5G Public Private Partnership

Test, Measurement and KPIs Validation Working Group

Whitepaper

Beyond 5G/6G KPIs and Target Values

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Executive Summary

The main objective of this document is to present the current view of the available B5G and 6G KPIs from 5G PPP phase III projects with a focus on projects of the ICT-52 call. This view includes mapping to KPIs previously defined for 5G and evaluating how they might evolve to fit the B5G and 6G visions.

We are presently at the start of the 6G research era, where visionaries and researchers are interplaying to define a vision for 6G. To ensure the direction of innovations towards realizing 6G it is critical that KPIs are defined at an early stage to help steer the process. The KPIs are either evolved from previous generation KPIs or are new and being defined in coordination with definition of new features and use cases. It is at this stage that this white paper makes its contribution, in collecting KPIs from active research projects based on work on new features and use cases.

The paper consists of two main technical parts. The first part gives an overview of standard network KPIs with defined target values for 5G system. These are well-known KPIs that will be evolved to 6G by changing target values. The second part presents KPIs collected from ICT-52 research projects aimed at B5G and 6G systems. These KPIs are processed in terms of being grouped according to KPI type or context, and they are presented with references to standards and target values where possible and available.

The white paper is intended to be updated and re-published every year to track the B5G and 6G KPIs evolutions. The evolutions will occur as projects, use cases and functionalities mature. KPI definitions from new B5G and 6G projects from projects participating in the 6G SNS R&I Work Programme will be taken into account when available (2023).

Future version of this report will also integrate more information on KPIs target values and the definition of methodologies for how to measure them.

1 Introduction

This document consolidates the available KPIs from 5G PPP phase III projects with a focus on projects of the ICT-52 call. It tries to consolidate an agreed definition for each KPI and along with provide method of measurement and target values where available. The document provides a view of how the KPI exist in the 5G system and how they may evolve in 6G.

1.1 Motivation

Today, at the start of the 6G research era, a diverse group of visionaries and researchers provide visions and use cases for 6G. These efforts lead to known spider diagrams showing e.g., latency, throughput localization accuracy, etc. These spider diagrams explain how 6G will be different from the 5G system. This while 5G systems are still not yet fully deployed and used today but rather still being rolled out and qualified in terms of the true benefits that the 5G system brings.

In order to properly steer the 6G research and innovations, it is vital to have clearly defined KPIs, but it is equally important to ensure that the defined KPIs can be measured and evaluated, such that the 6G technologies can be properly validated. This can be seen as a two-sided approach where the visions and use cases help define the KPIs, while the KPIs can also help drive the development of technologies and approaches to solving challenges.

The intention of this white paper is to provide an early analysis of possible 6G KPIs based on current work and perspectives from active B5G and 6G projects. The analysis of the KPIs from the project will seek to understand if the KPIs have existing definitions in standard documents (which imply a potential evolution of the KPI from 5G) or if they are new and thereby are candidates for being standardised (true 6G KPI).

Most KPIs are based on experiences from previous work related to 5G and will often be an increment in the target values of previously defined KPIs. These KPIs have existing definitions in the standard, while other KPIs are defined based on envisioned new features and capabilities of the upcoming 6G system. These new KPIs are not yet standardised and can be referred as true 6G KPIs.

With the early analysis of the 6G KPIs in the development process, the 5GPPP TMV group is also initiating the discussion around KPIs validation. Can all KPI be validated with existing measurement techniques or do we need to investigate new techniques? In case of new techniques, there is a need to have them invented and developed early to ensure a smooth 6G development.

It is the intention that this white paper will be updated once per year as the B5G and 6G projects evolve, but also new 6G projects are initiated and contribute to the collective development, e.g. through the SNS JU programme[13]. This will allow for continuous updates to the aggregated view of 6G KPIs.

