5G TDD Uplink

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Editor / Submitter:	**Ray Williamson, Huawei; Giovanna. D'Aria, TIM; Ruyue YN Li, ZTE**
Contributors:	**Wolfgang Fleischer, A1 Group; Johnny Dixon, BT; Alexey Shapin, Ericsson; Peter de Bruin, Ericsson; Ray Williamson, Huawei; Luca Rose, Nokia; Giovanna D'Aria, TIM; Antonio Orlando, TIM; Haibin Zhang, TNO; Ruyue YN Li, ZTE; Xianghui Han, ZTE**
Approved by / Date:	NGMN Board, 17th January 2022

NGMN e. V.
Großer Hasenpfad 30 • 60598 Frankfurt • Germany
Phone +49 69/9 07 49 98-0 • Fax +49 69/9 07 49 98-41

Executive Summary

This White Paper contemplates the challenges for Vertical Industries to achieve sufficient uplink throughput or cell capacity and low enough latency for their industrial use cases, when using 5G TDD bands for the realization of those use cases. After looking into the problem, various technical solutions are being considered, some of them providing solutions for the management of interference between base stations or mobile handsets, when deviating frame structures are being used to support the industries' requirements. The document concludes with specific recommendations to regulators and mobile industry partners who want to support the industry with adequate solutions.

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1 INTRODUCTION

This White Paper illustrates how the downlink/uplink (DL/UL) throughput requirements of several vertical use cases may require specific TDD network configurations which differ from the current configurations of most public macro networks and investigates how networks can fulfil the high throughput - particularly in uplink - and low latency requirements of verticals.

In this document increased throughput refers to an increase in the data rate of a single user using a service. Increased capacity refers to additional resources being made available for use by all users in a cell.

First, the White Paper shows the technical challenges that various operators are facing when trying to realize together with their customers a variety of industry use cases. This forms the basis for an accurate problem statement.

In section 4 we provide some background on the current configurations of TDD in public macro networks and introduce the challenges in the co-existence of TDD networks with differing frame structures. Section 5 goes on to introduce a number of techniques to enhance UL performance and also methods to mitigate interference which may be generated as a result of their implementation. Finally, recommendations to better support the throughput and latency requirements of verticals are provided.

2 INDUSTRY USE CASES

Vertical industry use cases are trying to take advantage of the 5G technology. In Europe, the main frequency band currently adopted for 5G technology is the 3.4-3.8 GHz (n78) band. This band is also of high interest for deployment in other world regions. It has become clear that with the currently deployed TDD DL/UL configurations the uplink capacity is not sufficient to satisfy the requirements of the vertical industry in quite a number of cases. The uplink is critical for vertical industries as many of them are producing data rather than consuming them. Therefore, more balanced or uplink oriented TDD configurations or other functionalities to improve uplink capacity could be of advantage for such vertical industry use cases.

Current TDD deployments are in line with heavy downlink traffic patterns typical of eMBB applications and in some countries led by regulatory constraints (coexistence with LTE TDD commercial networks).

Another particular issue is the Ultra-Low Latency. Particularly the event industry would need constant end to end latencies below 4 ms. This is currently not achievable with the deployed frame structures on band n78. Also, mm waves such as frequencies of 26 GHz (band n258) may help to improve the performance, but some challenges are encountered in real deployment e.g. the dampening due to obstacles getting in the way of transmission can become burdensome for the event industry.

In Table 1, 5G TDD Uplink requirements are listed for nine different use cases, as concretely received from respective industry customers (e.g. car manufacturer, event media company, etc.).

Table 1 Overview of Industry Vertical Use Case Requirements

Use cases	Purpose	5G TDD Uplink Requirements	Comments
Automotive test tracks (Car manufacturer)	Data readings during test drives on the test track	150 Mbps to 900 Mbps	Depending on the number of simultaneously driving cars.
Sports Entertainment (Event Media Company)	Data readings of biovital and telemetry data, as well as high quality media recordings	> 200 Mbps	Depending on type and number of sensors, as well as the number of media stream recorded and their quality.
TV News Broadcaster	Recording of high quality media from current events	> 200 Mbps	Depending on the number of simultaneously recording

(2 national broadcasters)			cameras and the number of people close by with mobile phones. Usually connected to a single radio cell. This scenario may require large scale coverage (e.g. Tour de France) and it is not limited to a single fixed location (e.g. stadium).
Virtual Reality (Event Media Company)	Recording via high quality 360° cameras	> 100 Mbps	Depending on the number of cameras connected to a single radio cell and the no of people close by with mobile phones.
Concert Entertainment	Media recording in high quality and 360° cameras of high quality for support of VR; additionally permit transport of digital music at very low latency	> 300 Mbps latency < 4 ms (end-to-end)	Depending on the no of recording cameras and no of 360° cameras on stage or in audience.
Robotics	Robots to move around on floor space and control their movement form the outside	latency < 2 ms (end-to-end)	The latency needs to be achieved in order to avoid damages to production facilities for fast moving robots. Throughput depends on the type and amount of sensors.

