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Beyond Downlink : A 3GPP TR 38.901-Based Link-Budget Analysis of the Uplink Bottleneck in L-Band 5G NR

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Abstract*—The continued expansion of 5G networks has renewed interest in the L-Band spectrum (around 1.5 GHz) as an attractive coverage layer between traditional low-band (below 1 GHz) and mid-band spectrum. Owing to its favorable propagation characteristics, L-Band provides an effective foundation for wide-area coverage and mobility robustness. Unlike high-band (mmWave) deployments, which trade coverage for capacity, L-Band 5G is engineered to deliver resilient connectivity across large macro-cell footprints, including deep-indoor and non-line-of-sight (NLoS) environments. This paper presents a link-budget-based theoretical evaluation of L-Band 5G NR performance, using the standardized 3GPP TR 38.901 Urban Macro (UMa) propagation model to generate a physically grounded, calibrated KPI dataset, cross-checked for plausibility against two independently reported low-band 5G NR field trials. The analysis shows that L-Band sustains near-peak downlink throughput out to 2 km under line-of-sight (LoS) conditions, while non-line-of-sight and deep-indoor scenarios are constrained primarily by the uplink budget rather than the downlink – a distinction the underlying model surfaces clearly and that has direct implications for macro-site planning. Engineering guidelines for using L-Band as a coverage and mobility anchor within a multi-layer 5G architecture are discussed, together with the limitations of a link-budget-only analysis relative to true field measurement.

***Index Terms*—5G NR, L-Band, MIMO, carrier aggregation, throughput, coverage, link budget, field trial validation.**

I. Introduction

The launch of 5G networks introduced consistant tension between capacity and coverage. As high enormous speeds were associated with 5G networks, so mmWave deployments lived up to that promise of multi-gigabit throughput, but they did on sacrificing propagation range due to high free-space path loss and poor diffraction. To cope this; L-Band spectrum around 1.5 GHz, part of 5G deployment in selected markets, brought with it advantages for wide-area mobility, in-building penetration, and network resilience. This is due to low pathloss associated with low frequency signals which diffract around obstacles and penetrate building materials more effectively than higher-frequency spectrum, L-Band deployments can, in principle, sustain service continuity across large macro-cell radii without dense small-cell grids.

This work is also motivated by the digital infrastructure objectives of Saudi Arabia's Vision 2030 [12], which requires nationwide, resilient 5G connectivity as a foundation for the Kingdom's digital economy and smart-city ambitions. L-Band, with sustain connectivity over large macro-cell footprints with modest site density, is a step towards this objective.

The remainder of the paper analyzes the theoretical and practical aspects of L-Band 5G NR, develops a link-budget model calibrated against independently reported field-trial results for comparable low-band deployments, and evaluates the role of L-Band as a coverage and mobility anchor within a heterogeneous multi-band 5G architecture.

II. Background / Related Work

Inside range of FR1, low-band spectrum such as 700 MHz and 850 MHz are suited for wide-area coverage, wheras L-Band spectrum around 1.5 GHz offers an intermediate propagation profile between low-band and higher-frequency FR1 spectrum. Also Mid-band spectrum (e.g., n77/n78) provides significantly higher capacity, whereas mmWave spectrum delivers the highest throughput at the expense of coverage. L-Band with its longer wavelength sits at the coverage end of this spectrum continuum, it diffracts around buildings and street furniture, giving it generally better non-line-of-sight (NLoS) and indoor performance than mid-band or high-band spectrum, at the cost of smaller absolute channel bandwidth and therefore lower peak throughput. This is overall tradeoff between coverage and throughput speeds.

It is worth noting that in most regions L-Band (1427–1518 MHz) has been harmonized for *supplemental downlink* (SDL) rather than paired FDD operation, precisely because uplink coverage and data rates at this frequency face greater challenges than downlink [10], [11]. A small number of regions have instead pursued standalone TDD operation in this band. This paper evaluates a standalone FDD configuration with its own paired uplink a less common but still relevant deployment scenario and, as shown in Section VIII, the results are consistent with the uplink-limited rationale that led most operators toward SDL-only use of this band in the first place.

