5G Extreme Requirements:
Radio Access Network Solutions

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5G Extreme Requirements:
Radio Access Network Solutions

by NGMN Alliance

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Abstract:

The aim of this work is to highlight what implications and trade-offs related to the delivery of new 5G services are relevant for mobile network operators. Some of these new services, in fact, require consistent ultra-low latency and high reliability across the service coverage area, which have very little in common with the targets that the telecommunications industry has worked towards until today. The new 5G requirements, in fact, now call for a re-think on how the future network will have to be designed and optimised in order to enable the new services.

The purpose of this document is to identify realistic radio access deployment configurations that can potentially deliver the 5G extreme services across their footprint and to highlight some of the key challenges that come into play in this context.

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Contents

1 EXECUTIVE SUMMARY

The next generation of mobile networks is currently being designed to deliver new services, which will enable new business opportunities in partnership with new vertical players.

4G networks today are designed to provide mobile broadband, and the applications that rely on this infrastructure are able to cope, to a certain extent, with variations in data rate, reliability and latency, which naturally occur in response to varying wireless channel conditions. The mobile broadband coverage area is thus an area within which the user experience will vary significantly, in particular from the edge to the centre of the cell.

Fifth generation mobile networks will support a wide range of new services, with requirements that strongly deviate from the traditional mobile broadband targets. Some new services, denoted as Ultra-Reliable and Low-Latency, inherently cannot tolerate variations in data rate, reliability and latency, as the consequences of these variations could translate into the failure of critical infrastructure or mission critical services. Hence, the network needs to be designed in a way so that wherever the user is in the service coverage area, it will experience the same guaranteed quality of service. This is a clear paradigm shift from the way mobile networks have traditionally been designed until today.

In this context, a very fundamental question is thus in order: given a radio access network solution, what is the extent of the coverage area that can be supported for these 5G critical services? In other words, over what percentage of a given mobile network's footprint can there be guaranteed low-latency and high reliability, in accordance with the service requirements? We refer to this percentage area as the service coverage, since it is only within this area that the service can be supported.

As pointed out in the first deliverable of this technical task force [1], decreasing latency by an order of magnitude on today's 4G deployments translates, at link level, into approximately a 10dB coverage loss. Coupling this with high reliability translates into even higher coverage losses.

Coverage for Ultra-Reliable and Low-Latency services is the key issue that this work aims at addressing at a system level. The radio performance of future 5G networks is rigorously assessed assuming different radio access network solutions in order to evaluate the extent of the coverage area that is achievable for a particular 5G service in a given radio access environment. Different measures to enhance this coverage are also considered and analysed.

To this aim, two main contributions are provided within this document:

- System simulation results obtained with Ericsson's simulation tools.

- Field trial results obtained by NTT DoCoMo in Japan.

1.1 System Simulations

The following **scenarios and assumptions** have been taken into account:

- Three different requirement targets are considered, as shown in Table 1 (with further details in Table 2), ranging from fast and reliable transfer of large messages to ultra-fast and ultra-reliable transfer of small messages. These requirements are generic and representative of a wide variety of use cases, and the approach is to observe how the service coverage varies as the requirements change.

Table 1 Scope of considered targets for the system simulations

Target 1	Fast and reliable transfer of large messages.
Target 2	Fast and reliable transfer of small messages.
Target 3	Ultra-fast and ultra-reliable transfer of small messages.

- Two independent networks are considered, one that operates at **4GHz** with 20MHz of service bandwidth and another one that operates at **700MHz** with 10MHz of service bandwidth, in accordance with 3GPP simulation methodologies for 5G.

- The considered networks are evaluated at different inter-site distance values and load points, and the effect of scaling system bandwidth is also observed.

- Different configurations of both **LTE and NR** are studied with different transmission time interval values and, for NR, both FDD and TDD configurations are studied. The radio access systems are configured according to **3GPP Release 15 (status in Q3 2017)**. However, since the standardization is currently ongoing (Q1 2018) some assumptions on the direction of Release 15 have been made, in alignment with the current 3GPP studies. Also, some of the features being standardized in LTE Ultra-Reliable Low-Latency Communications and NR Ultra-Reliable Low-Latency Communications are not taken into account. In particular, automatic repetitions in uplink / downlink are not considered in this study.

The **main output** of this work is summarised as follows:

- Characterisation of the **service coverage area** that is achievable for the targets described in Table 1 in the considered radio environments and for a fixed service bandwidth. This corresponds to the percentage of users that can be served across the network footprint for each service (since a uniform distribution of users is assumed).

- Characterisation of the **maximum message size** that can be delivered in a given radio environment and with a fixed service bandwidth by fulfilling the targets on latency, reliability, and coverage.

- Characterisation of the **required bandwidth** that would be needed to fulfil the targets on latency, reliability, message size, and coverage, in a given radio environment.

A summary of the results is as follows:

- **Service Coverage Area**:

  o **Target 1 (Fast and reliable transfer of large messages)**:

    This service requires fast and reliable transfer of a very large message. The best results are obtained with long transmission time interval lengths (for NR, this is considered in FDD configuration only). The limiting factor is the large size of the payload that needs to reliably be pushed through the radio interface.

    As can be seen in Section 5.4.5, the **700 MHz network** provides limited service coverage for both downlink and uplink. In downlink, up to 70% service coverage can be achieved with NR and 50% with LTE when there is a 50% network load. As the load increases to 90% the downlink coverage

drops to 50% with NR and to 30% with LTE. In uplink, when the network is at 50% load, 60% and 40% coverage levels can be obtained with NR and LTE respectively.

For the **4 GHz network**, both LTE and NR can achieve close to 100% coverage in the downlink at 50% load. This is obtained with an inter-site distance equal or below 350m. As the load increases to 90%, the downlink coverage drops by 5% and 10% for NR and LTE respectively. In the uplink, at 50% network load, 95% and 99% coverage levels are achieved by LTE and NR, respectively.

- o **Target 2 (Fast and reliable transfer of small messages)**:

This service can be delivered with the considered radio access network solutions in a pretty straightforward way. The required message size is small and requirements on latency and reliability are not as extreme as Target 3. We can consider this service as a "relaxed" version of Target 3.

As can be seen in Section 5.4.5, for the **700 MHz network**, 99% and 90% downlink coverage are achievable with NR and LTE respectively with 50% network load. These values then drop to 95% and 80% when the load goes up to 90%. A good uplink performance is also achievable: 99% (NR) and 95% (LTE).

The **4 GHz network** can support 99% of downlink coverage for both NR and LTE when the network is at 50% load. As the load increases to 90%, the downlink coverage drops to 95% for LTE, and remains at 99% for NR. In uplink, both radio technologies can deliver 99% coverage at 50% load when the inter-site distance is equal or below 350m.

- o **Target 3 (Ultra-fast and ultra-reliable transfer of small messages)**:

This service is the most challenging one of the three considered in this work. It requires transfer of small messages with ultra-low latency and ultra-high reliability. As shown in [1], coupling ultra-low latency with ultra-high reliability can have a substantial impact on the required link budget, and thus on coverage area. Some radio access configurations, which require long transmission time interval lengths, are not adequate for supporting this service.

As can be seen in Section 5.4.5, for the **700 MHz network** with 50% load, NR can deliver 70%, whereas LTE can achieve 30% coverage. When the load increases to 90% the downlink service coverage drops at 50% for NR and 15% for LTE. In the uplink direction, NR can deliver 60% coverage at 50% load, whilst LTE cannot support this service, due to timing and bandwidth constraints.

The **4GHz network** delivers up to 99% and 90% coverage with NR and LTE respectively at 50% load in the downlink direction. As the load increases to 90% the downlink coverage drops to 95% for NR and 65% for LTE, for the highest considered site density (inter-site distance of 250m). In the uplink direction, at 50% load, 99% and 70% service coverage area can be achieved with NR and LTE, respectively.

- **Maximum Message Size**:

For a fixed coverage target of 95%, the maximum message size that can be supported in a given radio environment and with different radio access configurations is evaluated for the three different target requirements described in Table 1. This is essentially the largest payload that can be carried over the air interface within a single transmission time interval. This is correlated with the amount of resource elements that are contained within a transmission time interval, which is the product of the carrier bandwidth and the transmission time interval duration. Clearly, as the requirements on latency and reliability become extreme,

the supported payload size decreases. Elements such as the type of radio access solution, the network load, system bandwidth, number of antennas at the base station, all play a role in determining what maximum message size can be supported. The detailed results deriving from this analysis can be found in Section 5.4.4.

- **Required Bandwidth**:

Since a 95% coverage target cannot be met in most of the considered radio access solutions, the effect of scaling up bandwidth has been studied with the objective of trying to meet the coverage requirement. As can be seen in Section 5.4.6, in some cases, an increase in bandwidth does help in improving the service coverage area. In other cases, increasing bandwidth is not helpful:

- When the signal-to-interference-plus-noise ratio is too low and the user equipment is power limited, increasing bandwidth merely translates in a reduction in power spectral density, which prevents any gain from increasing bandwidth availability.
- When the radio interface cannot support enough re-transmissions within the target latency bound to guarantee the desired reliability.

1.2   Field trials

NTT DoCoMo conducted field trials in an urban area in Yokohama, Japan. The objective was to capture coverage and mobility performance of Ultra-Reliable and Low-Latency services for different packet sizes using real hardware in a realistic environment with a single base station and single mobile terminal operating in TDD at 4.66GHz.

The results provide the relationship between the signal-to-noise ratio and supported packet size in both uplink and downlink for the considered Ultra-Reliable Low-Latency target (i.e., 99.999% reliability, 32 Bytes packet size within a 1ms user plane latency).

The difference in achievable coverage boundaries for small and large packets is also highlighted. When there is approximately an order of magnitude difference in packet size (from 32 Bytes to 200 Bytes), the coverage loss is shown to be between 9.8 dB and 15.7 dB in static conditions, which is in line with the conclusion drawn in the first phase of this work through a theoretical analysis [1]. In a mobile environment, the tests show that the Ultra-Reliable and Low-Latency targets can be achieved for a 100-Byte packet with a speed of up to 25Km/h. However, as the packet size grows to 200 Bytes, the reliability target cannot be met.

1.3   Key Messages

TIMING ON THE RADIO INTERFACE

- The extent of the **service coverage** has a strong dependency on the radio access configuration. Reliable and fast transfer of large messages is better supported by longer transmission time intervals, and packet segmentation across multiple transmission times is desirable to lower requirements on instantaneous bit rate, whereas ultra-fast and ultra-reliable transfer of small messages can only be supported by the shortest possible transmission time intervals, so that the target reliability can be achieved within the target latency bound.

- Reducing the transmission time interval to reduce the radio latency corresponds to an increased physical layer overhead, which has a knock-on effect on the system spectral efficiency. However, reducing transmission time also translates into allowing for re-transmissions within tight latency bounds,

and this in turn allows for the use of efficient modulation and coding schemes that would be too risky if a one-shot transmission only was allowed by the latency constraint.

- Mechanisms such as Semi-Persistent Scheduling, which are assumed in this work to pre-assign uplink resources to the user equipment in order to get rid of scheduling delays, come with the drawback of limiting system capacity. A resource is in fact pre-allocated without the certainty that it will effectively be used.

BEAMFORMING AND BANDWIDTH AVAILABILITY

- The 4GHz network provides better service coverage than the 700 MHz network for all the considered targets, and this is due to the fact that a more sophisticated antenna array is deployed on the base station that enables **beamforming** techniques to be used by both NR and LTE. For the 700 MHz network, vertical-only fixed beamforming is performed, whereas at 4GHz, vertical and horizontal beamforming is assumed both in uplink and downlink. Moreover, more service bandwidth is allocated to the 4 GHz network: 20 MHz are allocated to the 4GHz network, whereas 10 MHz are allocated to the 700MHz network.

- Increasing service bandwidth can help in extending overall service coverage but not when the signal-to-noise-ratio experienced by a user is too low. In the UL, in fact, the worst-off UEs are often power limited. This means that they cannot increase the bandwidth used for transmission without also lowering the SINR. Using a lower code rate in order to obtain lower error rate is therefore not efficient, and the performance is limited.

DENSIFICATION IN AN INTERFERENCE-LIMITED NETWORK

- In most cases, the results are strongly dependent on **cell load**, i.e., on interference. In the considered radio access network solutions, the results are less dependent on cell size, i.e., coverage (in some cases a smaller cell size even reduces performance). This means that techniques such as beamforming and network interference coordination are important for the service performance. The effect on service coverage of decreasing inter-site distance, i.e., increasing **site density**, is in fact observed. In this context, the overall network load is assumed to also increase with the site density as the traffic per cell is kept constant. For this reason, increasing site density for the 700 MHz network does not improve performance as the benefit of densification is balanced out by the increase in system interference. Differently, the 4GHz network benefits from densification because it is equipped with more sophisticated beamforming capabilities that better deal with inter-cell interference. If the total load was kept constant, densifying the 700MHz network would also provide benefits as the load could be distributed across more sites.

NR AND LTE

- The results show a performance gap between LTE and NR, where NR generally outperforms LTE by providing better coverage and by being more robust to load increase. Moreover, in this context, some configurations of LTE cannot support the most extreme targets in terms of latency and reliability. It is important though to put these results into the right context. In this study, NR has a higher sub-carrier spacing than LTE, which means it can support much shorter symbols in time. This means that more re-transmissions become possible within a short target latency bound, and this not only enhances the reliability of the message, but also allows for the usage of a more efficient modulation and coding scheme that would be too risky for a one-shot only transmission. Is some configurations, LTE cannot support any re-transmissions given the tight requirements on latency, and this in turn translates into not meeting the required reliability target and thus into not being able to provide service coverage. It is also important to point out that work is currently on-going within 3GPP to address these shortcomings, and

that new measures are being put in place to make LTE adequate for low-latency and highly reliable services as well. When requirements are extreme, even small modifications in processing time can make a large difference in the achievable performance.

FDD AND TDD OPERATIONS

- For LTE, the analysis has been limited to FDD operation in paired spectrum. In a TDD configuration the performance of LTE would be significantly lower and it is not considered as a primary option for Ultra-Reliable Low-Latency services. For NR, both TDD and FDD configurations are feasible and have been investigated. NR TDD in unpaired spectrum can support all the investigated services, and in fact, it typically outperforms LTE in a FDD configuration by combining short uplink / downlink configurations based on mini-slots, higher sub-carrier spacings, and faster processing.

THEORETICAL ANALYSIS, SIMULATIONS, AND FIELD TRIALS

- The theoretical analysis presented in Deliverable 1 of this task force [1], and the field trials and simulations presented in this deliverable all lead to conclusions that are in alignment with each other. Stretching requirements translates into loss of coverage, which, in some cases, can be compensated with an increase in site density, number of antennas at the base station and terminal, and bandwidth. In other cases, this is not enough, as it becomes difficult to deliver the services due to timing limitations of the radio access technology.

2   INTRODUCTION

New business opportunities for operators in a wide range of vertical industries (e.g., smart manufacturing, logistics, transportation, health, smart cities, agriculture, gaming, etc…) translate into new and sometimes challenging sets of targets that 5th-Generation mobile cellular networks need to meet to be able to successfully deliver the desired services. These targets include an evolution of traditional mobile broadband, which has been the main driver for network development until today, as well as requirements that are completely new to the cellular industry and that mainly address Internet-of-Things type of use cases, where, e.g., new industrial verticals may become customers.

In this context, a wide range of use cases with related business opportunities and required network capabilities was identified by NGMN in [2] and [3]. This work then became valuable input for 3GPP when it kicked off its own studies on new services for the next generation of mobile communications, summarized in [4]. 3GPP organised all the different use cases and their service-level requirements into three main categories: massive Internet of Things [5], Critical Communications [6], and enhanced Mobile Broadband [7]. These studies then formed the basis for a single specification [4]. In addition to these evaluations of service needs, ITU has defined the requirements for the 5G radio [8] [9], covering the same categories. Standardization work is now ongoing in different working groups within 3GPP [10] [11] aiming at meeting both these sets of requirements (service-level and radio link level). A refinement of use cases and requirements for vertical industries is currently ongoing in 3GPP [12] [13].

Massive-Internet-of-Things requires the network to support very large numbers of connections for machine-type traffic; Critical Communications often call for very low latency and highly reliable wireless access links for the delivery of advanced functionalities for controlling objects; and enhanced Mobile Broadband enables data-rich and immersive applications that rely on augmented and virtual reality features. Many actual use cases will extend into more than one category, and thus require enhancements from multiple dimensions such as coverage, quality-of-service, and capacity. To some extent, we can regard them as using different modes of the network; a long-range massive mode (massive Machine Type Communication mMTC), a highly reliable and low-delay mode (Ultra Reliable Low Latency Communication, URLLC), and a high-data-rate mode (enhanced Mobile Broadband, eMBB).

3   SCOPE

NGMN has recognised the need to gain deeper understanding in what impact new services will have on the future network architecture, both for the radio access and for the entire end-to-end network. Therefore, a task force on 5G Extreme Requirements was kicked off in May 2017. The new requirements are referred to as "extreme" since they go far beyond the boundaries of the traditional targets that have been the main driver for network design until today, and the focus of this work is the case when very high reliability and ultra-low latency are required at the same time.

This task force has the objective of answering the following questions:
1) To which extent can the 5G extreme services be delivered on existing deployments?
2) What modifications, if any, are required in the radio access network and/or in the core network to deliver the 5G extreme services?
3) How sensitive are the deployment models to the requirements? By relaxing the targets, does the deployment change considerably?

In order to answer the questions above, the 5G Extreme Requirements Task Force is structured into two main phases, which are mapped to a time line in Figure 2:

- **Phase 1: Operators' view on fundamental trade-offs**:
  This is a high-level study that provides preliminary insight for Question 1 [1]. The fundamental trade-offs among latency, reliability, message size, data rate, and service coverage area are analysed. More detailed and technology-specific analysis is the scope for Phase 2.

- **Phase 2: Network solutions for extreme services**:

The objective is to identify how and to what extent the service-level requirements and the radio link requirements can be supported, and compare different end-to-end network solutions that address those critical sets of requirements. This phase aims at answering in detail Questions 1, 2 and 3 and is broken down into two sub-phases that address radio access and end-to-end aspects respectively, as described below.

- o **Phase 2.1: Radio Access Network models**:
  A given set of services associated with requirements on latency, reliability, throughput, and coverage availability is considered. Different Radio Access Network (RAN) solutions are then applied, and their potential in being able to support the chosen services is assessed. Both LTE-Advanced (according to 3GPP Rel. 15) and New Radio (NR, defined in 3GPP Rel. 15) are considered as candidate radio access technologies with different bandwidth configurations. Both simulation studies and field trial results are presented.

- o **Phase 2.2: End-to-End considerations**:
  This phase extends the scope of Phase 2.1 by identifying what affects latency and reliability in an end-to-end deployment and which changes and new features are required from an end-to-end network perspective to meet the targets associated to the services identified in Phase 2.1 by minimising deployment costs.
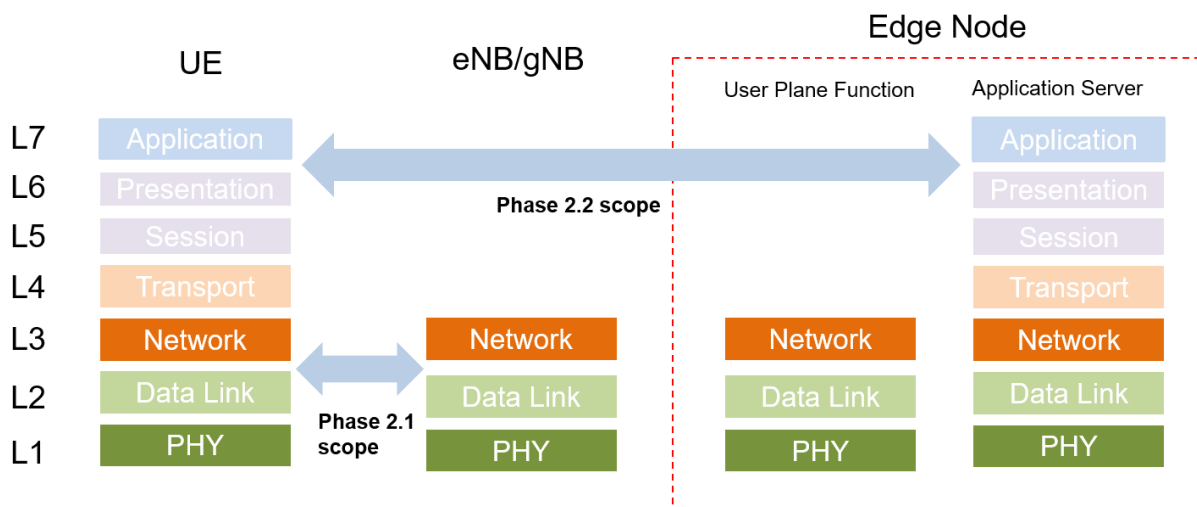
Figure 1 Scope of Phase 2.1 and Phase 2.2

This report outlines the outcome of Phase 2.1. More specifically, a range of network configurations is considered, with different carrier bands, service bandwidths, radio interface technologies, inter-site distances, and number of antennas, together with three target requirements for different services. The performance of each network solution is then evaluated in terms of spectral efficiency (SE), supported traffic density, service coverage, and maximum supported message payload for the three considered services. The analysis is then extended to identify what measures can be taken into consideration when the target cannot be met with the given radio access network solutions, for example, by increasing the service bandwidth. The rest of this deliverable is organised as follows:

- Section 4 provides a list of definitions and a description of the considered assumptions,
- Section 5 presents the results from the simulation study,
- Section 6 presents the results from the field trials,
- Section 7 provides conclusions,
- Section 8 describes limitations and provides guidelines for future work.

2017								2018				
May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May

Task Force Kick Off

Deliverable 1: Operators' perspective on fundamental trade-offs

Deliverable 2.1: RAN deployment models

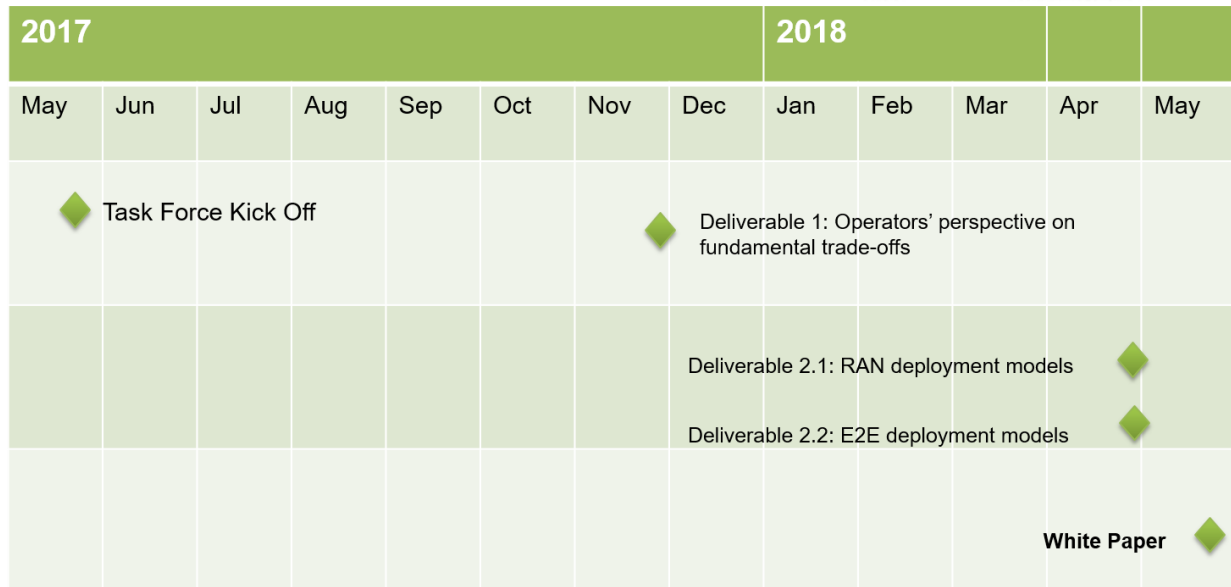Deliverable 2.2: E2E deployment models

White Paper

Figure 2 Extreme Requirements Task Force time line.