Machine Vision	AI/ML inference for image/video processing for AR display/gaming, remote driving, remote-controlled robotics etc.	80 Mbps~12 Gbps 2 ms (one way user plane latency)	The data rate depends on the split point of the Convolutional Neural Network (CNN) models used.
Fish Cage Supervision (H2020 5G-HEART project, D5.2 [1])	Delivery of video data collected by underwater and surface cameras in a remote fish farm, for identification of disease or behavioural irregularities and the optimisation of feeding procedure	about 200 Mbps per 4k underwater camera	The required data rate depends on the number of cameras.
Remote Control	Remote operation of vehicles and machines for e.g. public transport, logistics, mining	10-100 Mbps per vehicle/machine	Depending on number of cameras and adaptation capabilities. Normal mode of operation may be a mix of remote control, and autonomous mode.

3 PROBLEM STATEMENT

- Deploying 5G TDD networks in a multi-operator context requires synchronised operation[1] of adjacent networks and, in particular, the adoption among operators of a compatible frame structure to avoid any BS-BS and UE-UE interference and allow coexistence without the need for guard bands or additional filters supporting efficient spectrum usage.
- In Europe, to avoid potential interference situations and ensure efficient spectrum usage, current regulatory conditions are attached to spectrum rights in the 3.4 – 3.8 GHz frequency band (Band n78) to define common TDD frame structures at national level. Current frame structures consist of 8 timeslots in the downlink (DL) and 2 timeslots in the uplink (UL) which allows a maximum of 180 Mbit/s[2] peak throughput under optimum conditions in the uplink (with 100MHz spectrum bandwidth, 2x2 UL MIMO and without UL carrier aggregation) and a minimum latency of 2 - 4 ms one-way in the RAN. The obligation to adopt the common national TDD frame structure can possibly be relaxed for local/regional licensing, but obligations to avoid interference remain in place.
- On the other hand, there's the need to account for licensees' commercial service needs and the great variety of 5G use cases. Industry applications (e. g. manufacturing, entertainment, news production, autonomous vehicles), often require a much higher uplink capacity. For example, in 3GPP SA1 TS 22.261 [2] there are requirements for cloud rendering and virtual reality which range from 100 Mbps to 10 Gbps per user; even at the lower end of this requirement support within the constraints discussed in the previous paragraph would be limited to a very small number of users. In some examples it would need to be in excess of 600 Mbit/s[3]. Other use cases require UL capacity which exceeds the current capabilities, e.g. video surveillance with upload.
- Furthermore, among the frame structures that are defined for NR by the 3GPP, currently only a limited subset has been realized by base station vendors, chipset vendors and device vendors. For both bands, n78 (3.5 GHz) and n258 (26 GHz), NGMN recommends that base station vendors, chipset vendors and device vendors will also make available frame structures that provide a better balance between uplink and downlink throughput.

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[1] Implementing synchronized operation requires operators to agree on a common phase clock reference (e.g. UTC) and a compatible frame structure to avoid simultaneous UL/DL transmission and agreements would be simplified when the same type of services with associated desired user plane latency and performance are targeted.

[2] Bit rate and latency performance are estimates of what is achievable according to 3GPP TS 38.306 [3] in optimal radio conditions. Actual performance will be influenced by other factors such as network design and optimisation, system traffic load and local radio conditions, among others.

[3] Such situation exists when data from cars on a test track need to be received for near real time processing and just putting more antennas to manage the per antenna load is not an option due to prohibitive overall costs.

4 CURRENT SITUATION FOR TDD UPLINK

As mentioned above, in a multi-operator context, geographically localised deviations from the commonly agreed TDD frame structure to provide higher uplink capacity on the radio side produce BS-BS and UE-UE interference whose effects vary depending also on the deployment scenarios, e.g. indoor/micro/macro. To assure networks coexist, different interference mitigation countermeasures can be applied, such as guard bands, transmitted power reduction, radio signal isolation, etc. The effectiveness and possible drawbacks of such countermeasures depend on the radio deployment scenarios as well and are independent of how frequency rights are used either for nationwide public networks or local non-public networks[4].

Spectrum, particularly sub 6 GHz, is a critical and limited resource for mobile communications. Regulators need to carefully consider how it is assigned to ensure it can be used effectively and efficiently. Reserving spectrum for certain specific usages might be a solution provided that it is adopted after careful impact assessment on spectrum fragmentation which could undermine the assignments of sufficiently large contiguous frequency blocks for 5G networks. Such fragmentation could also lead to possible underutilisation, highly undesirable spectrum inefficiency, delayed maturity of the ecosystem in the selected bands, and last but not least lead to possible market distortions.

Generally, even though localised, a TDD network generates interference to other, in band and adjacent band, TDD networks unless compatible synchronised TDD frame structures are used. Currently, in all regulations, taking corrective actions in case of interferences is mandatory for a local network operator. Coexistence scenarios which mitigate interference also apply to local non-public networks. At the time of writing two bands, 3.4-3.8 GHz and 3.8-4.2 GHz, have been assigned, or are being considered, by different regulators to have some portion of this spectrum assigned for local licenses. The EC has issued a mandate to CEPT on technical conditions regarding the shared use of the 3.8-4.2 GHz frequency band for terrestrial wireless broadband systems providing local-area network connectivity in the Union [4]. In this context, solutions to alleviate coexistence issues with other services in the band and in adjacent bands should be carefully studied, including the possibility of SUL usage if not yet considered.

