



Uplink Coverage and Cell-Edge Performance Enhancement Features for 5G NR

Qualcomm Technologies, Inc.

12/16/2025



Contents

1	Background: What is coverage in legacy 5G-NR network?	2
1.1	Cell acquisition coverage (control channel).....	2
1.2	DL service coverage (data & voice)	2
1.3	UL service coverage (data & voice)	2
1.4	High-level 5G-NR link budget discussion.....	2
1.5	Limiting link for coverage for NR-FDD & NR-TDD-M-MIMO networks	3
2	What is the fallback option in case of no coverage?	3
2.1	NR-TDD to NR-FDD layer inter-frequency transition	4
2.2	NR-FDD layer to LTE-FDD layer inter-RAT transition.....	4
2.3	Impact to user experience for these transitions	4
3	Options for UL coverage / cell-edge performance enhancements	4
3.1	UL channel independent enhancements.....	4
3.1.1	Higher power class UE (PC2, PC1.5, PC1) 4	
3.2	UL control channel enhancements	6
3.3	UL Shared Channel Enhancements	7
3.3.1	Maximum Operating Power (MOP) 8	
3.3.2	Switched UL 8	
3.3.3	Supplemental UL 9	
3.3.4	RLC segmentation 10	
3.3.5	PUSCH slot aggregation 11	
3.3.6	Uplink Data Compression 12	
3.3.7	Coherent UL MIMO 13	
3.3.8	Low Spectral Efficiency CQI Table 14	
3.3.9	$\pi/2$ BSPK Modulation 14	
3.3.10	UL Configured Grant 15	
4	Deployment Recommendation.....	15
5	Conclusion	16
6	References	16
7	Abbreviations.....	16

1 Background: What is coverage in legacy 5G-NR network?

In 5G NR deployments, coverage refers to areas where devices can reliably access services, determined by signal strength and quality (RSRP and RSRQ). Coverage varies by deployment type—macro cells serve wide outdoor areas, while small cells enhance dense urban and indoor coverage. Frequency bands also influence coverage: low-band offers broad reach with lower speeds, mid-band balances range and capacity, and high-band (mmWave) delivers high speeds over short distances.

1.1 Cell acquisition coverage (control channel)

Cell acquisition coverage refers to the area where a device can detect, synchronize with, and initiate access to a 5G NR cell. This begins with reception of the Synchronization Signal Block (SSB), which includes the Primary and Secondary Synchronization Signals (PSS/SSS) and the Physical Broadcast Channel (PBCH), providing timing, cell ID, and system configuration. After successful synchronization and decoding, the device transmits a preamble over the Physical Random Access Channel (PRACH) to initiate access. PRACH is typically the limiting factor—especially at the cell edge—due to the UE's lower transmit power and limited antenna gain. Even if downlink signals are decodable, acquisition fails if the PRACH signal isn't reliably received by the base station.

1.2 DL service coverage (data & voice)

Downlink coverage for data and voice is limited by the UE's ability to decode the PDCCH, which carries essential scheduling info. Since access to the PDSCH depends on successful PDCCH decoding, the PDCCH often becomes the bottleneck at the cell edge due to stricter decoding needs. Enhancements like flexible CORESETs and beamforming can extend PDCCH reach and improve reliability.

1.3 UL service coverage (data & voice)

Uplink coverage is mainly constrained by the UE's transmit power and antenna limits. The PUSCH often becomes the bottleneck, especially at the cell edge due to high path loss. Unlike downlink, uplink lacks support from high-power base stations or advanced beamforming. Effective uplink planning—using power control, interference management, and optimized scheduling—is key to maintaining reliable service.

1.4 High-level 5G-NR link budget discussion

The 5G NR link budget defines coverage limits by measuring the maximum path loss that still supports a reliable connection. It factors in transmit power, antenna gains, receiver sensitivity, and system losses. Link budgets vary by frequency—low-band offers better propagation and higher margins, while mmWave faces greater loss and needs denser deployments. Accurate link budget planning is crucial for optimal cell sizing and consistent user experience.

