

Radio Coverage Quality Analytics Using Multi-Band 5G NR Drive Test Measurements

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Abstract—The heterogeneous multi-band architecture of 5G New Radio (NR) deployments spanning low-band (n28), mid-band (n1), and high-band (n78) introduces complex, frequency-dependent propagation behaviours that conventional aggregate coverage metrics fail to adequately characterize. This paper presents a comprehensive radio coverage analytics framework leveraging passive 5G NR drive-test scanner measurements to perform band-level and Physical Cell Identity (PCI)-level coverage assessment across a live operational network in Singapore. A composite Coverage Quality Metric (CQM) is proposed, integrating normalized SSB-RSRP, -SINR, and RSRQ metrics. Additionally, a novel interference ecology metric is introduced to capture the multi-PCI visibility dynamics inherent to passive scanner measurements, quantifying the dominance of the serving PCI relative to the aggregated interference contribution of neighbouring cells through a sigmoid-transformed dominance ratio. The CQM framework is evaluated over a extensive drive test dataset spanning diverse urban, express-way, and suburban environments. Band-level analysis reveals a CQM ranking of $n28 > n1 > n78$, consistent with propagation-limited network behaviour. Spatially correlated multi-band CQM degradation clusters are identified and attributed to structural coverage gaps compounded by high-attenuation environmental features including water bodies, lossy dielectric obstructions, and foliage which is further validated through publicly available crowdsourced mobile operator data. The proposed framework demonstrates the diagnostic capability of passive scanner analytics for operational 5G NR network planning and optimization.

Index Terms—5G NR, Coverage Quality Metric, Interference Ecology, Passive Scanner, Multi-Band, PCI Analytics, Drive Test, Radio Coverage Optimization.

I. INTRODUCTION

The evolution toward Fifth Generation (5G) New Radio (NR) wireless systems has fundamentally transformed cellular network architecture, introducing unprecedented spectral flexibility through the simultaneous utilization of low-band, mid-band, and high-band frequency layers [1]. Commercial 5G NR deployments increasingly adopt multi-band spectrum strategies to jointly optimize wide-area coverage continuity, indoor penetration robustness, mobility performance, and enhanced mobile broadband (eMBB) capacity, with operational objectives that no single frequency layer can fulfil in isolation [2]. In Singapore and comparable high-density urban deployments, telecom operators concurrently leverage sub-1 GHz bands (e.g., n28/700 MHz), mid-band allocations (e.g., n1/2100 MHz and n78/3500 MHz), each engineered to address

distinct propagation regimes and service requirements within a unified multi-layer radio access network (RAN) architecture [3].

Each frequency band exhibits fundamentally distinct physical-layer propagation characteristics such as free-space path loss exponent, diffraction capability, material penetration performance, atmospheric absorption, and beam sensitivity, resulting in substantially divergent user experiences under practical vehicular and pedestrian mobility conditions [4]. Consequently, conventional aggregate coverage evaluation methodologies, which collapse multi-band performance into a single composite indicator, are structurally inadequate for diagnosing band-specific coverage deficiencies, interference susceptibility, or synchronization robustness in heterogeneous 5G NR deployments [5]. Band-level and Physical Cell Identity (PCI)-level coverage analysis is therefore critical for enabling precise propagation characterization, targeted network optimization, and informed multi-band spectrum deployment strategy.

Traditional drive test methodologies relying on User Equipment (UE)-based measurements are inherently constrained by device-specific radio frequency (RF) chain behaviour, operator association policies, and the inability to simultaneously observe all active PCIs across multiple operators and technology layers at a given location [6]. In contrast, passive 5G NR scanners, being operator-agnostic and device-independent, provide a comprehensive spatial and temporal snapshot of the radio environment, capturing synchronization signal block (SSB) measurements, broadcast channel metrics, beam indices, and timing-of-arrival parameters across all visible PCIs simultaneously [7]. This multi-PCI observability is a defining capability that enables a richer characterization of the interference landscape compared to what is achievable through conventional UE-centric measurement frameworks.