1.2 5G PPP TMV WG

The Test, Measurement, and KPIs Validation (TMV) Working Group was founded as part of the 5G PPP effort to promote commonalities across projects that have strong interest in Testing & Monitoring (T&M) methodologies needed to provide support to the vertical use cases in 5G Trial Networks. Such efforts include the development of test and measurement methods, test cases, procedures as well as the KPI formalization and validation to the greatest possible extent, to ensure a unique European vision on how the entire lifecycle of the 5G network, ranging from R&D to actual deployed environments, can be supported.

The Group is comprised by several Phase II and Phase III 5G PPP projects, and deals with the following research areas and technology domains:

- Testing KPI definition, KPI sources, collection procedures and analysis
- Testing frameworks (requirements, environment, scenarios, expectations, limitation) and tools
- Testing methodologies and procedures
- KPI validation methodologies
- Testing lifecycle (i.e., testing execution, monitoring, evaluation and reporting)
- Common information models for 5G T&M

Another important topic is the use of and contribution towards open-source projects such as OSM, OPNFV or ONAP and the identification of relevant exploitation and dissemination targets to promote the European vision on T&M towards a more global adoption.

1.3 ICT-52 Projects

In response to the 5G-PPP ICT-52-2020 (ICT-52) call: 5G-PPP Smart Connectivity beyond 5G, 10 projects have been funded. 9 of them started on January 1st, 2021, while the last one (B5G-OPEN) started on November 1st, 2021.

HEXA-X is the flagship project for 6G vision and intelligent fabric of technology enablers. 6G BRAINS, AI@EDGE and DAEMON are related with Artificial Intelligence solutions, while DEDICAT 6G and REINDEER address smart connectivity approaches. RISE-6G vision capitalises on the latest advances on Reconfigurable Intelligent Surfaces (RIS) technologies and the design of the RIS-enabled wireless environment as a service, while TeraFlow targets cloud-native SDN controllers. MARSAL is related with network orchestration, while B5G-OPEN targets an integrated packet-optical transport architecture based on MultiBand (MB) optical transmission.

In the document, the available KPIs from 9 of 10 of the ICT-52 projects are consolidated. The KPIs of 5G-OPEN are not considered since it is in a very early stage. These KPIs will be consolidated in the updated version of the document.

The ICT-52 project abstracts are summarised in Annex A.

1.4 KPI Clustering Methodology

As aforementioned, being at the start of the 6G research era, a diverse group of visionaries and researchers provide visions and use cases for 6G. Following project development practices, these efforts start with the definition of the addressed scenarios and use cases and continue with the identification of relevant KPIs that need to be met. Depending on the scope of the projects, the nature of the applications/ services and the focus of the experts' groups, the reference level and the definition of these KPIs can be different. Standardised definitions used in previous generation networks are usually inherited, while at the same time new KPIs need to be defined addressing 6G-specific aspects. In order to provide a harmonized and formalised view of the B5G/ 6G KPIs across projects a three-step methodology was followed by the TMV WG.

As first step, the TMV defined the information to be collected by the research projects, related to the KPIs definitions, target values, as well as information relevant to the context of these definitions. In particular, the information to be collected have been the following:

KPI Category, referring to the targeted KPIs category for example: Data Rates and Capacity, Latency, Mobilty, Reliability and Availability, or other categories.

KPI Name, given in the context of the project.

KPIs Definition, detailed in order to ensure understanding of the true nature of the KPI.

Use case/ context of the KPIs, including details related to the context of a specific Proof of Concept.

Enhancement related to the KPI target value.

Information on where/how the KPIs will be measured, referring to the layer/ the reference points where measurements will be collected.

Any known information on the influence quantities of the KPI, being "the quantities that are not the measurand but that affects the result of the measurement"[4].

Relative or absolute evaluation of the KPIs

Other relevant information (e.g. Standardisation references)

In order to capture the ICT-52 projects' view on the KPIs, and not influence the results by means of predefining the KPI definitions and targets based on external references, the projects were asked to directly provide input (that is available at this stage) on the above.