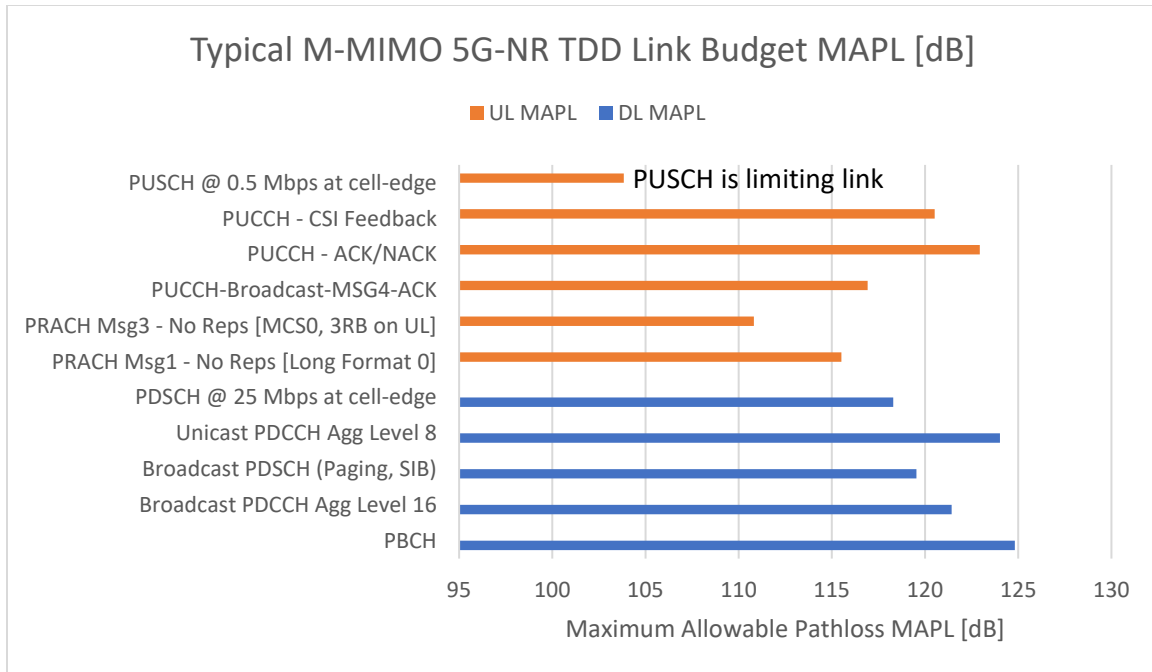


Figure 1 Typical M-MIMO 5G-NR TDD Link Budget

Figure 1 above shows a typical M-MIMO macro 5G-NR TDD link budget, 80% DL, 20% UL TDD ratio. The link budget assumes 3.5 GHz band with 23dBm PC3 smartphone users inside buildings in an urban area. The chart shows the maximum allowable pathloss [MAPL] for such a UE to maintain a link. As with any link budget, we look at channels in DL and UL, including control channels to determine the limiting link. For DL and UL shared channels, coverage is defined as 25Mbps DL and 0.5Mbps UL at cell-edge. We see that the PUSCH channel targeting 0.5Mbps UL data rate at cell-edge is the limiting link and overall coverage will be defined by the PUSCH MAPL.

1.5 Limiting link for coverage for NR-FDD & NR-TDD-M-MIMO networks

In NR-FDD, uplink coverage is limited by UE transmit power and lack of beamforming, while downlink benefits from higher base station power and continuous transmission. In NR-TDD, downlink gains from Massive MIMO and beamforming, but uplink is constrained by UE limitations, fewer uplink slots. Thus, uplink remains the primary coverage constraint in both NR-FDD and NR-TDD, especially at the cell edge.

2 What is the fallback option in case of no coverage?

For cell-edge scenarios where either DL, UL or control channels fail minimum link budget requirements, no 5G-NR service would be possible on that frequency band. In such cases, couple of options are possible as listed below.

2.1 NR-TDD to NR-FDD layer inter-frequency transition

When UE is in NR-TDD band and at edge of coverage, the most viable option is to do an inter-frequency transition to a NR-FDD band. NR-FDD bands are typically lower frequency bands as compared to NR-TDD bands, thereby providing better propagation and lower building penetration loss than NR-TDD bands. After NR-TDD to NR-FDD inter-frequency transition, the UE will continue to enjoy 5G-NR coverage.

2.2 NR-FDD layer to LTE-FDD layer inter-RAT transition

When UE is in NR-FDD band and at edge of coverage, the only other options would be to do an inter-RAT transition to an underlying LTE-FDD band. Since LTE-FDD has been deployed over 15 years or more, we would expect its coverage to be equal to or better than NR-FDD band. After the transition, the UE will lose 5G-NR coverage but will continue to maintain a 4G-LTE coverage.

2.3 Impact to user experience for these transitions

Typically, NR-TDD bands have much higher bandwidth compared to NR-FDD bands. Also since the coverage footprint of NR-FDD bands are larger than NR-TDD bands, NR-FDD bands tend to have more users and higher chances of congestion during busy hours. Due to these above two facts, likely after UE transition from NR-TDD to NR-FDD bands, even though 5G-NR service is maintained, likely the user experience on user using NR-FDD band would be inferior compared to NR-TDD bands. NR-FDD bands and LTE-FDD bands have similar bandwidths, but LTE-FDD has slightly lower capacity than NR-FDD and LTE-FDD bands is likely to have more number of users than NR-FDD due to higher LTE UE penetration. These factors will result in NR-FDD user experiencing inferior user experience when transitioning to LTE-FDD bands.

3 Options for UL coverage / cell-edge performance enhancements

Typically for any macro network, UL is the limiting link primarily due to limited UL transmit power. Hence, UL determines the overall coverage of a cell. In this section we look at different UL features and enhancements which enhance UL coverage and cell-edge performance. Some enhancements are targeted toward specific UL channels whereas others target all channels.

3.1 UL channel independent enhancements

3.1.1 Higher power class UE (PC2, PC1.5, PC1)

High Power User Equipment (HPUE) was standardized in 3GPP Release 11 for LTE, allowing UE to transmit at up to 31 dBm, compared to the standard 23 dBm. This increase enhances uplink reach and reliability, especially at the cell edge. With Release 17, HPUE support was extended to 5G NR, covering both FR1 (Sub-6 GHz) and FR2 (mmWave) bands. Devices convey their power capabilities through the *ue-PowerClass* parameter within the *UE Radio Access Capability* information element.

FR1 Power Classes and Coverage Impact:

- Power Class 3 (23 dBm): Standard coverage for handheld devices
- Power Class 2 (26 dBm): Moderate coverage extension

- Power Class 1.5 (29 dBm): Enhanced uplink reach, introduced in Release 16
- Power Class 1 (31 dBm): Maximum uplink coverage, ideal for industrial and fixed wireless use.

With higher power class, all UL channels are enhanced equally there by improving UL coverage and UL cell-edge performance. Power Class 2 was initially supported for TDD bands only but was extended to FDD bands also from Release 17 onwards. Power Class 1.5 is supported for TDD bands only. The concern of maximum exposure (MPE) and SAR associated with higher power and higher UL duty cycle (for FDD bands) limits use of higher power class for FDD bands in handheld devices. The coverage benefits of using higher power class UE are shown using few representative network simulations.