Existing literature on 5G NR coverage analysis has predominantly focused on simulation-based propagation modelling [8], controlled channel sounding experiments [9], or protocol-layer performance evaluation, with limited work addressing passive scanner-based, live network analytics at band and PCI resolution. Coverage quality frameworks proposed in prior work typically employ isolated RF metrics such as RSRP or SINR without accounting for the multi-cell interference

dynamics observable through scanner-level PCI visibility. The multi-PCI co-visibility phenomenon where a UE or scanner simultaneously detects signals from multiple neighbouring cells encodes critical information about network redundancy, interference ecology, handover candidate richness, and the structural trade-off between coverage resilience and over-planning risk that existing metrics do not capture.

To address these gaps, this paper presents a comprehensive radio coverage analytics framework developed from large-scale passive 5G NR drive test scanner measurements conducted across a live operational network in Singapore. The primary contributions are as follows: (i) a composite Coverage Quality Metric (CQM) incorporating normalized SSB-RSRP, -SINR, and -RSRQ components derived from 3GPP-aligned piecewise linear scoring functions; (ii) a novel Interference Ecology Metric that quantifies the dominance of the serving PCI relative to the aggregate power contribution of co-visible neighbouring PCIs, capturing the multi-PCI resilience-versus-interference trade-off through a sigmoid-transformed dominance ratio; and (iii) a band-level and geospatial CQM analysis across n28, n1, and n78 operating bands, with root-cause attribution of structural coverage degradation zones validated through crowdsourced gNodeB infrastructure data.

II. MEASUREMENT CAMPAIGN AND DATASET

A. Measurement Setup

The measurement campaign was conducted using a commercial 5G NR scanner traversing along a route shown in Fig. 1. This particular drive route is around 2hr and 30min long in duration and has multiple radio environment scenarios including dense urban areas, open express-way roads, and transitional suburban regions with reservoirs. The scanner continuously captured operator-level, band-level, PCI-level and beam-level synchronization and broadcast channel measurements from live operational 5G NR service deployed with mobility conditions representative of practical vehicular scenarios.

The measurement system recorded extensive physical-layer and synchronization-layer parameters including synchronization signal block (SSB) measurements, physical broadcast channel (PBCH) metrics, demodulation reference signal (DMRS) measurements, timing-of-arrival (ToA) information, and beam indices associated with detected cells and beams. The scanner was set to capture the network parameters once every 1 sec along the drive route. The collected measurements therefore provide both spatial and temporal visibility into the operational behaviour of the commercial 5G NR network.

B. Collected Measurements

The dataset contains a large number of radio parameters spanning synchronization-layer, data-layer, and timing-domain measurements. Table I summarizes the primary parameters used in this work. The data set captured 88776 points for the specific operator being analysed. The collected dataset includes measurements specifically from the n78, n28, and



Fig. 1: Route for drive test measurement campaign.

TABLE I: 5G NR Signal and Channel Parameters

Parameter	Description
Time	Time stamp of measurement
PCI	Physical Cell Identity
SSB Metrics	RSRP, SINR, RSRQ
SSB Idx	Beam Index
SS-Metrics	Synchronization Signal RSRP, RSRQ, SINR
DM-Metric	Demodulation Signal RSRP, RSRQ, SINR
ToA(CIR)	Time of Arrival from CIR
PBCH Metrics	Broadcast Channel RSRP, RSRQ, SINR
CarrierBW	Carrier Bandwidth
NR-ARFCN	NR Carrier Frequency

n1 5G NR operating bands, each representing distinct propagation and deployment characteristics that significantly influence practical radio coverage quality. The particular operator leverages on multi-band spectrum strategy. The n78 band, operating within the mid-band 3.5 GHz spectrum, is widely deployed for enhanced mobile broadband services due to its ability to support large carrier bandwidths and high network capacity. In practical coverage analysis, n78 typically exhibits strong achievable signal quality and spectral efficiency in favourable propagation conditions, but its higher carrier frequency also results in increased sensitivity to propagation loss, penetration attenuation, and environmental obstruction effects. Consequently, n78 coverage quality often demonstrates greater spatial variability and stronger degradation in dense urban or obstructed environments. In contrast, the n28 band operating around 700 MHz provides substantially improved propagation robustness due to its lower carrier frequency, enabling larger cell coverage footprints, superior diffraction capability, and stronger indoor penetration performance. As a result, n28 deployments generally exhibit more stable wide-area coverage quality and improved synchronization visibility under mobility conditions, although with comparatively lower available bandwidth and achievable throughput potential. The particular operator in this analysis, refarmed the legacy 3G spectrum, and operates the band with dynamic spectrum sharing between LTE Band 28 since the year 2025, with the