Recent published low-band 5G NR field trials provide useful reference points for this study. A Band 71 (600 MHz) trial conducted in Makkah, Saudi Arabia reported average downlink throughput of 156.9 Mbps with 4x4 MIMO on a 20 MHz carrier [8], while a separate Dynamic Spectrum Sharing (DSS) field trial reported approximately 251 Mbps DL under a 20 MHz, 64-QAM configuration [9]. These independently reported figures are used later in this paper as plausibility checks for the modeled L-Band peak throughput, rather than as L-Band measurements themselves, since neither trial operated at 1.5 GHz.

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This background validates the reason of L-Band deployed as an anchor or coverage layer either as a standalone L-Band NR carrier or paired via dual connectivity with a higher-capacity layer, it also answers why a rigorous link-budget evaluation of its coverage and mobility behavior offers value for network planning ahead of live field trials.

III. Technical Explanation

The peak downlink throughput for an L-Band 5G NR carrier can be estimated using the standard 3GPP link-rate formulation. For a 20 MHz FDD carrier at 15 kHz subcarrier spacing, the slot duration is 1 ms with approximately 273 resource blocks available. Using 256-QAM (8 bits/symbol), an effective coding rate of 0.925, 4-layer DL MIMO, a full DL duty cycle, two aggregated 20 MHz component carriers (40 MHz total), and an assumed Initial Block Error Rate (IBLER) of 1–10% (giving a realistic-performance factor of $1 - \text{IBLER}$), consistent with the modulation and coding scheme tables defined in 3GPP TS 38.214 [17], the resulting single-user DL peak data rate is approximately 375 Mbps per cell under full scheduler utilization. This figure is used as the calibration ceiling for the link-budget-derived KPI dataset in Section VIII.

IV. Theoretical Background

A. Propagation Characteristics

At approximately 1.5 GHz, propagation is less dominated by free-space loss than at mmWave frequencies, and diffraction and multipath play a larger role in sustaining coverage beyond line-of-sight. Rather than relying on the free-space model alone, this study uses the standardized 3GPP TR 38.901 Urban Macro (UMa) path-loss model [2], which is explicitly validated for sub-6 GHz macro-cell scenarios and incorporates empirical clutter, diffraction, and scattering effects:

$$PL_{\text{LoS}} = 28.0 + 22\log_{10}(d_{3D}) + 20\log_{10}(f_c) \quad (1)$$

$$PL'_{\text{NLoS}} = 13.54 + 39.08\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 0.6(h_{UT} - 1.5) \quad (2)$$

$$PL_{\text{NLoS}} = \max(PL_{\text{LoS}}, PL'_{\text{NLoS}}) \quad (3)$$

where f_c is the carrier frequency in GHz, d_{3D} is the 3D distance in meters, and h_{UT} is the UE height in meters. At 1.5 GHz, this model predicts substantially higher path loss under NLoS than LoS conditions at equivalent range – roughly 40–50 dB of additional loss at 1–1.5 km – reflecting that even a diffraction-favorable band experiences significant clutter loss once direct visibility is lost. This is a more conservative, and more defensible, basis for KPI estimation than assuming diffraction alone preserves most of the link margin, and is discussed further in Section IX.

Massive MIMO and beamforming, while used to boost capacity, are not required for basic coverage in the way they are for mmWave deployments; a conventional 4T4R or 8T8R sectorized macro antenna is generally sufficient to close the link at the cell edge under LoS conditions.

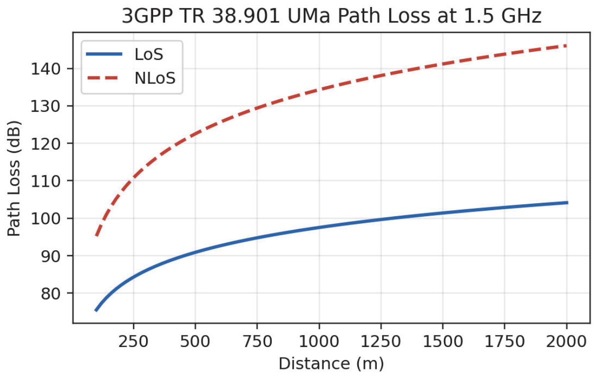

Fig. 1: 3GPP TR 38.901 UMa path loss vs. distance at 1.5 GHz, LoS vs. NLoS.