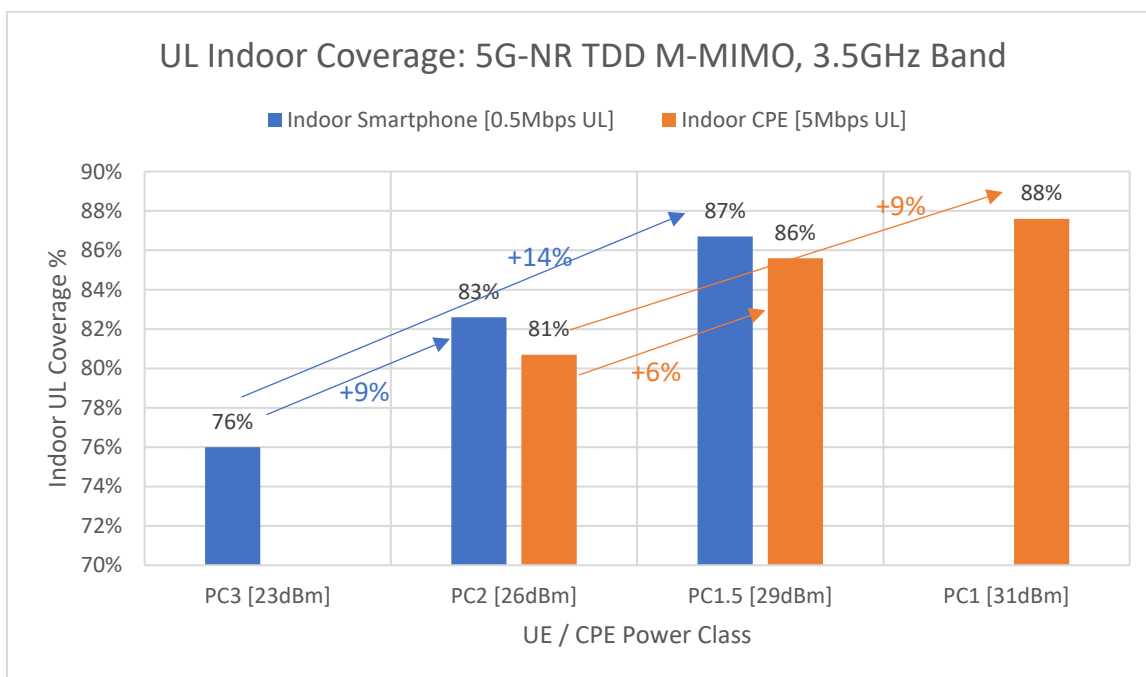


Figure 2 Indoor UE / CPE Coverage Gain with higher Power Class

System simulations were conducted to compare PC3, PC2 and PC1.5 indoor smartphones and PC2, PC1.5 and PC1 Indoor CPEs in real-world urban / suburban deployments to assess the cell-edge coverage benefits. Below are key simulation assumptions:

- Urban / Suburban cluster: 345 km², 75 macro sites
- Band: 3.5 GHz(n77), 100 MHz BW, 30 kHz SCS, 7DSUU TDD Ratio
- gNB Antenna: 64TRX, 192 Antenna Elements M-MIMO, 24dBi peak gNB antenna gain
- gNB EIRP: 77dBm
- UE Antenna: -3dBi peak UE antenna gain
- CPE Antenna: +5dBi peak CPE antenna gain
- Indoor Building Penetration Loss: 26.8dB

The simulations focused on two scenario for coverage evaluation; first considering indoor smartphones trying to get 500kbps UL data rate and next considering indoor CPE's trying to get 5Mbps UL data rate. As seen from Figure 2 , as we go from PC3 to PC2 UE's the indoor coverage for

smartphones improves by 9% and by 14% when going from PC3 to PC1.5 UE's. For Indoor CPE's as we go from PC2 to PC1.5, we see a 6% coverage gain and when going from PC2 to PC1 we see a 9% coverage gain for indoor CPE's.

Figure 3 below shows indoor cell-edge performance improvement on UL for UE's & CPE's with respect to reference performance. Reference for indoor UE's is a PC3 power class indoor UE and reference for indoor CPE is a PC2 power class indoor CPE. At indoor cell-edge, when going from PC3 to PC2 UE, we see 1.90x higher UL throughput and 3.42x higher UL throughput and when going from PC3 to PC1.5 UE. For indoor CPE's when going from PC2 to PC1.5 indoor CPE, we see 1.70x higher UL throughput and when going from PC2 to PC1 indoor CPE, we see 2.46x higher UL throughput.

In addition to Cell-edge performance improvement, higher power class devices also help mid and near cell performance.