Finally, using 5G TDD frequency bands in mm wave spectrum, e.g. 26 GHz, 28 GHz, and 39 GHz, with total spectrum availability of several hundreds of MHz per band, to support industry use cases with high requirements on UL performance has several advantages:

- The available bandwidth is large, and aggregating multiple component carriers (CCs) on the same band, contiguous or not, does not require additional radios or antennas
- The sub-carrier spacing (SCS) is larger than the 15-30 kHz for below 6 GHz, typically 4-8 times, so the transmission time interval (TTI) is reduced accordingly. This means the parts of the latency performance relating to radio transmissions are improved

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[4] Non-Public Network (NPN) is a network for non-public use (see 3GPP TS 22.261 [2]), which can be deployed as (see 3GPP TS 23.501 [5]) a Stand-alone Non-Public Network (SNPN) or a Public Network Integrated (PNI) NPN.

- The wavelength is short, so efficient beam forming antennas can be made sufficiently small also for indoor deployments
- The higher frequency implies higher propagation and penetration losses, which means that the coverage area is limited. Indoor deployments could be well isolated, due to sufficient distance from the outdoor network or with sufficient wall penetration loss.

4.1 TDD Configuration Options

The 3GPP NR specification provides flexible TDD frame structures. At the BS side, the number of uplink and downlink slots may be almost arbitrarily configured within the TDD frame periodicity. A guard period, when switching from downlink transmission to uplink transmission, is implemented in the special slots, which are configured with a combination of suitable uplink, and downlink symbols, interjected with a flexible number of silent symbols (or guard symbols).

At the UE side, formally any DL/UL symbol pattern is supported, as it's up to the base station signalling to the UE whether uplink or downlink is to be transmitted in a certain time slot/symbol.

In practice, deployment of specific TDD frame structures in a network needs to be implemented and verified by interoperability testing between chipset and device providers and infrastructure providers. The tradition of multi-vendor networks stipulates the need for, at least some level of, interoperability verification through testing/trials between any network-UE combination, to secure network-wide support and cross-border roaming.

A number of different frame structures have been adopted worldwide in 5G NR deployments so far. The TDD frame structure configurations are often described as, e.g. DDDSU or DDDSUUDDDD, where D/U indicates slots where downlink/uplink-only symbols are transmitted and S is the special slot. The special slot, in turn, consists of 14 symbols, and is often described as, for example, 4:6:4, which indicates that the first 4 symbols are downlink, the following 6 are silent, and the last 4 symbols are uplink. As can be seen from the examples, all currently supported TDD frame structures are more or less downlink heavy.

For some n78 5G NR national deployments, it is necessary to align with specific synchronisation requirements, for example, for coexistence with legacy TD-LTE networks at 3.4-3.6 GHz. Usually, in this case, national regulators define requirements on TDD frame structures for NR/LTE synchronization and the frame structure e.g. DDDSUUDDDD (4:6:4) is generally adopted for NR, as it is especially suitable for coexistence with TD-LTE and provides complete NR and LTE alignment, as shown in Figure 1. In this way, any harmful interference between the two systems can be avoided when NR and LTE are deployed in the same or adjacent frequency band.

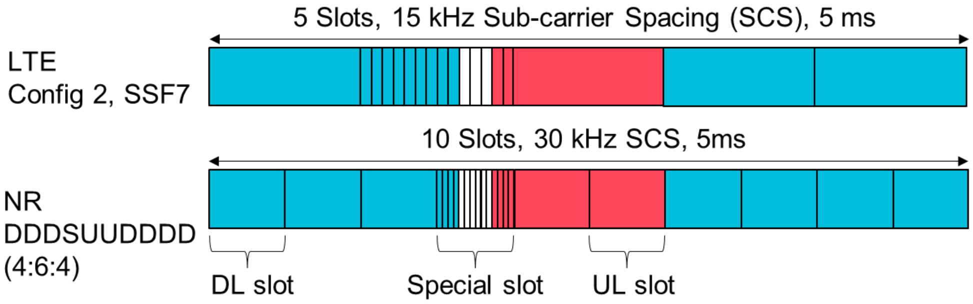

Figure 1 Example of an alignment between TD-LTE and 5G NR

In general, where 5G NR/TD-LTE coexistence is not required, national regulators may either define requirements on 5G NR TDD frame structures for synchronization or leave synchronisation under the responsibility of the national license holders. In the latter case, if there is disagreement, many regulators stipulate restrictions and fallback to a pre-defined 5G NR TDD frame structure, such as the DDDSU frame structure or the TD-LTE aligned one. In cases where national regulators mandate use of a given 5G NR TDD configuration for all deployments in a given band, license holders can agree and ask for an authorised/acknowledged use of a different frame structure. For countries where licenses for local non-public use are available or planned[5] in parts of bands adjacent to those assigned for national 5G NR use[6], there are examples of a similar approach, i.e. national TDD frame structure being defined as fallback to local licensees if they cannot reach bilateral/multilateral agreement with national spectrum users.

