WHITE PAPER

5G Uplink Enhancement Techniques

A Comprehensive Evaluation of 5G Uplink Transmit Switching & Uplink with Three-Antenna Transmission Solutions

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1. Introduction

The emergence of 5G technology has been a game-changer for the telecommunications industry, promising faster speeds, lower latency, and improved connectivity. While much of the conversation around 5G has been focused on its impressive download throughput, the importance of uplink performance cannot be underestimated. Uplink is set to play a pivotal role in enabling a plethora of applications and services that require high throughput and low latency.

5G networks are designed to support a diverse range of applications, many of which are uplink intensive. The improved uplink throughput in 5G is critical for several reasons:

- Applications that require significant data to be sent upstream, such as video uploads, live streaming, or real-time gaming.
- Low latency: 5G low latency is a boon for uplink-centric applications, ensuring that data sent from devices reaches the network quickly, which is crucial for time-sensitive applications.
- Capacity and connectivity: with the ability to connect more devices simultaneously, 5G's uplink capacity is vital for the Internet of Things (IoT), where numerous devices need to send data to the cloud.
- Reliability: enhanced uplink also means improved reliability, which is necessary for critical communications in areas such as telemedicine, public safety, and industrial automation.

TDD NR bands such as 3.5 GHz are fundamental spectrum resources for 5G deployment, offering substantial bandwidth and high downlink capacity. However, these bands often face challenges in uplink coverage and capacity due to the inherent constraints associated with mid-band frequencies propagation characteristics and TDD duplexing technique. TDD bands are typically asymmetric in terms of downlink and uplink capacity, downlink being more dominant.

As 5G is increasingly penetrating and has been deployed widely across the globe, the diverse range of applications demands exceptional performance not only in the downlink but also in the uplink and hence uplink coverage and capacity remains to be the important factors for consideration for better user experience with improved system efficiency.

Considering the above context this whitepaper introduces two critical features for uplink i.e., Uplink Transmit (Tx) switching which was introduced in Rel 16 and Uplink 3 Transmit (3Tx) antenna transmission solution. Along with the description, this whitepaper will also discuss the performance aspects of these features emerging from the two independent studies conducted in field. Hence, it is suggested to the readers to not correlate the data presented for each feature as the network, spectrum and bandwidth configurations will differ.

2. 5G Uplink Challenges and Enhancement Techniques

Since 3GPP Release 15 specifications were first published there were certain challenges that uplink performance had to deal with. Firstly, 5G deployment typically utilizes the mid-band TDD 3.5 GHz frequency, which is in higher range than the frequencies typically used in previous cellular technologies until 4G. This higher frequency range results in increased path loss, exceeding 4-5 dB, and greater penetration loss, exceeding 3-4 dB, compared to any FDD band. The above factors typically lead to suboptimal uplink coverage, although to some extent advanced techniques on the network side such as massive MIMO can compensate for the propagation loss but can't address the suboptimal 3.5GHz coverage challenges fully.

Secondly, TDD NR bands are the focal point of any 5G deployment, and these bands typically offer limited capacity in the uplink. Unlike FDD, TDD frame structure has both downlink and uplink slots, however 70-80% of the slots are dedicated for downlink. The TDD frame structure is normally asymmetric in favor of the DL and the configuration looks justified considering the traffic type which most networks observe to be DL centric. But with the introduction of uplink centric usage, applications, and use cases the discussed configuration becomes insufficient for the uplink. Consequently, while the wider bandwidth of TDD NR bands significantly enhances downlink performance, its impact on uplink is comparatively less substantial.

Additionally, the number of transmit paths is limited to two in most UEs (User Equipment) because of device form factor constraints and power capabilities. Unlike base stations, that can transmit at higher power levels, mobile devices have limited battery life and are subject to strict power output regulations to minimize interference and SAR (Specific Absorption Rate) to ensure safety of users. This power disparity can lead to uplink signals being weaker than downlink signals, affecting the uplink data rates and coverage, especially at the cell edge or in indoor environments.

There have been several directions in which the industry had worked to improve the UL performance of 5G devices:

- Increasing Tx power through enabling higher UE power classes like PC2 and PC1.5 for FR1 (PC- Power Class). Generally, the UEs with different power classes are referred to as High-Power UE (HPUE). On the one hand, HPUE delivers notable performance enhancements at the cell edge and indoor coverage, while on the other hand, it bolsters overall system capacity by improving spectral efficiency. However, higher power levels introduce certain constraints, such as the need for meticulous interference management, regulatory considerations, and elevated power consumption.

- Increasing the number of Tx antennas in the UE thus enabling UL MIMO (Multiple Input Multiple Output). UL MIMO is useful for diversity gains at the cell edge to improve coverage as well as throughput improvements in better radio conditions thanks to the possibility of multiplexing multiple layers.

- Adding more Component Carriers (CC) with Uplink Carrier Aggregation (ULCA). It brings throughput gains in the cell center proportional to added BW but has limitations on aggregated UE Tx power or say the power by which a UE can transmit on each carrier.

- At the onset of Rel 15, the techniques such as ENDC, Supplementary uplink (SUL) or Carrier aggregation (CA) were enablers of uplink enhancement. In case of ENDC the UE can transmit either on both LTE & NR or just on LTE to compensate for the insufficient uplink coverage delivered by NR. Thus, the user experience at the cell edge can be well addressed and coverage can be ensured because of LTE transmission on lower bands (FDD). Another aspect is that under good coverage UE can leverage the 2 transmit antennas and can transmit on both LTE and NR pushing the boundaries of uplink throughput. Although different from ENDC, the other two techniques such as CA and SUL also contributes to uplink enhancements. Conceptually these techniques are quite close to each other in terms of objectives and operations.

Although ENDC, SUL and CA bring significant improvements for the uplink, there are certain limitations that impact full utilization of available uplink resources. Below is the description of such limiting factors for ENDC and CA. Comprehending these factors is a key to better understanding of the need for required additional enhancements:

- In the context of E-UTRA-NR Dual Connectivity (EN-DC), the configuration limits the New Radio (NR) transmission on single Tx only in the uplink as the other Tx is on LTE; this restriction makes it impossible to support dual-stream transmission (MIMO) on single TDD NR carrier on the uplink and thus the opportunity for possible MIMO gains is totally lost resulting in capacity loss (considering the wider bandwidth that mid band brings). However, from the perspective of user experience the coverage will be better as the transmission at cell edge will be on LTE which is typically on FDD bands that provides robust coverage.