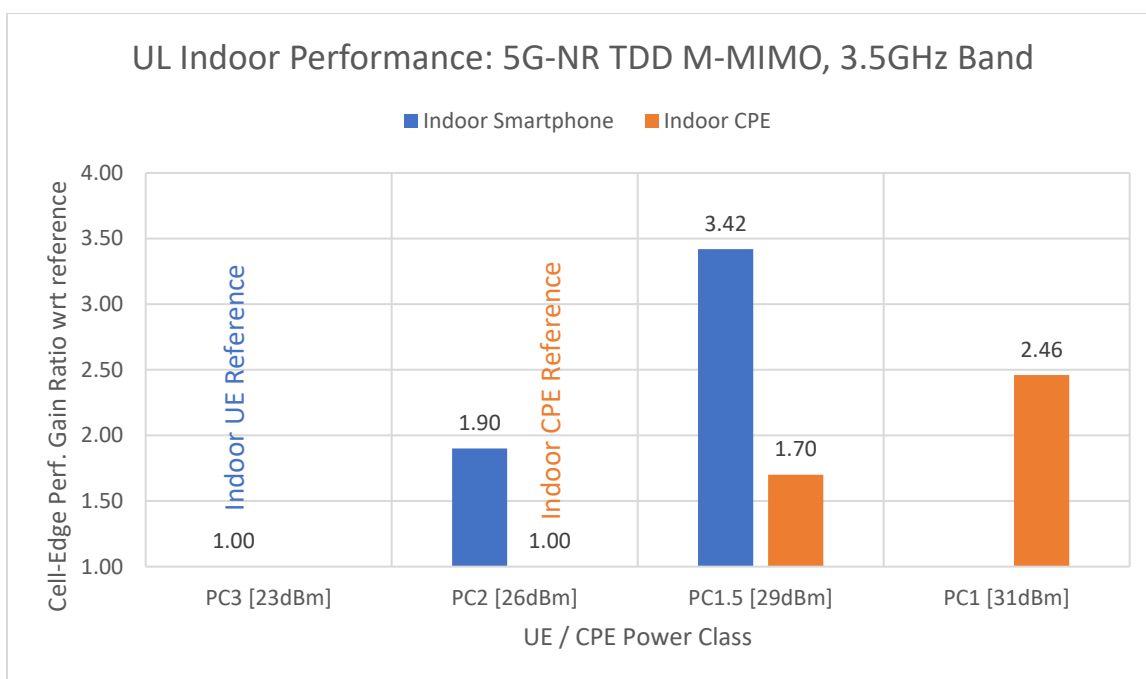


Figure 3 Indoor UL UE / CPE Cell-Edge Performance vs Power Class

3.2 UL control channel enhancements

In this section, we analyze the UL coverage features which are geared towards UL control channel link budget / coverage improvements only. Coming back to the typical deployment scenario where 5G-NR TDD is deployed using M-MIMO on high channel bandwidths (100MHz) but using an inferior propagation band like 3.5GHz band whereas 5G-NR FDD is deployed on lower frequency bands like 700MHz which has better propagation but lower channel bandwidth (10MHz). Figure 1 showed that for 5G-NR TDD M-MIMO networks, UL channels are limiting. If we are able to extend the higher bandwidth DL TDD footprint to its maximum, then users will benefit from higher data rates for a larger distance. Once way to do this is discussed in the FDD + TDD DL CA section. While doing FDD + FDD DL CA, UE may not need to use TDD PUSCH channel, but still may need to use TDD UL control channels. Hence, the motivation for improving UL control channels as well.

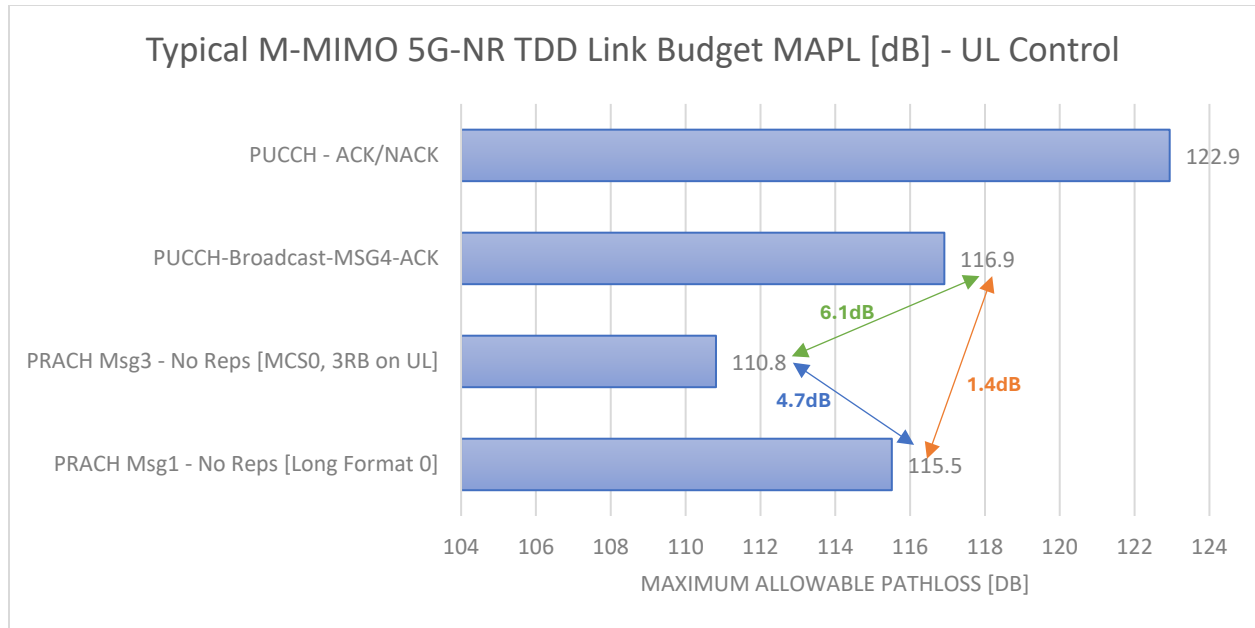


Figure 4 Typical M-MIMO 5G-NR TDD Link Budget for UL Control Channels

Figure 6 shows a zoomed in version of Figure 1 focusing on UL control channel link budget only which are required to support TDD DL transmissions and/or TDD channel acquisition. In this example, we see that the limiting control channel is RACH Message3 which is weaker to the next limiting control channel RACH Message1 by 4.7dB. So, the most important enhancement for UL control channels would be to target RACH message3 followed by RACH message1 and next PUCCH carrying ACK/NACKs for RACH Message4. Release 17 introduced up to 16 repetitions for MSG3 (*numberOfMsg3-Repetitions-r17* parameter). Release 18 introduced up to 8 repetitions for MSG1 are (*msg1-RepetitionNum-r18* parameter), and up to 8 repetitions for PUCCH with MSG4 HARQ-ACK (*SIB19* information element's *numberOfMsg4-Repetitions-r18* parameter).

Benefits Estimation

System simulations for Indoor + Outdoor smartphones on 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, was run to estimate the UL coverage enhancement gain.

If only MSG3 repetitions are targeted then to bridge the 4.7dB gap between MSG3 and MSG1 link budget, four MSG3 repetitions are sufficient. This showed about 8% UL coverage gain with simulations. However, if both MSG1 and MSG3 repetitions are targeted, then 2 MSG1 repetitions would be sufficient to bridge the 1.4dB gap between MSG1 and PUCCH-MSG4 ACK/NACK and 8 MSG3 repetitions would be required to bridge the 6.1dB gap between MSG3 and PUCCH-MSG4 ACK/NACK. This showed about 8% UL coverage gain with simulations. PUCCH-MSG4 ACK/NACK channel can be enhanced further with its own repetitions, if required (Release 19 feature).

3.3 UL Shared Channel Enhancements

Table 1 captures come of the features introduced by 3GPP for the purpose of cell range extension and UL performance improvement at cell edge.