4.2 Coexistence Under Different TDD Configurations

A straightforward solution to improve UL performance in terms of throughput is to increase the number of UL slots. Also, the latency performance may be improved shortening the waiting time for UL access by more frequently alternating UL/DL slots in the TDD frame. However, unless there is a wide acceptance of a common UL-heavy frame structure within the TDD band, different frame structure configurations will result in cross-link interference between systems in both the DL and the UL. The different interference scenarios that arise with synchronized and unsynchronized TDD configurations respectively are depicted in Figure 2.

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[5] For example, Swedish PTS – ongoing consultation, German BNetzA – Verwaltungsvorschrift Lokales Breitband

[6] In addition to current n78 licensing there are plans to assign mm wave spectrum for local licensing in some markets (e.g. Japan, Germany, Sweden).

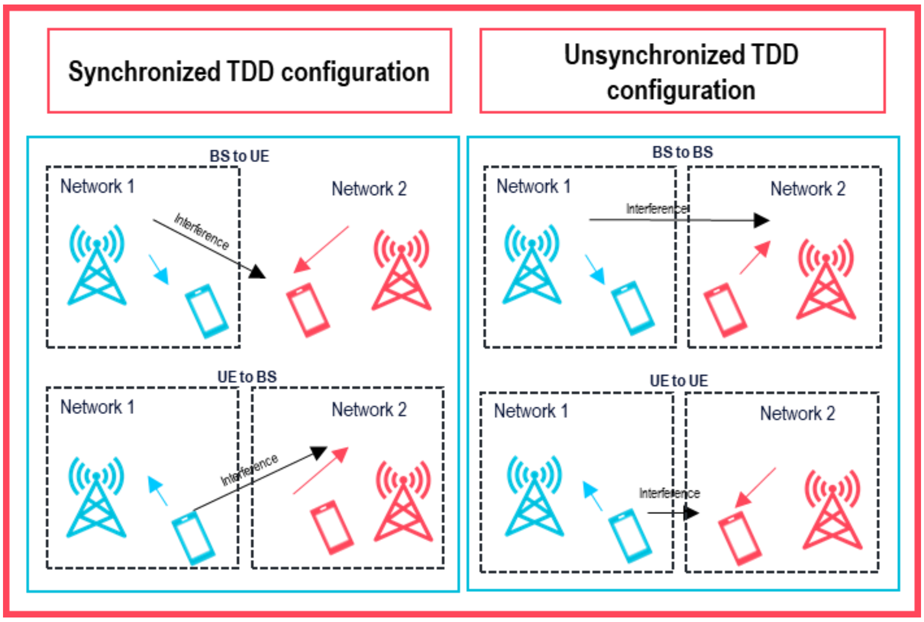

Figure 2 Interference scenarios under different TDD configurations

In general, the synchronized TDD configuration is beneficial when:

1. The transmit power of one type of equipment (e.g. the BS) is much higher than the transmit power of others (e.g. the UEs)
2. There is little isolation between both co-channel and adjacent channel networks

With respect to the interference that arises in unsynchronised TDD configuration, we consider two general scenarios:

1. Aside from corner cases of extreme UE density, such as in stadiums, arenas, etc., during unsynchronized DL/UL slots the network in UL does not create harmful interference to the network in DL, whereas the network in DL creates high level of interference to the network in UL. This is a consequence of the difference of power levels transmitted by a BS and a UE, respectively. Hence, turning a DL slot into an UL one typically does not increase the level of interference and does not pose problem for the network in DL. However, because of the (opposing) UL transmissions it will be necessary to consider ways to manage the BS to BS interference.[7]
2. If sufficient isolation is reached between the two unsynchronised networks a situation of no harmful interference could be reached. Such isolation can be obtained by means of geographical limitation of one or more networks (e.g. geographically isolated local networks and shielded indoor local networks) or by means of guard bands. In order to be quantified, isolation requires coordination among spectrum users. If correctly implemented, it can make any TDD configuration acceptable from the point of view of coexistence and

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[7] CBRS Alliance C-TG-20-553 "Semi-Synched TDD Frame Configuration Operation", 9-July-2020

interference. However, even in case of sufficiently isolated networks, the presence of UE connected to the macro network may disrupt the operation of UEs connected to the local network (UE to UE interference).

In conclusion, in order to assess the suitability of different TDD configurations to coexist, an accurate analysis is required of all conditions which influence coexistence, i.e. of the networks' deployment scenarios, occupation of the same or adjacent spectrum, level of isolation of the considered networks (e.g. to evaluate if walls could provide sufficient shielding to indoor local networks) and TDD configurations themselves, as well as a thorough assessment of involved performance degradation costs.

5 POTENTIAL SOLUTIONS

In this section we introduce a number of techniques which may improve UL throughput and, in some cases, latency and/or capacity. We also introduce some methods to mitigate interference which can be generated when employing alternative TDD configurations to other mobile networks in nearby locations or to different cells in the same network.

