UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

Reliability-Oriented Intra-Frequency Dual Connectivity for 5G Systems: Configuration Algorithms and Performance Evaluation

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Mohammed Al-Mshahde

In partial fulfilment

of the requirements for the degree of

MASTER IN TELECOMMUNICATIONS ENGINEERING

Advisors:

Klaus Pedersen, Daniela Laselva

Nokia Bell Labs

Nurul Huda Mahmood

Aalborg University

Jordi Pérez-Romero

Universitat Politècnica de Catalunya

Aalborg, Denmark, 2018

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

telecom
BCN

NOKIA Bell Labs

AALBORG UNIVERSITY
DENMARK

Title of the thesis: Reliability-Oriented Intra-Frequency Dual Connectivity for 5G Systems: Configuration Algorithms and Performance Evaluation

Author: Mohammed Al-Mshahde

Advisor: Klaus Pedersen, Nurul Huda Mahmood, Daniela Laselva, Jordi Pérez-Romero

Abstract

The 5th Generation (5G) New Radio (NR) interface is expected to continue utilising the existing homogenous networks for some time in the near future serving a wide range of use cases, one of those cases is Ultra-Reliable Low Latency Communications (URLLC) services. For URLLC, short data packets must be correctly transmitted and received within very short latency up to 1ms with a reliability of 99.999%. There are several options being proposed to meet this difficult design target. One very promising suggested solution is the dual connectivity with data duplication, where the same packet is duplicated and independently transmitted via two different nodes.

This work uses a system-level simulation to study how the data duplication at PDCP level for dual connectivity is functioning, where every copy of the designated packet is sent via the two connections that a certain User Equipment (UE) is connected. The studied scenario is a homogeneous network of 21 macro cells of 500m inter-site distance. The scenario is first optimized for the single connectivity mode, which supports less than 1Mbps URLLC offered load while meeting the IMT2020 latency requirements. As we enable dual connectivity, in a URLLC traffic only scenario, it is shown that dual connectivity provides some noticeable gain by enabling the support of up to 1.5Mbps URLLC load within the URLLC requirements but not improving the low load criteria in comparison to single connectivity results due to the low interference condition in single connectivity. As a second stage, the gain of DC is studied when the URLLC traffic coexist with a heavy full buffer background eMBB traffic. Results show that a latency gain as well as higher load support than the single connectivity case can be obtained by dual connectivity, however the sensitivity of this gain on the scenario conditions is very high. Finally, an enhanced duplication configuration is added, that is if a packet is successfully sent through one of the links and correctly decoded at the UE, the duplicated copy transmission on the other link is cancelled (i.e. the packet is dropped at the network side). This results in a significant performance improvement in terms of the latency and supported URLLC load especially at relatively high load because it avoids the queuing delay.

Acknowledgements

Firstly, I would like to express my gratitude to my supervisors Klaus Pedersen, Nurul Huda Mahmood and Daniela Laselva for their continuous support and guidance. It was great pleasure to come to Aalborg and learn from them that I will be always grateful for. Their encouragement and technical knowledge have been key for me to finish this project. I have learnt and improved a lot thanks to their advices.

Additionally, I am very thankful to Melisa, for the good discussions and the funny moments during what did seem an unachievable goal. I am also very grateful and thankful to Jens Steiner, for his great patience and help he provided with the software development to make this project done. Thanks also to Guillermo Pocovi and Ali Karimi, for their contributions and guidance in several aspects of the project. I would also like to thank Mads Brix for his technical assistance with all the IT issues and the rest of the team at Nokia Bell Labs office for their kind conversation and hospitality which made my stay very nice and easy going. I really enjoyed working there for the last 8 months.

On the personal side, many thanks to all the friends and relatives in Iraq who were such a support to me even in the distance.

I want to express my biggest gratitude to the most influential people in my life: my family. Despite the thousands of miles in distance, their unconditional love and support has been essential these months. I owe them all my successes.

Revision history and approval record

Revision	**Date**	**Purpose**
0	27/11/2017	Document creation
1	11/06/2018	Document 1st revision
2	18/06/2018	Document 2nd revision
3	26/06/2018	Document Approval

Written by:		Reviewed and approved by:	
Date	29/05/2018	Date	20/06/2018
Name	Mohammed Al-Mshahde	Name	Klaus Pedersen Nurul Huda Mahmood Daniela Lasleva Jordi Pérez-Romero
Position	Project Author	Position	Project Supervisors

Table of contents

List of Figures

List of Tables

1. Introduction

Wireless communication is experiencing extensive improvements to meet the evolution in user demands. The number of devices that need to be connected, and the throughput demands of each user, have increased manifold. This is driven by the variety of user devices such a tables and wearables. The introduction of Internet of Things also requires to connect everything in our surroundings from smart homes to E-Health and E-Transport.

One of the 5th generation (5G) of mobile communications evolving vision is trying to leverage all the possible bands (below and above 6GHz). The 5G networks are highly expected to fulfil the all the demands of the new technologies requirements, with data rates of up to 20 Gbps and a capacity a thousand times greater. 5G networks must also provide a flexible platform for new services such as massive IoT and critical machine communication. The demands require a number of new technologies [1]. The basic performance criteria for 5G systems have been set by the International Telecommunication Union (ITU) in their IMT for 2020 and beyond Recommendation. ITU-R M.2083 describes three overall usage scenarios for 5G systems: Enhanced Mobile Broadband (eMBB), Massive Machine-type Communications (mMTC), and Ultra-reliable and Low Latency Communications (URLLC) [2].

In 5G systems, several solutions and techniques were proposed related to enable URLLC such as Network Slicing and Function Virtualization (NFV), Software Defined Air Interface for URLLC, new frame structure (PHY numerology to enable short TTI, reduced gNB and User Equipment (UE) processing time, Enhanced Hybrid Automatic Repeat Request (HARQ), and more robust control channels. In addition to the previous solutions Multi-Connectivity was proposed as a very promising technology and a key enabler of 5G so that it can meet the increasingly demanding requirements of 5G networks. This is possible by exploiting Dual Connectivity (DC)- which is the multi connectivity of the LTE technology and mainly transmitting the data assigned to a certain user via two different cells by splitting it into two MAC PDUs depending on the channel conditions of those cells- and carrier aggregation (CA) techniques. In this project we are focusing on another form of DC which essentially duplicates the data assigned to the user in a PDCP layer and transmit it to the user through two nodes. This is to increase the reliability of the transmission in order to meet the 5G requirement of 99.999% reliability without exceeding the 1ms latency requirement.

Multi Connectivity of one UE to multi access nodes at the same time giving the mobile terminal a diversity of resources using the UE's multiple physical connections to the access network promising high performance which is- if exploited in an intelligence manner- can't be achieved otherwise.

In this work, we present the case where the study is focusing on the Multi-Connectivity (MC) technique user plane perspectives showing the potential of multi connectivity to provide a highly reliable communication within the latency requirement of 5G mobile network. We are considering an architecture with a centralized PDCP layer where all the data split and processed in the master node. Since the LTE dual connectivity architecture is not efficient and not suitable for multi connectivity by means of the requirements of 5G specifically to fulfil the ultra-reliable low latency communications applications demands.

1.1. Statement of purpose

The next generation mobile network will be continuing to use the existing homogeneous macro network with intra-site comprising of the deployed macro systems. Multi-Connectivity (MC), where a User Equipment (UE) is aggregating the radio resources from multiple cells/base stations. Mainly to provide an efficient way to fulfil the 5G requirements of high reliability and low-latency by leveraging the mobile network and deployments. There have been efforts in 3GPP to specify and standardize potential solutions to achieve the above requirements like multi-connectivity or carrier aggregation. This project will study the performance of multi connectivity in 5G new radio and investigate efficient scheduling and configuration algorithms for it. The study will be focusing on the Ultra-Reliable Low-Latency Communications (URLLC) service class.

The study is based on system level simulation based on a scenario as suggested in [2], where we have seven sites, each consisting of three sectors. In total 21 next generation NodeBs (gNodeBs) are considered, all operating in the same frequency. We are assuming a high-priority bursty URLLC traffic and we would like to achieve low over the-air transmission delay [3].

The objective is to improve the performance of target URLLC users with multi-connectivity. As benchmark we will consider the single connectivity case, where the target URLLC user is served by a single gNodeB.

We have studied the optimal configuration for multi-connectivity and data duplication control. The work focuses first on reducing the effect of the co channel interference from the close nodes that are working on the same carrier frequency which is the main challenge of our scenario. This can lead to have the best performance for this service.

1.2. Main Research Questions

The project can be divided into two different parts: (i) Multi-Connectivity Mode activation in and (ii) Data Duplication Configuration for URLLC.

On one hand, the first part should solve questions related to the decision of which nodes should take part in the Multi-Connectivity mode for a specific UE. This solution is expected to improve the performance in terms of reliability and latency as we will be connecting the designated UE to the cells with the best condition. On the other hand, this will come with a cost of using more network resources and/or increasing the interference to the rest of the users. The research in this case would be focused on the following questions:

- *For a given UE is the Master node sufficient to meet the service requirements? Is it optimal to apply MC? For which nodes?*
- *Which is the optimal criteria for the Master gNodeB (MgNb) to be considered as a node for Multi-Connectivity? And which is the optimal Secondary gNodeB (SgNb) selection criteria option? And how to manage the interference from the different transmissions at the UE?*

The latter leads to another research question:

- *Which is the best way to perform MC operation?*

Finally, as our work is focusing on the Ultra-Reliable Low Latency Communications (URLLC) then:

- *How Multi Connectivity can improve reliability?*
- *How to reduce Latency?*

1.3. Research Stages

The research plan tabulated below maps the project into three research activities with distinct objectives and associates them to clearly defined research tasks.

Table 1. Research Stages and Periods

Research Activities (RA) and Research Objectives (RO)	Tasks (T)	Period to do Tasks
RA1: Background study and Simulator acquaintance	T1.1: Identification of relevant scenarios of definition of the study cases.	3 Weeks
RO1.1: In depth study of State of the art	T1.2: Identification and setting up of simulation environment	6 Weeks
RO1.2: To familiarize with the FREAC simulator		
RA2: MNC Performance Evaluation	T2.1: In depth performance evaluation targeting URLLC services. (E.g. Understanding the reliability KPI variation when changing the arrival rates of new packets as a baseline to compare to and build up the Intra-Frequency MC.	5 Weeks
RO2.1: To evaluate the performance of Single Connectivity considering the identified scenarios		
RO2.2: To gain insights into different factors affecting the performance of Single connectivity		
RA3: MNC configuration algorithm development	T3.1: Proposing MC configuration algorithms	3 Weeks
RO3.1: To propose dynamic autonomous MNC configuration algorithms for URLLC services	T3.2: Performing system level simulations to validate the proposed algorithms under standard 5G NR scenarios.	2 Weeks
RA4: Data Duplication algorithm optimizing	T4.1: Proposing different PDUs duplication algorithms.	1 Week
RO4.1: To propose the optimal way to duplicate PDUs.	T4.2: Performing system level simulations to test and validate the best duplication algorithm.	2 Week
	T4.3: Proposing duplication enhancement – Packet Cancelation	1 Week
	T4.4: Performing system level simulations to test and validate the Packet Cancelation feature.	1 Week

1.4. State of the art of the technology used or applied in this thesis

The previous years have witnessed a huge growth in wireless communications applications, services and the industry overall which increased the need to provide a better capacity and availability to cope up with these requirements. It is the main reason that opens the horizon for the researchers around the world in the both the academia and the industry to come up with a comprehensive body for the next/fifth generation (5G) of the mobile communication network.

The evolution of mobile communications from the first generations to the 4th generation (4G) lead to providing a better spectral efficiency, simplifying the integration with non-wireless networks and full IP deployment of the real-time services. Subsequently, enhancements to further improve the efficiency, capacity and availability in a more intelligent manner will be more formalized and utilised in the coming 5G that has recently been standardized in the last release at the beginning of 2018 and will be fully deployed by 2020. This will make communication systems more environmentally friendly and less costly.

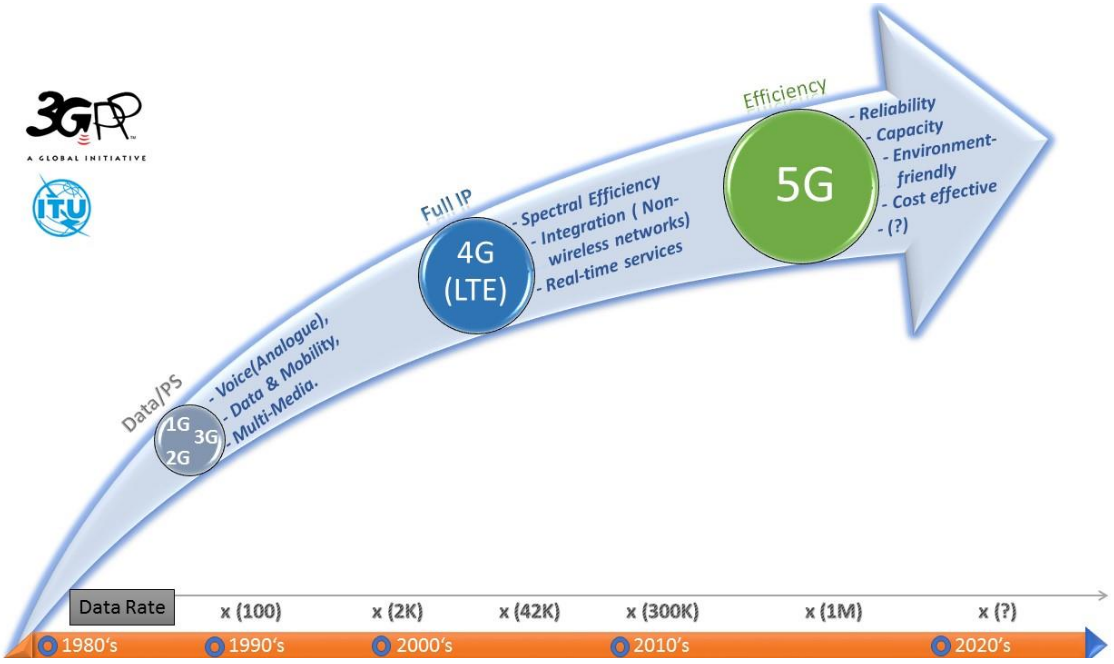
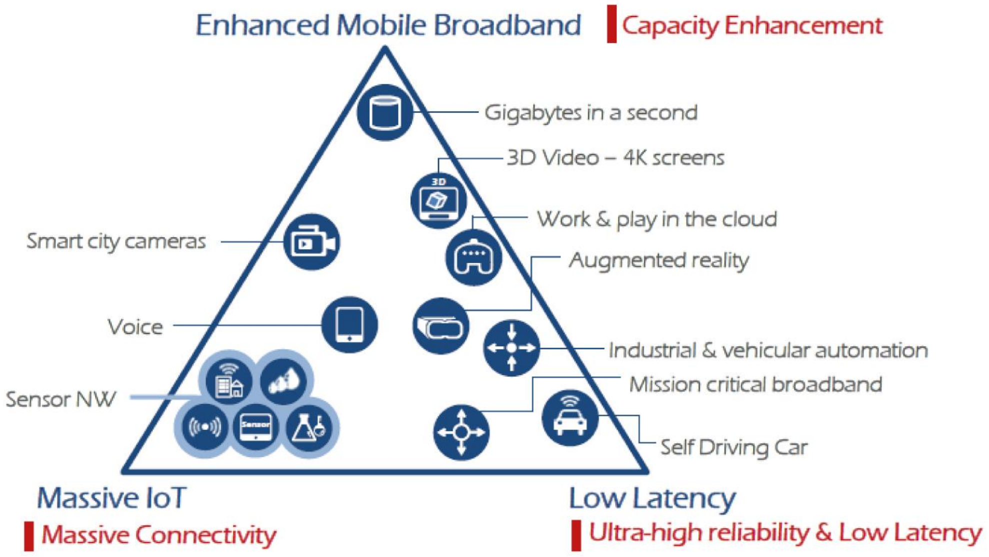


Figure 1. Evolution of wireless communication

1.5. 5G Motivation and Requirements

There is an ever-growing increase in the demand for wireless services requiring faster, higher capacity networks due to a huge number of devices that needs to be connected to the Internet such as mobile phones, computers, tablets, smart watches, etc. The trending Internet of Things (IoT) whose applications -such as but not limited to the high-speed broadband connection, E-Health and E-Transportation- is fueling a need for massive connectivity of devices, and also the need for ultra-reliable low latency communication (URLLC). These devices always demand higher reliability communications within low latency limitation. Moreover, several industries are going through a digital transformation like the emerging ideas for connected cars and autonomous driving applications, human machine interaction, sensor network, critical control of remote devices, etc. This implies that existing mobile networks won't be able to provide the required capacity and reliability to all those applications.

Communication procedures addressing these new services are different from the human-to-human communication use case. Thus, to ensure a certain quality of the service (QoS), requirements like reliability, latency, throughput, and availability should be met. The current Radio Access Technologies (RATs) are not able to deal with all these requirements. Therefore, the 3rd Generation Partnership Project (3GPP) defined the 5G New Radio (NR) access technology, a new air interface which is supposed to handle all the capacity and performance requirements of those services. 5G should be able to deal with several distinct service types such as mMTC, eMBB or URLLC.



(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

Figure 2. 5G Use cases

The aim of mMTC service is to provide efficient connectivity to a large number of devices, each transmitting sporadically with a small data payload. The requirements, therefore, are low cost, low battery consumption and high number of connected devices. Applications of this kind of service include e-Health, transport and logistics, smart agriculture, Internet *of* Animal Health Things *(IoAHT),* and smart cities and energy networks, etc.

On the other hand, eMBB addresses human-focused use cases where scenarios include indoor hotspot, dense urban, rural, urban macro, and high speed. It aims to improve consumer experience when accessing multimedia content, services and data. eMBB services requires the capability of having faster peak and average data rates.

Finally, URLLC services are intended for mission-critical links, which means that they have strict to end to end latency and high reliability targets. Some of its applications are vehicle-to-everything communication, drone delivery and smart manufacturing.

The European Union Commission, jointly with telecommunications operators, industry manufacturers, service providers, small and medium-sized enterprises and research centers, formed the 5G Infrastructure Public Private Partnership (5G PPP). 5G PPP is working to deliver solutions, architectures and standards for 5G NR.

1.6. Ultra-Reliable Low Latency Communications (URLLC)

The newly introduced Ultra-Reliable Low Latency communications (URLLC) service class is an important aspect of 5G New Radio (NR). It is intended for mission-critical communications and is the enabler for a vast set of applications. Services such as advanced energy networks, self-driving cars or intelligent industrial processes have in common the high reliability requirements in terms of packet delivery success rates, which is as high as 99.999% while the acceptable latency is as low as 1 ms [4]. There are several studies focusing on how to decrease the latency in 5G NR, e.g., by reducing the Transmission Time Interval (TTI) [5,6], fast uplink access [7], or by puncturing URLLC resources on top of eMBB [8].

At its core, enabling URLLC is a transition from mean performance utility-based approaches (average throughput, average response time, average data rates, etc.) towards tail, risk, scale centric design [9]. Figure 3 shows the overall requirements for URLLC to be met which will be described more in details in the section 2.2.1.

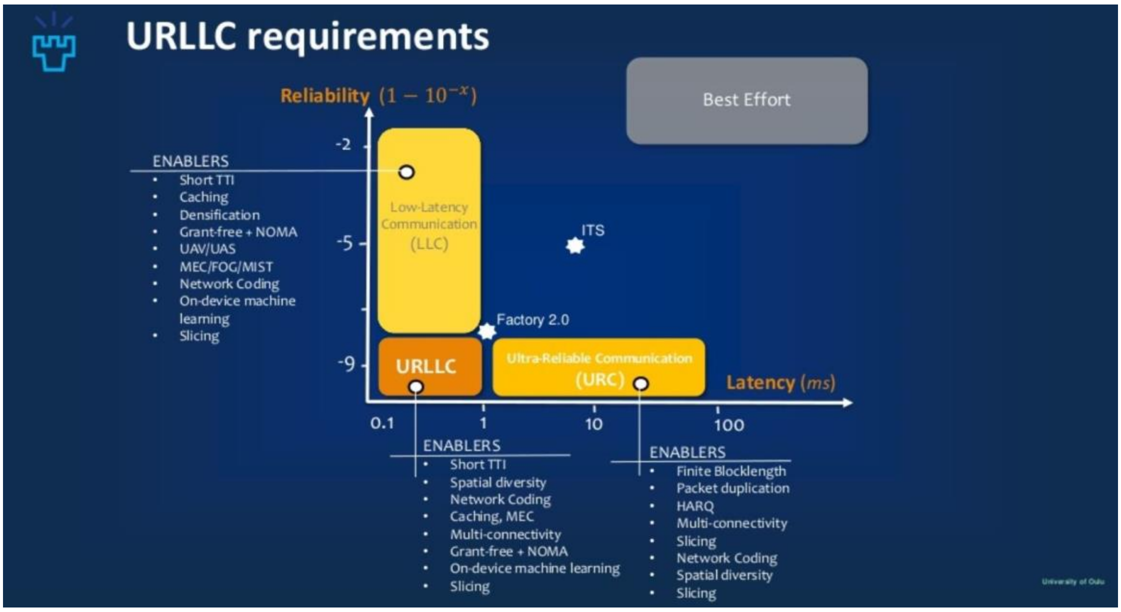


Figure 3. URLLC overall requirements. Extracted from [9].

1.6.1. Requirements

In the most demanding case, URLLC general requirements according to 3GPP state that short packets (32,50, and 200 bytes) should be transmitted and received within a 1ms latency window with 99,999% ($1 - 10^{-5}$) reliability [10]. However, as previously said and apart from the ITU IMT2020 high level requirements, the requirements mentioned above are not strictly fixed as it can be changed according to different applications that doesn't specifically required a low latency of 1ms but can be tolerate up to 5 or even 10ms.

Latency is the period that sums all the steps from the assignment of the transmission resources until the receiver finishes processing the data (potential queuing that may happen before assignment of transmission resources could be included), as it is shown in Fig. 2 [11]. Reliability is defined such that the ratio of lost, erroneous or delayed messages is very low.

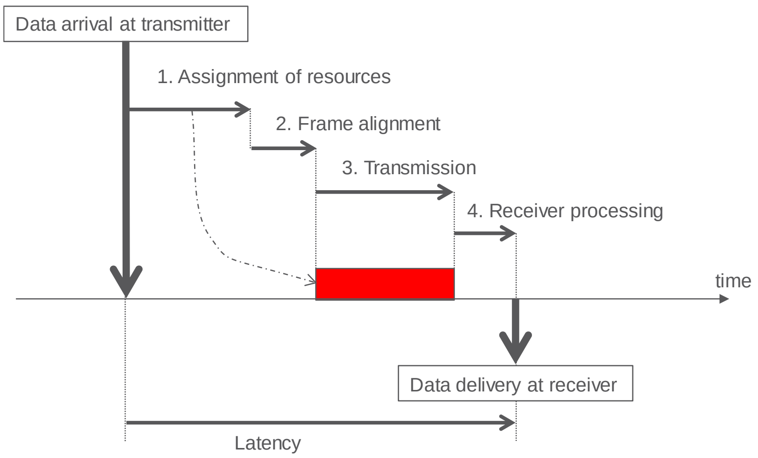


Figure 4. Latency Components. Extracted from [10].

In a wireless system, it is difficult to meet simultaneously stringent reliability, within the required latency and provide the throughput demand due to the main issue of uncertainty of the wireless channel and the origin of the data traffic. There is a fundamental trade-off among latency, reliability and throughput in a cellular network [12], i.e., we can achieve a maximum transmission rate with a certain reliability within a given latency to meet for the desired application. Such a trade-off will always be considered even when multi-node connectivity is introduced but it can be used to improve the reliability and reduce the delay at the same time.

1.7. Multi-Connectivity Options

Multi-Node Connectivity, relies on utilising the radio resources from multiple cells to simultaneously serve a single UE. MC improves throughput for both Uplink (UL) and Downlink (DL), mobility, ultra-reliability and latency reduction. We focus on MC type where the latter two are the main concentration as we study more reliability-oriented case. A multi-connectivity capable user should be able to support simultaneous connections and aggregation of resources. Some users can support a subset of different radio technologies (LTE, Wi-Fi, etc.), and be able to connect to different network layers (macro and small cells). There are different ways to realize MC, mainly we are classifying in two types depending on the frequencies of the aggregated links, multi connectivity can be categorized in: inter-frequency MC, where multiple links at different frequencies are aggregated; and intra-frequency MC, targeted at boosting the performance of cell-edge users. In this study we focus on the case of intra-frequency scenario with only macro cells deployed.