Feature	Cell range extension	Cell-edge performance enhancement
Max Operating Power	Yes	Yes
Switched UL	Yes	Yes
Supplemental UL	Yes	Yes
RLC Segmentation	Yes	No
PUSCH slot Aggregation	Yes	No
UL Data Compression	Yes	Yes
Coherent UL MIMO	Yes	Yes
LowSE CQI Table	Yes	No
$\pi/2$ BPSK	Yes	No
UL Configured Grant	No	Yes (battery performance)

Table 1 UL Shared Channel Features

3.3.1 Maximum Operating Power (MOP)

When doing UL CA or DC, UE's (or CPE's) maximum power is limited to either of the UL CA band's power class. For example, if a UE is doing UL CA or DC between a FDD band which is power class 3 (23dBm) and a TDD band which is power class 2 (26dBm) the maximum operating power (MOP) for the UE at any given time is limited to power class 2 (26dBm). With the MOP feature introduced in Release 17, UE can signal its capability to use higher power limit and can be configured via RRC to transmit up to 27.8dBm (23dBm + 26dBm) during FDD and TDD CA or DC UL duty cycles. *higherPowerLimit-r17* is the RRC parameter which the network uses to signal the use of MOP 27.8dBm. This feature improves UL cell-edge throughput for UL CA or DC users.

MOP Benefits Estimation

System simulations for Indoor + Outdoor smartphones doing FDD + TDD UL CA using 20MHz bandwidth FDD at n28 band and 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of MOP feature, UL throughput performance improved up to 18% due to higher power transmission during UL TDD slots. Higher power on UL TDD slots enabled the expansion of usable high BW TDD footprint which results in this gain.

In addition to Cell-edge performance improvement, MOP devices also help mid and near cell performance.

3.3.2 Switched UL

To reduce UE cost, complexity and power consumption, the UE transmitter is limited to two transmit chains, so the UE is capable of aggregating one TDD carrier with one FDD carrier, with each carrier limited to one-layer transmission.

Since NR TDD bands have wider bandwidths than FDD bands, it would be beneficial for the UE to be able to support 2-layer transmission on the TDD bands, for higher throughput, as long as the coverage permits that.

Release 16 switched UL was introduced restricting the first carrier (typically FDD) to maximum one layer UL and the second carrier (typically TDD) with maximum two-layer UL, with maximum of simultaneous two layers on UL across both carriers.

Release 17 enhanced switched uplink to support 2 layers on either the FDD or the TDD bands, thus enabling UL MIMO on both bands, still with a total of 2 transmit chains.

If UE is limited to two transmit chains, then either it can do 1L UL on FDD or 2L UL on TDD, never both. With switched UL, such two transmit chain UE's can now do both 1L UL on FDD (when TDD duty cycle is DL slots) and 2L UL on TDD (when TDD duty cycle is UL slots). In order to do so a small time switching penalty is used on FDD slots (1 to 3 OFDM symbols) for the UE to switch its transmit chain from FDD band to TDD band and corresponding penalty of 1 to 3 symbols on FDD band again to switch from TDD band to FDD band. This results in minor loss of FDD resources but gains are very high due to the possibility to use higher bandwidth TDD slots which are also capable for 2L UL MIMO. Figure 4 below illustrates the switching penalty concept.

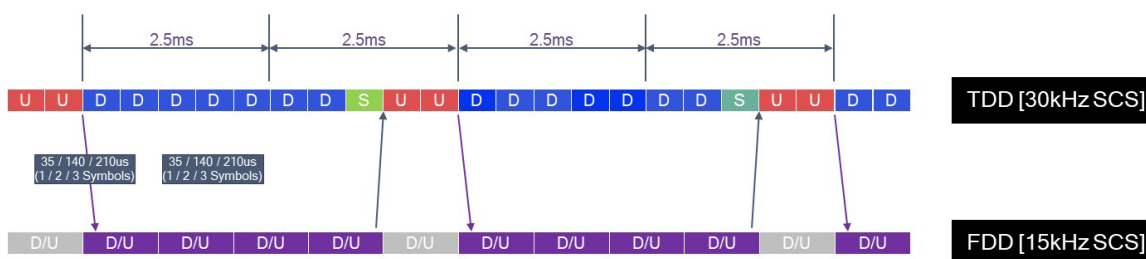


Figure 5 How Switched UL switching Penalty is applied?

Two options were introduced in Release 16 namely, Option-1 (or SwitchedUL) and Option-2 (or dualUL).

Switched UL Benefits Estimation

System simulations for Indoor + Outdoor smartphones doing FDD + TDD UL CA using 20MHz bandwidth FDD at n28 band and 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of SwitchedUL feature vs Release 15 2L UL CA, CPE UL throughput performance improved by up to 25% due to ability to use both UL TDD & UL FDD slots with minor switching penalty.

In addition to Cell-edge performance improvement, SwUL devices also see mid and near cell performance improvements.

3.3.3 Supplemental UL

Supplemental UL (SUL) was introduced in Release 15 to solve DL-UL imbalance. As the cell UL coverage is inferior to that of the DL, the cell-edge UE performance in the UL is significantly impacted by the UL limitation.

SUL extends the UL coverage by providing supplemental (SUL) carrier in the low frequency bands, with enhanced UL coverage.

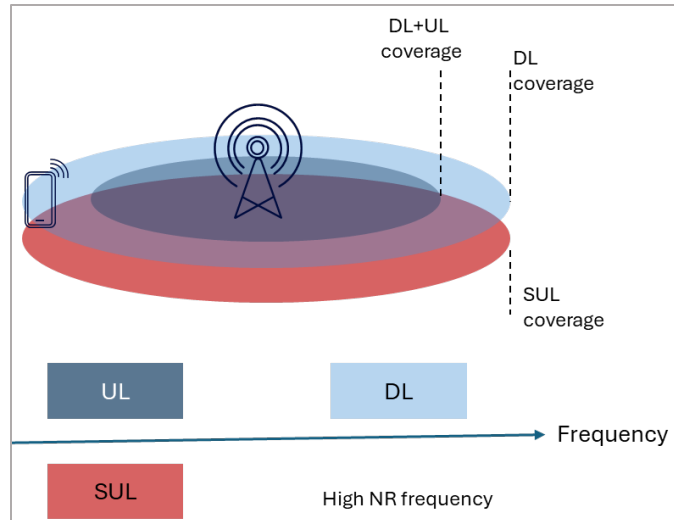


Figure 6 Supplemental Uplink (SUL)

When SUL is enabled, the cell is configured with one DL frequency carrier (NR band) and two UL frequency carriers (one NR frequency band and one SUL in a lower band).