4 DEFINITIONS AND ASSUMPTIONS

Throughout this document, the following terms are used:

- **Latency**: it refers to one-way user-plane radio latency between transmitter and receiver and it corresponds to the time it takes to deliver a message of X bytes of data from the radio protocol layer 2/3 Service Data Unit (SDU) ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface [8], where neither device nor base station (BS) reception is restricted by discontinuous reception [14]. The latency is measured for the message and can therefore include retransmissions. Latency is measured in milliseconds.

- **Reliability**: the probability of successfully receiving and decoding a message of X bytes of data within a certain user plane latency [8].

- **Error Rate**: the probability of not being able to successfully transmit a message of X bytes within a certain latency. This is equivalent to *1-Reliability*.

- **BLER**: Block Error Rate, the instantaneous error rate for a radio transmission.

- **Transmission Timing Interval** (TTI): refers to the duration of a schedulable transmission period on the radio link. It is measured in milliseconds.

- **Transport Block**: the data from the upper layers that is given to the physical layer. This includes application data plus overhead (OH) (such as MAC headers and higher layer protocol headers), but not layer 1 control OH. It is measured in bytes.

- **Payload**: refers to the transport block size plus the cyclic redundancy check, i.e., all that is transmitted over the radio interface. The payload is either sent in one TTI (no segmentation) or in multiple TTIs (segmentation) It is measured in bytes.

- **SINR**: Signal-to-Interference-plus-Noise Ratio. It is measured in dB.

- **Spectral Efficiency (SE)**: the amount of payload that can be transferred over a given unit of bandwidth. This means that the cost of layer 1 control but not of the higher layer headers is accounted for and discarded from the calculation. It is measured in bits/s/Hz.

- **Raw Spectral Efficiency:** the amount of raw information (application-layer plus all OH, including layer 1 control) that can be transferred over a given unit of bandwidth. It is measured in bits/s/Hz.

- **Service Coverage:** the percentage of the user population that fulfils a certain requirement, e.g. for a specified service.

- **Cell Load**: the average utilization level of the cell, meaning the fractional usage of radio resources.

- **Transmission Rank**: the number of layers of a transmission, i.e. the number of data streams in a MIMO connection. In this context, Single-User MIMO is considered.

- **ISD**: Inter-Site Distance, the distance between 3-sector sites in a hexagonal deployment.

5 SYSTEM SIMULATIONS

5.1 Target requirements

For the purpose of this study, three sets of requirements for latency, error rate, payload size, and coverage are considered and represented in Table 2 in line with the definitions provided in Section 4. The targets in Table 2 span a wide variety of scenarios, in accordance with [4], [14], and [9]. A default target is also defined, which is representative of an eMBB-type of use case and which is used as a benchmark for the studies.

The approach has been to take the 3GPP requirement target for URLLC as a starting point (Target 3), and see how network solutions change as the requirement is either relaxed in terms of latency and reliability, (Target 2), or replaced with fast and reliable transfer of large messages (Target 1).

Table 2 Studied target requirements for both outdoor and indoor users.

	Latency	Error Rate	Payload	Service Coverage	Example of use cases
Target 1	10ms	1E-3	1500B	95%	A data-rich application for media and entertainment such as, e.g., Augmented Reality, Virtual Reality, collaborative gaming, etc. This is a use case that requires fast and reliable transfers of large payloads.
Target 2	5ms	1E-4	40B	95%	A low-payload application for use cases that require interaction between sensors/actuators and a controller such as remote control for smart manufacturing, electricity distribution, etc… Typically the interaction happens in periodic patterns. Reliability is high as it reflects the need for robust wireless links.
Target 3	1ms	1E-5	40B	95%	This is the target with the most challenging requirements for 5G, and it represents use cases such as tactile interaction, discrete automation, etc… The payload requirement is low, but very high reliability needs to be met within an extremely low latency budget.
Default	10ms	1E-1	1500B	95%	For comparison and used as benchmark. It is representative of an eMBB-like service.

5.2 Simulation Scenarios

TablesTable 3, Table 4, Table 5, outline the considered network, link, and radio interface configurations. Different radio access system configurations have been studied, based on NR and LTE-Advanced (Rel. 15, status in Q3 2017), as listed in Table 5. They differ in the TTI lengths, which are configured to comprise different number of OFDM Symbols (OS). For NR both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) configurations are studied, for LTE, only the FDD configuration is adopted. A description of system configurations for URLLC in LTE and NR can be e.g. found in [15].

The division between link and system domains means that from system simulation the SINR distributions generated for a one-polarized beam including array gain are obtained, while from link simulations the performance of a one-polarized beam on a cross-polarized antenna at an SINR point is calculated. Taken together the array gain and polarization aspect are both considered.

It is important to note that the chosen simulation scenario reflects a network configured for a URLLC type of service, which is the most demanding target considered in Table 2. One example of such a configuration is to adopt a transmission scheme with only one MIMO-layer to ensure robustness, as shown in Table 2. If the network had to deliver eMBB services only, different choices of parameters would have been considered. Another example is that the user equipment (UE) antenna has 4 elements, which is crucial for reliability. For the case of 4GHz carrier

frequency this is expected, whereas for the case of 700MHz this would require fairly large antennas and may therefore be an optimistic assumption. However, considering dedicated URLLC UEs it may still be realistic.

Some properties are important for timing and bitrate such as TTI length, number of Physical Resource Blocks (PRBs), and layer 1 and layer 2 OH. These values are given in Table 8, where a 20 MHz bandwidth is assumed. In Uplink (UL) 1 OS for the Demodulation Reference Signal (DMRS) is assumed for a 7-OS TTI and shorter, and a 2-OS DMRS for a 14-OS TTI is considered. In LTE Downlink (DL), 1-OS Physical Downlink Control Channel (PDCCH) and 8 Control Channel Elements (CCE) Short PDDCH (sPDCCH) OH was assumed. For NR DL, a 4-CCE PDCCH is assumed. The layer 1 DL and UL percentage OH values are shown in Table 8. As can be seen from the table, as the TTI length decreases, the amount of resource elements available to transmit user data decrease and the percentage of OH increases accordingly.

The required payload for each target can be translated into a minimum required bitrate. Here it is important to distinguish between average information rate and instantaneous bitrate. Sending a payload of X bits within Y seconds means the average information rate is X/Y bps. However, having to meet strict reliability targets within low latency bounds makes message re-transmissions necessary and thus it is crucial to be able to send the target information into a single TTI in order to have time for re-transmitting the same message within the latency bound. This means that a much higher instantaneous rate is required in that specific TTI where the whole of the information needs to be conveyed, and the larger the payload the higher the instantaneous bit rate. This instantaneous bitrate will then limit the system performance, since messages of certain sizes will not fit in one TTI given a specific code rate and bandwidth. A message can be segmented into several chunks to fit within the TTI, which leads to lower requirements on instantaneous bitrate, at the expense of reliability. In this case, the reliability per chunk needs to increase to ensure that all segments are delivered with the total target reliability. The instantaneous and average bitrates are given in Table 6 and Table 7, respectively.

The systems assume hybrid automatic repeat request (HARQ) timing according to capability, with values given in Table 9. In this derivation, the processing delay at the UE and BS is assumed to be 3 OS for NR, and [3, 11, 14] OS for [2, 7, 14] OS TTI for LTE. In LTE the PDCCH duration is 1 OS, and the timing for 14 OS TTI is n+3 TTI (reduced latency), which means that a failed transmission during a TTI "n" can be retransmitted 3 TTIs later. With 7 OS and 2 OS sTTI in LTE the timing is set to n+4 sTTI. For NR, short Physical Uplink Control Channel (sPUCCH) is assumed, which is a new UL control channel for NR, and for TDD 1 OS is assumed as a gap period in-between UL and DL transmissions. Each value in the table provides the one-way RAN latency (UL or DL) for a single transmission (first row). The values assume a worst-case latency with the largest frame-alignment latency at the transmitter; this is motivated by the fact that URLLC services are required to guarantee a latency with a certain reliability; therefore, a worst-case timing is more relevant than e.g. an average timing. The second row in Table 9 shows the additional latency introduced by one round of HARQ re-transmission. Semi-Persistent Scheduling (SPS) is considered, which means that the device is configured in advance with resources that can be used for UL data transmission or DL data reception. Once a device has data available, it can immediately start UL transmission without going through the scheduling request-grant cycle [16]. As can be seen, the shortest latencies can be achieved by NR with a 4-OS TTI, and an FDD configuration.

The latency requirement in the targets can thus be interpreted as a maximum number of allowed transmission attempts for a message in the studied radio access configurations. This is given in Table 10. It should be noted here that some latency requirements are stricter than what is possible to deliver in some configurations, and the maximum number of transmissions is therefore set to zero. These configurations are highlighted in orange in the table and they correspond to Target 3 with NR FDD with 14-OS TTI FDD, and LTE FDD 14- and 7-OS TTI. Other configurations allow for a single transmission only, which poses challenges when a highly reliable wireless link is required. In this study up to 3 transmission attempts are considered. The reason for this is that the reliability of the feedback channel (which is required for triggering a retransmission) becomes a limiting factor around this level, and the modelling used therefore becomes uncertain.

In 3GPP there are two ongoing Work Items (WIs) targeting URLLC services; the New Radio (NR) WI, and the LTE URLLC WI. These WIs are part of 3GPP RAN Release 15, which is scheduled for finalization in Q2 2018. In Q3 2018 it is expected that Release 16 WIs on URLLC will start.

The radio access systems studied in this report are configured according to the Release 15 LTE and NR standards. However, since the standardization is currently ongoing (Q1 2018) some assumptions of the direction of Release 15 have been made, and an overall alignment with 3GPP standard has been the guiding principle.

Table 3: Network Configuration

| Network Parameters	Configurations
Propagation scenario	URLLC Urban Macro configuration B as defined in [8]. In this scenario 20% of users are indoors.
Channel model	UMa channel model B with spatial cluster model, as defined in [8]
Inter-Site Distance (ISD)	[500, 350, 250] m
Carrier frequencies	[0.7, 4] GHz
Cell loading (utilization)	[0, 50, 90] %
Bandwidth	[10, 20, 40, 80] MHz
User Equipment power	0.2 W, power control with 10dB target SINR, and path loss compensation factor alpha = 1
Transmission scheme	1 layer (rank 1) transmission in UL and DL, no data segmentation for Targets 2 and 3. Segmentation is considered for Target 1.
User Equipment antenna	1x2x2 (Vertical x Horizontal x Polarization) elements (see Figure 3), with 4 antenna ports TX/RX beamforming, ideally beamformed towards serving BS.
Base station antenna for the 4GHz carrier	8x4x2 (Vertical x Horizontal x Polarization) elements steered in subarray groups of 2x1x1 (see Figure 3), giving 32 antenna ports TX/RX beamforming. Ideal long-term average beamforming in DL assumed, and same beam is used in UL. 40 W transmission power.
Base station antenna for the 0.7GHz carrier	8x1x2 (Vertical x Horizontal x Polarization) elements steered in groups of 8x1x1, giving 2 antenna ports, i.e. one port per polarization (sector column antenna, see Figure 3). Antenna tilted towards cell-center. 40 W transmission power.
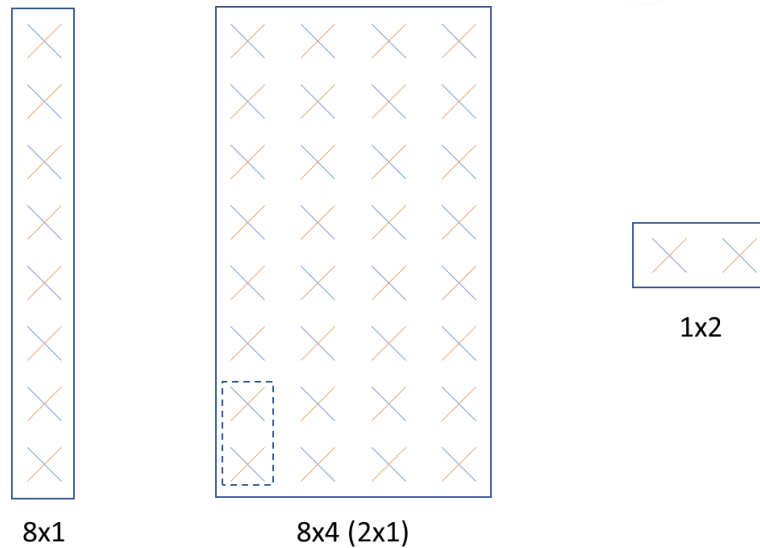
Figure 3. Illustration of the adopted antenna configurations with cross-polarized antenna elements. From the left: sector antenna for the 700MHz band, 8x4 antenna array with 2x1 subarrays for the 4GHz band, 1x2 UE antenna array, for which the form factor will depend on the adopted bands.

Table 4 Physical Layer link simulation configurations

Parameters	Configurations
Channel model	TDL C channel [8], 300ns spread
Antenna configuration	1TX 2RX, corresponding to the case of no transmit diversity and 2 uncorrelated receive antennas (corresponding to 2 polarizations)
Data channel	LDPC, BG2
Bandwidth	20MHz
Data modulation	QPSK, 16QAM, 64QAM
Transmission rank	1 layer
Code rate	1/20, 1/10, 1/5, 1/3, 1/2, 2/3
Receiver model	IRC
DL control channel	Polar code, 30b payload, 1-8CCEs
UL control channel	Short PUCCH (sequence selection), 2 OS including frequency hopping.

Table 5 Radio Interface system simulation configurations

Radio Interface	Sub-Carrier Spacing (SCS)	Number of OFDM Symbols (OS)	TTI duration [ms]	Duplexing Scheme
New Radio (NR)	30 kHz	7	1/4	LTE TDD conf. 1 (DL-DL-UL-UL-DL sequence)
		14	1/2	FDD
		7	1/4	FDD
		4	1/7	FDD
LTE	15 kHz	14	1	FDD
		7	1/2	FDD
		2	1/7	FDD

Table 6. Equivalent instantaneous bitrates [Mbps] of targets for the studied radio access configurations, based on payload per TTI.

[Mbps]	NR 30kHz				LTE, FDD		
	14OS TTI, FDD	7OS TTI, FDD	7OS TTI, TDD	4OS TTI, FDD	14OS TTI	7OS TTI	2/3OS TTI
Target 1	4.8	9.6	5.8	17	2.4	4.8	17
Target 2	0.64	1.3	0.77	2.3	0.32	0.64	2.3
Target 3	0.64	1.3	0.77	2.3	0.32	0.64	2.3

Table 7. Average information rates, and payload per TTI.

	Latency	Payload	Minimum average bitrate	#Segments	Payload per TTI
Target 1	10ms	1500B	1.2Mbps	5	300B
Target 2	5ms	40B	64kbps	1	40B
Target 3	1ms	40B	320kbps	1	40B

Table 8. TTI length, PRBs in carrier, assumed overhead for studied radio access configurations.

	NR 30kHz				LTE, FDD		
	14OS TTI, FDD	7OS TTI, FDD	7OS TTI, TDD	4OS TTI, FDD	14OS TTI	7OS TTI	2/3OS TTI
System #	1	2	3	4	5	6	7
TTI length (ms)	0.50	0.25	0.25	0.14	1.0	0.50	0.14
PRBs per 10MHz	25	25	25	25	50	50	50
Layer 1 DL overhead	12%	23%	32%	26%	24%	27%	43%
Layer 1 UL overhead	18%	18%	29%	28%	17%	17%	52%

Table 9. One-way RAN latencies (DL or UL Semi Persistent Scheduling - SPS) for the studied radio access configurations.

[ms]	NR 30kHz				LTE, FDD		
	14OS TTI, FDD	7OS TTI, FDD	7OS TTI, TDD	4OS TTI, FDD	14OS TTI	7OS TTI	2/3OS TTI
First transmission	1.2	0.71	0.96	0.50	4.0	2.6	0.86
Per HARQ retransmission	1.5	0.75	1.0	0.43	8.0	5.0	1.7

Table 10. Maximum number of allowed transmission attempts, assuming HARQ retransmissions, for a payload within a given latency budget for a given radio access configuration.

	NR 30kHz				LTE, FDD		
	14OS TTI, FDD	7OS TTI, FDD	7OS TTI, TDD	4OS TTI, FDD	14OS TTI	7OS TTI	2/3OS TTI
Target 1	6	13	10	23	1	2	6
Target 2	3	6	5	11	1	1	3
Target 3	0	1	1	2	0	0	1
Default	6	13	10	23	1	2	6

5.3 Methodology

This section outlines the methodology that has been adopted to carry out the analysis.

5.3.1 Assumptions on traffic modelling

The users have periodic traffic in UL and DL on a carrier also used for other traffic (e.g., eMBB). The level of activity on the carrier is characterized by the cell load, which determines the level of interference assuming that there is no inter-cell interference avoidance scheduling. The cell load determines the SINR in the system. For the purpose of analysis, it does not matter if the cell load is originating from background eMBB or URLLC traffic. Therefore, the load can consist of any combination of eMBB and URLLC proportions.

It should be noted that a certain load level will correspond to a certain traffic volume in a cell. If the cell density is increased by reducing the ISD, the total traffic volume served by the network will increase even if the utilization level remains constant. This is because there are more cells carrying traffic. This should be kept in mind when comparing results for different ISD. In a real system, the utilization level would be reduced when ISD is decreased, since the traffic would be distributed among more cells, and hence each cell would not need to be used as often.

The DL data analysis considers the BLER of DL control, DL data, and in the case of retransmissions also UL control, as illustrated in Figure 4.
The UL data analysis assumes Semi-Persistent Scheduling (SPS) with configured UL resources in every TTI, such that the user can transmit in any TTI without first receiving an UL grant. The BLER of the UL data is then considered, and in the case of retransmissions the DL control also, as shown in Figure 4. It should be noted that while this configuration gives low latency since the exchange of Scheduling Request (SR) and UL grant is not required, it can

limit the capacity. This is because each user is pre-allocated a certain radio resource, regardless of whether this resource will actually be used or not, and therefore a limited number of users can be supported.

Blocking of DL control is not considered, and queueing delay is not considered, which is reasonable for the assumption of periodic data and perfect scheduling.
Each physical channel transmission is seen as independent, and the total error rate is therefore computed based on the BLER of the physical channels at the SINR values for UL and DL.
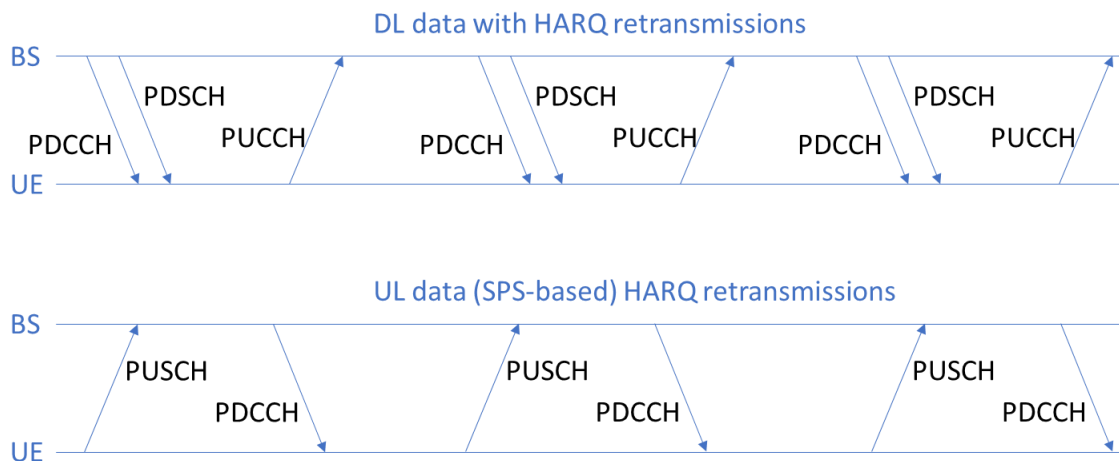

Figure 4. Schematic illustration of physical channels involved in DL and UL data transmission with up to 2 HARQ retransmissions, in total 3 attempts.

5.3.2 Analysis

Two datasets, which we here refer to as Data Set A and Data Set B, are generated with two different simulators based on the network configurations outlined in Section 5.2:
1. Data Set A: SINR distributions from Ericsson's system-level simulator
2. Data Set B: SE distributions from Ericsson's link-level simulator.

