA in Croatian cities; Pan et al. (2022), which examines LTE and 5G NSA and SA under high-speed railway mobility; and Moreno et al. (2024), which performs throughput measurements of 5G NSA using a commercial device and protocol analyzer. Hu et al. (2025) continue the research of mobility issues through cross-layer measurements in walking, biking, bus, tram, and driving scenarios. Another conference paper presenting the results of a field trial by Tsoulos et al. (2024b) provides simultaneously gathered 4G /5G measurements from different operators in typical operational scenarios. Khan et al. (2025) performed uplink measurements over the course of a year in eight cities across seven countries and found that 5G did not always surpass LTE in latency. Fezeu et al. (2024) provide measurements of commercial mid-band 5G deployments in Europe and the United States. All these papers support the idea of stratifying 5G performance claims based on scenarios. Al-Hameed et al. (2026) re-analyze the AERPAW 5G NSA UAV flight traces to predict handovers. Their study reports 2,949 and 2,898 samples, respectively, 27 LTE PCI transitions in total, and AUC from 0.934 to 0.961. Since this paper uses the

AERPAW dataset published by Asokan et al. (2025), it is classified as a published analysis of the same measurement campaign.

2.6. Additional LiFi and Optical Wireless Evidence:

Optical wireless research contributes to both theoretical models and experimental data. Kahn and Barry (1997) described fundamental principles of short-range wireless infrared links, including propagation, multipath, and receiver design. Komine and Nakagawa (2004) analyzed LED-based visible-light communication systems, and Zeng et al. (2009) researched optical MIMO with white LED lighting. Tsonev et al. (2013) discussed LiFi as an optical attocell networking technique, while Pathak et al. (2015) surveyed visible-light communication, networking, and sensing. All these papers provide necessary technical details, but they are not used as comparative throughput datasets. Later experimental studies address the gap between ideal optical links and real-world deployment. Fortes and González (2021) created an indoor VLC testbed where it is possible to vary the position and orientation of the receiver, demonstrating the significance of reflections and proper orientation. Ma et al. (2024) explored the possibility of mobile LiFi under the conditions of device movement and change in its orientation. Shao et al. (2015) designed a hybrid WiFi-VLC Internet access system as a solution to the problem of optical uplink. Alshaer and Haas (2023) created an experimental software-defined LiFi/Wi-Fi integration platform. Abumarshoud et al. (2020) discussed optical wireless communications as a complementary medium for cyber-secure ubiquitous wireless networks. Beguni et al. (2025) presented a VLC and smart-lighting prototype with adaptive dimming. These papers help to understand limitations of indoor LiFi deployment and role of hybrid networks, but are not used to estimate values for the Navarro-Ortiz testbed.

Boz and Manner (2020) addressed methodological problems of cellular QoS measurement, stating that the measurement results depend on the load of the cell, interference, fading, mobility, and capabilities of devices. This paper confirms the choice made in the current study to keep the context of measurements and not to use isolated speed-test values as the characteristics of the network.

Asokan et al. (2025) provided radio -frequency and throughput measurements of Ericsson 5G NSA network during UAV flight experiments. The dataset contains radio indicators, such as RSRP, SINR, CQI, and MCS, along with throughput. This paper is another example of empirical 5G data obtained in a specialized condition of mobility. It is included in the literature base, but it is not pooled with the Rome measurements due to different platform, mobility pattern, and measurement setup.

3. Methodology

3.1. Study Design:

The present research is a quantitative secondary analysis of data that has been collected using statistical calculations in scientific literature. New measurements are not conducted for this research, either by performing field research or simulation or laboratory experimentation. The secondary data analysis is performed using the reported measurements.

3.2. Evidence Identification and Eligibility:

Relevant literature was identified through selected searches of publishers' websites, institutional repositories, and bibliographic entries. Relevant search terms were “4G LTE”, “5G NSA”, “5G NR”, “LiFi”, “empirical measurement”, “field trial”, “throughput”, “latency”, “mobility”, and “testbed”. A paper was deemed relevant when it provided empirical measurement results or field trials, technology details, and performance metrics relevant to this analysis. Studies which were conceptual or based on simulations only were not used as numeric data sources. The search was selective and not systematic; it was not registered, and no claim of comprehensiveness is asserted.

3.3. Data Sources and Scope:

Empirical sources along with their use are detailed in Table 1 below. Major statistical data are derived from two measurement surveys. Kousias et al. (2024) provide operator -and scenario-specific subgroup medians for LTE, 5G Partial, and 5G NSA in Rome. Navarro -Ortiz et al. (2024) provide average throughput, one-way latency, and MPTCP interruption-recovery measurements from a controlled 5G NR SA, Wi-Fi 6, and LiFi testbed. For the UAV mobility case, Asokan et al. (2025) are cited as the source of the AERPAW dataset, while the sample counts, LTE PCI-transition counts, and handover -prediction AUC range used in this paper are taken from the published re-analysis by Al-Hameed et al. (2026). The latter uses the same AERPAW flight traces and is therefore not treated as an independent measurement campaign. The raw AERPAW CSV archive was not independently downloaded or reprocessed for this study. These evidence groups are kept separate because their architectures, environments, and measurement procedures differ.

Table (1): Overview of empirical evidence sources and their roles in the analysis.