With the collection of the responses and the aggregation and streamlining of the information the TMV WG further clustered the KPIs in a number of KPI families representing the ICT-52 projects vision on key B5G/6G qualities. These families are the following:

Latency: "Latency" is usually defined as the contribution of a network unit to the time from when the source sends a packet to when the destination receives it. A network unit can be a network segment or processing node (implemented as SW or as HW). On the basis of this definition, the "Latency KPIs" category defined in the context of this work includes all KPIs that refer to latency or to latency components (contribution) of various segments/ functions/ components, at various planes; namely user plane, control plane and orchestration plane in the performance of various application of network functionalities/processes. This classification has taken under consideration besides the standardised KPI definitions the work performed in [1], and [3] on the decomposition and definition of the latency contributions in 5G networks.

Capacity: The "Capacity" KPIs category refers to metrics that are used to evaluate the amount of network resources provided to end-users. From this perspective, the "Capacity KPIs" category includes KPIs evaluating the bandwidth resources provided per user (i.e. user data rate), the bandwidth resources provided per area surface or node (i.e. node capacity, area traffic density, etc.), and the number of connections/devices that can be served per area (i.e. connection density); as being multiple metrics of the network resources capability.

Packet Loss: The "Packet Loss" KPIs category refers to KPIs used for evaluating the packet transmission success rate of a system to transmit defined amount of traffic within a predetermined time. Packet Loss and Frame Loss are also considered as success rate measure of a transmission system.

Compute: Computing resources are expected to play a major role in the performance of B5G/6G networks, beside communication and storage resources. The "Compute" KPIs category reflects the importance of computing elements, and the fact that the use of computing resources is determinant in 6G implementation, usage and performance.

Energy: Energy KPIs family refers to KPIs used for evaluating the energy efficiency of a system. This system can be the B5G/6G network, the user device or even a VNF responsible for specific functionalities. The ultimate target in all KPIs is to decrease the energy consumption of the system.

Security: This KPI family covers KPIs related to security, anomaly detection and privacy. The KPIs are defined at different levels and are meant to be evaluated at different segments, and between different end-points in B5G/6G systems.

Channel: The "Channel" KPIs family refers to KPIs specifically addressing the evaluation of the communication channel and the efficiency of the use of the physical channel resources.

Electric and Magnetic Fields (EMF): This KPI family covers KPIs related to Electric and Magnetic Fields (EMF) - and in particular refer to measures of exposure to it.

Localisation: This KPI family addresses aspects of B5G/6G networks with regard to the localisation accuracy.

Service Availability and Reliability: This KPI family cover KPIs related to service availability and reliability. The service not being specifically defined it can cover different entities, related to different domains.

Following this clustering, the standardised KPI definitions from international and European Standardisation Organisations such as ITU-R, 3GPP and ETSI - and target values set available in previous generation networks - were reviewed and used as reference for the relevant KPI families. Main families addressed are: Capacity related (Peak Data Rate, User Experienced Data Rate, Area Traffic Capacity, Connectivity Density), Latency related (User Plane and Control Plane latency), Reliability, Energy Efficiency related (including Energy Efficiency in NFV) and Positioning related. These definitions are repeated in the following chapter.

2 Standard Network KPI Definitions

This section presents standard network KPIs as defined for 5G networks, including target values set for the 5G system. The definitions of the KPIs and how they are evaluated will be reused for B5G and 6G but the target values will be updated. In this section the KPIs are described along with 5G target values - new target values for B5G and 6G are proposed in Section 3 based on input from ICT-52 projects. The KPIs from standards covered in this section are selected based on presence of related KPIs from ICT-52 projects, meaning that some KPIs previously described in standards are left out, e.g. KPIs related to mobility.

2.1 Peak Data Rate

The following definition of Peak Data Rate is from ITU-R M.2410-0 (11/2017)[4].

Peak data rate is the maximum achievable data rate under ideal conditions (in bit/s), which is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilized (i.e. excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times).

