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Authors:	Sandrine Destouet Roblot, Nadège Varsier, Yu Bao, Serge Langouet, Marie-Hélène Hamon, Sébastien Jeux (ORANGE), Mythri Hunukumbure, Galini Tsoukaneri (SEUK), Elena Serna Santiago, Juan Francisco Esteban Rivas, Francisco Javier Lorca Hernando, Beatriz Solana Menéndez Vigo (TID), David Palacios, Isabel de la Bandera Raquel Barco (UMA), Panagiotis Vlacheas, Andreas Georgakopoulos, Vassilis Foteinos, Ioannis-Prodromos Belikaidis, Yiouli Kritikou, Ioannis Stenos, Paraskevas Bourgos, Evangelos Kosmatos, Nelly Giannopoulou, Apostolos Voulkidis, Konstantinos Tsoumanis, Ioannis Maistros, Konstantinos Trichias, Ioannis Tzanettis, Aspa Skalidi, Evangelia Tzifa, Christos Ntogkas, George Loukas, Ioanna Drigopoulou, Ilias Romas, Michalis Mitrou, Kostas Tsagkaris, Panagiotis Demestichas, Vera Stavroulaki (WINGS), Renato Abreu, Gilberto Berardinelli (AAU), Martin Kurras (HHI)
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Abstract

This deliverable presents the final results from the System Level Simulations of selected technical components and the techno-economic studies which are led on different vertical use cases from the ONE5G project. The simulation results indicate notable gains from the deployment of these technical components and also show the significant benefits when some of these components are combined together. The techno-economic studies provide useful insights on the total cost of ownership variations with different deployment options, particularly the 3GPP RAN centralization options. These studies are a useful basis for any preparations to deploy/adapt networks to support the different 5G vertical areas considered.

Keywords

5G, Centralized RAN, Component carrier, Drone based communications, enhanced HARQ, Long range connectivity, massive MIMO, Multi-cell scheduler, System Level Simulator, Smart cities, Techno-economic analysis, V2X communications

Executive Summary

This final deliverable from work package WP2 "System Requirements, Integration, and Evaluation" contains the final results of the system level simulations carried out by WP2, based on technical components proposed by the other ONE5G work packages WP3 "End to End multi-service performance optimization" as well as WP4 "Multi-antenna access and link enhancement". It further presents quantitative techno-economic and business analyses of different vertical deployments related to selected use cases defined in D2.1. Both Megacities and underserved areas are addressed by the performed system simulations and techno-economic analyses.

Specifically, the selected technical components (TeC) from WP3 and WP4 are:

- Centralized multi-cell scheduling that exploits cooperative multi-point and non-orthogonal multiple access (in power domain) techniques
- Dynamic component carrier management based on network state, service category, and context information
- Traffic steering based on predictive intelligence algorithms leveraging previous network observations and context data
- Comparison of uniform circular arrays and uniform rectangular arrays for massive MIMO in a multi-cell context
- Enhanced hybrid automatic repeat request that uses the K-rep scheme
- Optimized functionality placement and resource allocation in centralized and distributed radio access networks (CRAN/DRAN)

These technical components address different service categories (eMBB, URLLC, mMTC) and the corresponding benefits with respect to, e.g., throughput and/or latency are highlighted for each case. Also, some results are presented where two of the technical components (dynamic component carrier management and massive MIMO arrays) are jointly analyzed. Furthermore, system level simulations are conducted for the evaluation of connection density in mMTC environments for different system bandwidths. The goal of this study is to investigate whether the International Mobile Communications (IMT)-2020 connection density requirements are satisfied.

A thorough techno-economic and business analysis is carried out for different deployment options related to selected use cases that were defined within the project. These studies analyse the expected costs for different 3GPP RAN centralization deployment options. The automotive use case aided by multi-access edge computing (MEC) is first considered and the impact of different MEC implementations on the CAPEX and OPEX is studied. The mMTC scenario is considered next and the number of additional resources that would be necessary to accommodate the number of mMTC connections envisioned for a future Smart city is investigated. The long-range connectivity use case is presented afterwards and the viability of extension of 5G coverage in far remote and rural areas is investigated. From a site configuration perspective, several options (e.g. increasing antenna height, sectorization) are assessed in order to evaluate their impact on the coverage or capacity of the cell and find the configuration that provides the best trade-off between site cost and cell radius. The best backhaul deployments for large cell radii are studied as well. Finally, different aspects of drone based 5G provision to emergency services are studied. A total cost of ownership (TCO) comparison for two centralization options, 3GPP split 7 and 2, is presented, and a cost sensitivity analysis on factors that influence the TCO is conducted. A framework for quantifying the opportunity cost of using a fixed portion of the 5G commercial spectrum in a prioritized licensed shared access for emergency services is then presented. A comparison of results across use cases is performed as well.

Table of Contents

1 Introduction............ 12

2 TeC overview and final simulation results 13
2.1 Simulator overview and evaluation methodology of various TeCs............ 13
2.2 TeC#1 evaluation - Centralized multi-cell scheduling 14
2.2.1 Overall description of the component............ 14
2.2.2 Component evaluation............ 14
2.3 TeC#2 evaluation - Component carrier management 17
2.3.1 Overall description of the component............ 17
2.3.2 Component evaluation............ 17
2.4 TeC#3 evaluation - Context-aware proactive QoE traffic steering............ 20
2.4.1 Overall description of the component............ 20
2.4.2 Component evaluation............ 20
2.5 TeC#4 evaluation – mMIMO 22
2.5.1 Overall description of the component............ 22
2.5.2 Component evaluation............ 22
2.6 TeC#5 evaluation – Enhanced HARQ............ 25
2.6.1 Overall description of the component............ 25
2.6.2 Component's evaluation 26
2.7 TeC#6 evaluation - Optimised functionality placement and resource allocation in CRAN/DRAN............ 27
2.7.1 Overall description of the component............ 27
2.7.2 Component evaluation............ 27
2.8 Combined results for TeC#2 and TeC#4 integrated simulations............ 28
2.9 IMT-2020 Study: Evaluation of connection density through system-level simulations............ 29
2.9.1 Evaluation methodology............ 29
2.9.2 Simulation results 29
2.9.3 Summary............ 31
2.10 High-level benefits of technical components............ 32

3 Techno-economic quantitative analyses............ 33
3.1 Methodologies and common aspects for the quantitative study 33
3.2 Analysis for the Automotive use case............ 34
3.2.1 UC1 deployment considerations............ 34
3.2.2 UC1 quantitative assessments............ 35
3.3 Analysis for the Smart city mMTC use case 40
3.3.1 Quantitative techno-economic analysis approach............ 41
3.3.2 LTE-M and NB-IoT performances............ 41
3.3.3 mMTC use cases in a dense urban city in 2020 and 2030............ 43
3.3.4 Conclusions 44
3.4 Analysis for the long range connectivity use case............ 46
3.4.1 Extension of the 5G network coverage in far remote and rural areas............ 46
3.4.2 Evaluation of the backhaul options............ 50
3.4.3 TCO evaluation............ 51
3.5 Analysis for the Non Terrestrial Networks for Disaster and Emergency communications use case............ 53
3.5.1 Network configuration for the analysis 53
3.5.2 TCO calculations for the centralization options 55
3.5.3 Cost Sensitivity Analysis............ 55
3.5.4 Spectrum usage - opportunity cost analysis............ 58
3.6 Comparison of results across the use cases............ 61

4 Conclusions **63**

References **66**

Annex **68**

List of Figures

Figure 2-1: Evaluation methodology approach [ONE18-D22] 14

Figure 2-2: Evaluation of centralized multi-cell scheduling with different NOMA and CoMP factors 16

Figure 2-3: CQI distribution percentages (average) for (a) No NOMA, (b) NOMA factor 1, (c) NOMA factor 2 16

Figure 2-4: Evaluation of throughput at a bandwidth of up to 20MHz 18

Figure 2-5: Evaluation of throughput at a bandwidth of up to 10MHz (a) 1MB file size, (b) 8MB file size 19

Figure 2-6: Evaluation of throughput at a bandwidth of up to 100MHz 20

Figure 2-7: Evaluation of QoE for 2000 web users and 3000 FTP users 21

Figure 2-8: Evaluation of QoE for 3000 web users and 3000 FTP users 21

Figure 2-9: Evaluation of QoE for 1000 web users and 2000 FTP users 21

Figure 2-10: Evaluation of QoE for 1000 web users and 3000 FTP users 21

Figure 2-11: Figure of merit evaluation for FTP service 22

Figure 2-12: Figure of merit evaluation for Web service 22

Figure 2-13: Spectral efficiency when using UPA 23

Figure 2-14: Spectral efficiency when using UCA 23

Figure 2-15: Evaluation of (a) average throughput and (b) average latency for scenarios A-F .. 24

Figure 2-16: Evaluation of (a) average throughput and (b) average latency for scenarios A2-F2 25

Figure 2-17: Evaluation of impact of HARQ on URLLC radio-related latency when considering eMBB and URLLC traffic 26

Figure 2-18: Evaluation of eMBB radio-related latency when considering eMBB and URLLC traffic 26

Figure 2-19: Traffic distribution percentage to distributed units for different QoS requirements (a) for low load case with not strict requirements, (b) for high load case with strict requirements 27

Figure 2-20: Decrease of cost function for different service type mix 28

Figure 2-21: Average downlink throughput of different scenarios A & B compared with the baseline (without taking into account the impact of MIMO). 28

Figure 2-22: Connection density success rate for different number of devices per km^2. 30

Figure 2-23: Success rate depending on bandwidth (ISD 500m). 30

Figure 2-24: Connection density success rate for different number of devices per km^2 31

Figure 2-25: Success rate depending on bandwidth (ISD 1732m) 31

Figure 3-1: CAPEX for megacities (UC1) 35

Figure 3-2: OPEX for megacities (UC1) 36

Figure 3-3: TCO per sector for megacities (UC1) 37

Figure 3-4: CAPEX for rural (UC1) 38

Figure 3-5: OPEX for rural (UC1) ... 38

Figure 3-6: TCO per sector for rural (UC1) ... 39

Figure 3-7: Illustration of the approach for the quantitative techno-economic analysis for the Smart city mMTC use case ... 41

Figure 3-8: Needed resources for NB-IoT to satisfy to the number of devices envisioned for Smart cities applications in Rel. 15 and 16... 45

Figure 3-9: Needed resources for LTE-M to satisfy to the number of devices envisioned for Smart cities applications in Rel. 15 and 16... 45

Figure 3-10: Impact of the mast elevation (antenna height) on the coverage and the TCO per km², example in far remote context ... 47

Figure 3-11: Impact of the number of antenna floors on the coverage and the TCO per km ... 48

Figure 3-12: Impact of the number of antennas used for MIMO on the coverage and the TCO per km² ... 48

Figure 3-13: Impact of the number of sectors on the coverage and the TCO per km² ... 49

Figure 3-14: Impact of the UL ratio on the coverage and the TCO per km² ... 50

Figure 3-15: Impact of the UL throughput objective on the coverage and the TCO per km² ... 50

Figure 3-16: TCO 5 years with different backhauls – rural case (left) and far remote rural (right) ... 51

Figure 3-17: TCO 1 year & 5 years for rural – CRAN split 2, microwave backhaul or with fiber ... 52

Figure 3-18: TCO 1 year & 5 years for far remote rural – CRAN split 2, microwave backhaul 52

Figure 3-19: TCO comparison for CRAN split options ... 55

Figure 3-20: TCO sensitivity to incrementing drone numbers per wireless link ... 56

Figure 3-21: TCO sensitivity to the incrementing drone RRH unit costs ... 56

Figure 3-22: 1 year TCO sensitivity to incrementing drone link capacity ... 57

Figure 3-23: 5 year TCO sensitivity to incrementing drone link capacity ... 58

Figure 3-24: Temporal distribution of probability of emergency events in a day... 59

Figure 3-25: Illustration of the spatial distribution of the 5G small cells in 4 service areas (1 commercial and 3 residential areas) with emergency events ... 59

Figure 3-26: Temporal distribution (predicted) of normal 5G traffic ... 60

Figure 3-27: Impact on normal traffic for the commercial and residential areas ... 60

Figure 3-28: Fraction of impacted capacity due to drone support for emergency events ... 61

List of Tables

Table 2-1: Simulation parameters for TeC#1 evaluations 15
Table 2-2: Simulation parameters for TeC#2 evaluations 17
Table 2-3: Simulation parameters 18
Table 2-4: Simulation parameters 19
Table 2-5: Simulation parameters 20
Table 2-6: General simulation parameters 23
Table 2-7: MIMO UPA and UCA simulation parameters (Scenarios A-F) 24
Table 2-8: MIMO UPA and UCA simulation parameters (Scenarios A2-F2). 25
Table 2-9: General simulation parameters 26
Table 3-1: Scenario Parameters 34
Table 3-2: Capacity per sector (Mbps) for Megacities. 40
Table 3-3: Capacity per sector (Mbps) for Rural. 40
Table 3-4: Urban macro test environment for mMTC 42
Table 3-5: LTE-M and NB-IoT performance metrics 43
Table 3-6: Key numbers for Paris in 2018 44
Table 3-7: Key numbers scaled to Paris 2030 44
Table 3-8: Summary of the KPIs targeted by the long range connectivity use case 46
Table 3-9: Increase of the coverage when improving the antenna height 47
Table 3-10: Scenario parameters for NTN use case 53
Table Annex-1: Number of devices, number of transactions (per year) derived for Paris in year 2020 68
Table Annex-2: Number of devices, number of transactions (per year) derived for Paris in year 2030 69

List of Acronyms and Abbreviations

Term	Description	Term	Description
3GPP	3rd Generation Partnership Project	KPI	Key Performance Indicator
5G-NR	5th Generation New Radio	KQI	Key Quality Indicator
BBU	BaseBand Unit	K-Rep	K Repetitions
BS	Base Station	LEO	Low Earth Orbit
CA	Commercial Area	LPWA	Low Power Wide Area
CAPEX	Capital EXpenditure	LTE	Long Term Evolution
CC	Component Carrier	LTE-M	LTE - Machine Type
CRAN	Centralized Radio Access Network	MAC	Medium Access Control
CQI	Channel Quality Indicator	MEC	Multi-access Edge Computing
CoMP	Co-ordinated Multi Point	MEO	Medium Earth Orbit
CSI	Channel State Information	MIMO	Multiple Input Multiple Output
CU	Central Unit	mMIMO	massive MIMO
D&E	Disaster and Emergency	MMSE	Minimum Mean Squared Error
DL	Down Link	mMTC	massive Machine Type Communication
DRAN	Distributed Radio Access Network	MNOs	Mobile Network Operators
DU	Distributed Unit	NB	Narrow Band
eMBB	enhanced Mobile Broadband	NB-IoT	Narrow Band-IoT
E2E	End to End	NOMA	Non-Orthogonal Multiple Access
FTP	File Transfer Protocol	NR	New Radio
GEO	Geostationary Earth Orbit	NTN	Non-Terrestrial Networks
gNB	(5)g Node B	OPEX	OPerational EXpenditure
GUI	Graphical User Interface	PDCP	Packet Data Convergence Protocol
HARQ	Hybrid Automatic Repeat reQest	PHY	PHYsical layer
IMT 2020	International Mobile Telecommunications-2020	PF	Proportional Fair
INSEE	Institut National de la Statistique et des Etudes Economiques	PRB	Physical Resource Blocks

IoT	Internet of Things	PDSCH	Physical Downlink Shared Channel
ISD	Inter-Site Distance	PDU	Protocol Data Unit
ITU	International Telecommunications Union	PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service	QoE	Quality of Experience
RA	Residential Area	TDD	Time Division Duplex
RRH	Remote Radio Head	TTI	Transmit Time Interval
RU	Remote Unit	UC	Use Case
RRM	Radio Resource Management	UCA	Uniform Circular Array -
RSRP	Reference Signal Received Power	UE	User Equipment
RSRQ	Reference Signal Received Quality	UL	Up Link
SIMO	Single Input Multiple Output	UPA	Uniform Planar Array
SINR	Signal to Noise and Interference Ratio	URLLC	Ultra Reliable Low Latency Communication
SRS	Sounding Reference Signal	WP	Work Package
TCO	Total Cost of Ownership	V2X	Vehicle to Everything

1 Introduction

Deliverable D2.3 presents the final system level simulations results of selected technical components and techno-economic studies on selected use cases from the ONE5G project. This deliverable builds on the previous deliverable D2.2, where the initial simulation results and the qualitative framework for the techno-economic studies were presented.

The major contributions from this deliverable are two-fold. Firstly, it presents a comprehensive system level evaluation for the selected technical components, including their performance with 5G-NR features. Some of the analyses are extended to cover scenarios where two technical components are integrated to yield combined gains from the application. This effort from WP2 helps to demonstrate the realistic gains achievable with the proposed technical components in a system context. Secondly, the deliverable provides a detailed set of techno-economic studies on the 5G deployment options to support key verticals. These studies will be invaluable for operators/ other parties planning to deploy similar 5G operations in near future, in an environment where little or no such information is publically available.

D2.3 is structured as follows.

Chapter 2 presents an overview of selected technical components as well as the corresponding simulation results. It also presents results where some technical components are jointly simulated. Overall, the simulation results show significant gains from the usage of these components. The gains are quantified with regards to spectral efficiency and/or latency, energy consumption, etc. according to the service category at hand (e.g. eMBB, URLLC, etc.). Also, our results on connection density for mMTC deployments, which has been contributed to the IMT-2020 Evaluation Group, is presented. Chapter 2 is concluded with a look at the gains and benefits illustrated by the technical components, particularly in view of the 5G features/ challenges in the simulation context.

Chapter 3 details the techno-economic analysis for the following use cases: automotive aided by multi-access edge computing, smart cities with massive machine type communications, long range connectivity in remote areas, and non-terrestrial networks for disaster and emergency communications. These studies provide important insights into the incurred cost with different deployment options, particularly the 3GPP RAN centralization options, which also form a basis for some broad comparison of the deployment costs across the use cases. The unique technical requirements of each of the use cases are captured in these studies and the comparisons make clear that a generic deployment model across all the verticals will be highly impractical and also expensive. Some insights into opportunities for shared spectrum usage with the main commercial 5G operations are also provided in this chapter.

This deliverable is concluded in Chapter 4.

2 TeC overview and final simulation results

2.1 Simulator overview and evaluation methodology of various TeCs

As mentioned in [ONE18-D22], system level evaluation through simulations need to take into account different aspects related to configuration, environment models, network (simulated system) models, analytics and event handling. All of these are accessible in a user-friendly graphical user interface (GUI). The main simulator components are described as follows:

Environment models and configuration: A first step of system-level simulations is to specify the simulated system (i.e., define the considered parameters), designate the environments and select analytics. Environment concerns aspects related to traffic (e.g. proper modelling of eMBB, mMTC, anticipated load, mobility) and radio conditions (e.g. propagation models). The aforementioned parameters and details have been reported also in the project's internal report [ONE18-IR21]. This is triggered by the fact that project use cases are part of the scenarios "megacities" and "underserved areas" and as a result, different traffic characteristics apply depending on the use case. Such aspects will be properly documented for the considered use cases in order to consider them in the simulations later on.

Network/ Simulated System models: System aspects include network deployment e.g. small cells and macro cells (depending on the deployment) for use cases in underserved areas and megacities. Also, spectrum aspects are considered for utilization of bands below 6GHz and to be expanded in mmWave. As an example, the model defines the bands allowed to be used, number of channels, bandwidth etc. Abstraction of PHY/MAC is taken into account (e.g. spectral efficiency mapping curves and Radio Resource Management (RRM) algorithms are also considered.

Analytics: The simulation results will be evaluated against the Key Performance Indicator (KPI) targets (e.g. throughput, latency). The results are analysed and visualised. KPIs are carefully elaborated in WP2 as well as related standards. Key Quality Indicators (KQI) are also studied in the context of WP2 [ONE17-D21] and WP3 [ONE18-D31] in order to offer a framework to reflect objectively the service performance and quality, inherently from an E2E perspective.

Event Handling: An event may be distinguished by time, location, type (e.g., session set up, call request, packet transmission), services, devices, users and supplementary information. Details on event handling are provided later in the document.

Graphical User Interface (GUI): A user-friendly GUI is essential for easy handling of simulations and demonstrations. The GUI consists of user-friendly tabs, text boxes, and input fields, in order to create an easy to use environment for data input as well as extraction of results by visualizing results in graphs and charts.

Regarding the evaluation methodology, we follow the approach introduced in [ONE18-D22]. The defined scenarios and use cases are described in the project's deliverable [ONE17-D21]. They provide the essential information for building environment models and KPI targets. Technical components are developed in WP3 and WP4. In the first phase of the development, initial evaluations via system level simulations are performed. Finally in the second phase, comprehensive system level simulations are conducted in the context of WP2 to analyse the evaluation of technical components with 5G-NR features, analysing the combined gains when some TeCs are integrated in the simulator together as well as validation studies through PoCs (in the context of WP5). TeCs have been selected based on maturity, compatibility with system-level simulator and are a representative sample of WP3 and WP4 related tasks. It is the results of the integration of TeCs developed by different partners into the developed system-level simulator. The aforementioned approach is depicted in Figure 2-1

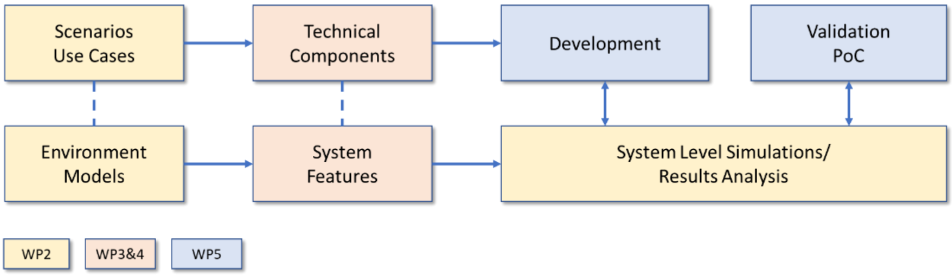


Figure 2-1: Evaluation methodology approach [ONE18-D22]

2.2 TeC#1 evaluation - Centralized multi-cell scheduling

2.2.1 Overall description of the component

The basic idea of centralized multi-cell scheduling is that a "super-cell" managed by a Central Unit (CU) performs all radio tasks above the MAC layer corresponding to the different cells. This CU will perform all the scheduling decisions and allocate the users to the resource blocks and Remote Unit (RU) where the channel conditions are the best by taking advantage of the Channel Quality Indicator (CQIs) reported by the users. More details can be found in ONE5G deliverable D3.1 [ONE18-D31].

Using channel conditions represented by CQI values, the centralized multi-cell scheduler will create a 3D-table populated with Proportional Fair (PF) metrics that it will use to schedule users at the available sub-bands and RUs. The 3D-table contains the metrics from all the crossing links, i.e. from each UE to each RU. Therefore, the centralized scheduler will rely on this table to decide which RU has to transmit to a certain UE at some certain sub-bands in every subframe, TTI – 1ms.

In order to be more flexible, the centralized multi-cell scheduler allows frequency reuse by means of techniques such as CoMP and NOMA in power domain. The decision to apply these techniques is determined by a threshold that the SINR values between different RUs must fulfil at certain sub-bands, and by a cluster size which limits the maximum number of RUs to be coordinated.

Margins to apply CoMP, NOMA and RF isolation techniques are shown below, where i and i' indicate different RUs and j a certain subband where the study is being carried out:

- CoMP is applied whether the following relation is met:

$$\left|SINR_{ij} - SINR_{i'j}\right| < thresholdCoMP < 2 - 3\ dB$$

- NOMA is applied whether the following relation is met:

$$thresholdRNOMA \ < \ \left|SINR_{i'j} - SINR_{ij}\right| < thresholdRFisolation$$

$$6\ dB \ < \ \left|SINR_{i'j} - SINR_{ij}\right| < 25\ dB$$

- Otherwise, RF isolation method will be applied.