The 3GPP release which introduces each feature is provided for reference. It should be noted that the commercial availability of these features is also determined by factors such as infrastructure, chipset and device availability, interoperability testing, and market demand.

Some techniques, such as those in the carrier aggregation section, require access to multiple carriers and/or frequency bands which can be combined.

When evaluating the different options, it should also be noted that some techniques may have an impact on equipment complexity, battery life and costs.

5.1 Current Solutions

This sub-section describes solutions for increasing TDD UL performance which are supported by existing standards or are specific proprietary implementations. If supported by an existing standard their actual implementation may be market driven and/or vendor dependent.

5.1.1 Interference Coordination

Deploying non-synchronized frame structures in two neighbouring networks results in BS-BS and UE-UE interference that could impact the overall system performance. In such circumstances and under the condition that there is cooperation between the networks, 3GPP Release 16 interference coordination methods for Cross-link Interference (CLI) mitigation could be applied to reduce the negative effects of such interference (3GPP TR 38.828 [6]).

As mentioned above, in the case of CLI, there are two types of interference, namely BS-BS interference and UE-UE interference. As to the BS-BS interference, there’s no solution specified in 3GPP, and its mitigation is left to network operators’ coordination by accurate networks planning. As to the inter-cell UE-UE CLI, in 3GPP Release 16 interference measurements fields are specified that could be exploited by BSs to reduce interference and collisions. For example, considering these measurements as well as information received on Xn and F1 interfaces, BSs may decide the transmission and reception of DL/UL slots and adapt the scheduler in order to avoid CLI.

5.1.2 UL MIMO

While MIMO has been widely used to enhance DL performance for some time, it is only in the last few years that this has become available for UL on mainstream devices. UL MIMO is used to increase cell capacity and throughput and can be implemented in two ways:

- Single-User (SU-MIMO) uses multiple antennas to implement transmit diversity for improving reliability or spatial multiplexing of time-frequency resources to create multiple

data streams (PUSCH layers) at the BS to improve the performance for that UE. The maximum number of layers for a single UE is the lower value between the number of BS Rx antennas and the number of UE Tx antennas
- Multi-User (MU-MIMO) also uses multiple antennas to implement spatial multiplexing of time-frequency resources but in this case the objective is for multiple UEs, served by different beams of the antennas, to re-use the same resource, aiming at higher uplink capacity. Multiple UEs with a high level of orthogonality in their channels will generate low levels of interference and can be "paired" to re-use radio resource. The number of layers increases with the number of BS antennas, up to 4 layers could be expected in a typical network with higher capabilities being possible with a favourable environment.

Up to 4 UL Tx antennas are supported since Release 15 (more than 4 are being considered for Release 18).

5.1.3 Carrier Aggregation

In Carrier Aggregation (CA), two or more Component Carriers (CCs) are aggregated to increase user throughput and possibly cell capacity by adding more bandwidth. A UE may simultaneously receive or transmit on one or multiple CCs depending on its capabilities. CA is supported for both contiguous and non-contiguous CCs, in the same or different spectrum bands. When CA is configured, the UE only has one Radio Resource Control (RRC) connection with the network. One serving cell provides the NAS mobility information at RRC connection establishment/re-establishment/handover and also provides the security input at RRC connection re-establishment/handover. This cell is referred to as the Primary Cell (PCell). Depending on UE capabilities, Secondary Cells (SCells) can be configured together with the PCell to form a set of serving cells. The configured set of serving cells for a UE therefore always consists of one PCell and one or more SCells. Standardized enhancements for high capacity and low latency based on carrier aggregation are discussed in this section.

Unaligned frame boundary and Tx switching

Unaligned frame boundary together with Tx switching could provide higher UE throughput and lower latency for UL in case of CA operation.

- Unaligned frame boundary is introduced in Release 16 to provide more flexible beginning of NR TDD frame structures among different carriers in CA operation [3GPP TS 38.211 [7].
- Tx switching, introduced in Release 16 with further enhancements in Release 17, enables CA capable UEs to dynamically switch between 2 CCs for UL transmission [3GPP TS 38.214 [8].
- In Release 16, one of the Tx chains is capable of being switched between the two CCs, whilst the second Tx chain cannot switch. However, in Release 17, both of the Tx chains are capable of switching between the two CCs
- With both unaligned frame boundary and Tx switching, a UE can effectively have more uplink transmission opportunities in time domain. Moreover, these uplink transmissions

happen at different times in different carriers such that power/antenna resources of the UE can be fully utilized in each of these transmissions.

Unaligned frame boundary and Tx switching when implemented together can achieve larger uplink throughput for TDD CA operation. In Figure 3, an example of TDD CA employing the two techniques is shown.

