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Method for Systematic Assessment of Mobile Network Coverage for Logistic Applications on the German Highway

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Abstract: Smart logistics, combining the capabilities of logistics with methods and techniques of the Internet of Things, Information and Communication Technologies, and the highest levels of automation are key to addressing the challenges of the 21st century and minimizing emissions while maximizing logistic performance. High-performance cellular networks are a prerequisite to fully using and leveraging their possibilities. These communication networks were developed based on the need for voice communication and streaming services. While the upcoming requirements are included in the latest versions of cellular networks, the existing infrastructure requires significant improvements and will have to adapt significantly. This study evaluates the performance of the current state of implementation of cellular networks on the German highway experimentally and analytically. The known indicators RSRP, RSSI, and RSRQ are analyzed spatially, over time, and for different driving conditions. The results indicate a high level of spatial correlation and a sufficient level of confidence, which are needed to ensure consistency and repeatability of these measurements. The procedure and the results can be used to assess the suitability of cellular networks for smart logistics applications and continuously monitor their improvement. The results indicate the status of the cellular network on the German highway which is worse compared to the network operator's self-assessment.

Keywords: cellular networks; ICT; ITS; automation; smart logistics; IoT; RSSP; RSSI; RSRQ; highway

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1. Introduction

The Internet of Things in Logistic applications (IoTL) is considered to be a key to tackling the existing and upcoming challenges of the 21st century in the logistics industry. Specifically, consistent real-time knowledge of the position and condition of trucks and their load can significantly improve the efficiency of the logistic chain, reduce cost and greenhouse gas emissions, and improve overall performance to customer requirements. According to the World Economic Forum, "Supply-chain decarbonization will be a "game changer" for the impact of corporate climate action" [1]. However, consistent and reliable real-time communication is a prerequisite to leveraging the full potential of these smart logistics. A significant part of this communication will be based on cellular communication because of its high level of standardization and availability. However, up to Long Term Evolution (LTE) technology, the development and implementation of these networks have been strongly driven by voice communication and (video-)streaming applications, which rely on a different set of requirements compared to smart logistics. With the introduction of LTE-advanced, systems were expected to support mobile speeds up to 350 km/h or even up to 500 km/h [2,3]. The expected "level of performance" at these speeds was not specified in further detail. With the development of 5G requirements, Ultra Reliable Low-Latency Communication (URLLC) and massive Machine Type Communication (mMTC) were considered [4], which are a must in the field of smart logistics for use-cases like mobile load condition control or remote driving of logistic vehicles. However, the implementation of 5G networks on German highways with strong logistic relevance lags behind. The path from specification to real-life implementation requires means of assessment and control. Currently, network operators offer LTE-based services along the route under investigation in this study, which are, according to their websites, delivering consistent LTE coverage and "best in class" performance [5,6]. As this study shows, this is not the case. Thus, there is a need to consistently and systematically assess the performance of the current state of mobile networks with respect to logistic applications and provide means to continuously measure the status with significant reproducibility.

1.1. Smart Logistic Applications

Smart logistics applications, like intelligent trucks, containers, or cargo, rely on integrating advanced Information and Communication Technologies (ICT) to consistently and continuously exchange relevant information in real time [7–9]. The transmitted information can include position, speed, and condition of the vehicle [10,11], environmental data like temperature or weather conditions, or certain special emergency events that require immediate action by the operator. A container can transmit similar information, which is relevant for multi-modal transportation involving different carriers [12]. Finally, monitoring the cargo condition allows a delivery in the best possible condition [13], which is specifically relevant for the transportation of food [14,15] or medical goods. Thus, the IoTL enables functionalities like the dynamic and exact prediction of the time of arrival for a perfect unloading/loading operation and handover of goods in interconnected fleets. The collection and transmission of technical conditions and errors would allow predictive and preventive maintenance with minimal impact on operating times. Recharging of Battery Electric Vehicles (BEVs) can be optimized for both cost and time by transmitting their current energy status. By assessing logistic Key Performance Indicators (KPIs) [16], like "full and operational logistics cost" or the "length of logistics cycles", the IoTL can significantly improve transparency by making these automatically measurable and at the same time deliver the toolset for improvement. In 2021 more than 80% of all goods have been transported on the roads in Germany [17]. Since transportation on roads is strongly dependent on e.g., traffic and weather conditions, the opportunities for ICT-based smart logistics are significant and worth assessing as part of this study.

1.2. Cellular Networks

As indicated, cellular communication is expected to be the main base for communication in smart logistic applications because of its high level of standardization and broad availability. However, the development of cellular networks up to LTE [18–20] has mostly been driven by voice communication, (video-)streaming, and to a lesser degree by online gaming. Thus, current standards for the Quality of Service (QoS) consider services like the File Transfer Protocol (FTP), streaming video, or IMS Multimedia Telephony service (MTSI) [21]. Under most conditions, these types of data communication are either not safety relevant or can accept short interruptions. For logistic applications, specifically, when closely linked to Intelligent Transportation Systems (ITS) such as highly-automated or autonomous transportation, this is not acceptable. Unlike the common user, who can tolerate minor interruptions in cellular service along the highway, IoTL applications with potential safety relevance require a continuous, constant data rate, low-latency cellular connection without any loss of signal. Besides the static assessment in constant positions, these applications also need a quick and lossless handover between cells when traveling at significant speeds. In contrast to Human-to-Human (H2H) voice communication, the required type of communication can be categorized as Machine-to-Machine (M2M) type. Different ways of assessing the performance of cellular networks are described in the literature. On one hand, mobile phone and network scanner-based drive tests are used, partially in combination with simulation and interpolation techniques, to obtain information for areas not experimentally covered [22]. On the other hand, cellular operator performance is analyzed based on crowd-sourced, end-user device-based data [23], which promises a huge amount of information with very little investment. However, this approach is limited by a lack of both hardware and software control of the devices acting as sensors in the cellular network. The capability to measure the location of these devices based on Global Navigation Satellite Systems (GNSS) is typically very limited with respect to both measurement frequency and quality, because of the integrated GNSS hardware and antenna. This is also valid for the cellular network receiver hardware and position of the device within a vehicle: in crowd-sourced datasets, some mobile phones could be hidden inside a bag and encapsulated within the metallic chassis of the vehicle while others could be connected to a roof antenna. While for logistic applications, like remote driving, a roof antenna for both the cellular network and the satellite-based localization is a prerequisite, end-user devices do not offer this option. Finally, the diversity of devices used in crowd-sourced studies limits reproducibility and thus, the quality of the overall results. For the service-specific overall performance of a cellular network, represented by the End-to-End QoS, and suitability of the network for an application like remote driving, the full chain of communication including the destination device has to be considered [24]. However, to assess the quality of extension of a cellular network, an assessment of simple, directly measurable parameters, which directly limit the End-to-End QoS, is an advantage, since external complex factors can be minimized. An overview of complex and simple parameters for quality assessment of cellular networks is included in Table 1. The part most easily measurable from the terminal device is the performance of the access network at the terminal equipment. This can be characterized by standard physical layer indicators like the Reference Signal Received Power (RSRP), the Received Signal Strength Indicator (RSSI), or the Reference Signal Received Quality (RSRQ). Existing studies analyze and model these in constant positions over time [25]. Others include the analysis of spatial and temporal characteristics and in some cases compare cellular and WiFi performance [26–30].