- In uplink CA, the 2 Tx will be used by each component carrier (Inter band 2 Carrier aggregation, 1 Tx per carrier) and thus the possibility of dual transmission on TDD NR becomes impossible which translates to capacity loss. However, FDD carrier can help push the user experience by offering better coverage at the cell edge.

Given these challenges, it is imperative to optimize the utilization of transmission opportunities on TDD NR bands to boost capacity and spectral efficiency in the uplink.

SA architecture brings a lot of flexibility from deployment perspective to enhance the uplink. Features such as UL MIMO and UL CA in 5G can be fully exploited on SA networks only as as the dependency on compulsive LTE transmission is removed. As the eventual path of 5G deployments is centered around SA and more and more SA rollouts are progressing globally, it offers an opportunity to fully leverage the uplink advancements for better capacity and user experience.

Solutions that we discuss in this paper are designed to make the most of both UL MIMO (MIMO which is typically more feasible on TDD bands) and ULCA by eliminating limitations that come with these standard techniques. In addition to introduction of these features, we will also evaluate their performance to gain insights into their potential effectiveness.

3. Uplink Transmit (Tx) Switching Overview

Uplink (UL) Transmit Switching, introduced in 3GPP Release 16, is designed for dynamic management of uplink data transmission. This feature aims to enhance uplink performance in various scenarios, including E-UTRA-NR Dual Connectivity (ENDC), Supplementary Uplink (SUL), and Uplink Carrier Aggregation (UL CA).

The fundamental concept behind UL Transmit Switching is to optimize the use of transmission opportunities with 2 transmit antennas in the uplink to maximize efficiency whenever possible. Refer figure 1 to understand the transmission techniques in different scenarios.

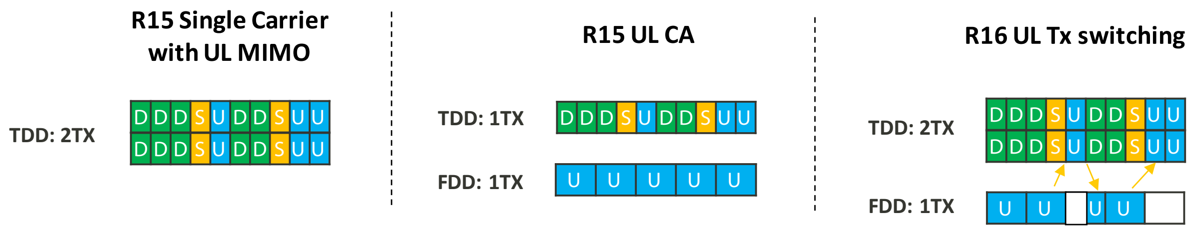

Figure 1: Overview of UL Enhancement Transmission Techniques

Rel 16 uplink Tx switching allocates one transmitting channel to either carrier 1 or carrier 2, while dedicating the other transmitting channel solely to carrier 2. The switching process involves the selective activation and deactivation of uplink transmission.

This can be better understood by studying different modes of transmission. In one mode 1 Tx will be dedicated for FDD band and the second Tx for TDD band. Whereas, in the other mode 1 Tx is switched to TDD band from FDD band and the other is still used for TDD band which supports UL MIMO. Uplink Tx switching is triggered when the mode of transmission is changed in time domain.

According to TS 38.306 [1] the UL switching can be based on one of 3 scenarios: inter-band NRCA, SUL or EN-DC.

Note that this whitepaper focuses on the concept of Uplink (UL) transmit switching within the context of Carrier Aggregation (CA), specifically addressing scenario in which TDD + FDD ULCA (Uplink Carrier Aggregation) is employed on SA network.

To have better clarity, let's understand the difference between Rel 15 uplink CA and Rel 16 uplink CA with Tx switching with the help of figure 2 below. In case of traditional CA, the transmission is straightforward with each Tx per carrier whereas in case of Tx switching at any time when UL transmission is available on TDD carrier, it will be configured with 2x2 MIMO to utilize the maximum available capacity. But whenever TDD carrier is occupied with DL, Tx is switched to FDD CC to use currently available resource. Eventually the transmission will be either 2Tx on TDD or 1 Tx on FDD in the uplink, this is also called "Switched Uplink"

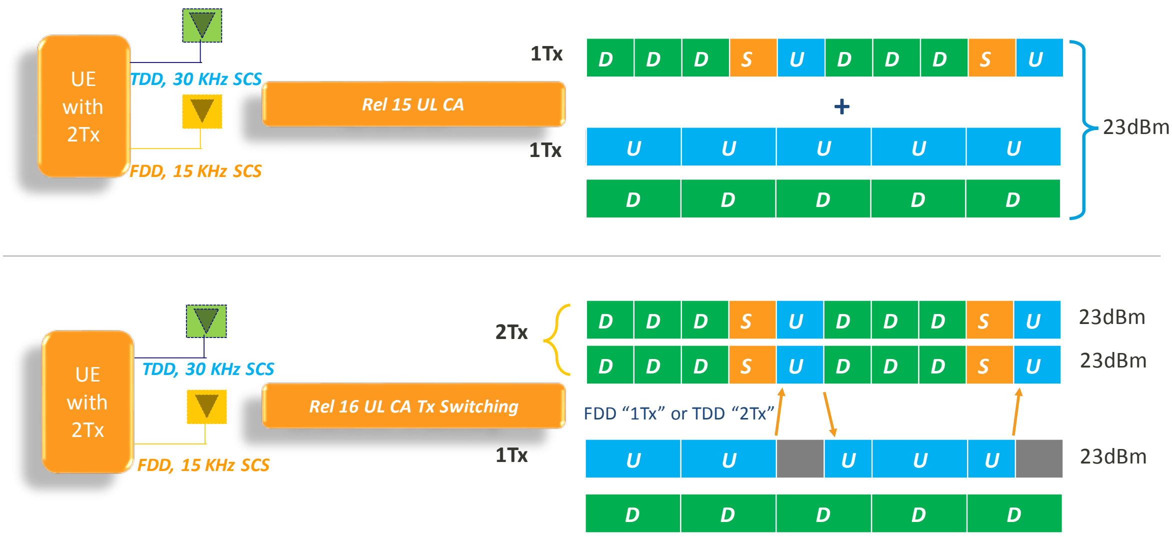

Figure 2: Rel 15 UL CA Vs Rel 16 UL CA with Tx switching operation

In a typical network deployment, there will be coverage area with overlapping TDD and FDD coverage. Normally a TDD carrier operates over much larger bandwidth than that of FDD one. That means more throughput gain by using 2 UL MIMO layers on TDD carrier against SISO on both carriers. However, as discussed before the TDD band performance has dependency on TDD duty cycle. With DL-oriented TDD configuration, most of the time there will be no UL transmission at all. If we decide to use one of Tx paths for FDD UL Tx, we will underutilize TDD potential, keeping it with 1 UL layer only.