The analysis has been carried out in the following steps, and a summary is provided in the flow chart in Figure 5:
1. Data set A, which is the cumulative distribution function (CDF) of the SINR, is generated according to the assumptions in Section 5.2 for the following combinations:
    a. UL and DL
    b. 700MHz and 4GHz carrier frequency
    c. 0%, 50%, and 90% cell utilization (cell load), determining the level of interference
    d. 250m, 350m, and 500m ISD assuming a hexagonal deployment of 3-sector sites
    e. 10MHz, 20MHz, 40MHz, and 80MHz carrier bandwidth
2. Data set B, which is the SE at a given SINR value, is generated according to the assumptions in Section 5.2 for the combinations:
    a. UL (SPS-based scheduling) and DL (dynamic scheduling)
    b. 1, 2, 3 transmission attempts
    c. 1E-1, 1E-2, 1E-3, 1E-4, and 1E-5 total error rate
3. The set of target requirements that are defined in Table 2, with values on latency (L), reliability (R), coverage (C), and payload (P) is considered.
    The SINR values (V) at the coverage level C are found from data set A. It is important to note that the values V are not taken for the entire coverage region, but from the cell edge values, which are then used in Steps 9-10 to see if the coverage target is reached

4. For the studied radio access configurations in Table 4 the maximum number of transmissions N is calculated from the target requirement on the latency L (see Table 10)
5. A subset B* of Data set B is selected based on the number of transmissions N and the reliability requirement R
6. The data sets A and B* are convolved to find the average SE for each target and configuration
7. From the SE, the total traffic volume (T) that can be supported for each target and configuration is calculated
8. At the SINR points V in set B*, the achievable coverage cell-edge bitrate (E) is found
9. From the cell-edge bitrate E, and the configuration specific parameters (Table 8), the maximum payload (M) that can be transmitted in UL and DL at the cell-edge is calculated
10. An assessment of target fulfillment is done by comparing the maximum payload M with the target payload P
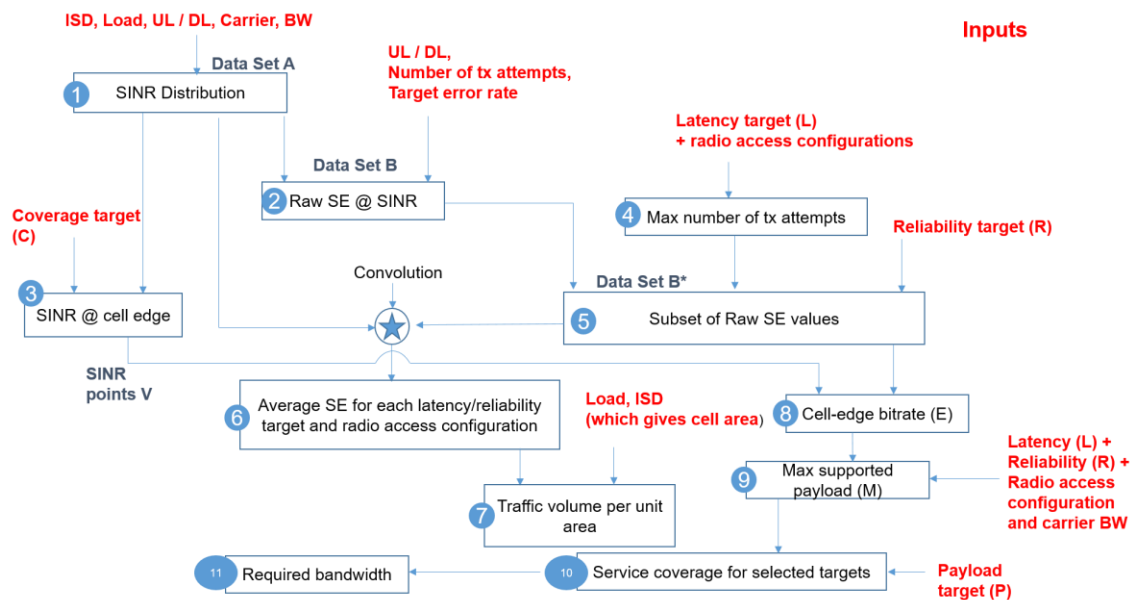11. The required bandwidth to fulfill all the targets is also calculated.

Figure 5 Flow chart for the analysis

5.4 Results

5.4.1 SINR Distributions

The SINR distributions are generated according to the setup described in Section 5.2, and are shown in Figures Figure 6-Figure 9. This data only covers the received radio signal properties, and is therefore independent of radio access configuration, and other requirements on latency, reliability, and payload. Three ISD values are considered: 500m, 350m, and 250m, as well as two percentage values of network load: 0% and 90%. A 20 MHz bandwidth allocation is assumed for the 4GHz carrier, and a 10MHz bandwidth allocation is assumed for the 700MHz carrier. It is important to note that the overall network load increases with densification, hence different load percentage values correspond to different values of overall traffic load per area for different ISD values and different bandwidth allocations.

As described in Section 5.2, Table 2, the UE is beamforming towards the BS both in the UL and DL directions both at 4GHz and 700MHz. On the BS side, at 700MHz, vertical-only fixed beamforming is performed and the antenna is tilted towards the cell centre. At 4GHz, vertical and horizontal beamforming is assumed both in UL and DL.

Figures Figure 6Figure 7 represent the CDF of the SINR for the 4GHz carrier for DL and UL respectively. Figure 8 and Figure 9 represent the CDF of the SINR for the 700MHz carrier for DL and UL respectively.

The following remarks are in order:

- The sharp curve in the UL distributions are due to the power control aiming to maintain a 10 dB SNR. The SNR fall below 10 dB is caused by UE transmit power limitations, where the UE is transmitting at its maximum power and cannot compensate the path loss any more by power control.

- The 700MHz band is not coverage limited, and the results are therefore not improved for a reduced ISD. The impact from interference is on the other hand strong, due to the wide antenna in the BS.

- The 4GHz network is more robust to interference thanks to the fact that the BS is beamforming in DL and UL. This also accounts for the fact that the SINR is higher at this frequency compared to 700MHz even though the frequency is higher. As a consequence, reducing ISD translates into improving the SINR performance.
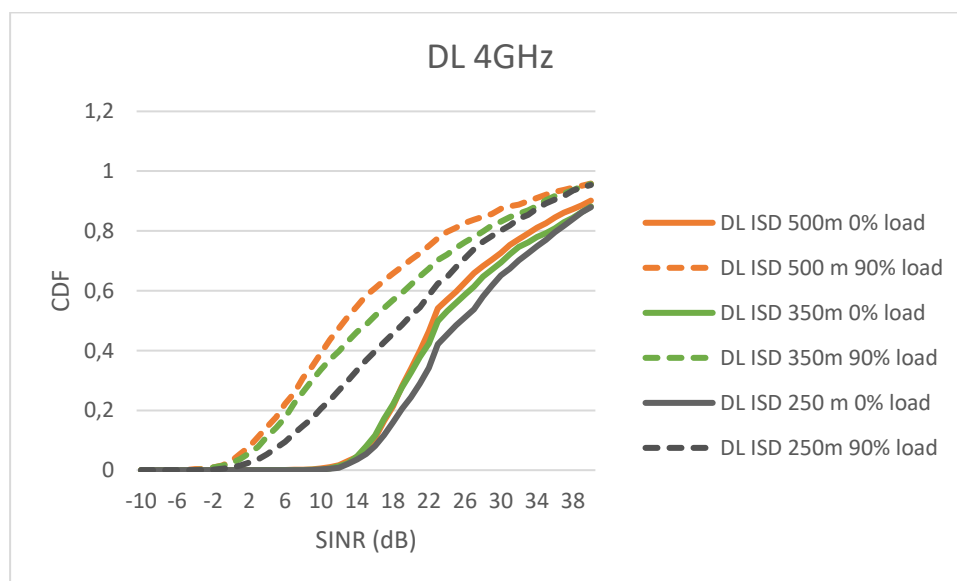

Figure 6. DL SINR distribution for the 4GHz band, 20MHz bandwidth.
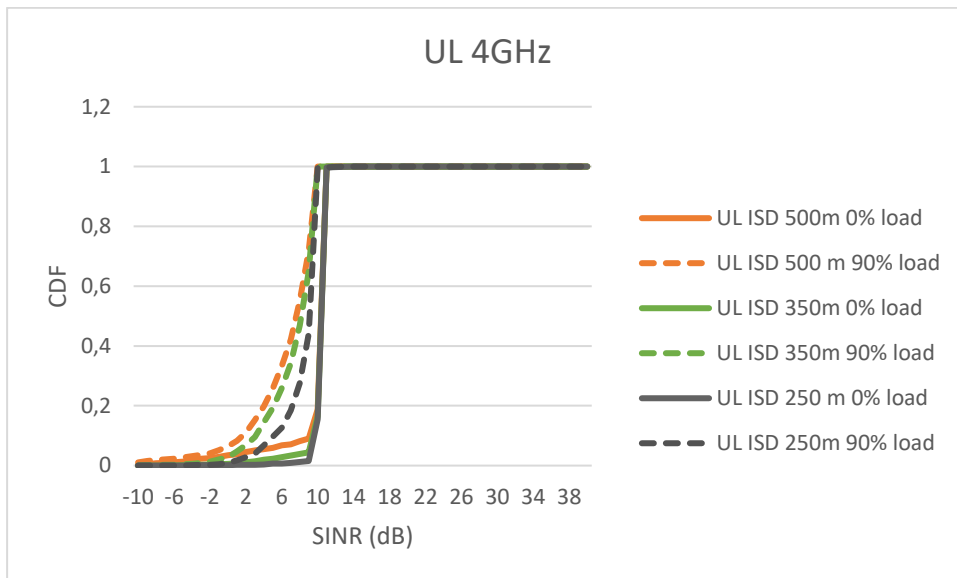
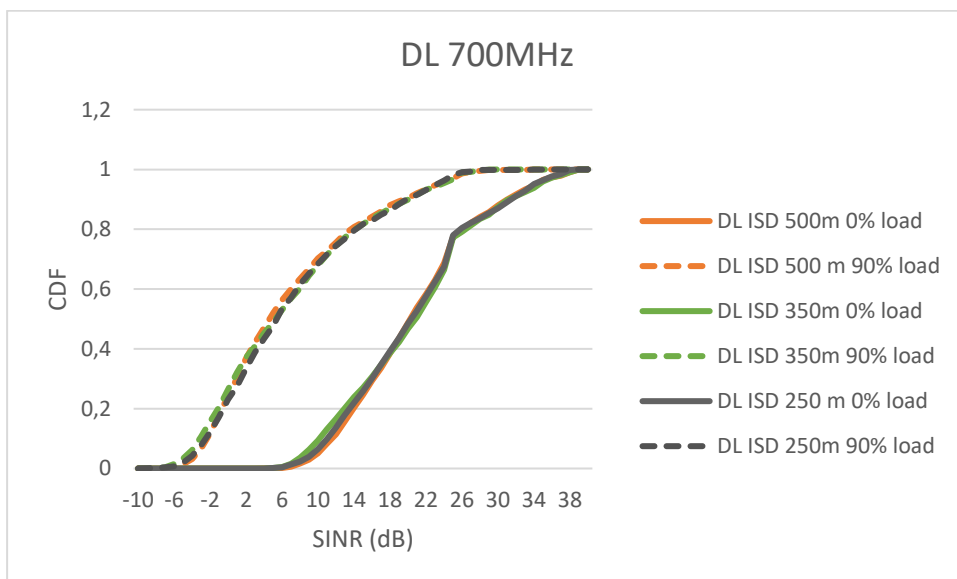**Figure 7. UL SINR distribution for the 4GHz band, 20MHz bandwidth.**

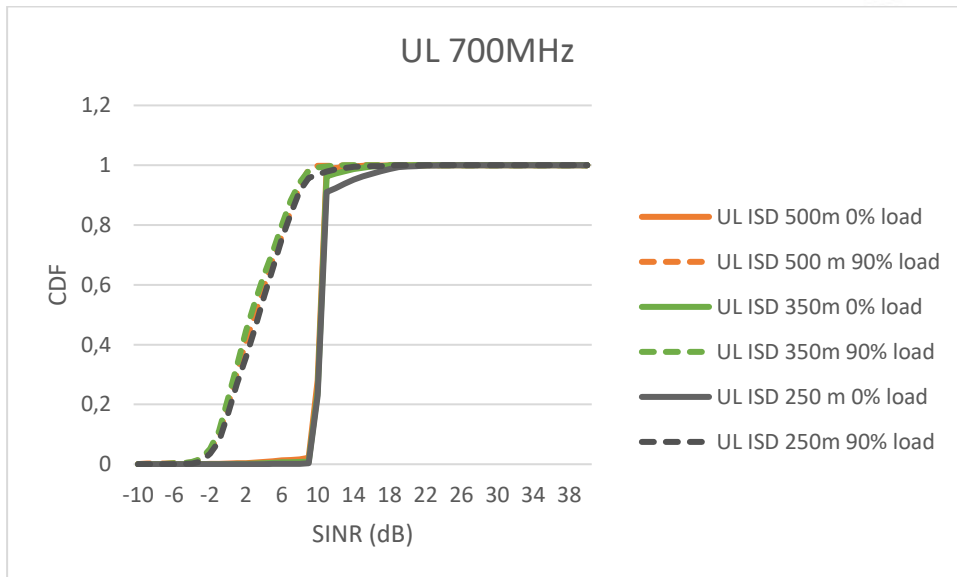**Figure 8. DL SINR distribution for the 700MHz band, 10MHz bandwidth.**

Figure 9. UL SINR distribution for the 700MHz band, 10MHz bandwidth.

5.4.1.1 Cell-Edge SINR

Starting from the SINR distributions shown in Section 5.4.1, the coverage at cell-edge, as defined in Table 2 (95th percentile of the population), can be found for different network load values (0%, 50%, 90%). The results are presented in Figures Figure 10Figure 11.

The following remarks are in order:

- All scenarios are interference limited, as they all have a good cell-edge performance at 0% load, which drops as the load increases to 90%, (shape determined by utilization) except for the 4GHz 500m ISD in UL, which has a low level already in an empty system (0% load), and that is thus coverage limited.

- The UL is relatively less impacted by interference compared to the DL. This is due to the fact that power control is not used in DL and also due to the better receive antennas in UL (at the BS), which limit the impact of interference.

- By comparing the two bands, it can be seen that - perhaps contrary to expectation - the 4GHz band gives a better cell-edge performance than 700MHz. This is an effect of beamforming with the large array at the BS.
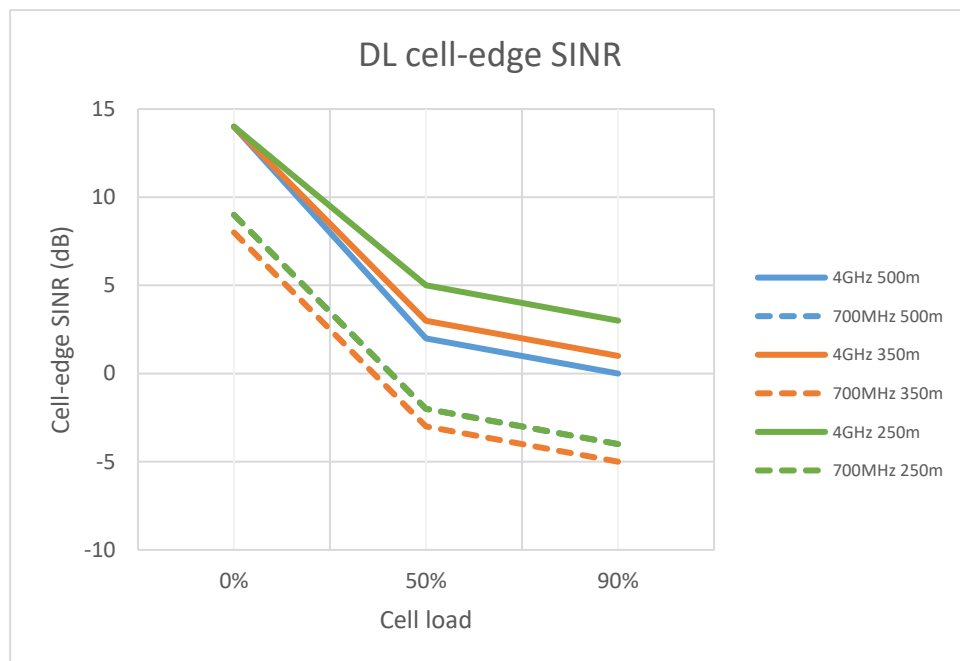

Figure 10. Coverage cell-edge SINR in DL for different ISDs. Please note that the 700MHz 500m ISD curve overlaps with the 700MHz 250m ISD curve.
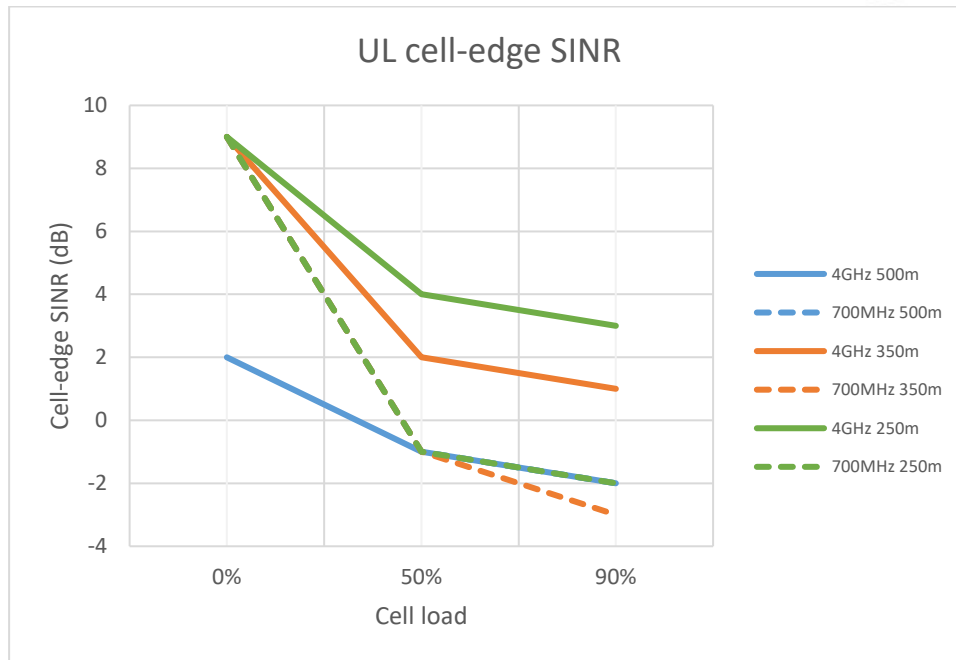
Figure 11. Coverage cell-edge SINR in UL for different ISDs. The 700MHz 500m ISD curve overlaps with the 700MHz 250m ISD curve, and partially with the 700MHz 350m ISD curve.

5.4.2   Spectral Efficiency

5.4.2.1   Raw spectral efficiency

The raw per-link SE, as defined in Section 5.3, is shown in Figure 12 and Figure 13 for DL and UL, respectively, for one and two transmission attempts and different total error rates.

The input data for this calculation covers a range of SINR values, total target error rate values, and the number of possible transmission attempts. It should be noted that these results are theoretical and general. Actual latency and payload targets have in fact not been considered for the purpose of this calculation. In addition, no L1 OH has been taken into account. What these results show then is the theoretical performance for a certain error rate requirement at an SINR after one or two transmission attempts.

The raw SE values that are obtained are independent of the radio network deployment and of the radio access technology (given that the SINR distributions calculated in Section 5.4.1 are independent of the radio access), and are here also taken to be independent of carrier frequency and bandwidth. The latter assumption is an approximation; in reality there are differences arising from coding in LTE versus NR, band, and transmission lengths. These differences are however not expected to dominate over other uncertainties in the model. The total error rate is calculated from a sequence of independent (i.e. uncorrelated) transmissions of the physical channels for the data communication, taking their individual BLER into account. The considered sequences are as follows

- DL: DL control, DL data, UL control, etc. for up to 3 attempts
- UL (SPS-based): UL data, DL control, etc. for up to 3 attempts.

The sequences of physical channels are illustrated in Figure 4. It is assumed that the SINR of a user is stable, and therefore that all transmission attempts are equal. No soft combining of data is assumed.

As can be seen from the curves in FiguresFigure 12Figure 13, having more transmission attempts improves SE, as it allows to choose for more efficient modulation and coding schemes. When there is only one transmission attempt allowed, the modulation and coding schemes need to be very robust and thus not very spectrally efficient in carrying useful data.

5.4.2.2 Average spectral efficiency

From a convolution of the raw SE with the SINR distribution, it is possible to obtain the raw SE distribution. From the distribution, the average raw SE can be calculated. By taking the layer 1 OH into account, the average system SE obtained can be calculated for different radio interface configurations, as shown in Figure 14 -Figure 17. Moreover, for a certain radio access configuration and latency and reliability targets, it is possible to identify how many transmission attempts can be done, according to Table 10. It should be noted that the target on payload size is still not considered in this calculation.

The studied case here is a variable ISD (500m, 350m, 250m) and 50% load. This value is calculated for the different radio access configurations and the target requirements. As a comparison, the default target, with 10% error rate and 10ms latency, is also shown.

The following remarks are in order:

- For a given carrier frequency, bandwidth allocation, and antenna configuration, the average SE for each target is highly variable according to what radio access technology is adopted. As an example, as can be seen from Figure 14Figure 15, for a 700MHz system with a 10MHz bandwidth allocation, the DL average SE for Target 1 is between 1.1 and 1.3 bps/Hz when the system uses NR, and it is between 0.5 and 0.9 bps/Hz with LTE (the values within the ranges correspond to different configurations such as SCS, duplexing mode, and number of OS).

- For all targets, there is a performance gap between NR and LTE, and this is due to the fact that, in the considered configurations, NR enables faster transmissions in time (largely due to a higher sub-carrier spacing). This means that more re-transmissions become possible within a short target latency bound, and this not only enhances the reliability of the message, but also allows for the usage of a more efficient modulation and coding scheme that would be too risky for a one-shot only transmission.

- Target 3 can only be achieved with some (not all) system configurations. LTE with 1 or 0.5 ms TTI and NR with 14OS, 30KHz SCS, FDD cannot achieve this target, and this is the case for all the considered ISDs and bandwidth / antenna configurations. This is due to the fact that these configurations do not allow for retransmissions, as shown in Table 10.

- There is no substantial difference between NR FDD and NR TDD in terms of SE for all considered targets. The reason is that in both duplex modes it is possible to perform enough transmission attempts for good performance. However, this is true for the particular TDD configuration that has been adopted, which is the best option for achieving low latency. Adopting different UL / DL patterns that are more aligned with eMBB-type traffic will lead to different results.

- For 700 MHz, changing ISD does not make a huge difference in terms of SE for either DL nor UL. Differently, it makes a big difference for the 4GHz DL system, where changing ISD from 500m to 250m can bring SE gains up to almost 50%. For the 4GHz UL system, the performance dependency on ISD is weaker. This is in line with the key observations highlighted in Section 5.4.1 for the SINR distributions.

- For the average DL SE, there is a big difference between the 700MHz system and the 4GHz system for the different targets. The best performance is as follows:

    o For Target 1, the 700MHz system achieves approximately 1.2 bps/Hz (independent of ISD) and the 4GHz system delivers up to 5.0 bps/Hz with a 250m ISD. Both these results are achieved with NR, 30KHz SCS, FDD 14OS.

    o For Target 2, the 700MHz system achieves approximately 1.3 bps/Hz (independent of ISD) and the 4GHz system delivers up to 5 bps/Hz with a 250m ISD. Both these results are achieved with NR, 30KHz SCS, FDD 14OS.

    o For Target 3, the 700MHz system achieves approximately 0.8 bps/Hz (independent of ISD) and the 4GHz system delivers up to 3.5 bps/Hz with a 250m ISD. Both these results are achieved with NR, 30KHz SCS, FDD 4OS.

- For the average UL SE, there is a performance gap between the 700 MHz system and the 4GHz system for Targets 1 and 2, but the gap is much lower than what is observed for the DL, and there is no gap for Target 3.

It is important to highlight that these results have been obtained with the specific traffic pattern described in Section 5.3.1, which is representative of URLLC services. For a more DL-biased asymmetry ratio targeting eMBB scenarios, which are out of the scope of this work, these conclusions would be different.