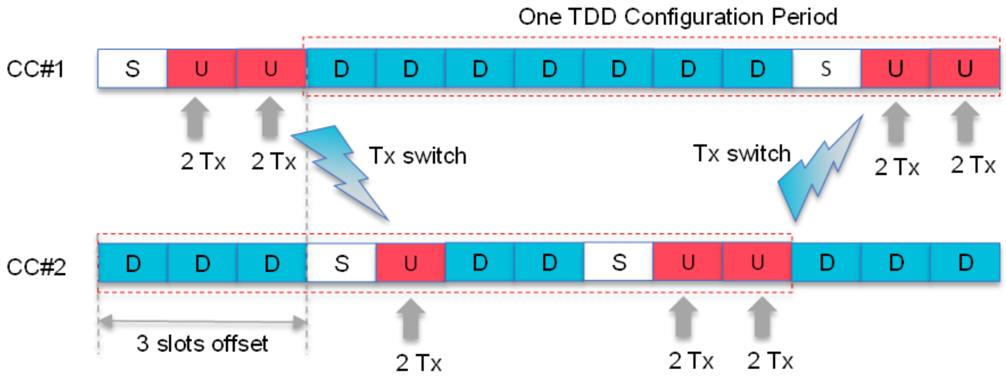

Figure 3 Unaligned frame boundary and Tx switching for TDD CA (Release 17)

The TDD configurations ‘DDDDDDDSUU’ and ‘DDDSUDDSUU’ are configured for CC#1 (Component Carrier #1) and CC#2 (Component Carrier #2), respectively. To obtain more transmission opportunities in the time domain, a 3-slot offset is applied for the TDD configuration at CC#2 carrier. As observed from the example in Figure 3, compared to CA with aligned frame boundary without Tx switching, switching of two Tx chains between CC#1 and CC#2 can improve UL throughput about 66.7%, assuming the same bandwidth for both carriers. Note that, if no slot offset is applied, there would be two uplink slots overlapping in the time domain, and a UE can only support 1Tx transmission in each carrier or up to 2Tx transmission only in one carrier, which will limit the uplink throughput.

PUCCH carrier switching for CA

PUCCH carrier switching could reduce the latency of PUCCH transmissions significantly for CA operation. In NR Release 16, in one cell group, PUCCH can only be transmitted on the PCell. This limits the transmission occasion of PUCCH, and therefore impacts the latency of PUCCH transmission. In NR Release 17 PUCCH carrier switching, semi-statically or dynamically, will be supported. Take Figure 4 as an example. Compared to transmitting PUCCH carrying HARQ-ACK only on PCell CC#1, HARQ-ACK feedback latency can be reduced significantly by allowing PUCCH carrier switching to CC#2 with adding three additional UL transmission occasions. UL capacity can also be potentially improved with the increased flexibility of PUCCH resources.

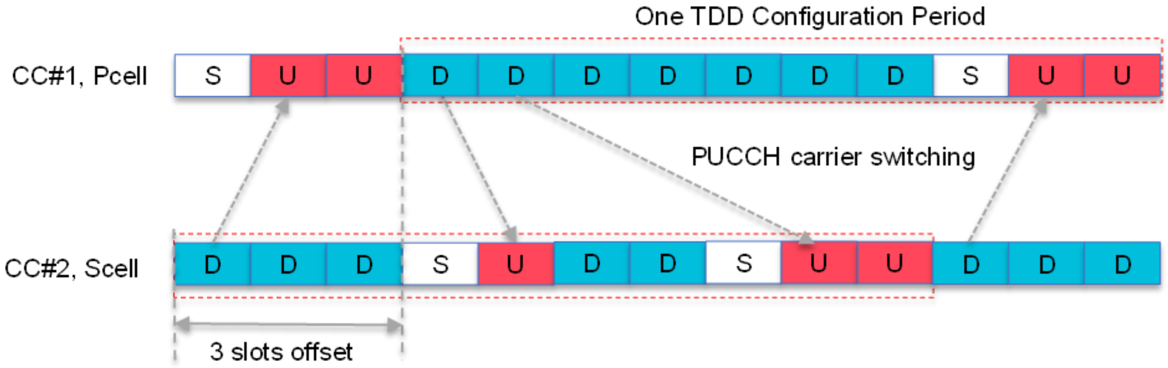

Figure 4 PUCCH carrier switching for CA

Supplementary Uplink (SUL)

Supplementary uplink differs from carrier aggregation in that the UE may be scheduled to transmit either on the supplementary uplink carrier or on the uplink of the carrier being supplemented, but not on both at the same timeslot. SUL combines and coordinates the radio resource in two different bands to improve uplink performance. SUL enables support of one extra uplink carrier in addition to one TDD carrier. 3GPP (TS38.101 [9]) has re-used the UL operating band of a number of FDD bands to create additional NR SUL bands. For example, the 1800 MHz frequency band 1710-1785 MHz is allocated as both FDD UL (n3) and SUL (n80). The associated downlink operating band (e.g. 1805-1880 MHz for n3) continues to be used in FDD mode and can be combined with other DL spectrum to enhance DL throughput. The combination of a sub-3 GHz SUL band and a mid-band TDD band e.g. n78 (3300-3800 MHz) can be effective in improving UL performance. In addition to the continuous UL resource availability to boost capacity and reduce latency, the sub-3 GHz SUL band extends coverage and improves cell edge performance. These performance improvements are illustrated in the figure below where the UL timeslots coloured blue are used in preference to those in grey.