Study	Technology	Environment / design	Metrics used here
Kousias et al. (2024)	4G LTE; 5G NSA; 5G Partial	Commercial networks; Rome; indoor static, outdoor walking, outdoor driving	DL, UL, interaction score
Navarro-Ortiz et al. (2024)	5G NR SA; Wi-Fi 6; LiFi	Real-equipment controlled testbed; static measurements	Average DL throughput; one-way latency; interruption recovery range
Rochman et al. (2023)	4G LTE; 5G SA/NSA	Commercial deployments in Chicago and Miami	Contextual evidence: coverage, throughput, latency
Tsoulos et al. (2024)	4G; 5G	Approx. 180-km highway field route; three operators	Contextual evidence: availability and radio quality
Tsoulos et al. (2024a)	4G; 5G	Typical town settings; multi-operator measurements	Contextual evidence: throughput, network quality
Caso et al. (2024)	5G NSA	Two measurement phases; six operators in Italy and Sweden	Contextual evidence: deployment evolution and service performance
Ungolo et al. (2025)	LiFi	Real office testbed	Maximum measured bit rate; distance/orientation/obstruction
Ma et al. (2024)	Mobile LiFi	Measured movement and rotation data; experimental channel analysis	Contextual evidence: channel coherence and MIMO rate

Study	Technology	Environment / design	Metrics used here
Alshaer & Haas (2023)	LiFi; Wi-Fi	Experimental software-defined integration platform	Contextual evidence: mobility and traffic engineering
Asokan et al. (2025)	5G NSA (LTE/NR)	AERPAW UAV flight; 30 m altitude; two yaw orientations	Dataset metadata and variable inventory only; not numerically analyzed
Al-Hameed et al. (2026)	5G NSA	Two AERPAW UAV flight traces; published re-analysis of Asokan et al. (2025) data	LTE PCI transitions and handover-prediction AUC; not throughput/latency
Rojas-Mora et al. (2026)	4G; 5G	Municipal-level crowdsourced measurements; 634 municipalities in Colombia	External contextual evidence: download, upload, latency, jitter, packet loss; not pooled with the principal datasets

3.4. Data Extraction and Harmonization:

For Kousias et al. (2024), the extracted values were the published operator- and scenario-specific subgroup medians for downlink throughput, uplink throughput, and interaction score; LTE, 5G Partial, and 5G NSA were retained as separate configurations. The throughput and one-way-latency values for the 5G NR SA, Wi-Fi 6, and LiFi testbed were transcribed from Navarro-Ortiz et al. (2024). For the AERPAW flights, the sample counts and LTE PCI-transition counts were taken from Al-Hameed et al. (2026): 2,949 samples and 15 transitions for yaw45, and 2,898 samples and 12 transitions for yaw315. The reported AUC range of 0.934–0.961 was recorded as a model-prediction metric. No raw AERPAW CSV observations were recalculated.

The measurements were not pooled across studies. In particular, the Rome commercial 5G NSA results were kept separate from the 5G NR testbed results. Likewise, the LiFi maximum bit rate reported by Ungolo et al. (2025) was not averaged with the mean LiFi throughput reported by Navarro-Ortiz et al. (2024). Round-trip time (RTT) and one-way latency were also treated as different measures.

3.5. Descriptive Calculations:

For each Rome scenario, the study calculated the arithmetic mean of the two operator-specific subgroup medians reported by Kousias et al. (2024). For example, the indoor-static LTE downlink summary is (36.30 + 31.95)/2 = 34.125 Mbps. The former is a median of subgroups whereas the latter is a mean pooling the actual observations. The ratio for downlink was computed by dividing the 5G NSA summary by the LTE summary. Interaction score differences are given in percentages. For AERPAW, the frequency of transition PCI per sample was calculated as (transition count / sample count) × 1,000. Since the denominator is the number of transitions rather than the elapsed time, this metric does not represent any transition rate per unit of time. AUCs are taken from Al-Hameed et al. (2026).

The inferential tests, confidence intervals, and standard deviations were not computed. No data is provided that could be used for calculation of these statistics since the extracted subgroup medians cannot serve as actual observations.

3.6. Condition-Aware Interpretation Framework:

Each result is classified using four attributes: (1) network architecture and access technology; (2) operating environment and mobility; (3) performance metric and its definition; and (4) evidence type, such as a raw-data analysis, reported median, reported mean, maximum value, or qualitative finding. Numerical comparisons are made only when the measurement definitions and experimental conditions are sufficiently similar. Otherwise, the findings are presented side by side without pooling.

4. Results

4.1. Commercial 4G LTE and 5G NSA Throughput:

Table (2): Published subgroup median throughput values from Kousias et al. (2024).

Scenario	Operator	Technology	DL (Mbps)	UL (Mbps)
Indoor static	Op1	4G LTE	36.3	8.74
Indoor static	Op1	5G NSA	618.5	13.9
Indoor static	Op2	4G LTE	31.95	22.8
Indoor static	Op2	5G NSA	455.0	23.15
Outdoor walking	Op1	4G LTE	27.15	23.95
Outdoor walking	Op1	5G NSA	527.0	18.8
Outdoor walking	Op2	4G LTE	20.7	31.6
Outdoor walking	Op2	5G NSA	254.5	10.7
Outdoor driving	Op1	4G LTE	37.4	26.0
Outdoor driving	Op1	5G NSA	372.0	11.3
Outdoor driving	Op2	4G LTE	27.3	24.1
Outdoor driving	Op2	5G NSA	340.5	17.1

The detailed operator-level measurements are presented in Table 2. Figure 1 and Table 3 provide the corresponding scenario-level downlink summaries. Table 2 shows that the 5G NSA downlink medians are higher than the corresponding LTE medians for both operators in all three scenarios. The uplink pattern is different: LTE exceeds 5G NSA in both outdoor mobility scenarios for both operators, while indoor results are close or favor 5G NSA depending on the operator.