It should be noted that these SE values account for OH introduced by the physical layer, but not for the OH introduced by the L2 radio protocols, like medium access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP) and for NR also service data adaptation protocol (SDAP). Those protocols would add in the order of 5-7 bytes of protocol OH to any application packet entering the radio access network. For large messages sizes, like the 1500 bytes for Target 1, this adds a marginal OH of around 1%-2%; for small message sizes like the 40 bytes of targets 2 and 3 the OH would be around 10%-12%. It should also be noted that further higher layer protocols may be used to transfer messages end-to-end, like e.g. UDP/IP or Ethernet. Those would add additional headers, which may however be compressed again by the header compression schemes applied by the PDCP layer in the radio access network.
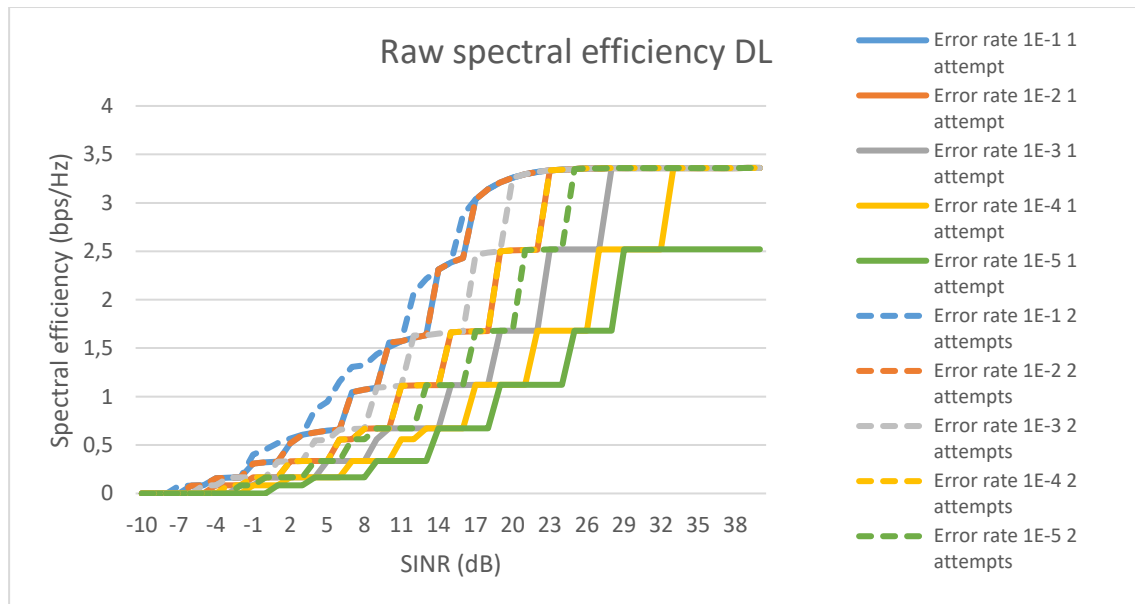
Figure 12. DL raw per-link spectral efficiency as function of SINR for 1 and 2 transmission attempts and different target error rate.
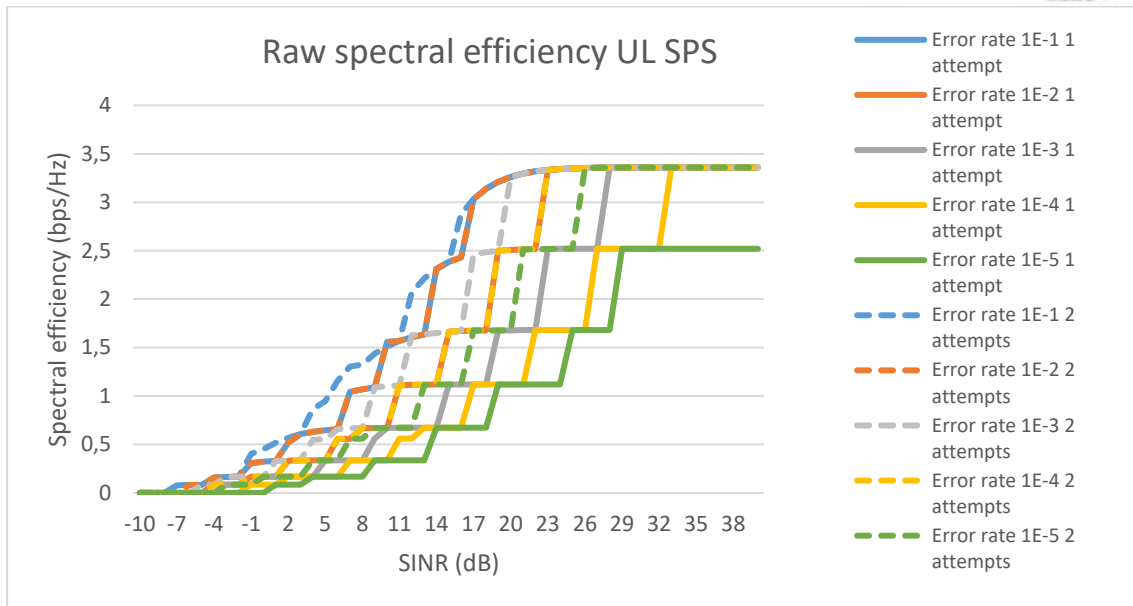
Figure 13. UL raw per-link spectral efficiency with Semi-Persistent Scheduling (SPS) as function of SINR for 1 and 2 transmission attempts and different target error rate.
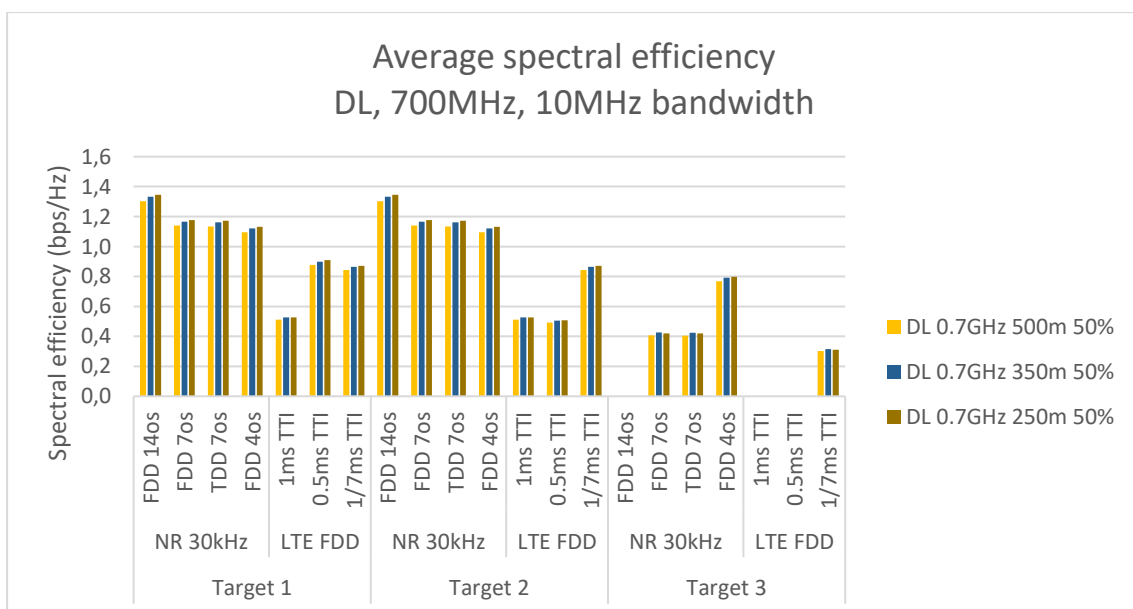
Figure 14. Average DL spectral efficiency. 700MHz carrier 10MHz bandwidth.
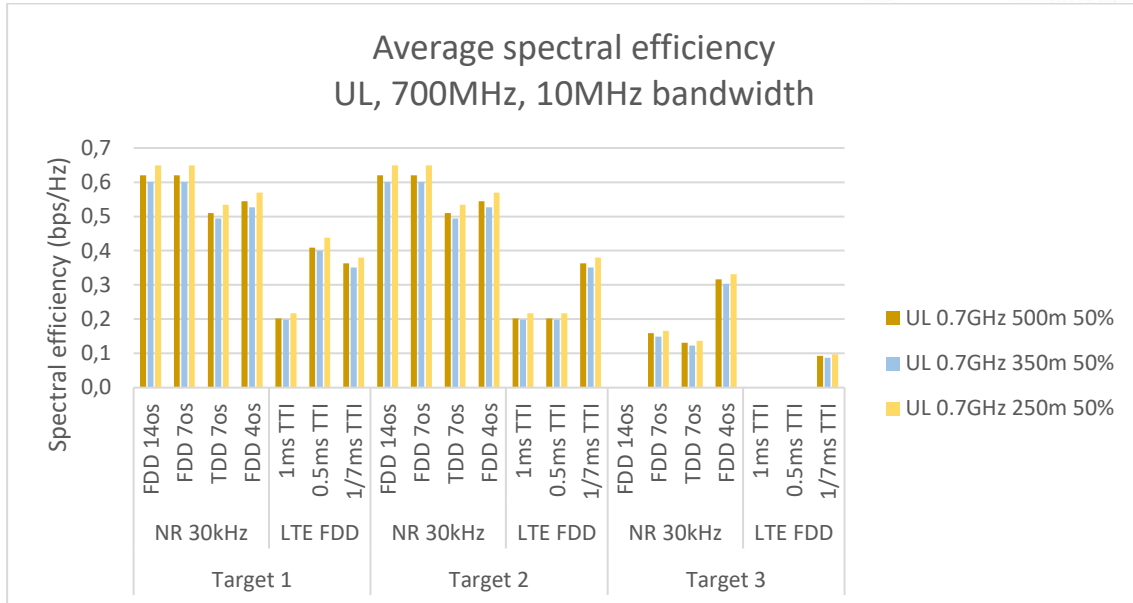
Figure 15. Average UL spectral efficiency. 700MHz carrier 10MHz bandwidth.
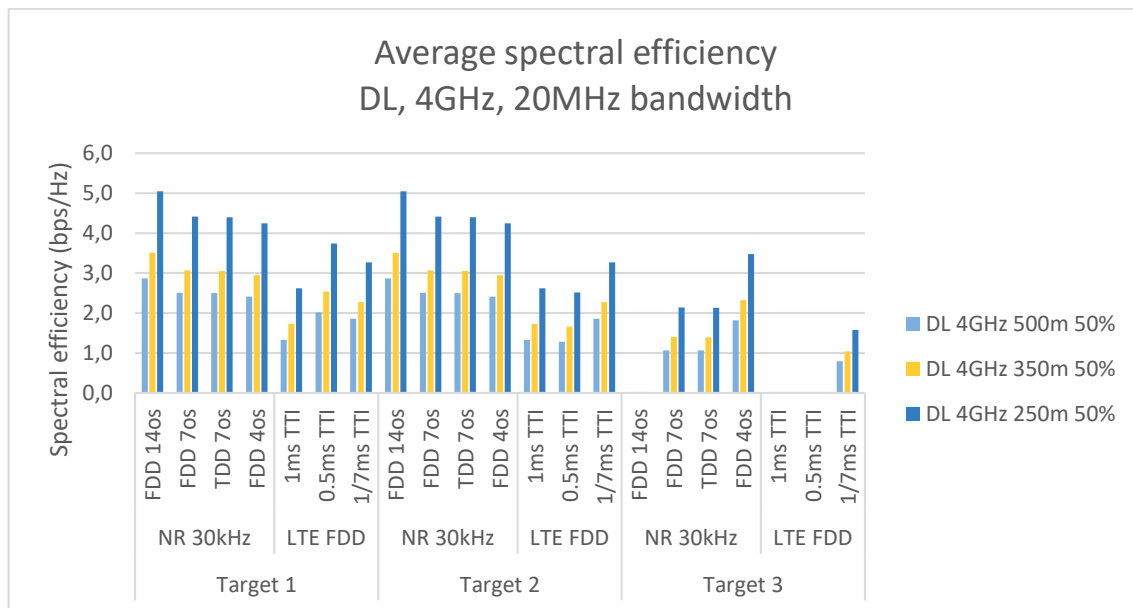
Figure 16. Average DL spectral efficiency. 4GHz carrier 20MHz bandwidth.
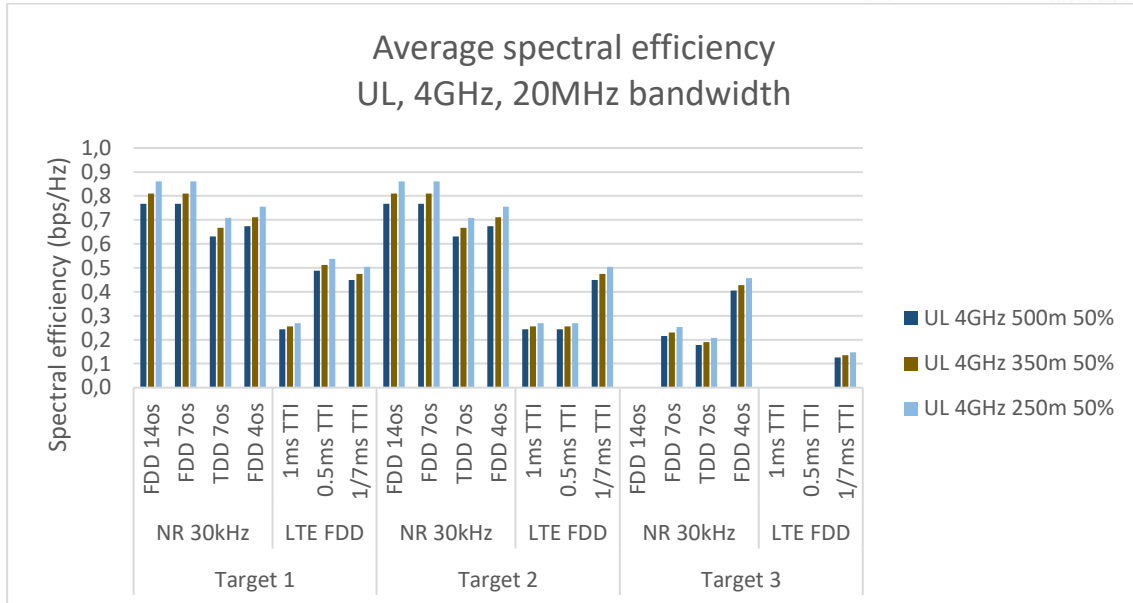
Figure 17. Average UL spectral efficiency. 4GHz carrier 20MHz bandwidth.

5.4.3   Traffic capacity

Based on the average SE from Section 5.4.2.2, the traffic capacity per unit area can be derived from the cell area. Here, the idea is that the traffic is generated over the area of the cell, and the traffic area capacity should be interpreted as the amount of traffic per unit area that can be handled by the network. A denser network here obviously leads to higher capacity, since the spectrum is reused more times within the area. In this study 50% network load is considered as a reference point. It should be noted that the requirement on payload size to be sent in one (or more, if segmentation is assumed) TTIs is still not considered in these calculations, but only total error rate and latency targets are considered.

The results are shown in Figure 18 -Figure 21. As can be seen, the combination of very low latency and high reliability of Target 3 leads to a lower traffic capacity compared to the other targets. As these results are derived directly from the average SE results, the same key remarks that are outlined in Section 5.4.2 are in order.
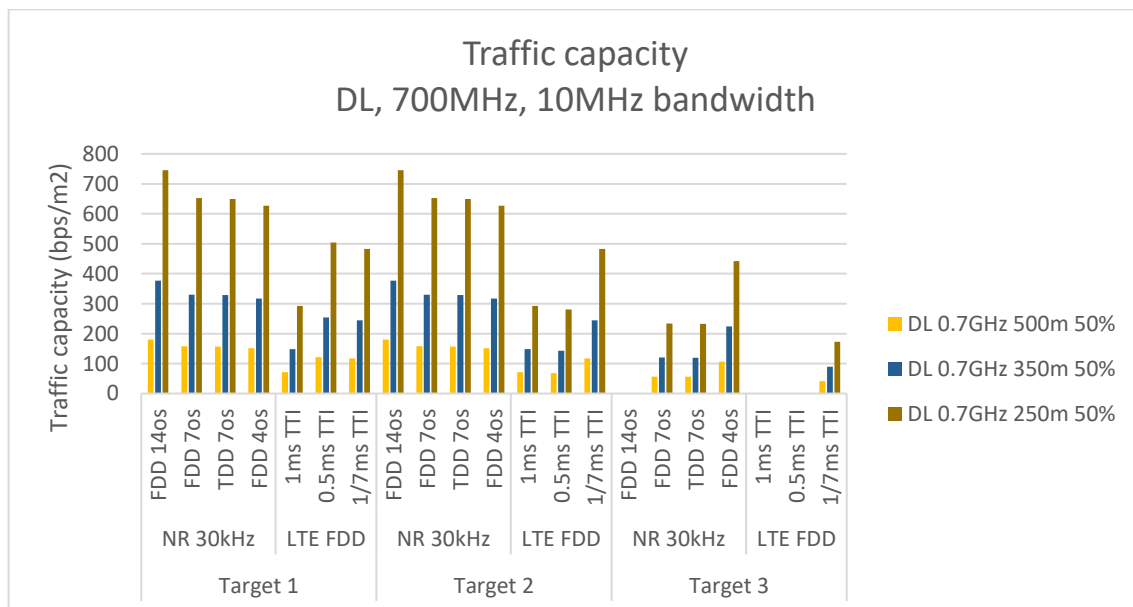
Figure 18. DL traffic capacity, 700MHz carrier 10MHz bandwidth.
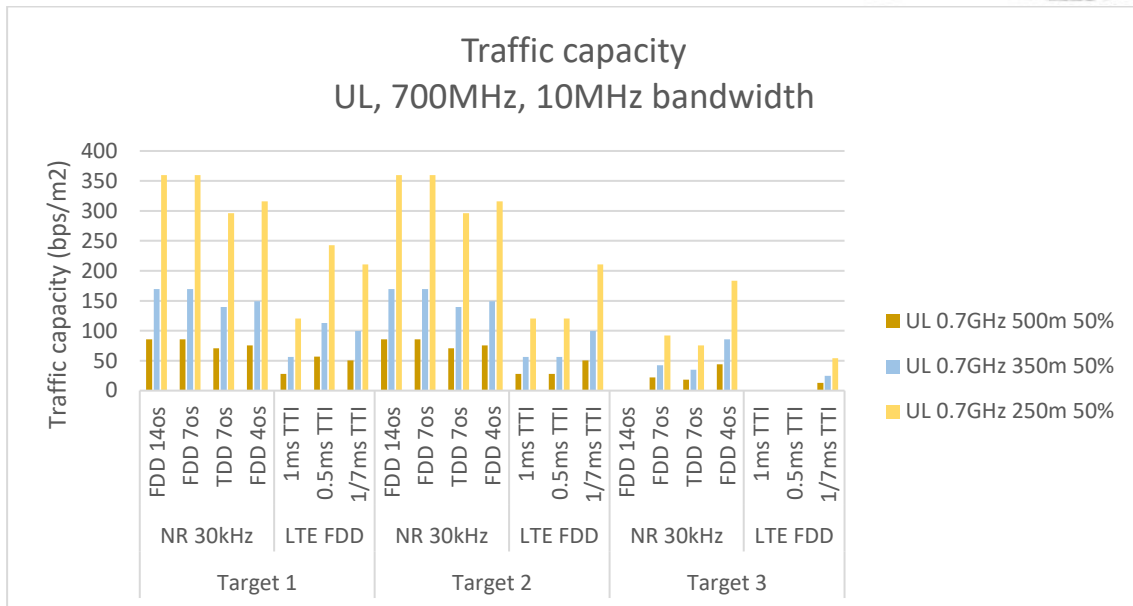
Figure 19. UL traffic capacity, 700MHz carrier 10MHz bandwidth.
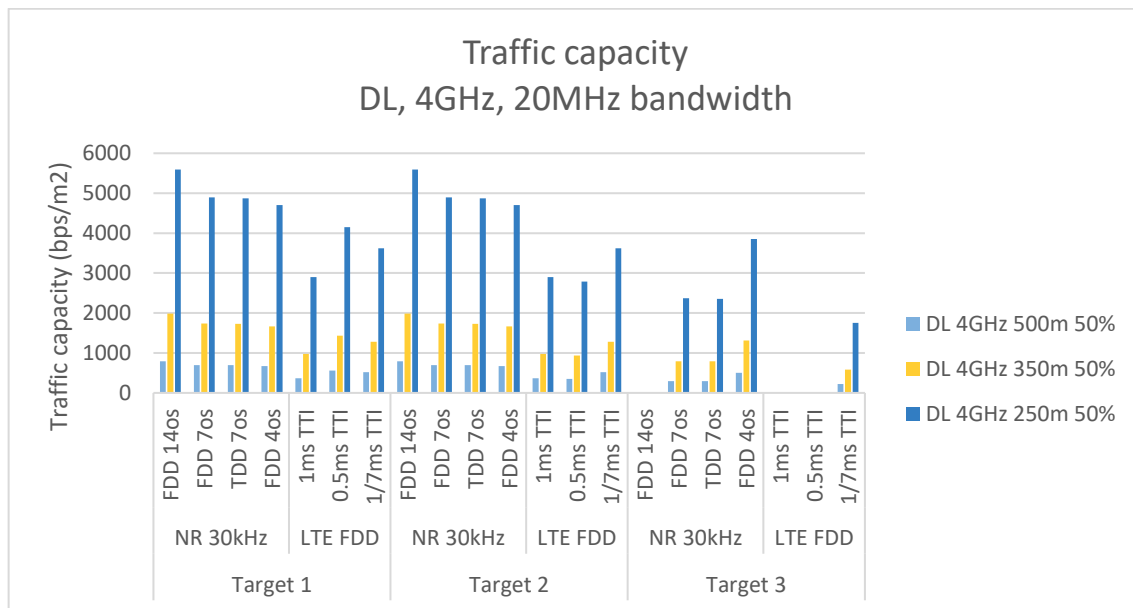
Figure 20. DL traffic capacity, 4GHz carrier 20MHz bandwidth.
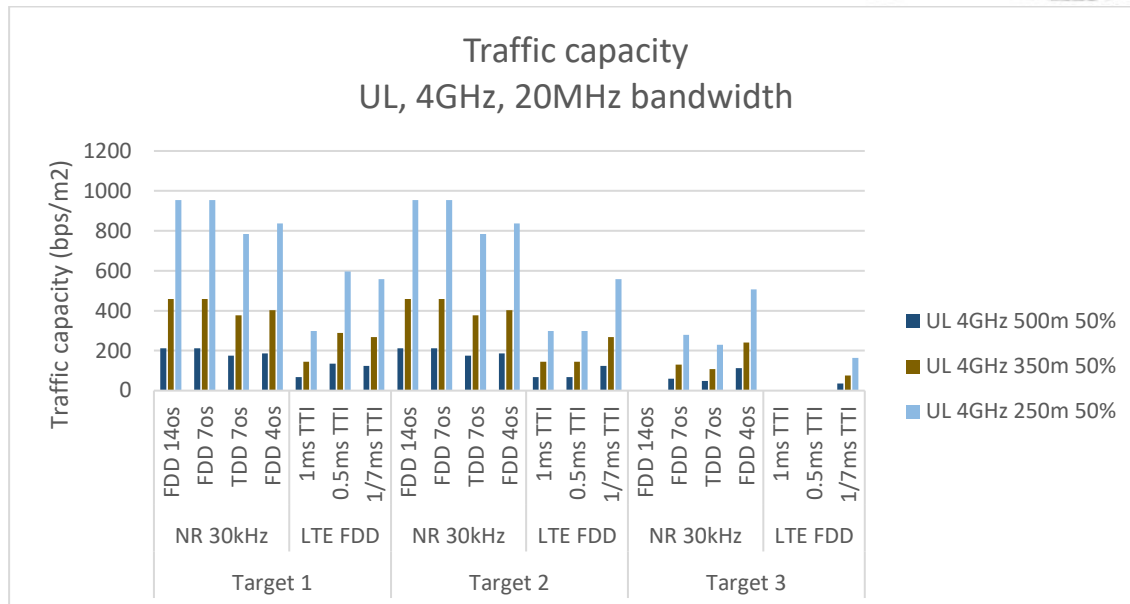
Figure 21. UL traffic capacity, 4GHz carrier 20MHz bandwidth.

