Qualcomm

2023 Switched Uplink in 5G-NR: Benefit & Deployment Consideration

Contents

1. Introduction: Switched UL in 3GPP NR

3GPP has defined both FDD and TDD bands for 5G-NR. TDD bands, however, remain most popular among cellular network operators; primarily due to their wider bandwidth availability when compared with FDD bands. Most operators today own at least one large-bandwidth TDD band and at least one smaller bandwidth FDD band for their 5G-NR networks. Advanced UL features like 2x2 UL MIMO (2-layer) are commonly supported for TDD bands only due to the infrastructure ecosystems. Even though FDD bands do not support UL MIMO today (1-layer UL only for FDD bands), features like FDD + TDD UL CA are supported. 2-layer (2L) UL MIMO on TDD band plus 1-layer (1L) UL on FDD band would require that the UE supports 3 RF chains for simultaneous 2L TDD plus 1L FDD UL transmissions. This increases UE complexity and cost and is not commonly available today. To address this, 3GPP in release 16 introduced the switched UL feature which would enable a UE to use 2L on TDD (to benefit from 2L on wider bandwidth for shorter UL duty cycle) and 1L on FDD (to benefit from longer UL duty cycle) while still requiring only 2 UE RF chains.

1.1 Release 16 Switched UL [Option-1 and Option-2]

Release 16 switched UL was introduced restricting carrier-1 with maximum 1L UL and carrier-2 with maximum 2L UL support, with maximum of simultaneous 2L on UL across both carriers. The most common combination being 1L UL FDD carrier and 2L UL TDD carrier, with the use of memory-based operation.

Two options are defined in release 16. Option-1 (also known as "switchedUL") where UE can transmit only on any one of the two carriers in a slot and Option-2 (also known as "dualUL") where UE can transmit on both carrier-1 and carrier-2 in a slot but limited to maximum 2L on UL across both carriers.

Figure 1-1 below illustrates release 16 switched UL operation between one FDD carrier at 15kHz sub-carrier spacing and one TDD carrier at 30kHz sub-carrier spacing. Slot duration for FDD is 1ms and for TDD is 0.5ms.

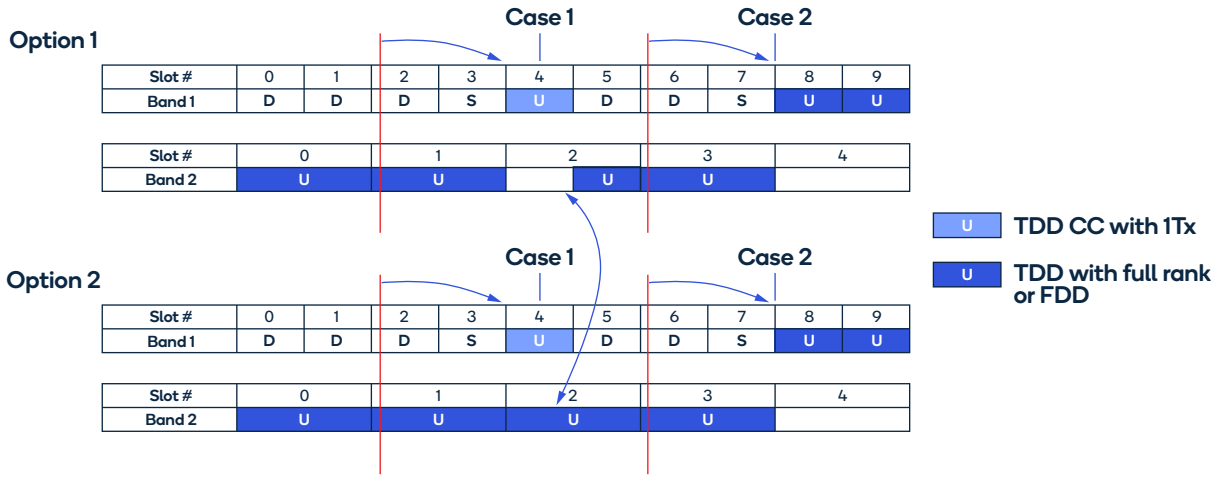


Figure 1-1 Release 16 Switched UL Operation

Within both Option-1 and Option-2, two further cases are possible.

Figure 1-2 below summarized switched UL Case-1 and Case-2 scenarios in a simple table.

Case 1	1 Tx on carrier 1 and 1 Tx on carrier 2
Case 2	0 Tx on carrier 1 and 2 Tx on carrier 2

Figure 1-2 Switched UL Case-1 and Case-2 Summary

As in the example shown above in Figure 1-1, Option-1, Case-1 1L TDD UL is transmitted for 0.5ms TDD slot and 1L FDD UL is transmitted for 2nd half of FDD slot, but both FDD and TDD never transmitted together simultaneously. PUSCH Mapping Type B support is required at both UE and gNB for supporting Option-1, Case-1.

Continuing with the same example, in Option-2, Case-1 1L TDD UL is transmitted for 0.5ms TDD slot and 1L FDD UL is transmitted for entire 1ms FDD slot, where simultaneous FDD+TDD UL transmissions exist for first half of FDD slot. In Case-2 for both Option-1 and Option-2, 2L UL is transmitted on TDD carrier and no UL transmissions on FDD carrier.

Since switched UL aims to support 1L UL on Carrier-1 and 2L UL on Carrier-2 with 2 RF chains in the UE, the RF chains must switch between Carrier-1 and Carrier-2. Figure 1-3 below shows an example of Option-2, Case-2 transient time. This also applied for Option-1, Case-2. In this Case-2 example, FDD UL operates with 1L UL which switches to TDD UL which operates with 2L UL. For the UE's RF chain to detune from FDD carrier to TDD carrier a transient time is required. Similarly, at the end of 2L UL TDD slot to switch back to 1L UL FDD slot a transient time is required. In this example, the transient time is absorbed on the FDD band.