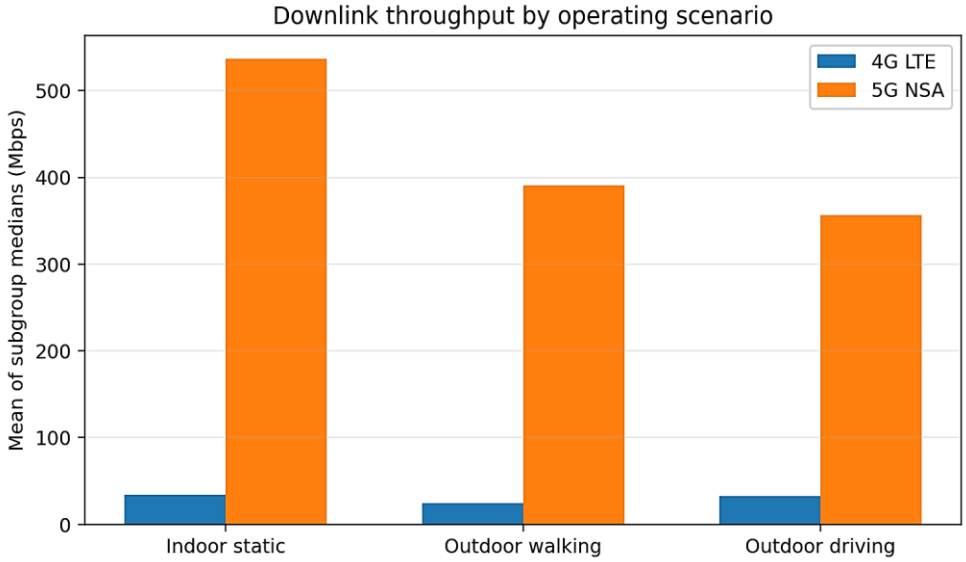


Figure (1): Scenario-level mean of operator-specific downlink subgroup medians. The plotted values are descriptive summaries, not pooled sample means.

Table (3): Descriptive downlink comparison derived from the published subgroup medians.

Scenario	4G LTE DL (Mbps)	5G NSA DL (Mbps)	5G/LTE ratio
Indoor static	34.13	536.75	15.73×
Outdoor walking	23.93	390.75	16.33×
Outdoor driving	32.35	356.25	11.01×

4.2. Uplink Throughput:

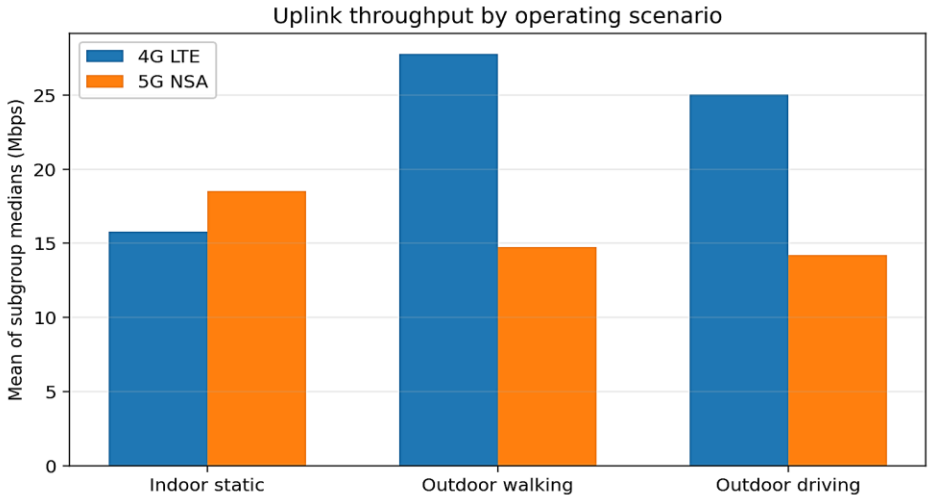


Figure (2): Scenario-level mean of operator-specific uplink subgroup medians.

Table (4): Descriptive uplink comparison derived from the published subgroup medians.

Scenario	4G LTE UL (Mbps)	5G NSA UL (Mbps)
Indoor static	15.77	18.53
Outdoor walking	27.78	14.75
Outdoor driving	25.05	14.20

The scenario-level uplink results are summarized in Figure 2 and Table 4. The uplink results do not reproduce the strong downlink advantage. The 5G NSA scenario summary is slightly higher indoors, whereas LTE has higher uplink summaries during walking and driving. This asymmetry is important for applications involving uploads, uplink video, sensing, or interactive services.

4.3. Interaction Score:

Table (5): Published interaction-score subgroup medians. 5G Partial is kept separate from full 5G NSA.

Scenario	Operator	4G LTE (%)	5G Partial (%)	5G NSA (%)
Indoor static	Op1	65.50	65.10	70.70
Indoor static	Op2	61.40	85.30	86.50
Outdoor walking	Op1	58.40	52.20	71.40
Outdoor walking	Op2	65.20	44.40	46.00
Outdoor driving	Op1	59.55	58.35	75.75
Outdoor driving	Op2	67.60	59.90	83.40

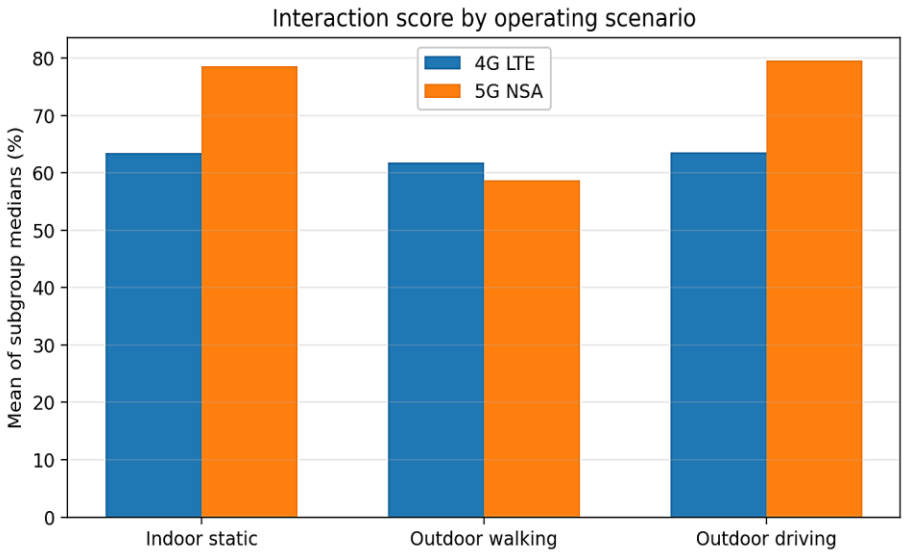


Figure (3): Scenario-level mean of operator-specific interaction-score subgroup medians.