objective to improve indoor penetration and coverage. The n1 band, operating around 2100 MHz, occupies an intermediate propagation regime between n28 and n78, providing a balance between coverage continuity and spectral efficiency. The number of sample points for each of the three bands along with the number of PCIs seen and the carrier bandwidth allocated for each band is summarized in Table II where it is noticed that a fairly uniform distribution of the bands in the dataset is noticed.

TABLE II: Dataset features of the three 5G NR bands

Band	DataPoints	#PCI	CarrierBW [MHz]
n78	27,232	204	98.28
n28	29,410	209	19.08
n1	32,134	222	19.08

The geospatial distribution of the PCIs for each band across the drive test route is shown in Fig. 2. The temporal occurrences of the different PCIs serving each of the 3 bands is shown in Fig 3. At least one PCI for each band was seen along the entire route of the drive test and in some time instances (or equivalently locations), it was noticed that at certain locations, more than 8 PCIs were seen by the scanner. The time instances when more than 3 PCIs were captured is highlighted in Fig 3.

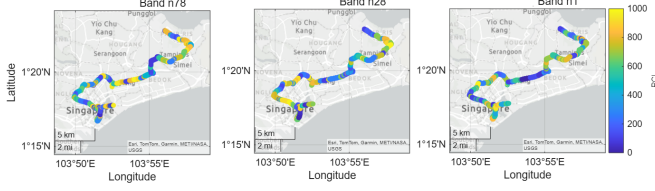


Fig. 2: Geospatial distribution of PCIs seen over the route of the drive test, from a particular operator serving bands n78, n28 and n1.

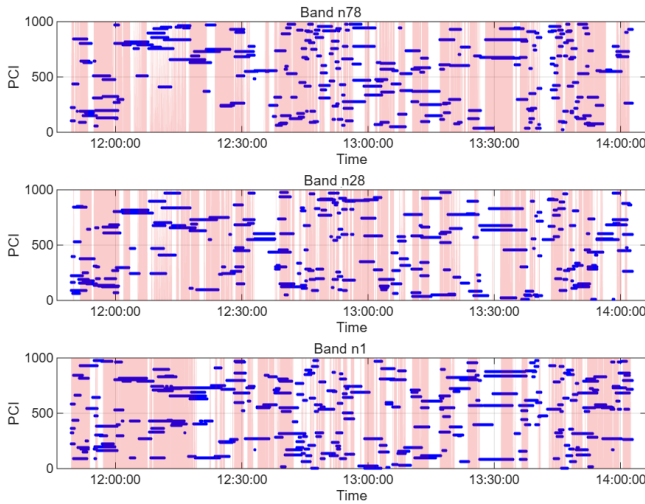


Fig. 3: PCIs from a particular operator seen over the entire time of the drive test for the bands n78, n28 and n1.

III. RADIO ANALYTICS FRAMEWORK

A. Coverage Quality Metric

Traditional cellular coverage evaluation methods typically rely on isolated RF metrics such as RSRP or SINR measurements. However, such approaches may not adequately capture the complex radio interference ecology encountered in operational 5G NR deployments where multiple neighbouring PCIs and beams coexist simultaneously. To address such limitations, a composite Coverage Quality Metric (CQM) is proposed by jointly considering synchronization signal metrics such as received signal power, quality, and interference conditions. Furthermore, an interference ecology metric is proposed to account for multiple PCIs visible at a particular drive test route. For the RSRP, SINR and RSRQ metrics, a normalization based on piece-wise linear technique based on 3GPP defined classification for *RSRP*, *RSRQ* and *SINR* is implemented as shown in eq (1), (2) and (3) respectively.

