

Volumetric visualization of spatial radio link performance for anomaly monitoring and weather-related attenuation in modern mobile networks

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Modern cellular networks lack a unified, vendor-independent mechanism for observing radio-link performance directly at the end-user segment of the Uu interface, where the combined effects of propagation conditions, cell load, and environmental factors are ultimately experienced. The prototype system presented in this work addresses this gap by continuously monitoring key downlink radio metrics – RSRP and RSRQ – directly from the client devices and correlating them with the serving cell in real time. Unlike traditional network-side counters, this approach captures impairments that cannot be reliably inferred from centralized base-station statistics alone, including weather-induced attenuation like rain, and user-specific degradation.

Atmospheric conditions can be correlated with degrading signal performance, for instance ITU-R P.838-3 specifically addresses the effects of rain on the signal quality and power. By integrating volumetric visualization of rain-related signal attenuation with live radio measurements, and data points from end user devices, following standards like ITU-R P.838-3, the system provides immediate spatial context for performance anomalies that would otherwise require manual labor across multiple systems.

Keywords – monitoring, weather, performance, end-user, visualization

Обемна визуализация на производителност на радиовръзките, мониторинг на аномалии и метеорологично затихване в съвременните мобилни мрежи (Станислав Иванов). Съвременните клетъчни мрежи не разполагат с единен, независим от производителя механизъм за наблюдение на производителността на радиовръзката директно в потребителския сегмент на Uu-интерфейса – където често се изпитва ефекта от натоварената мрежа и моментните условия на заобикалящата среда. Разработената прототипна софтуерна система измерва качеството на услугите в една телекомуникационната мрежа, като следи RSRP и RSRQ индикаторите на ниво крайно потребителско устройство, в комбинация с данни от обслужващата базова станция в реално време. За разлика от традиционните мрежови индикатори за следене на качеството на една телекомуникационна мрежа, този подход успешно измерва ефективната деградация на услугите, които трудно биха се измерили едностранно от страна на базовата станция. В това число влизат и измервания на атмосферните условия и техният ефект върху получения сигнал, както и такива поради качеството на клиентското оборудване.

Съществува връзка между атмосферните условия и деградацията на радиосигнала. Стандарт ITU-R P.838-3 разглежда конкретно ефектът на валежите върху качеството и мощността на сигнала. Системата интегрира модела описан в стандарта, като корелира информация за атмосферните условия на дадена точка, с измервания на качеството на радиосигнала в реално време, както и метаданни от клиентските устройства. Платформата предоставя възможност за навременното диагностициране на аномалии в производителността на една мрежа – нещо, което днес налага ръчната обработка на данни от няколко системи.

This work examines two distinct functional capabilities for monitoring end-user radio link between user equipment (UE) and its serving cell within a cellular network. The first capability, radio performance monitoring, provides direct, real-time visibility into radio-link quality as experienced at the device level. The second enables spatial interpretation of existing atmospheric conditions influencing signal propagation. Together, these functions support centralized operational monitoring and engineering analysis by exposing conditions on the *Uu interface* that are not readily observable through conventional network-side metrics alone.

A software prototype system was designed and developed that unifies those capabilities, supporting the process of radio link performance monitoring, from the point of view of the UE device.

Work in the field of radio link and wave measurements is nothing new. A paper [9] was published in 2024 that is an empirical field-measurement study of a commercial 5G Non-Standalone network. The paper dealt with how much downlink performance can a real commercial 5G NSA deployment deliver, and how can variations in that performance be explained. The conclusion was that 5G NSA can deliver close to 1Gbit/s thus substantially outperform LTE, but throughput remains highly dependent on line of sight, modulation and rate adaptation.

4G networks and measurements for the same were also studied [10] which is an applied 4G LTE radio-network planning and optimization analysis. The authors combined conventional link-budget and propagation model calculations, with a real drive test (Tiaret, Algeria), and before-and-after comparison of LTE radio KPIs following what they call network “treatment” or optimization. The basic engineering loop established was: Measure the network; Identify weak coverage and interference areas; Modify the radio network; Repeat the drive test; Check whether QoS has improved. This operational optimization loop is considered one of the key deliverables of the paper.