5.4.4 Maximum payload

In Sections 5.4.2 and 5.4.3, the general performance for different radio access configurations considering different targets on error rate and latency has been evaluated. The requirements on sending a certain payload in one or more (if segmentation is assumed) TTI on a given carrier is now here considered, which has an impact on the coverage area of a given service.

In this section, instead of studying the service coverage for a fixed setup of target requirements or varying the bandwidth in order to reach the requirements, the largest payload that a message can carry within one TTI is evaluated. This is calculated for the different target requirements according to Table 2, so that the requirements on latency, error rate, and coverage are fulfilled. This points at what services can actually be supported if not exactly the ones in Table 2. The maximum supported message size (payload) is shown in Figures Figure 22 Figure 27 for DL and UL and the studied radio access configurations, and in

Table 17 in the Appendix. The supported payload is correlated with the amount of resource elements that are contained within a TTI, which is the product of the carrier bandwidth and TTI duration. For example, on the same carrier an LTE configuration with a 1ms TTI has double the amount of resource elements as an NR configuration with 14OS (i.e. 0.5ms TTI duration), whereas a LTE configuration with 0.5ms TTI has the same amount of resource elements per TTI as the NR 14OS configuration.

The following remarks are in order:

- As can be seen from FiguresFigure 22Figure 27, different targets on latency and reliability allow for very different payload sizes. Moreover, for a given target, different radio access technologies will support different payload sizes, which, as explained above, depend on the number of symbols that the radio access technology can support within the TTI duration and the amount of bandwidth allocated to the service.

- Network load strongly affects the capability of delivering a given message size within latency and reliability bounds, and this applies to both the 700MHz and the 4GHz networks. This can be observed in Figures Figure 23Figure 26, which show the DL performance for the two different networks at different load points. In some cases, as the load increases to 90%, it is not even possible to deliver the service.

- The 4GHz network is more sensitive to changes in ISD than the 700MHz network, as explained in Section 5.4.1.

Figure 22. DL maximum payload for coverage of the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Zero indicates no service. Sensitivity to ISD.

Figure 23. DL maximum payload for coverage of the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Zero indicates no service. Sensitivity to cell load.

Figure 24. UL maximum payload for coverage of the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Zero indicates no service. Sensitivity to ISD.

Figure 25. DL maximum payload for coverage of the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Zero indicates no service. Sensitivity to ISD.

Figure 26. DL maximum payload for coverage of the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Zero indicates no service. Sensitivity to cell load.

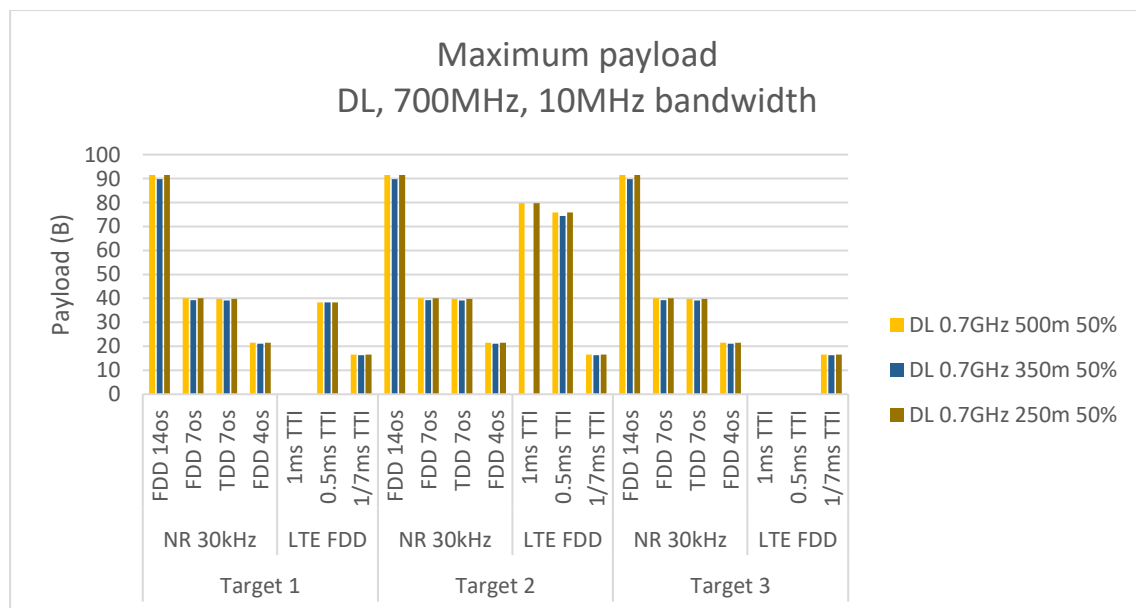**Figure 27. UL maximum payload for coverage of the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Zero indicates no service. Sensitivity to ISD.**
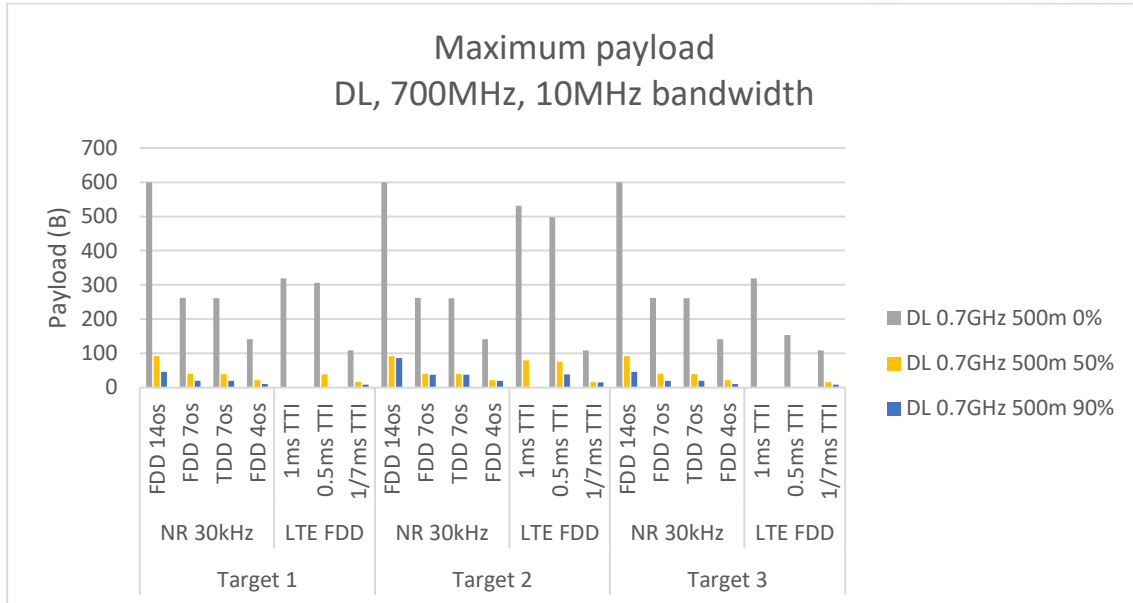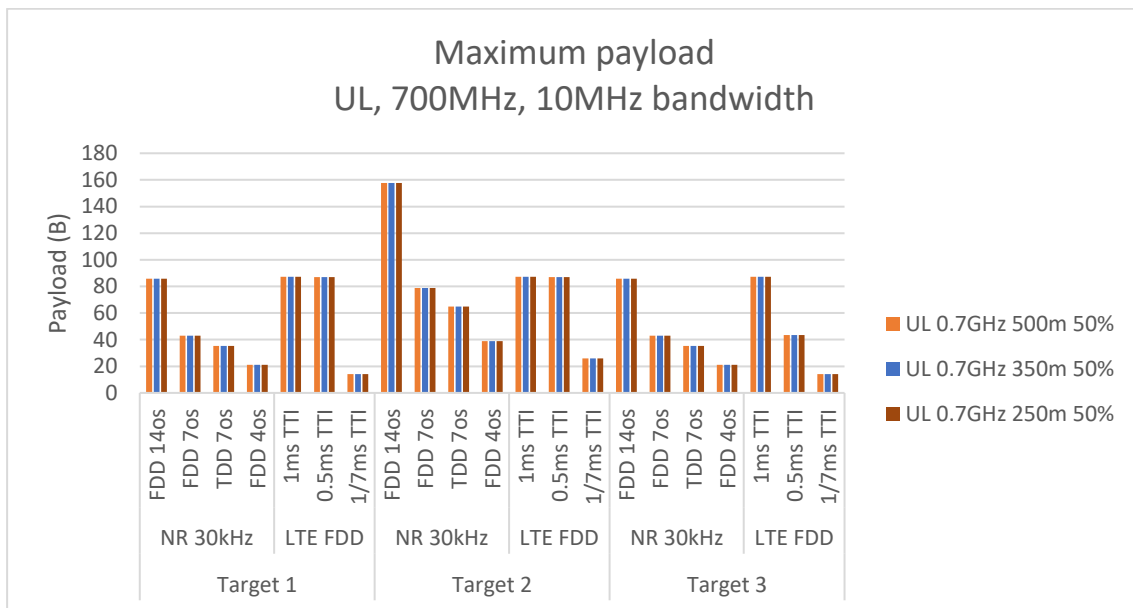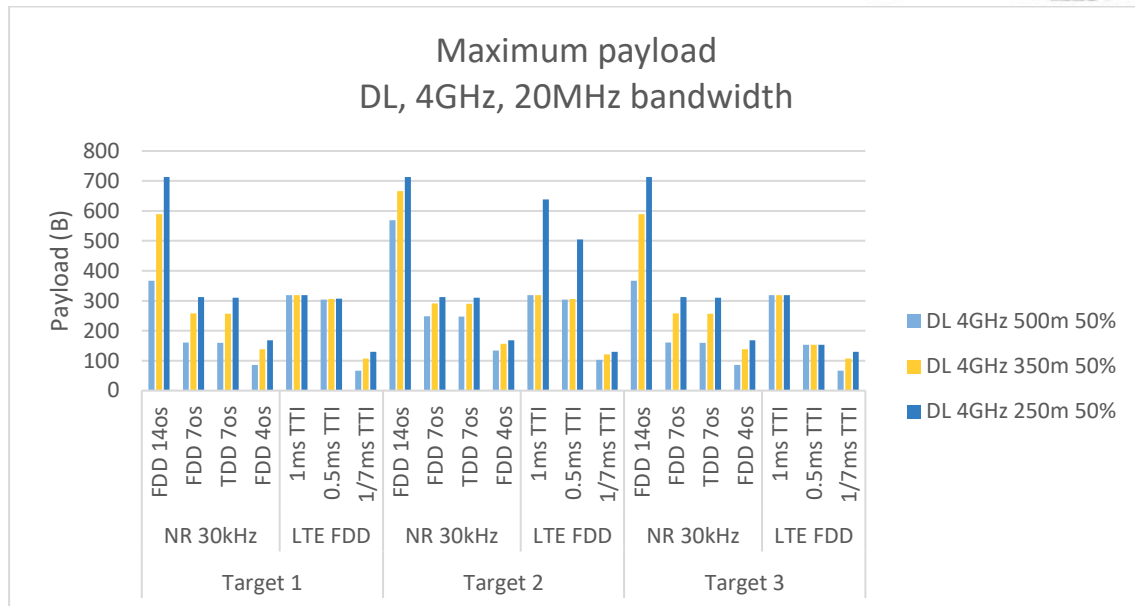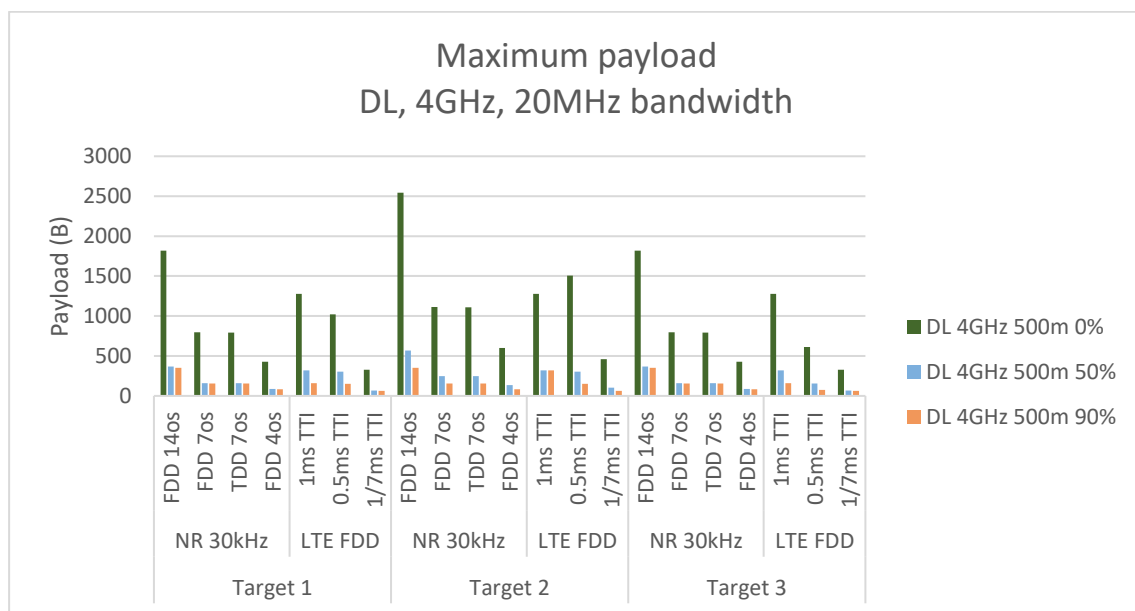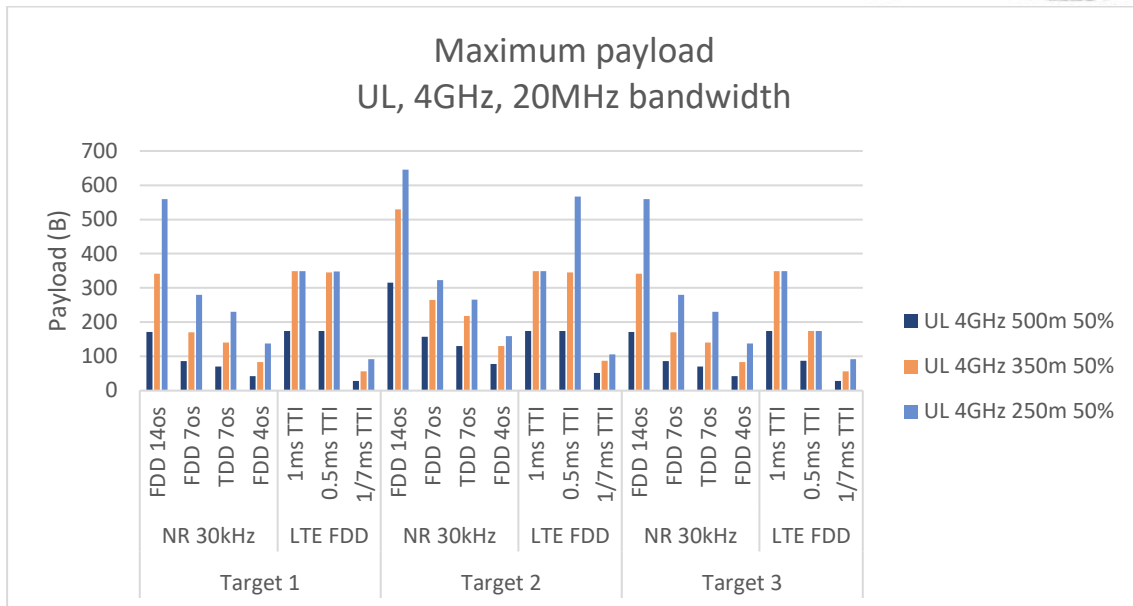
5.4.5 Service coverage

From the target requirements on latency, error rate, and payload size, and the SINR distribution of the radio access configuration, the percentage of the users that can be served according to the targets described in Table 2 can be found. Since the users are uniformly distributed on the coverage area (with 20% of users located indoors), this percentage is the service coverage as defined in Section 4, and is shown in Figure 28 - Figure 33 for DL and UL and the studied radio access configurations. The values for all combinations are given in Table 15 in the Appendix. In some cases the service coverage is equal to or higher than the required coverage of Table 2, and in other cases it is lower, which in the latter case corresponds to not meeting the target. Still, even if the target is not fully met, it is interesting to study to what extent the target can be met. When the coverage value is zero, this means that the system cannot support the targets, i.e., a specific combination of latency, reliability, and payload size.

As mentioned in Section 5.2, a large message can be segmented into several chunks that can fit within the considered TTI, which leads to lower requirements on instantaneous bitrate, at the expense of reliability. In this case, the reliability per chunk needs to increase to ensure that all segments are delivered with the total target reliability. Segmentation is applied to Target 1, which requires fast transfer of large messages, for which the requirements on latency and reliability are not extreme. Transmitting 1500B in a single TTI without segmentation across multiple TTIs is in fact challenging in several configurations. If the bandwidth is limited, e.g. 10MHz, or if the TTI is short, there are not enough resource elements to transmit the data with low enough code rate. This has the effect that the error rate can't be arbitrarily low.

As already mentioned in Section 5.3, it should be noted that a certain load level corresponds to a certain traffic volume in a single cell. If the cell density is increased by reducing the ISD, the total traffic volume served by the network will increase even if the utilization level per cell remains constant. This is because more cells carry the same amount of traffic per cell. This should be kept in mind when comparing results for different ISDs. In a real system, the utilization level would typically be reduced when the ISD is decreased, since the load would not scale up with the number of cells but instead remain constant.

The following key remarks are in order:

- At 700 MHz:

  o The service coverage is basically independent from ISD. Since the network load scales with the site density, the benefit of densifying is counterbalanced by the increase in system interference and the service coverage is greatly impacted by network load.

  o Both FDD and TDD are considered for NR with 7 OS and the performance of the two duplexing schemes across the three targets is always similar except for Target 3 in the UL direction at 50% network load. In the latter scenario, in fact, TDD achieves 15 % UL coverage, whereas 65% is achieved with FDD. This is due to the fewer retransmissions possible with TDD within a certain latency limit.

  o For Target 1-type of services, which require fast transfers of large messages (assuming segmentations into 5 different packets), up to 70% service DL coverage can be achieved with NR and 50% with LTE when there is a 50% network load. As the load increases to 90% the DL coverage drops to 50% with NR and to 30% with LTE. In UL, when the network is at 50% load, 60% and 40% coverage levels can be obtained with NR and LTE respectively.

  o Target 2 services can be delivered across most of the coverage area for both air interface technologies: 99% and 90% DL coverage area are in fact achievable with NR and LTE respectively with 50% network load. These values then drop to 95% and 80% when the load goes up to 90%. A good UL performance is also achievable: 99% (NR) and 95% (LTE).

- o Target 3 services can be provided only with reduced service coverage: with 50% load, NR can deliver 70%, whereas LTE can achieve 30% coverage. When the load increases to 90% the DL service coverage drops at 50% for NR and 15% for LTE. In the UL direction, NR can deliver 60% coverage at 50% load, whilst LTE cannot support this service. This is due to the fact that LTE cannot support enough message retransmissions to deliver the required reliability within the latency bound. With only one transmission attempt the lowest code rate that can be supported given the considered bandwidth is not sufficiently robust.

- At 4 GHz:

    - o Both FDD and TDD are considered for NR with 7 OS and the performance of the two duplexing schemes with this TTI length across the three targets and different network loads is always similar except for Target 1 in the UL direction with 50% network load. In this case, in fact, there is a 20 % coverage difference at 500m ISD (with FDD achieving 80% and TDD 60%), and a 10% coverage difference at 250m ISD (with FDD achieving 90% coverage and TDD 80%). Also here, the increased latency in TDD has an impact on the number of possible retransmissions within the latency budget, restricting coverage.

    - o Target 1 services, assuming segmentations into 5 packets, can be provided with both LTE and NR: both LTE and NR can in fact achieve close to 100% coverage in the DL at 50% load. This is obtained with an ISD equal or below 350m, a 1ms TTI, and FDD. As the load increases to 90%, the DL coverage drops by 5% and 10% for NR and LTE respectively. In the UL, at 50% network load, 95% and 99% coverage levels are achieved by LTE and NR FDD, respectively, both with a 1ms TTI.

    - o Target 2 services can be provided by both LTE and NR: 99% of DL coverage can be delivered by both NR and LTE when the network is at 50% load. As the load increases to 90%, the DL coverage drops to 95% for LTE, and remains at 99% for NR. In UL, both radio technologies can deliver 99% coverage at 50% load then the ISD is equal or below 350m.

    - o Target 3 service can be provided by NR; LTE can provide such services only with reduced coverage. The network in fact delivers up to 99% and 90% coverage with NR and LTE respectively at 50% load in the DL direction. As the load increases to 90% the DL coverage drops to 95% for NR and 65% for LTE, for the highest considered site density (ISD of 250m). In the UL direction, at 50% load, 99% and 70% service coverage area can be achieved with NR and LTE, respectively.