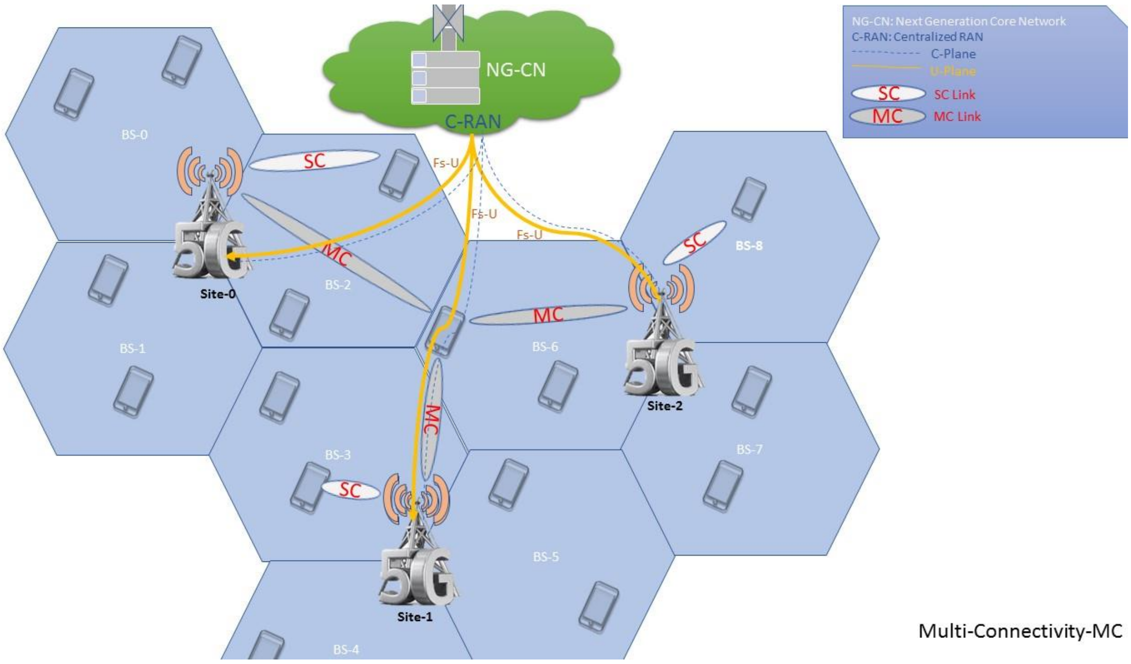


Figure 5. Multi Connectivity in Macro-Site Scenario Layout

This study is evaluating an intra-frequency MC through system level simulations to illustrate how the signal-to-interference-noise ratio and the reliability is improved, see [13]. Furthermore, in [14] it is shown that mobility problems can be resolved by utilizing intra-frequency MC. In another study [15], multi-radio access-technology architectures are compared regarding their latency, which is significantly improved by MC techniques.

Multi Connectivity can increase the reliability. Nevertheless, most of the existing concepts and studies on MC assume data rate enhancement. The investigations related to reliability enhancement (i.e. data duplication) via MC are less present (so far) and have a higher level of abstraction, see [16]. Studies regarding which is the optimal 5G architecture for multi-connectivity to improve reliability performances can be found in [17]. Specifically, works targeting performance aspects with URLLC services and proposing dynamic configuration algorithms are limited and leaves the room for contribution in this domain.

We are building the definition of the multi connectivity based on the DC definition in the standardization. On one hand, the C-Plane in our scenario is presented only in the Core Network (CN) for signalling overhead reduction and the master cell is directly connected to the Core Network (CN) through S1 interface or the interface that will be introduce in the NR. The connections between the gNB is Xn which enable the UE to be communicated through the U-Plane to the serving cells. On the other hand, for U-Plane, as in the DC architecture that was introduced for LTE networks where both master node and secondary node operates in the same frequency. The duplication of the data transmission in multi connectivity is at packet level where both cells share the same radio bearer but the data packets are transmitted to UE either by the master or by the secondary cell.

In LTE Release 12 Dual Connectivity (DC), data splitting technique is being used which is basically utilising two distributed independent schedulers one in each cell allowing the UE to receive two different PDUs and combine them to get the original data assigned for the UE. The splitting depends on the channel condition to the relevant cells. The data duplication is being done at PDCP layer to utilise its' functions such as data transfer, routing, reordering and flow control or user/control plane split functionalities to duplicate the data into two PDUs. The two packets are transmitted via two different gNodeBs. Hence, the network stack is such that each copy of the packet is pass through two different RLC, MAC, and PHY layer, exploiting some functions from the RLC layer like duplicate detection and re-assembly, etc, and link adaptation of the MAC layer and other functions would be required such as but not limited to common priority handling and radio network identities, etc, see [18].

The original PDCP PDU and the corresponding duplicate in the duplication process can be transmitted on the same carrier. The duplication applies for the cases where two different logical channels can either belong to the same MAC entity in Carrier Aggregation (CA) or to different ones in Multi connectivity (MC) [19].

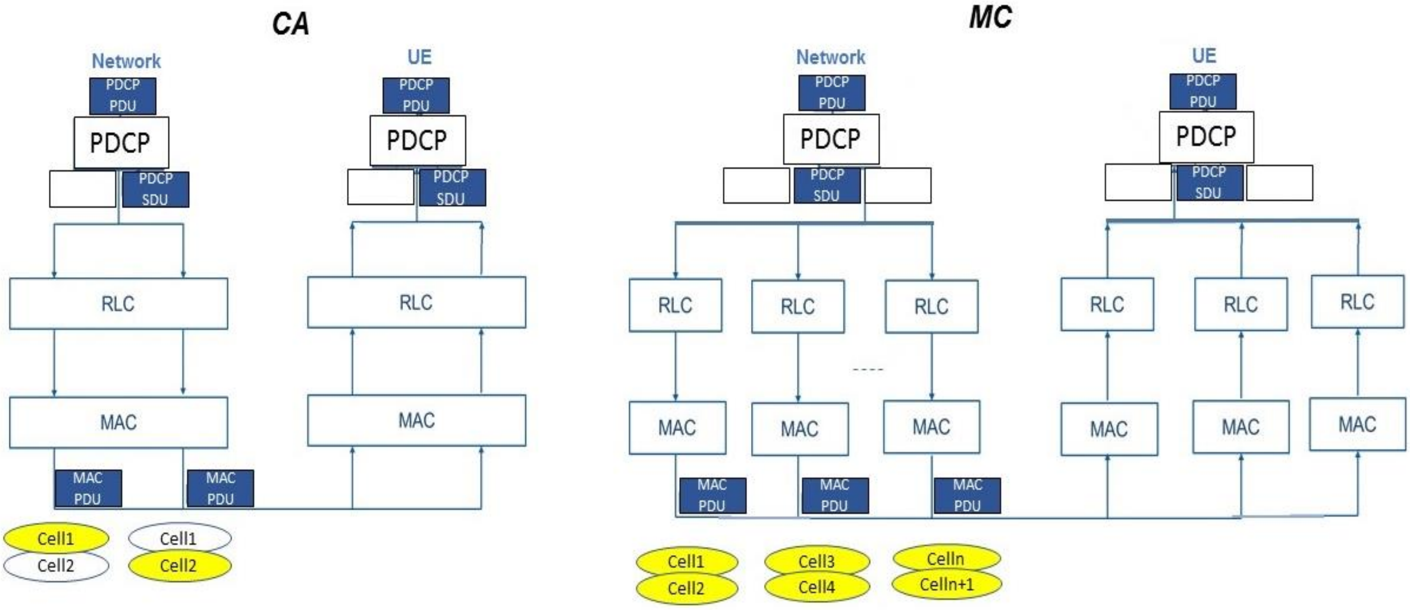


Figure 6. Data Duplication in CA and MC cases

In addition, in [20], The stack layer that is responsible for the Data Duplication is the Packet Data Convergence Protocol (PDCP)- as it is the layer whose among its' functionalities: transfer the user data, duplicate detection (DD), PDU routing and timer based duplicate discard. Once the data duplication is enabled for a radio bearer by the Radio Resource Control (RRC), there is another Radio Link Control (RLC) element and a logical channel are added to it to deal with the PDCP PDU replicas.

1.7.1. Dual Connectivity

The conceptual idea of multi connectivity is not new to mobile communications. There are some mechanisms in the standardization and literature- e.g. Soft Handover in WCDMA and LTE Joint Transmission Coordinated Multi-Point (JT-CoMP)- based-on MAC/PHY layer functionalities- was previously introduced. Moreover, in Release 12 of LTE-A, Dual connectivity for instance was introduced and supported only in the DL- where the UEs are configured to consume radio resources provided by at least two different cells connected via backhaul over the X2 interface to transmit and receive data reliably from those nodes. There is a Master node and one Secondary node. Data plane is split between both. In a typical scenario to reduce the signalling overhead if we are considering that both nodes are macro cell. The Dual Connectivity technique is between a Master node and one Secondary node which is the first step towards Multi-Connectivity that's building on this to have for example but not limited a master node and more than one secondary node.

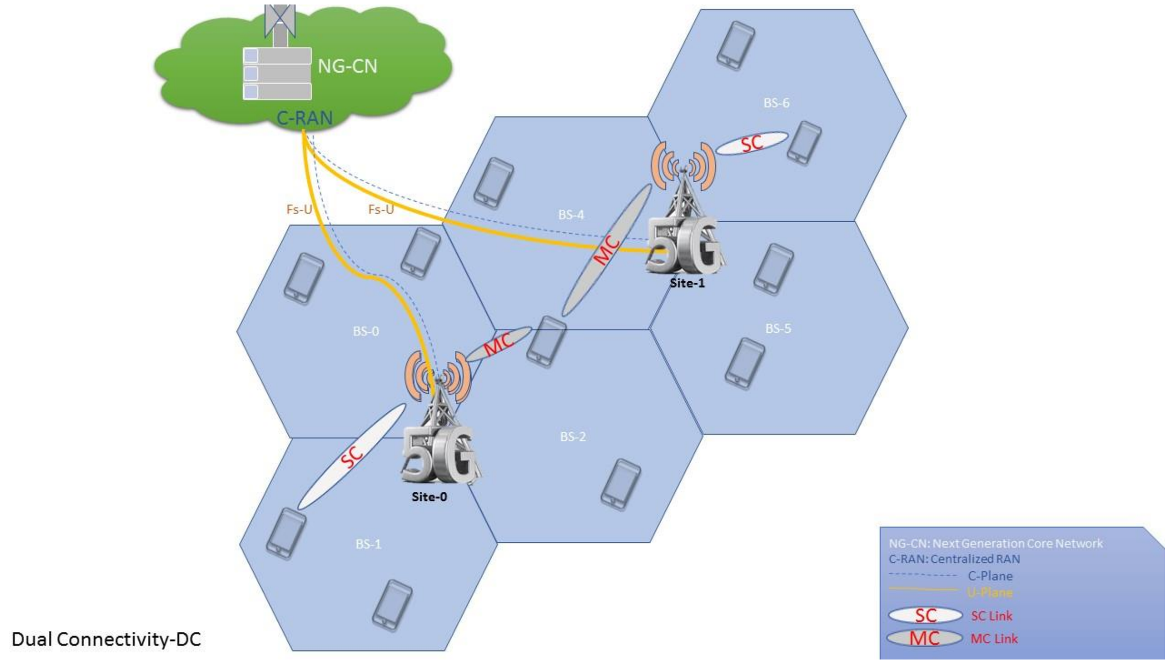


Figure 7. Typical 3C DC Scenario Layout

There are two different DC solutions depending on where the split of the user plane is done. It can be a fronthaul split-based or X2-based split, so that MgNb and SgNb serves a separated radio bearer or the same radio bearer in the MgNb [21]. In the latter case, the data of the same radio bearer can be transmitted via both the MgNb and the SgNb, so this offers higher flexibility. However, this is at the cost of increased transport and processing capabilities in the MgNb and in the X2 interface. There is also the need for flow control feedback to avoid congestion and increase the rate control efficiency across cells.

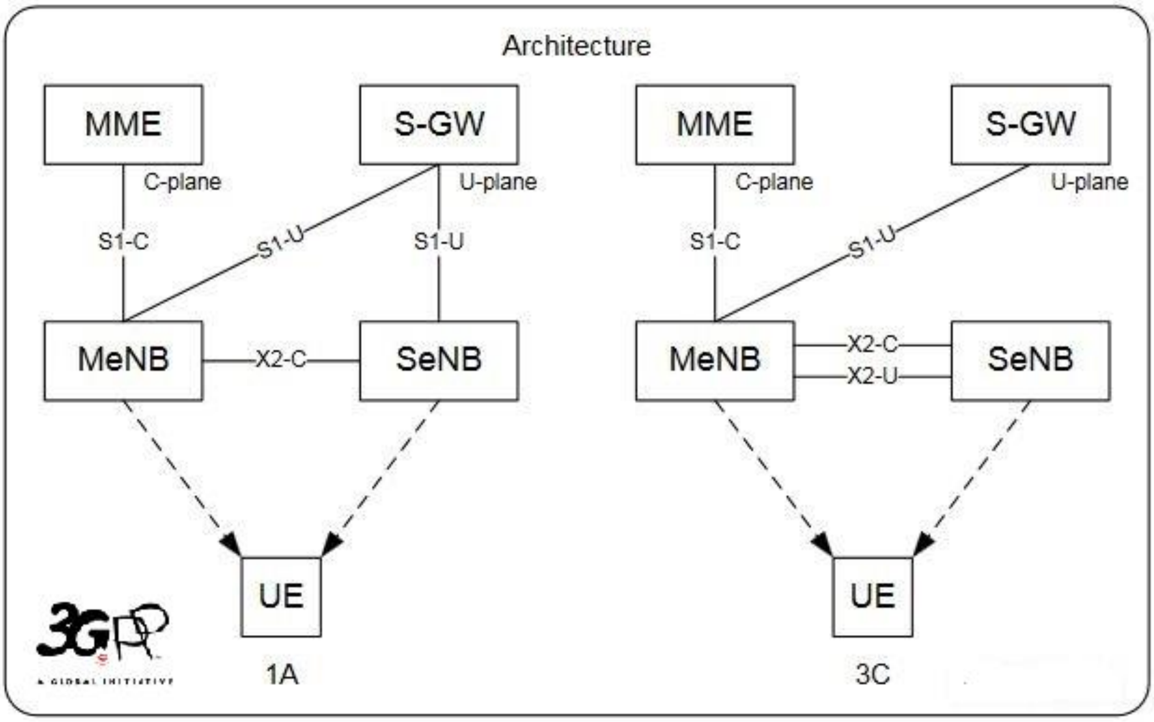


Figure 8. DC Architecture

So far, DC has been utilized to boost user throughput performance by splitting data between MgNb and SgNb. However, its performance in the context of reliability enhancement as envisioned in 5G NR is not well understood. This is especially true when considering the URLLC service class for which data duplication seems suitable to increase reliability, unlike data splitting for data rate boosting. In addition, enabling MC options calls for dynamic autonomous algorithms that will configure this option, for example, by determining the number of required links and selecting dynamically how much data to transfer among the selected links to meet given performance targets. DC can increase the UE throughput and mobility robustness [21], by allowing users to be connected simultaneously to two nodes, especially for cell edge users by transmitting/receiving multiple streams.

Depending on this DC splitting technique which is basically utilising two distributed independent schedulers one in each cell. Those are based on the transport block size information provided by the physical layer depending on the channel condition of each cell allowing the UE to receive two different PDUs. After this the UE combines the PDUs to get the original data assigned for it. As for data duplication, we are utilizing functions as data transfer, routing, reordering and flow control or user/control plane split functionalities of the PDCP layer in order to duplicate the data into two PDUs of the same data. This is dividing the rest of the network stack in such a way that we have two virtually RLC, MAC, and PHY layer exploiting some functions from the RLC layer like duplicate detection and re-assembly, etc, and link adaptation of the MAC layer and other functions would be required such as but not limited to common priority handling and radio network identities, etc, see [18].

A link adaptation strategy is presented where the modulation and coding scheme (MCS) is selected according to the target reliability and feedback channel imperfections [22]. As we are assuming that our scenario configuration allows six Hybrid Automatic Repeat/Request (HARQ) retransmissions of the PHY layer which can substantially relax the block error probability (BLER) constraint that the URLLC transmission needs to fulfil [23]. Dual connectivity advantages come from using multiple transmission attempts, as compared to a single transmission, which is going to increase the transmission reliability by ensuring that the designated mobile terminal will receive the data assigned to it with less error probability within the latency target. This in one hand, will provide a gain in using DC in certain situations according to certain conditions in the network. On the other hand, it comes with a cost that is the average amount of radio resources required to transmit the small data payloads will increase to transmit two PDUs of the same data from each of the cells that the UE is connected to. This will increase the network resources utilization.

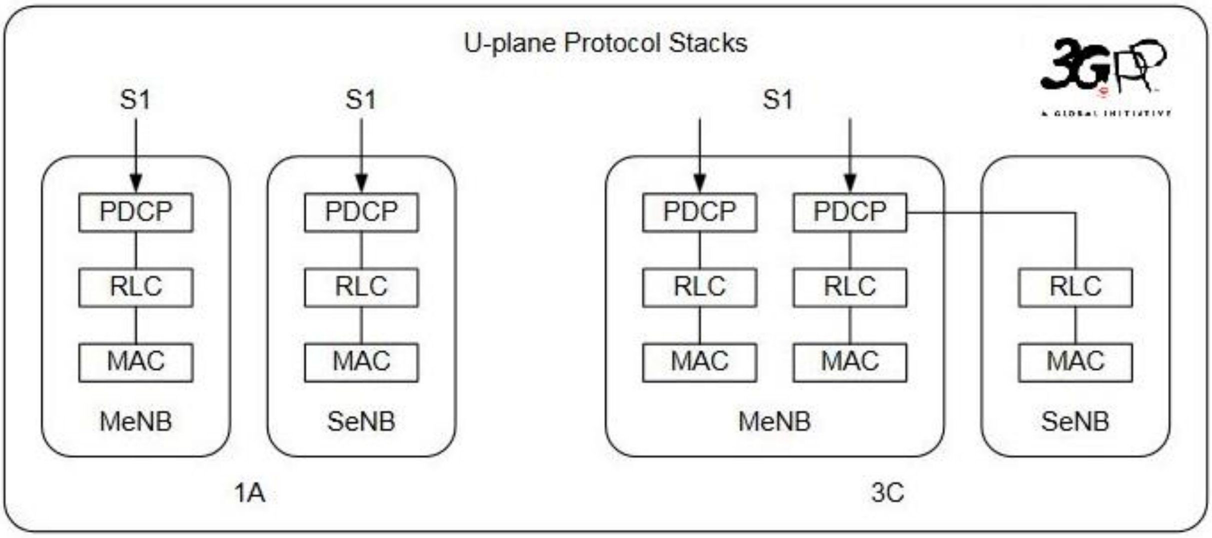


Figure 9. DC User Plane Protocol Stack

PDCP operation in our scenario (3C DC)- that we have a centralized PDCP layer between the two cells where the packets are being copied from the master node to the secondary node. This will split the other layers into two virtual stacks one for each cell –. This has some challenges such as Out-of-order arrival of PDCP PDUs. Therefore, the PDCP reordering should be always enabled in contrast to the legacy LTE system in which PDCP reordering is only needed upon handover and RRC re-establishment [21]. Here, a reordering timer is utilized to prevent too much delay. In other words, the PDCP receiving end can move on window without considering the gap after reordering timer expiry.

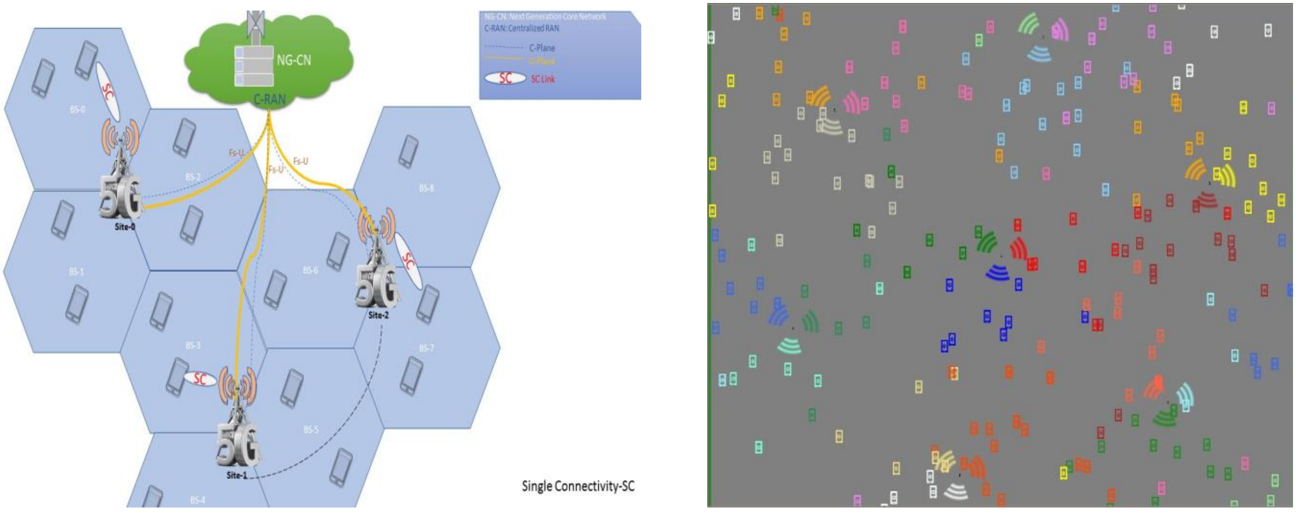
2. Methodology / project development

Motivated by the potentials of the multi connectivity observed by previous studies to satisfy the URLLC requirements, we present a system model that complies with MC architecture that can answer our research questions in which we can find what the optimal criteria for a cell so that it can be considered as a Primary Cell (PCell) and what makes the best connection the UE can exploit sufficiently to receive the assigned data. Then, how to select a Secondary Cell (SCell) to be utilised as a proper connection to transmit the duplicated data to the same UE.

Using the same methodology of DC, the Master node configures the UE to send a Measurement Reports (MR) for the neighboring cells. Specifically, the UE reports the Reference Signal Received Power (RSRP) and the Reference Signal Received Quality (RSRQ). It is configured to test an event, which after a certain Time to Trigger (TTT) is reported to the PCell.

2.1. Intra-Frequency Scenario

The chosen scenario is defined by the 3GPP specifications [24], which comprises of a macro-cellular network composed of seven 3-sectors sites with 500m inter-site distance, as shown in Figure 10. As it can be seen in Table 2, the same carrier frequency is used for the deployment of the macro cells- 2 GHz, so it is an intra-frequency site with a bandwidth of 10 MHz and a Transmitting power of 46 dBm and 2 x 2 cross polar antennas. We are using a Proportional Fair algorithm as packet scheduler, and an In-resource control channel scheduling grants with dynamic link adaptation as proposed in [24] with Modulation and coding Scheme for data channel from QPSK to 64QAM with the same rates as LTE [22]. It is worth to mention that we investigated two different possible ways to set such scenario. The first way was by setting one logical base station that consists of 7 Transmission and Reception Point (TRP), each TRP have of 3 sectors each one of them has two beams. This way showed some complexity to be implemented in the the time frame suggested for this project. Such complexity made us change to the second way which is the one mentioned in the beginning of this section.



(a) **(b)**

Figure 10. Site Deployment (a) Layout & (b) Simulation

Table 2. Parameters and Configurations

Parameters	Macro-NR
Layout	7 Macro Nodes, 21 cells, wrap around with 500m ISD [24]
Carrier frequency	2 GHz
Simulation bandwidth	10 MHz
Channel model	3D UMa
BS power	46 dBm
Antenna configuration	2x2 x-polar single stream MIMO with LMMSE_IRC receiver type [25]

BS antenna pattern	TR36.814
BS antenna height	25m [10]
Subcarriers/RB	12
Subcarrier spacing(kHz)	15
Symbol/Second	14000
Cell Selection Criteria	RSRP
SCell selection event	A4 and Modified A3 for DC

2.1.1. Data Duplication for URLLC requirements

Data duplication at PDCP layer is basically consists of sending the same PDCP PDU twice: the first through the master node RLC element and a second copy of the same PDCP PDU on the second RLC structure. This operation occurs through two independent transmission routes. The data duplication then improves reliability within a reduced latency by ensuring the reception of the designated packet to the UE from two different links and depending on the condition of the cells. This is especially beneficial for URLLC services and to meet the strict user plane latency requirement of URLLC the RLC retransmission Automatic Repeat/Request (ARQ) is not assumed to be used.

The moment data duplication is configured, it can be enabled and disabled per Data Resource Bearer (DRB). In MC case, the UE applies a MAC Control Element (CE) commands regardless of the cell they were transmitted from master or secondary.

The dual connectivity implementation in FREAC was for a scenario where the data to be split and send over two connections Therefore, to have data duplication feature we had to add an extension to the simulator code. In this extension, we introduced a totally new feature to the system level simulator starting with studying the additional code, then how to model it based on the available code and contributing the new extension to the system to be tested. This process includes verifying and debugging the system to be ready work properly which consumes some time in this project.

2.1.2. Simulation Assumptions

The system level simulation is performed using Nokia Bell Labs propriety FREAC simulator and based on 3GPP 5G NR numerology [25]. In our simulation we are assuming a fixed number of UEs of 210 and all of them are URLLC users (with 10 UEs per macro cell uniformly distributed). We will compare the latency distribution of the URLLC UEs with different URLLC offered loads. We are considering a 3D channel propagation model. The simulator has been used to generate only 5G NR performance results, where at each TTI the simulator calculates the SINR experienced by each UE per resource element assuming a minimum mean square error interference rejection combining (MMSE-IRC) receiver [26].

Asynchronous adaptive HARQ with Chase Combining is applied in case of failed transmissions, and the SINRs for the different HARQ transmissions are linearly added

[27]. Closed-loop single-stream single-user 2x2 MIMO transmission mode is assumed, i.e. benefiting from both transmission and reception diversity against fast fading radio channel fluctuations [13]. A static mobile terminal configuration is assumed when there is no mobility; although the channel conditions is still considerably varying due to the fast fading effect and FTP dynamic traffic model that is used in the simulation. Unless otherwise mentioned, we assume low-pass IIR CQI measurements at the UE (as explained in section 3.1.3). and unless otherwise mentioned the simulation is generating a payload size of 200 Bytes, the offered load refers to the average URLLC traffic offered per macro cell (as explained in section 3.2.1.1). The BLER target was controlled using the Outer Loop Link Adaptation (OLLA), which updates the existing link condition information based on the Inner Loop Link Adaptation (ILLA) or the previous measurement information received from the UE to the latest measurement report information.

The latency (as described in section 2.2.1) for every single received FTP packet is collected and used to form an empirical complementary cumulative distribution (CCDF). Our adopted Key Performance Indicator (KPI) is the achievable latency for 10^{-5} reliability (i.e. 99.999% probability), see [28].