However, all existing studies and standards stay vague on the question of validity or reproducibility, which is a key goal of the research presented here.

Table 1. Typically assessed parameters , based on [21,27,31,32].

Service Specific, Complex Characteristics	Simple, Directly Measurable Parameters
Quality of Experience (QoE)	Reference Signal Received Power (RSRP)
Quality of Service (QoS)	Reference Signal Received Quality (RSRQ)
	Received Signal Strength Indicator (RSSI)
	Delay, Latency
	Packet Loss

1.3. Questions of Research and Contribution

Proven experimental methods and validated data analysis are a prerequisite to systematically assessing the cellular network for logistic applications to control and enforce their further expansion. For this study, the authors focus on the German highway, driving at speeds relevant for logistics, to find out if existing or slightly modified methods for cellular network analysis deliver reliable and reproducible results with sufficient confidence. The effects of the time of measurement, the vehicle speed, and the direction are evaluated. Furthermore, a method for comparison of two network operators is proposed and implemented to assess the quality and create a ranking based on objective data. In summary, this publication describes the method, its validation, and the first tests performed to assess the usability and performance of cellular LTE networks for smart logistic applications. It addresses the following questions of research:

1. Does the experimental setup used in this study provide reproducible and consistent measurement results?
2. How can different measurements, with spatial variation in vehicle position along the road under analysis, be compared?

3. What is the level of consistency assessed by the spatial correlation between different measurements with variation in time, speed, and direction?
4. What is the level of consistency based on the confidence per measured position?

1.4. Organization of this Publication

After a review of related work based on existing standards and publications in Section 2, the experimental setup and measurement configuration are described in Section 3. Furthermore, the data flow for analysis and the description of the highway under investigation are included in this section. The results of the measurements for RSRP, RSRQ, and RSSI, and their further analysis are presented in Section 4. The paper concludes with a discussion and summary of the results with respect to the questions of research, followed by an outlook on further investigations in Section 5.

2. Related Work

In this section, existing publications and standards are briefly reviewed in the context of this study.

2.1. Smart Logistics

The use of communication and IoT technologies has been subject to research since about 2008 and is still ongoing. In most recent research, Song et al. [8] provide an overview of smart logistics applications and use cases enabled by IoT technologies and includes an overview of the respective requirements. Similarly, Tran-Dang et al. [9] point out that Information and Communication Technologies (ICT) are a key enabler for efficient and sustainable logistics. In [16] the authors describe the potential of IoT technologies to measure logistics KPIs and improve the efficiency and quality of logistics processes within a balanced scorecard approach. In the publications [14,15], Jedermann and Lang describe the development and advantages of an intelligent container for fruit transportation, which is equipped with localization and communication devices. The requirement of "real-time response in case of unexpected situations detected during the transportation phase" is addressed in [10], while the idea of an IoT-based cargo tracking system was published in 2012 [13]. In the same year, Mondragon et al. [12] described the connection of ITS with multimodal logistics for a sea port location in a simulation-based approach. In 2009, an intelligent freight transportation system based on advanced fleet management, improved city logistics, and e-business was subject to research published in [11].

In summary, smart logistics have been continuously addressed in research since 2008. However, until today, the implementation of advanced use-cases was very much limited to research prototypes. Limited quality and performance of the existing cellular network are considered to be the main constraints limiting their commercial implementation and roll-out.

2.2. Performance Measurement of Cellular Networks

The performance requirements of cellular networks with respect to logistic applications in the context of Industry 4.0 was subject to recent research [7]. The authors consider 5G to be the connectivity solution addressing all logistics needs from manufacturing floors and warehouses to worldwide material transportation. The temporal behavior of the LTE standard parameters RSRP and RSRQ has been subject to research by Raida et al. [25,33] in 2020. RSRP in three specific, static locations was found to be almost constant over periods up to several days. Thus, in this study, RSRP is measured and analyzed to figure out, if it is a valid indicator also for the spatial characterization of LTE networks. The measurement of the QoS of LTE networks is addressed by several standards [21,24], that define the End-to-End QoS and include the assessment based on the perspectives of the final user and the service provider. The more recent norm ETSI TS 102 250-2 [21] includes the QoS for the applications E-mail, File Transfer, Multimedia Messaging Services (MMS), Mobile Broadcast, Ping, Push-to-talk over Cellular (PoC), Short Message Service (SMS), Streaming, Telephony, Video Telephony, and Web Browsing. Obviously, upcoming applications with relevance to smart logistics have not been included. The experimental analysis of cellular networks has been subject to continuous research. Poncela et al. [31] emphasize the need to monitor objective parameters to automatically measure and improve the end user's Quality of Experience (QoE). Lottermann et al. [32] identify the limitations of LTE for automotive off-board applications with respect to transmission delays and packet discard rates. In [26], the authors measure and compare the spatio-temporal performance of cellular and 802.11 WiFi communication based on speed-tests on end-user devices. They find a strong variation over the time of day and a significant spatial consistency. Using end-user devices and crowd-sourced datasets has also been the base for a study by Egi et al. [22]. The authors confirmed that the QoS and coverage of cellular networks can be explained by measuring RSRP, which is one of the three parameters analyzed within this study. In a text by Kousias et al. [23], different crowd-sourced parameters are analyzed to identify an operator. The latency was found to be the most important feature. However, in contrast to this study, the dataset did not contain any position information. In a more recent study by Herrera-Garcia et al. [34], lower-layer indicators, like RSRP, RSRQ, and RSSI, are used to generate higher layer metrics and assess overall End-to-End (E2E) performance. The article confirms the relevance of the parameters under investigation in this study. According to [35], Radio Access Network (RAN) problems are causing 48% of all network performance issues. The authors create a technology-agnostic methodology to assess the QoE based on Key Quality Indicators (KQIs). In [28], the authors perform drive tests in rural Malaysia based on mobile phones to measure the performance of the 3G and 4G networks for web browsing and video streaming applications. In comparison, based on an overall statistical evaluation, they find the 4G network to perform better than the 3G cellular network. In a similar study for urban areas of Malaysia [29], a better performance than in rural areas was observed. However, the evaluation was limited to an overall statistical assessment, and neither time- nor position-related dependencies were considered. In a very recent study by El Saleh et al. [30], 3G and 4G networks were assessed for different cities in Oman in mobile phone-based, one-time drive tests. The authors observed local RSRP levels below −100 dBmW, which potentially lead to the described packet losses. An overview of the related publications is given in Table 2.