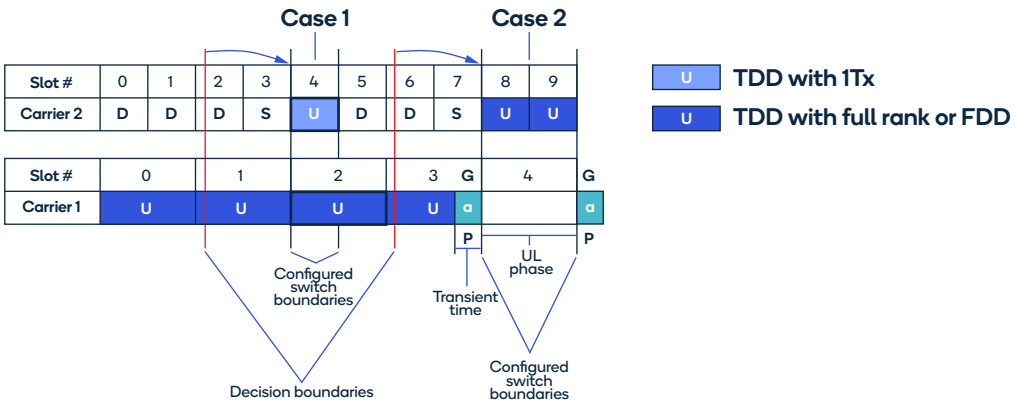


Figure 1-3 Switching Transient Time for Switched UL

3GPP has defined this transient time to be either 35us, 140us, or 210us, which corresponds to 1, 2 and 3 OFDM symbols, respectively, for a 15kHz SCS carrier or 1, 4 and 6 OFDM symbols, respectively, for a 30kHz SCS carrier. It may however be noted that while 35us is typically considered as lowest granularity, 3GPP has also defined half-symbol transmission in case of DFT-S-OFDM.

From a user experience perspective, this transient time can be seen as a throughput penalty to support 2L UL on carrier-1 and 1L UL on carrier-2 with total 2 RF chains. Note that the transient time is not required for Case-1 where both carriers transmit on 1L UL each and each RF chain is tuned to each carrier (no need for switching).

Validity period of the switching is the period of the consecutive UL slots in TDD carrier (shown as UL phase) in Figure 1 3. No switching back to FDD carrier is allowed during the validity period.

1.2 Release 17 Switched UL Enhancement

In release 16, 3GPP specified 1 Tx – 2 Tx (1L UL to 2L UL) switching between two bands; while one of the bands is with 1 Tx, the other one is with 2 Tx. With release 17 enhancement, 2 Tx - 2 Tx (2L UL to 2L UL) switching is possible. The key objective of release 17 UL Tx Switching enhancements was to enable UL MIMO in both bands, still with a total of 2 Tx chains.

Figure 1-4 below shows the possibility of both carriers transmitting 2L UL one at a time in release 17. In release 16, if carrier-2 can transmit 2L UL, then carrier-1 can never transmit 2L UL, even if the device supports it. This enhancement primarily targets the case where both carriers are TDD bands, each supporting 2x2 UL MIMO. Due to channel conditions carrier-1 may have better rank conditions vs carrier-2 and vice-versa over time. So, release 17 switched UL enhancement allows 2Tx on either carrier-1 or carrier-2 opportunistically.

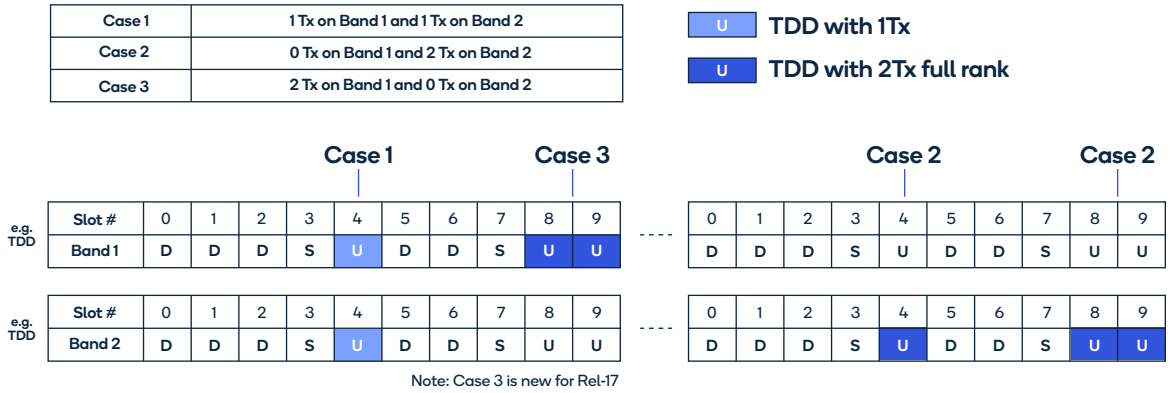


Figure 1-4 Release 17 Switched UL

If the UL slots for both TDD carriers are aligned such that UL slots for both carriers do not overlap, then both carriers can enjoy benefits of 2L UL transmissions. The UL switching penalty due to the transient time of 35us, 140us or 210us will apply when consecutive UL slots are scheduled across carriers. If UL slots overlap or UL slots across the carriers are not consecutive slots, then the transient time gap is not required since there would be sufficient non-UL slot time for the switching transient to happen. In the below example, the switching transient is not required.