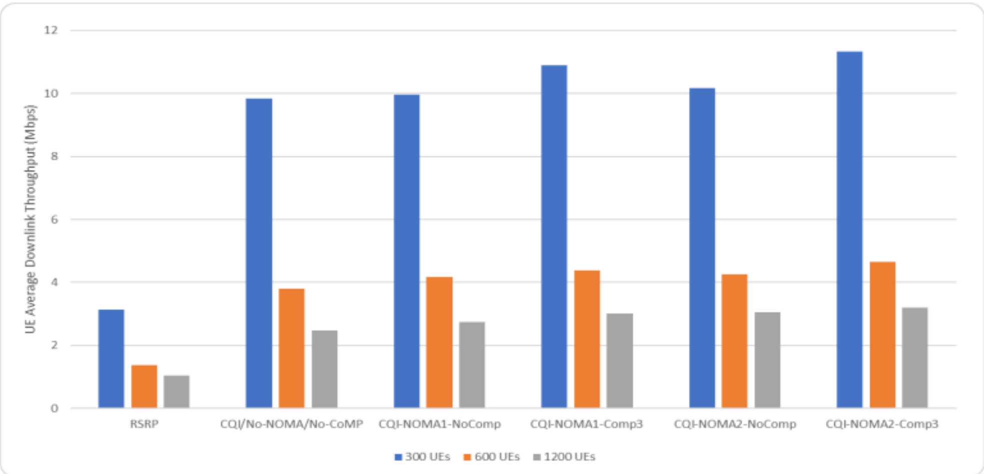
2.2.2 Component evaluation

In this subsection, we provide the component evaluation which takes into account the implementation in the system-level simulator of the centralized multi-cell scheduling technical component. The results have been validated by the respective technical component owner who is a member of the project's consortium. In this respect, the implementation takes into account the described procedure and principles for multi-cell scheduling including NOMA and CoMP aspects. The following simulation parameters have been considered:

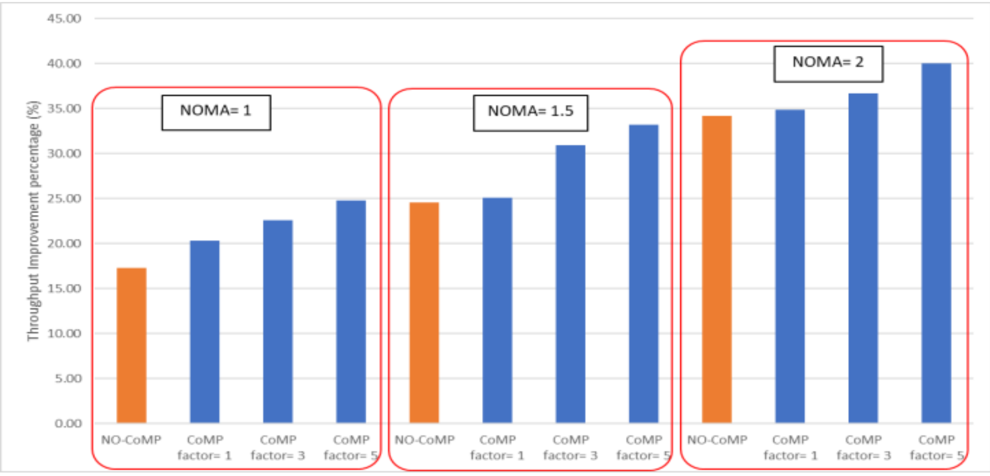
Table 2-1: Simulation parameters for TeC#1 evaluations

Number of cells	21
Base station Tx power	46 dBm
Inter-site Distance (ISD)	500 m
Type of environment	Urban
Location of base stations	Rooftop (10 m)
MIMO scheme	2x2
Total number of UEs	300, 600, 1200
UE Tx power	23 dBm
Height of UEs	1.5 m
Location of UEs	Uniform
Path loss	L = 128.1 + 37.6 log10(R), R in kilometers
Bandwidth	10MHz downlink and 10MHz uplink
Frequency	2 GHz
Traffic type and model	eMBB, 3GPP FTP Model 1
Simulation time	60s

As illustrated in Figure 2-2, we evaluate the impact of different NOMA and CoMP factors to the centralized multi-cell scheduling. In Figure 2-2a, the UE average downlink throughput is plotted for different number of users, namely, 300, 600 and 1200 users. In this plot, it is evident that when both CQI and NOMA-CoMP is not taken into account for the scheduling, we experience a lower downlink throughput. Then, as NOMA and CoMP are used, throughput improves. Specifically, when NOMA factor 1 and CoMP factor 3 are used (these factors represent the NOMA and CoMP gain that the system shall consider for reducing the hardness interferences), the throughput results are better compared to not using NOMA/CoMP by around 15%, and this percentage goes near 20% when NOMA factor 2 and CoMP factor 3 are used. The combination of NOMA factor 2 and CoMP factor 3 method gains the highest throughput among the six scheduling methods shown in Figure 2-2a. Figure 2-2b summarizes the throughput improvement percentages of when applying fixed NOMA factor 1, 2, 3, while varying the CoMP factors ranging from 20% up to 40%.



(a)



(b)

Figure 2-2: Evaluation of centralized multi-cell scheduling with different NOMA and CoMP factors

Furthermore, in Figure 2-3 the CQI distribution of served / selected users is illustrated in order to capture the impact of NOMA implementations. In all cases, we see a rather balanced performance in which users with various CQIs are selected by the algorithm to be served and not only the best ones. The composition of each category of CQI users under NOMA method remains almost the same as that of the No-NOMA method.

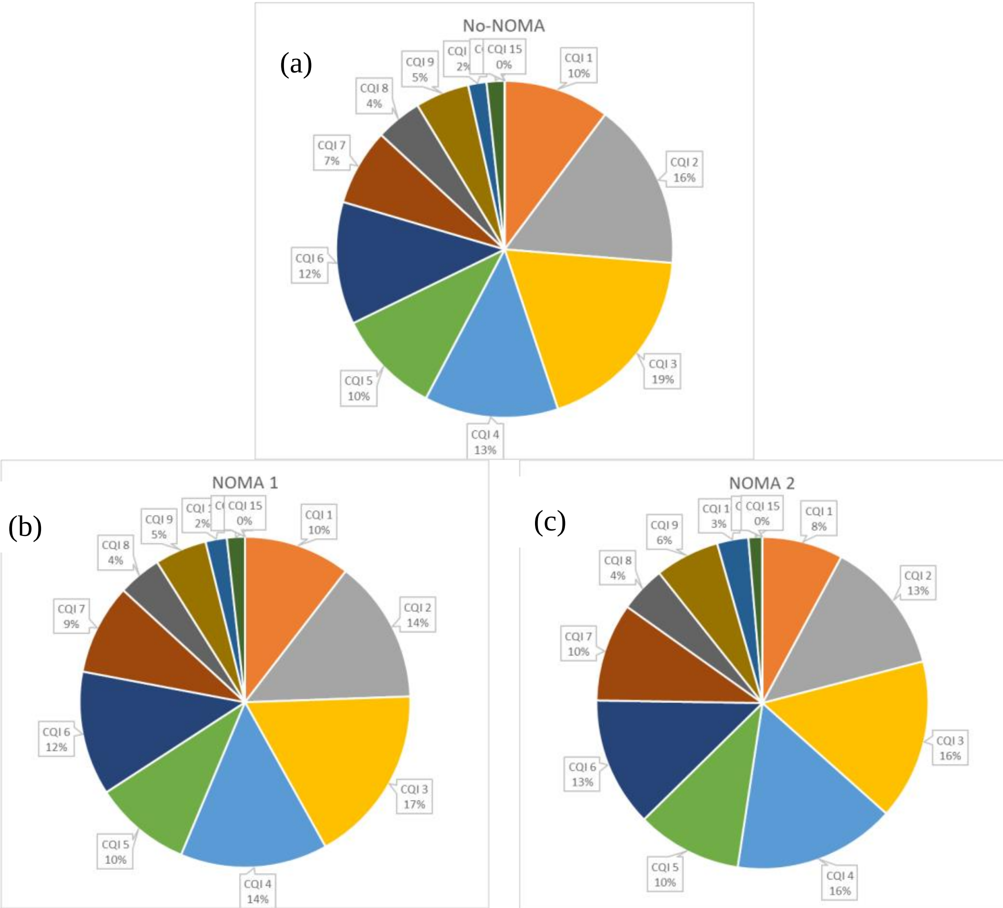


Figure 2-3: CQI distribution percentages (average) for (a) No NOMA, (b) NOMA factor 1, (c) NOMA factor 2

2.3 TeC#2 evaluation - Component carrier management

2.3.1 Overall description of the component

Several techniques for component carrier management have been proposed, each of them following different criteria [WPS10, LVM17]. The most immediate research line could be the load balancing among component carriers. In the same way, dual connectivity has been addressed in recent works, showing its advantages and capabilities in different scenarios [RPW16, LGA16], for example, regarding its ability to reduce radio link failures given a fast-moving UE. Finally, some recent works propose addressing multi-connectivity component carrier management in a similar way than active set management for 3G mobile networks [TAV16]. However, in these works, only the radio channel conditions are considered as the inputs for the component carrier management.

The aim of this work is to dynamically assign *Component Carriers* from multiple (more than two) nodes (extending dual connectivity) according to the network state (e.g., network load or coverage hole), as well as the service category and context information as presented in Subsection 3.2.2 of D3.2 deliverable [ONE18-D32]. In this study, eMBB is considered (i.e., ONE5G use cases no. 2, 5 and 6 [ONE17-D21]). For this service category, given its need for higher throughput, a data aggregation scheme should be followed. To this end, a Component Carrier (CC) manager is proposed to determine the number of carriers to be assigned to a user. This CC manager could be implemented in the gNodeB and necessary information could be exchange by gNodeB by using Xn interfaces. Additionally, the carrier indices, the source nodes, and flow are also proposed by the CC manager.

Regarding the evaluation of the solution, an implementation based on eMBB has been selected. For this implementation, different types of inputs are considered, such as: (a) metrics reported by the user, like the Reference Signal Received Quality (RSRQ) and (b) metrics from the carriers (like their load). Based on these inputs, the CC manager computes a score for each of the available carriers indicating the carrier suitability for a specific user. This score can be computed in different ways depending on the target criterion (e.g., if a load balancing approach is followed, those CC with a lower load will receive a higher score; in the case of a target focused on signal quality, CC with higher RSRQ will be selected).

2.3.2 Component evaluation

In this subsection, we provide results obtained with the implementation in the system-level simulator of the component carrier management technical component. In this specific evaluation, we consider only eMBB traffic and selecting cells with the criterion of Reference Signal Received Power (RSRP). The proposed solution is based on signal quality (RSRQ) and the load of candidate component carriers.

Table 2-2: Simulation parameters for TeC#2 evaluations

Number of Macro BS	19 macro 3-sector base stations
Number of Small BS	57 small base stations
Number of users	1000 users
Network area	2200x2200 meters
ISD	500 meters for macros
Frequencies	2GHz
Request arrival time	Poisson
Traffic data generation	1440 files per user per day
File Size	1MB

Simulation time	60 sec
Bandwidth	20MHz
Component Carriers	1 to 7
FTP direction	Downlink

Figure 2-4 illustrates the result of throughput by considering different number of component carriers and by taking into account the simulation parameters of Table 2-2. The proposed approach takes into account the selection of CCs, the RSRQ and load metrics while comparing it with the RSRP metric. For all values of CCs, the RSRQ & load approach performs slightly better in terms of throughput as compared to the RSRP case.

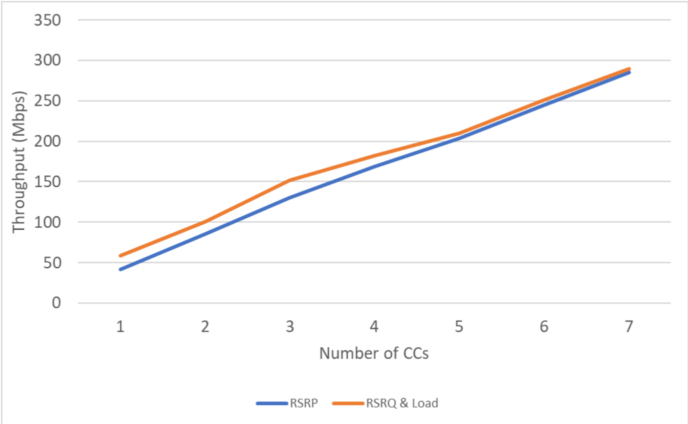
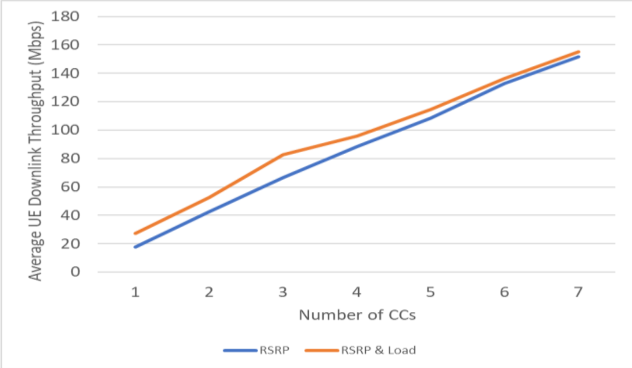


Figure 2-4: Evaluation of throughput at a bandwidth of up to 20MHz

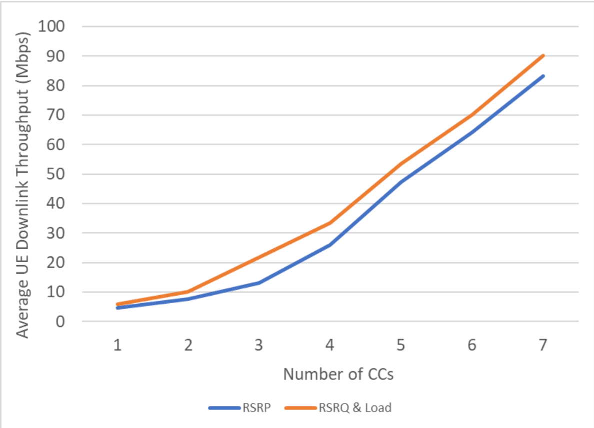
Table 2-3: Simulation parameters

Number of Macro BS	19 macro 3-sector base stations
Number of Small BS	57 small base stations
Number of users	1000 users
Network area	2200x2200 meters
ISD	500 meters for macros
Frequencies	2GHz
Request inter-arrival time	Poisson
Traffic data generation	1440 files per user per day
File Size	1MB & 8MB
Simulation time	60 sec
Bandwidth	10MHz
Component Carriers	1 to 7
FTP direction	Downlink

Figure 2-5 illustrates the average throughput numbers for various values of component carriers using the simulation parameters from Table 2-3. In all cases, the RSRQ & load approach is slightly superior to RSRP in terms of throughput as shown in Fig. 2-5.



(a)



(b)

Figure 2-5: Evaluation of throughput at a bandwidth of up to 10MHz (a) 1MB file size, (b) 8MB file size

Table 2-4: Simulation parameters

Number of Macro BS	19 macro 3-sector base stations
Number of Small BS	57 small base stations
Number of users	1000 users
Network area	2200x2200 meters
ISD	500 meters for macros
Frequencies	2GHz
Request inter-arrival time	Poisson
Traffic data generation	1440 files per user per day
File Size	8MB
Simulation time	60 sec
Bandwidth	100MHz
Component Carriers	1 to 4
FTP direction	Downlink

Finally, Figure 2-6 illustrates the result of throughput by considering different number of component carriers when considering higher bandwidths of up to 100MHz (for taking into account 5G assumptions of higher bandwidths) for each CC. Similar to previous results, for all values of CC, the RSRQ & load approach achieves slightly higher throughput compared to the RSRP .

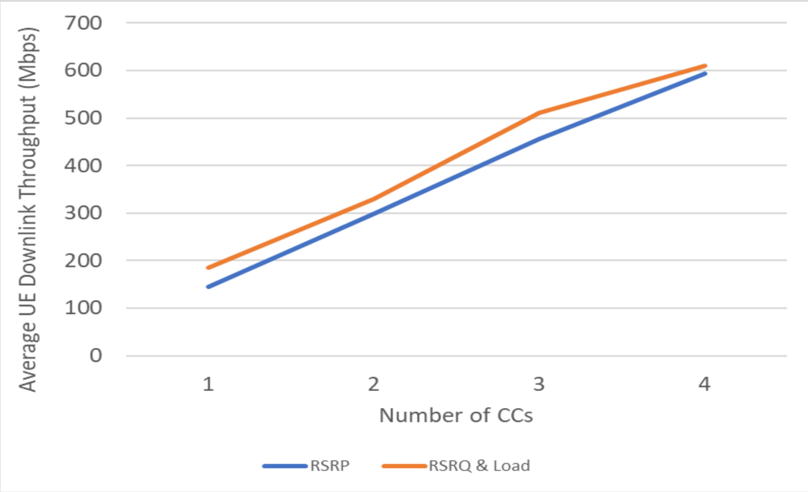


Figure 2-6: Evaluation of throughput at a bandwidth of up to 100MHz

2.4 TeC#3 evaluation - Context-aware proactive QoE traffic steering

2.4.1 Overall description of the component

The global objective of this technical component is to develop a set of tools to improve mobility management in 5G NR in order to optimize the quality of experience (QoE) perceived by an end user. To that end, and in order to emphasize the end user perspective, radio access network performance indicators are left aside in favor of metrics related to the QoE associated to a certain service. These will be used as the input for mobility management use cases, like load balancing, leading to a balanced QoE. The proposed QoE traffic steering method considers QoE metrics for different eMBB services as inputs, in order to obtain a balanced situation regarding user experience in the different cells of the network. This solution can be completed by applying predictive intelligence algorithms, in order to forecast traffic behavior and thus, a possible QoE degradation. This will allow network operators to prevent such degradation by a proactive end-to-end optimization. These predictive intelligence algorithms will rely both on past observations from the network as well as on context and social network data as described in Subsection 4.2.2 of D3.2 deliverable [ONE18-D32]. Overall, the main objective of this TeC is to achieve a QoE balancing by adjusting handover margins on a per-service basis (i.e., all UE with the same service in a certain cell have the same value of handover margin).

2.4.2 Component evaluation

In this subsection, we provide results which take into account the implementation of the "QoE traffic steering" technical component. The following simulation parameters are considered:

Table 2-5: Simulation parameters

Number of Macro BS	19 macro 3-sector base stations
Network area	2200x2200 meters
Frequencies	2GHz
Simulation time	60 sec
Bandwidth	10MHz
FTP/web direction	Downlink

Figure 2-7 to Figure 2-10 illustrate the evaluation of QoE for different combinations of web and FTP users. The QoE is evaluated for different simulation loops. Loops represented different simulation runs. The aim of these loops is to show that the QoE metric converges and does not exhibit large fluctuations. As such, all cases show a convergence of QoE metric after 2-3 loops and stays almost stable till 10 loops.

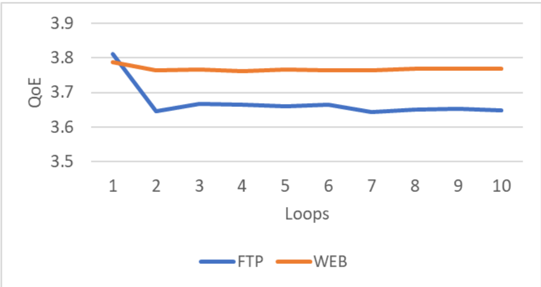


Figure 2-7: Evaluation of QoE for 2000 web users and 3000 FTP users

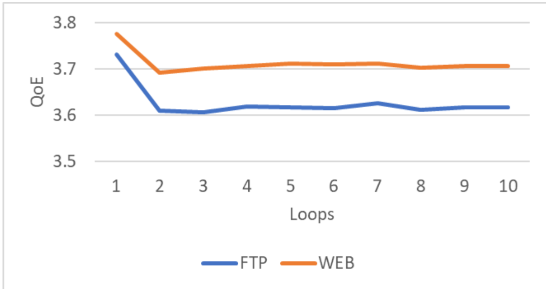


Figure 2-8: Evaluation of QoE for 3000 web users and 3000 FTP users

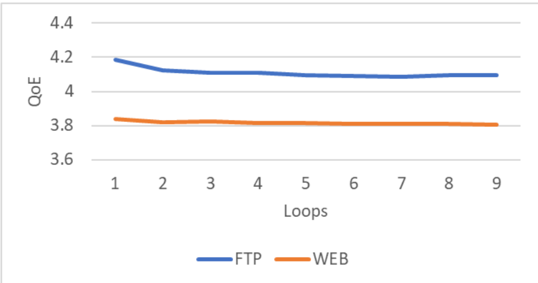


Figure 2-9: Evaluation of QoE for 1000 web users and 2000 FTP users

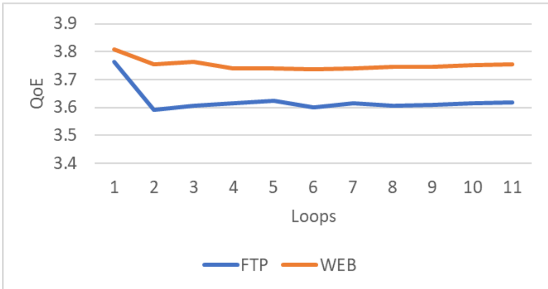


Figure 2-10: Evaluation of QoE for 1000 web users and 3000 FTP users

Moreover, a figure of merit has been identified. The considered figure of merit measures the level of QoE imbalance in the scenario. For that, the average QoE per cell and service for a certain cell is compared to the average QoE for neighboring cells. Expression (1) presents the figure of merit calculation. For a given cell c_i and service s_l, the QoE is computed as an average QoE perceived by the users with service s_l in cell c_i as $\overline{QoE}(c_i, s_l)$. In the case of the neighboring cells, the average QoE is computed as an average QoE per cell and service of the n neighboring cells (in this work, a maximum of n=6 neighbors are considered), $\overline{QoE}_n(c, s)$. Finally, N_c represents the number of considered cells.

$$\overline{QoE}_{imb} = \frac{\sum_{\forall c_i} |\overline{QoE}(c_i,s_l) - \overline{QoE}_n(c,s)|}{N_c} \qquad (1)$$

The convergence of the QoE to certain values is shown in Figure 2-11 and Figure 2-12.

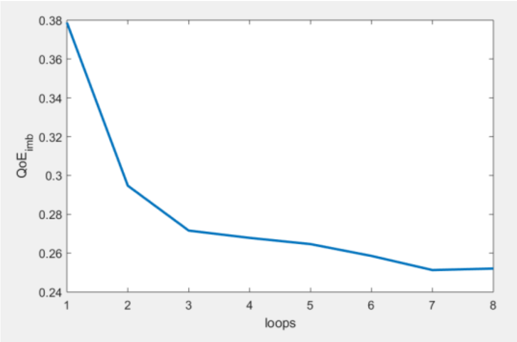


Figure 2-11: Figure of merit evaluation for FTP service

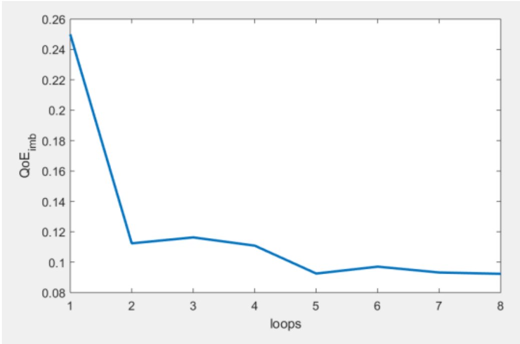


Figure 2-12: Figure of merit evaluation for Web service

2.5 TeC#4 evaluation – mMIMO

2.5.1 Overall description of the component

By now, the advantages and trade-offs of massive MIMO are well understood [BSW+19], and with the introduction in the 3GPP-NR standard, it can be regarded as a mature technology [GPB+18]. However, when it comes to the deployment of antennas in centralized arrays, the focus is limited to planar antenna structures [KMT+18]. In this component, a circular array structure is proposed in order to reduce outage of the directional planar antenna arrays.