Table 2. Related work and analysis carried out in this study.

Reference	Networks Assessed	Measurement Method	Parameters Controlled	Parameters Under Investigation
[23]	4G	crowd sourced	-	RSRP, RSRQ, latency, data rate
[22]	4G	phone, scanner	position	RSRP
[25]	4G	phone	time	RSRP
[33]	4G	phone	time	RSRP, RSRQ, RSSI, others
[26]	2G–4G, WiFi	crowd sourced	time, position	data rate, latency
[27]	4G	modem	position	RSRP, RSRQ, RSSI, others
[28]	3G,4G	phone	-	CSS, web browsing, streaming
[29]	3G, 4G	phone	-	CSS, web browsing, streaming
[30]	3G, 4G	phone	position	RSRP, RSRQ, RSSI, others
[31]	2G–4G	phone	position	RSRP, others
this study	4G	dedicated setup	time, position direction	RSRP, RSRQ, RSSI

The status of the extension and quality of the cellular network is regularly self-assessed by the providers in Germany [5,6,36]. Based on this self-assessment, the quality of the LTE is classified as consistently "excellent" or "very good" both outside and inside buildings on the highway under investigation. The criteria for this assessment, however, are not given. This study delivers independent and reproducible measurement results, which do not comply with the self-assessment.

3. Materials and Methods

3.1. Experimental Setup

The system in Figure 1 consists of six independent measurement units, each comprising of a standard LTE modem connected to a microcontroller board, and separate power supplies. Each unit is connected to its own roof antenna as indicated in Figure 2. The antennas are set up on a defined, conductive steel surface with sufficient distance to minimize cross-coupling effects. With this setup, parallel measurement of three providers with two technologies each is possible. For this study, a subset of two providers and LTE (4G) technology was chosen. All measurement units and an independent GNSS module are connected to a mobile personal computer to collect and save data during the measurements. The relevant measurement parameters are summarized in Table 3. Since 3G service has been terminated in Germany in 2021 and the roll-out of 5G is still ongoing, the measurement setup provides a good balance between cost, complexity, and benefit.

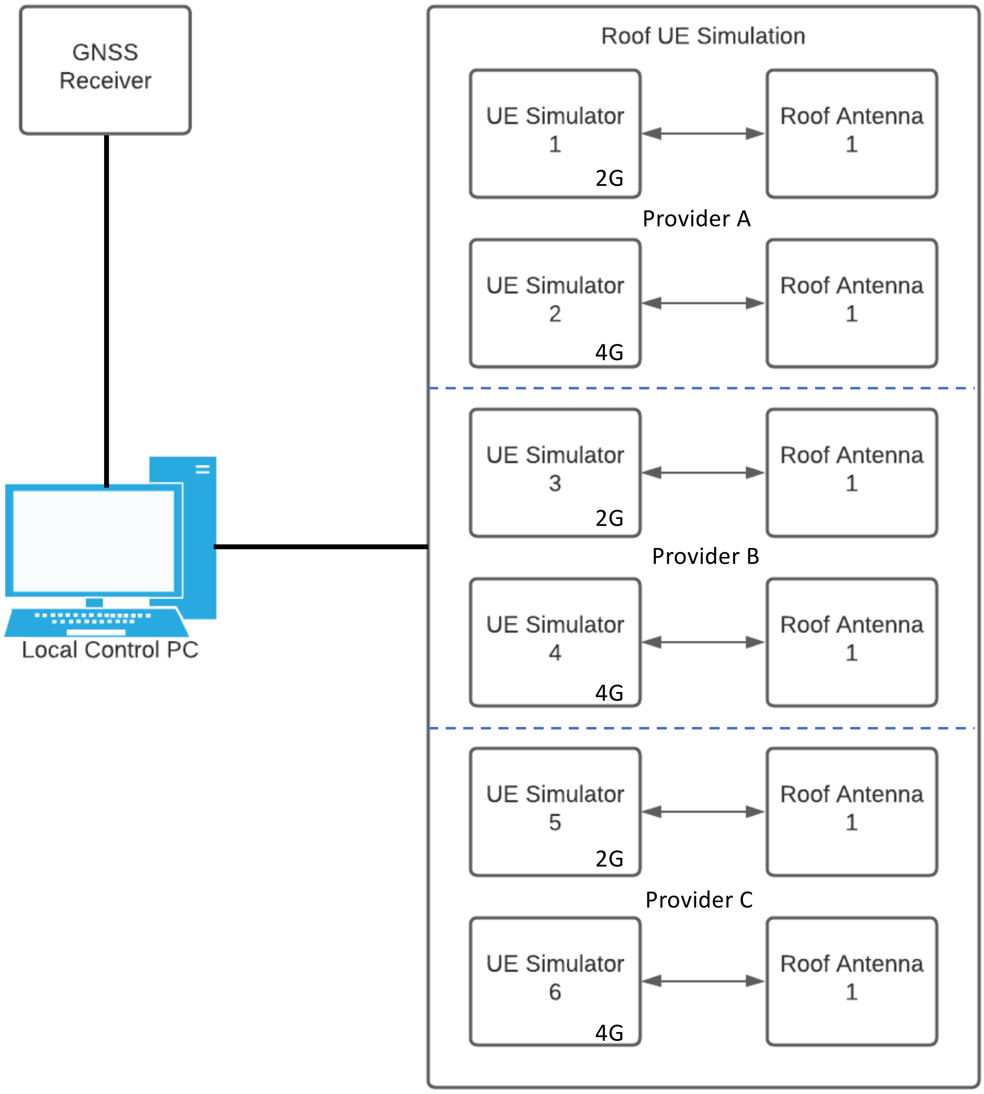

Figure 1. The setup of the measurement system.

Figure 2. The antenna setup of the vehicle.

Table 3. Measured parameters.

Parameter	Range/Resolution /Format	Unit
Latitude	0.000001	° dec.
Longitude	0.000001	° dec.
Time of day	YYYY-MM-DD HH:MM:SS.000	-
Data rate	1	Hz
RSRP	−120 ... 0	dBmW
RSSI	−120 ... 0	dBmW
RSRQ	−10 ... 0	dB
Number of operators LTE (4G)	3	-
Number of operators GSM (2G)	3	-

3.2. Data Preparation and Analysis Flow

The dataset was prepared as indicated in Figure 3. The data was measured with a timestamp and contained latitude and longitude information as summarized in Table 3. The area of interest was marked by its latitude and longitude range. The respective timestamps were identified and the relevant data was extracted. The dataset was transformed from a two-dimensional, latitude/longitude base to a one-dimensional, virtual-odometer base to simplify the following steps and allow comparative analysis. Special care was taken to ensure that the extracted data contained exactly the same start and endpoint. Since the data were collected at various speeds resulting in various distances between the actual measurement points, the data points were resampled with a constant distance interval of one meter. Missing data points were filled in based on linear interpolation.