The UE may need a longer switching period with 2Tx-2Tx switching than for 1Tx-2Tx switching. The UE reports Tswitch values separately for 1Tx-2Tx and 2Tx-2Tx switching (but setting them to the same value is possible). In a configured switching mode, the switching gap duration for a triggered uplink switching is equal to the switching time capability value reported for the switching mode. Figure 1-5 below illustrates the switching modes and switching periods.

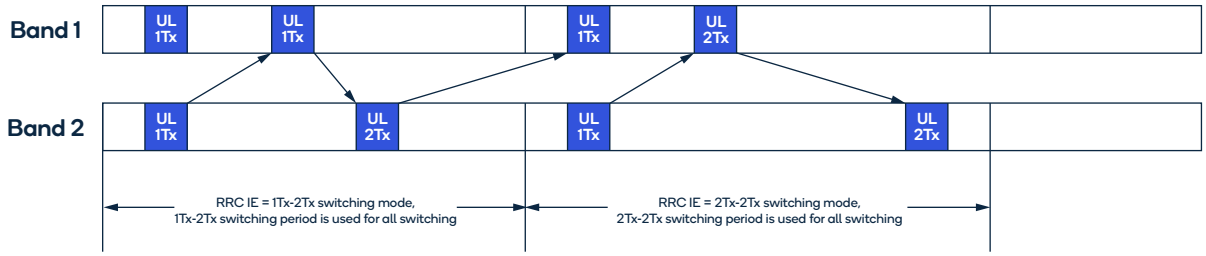


Figure 1-5 1Tx-2Tx and 2Tx-2Tx Switching Modes and Switching Periods

1.3 Release 16 and Release 17 Switched UL: How Do They Compare

Description	Release 16 Switched UL	Rel 17 Switched UL Enhancement
Switching Scenarios	Case 1: 1Tx on each band Case 2: 2Tx on UL MIMO band	Case 1: 1Tx on each band Case 2: 2Tx on UL MIMO band Case 3: 2Tx on other band as well
Intra-band CC support	No	Yes, 2 contiguous carriers in one band
Target band combo	FDD (1L UL) + TDD (2L UL)	TDD (2L UL) + TDD (2L UL)
UL Switching modes	One mode (1Tx-2Tx)	Two modes (1Tx-2Tx, 2Tx-2Tx)
Switching Periods configurable	One (35us, 140us or 210us)	Two (one per switching mode) 35us, 140us, or 210us

Figure 1-6 1Tx-2Tx and 2Tx-2Tx Switching Modes and Switching Periods

It may be noted that, Rel17 Switched UL Enhancement also supports FDD+TDD combination, not just TDD+TDD, as shown in the example above.

2 Switched-Uplink (SwUL) and Supplemental Uplink (SUL) in 3GPP NR

3GPP release 15 had originally envisioned the challenge of UL/DL link imbalance which would be introduced in 5G-NR M-MIMO FR1 TDD bands. These M-MIMO systems would have very high DL EIRP but similar UL EIRP as previous generation UE's, thereby resulting in the link imbalance. Both release 15 supplemental UL and release 16 switched UL utilize a low band FDD carrier, but some differences exist.

2.1 Supplemental Uplink (SUL)

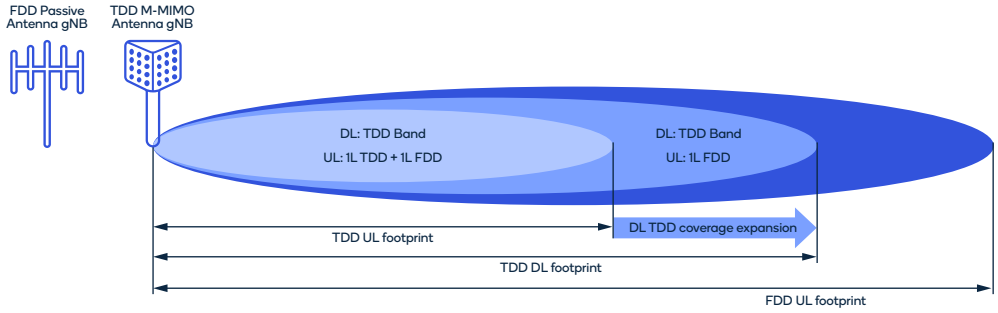


Figure 2-1 3GPP release 15 Supplemental UL

Figure 2-1 above illustrates the 3GPP release 15 supplemental UL feature at a high level. One of the motivations for Both release 15 supplemental UL and release 16 switched UL is to extend the inferior propagating high band/large bandwidth TDD DL footprint with a corresponding better propagating, low band FDD carrier's UL. In supplemental UL operation, either 1 layer or 2 layer of UL transmission per band is allowed from UE perspective.

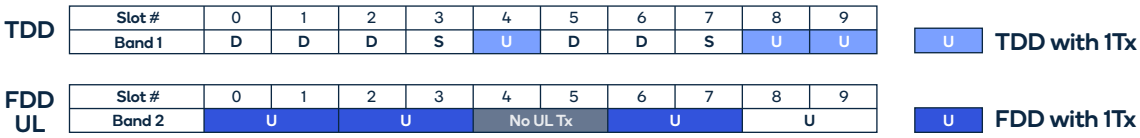


Figure 2-2 3GPP Supplemental UL timeslot view

Figure 2-2 above shows the operation of supplemental UL on a time slot view. The FDD carrier assumes 15kHz sub-carrier spacing and TDD carrier 30kHz sub-carrier spacing. Note that when TDD DL slots are present, UL transmissions happen on FDD UL and when TDD UL slots are available, UL transmissions will likely happen on the large BW TDD UL slots. However, for both FDD and TDD UL transmissions UE may in reality transmit only use 1 layer on UL, even if UE supports more than 2 layers on a single band. For a 2 layer UL UE, one RF chain associated with one layer is likely to be tuned to TDD band and other tuned to the FDD band. Hence a switching delay due to FDD and TDD bands is not required.