Peak data rate is defined for a single mobile station. In a single band, it is related to the peak spectral efficiency in that band. Let W denote the channel bandwidth and SE_p denote the peak spectral efficiency in that band. Then the user peak data rate R_p is given by:

$$R_p = W \times SE_p \tag{1}$$

Peak spectral efficiency and available bandwidth may have different values in different frequency ranges. In case bandwidth is aggregated across multiple bands, the peak data rate will be summed over the bands. Therefore, if bandwidth is aggregated across Q bands then the total peak data rate is

$$R = \sum_{i=1}^{Q} W_i \times SEp_i \tag{2}$$

where W_i and SEp_i (i = 1,…Q) are the component bandwidths and spectral efficiencies respectively.

This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

The minimum requirements for peak data rate are as follows:

- Downlink peak data rate is 20 Gbit/s.
- Uplink peak data rate is 10 Gbit/s.

2.2 User Experienced Data Rate

The following definition of User Experienced Data Rate is from ITU-R M.2410-0 (11/2017)[4].

User experienced data rate is the 5% point of the cumulative distribution function (CDF) of the user throughput. User throughput (during active time) is defined as the number of correctly received bits, i.e. the number of bits contained in the service data units (SDUs) delivered to Layer 3, over a certain period of time.

In case of one frequency band and one layer of transmission reception points (TRxP), the user experienced data rate could be derived from the 5^{th} percentile user spectral efficiency through equation (3). Let W denote the channel bandwidth and SE_{user} denote the 5th percentile user spectral efficiency. Then the user experienced data rate, Ruser is given by:

$$R_{user} = W \times SE_{user} \quad (3)$$

In case bandwidth is aggregated across multiple bands (one or more TRxP layers), the user experienced data rate will be summed over the bands.

This requirement is defined for the purpose of evaluation in the related eMBB test environment.

The target values for the user experienced data rate are as follows in the Dense Urban – eMBB test environment for 5G networks:

- Downlink user experienced data rate is 100 Mbit/s.
- Uplink user experienced data rate is 50 Mbit/s.

These values are defined assuming supportable bandwidth as described in Report ITU-R M.2412-0[5] for each test environment. However, the bandwidth assumption does not form part of the requirement. The conditions for evaluation are described in Report ITU-R M.2412-0[5].

2.3 Area Traffic Capacity

The following definition of Area Traffic Capacity is from ITU-R M.2410-0 (11/2017)[4].

Area traffic capacity is the total traffic throughput served per geographic area (in $Mbit/s/m^2$). The throughput is the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time.

This can be derived for a particular use case (or deployment scenario) of one frequency band and one TRxP layer, based on the achievable average spectral efficiency, network deployment (e.g. TRxP (site) density) and bandwidth.

Let W denote the channel bandwidth and ρ the TRxP density ($TRxP/m^2$). The area traffic capacity C_{area} is related to average spectral efficiency SE_{avg} through equation.

$$C_{area} = \rho \times W \times SE_{avg} \quad (6)$$

In case bandwidth is aggregated across multiple bands, the area traffic capacity will be summed over the bands.

This requirement is defined for the purpose of evaluation in the related eMBB test environment.

The target value for Area traffic capacity in downlink is 10 $Mbit/s/m^2$ in the Indoor Hotspot – eMBB test environment for 5G networks.

The conditions for evaluation including supportable bandwidth are described in Report ITU-R M.2412-0[5] for the test environment.

2.4 Bandwidth

The following definition of Bandwith is from ITU-R M.2410-0 (11/2017)[4].

Bandwidth is the maximum aggregated system bandwidth. The bandwidth may be supported by single or multiple radio frequency (RF) carriers. The bandwidth capability of the RIT/SRIT is defined for the purpose of IMT-2020 evaluation.

The requirement for bandwidth is at least 100 MHz.

The RIT/SRIT shall support bandwidths up to 1 GHz for operation in higher frequency bands (e.g. above 6 GHz).

Proponents are encouraged to consider extensions to support operation in wider bandwidths considering the research targets expressed in Recommendation ITU-R M.2083[6].

The RIT/SRIT shall support scalable bandwidth. Scalable bandwidth is the ability of the candidate RIT/SRIT to operate with different bandwidths.

2.5 Connection Density

The following definition of Connection Density is from ITU-R M.2410-0 (11/2017)[4].