While this work is beneficial for the industry and the adoption of 5G, it keeps the focus on the process of measuring signal behavior, and quality, in certain conditions. The prototype system is aiming to establish a causal link between end user experience, weather conditions and the servicing telecom infrastructure, based on already established and standardized measurement techniques.

Data source

Data is collected from multiple independent sources and aligned into a unified, time-indexed data point. Only through normalization and correlation of these heterogeneous datasets can a coherent view of radio-link conditions be obtained. This approach inherently depends on the availability and near-real-time delivery of all contributing data sources. Consequently, data quality becomes critical, as partial or missing inputs can invalidate an entire data point.

The user equipment (UE) plays a **central role by providing the primary dimensions of the data** for both radio link performance assessment and weather-related attenuation analysis. In addition to *device metadata*, the UE computes *Reference Signal Received Power (RSRP)* and *Reference Signal Received Quality (RSRQ)* through its on-board radio electronics. Together, these metrics provide a reliable identification of downlink signal strength, quality, and stability, as experienced at the receiver. Additional UE-provided information, including device metadata and geospatial coordinates, further enable precise spatial contextualization of measurements and support map-based correlation.

To form the complete path between the UE and the serving cell, **additional data feed is taken**, based on the context from the UE metadata. Resolving the connected cell to its geospatial coordinates is the next critical bit, since that gets linked to the UE.

Once both the UE and the cell are correlated, the data requires an additional **dimension to form a valid 3D volumetric representation**, for what we are trying to achieve. This is done by cross-feeding weather-related data, e.g. precipitation. The final shape takes place by unifying and displaying all these data sets in a single visual scenario, as depicted below.

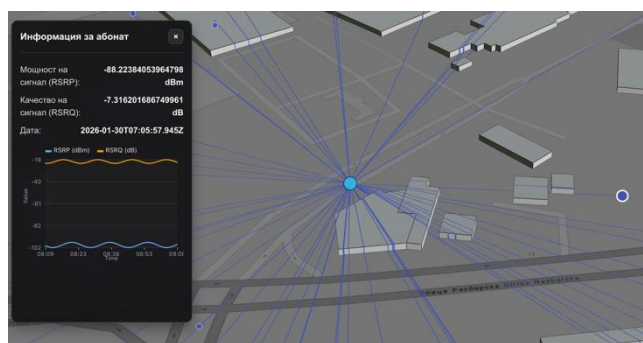


Fig.1. Rendering of UE (right) – Cell (center) relation.

Reliability of reference indicators

Both RSRP and RSRQ are standardized by 3GPP – LTE (4G) *TS 36.214* (Physical layer) [5], *36.133* (UE) [6] and NR (5G) *TS 38.215* (Physical layer) [7], *38.133* (UE). The specifications are exact mathematical definitions, measurement bandwidths, filtering (L1/L3), reporting ranges and quantization, as well as accuracy requirements per UE category.

RSRP is measured in *dBm* or *decibel-to-1-milliwatt* – the average received power of one reference *resource element* (RE) from a cell. The typical range being from -140dBm (weak) to -44dBm (excellent, i.e. better connectivity for the UE). Since RSRP is not total signal power, and is normalized to a single RE, this makes it comparable across bandwidths.

RSRQ is dimensionless (no physical unit) quality metric that relates RSRP reference RE power to total received power (RSSI), measured in dB or decibels.

$$(1) \quad RSRQ = \frac{N \times RSRP}{RSSI}$$

Where N is the number of resource blocks, $RSSI$ is the total received wideband power that includes signal, interference and noise.

The typical range of RSRQ is from -19dB (weak) to -3dB (excellent). Unlike RSRP however, RSRQ captures interference and load. Below table lists the various threshold levels widely accepted by vendors, although not standardized.

Level	RSRP	RSRQ
Excellent	≥ -80	≥ -10
Good	from -80 to -90	from -10 to -15
Medium	from -90 to -100	from -15 to -20
Low	≤ -100	< -20

Table 1. Vendor recognized levels of reference signals.