2.2 Switched UL vs Supplemental UL Comparison

Description	Release 15 Supplemental UL	Rel 16 Switched UL
UL Tx Scenarios	Case 1: 1Tx on each band	Case 1: 1Tx on each band, OR Case 2: 2Tx on UL MIMO band
Peak UL Throughput	Low, due to limit on only 1Tx on each band	High, due to 2Tx on TDD band allowed, which is larger BW band as well
2L UL MIMO	No possible	Possible (Case 2 for both Option 1 & Option 2)
UL Switching Delay	No, since each of 2 UE RF chains locked to FDD band and TDD band	Yes, switching delay (35/140 /210us), except Option 2, Case 1.

Figure 2-3 Switched UL vs Supplemental UL Comparison

It may be noted that, although the example in Figure 2-3 shows 1L for FDD UL (typically low-band) given current ecosystem readiness, from a technology standpoint 3GPP allows SUL transmission of 2Tx in TDD.

3. Device and Infrastructure Requirement

3.1 UE Capability Requirement

Being a 3GPP release 16 feature (and beyond), explicit UE-support indication is used as part of the capability message to inform gNB of its capability to support switched UL. The UE-capability indications defined in 3GPP release 16 to standardize the process are listed below:

- UE must be able to convey which switched UL formats it supports (uplinkTxSwitching-OptionSupport-r16 - switchedUL, dualUL, both)
- UE must be able to convey which band pairs it can support for switched UL (ULTxSwitchingBandPair-r16)
- UE must be able to convey which band it will support as 1 layer FDD (bandIndexUL1-r16 aka carrier1) and which band it will support for 2L TDD (bandIndexUL2-r16 aka carrier2) for dynamic switching between 1Tx-2Tx
- UE must be able convey how much switching penalty (uplinkTxSwitchingPeriod-r16 - n35us, n140us, n210us)

3.2 gNB Infrastructure Requirement

Similar to the UE-capability, and being a 3GPP release 16 feature (and beyond), the gNB is required to support switched UL. Upon receipt of UE-capability-message, gNB may decide to configure the UE appropriately, which could be treated as an indirect indication of its capability to support such features.

- gNB shall request specific UE capability related to switched UL (uplinkTxSwitchRequest)
- gNB shall indicate to a UE via RRC the switching band location (uplinkTxSwitchingPeriodLocation-r16)
- gNB shall configure for a UE 1 layer FDD (bandIndexUL1-r16 aka carrier1) and 2 layer TDD bands (bandIndexUL2-r16 aka carrier2)
- gNB shall indicate to a UE via RRC the switched UL option (uplinkTxSwitching-OptionSupport-r16 – switchedUL or dualUL)
- gNB shall indicate to a UE via RRC the switching penalty (uplinkTxSwitchingPeriod-r16 - n35us, n140us, n210us)

4. Simulation Result: UE Performance Benefit

To estimate realistic benefit of switched UL against a baseline references of current release 15 SUL and Non-SUL ecosystem, system simulations were done for both types of switched UL, with real world urban site deployment, spectrum scenario and smartphone user distribution.

Four sets of comparative results as outlined below are discussed in the subsequent sections:

- Non-SUL release 15 scenario where UE is capable of 1L FDD or 1/2L TDD, but never together [Baseline]
- Release 15 SUL scenario where UE is capable of 1L FDD + 1L TDD, but never 2L TDD

- Release 16 switchedUL (Option 1) scenario where UE is capable of 1L FDD switching to 2L TDD and 2L TDD switching to 1L FDD with 140us switching period on FDD carrier
- Release 16 dualUL (Option 2) scenario where UE is capable of 1L FDD switching to 2L TDD and 2L TDD switching to 1L FDD with 140us switching period on FDD carrier or 1L FDD + 1L TDD with no switching

The UL user throughput for each scenario for cell-edge, mid-cell, and near-cell UEs are compared.

The assumptions we used for these simulations as well as the comparative results are presented in the following sections.

4.1 Simulation Assumptions

Figure 4-1 below lists the high-level simulation assumptions.

Item	FDD Carrier	TDD Carrier
Freq. band	700 MHz	2.5 GHz
Channel BW	10 MHz FDD	100 MHz TDD 4:1 DL:UL Ratio
SCS	15 kHz	30 kHz
UE Tx power (Max)	23 dBm (FDD) 26 dBm (F+T)	26 dBm (TDD) 26 dBm (F+T)
gNB EIRP	61 dBm	77dBm
gNB Antenna gain	14 dBi	24 dBi
# of TXRU	2T4R	64T4R, 192 Ant Elements
Building Penetration Loss (average)	17 dB	23 dB
Building Penetration Loss (sigma)	6.5 dB	6.5 dB
UE Antenna Gain	-5 dBi	-2 dBi
Body Loss	1 dB	3 dB
Max Single Band UE Tx	1 Layer	2 Layers
SUL UE Tx	1 Layer	1 Layer
1Tx-2Tx UL Switching Period	140 us	0 us

Figure 4-1 Switched UL Simulations Assumptions

The simulations were performed for a cluster in a tier-1 global city with following high-level details.