Connection density is the total number of devices fulfilling a specific quality of service (QoS) per unit area (per km2).

Connection density should be achieved for a limited bandwidth and number of TRxPs. The target QoS is to support delivery of a message of a certain size within a certain time and with a certain success probability, as specified in Report ITU-R M.2412-0[5].

This requirement is defined for the purpose of evaluation in the mMTC usage scenario.

The minimum requirement for connection density is 1 000 000 devices per km2.

2.6 Latency

The following definition of User and Control Plane Latency is from ITU-R M.2410-0 (11/2017)[4].

2.6.1 User Plane Latency

User plane latency is the contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). It is defined as the one-way time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface in either uplink or downlink in the network for a given service in unloaded conditions, assuming the mobile station is in the active state.

This requirement is defined for the purpose of evaluation in the eMBB and URLLC usage scenarios.

The minimum requirements for user plane latency in 5G networks are:

- 4 ms for eMBB
- 1 ms for URLLC

assuming unloaded conditions (i.e. a single user) for small IP packets (e.g. 0 byte payload + IP header), for both downlink and uplink.

2.6.2 Control Plane Latency

Control plane latency refers to the transition time from a most “battery efficient” state (e.g. Idle state) to the start of continuous data transfer (e.g. Active state).

This requirement is defined for the purpose of evaluation in the eMBB and URLLC usage scenarios.

The minimum requirement for control plane latency is 20 ms. Proponents are encouraged to consider lower control plane latency, e.g. 10 ms.

2.7 Reliability

The following definition of Reliability is from ITU-R M.2410-0 (11/2017)[4].

Reliability relates to the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability.

Reliability is the success probability of transmitting a layer 2/3 packet within a required maximum time, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface at a certain channel quality.

This requirement is defined for the purpose of evaluation in the URLLC usage scenario.

The minimum requirement for the reliability is 1-10-5 success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-URLLC test environment, assuming small application data (e.g. 20 bytes application data + protocol overhead).

Proponents are encouraged to consider larger packet sizes, e.g. layer 2 PDU size of up to 100 bytes.

2.8 Peak Spectral Efficiency

The following definition of Peak Spectral Efficiency is from ITU-R M.2410-0 (11/2017)[4].

Peak spectral efficiency is the maximum data rate under ideal conditions normalised by channel bandwidth (in bit/s/Hz), where the maximum data rate is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilized (i.e. excluding radio resources that are used for physical layer synchronization, reference signals or pilots, guard bands and guard times).

This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

The minimum requirements for peak spectral efficiencies are as follows:

- Downlink peak spectral efficiency is 30 bit/s/Hz.
- Uplink peak spectral efficiency is 15 bit/s/Hz.

These values were defined assuming an antenna configuration to enable eight spatial layers (streams) in the downlink and four spatial layers (streams) in the uplink. However, this does not form part of the requirement and the conditions for evaluation are described in Report ITU-R M.2412-0[5].

2.9 5th Percentile User Spectral Efficiency

The following definition of 5th Percentile User Spectral Efficiency is from ITU-R M.2410-0 (11/2017)[4].

The 5th percentile user spectral efficiency is the 5% point of the CDF of the normalized user throughput. The normalized user throughput is defined as the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time, divided by the channel bandwidth and is measured in bit/s/Hz.

The channel bandwidth for this purpose is defined as the effective bandwidth times the frequency reuse factor, where the effective bandwidth is the operating bandwidth normalized appropriately considering the uplink/downlink ratio.

With Ri (Ti) denoting the number of correctly received bits of user i, Ti the active session time for user i and W the channel bandwidth, the (normalized) user throughput of user i, ri, is defined according to equation (4).

$$r_i = \frac{\mathrm{R}_i(T_i)}{T_i \cdot \mathrm{W}} \tag{4}$$

This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

The minimum requirements for 5th percentile user spectral efficiency for various test environments are summarized in Table 1.