2.1.3. Interference filtering configurations

The first challenge we faced by choosing this scenario was the co channel interference where the two links are interfering on each other and on the rest of the connections in the network as all cells are operating on the same frequency. Therefore, and as proposed in [22], the interference is averaged by including a historic information of the previously experienced interference in the UE CQI measurements report, that is at each TTI (n) the UE measures the interference with a sub-band PRB $x_i[n]$ and it is being filtered using a low-pass Infinite Impulse Response (IIR) filter [22]:

$$s_i[n] = \alpha * x_i[n] + (1 - \alpha) * s_i[n-1], \qquad [1].$$

Here, α is the Forgetting Factor (FF) of the low- pass filter ($0 < \alpha < 1$). This means that the CQI is reported periodically to the base station including the filtered interference measurements together with the latest desired fading information [22]. The averaging of the measured interference will simply present a comparison between the new latest CQI report measurements with the previous reports information. Pocovi et al, found that a FF $\alpha = 0.01$ is beneficial for the latency performance that we need for URLLC requirements. With such approach the base station knows the history of the interference in the network that is affecting the channel condition for mobile terminals which means it is possible to track the channel variations with relatively high accuracy [29].

2.1.4. General Parameters

2.1.4.1. Traffic Model

In Table 4, we present the cell load configurations in our scenario which was discussed in [30], [31] where we are assuming that there is one logical base station consisting of seven base stations set to be Macro type of cells each of them has three sectors, each has two wide beams. A fixed number of 210 URLLC User Equipment (UEs))- 10 UEs per macro cell- are uniformly distributed across the network. Unidirectional downlink traffic following the so-called FTP Model 3 (FTP3) is applied which consists of relatively small packets (50B) that are generated for each UE in the downlink, arriving in different average rates (packets/s) to achieve an offered load varies from 250Kbps up to reach 4Mbps.

With the baseline settings, we are expecting to fulfil the 5 nines reliability requirement for the offered loads up to 1Mbps within the required latency of 1ms and a different latency results for offered loads above 1Mbps to achieve the targeted reliability. The offered load per macro cell is calculated according Equation [2], where (λ) is the arrival rate, (B)is the payload size in bits and (N) is the average number of Low Latency Communication UEs per macro cell. (L) is given then in bits per second.

$$L = \lambda \cdot B \cdot N \qquad [2]$$

As shown in Table 3, our plan is to connect 210 User Equipment (UEs)- 10 UEs per macro cell- with a packet load of 50B arriving in three different timings every 62.5, 125, 250, 375 and 500 (packets/s) to achieve an offered load varies from 1Mbps up to reach 4Mbps. We chose the 50B packet size based on packet size sensitivity tests as detailed in section 3.2.4.

Table 3. Cell load configurations

Total Number of UEs	210
Number of UEs / macro (*N*)	10
Arrival rate $\lambda(packets/s)$	62.5, 125, 250, 375, 500
Packet Size (B= *Bytes*)	50
Offered Load per cell (L= *Mbps*)	0.25, 0.5, 1, 2,3, 4

2.1.4.2. Short TTI Paramaeters

Since the air interface delay cannot be any shorter than the Transmission Time Interval (TTI), introducing shorter TTIs is a promising approach to reduce the transmission latency. A shorter TTI is introduced by reducing the number of symbols in a single transmission while seeking to maintain the backward compatibility and usability with LTE [32]. As discussed in [22], at the10^{-5} percentile, there is a significant benefit of using short TTI size as it reduces the latency by considering a maximum 1 TTI for the frame alignment and performing the scheduling decision and the over-the-air transmission. Also, UE processing, and the base station processing time of the Negative Acknowledgement (NACK) are reduced.

In this work, we consider a short TTI of 0.143 ms corresponding to two OFDM symbols in a 15 KHz subcarrier. With these conditions the maximum latency with one HARQ retransmission can be reduced to 6 TTIs (6 * 0.143ms = 0.86 ms). This is lower than the URLLC latency target of 1 ms. In our study we are utilizing most of the TTI duration for the data transmission by using a reduced configuration for the control symbols per TTI as depicted in Figure 11 This reduction requires an improvement of the UE and base station processing [22].

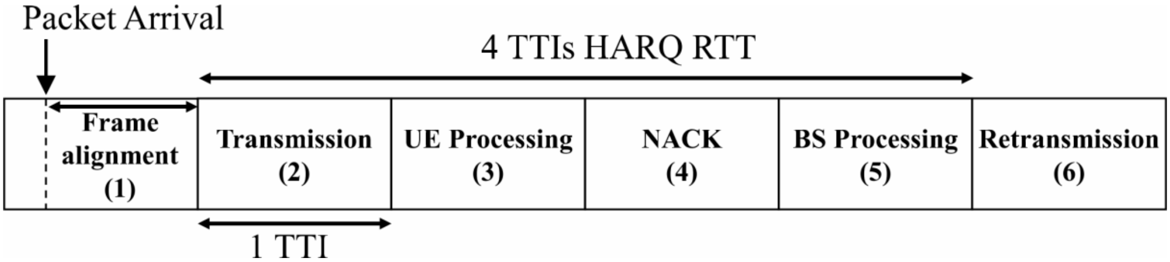


Figure 11. HARQ Operation with a Round Trip Time (RTT) of four TTIs [22].

2.2. Baseline Optimization

Our scenario will be based and first compared to a single connectivity scenario which was discussed in [33]. This scenario was chosen following 3GPP requirement, see [25]. DC mode will be applied in such scenario to confirm the capablity of achieving the expected gain in latency and reliability for the 5G requirement.

2.2.1. Cell Selection Criteria

The mobile terminal depends on the measurements reports of the Reference Signal Received Power (RSRP) which is the average received power from the resource element that carry Cell-specific Reference Signals (CRSs) to check which cell is the best to be connected to. On the other hand, the *Reference Signal Received Quality* (*RSRQ*) is the ratio of RSRP to Received Signal Strength Indicator (RSSI), where RSSI is the total received power including interference from all sources (serving and non-serving cells) and thermal noise. Due to the consideration of interference and noise in RSRQ measurement, a UE may experience different received signal qualities at different locations [34]. Since we are not considering mobility in this scenario, the RSRQ cell selection criteria is not included in the simulation.

2.2.2. Interference filtering

The impact of filtering the interference (as explained in section 2.1.3) on the latency is presented in Figure 12, where we can see that different level of effect according to offered load level in each sub-figure. The curves show the different transmission modes from the first transmission in the second TTI and the retransmissions in the 2 next TTIs then the second transmission within the 5th TTI until the packet is completely transmitted in the 6th TTI. We observe that the performance from the latency point of view is not actually affected at low loads like 250Kbps and 500Kbps, as shown in Figure 12 (a):

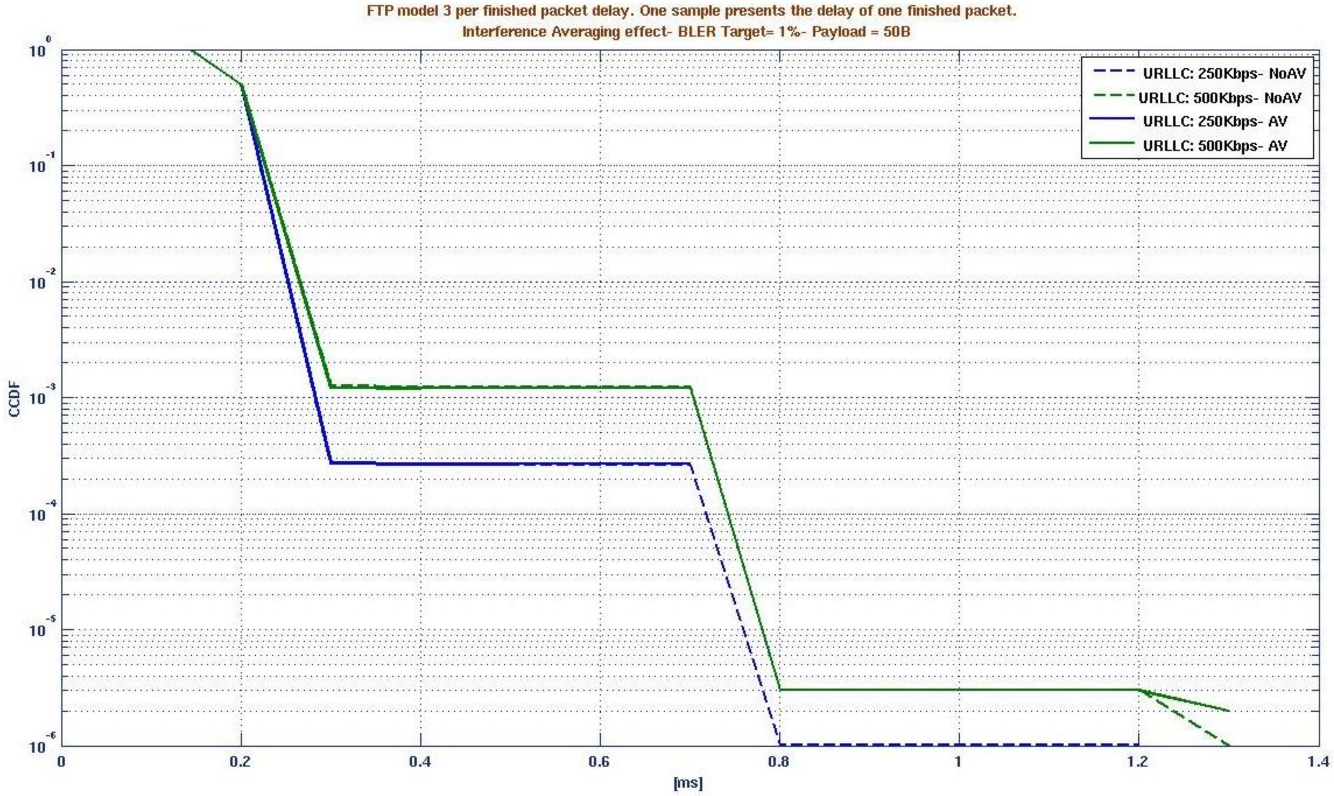


Figure 12 (a). Interference Filtering with Forgetting Factor (FF = 0.01), (a) 250Kbps and 500Kbps Offered Loads

On the other hand, this mechanism starts to have some slight effect on the latency performance in a mid-level offered loads such as 1Mbps and 1.5Mbps, where we can see that in the case of filtering the delay reduced and the reliability was slightly improved, see Figure 12 (b):

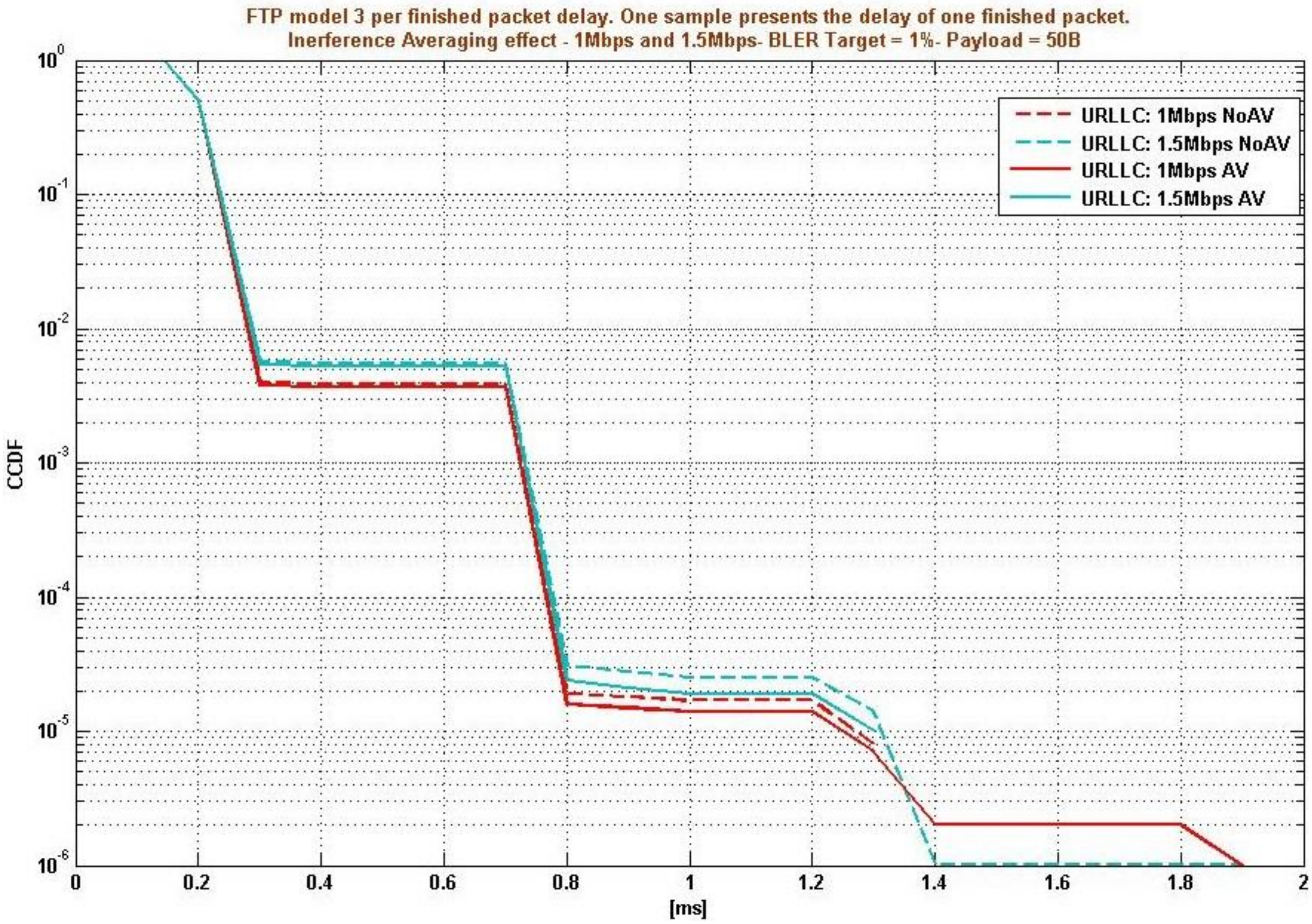


Figure 12. Interference Filtering with Forgetting Factor (FF = 0.01), (b) 1Mbps and 1.5Mbps Offered Loads

As shown in the previous cases, the Interference filtering effect is increasing proportionally with the offered load. This trend can be shown in the next two figures (Figure 12 (c) and (d)) where the results for the 2Mbps and 3Mbps offered load shows more reduction than the mid—level offered loads (1Mbps and 1.5Mbps). The 4Mbps case reduction in latency is doubled (going from 4.5ms at 10^{-5} reliability without filtering to 2.7ms when it is being used) compared to the 3Mbps case:

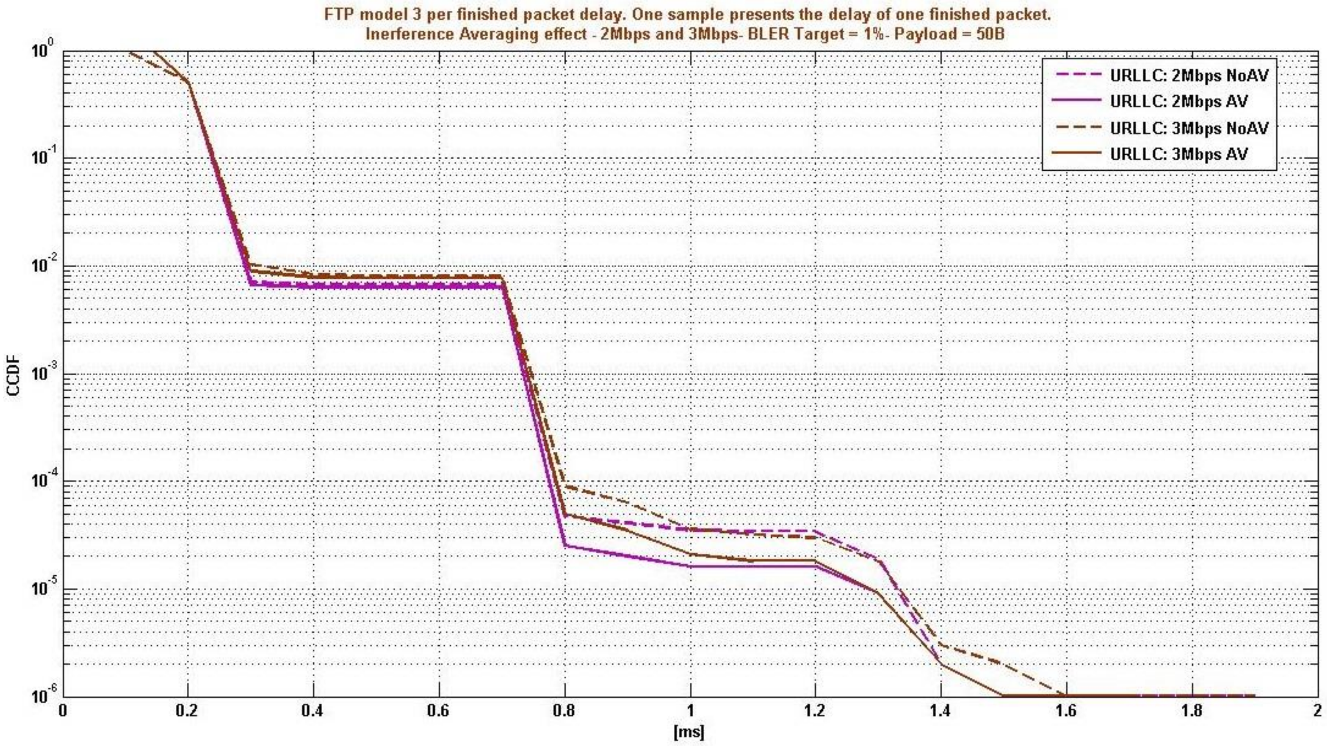


Figure 12. Interference Filtering with Forgetting Factor (FF = 0.01), (c) 2Mpbs and 3Mbps Offered Loads

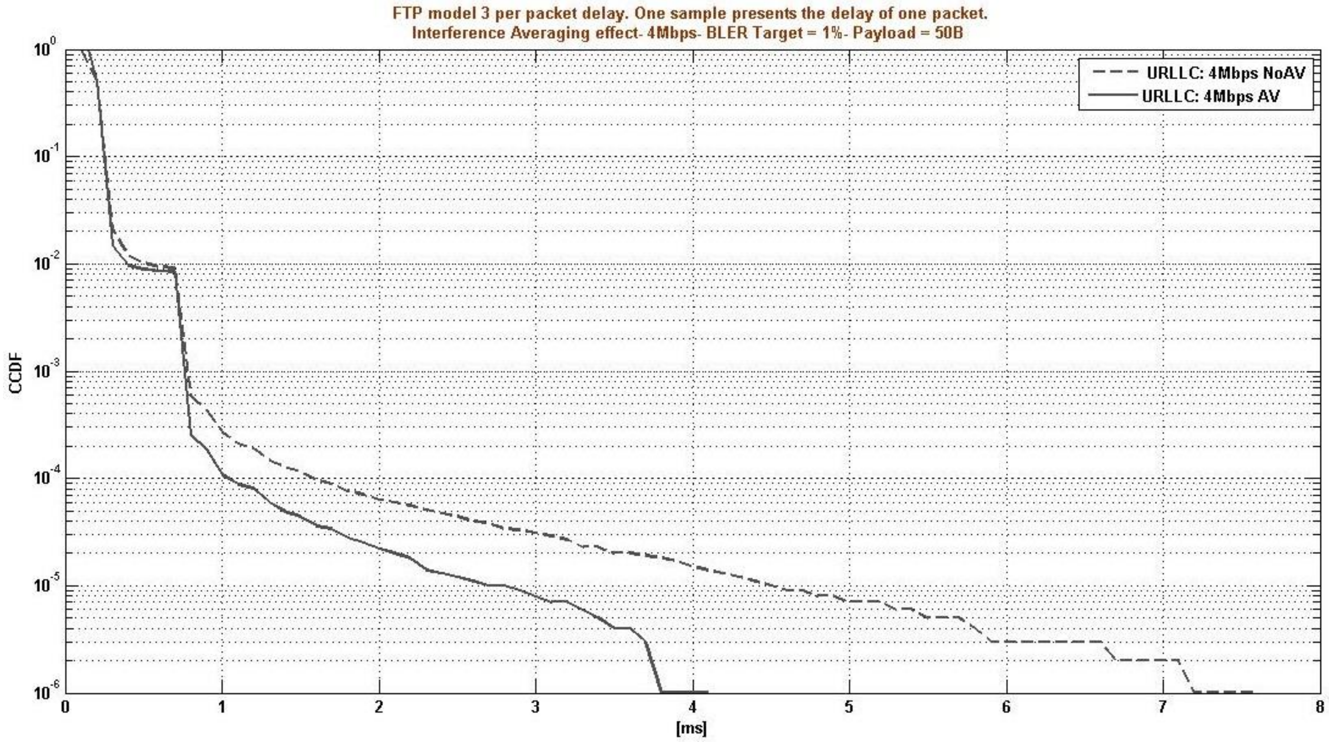


Figure 12. Interference Filtering with Forgetting Factor (FF = 0.01), (d) 4Mbps Offered Load.

2.2.3. BLER Optimization

In order to have very realistic configuration for our scenario, we investigated two different cases where we have a conservative transmission and an aggressive transmission by adjusting the BLock Error Rate (BLER) targets to 1% and 10% correspondingly. In theory, it is expected that the lower loads simulations would have better performance with 1% BLER target because it will have lower error probability. The results confirmed this aspect even though the difference is slightly small with small offered loads like 250Kbps and 500Kbps but it is clearer in higher loads up to 1Mbps where the case of 10% BLER target start to cause noticeable effect not allowing the transmission to meet the latency requirement that we were meeting with 1% BLER target, as we can see below:

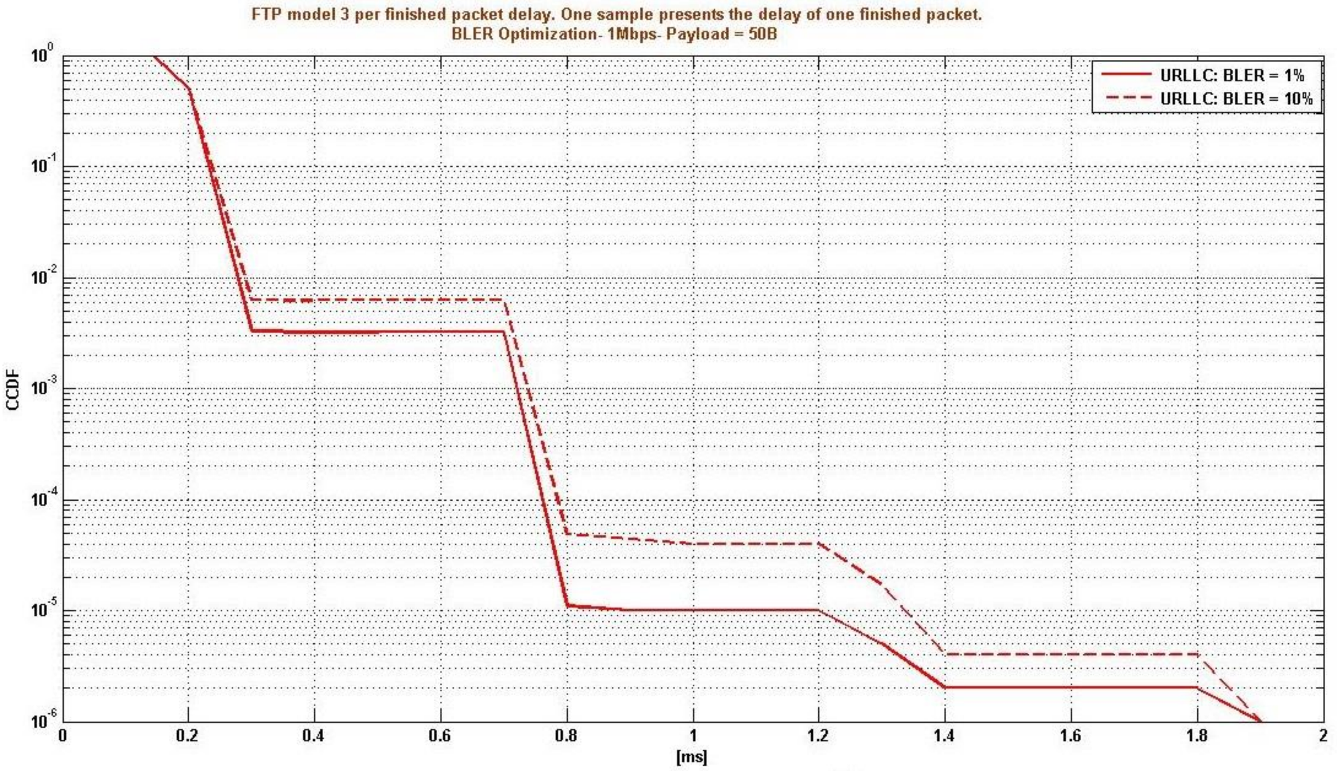


Figure 13. Delay per finished Packet for conservative (BLER Target = 1%) and more aggressive (BLER Target = 10%) Transmissions – 1Mbps offered load.