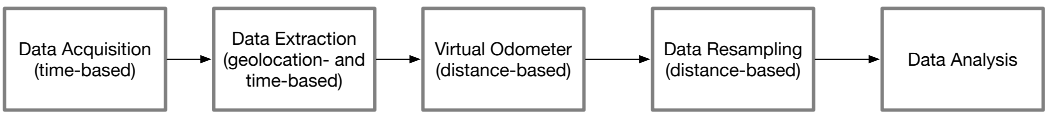

Figure 3. The data preparation flow used for this study.

The prepared data were analyzed based on the flow presented in Figure 4. A spatial correlation was performed for RSRQ, RSRP, and RSSI to check the degree of consistency for independent measurements of the same parameters. In the next step, an assessment for each provider was performed followed by a comparative analysis of the overall assessment. To check the quality of the overall measurements the three measured quantities were analyzed for correlations.

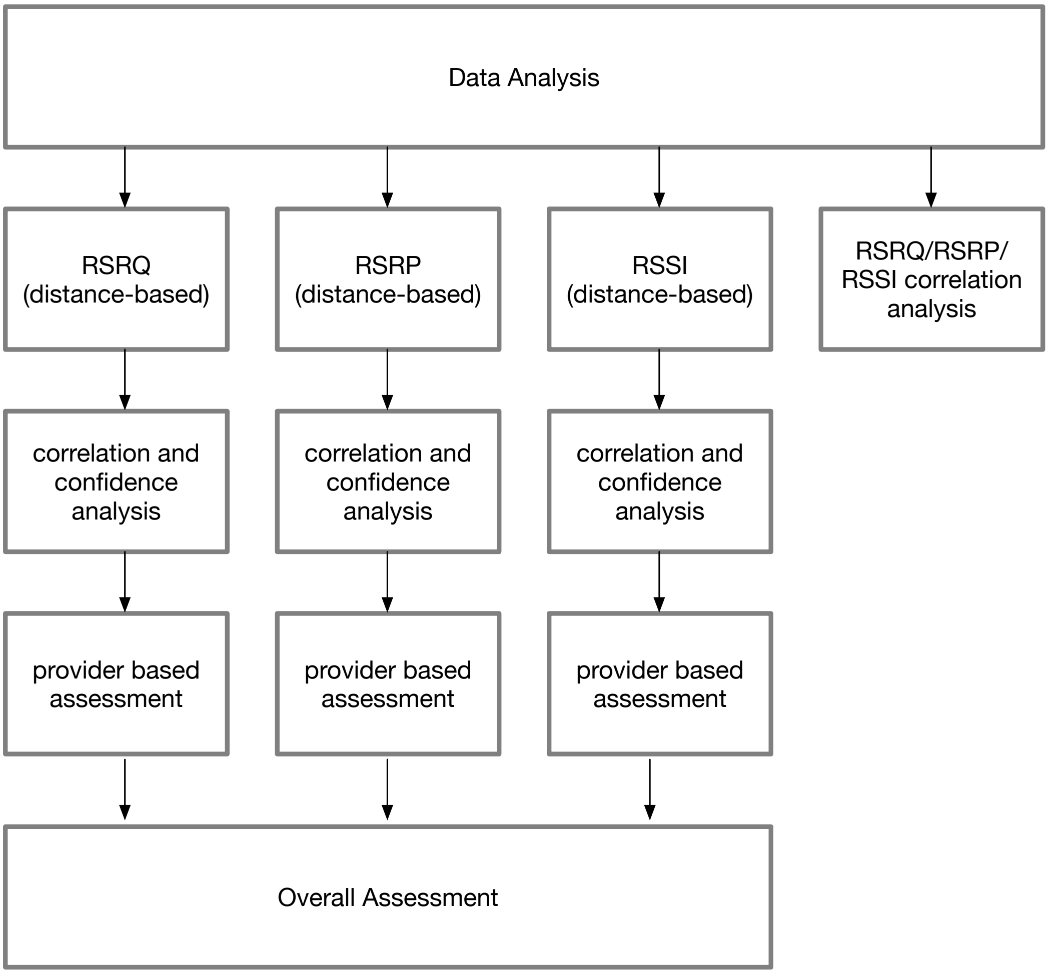

Figure 4. The data assessments performed within this study.

3.3. Region of Analysis

A dataset was extracted to validate and assess the performance of the measurement method, which contained information on several independent measurements obtained based on different experimental parameters. The region of analysis is marked in Figure 5. The length of the analyzed distance of highway A1 in the south of the City of Hamburg is 3 km. The typical speed was set to 90 km/h. However, the actual speed across all measurements varied between 45 km/h and 120 km/h because of the traffic variation on the highway. The highway under analysis was assessed in both directions, on different days, and at different times of day.

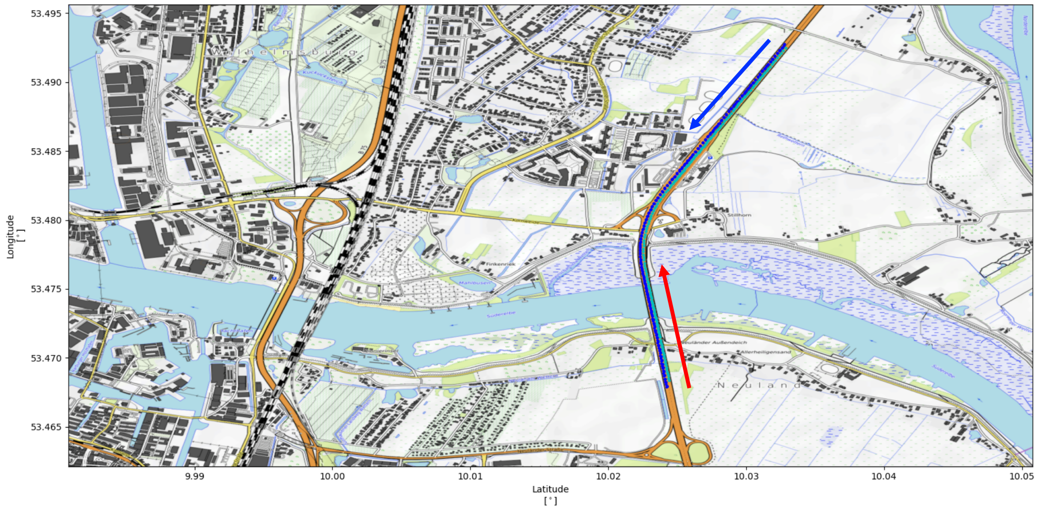

Figure 5. Highway under analysis. Test drives were performed in both directions as indicated by the arrows , based on [37].