Considering different coverage levels, the different transmission mechanisms will be as follows

- Transmission on TDD NR with 2 Tx or FDD 1Tx- When UE is close to base station and uplink Tx switching is activated for inter band CA.
- Transmission on FDD NR 1Tx- When UE is at cell edge and TDD coverage is not sufficient and doesn’t overlap with the FDD coverage.

In case gNB sends an uplinkSwitchRequest-R16 in UE capability enquiry, the supporting UE provides the following Information Elements (IEs) related to the feature, as described in Table 1 [2] *38.331

Table 1: UL Tx Switching IEs in UE Capabilities

IE	***Description***
Uplink Switching-OptionSupport-R16	Indicates which option is supported for dynamic UL Tx switching for inter-band UL: • Option 1- SwitchedUL, switch transmission between two bands, “FDD 1L” or “TDD 2L” • Option 2 - DualUL, dual transmission for two bands (ULCA), “FDD 1L”, “TDD 2L” or “FDD 1L + TDD 1L
SupportedBandCombinationList-UplinkTxSwitch	Report as many NR-only band combinations that supported UL TX switching as possible starting from the first entry

ULTxSwitchingBandPair-r16	Indicates UE supports dynamic UL Tx switching in case of inter-band CA. The capability signaling comprises of the following parameters: • bandIndexUL1-r16 and bandIndexUL2-r16 indicate the band pair on which UE supports dynamic UL Tx switching. bandindexUL1/bandindexUL2 n refers to the n-th band entry in the band combination • uplinkTxSwitchingPeriod-r16 indicates the length of UL Tx switching period per pair of UL bands per band combination when dynamic UL Tx switching is configured

Actual Tx switching configuration is delivered to the UE via RRCReconfiguration message from gNB which contains the following parameters as described in Table 2:

Table 2: UL Tx Switching IEs in RRCReconfiguration

IE	***Description***
uplinkTxSwitchingPeriodLocation	Indicates whether the location of UL Tx switching period is configured in this uplink carrier in case of inter-band UL CA or SUL. In case of inter-band UL CA, for dynamic uplink Tx switching between 2 bands with 2 uplink carriers, network configures this field to TRUE for the uplink carrier(s) on one band and configures this field to FALSE for the uplink carrier(s) on the other band.
uplinkTxSwitchingCarrier	Indicates that the configured carrier is carrier1 or carrier2 for dynamic uplink Tx switching. In case of inter-band UL CA, for dynamic uplink Tx switching between 2 bands with 2 uplink, network configures the uplink carrier(s) on one band as carrier1 and the uplink carrier(s) on the other band as carrier2.
uplinkTxSwitchingOption	Indicates which option is configured for dynamic UL Tx switching for inter-band UL CA. The field is set to switchedUL if network configures option 1, or dualUL if network configures option 2. Network always configures UE with a value for this field in inter-band UL CA case where UE supports dynamic UL Tx switching

3.1. Uplink Tx Switching Performance Analysis

MediaTek performed Uplink Tx switching feature evaluation in one of the trial clusters with the Uplink CA combination of n78A_n1A in which n78 and n1 was PCell and SCell respectively. The bandwidth of n78 band was 80 MHz with 2x2 MIMO whereas the bandwidth of n1 was 10 MHz. The n78 TDD slot configuration common pattern 1 was in use as shown in the table below. Other key factors being 14 PUSCH symbols / PRB, 217 resource blocks (over 80 MHz bandwidth) and 4 UL grant opportunity per frame of 10 ms.

Considering similar factors for n1 FDD peak uplink throughput calculation, the expected throughput comes to around 35 Mbps. Factors being varying PUSCH symbols (12, 5, 14) per PRB, 52 resource blocks (over 10 MHz bandwidth) and varying UL grant opportunity per frame of 10 ms. Reasons for unavailability of some of the FDD PUSCH symbols is described towards the end of this section.

Below is the demonstration of how UL CA (without Tx switching) and UL MIMO (n78) performs against each other to highlight the potential gains that UL MIMO can offer over CA. In our study we clearly observed that UL MIMO has an edge over UL CA, and the gain observed was around 24% as shown in figure 3 below. The gain clearly indicates that the additional transmission layers (2 layers) on a single band outperforms uplink CA by a huge margin (with 1 layer on each band).

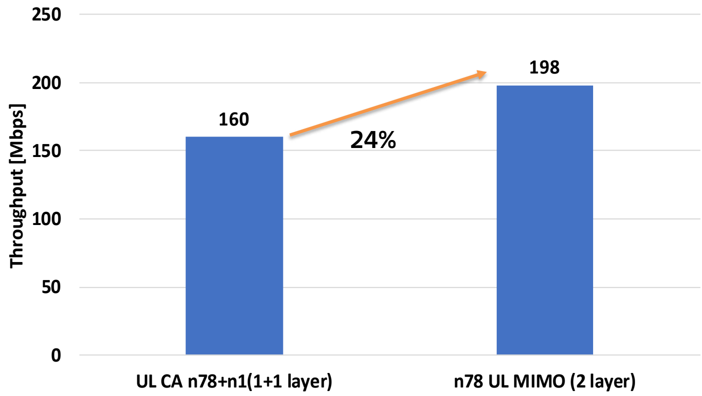

Figure 3: UL CA Vs UL MIMO Throughput gains

The figure 4 below shows a broader picture and captures the performance of different techniques/configurations evaluated in the trial including n1 UL MIMO and UL Tx switching itself which was a goal of the exercise.