The above results show that in both cases the actual BLER measured in the network didn’t exceed the 1% as shown in Table 4. This is because with such low loads we don’t have enough interference to load the network so that the error probability is less than that targeted by the link adaptation algorithm. Nevertheless, we can clearly see from Table 4 that the measured BLER is proportionally increasing with offered load and especially starting from the 1Mbps case; the difference starts to be bigger as we increase the load. This difference is consequently affecting the latency performance as we can observe in the Figure 14:

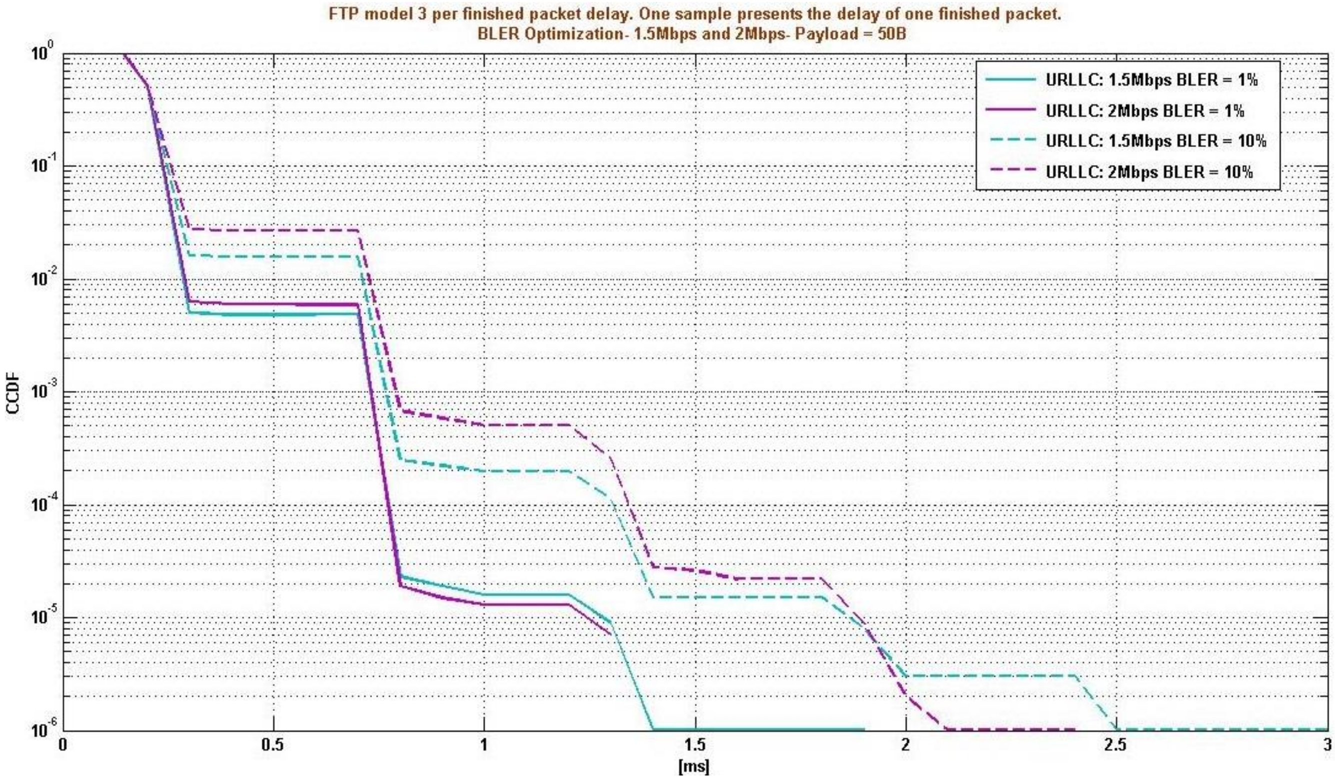


Figure 14. Delay per finished Packet for conservative (BLER Target = 1%)and more aggressive (BLER Target = 10%) Transmissions – 1.5Mbps and 2Mbps offered loads.

Table 4. Actual BLER measured in the network for different BLER Targets (1% and 10%)

Offered Load	Actual BLER - BLER Target = 1%	Actual BLER - BLER Target = 10%
250Kbps	0.025 %	0.028 %
500Kbps	0.105 %	0.133 %
1Mbps	0.323 %	0.621 %
1.5Mbps	0.484 %	1.577 %
2Mbps	0.596 %	2.663s %

2.2.4. Packet Size Sensitivity

Based on the results in the previous section, in this section we are presenting the sensitivity of using different settings of packet size in accordance with 3GPP short packets sizes (32B, 50B, 200B) [10] with 1% BLER target. Table 5, shows that the cases with smaller packet sizes (such as 32B or 50B) experience better actual BLER and consequently by far less queuing delay than the 200B packet size case. At an offered load as high as 4Mbps the difference of the sizes effect is smaller than the difference with lower offered loads which showed in the results to have a slightly small delay distinct.

Table 5. Actual BLER measured in the network for different Packet sizes

Offered Load	Actual BLER – 32B	Actual BLER – 50B	Actual BLER – 200B
500Kbps	0.04 %	0.105 %	0.126 %
1Mbps	0.213 %	0.323 %	0.364 %
1.5Mbps	0.398 %	0.484 %	0.528 %
2Mbps	0.525 %	0.596 %	0.678 %
4Mbps	0.779 %	0.82 %	0.906 %

Based on those results we observe that smaller packet sizes (32B and 50B) difference in terms of latency performance is not as significant as the difference between smaller sizes results compared to 200B packet size. This latter difference is more observed in high offered load cases as shown in Figure 15, which is a major focus in our project. Therefore, we are considering a packet size of 50B unless otherwise mentioned. The main reason causing the observed difference in the performance of 200B is that many of the packet cannot be transmitted in the same TTI (segmentation of packet over different TTIs) due to the available bandwidth that we have (10MHz).

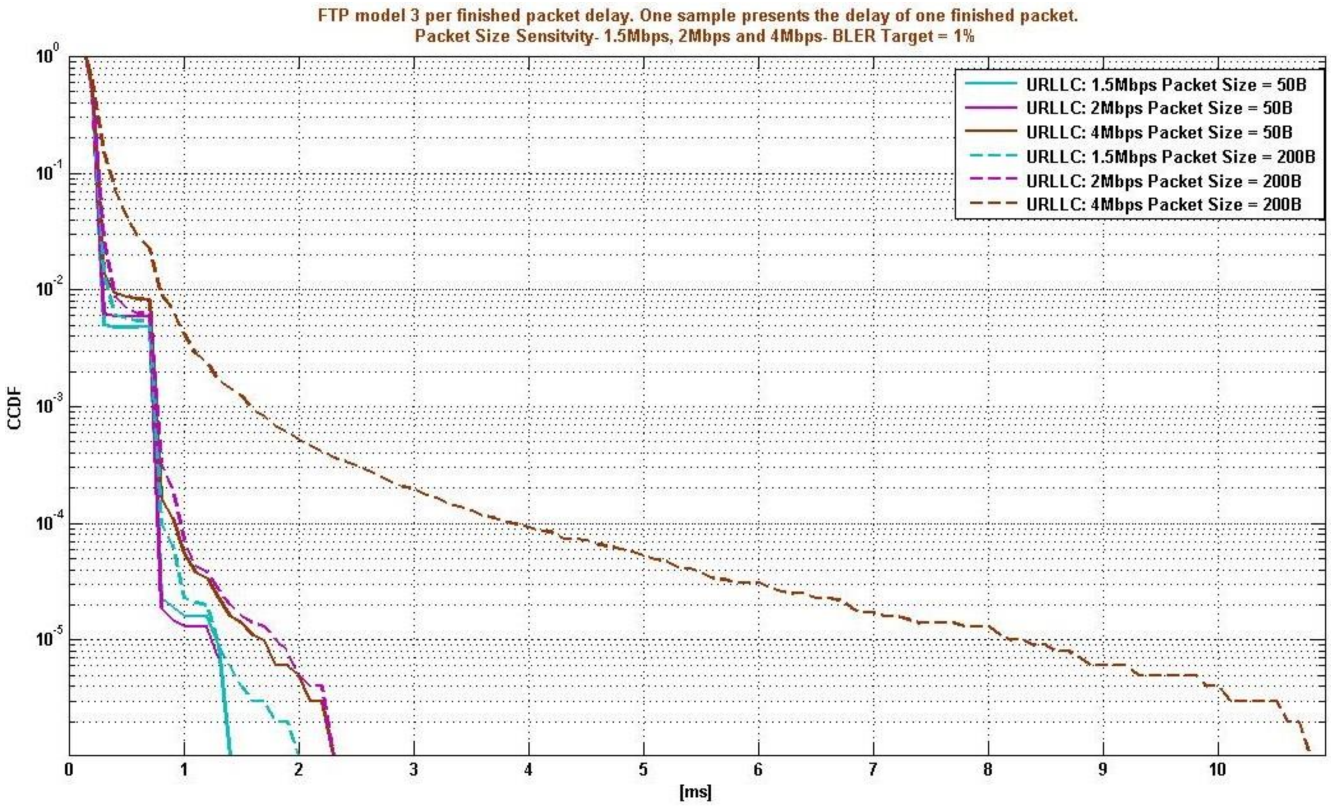


Figure 15. Delay per finished Packet for different packet sizes– 1.5Mbps, 2Mbps and 4Mbps offered loads.

2.2.5. Single Connectivity Baseline

Then, based on the above subsections, we are using different packet arrival rate configurations and maintaining the packet size to 50B with BLER Target of 1%. Figure 16, is showing the above-mentioned configurations results in which, we could only achieve the required reliability for URLLC offered load lower than 1Mbps within the 1ms which meets the latency requirements of IMT2020. In contrast, we can meet that reliability requirement within 1.3ms at around 99.9998% reliability with 1Mbps, 1.5Mbps, 2Mbps and 3Mbps offered loads. The 4Mbps offered load case shows a higher delay than the other cases which is expected due to the interference this relatively high load for the Intra Frequency scenario start to introduce.

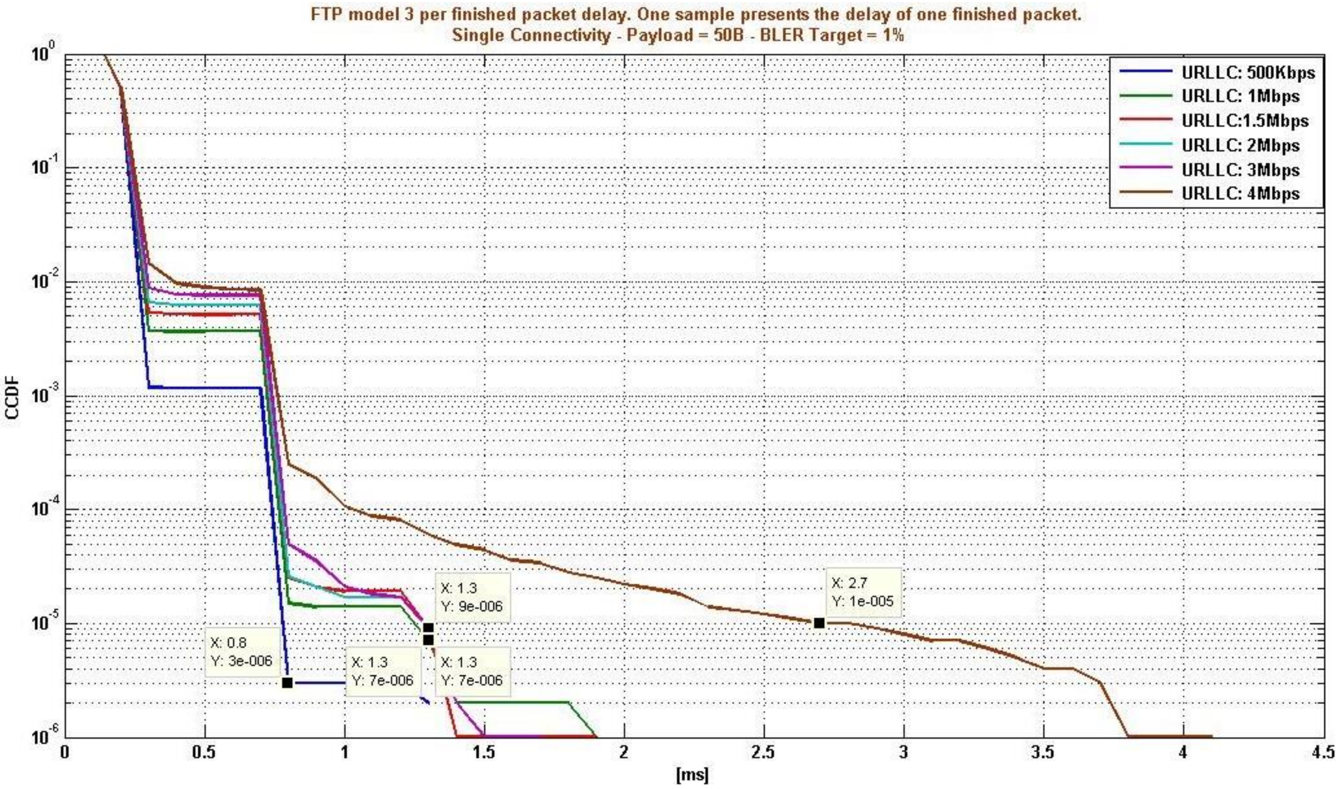


Figure 16. URLLC latency distribution for six different URLLC offered loads (250Kbps 500Kbps, 1Mbps, 1.5Mbps, 2Mbps, 3Mbps and 4Mbps), with packet size = 50B and BLER Target = 1%.

2.3. Multi-Node Connectivity Mode Configuration

2.3.1. Dual Connectivity (DC) in FREAC

As described in section 2.1.1, dual connectivity implementation in FREAC with data duplication was introduced and modelled along the process of this work. This contribution was basically checks a FR_CellConnKey class in addition to the already existing FR_ServiceConnection class. The FR_CellConnKey consists of two factors (cell_id, cc) that decides which cells the UE will select and to which component carrier it belongs with the extra conditions to prevent the MT from selecting a cell id for SCell similar to PCell.

Existing DC implementation in FREAC was using data splitting technique based on LTE DC to provide service to the users. In our simulations we needed to extend the simulator code to have data duplication technique for dual connectivity. The FR_DuplicatioDC class was added to FREAC whose responsibility is to do data duplication for our scenario. The PDCP layer in the OSI stack is emulated in the simulator as FR_Traffic and from the duplication class controlling wise, it is set to be common for both cells the master and secondary in our configurations. The classes that are responsible of the functions of the other stack layers (RLC, MAC, and PHY) for the 3C option (as explained in section 1.8.2) which is used in this scenario is depicted in Figure 15, are FR_ConnL3, FR_RLC, FR_ConnL2 and FR_ConnL1 respectively with some other subclasses to do specific functions of the aforementioned classes such as FR_ConnL1HARQ (which is responsible of doing the Hybrid Automatic Repeat Request (HARQ) process), FR_PhyLayer, etc.

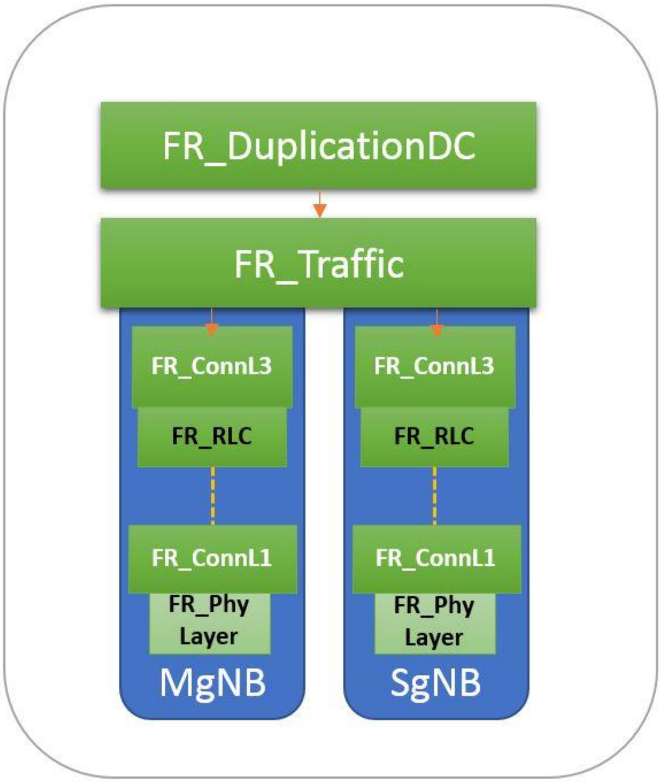


Figure 17. OSI Layers emulation in FREAC

2.3.2. Secondary Cell Selection Criteria Optimization

The dual connectivity mode depends on several factors in order to improve the performance of the mobile terminals. The main question here is which users can utilize this feature and how much the network can afford as a cost in return of using dual connectivity. The mobile terminals which are capable of fulfilling the condition so that an ideal usage of dual connectivity can be accomplished. This is only when the users require a supplementary connection to a secondary cell to carry out the load assigned to those users. This can at least reduce the extra burden on the network resources in more realistic situation. However, there is an expected cost of duplicating the data and transmitting to the same mobile terminal from two different base stations. The mobile terminal is served by only a Primary Cell (PCell) if that cell can provide the best connection to that MT and having a second connection won't enhance the packet error rate (PER) for that transmission such as the cases of UE-1, and UE-3 in Figure 18. On the other hand, if the secondary cell will reduce the PER, which is the case of UE-0 and UE-2. As shown in Figure 18 these users can utilize two connections to PCell and SCell which can belong to the same site or different sites since the secondary cell selection depends on the RSRP measurement.

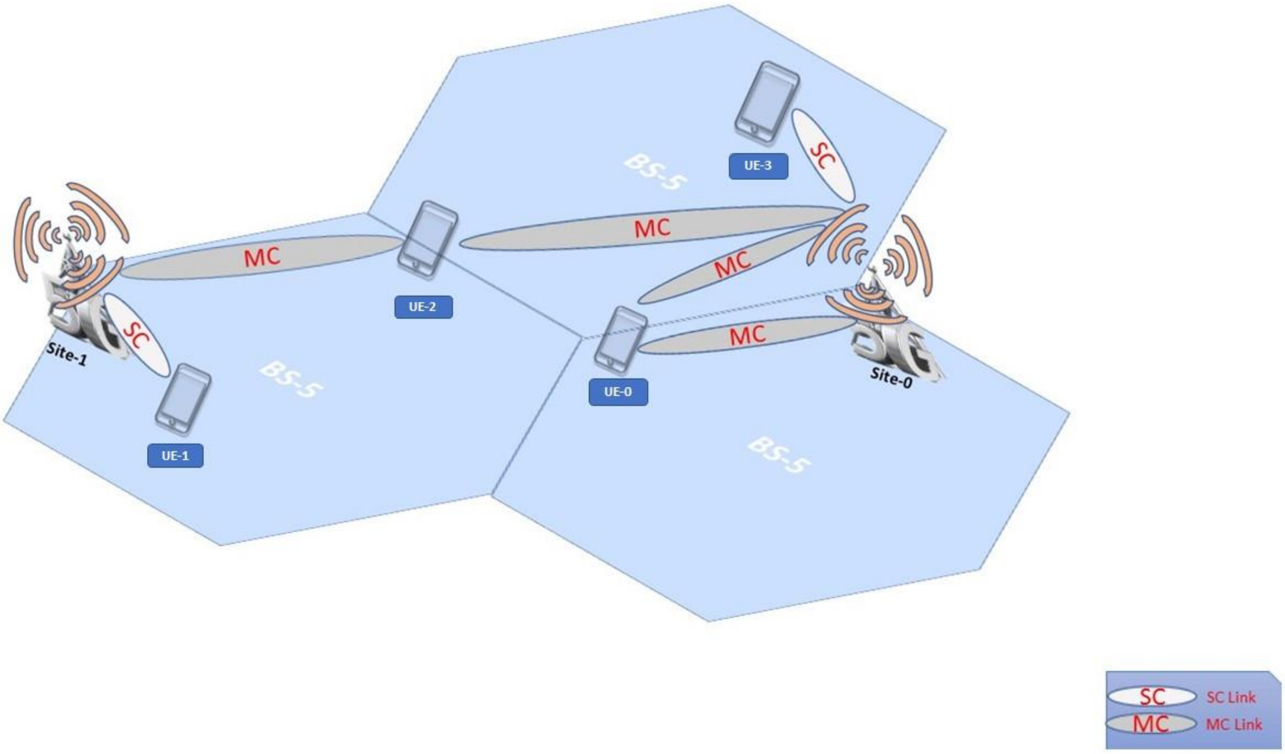


Figure 18. SCell Selection based on RSRP

It is required that the mobile terminal connections to the two cells must be based on the power measurements reported by the mobile terminal to the base station. The condition mentioned above is what decides if a certain user will have gain from a secondary connection to configure a SCell and activate dual connectivity or not. This condition is implemented based on the LTE and NR Events in 3GPP. The event shouldn't be triggered until it is within a certain criterion set for triggering it. The evaluation process shouldn't exceed the Time To Trigger (TTT)) in order for the event to be reported. In our work we are investigating two different LTE events as shown in Figure 19, so that we can meet the combination of the above-mentioned criteria to have DC and enhance the cell selection for the data duplication feature in such a way to check which of the users can gain from using it with minimal cost on the network utilisation in return. Those events are:

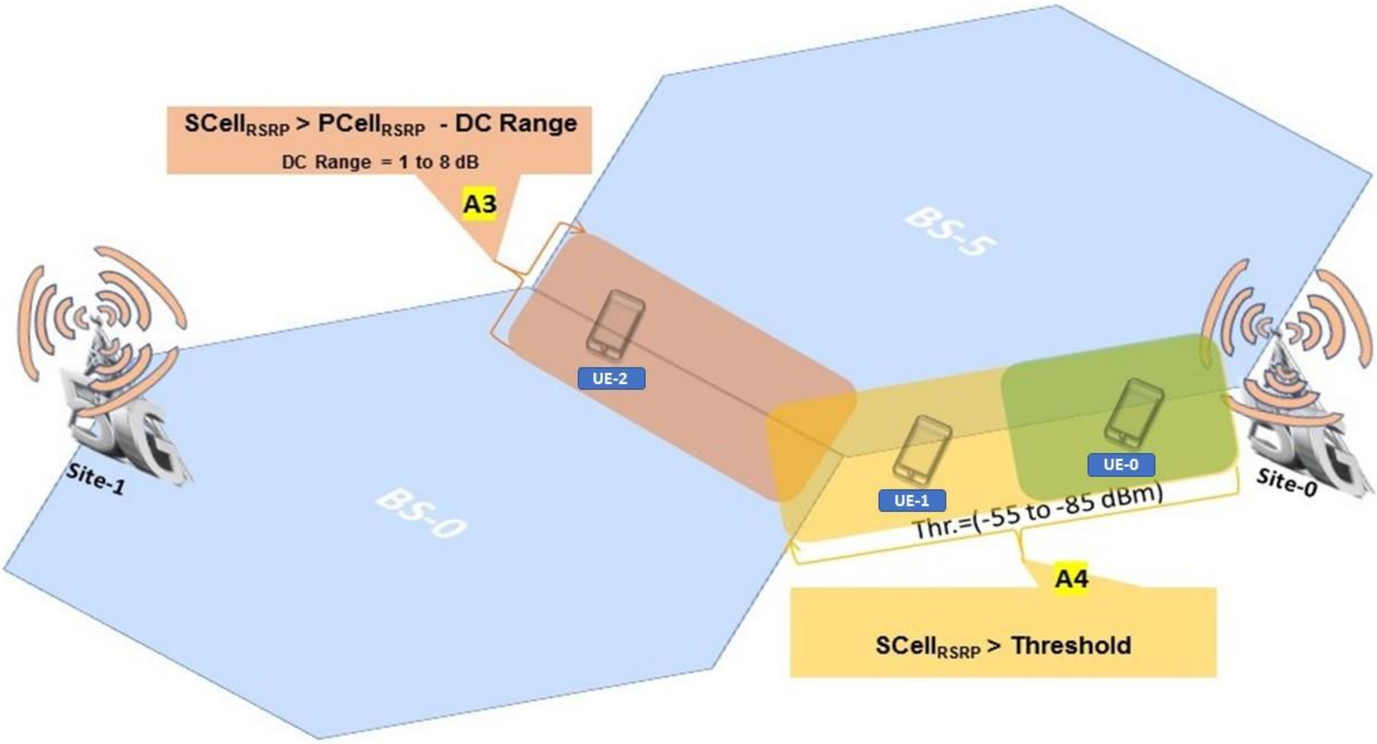


Figure 19. SCell Selection events condition

- **<u>Event A3- When the Neighbouring cell becomes better than the serving one.</u>**

For this study, the event A3 is being investigated. A UE needs to satisfy the following condition for the SCell to be configured:

$$\textbf{SCell}_{\textbf{RSRP}} > \textbf{PCell}_{\textbf{RSRP}} - \textbf{DC Range}$$

The DC range will decide how many users will be using DC mode. We considered 4 different DC ranges for this event investigation (1dB, 3dB, 6dB, and 8dB) in which each of them decides how many Dual Connected User (DCU) we have in the network. Two main factors we considered to decide whether this event meets our goal for DC. The first, which users it is targeting and how effective is DC mode to provide the required gain.

We observed that the choice of DC range noticeably changes how many users will be configuring a SCell. as shown in Table 6. This event and as depicted in the case of UE-2 in Figure 19, is targeting mostly the inter Site cell edge users between cells belongs to two different eNB.

Table 6. DC Users based on DC range and gain possibility over SC in at least one case of the offered loads

DC Range	# DCU	DCU% of 210 UE	Gain Possibility
1 dB	26	12 %	No
3 dB	65	31 %	Yes (1.5Mbps-2Mbps)
6 dB	120	57 %	Yes (1Mbps-1.5Mbps)
8 dB	139	66 %	Yes (1Mbps-1.5Mbps)

- **Event A4- When a neighbouring cell becomes better than a certain threshold**

  For further investigation to ensure that we are targeting the best region for our DC mode study, the A4 event is being investigated. A UE needs to satisfy the following condition for the SCell to be configured:

  $$\mathbf{SCell}_{\mathbf{RSRP}} > \mathbf{Threshold}$$

  The idea behind considering this event is due to the fact that we actually have another cell edge users that we can’t target with previous event with most of the DC ranges used. These are the Intra-Site users in which lie between two cells that belongs to the same site (gNB). The threshold value will decide whether the SCell RSRP reported by the UE to the BS is within the targeted criteria to be using DC mode. We considered 4 different thresholds for this event investigation (-55dBm, -65dBm, -75dBm, and -85dBm) in which each of them decides how many DCU we have in the network.