- As can be seen from Figure 30, there is substantial difference between the performance of FDD and TDD for the UL service coverage delivered by NR with 7OS at 700MHz. Differently, this difference is not reflected in Figure 33 for the UL service coverage delivered by the 4GHz network. This is because the timing differences between FDD and TDD have a strong impact due to fewer retransmissions close to the service coverage limit, and because of bandwidth limitation at 700MHz. 10MHz are in fact allocated for the 700MHz network whereas 20MHz are available for the 4GHz network.
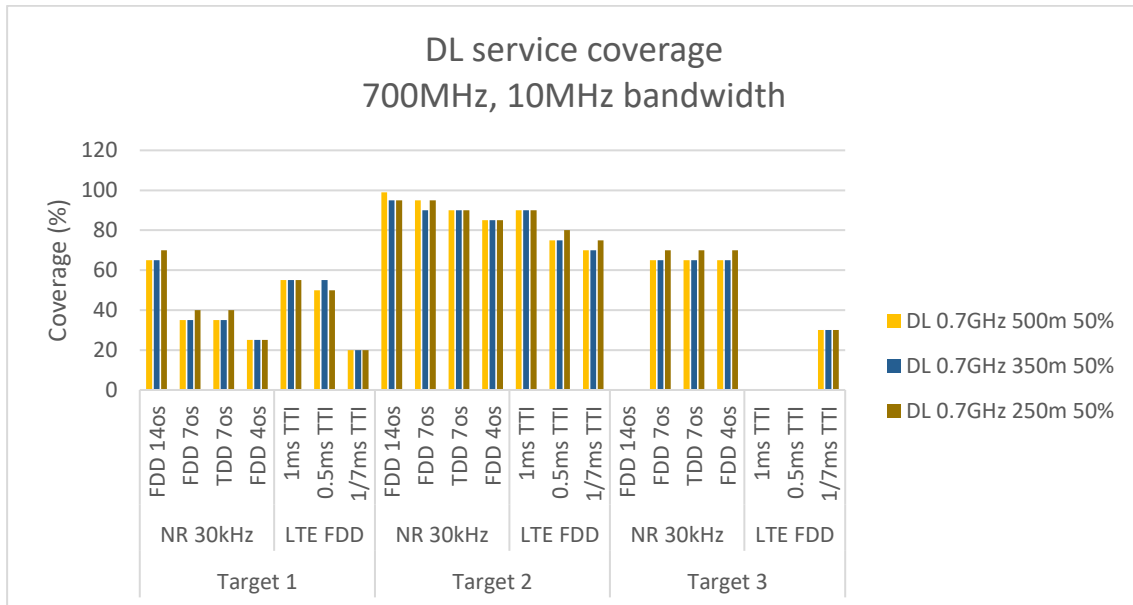
Figure 28. DL service coverage for the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Sensitivity to ISD.
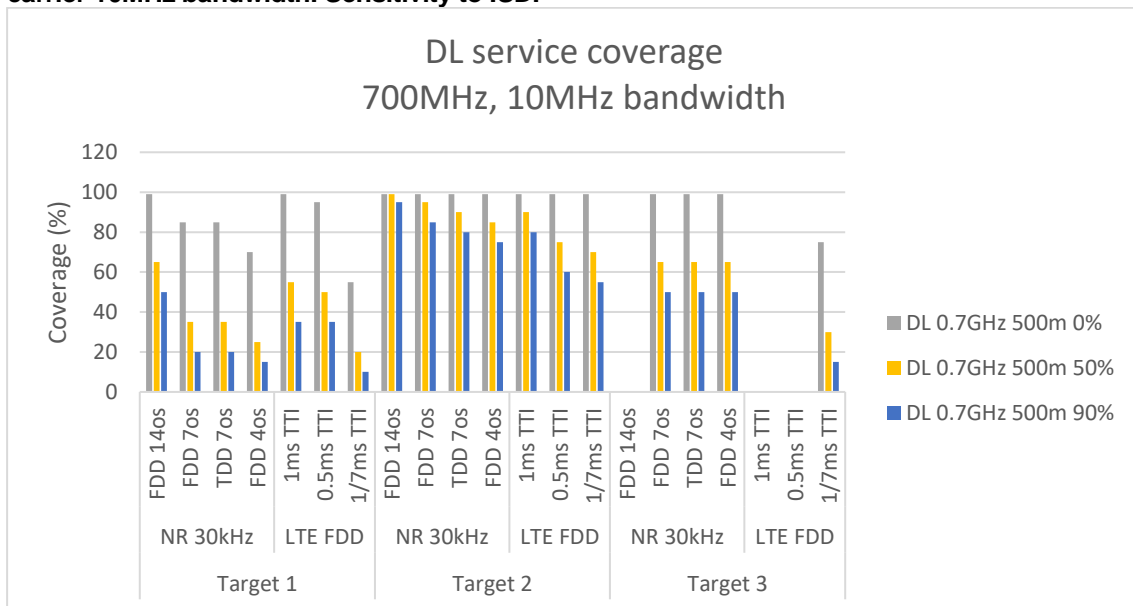
Figure 29. DL service coverage for the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Sensitivity to cell load.
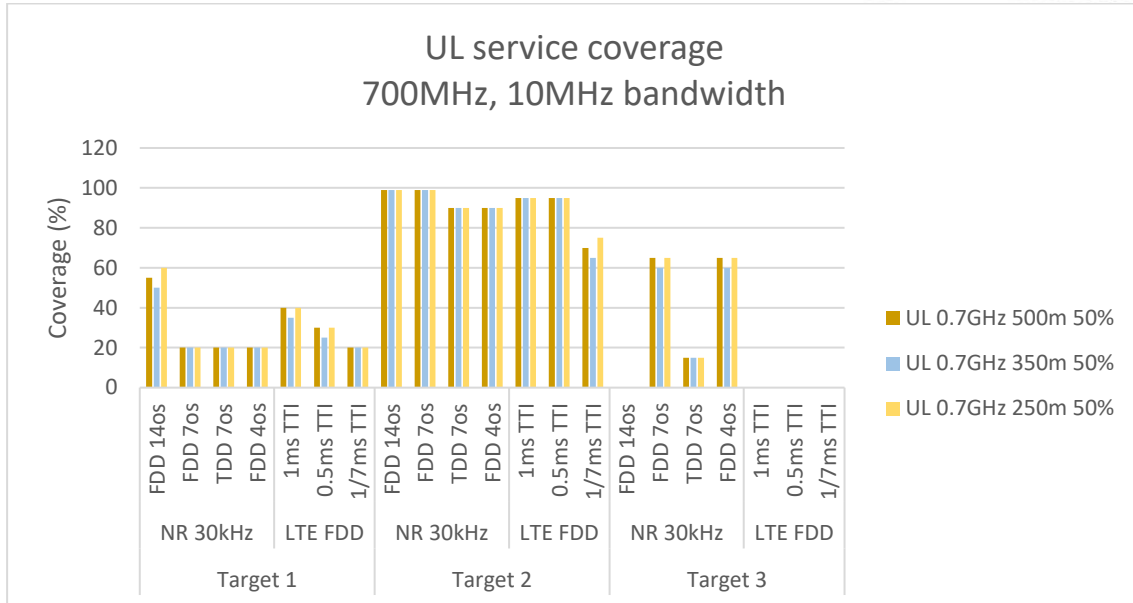
Figure 30. UL service coverage for the studied targets and radio access configurations, 700MHz carrier 10MHz bandwidth. Sensitivity to ISD.
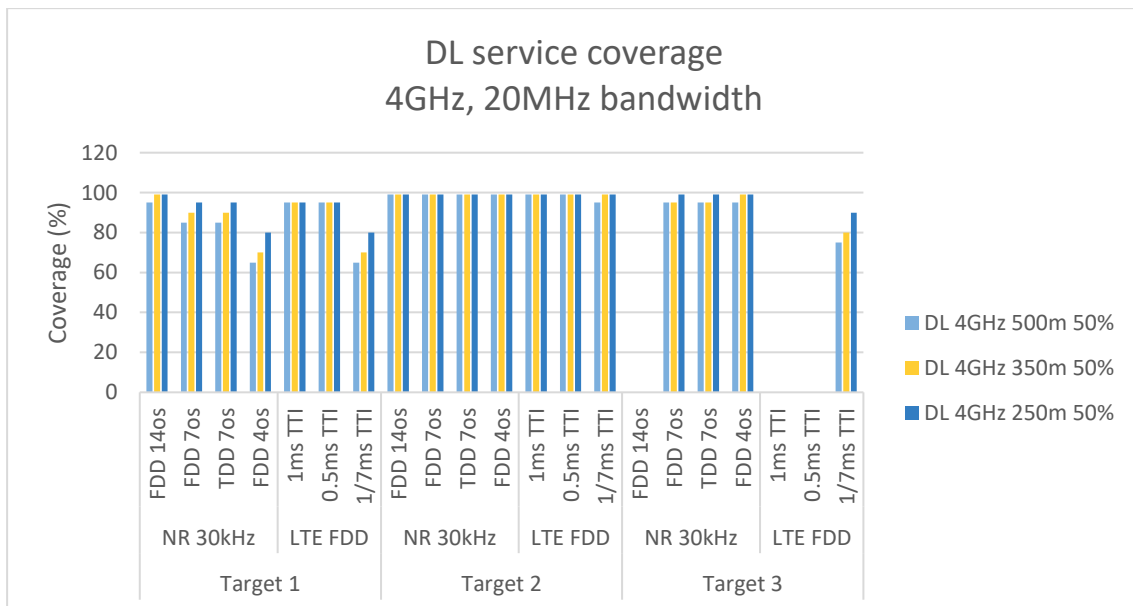
Figure 31. DL service coverage for the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Sensitivity to ISD.
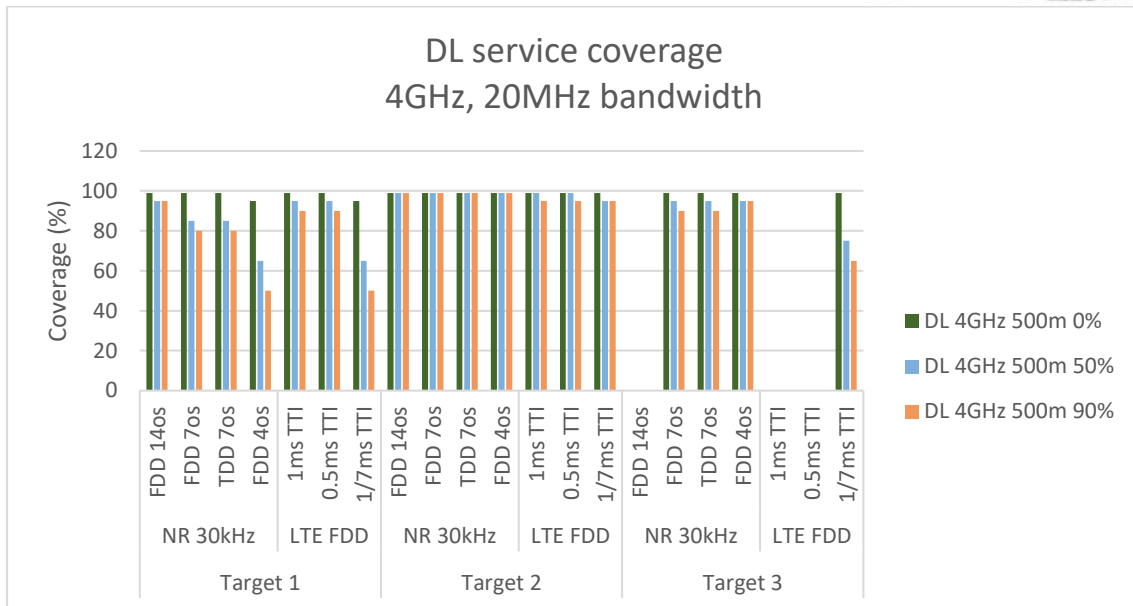
Figure 32. DL service coverage for the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Sensitivity to cell load.
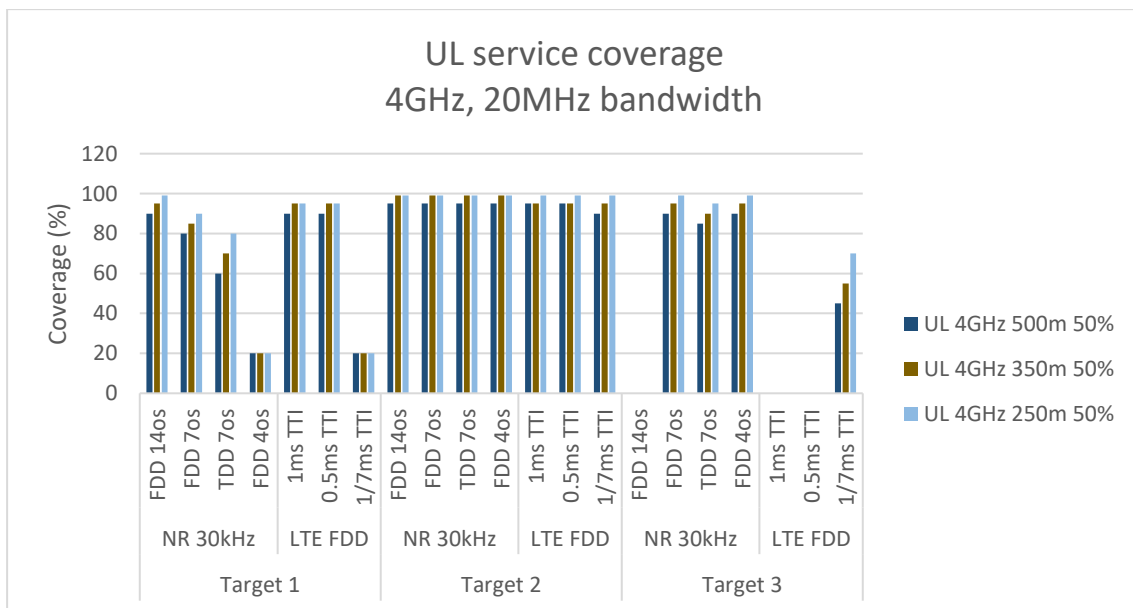
Figure 33. UL service coverage for the studied targets and radio access configurations, 4GHz carrier 20MHz bandwidth. Sensitivity to ISD.

5.4.6 Required bandwidth

In order to meet the targets defined in Table 2, different radio access configurations are studied, as shown in Table 5. As can be seen in Section 5.4.5, the service coverage does not always meet the required level, meaning that only part of the UE population is served. In that scenario, the bandwidth was fixed for each of the studied bands.

By increasing the bandwidth, a higher fraction of UEs can meet the target requirements and thus the service coverage area can be extended. This is an alternative way of improving coverage if the SINR cannot be improved by densification or if the radio access cannot be improved either. However, since the UL power can be limited, adding more bandwidth is not beneficial for low UL SINR.

In Figure 34 - Figure 39 the required bandwidth values to reach the latency, reliability, payload size, and coverage targets from Table 2 are shown for DL and UL with the studied radio access configurations. Here, zero means the target can't be met even at the maximum considered bandwidth. The numbers for all combinations are given in

Table 16 in the Appendix.

As can be seen in the graphs, in some cases an increase in bandwidth does help in improving the service coverage area. In other cases, increasing bandwidth is not helpful: this applies to the cases when the SINR is too low and the radio interface cannot support enough re-transmissions within the target latency bound to guarantee the desired reliability. In the UL the worst-off UEs are in fact power limited. This means that they cannot increase the bandwidth used for transmission without also lowering the SINR. Using a lower code rate in order to obtain lower error rate is therefore not efficient, and the performance is limited.
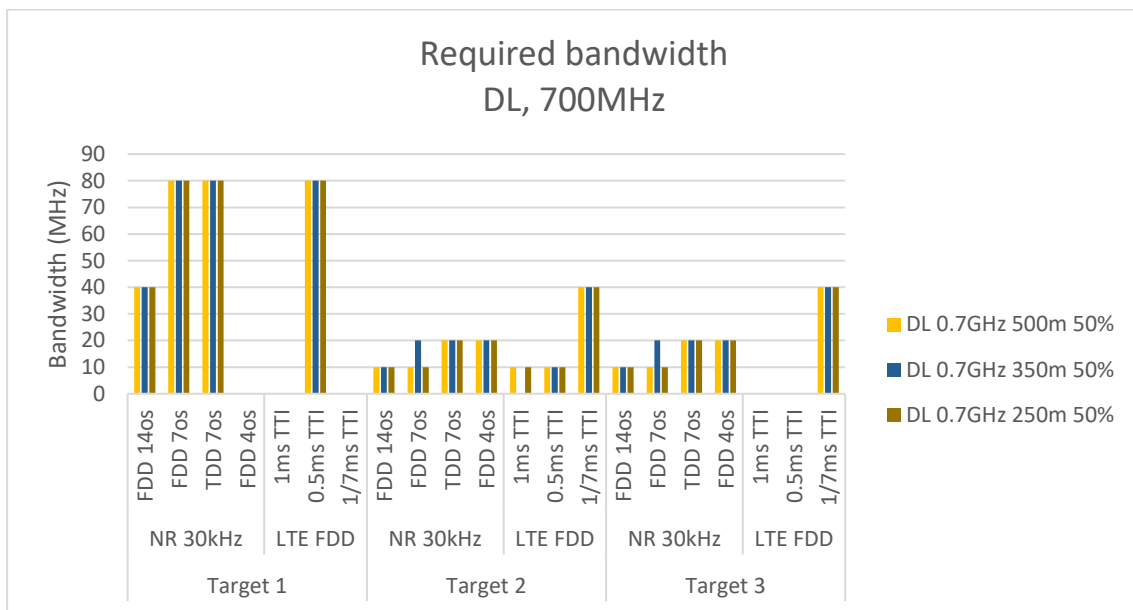
Figure 34. DL required bandwidth for required coverage of the studied targets and radio access configurations, 700MHz carrier. Zero indicates no service can be maintained within the target coverage area. Sensitivity to ISD.
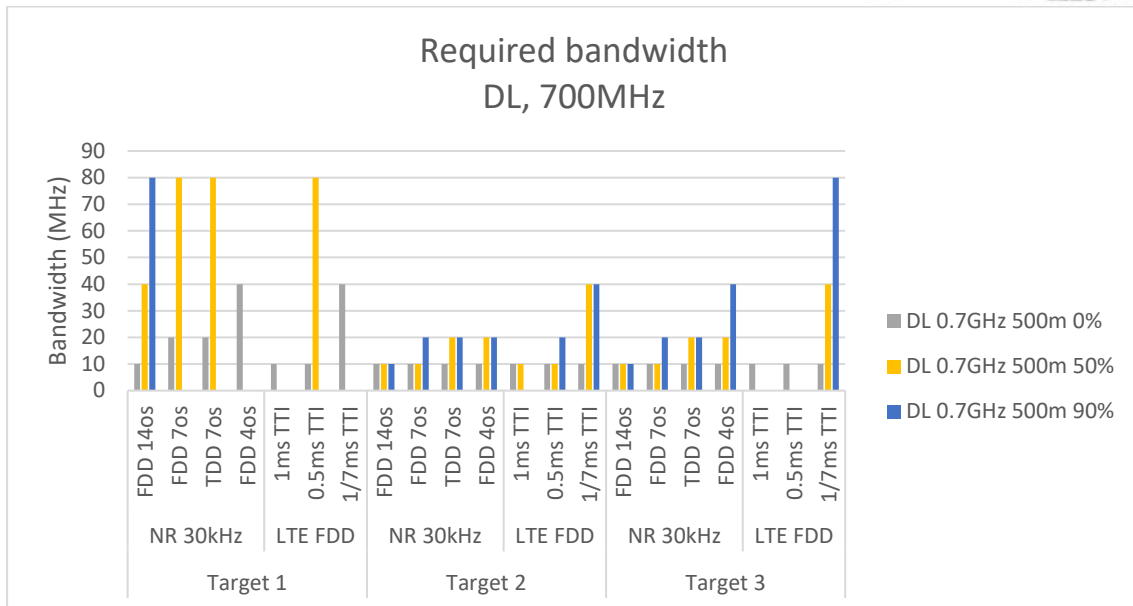
Figure 35. DL required bandwidth for required coverage of the studied targets and radio access configurations, 700MHz carrier. Zero indicates no service can be maintained within the target coverage area. Sensitivity to cell load.
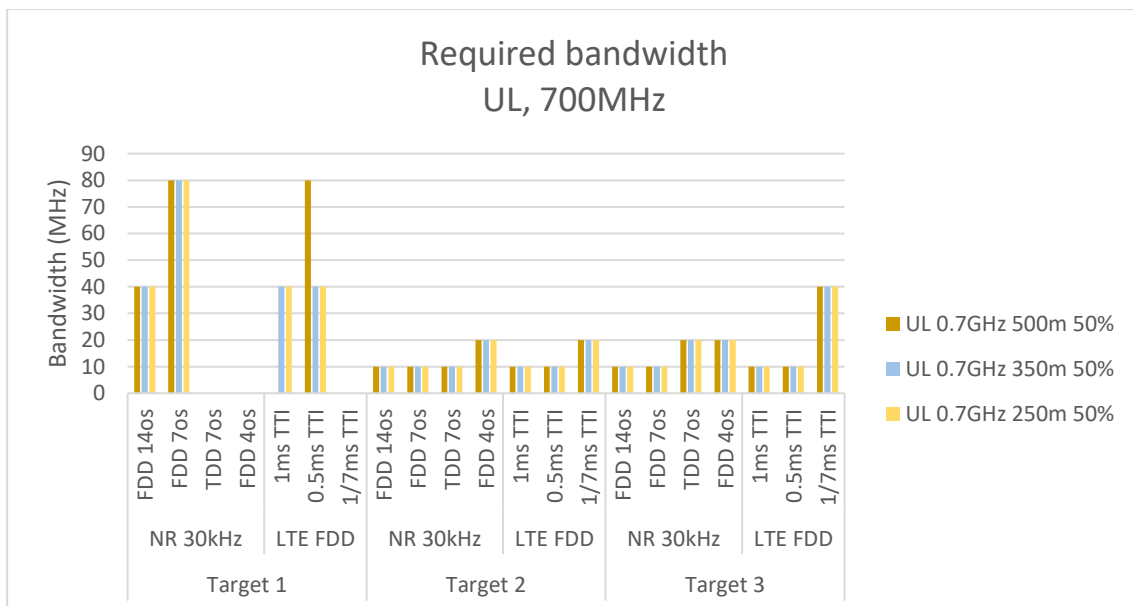
Figure 36. UL required bandwidth for required coverage of the studied targets and radio access configurations, 700MHz carrier. Zero indicates no service. Sensitivity to ISD.
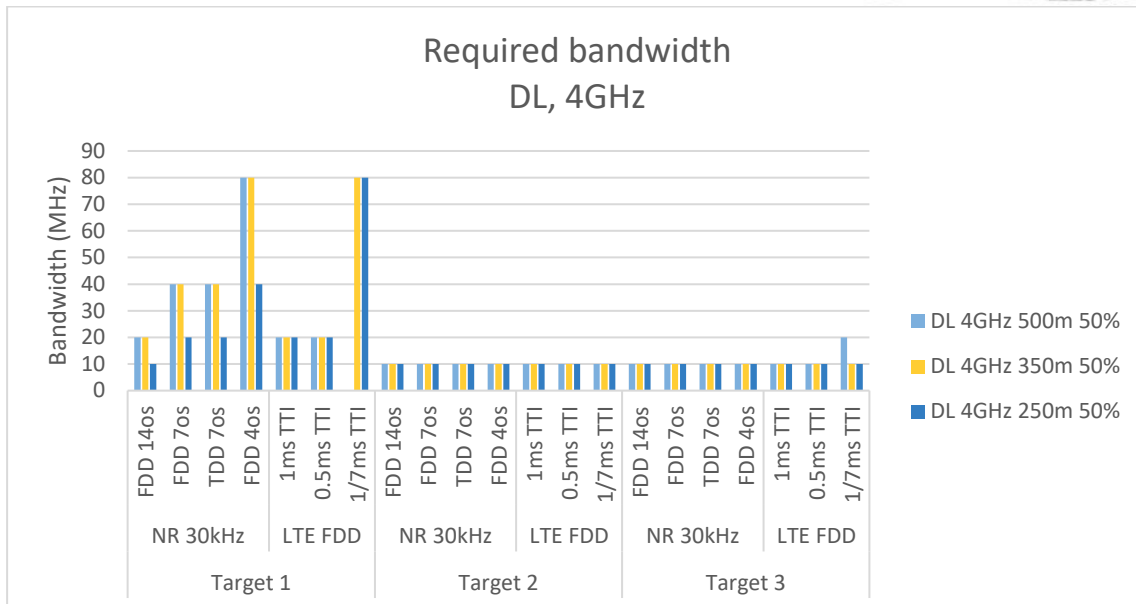
Figure 37. DL required bandwidth for required coverage of the studied targets and radio access configurations, 4GHz carrier. Zero indicates no service can be maintained within the target coverage area. Sensitivity to ISD.
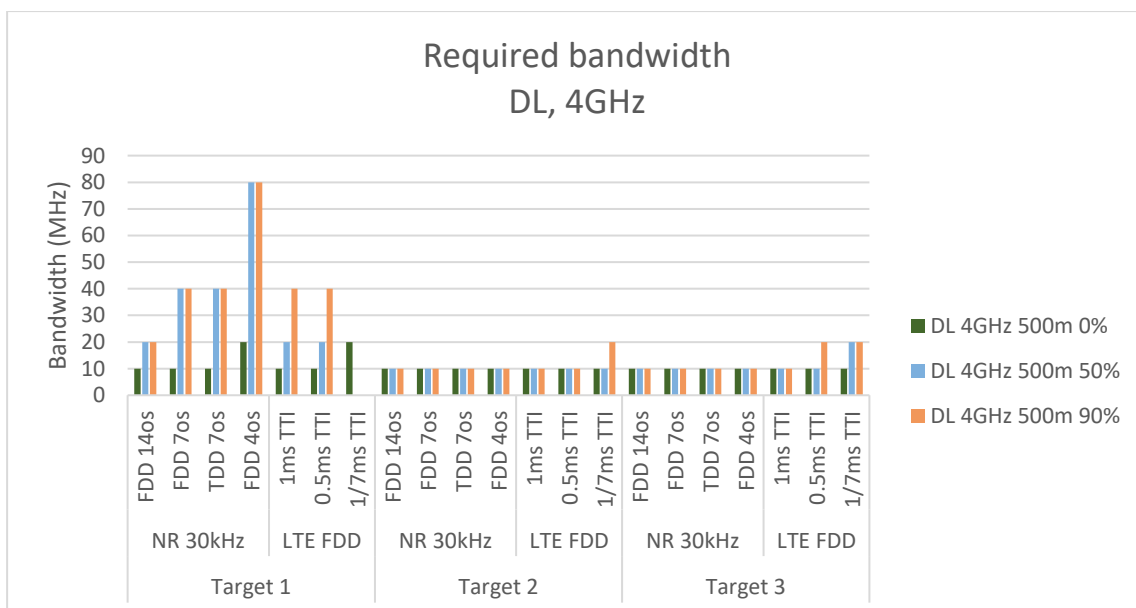
Figure 38. DL required bandwidth for required coverage of the studied targets and radio access configurations, 4GHz carrier. Zero indicates no service can be maintained within the target coverage area. Sensitivity to cell load.
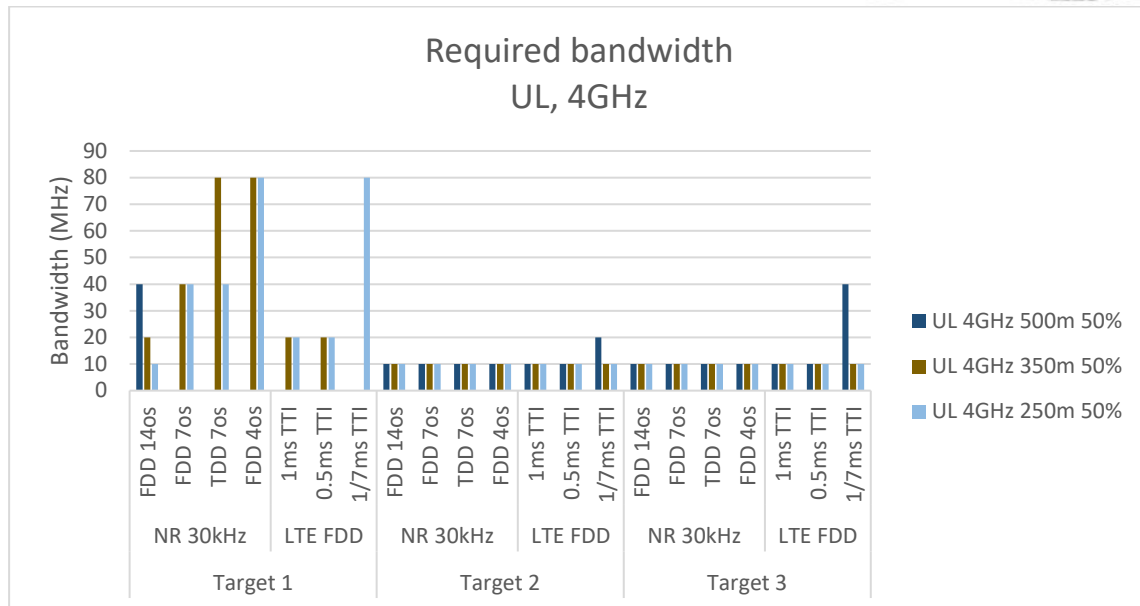
Figure 39. UL required bandwidth for required coverage of the studied targets and radio access configurations, 4GHz carrier. Zero indicates no service can be maintained within the target coverage area. Sensitivity to ISD.