$$\overline{RSRP}(x) = \begin{cases} 1.0 & \text{if } x > -70 \\ 0.75 + 0.25 \left(\frac{x+80}{10} \right) & \text{if } -80 < x \leq -70 \\ 0.50 + 0.25 \left(\frac{x+90}{10} \right) & \text{if } -90 < x \leq -80 \\ 0.25 + 0.25 \left(\frac{x+100}{10} \right) & \text{if } -100 < x \leq -90 \\ 0.25 \left(\frac{x+115}{15} \right) & \text{if } -115 \leq x \leq -100 \\ 0.0 & \text{if } x < -115 \end{cases} \quad (1)$$

$$\overline{RSRQ}(x) = \begin{cases} 1.0 & \text{if } x > -3 \\ 0.75 + 0.25 \left(\frac{x+10}{7} \right) & \text{if } -10 < x \leq -3 \\ 0.50 + 0.25 \left(\frac{x+12}{2} \right) & \text{if } -12 < x \leq -10 \\ 0.25 + 0.25 \left(\frac{x+15}{3} \right) & \text{if } -15 \leq x \leq -12 \\ 0.25 \left(\frac{x+20}{5} \right) & \text{if } -20 \leq x < -15 \\ 0.0 & \text{if } x < -20 \end{cases} \quad (2)$$

$$\overline{SINR}(x) = \begin{cases} 1.0 & \text{if } x > 30 \\ 0.67 + 0.33 \left(\frac{x-20}{10} \right) & \text{if } 20 < x \leq 30 \\ 0.33 + 0.34 \left(\frac{x-13}{7} \right) & \text{if } 13 < x \leq 20 \\ 0.33 \left(\frac{x}{13} \right) & \text{if } 0 \leq x \leq 13 \\ 0.0 & \text{if } x < 0 \end{cases} \quad (3)$$

Since multiple PCIs, can be seen at each unique timestamp or equivalently location in the drive test, we define an interference ecology metric which serves as a component in the score that factors both resilience and over-planning in the intended radio coverage planning. Allocating multiple PCIs per site (e.g., per sector or beam) improves handover granularity and load balancing, but risks PCI confusion/collision if not carefully managed across the reuse pattern. The trade-off lies in over-planning where assigning too many PCIs inflates neighbour list complexity and signalling overhead. On the other hand under-planning, which reduces resilience

when a cell fails and neighbouring cells must absorb coverage without distinct identities. From the scanner data that captures the metrics of all visible PCIs, we gather the vector $P = \{P_1, P_2, \dots, P_N\}$ of the SSB-RSRP for each unique time stamp where N is the number of visible PCIs at that time instance. We define the maximum power as

$$P_{\max} = \max_{1 \leq j \leq N} P_j \quad (4)$$

where $P_j = 10^{SSB-RSRP_j/10}$. Assuming the serving PCI to be the one with maximum SSB-RSRP, we define the dominant serving PCI dominance ratio α , as the ratio of the sum of the remaining power values to the maximum power given as:

$$\alpha(t) = \frac{\left(\sum_{i=1}^{N(t)} P_i\right) - P_{\max}}{P_{\max}} \quad (5)$$

The interference ecology metric, $\bar{I}(t)$ is then obtained from α as a metric between 0 and 1 using the sigmoid function defined as

$$\bar{I}(t) = 2 \left(1 - \frac{1}{1 + e^{-\alpha(t)}} \right) \quad (6)$$

Note that $\bar{I}(t) \in [0, 1]$ similar in range as the $\overline{RSRP}$, $\overline{RSRQ}$ and $\overline{SINR}$ metrics. The interference ecology term represents the relative contribution of neighbouring PCI power with respect to the serving PCI. When there is only one active PCI visible, $\bar{I}(t) = 1$.