System level evaluation of massive MIMO in cellular systems is computationally and storage wise very demanding due to the large antenna dimension and high number of devices required to utilize spatial multiplexing gains. Considering also realistic traffic models, simulations have to cover a time range in the order of hundreds of milliseconds, an additional abstraction model besides the SINR-to-rate mapping is required and described in the following.

In [WU+14] a PHY-layer abstraction model is proposed and adapted to fit in the 5G system-level platform. First, the PHY layer MIMO simulation is performed with parameter configuration according to the use case or scenario requirements. From the system level simulations, the following two outputs are required as input to the system level abstraction, see Section 5.4 in [ONE18-D41]:

1. The number of spatially multiplexed users per time-frequency resource
2. The achieved user spectral efficiency over the unprecoded wideband SINR (also referred to as geometry) or SNR

In the second step, the system level or network layer simulation is performed assuming MIMO technology component. Therein, multiple users on a time-frequency resource have to be selected according to the mapping table or curve from PHY layer simulation. The mapping from SNR to spectral efficiency can be done by selecting a point out of the distribution requiring some complexity or in the simplest case to use always the median value. Note that the active user selection in the system level simulation may depend on traffic and mobility models. After the user selection, the SNR or unprecoded wideband SINR of these users is determined and used as input to the mapping from SNR or geometry to user spectral efficiency.

2.5.2 Component evaluation

In this subsection, we provide some results which take into account the implementation of the "mMIMO" technical component. The following simulation parameters are considered, where UPA stands for uniform planar array and UCA for uniform cylindrical array:

Table 2-6: General simulation parameters

Parameter	Value
Carrier frequency	3.75 GHz
Bandwidth	10MHz, 5X20MHz
Multiplexing	OFDM – 5G NR
Resource block configuration	12 subcarrier, 14 symbols
Subcarrier bandwidth	15 kHz
Duplex Mode	Time Division Duplex
Channel state information (CSI) knowledge at BS	Full and error free CSI
Multiple-user transmission scheme	MMSE
Number of Macro Cells	19
Number of BS antennas	UPA: triple sectorized [8x8] UCA: [8x24], columns on circle
XY-Deployment	Hexagonal grid
Inter side distance	300 m
Height	25 m
Transmit power	40 dBm
User Height	1.5 m
Element pattern	Omni
UE Velocity	3 km/h
Number of Users	500-16000
Area	1500x1500 meters

The spectral efficiency curves are provided in Figure 2-13 and Figure 2-14 which are taken into account in the system level simulations:

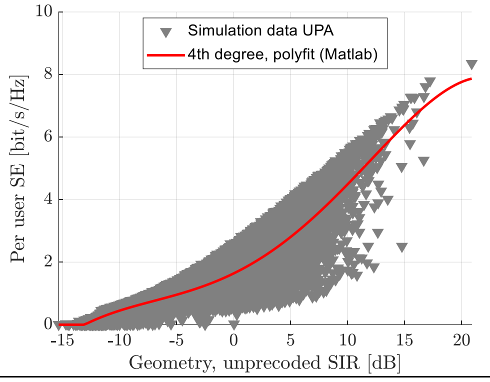


Figure 2-13: Spectral efficiency when using UPA

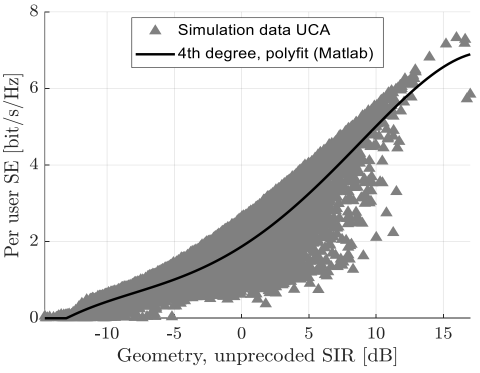


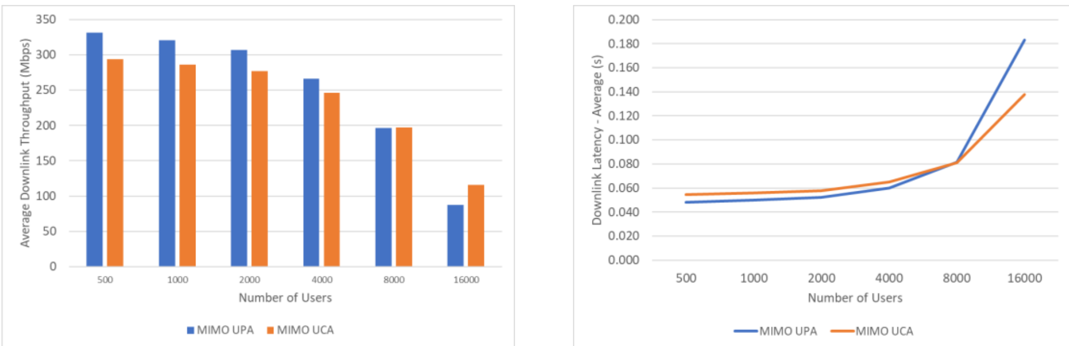
Figure 2-14: Spectral efficiency when using UCA

Table 2-7: MIMO UPA and UCA simulation parameters (Scenarios A-F)

	MIMO UPA					
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
Number of Users	500.00	1000.00	2000.00	4000.00	8000.00	16000.00
File Size	2.0	2.0	2.0	2.0	2.0	2.0
File per day	1440.0	1440.0	1440.0	1440.0	1440.0	1440.0

	MIMO UCA					
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
Number of Users	500.00	1000.00	2000.00	4000.00	8000.00	16000.00
File Size	2.0	2.0	2.0	2.0	2.0	2.0
File per day	1440.0	1440.0	1440.0	1440.0	1440.0	1440.0

Figure 2-15 illustrates the evaluation of (a) average throughput per cell and (b) average latency per cell for scenarios A-F., as described in Table 2-7. The main difference of the scenario A-F is the number of users reflecting a certain network load ranging from 500 for Scenario A to 16.000 in Scenario F.We see that the UCA antennas work better in cases of lower SINR values, meaning that in scenarios with high numbers of users (i.e. higher interference levels) the results of proposed UCA antennas are better than of those with UPA antennas. Compared to gains observed in the single-BS scenario, [KMT+18, ONE19-D42], the gains in the multiple-cell scenario are lower. The main reason for this is, that the regular hexagonal deployment of the triple-sectorized UPA base stations provides inherently some interference coordination. Therefore, the advantage of the UCA, providing homogeneous coverage and thus the outage reduction is partly compensated by triple sectorized UPA in the cellular environment. However, readers should be aware that the regular deployment of sectorized UPAs is demanded by system-level assumption of the 3GPP standardization [GPB+18] but for this particular technology component an irregular and more realistic deployment of base stations would be more suited to show the benefits.



(a) (b)

Figure 2-15: Evaluation of (a) average throughput and (b) average latency for scenarios A-F

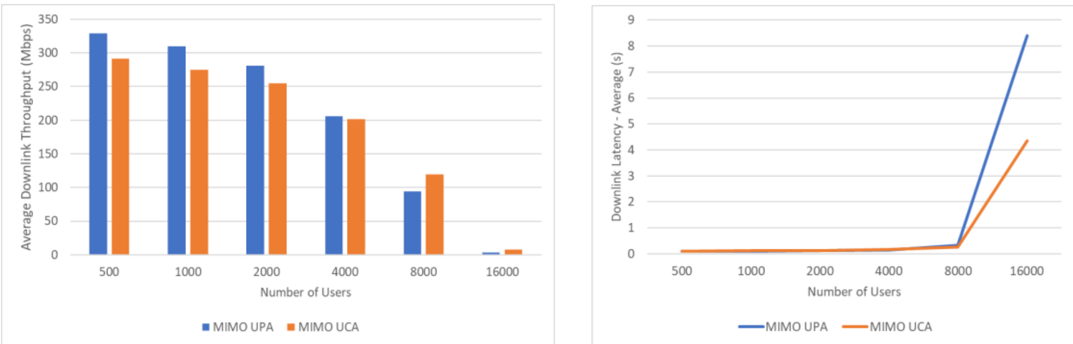
Table 2-8: MIMO UPA and UCA simulation parameters (Scenarios A2-F2).

	MIMO UPA					
	Scenario A2	Scenario B2	Scenario C2	Scenario D2	Scenario E2	Scenario F2
Number of Users	500.00	1000.00	2000.00	4000.00	8000.00	16000.00
File Size	4.0	4.0	4.0	4.0	4.0	4.0
File per day	1440.0	1440.0	1440.0	1440.0	1440.0	1440.0

	MIMO UCA					
	Scenario A2	Scenario B2	Scenario C2	Scenario D2	Scenario E2	Scenario F2
Number of Users	500.00	1000.00	2000.00	4000.00	8000.00	16000.00
File Size	4.0	4.0	4.0	4.0	4.0	4.0
File per day	1440.0	1440.0	1440.0	1440.0	1440.0	1440.0

The antenna configurations of the MIMO UPA (top) and MIMO UCA (bottom) are given in Section 8.1 in [ONE18-D41]

Similarly, Figure 2-16 illustrates the evaluation of (a) average throughput and (b) average latency for scenarios A2-F2, as described in Table 2-8. As in previous cases, the results of proposed UCA antennas are better than of those with UPA antennas as well by around 15%. Increased latency is mainly experienced due to congested network (especially in the case of 16,000 users in the area of 1500m x 1500m).



(a) (b)

Figure 2-16: Evaluation of (a) average throughput and (b) average latency for scenarios A2-F2

2.6 TeC#5 evaluation – Enhanced HARQ

2.6.1 Overall description of the component

The hybrid automatic repeat request (HARQ) scheme mainly considered for evaluation is the *K-Rep* scheme. In the K-Rep scheme, the UE is configured to autonomously transmit the same packet K times before waiting for feedback from the BS. In Release 16, such K-repetition can be supported on a mini-slot basis rather than on a subframe basis as in TTI bundling. Each repetition can be identical or it can consist of different redundancy versions of the encoded data. This method can reduce the delay in the HARQ process, with a potential waste of resources if the number of repetitions is overestimated. More details of the component are available in the ONE5G publication [JAB+17], and in the ONE5G deliverables [ONE18-D41, Section 2.2.1] and [ONE19-D42, Section 2.2.1 and 2.2.5].

2.6.2 Component's evaluation

In this subsection, we provide results which take into account the implementation of the "HARQ" technical component. The simulation parameters are listed in Table 2-9:

Table 2-9: General simulation parameters

Parameter	Value
Carrier frequency	4 GHz
Bandwidth	10MHz
Subcarrier bandwidth	15 kHz
Number of cells	21
Inter side distance	500 m
Traffic	FTPModel3 with 32B packet size and Poisson arrival of 10 packets per second per UE for URLLC, and packet of 1MB for eMBB
Low load / High load	10UE per cell / 40UE per cell

The results in Figure 2-17 and Figure 2-18 show the impact on radio-related latency for different 'k' re-transmissions as described in [JAB+17]. As mentioned above, the UE transmits K times the same packet (either identical copies or different redundancy versions of the same transport block). This method can reduce the delay in the HARQ process, with a potential waste of resources if the number of repetitions is overestimated. It is worth to mention that, for the sake of simplicity, the HARQ scheme is only applied to URLLC services. This is because we are using HARQ for improving reliability, and we are not optimizing eMBB services for reliable communication. In the evaluation of eMBB latency, the latency tends to slightly increase with the number of repetitions when considering eMBB and URLLC traffic and high load. In addition, in the evaluation of URLLC latency when considering eMBB and URLLC traffic (HARQ applied only to URLLC), the latency tends to decrease as the number of repetitions increases because more identical packets are transmitted, so messages are more probable to be successfully decoded.

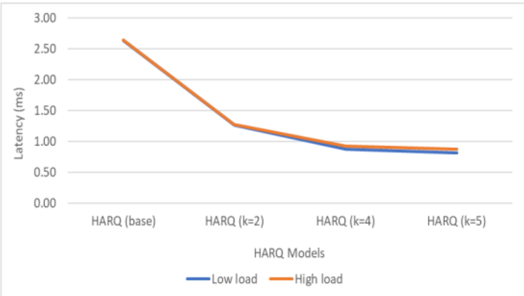


Figure 2-17: Evaluation of impact of HARQ on URLLC radio-related latency when considering eMBB and URLLC traffic

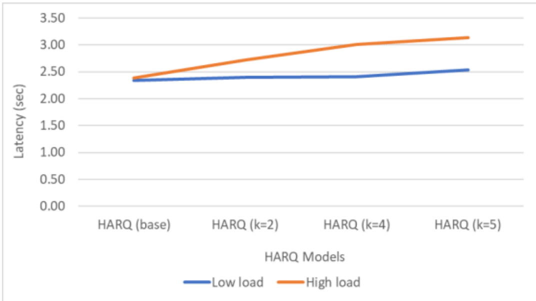


Figure 2-18: Evaluation of eMBB radio-related latency when considering eMBB and URLLC traffic

2.7 TeC#6 evaluation - Optimised functionality placement and resource allocation in CRAN/DRAN

2.7.1 Overall description of the component

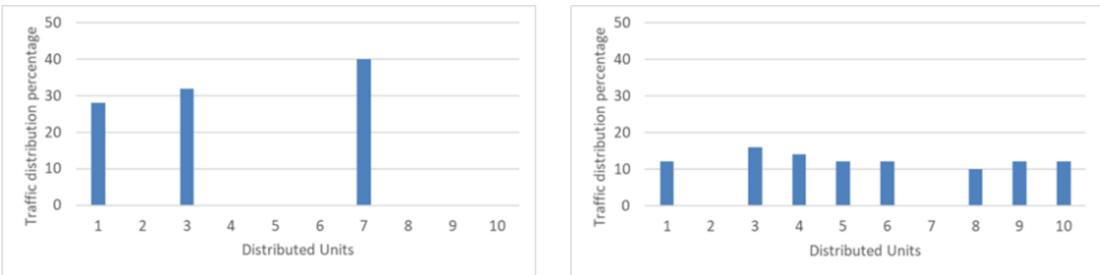
We consider a network architecture that contains a Central Unit (CU) and several Distributed Units (DUs), integrating the DU and remote radio head (RRH) in the same node. A CU (e.g. Baseband Unit-BBU) is a node that includes the gNB functions, except those functions allocated exclusively to the DU. It controls the operation of DUs over front-haul interface. A DU (also referred to as RRH) is a node that includes a subset of the gNB functions, depending on the functional split option. Its operation is controlled by the CU.

Based on the functional split options proposed in [5GPPP-ARCH] and also discussed in Section 2 of [ONE18-D31], we study the functions of the LTE protocol stack, which can be partitioned in distinct elements and assigned to different network units. Our objective is to assign these functional elements to network units finding the minimum cost allocation that satisfies a set of capacity and performance constraints, as well as the distribution of network traffic to each DU.

The factors contributing to cost are mainly energy consumption and latency, for computation as well as data transfer among the functional components. The applied constraints address capacity and QoS requirements.

2.7.2 Component evaluation

In this subsection, we provide results which take into account the implementation of the "optimised functionality placement and resource allocation in CRAN/DRAN" technical component. In Figure 2-19, the distribution of traffic to the distributed units for two different use cases with their respective QoS requirements is depicted. In case a), the QoS requirements are not that strict, so only 3 of the available DUs are activated, leading to reduced operational costs. However, in case b), QoS requirements are higher (resulting from a higher ratio of URLLC use cases). Therefore, more DUs are required in order to handle the traffic. These are proof of concept results, showing that the solution adapts to varying conditions and decisions intuitively show some improvement. The objective function and parameters used are described in [ONE19-D42].



a) b)

Figure 2-19: Traffic distribution percentage to distributed units for different QoS requirements (a) for low load case with not strict requirements, (b) for high load case with strict requirements

In addition, a numerical evaluation of the achieved improvement is provided. Considered tests differ in the service type mixture assumed in the network. As a result, the weights corresponding to a) Computational Latency, b) Data Transmission Latency and c) Energy consumption in the cost function studied by the algorithm adjust to the mixture. Starting from a mixture of 80% URLLC, 10% eMBB, 10% other services (Test case 1), towards a mixture of 10% URLLC, 80% eMBB, 10% other services (Test case 8), the cost function of our proposed solution is compared to that of a baseline centralised approach. Figure 2-20 shows the percentage decrease in the cost function. We can see that about 30-50% improvement of the considered cost is achieved. The objective function and parameters used are also described in the respective section of D4.1 [ONE18-D41].

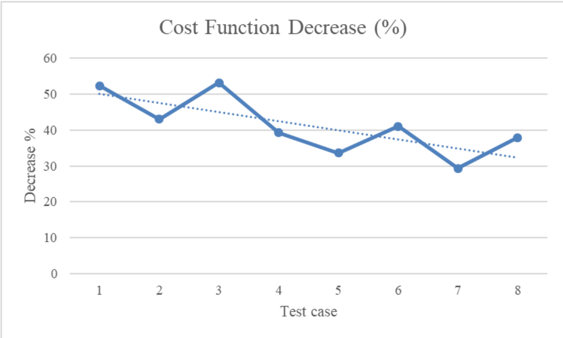


Figure 2-20: Decrease of cost function for different service type mix

2.8 Combined results - TeC#2, TeC#4 integrated simulations

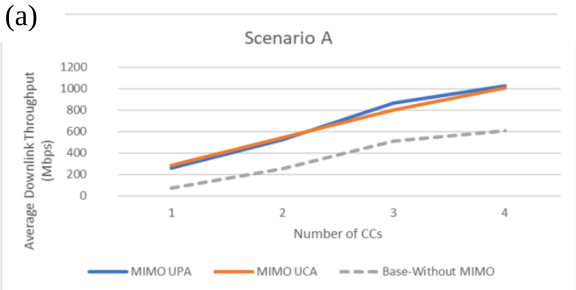
In this subsection, we present the results of the combined evaluation for TeC#2 (component carrier management) and TeC#4 (mMIMO). It makes sense to combine these two use cases for dense urban environments (Megacities) with high traffic density. Through this combination, it is possible to show potential synergies between different technical components (in addition to the standalone evaluations that were shown in the previous subsections). The following simulation parameters have been considered for different scenarios A, B.

	Scenario A								
	MIMO UPA					MIMO UCA			
Files/Day/User	1440	1440	1440	1440		1440	1440	1440	1440
Users	2000	2000	2000	2000		2000	2000	2000	2000
File Size	4 MB	4 MB	4 MB	4 MB		4 MB	4 MB	4 MB	4 MB
Selection	RSRQ & Load	RSRQ & Load	RSRQ & Load	RSRQ & Load		RSRQ & Load	RSRQ & Load	RSRQ & Load	RSRQ & Load
Number CCs	1	2	3	4		1	2	3	4
Per Macro MHz	100 MHz	100 MHz	100 MHz	100 MHz		100 MHz	100 MHz	100 MHz	100 MHz

	Scenario B								
	MIMO UPA					MIMO UCA			
Files/Day/User	1440	1440	1440	1440		1440	1440	1440	1440
Users	4000	4000	4000	4000		4000	4000	4000	4000
File Size	4 MB	4 MB	4 MB	4 MB		4 MB	4 MB	4 MB	4 MB
Selection	RSRQ & Load	RSRQ & Load	RSRQ & Load	RSRQ & Load		RSRQ & Load	RSRQ & Load	RSRQ & Load	RSRQ & Load
Number CCs	1	2	3	4		1	2	3	4
Per Macro MHz	100 MHz	100 MHz	100 MHz	100 MHz		100 MHz	100 MHz	100 MHz	100 MHz

Figure 2-21 (a) and (b) illustrates the impact of MIMO to component carrier management TeC. Specifically, it is shown that as more CCs are utilized, the downlink throughput increases. This is compared with component carrier management without MIMO. Throughput with the usage of MIMO tends to be around 20-30% higher compared to the baseline.

(a)



(b)

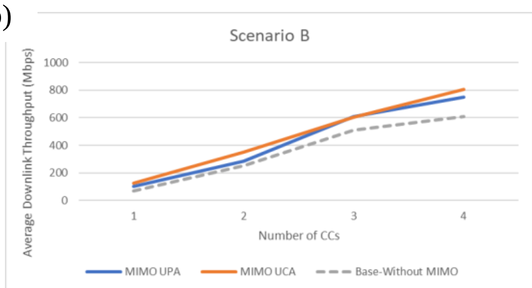


Figure 2-21: Average downlink throughput of different scenarios A & B compared with the baseline (without taking into account the impact of MIMO).

2.9 IMT-2020 Study: Evaluation of connection density through system-level simulations

This subsection presents the simulation work carried out in the framework of IMT-2020 Evaluation Group [ITU2020], involving to conform to ITU requirements. The "Connection density" KPI assessment was assigned to ONE5G. This work also shows that the system-level simulator developed has been exploited outside of the project as well.

2.9.1 Evaluation methodology

In mMTC environments, one of the important parameters is the connection density of devices. According to ITU document [ITU] the connection density is the total number of devices fulfilling a specific quality of service (QoS) per unit area (per km^2). Connection density should be achieved for a limited bandwidth and number of connectivity points. The target QoS is dimensioned to support the delivery of a message of a certain size within a certain time and with a certain success probability. This requirement is defined for the purpose of evaluation in the mMTC usage scenario. According to ITU, the minimum requirement for connection density is 1,000,000 devices per km^2.

Also, ITU has defined the following steps, for the evaluation of connection density:

- Step 1: Set system user number per TRxP as N.
- Step 2: Generate the user packet according to the traffic model.
- Step 3: Run non-full buffer system-level simulation to obtain the packet outage rate. The outage rate is defined as the ratio of the number of packets that failed to be delivered to the destination receiver within a transmission delay of less than or equal to 10s to the total number of packets generated in Step 2.
- Step 4: Change the value of N and repeat Step 2-3 to obtain the system user number per TRxP N′ satisfying the packet outage rate of 1%.
- Step 5: Calculate connection density by equation C = N' / A, where the TRxP area A is calculated as A = ISD2 × $\sqrt{3}/6$, where ISD is the inter-site distance.
- The requirement is fulfilled if the connection density C is greater than or equal to 1,000,000. The simulation bandwidth used to fulfill the requirement should be reported.

The considered traffic model for such an evaluation is message size of 32 bytes with either 1 message/day/device or 1 message/2 hours/device. Packet arrival follows Poisson arrival process for non-full buffer system-level simulation.

2.9.2 Simulation results

System-level simulations have been conducted for the evaluation of connection density in mMTC environments. Narrowband parameters are taken into account in the simulation. As such, considered bandwidth is from 180 kHz up to 1.08 MHz. The success rate (i.e. successful transmission of messages) is calculated in order to check the acceptable level of connection density for meeting the threshold of 99% of success (1% of loss). During the evaluation process, the lower number of considered message generation frequency (e.g. 1 message/day/device) fulfills the requirements of the connection density. The results showed that the 99^{th} percentile of the delay per user was less than 10s for both the 180 kHz and 1.08 MHz tests. Two configurations for ISD of 500m and 1732m were examined during the evaluation. As a result, the focus was given on the investigation and analysis of the higher frequency of messages with the frequency of 1 message/2 hours/device which had a different behavior than the previous.

Figure 2-22 shows the success rate for different number of devices when bandwidth of 180 kHz is considered. According to the results, it is evident that with such bandwidth, around 2 million devices per km^2 assuming messages of 32 bytes and 1 message/2 hours/device can be served. When 3 million devices per km^2 were simulated, the success rate dropped below 99%.