In LTE and NR systems, reference signals are an integral part of the air interface and are transmitted continuously within the orthogonal resource structure of the serving cell radio signal.

The UE can isolate the desired reference signal from interference and noise, allowing independent measurement of signal power, interference levels, and resource utilization. In contrast, second- and third-generation networks primarily relied on composite received power measurements, where signal, interference, and noise were not distinctly separable. By introducing OFDMA and subcarrier-level transmission, fourth- and fifth-generation mobile networks substantially improved the accuracy and reliability of radio signal quality measurements reported by user equipment.

Reference measurement

UE devices cannot replace professional equipment in terms of data accuracy for measuring reference signal quality and power. While it is true that measurements are less accurate, the provided metrics of RSRP and RSRQ are standardized and reliable-enough to reach a conclusion to the quality of the user connection, and whether they (users) are impacted by it. This scenario is nothing new, with work in the field already being done in the past.

A 2016 paper by the University of Aalborg, Denmark, investigated how consumer grade Android smartphones compare to professional Radio network scanners for RSCP (3G) and RSRP (LTE) [1]. *NetMap* software was used on Google Nexus Android phones, and its results compared to phones connected to passive Radio network scanners. The scanner was configured with the best resolution and sampling time.

Scenario	RMSE (scanner)	RMSE (phone)
Indoor	3.0 dB	2.1 dB
Outdoor	3.0 dB	0.8 dB
City center	5.8 dB	1.9 dB
Highway	7.3 dB	1.8 dB
Average	4.7 dB	1.7 dB

Table 2. Simplified RSRP results table (scanner vs phone).

The Root Mean Square Error (RMSE) is expressed as:

$$(2) \quad RMSE(x, y) = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2} \quad [dB]$$

Where x_i = RSRP reported by the phone, y_i = RSRP measured by the scanner device and N is the number of synchronized samples. RMSE is an absolute error metric, expressed in dB, that shows how far apart are the phone's RSRP values from the scanners.

The study concluded, that when comparing LTE RSRP measurements, the RMSE between a crowdsourcing smartphone application and a professional tool running on the same handset is approximately 2 dB across environments, indicating high measurement accuracy.

Centralized monitoring platform

The system is created from the ground up, leveraging open frameworks. The key ideology of the platform is correlating the various data sources as one user-centric view, rather than a disconnected set of data layers (what many software systems choose to do).

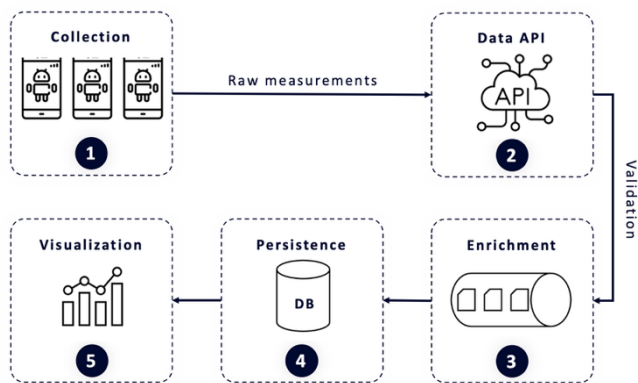


Fig.2. Cell – UE connection and details

To make this work the Figure 2 architecture was realized. Relying on industry standard radio metrics was critical, which is why RSRP and RSRQ were selected, offering a common view across vendors and even generations of equipment. The (1) Collection layer is responsible for gathering and relaying of the raw measurements to the (2) API. This is where various data sources are reviewed and correlated, so a more complete picture is painted. A radio measurement data point makes more sense when combined with the UE's geospatial data, and the location of the cell. Validation and Enrichment (3) is a critical process, which guarantees data is reliable, and there are no missing attributes. At this stage the data is correlated and ready to be (4) persisted (*work done in the field of specialized databases for spectrum management research of electromagnetic fields created by a wide range of devices and systems [4] was technically inspirational for identifying the key challenges a multi-dimensional metric system would have today*), which makes it available to (5) display in the web user interface. Storing data in an efficient and performing way is essential for such a system.