- 371 sites || 61.5sqkm || 350m inter-site distance
- 70% indoor and 30% outdoor users || On the average, 10 users per-sector
- Fully-loaded network (100% UL PRB loading), with full-buffer traffic

4.2 Simulation Results: Smartphone

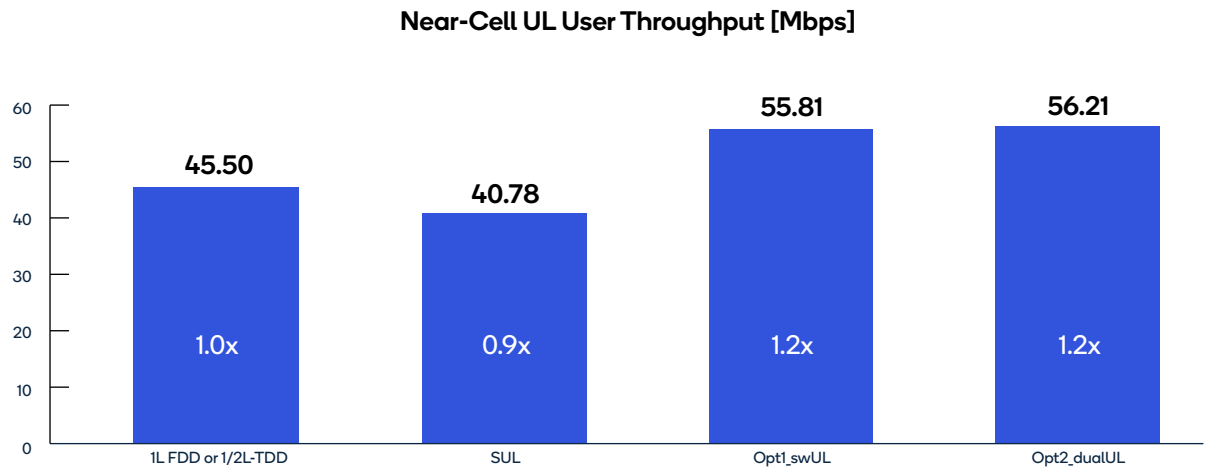


Figure 4-2 Near-cell UL user throughput results

Figure 4-2 Near-cell UL user throughput results above shows the near-cell user throughputs for all scenarios. At near-cell, due to high SINR, typically 2L TDD and 1L FDD bands are accessible. For baseline case, near-cell UE gets 2L TDD which gives it higher throughput due to larger TDD BW. For SUL case, near-cell UE gets about 10% lower throughput than baseline case of no SUL. For switched UL case, both options of switched UL provide similar UL user throughput benefit over baseline [~23-25%]. Both switched UL options and baseline gets 2L TDD, plus the switched UL options also get 1L FDD.

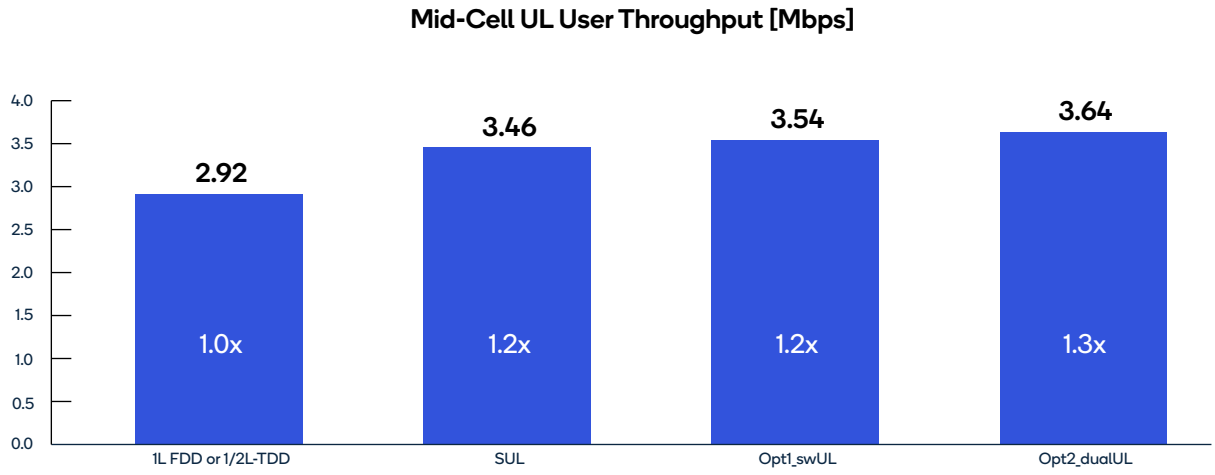


Figure 4-3 Mid-cell UL user throughput results

Figure 4-3 Mid-cell UL user throughput results above shows the mid-cell user throughputs for all scenarios. At mid-cell, due to moderate SINR, typically 1L TDD and 1L FDD bands are accessible. Sometimes 2L TDD is also possible depending on channel conditions. Due to simultaneous use of both FDD and TDD bands in mid cell, SUL gets about 18% UL user throughput benefit, Switched UL Option 1 gets about 21% benefit and switched UL Option 2 gets about 30% benefit in UL user throughput over baseline.