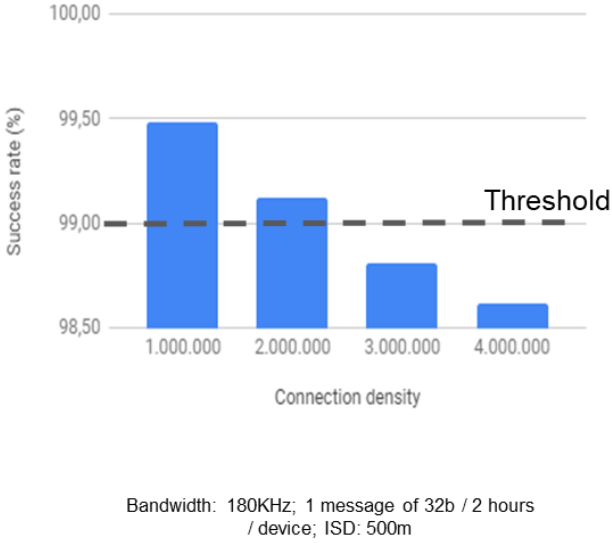


Figure 2-22: Connection density success rate for different number of devices per km^2.

Figure 2-23 shows required bandwidth to serve 1 million devices with 1 message of 32 bytes/2 hours/device as we have seen in Figure 2-22, but this time by examining at which level the success rate will reach the highest level. The results show that even from 180 kHz, the success rate of 99% is fulfilled and as the bandwidth increases, the success rate is even higher, reaching almost the 100% at 720 kHz.

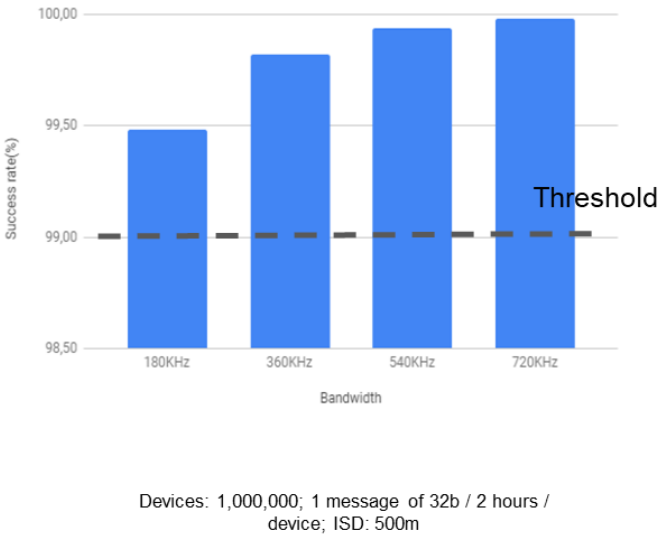


Figure 2-23: Success rate depending on bandwidth (ISD 500m).

As the next step we change the simulation parameters to higher ISD value of 1732m and run the same evaluation process as before. Figure 2-24 shows the success rate for different numbers of devices when bandwidth of 1.08 MHz is used. According to the results, it is evident that with such bandwidth, up to 40 million devices per km^2 can be supported in the area assuming messages of 32 bytes and 1 message/2 hours/device.

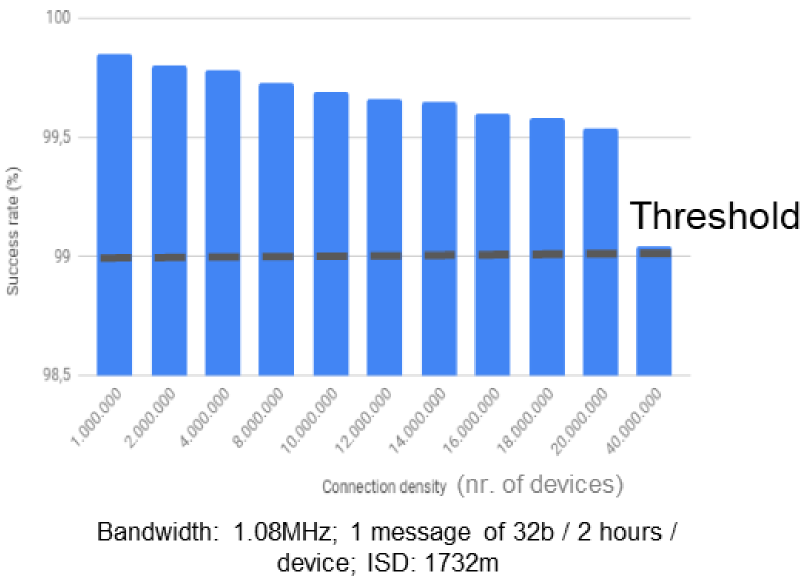


Figure 2-24: Connection density success rate for different number of devices per km^2

Figure 2-25 shows the required bandwidth to serve 1 million devices with 1 message of 32 bytes/2 hours/device. The results show that from 540 kHz and above, the success rate of 99% is met. However, with smaller bandwidths (e.g., between 180 and 360 kHz) the success rate is slightly less than 99%.

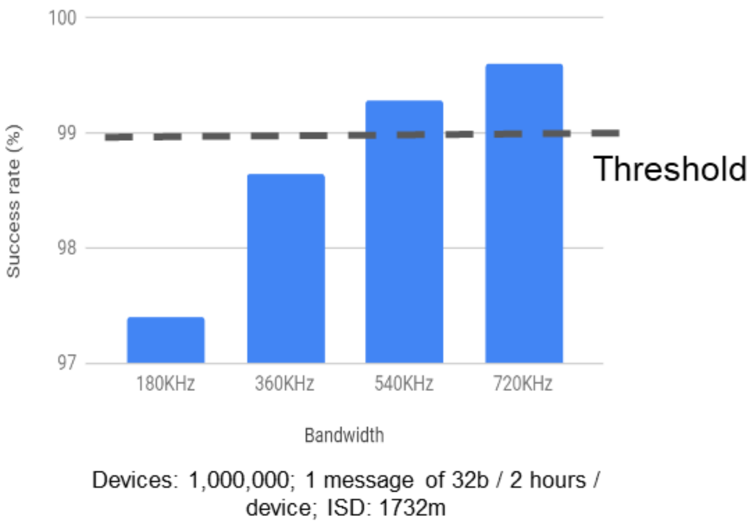


Figure 2-25: Success rate depending on bandwidth (ISD 1732m)

2.9.3 Summary

Connection density is an important metric in mMTC environments. Also, the usage of narrowband technologies is encouraged, especially for small and frequent transmissions. As a result, the provided evaluations take into account these assumptions in order to show how many devices can be supported with a specific QoS. In case of 180 kHz bandwidth and an ISD of 500m, the target was met for a message density of 1 message (32 bytes)/2 hours/device is considered. Additionally, the results for ISD of 1732m reveal that there is a need for higher bandwidths to meet the proposed success rates (99%), which in many cases requires more than three times of the initial bandwidth. Also, the results are consistent with the results of vendors (such as Huawei and Ericsson) [3GPP-WS] who followed the same evaluation process, utilizing the same parameters at their proprietary simulator. For the bandwidth of 1.08MHz the evaluation process showed that it is possible to handle effectively more than 1 million devices per km^2.

2.10 High-level benefits of technical components

This subsection summarizes the high-level benefits for the six aforementioned technical components in Sections 2.2 to 2.7 of this document.

For the first technical component, the main benefit is the improved performance compared to traditional schedulers in terms of aggregated throughput as the proposed algorithm handles more efficiently undesired interferences.

Regarding the second technical component, it is shown that as the number of component carriers increases, the throughput increases proportionally, and the delay decreases.

The third technical component targets the QoE optimization for the services provided under eMBB in 5G by defining and evaluating a figure of merit.

Regarding the fourth technical component on massive MIMO, the main benefit from such an approach is the increased user spectral efficiency. The user spectral efficiency from the PHY layer MIMO simulation can also include the case that users have multiple antennas and maybe receive multiple data streams. With spectral efficiency of the active users, the sum spectral efficiency for the given time-frequency resource is obtained in the system level simulation for the given MIMO technology component.

Regarding the fifth technical component on enhanced HARQ, it is shown that under the scheme K-rep (e.g., K=2, 3, 4 repetitions), we achieve lower latency.

Finally, regarding the sixth technical component on optimized functionality placement, it is shown that in contrast to the fixed functional split provided by the CRAN and DRAN architectures, a flexible split to choose an optimal operating point between full centralization and local execution adapts network characteristics as well as current service requirements. According to available results, the system adjusts to traffic load and QoS requirements leading to a lower value of cost function. Therefore, the combination of energy consumption, computational, and data latency with their respective weights is improved, while the applied constraints are ensured under varying circumstances.

These system simulations have therefore illustrated that a sample of the TeCs developed within the project allow to improve the performance with respect to several distinct KPIs.

3 Techno-economic quantitative analyses

The techno-economic studies address four selected use cases, namely Automotive, Smart city IoT, long range connectivity and Drone based communications for emergency services. The rationale for selecting these use cases and the qualitative techno-economic analyses are provided in Deliverable D2.2 [ONE18-D22]. Stated briefly, the four use cases represent emerging vertical areas and also give a good balance of the Megacities and Under-served areas highlighted in the ONE5G project scope. The qualitative studies in D2.2 defined the scope of the analysis for each use case and also identified main parameters that will be analyzed in the subsequent quantitative study. In this chapter, we present the thus developed quantitative analyses.

3.1 Methodologies and common aspects for the quantitative study

The four use cases stated above address different service classes, which also require some tailor-made, distinct network deployments. It is challenging to develop a common framework for the studies under this context. However, we have endeavored to have some common aspects and methodologies in the studies, such that some comparisons between these different deployments become possible. We note these commonalities below:

- We utilize 3GPP Release 15 5G-NR as a baseline network in all the use cases. Some of the use cases rely on service provision into areas which are currently not served by 5G-NR. In these cases, we assume an LTE-Advanced baseline as the existing network.
- We have assumed common network centralization (CRAN) options in UC1, UC4 and UC9 as per the 3GPP specified centralization options [3GPP-38.901]. We specifically look at CRAN options 2 and 7, which offer contrasting outcomes in terms of the cost/complexity of the RRH units and the required fronthaul capacities.
- As a part of the centralization mechanism, fronthaul and backhaul cost dimensioning becomes necessary. We utilize common reference models from the D1.4 of the previous mmMAGIC project [mmM17-D14]. This again makes certain aspects of the studies comparable across the use cases.
- We also consider the 5G feature of network slicing to be prevalent in delivering these solutions. With the CRAN options, we assume these specific networks connect to an overall core network, which can be sliced to provide the specific latency, reliability and data rate requirements in the core. Although the cost dimensioning aspects in the studies fundamentally address the RAN, this slicing assumption is important to visualize the overall end-to end service provisions.
- The use case studies have made a concerted effort to address the Underserved Areas scenario. Specifically Use Case 4 is focused on extending mobile broadband coverage to rural and far remote areas. Use Case 1 has a component for rural coverage as the V2X services are envisaged to be provided throughout motorways. The current focus of Use Case 9 is in an urban city-wide deployment, but the developed concepts can be easily adapted to provide cost analysis for drone networks extending the coverage to adjacent underserved areas.

With these common aspects in place, we are able to make some meaningful comparisons of the cost trends across the use cases in Section 3.6.

3.2 Analysis for the Automotive use case

This section presents the techno-economic and business analysis carried out for the Automotive use case, being focused on three main services:

- Service #1: assisted driving aided by roadside infrastructure.
- Service #2: cooperative driving between nearby vehicles.
- Service #3: tele-operated driving.

These services pose stringent requirements on the network in terms of availability, reliability and latency, as it was detailed in [ONE17-D21] and [ONE18-D22]. Thus, they will require the presence of additional network nodes that assist the network to fulfil these requirements, such as multi-access edge computing (MEC) and slicing features at the network to deliver the specific KPI's of these services.

3.2.1 UC1 deployment considerations

In this section we analyse the deployment of the MEC between the core and radio access network with the aim of reducing latency for V2X services, incorporating processing capacity and intelligence at the edge of the mobile network. The location of the MEC server depends mainly on the considered topology. Three different topologies [3GPP 38-801] have been considered for this techno-economic analysis with 3GPP Release 15 as the underlying technology:

- **DRAN architecture:** the processing is done at the site. The MEC server is located somewhere in the backhaul network aggregating a number of sectors.
- **CRAN split 7 architecture:** the PHY layer processing is done at the site, whereas the rest of the layers are executed at the CU. MEC server is co-located with the CU at the central office.
- **CRAN split 2 architecture:** all the processing tasks are done at the site except PDCP layer that is executed at the CU. MEC server is co-located with the CU at the central office.

Two different scenarios have been considered for this analysis so as to be in line with the goal of this project: Megacities and Underserved Areas (rural) scenarios, where V2X services are available but the deployment considerations are different due to the network density. For both scenarios, different conditions have been defined.

The following table shows the main parameters that have been taken into account for each scenario.

Table 3-1: Scenario Parameters

	Megacities	Rural areas
Modulation order	64 QAM, 256 QAM	64 QAM
Bandwidth	10 MHz	5 MHz, 10 MHz
MIMO	2x2, 4x4	1x1, 2x2
Number of sectors	15, 20, 25, 30	5, 10, 15

The number of sectors that have been considered for the rural scenario are lower than for megacities, due to the low density of users per km^2. In addition, the MIMO and modulation schemes of different order that have been considered for compiling the results are lower in rural areas since high traffic demands, which are only expected in megacity environments.

3.2.2 UC1 quantitative assessments

Megacities scenario

Considering the above considerations, we have first studied the impact of MEC implementation in terms of CAPEX and OPEX over 1 and 5 years, for the different possible configurations CRAN Split 2, 7 and purely distributed scenario (DRAN). To this end, we have taken as reference the fronthaul and backhaul cost models from mmMAGIC project detailed in D1.4 [mmM17-D14], where we have considered the "owned lines" model. In addition, the fronthaul and backhaul deployments model the investment to be as a green field, assuming it would be used only for the services depicted at the beginning of this section. Thus, the network dimensioning is aligned with UC1 in which the typical payload values can vary from 60 to 1500 bytes. Therefore, data rate required for each user depends on the service: from 5 kbps up to 1.3 Mbps for assisted driving and cooperative driving, and 10 Mbps for tele-operated driving.

As it was expected from the qualitative analysis done in D2.2 [ONE18-D22], for the three deployments (DRAN and both splits CRAN) the CAPEX and OPEX (per site) decrease proportionally with the number of sectors that are aggregated by one MEC node as it is shown in Figure 3-1. The CAPEX value does not depend on the capacity of the fronthaul and backhaul networks; therefore, it is independent of MIMO and modulation orders (Figure 3-3).

The best option in terms of CAPEX is the CRAN split 7, as can be seen in Figure 3-1. By using this architecture it is not necessary to deploy any specific equipment at the site (only for the PHY layer) and the capital needed to invest is reduced by the use of general purpose hardware in the CU. This results in saving of capital investment up to 44% compared to classical DRAN.

Regarding the OPEX, it highly depends on the capacity of the backhaul and fronthaul networks due to the increase of the fiber costs. MIMO and modulation orders directly affect the required capacity of the fronthaul (CRAN) and backhaul (CRAN, DRAN) networks. Fronthaul cost appears only in CRAN architectures, as it is needed to connect DU and CU. Thus, the derived cost of this connection is greater in the case of CRAN split 7, as sufficient fronthaul capacity is required to support IQ samples as shown in Figure 3-2.

Although apparently it can be thought that CRAN deployments will result in extra cost due to high OPEX, the truth is that CRAN scenarios are more attractive as they reduce the amount of equipment that is needed to deploy at the site. This will undoubtedly reduce the leased cost in rooftops. Nonetheless, for this study these costs have not been considered as it highly depends on the country, regulator, and agreements between operators and government.

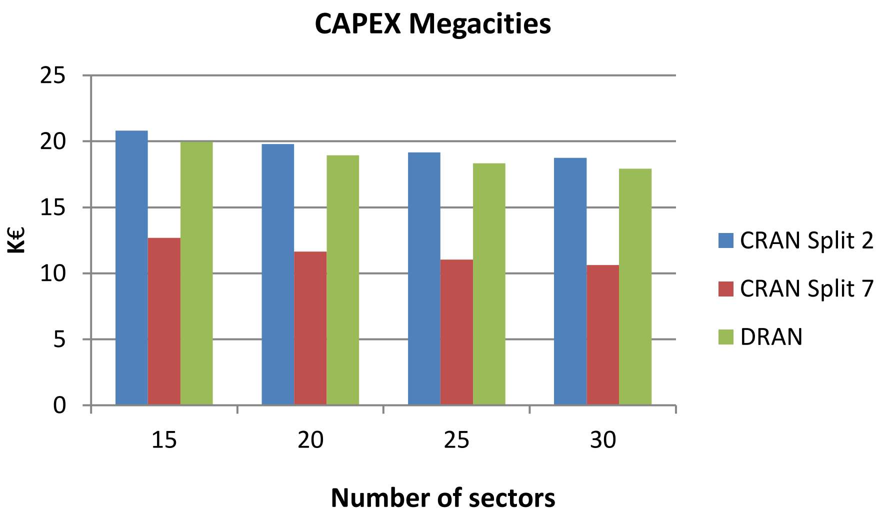


Figure 3-1: CAPEX for megacities (UC1)

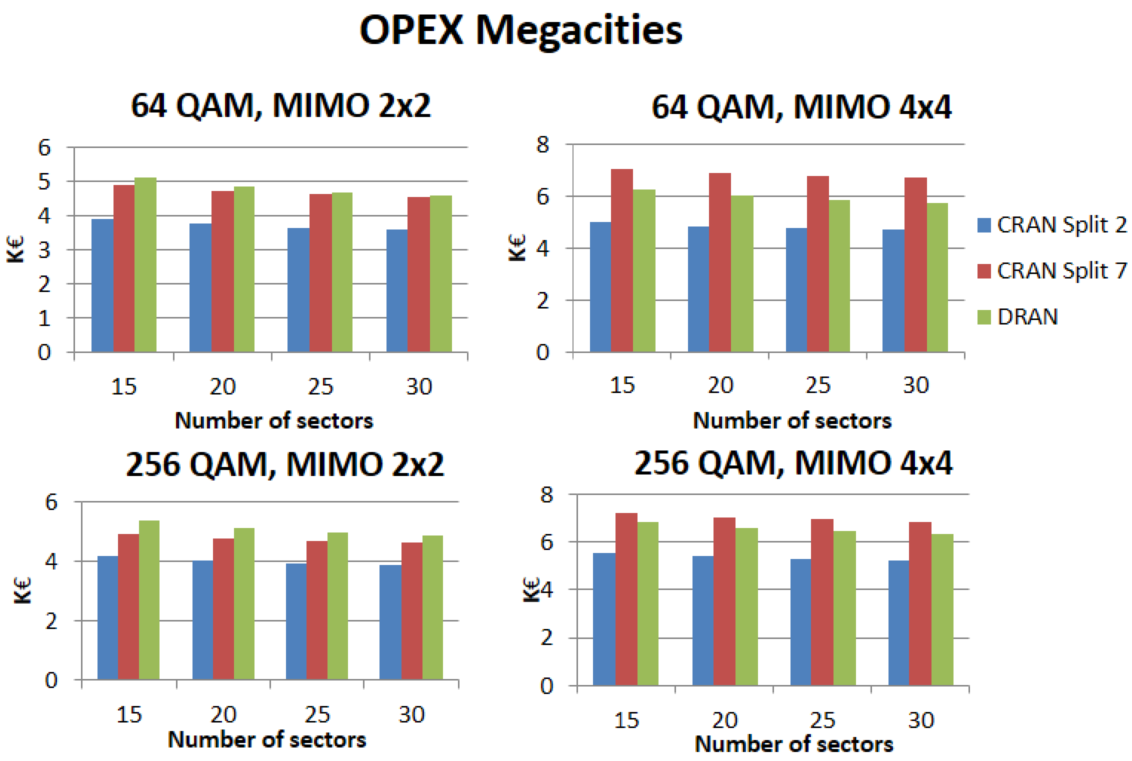


Figure 3-2: OPEX for megacities (UC1)

From Figure 3-2, we can observe that increasing the modulation order (64 QAM to 256 QAM) increases the OPEX from 300 to500 € and increasing the number of antennas results in an increment of around 1000-1300 € in OPEX.

Figure 3-3 illustrates the total cost of ownership (TCO) for different configurations of MIMO and modulation orders stated in Table 3-1, for a given number of sectors, e.g., 20 sectors. From Figure 3-3, it can be seen that most cost-effective solution is CRAN split 7, although the OPEX of this solution is slightly higher than for a traditional deployment (D-RAN) due to increase of fronthaul capacity.

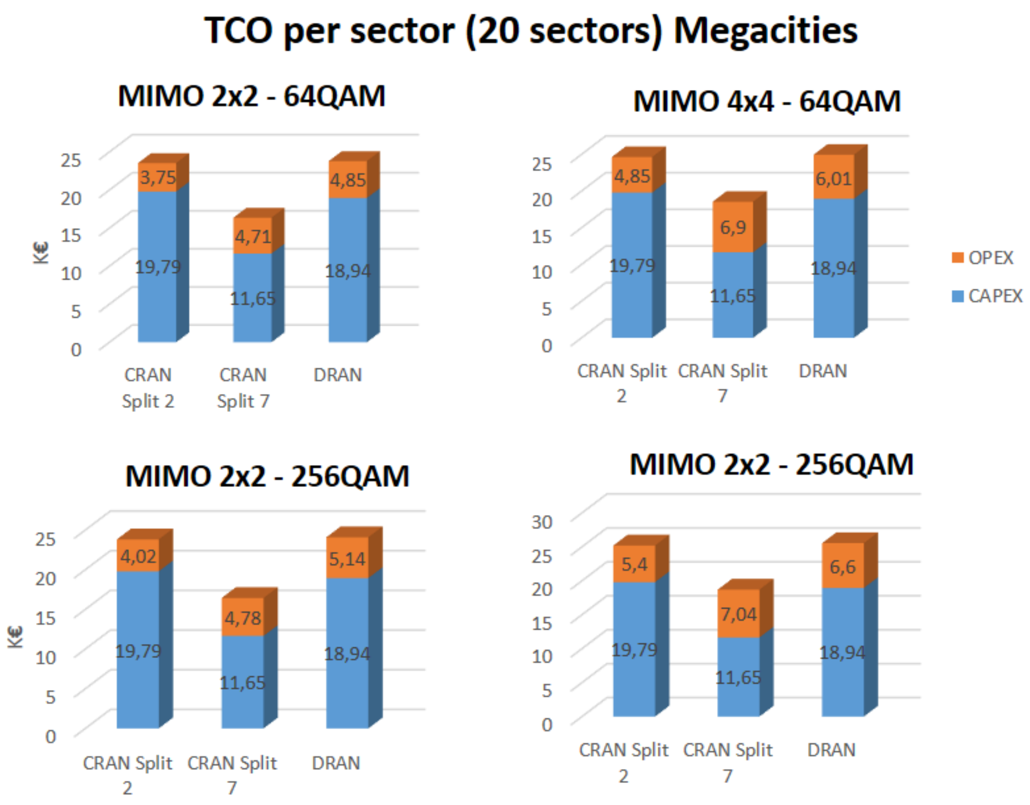


Figure 3-3: TCO per sector for megacities (UC1)

Rural scenario

For the rural scenario case, we have considered a smaller number of sectors and a lower bandwidth and MIMO orders as compared to the megacities scenario, since in this case it is not foreseen to have high traffic demands.

Results obtained from the analysis show the same behaviour for the CAPEX as in megacities scenarios where it decreases with the number of sectors. The best option remains CRAN split 7 as it needs to deploy less specific equipment at the site (general purpose hardware), allowing to save up to 40% of total CAPEX as shown in Figure 3-4.