The UL MIMO (n1) configuration demonstrates a throughput of 108 Mbps, indicating its baseline performance. Moving to UL CA (n78_n1), we observe a notable increase in throughput to 160 Mbps, showcasing the benefits of Carrier Aggregation and representing a gain of approximately 48% over UL MIMO (n1).

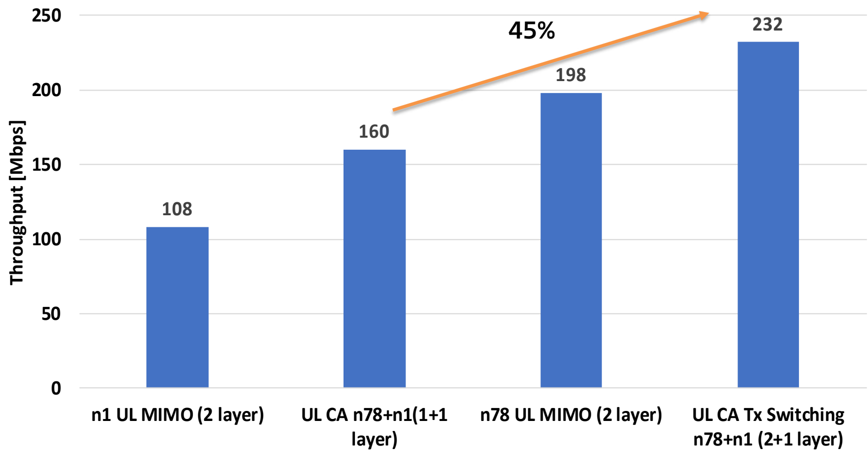

Figure 4: Performance comparison of different techniques

Notably, UL CA Tx Switching (n78 (2) _n1(1)) achieves a throughput of 232 Mbps which is in line with the theoretical calculation, highlighting the effectiveness of Uplink Tx Switching in optimizing the utilization of available transmitting channels and representing a gain of approximately 45% over UL CA (n78_n1). These results underscore the potential for significant performance gains through strategic configuration selection, with UL CA Tx Switching (n78 (2) _n1(1)) emerging as a promising option for enhancing uplink throughput in 5G networks.

Throughput performance of UL CA Tx switching in different RF conditions is depicted in the figure 5 below. The degradation in throughput begins to appear in areas with medium coverage, typically around RSRP -92 dBm.

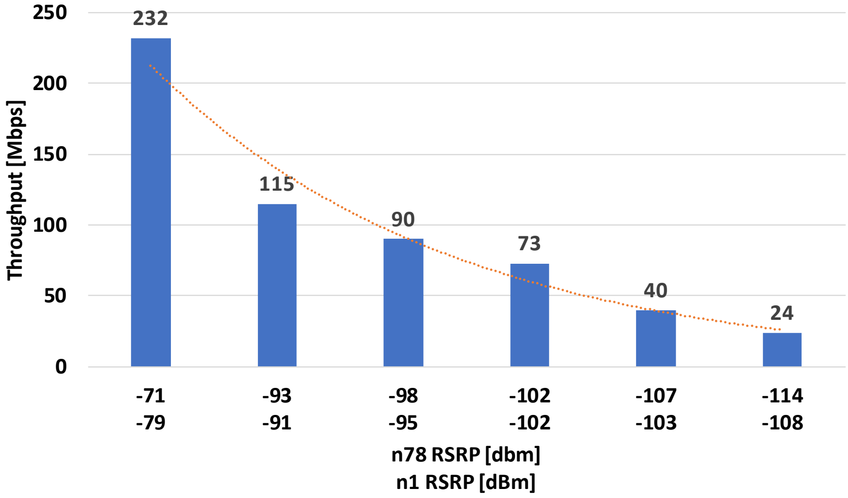

Figure 5: RSRP Vs Throughput Distribution

Throughput performance on each band of the UL CA (with Tx switching) is shown in the figure 6 below along with MIMO layers of n78. Tx Switching performs well in conditions where the signal is strong. In scenarios where the user is near cell condition or at mid-cell condition, TDD can effectively maintain a 2-layer configuration, which is crucial for achieving high data throughput rates. However, when RSRP falls to around -110 dBm as shown in the figure below, TDD struggles to configure and maintain 2 layers. At this lower threshold of signal strength, TDD's inability to maintain a 2-layer configuration has significant implications on the user experience.