When the UE is within the good UL coverage of the NR carrier, the UE uses the NR carrier to transmit and receive data. When the UE moves outside the UL coverage of the NR carrier, it uses the lower-band SUL carrier to transmit data. UE can use either the NR carrier or the SUL carrier UL NR or SUL to transmit data but cannot use both carriers at the same time. SUL extends the cell UL coverage on a lower band when enabling the use of higher bandwidth DL cell from a higher TDD band, resulting in higher DL and UL performance. Note that simultaneous Physical Uplink Shared Channels (PUSCHs) are not supported in Rel. 15 from multiple UL bands. Uplink transmissions on the two ULs are controlled by the network to avoid overlapping PUSCH transmission in time.

SUL Benefits Estimation

System simulations for Indoor + Outdoor smartphones doing FDD + TDD UL CA using 20MHz bandwidth FDD at n28 band and 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of SUL feature, UL throughput performance improved up to 25% due to better propagating low band FDD band.

In addition to Cell-edge performance improvement, when SUL is used in conjunction with SwUL devices also see mid and near cell performance improvements.

3.3.4 RLC segmentation

In cell-edge conditions, UE's are typically power limited and get allocated a smaller number of RB's and smaller transport block size to enhance their received power spectral density. The MAC layer will send a notification to the RLC layer indicating the transport block size limitation. This will cause the RLC to break down its data packets (SDUs) into smaller segments (PDUs) to ensure they fit within the MAC transport blocks. This benefits from better link budget due to higher power spectral density over smaller RB. If a segment (PDU) gets corrupted during transmission and mis-detected by the receiver, only that segment needs to be retransmitted, thus improving efficiency at cell edge conditions.

RLC Segmentation Benefits Estimation

System simulations for Indoor + Outdoor smartphones on 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of RLC segmentation feature with 2 segments, UL VoNR coverage improved up to 9%.

RLC Segmentation Deployment Considerations

Due to RLC & MAC overheads for all packets, many smaller packets result in higher overall overheads. Proper parameter configuration at the gNB is needed to ensure RLC segmentation is triggered at the right coverage level. Early trigger leads to unnecessary impact on capacity and latency. Late trigger can result in radio link failure. This feature is recommended for cell-edge UE's only and primarily targeted toward voice applications; however, it is applicable to all other applications.

3.3.5 PUSCH slot aggregation

PUSCH slot aggregation lets the UE transmission span over two or more slots, i.e., the UE would transmit the same data over several slots.

The number of UL repetitions is pre-configured by the gNB via RRC signaling. For FDD bands, 3GPP Release 15 allows for UL repetitions up to 8 consecutive slots, whereas Release 16 and 17 allow for UL repetitions of up to 16 and 32 consecutive slots respectively.

For TDD bands, 3GPP Release 15 allows for UL repetition factor of up to 8 consecutive slots, whereas Release 16 and 17 allow for UL repetitions of up to 16 and 32 respectively.

PUSCH slot aggregation extends UL coverage and improves cell edge UL reliability and performance.

Figure 7, below, illustrated the application of UL slot aggregation with repetition factor of 4 for an FDD slot configuration.

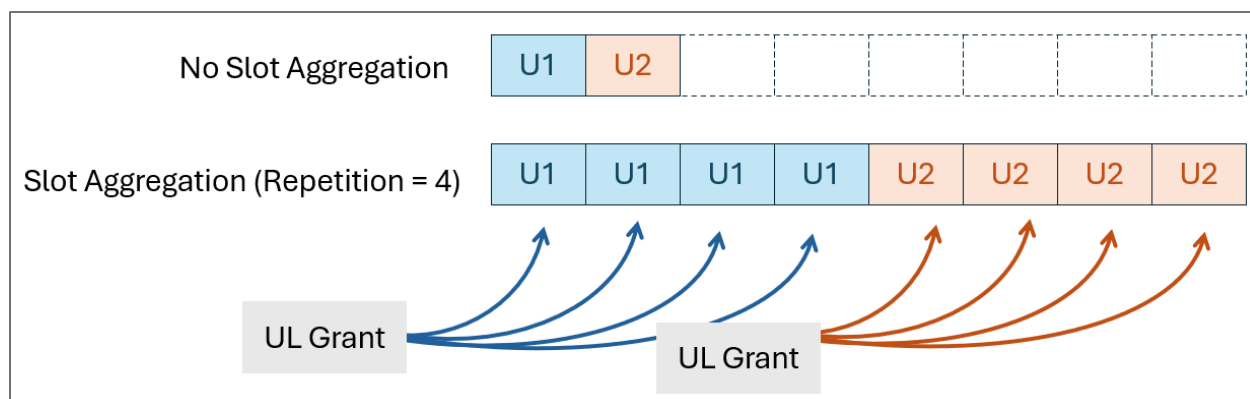


Figure 7 FDD Slot Aggregation with Repetition Factor = 4

Figure 8, below, illustrates the application of UL slot aggregation with repetition factor of 2 for the commonly adopted DDDSU TDD configuration.

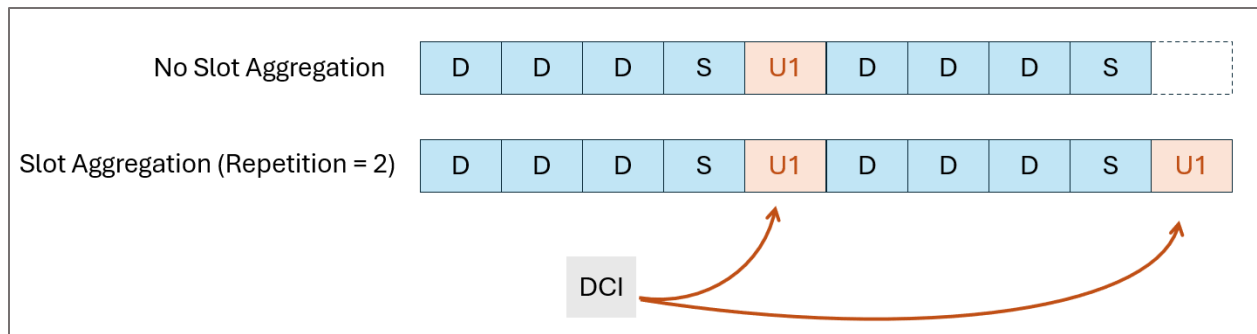


Figure 8 TDD Slot Aggregation with Repetition Factor = 2

PUSCH Slot Aggregation Benefits Estimation

System simulations for Indoor + Outdoor smartphones on 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of RLC segmentation feature, UL VoNR coverage improved up to 15% with 4 repetitions.