4. Results

The measurement results were visualized, assessed, and evaluated based on the scheme presented in Table 4, which is based on [38].

Table 4. LTE assessment criteria , based on [38].

Assessment	**RSRP**	**RSRQ**	**RSSI**
excellent	>= −10 dBmW	>= −10 dB	> −15 dBmW
good	−10 dBmW . . . −10 dBmW	−10 dB . . . −15 dB	−15 dBmW . . . −15 dBmW
fair	−10 dBmW . . . −100 dBmW	−15 dB . . . −10 dB	−15 dBmW . . . −15 dBmW
poor			−15 dBmW . . . −15 dBmW
risk of disconnect or no signal	<= −100 dBmW	<= −10 dB	< −15 dBmW

4.1. RSRP Measurements

The results of the RSRP measurements as a function of the distance are visualized in Figure 6. The plots (a), (b), and (c) show the results for provider A, with data taken at different times and for both directions. In plots (d) and (e) the RSRP has been logged for two independent test drives covering both directions for provider B. Each of these measurements has been spatially correlated with all others to check consistency for a single provider and prove sufficient differentiation between different providers. The result of this analysis is presented in Table 5. While repeated measurements under various conditions including speed, direction, and time of day indicate a spatial correlation $0.8 < sc < 0.9$, a value of $sc \leq 0.8$ is found when correlating measurements for different providers.

Table 5. Spatial correlation of RSRP. A and B indicate the respective providers under investigation.

		(a) A	**(b) A**	**(c) A**	**(d) B**	**(e) B**
(a)	A	1	0.84	0.82	0.76	0.59
(b)	A	0.84	1	0.86	0.75	0.60
(c)	A	0.82	0.86	1	0.78	0.67
(d)	B	0.76	0.75	0.78	1	0.85
(e)	B	0.59	0.60	0.67	0.85	1

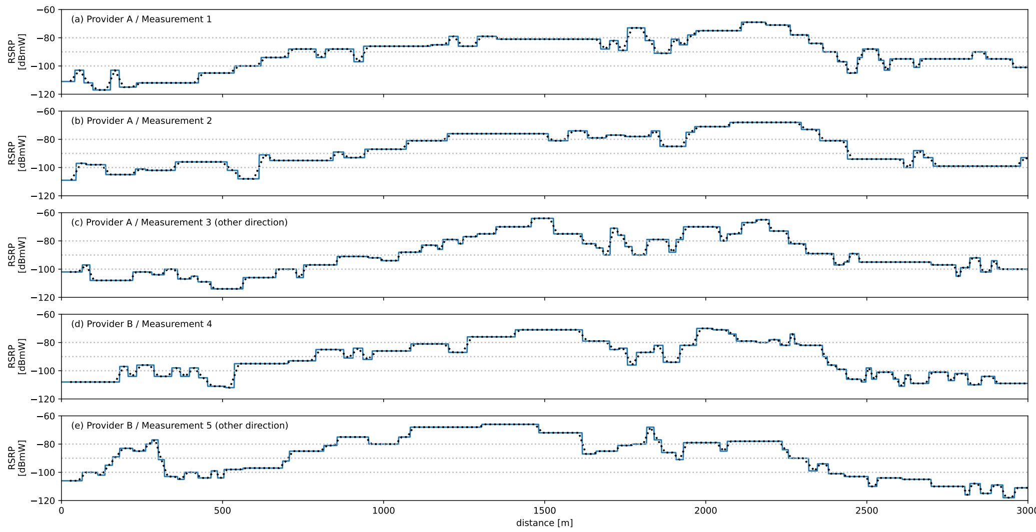

Figure 6. RSRP as a function of distance based on five independent measurements (solid lines: raw data; dots: resampled, interpolated data). Gray, dotted horizontal lines indicate ranges according to Table 4.

The average of the RSRP for each position was calculated for each provider. The results are shown in Figure 7. Furthermore, the confidence interval for a confidence of 0.8 was calculated and included. When comparing Figure 7a, based on three measurements, to Figure 7b, based on two measurements, the reduction of the width of the confidence interval due to the higher number of measurements is obvious.

The width of the confidence intervals has been included in a histogram in Figure 8 to allow further analysis. Though the distributions are different in their overall characteristic, the mean values of the widths of the confidence intervals are almost identical at 14 dBmW (Figure 8a) and 13 dBmW (Figure 8b), respectively. A significant variance across different measurements for identical positions is expected if the system is connected to different network cells while performing the measurement.

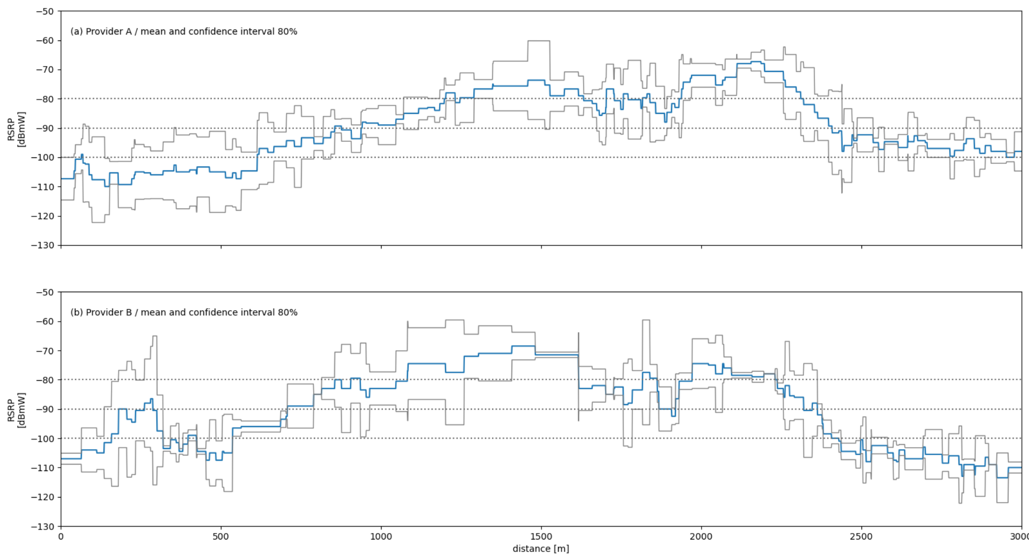

Figure 7. Mean values of RSRP as a function of distance including the limits of the confidence interval for a confidence of 0.8.