6 COVERAGE AND MOBILITY TRIALS FOR URLLC

In this chapter, the coverage and mobility performances of URLLC are investigated for several packet sizes by field experimental trials. The target is to clarify the coverage and mobility speed for achieving URLLC requirements defined by 3GPP using real hardware and in real environments. To meet URLLC requirements, a new frame structure, which adopts wider subcarrier spacing and acknowledgement/negative acknowledgement-less (ACK/NACK-less) retransmission are used to reduce the user-plane latency and improve the packet success probability.

6.1 Frame Structure for URLLC

The new frame structure used in the trial test-bed for URLLC is introduced and the latency of using the new frame structure is estimated.
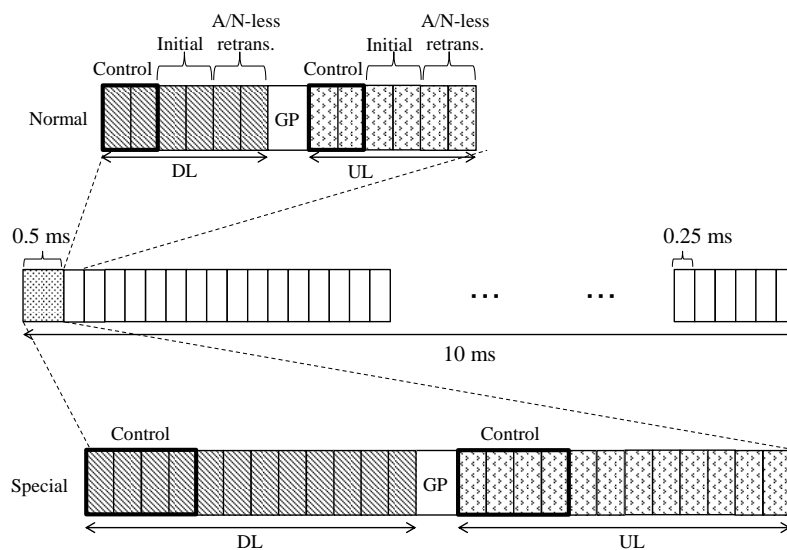
Figure 40 Frame structure for URLLC.

As shown in Figure 40, a new frame structure is introduced with reduced transmission time (minimum slot length of 0.25 ms (normal slot hereafter)). The subcarrier spacing used in the testbed is 60 kHz, and the OFDM symbol duration is 16.67 µs. The frame length is 10 ms and the frame is divided into 40 slots. The slot duration is 0.25 ms with 14 OFDM symbols including 6 DL symbols, 6 UL symbols and guard period (GP). The first two slots of each frame are combined in order to transmit additional UL control signals, e.g., a synchronization signal. The duration of this specially designed slot is 0.5 ms (special slot hereafter).

Each slot is divided into a DL part and UL part. Furthermore, the frame structure adopts ACK/NACK-less (A/N-less) retransmission method (repetition transmission) to reduce the latency from retransmission and achieve high reliability. In this method, the transmitter is pre-configured to send always the transmit signal multiple times irrespective of receiving the ACK or NACK feedback from the receiver. Although the A/N-less retransmission reduces the resource utilization efficiency since the same signal is redundantly transmitted, it improves the packet success probability while achieving lower latency compared to A/N-based retransmission. In many URLLC applications, since priority is given to reliability over data rate, A/N-less retransmission represents one attractive method for URLLC.

In Table 11, we show the examples of the observed values for processing time and transmission time using the new frame structure and assuming the normal slot.

The maximum and minimum user-plane latency using the frame structure of the trial is as illustrated in Figure 41 taking into account impact of frame alignment. If the delay associated with frame alignment time is included, the user plane latency increases by up to 250 µs for the normal slot and up to 500 µs for the special slot. The probability of an

application message arriving during a special slot is 5%. For URLLC services, where a latency bound is guaranteed with the defined reliability value, the maximum user-plane latencies of the special slots should be considered.

If a packet exceeds the transport block (TB) size depending on the selected modulation and coding scheme (MCS), the packet is divided into several TBs. Then, several slots are used to send the packet because one TB is transmitted using one DL or UL slot. As a result, the latency increase. Since the normal slot length is 250 μs, the user-plane latency increases by 250 μs for each additional TB. Also, when the special slot is used, the user-plane latency increases by 250 μs because the special slot length is 250 μs longer than the normal slot. If a packet is transmitted by using the special slot. Furthermore, A/N-based retransmissions incur longer latencies. When A/N-based retransmissions occurs, then the HARQ RTT, which is 750 μs in the normal slot, is added to the user-plane latency. In our experiment, the user plane latency could still be within 1 ms for up to two TBs without A/N-based retransmission for the normal slot. When a packet is divided into more than three TBs or A/N-based retransmission occurs, the user-plane latency exceeds 1 ms. Considering the special slot and the frame alignment time, up to only one TB can satisfy the requirement. If a packet is segmented, the user-plane latency exceeds 1 ms in this case. Note that there is a difference between the DL and UL processing times because the processing time increases as the number of receiver antennas increases.

Table 11 Examples of Observed Values for Processing and Transmission Time (Normal Slot)

	Delay type	Value
a	BS DL processing time	175 μs
b	UE DL processing time	240 μs
c	UE UL processing time	195 μs
d	BS UL processing time	305 μs
t	Transmission time	110 μs

Downlink

(1) Normal slot
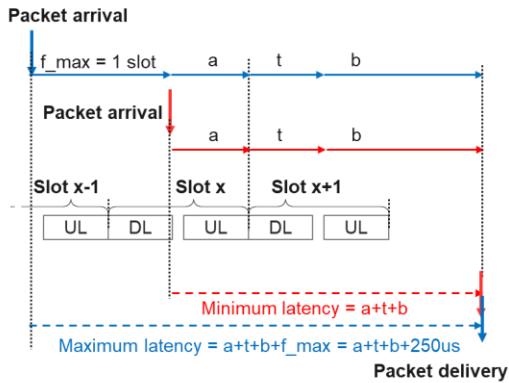
Note: in the special slot the transmission time is increased by s (i.e. 6 OFDM symbols) compared to normal slot
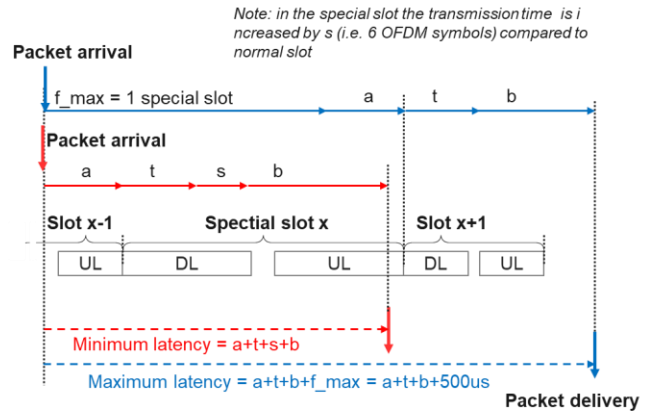
(2) Special slot

Uplink

(1) Normal slot
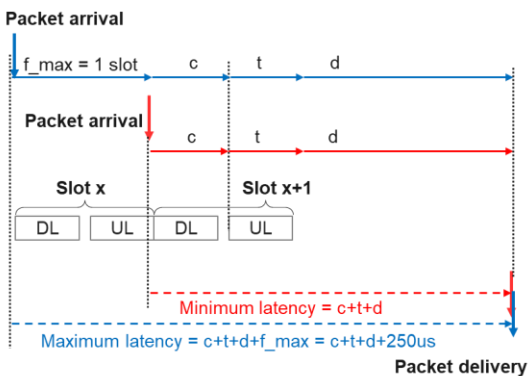
Note: in the special slot the transmission time is increased by s (i.e. 6 OFDM symbols) compared to normal slot
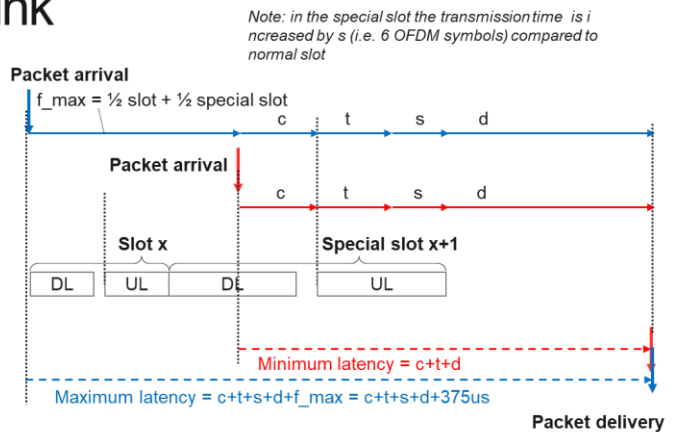
(2) Special slot

Figure 41 Illustration of Minimum and Maximum User Plane latency (Downlink & Uplink).

6.2 Field Experimental Trials

The trial configuration is described in this section. The field experimental trial was conducted in an urban area in Yokohama, Japan.

6.3 Trial Environment

Figure 42 shows a picture of the trial environment. The picture was taken from the point where the BS was installed. Several measurement locations are also shown in Figure 42. Other measurement locations are non-line-of-sight locations behind buildings.
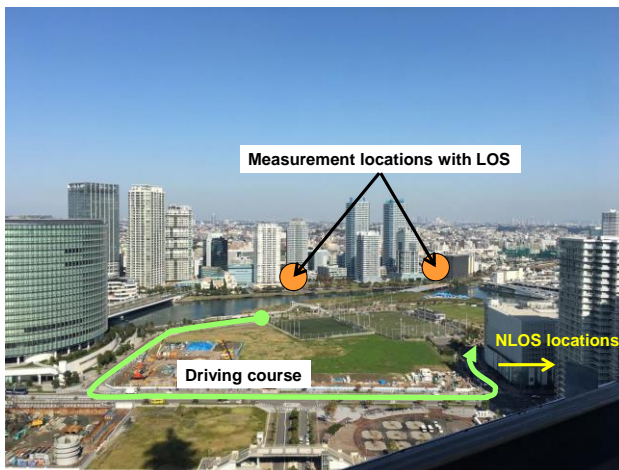
Figure 42 Trial environment and driving course for the mobility test.

6.4 Experimental Hardware

Figure 43 shows the experimental hardware. On the BS side, the radio frequency unit (RFU) and the inter-frequency unit are installed on the roof of a high-rise building, and the antenna height is approximately 108 m. The baseband unit (BBU) is placed in an indoor facility and an optical fiber connects the RFU and BBU. On the UE side, the experiment hardware is installed in the test vehicle. The UE antenna is set on the roof of the test vehicle and the antenna height is approximately 3 m. We measured the performance with the vehicle stopped at each point.

The experimental hardware supports TDD mode. The parameters for this trial are summarized in Table 12. The experiment hardware transmits and receives signals in the 4.5 GHz band and the bandwidth is 20 MHz. In this trial, the center carrier frequency is 4.66 GHz and the subcarrier spacing is 60 kHz. Throughout this trial, the signal is transmitted using spatial frequency block coding (SFBC). The number of antennas in the BS and UE are 8 and 2, respectively. In order to avoid packet segmentation, the minimum modulation and coding scheme (MCS) index, which can send a packet by using one transport block (TB), is selected based on a packet size and is kept fixed during the trial. Therefore, adaptive modulation and coding was not applied. The correspondence between packet size and MCS used in this trial is shown in Table 13.
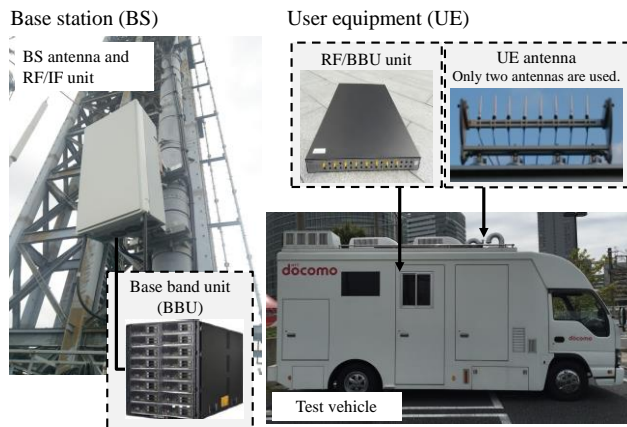
Figure 43 Experimental hardware.

Table 12 Experiment Parameters

Parameter	Value
Carrier frequency	4.66 GHz[*1]
Carrier bandwidth	20 MHz
Subcarrier spacing	60 kHz
Slot length	0.25 µs
OFDM symbols	14 symbols/slot[*2]
Guard period	31.25 µs
CP length	1.56 µs
Waveform	Filtered-OFDM
FFT length	512
Number of subcarriers	330
Channel coding	Polar code
List size	8
MIMO mode	SFBC
Number of layers	1
MCS	Fixed
Traffic	Periodic arrivals every 2 ms
Number of BS antennas	8 Tx/8 Rx
Number of UE antennas	2 Tx/2 Rx
BS sector direction	North 0 deg.
BS antenna tilt	16.4 deg.
UE cable loss	~ 1 dB
Number of UEs	1

*1) This trial is a point to point communication trial with one BS and one UE (no external interference).

*2) 14 OFDM symbols including 6 DL OFDM symbols, 6 UL OFDM symbols and GP.

Table 13 The Relationship between Packet Size, MCS and Transport Block Size.

Packet size	MCS#	Modulation	Coding rate	TB size
32 bytes	4	QPSK	0.25	328 bits
50 bytes	6	QPSK	0.38	504 bits
100 bytes	11	16QAM	0.33	872 bits
200 bytes	19	64QAM	0.45	1800 bits

6.5 Results

The trial results of evaluating the URLLC coverage and the mobility performance are introduced in the following.

6.5.1 URLLC Coverage

To verify coverage that URLLC requirement (1-10^{-5}) packet success probability within 1 ms user plane latency) can be achieved, we evaluate reliability at several locations with different SNR. In this test, we measure CRS SNR and reliability in both UL and DL, and the measurement is conducted without mobility. The UL data SNR can be obtained from UL CRS SNR plus 9 dB (9 dB is diversity gain with 8 received antennas.), while the DL data SNR can be obtained from DL CRS SNR per antenna port plus 3 dB (3 dB is diversity gain with 2 received antennas). The reliability is calculated as the packet success probability within user-plane latency of 1 ms. In the trial, a total of 10^6 IP packets were transmitted for each measurement. The success probability was measured as number of successfully received packets divided by number of total transmitted packets. The reliability was measured as number of successfully received packets (within 1ms) divided by number of total transmitted packets. The measurement of success probability of (1-10^{-5}) at each SNR point took about 30 min. The reliability requirement is achieved when the number of non-successfully received packets within 1ms (among all 10^6 packets transmitted) is less than 10.

Figure 44Figure 45 give the relationship between CRS SNR and packet size in both UL and DL, respectively. The maximum packet size which can achieve URLLC requirement and the minimum packet size which cannot achieve the requirement are plotted in this figure. Note that the difference in performance between UL and DL is about 6 dB, equivalent to the data SNR gap between UL and DL. In the following we focus on UL. focusing on the packet size of 32 bytes, As shown in Figure 44, the URLLC requirement can be achieved with approximately -3.1 dB, while SNR of approximately -6.6 dB is not enough to satisfy the requirement. Therefore, the coverage boundary for the packet size of 32 bytes exists between -6.6 dB and -3.1 dB. On the other hand, in the case of the packet size of 200 bytes, the required SNR is at least 6.6 dB to achieve URLLC requirement, and we verified 200 bytes packet can achieve the requirement with approximately 9.1 dB in this test. In order to achieve low latency of 1 ms, information of a packet is needed to accommodate in one TB. Therefore, high MCS, e.g. 64QAM, has to be applied for the transmission of 200 bytes packet. Therefore, the SNR required for 200 bytes packet becomes higher. This test clarified that the difference of the required SNR between 32 bytes and 200 bytes packet is from 9.8 dB to 15.7 dB. Since the coverage changes according to the packet size, the required packet size has an impact on the development of URLLC.
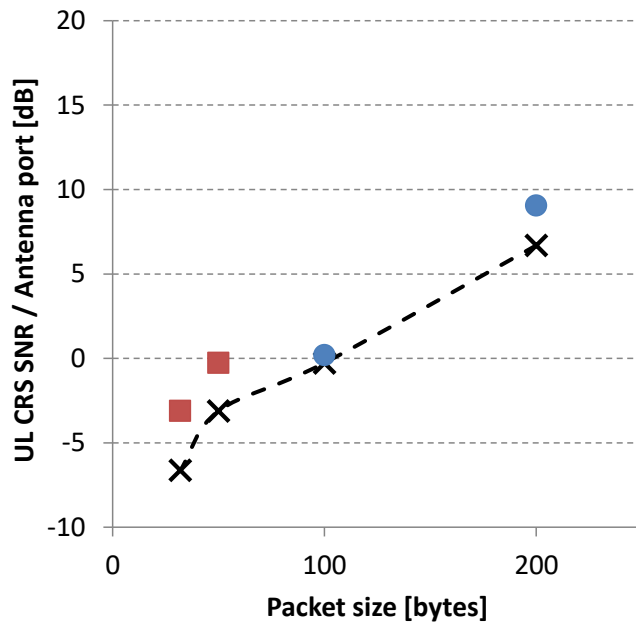
Figure 44 URLLC coverage in UL (Red points indicate NLOS measurements were URLLC requirements were met; Blue points indicate LOS measurements were URLLC requirements were met; Black points indicate measurements that were conducted but URLLC requirements could not be met).
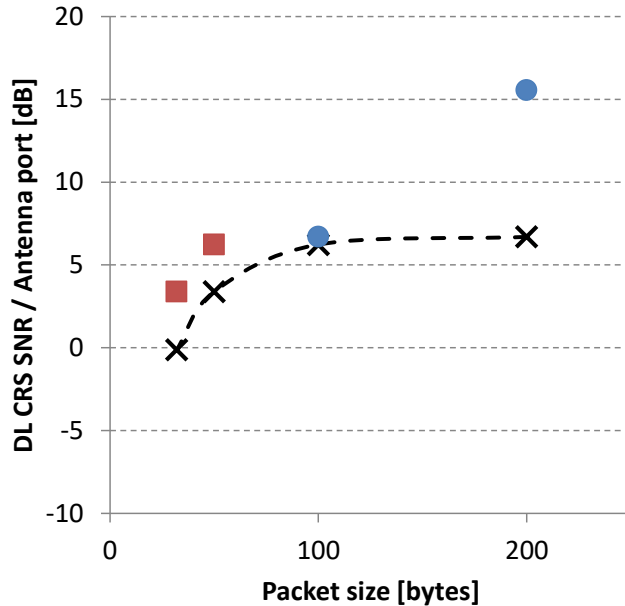
Figure 45 URLLC coverage in DL (Red points indicate NLOS measurements were requirements were met; Blue points indicate LOS measurements were requirements were met; Black points indicate measurements that were conducted but URLLC requirements could not be met).