Table (6): Descriptive interaction-score comparison.

Scenario	4G LTE (%)	5G NSA (%)	Difference (percentage points)
Indoor static	63.45	78.60	+15.15
Outdoor walking	61.80	58.70	−3.10
Outdoor driving	63.58	79.58	+16.00

The interaction scores obtained from the source are shown in Table 5. Figure 3 and Table 6 show the scenario-specific descriptive statistics. Interaction score comparison depends on the scenario. In the 5G NSA scenario, the interaction score is higher when indoors and while driving but is lower while walking. The interaction score is maintained as the service-related composite indicator as defined in the source study and is not renamed to latency/packet loss.

4.4. Controlled-Testbed Results for 5G NR, Wi-Fi 6, and LiFi:

Table (7): Static testbed results reported by Navarro-Ortiz et al. (2024).

Wireless access technology/configuration	Average downlink throughput	Average one-way latency
5G NR SA (high-throughput configuration)	342 Mbps	10.10 ms
5G NR SA (low-latency configuration)	116 Mbps	5.60 ms
Wi-Fi 6	1.19 Gbps	1.28 ms
LiFi	12.1 Mbps	1.08 ms

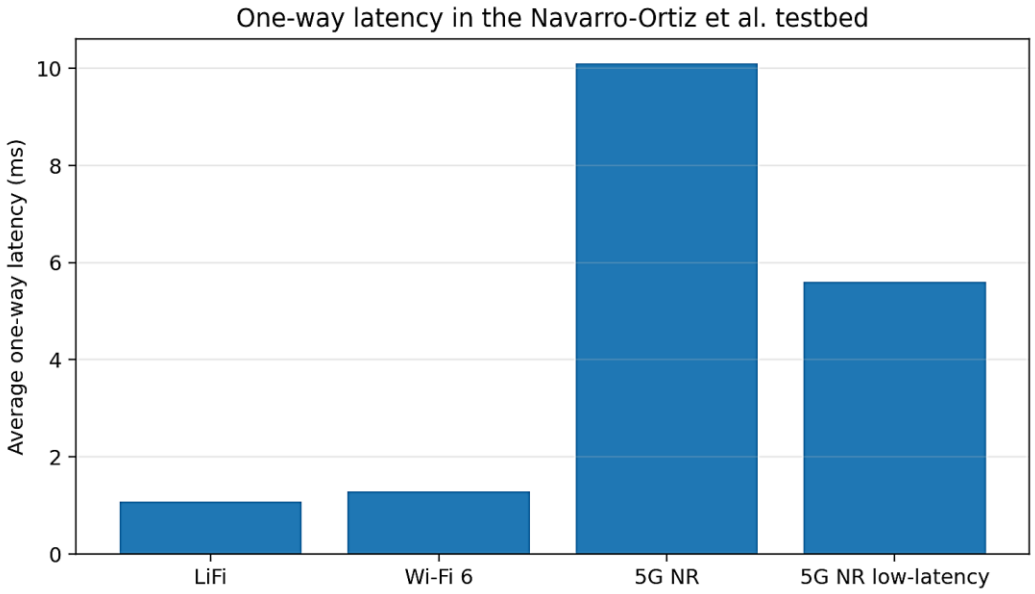


Figure (4): Average one-way latency reported in the Navarro-Ortiz et al. (2024) testbed.

Comparison of latency times is illustrated in Figure 4, whereas Table 7 provides throughput and latency values for each testbed setup. In static testbeds, LiFi demonstrated the least average latency time (1.08 ms), which was slightly followed by Wi-Fi 6 (1.28 ms). Standard 5G NR latency time is 10.1 ms, and low-latency 5G NR latency is 5.6 ms. As for throughput, the order was different: Wi-Fi 6 achieved a throughput of 1.19 Gbps, high-throughput 5G NR of 342 Mbps, low-latency 5G NR of 116 Mbps, and LiFi of 12.1 Mbps. These results illustrate a testbed-specific throughput/latency trade-off. They do not establish a universal ranking because the technologies were tested with different radio/optical configurations and environmental controls.

The authors report that the LiFi throughput varied between 5 and 20 Mbps in their setup. The same paper reports a 5G NR high-throughput configuration and a separate low-latency configuration. These must remain separate rows because they represent different configurations.

4.5. Interruption Recovery:

Navarro-Ortiz et al. (2024) report average MPTCP reconnection times of 393.3 ms for Wi-Fi, 504.8 ms for LiFi, and 517.2 ms for 5G NR SA. These are MPTCP reconnection times after an interruption and are distinct from the time required to associate with or register to the wireless network. The values are specific to the tested hardware, firmware, drivers, and MPTCP implementation; they should not be interpreted as universal handover delays.

4.6. Independent Open 5G NSA Dataset: Scope and Analytical Status:

The scope and variables in the open AERPAW dataset, along with the analytical context of the dataset in this manuscript, are summarized in Table 8. Asokan et al. (2025) published an open dataset consisting of Ericsson 5G NSA measurements from a zigzag flight UAV testbed at an altitude of 30 meters. The measurements cover the application-layer throughput, LTE and NR RSRP/SINR, and NR CQI, MCS, and rank-indicator measurements, with synchronization of UAV telemetry data. The variables make the dataset appropriate for analysis of relationships between the radio environment, UAV orientation, and throughput in case of aerial mobility. At the same time, the present manuscript verified the description and file structure of the dataset only; the processing of CSV records was not performed in the present study. Hence, the dataset is considered an identified open-data source that is not applied to calculate means/medians and other statistics.

This dataset is an independent evidentiary source rather than the new set of analyzed data. By providing the dataset, we increase the openness of available reproducible data without making unfounded statements in numbers.

Table (8): Open AERPAW dataset: documented scope and status.