  We observed that the range of threshold noticeably changes how many users will be configuring a SCell even more than the A3 case, as shown in Table 7. This event and as depicted in the case of UE-0 and UE-1 in Figure 19, is targeting mostly the Intra-Site cell edge users between cells belongs to the same gNB. It is worth to mention that the results showed a slightly better performance than A3 event with low offered load cases such as 500Kbps with small number of DCU (High RSRP threshold value) which is highlighted in green as in the case of UE-0 in Figure 19, but still no gain provided over SC mode.

Table 7. DC Users based on Threshold and gain possibility over SC in at least one case of the offered loads

RSRP Threshold	# DCU	DCU% of 210 UE	Gain Possibility
-55 dBm	7	4 %	No
-65 dBm	34	16 %	No
-75 dBm	87	41 %	Yes (1.5Mbps)
-85 dBm	179	85 %	Yes (1Mbps)

We concluded that the targeted users with the modified A3 event are the MT that we want to configure for DC mode rather than the A4 event; as we can see that it is providing more gain in different cases both DCU number and higher offered load point of view. Furthermore, we can have even more gain when applying the Packet Cancelation feature, to be introduced later. Therefore, in the next sections we are considering the A3 event for all the cases unless otherwise mentioned.

2.4. Data Duplication Configuration

2.4.1. DC Baseline

The data duplication technique was implemented at the first place to occur for all users that are in dual connectivity which means, once the packet is received by the Master node it is directly copied and send to the secondary node. The transmission process from each cell is performed independently without checking whether the packet had been delivered correctly by the other cell since each cell has its' own independent schedulers and buffers depending on the load on that cell.

The MT will send an Acknowledgement (ACK)/ Non-Acknowledgement (NACK) as part of the HARQ process to each of the cells it received the packet from depending on if the packet was decoded correctly or not. This process is done in FREAC by Notify() function which is responsible of sending a notification to the upper layers up to the PDCP layer where the duplication was done. This implementation also controls the delay statistics to produce the CDF only for the fastest packet transmission.

Such duplication has the drawback that the transmission from a particular cell will undergo retransmission even if the packet is received successfully through the other link. This leads to an extra load on the network increasing the resources utilization which will introduce more interference that consequently results in low spectral efficiency.

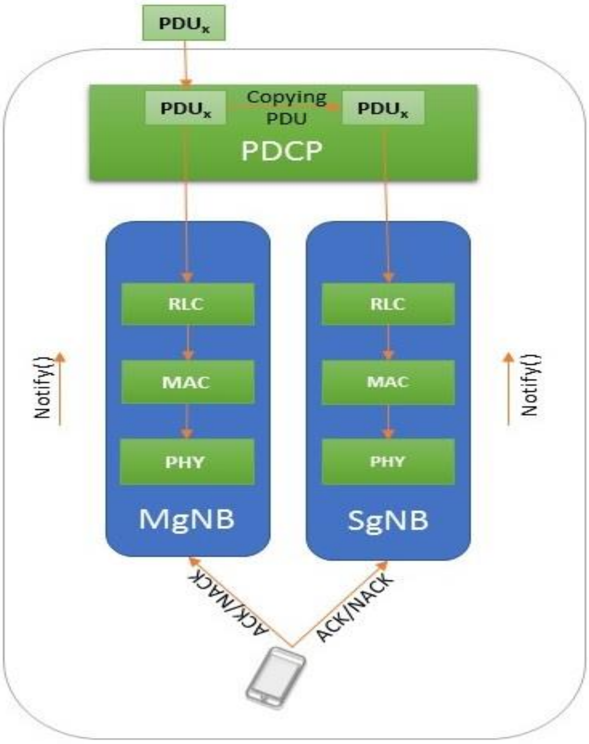


Figure 20. DC Baseline Implementation

2.4.2. Enhanced version: Packet Cancelation

In order to reduce the interference and extra load in the network as mentioned in the previous section, we add new extension to the duplication implementation by adding more intelligence to the different processes. We thus introduce a packet cancellation scheme in FREAC to inform the other cell of a successful reception through one of the links. In real system, the Acknowledgement information received from the UE is basically the main factor in proposed cancellation feature that is when the UE correctly decode the designated data it sends an ACK to the corresponding cell. Depending on this, The Packet Cancelation technique in FREAC sends a cancelation notification (CancelPDU()) to the SCell once the packet was received and acknowledged to the PCell by the UE, and vice versa. Once the SCell receive the cancelation notification it will cancel the transmission regardless to which layer the packet and in which stage the transmission of that packet is on the second link the cancelation will take place for the rest of the packet. Then, the unnecessary packet will be cancelled and no extra resources will be used.

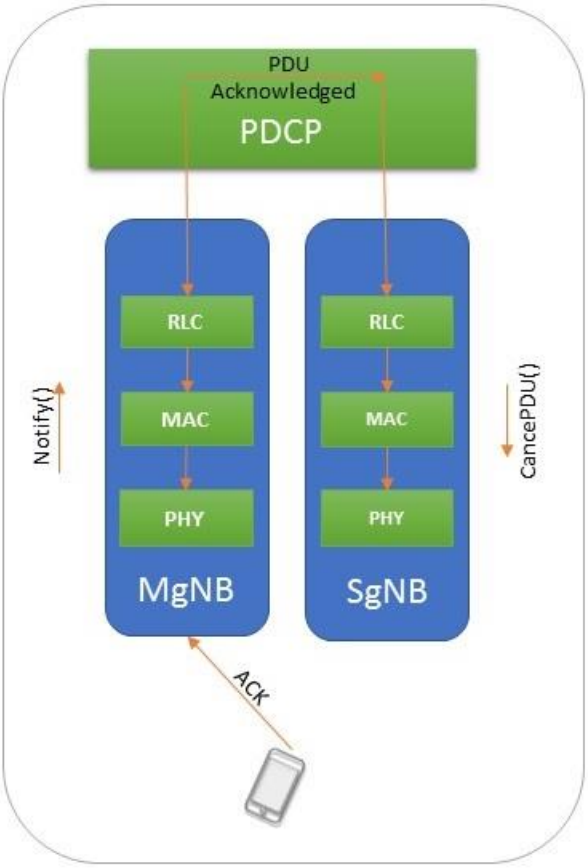


Figure 21. Enhanced Data Duplication Implementation – Packet Cancelation

3. Dual Connectivity with Data Duplication Results

In our work we considered different offered load from low loads such as 500Kbps up to relatively high load for the Intra frequency scenario like 2Mbps. As we already saw in section 3.2, the Baseline Optimization of the single connectivity (SC) simulations results weren't meeting the IMT2020 latency requirement for any load from 1Mbps and above. Therefore, in this section we are going to present results, first for low loads and consequently low interference level to show how dual connectivity affect those situations. Relatively higher loads (1.5Mbps and 2Mbps) that introduce higher level of interference are then considered.

3.1. Initial version of Data Duplication – Without Packet Cancelation

In this section, we are presenting the results of simulation campaigns to see the effect of DC mode with the initial version of data duplication on latency performance in comparison to SC mode latency performance

3.1.1. URLLC Traffic – Low Interference

- **Low loads**

Firstly, we simulated the case where we have offered load of 500Kbps in the network. We observed that the single connectivity (SC) performance is way better than dual connectivity in its best condition and lowest (best) DCU range when we have 1 dB DC range as shown in Figure 22. Nevertheless, the performance for the rest of the DC ranges are similar and close to each other.

The reason why SC is performing better than all cases of DC is due to the lack of interference in SC mode for this low load. On the other hand, DC mode we introduce some interference due to an increase in the network resources utilization by having more transmissions. Moreover, as we can see that the first transmission in SC mode achieves a very low BLock Error Rate (BLER) = 10^{-3} which is better than that with DC mode. Note that both BLERs are lower than the BLER target we set for this transmission which was10^{-2}.

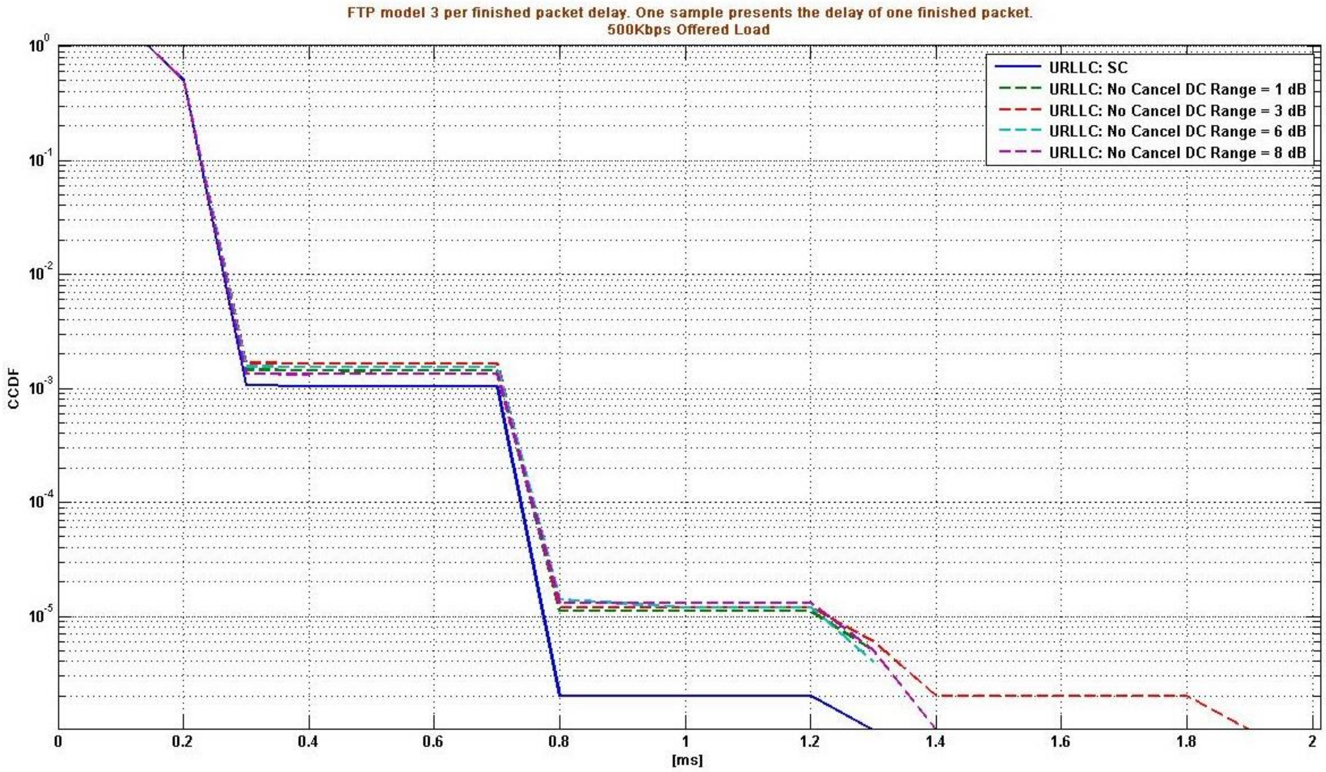


Figure 22. DC performance (Different ranges) vs SC performance for 500Kbps offered load

- **Mid-level loads**

We then increase the offered load, which starts to introduce relatively higher interference levels compared to the previous case. Notice that due to the fact of operating on a single frequency carrier (2GHz), both master node and secondary node interferes with each other. The actual BLER with such level of loads is lower than 10^{-3} that we had shown in the previous paragraph. At such measured BLER we can obviously see that DC mode cases are either having the same BLER as SC (with low DC range values) or better (with higher DC range) for the first transmission.

- **1Mbps offered load**

In Figure 23 we observed a little bit higher interference introduce with 1Mbps offered load case compared to the lower offered load case shown in Figure 22.

In this case we can see that DC mode is providing a good gain compared to SC mode performance as we increase the DC range that we are targeting. In the cases when the DC range is equal to 6dB and 8dB where we have respectively, 57% and 66% of the total number of MTs in the network in DC mode. The transmission starts meeting the 1ms latency at 99.999% reliability. On the other hand, in the cases where less number of users benefits from DC mode the performance is worse than SC, this can be due to the same reason as low loads where there is SC mode is still having less interference than the DC mode with such number of DCU which consequently results in a better SC mode performance.

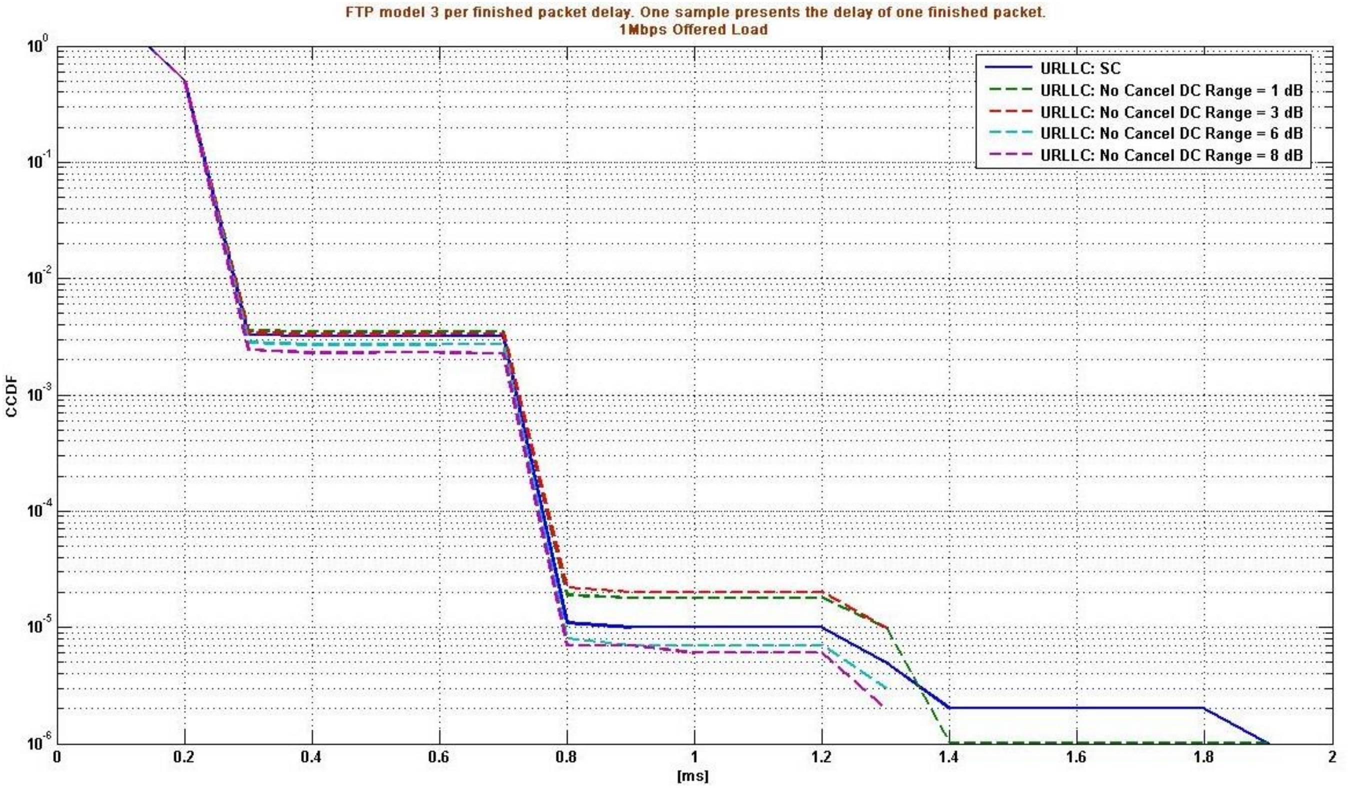


Figure 23. DC performance (Different ranges) vs SC performance for 1Mbps offered load

- **1.5Mbps offered load**

Continuing the same level of offered load increment, we observed that moving to a higher load of 1.5Mbps we can maintain the level of interference that make DC mode providing very good gain in all the cases when the DC range is above 1dB (for a DC range = 1dB the DC mode is not providing any gain over SC mode). This gain can be obviously seen with the mid-range DCU when we have 31% and 57% of the total number of users in the network are in DC mode and it reaches the peak of its gain with DC range of 6dB. This is because at that level of offered load adding the effect of the reasonably increased number of DCU we are targeting the users who can have the gain with the lowest cost on the overall network performance in return. On another hand, we can see in Figure 24, having more DCU (the case where DC range is 8dB with 66% DCU) starts to worsen the performance of DC mode even though it is still having some gain over the SC mode.

The main gain in this case is that for this offered load SC couldn’t meet the IMT2020 latency requirement while using DC mode gives the ability to meet the requirement even with the latter case at 8dB DC range.

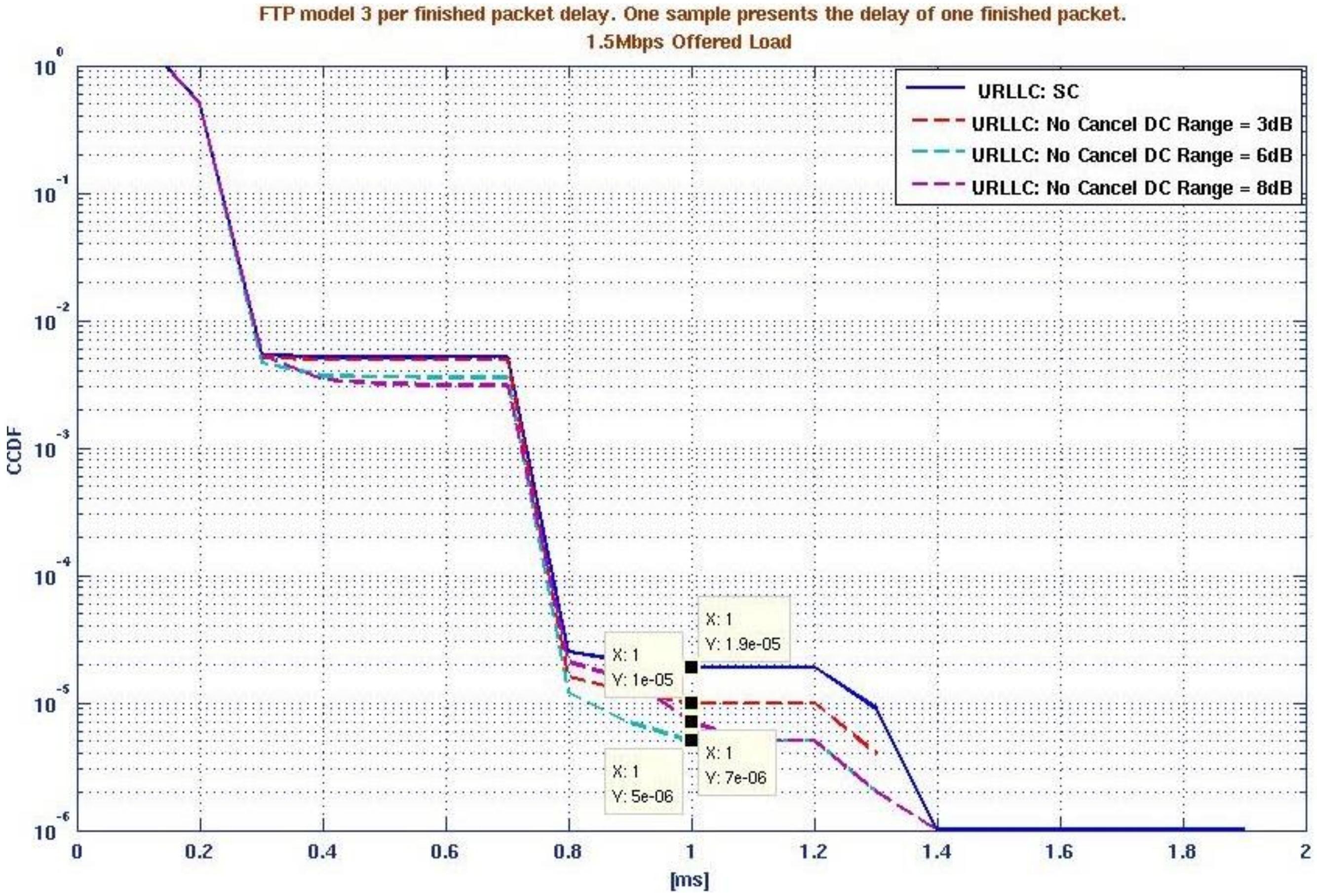


Figure 24. DC gain (Different ranges) vs SC performance for 1.5Mbps offered load

- **2 Mbps Load**

In this paragraph, we can see how increasing the offered load can affect the latency performance of DC mode results. We can obviously observe that the network starts to suffer from a quite high interference compared to the lower offered loads for the case of having only URLLC traffic in the network. This level of interference results in long delay when we have large number of DCU in the network that reaches up to 132.1ms when we have 66% of DCU as shown in Figure 25-a. Similarly, with DC range of 1dB and 6dB, where we have 12% and 57% DCU respectively, the latency target of 1 ms at 10^{-5} reliability cannot be met. This indicates that DC mode performance proportional to the load level and DC range.

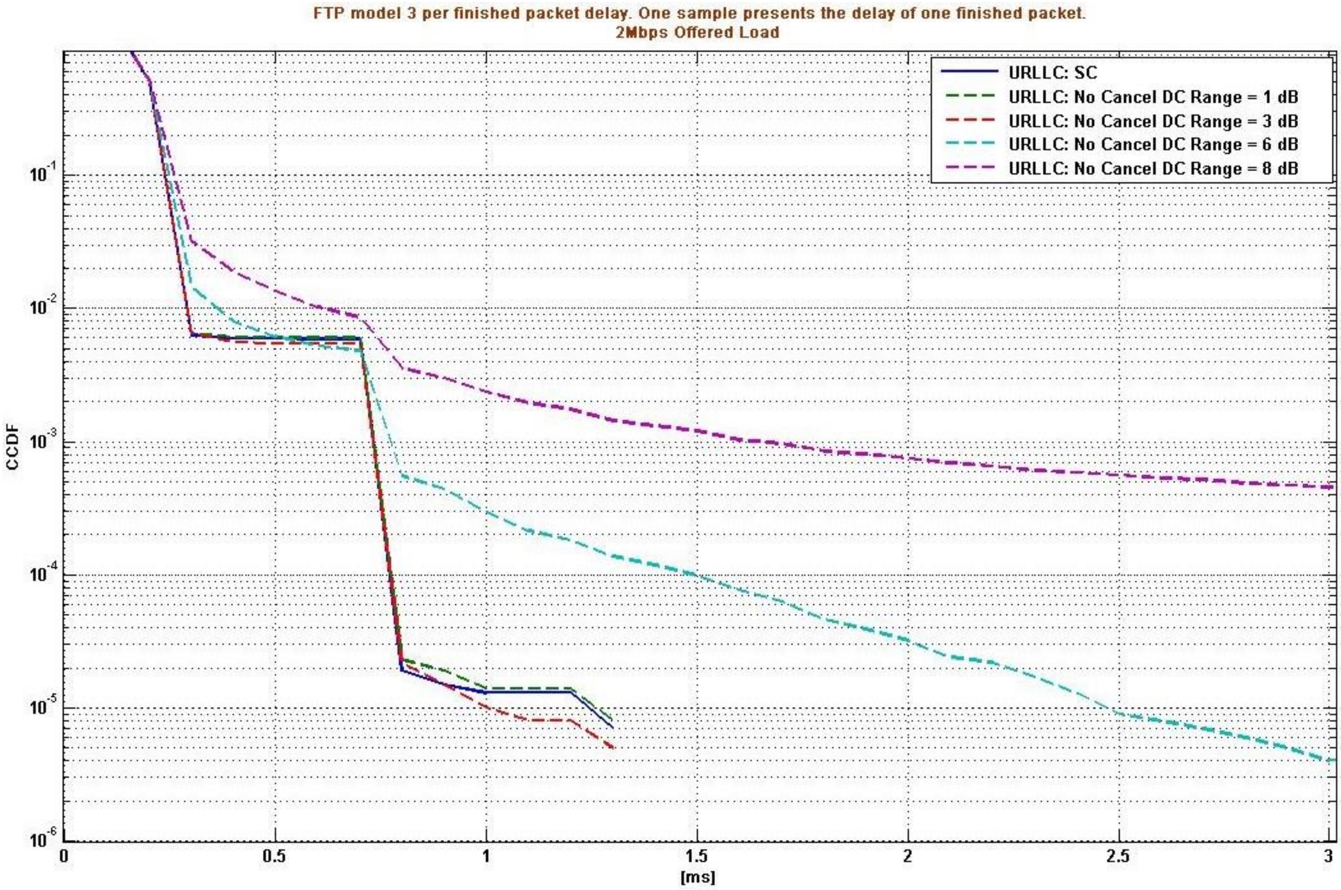


Figure 25-a. DC performance (Different ranges) vs SC performance for 2Mbps offered load.

Despite the abovementioned, DC mode still provide some good improvement in some cases with different levels. As shown in Figure 25-b, DC mode with mid-range DCU of 31%, corresponding to a DC range of 3 dB, can still provide a good gain over SC mode latency performance and meet the requirements of 1ms with 10^{-5} reliability.