6.5.2 URLLC Performance with Mobility

Next, we evaluate the mobility performance of URLLC. The driving course of the mobility test is shown in Figure 42, and the target of the mobility speed is 25 km/h. However, because the measurement is performed according to the traffic condition, the mobility speed is not constant. We evaluate the URLLC performance of 100 bytes and 200 bytes packets and apply the fixed MCS shown in Table 13.

The results in UL are shown in Table 14. With 100 bytes packet, the URLLC requirement can be achieved with mobility of 25 km/h. Then, the SNR is from 3.8 dB to 19.8 dB. In the case of 100 bytes packet, Figure 44 shows SNR of 0.19 dB or more is required to achieve the URLLC requirement. Since the required SNR is satisfied in this test, the reliability becomes more than 99.999%. Thus, even if UE is moving and the SNR is changing, the URLLC requirement can be achieved by satisfying the SNR shown in Figure 44. On the other hand, the reliability and the packet success probability with 200 bytes packet is lower than 99.999%, and the maximum user-plane latency is 2874 μs. The SNR is from 7.9 dB to 20.1 dB in this case. Because SNR that achieved the URLLC requirement with 200 bytes packet was approximately 9.1 dB, it is considered that the required SNR could not be achieved in this test. As a result, retransmission and packet loss cause degradation of the reliability and the packet success probability, respectively.

Table 14 Reliability, Packet Success Probability, Maximum and Average User-plane Latency with 25 km/h Mobility

Packet size	Reliability	Success prob.	U-plane latency (Max.)	U-plane latency (Ave.)
100 bytes	100%	100%	908 μs	646 μs
200 bytes	99.989%	99.990%	2874 μs	641 μs

During the driving course of the trial, 10^6 IP packets were transmitted and the success probability was measured as number of successfully received packets divided by number of total transmitted packets. The reliability was measured as number of successfully received packets (within 1ms) divided by number of total transmitted packets. The measurement of success probability and reliability was obtained by driving over the trial driving course with about 25 km/h mobility speed.

7   CONCLUSION

This work follows the preliminary analysis presented in [1].

The implications of delivering extreme services on future networks has been studied from a radio access performance perspective. Both simulation studies and field trial results have been presented. Overall, delivering Ultra-Reliable and Low-Latency communications has a clear impact on network coverage, bandwidth utilisation, and achievable payload size. Moreover, the use of sophisticated antenna arrays that enable beamforming techniques both at the user equipment and at the base station becomes necessary.

In the simulation studies, different radio access network solutions have been considered based on both NR and LTE (Release 15, Q3 2017 status but not including all URLLC enhancements) with different site densities, levels of load, bandwidth allocations, and carriers (700MHz and 4GHz). For LTE an FDD configuration in paired spectrum was assumed, as it is the focus of URLLC enhancements in LTE. For NR, both FDD and TDD configurations have been investigated.

Different carrier spacings have been considered for NR (30 KHz) and LTE (15KHz), which gives NR an advantage in being able to better support high-reliability within stringent latency bounds as more re-transmissions become possible within the acceptable delay targets given that transmission slots are shorter in time. It is important to note that 3GPP is currently adding new features to LTE in order to support Ultra-Reliable and Low-Latency communications. These features have not been considered in this work as they were not part of the specification at the time these studies were carried out (simulations were carried out in Q3 2017).

In most cases, the results are strongly dependent on cell load, i.e. on interference. In the deployment options considered in this study, the results are less dependent on cell size, i.e. coverage (in some cases a smaller cell size even reduces performance). This means that techniques such as beamforming and network interference coordination are important for the service performance.

It is clear from the simulation studies that using shorter transmission time intervals is beneficial for achieving low error targets, whereas longer transmission time intervals are best suited for transferring large payloads when latency and reliability targets are not extreme. This means that a flexible configuration of the radio access system is important for service flexibility.

From these studies, we can conclude that it is possible to provide wide-area services with extreme requirements given the assumptions considered in the simulation study. The services, however, require a significant amount of resources in terms of bandwidth, site density, number of antennas and have lower spectral efficiency compared to eMBB services. Therefore, future optimizations for efficiency is important. A range of available tools not considered in this study can be used to improve the efficiency, e.g., interference coordination.

In the field trials, the focus has been to capture coverage and mobility performance of Ultra-Reliable and Low-Latency services for different packet sizes using real hardware in a realistic environment with a single base station and single mobile terminal operating in TDD at 4.66GHz. The results provide the relationship between the cell-specific reference signal SNR and supported packet size in both UL and downlink for the considered Ultra-Reliable Low-Latency target. The difference in achievable coverage boundaries for small and large packets is also highlighted. When there is approximately an order of magnitude difference in packet size (from 32 Bytes to 200 Bytes), the coverage loss is shown to be between 9.8 dB and 15.7 dB in static conditions, and this is in clear alignment with the theoretical analysis carried out in Phase 1 of this task force [1]. In a mobile environment, the tests show that the Ultra-Reliable and Low-Latency targets can be achieved for a 100 Byte packet with a speed of up to 25Km/h. However, as the packet size grows to 200 Bytes, the reliability target cannot be met.

The field trial and the simulation studies carried out in Phase 1 [1] and in Phase 2.1 have been conducted as separate and independent pieces of work. However, the conclusions that can be drawn from Phase 1 and Phase 2.1 of this task force are very much aligned with what has been measured in the field, i.e., extreme requirements have a fundamental impact on coverage, and this impact is a function of the targets expressed as packet size, latency, and reliability.

8 LIMITATIONS AND FUTURE WORK

Regarding the simulation studies:

- It is important to bear in mind that the parameters chosen to configure the network (e.g., number of MIMO layers, number of antennas on the user equipment side) are tuned to address specifically those scenarios that require strict low latency and high reliability for small messages. If the same network had to deliver enhanced mobile broadband, a different configuration of the physical layer would likely be used. Especially for TDD it can be expected that the UL-DL sequence would be more DL heavy and slots would be longer, leading to reduced service coverage in TDD bands.

- Future 5G services will also require very low latency without a strict reliability requirement, or very high reliability without an extremely low latency requirement. These cases have been out of the scope of this work, but it is worth pointing out that these scenarios should also be the focus of future studies as they are also representative of a wide range of future services.

- The results in this work capture 3GPP's Release 15 status in Q3 of 2017. Since then the discussions moved fast and assumptions on scenarios and methodologies have been updated. However, although some results might appear slightly different if they were to be re-assessed with a more up-to-date version of the standard, we believe that the overall trends and essence of the messages that we are outlining would not change.

- For this study, a 4-antenna user equipment is assumed to improve transmission reliability. At 700 MHz, this translates into a larger form factor with respect to today's smartphones. However, for some use cases this size might be acceptable (e.g., automotive).

- It is important to highlight that, as these simulations were carried out, 3GPP was working on making LTE-Advanced equipped to address Ultra-Reliable and Low-Latency use cases. Hence, a version of LTE that is not fully optimised to address these use cases has been used for the purpose of these studies.

- Following the previous point, in this study, LTE and NR have different sub-carrier spacings (15 KHz and 30 KHz, respectively). This puts NR in an advantageous situation when it comes to delivering high-reliability within short latency bounds. More re-transmissions become possible within a short target latency bound, and this not only enhances the reliability of the message, but also allows for the usage of a more efficient modulation and coding scheme that would be too risky for a one-shot only transmission. In some configurations, LTE cannot support any re-transmissions given the tight requirements on latency, and this in turn translates into not meeting the required reliability target and thus in not being able to provide service coverage.

- As has been shown, NR can cope with a 1ms one-way radio latency better than LTE. However, if a vertical application needed a 1ms one-way end-to-end, the acceptable radio delay would need to decrease to allow for transmission delays in the network and for the core network nodes (and upper layer in the device) processing times. A reduction to a sub-millisecond requirement could have a significant impact on the amount of re-transmissions that NR can support. End-to-end trade-offs and considerations are the scope of Phase 2.2 of this task force.

- If LTE and NR were to coexist on the same carrier, having different subcarrier spacing translates into non-orthogonal transmissions. This implies having to insert a guard band between the two technologies. Alternatively, the same sub-carrier spacing can be chosen to preserve orthogonality, and this would have to be 15 KHz, which is the only option for LTE.

- Most of the 4GHz results are for FDD. However, it is most likely that spectrum at this band will be TDD, so a future study would need to be more focussed on this scenario.

- The TDD configuration chosen in this work is the best possible one to achieve low-latency transmissions. Since different operators need to coordinate when deploying TDD, this implies that, in this context, all operators would need to agree on prioritising low-latency services. It would also be interesting to explore what the impact on URLLC coverage is when the TDD configuration is optimised to address eMBB-type traffic.

- Other TDD configurations should also be considered. For NR, it is worth exploring the following scenarios: 2.5ms periodicity DDDUU, 1ms periodicity DU and 0.5ms periodicity with self-contain frame structure (DL:GP:UL=6os:2os:6os). In order to balance the uplink and downlink latency, the same ratio of UL and DL should be used.

- Slot based scheduling as well as mini-slot based scheduling are also expected to be analysed for TDD. And according to the conclusion from RAN plenary, 2-symbol, 4-symbol and 7-symbol TTI length are supported. Therefore, the results can be expanded to account for these additional TDD configurations.

- A 95% coverage target has been assumed, which allows for acceptable simulation run times. In reality, a service needing ultra-high reliability might require a 99% guaranteed level of coverage, which means that delivering these services might become possible only in very localised areas.

- A 40-Byte payload may prove to be too small in realistic scenarios, as also pointed out in Deliverable 1 of this task force [1]. This is because overhead introduced by each layer of the protocol stack might use all the available payload without leaving any space for application-layer bits.

Regarding the field trials:

- The radio access configuration considered in the field trials and the ones considered in the simulations studies are different, as well as the scenario. Moreover, while the objective of the field trial is to focus on a single link in an unloaded network, the simulation studies reveal what happens in a loaded network to a distribution of users. However, both studies are aligned in highlighting how requirements on packet size, latency, and reliability have an impact on service coverage.

9   LIST OF ACRONYMS

3GPP: 3rd Generation Partnership Project
BLER: Block Error Rate
BS: Base Station
CCE: Control Channel Element
CDF: Cumulative Distribution Function
CSRS: Cell-Specific Reference Signal
DL: Downlink
DMRS: Demodulation Reference Signal
eMBB: Enhanced Mobile Broadband
FDD: Frequency Division Duplexing
HARQ: Hybrid Automatic Repeat Request
IP: Internet Protocol
ISD: Inter-Site Distance
LTE: Long Term Evolution
MAC: Medium Access Control
mMTC: massive Machine Type Communications
NR: New Radio
OH: Overhead
OS: OFDM Symbol
PDCCH: Physical Downlink Control Channel
PDCP: Packet Data Convergence Protocol
PRB: Physical Resource Block
PUCCH: Physical Uplink Control Channel
RAN: Radio Access Network
RLC: Radio Link Control
SDAP: Service Data Adaptation Protocol
SE: Spectral Efficiency
SINR: Signal-to-Interference-plus-Noise Ratio
SCS: Sub-Carrier Spacing
SDU: Service Data Unit
sPDCCH: Short Physical Downlink Control Channel
SPS: Semi-Persistent Scheduling
SR: Scheduling Request
TCP: Transmission Control Protocol
TDD: Time Division Duplexing
TTI: Transmission Time Interval
UE: User Equipment
UL: Uplink
URLLC: Ultra-Reliable Low-Latency Communications

10 ANNEX

Table 15. Service coverage (%) for the studied targets requirements and radio access systems.

Requirement				Target 1							Target 2							Target 3						
Radio access system #				1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Direction/Band/ISD/Load																								
DL	0.7GHz (10MHz)	500m	0%	65	0	0	0	55	45	0	99	99	99	99	99	99	99	0	99	99	99	0	0	75
			50%	20	0	0	0	20	15	0	99	95	90	85	90	75	70	0	65	65	65	0	0	30
			90%	10	0	0	0	10	5	0	95	85	80	75	80	60	55	0	50	50	50	0	0	15
		350m	0%	65	0	0	0	55	45	0	99	99	99	99	99	99	99	0	99	99	99	0	0	75
			50%	25	0	0	0	20	15	0	95	90	90	85	90	75	70	0	65	65	65	0	0	30
			90%	10	0	0	0	10	5	0	90	80	75	70	75	60	55	0	50	50	50	0	0	20
		250m	0%	65	0	0	0	55	45	0	99	99	99	99	99	99	99	0	99	99	99	0	0	75
			50%	25	0	0	0	20	15	0	95	95	90	85	90	80	75	0	70	70	70	0	0	30
			90%	15	0	0	0	10	5	0	95	85	80	75	80	65	60	0	55	55	55	0	0	20
	4GHz (20MHz)	500m	0%	99	75	75	0	90	95	0	99	99	99	99	99	99	99	0	99	99	99	0	0	99
			50%	70	40	40	0	50	55	0	99	99	99	99	99	99	95	0	95	95	95	0	0	75
			90%	60	30	30	0	40	45	0	99	99	99	99	95	95	95	0	90	90	95	0	0	65
		350m	0%	99	75	75	0	90	95	0	99	99	99	99	99	99	99	0	99	99	99	0	0	99
			50%	75	50	50	0	60	60	0	99	99	99	99	99	99	99	0	95	95	99	0	0	80
			90%	65	40	40	0	50	50	0	99	99	99	99	95	95	95	0	95	95	99	0	0	65
		250m	0%	99	80	80	0	90	95	0	99	99	99	99	99	99	99	0	99	99	99	0	0	99
			50%	85	60	60	0	70	75	0	99	99	99	99	99	99	99	0	99	99	99	0	0	90
			90%	75	50	50	0	60	65	0	99	99	99	99	99	99	99	0	95	95	99	0	0	80
UL	0.7GHz (10MHz)	500m	0%	0	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	95	99	0	0	0
			50%	0	0	0	0	0	0	0	99	99	90	90	95	95	70	0	65	15	65	0	0	0
			90%	0	0	0	0	0	0	0	99	95	80	80	85	85	45	0	40	0	40	0	0	0
		350m	0%	0	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	99	99	0	0	0
			50%	0	0	0	0	0	0	0	99	99	90	90	95	95	65	0	60	15	60	0	0	0
			90%	0	0	0	0	0	0	0	99	95	75	75	85	85	45	0	35	0	35	0	0	0
		250m	0%	0	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	99	99	0	0	0
			50%	0	0	0	0	0	0	0	99	99	90	90	95	95	75	0	65	15	65	0	0	0
			90%	0	0	0	0	0	0	0	99	99	80	80	90	90	50	0	40	0	40	0	0	0
	4GHz (20MHz)	500m	0%	80	0	0	0	0	0	0	95	95	95	95	95	95	95	0	95	90	95	0	0	90
			50%	0	0	0	0	0	0	0	95	95	95	95	95	95	90	0	90	85	90	0	0	45
			90%	0	0	0	0	0	0	0	95	95	95	95	90	90	90	0	90	80	90	0	0	25
		350m	0%	80	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	95	99	0	0	95
			50%	0	0	0	0	0	0	0	99	99	99	99	95	95	95	0	95	90	95	0	0	55
			90%	0	0	0	0	0	0	0	99	99	99	99	95	95	95	0	95	85	95	0	0	35
		250m	0%	80	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	99	99	0	0	95
			50%	0	0	0	0	0	0	0	99	99	99	99	99	99	99	0	99	95	99	0	0	70
			90%	0	0	0	0	0	0	0	99	99	99	99	99	99	99	0	95	90	99	0	0	55

Table 16. Bandwidth (MHz) required to meet target in a radio access system.

Requirement				Target 1							Target 2							Target 3						
Radio access system # Direction/Band/ISD/Load				1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
DL	0.7GHz	500m	0%	20	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	10	20	20	10	10	40	10	10	20	20			40
			90%								10	20	20	20		20	40	10	20	20	40			80
		350m	0%	40	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	20	20	20		10	40	10	20	20	20			40
			90%								10	40	40	40		20	80							
		250m	0%	20	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	10	20	20	10	10	40	10	10	20	20			40
			90%								10	20	20	20		20	40	10	20	20	40			80
	4GHz	500m	0%	20	40	40	80	10	20	80	10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%	80				40	80		10	10	10	10	10	10	10	10	10	10	10	10	10	20
			90%	80				80	80		10	10	10	10	10	10	20	10	10	10	10	10	20	20
		350m	0%	20	40	40	80	10	20	80	10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%	80				40	80		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			90%	80				80	80		10	10	10	10	10	10	20	10	10	10	10	10	20	20
		250m	0%	20	40	40	80	10	20	80	10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%	40	80	80		40	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			90%	80				40	80		10	10	10	10	10	10	10	10	10	10	10	10	10	10
UL	0.7GHz	500m	0%	40	80			20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	10	10	20	10	10	20	10	10	20	20	10	10	40
			90%								10	10	20	20	10	10	40	10	10	20	20			40
		350m	0%	40	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	10	10	20	10	10	20	10	10	20	20	10	10	40
			90%								10	10	20	20	10	10	40	10	10	20	20			40
		250m	0%	40	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10		10	10
			50%	80				80	80		10	10	10	20	10	10	20	10	10	20	20	10	10	40
			90%								10	10	20	20	10	10		10	10	20	20			40
	4GHz	500m	0%								10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%								10	10	10	10	10	10	20	10	10	10	10	10	10	40
			90%								10	10	20	10	10	40		10	10	20	20	10	10	
		350m	0%	40	80			20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%	80				80	80		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			90%	80				80	80		10	10	10	10	10	10	20	10	10	10	10	10	10	20
		250m	0%	40	80	80		20	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			50%	40	80			40	40		10	10	10	10	10	10	10	10	10	10	10	10	10	10
			90%	80				40	80		10	10	10	10	10	10	10	10	10	10	10	10	10	10

Table 17. Maximum payload (B) for a target in a radio access system.

Requirement				Target 1							Target 2							Target 3						
Radio access system #				1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Direction/Band/ISD/Load																								
DL	0.7GHz (10MHz)	500m	0%	789	345	344	186	1036	655	143	600	262	261	141	532	498	109	600	262	261	141	319	153	109
			50%	91	40	40	22	158	76	17	91	40	40	22	80	76	17	91	40	40	22	0	0	17
			90%	86	38	38	20	149	72	16	86	38	38	20	0	38	16	46	20	20	11	0	0	8
		350m	0%	728	318	317	171	1018	604	132	589	258	257	139	319	305	107	589	258	257	139	319	153	107
			50%	90	39	39	21	155	74	16	90	39	39	21	0	74	16	90	39	39	21	0	0	16
			90%	46	20	20	11	79	38	8	46	20	20	11	0	38	8	0	0	0	0	0	0	0
		250m	0%	789	345	344	186	1036	655	143	600	262	261	141	532	498	109	600	262	261	141	319	153	109
			50%	91	40	40	22	158	76	17	91	40	40	22	80	76	17	91	40	40	22	0	0	17
			90%	86	38	38	20	149	72	16	86	38	38	20	0	38	16	46	20	20	11	0	0	8
	4GHz (20MHz)	500m	0%	2543	1113	1108	599	4393	2110	461	2543	1113	1108	599	1277	1507	461	1817	795	791	428	1277	613	329
			50%	623	273	271	147	982	517	113	568	249	248	134	319	304	103	366	160	160	86	319	153	66
			90%	495	216	216	116	611	413	90	354	155	154	83	319	153	64	354	155	154	83	160	77	64
		350m	0%	2543	1113	1108	599	4393	2110	461	2543	1113	1108	599	1277	1507	461	1817	795	791	428	1277	613	329
			50%	666	291	290	157	1150	553	121	666	291	290	157	319	306	121	589	258	256	139	319	153	107
			90%	571	250	249	134	625	473	104	362	158	158	85	319	300	66	362	158	158	85	160	77	66
		250m	0%	2543	1113	1108	599	4393	2110	461	2543	1113	1108	599	1277	1507	461	1817	795	791	428	1277	613	329
			50%	1040	455	453	245	1231	863	189	713	312	310	168	638	504	129	713	312	310	168	319	153	129
			90%	666	291	290	157	1150	553	121	666	291	290	157	319	306	121	589	258	256	139	319	153	107
UL	0.7GHz (10MHz)	500m	0%	735	368	303	181	1132	744	121	559	280	230	137	581	566	92	559	280	230	137	349	174	92
			50%	206	103	85	51	319	209	34	158	79	65	39	87	87	26	86	43	35	21	87	44	14
			90%	85	43	35	21	173	86	14	85	43	35	21	87	86	14	85	43	35	21	0	0	14
		350m	0%	735	368	303	181	1132	744	121	559	280	230	137	581	566	92	559	280	230	137	349	174	92
			50%	206	103	85	51	319	209	34	158	79	65	39	87	87	26	86	43	35	21	87	44	14
			90%	84	42	34	21	169	85	14	84	42	34	21	87	85	14	84	42	34	21	0	0	14
		250m	0%	735	368	303	181	1132	744	121	559	280	230	137	581	566	92	559	280	230	137	349	174	92
			50%	206	103	85	51	319	209	34	158	79	65	39	87	87	26	86	43	35	21	87	44	14
			90%	85	43	35	21	173	86	14	85	43	35	21	87	86	14	85	43	35	21	0	0	14
	4GHz (20MHz)	500m	0%	581	290	239	143	1072	588	95	530	265	218	130	349	345	87	341	171	140	84	349	174	56
			50%	412	206	170	101	639	417	68	315	158	130	78	174	174	52	172	86	71	42	174	87	28
			90%	170	85	70	42	345	173	28	170	85	70	42	174	173	28	170	85	70	42	0	0	28
		350m	0%	1471	735	605	362	2264	1489	241	1118	559	460	275	1161	1132	183	1118	559	460	275	697	349	183
			50%	581	290	239	143	1072	588	95	530	265	218	130	349	345	87	341	171	140	84	349	174	56
			90%	532	266	219	131	683	538	87	337	169	139	83	349	341	55	337	169	139	83	174	87	55
		250m	0%	1471	735	605	362	2264	1489	241	1118	559	460	275	1161	1132	183	1118	559	460	275	697	349	183
			50%	885	443	364	218	1307	896	145	646	323	266	159	349	567	106	560	280	230	138	349	174	92
			90%	621	310	255	153	1256	628	102	621	310	255	153	349	347	102	548	274	226	135	349	174	90

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