Table 1 5th percentile user spectral efficiency

Test environment	Downlink (bit/s/Hz)	Uplink (bit/s/Hz)
Indoor Hotspot – eMBB0.3	0.3	0.21
Dense Urban – eMBB (NOTE 1)	0.225	0.15
Rural – eMBB	0.12	0.045

NOTE 1 – This requirement will be evaluated under Macro TRxP layer of Dense Urban – eMBB test environment as described in Report ITU-R M.2412-0[5].

The performance requirement for Rural-eMBB is not applicable to Rural-eMBB LMLC (low mobility large cell) which is one of the evaluation configurations under the Rural- eMBB test environment.

The conditions for evaluation including carrier frequency and antenna configuration are described in Report ITU-R M.2412-0[5] for each test environment.

2.10 Average Spectral Efficiency

The following definition of Average Spectral Efficiency is from ITU-R M.2410-0 (11/2017)[4].

Average spectral efficiency is the aggregate throughput of all users (the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time) divided by the channel bandwidth of a specific band divided by the number of TRxPs and is measured in bit/s/Hz/TRxP.

The channel bandwidth for this purpose is defined as the effective bandwidth times the frequency reuse factor, where the effective bandwidth is the operating bandwidth normalized appropriately considering the uplink/downlink ratio.

Let Ri (T) denote the number of correctly received bits by user i (downlink) or from user i (uplink) in a system comprising a user population of N users and M TRxPs. Furthermore, let W denote the channel bandwidth and T the time over which the data bits are received. The average spectral efficiency, SEavg is then defined according to equation (5).

$$\mathrm{SE}_{\mathrm{avg}} = \frac{\sum_{i=1}^{N} \mathrm{R}_i(T)}{T \cdot \mathrm{W} \cdot M} \quad (5)$$

This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

The minimum requirements for average spectral efficiency for various test environments are summarized in Table 2.

Table 2 Average spectral efficiency

Test environment	Downlink (bit/s/Hz/TRxP)	Uplink (bit/s/Hz/TRxP)
Indoor Hotspot – eMBB0.3	0.3	0.21
Dense Urban – eMBB (NOTE 1)	0.225	0.15
Rural – eMBB	0.12	0.045

NOTE 1 – This requirement applies to Macro TRxP layer of the Dense Urban – eMBB test environment as described in Report ITU-R M.2412-00[5].

The performance requirement for Rural-eMBB is also applicable to Rural-eMBB LMLC which is one of the evaluation configurations under the Rural- eMBB test environment. The details (e.g. 8 km inter-site distance) can be found in Report ITU R M.2412-0[5].

The conditions for evaluation including carrier frequency and antenna configuration are described in Report ITU-R M.2412-0[5] for each test environment.

2.11 Energy Efficiency

The following definition of Energy Efficiency is from ITU-R M.2410-0 (11/2017)[4].

Network energy efficiency is the capability of a RIT/SRIT to minimize the radio access network energy consumption in relation to the traffic capacity provided. Device energy efficiency is the capability of the RIT/SRIT to minimize the power consumed by the device modem in relation to the traffic characteristics.

Energy efficiency of the network and the device can relate to the support for the following two aspects:

a) Efficient data transmission in a loaded case;
b) Low energy consumption when there is no data.

Efficient data transmission in a loaded case is demonstrated by the average spectral efficiency.

Low energy consumption when there is no data can be estimated by the sleep ratio. The sleep ratio is the fraction of unoccupied time resources (for the network) or sleeping time (for the device) in a period of time corresponding to the cycle of the control signaling (for the network) or the cycle of discontinuous reception (for the device) when no user data transfer takes place. Furthermore, the sleep duration, i.e. the continuous period of time with no transmission (for network and device) and reception (for the device), should be sufficiently long.

This requirement is defined for the purpose of evaluation in the eMBB usage scenario.

The RIT/SRIT shall have the capability to support a high sleep ratio and long sleep duration. Proponents are encouraged to describe other mechanisms of the RIT/SRIT that improve the support of energy efficient operation for both network and device.