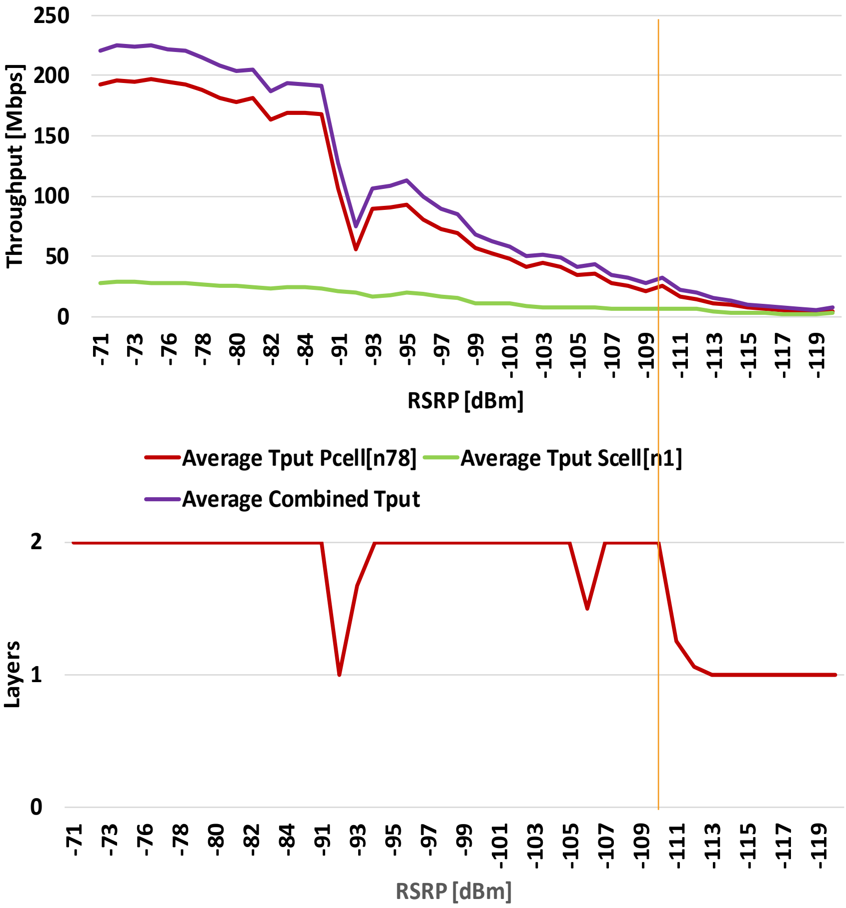

Figure 6: RSRP Vs Uplink Throughput and MIMO layers on n78

Another important aspect that needs to be highlighted is the UE transmit power in the case of Tx switching. As the UE transmission switches between the bands in time domain, UE can transmit with the full power per band (depending on UE power class) unlike in the case of Rel 15 UL CA where the UE power is divided between the two bands because of simultaneous transmission. UE Tx Power is available for each band separately since PCell & SCell don't transmit at the same time.

UE used in this trial was supporting Power Class 3 (23 dBm) on n1 band whereas Power Class 2 (26 dBm) on n78, because of transmit switching UE was observed transmitting with full power on each band depending on RF conditions as evident in the figure below

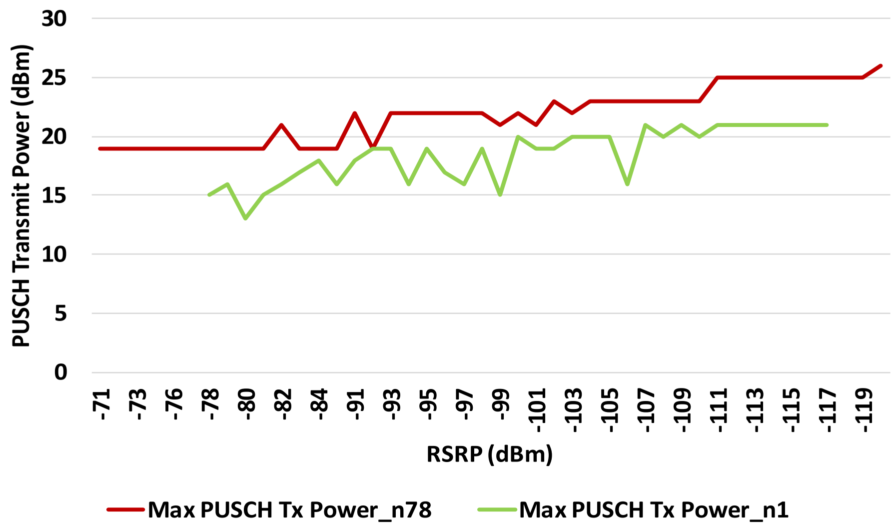

Figure 7: RSRP Vs PUSCH Transmit Power

Considering the hardware design, transmit antenna limitations, and based on the observations presented in this study we can conclude that the uplink Tx switching outperforms all the other traditional techniques and can be considered as one of the best possible uplink solutions for the carriers planning to level up the experience for its users. UL Tx switching function requires sophisticated scheduling mechanisms at gNB side to ensure proper timing for switching between the carriers. It is also important to highlight that there is a notable loss of throughput on FDD carrier because of the 2 main factors as follows.

- One of the key factors is that some of the FDD resources may not be available because of the several reasons listed here

1. Switching delay defined by uplinkTxSwitchingPeriod-r16: During the period of switching, some of the FDD resources will not be available for UL transmission. The actual loss will depend on configuration. For example, in the case of 15 kHz subcarrier spacing (SCS) on FDD carrier, and since UE is using 140us switching delays, this translates to 140/71 = 2 FDD symbols. This means that 2 FDD symbols will not be available for transmission when the UL switching happens from TDD to FDD.
2. SRS is sent in "S" slots in TDD as shown below:

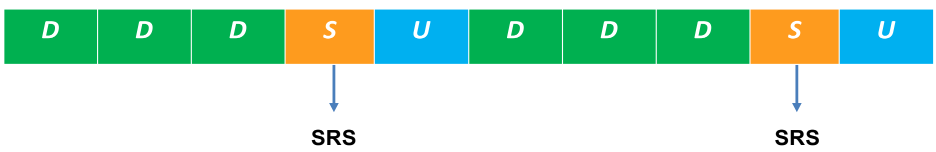

Figure 8: TDD frame structure

3. TDD SRS in the UL symbols inside the "S" slot that you see in TDD Slot Structure above occupies 2 TDD symbols + 2 Guard Period symbols, with 30KHz SCS, which translates to 4*35/71 = 2 FDD symbols, this means 2 FDD symbols will not be available for transmission.
4. UL TDD when sent, it creates a gap in FDD (which means FDD can't transmit), and in UL TDD Slot we have 14 symbols which translate to 14*35/71 = 7 FDD symbols, this means 7 FDD symbols will not be available for transmission

- Secondly, the inability of the UE to transmit simultaneously on both CCs is a limiting factor of this technique Our in-depth analysis revealed a notable decrease in FDD throughput, a degradation of approximately 41%. Uplink 3 Tx antenna transmission solution, which is the next section, overcomes these downsides with the changes in hardware and transmission techniques.

4. Uplink 3 Tx Antenna Transmission Overview

Although UL Tx Switching significantly improves UE UL performance, its natural limitations lead to suboptimal usage of available resources. Addition of third permanent Tx path would allow the UE to get rid of switching delays and use UL MIMO and ULCA simultaneously. MediaTek has developed an UL 3Tx solution with limited changes to device's hardware and hence a minimal impact on the end price. Due to form factor constraints, it is offered exclusively for FWA platforms and not available for handheld devices. The general principle of UL 3Tx is shown in Figure 9 (with reference to Figure 1 of this document).