Unifying data from different sources brings its own unique set of challenges. One of the key moments this platform is addressing is the correct resolution and visualization of the interaction between the UE and the serving cell (Uu interface). In all studied cases, the UE devices (especially commercial ones) do not provide sufficient information for resolving cell information. Which is why we require correlation of multiple data sources, to be able to complete the full story.

Coming to the web user component and how data is visualized, each active Cell is rendered with the minimum available metadata – cell identifier, operator, number of active UEs, bandwidth, and EARFCN.

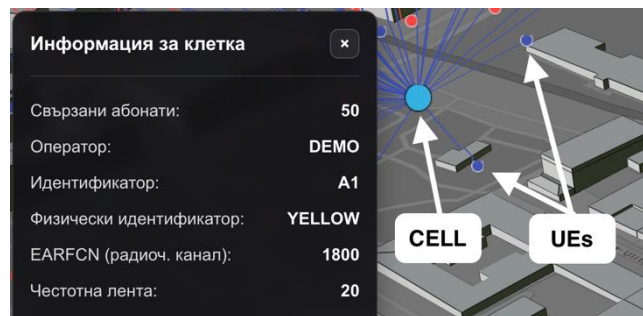


Fig.3. Cell – UE connection and details

The cell object is a larger circle, compared to the UEs it serves – each depicted by a smaller one. A straight line represents the active Uu radio interface, established between the cell and the UE. A line does not represent the physical characteristics of the radio signal but is used to show that an active connection is in process. Both the cell and the UE circles are available for selection, which then brings up a context menu of details about the selected object.

When a UE is selected, this brings up its own measured RSRP and RSRQ values – the last reported value and a brief historical timeseries depiction of the same (up to 1 hour, as seen on figure 4).



Fig.4. Cell – UE reported values and details

Each data point on the timeseries is one reported measurement sent by the end device. The data is presented raw i.e. there is no aggregation, since the depicted historical period is short and we are interested in data precision.

A web user can interact with the live map, by exploring the available filters to narrow down problematic UEs and their serving cells in free floating mode. The immediate benefit of this perspective is speed, when it comes to analyzing more busy areas or cells, subject to peak traffic.

The diagnostic area of the interface allows the user to activate various algorithms that analyze the available data for painting different perspectives. Data can be evaluated for wrongfully connected UEs, which can be caused by mis-configured serving cells and their thresholds, as seen on *Figure 5*.

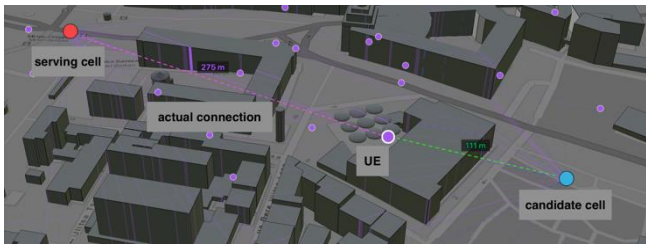


Fig.5. Auto-detecting anomaly connections in a network.

The system can automatically detect UEs connected to the wrong cell, based on environment parameters such as distance. If an active cell exists within range, closer to the currently serving one for the UE, the system will flag this as an anomaly. This is done by measuring the distance between the UE and the serving cell and then looking for cells in closer proximity on the map from the same operator (the figure shows the UE is 111 meters away from a prospect cell, while it is 275 meters away from its currently serving one). One can argue distance should not be the only factor for deciding what is an anomaly – for instance, obstructions can easily make the prospect cell connection signal weaker and therefore explain why a more distant cell is used. The algorithm allows to be extended with additional dimensions of data for a more comprehensive decision-making process. For one, information from the cell's configuration pane can be integrated to make the anomaly detection more robust and precise.

A similar perspective is shown on a busier area, Figure 6, where closely positioned and mis-configured cells can create an overlap area with strong signals from both – creating an opportunity for smaller mistakes in the configuration to lead to the UEs connecting to a more distant cell.