Dataset attribute	Documented information	Potential analysis	Status in this study
Platform and condition	Ericsson 5G NSA; UAV zigzag flight; 30 m altitude; two yaw orientations	Stratified throughput and RF analysis by orientation/flight segment	Metadata screened; no raw-record calculations
Application performance	Throughput CSV and iperf3 logs	Distribution, median/percentiles, throughput variation	Not calculated
Radio/channel indicators	LTE/NR RSRP and SINR; NR CQI, MCS, RI	Association between radio quality and throughput	Not calculated
Mobility/context	Timestamp, GPS position, altitude, yaw, and UAV telemetry	Spatial/temporal stratification and mobility-context analysis	Not calculated

4.7. Aerial Mobility and Handover Evidence from AERPAW:

The flight-level sample counts, PCI-transition counts, and derived sample-normalized frequencies are presented in Table 9. Al-Hameed et al. (2026) re-analyzed two real AERPAW UAV flight traces collected over an Ericsson 5G NSA network. The yaw45 trace contained 2,949 samples and 15 observed LTE physical-cell identity (PCI) transitions, which the source study used as handover labels, whereas the yaw315 trace contained 2,898 samples and 12 LTE PCI transitions, likewise used as handover labels. The corresponding descriptive frequencies are 5.09 and 4.14 PCI transitions per 1,000 recorded samples, respectively, with a total of 27 transitions in 5,847 samples (4.62 PCI transitions per 1,000 samples). These ratios provide an indication of events relative to recorded samples and should not be confused as time-normalized transition rates or as an indicator that every transition was a successful handover. In addition, the source study reports a 5-s look-ahead prediction task and AUC in the range of 0.934–0.961 for the flight-level evaluations. AUC is a metric used to indicate the discrimination power of the predictive model; it does not provide an indication of network availability, throughput, latency, or handover success probability. Because this study uses the same AERPAW traces reported by Asokan et al. (2025), these two works are not considered separate measurement campaigns.

Table (9): Published AERPAW flight-level PCI-transition counts and derived sample-normalized frequencies.

Flight trace	Samples	Observed LTE PCI transitions	PCI transitions per 1,000 samples	Published model AUC
yaw45	2,949	15	5.09	Not separately reported
yaw315	2,898	12	4.14	Not separately reported
Combined	5,847	27	4.62	0.934–0.961 (reported range across evaluations)

Note. For the source study, the LTE PCI transitions have been considered as handover events for prediction purposes. The sample normalized frequencies are calculated based on the published number of events and samples. They are not time normalized rates, nor do they indicate that each transition was a successful handover. The AUC range has been taken from Al-Hameed et al. (2026); the publication does not give AUC for each flight separately. These figures are not pooled with the Rome commercial network sub-group medians or indoor 5G NR /LiFi testbeds.

5. Discussion

5.1. Downlink and Uplink Are Not Interchangeable Performance Indicators:

For the Rome campaign, the average median for the operator-specific 5G NSA downlink was around 11.01 to 16.33 times the LTE summary, based on the scenario. The uplink results were different: LTE had the higher summary in both outdoor mobility scenarios. Thus, downlink throughput alone would give an incomplete account of the comparison. This pattern is consistent with field studies showing that observed cellular performance varies with deployment, radio conditions, and network configuration (Rochman et al., 2023; Tsoulos et al., 2024a, 2024b).

5.2. Mobility and Service-Interaction Performance:

The interaction score does not show a uniform 5G NSA advantage. Its 5G NSA summary was higher indoors and while driving, but lower during outdoor walking. The walking result is important because it shows that higher downlink throughput does not necessarily correspond to a higher score for the service interaction measured by Kousias et al. (2024). The score is composite and should not be interpreted as a substitute for RTT, packet delay variation (PDV), or packet loss.

5.3. LiFi and 5G NR in the Controlled Testbed:

In the Navarro-Ortiz et al. (2024) testbed, LiFi had the lowest reported average one-way latency, but its average throughput was below the tested 5G NR and Wi-Fi 6 configurations. The same study reported LiFi throughput between 5 and 20 Mbps. This does not conflict with the 250 Mbps maximum reported by Ungolo et al. (2025): the studies used different LiFi implementations, and one value is an average range while the other is a maximum. The figures therefore describe different experimental conditions rather than a common performance scale.

5.4. Mobility and Optical Blockage:

Office measurements by Ungolo et al. (2025) show that LiFi performance is affected by line-of-sight conditions and physical obstacles. Ma et al. (2024) examined mobility-related channel variation and the use of multiple photodiodes to mitigate changes in device orientation. In a separate hybrid testbed, Alshaer and Haas (2023) integrated LiFi with Wi-Fi, illustrating how radio-frequency access can provide an alternative path when the optical link is obstructed. Together, these studies identify alignment, movement, and optical blockage as relevant deployment considerations.

5.5. Condition-Aware Interpretation:

The evidence examined here does not justify a universal ranking of LTE, 5G, and LiFi. In the Rome campaign, 5G NSA had higher downlink summaries, whereas LTE had higher uplink summaries during walking and driving. In the separate indoor testbed, LiFi had the lowest average one-way latency but the lowest average throughput among the compared access technologies. However, the results of the AERPAW reassessment provide a different kind of evidence in studying LTE PCI handovers used as handover indicators and the performance of prediction models instead of comparing users' throughput and latency. It proves that technology evaluation should include consideration of the operating conditions and mobility factors. However, these findings do not prove that any access technology is better than the other technologies.

6. Proposed Condition-Aware Evidence Framework

Table (10): Condition-aware dimensions and rules for interpreting cross-study evidence.