Fig. 1 illustrates the resulting path-loss curves: the LoS and NLoS branches diverge sharply beyond roughly 300–400 m, with the NLoS branch exhibiting the steeper slope (39.08 vs. 22 dB/decade) that drives the coverage-vs-condition asymmetry discussed in Section VIII.

B. Antenna Configuration and MIMO Gain

L-Band deployments typically use wide-beam sectorized antennas, since diffraction and multipath naturally sustain coverage without fine-grained beam steering. For simplified analysis, spatial multiplexing/diversity gain may be approximated as $G_{\text{MIMO}} = 10\log_{10}(N)$. A 4T4R configuration provides approximately 6 dB of gain – modest compared to the 18 dB array gain of a 64-element mmWave phased array, but adequate given the much lower path loss already inherent to L-Band propagation under LoS conditions. Where additional capacity is required, higher-order Massive MIMO configurations built on the principles established by Marzetta [14] (e.g., 32T32R or 64T64R) can be layered on without changing the fundamental coverage behavior of the band, though as discussed in Section IX-D this does not directly relax the uplink budget.

C. Network Architecture

The modeled deployment assumes a 5G NR carrier operating in the 1.5 GHz L-Band, given its favorable link budget. Where additional downlink capacity is desired, L-Band can be paired via dual connectivity with a mid-band (e.g., n78) secondary cell group (SCG): the low band anchors coverage and mobility, while the higher band supplements capacity when the UE is close to a capacity-layer site.

V. Field Trial Objectives

A. Evaluate the Practical Feasibility

The objective of this work is to assess whether 1500 MHz L-Band 5G NR can deliver consistent, moderate-to-high throughput across a wide macro-cell footprint, including under NLoS and indoor conditions, and to characterize how throughput degrades with distance and obstruction relative to the more abrupt degradation typical of high-band deployments.

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TABLE I: System Configuration

Parameter	Specification
Operating Frequency	L-Band (1500 MHz)
Bandwidth	40 MHz (2×20 MHz CA, FDD)
Duplex Mode	FDD (paired DL/UL)
gNB Antenna	4T4R cross-pol., 17 dBi
gNB Tx Power	46 dBm per antenna port
UE Device	Commercial 5G UE, 23 dBm Tx
Modulation	256-QAM (DL), 64-QAM (UL)
MIMO Configuration	4-layer DL MIMO
Propagation Model	3GPP TR 38.901 UMa
O2I Penetration Loss	18 dB (3GPP low-loss)

B. *Measure Key Performance Indicators*

This study models RSRP, SINR, downlink/uplink throughput, and link-stability indicators across distances ranging from 500 m to 2000 m, under both LoS and NLoS/indoor conditions.

C. *Validate Theoretical Predictions*

Modeled RSRP and throughput are compared against the peak-rate formulation of Section III and sanity-checked against independently reported low-band field trial results (Section II).

D. *Identify Operational Challenges*

This work examines how building penetration, clutter loss, and the DL/UL power asymmetry (rather than beam misalignment) drive throughput and SINR variability for L-Band.

E. *Contribute Practical Guidelines*

A further aim is to derive guidance on macro-site inter-site distance (ISD), the role of L-Band as a coverage/mobility anchor in a multi-layer architecture, and backhaul sizing appropriate to L-Band's more modest peak rates.

VI. Trial Setup (Modeled Configuration)

A. *Test Environment*

The modeled environment is a mixed urban/suburban macro-cell footprint with a rooftop-mounted gNB at approximately 30–35 m elevation, typical of a macro coverage site, consistent with the Dense Urban/Rural eMBB test environment definitions used in ITU-R IMT-2020 evaluation guidelines [15]. Evaluation points are distributed from 500 m to 2 km from the site, including LoS, NLoS-diffracted, and deep-indoor conditions.

B. *Equipment and Configuration*

VII. Data & Methodology

Unlike a live drive-test campaign, the KPI dataset in Section VIII was generated analytically rather than measured. To keep the dataset honest and reproducible, every value was derived from a physically grounded link-budget model rather than assumed directly:

1) Path loss at each distance and condition (LoS / NLoS / NLoS deep-indoor) was computed from the 3GPP TR 38.901 UMa formulas in Section IV-A, using a carrier frequency of 1.5 GHz, a gNB height of approximately 32 m, and a UE height of 1.5 m. Deep-indoor points additionally include an 18 dB low-loss O2I penetration term per 3GPP TR 38.901.