Fig.6. Spotting wrongfully connected UEs.

RSRP Rain attenuation

The attenuation (rain) function, when activated, calculates precipitation and its negative contribution to the measured RSRP values, measured by the UE, as seen on *Figure 7* below. This calculation method is based on the ITU recommendation ITU-R P.838-3, and aims to show the impact of rain to the overall measured RSRP value.

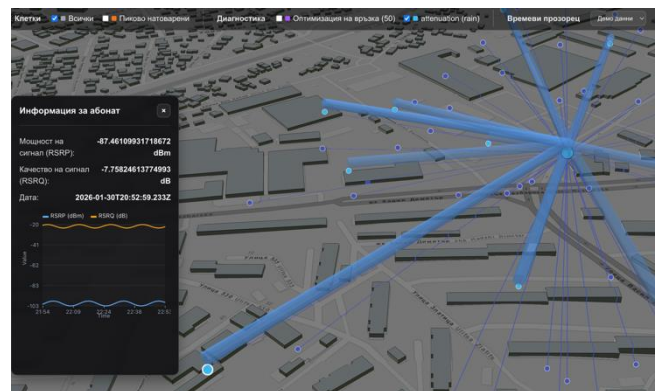


Fig.7. Rain Attenuation for a Cell-UE scenario.

According to the ITU recommendation for rain attenuation calculation [2] the negative effects of rain can be proven, granted certain input data is available per geo spatial point. Rain is modeled as an extra, frequency-dependent path loss via the specific attenuation:

$$(3) \quad \gamma R [dB/km] = k R \alpha$$

γR is the specific attenuation caused by rain, measured in decibels per kilometer; where R is rain rate in mm/h (usually 1-minute integration), k and α depend on frequency, polarization, and elevation angle handling. For the last two ITU also provides parameterization tables to be used for computation, as part of the same recommendation work.

Weather precipitation (rain) data is available from multiple open-source weather API systems on the world wide web. Leveraging this data and correlating it with data produced by the collector system of the platform creates a new dimension for analysis.

While the accuracy of the attenuation model described in ITU-R P.838-3 is disputed by other research papers [3] the key focus of this platform is the ability to build a common data model and drive various perspectives through it for faster telecommunication network diagnostics.

Conclusion

Weather conditions are rarely a problem for telecommunications infrastructure in non-extreme weather regions. In such cases, the impact to the radio signal is negligible. That said, when weather deteriorates, impact factors can quickly stack and lead to a degraded signal – which is why engineers and operators need a tool that visually breaks down information, otherwise requiring hours or even days to process. What is more, engineers require to know if an outage or a performance degradation on the network, has any real significant impact on the serviced UEs in the area. The prototype system was designed to answer those questions.

The existing weather models can be used as another data source – to pre-calculate anticipated radio signal impact caused by predictable or reoccurring seasons weather patterns. Additionally, climate change (often referred to as global warming in public slang) is a factor that is worth considering here. Described as long-term shifts in temperature and weather patterns, but also often materializing through rapid or severe weather conditions in unusual geographic locations. Such events require systems that can quickly adapt to the new conditions and provide real-time measurements for adequate analysis. The developed prototype system enables rapid response.

Using a system like the one described here enables engineers to understand weather impact on telecommunication networks as the anomalous weather conditions develop, in real-time, rather than as a follow-up case study.

The main use case for this system is enabling telecommunication engineers and NOC operators to understand how end users are impacted by the current state of the final leg of the network, that directly connects to and services the UEs. The serving cell is a concentration point – from one hand it interfaces directly with the UE through the Uu interface [8], from

the other it is connected to the rest of the mobile network backbone. Due to this, the level of information available for extract is multi-layer and comprehensive, which is why this makes it a great diagnostic target.

Bringing together data dimensions that are related in terms of the overall use case but have no structural or physical characteristics similarities is an engineering challenge. Often the different feeds of data come with their unique synchronization frequency, data granularity, and aggregation policies. Which is why the data normalization process is a key moment in designing and realizing this system.

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