Dimension	Indicators	Context that must be retained	Comparison rule
Throughput	Downlink and uplink rate	Direction, test duration, traffic type, operator, access configuration	Compare directly only under sufficiently matched tests
Latency	RTT or one-way delay	Measurement endpoint, synchronization method, protocol, load	Never mix RTT and one-way delay
Stability	PDV and jitter	Packet definition, sampling interval, traffic pattern	Use source-specific definitions
Reliability	Packet loss, missed packets, interruptions	Loss threshold, delay budget, recovery mechanism	Do not equate packet loss with interaction score
Mobility	Static, walking, driving, device movement	Speed, route, coverage, handover behavior	Stratify by mobility scenario
Architecture	LTE, 5G NSA, 5G SA/NR, LiFi, hybrid access	Core/RAN configuration and integration mode	Do not merge NSA and SA without justification
Evidence type	Raw records, median, mean, maximum, qualitative result	Sample size and summary-statistic type	Do not calculate unavailable variance or significance

Table 10 shows the dimensions and decision rules used in the evidence framework. This framework was developed for classifying and interpreting existing research findings and has not been tested for predictive validity nor for use as a scoring system. There is no claim of a universal suitability score.

To provide some background, Table 11 provides the 5G-to-4G ratios from the Colombian study at the municipal level. This data is provided as background and is not combined with the measurements used in this paper.

Table (11): Municipal-level 5G-to-4G geometric-mean ratios reported for Colombia by Rojas-Mora et al. (2026).

Performance indicator	5G/4G geometric-mean ratio
Download speed	1.94
Upload speed	1.19
Latency	0.90
Jitter	0.78
Packet loss	0.68

Note. Ratios are reported under equal-municipality weighting. Values below 1.00 indicate a lower reported 5G value than 4G for that indicator; for latency, jitter, and packet loss, lower values generally represent better performance. These ratios summarize the external study and are not direct estimates from the datasets analyzed in this manuscript. Source: Rojas-Mora et al. (2026).

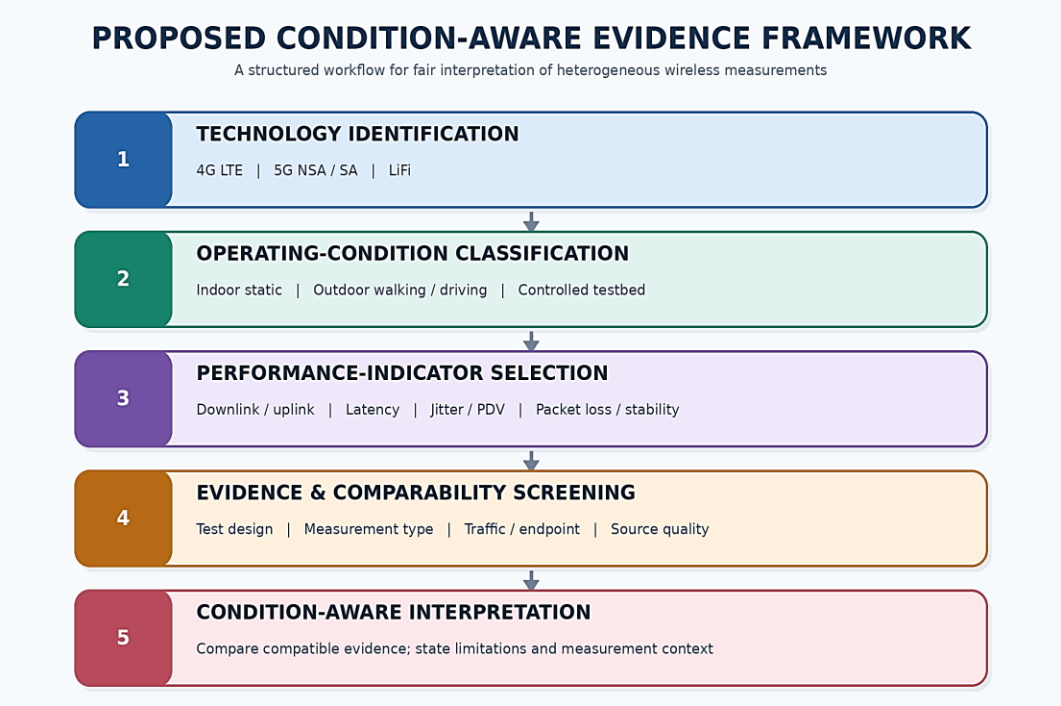


Figure (5): Suggested Condition-Sensitive Evidence Model to Compare Wireless Access Techniques.

The framework establishes the comparison through five subsequent stages: (1) identification of the access technology, (2) classification of the operating conditions, (3) selection of performance measures, (4) assessment of the comparability of the underlying data, and (5) interpretation of the findings based on the measurement context. In this research, it is applied as an analysis model for the synthesis of published measurements. This framework is used for this research and has not been independently validated via a new experiment.

7. Limitations

- This study is based on past measurement data and does not include any new experiments or simulations. The main number comparisons used come from Kousias et al. (2024) and Navarro-Ortiz et al. (2024), along with the AERPAW transition statistics provided by Al-Hameed et al. (2026). The latter study reuses the flight traces released by Asokan et al. (2025), so it does not constitute an independent measurement campaign. The raw AERPAW CSV files were not processed in this study because the repository download endpoint returned an access error. AERPAW values are therefore identified as source-reported results, except for the sample-normalized ratios calculated from the published counts.
- LTE/5G NSA commercial measurements and 5G NR /LiFi testbed measurements were not collected in a common environment. They are consequently analyzed as separate evidence groups

rather than as a direct head-to-head comparison.

- The Rome scenario summaries are arithmetic means of two operator-specific subgroup medians. They should not be interpreted as pooled means of all measurements.
- In some cases, individual data points and compatible variance estimates could not be obtained, thus, inferential tests and confidence intervals could not be calculated from the reported information.
- There were different hardware setups, optical configurations, and experimental conditions in the LiFi experiments which means that the maximum bit rate obtained in one setup could not be compared to the average throughput obtained in another.
- The literature search was specific and targeted rather than a systematic review; therefore, the study is not claiming to find all the publications on the topic.
- The suggested framework offers a system for structuring the information and creating rules of comparison, but it has not been validated using a new measurement campaign.