PUSCH Slot Aggregation Deployment Consideration

Proper parameter configuration at the gNB is needed to ensure PUSCH slot aggregation is triggered at the right coverage level. Early trigger leads to unnecessary impact on capacity and latency. Late trigger can result in radio link failure. This feature is recommended for cell-edge UE's only and primarily targeted toward voice applications; however, it is applicable to all other applications.

3.3.6 Uplink Data Compression

Uplink Data Compression (UDC), aims to reduce the size of the packets transmitted by the UE over the air interface, thus reducing the bandwidth requirement and improving the decode performance at the gNB receiver, particularly in poor coverage conditions.

Unlike RoHC, which only compresses the packet IP header, UDC offers substantial compression gain across wide-ranging apps, so the benefit is recognized irrespective of payload size.

UDC Benefits

With improved compression performance, all cell regions including cell edge conditions, the UL coverage will significantly benefit from UDC, as well as improve network capacity.

Qualcomm field testing and data analysis have demonstrated the UDC compression gains shown in Figure 9.

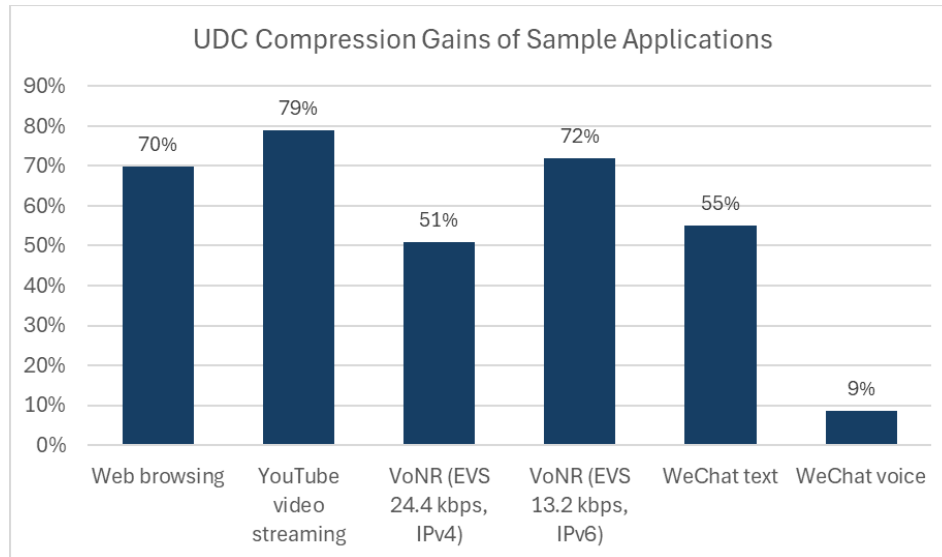


Figure 9 UDC Compression Gains of Sample Applications

UDC Limitations

- UDC cannot coexist with RoHC.
- UDC would not compress SIP signaling messages. This is not a significant limitation as the ratio of SIP messages to RTP messages is typically low.
- UDC would not compress encrypted data.

UDC Considerations

- UL scheduling grant should align with compressed payload, otherwise benefits would not be realized
- Packet inscription may result in a lower compression gain.
- Ipv4 compression gain is typically lower than that of IPv6

3.3.7 Coherent UL MIMO

UL MIMO is key to improving data throughput and spectral efficiency, as well as cell edge performance, which improves both UL coverage and capacity.

NR supports 3 levels of UE capability for UL MIMO transmission defining coherence between different device antennas. The 3 levels define how well the relative phase between the signals transmitted on two antennas can be controlled.

- Full coherence. Device can control the relative phase between antenna ports, so all ports can be transmitted coherently
- Partial coherence. Device can control relative phase within pair of antenna ports, so port pairs can be transmitted coherently
- Non-coherence. No coherence between device antenna ports

Without coherence, UL MIMO transmission cannot be performed, as the antenna ports would introduce a random relative phase.

Coherent UL MIMO Benefits

Enhanced UL coverage & Improved network capacity and UL user throughput

Coherent UL MIMO Dependencies and Considerations

UL MIMO requires precise synchronization. It is recommended to use Coherent UL MIMO opportunistically.

3.3.8 Low Spectral Efficiency CQI Table

3GPP release 15 provides the option to use 3 different CQI tables as defined in 3GPP TS 38.214. All three tables have CQI ranging from 1 to 15. Table 1 goes from QPSK to 64QAM modulation, Table 2 goes from QPSK to 256QAM modulation and Table 3 (also known as LowSE Table) goes from QPSK to 64QAM but with more robust channel coding rates. UL coverage can stretch as far as CQI 1 coverage. For Table 1 and Table 2, CQI 1 uses QPSK modulation with coding rate 78/1024 whereas Table 3 CQI 1 uses QPSK modulation with coding rate 30/1024. The more robust coding in Table 3 CQI 1 helps attain larger UL coverage and improves reliability (lower BLER) at the expense of lower spectral efficiency.

LowSE CQI Table Benefits Estimation

System simulations for Indoor + Outdoor smartphones on 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of LowSE Table feature, UL coverage improved up to 8%.

LowSE CQI Table Deployment Consideration

Proper parameter configuration at the gNB is needed to ensure LowSE table is triggered at the right coverage level. Early trigger leads to unnecessary impact on capacity. Late trigger can result in radio link failure. This feature is recommended for cell-edge UE's only and primarily targeted toward ultra reliable applications; however, it is applicable to all other applications.

3.3.9 $\pi/2$ BPSK Modulation

$\pi/2$ BPSK was introduced in Release 15 for uplink to reduce PAPR compared to QPSK and improve RF amplifier efficiency. It can be used with PUSCH when using DFTs-OFDM waveform and for some formats of PUCCH. In Release 16/17, $\pi/2$ BPSK can enable *powerBoostPi2BPSK* capability for certain TDD bands (n40, n41, n77, n78, n79) and power classes (PC3 mainly). This increases UE reference power from 23 dBm to 26 dBm. Lower Maximum Power reduction (MPR) due to lower PAPR properties and power boost capability, $\pi/2$ BPSK improves UL coverage.