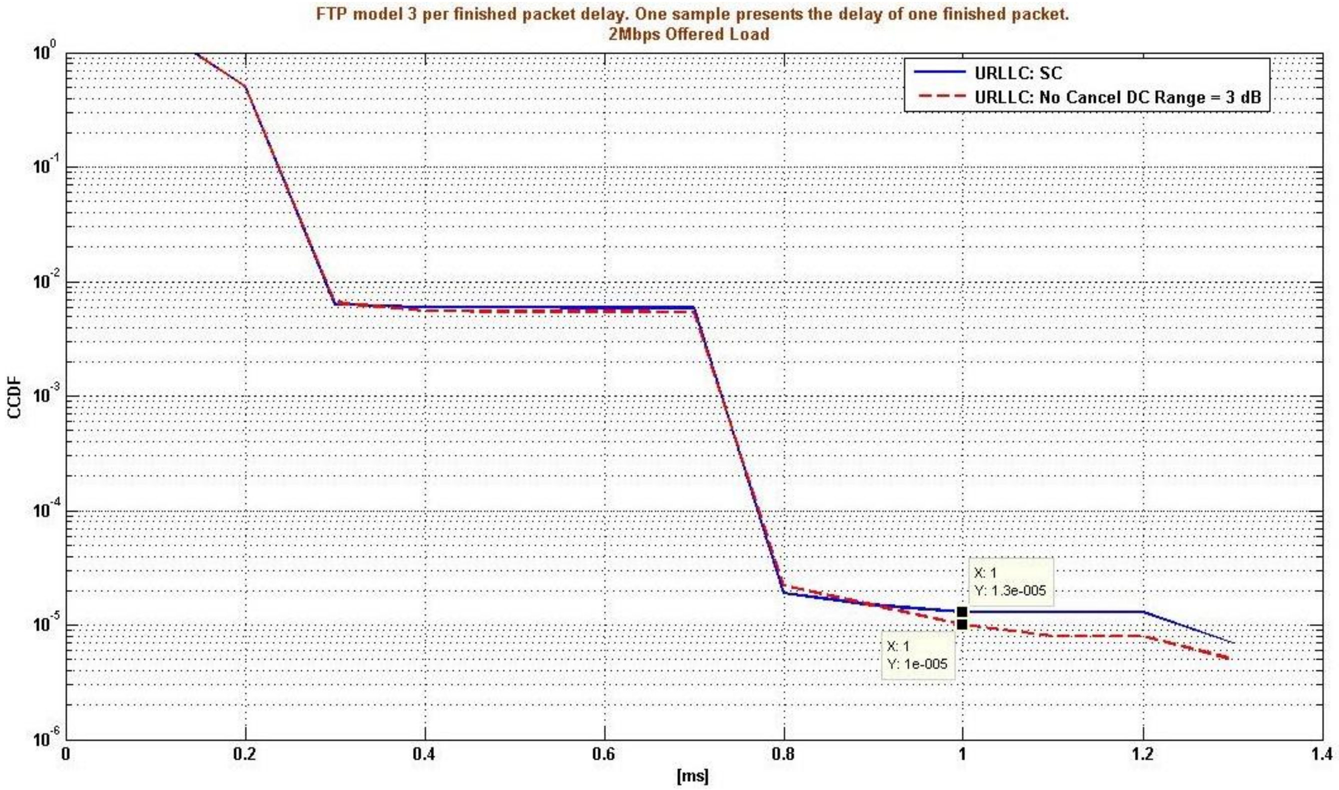


Figure 25-b. DC (3dB range with 31% DCU) vs SC performance for 2 Mbps load

3.1.2. Multi-Service Scenario

So far, we have investigated a URLLC only scenario, where the interference level is moderate. Under such scenario, a performance gain with DC mode is observed, depending on he offered loads and considered DC range value.

However, practical network traffic is generally multi-service, i.e., a mix of URLLC and eMBB traffic with a priority given to the URLLC over eMBB by the MAC scheduler. To emulate such a scenario, we decided to include background eMBB traffic to our scenario. A service-specific link adaptation is being applied here with 1st transmission BLER target of 10% for the eMBB traffic and we are using a lower BLER target for URLLC traffic (as low as 1%). This resulted in a heavy traffic situation with persistent background interference. Hence, the interference conditions are somewhat similar in SC and DC modes. This enables the observer to see the gain of DC mode in almost all the different cases.

This setting was already available in FREAC for SC case by configuring some parameters to enable eMBB traffic of an additional 5 users per cell. As a result, the total number of users is 15 per cell with URLLC and eMBB combined, and 315 users in the overall network. On the other hand, enabling DC mode for eMBB traffic users was not available in FREAC. Therefore, the author had to contribute in adding a new extension to FREAC code to enable this feature for the eMBB traffic users.

3.1.2.1. Full-Buffer eMBB Traffic

The results after adding the background interference shows a larger delay in comparison to the ones without it. As we can see in Figure 26 the latency performance of the SC mode increases very much to reach up to 46ms in the case of 2Mbps offered load. Nevertheless, we added the eMBB traffic to maintain a certain level of interference when we have low offered loads. This enables to appreciate the performance of DC since both cases have similar background interference. We also expect that it will have further impact on the higher loads due to the interference those loads are already introducing without the additional background interference (as we observed in subsection 4.1.1.). The below results present how DC mode is optimizing the latency performance in the network.

- **Low loads**

In contrast to what we had observed in section 4.1.1- where DC mode couldn't provide any gain in loads below 1Mbps, we can clearly see in the results below that after having the full-buffer traffic DC mode starts to show a significant gain regardless of how many DCU we have in the network. The results below start from as low as 250Kbps.

- **250Kbps offered load**

For very low load of 250Kbps, we can clearly observe in Figure 26 the gain DC mode is providing with all DC ranges but the gain is remarkably improving with increasing the number of DCU in the network. This gain starts to be really close for all ranges above 1dB and the mid-range DCU number is providing the best performance in term of reliability and latency

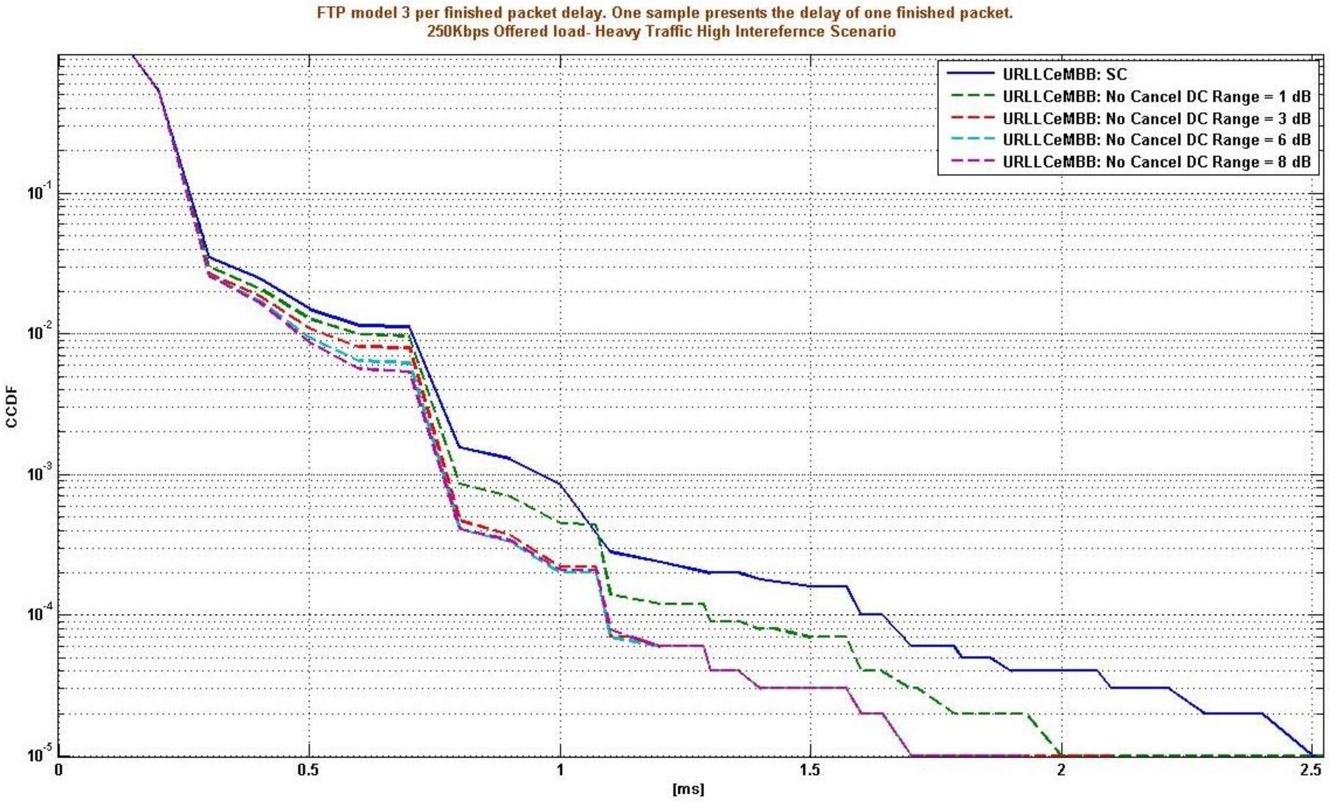


Figure 26. DC (Different ranges) vs SC performance for 250Kbps offered load with eMBB Traffic

This applies to the 500Kbps case also, where DC mode is giving an obvious gain to reduce the delay by around 30% when setting the DC range to 3dB or above to target between 31%- 66% of the total number of users in the network. These results of the different DC ranges show that with DC mode we can provide a better latency performance within the requirements for applications that are not latency-restricted and can tolerate higher delays at high reliability. Examples include remote controlling and monitoring of distributed control systems (DCS) in plants where the monitoring and managing typically takes place in a dedicated control room and the deployed staff for commissioning or maintenance on location need to view an inaccessible information in high definition and their colleagues in the control room can benefit from footage from the local body cameras [35].

- **Mid-level loads**

In next two figures we present the improvement that DC mode can provide while increasing the offered load which with the background interference causes a relatively high delay.

- **1Mbps offered load**

With an offered load of 1Mbps, the SC mode results show a relatively higher delay to deliver a packet in around 3.5ms, while DC mode results are significantly reducing this delay to be between 2ms - 2.7ms in all of the cases (DC range of between 1dB and 8dB). The best latency performance of around 2.1ms (at 10^-5 reliability) is observed with DC range of 6dB. These cases can be used to provide services like remote control applications- that requires less than 5ms [35]- and like Intelligent Transport Systems (ITS)- safety related applications- with latency requirement of 10ms.

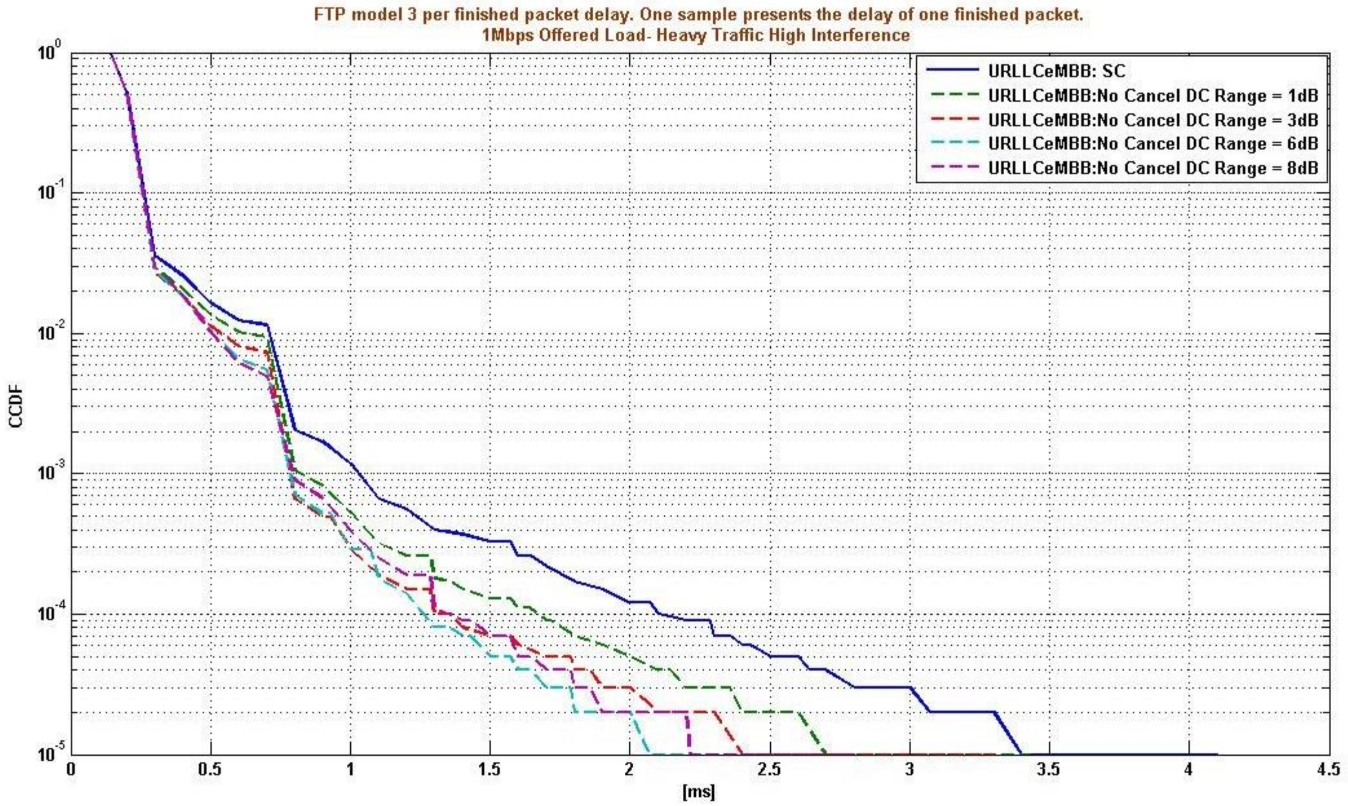


Figure 27. DC (Different ranges) vs SC performance for 1Mbps offered load with eMBB Traffic

- **1.5Mbps offered load**

Increasing the offered load to 1.5Mbps introduces extra queuing in the large DC range case of 8dB due to the additional interference that relatively high loads can add from this level of offered load and above. This interference results in an actual BLER that exceeded the target we set in our configuration for this scenario (10^{-2}) to cause the queuing delay. Notwithstanding the abovementioned, DC mode still provide a noticeable gain in latency performance by 15% at DC range of 3dB case going from 4.1ms SC mode performance to around 3.5ms. With such offered load, continue to provide even more gain when 57% of the users are dual connected, the gain in this case reduces the delay to be around 3.1ms as shown in Figure 28.

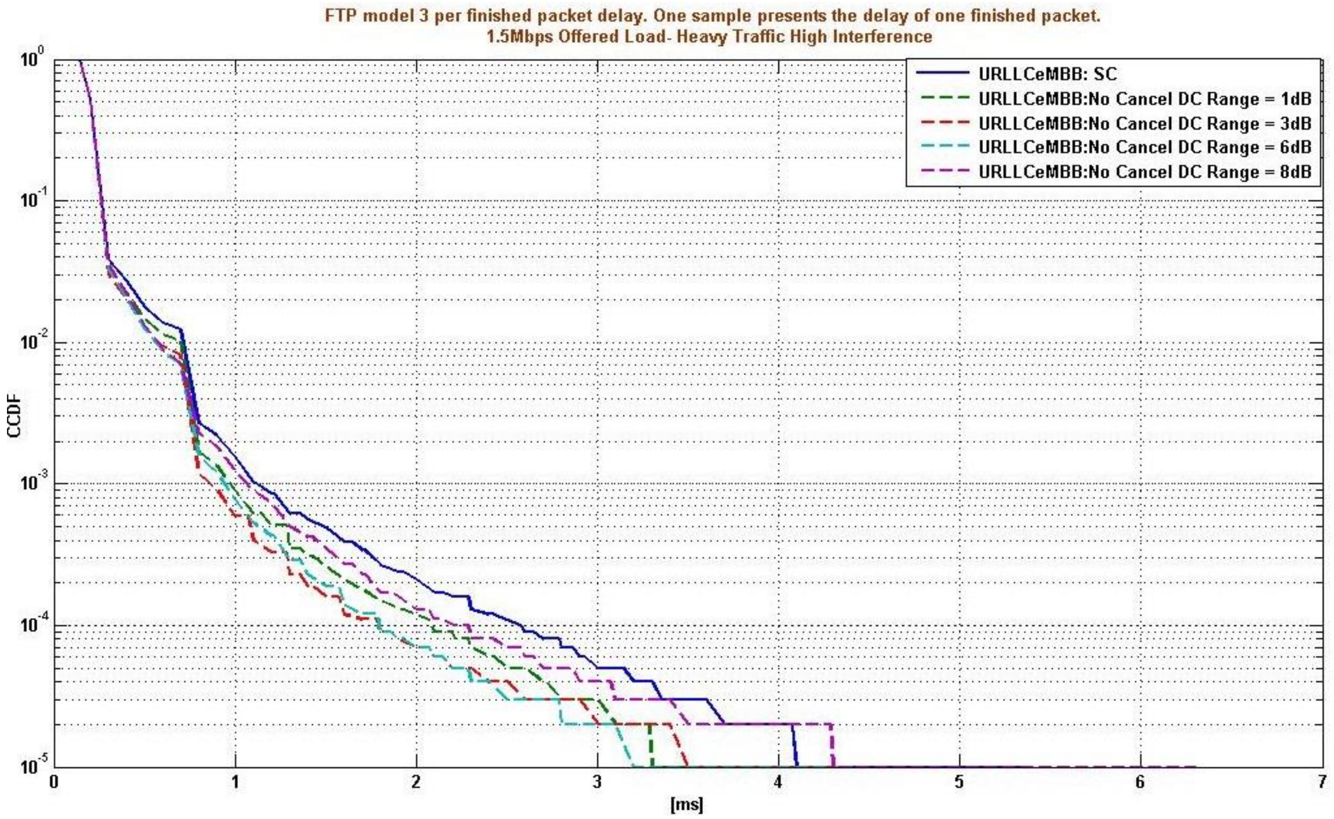


Figure 28. DC (Different ranges) vs SC performance for 1.5Mbps offered load with eMBB Traffic.

3.2. Enhanced Data Duplication version – with Packet Cancelation

3.2.1. URLLC Traffic only– Low Interference

As explained in section 3.4.2, we extend the simulator code to have more intelligent duplication by cancelling the unnecessary transmissions. This enhancement proved to be very effective and helped to improve the results for most cases and especially the critical ones in which DC mode initial duplication was extremely worsening the performance.

- **Mid-level loads**

  For this level of offered loads we observed that DC mode is providing some gain over SC mode performance, the enhanced version of duplication with cancelation improved the reliability noticeably in the higher DC range cases.

- **1Mbps offered load**

At 1Mbps offered load, the cancelation effect is mainly limited to improving the reliability for a given delay. As shown in Figure 29, the trend is similar to the DC mode gain in the initial version of duplication, the higher the DC range is the better the performance with the optimal gain in the 8dB case. In this simulation, cancelation is providing slight gain in the case of 3dB DC range over the SC mode performance which wasn't achieved without cancelation and finishing the packet transmission earlier than initial version at 1.3ms which is the same as the other two cases but with different error probability.

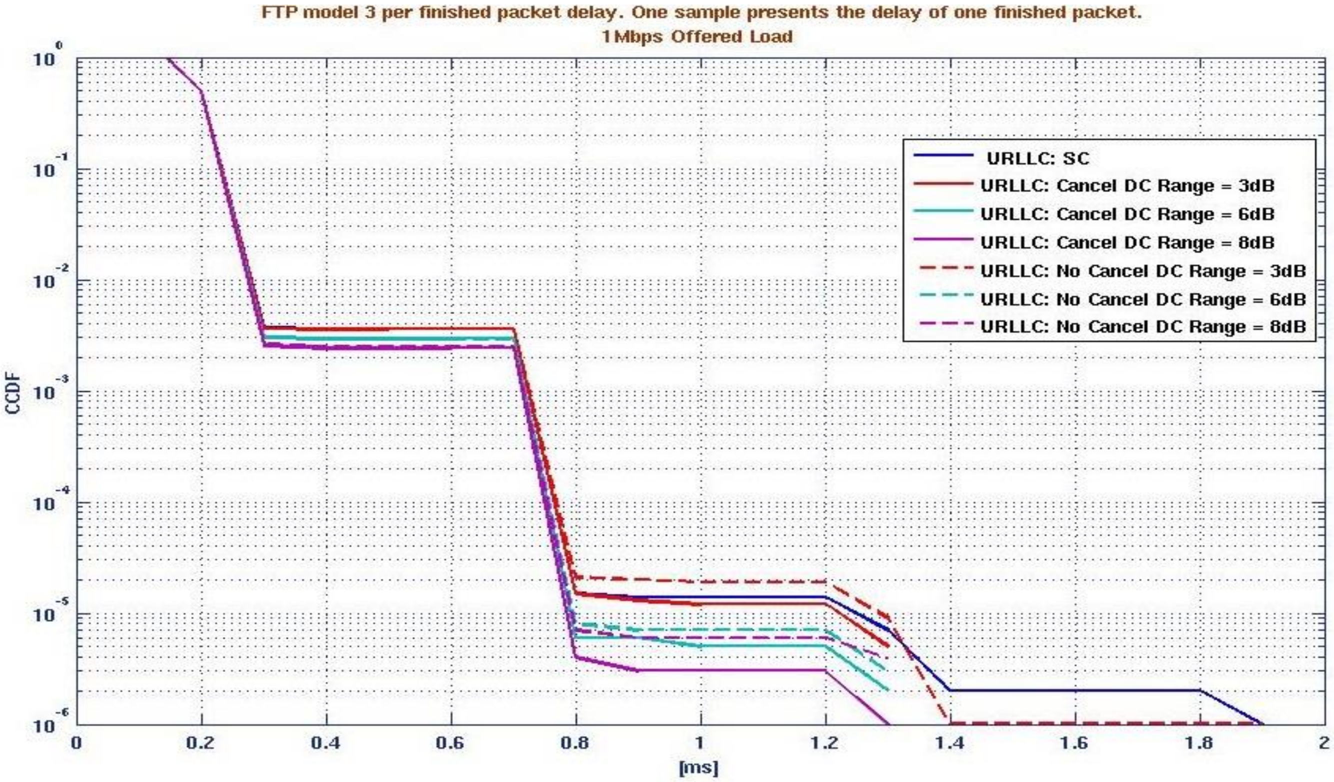


Figure 29. DC (Different ranges- with and without Cancelation) vs SC performance for 1Mbps offered load

- **1.5Mbps offered load**

Increasing the offered load in the network introduces more error probability than the 1Mbps case. That is, as much as we increase the DCU in the network the results tend to act similarly to the Initial duplication results. This adds some queuing delay as shown in Figure 30, which is an indication that increasing the offered load more than that will show some limitation in the performance. Nevertheless, Packet cancelation is providing good gain where we are able to meet the latency requirement with even higher reliability in high DC range. In addition, the results show that we can improve the DC mode performance for the 3dB range case from reliability point of view and increase the DC mode capability over the SC mode even more to include the 1dB range which shows slight gain now with packet cancelation.

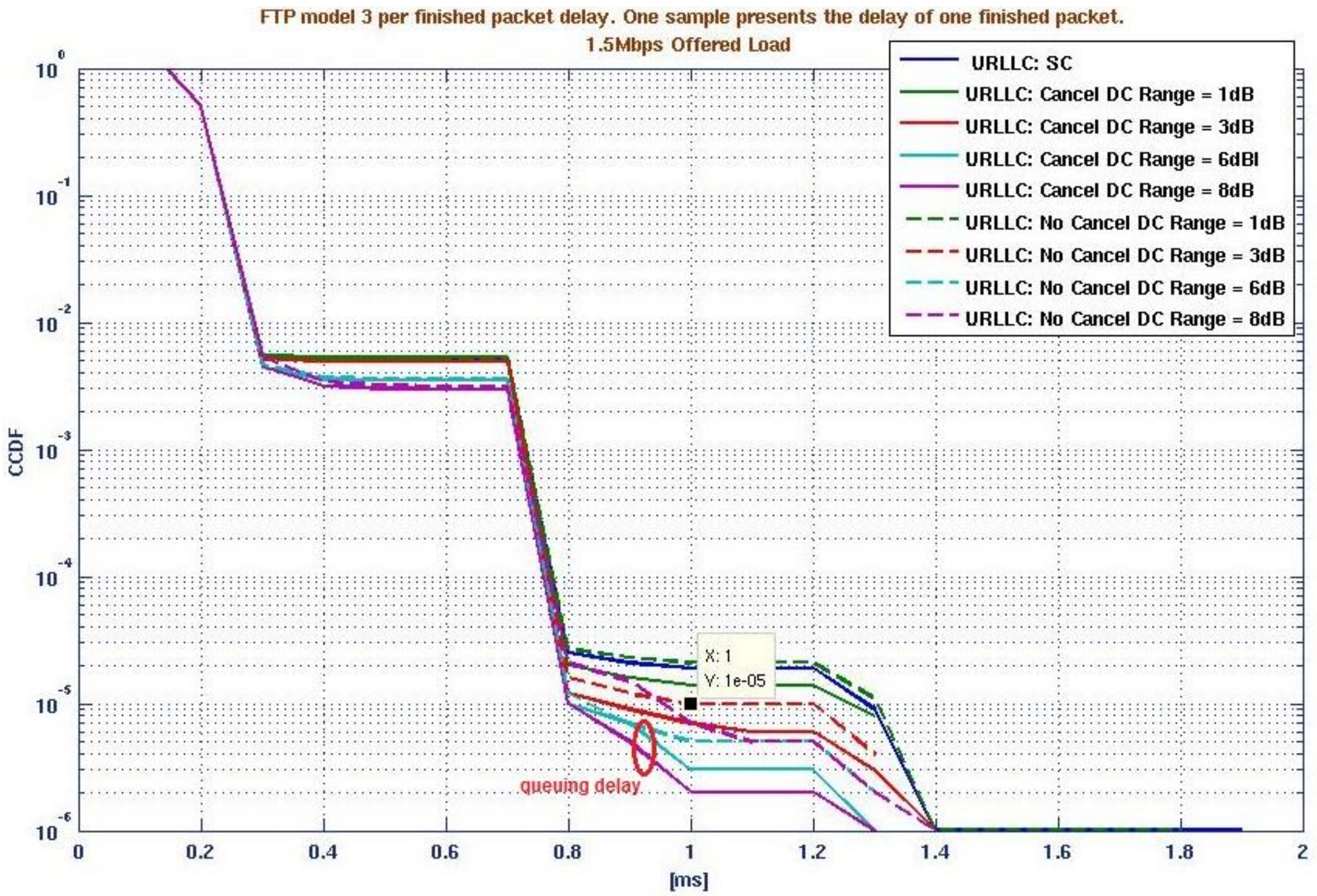


Figure 30. DC (Different ranges- with and without Cancelation) vs SC performance for 1.5Mbps offered load – queuing delay reduced.