8. Conclusion and Future Work

This work provides a review of scientific articles on LTE, 5G, and LiFi in their empirically-measured conditions. While in the commercial-network Rome case, the downlink subgroup medians of 5G NSA were noticeably higher than those of the LTE network, both uplink and interaction-score cases differed. Moreover, in the second indoor study, LiFi had a lower average one-way latency and lower average throughput compared to 5G NR SA and Wi-Fi 6 in their respective configurations. These observations only refer to the studied cases and do not create a universal rank of technologies under consideration. In the AERPAW case study re-analysis, there were 27 LTE PCI transitions used as handovers with 5,847 samples, while the range of AUC scores for the handover prediction was 0.934–0.961.

Thus, these results are different from the throughput and latency scores. The comparisons show that mere technology labels cannot be used for assessing wireless performance; network architectures, mobility, and traffic conditions must be taken into account, and definition of the measurement to be able to correctly interpret the results. The AERPAW data archive will be useful to use for future raw data analysis; however, its CSV records were not analyzed in this paper. Hence, the proposed framework can be seen as a way of structuring the available evidence. A reasonable next step would involve collecting and analyzing Asokan et al. (2025) data of AERPAW in CSV format directly. This would involve timestamp matching, segmenting of flights based on orientation and movement, distribution of throughputs, and association of throughputs with the radio indicators such as SINR, RSRP, CQI, and MCS. Moreover, it would enable a separate evaluation of the flight traces used for the handover prediction in Al-Hameed et al. (2026). Concerning LiFi, further cross-study analysis will require extra experimental measurements with sufficient equivalence in terms of the

measurement setup and definition of the measure.

References

- Abumarshoud, H., Chen, C., Islim, M. S., & Haas, H. (2020). Optical wireless communications for cyber-secure ubiquitous wireless networks. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 476(2242), Article 20200162. https://doi.org/10.1098/rspa.2020.0162
- Al-Hameed, A. A., Abdulfattah, A. N., Alhazmi, A. S., Showail, A. J., Younus, S. H., & Ahmed, M. A. (2026). Explainable and physics-aligned handover prediction for cellular-connected UAV networks. IEEE Open Journal of Vehicular Technology, 7, 1917–1931. https://doi.org/10.1109/OJVT.2026.3702540
- Alshaer, H., & Haas, H. (2023). An end-to-end experimental software-defined LiFi and Wi-Fi networks integration platform. In 2023 IEEE Wireless Communications and Networking Conference (WCNC). IEEE. https://doi.org/10.1109/WCNC55385.2023.10119054
- Asokan, R., Fahim Raouf, A. H., Ozdemir, O., Guvenc, I., & Sichitiu, M. (2025). Ericsson 5G NSA network RF and throughput measurements on AERPAW network [Data set]. Dryad. https://doi.org/10.5061/dryad.wh70rxx06
- Beguni, C., Zadobrischi, E., & Cailean, A.-M. (2025). Merging visible light communications and smart lighting: A prototype with integrated dimming for energy-efficient indoor environments and beyond. Sensors, 25(19), Article 6046. https://doi.org/10.3390/s25196046
- Boz, E., & Manner, J. (2020). A hybrid approach to QoS measurements in cellular networks. Computer Networks, 172, Article 107158. https://doi.org/10.1016/j.comnet.2020.107158
- Caso, G., Rajiullah, M., Kousias, K., Ali, U., Bouzar, N., De Nardis, L., Brunstrom, A., Alay, Ö., Neri, M., & Di Benedetto, M.-G. (2024). the chronicles of 5G non-standalone: An empirical analysis of performance and service evolution. IEEE Open Journal of the Communications Society, 5, 7380–7399. https://doi.org/10.1109/OJCOMS.2024.3499370
- Fezeu, R. A. K., Fiandrino, C., Ramadan, E., Carpenter, J., Coelho de Freitas, L., Bilal, F., Ye, W., Widmer, J., Qian, F., & Zhang, Z.-L. (2024). Unveiling the 5G mid-band landscape: From network deployment to performance and application QoE. In Proceedings of the ACM SIGCOMM 2024 Conference (pp. 358–372). Association for Computing Machinery. https://doi.org/10.1145/3651890.3672269
- Fortes, M., & González, O. (2021). Testbed for experimental characterization of indoor visible light communication channels. Electronics, 10(11), Article 1365. https://doi.org/10.3390/electronics10111365