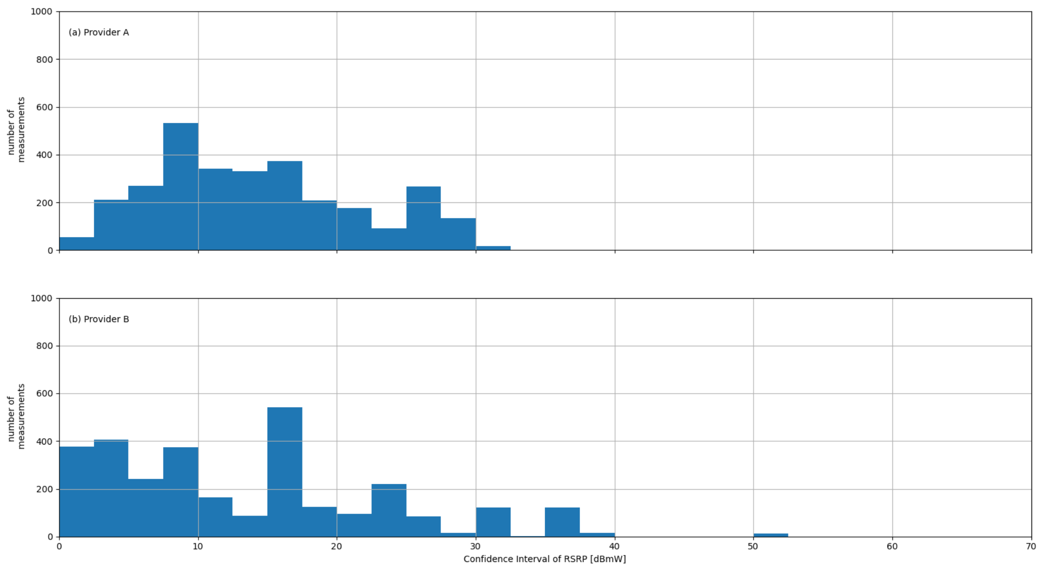

Figure 8. Histogram of the confidence intervals for RSRP.

The measurement shown in Figure 6 has been evaluated based on the criteria in Table 4 and the result is presented in Table 6. It indicates a significant number of measurements with RSRP < -100 dBmW for both providers, which is assessed as "risk of disconnect or no signal" (Table 4). However, for provider A the coverage is better compared to provider B when comparing the range of "risk of disconnect or no signal" as indicated in Table 6. While for provider A the measurements show a "risk of disconnect or no signal" for distances between 361 m and 671 m, those for provider B indicate a range between 831 m and 949 m.

Table 6. Provider based assessment RSRP.

Measurement	Provider	Excellent	Good	Fair to Poor	Risk of Disconnect or No Signal	Range under Analysis
(a)	A	520 m	1164 m	663 m	654 m	3001 m
(b)	A	1014 m	584 m	1078 m	361 m	3001 m
(c)	A	881 m	500 m	949 m	671 m	3001 m
(d)	B	715 m	735 m	602 m	949 m	3001 m
(e)	B	1176 m	555 m	439 m	831 m	3001 m

4.2. RSSI Measurements

Figure 9 shows the measurement results of the value of RSSI as a function of distance for provider A (marked as a, b, and c) and provider B (marked as d and e). The measurements presented include a variation in speed, direction, and time. Following the same approach as for RSRP, each of these measurements has been spatially correlated with all others to check consistency for a single provider and prove sufficient differentiation between different providers. The result of this analysis is presented in Table 7. While repeated measurements under various conditions including speed, direction, and time of day indicate a spatial correlation $0.8 < sc < 0.9$, a value of $sc \leq 0.8$ is found correlating measurements for different providers.

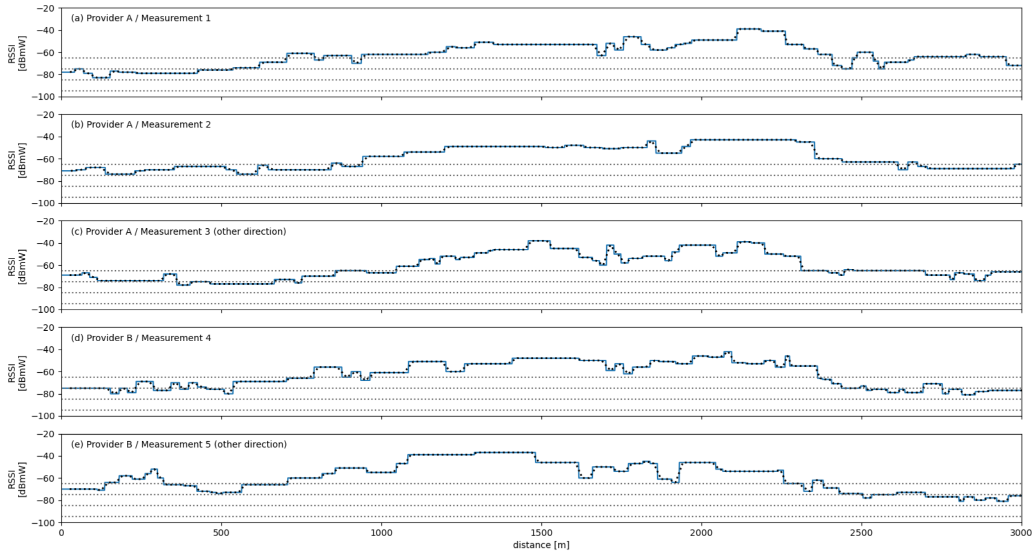

Figure 9. RSSI as a function of distance (solid lines: raw data; dots: resampled, interpolated data). Gray, dotted horizontal lines indicate ranges according to Table 4.

The average of the RSSI value for each position was calculated for each provider. The results are shown in Figure 10. Furthermore, the confidence interval for a confidence of 0.8 was calculated and included in the figure. As in the case of the assessment of RSSI, the reduction of the width of the confidence interval due to the higher number of measurements is obvious when comparing Figure 10a to Figure 10b.