As stated earlier, OPEX depends mainly on the deployed technology since it directly impacts fronthaul and backhaul capacities and, in turn, operational cost. Thus, equipping the site with most advanced radio features will shoot up the OPEX. In this scenario, the number of antennas and channel bandwidth are lower than for megacities, hence, there is not a significant difference between the two different split options considered for CRAN scenario, as it can be observed from Figure 3-5.

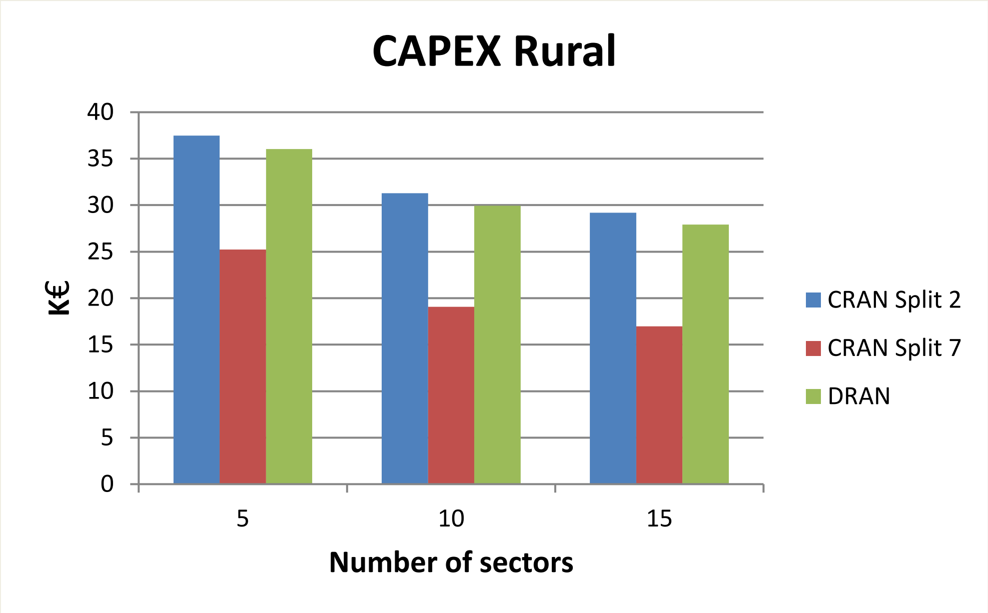


Figure 3-4: CAPEX for rural (UC1)

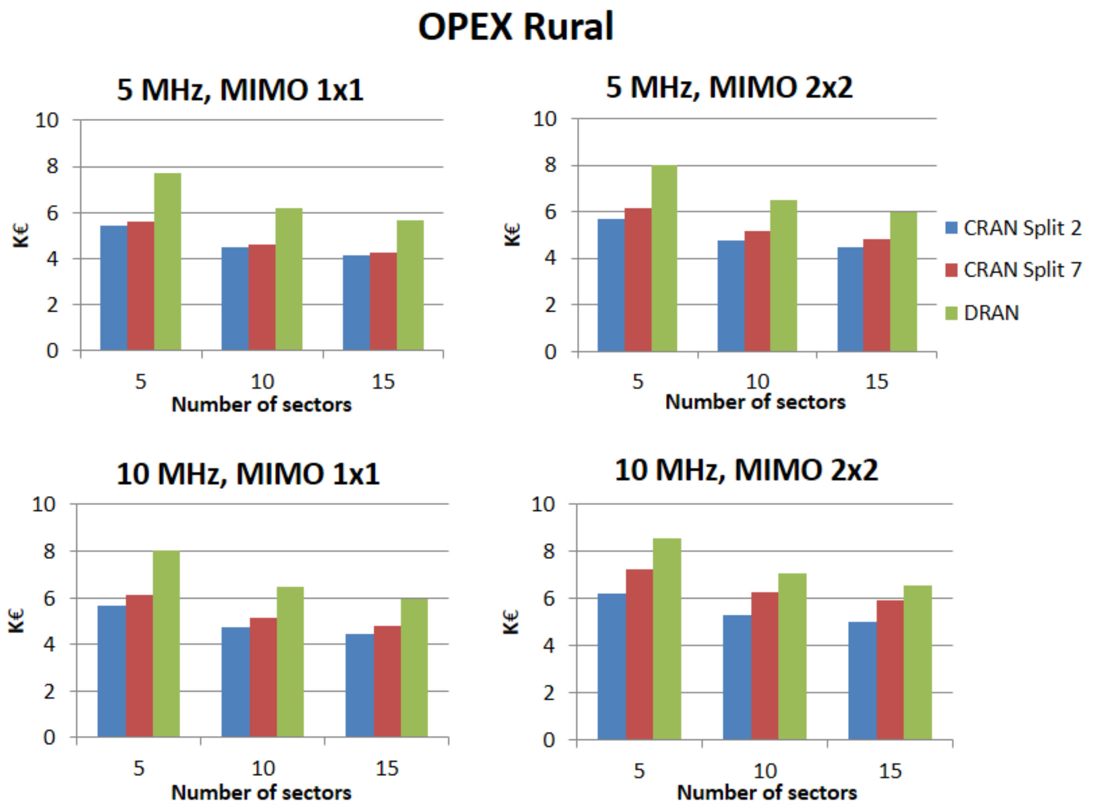


Figure 3-5: OPEX for rural (UC1)

Lastly, we have obtained the TCO for all the different combinations of MIMO order and bandwidth stated in Table 3-1, for a given number of sectors, e.g. 5 sectors, as it is illustrated in Figure 3-6. It can be noticed that, as before, CRAN Split 7 is the most cost-effective solution in all the situations considered, mainly due to lower investment needed in deployment.

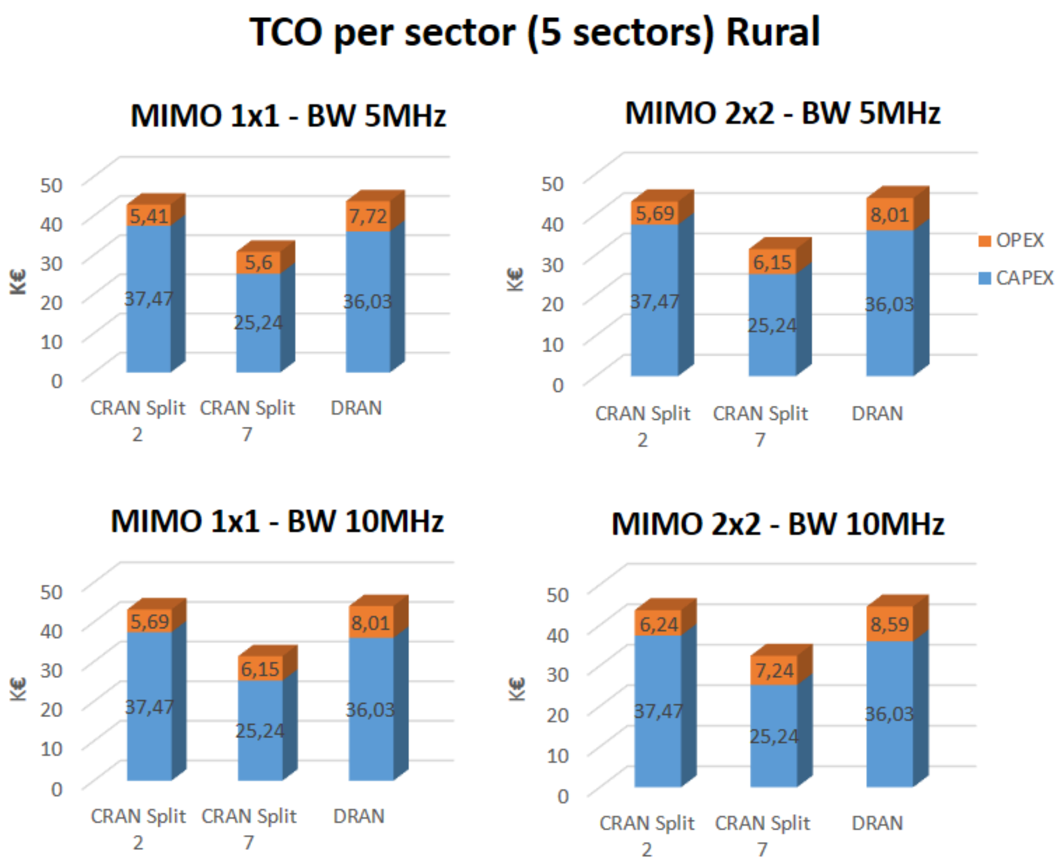


Figure 3-6: TCO per sector for rural (UC1)

Conclusions

From the above results we can draw the following conclusions:

- The CAPEX directly depends on the number of sectors that are aggregated by one MEC in a central office. CRAN split 7 deployment presents the lowest CAPEX as it mainly relies on the use of general purpose hardware at the central office instead of using dedicated hardware. However, CAPEX derived from CRAN split option 2 configuration is slightly higher than DRAN traditional deployments. This is because an extra unit (CU) has to be deployed with the general purpose hardware used in CRAN. This results in increasing the CAPEX, despite the benefits of centralization of CRAN.
- A CRAN low-layer split deployment presents higher OPEX than a high-layer split deployment, due to the required extra capacity at the fronthaul network that is required in split option 7. Nonetheless, the most cost effective topology is CRAN split 7 due to the notable CAPEX reduction at the expenses to shorten the distance between CU and DU to meet the strict latency requirements (e.g. tens of kms).

- Comparing the results from rural scenarios and megacities it can be observed that the TCO for rural scenario is higher than for megacities. The OPEX cost is lower for rural scenarios, since these scenarios do not need a high capacity at the fronthaul and backhaul networks. However, the number of sectors aggregated per CU is lower for rural scenario, therefore, the capital invested is significantly higher and results in higher total cost per sector for rural scenarios.
    - The fronthaul capacity required in rural scenarios is lower than in megacities due to the deployment of less technology capabilities (number of antennas, modulation order) and the lower number of connected users in such scenarios, as shown in Table 3-2 and Table 3-3.

Table 3-2: Capacity per sector (Mbps) for Megacities.

		CRAN Split 2		CRAN Split 7		DRAN	
Modulation	**MIMO order**	Fronthaul	Backhaul	Fronthaul	Backhaul	Fronthaul	Backhaul
64QAM	**2x2**	132	110	459	110	0	125
	4x4	264	220	918	220	0	250
256QAM	**2x2**	165	138	430	138	0	156
	4x4	330	275	860	275	0	313

Table 3-3: Capacity per sector (Mbps) for Rural.

		CRAN Split 2		CRAN Split 7		DRAN	
BW	**MIMO order**	Fronthaul	Backhaul	Fronthaul	Backhaul	Fronthaul	Backhaul
5 MHz	**1x1**	33	28	115	28	0	31
	2x2	66	55	229	55	0	63
10 MHz	**1x1**	66	55	229	55	0	63
	2x2	132	110	459	110	0	125

3.3 Analysis for the Smart City mMTC use case

The Smart City mMTC use case focuses on the use of massive Machine Type Communication (mMTC) in smart cities. The applications are numerous, from traffic management, waste collection and management, parking detection and information, to air monitoring. They are characterized by small payloads and light constraints on latency.

3.3.1 Quantitative techno-economic analysis approach

3GPP considers that NB-IoT and LTE-M are part of 5G and sufficient to provide Low Power Wide Area (LPWA) usages in Rel.16 [GSMA18]. The two technologies will evolve as to satisfy the 5G requirements for mMTC applications. NR mMTC might be needed in future releases for new usages (requiring higher throughputs or that are more latency constrained).

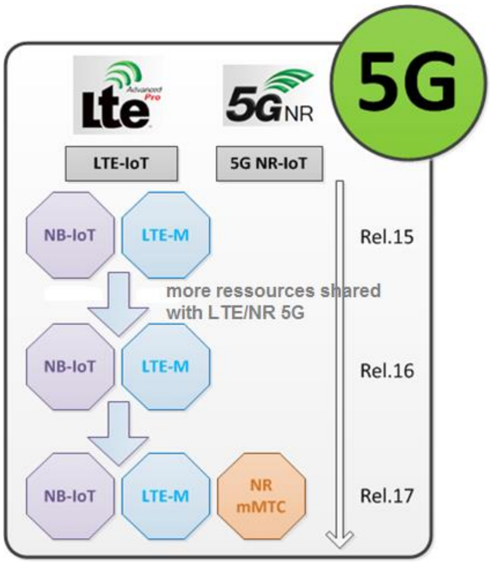


Figure 3-7: Illustration of the approach for the quantitative techno-economic analysis for the Smart city mMTC use case

For the techno-economic analysis of the Smart city mMTC use case, we considered that both NB-IoT and LTE-M will be present as a start in Rel. 15. The techno-economic study for the Smart city use case targeted the evaluation of Rel.15 to Rel.16 new costs (see Figure 3-7). NB-IoT and LTE-M will evolve within Rel. 16 and will still be sufficient to manage mMTC applications. Therefore, the quantitative techno-economic analysis considers that LTE-M and NB-IoT will use the 5G available bandwidth for eMBB applications and URLLC applications. Indeed, most of the MNOs started to deploy In-Band LTE-M and NB-IoT. Hence, we consider the In-Band deployment of LTE-M on one side and NB-IoT on the other side and we evaluate the following two open questions: how many additional resources would be necessary between Rel. 15 and Rel. 16 to satisfy the number of devices envisioned for the Smart city use case, and what it means in terms of cost.

For that purpose performance studies carried out for 3GPP by Ericsson were considered (see Section 3.3.2) to estimate the resources that will be needed in Rel. 15 and Rel. 16 for the number of envisioned devices. To evaluate the numbers of devices envisioned for the smart city use case at the time of Rel.15 and Rel.16 deployments, we extrapolate the numbers for Paris city for the year 2020 and year 2030 (see Section 3.3.3).

3.3.2 LTE-M and NB-IoT performances

In order to evaluate the number of additional resources (in terms of Physical Resource Blocks (PRBs)) required for LTE-M and NB-IoT from Rel.15 to Rel.16, we used simulations performed by 3GPP for both technologies from [R1-1809780].

In order to see whether LTE-M and NB-IoT would meet the 5G requirements in term of density connection (1 million devices/km^2), Ericsson carried out non-full buffer system simulations. The urban macro test environment is described in Table 3-4 (extracted from [R1-1809780]), with two different configurations: Configuration A considering an ISD of 500 m for very dense urban area and Configuration B considering an ISD of 1732 m. Other simulation parameters can be found in

Table 3 of [R1-1809780]. Ericsson carried out these simulations using the following traffic model: devices were considered to emit one message every 2 hours. In order to evaluate the performances in terms of density connection a QoS of 99% was considered. Ericsson evaluated the number of supported devices per PRB or narrowband (NB) with a targeted QoS of 99%. Results are shown in Table 3-5 for the two different configurations (conf A and conf B whose parameters are detailed in Table 3-4 and two different channel models, A and B [R1-1809780]. Channel model A contains aggressive assumptions for the indoor to outdoor loss.

Table 3-4: Urban macro test environment for mMTC

Parameters	**Configuration A**	**Configuration B**
Carrier frequency for evaluation	700 MHz	700 MHz
BS antenna height	25 m	25 m
Total transmit power per TRxP	46 dBm for 10 MHz bandwidth	46 dBm for 10 MHz bandwidth
UE power class	23 dBm	23 dBm
Percentage of high loss and low loss building type	20% high loss, 80% low loss Note: Applies only to Channel model B.	20% high loss, 80% low loss Note: Applies only to Channel model B.
Inter-site distance	500 m	1732 m
Number of antenna elements per TRxP	Up to 64 Tx/Rx	Up to 64 Tx/Rx
Number of UE antenna elements	Up to 2 Tx Up to 2 Rx	Up to 2 Tx Up to 2 Rx
Device deployment	80% indoor, 20% outdoor Note: Randomly and uniformly distributed over the area	80% indoor, 20% outdoor Note: Randomly and uniformly distributed over the area
UE mobility model	Fixed and identical speed |v| of all UEs of the same mobility class, randomly and uniformly distributed direction.	Fixed and identical speed |v| of all UEs of the same mobility class, randomly and uniformly distributed direction.
UE speeds of interest	3 km/h for indoor and outdoor Note: Corresponds to 2 Hz Doppler	3 km/h for indoor and outdoor Note: Corresponds to 2 Hz Doppler
Inter-site interference modeling	Explicitly modelled	Explicitly modelled
BS noise figure	5 dB	5 dB
UE noise figure	7 dB	7 dB
BS antenna element gain	8 dBi	8 dBi
UE antenna element gain	0 dBi	0 dBi
Thermal noise level	-174 dBm/Hz	-174 dBm/Hz
Traffic model	With layer 2 PDU(Protocol Data Unit) message size of 32 bytes: 1 message/day/device or 1 message/2 hours/device	With layer 2 PDU(Protocol Data Unit) message size of 32 bytes: 1 message/day/device or 1 message/2 hours/device Note: Only 1 message/2 hours/device studied herein.

	Note: Only 1 message/2 hours/device studied herein.	
Simulation bandwidth	Up to 10 MHz	Up to 50 MHz
UE antenna height	1.5 m	1.5 m

Table 3-5: LTE-M and NB-IoT performance metrics

	Connection density @ 99 percent QoS [devices/NB or PRB]	Bandwidth to support 1 000 000 devices per km2 [NB or PRB]	Connection efficiency [devices/Hz]	Spectral efficiency [bits/s/Hz]
LTE-M: Channel model A, Conf A	5.680.683 devices/NB	1 NB	5.26 devices/Hz	0.19 bits/s/Hz
LTE-M: Channel model B, Conf A	5.680.683 devices/NB	1 NB	5.26 devices/Hz	0.19 bits/s/Hz
LTE-M: Channel model A, Conf B	342.218 devices /NB	3 NB	0.32 devices/Hz	0.01 bits/s/Hz
LTE-M: Channel model B, Conf B	444.983 devices /NB	3 NB	0.41 devices/Hz	0.01 bits/s/Hz
NB-IoT: Channel model A, Conf A	1.233.109 devices /1 PRB	1 PRBs	6.85 devices/Hz	0.24 bits/s/Hz
NB-IoT: Channel model B, Conf A	1.225.128 devices/1 PRB	1 PRBs	6.81 devices/Hz	0.24 bits/s/Hz
NB-IoT: Channel model A, Conf B	67.928 devices/1 PRB	15 PRBs	0.38 devices/Hz	0.01 bits/s/Hz
NB-IoT: Channel model B, Conf B	94.035 devices/1 PRB	11 PRBs	0.52 devices/Hz	0.02 bits/s/Hz

To summarize, in case of NB-IoT one PRB must be dedicated to the uplink traffic. Depending on this traffic more resources can be allocated: 1 to 15 PRBs would be necessary to fulfil the 5G mMTC requirements, depending on the considered ISD and channel model.

For LTE-M, 6 PRBs are allocated for DL control channels. Then, if there is uplink traffic, there are no allocated uplink resources. And as soon as there is some uplink traffic one LTE-M NB is allocated. More NBs can be allocated in parallel in case of higher traffic load, with the appropriate scheduling of MTC devices (1 to 3 NBs would be necessary to fulfil the 5G mMTC requirements, depending on the considered ISD and channel model).

3.3.3 mMTC use cases in a dense urban city in 2020 and 2030

A study was carried out in order to identify the main Smart city applications and evaluate for each identified application the number of devices per home / person / company, the traffic frequency and the average payload. These numbers were scaled to Paris city for year 2020 and extrapolated for year 2030. The identified applications are: smart metering, smart parking, home applications (fire alarm, security alarm, home appliances), city automation applications (street lightning, urban sensors, waste management, bike renting), personal asset tracking, car monitoring, mail and parcel tracking and supply chain management.

Paris was taken as an example for dense urban area and key numbers were extracted, provided by Institut National de la Statistique et des Etudes Economiques (INSEE) (see Table 3-6. Then the numbers were scaled to Paris in 2030 (see Table 3-7). Then, for each identified application, number of envisioned devices and quantity of traffic were derived for 2020 and 2030 (see Table Annex-1 and Table Annex-2 in the Annex).

Table 3-6: Key numbers for Paris in 2018

Paris population						
City Size (km²)	Number of Inhabitants	Number of Companies or Offices	Number of Households	Ratio of flats with central heater	Number of Buildings	Total of premises
105,4	2 250 000	281 338	1 357 000	40%	67 700	1 638 000

Paris Public Space				Mobile network in Paris			Mail and logistic	
Number of public parking places	Number of private parking places	Number of rental bikes	Number of streetlights per km²	Number of tri-sector antennas (GSM900)	Cell area (km²)	ISD (km)	Number of delivery points	Express mail
310 000	510 000	25000	1 900	122	0,29	1	80000	500 000

Table 3-7: Key numbers scaled to Paris 2030

Paris population					
City Size (km²)	Number of Inhabitants	Number of Companies or Offices	Number of Households	Ratio of flats with central heater	Total of premises
105,4	2 500 000	576 000	1 497 000	40%	2 073 000

Paris Public Space				Mobile network in Paris			Mail and logistic	
Number of public parking places	Number of private parking places	Number of rental bikes	Number of streetlights per km²	Number of tri-sector antennas (GSM900)	Cell area (km²)	ISD (km)	Number of delivery points	Express mail
310 000	560 000	35000	2 100	122	0,29	1	80000	1 080 000

3.3.4 Conclusions

Considering the numbers for Paris 2020 as a basis for Rel. 15 and those for Paris 2030 as a basis for Rel. 16 the analysis has shown that, depending on the deployment settings and the traffic model, up to 6 additional PRBs (one additional narrowband respectively) would be necessary for NB-IoT (LTE-M respectively) between Rel. 15 and Rel. 16 to satisfy the number of devices envisioned for Smart cities applications as illustrated in Figure 3-8 and Figure 3-9.

In terms of bandwidth our study has shown that up to additional 1.08 MHz in the 700 MHz frequency band would be necessary between Rel. 15 and Rel. 16 to satisfy the number of devices envisioned for Smart cities applications. This represents around 5 % of the maximal 20 MHz bandwidth that should be assigned for each 5G network at this frequency band [HUAWEI17]. In fact, 5G mMTC services should be deployed in low frequency bands but also in medium frequency bands (between 2 GHz and 6 GHz) for which the recommendations are to assign at least 100 MHz contiguous bandwidth [HUAWEI17].

We can finally stress that, for dense urban areas with a dense deployment of gNodeB (ISD of 500 m), we have shown that no additional resources would be needed between Rel. 15 and Rel. 16.

In terms of cost, a software upgrade might be necessary between the two releases, but there are no estimations to accurately quantify this as well as the cost of additional resources that might be needed, depending on the considered configuration. Nevertheless we have shown that these hypothetical additional resources are very reasonable (a maximum of 5% of the available bandwidth) and, considering that the resource allocation for both NB-IoT and LTE-M is very dynamic, the cost of smart cities applications over eMBB and URLLC applications should not be too high.