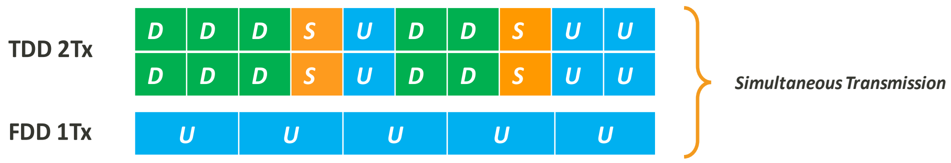

Figure 9: UL 3 Tx Transmission

From standards and protocol point of view, UL 3Tx is based on UL CA of FDD CC complemented by 2x2 MIMO TDD CC. This configuration does not require any additional UE capabilities on top of support of UL CA and 2 layers (SU-MIMO) on one of CCs, as in example below. Table 3 demonstrates the UE capabilities required for UL 3Tx from a device supporting UL CA between 2 CCs in n1 and n78 bands with 2 UL MIMO layers supported on n78

UL CA capability	UL MIMO capability
BandCombination bandList: 2 items Item 0 BandParameters: nr (1) nr bandNR: 1 ca-BandwidthClassDL-NR: a (0) **ca-BandwidthClassUL-NR: a (0)** Item 1 BandParameters: nr (1) nr bandNR: 78 ca-BandwidthClassDL-NR: a (0) **ca-BandwidthClassUL-NR: a (0)**	*FeatureSetUplinkPerCC* *supportedSubcarrierSpacingUL: kHz30 (1)* *supportedBandwidthUL: fr1 (0)* *fr1: mhz100 (10)* *channelBW-90mhz: supported (0)* *mimo-CB-PUSCH* *maxNumberMIMO-**LayersCB-PUSCH: twoLayers (1)*** *maxNumberSRS-ResourcePerSet* *supportedModulationOrderUL: qam256 (5)*

Processing of such capability on network side requires supporting software for gNB. Such software must be capable of performing simultaneous scheduling on 2 CCs along with 2x2 MIMO on one of the carriers.

There are certain constraints that impact resulting throughput. Current 3GPP specifications imply limitation on 3Tx preventing it from utilizing 100% of UL resource with this technique. This limitation is formulated in TS 38.213 Clause 9 "*A UE does not expect to multiplex in a PUSCH transmission in one slot with SCS configuration* μ_1 *UCI of same type that the UE would transmit in PUCCHs in different slots with SCS configuration* μ_2 *if* $\mu_1 < \mu_2$ ". This decision was taken due to complicated additional procedures that would have been required to support a scenario shown in Figure 10:

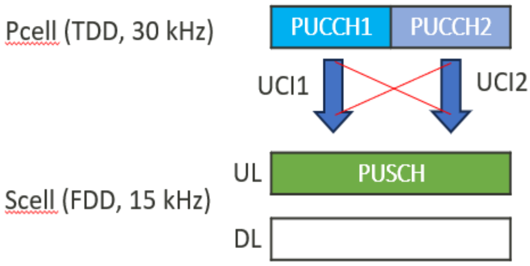

Figure 10: Scheduling limitation per TS 38.213

At the time the specification was created, the impact of such restriction was not properly understood. Currently, as operators are increasingly investing in 5G and deploying CA features, a sufficient loss in system throughput is observed in the real field deployment due to this restriction. This forces the scheduler to avoid overlapping by not scheduling PUCCHs or PUSCH in overlapping UL slots in PCell and SCell that in turn reduces the served traffic.

The issue was addressed in proposal formulated in R1-2310345 document by Ericsson and Verizon and accepted by 3GPP [3]. Optional UE capabilities were added to TS 38.306 from Release 17.7 [4].

- parallel*TxPUCCH-PUSCH-r17* which indicates that the UE supports simultaneous PUCCH and PUSCH transmissions of different priority on different cells for inter-band CA.
- parallel*TxPUCCH-PUSCH-SamePriority-r17* which indicates whether the UE supports simultaneous PUCCH and PUSCH transmissions of same priority on different cells in different bands for inter-band CA as specified in clause 9 of TS 38.213 [5].

This R17 improvement allows to significantly increase FDD cell UL utilization in 3Tx scenario with the 100% resource becoming available for transmission at any time.

Besides, depending on the implementation by RAN vendor, FDD transmission can be skipped in the subframe that is overlapping with SRS transmission to avoid SRS performance impact. This also can cause certain FDD throughput degradation.

Finally, 3Tx uses UL CA framework which means that there is a restriction in terms of total Tx power which cannot exceed the highest power class of involved carriers. Tx power for UL CA for each CA combination is described in 3GPP TS 38.101-1 6.2A [6]. 3GPP TS 38.213 sets prioritization for Tx power reductions. In case of the same priority order, for operation with carrier aggregation, the UE prioritizes power allocation for transmissions on the primary cell over transmissions on a secondary cell. This means that the primary cell transmission will be allocated with maximum available power leaving secondary cell with remaining power.

These Tx power constraints reveal the most beneficial scenario of 3Tx application. Higher throughput gains will be achieved in the areas that do not require high power transmission, while being able to maintain 2 MIMO layers on TDD carrier. So ultimately 3Tx is suitable for good radio conditions. Once they will deteriorate, Tx power will be distributed in favor of a primary cell.

4.1. Uplink 3Tx Antenna Performance Analysis

Since MediaTek first introduced 3Tx in its T830 FWA platform, it went through interoperability tests with major infrastructure vendors. Several public announcements in partnership were made about the lab tests that confirmed 3Tx efficiency. To understand the performance of the feature in the live network, MediaTek performed 3Tx evaluation in one of the trial clusters in cooperation with network carrier and RAN vendor.

Live network deployment uses Uplink CA combination of n77A and n5A in which n77 and n5 were PCell and SCell respectively. The bandwidth of n77 band was 100 MHz with 2x2 MIMO whereas the bandwidth of n5 was 15 MHz.

Due to market specifics, 3Tx feature for FWA was initially of more interest for the US carriers. The trial conducted by MediaTek, that is described in this paper, was done with the North American network that didn't have R16 UL Tx Switching immediately available for direct comparison. Due to this we decided to avoid a direct faceoff between two techniques as we believe the conditions in which evaluation is performed should be identical. In this paper, we are rather focusing on comparing the performance of UL CA (TDD 1L, FDD 1L), UL MIMO (n77) & UL 3Tx (TDD 2L, FDD 1L).