3.2.2. Multi-Services Scenario

Packet cancelation with the additional eMBB traffic, is significantly affecting the performance of DC mode especially with relatively higher loads. In low loads below 1Mbps cancelation is not as effective as it is with loads above 1Mbps.

- **Mid-level loads**

  In Figure 31, present the gain that cancelling the unnecessary packets of the second transmissions of DC mode could be provided. As we can observe, the higher DC range we have (the more DCU in the network) the higher gain we can get in terms of latency performance as it is reduced by more than 28% than DC mode without cancelation with the highest DC Range cases (6dB and 8dB) with 1Mbps offered load. Then, reducing the DC range still provide a good gain but less than the one provided in latter case as it is reducing the delay by around 17% at 3dB DC range. This effect of packet cancelation is due to the fact that DC mode with such load and larger number of DCU is introducing a higher queuing probability as the error rate gets higher with the extra interference. This results in too much delayed secondary transmissions even when the packet had already been delivered to the users. Eliminating those unnecessary transmissions, which can reach up to 25% of the total transmitted packets made in the network, reduces overloading the network resources.

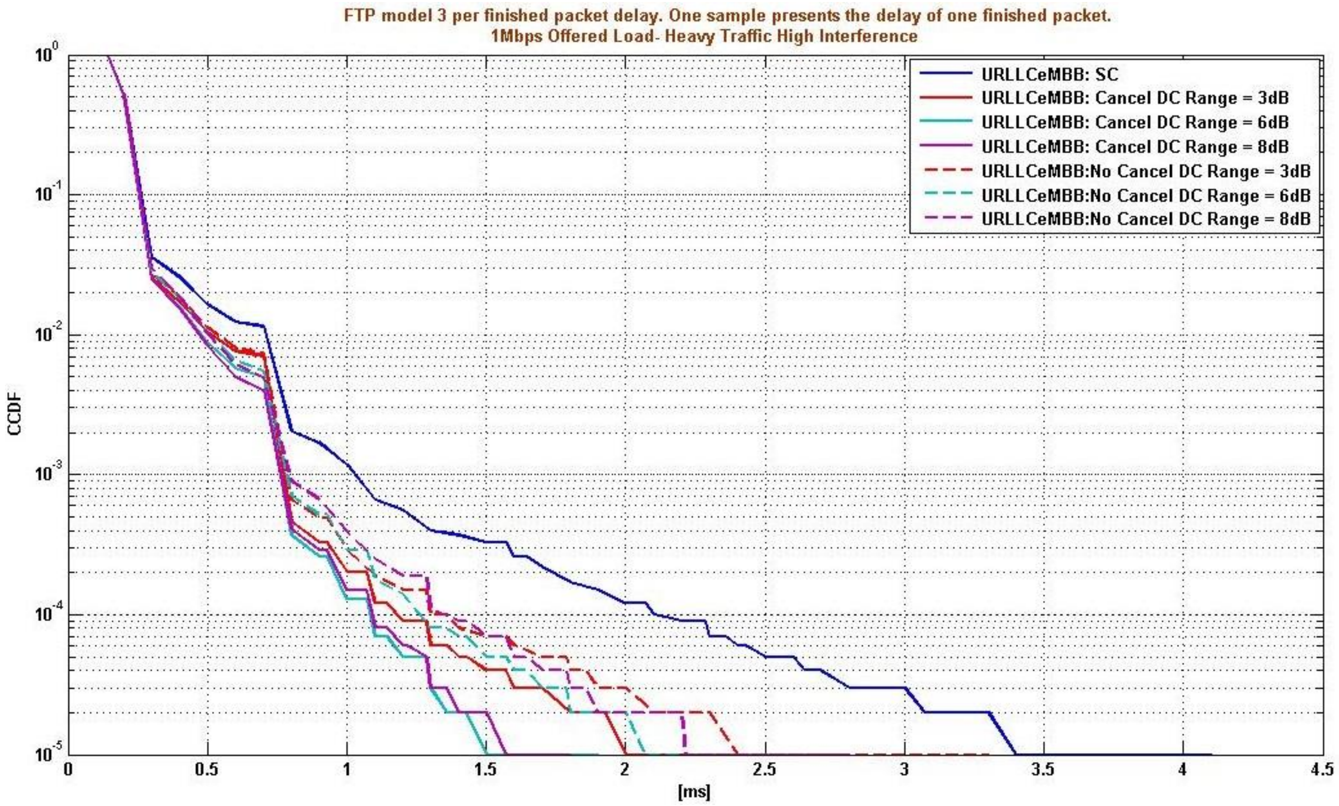


Figure 31. DC (Different ranges) vs SC performance for 1Mbps offered load with eMBB Traffic

For 1.5Mbps offered load, the same effect is observed where the delay with cancelation is reduced by at least 10% to reach up to 50% of the initial duplication implementation results for the case of the highest DC range.

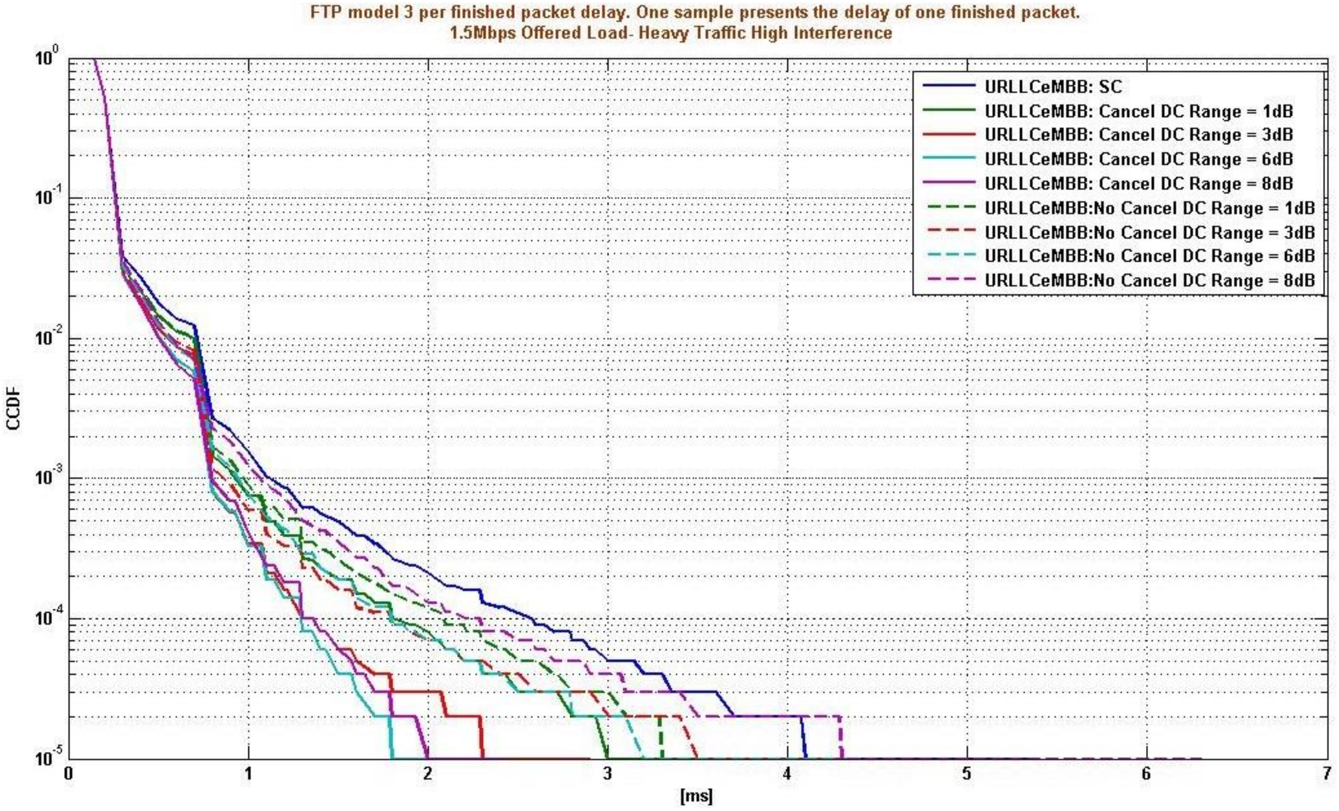


Figure 32. DC (Different ranges) vs SC performance for 1.5Mbps offered load with eMBB Traffic

3.3. Results Summary

Based on the abovementioned results, we can summarize the gain that dual connectivity provides into number of cases as shown in Figure 33. The main gain of dual connectivity over single connectivity can be clearly seen in the cases of mid-level offered load where DC starts to meet the IMT2020 latency requirements for the URLLC Traffic only scenario with a latency gain of 24 % over SC. Then, as we enhance the way duplication is being done with packet cancellation we could improve the latency even more to reduce it by 14 % gain for the same offered load.

After adding the eMBB background traffic to have a heavy multi-services scenario, we encountered some extra delay on all the previous results due to the introduced interference. This Interference gave us the chance to see the gain of dual connectivity in all the cases even for loads as low as 250Kps and 500Kbps. The latter gain is obviously seen in Figure 33, where the DC Baseline reduced the latency from 2.5ms to 1.7ms with doubled offered load. On the other hand, we could see that the packet cancellation not just improved the latency only but also gave better performance for loads as high as 1Mbps within less time even than the low loads cases without cancellation where the enhanced data duplication provided 3 times offered load improvement with latency gain of 40 % over SC performance.

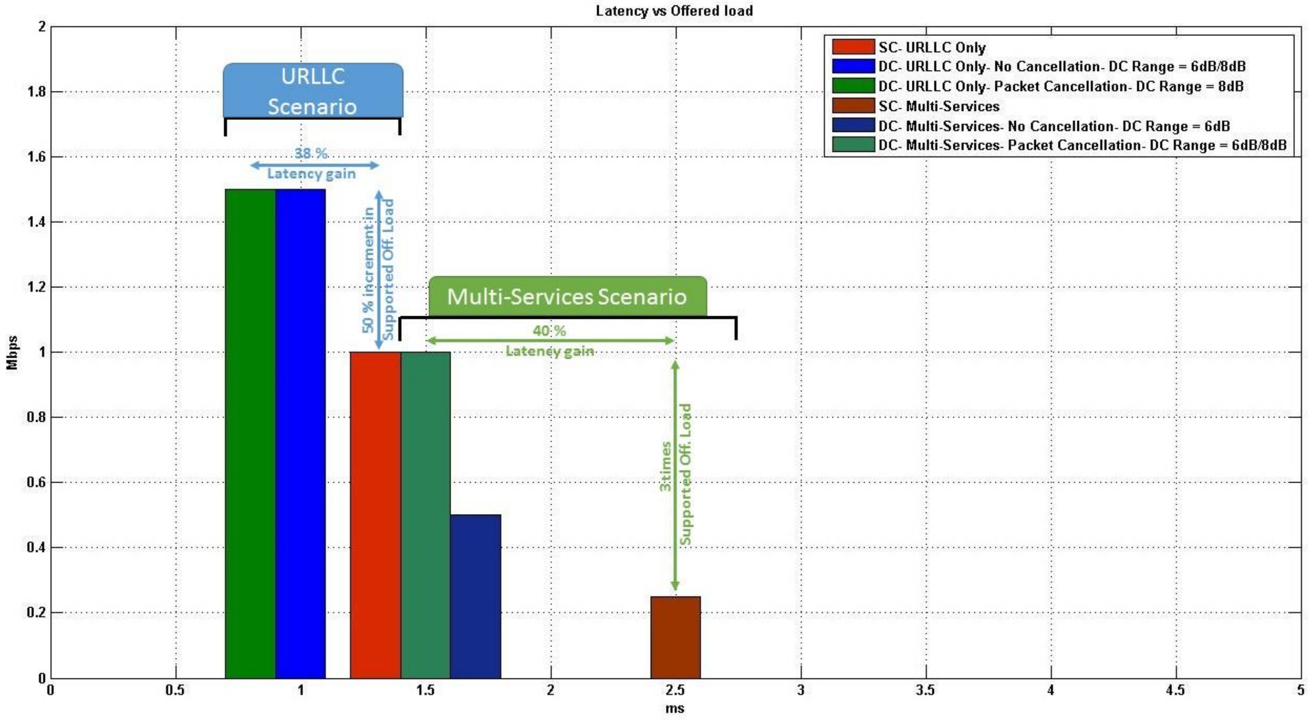


Figure 33. DC and DC w/ Cancellation Gain Summary

In Figure 34, It is shown that the main improvement in most of the cases is in the highest loads in our DC study between 1.5Mbps and 2Mbps. And this gain in some of the cases is improving the results in latency and increasing offered load in the network as well. These improvements apply to both URLLC scenario and Multi-Services scenario.

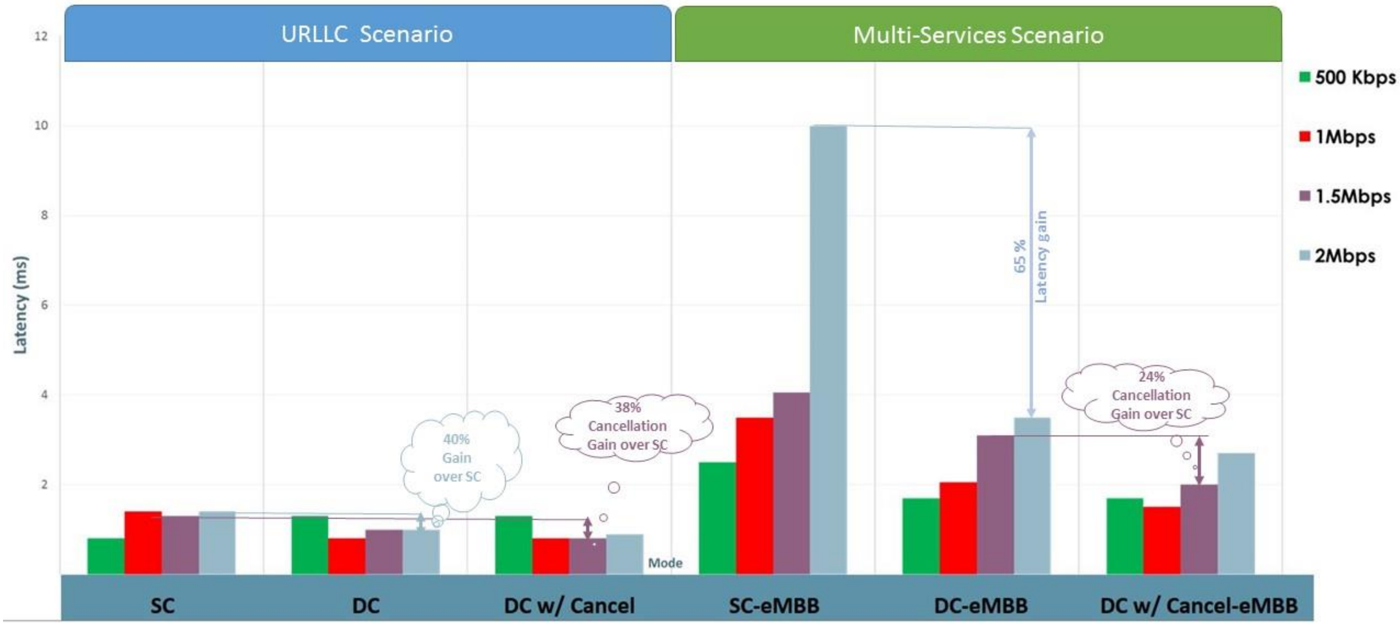


Figure 34. All Results Summary

4. Conclusions and future development

The main goal of this study was to increase URLLC offered load by using DC with PDCP-layer data duplication and understand its main gain points. The work was done through system-level simulations, with main focus on the NR technology properties and performance.

On one hand, if the packet is sent twice through two different connections a gain is expected in the latency. On the other hand, data duplication has a cost in terms of network resources utilization. Higher resources utilization causes a higher level of interference, with lower SINR and consequently, lower MCS selection, which can lead to an increment in queueing delay if data duplication for DC is not operated intelligently.

In order to solve this issue, two different points were studied in this research. First, controlling the number of UEs that benefit from dual connectivity. Increasing or decreasing the region where the UEs enable this solution depending on the cell load helps to optimize resource utilization. Furthermore, to avoid wasting the network resources, the network is forced to discard and cancel any ongoing transmission of packets that are already received at the UE.

The studied scenario is a homogeneous network that consist of 21 macro cells of 7 sites (gNB), and 3D channel model. The first illation that can be seen is that the studied scenario is capable of supporting a URLLC load below 1Mbps only with single connectivity mode. Under low URLLC load and low interference conditions, single connectivity is therefore sufficient to fulfil URLLC requirements in this scenario. Activating DC with data duplication only worsens the channel conditions due to the interference caused by the additional traffic created by the transmissions of the duplicated copies and so, the URLLC delay performance is worse than with SC. On the other hand, with mid-level offered load of 1Mbps up to 2Mbps, data duplication provides a noticeable gain over single connectivity by starting to meet the latency requirement of 1ms.

Creating a heavy full buffer background eMBB traffic on the above scenario, not only demonstrates the performance under some more realistic conditions but also predestines an improvement in the latency that can be achieved with dual connectivity with low loads too. However, this gain is highly sensitive to DC mode configuration and network conditions. Furthermore, even for the low load case (i.e., 250kbps) URLLC target is not met.

We have also studied Packet Cancelation, i.e. the network drop of copies already correctly decoded by the UE and showed that it provides a significant gain with respect to baseline duplication in DC, where the duplication rate is high and a very long queueing delay can be averted by this feature. The gain of Packet cancellation is also obviously observed over SC mode. 5G will include some services with less restricted latency requirement such as 5ms with 99.999% reliability requirement for DCS monitoring. Therefore, DC could be used to enhance the delay performance for other 5G applications than URLLC.

With these findings, dual connectivity with PDCP level duplication is considered as a very promising solution to meet the URLLC requirements (1ms latency requirement with 99.999% reliability). As future work, many options yet to be studied to optimize it. First, some interference management mechanisms that could be used to reduce co channel interference between cells. It should also be studied a multi-connectivity cases other than dual connectivity, i.e. when duplicated packets are sent through more than two nodes. With main concentration on the configuration of data duplication, there are further enhancement options can be considered. The present design works in such a way that duplication is performed through all the connected links. Even if cancelation of a copy in case the packet is correctly received through one of the links is being done, the packets are basically copied and sent to both cells without any kind of intelligence such as duplicating the packets at PDCP layer but transmits it only by the best cell based on the cell and channel condition.

5. References

[1] 5G Technology Components, Building blocks of 5G networks, Whilte Paper, Nokia 2015.

[2] 5G technologies, ETSI technologies clusters.

[3] 3GPP TR 36.881 v14.0.0, “Study on latency reduction techniques for LTE”, June 2016.

[4] R. Ratasuk, A. Prasad, Z. Li, A. Ghosh, and M. Uusitalo, “Recent advancements in m2m communications in 4g networks and evolution towards 5G”), 18th International Conference on Intelligence in Next Generation Networks (ICIN. IEEE, 2015, pp. 5257.

[5] E. L ahetkangas, K. Pajukoski, J. Vihriala, G. Berardinelli, M. Lauridsen, E. Tiirola, and P. Mogensen, “Achieving low latency and energy con- sumption by 5g tdd mode optimization,” IEEE International Conference on Communications Workshops (ICC), IEEE, 2014, pp. 1–6.

[6] H. Tullberg, Z. Li, A. Hoglund, P. Fertl, D. Gozalvez-Serrano, K. Pawlak, P. Popovski, G. Mange, and O. Bulakci, “Towards the METIS 5G concept: First view on horizontal topics concepts,” in Networks and Communications (EuCNC), European Conf. on . IEEE, 2014, pp. 1–5.

[7] 3GPP,TR 36.872, “Technical Specification Group Radio Access Network; Small Cell enhancements for E-UTRA and E-UTRAN - Physical layer aspects (Release 12),” December 2013.

[8] H. Ji, S. Park, J. Yeo, Y. Kim, J. Lee, and B. Shim, “Introduction to ultra-reliable and low latency communications in 5G,” arXiv preprint arXiv:1704.05565, 2017.

[9] Dr. Mehdi Bennis, Building the foundations of Ultra-RELIABLE and Low-LATENCY Wireless Communication at The International Conference on Wireless Networks and Mobile Communications (WINCOM'17), November 01-04, 2017, Rabat, Morocco.

[10] 3GPP 38.802, Technical Specification Group Radio Access Network; Study on New Radio Access Technology Physical Layer Aspects’ Rel-14 V.14.2.0, Sep 2017.

[11] 3GPP, “Technical specification group services and system aspects; Feasibility study on new services and markets technology enablers for critical communications; Stage 1,” TR 22.862, Rel-14 V.14.1.0, Sept. 2016.

[12] K.Pedersen M. K. P. M. A.-T. Beatriz Soret, “Fundamental tradeoffs among reliability, latency and throughput in cellular networks” *Proc. Globecom Workshops (GC Wkshps),* pp. 1391-1396, 2014.

[13] F. B. Tesema, A. Awada, I. Viering, M. Simsek, and G. P. Fettweis, “Mobility modeling and performance evaluation of multi-connectivity in 5G intra-frequency networks,” in Proc. IEEE Globecom Workshops (GCW), San Diego, USA, Dec. 2015, pp. 1–6.

[14] J. J. Nielsen and P. Popovski, “Latency analysis of systems with multiple interfaces for ultra-reliable M2M communication,” in Proc. IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Edinburgh, UK, Jul. 2016, pp. 1–6.

[15] D. S. Michalopoulos, I. Viering, and L. Du, “User-plane multi-connectivity aspects in 5G,” in *Proc. IEEE 23rd International Conference on Telecommunications (ICT)*, Thessaloniki, Greece, May 2016, pp. 1–5

[16] Ericsson, “On URLLC design principles,” 3GPP, TSG-RAN WG1 #86bis R1-1609634, Lisbon, Portugal, Oct., 2016

[17] D. L. D. W. E. P. L. P. V. E. L. P. ,. E. López-Pérez, “Long Term Evolution-Wireless Local Area Network Aggregation Flow Control,",” *IEEE Access, vol. 4,,* pp. 9860-9869, 2016.

[18] A. Ravanshid, P. Rost, D. S. Michalopoulos, V. V. Phan, H. Bakker, D. Aziz, S. Tayade, H. D. Schotten, S. Wongand, O. Holland, “Multi-Connectivity Functional Architectures in 5G”, IEEE International Conference on Communications Workshops (ICC), May 2016.

[19] 3GPP, Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; stage 2; Release 15, 3GPP TS 38.300 V1.1.1 (2017-10).

[20] 3GPP, Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; stage 2; Release 15, 3GPP TS 38.300 V1.1.1 (2017-10).

[21] Outlook: Visions and Research Directions for the Wireless World*, WWRF, No15 2014.*

[22] Guillermo Pocovi, Beatriz Soret, Klaus I. Pedersen, Preben Mogensen, “MAC Layer Enhancements for Ultra-Reliable Low-Latency Communications in Cellular Networks”, IEEE International Conference on Communications Workshops (ICC Workshops), May 2017.

[23] H. Shariatmadari, Z. Li, M. A. Uusitalo, S. Iraji, R. Jäntti, “Link adaptation design for ultra-reliable communications”, IEEE International Conference on Communications (ICC), May 2016.

[24] K. I. Pedersen, G. Berardinelli, F. Frederiksen and A. Szufarska, “A flexible 5G frame structure design for frequency-division duplex cases”, IEEE Communications Magazine, vol. 54, no. 3, pp. 53-59, March 2016

[25] 3GPP, “Technical specification group radio access network; Study on scenarios and requirements for next generation access technologies,” TR 38.913,Rel-14 v.14.1.0, 3GPP, Dec. 2016.

[26] M. Lampinen, F. Del Carpio, T. Kuosmanen, T. Koivisto, and M. Enescu, “System-Level Modeling and Evaluation of Interference Suppression Receivers

in LTE System", IEEE Vehicular Technology Conference, May 2012

[27] D. Chase, "Code combining: A maximum-likelihood decoding approach for combining an arbitrary number of noisy packets", IEEE Transactions on Communications, vol. 33, no. 5, pp. 385-393, May 1985.

[28] Pocovi, B. Soret, M. Lauridsen, K. I. Pedersen, and P. Mogensen, "Signal quality outage analysis for ultra-reliable communications in cellular networks," in Proc. IEEE Globecom Workshops (GCW), San Diego, USA, Dec. 2015, pp. 1–6.

[29] H. Holma and A. Toskala, "LTE Advanced: 3GPP Solution for IMT Advanced", John Wiley & Sons Ltd, 2011.

[30] 3GPP TR 38.802 v2.0.0, "Study on new radio access technology physical layer aspects", March 2017.

[31] Eunjeong Shin, Gweondo Jo, "Uplink frame structure of short TTI system", 19th International Conference on Advanced Communication Technology (ICACT), Mar 2017.

[32] Guillermo Pocovi, Klaus I. Pedersen, Preben Mogensen, Beatriz Soret, "Radio Resources Management for Ultra-Reliable Low-Latency communications", IEEE Transactions on Vehicular Technology , 2017

[33] Karandikar Abhay, Akhtar Nadeem, Mehta Mahima , "Mobility Management in LTE Heterogeneous Networks", 2017

[34] 3GPP TS 22.261, Group Services and System Aspects; Service requirements for the 5G system; Stage 1 Release 16 2018.

.

.