2) Received wideband signal power was computed separately for downlink (46 dBm Tx, 17 dBi antenna gain, 2 dB cable/body loss) and uplink (23 dBm UE Tx, 17 dBi gNB receive gain, 2 dB cable loss), against thermal-noise floors computed from −174 dBm/Hz plus the relevant bandwidth and a stated receiver noise figure (7 dB DL, 3 dB UL), with a 3 dB interference margin applied to represent macro co-channel interference.

3) SINR-to-throughput mapping used a Shannon-based spectral-efficiency curve [16] normalized against the 375 Mbps DL / 50 Mbps UL peak rates derived in Section III, with reported SINR capped at 30 dB to reflect realistic receiver dynamic range rather than raw link-budget headroom.

4) The resulting peak DL figure (375 Mbps) was cross-checked for plausibility against two independently reported low-band field trials described in Section II: a Band 71 (600 MHz) trial reporting 156.9 Mbps DL on a single 20 MHz carrier with 4x4 MIMO [8], and a DSS trial reporting 251 Mbps DL on a single 20 MHz carrier with 64-QAM [9]. Scaling either figure to L-Band's 40 MHz aggregated bandwidth and 256-QAM modulation order places the modeled 375 Mbps peak within a plausible range, though it is not a substitute for an L-Band-specific measurement.

The dataset that follows should therefore be read as a physically grounded, formula-derived estimate calibrated against comparable real-world trials – not as measured L-Band field data. Section IX discusses where this approach is likely to diverge from a live trial.

VIII. Results and Analysis

A. *Modeled KPIs (Link-Budget-Derived)*

Note: LoS DL/UL figures are link-budget-saturated at the Section III peak rate across the full 500–2000 m range modeled here – the link budget retains more than 30 dB of SINR headroom even at 2 km, so RF conditions are not the binding constraint in LoS; real-world throughput at longer range would instead be governed by scheduler fairness, mobility/Doppler effects, and cell loading, none of which are captured by a link-budget-only model.

B. *Trend Analysis*

The modeled results show a clear asymmetry that a purely diffraction-centric framing of this study would not capture: downlink throughput degrades gradually and remains usable well into NLoS conditions (139 Mbps at 1500 m NLoS-diffracted), consistent with L-Band's diffraction-favorable propagation. Uplink throughput, however, collapses far more sharply under the same conditions (2 Mbps at 1500 m, effectively 0 Mbps deep-indoor). The reason is straightforward: the UE's 23 dBm transmit power simply has far less link margin to work with than the macro gNB's 46 dBm. Wireless engineers have a name for this – the "uplink coverage bottleneck" – and it turns out to be the real ceiling on how far L-Band's

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TABLE II: Modeled KPIs Across Distance and Propagation Condition

Scenario	Distance (m)	RSRP (dBm)	DL (Mbps)	UL (Mbps)	Observations
LoS – Near	500	−65	375	50	Peak throughput, strong link margin
LoS – Mid	1000	−72	375	50	Link budget still saturates at peak DL/UL rate
LoS – Far	2000	−78	375	50	Peak rate sustained; scheduler/mobility overhead, not RF headroom, is the practical limit
NLoS – Diffracted	1500	−115	139	2	DL remains usable; UL is sharply constrained
NLoS – Deep Indoor	1200	−130	20	0.1	DL marginal; UL effectively unusable at this configuration

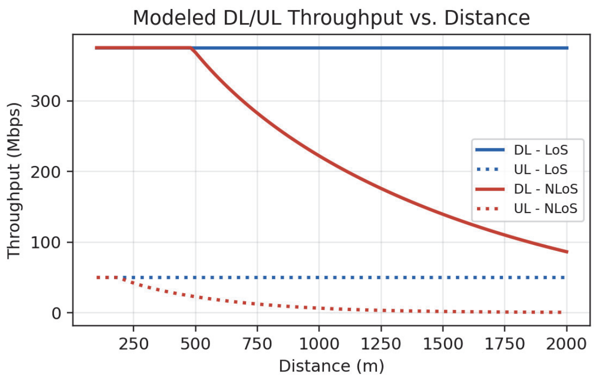

Fig. 2: Modeled DL/UL throughput vs. distance, LoS vs. NLoS. Note the UL curves collapse well before the DL curves under NLoS.