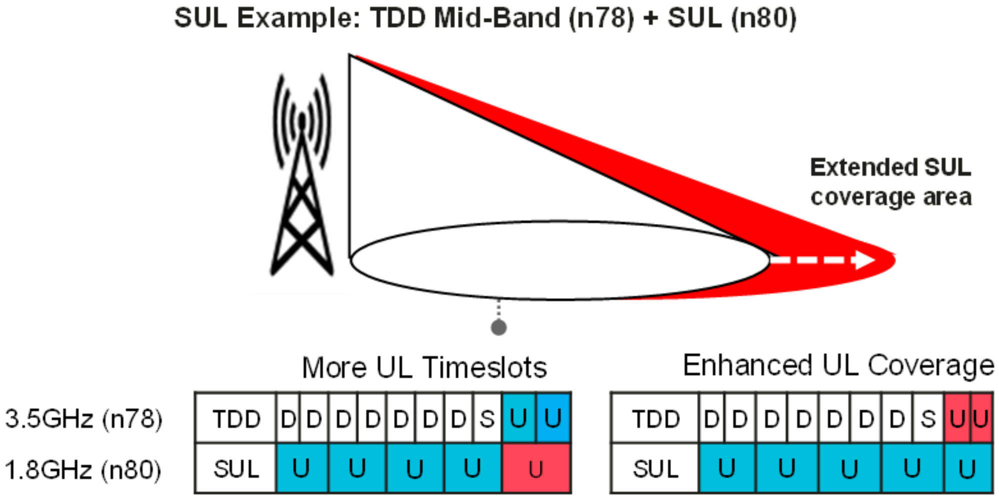

Figure 5 SUL example

NR-U carrier aggregation

Yet another option to employ carrier aggregation to increase the UL resources is to employ an NR carrier on unlicensed spectrum, also referred to as NR-U, together with a licensed carrier. NR technology operating on unlicensed bands is standardized in 3GPP with necessary additions like listen before talk (LBT) to avoid collision with other transmissions on the same unlicensed band. NR-U could not offer the same required reliability and consistent performance as NR on a licensed carrier[8]. However, in some cases, like in a reasonably isolated network deployment, aggregating NR-U with a licensed carrier could serve as an UL capacity booster for services with less strict requirements on reliability and consistent latency

5.2 Future Potential Solutions

The features in this section are currently being discussed as candidates for 3GPP Release 18. In some cases, there are different views on the feature which may result in the proposal being modified, redirected to a later 3GPP release, or rejected. Brief descriptions of the most UL-relevant feature proposals which could improve throughput and/or capacity are provided below. Please refer to the references provided for further details.

5.2.1 Enhancements of UL MIMO

There is currently a clear imbalance between DL-MIMO and UL-MIMO, in terms of the number of antennas/layers, precoding, flexibility for multi-panel operation, etc. Therefore, enhancements to UL MIMO [10] are a target for Release 18.

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[8] NR-U can also be used in standalone mode, however, in case of unlicensed networks interference mitigation effectiveness to licensed networks can even be largely nullified. In fact, unlicensed networks do not share their technical parameters with national regulatory body and neither with licensed subjects (public or private). Therefore, it is not possible to enforce most possible countermeasures.

- Up to 4 layer UL transmission is currently specified. More MIMO antennas/layers e.g. up to 8 layers for SU-MIMO and up to 12 layers or more for MU-MIMO and UE-aggregation can be considered.
- Frequency-selective precoding with acceptable DCI overhead increase can be considered in large UL bandwidths.
- Spatial multiplexing and diversity techniques, e.g. enhanced multi-panel/multi-TRP uplink operation based on simultaneous Tx across multiple panels (e.g. FDM and SDM).
- Support of 2 codewords (CW) for handling the performance degradation due to a significant SNR gap between different UL Tx layers when using one codeword.

5.2.2 Enhancements of UL CA

The current proposal supporting more flexible CA configuration is based on existing CA framework and suggests removing current CA configuration restrictions [11][12], e.g. 1) DL and UL physical carrier frequency for one serving cell has to be from the same band, 2) the number of UL physical carriers cannot be larger than the number of DL physical carriers. Since time alignment at UEs is achieved by means of DL synchronization signals (SSB), UE capability is required to align synchronization between UL and DL carriers which also may require testing for different band combinations.

5.2.3 NR-Multi-Band Serving Cell

This feature [11][12] also increases flexibility. Different from the existing CA framework, it allows one serving cell to have one DL carrier and more than one UL carrier, which may be from different bands. A UE can perform random access on any of these uplink carriers, and perform UL data transmission in multiple bandwidth parts (BWP) in different bands without the activation/deactivation of SCells. The same UE capability and testing requirements described in 5.2.2 would apply.

5.2.4 Full Duplex Operation

Full duplex operation, which does not require the DL resources and UL resources to be partitioned in time-domain, can increase the resources for UL, and therefore it can increase the UL throughput and reduce the latency in some scenarios. Release 18 only considers full duplex operation in TDD bands.

5.2.5 Higher Order Modulation

According to current NR specifications, the maximum modulation order supported for UL data transmission is 256 QAM. Further to support 1024 QAM could boost the uplink capacity in deployments where very good SINR is achieved e.g. fixed wireless access.