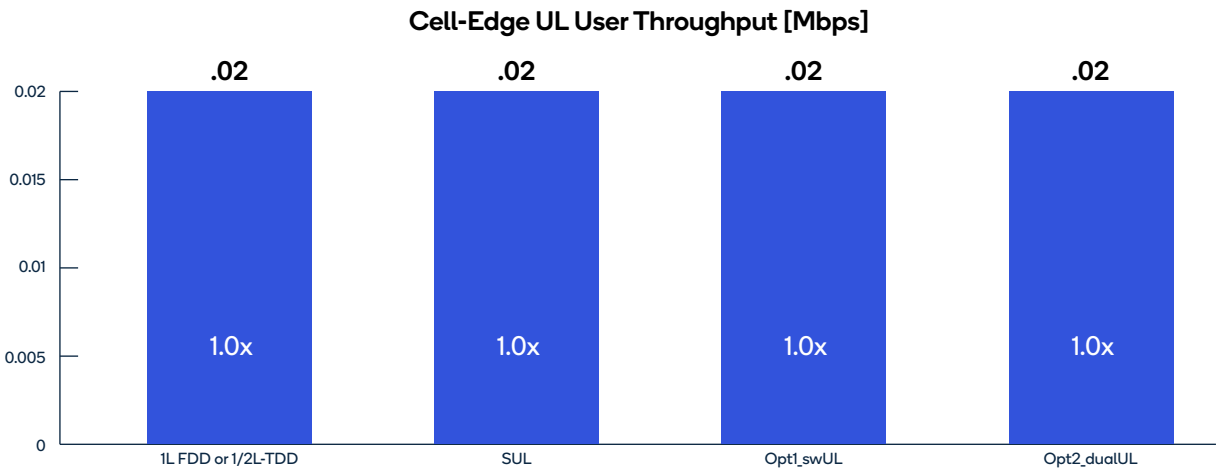


Figure 4-4 Cell-edge UL user throughput results

Figure 4-4 Cell-edge UL user throughput results above shows the cell-edge user throughputs for all scenarios. All scenarios get similar user throughput at cell-edge. At cell-edge, which are typically the deep-indoor UE's, high band TDD carrier is not accessible due to high pathloss and high building penetration loss. Only low band FDD carrier is accessible. For all scenarios, UE's at cell-edge use the FDD carrier only and hence user throughputs are same. No advantage of switched UL is seen for cell-edge users.

4.3 Simulation Result: Fixed-Wireless-Access

While the previous section focused on smartphone-centric study around the benefit of optimizing the number of UL-transmit chains while trying to maximize the user-experience, this section focuses on CPE-centric simulation studies and their comparison with 3-UL-Transmit chains for following reasons.

- BOM optimization consideration which had been the primary driver to smartphone may not be as critical in FWA
- FWAs may operate with directional antenna, leading to superior RF condition
- FWAs are stationary in nature, and in absence of any mobility, may experience better channel condition

The simulation case-study was performed on a network-layout of a tier-1 US city with following details.

- FR1-TDD (100MHz || 80:20 DL:UL) || FR1-FDD (20MHz)
- Indoor-CPE assumed, behind standard glass-window
- An average of 10-CPEs per sector of gNB
- UL bursty-traffic profile, to realistically represent multi-user, multi-device activity in a typical home along with ACK/NACK for DL transmission
- A dense-urban cluster of 29sqkm, with 51 macro-sites
- 2m resolution 3D map used to accurately factor-in CPE-location and height impact

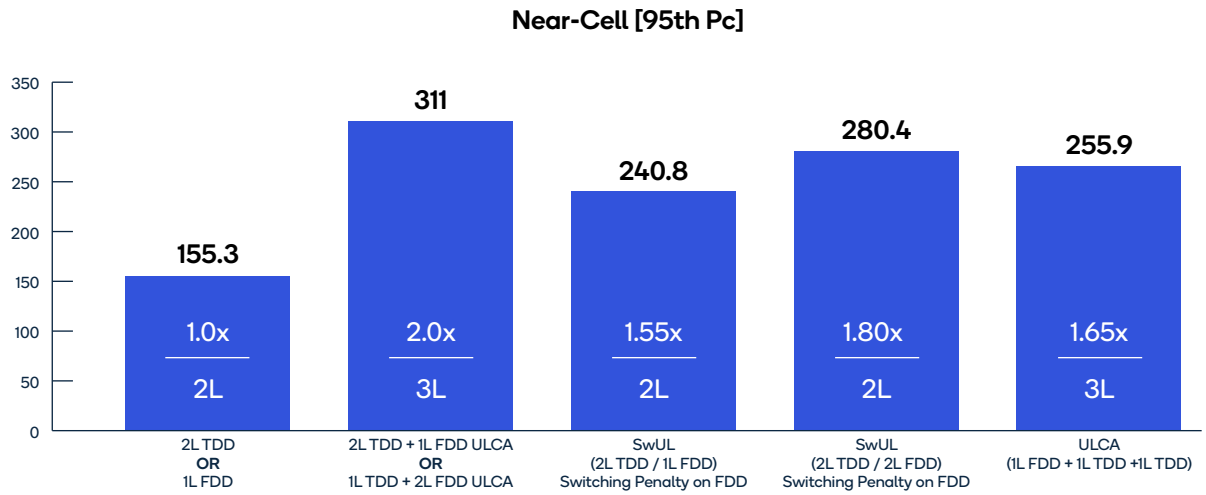


Figure 4-5 Near-cell UL CPE throughput result

Figure 4-5 Near-cell UL CPE throughput result above shows that both switched-UL with 2Tx and UL-CA with 3Tx would enhance user-experience significantly. It is also evident that, despite switching-penalty causing some reduction to the UL-data-rate, 2Tx-Switched-UL performance comes very close to the 3Tx-ULCA, so could be considered as a very effective means with optimized BOM.