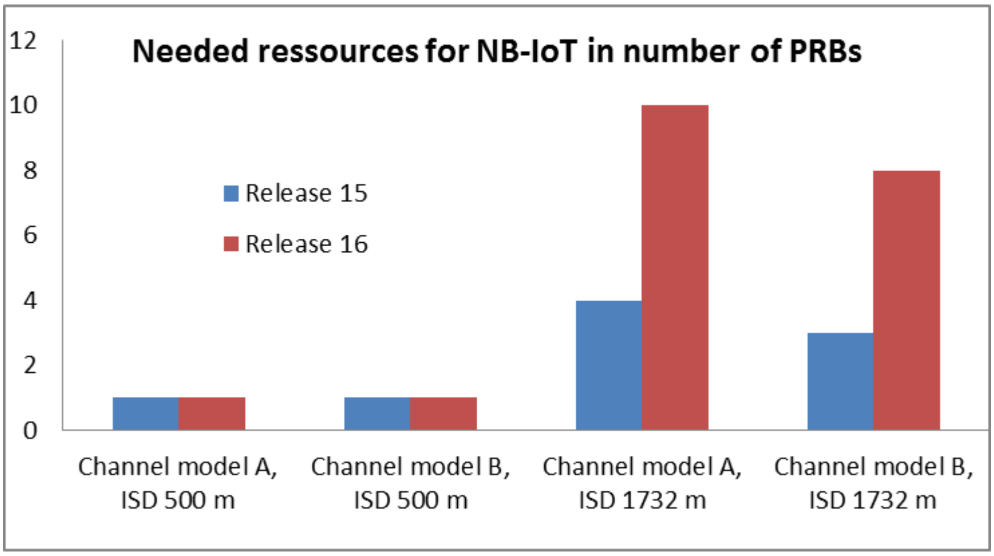


Figure 3-8: Needed resources for NB-IoT to satisfy to the number of devices envisioned for Smart cities applications in Rel. 15 and 16

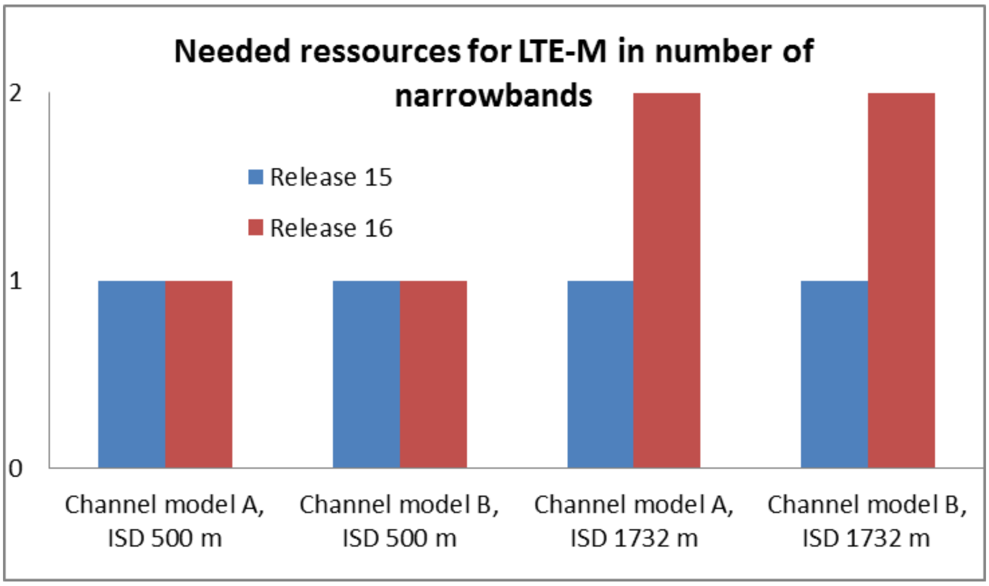


Figure 3-9: Needed resources for LTE-M to satisfy to the number of devices envisioned for Smart cities applications in Rel. 15 and 16

3.4 Analysis for the Long Range Connectivity use case

This section analyzes the Long Range Connectivity use case in remote areas, a use case dedicated to underserved areas, for the provision of minimal voice and data services over long distances in low density areas [ONE17-D21], [ONE18-D22]. The applications targeted are minimal services including voice over long distances plus best effort data services for smartphones, tablets, etc. Radio coverage is the main KPI to tackle when assessing this use case with the provision of service on a maximum coverage of up to 50 km in rural and 100 km or more for ultra-rural. The traffic is lower compared to other use cases more dedicated to Megacities scenario. Nevertheless, minimum uplink and downlink user throughputs are required to allow provision of minimal services. The main KPIs targeted are summarized in Table 3-8.

Table 3-8: Summary of the KPIs targeted by the long range connectivity use case

	Traffic model	User experienced throughput at cell edge	Minimum expected coverage
Far remote area	1,7 users / km²	DL: 2 Mbps UL: 0.256 Mbps	up to 100km or more
Rural areas	33 users / km²	DL: 50 Mbps UL: 25 Mbps	50 km

3.4.1 Extension of the 5G network coverage in far remote and rural areas

A coverage study was performed to evaluate which solution at the base station would permit the provision of service on long range distances in rural (up to 50km) and far remote areas (up to 100km) while considering the UL and DL throughputs mentioned in Table 3-8.

For this purpose, the link budgets of 5G NR uplink Sounding Reference Signal (SRS) PUSCH and PDSCH were calculated. The maximum path losses of PUSCH and PDSCH are respectively determined by the targeted user experienced throughputs at cell edge for uplink and downlink. The minimum value of allowed maximum path losses among three calculations is chosen to calculate the site radius. The site radiuses in far remote areas are so large that the classic propagation model is not any more valid. A modified Hata radio channel model [Hata01] was used at 700 MHz in far remote areas in our study, while at 3.5 GHz in rural areas the 5G propagation model adopted by 3GPP was used [3GPP-38.901].

Long Range solutions in extreme rural environments were assessed in low-band frequencies (700MHz) to benefit from their good propagation characteristics. For rural environment, the ambitious targeted throughput lead to the use of higher carrier frequency (3.5 GHz). Massive MIMO features were considered at 3.5 GHz with the DL: 64x2, UL: 1x64 scheme.From a site configuration perspective, several options were assessed in order to evaluate their impact on the coverage or capacity of the cell to find the best trade-off between site cost and cell radius. In the following some examples of the results obtained are shown.

Increasing antenna height

Different antenna heights were evaluated: 60m, 75m and 108m in both rural and far remote areas. For all the configurations tested, we could notice that increasing the antenna height improves the coverage in both environments (Table 3-9).

Table 3-9: Increase of the coverage when improving the antenna height

		Antenna height increase		
		from 60m to 75m	from 75m to 108m	from 60m to 108m
Environment	rural	+9%	+17%	+25%
	far remote	+9%	+14%	+22%

Nevertheless, the higher the antenna the higher the cost and even if the coverage is improved, the cost per km² in far remote areas is not reduced but stays relatively constant, as shown in Figure 3-10. This is mainly due to the need of using backhaul relay sites when increasing the coverage. This tendency is different in rural environment where the TCO per km² decreases when the antenna height is increased (Figure 3-14 and Figure 3-15). In this case the backhaul is different from the one in far remote areas and does not require relay (and costly) sites.

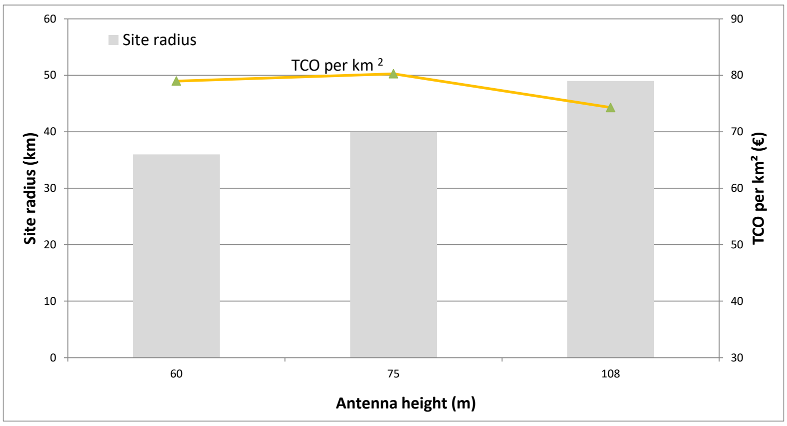


Figure 3-10: Impact of the mast elevation (antenna height) on the coverage and the TCO per km², example in far remote context

Increasing the number of antenna floors (vertically stacked)

The high targeted throughputs in rural areas make the mMIMO in 3.5 GHz the only solution potentially capable of providing such high throughputs. Furthermore, only in 3.5 GHz frequency band, there is enough available frequency bandwidth to eventually achieve such performances. For far remote areas, the need of improved link budget led to using multiple antenna vertically stacked to improve the antenna gain; we then talk about multiple antenna floors. Three options of vertical diversity were thus envisioned, considering either one, two or four floors of antennas.

Results are pictured in Figure 3-11 where it appears that augmenting the number of antenna floors results in a higher vertical antenna gain and thus a better cell coverage while it permits a decrease in the TCO per km² as well.

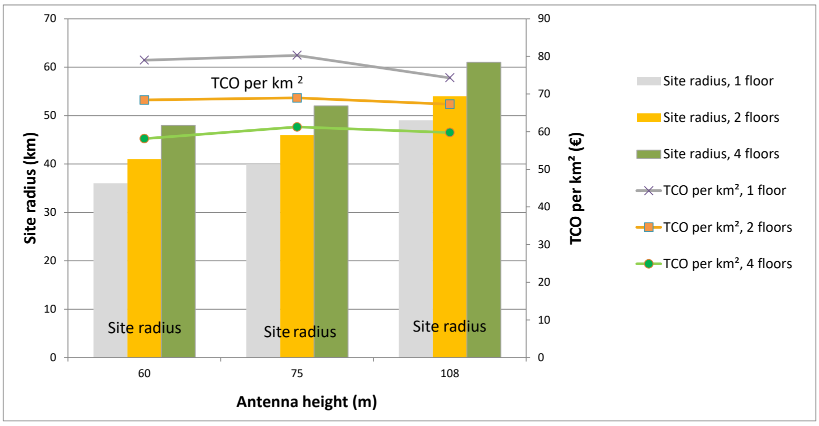


Figure 3-11: Impact of the number of antenna floors on the coverage and the TCO per km²

We observe that increasing the number of antennas permits to improve the coverage. In fact, since the uplink is often the most constrained direction, the increase of antenna numbers necessary for higher MIMO schemes brings reception diversity gain in uplink direction.

For far remote areas, two configurations were studied: DL 2x2 / UL 1x2 and DL 4x2 / UL 1x4. We observed (Figure 3-12) a coverage gain of 15% when applying DL 4x2 / UL 1x4 over DL 2x2 / UL 1x2. In parallel, it permits a reduction of the TCO per km², even though DL 4x2 is an expensive solution compared to MIMO 2x2.

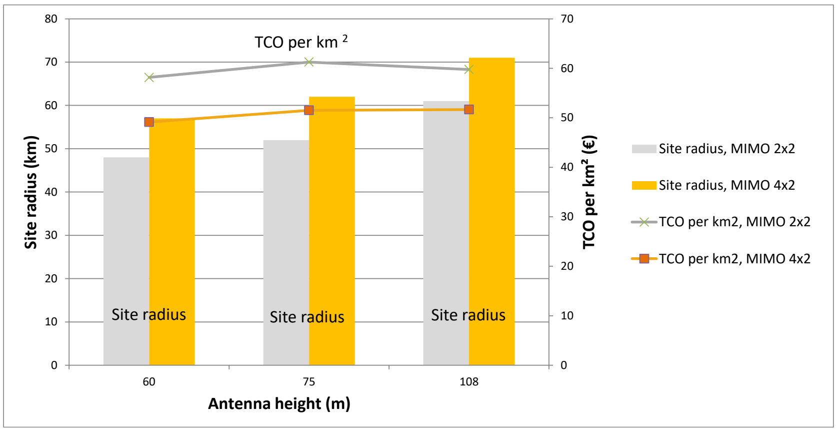


Figure 3-12: Impact of the number of antennas used for MIMO on the coverage and the TCO per km²

For rural environment, the 3.5GHz band was used thus enabling the use of massive MIMO. The massive MIMO scheme DL: 64x2, UL: 1x64 was applied in the study. The mMIMO considerations prevented us from performing the same kind of antenna combination analysis as for MIMO antennas in 700 MHz band.

Increasing sectorization

By increasing the number of sectors, antennas with thinner horizontal aperture and higher antenna gain would be needed for each sector. Doubling the number of sectors, and thus the total number of antennas, results in 3 dBi antenna gain which leads to an improved capacity and a better coverage. That is what we observed (Figure 3-13) when comparing the two configurations tested in far remote areas, with 3 and 6 sectors.

A coverage gain of 11% is obtained when doubling the number of sectors from 3 to 6. In addition, the site capacity is dramatically increased since the total spectrum per site is doubled when a tri-sector site is upgraded to a 6 sector one. The TCO per km² decreases dramatically as well.

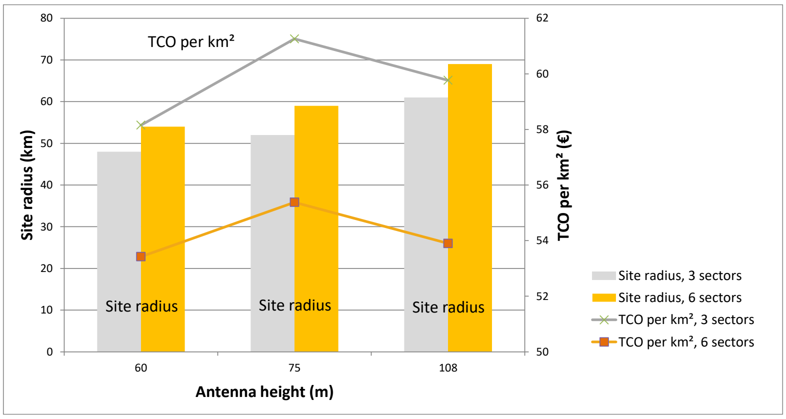


Figure 3-13: Impact of the number of sectors on the coverage and the TCO per km²

Decreasing the Tx power

In different cases, the question of the transmitted power was raised. In particular, when increasing the number of antenna floors or the number of sectors, a real increase of the power per site is generated at the base station side while we observed that the uplink is the limiting link in the dimensioning of the network. A reduction of the transmitted power was then simulated in the far remote rural case.

- When dividing by two (from 80W to 40W) the transmitted power per sector in the case of 6 sectors, there is no impact on the coverage.
- When dividing by two (from 80W to 40W) the transmitted power per sector in the case of 4 floors, there is no impact on the coverage.
- When dividing by two (from 80W to 40W) the transmitted power per sector in the case of MIMO4x2 DL, there is no impact on the coverage.

As far as the uplink is the limiting direction in coverage, the transmitted power reduction on base station side does not reduce the cell radius. Furthermore, the reduction of the transmitted power results in reduction of the cost.

Increasing the UL ratio and/or reducing the UL throughput target

To meet the fixed targeted performances in D2.2, the best configurations found are:

- Far remote rural: 700MHz, MIMO4x2, 6 sectors, 4 floors of antennas, 80W per sector
- The site radius obtained in that configuration is 80 km.
- Rural: 3.5GHz, MIMO64x2 DL & SIMO1x64 UL

The site radius obtained in that configuration is 15km. We keep the site traffic and user experienced throughput at cell edge as shown in Table 3-8. The ambition was to reach 50km but we did not find a configuration able to respect all the KPIs and leading to a 50 km cell coverage.

Some additional aspects are presented in Figure 3-14, where we show a decrease of the resource allocated to the downlink (from 60% to 40%) and an increase of the resource allocated to the uplink (from 30% to 40). The sum of the DL and UL resource is less than 100% mainly due to the guard period in TDD mode. We observe that increasing the UL ratio leads to a better coverage as more resource is allocated to the limiting link, whose performance is thereby improved. Nevertheless, this would lead to the reduction of the DL capacity.

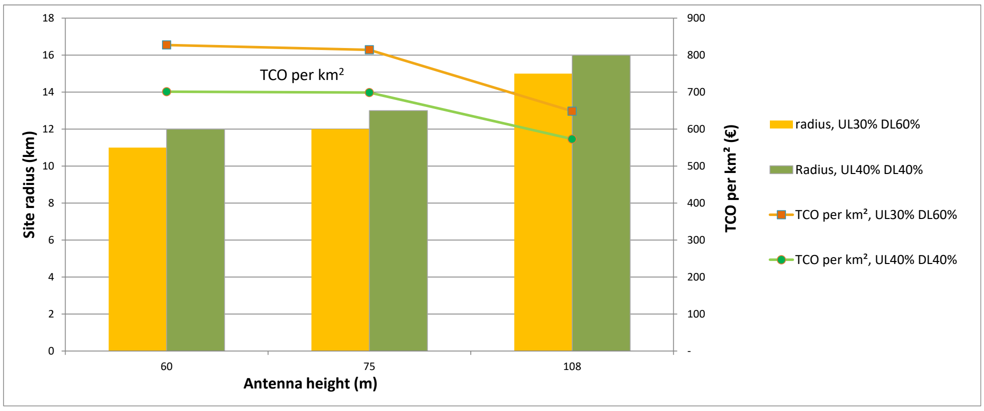


Figure 3-14: Impact of the UL ratio on the coverage and the TCO per km²

The same way, some additional simulations were performed when reducing the uplink throughput objective from 25Mbps to 10Mbps, and from 5Mbps and 1 Mbps. Figure 3-15 shows the results obtained and highlights that such reduction of the UL throughput would permit an increase of the coverage (up to 21km) and a reduction of the TCO per km².

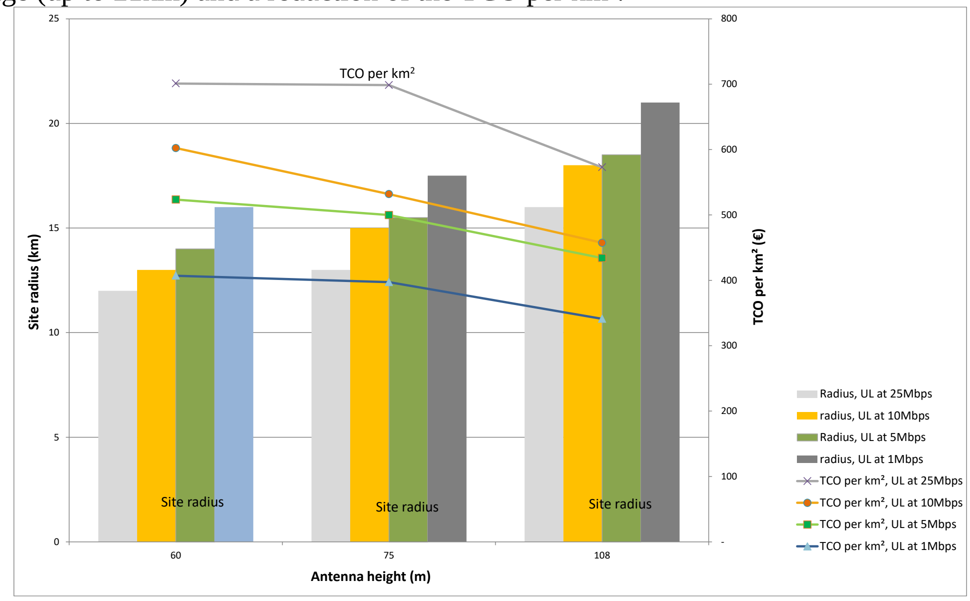


Figure 3-15: Impact of the UL throughput objective on the coverage and the TCO per km²

As a conclusion, the tradeoff among targeted uplink throughput, targeted radio coverage and deployment cost should be carefully considered in rural areas.

3.4.2 Evaluation of the backhaul options

We study here how to perform the backhaul of such large cell radius and long range solutions. The transport network model considers the work performed in mmMAGIC [mmM17-D14] taking into consideration both D-RAN and C-RAN options, with split points 2 and 7 (see Sec. 3.1).

The three following backhaul options have been evaluated in this study:

- The optical fiber was studied only in rural environments. A dark fiber model based on CAPEX according to the distance (mixed with/without civil work) and OPEX for maintenance was used. Such option is limited by the technical and cost feasibility of building a fiber network or reusing an existing network in rural or far remote rural areas.

That is why we did not envision such solution for far remote areas where we consider that no network exists.

- The microwave option was studied for both rural and far remote rural environments. “Traditional” microwave at 7 GHz was considered. The cost model is based on CAPEX for equipment and OPEX for frequency license and maintenance. This solution allows few Gbps throughput and hop distance is limited to 60km due to path attenuation. Its limitation is linked to the distance of the microwave hop because some intermediate sites can be necessary.
- The satellite solution was considered for both rural and far remote rural environments. Three types of orbital might be envisioned: Low Earth Orbit (LEO), Medium Earth Orbit (MEO) or Geostationary Earth Orbit (GEO). The model is based on CAPEX for equipment and OPEX for frequency license, bandwidth (throughput) and maintenance.
- The satellite option is presented here for cost comparison purpose but technically speaking, it could not be used in CRAN deployments because of latency constraints between RRU and BBH (below 10ms requirement): LEO has a latency of 20-30ms, MEO of approximatively 150ms and GEO of 500ms.

Figure 3-16 shows a cost comparison of those different options of backhaul on the total cost (TCO 5 years) in the case of rural and far remote rural environments while considering as well the split position as described in Section 3.1. We can notice that in both cases, there is not a big difference between split 2 and split 7 but that the satellite option is much more expensive than any other solution.

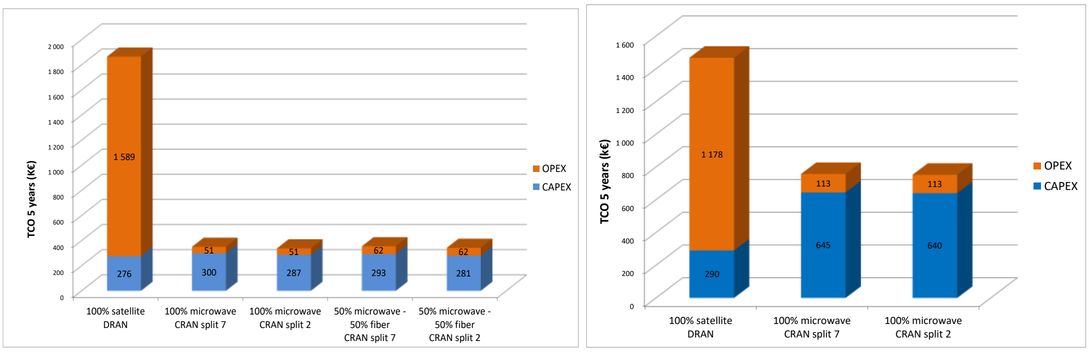


Figure 3-16: TCO 5 years with different backhauls – rural case (left) and far remote rural (right)

Microwave backhaul has to be considered in far remote rural areas while a mix of fiber and microwave can be envisioned in rural environments.

3.4.3 TCO evaluation

The following cost items have been taken into account to estimate the network costs of different site configurations under the assumption that all sites are built from scratch.

- Site building CAPEX, including all costs related to mast of different heights, site negotiation, site engineering, site infrastructure, etc.
- Energy equipment CAPEX, assumes all sites are equipped with solar energy equipment.
- 5G radio equipment CAPEX, including hardware, embedded software and installation and commissioning. The assumptions are made concerning 5G radio equipment price.
- Backhaul CAPEX, including backhaul of access network, backhaul of hop for access network and backhaul collect network CAPEX.
- CAPEX related to different configurations of antenna and their installation.
- Site rent.
- Passive and active site maintenance OPEX.

- Backhaul OPEX, including backhaul of access network, backhaul of hop for access network and backhaul collect network OPEX.

The 5G spectrum cost is not included in our cost model. The spectrum cost is country dependent. The RAN sharing economy is not considered in our cost model either.

The TCO is calculated with CAPEX and OPEX during a period of 5 years. The present value of TCO is deduced with an annual discount rate of 10%. All numbers are presented in euros, the costs in US dollar have been converted with an exchange rate of 1.2 US$ for 1 Euro. The TCO per km² has been calculated for all studied configurations in order to evaluate the configurations from techno-economic point of view. Finally, the TCO per user is also given as useful information for profitability consideration.

In rural environments, when focusing on the case where the backhaul is performed with a centralized backhaul with split 2 (slightly less expensive), Figure 3-17 shows more accurately the TCO at 1 year and 5 years. For both options, the TCO per user is approximately 18€ (TCO over 5 years in net present value).