5.2.6 UE Aggregation (User Virtualisation and Cooperation)

Multiple devices can form a virtual user to collaboratively transmit and receive data from the network, e.g.one device helps another device to transmit uplink data to effectively boost up the antenna/power/processing capabilities

5.2.7 Downlink Symbol Blanking

This feature was introduced to avoid intra-band, cross-border interference between countries which have implemented different frame structures (DDDSU & DDDDDDDSUU), where one MNO will agree not to transmit on certain DL slots when used in UL by the neighbouring MNO. The feature could, potentially, also be used to avoid interference between public macro and local networks using different frame structures in the same coverage area but such deployments will need to be coordinated. However, further implementations of additional frame structures and analysis of operational complexities will be required.

6 RECOMMENDATIONS

1. A number of vertical use cases require significantly higher UL throughput and lower latency than that required by typical MBB consumer mobile users. There are solutions available to address this UL problem (throughput and latency). Using different TDD configurations, as one of the solutions, requires coordination between operators in order to minimize possible interference and support by regulators in order to achieve sufficient operational flexibility to deliver customer use cases with higher UL requirements.

2. Frame structure selection is an effective way of varying UL/DL throughput. Additional balanced or UL oriented frame structures should be made available and interoperable by ecosystem partners (chipset, user equipment and infrastructure providers). NGMN has identified DDSUU (balanced) and DSUUU (UL oriented) as candidates for both FR1 and FR2. Ecosystem partners should also support operators in making available and interoperable other possible alternative solutions identified in this White Paper to address this UL problem.

3. Careful selection of more balanced or uplink oriented TDD frame structures in a local network is recommended to limit the interference impact between local and wide-area public networks. However, if isolation between networks is sufficient (through physical separation, indoor with sufficient wall penetration loss, guard bands, etc.), the selection and use of TDD frame structures is less constrained and may be beneficial for services with a more balanced or uplink oriented traffic profile.

4. In scenarios where sufficient isolation between networks is not achievable, e.g. local outdoor networks in the same or adjacent spectrum, using different TDD frame structures will be extremely difficult, if not impossible. In such cases, adoption of other uplink enhancing features such as SU-MIMO and MU-MIMO should be considered.

5. Future 3GPP specification enhancements, including 5G advanced and 6G, should ensure the requirements of vertical industries are fulfilled with respect to UL throughput, latency,

and support for the co-existence of different frame structures.

6. Spectrum, particularly sub 6 GHz, is a critical and limited resource for mobile communications. Regulators need to carefully consider how it is assigned to ensure it can be used effectively and efficiently. Reserving spectrum for certain specific usages might be a solution provided that it is adopted after careful impact assessment on spectrum fragmentation which could undermine the assignments of sufficiently large contiguous frequency blocks for 5G networks. Such fragmentation could also lead to possible underutilisation and highly undesirable spectrum inefficiency.

LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
AR	Augmented Reality
BS	Base Station
BWP	Bandwidth Part
CA	Carrier Aggregation
CCs	Component Carriers
CEPT	Confederation of European Posts and Telecommunications
CLI	Cross-link Interference
CNN	Convolutional Neural Network
CW	CodeWord
DCI	Downlink Control Information
D	Downlink Timeslot (used when depicting frame structures)
DL	Downlink
EC	European Commission
eMBB	enhanced Mobile Broadband
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FR2	Frequency Range 2
HARQ-ACK	Hybrid Automatic Repeat-reQuest Acknowledgement
HB	High Band
HD	High Definition
LBT	Listen Before Talk
LOS	Line of Sight
LTE	Long Term Evolution
MBB	Mobile Broadband
ML	Machine Learning
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MU-MIMO	Multi-User Multiple-Input Multiple-Output
NAS	Non Access Stratum
NGMN	Next Generation Mobile Networks Alliance
NPN	Non-Public Network
NR	New Radio
NR-U (NR_unlic)	NR-based Access to Unlicensed Spectrum
PCell	Primary Cell
PNI-NPN	Public Network Integrated-Non-Public Network
PUCCH	Physical Uplink Control CHannel
PUSCH	Physical Uplink Shared CHannel

QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RRC	Radio Resource Control
Rx	Receiver / Reception / Receiving
SA1	System Architecture Group 1 (3GPP Work Group)
SCells	Secondary Cells
SCS	Sub-Carrier Spacing
SDM	Spatial Division Multiplexing
SIB	System Information Block
SINR	Signal to Interference and Noise Ration
SNPN	Stand-alone Non-Public Network
SNR	Signal to Noise Ratio
SSB	Synchronization Signalling Block
SUL	Supplementary uplink
SU-MIMO	Single-User Multiple-Input Multiple-Output
TDD	Time-Division Duplex
TD-LTE	Time-Division Long-Term Evolution
TRP	Transmission Reception Point
TS	Technical Specification (regarding 3GPP documents)
TTI	Transmission Time Interval
Tx	Transmission / Transmitter / Transceiving
U	Uplink Timeslot (used when depicting frame structures)
UE	User Equipment
UL	Uplink
VR	Virtual Reality

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