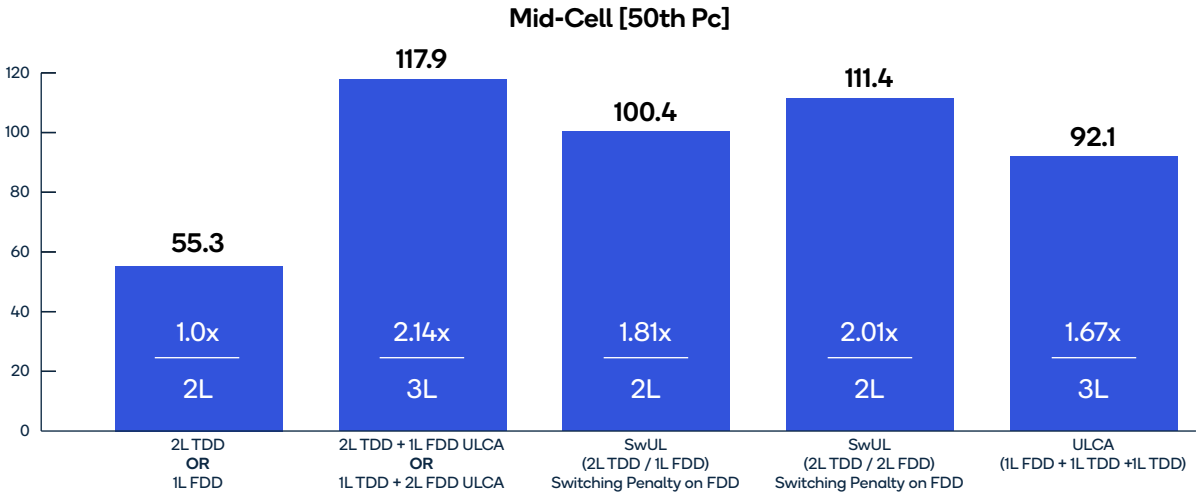


Figure 4-7 Mid-cell UL CPE throughput result

Figure 4-7 Mid-cell UL CPE throughput result above shows similar outcomes, with 3Tx-ULCA having slight edge over 2Tx-Switched-UL, although owing to sustainable RF-condition being not so conducive to support 2L TDD UL-MIMO consistently, the performance-gap between the two goes down further.

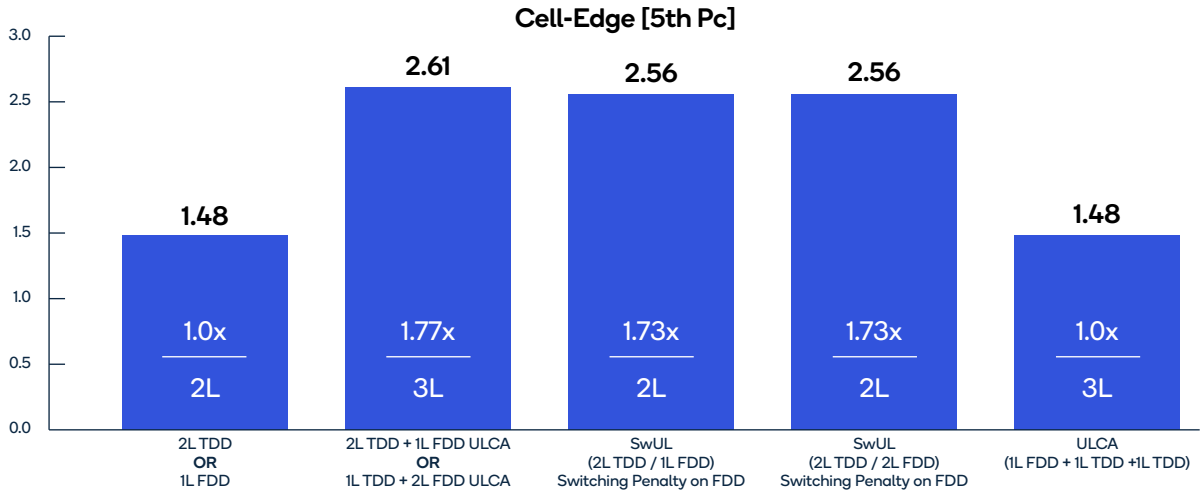


Figure 4-9 Far-cell UL CPE throughput result

Figure 4-9 Far-cell UL CPE throughput result above shows somewhat similar outcome, although with a significant difference that the gap between 3Tx-ULCA and 2Tx-Switched-UL disappears entirely at such relatively inferior RF-condition.

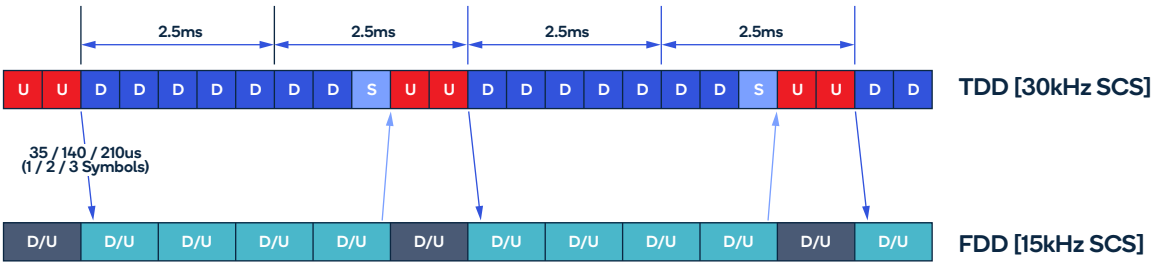
5 Deployment Recommendation

Typical TDD bands are higher frequency bands with larger BW / low TDD UL duty cycle and with smaller cell footprints than typical FDD bands which are lower frequency bands with smaller BW with larger cell footprints. Keeping this in mind below are few deployment recommendations:

- **Near-cell UEs (UL 2L MIMO is Sustainable):** UE in great UL conditions for both TDD and FDD bands. Since TDD bands support 2L UL MIMO and have larger BW, schedule UE in Release 16 Option-1 or 2, Case-2 mode. UE does not use FDD slots for UL and uses 2L UL on TDD slots.
- **Mid-cell Ues (UL 2L MIMO may not be Sustained):** UE in reasonable UL conditions for TDD band, still better conditions for FDD bands. Here UE can support TDD band but may not sustain 2L UL MIMO. Therefore, recommendation is to schedule UE in Option-2, Case-1 mode (dualUL or 1L FDD + 1L TDD UL CA). The UE gets benefit from wider TDD BW plus good FDD link. However, depending on UL PHR available, 1L on FDD + 1L on TDD may not always be the most optimal; rather 1L on FDD + 0L on TDD with FDD using all power may in certain cases produce better performance. It is therefore necessary for the scheduler the make such decision on UE-specific basis, and optimize the mode of operation as a function of RF-condition and loading scenarios.
- **Cell-edge Ues (UL TDD Coverage not Available):** Ues are likely out of TDD coverage, but still within FDD coverage. Only option for UE is to use 1L FDD, so disable switched UL for far-cell Ues.
- **2-TDD Carriers:** When 2 TDD carriers are involved with both carriers supporting 2L UL MIMO, it is preferable to configure release-17 enhanced-switched-UL with TDD slots offset such that both bands' TDD UL slots do not overlap in time. This maximizes potential for 2L UL MIMO on both TDD carriers. In case of no slot-offsets, any switched-UL benefit will not be realizable.

- **Switching Penalty Implication:** As there is carrier-switching involved, say at every to-and-fro transition between TDD and FDD carrier, depending on ecosystem implementation there will be a finite time-gap for switching to take place. If such transition happens very frequently, there might be unwanted impact to the data-rate. In addition, since FDD-ecosystem operates at 15kHz SCS (i.e. 1ms slot) with typically lower channel bandwidth like max 20MHz & 1L UL, as against TDD-ecosystem that operates at 30kHz SCS (i.e. 0.5ms slot-duration) and with typically larger channel bandwidth like max 100Mhz & 2L UL-MIMO, from data-rate enhancement perspective it is strongly recommended to apply the switching-penalty to the FDD channel. Figure 5-1 below depicts an example of scheduler should apply switching-gap on per-UE basis.

It may however be noted that In certain deployments where FDD bandwidth is larger (say up to 40MHz channel), and also in future when 2L UL-MIMO becomes available, the relative benefit would need to be revisited – as a function of UE location as to whether 2L UL-MIMO in TDD is sustainable – and intelligent decision-making would need to be done by the scheduler for optimal performance.



Note-1 : TDD and FDD operate at 30kHz and 15kHz PUSCH SCS respectively
Note-2: PUSCH Type-B assumed to be implemented at network and UE
Note-3: 35u = 1 FDD symbol; 140us = 2 FDD symbols; 210 us = 3 FDD symbols
Note-4: Total number of FDD symbols lost (per 10ms) = 4 / 10 / 15
Note-5: Perfect scheduling operation with no other symbol / slot loss assumed
Note-6: 10:2:2 (D:G:U) assumbed for S-slot

Figure 5-1 Cell-edge UL user throughput results

6 Conclusion

Both switched UL options, namely Option 1 switchedUL and Option 2 dualUL, are expected provide enhanced UL smartphone user throughput, when compared against baseline release 15 SUL and Non-SUL UEs.

The estimated benefit to the smartphone users for typical 10MHz FDD and 100MHz TDD band combination is about 20-25% for switched UL over non-SUL release 15 UEs. dualUL – option 2 provides better gains at mid-cell and is more flexible and would be the recommended choice.

Since typical FDD bands use 15kHz SCS and typical TDD bands use 30kHz SCS, to maximize the dualUL – Option 2 benefits, both FDD gNB and UE must support PUSCH mapping Type B. This will ensure that partial FDD slots can be used during 1L FDD + 1L TDD simultaneous UL transmissions.

In the case of FDD-TDD switching scenario, considering wider TDD channel bandwidth as well as ecosystem support of 2L UL-MIMO, switching-penalty should be applied to the FDD-channel.

Release 15 SUL may provide similar benefits at mid-cell, but due to limitation of 1L on TDD band, will provide lower peak user throughput, especially at near cell where 2L TDD is easily achievable.

As for the CPE-centric deployment where BOM optimization may not be as critical as smartphone, the gap between 2Tx-Switched-UL and 3Tx-ULCA ranges between ~15% (near-cell) and ~10% (mid-cell), with no gap for the cell-edge CPEs.

Considering all of the above, Rel16 switched UL Option 2 (dualUL) is recommended for expedited commercialization, for both smartphone and CPE, while keeping a future outlook to expand to Rel17 switched-UL version, and also facilitate 3Tx ULCA enablement for CPE in scenarios where BOM optimization is not critical.

References

3GPP TS 38.211 NR; Physical channels and modulation

3GPP TS 38.213 NR; Physical layer procedures for control

3GPP TS 38.214 NR; Physical layer procedures for data

3GPP TS 38.306 NR; User Equipment (UE) radio access capabilities

3GPP TS 38.311 NR; NR; Radio Resource Control (RRC); Protocol specification

Abbreviations

3GPP	3rd Generation Project Partnership (www.3gpp.org)
BW	Bandwidth
CC	Component Carrier
DL	Downlink
gNB	5G NR NodeB (the 5G NR base station)
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PUSCH	Physical Uplink Shared Channel
RRC	Radio Resource Control
SCS	Sub Carrier Spacing
SPEF	Spectral Efficiency
FDD	Frequency Division Duplexing
TDD	Time Division Duplexing
UE	User Equipment (the cellphone, cellular IoT device, ...)
UL	Uplink

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