First experiment was conducted to evaluate maximum performance in good RF condition, as this is the most suitable application for 3Tx feature. Device under test and reference devices were placed at the location where RSRP was approximately -60 to -56 dBm. Test results are shown in Figure 11:

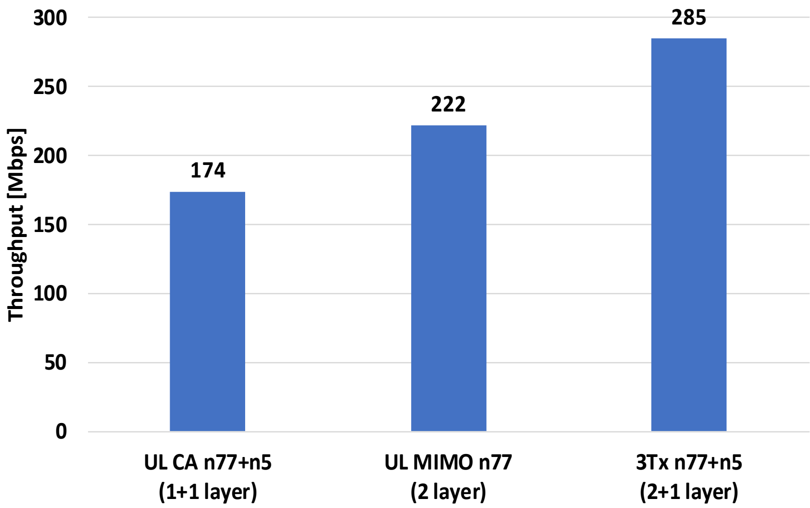

Figure 11: Performance Comparison different configuration

UL CA (TDD 1L, FDD 1L) achieved the throughput of 174 Mbps, followed by UL CA (n77) with 222 Mbps. 3Tx demonstrated improvements compared to both techniques. We managed to achieve 285 Mbps throughput which is 63% higher compared to ULCA performance and 28% higher than UL MIMO on TDD band. This is generally in line with pre-test theoretical calculations, indicating that the feature performs according to expectations.

Mobility scenario for 3Tx doesn't bring a lot of practical value because the feature is applicable exclusively for stationary CPE devices. However, it is important to understand how 3Tx will perform in different radio conditions, including poor coverage. For this task we have carried out an experiment with moving the UE from cell center to the edge.

As shown in Figure 12, 2 MIMO layers on TDD carrier are consistently maintained in near cell condition (-85 dBm and above). This keeps 3Tx feature active. Thus, we can state that the maximum performance is achieved until the RSRP approaches this threshold. At this point TDD CC begins to exhibit a slight reduction in its 2-layer configuration. You can observe stable throughput until around -85 dBm. Then, with less 2-layer scheduling, it starts to decrease with significant drop which kicks off at around -92 dBm. As the second layer totally fades at -108 dBm, the throughput steadily decreases until the coverage is gone.

As the signal weakens further, becoming more attenuated at levels around -92 dBm, there is a marked reduction, with TDD experiencing a substantial loss of approximately 50% of its 2-layer capability. The situation becomes more pronounced when the signal degrades beyond -108 dBm; at this lower threshold TDD CC is unable to get 2 layers.

The change in throughput performance, shown in the same Figure 12, generally follows the scheduling pattern of UL MIMO of TDD carrier. You can observe stable throughput until around -85 dBm. Then, with less 2-layer scheduling, it starts to decrease with significant drop which kicks off at around -92 dBm. As the second layer totally fades at -108 dBm, the throughput steadily decreases until the coverage is gone.

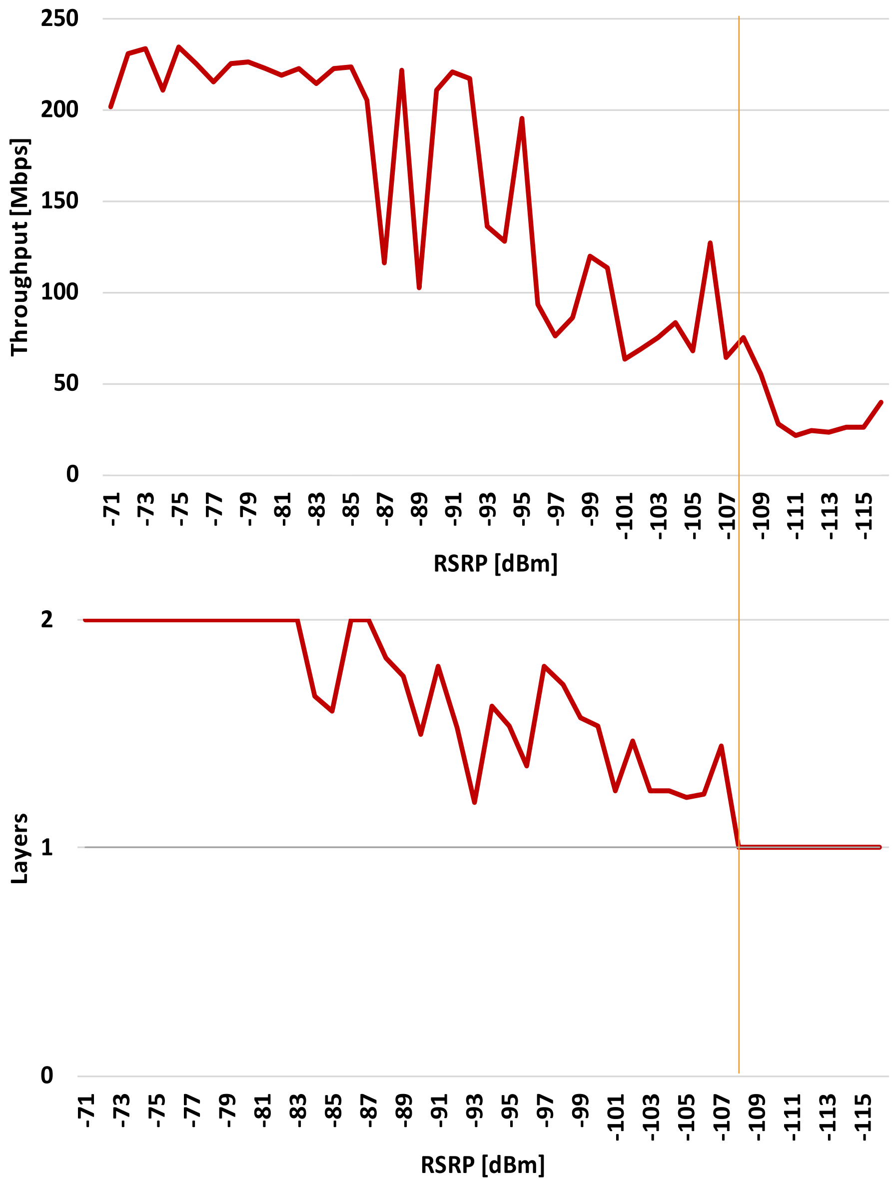

Figure 12: RSRP Vs Uplink Throughput and MIMO layers on n77

The network configuration for the trial had TDD carrier configured as PCell. This secures UE Tx power distribution in favor of n77 band which is prioritized over n5 in total CA Tx power. UL CA combination of n5 and n77 bands supports PC2, so the maximum UL Tx power is 26 dBm. Figure 13 demonstrates the distribution of PUSCH Tx power between TDD and FDD carrier as RF conditions degrade.