$\pi/2$ BPSK Benefits Estimation

System simulations for Indoor + Outdoor smartphones on 100MHz bandwidth TDD at n77 band, 20% UL TDD ratio, has shown that with the introduction of $\pi/2$ BPSK feature, UL coverage improved up to 5%.

$\pi/2$ BPSK Deployment Consideration

Proper parameter configuration at the gNB is needed to ensure $\pi/2$ BPSK is triggered at the right coverage level. Early trigger leads to unnecessary impact on capacity due to lower SPEF. Late trigger can result in radio link failure. This feature is recommended for cell-edge UE's only; however, it is applicable to all other applications.

3.3.10 UL Configured Grant

3GPP release 15 enabled UL Configured Grant (CG) which is a grant-free uplink transmission mechanism in 5G NR that allows a UE to send data on the PUSCH without waiting for a dynamic uplink grant via PDCCH Downlink Control Information (DCI). CG can be configured via RRC (CG Type 1) or RRC + DCI activation (CG Type 2). The grants are preconfigured; hence UE saves battery power since it does not have to keep monitoring PDCCH. It also improves latency since it does not have to send SR / BSR to get a UL grant. This is advantageous over proprietary UL pre-scheduling techniques.

UL Configured Grant Benefits Estimation

CG is designed to reduce latency and control signaling overhead. It also helps reduce UE battery consumption when compared against UL pre-scheduling techniques.

UL Configured Grant Deployment Consideration

Proper parameter configuration at the gNB is needed to ensure CG is triggered for the right applications. It is ideal for VoNR, XR, industrial IoT, gaming, URLLC like applications which have periodic, predictable UL traffic bursts. If configuration periodicity does not match with application data bursts then it can result in inefficiencies and loss of preconfigured capacity.

4 Deployment Recommendation

To maximize uplink coverage and cell-edge performance in 5G-NR FR1 TDD networks, the following deployment strategies are recommended:

Prioritize High Power User Equipment (HPUE):

Deploy PC2, PC1.5, and PC1 class devices where SAR/MPE constraints allow, especially for CPEs and industrial applications. This delivers substantial uplink coverage and throughput gains.

Enable Uplink Control Channel Enhancements:

Configure repetition features for PRACH Msg3, Msg1, and PUCCH ACK/NACK (as per Release 17/18) to close link budget gaps and improve acquisition reliability at the cell edge.

Leverage Uplink Shared Channel Features:

Activate Maximum Operating Power (MOP), Switched UL, Supplemental UL (SUL), RLC segmentation, PUSCH slot aggregation, Uplink Data Compression (UDC), Coherent UL MIMO, Low Spectral Efficiency CQI tables and $\pi/2$ BPSK modulation. These features should be optimized for cell-edge and voice/URLLC profiles to avoid unnecessary capacity or latency impacts. Carefully configure feature triggers, repetition factors, and periodicity to align with application requirements and minimize radio link failures or resource inefficiencies.

Implement uplink enhancement features on TDD bands first, followed by FDD bands, to maximize coverage and performance with existing macro site density. Continuously assess network performance and feature adoption, adjusting configurations as device ecosystem support and traffic profiles evolve.

5 Conclusion

The deployment of Massive MIMO on TDD bands and utilization of wide channel bandwidths in 5G-NR have substantially improved downlink throughput and spectral efficiency. Nevertheless, uplink coverage remains the limiting factor, particularly as networks migrate to higher frequency bands with more challenging propagation characteristics. The integration of advanced uplink enhancement features—including higher power classes, supplemental uplink, slot aggregation, coherent UL MIMO, and robust coding schemes—enables significant improvements in uplink reliability and cell-edge performance for both user equipment and customer premise equipment.

These enhancements not only facilitate deeper indoor coverage and better service continuity but also allow operators to align 5G-NR coverage with existing LTE footprints using current site densities. For optimal network performance, prioritizing the deployment of these uplink features on TDD bands, followed by FDD bands, is recommended. Continued evolution and adoption of these technologies will be critical for addressing coverage gaps and supporting diverse application requirements in next-generation wireless networks.

6 References

- [1] 3GPP TS 38.211 NR; Physical channels and modulation
- [2] 3GPP TS 38.212 NR; Multiplexing and channel coding
- [3] 3GPP TS 38.214 NR; Physical layer procedures for data
- [4] 3GPP TS 38.306 NR; User Equipment (UE) radio access capabilities
- [5] 3GPP TS 38.311 NR; Radio Resource Control (RRC) protocol specification
- [6] 3GPP R1-2008626, Potential coverage enhancement techniques for PUSCH

7 Abbreviations

3GPP – 3rd Generation Project Partnership (www.3gpp.org)

CPE / UE – Customer Premise Equipment / User Equipment (typically a smartphone)

CQI – Channel Quality Indicator

FDD / TDD – Frequency Division Duplexing / Time Division Duplexing

gNB – 5G NR NodeB (the 5G NR base station)

MCS – Modulation and Coding Scheme

PDCCH – Physical Downlink Control Channel

PDSCH – Physical Downlink Shared Channel

PUSCH – Physical Uplink Shared Channel

PUCCH – Physical Uplink Control Channel

PRACH – Physical Random Access Channel

RRC – Radio Resource Control

SE or SPEF – Spectral Efficiency

SRS – Sounding Reference Signal

SU-MIMO – Single User Multiple Input Multiple Output

Nothing in these materials is an offer to sell any of the components or devices referenced herein.

"Qualcomm" may mean Qualcomm Incorporated, Qualcomm Technologies, Inc., and/or other subsidiaries.

©2024 Qualcomm Technologies, Inc. and/or its affiliated companies. All Rights Reserved.

Snapdragon and Qualcomm branded products are products of Qualcomm Technologies, Inc. and/or its subsidiaries. Other products and brand names may be trademarks or registered trademarks of their respective owners.