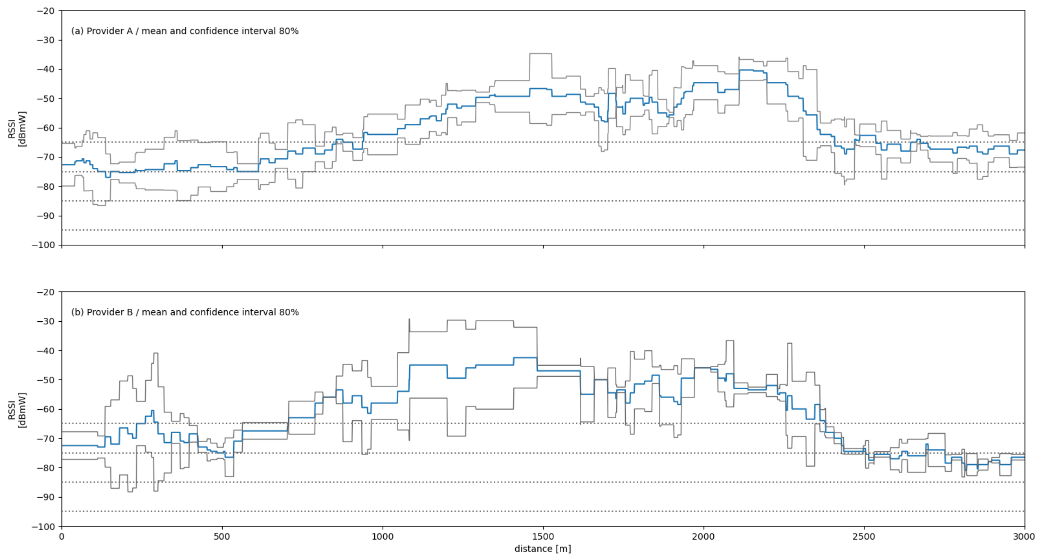

Figure 10. Mean values of RSSI as a function of distance including the limits of the confidence interval for a confidence of 0.8.

Table 7. Spatial correlation of RSSI, A and B reference to two providers under investigation.

		(a) A	(b) A	(c) A	(d) B	(e) B
(a)	A	1	0.86	0.84	0.74	0.55
(b)	A	0.86	1	0.88	0.80	0.64
(c)	A	0.84	0.88	1	0.78	0.67
(d)	B	0.74	0.80	0.78	1	0.82
(e)	B	0.55	0.64	0.67	0.82	1

The measurement shown in Figure 9 has been evaluated based on the criteria in Table 4 and the result is presented in Table 8. In contrast to the evaluation of RSRP, the RSSI indicates at least fair to poor coverage for the full range. Nevertheless, provider A delivers better performance than provider B in the overall assessment of RSSI.

Table 8. Provider-based assessment RSSI.

Measurement	Provider	Excellent	Good	Fair to Poor	Risk of Disconnect or No Signal	Range under Analysis
(a)	A	1983 m	431 m	587 m	-	3001 m
(b)	A	1737 m	1264 m	-	-	3001 m
(c)	A	1294 m	1380 m	327 m	-	3001 m
(d)	B	1515 m	599 m	887 m	-	3001 m
(e)	B	1767 m	828 m	406 m	-	3001 m

4.3. RSRQ Measurements

Experimental values for RSRQ have been obtained and are shown in Figure 11 following the same pattern as in the Figures 6 and 9. A spatial correlation has been performed and the results are included in Table 9. In contrast to the results obtained for RSRP and RSSI, the spatial correlation does not indicate a high level of consistency between related measurements for the same provider. Furthermore, the values for spatial correlation are significantly lower.

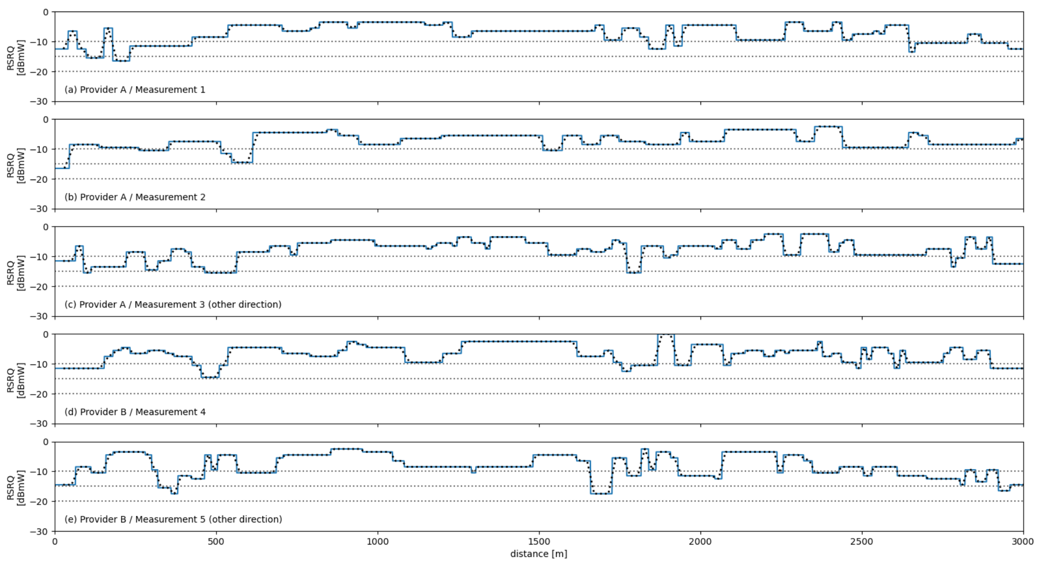

Figure 11. RSRQ as a function of distance (solid lines: raw data; dots: resampled, interpolated data). Gray, dotted horizontal lines indicate ranges according to Table 4.

The average RSRQ for each position was calculated for each provider. The results are shown in Figure 12. Furthermore, the confidence interval for a confidence of 0.8 was calculated and included in the figure. As in the case of the previous assessments, the reduction of the width of the confidence interval due to the higher number of measurements is obvious when comparing Figure 12a to Figure 12b.

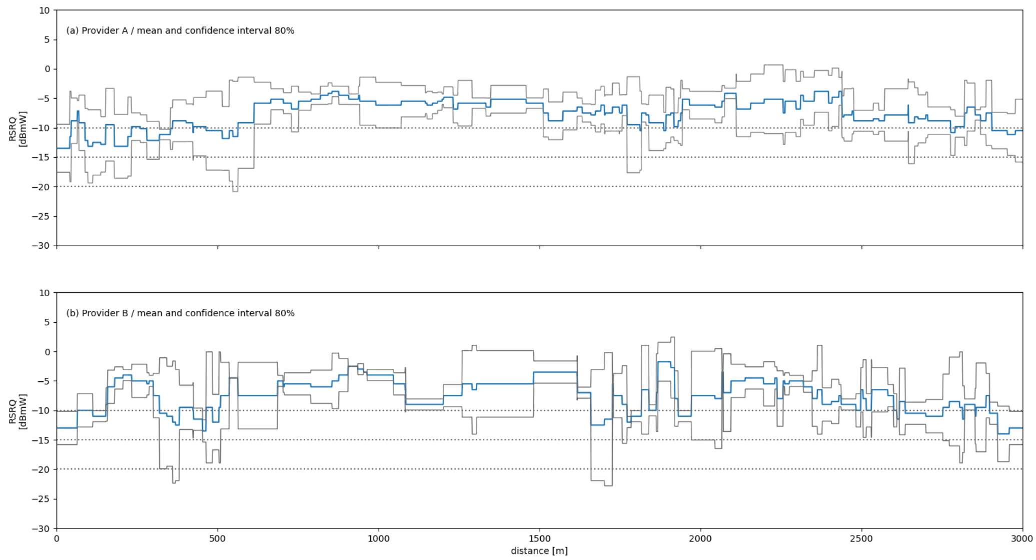

Figure 12. Mean values of RSRQ as a function of distance including the limits of the confidence interval for a confidence of 0.8.