- Hu, J., Wang, L., Wu, J., Pei, Q., Liu, F., & Li, B. (2025). A comparative measurement study of cross-layer 5G performance under different mobility scenarios. Computer Networks, 257, Article 110952. https://doi.org/10.1016/j.comnet.2024.110952
- Kahn, J. M., & Barry, J. R. (1997). Wireless infrared communications. Proceedings of the IEEE, 85(2), 265–298. https://doi.org/10.1109/5.554222
- Khan, I., Ghoshal, M., Angjo, J., Dimce, S., Hussain, M., Parastar, P., Yu, Y., Deng, X., Hawal, S., Huang, S., Rane, A., Wang, Y., Fiandrino, C., Orfanidis, C., Aggarwal, S., Aguiar, A. C., Alay, O., Chiasserini, C. F., Dressler, F., . . . Widmer, J. (2025). How mature is 5G deployment? A cross-sectional, year -long study of 5G uplink performance. Computer Communications, 237, Article 108153. https://doi.org/10.1016/j.comcom.2025.108153
- Komine, T., & Nakagawa, M. (2004). Fundamental analysis for visible-light communication system using LED lights. IEEE Transactions on Consumer Electronics, 50(1), 100–107. https://doi.org/10.1109/TCE.2004.1277847
- Kousias, K., Rajiullah, M., Caso, G., Alay, O., Brunstrom, A., Ali, U., De Nardis, L., Neri, M., & Di Benedetto, M.-G. (2024). Empirical performance analysis and ML-based modeling of 5G non-standalone networks. Computer Networks, 241, Article 110207. https://doi.org/10.1016/j.comnet.2024.110207
- Ma, S., Sheng, H., Sun, J., Li, H., Liu, X., Qiu, C., Safari, M., Al-Dhahir, N., & Li, S. (2024). Feasibility conditions for mobile LiFi. IEEE Transactions on Wireless Communications, 23(7), 7911–7923. https://doi.org/10.1109/TWC.2023.3346056
- Milde, A., & Pilinsky Zentner, S. (2022). Comparison of 4G and 5G NR NSA QoE measurements in Croatian cities. In Proceedings of the 64th International Symposium ELMAR 2022 (pp. 13–18). IEEE. https://doi.org/10.1109/ELMAR55880.2022.9899789
- Mohamed, R., Zemouri, S., & Verikoukis, C. (2021). Performance evaluation and comparison between SA and NSA 5G networks in indoor environment. In 2021 IEEE International Mediterranean Conference on Communications and Networking (MeditCom) (pp. 112–116). IEEE. https://doi.org/10.1109/MeditCom49071.2021.9647621
- Moreno, J., Contini, M., & Aguiar, A. (2024). 5G NSA performance: A measurement study. In 2024 19th Wireless On-Demand Network Systems and Services Conference (WONS). IEEE. https://doi.org/10.23919/WONS60642.2024.10449590
- Narayanan, A., Zhang, X., Zhu, R., Hassan, A., Jin, S., Zhu, X., Zhang, X., Rybkin, D., Yang, Z., Mao, Z. M., Qian, F., & Zhang, Z.-L. (2021). A variegated look at 5G in the wild: Performance, power, and QoE implications. In Proceedings of the ACM SIGCOMM 2021 Conference (pp. 610–625). Association for Computing Machinery. https://doi.org/10.1145/3452296.3472923

- Navarro-Ortiz, J., Ramos-Muñoz, J. J., Delgado-Ferro, F., Canellas, F., Camps-Mur, D., Emami, A., & Falaki, H. (2024). Combining 5G New Radio, Wi-Fi, and LiFi for Industry 4.0: Performance evaluation. Sensors, 24(18), Article 6022. https://doi.org/10.3390/s24186022
- Pan, Y., Li, R., & Xu, C. (2022). The first 5G-LTE comparative study in extreme mobility. Proceedings of the ACM on Measurement and Analysis of Computing Systems, 6(1), Article 20. https://doi.org/10.1145/3508040
- Pathak, P. H., Feng, X., Hu, P., & Mohapatra, P. (2015). Visible light communication, networking, and sensing: A survey, potential and challenges. IEEE Communications Surveys & Tutorials, 17(4), 2047–2077. https://doi.org/10.1109/COMST.2015.2476474
- Rischke, J., Sossalla, P., Itting, S., Fitzek, F. H. P., & Reisslein, M. (2021). 5G campus networks: A first measurement study. IEEE Access, 9, 121786–121803. https://doi.org/10.1109/ACCESS.2021.3108423
- Rochman, M. I., Sathya, V., Fernandez, D., Nunez, N., Ibrahim, A. S., Payne, W., & Ghosh, M. (2023). A comprehensive analysis of the coverage and performance of 4G and 5G deployments. Computer Networks, 237, Article 110060. https://doi.org/10.1016/j.comnet.2023.110060
- Rojas-Mora, J. M., Bru-Cordero, O. E., & Correa-Álvarez, C. D. (2026). Comparative performance assessment of 4G and 5G mobile networks: Evidence from municipal-level measurements in Colombia. Telecom, 7, Article 145. https://doi.org/10.3390/telecom7060145
- Shao, S., Khreishah, A., Rahaim, M. B., Elgala, H., Ayyash, M., Little, T. D. C., & Wu, J. (2015). An indoor hybrid WiFi-VLC internet access system. In Proceedings of the 11th IEEE International Conference on Mobile Ad Hoc and Sensor Systems (pp. 569–574). IEEE. https://doi.org/10.1109/MASS.2014.76
- Tsonev, D., Videv, S., & Haas, H. (2013). Light fidelity (Li-Fi): Towards all-optical networking. In B. B. Dingel & K. Tsukamoto (Eds.), Broadband access communication technologies VIII (Vol. 9007, Article 900702). SPIE. https://doi.org/10.1117/12.2044649
- Tsoulos, G., Athanasiadou, G., Nikitopoulos, G., Tsoulos, V., & Zarbouti, D. (2024). Empirical insights into 5G deployments in highway operational environments and comparative performance with 4G. Electronics, 13(8), Article 1533. https://doi.org/10.3390/electronics13081533
- Tsoulos, G., Athanasiadou, G., Zarbouti, D., Nikitopoulos, G., Tsoulos, V., & Christopoulos, N. (2024a). Empirical analysis of 5G deployments: A comparative assessment of network performance with 4G. AEU—International Journal of Electronics and Communications, 186, Article 155479. https://doi.org/10.1016/j.aeue.2024.155479

- Tsoulos, G., Athanasiadou, G., Zarbouti, D., Nikitopoulos, G., Tsoulos, V., & Christopoulos, N. (2024b). 5G and 4G in the field: Performance assessment through trials. In 2024 Panhellenic Conference on Electronics & Telecommunications (PACET) (pp.1–4). IEEE. https://doi.org/10.1109/PACET60398.2024.10497064
- Ungolo, A., Cisternino, A., & Anastasi, G. (2025). Assessing the performance of LiFi wireless networks through experimental measurements. In 2025 IEEE Symposium on Computers and Communications (ISCC). IEEE. https://doi.org/10.1109/ISCC65549.2025.11326389
- Zeng, L., O'Brien, D., Le Minh, H., Faulkner, G., Lee, K., Jung, D., Oh, Y., & Won, E. (2009). High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting. IEEE Journal on Selected Areas in Communications, 27(9), 1654–1662. https://doi.org/10.1109/JSAC.2009.091215