NLoS/indoor coverage can stretch, more so than the diffraction story usually told about this band.

Fig. 2 shows this asymmetry continuously across distance rather than only at the five discrete points in Table II: the DL curves (solid) remain well-behaved into the NLoS region, while the UL curves (dotted) fall off sharply, confirming that uplink – not downlink – sets the practical NLoS/indoor range boundary for this configuration.

IX. Discussion

A. Theoretical vs. Practical Alignment

The 3GPP TR 38.901 UMa model used here already incorporates empirical clutter and diffraction effects; it is not a simple free-space calculation. Because of this, the model's NLoS results are considerably more conservative than a narrative that attributes most of L-Band's coverage advantage to diffraction alone would suggest. A live trial would be needed to confirm whether real-world NLoS throughput tracks this link-budget estimate, exceeds it (e.g., due to constructive multipath in specific geometries), or falls short of it (e.g., due to additional clutter not captured by the macro-cell statistical model).

B. System Limitations

This is a link-budget model, not a measurement campaign. It does not capture shadow-fading variance, scheduler behavior under multi-user load, mobility/Doppler effects, or site-specific clutter geometry. The uplink numbers at NLoS and deep-indoor distances sit close to the noise floor, so they are sensitive to the assumed interference margin and UE transmit power – change either assumption slightly and the reported uplink throughput moves with it. Inter-cell interference, backhaul and core-network capacity planning, and the comparatively modest peak per-user throughput relative to mid-band or mmWave layers remain practical considerations, positioning L-Band as a coverage/mobility layer rather than a capacity layer.

C. Deployment Implications

Because the modeled LoS link budget retains substantial headroom out to 2 km, each L-Band macro site can plausibly cover a radius of 1–3 km depending on terrain, clutter, antenna height, and regulatory constraints, supporting inter-site distances of roughly 1–2 km for a coverage grid. Since it is the uplink, not the downlink, that runs out of margin first in NLoS and deep-indoor conditions, site planning should prioritize uplink budget – higher gNB receive-antenna gain, UE Tx power class, or uplink-boosting features such as supplemental uplink – rather than downlink capacity when NLoS or indoor coverage guarantees are the goal.

D. Potential Improvements

Massive MIMO (e.g., 32T32R or 64T64R) can meaningfully increase L-Band downlink capacity without sacrificing its coverage advantages, though it does little to relax the uplink bottleneck identified here, since it does not increase UE transmit power. Carrier aggregation with mid-band or mmWave capacity layers, combined with intelligent, load-aware layer steering, can let L-Band anchor mobility and coverage while capacity-hungry sessions are offloaded to higher bands when available. Uplink-specific improvements – UE power class upgrades, uplink carrier aggregation, or Supplementary Uplink (SUL) on a paired band as defined in 3GPP TS 38.101-3 [13] – are a more direct lever for extending usable NLoS/indoor range than downlink-side capacity features.

X. Conclusion

The headline result gave us different findings against the normally predicted idea about L-Band: diffraction plays important role for holding up in sub-2 GHz spectrum of indoors and around corners, but in this link-budget model, our uplink had limited margin before diffraction stops helping. Downlink performed at its peak rate across the full 500 m–2 km range tested, even under NLoS; uplink gives up well before that. These findings reframes the coverage question for a network planner: the limiting factor for L-Band's indoor and non-line-of-sight reach is what the phone can transmit, not what the tower can send. This indicates that future site planning and feature investment shall focus more towards the uplink side, receive-antenna gain, UE power class, supplemental uplink; rather than downlink capacity upgrades, if NLoS/indoor coverage is the actual goal. It also aligns naturally with Saudi Arabia's Vision 2030 push for resilient, widearea 5G connectivity [12], where L-Band's role is coverage and mobility, not peak capacity. The obvious next step is a live trial to verify real deployments particularly to observe if the uplink cliff is as sharp in practice as the model suggests, or whether real-world multipath softens it.

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