Abbreviations

BLER	Block Error Rate
PER	Packet Error Rate
BS	Base Station
CA	Carrier Aggregation
CC	Component Carrier
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CN	Core Network
TRP	Transmission and Reception Point
CQI	Channel Quality Indicator
DL	Downlink
UL	Uplink
DC	Dual Connectivity
DCU	Dual connected User
DCS	Distributed Control System
eMMB	Enhanced Mobile Broadband
ACK	Acknowledgement
NACK	Non-Acknowledgement
gNB	GNode-B
HARQ	Hybrid Automatic Repeat Request
ICIC	Inter-Cell Interference Coordination
JT-CoMP	Joint Transmission- Coordinated MultiPoint
LTE	Long Term Evolution
MAC	Medium Access Control
MC	Multi-Connectivity
MCS	Modulation Coding Scheme
MgNB	Master gNode-B
SgNB	Secondary gNode-B
mMTC	Massive Machine Type Communication
PCell	Primary Cell
SCell	Secondary Cell
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit

PRB	Physical Resource Block
RAN	Radio Access Network
RAT	Radio Access Technology
RRC	Radio Resource Control
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Reference Signal Strength Indicator
RTT	Round Trip Time
SA	Service and Systems Aspects
SC	Single Connectivity
SDAP	Service Data Adaptation Protocol
TTI	Time To Interval
TTT	Time To Trigger
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communications
FF	Forgetting Factor

Appendix

- **A4 Event Investigation results:**

  - **DC without Packet Cancellation**

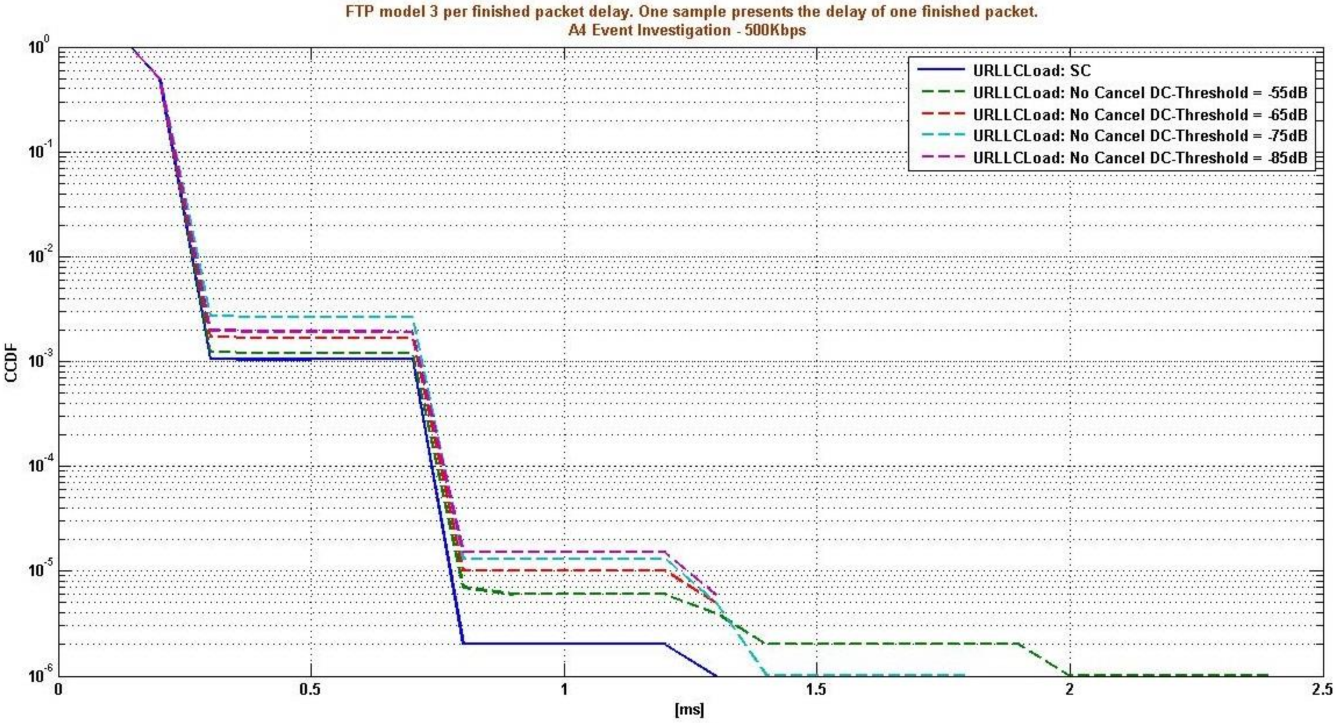


Figure 35. DC (Different Thresholds) vs SC performance for 500Kbps load

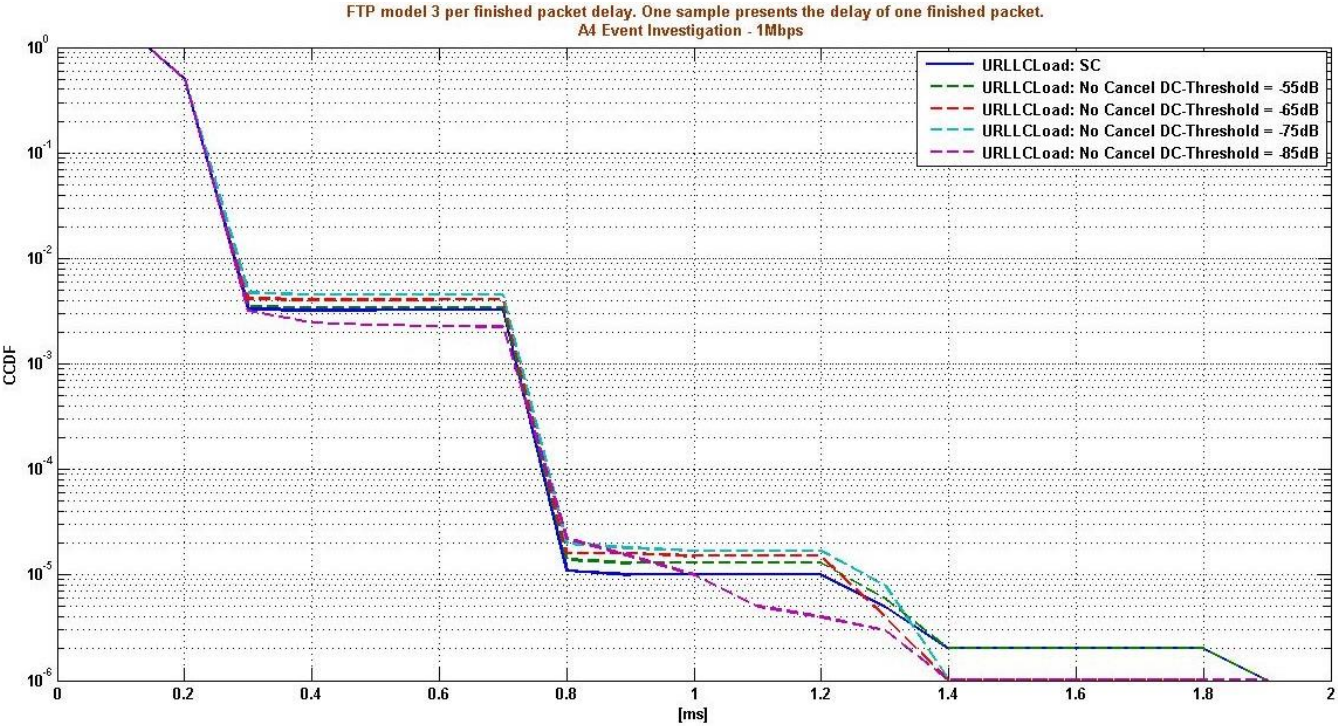


Figure 36. DC (Different Thresholds) vs SC performance for 1Mbps load

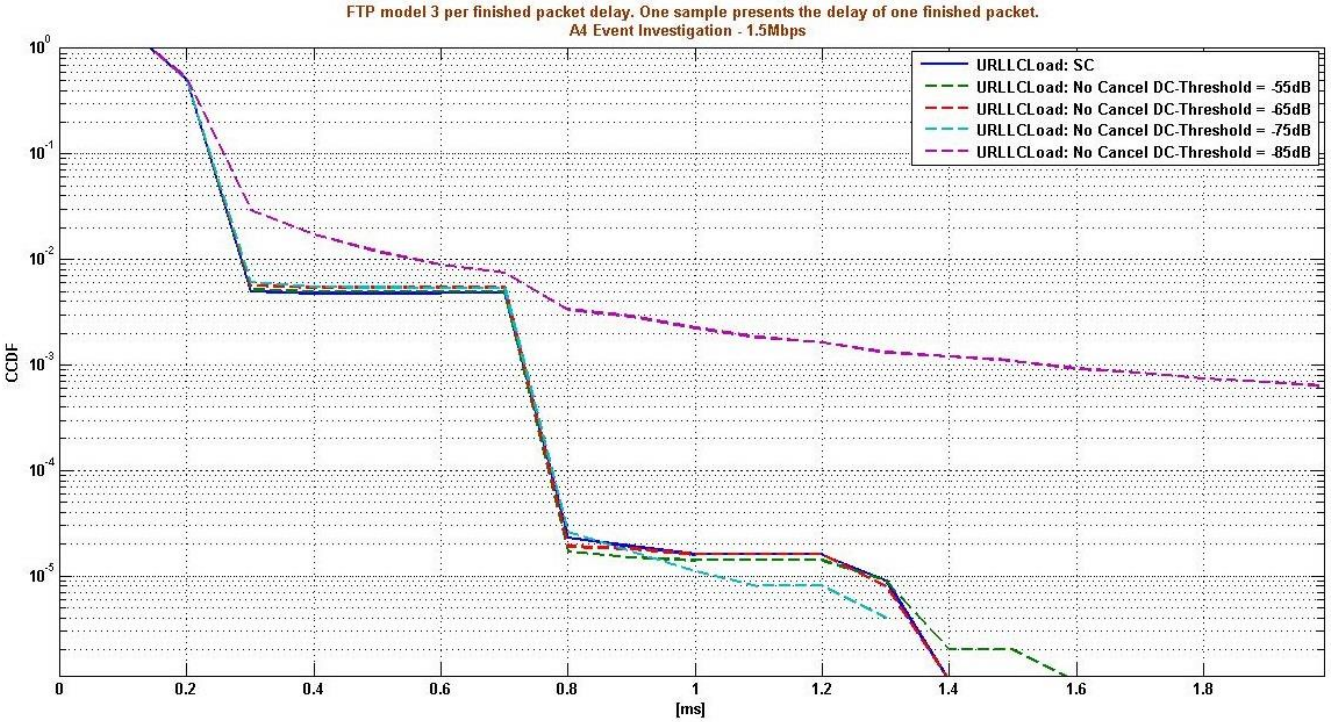


Figure 37. DC (Different Thresholds) vs SC performance for 1.5Mbps load

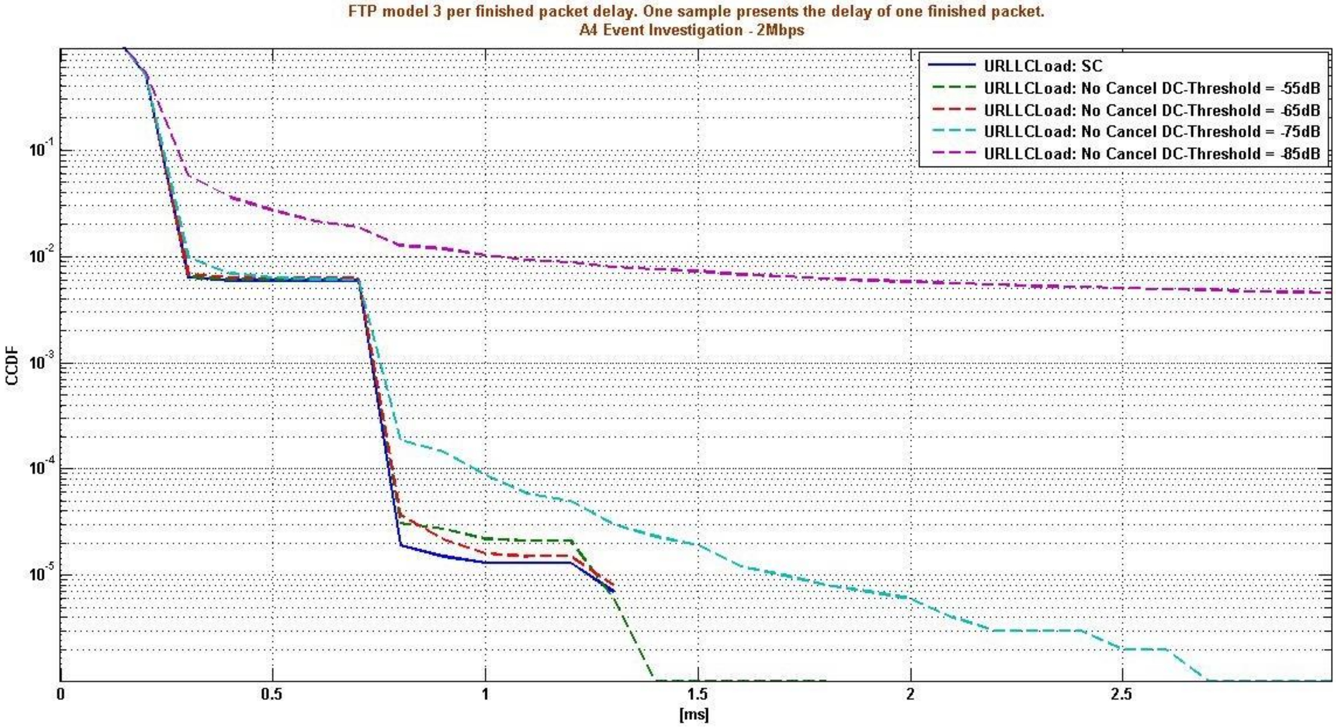


Figure 38. DC (Different Thresholds) vs SC performance for 2Mbps load

- **DC with Packet Cancellation**

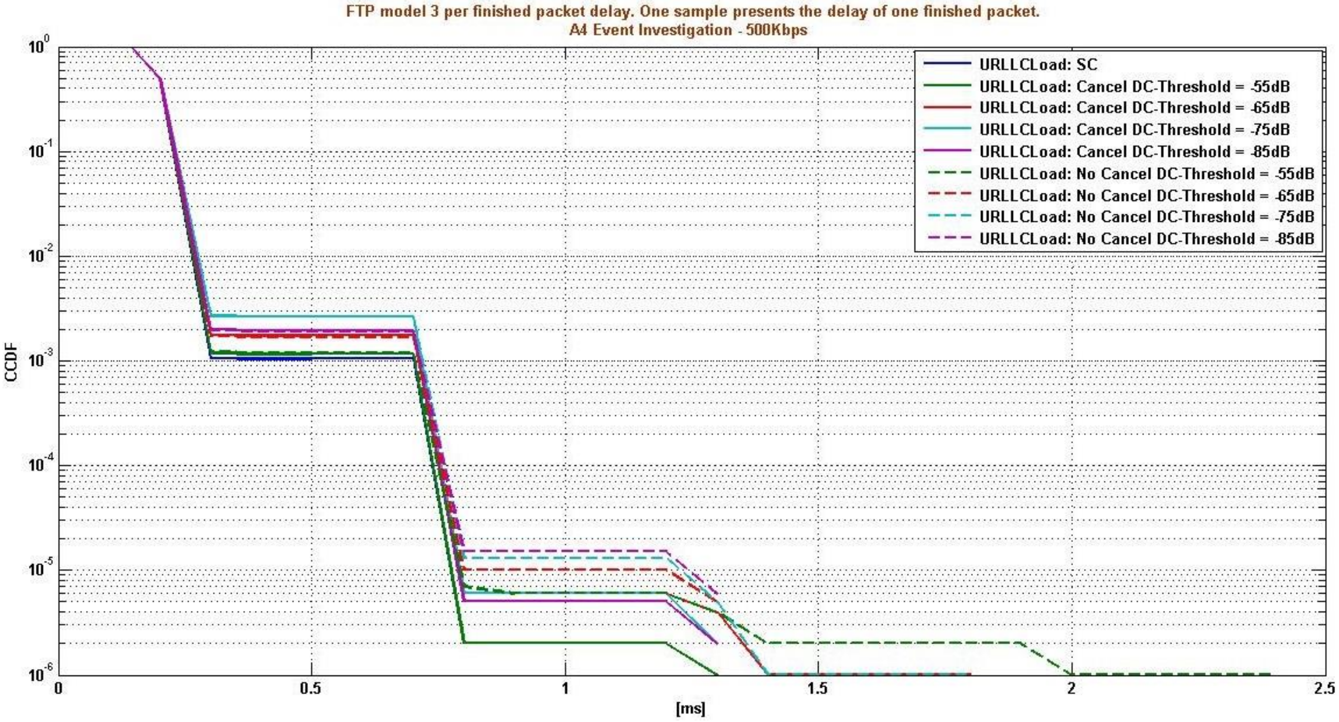


Figure 39. DC with Cancellation (Different Thresholds) vs SC performance for 500Kbps offered load

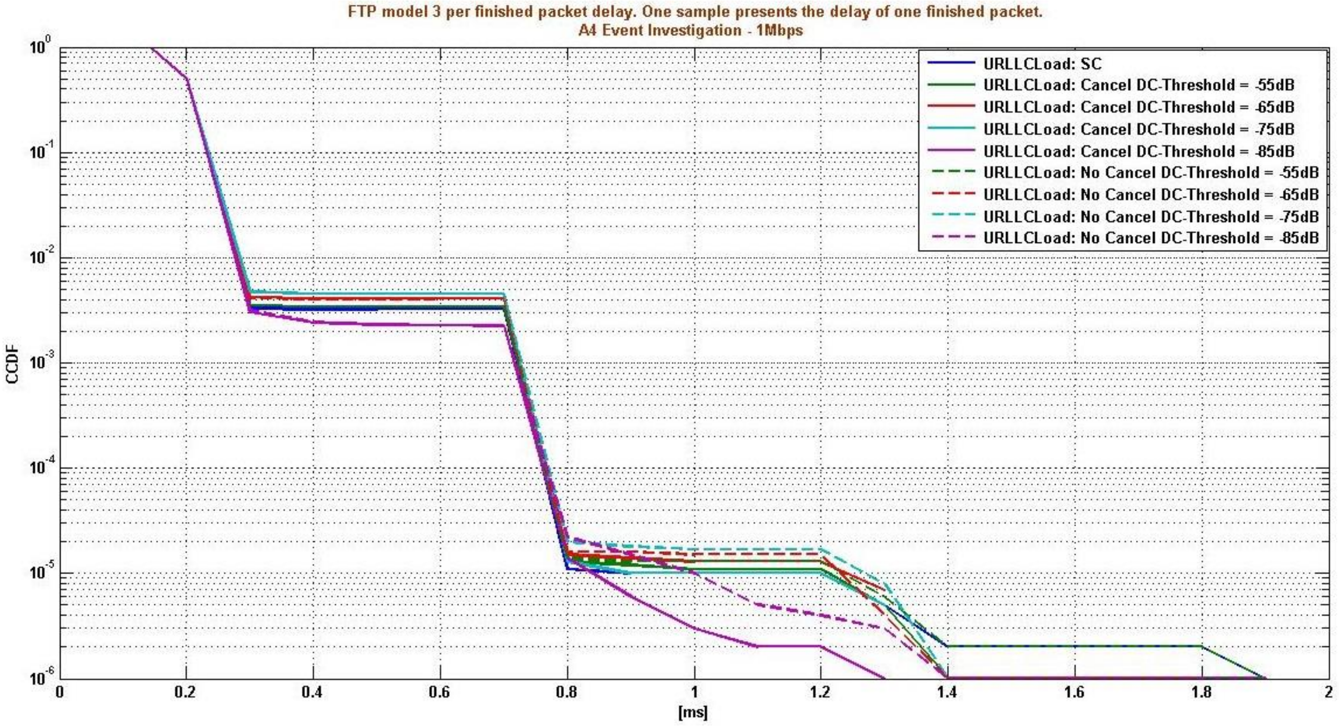


Figure 40. DC with Cancellation (Different Thresholds) vs SC performance for 1Mbps offered load

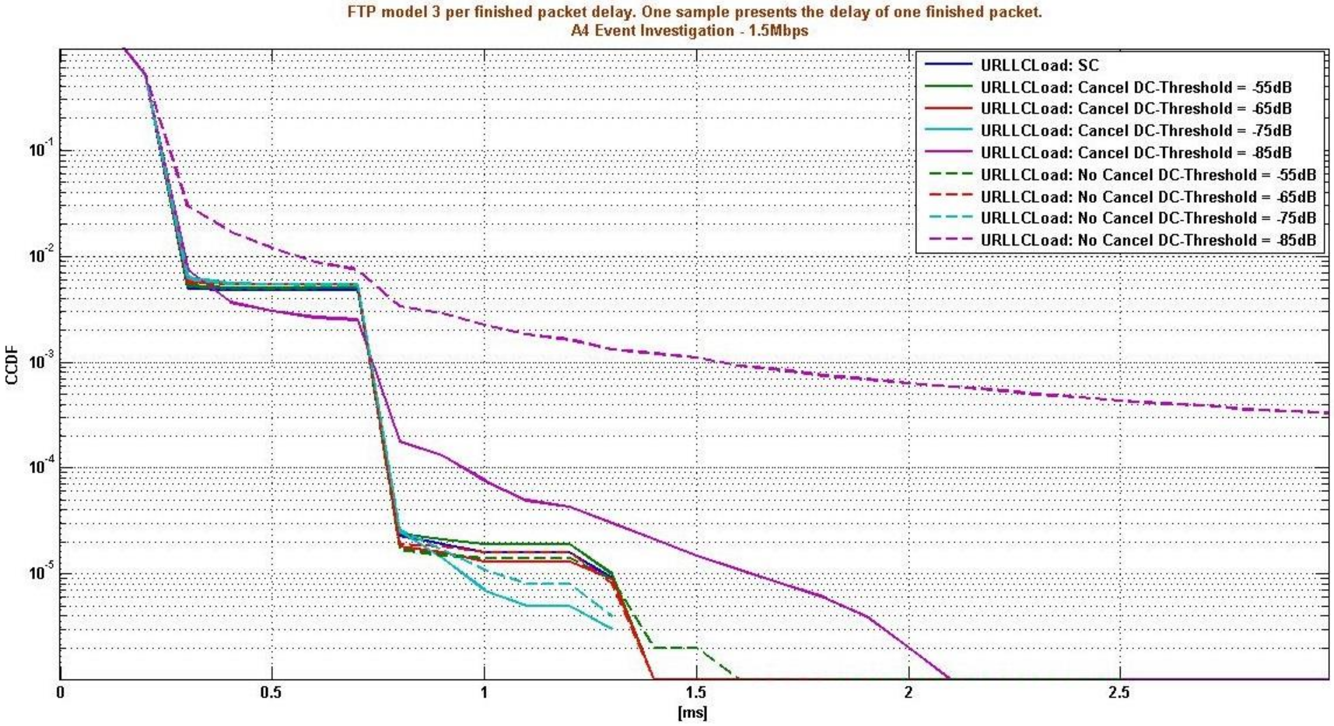


Figure 41. DC with Cancellation (Different Thresholds) vs SC performance for 1.5Mbps offered load

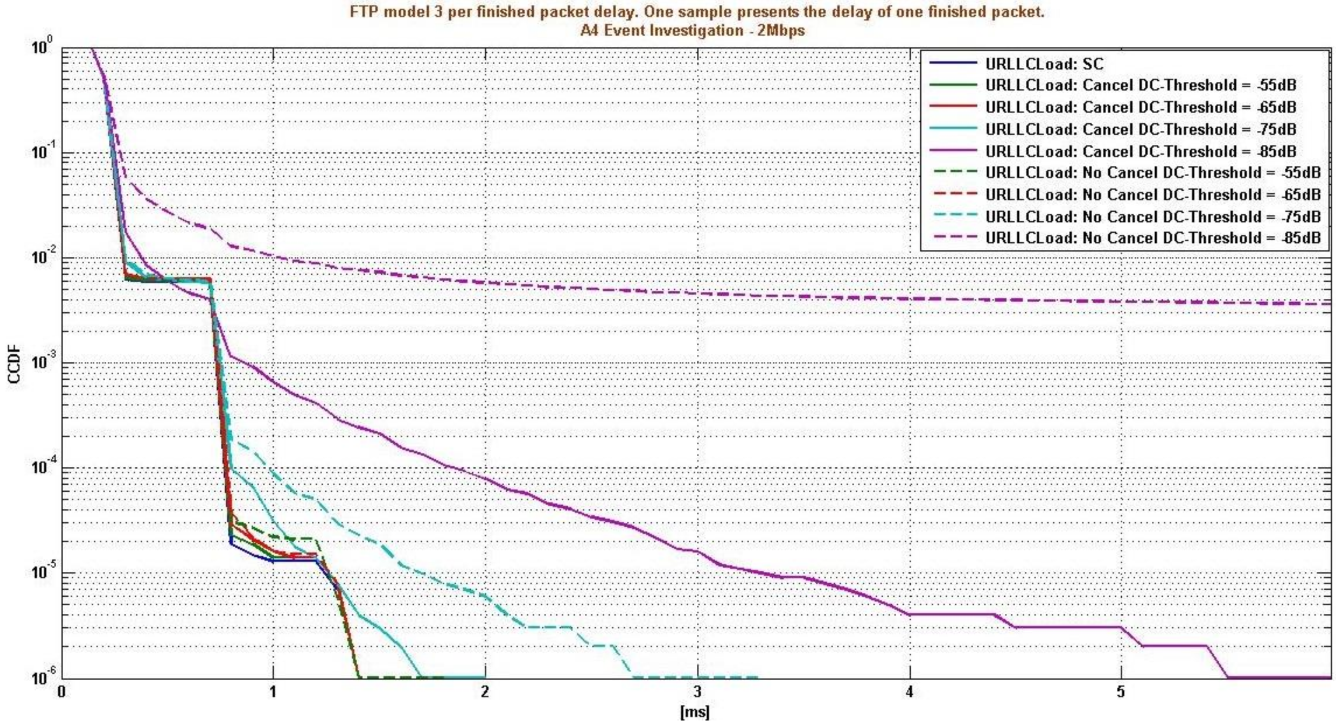


Figure 42. DC with Cancellation (Different Thresholds) vs SC performance for 2Mbps offered load