Table 9. Spatial correlation of RSRQ.

		(a) A	(b) A	(c) A	(d) B	(e) B
(a)	A	1	0.22	0.33	0.39	0.34
(b)	A	0.22	1	0.48	0.11	0.16
(c)	A	0.33	0.48	1	0.33	0.21
(d)	B	0.39	0.11	0.33	1	0.41
(e)	B	0.34	0.16	0.21	0.41	1

The measurement shown in Figure 11 has been evaluated based on the criteria in Table 4 and the result is presented in Table 10. Similar to the result for RSSI, the evaluation for RSRQ indicates at least fair to poor coverage for the full range for both providers. Furthermore, the results do not indicate a clearly superior provider.

Table 10. Provider based assessment RSRQ.

Measurement	Provider	Excellent	Good	Fair to Poor	Risk of Disconnect or No Signal	Range under Analysis
(a)	A	2238 m	655 m	108 m	-	3001 m
(b)	A	2702 m	253 m	46 m	-	3001 m
(c)	A	2377 m	456 m	168 m	-	3001 m
(d)	B	2413 m	588 m	-	-	3001 m
(e)	B	1909 m	927 m	165 m	-	3001 m

4.4. Correlation Analysis

A correlation between RSRP, RSSI, and RSRQ is included as a scatterplot in Figure 13 to further analyze the relation of these quantities. While RSRP and RSRQ show no visible correlation, the scatterplot in Figure 13b indicates a linear relationship between RSRP and RSSI.

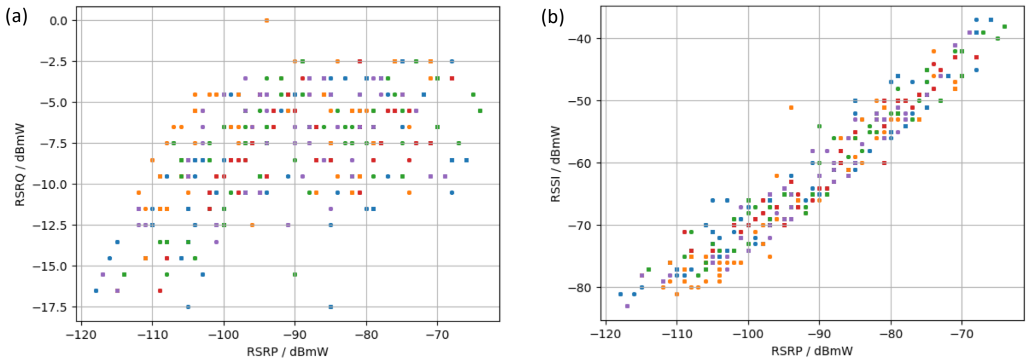

Figure 13. Correlation of (**a**) RSRP and RSRQ; (**b**) RSRP and RSSI.

5. Discussion, Conclusions, and Outlook

A setup for automated, high-resolution driving measurements of cellular network performance on highways has been developed and installed. Repeated measurements have been performed on a specific range of the German highway with variations in time, speed, and direction. A data preparation and analysis flow was implemented to obtain and evaluate data with consistent spatial resolution. The presented results for the measurement of RSRP and RSSI indicate significant repeatability and spatial correlation for a chosen provider, which is a prerequisite for a regular, standardized performance assessment. Correlation coefficients above 0.8 were found for different measurements of RSRP and RSSI for the same provider while values lower than 0.8 were found for the correlation for different providers. For RSRQ, the correlation coefficient for non-identical measurements was below 0.5 and different providers could not be distinguished. This can be explained based on the definition: while RSRP and RSSI are basically power measurements, RSRQ additionally depends on the number of available resource blocks which can vary depending on provider, time, and position. Nevertheless, the value is relevant for network performance in terms of data rate or latency. The confidence interval for a confidence level of 0.8 was calculated considering multiple measurements for each location under analysis. The average total width of the confidence interval for RSRP was found to be 13 dBmW to 14 dBmW, which confirms the validity of the measurements performed. The self-assessments of the providers of the respective cellular networks [5,6] have been compared in the exact same locations to the results of this study. Both providers promise a "very good" coverage of LTE both outside and inside buildings. In contrast to the self-assessment, the authors cannot confirm a "best in class" cellular network. The assessment provided in this study indicates significant areas with a "risk of disconnect or poor signal" (Table 6). With respect to the questions of research, presented in Section 1.3, this study contributes as follows:

1. Does the experimental setup used in this study provide reproducible and consistent measurement results? Yes, the measurements were spatially and temporarily consistent.
2. How can different measurements, with spatial variation in vehicle position along the road under analysis, be compared? The authors implemented a GNSS-based, virtual odometer which provided the base for the vehicle position. The correlation of different measurements indicates a good ability to distinguish between different network operators.
3. What is the level of consistency assessed by the spatial correlation between different measurements with variation in time, speed, and direction? The spatial correlation for different measurements for the same provider was above 0.8, while the correlation coefficient across providers showed values below 0.5.
4. What is the level of consistency based on the confidence per measured position? The confidence intervals for a confidence of 0.8 provided consistent limits across all measurements. However, additional measurements are required for further improvement.

The analysis presented indicates that the setup and analysis method is suitable for reliable performance measurements of cellular networks. It allows a detailed assessment to identify weaknesses and develop corrective actions.

The authors intend to increase the range of interest to larger distances and cover full highways between German cities. Additionally, parameters like latency or data rate are to be included in the assessment to finally allow a classification of certain routes as suitable for smart logistics.

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Abbreviations

The following abbreviations are used in this manuscript:

BEVs	Battery Electric Vehicles
CSS	Cellular Signal Strength [28,29]
E2E	End to End
FTP	File Transfer Protocol
GNSS	Global Navigation Satellite System
GSM	Global System for Mobile communication (2G cellular network)
H2H	Human to Human
ICT	Information and Communication Technologies
IMS	IP Multimedia Subsystems
IoTL	Internet of Things Logistics
KPIs	Key Performance Indicators
KQI	Key Quality Indicators
LTE	Long Term Evolution (4G cellular network)
M2M	Machine to Machine
MMS	Multimedia Messaging Services
MTSI	Multimedia Telephony Services over IMS
PoC	Push-to-talk over Cellular
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
sc	spatial correlation
SMS	Short Message Service
WiFi	Wireless Fidelity

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