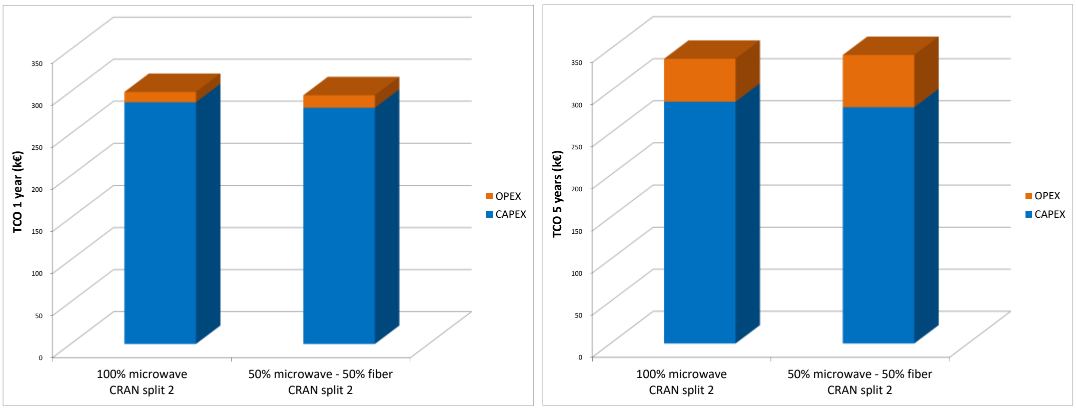


Figure 3-17: TCO 1 year & 5 years for rural – CRAN split 2, microwave backhaul or with fiber

In far remote rural environment, the backhaul would be performed with microwave. Figure 3-18 shows the corresponding TCO at 1 year and 5 years for centralization with either split 2 either split 7. In both cases, the TCO per user would be approximately 27€.

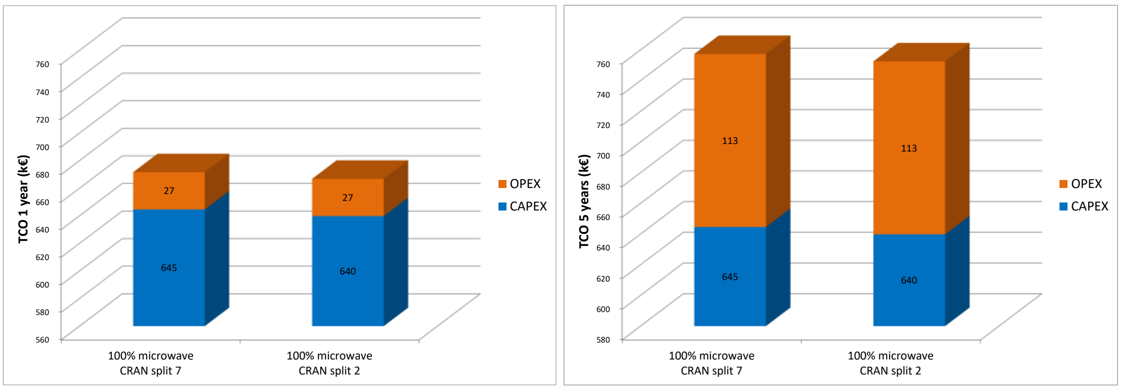


Figure 3-18: TCO 1 year & 5 years for far remote rural – CRAN split 2, microwave backhaul

3.5 Analysis for the Non Terrestrial Networks for Disaster and Emergency Communications use case

3.5.1 Network configuration for the analysis

The drone networks are part of the Non-Terrestrial Networks (NTN) family, where NTN has gained recent significance as a study item in 3GPP RAN1 and RAN2 [3GPP-38.811]. Supporting disaster and emergency situations with NTN is a particular use case identified in the study. The overall network configuration for the drone based 5G provision to the emergency services was detailed in D2.2 [ONE18-D22]. This configuration depends on an extensive, pre-planned network of 4G/5G small cells and BBUs (on the ground) to provide the transport network (Fronthaul and Backhaul) to the drones. As detailed in Section 3.2, we rely on a common network centralization approach, in-line with the 3GPP recommendations. In this quantitative analysis we first provide a TCO comparison for the two centralization options, the 3GPP split 7 (upper PHY split) and the 3GPP split 2 (PDCP split). Secondly, we look at the main factors that can influence the TCO – the number of drones for the wireless link, the unit cost of drones and the total capacity provision for the emergency services – and conduct cost sensitivity analyses on these. The drones per wireless link is defined as the number of drones used to connect the emergency site to the ground anchor base station, as illustrated in Figure 3-10 in D2.2 [ONE18-D22]. Thirdly, we develop a framework to help quantify the opportunity cost of using a fixed portion of the 5G commercial spectrum in a prioritized LSA (Licensed Shared Access) mechanism for this emergency service communications.

As the quantitative analysis is quite detailed and is based on a future 5G network, a number of assumptions have been made. The ground network of 4G/5G small cells are assumed to be sufficiently spread within the city, to support a drone link configured in order to cover an emergency case anywhere in the city. All the small cells are supposed to be connected through dark fiber to the BBU, where the provision of additional fronthaul capacity will be straight forward. The related cost models (below) assume leased line provision to the operator. Also, the number of BBUs in the city is assumed to be over-dimensioned to meet future capacity/ coverage needs, so they could absorb the additional number of small cells configured through the drone links. Basically, we assume that the ground based network in the city can handle the additional capacity/ connections resulting from this drone network, without having to deploy new hardware.

The main network parameters considered in this analysis are tabulated below.

Table 3-10: Scenario parameters for NTN use case

Parameter	**Value**
City area/ coverage area for the emergency services	100 km^2
Drone relay link distance	200 m
Average cell radius for 4G/ 5G small cells	150 m
4G/5G Small cell penetration in the city	66.7%
Maximum number of small cells connected to a BBU	323
Maximum number of near parallel* emergencies drones need to support	8
Bandwidth employed by a 4G/5G small cell	400 MHz
Bandwidth to be assigned to a drone cell ‘on demand’	100 MHz
Base capacity for the 4G/5G small cell	2.66 Gbps

Base capacity for the drone cell	665 Mbps
Fronthaul capacity multiplication factor – CRAN split 7	1.5194
Fronthaul capacity multiplication factor – CRAN split 2	1.2
Multiplexing gain for Backhaul	35%
IP security overhead for Backhaul	25%

* The near parallel term refers to the fact that drones are 'tied' to an event even after its completion. Re-charging of the batteries and some equipment re-checks will take time and hence a given drone is not available for service right after the completion of the event.

The drone network will be configured with a maximum number of drones per wireless link as a pre-defined parameter. With a higher number of drones per link, there is longer reach and a fewer number of ground base stations will be needed to support the drone network. This ground base station support node number is *inversely* proportional to n^2, where n is the maximum number of drones for the wireless link. On the other hand, having a fewer ground support nodes would mean that these nodes may have to support multiple parallel events. Thus, we dimension the costs for the small cell upgrades and the incremental fronthaul costs to be linearly proportional to n, although the *number* of small cell needing upgrade scales down with n^2.

We look at the *incremental* costs of providing fronthaul and backhaul to support this drone network, through leased lines. While the drone network will be utilized only 'on demand', dedicated fronthaul and backhaul capacity will be provisioned. This is to ensure a smooth data flow to the core network and beyond to the emergency command/control center, wherever or whenever the demand for this communication occurs. The fronthaul and backhaul costs are related to the capacity of these links and the related equations are adapted from the techno-economic study in the mmMAGIC project [mmM17-D14]. The incremental OPEX cost for the fronthaul provision is calculated as follows.

$$OPEX_{FH} = A \cdot ((FH_E + FH_D)^B - (FH_E)^B) \tag{3.1}$$

Where FH_E is the existing fronthaul capacity for the ground small cell and FH_D is the additional fronthaul capacity coming from the drone cell, both measured in Mbps. The parameter A has a value of 3840 and the power co-efficient B is taken as 0.2 [mmM17-D14].

The incremental cost for the backhaul is estimated as follows;

$$OPEX_{BH} = A \cdot (((BH_E + BH_D).(1 - mux))^B - (BH_E.(1 - mux))^B). \tag{3.2}$$

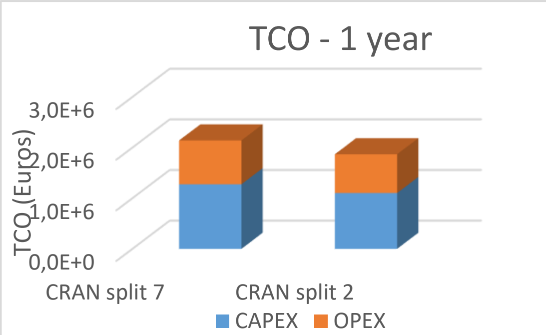
Similarly, BH_E refers to the existing backhaul capacity in the ground small cell network (per BBU) and BH_D refers to the additional backhaul capacity coming from the drone cells (again, per BBU). The multiplexing gain, taken as a percentage, is denoted by mux. The values of A and B remain the same as in fronthaul calculations.

The existing fronthaul capacities stem from the peak capacities supported in the 4G and 5G ground cells. While these peak capacities can be significantly different for 4G and 5G cells in practice, we take an average, representative value for all small cells. This is taken as the maximum Shannon capacity to be achieved at 20 dB SINR with a 400 MHz bandwidth, reaching to 2660 Mbps. The maximum capacity for a drone cell is estimated at the same SINR with 100 MHz bandwidth, reaching 665 Mbps. These capacities are scaled with the relevant factors (in Table 3 13) as per the split point applied to yield the fronthaul capacities and then accumulated to give the backhaul capacities.

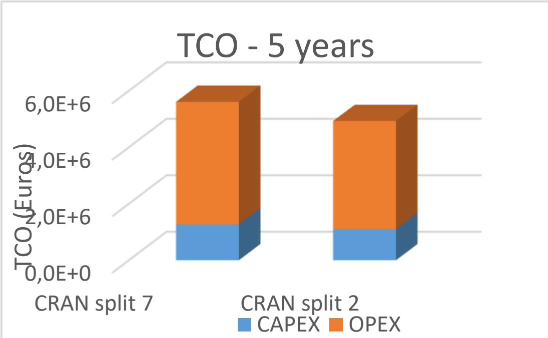
3.5.2 TCO calculations for the centralization options

The centralization options with split 2 and 7 bring about interesting trade-offs for this particular deployment. The CRAN split 7 would make the communication kit on the drones simpler and less power hungry, driving down the cost of the drone units. On the other hand, the fronthaul and cumulative backhaul capacity requirements will increase for this split, driving up the costs of fronthaul/backhaul and also of the small cell upgrades. The opposite factors are true for the CRAN split 2. The TCO is a combination of these cost factors and the comparison brings out the net outcome of the above trade-offs.

In this analysis, we keep the number of drones in the wireless link as fixed to 2. The cost of the drone unit is considered to be equal to the ground small cell (with relevant CRAN options) costs and the base capacity of 665 Mbps is assumed to be provided by the drone link. All other parameters are taken as detailed in section 3.5.1 and in Table 3-10.



(a) 1 year TCO



(b) 5 year TCO

Figure 3-19: TCO comparison for CRAN split options

The results indicate that the CRAN split 2 produces lower TCO in both 1 year and 5 year TCO analysis. The OPEX costs of fronthaul provision has a bigger bearing on the TCO than the CAPEX costs of drone RRH procurement. This is evident as the gap between the TCOs for the split 2 and split 7 are more pronounced in the 5 year comparison, where the OPEX costs are dominant.

3.5.3 Cost Sensitivity Analysis

We evaluate the sensitivity of the 3 main parameters of this study to the TCO in this sub-section. These parameters are: the number of drones that can be combined to formulate the wireless link, the cost of the drone RRH unit and the capacity that can be provisioned to the emergency services in these drone links. The baseline values for these parameters are detailed in Section 3.5.2 and the overall analysis remain as per the parameters defined in Table 3-10.

Cost sensitivity to number of drones per wireless link

As detailed in Section 3.5.1, increasing the number of drones per wireless link will increase the reach of this link from the anchor base station, reducing the number of ground small cells needing upgrades. However, having a greater drones per wireless link will increase the total cost of the drone fleet. This analysis looks at the trade-off between these competing factors. We evaluate the TCO for CRAN split 2 (lower TCO option) for the lower end of drone unit cost. We assume the drone RRH units to cost the same as the ground RRH (gRRH) units, but the following analysis will consider higher drone costs as well. Figure 3-20 below illustrates the TCO variation as the drone numbers per wireless link is increased from 1 to 9. Although having 9 drones per link will cause some practical issues like link alignment between relay drones, we are interested in seeing purely the TCO variation trends here.

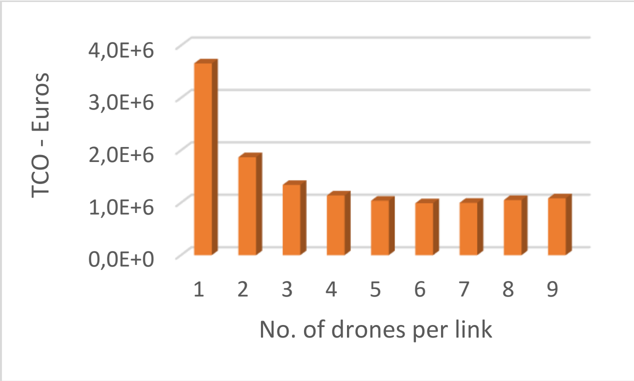


Figure 3-20: TCO sensitivity to incrementing drone numbers per wireless link

The TCO drops exponentially up to the point of having 6 drones per wireless link, and then show a gradual increment. The costs of deploying a network with only 1 drone per link is prohibitively expensive at double the cost of a 2 drones per link system. With multiple drones per link, the TCO related 'sweet spot' for operations will also depend on the drone RRH unit cost and the capacity provisioned from the drone link. This sweet spot can be inferred from the results presented in the next sub-sections, for the relevant sensitivity studies.

Cost sensitivity to cost of the drone RRH units

The likely cost of a drone RRH unit shows huge variations, according to different sources. The higher reliability needed for this emergency communication service is likely to push the drone RHH unit costs higher than the normal drone communication kits. As there are no firm indications of this cost available at this point of time, we consider a range of values in this sensitivity analysis. Starting from a lower drone RRH cost point equal to a ground RRH station (Euro 9.2k), we increment the costs by Euro 4k steps, until the cost reaches a maximum of Euro 25.2k. The sensitivity of the drone unit cost to the TCO is shown below in Figure 3-21.

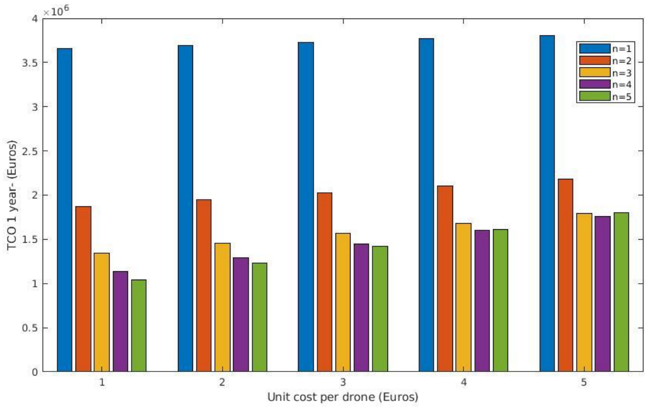


Figure 3-21: TCO sensitivity to the incrementing drone RRH unit costs

The TCO values in step 1 of the unit drone RRH cost resemble the values in Figure 3-20, as these are with the lowest drone RRH cost. The rate of TCO reduction slows down as the drone numbers per link increase across the different drone RRH unit cost considerations. The general trend is that the overall TCO increases with the drone unit cost, but the 'sweet spot' where the minimum TCO occurs (as per the number of drones per link) varies across the graphs. We recall that this 'sweet spot' for lowest drone unit cost for Figure 3-20 (step 1 in Figure 3-21) is at 6 drones per wireless link. This sweet spot can be seen to occur at progressively lower number of drones per wireless link as the unit costs increase. For the higher drone unit costs of 21.2k€ and 25.2k€, this lowest TCO occurs when the number of drones per link is at 4. Higher drone RRH costs offset the savings of having lower number anchor RRH on the ground network, thus having higher number of drones per wireless link is no longer profitable in this scenario.

Cost sensitivity to capacity of the drone link

The capacity that can be provided by the drone wireless link is a central point in this whole study. While the actual capacity can be heavily impacted by the radio conditions (achievable SNR) for this drone based wireless link, we make a number of assumptions to streamline the analysis. We assume that a 20 dB average SNR can be maintained for the drone wireless link (radio access part), with a 100 MHz spectrum provision. With the Shannon capacity formula, this will enable a maximum capacity of roughly 665 Mbps. We also assume a dynamic TDD mode of operation, so this capacity can be flexibly partitioned to the uplink and downlink as the needs dictate.

The capacity increases are assumed to be achieved by increasing the SNR from the 20 dB baseline. The SNR increase is considered in 3 dB steps and this can be achieved by either doubling the number of antenna elements and associated RF kit in the drone RRH or by increasing output of the RF power amplifier. For both these measures, the cost of the drone RRH is assumed to double for each 3dB increase in average SNR. The 3 dB increase in average SNR translates to a 100 Mbps increase in the capacity provision. We analyze the impact on the TCO from these 100 Mbps capacity increment steps. Figure 3-22 shows the sensitivity of the 1 year TCO to incrementing the drone link capacity.

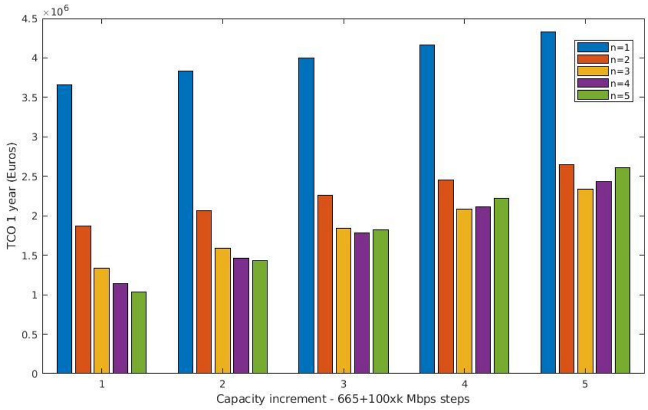


Figure 3-22: 1 year TCO sensitivity to incrementing drone link capacity

Incrementing the drone link capacity increases both the drone RRH unit cost and the cost of provisioning Fronthaul and Backhaul. These factors demonstrate interesting behavior when the number of drones per link is also considered, as in Figure 3-21. For the 1 year TCO, the CAPEX of the drone RRH unit costs play a significant role, so the trends are similar to the ones seen in Section 3.5.3.2. With increasing capacity, the TCO increases overall, but the operating 'sweet spot' in terms of lowest TCO occurs with reduced number of drones per wireless link for higher capacities.

We also compare the 5 year TCO trends in a similar capacity analysis below, in Figure 3-23. With 5 year TCO, the OPEX cost are dominant and the costs of provisioning larger Fronthaul and Backhaul capacities play a bigger role. With higher number of drones per wireless link, the number of ground RRH needing these Fronthaul upgrades reduce and this acts as a counter-balance to the incrementing drone RRH unit costs. Hence, we can see that the higher number drones per wireless link still providing lower TCO for higher capacities, even though with diminishing gains. The 'sweet spots' of lowest TCO will occur beyond the 5 drones per wireless link considered here, but the contrasting trends of Figure 3-22 and Figure 3-23 give a good indication of the short term and long term TCO behaviour for incrementing capacity provisions.

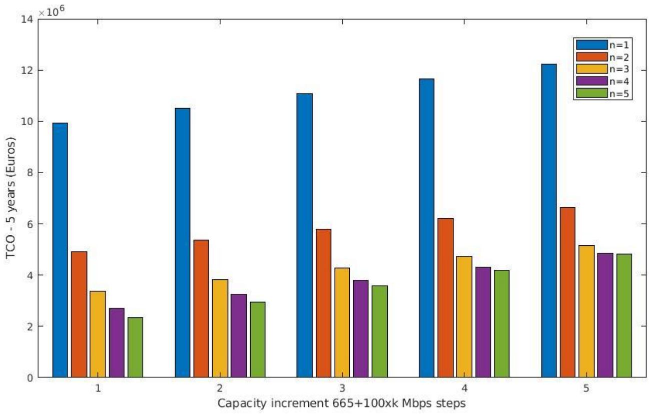


Figure 3-23: 5 year TCO sensitivity to incrementing drone link capacity

3.5.4 Spectrum usage - opportunity cost analysis

As noted in D2.2 [ONE18-D22], we envisage a spectrum usage model where the operator providing this emergency network will allocate some of his commercial spectrum on a priority basis, for this on-demand service. The sharing basis will be an internal Licensed Shared Access (LSA) [GCP+18] model, where the operator would free-up a fixed amount of bandwidth for this emergency service for use in the specific emergency locality. We assume a fixed bandwidth part of 100 MHz is taken out from the operating bandwidth of 400 MHz for the 5G small cells. Under this framework, an impact on the commercial network occurs if the locality of the emergency correlates with a 5G small cell with traffic demand at that point of over 75% of its total capacity. We develop the framework to assess the opportunity cost of having some impact on the commercial operations of the operator through some statistical modelling in this section.

As we are considering an early 5G deployment, the commercial 5G network will itself be in a nascent state. In year 1 of the deployment, we would assume that the 5G services will only be provided in a city center commercial area (CA). In year 2 to 5, we establish an additional residential area (RA) each for the 5G service. Each of these commercial and residential areas would occupy 8 km^2 each out of the 100 km^2 city area under study. In dropping 5G small cells in these areas, we make use of a Poisson Point Process (PPP) as detailed in [ZLL+15]. For the commercial area we assumed a lambda value of $\lambda = 53.4$ that produces 387 base stations on average, while for the residential area, we used a lambda value of $\lambda = 0.5217$ that produces 61 base stations on average. The Poisson parameter λ equates the mean and variance of the distribution. We also allow for up to 10% spatial overlap between the commercial area and any of the residential areas. However, we do not consider any spatial overlap between residential areas.

For the emergency events we have acquired information from the fire brigade services in the London area that spans a period of 3 years [LFB17]. We have removed days with large number of incidents (31st of December, 1st of January and 5th of November), and of the remaining entries we only consider the major events (fires, floodings) that would likely require this drone based communication service for the emergency crew. In total the number of entries that we consider as our emergency services data is 41547. The temporal distribution of the probability of emergency events is depicted in Figure 3-24. It is observed that the events are more probable to happen in the evening hours, when people have returned home. In fact, an analysis of the emergency dataset revealed that the majority of events were categorized as “house fires”.

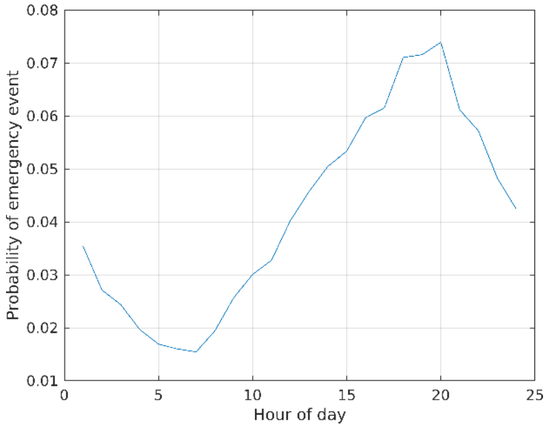


Figure 3-24: Temporal distribution of probability of emergency events in a day

According to our emergency dataset, the average number of emergency events within a day for the whole 100km^2 area is 53, and the average duration of an emergency event is 244 minutes (~4 hours). The spatial distribution of the emergency events is considered as a random process, and the emergency events are dropped accordingly in the whole city area. Figure 3-25 illustrates an instance for the spatial distribution of the 5G small cells in 4 service areas (1 commercial and 3 residential areas) and the spatial distribution of the 53 emergency events. In the figure, the blue and black dots denote the 5G base stations, corresponding to the commercial and residential areas respectively. We have also encircled the residential areas for better clarity. The emergency events are depicted with red stars.