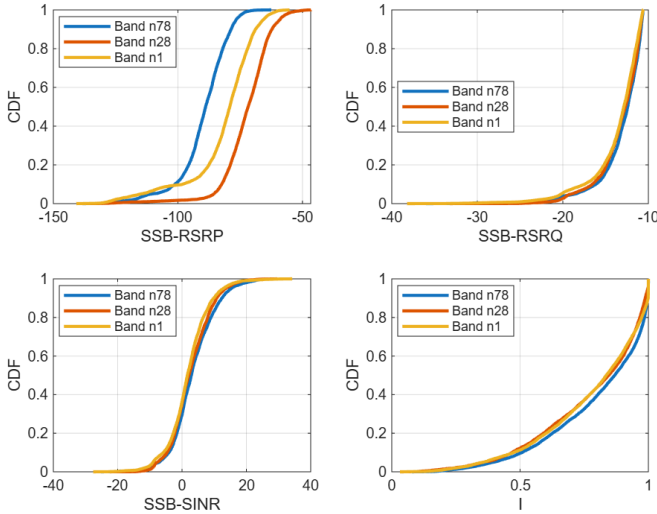


Fig. 4: Empirical CDF of the 4 metric used in the coverage quality metric analysis, for the different 5G NR bands.

The overall coverage quality metric is defined as:

$$CQM(t) = w_1 \overline{RSRP}(t) + w_2 \overline{SINR}(t) + w_3 \overline{RSRQ}(t) + w_4 \bar{I}(t) \quad (7)$$

where the weights w_1, w_2, w_3 and w_4 are set as 0.4, 0.3, 0.15 and 0.15 respectively. Note that the sum of the weights is 1 with the SSB-RSRP contributing the most to the quality score. The empirical CDF of the four individual metrics in the composite CQM score is shown in Fig. 4. The trend observed in

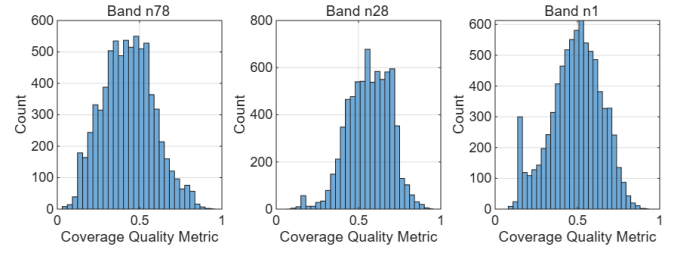


Fig. 5: Distribution of computed coverage quality metric across the different bands.

SSB-RSRP, is expected behaviour rooted in radio propagation behaviour with n28 (700 MHz) having the longest wavelength, giving it superior penetration and path loss characteristics while n1 (2100 MHz) sits in the mid-band with moderate free-space path loss and finally n78 (3500 MHz) suffers the highest path loss exponent and greater atmospheric/material absorption. Additionally, base-station antenna with n28 have wider coverage footprint where as n78 SSB beams are narrower and more sensitive to blockage and angular misalignment. This is also therefore reflective in the distribution of CQM scores for each of the 3 bands shown in Fig. 5. Based on the CQM threshold values defined in Table III, we are therefore able to categorize coverage quality related radio environment state along the drive test route. The band-level classification for the state of radio environment is shown in Fig. 6. The observed distribution gives a ranking of n28 performing better than n1 and while n78 being relatively lower than n1 band. This ranking confirms the network is propagation-limited and the coverage metric naturally favouring n28 band with superior reach over n78. From a deployment strategy standpoint, this indicates that n78 should be treated as a capacity/hotspot layer anchored within n28 or n1 umbrella coverage.

TABLE III: CQM based definition of state of radio environment

CQM	Threshold	Meaning
Excellent	0.75 - 1	Stable high-quality coverage
Good	0.5 - 0.75	Reasonable coverage
Moderate	0.25 - 0.5	Usable but interference-limited
Low	0 - 0.25	Unstable or degraded coverage

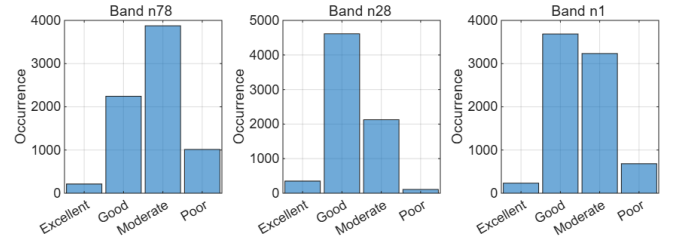


Fig. 6: Classification of the state of radio environment along the route based on CQM