2.12 Energy Efficiency in NFV

The following definition of Energy Efficiency in NFV is from ETSI EN 303 471 V1.1.1 (2019-01)[8] and the metric is defined in 3GPP TS 22.261 V16.4.0 (2018-06)[23].

Energy efficiency in NFV is calculated based on data transfer (KPIEE-transfer). The document specifies two variants of KPIEE-transfer (KPIEE-bit_transfer and KPIEE-packet_transfer) which are measures of the data volume transferred to and from the NFVI per unit of energy consumed by the NFVI as shown schematically in Figure 1.

The determination of the effectiveness of such NFVI in effecting a reduction of energy consumption depend upon knowledge of the energy consumption of the NFVI and data volume transmitted and received by the NTE with the NFVI.

KPIEE-bit_transfer is based on the data volume defined by the arithmetic sum of Layer 2 payload content of the number of successfully transmitted and received bits.

KPIEE-packet_transfer is based on the data volume defined by the arithmetic sum of successfully transmitted and received packets.

KPIEE-bit_transfer and KPIEE-packet_transfer do not take account of:

- the energy consumption involved in the transport of the data to and from the NFVI beyond the physical interface
- the energy consumption of any processing of the data (e.g. routing, etc.) beyond the physical interface

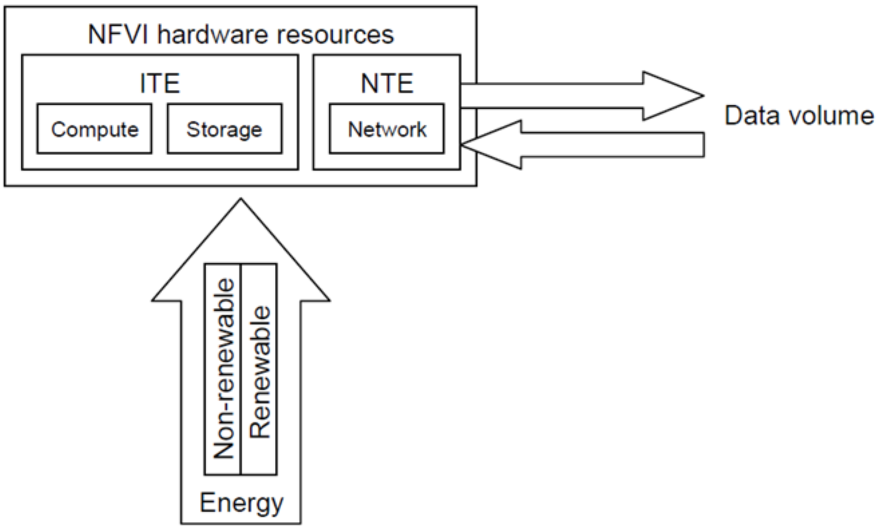

Figure 1 Energy efficiency in NFV based on data transfer[8]

2.13 Higher-Accuracy Positioning

The following definition of Higher-Accuracy Positioning in NFV is from 3GPP TS 22.261 V16.4.0 (2018-06)[23].

Higher accuracy positioning is characterized by ambitious system requirements for positioning accuracy. One typical area where "higher-accuracy positioning" is needed is collision avoidance of vehicles: every vehicle must be aware of its own position, the positions of near-by vehicles, and also their expected paths, to avoid collisions. On the factory floor, it is important to locate moving objects such as forklifts, or parts to be assembled.

The 5G system shall support the use of 3GPP and non-3GPP technologies to achieve higher-accuracy positioning.

The corresponding positioning information shall be acquired in a timely fashion, be reliable, and be available (e.g., it is possible to determine the position).

UEs shall be able to share positioning information between each other e.g., to a controller if the location information cannot be processed or used locally.