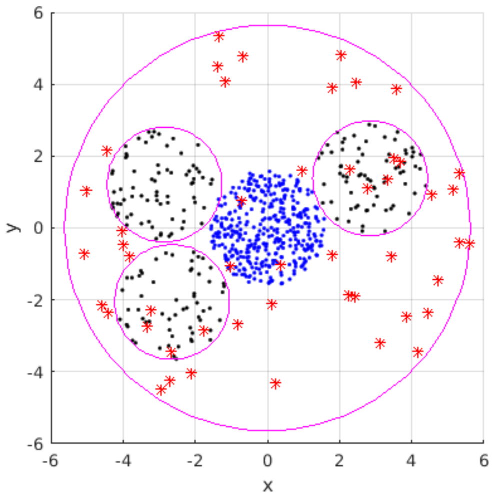
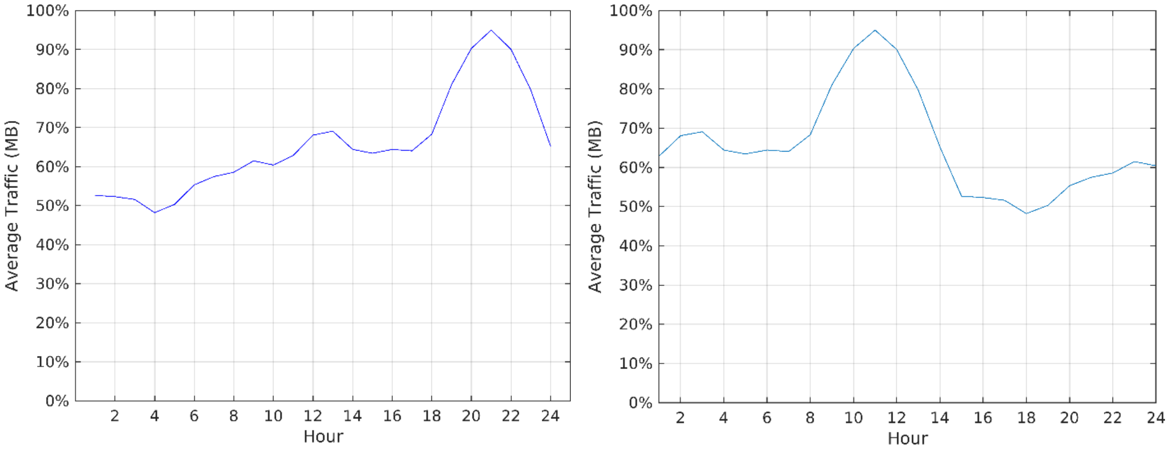


Figure 3-25: Illustration of the spatial distribution of the 5G small cells in 4 service areas (1 commercial and 3 residential areas) with emergency events

To model our normal 5G traffic we acquired data from Kaggle, an open platform for sharing data sets [KAG18]. Specifically, our dataset includes traffic volumes in MB in 1-hour intervals from 57 cells, and we have averaged the traffic volumes for each cell and each hour of the day. The temporal distribution of the normal traffic for residential areas is depicted in Figure 3-26 (left). Please note that in the y-axis we show the percentage of the maximum capacity that can be supported by a 5G cell. As we do not have a similar dataset for a commercial area, we shifted the traffic by 14 hours to align the peak demand with the core working hours in UK (Figure 3-26 (b)).



(a) Residential Area (RA) **(b) Commercial Area (CA)**

Figure 3-26: Temporal distribution (predicted) of normal 5G traffic

We assume that the commercial 5G traffic is affected only when the emergency event occurs within any of the areas covered by 5G deployments. However, as the commercial traffic demand does not always exceed the 75% of capacity, there will only be an impact if the event also occurs in any of the residential areas during the evening hours or in the commercial area during the morning hours. Therefore, the impact on the commercial traffic for the commercial area and one residential area with spatial and temporal correlation is shown in Figure 3-27. In the figure, the blue lines represent the impact in a single cell given that emergency events have happened in the respective area, the red lines represent the impact on a single cell given the probabilities of an emergency event happening (as per Figure 3-24), and the black lines represent the impact on the whole respective area (the relevant CA or RA area) given the probabilities of an emergency event happening (Figure 3-24).

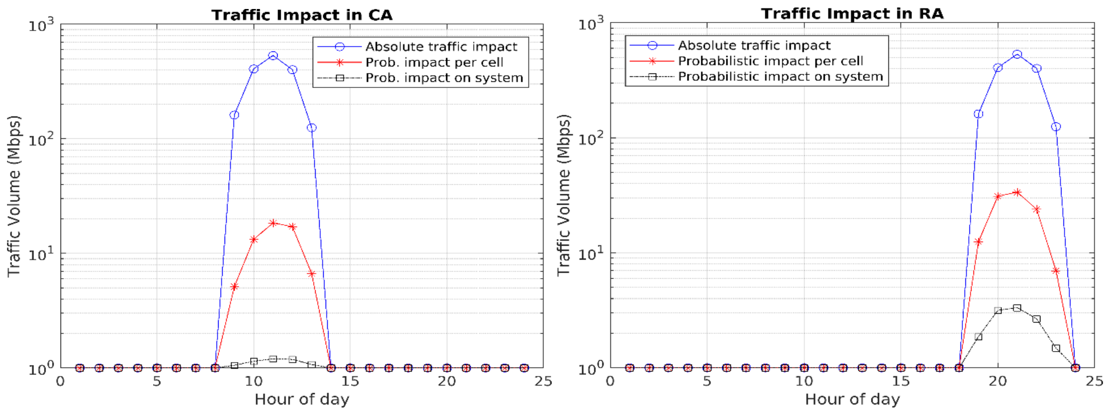


Figure 3-27: Impact on normal traffic for the commercial and residential areas

Finally, we show the impact of emergency events throughout the five years with spatial and temporal correlation, given the probability of emergency events happening as per Figure 3-24, and the average duration of an emergency event. The impact is depicted in Figure 3-28 as a fraction of the total capacity of the system in the 5 years of operation.

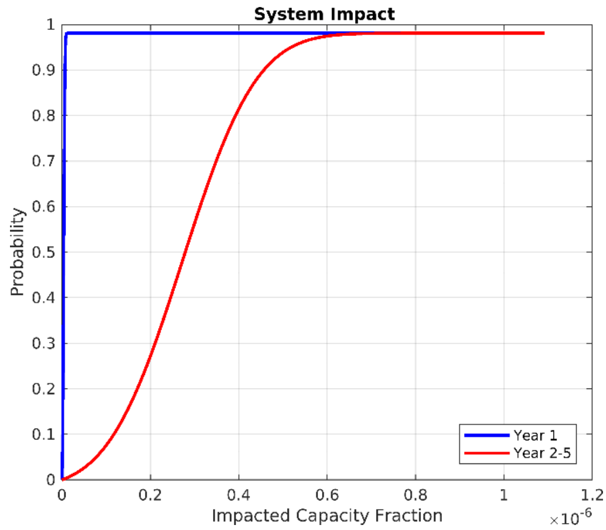


Figure 3-28: Fraction of impacted capacity due to drone support for emergency events

The results in both Figure 3-27 and 3-28 indicate that the overall impact is very low from this spectrum sharing arrangement on the commercial operations. The impact on the CA is much lower than the impact on the RA and thus the full system as a whole depends on the RAs. The emergency event probabilities correlate with the traffic patterns in the RAs so the likely impact in these areas are higher. Another reason is that there are more 5G small cells densely packed in the commercial area and in this analysis we assume only one small cell is impacted by the emergency event.

3.6 Comparison of results across the use cases

Although the aforementioned network deployments related to the use cases are quite different, the use of common methodologies (detailed in Section 3.1) enable some level of result comparison. It should be emphasized that the trends in the respective results are more indicative than the absolute values, hence we focus on the relative trends across the use cases.

The first comparison relates to the variations of the TCO in relation to the centralization options used. Studies related to use cases 1, 4 and 9 employed common centralization split points, in the form of 3GPP CRAN split 2 and 7. A general observation is that; with the split 2 the RRH needs to handle more processing and hence the complexity and costs of the RRH is higher, while the fronthaul data rates and the corresponding costs are lower. The opposite factors are true in general for the CRAN split 7. The RRH costs are attributed to CAPEX, while the fronthaul costs are attributed to OPEX.

UC1 is based on an entirely new green field deployment and hence the CAPEX costs are much higher than the OPEX costs (for the 1 year TCO). A significant portion of these costs relate to deploying multiple RRH nodes by the highways in the mega-city and under-served area environments. Thus, a reduction in the unit cost of the RRH has a notable impact in reducing the CAPEX, making the CRAN split option 7 more cost efficient for UC1, as seen in Figures 3-5 and 3-6. This option incurs more OPEX spending on the fronthaul but the OPEX contribution is less than 25% of the TCO in most of the studied cases in UC1. The relatively smaller data packet sizes seen in V2X deployments leads to lower aggregated fronthaul capacities. For example, the fronthaul capacities in Table 3-3 for rural environments are less than the fronthaul capacities considered in UC9, even when scaled up to a per site basis. Due to these factors, the split 7 option has provided significantly lower TCO for the UC1, when compared to CRAN split 2.

In UC4 as well, the CAPEX costs are much higher than the OPEX costs, in both rural and far remote rural environments. This is due to the need of deploying new networks to provide sufficient capacity for rural areas and create services in currently uncovered far remote rural areas. Both split options produce approximately equal TCO in many of the rural and far-remote deployments studied. The UC4 deployments will have many unique components (like the relays for microwave backhaul links) that will impact both the CAPEX and OPEX and will be needed in both CRAN split options. Also, the coverage enhancement techniques used, like sectorisation and antenna height increment, are common to both CRAN split options so the main CAPEX costs are similar. The CAPEX proportion in the TCO is dominant in both rural and far-remote deployments, but due to the above reasons, this does not convert to a clear cost difference between the 2 CRAN split options.

UC9 on the other hand is based on deploying the minimal amount of new infrastructure (in the form of drones) and upgrading the existing ground small cells to operate as anchors plus the use of the same BBUs (or CUs). In contrast to UC1, UC9 needs intermediate hardware within the fronthaul link, to convert the wireless fronthaul to wired fronthaul in the anchor small cells. There is a CAPEX cost and it is relatively higher for the higher fronthaul rates experienced with split option 7. Thus, any CAPEX reductions seen with the less complex RRH (drone units) with the split option 7 is offset by these higher hardware costs at the anchor small cell. Figure 3-19 depicts that both the CAPEX and OPEX are lower for split 2 and this gives a moderately reduced 1 year TCO. The OPEX fraction in the 1 year TCO is relatively higher than in UC1, as the UC9 is dimensioned for more fronthaul capacities aimed at providing 5G eMBB services. This higher TCO gap between split options 2 and 7 in the 5 year TCO estimate highlights this aggregated effect on the fronthaul capacities and thus the OPEX.

The second comparison is based on the impact of allocating some of the commercial spectrum for these specific use cases in UC3 and UC9. In UC9 there is a detailed study of the likely impact of allocating 25% of the commercial spectrum to the emergency scenarios. Looking at the random spatial nature of these emergency events and the fact that temporal probability distribution is skewed towards evening hours, the analysis predicts minimum impact to the commercial areas, while some higher impact is seen in the residential areas. The UC9 analysis is based on the behavior of 5G small cell traffic and its correlation with the emergency events. Along these lines of analysis, it would be interesting to see the impact of allocating some PRBs to the IoT services in UC3, in a Smart City context. The current analysis predicts that up to 6 additional PRBs will be needed for the Smart city IoT applications when moving from release 15 to release 16. In terms of a 20 MHz BW system, this will be 5% of the resources and for a narrower 10 MHz bandwidth, this can be as high as 10%. However, this bandwidth portion is taken from the 5G Macro cells, which will be primarily tasked with providing coverage. The higher capacity 5G eMBB applications will be supported by a dense underlay of 5G small cells. This small cell network will be fairly matured by the time of release 16 deployments, and this will reduce the capacity pressures on the Macro cell networks. We can hence argue that the likely impact of releasing even 10% of spectrum to the IoT services from the commercial Macro cell network will not have a significant detrimental impact. In fact, if the IoT data streaming can be co-ordinated to de-correlate with the commercial traffic peaks, this Smart city solution can easily co-exist and also enhance the revenue streams for the operators.

4 Conclusions

The first part of the presented WP2 work in this D2.3 includes the system level implementation and evaluation of a set of technologies and optimization techniques proposed in WP4 and WP3 respectively. The implementation was realized on a 5G system level simulation tool which was extended for including the proposed ONE5G TeC features. Specifically, the simulator was extended in order to support the main enabling technologies targeted by the project including the centralized multi-cell scheduling, component carrier management, context-aware proactive QoE traffic steering, mMIMO, enhanced HARQ and optimized functionality placement and resource allocation in CRAN/DRAN. In addition, a set of environmental models were implemented in order to capture the different characteristics of the defined cases of the project. In detail, we have implemented realistic user/device spatial-temporal distribution models, mobility models, service/traffic models and node distribution models taking into consideration the characteristics of the targeted cases to be evaluated.

The set of technologies and optimization techniques designed in WP3 and WP4 of ONE5G was implemented and integrated into the simulation tool. Then, the integrated technical components were evaluated through a set of meaningful simulation scenarios, from the scenario and vertical perspective. The technical components were evaluated as standalone components (subsections 2.2-2.7) and their combined performance has been evaluated (specifically the combined evaluation of component carrier management and mMIMO was studied and presented in Subsection 2.8).

The basic idea of TeC#1 "Centralized multi-cell scheduling" is that a "super-cell" being managed by a Central Unit will perform all the radio tasks above the MAC layer, for all the active users connected to the different cells. This CU will perform all the scheduling decisions and allocate the users to the resource blocks and RU where the channel conditions are the best by taking advantage of the CQIs reported by the users. In order to be more flexible, the centralized multi-cell scheduler allows frequency reuse by means of applying techniques such as CoMP and NOMA in power domain. Detailed evaluation results are presented in Subsection 2.2.

The main aim of TeC#2 "component carrier management" is to dynamically assign Component Carriers from multiple nodes as well as the service category and context information. In this study, eMBB traffic is considered. To this end, a Component Carrier (CC) manager was proposed to determine the number of carriers to be assigned to a user. Detailed evaluation results are presented in Subsection 2.3.

The main objective of TeC#3 "context-aware proactive QoE traffic steering" is to achieve a QoE balancing by adjusting handover margins as well as by calculating a figure of merit which is evaluated and presented in detail in Subsection 2.4.

The aforementioned technical components depict the work conducted in the context of WP3. The technical components that follow have been introduced in WP4. Specifically, the main goal of TeC#4 "mMIMO" is to evaluate the performance of UEs by taking into account the provided mapping from SNR to spectral efficiency in a mMIMO context. Detailed evaluation results are presented in Subsection 2.5.

Also, the basic idea of TeC#5 "HARQ" is based on the implementation and evaluation of a K-Rep scheme in which a UE is configured to autonomously transmit the same packet K times before waiting for feedback from the BS. Detailed evaluation results are presented in Subsection 2.6.

Finally, the main objective is to implement and evaluate an algorithm for optimized functionality placement and resource allocation in CRAN/DRAN. Based on the functional split options we studied the functions of the LTE protocol stack, which can be partitioned in distinct elements and assigned to different network units. Our objective was to assign these functional elements to network units finding the minimum cost allocation that satisfies a set of capacity and performance constraints, as well as the distribution of network traffic to each distributed unit. Detailed evaluation results are presented in Subsection 2.7.

All these TeCs have been integrated into the system level simulator, that they have been assessed and validated with the TeC owner.

Section 2 finishes with the combined simulations between TeC#2 and TeC#4 as well as a subsection dedicated to the evaluation of connection density KPI through system-level simulations which have been conducted in the context of a study related to IMT-2020.

After the technical assessment of some of the TeCs through system level simulations, WP2 focused on analyzing the cost KPI on some of the use cases through a series of techno-economic analyses. These give valuable indications about the overall cost of deploying 5G networks to support various vertical industries, in both Megacities and underserved areas. As none of these 5G vertical areas are not yet fully realized as physical networks, these techno-economic studies carry a number of assumptions in the respective cost modelling. In this sense, the absolute TCO values stated should be considered as only indicative. The cost trends between various options and across the use cases in certain cases are highlighted in this study. Some of the TCO comparisons for different CRAN split options are presented in section 3.6. Generally, centralization is seen as a useful tool in reducing the TCO and the best split point for centralization is very much dependent upon the particular traffic profile and the other RAN requirements of the use case.

In looking at the specific use cases, the TE analysis on the automotive use case (UC1) envisages a Greenfield deployment, with the RRH, the MEC and the Central units are exclusively deployed for this UC. The CAPEX element of the TCO is high and with packet sizes in the V2X applications deemed to be low or moderate, the OPEX component is comparatively smaller. The CRAN split option 7, with lower RRH costs produces lower TCO for UC1.

The UC3 analysis on Smart city IoT networks takes the Release 15 NB-IoT and mMTC networks as the baseline and analyses the cost elements for upgrading to Release 16. The software upgrade needed is deemed to be free of deployment costs and also the existing Macro cell network is assumed sufficient to cover a large city like Paris. The costs in terms of the required number of PRBs for this release 16 IoT network is calculated using traffic assumptions for 2020 and 2030, considering different ISDs for the Macro cells and focusing on the 700 MHz frequency band. The spectrum requirement of roughly 1 MHz represents about 5% of the total bandwidth allocated in the 700 MHz band for the Macro cells. Medium frequency bands (between 2 and 6 GHz) should also be allocated to 5G mMTC services. Considering the fact that 5G Macro cells in Rel. 16 will be supported by a dense underlay of small cells for eMBB 5G applications, releasing this amount of spectrum is seen as manageable and also as a potential to increase the operator revenues by better utilization of spectrum.

In the UC4 - long range connectivity analysis, the CAPEX costs are dominant as different network equipment and upgrades are needed to extend the coverage to rural and far remote areas. These costs are similar for both the CRAN split options 2 and 7, so there is no marked difference in the TCO for these options. The uplink coverage becomes a limiting factor for many of the considered coverage enhancement options. It is deemed that some reductions in the target capacity levels (especially the 50 Mbps for rural area DL) is needed to achieve coverage distances closer to the original targets.

The UC9 on providing 5G eMBB to emergency services through drones provides a detailed TCO and cost sensitivity analyses on the number of drones per wireless link, the drone unit cost and the link capacity factors. The TCO consists of roughly equal parts of CAPEX and OPEX, as the drone RRH units are incorporated to an existing centralized network with a sizable network of small cells and BBUs. The OPEX is also boosted by the higher data capacities the fronthaul and backhaul networks need to support. In contrast to UC1, these factors contribute to make the CRAN split 2 option more cost effective in UC9. The cost sensitivity analyses provide different ‘sweet spots’ (or lowest TCO points) in terms of the number of drone RRHs to be operated per wireless link, for the different drone unit costs and capacity levels considered. The spectrum analysis on the impact of allocating 25% of the commercial spectrum ‘on demand’ for this emergency deployment looked at the likely proliferation of 5G small cells in the early stages (up to 5 years). The impact on the commercial network is found to be minimal for the commercial (business) areas and while the residential areas see more impact, the capacity penalty is seen as highly manageable.

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Annex

Table Annex-1: Number of devices, number of transactions (per year) derived for Paris in year 2020

Application	Devices / household	Number of devices	UL / day	DL / Day	UL Payload	DL Payload	Delay Tolerance	Transactions	Trafic (Mbytes)
Security alarm	0,66	1 242 780	24	1	20	10	no	31069500	570
Electric Meter reading	1	1 883 000	144	144	40	45	limited	542304000	21980
Electric Meter - Load monitoring	NA	NA	1	1	45	1200	yes	3766000	2235
Gas Meter	1	1 883 000	24	1	80	100	yes	47075000	3627
Water Meter	1,5	2 824 500	2	1	80	100	yes	8473500	700
Heat Meter	4,2	2 279 760	2	1	80	100	yes	6839280	565
Fire detection	1,5	2 824 500	1	1	20	10	no	5649000	80
Street Lighting		200 260	1	3	1024	100	limited	801040	252
Smart Parking - public	NA	310 000	24	1	100	50	no	7750000	724
Smart Parking - private	NA	510 000	4	4	100	50	limited	4080000	291
Bike fleet	NA	25 000	48	48	150	50	no	2400000	228
Car monitoring	0,45	1 136 650	12	6	150	100		20459700	2601
Home Appliance	4	5 428 000	1	1	60	100	limited	10856000	828
Personal Asset Tracker	1	2 250 000	4	4	100	40	no	18000000	1201,6
Urban sensor	0,44	990 000	48	1	100	150	limited	48510000	4673
Waste Management	0,5	941 500	2	1	80	100	yes	2824500	233
Supply chain	1	80000	12	12	100	50	yes	192000	1344
Mail		500 000	2	0	50		yes	100000	100

Overall Total of UE		26 192 630				Overall Total traffic	767 628 820	41 698
Total UE per cell		71735				Overall traffic per cell	2 102 361	114

Table Annex-2: Number of devices, number of transactions (per year) derived for Paris in year 2030

Application	**Devices / household**	**Number of devices**	**Uplink / day**	**Downlink / Day**	**Uplink Payload**	**Downlink Payload**	**Delay Tolerance**	**Transactions**	**Trafic (Mbytes)**
Security alarm	0,66	1368180	24	1	20	10	no	34204500	627
Electric Meter reading	1	2073000	144	144	40	45	limited	597024000	24198
Electric Meter- Load/Rate management	0	0	0,5	0,5	4000	4000	No	2073000	7907
Electric Meter - Load monitoring	0	0	1	1	45	1200	yes	4146000	2461
Gas Meter	1	2073000	24	1	80	100	yes	51825000	3993
Water Meter	1,5	3109500	2	1	80	100	yes	9328500	771
Heat Meter	4,2	3482640	2	1	80	100	yes	10447920	
Fire detection	1,5	3109500	1	1	20	10	no	6219000	89,
Street Lighting		221340	1	4	1024	100	limited	1106700	300
Smart Parking - public	0	310 000	24	1	100	50	no	7750000	724
Smart Parking - public - Charging	0	0	24	24	4000	4000	limited	14880000	56762
Smart Parking – private	0	560 000	4	4	100	50	limited	4480000	320
Bike fleet monitoring		35000	48	48	150	50	no	3360000	320
Bike fleet - Self renting			24	24	4000	4000	no	1680000	6408
Car monitoring	0,45	1249650	12	6	150	100	limited	22493700	2860
Car - Access control			0,14285714	0,14285714	8000	8000	limited	357042,857	2724

Home Appliance	20	29940000	1	1	60	100	limited	59880000	4568
Home Appliance - Automatic orders			0,06666667	0,06666667	4000	40000	yes	3992000	83755
Personal Asset Tracker	5	12 500 000	4	4	100	40	no	100000000	6675
Urban sensor	0,88	2200000	48	1	100	150	limited	107800000	10385
Waste Management	0,5	1036500	2	1	80	100	yes	3109500	257
Waste Management - AC & Charging			1	1	4000	4000	limited	2073000	7907
Supply Chains	5	400000	12	12	100	100	limited	9600000	915
Mail	1	1080000	2	2	50	50	yes	4320000	76
Connected Credit Card	1,5	3750000	5	5	10000	10000	no	37500000	102996
Overall Total		68498310				Overall Total traffic		1019649863	328871
Total / cell		187601				Overall traffic per cell		2792589,44	900