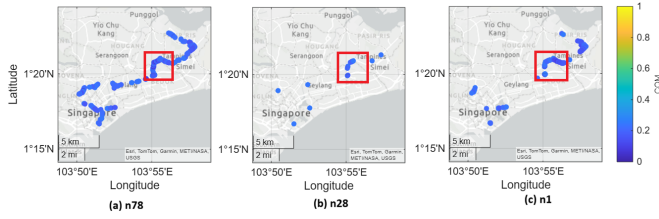


Fig. 7: Locations with low QCM score for n78, n28 and n1 bands

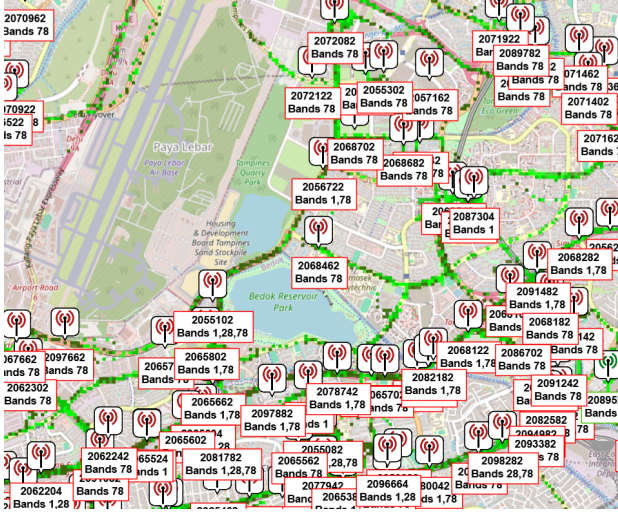


Fig. 8: gNodeB located around the routes with low QCM scores, courtesy of CellMapper [10].

Further investigation of locations exhibiting persistently low CQM across all three bands (n78, n1, n28), as shown in Fig 8, reveals a spatially correlated degradation cluster in which is a strong indicator of a structural coverage gap rather than band-specific effects or configuration anomaly. Cross-referencing the affected drive test route against crowdsourced capacity and estimated gNodeB positions from CellMapper [10] confirms a notably sparse gNodeB density in the implicated region.

Geospatial analysis of the degraded corridor identifies a combination of high-attenuation environmental features. Specifically, a reservoir and water-filled quarry introduce specular reflection and signal scattering effects that distort the multipath profile, while the adjacent sand stockpile presents a lossy dielectric obstruction with high absorption characteristics across sub-6GHz frequencies. The proximate park vegetation further contributes foliage-induced attenuation. Collectively, these terrain and land-use features form a compounded effect that systematically suppresses RSRP and degrades the coverage quality independent of frequency band. This explains the consistent CQM underperformance observed across n28, n1, and n78 simultaneously.

IV. CONCLUSION

This paper presented a passive scanner-driven radio coverage analytics framework for multi-band 5G NR networks,

enabling band-level and PCI-level diagnostic assessment beyond the capability of conventional UE-based drive test methodologies. The distinguishing contribution of this work is the interference ecology metric, which is a sigmoid-normalized dominance ratio that quantifies the relative interference pressure exerted by co-visible neighbouring PCIs upon the serving cell, capturing the tional trade-off between network resilience through multi-PCI redundancy and the degradation risks of over-planned, interference-dense radio environments. Evaluation across a large-scale drive test dataset from a live Singapore 5G NR deployment confirms that band-level CQM performance follows the propagation hierarchy $n28 > n1 > n78$, validating the framework's sensitivity to frequency-dependent path loss and diffraction characteristics. The identification of spatially correlated, multi-band CQM degradation clusters demonstrates the framework's capacity for root-cause localization of structural coverage deficiencies that transcend individual band behaviour. Cross-validation against crowdsourced gNodeB infrastructure data further confirms the role of sparse node density as a primary contributor to the degraded zones. Collectively, the proposed framework establishes a scalable, operator-agnostic foundation for data-driven 5G NR coverage diagnostics, with direct applicability to network planning, post-deployment optimization, and multi-band spectrum strategy refinement.

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