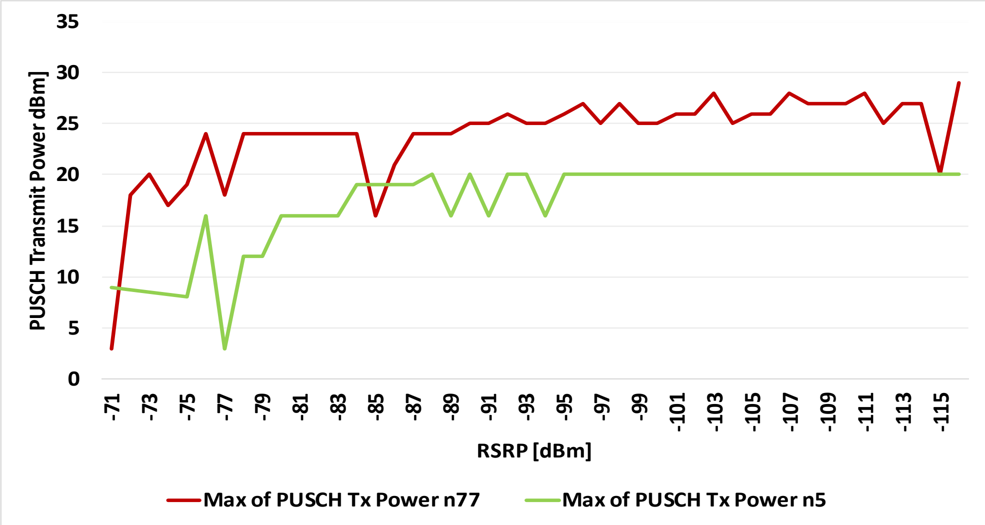

Figure 13: PUSCH Tx Power in Changing RF Conditions

CA constraints prevent the UE from reaching the maximum power available on each carrier separately. In poor RF conditions n77 carrier starts to prevail, obtaining maximum available power and leaving no more than 20 dBm to n5 carrier. This also contributes to overall throughput decrease at the cell edge.

5. Conclusion

The implementation of Uplink Tx switching and Uplink 3 Tx antenna transmission in 5G networks represents a significant advancement in optimizing uplink performance and spectral efficiency. The results on field are promising and shall encourage the carriers to adopt such techniques for advancing their networks.

Uplink Tx switching allows for efficient allocation of transmitting channels, enhancing system capacity, and improving overall spectral efficiency. On the other hand, Uplink 3 Tx antenna transmission provides increased diversity and higher throughput boost by leveraging UL CA and MIMO simultaneously. By enabling these technologies, operators can achieve higher throughput, better spectral efficiency, and enhanced user experience in 5G networks. Tx Switching and 3Tx are impressive strides in pushing the UL performance limits and these features are commercially ready at both UE and network side.

UL Tx Switching has its own development roadmap. Currently it is limited to switching between 2 CCs in 2 bands. Release 17 adds the following enhancements:

- The feature is extended to dynamic Tx switching between 2CCs 2Tx-2Tx switching, 3CC 1Tx-2Tx switching, and 3CC 2Tx-2Tx switching. This allows for more flexibility and efficiency in UL transmission by dynamically switching transmission chains between different carriers over 2 bands.
- UL-MIMO Coherence: Capability to indicate whether UL-MIMO coherence is supported when dynamic Tx switching between 3CC (within 2 bands) 1Tx-2Tx switching and 2CC or 3CC (within 2 bands) 2Tx-2Tx switching are introduced. This is important for maintaining the coherence of the MIMO transmission when switching occurs.
- Relevant UE capabilities to indicate that the UE can support these functions.

Release 18 even further extends the feature scope to allow switching over 3 or 4 bands.

Way forward for 3Tx is removing of scheduling limitation, described in details in this document and available in 3GPP R17. Specifically, UE will gain the ability to support the simultaneous transmission of PUSCH within a single slot designated for PUCCH. This enhancement is expected to substantially improve the 3Tx performance by potentially achieving a 100% FDD duty cycle.

As we have witnessed that UL 3Tx has the potential to outperform all competing options, it shall be noted that the feature remains unique to MediaTek products. It was first introduced in M80 modem, which is responsible for cellular connectivity in FWA SoC T830, currently the only commercial SoC supporting UL 3Tx. Next generations of MediaTek products will add more enhancements to these features. As the industry continues to evolve, the adoption of these innovative techniques will play a crucial role in shaping the future of wireless communication and meeting the growing demands of mobile connectivity.

6. References

[1] 3GPP TS 138 306 V16.6.0 5G; NR; User Equipment (UE) radio access capabilities (3GPP TS 38.306 version 16.6.0 Release 16)

[2] 3GPP TS 138 331 5G; NR; Radio Resource Control (RRC); Protocol specification (3GPP TS 38.331 version 16.6.0 Release 16)

[3] R1-2310345 3GPP TSG-RAN WG1 Meeting #114 Agenda Item: 7.1 Scheduling restriction for FDD-TDD UL CA

[4] 3GPP 138 306 5G; NR; User Equipment (UE) radio access capabilities (3GPP TS 38.306 version 17.7.0 Release 17)

[5] 3GPP TS 138 213 5G; NR; Physical layer procedures for control (3GPP TS 38.213 version 17.7.0 Release 17)

[6] 3GPP TS 138 101-1 5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 17.7.0 Release 17)

Other References: 5G NR Uplink Enhancements, Better Cell Coverage & User Experience White Paper

https://newsletter.mediatek.com/hubfs/mwc/download/ul-enhancements.pdf

7. Authors

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