For mobile objects on factory floor, 3GPP TS 22.261[23] defines:

- Position acquisition time: 500 ms
- Survival time: 1 s
- Availability: 99.99%
- Dimension of service area: 500x500x30m
- Position accuracy: 0.5 m

2.14 Quality of Experience

The Quality of experience (QoE) has been defined by the ITU-T Recommendation P.10/G.100 (ITU-T 2017)[27] as "*the overall acceptability of an application or service, as perceived subjectively by the end-user*", covering the complete end-to-end system effects (client, terminal, network, services infrastructure, etc.). Hence, the QoE is subjective by definition, because of its relationship with user's viewpoint, expectations and context. Hence, since measuring a subjective QoE may differ from one client to another, it is usually estimated using objective parameters. For example, the most popular objective video quality estimation methods are Human and non-Human Visual System (HVS) perception, covering QoS parameters, such as peak SNR, Video Quality Model (VQM), Perceptual Video Quality of Experience (PEVQ), Perceptual Quality Index (PQI), etc.

The ability to measure QoE would provide network operators with some sense of the contribution of the network's performance to the overall customer satisfaction, in terms of reliability, availability, scalability, speed, accuracy and efficiency. The factors that affect the user-perceived QoE are bandwidth, jitter, delay and packet loss rate. The mean opinion score (MOS), is an example of a subjective measurement method in which users rate the service quality by giving five different point scores, from 5 to 1, where 5 is the best quality and 1 is the worst quality. Quality can be classified as Bad [0 – 1], Poor [1 – 2], Fair [2 – 3], Good [3 – 4] and Excellent [4 – 5].

The minimum requirement is to have MOS values > 4.3.

3 Clustering of KPIs Provided by ICT-52 Projects

In the following are the collected inputs from the ICT-52 projects, aggregated and streamlined the presentation of them. The clustering methodology is described in Section 1.4 and the ICT-52 projects and their aims are described in Section 1.3.

3.1 Latency

The "Latency KPIs" category defined in the context of this work includes all KPIs that refer to latency or to latency components (contribution) of various segments/ functions/ components, at various planes; namely user plane, control plane and orchestration plane in the performance of various application of network functionalities/processes. The following tables summarise the views of ICT-52 projects on various Latency-related KPIs. [1][3]

KPI name (project)	**E2E Service Latency**
Projects	6G BRAINS, DAEMON, TeraFlow, MARSAL, Hexa-x, DEDICAT-6G
3GPP Rel. 18 docs	n/a
Project definition	Projects use standard definition, see ITU-R M.2410-0 (11/2017)[4] below. Target values according to 3GPP TS 22.261[23] and similar.
Standard definition	ITU-R M.2410-0 Report (2017)[4]: User plane latency is the contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). It is defined as the one-way time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface in either uplink or downlink in the network for a given service in unloaded conditions, assuming the mobile station is in the active state. This requirement is defined for the purpose of evaluation in the eMBB and URLLC usage scenarios. The minimum requirements for user plane latency are: – 4 ms for eMBB – 1 ms for URLLC assuming unloaded conditions (i.e. a single user) for small IP packets (e.g. 0 byte payload + IP header), for both downlink and uplink.
Target value (project)	6G BRAINS: Maximum tolerated E2E delay is 7 ms, best case 5ms, unacceptable 10ms DAEMON: O(sec) MARSAL: <10ms Hexa-X: Depends on the Use Case [10] DEDICAT-6G: User Plane - 1 ms, Control Plane - 10ms

Other remarks	n/a

KPI name (project)	**New Latency contribution components**
Projects	RISE-6G, DAEMON, MARSAL
3GPP Rel. 18 docs	n/a
Project definition	RISE-6G: The definition of latency in the context of computing depends on the kind of computation offloading request which can be categorized as either static or dynamic. It can take various forms: execution latency, service latency, RIS control latency, processing latency, etc. Includes "Static Computation Offloading" & "Dynamic computation Offloading"[12]. DAEMON: Latency between requests/responses of AI-based NI algorithms MARSAL: Increased network efficiency in terms of communication resource utilization and latency.
Standard definition	ITU-R M.2410-0 Report (2017) [4]-User plane latency definition
Target value (project)	DAEMON: Latency between requests/responses of AI-based NI algorithms <1 ms. MARSAL: In case of unbalanced demands the ability to re-direct traffic increasing the network resource utilization will be showcased while keeping the latency for time critical applications below 1 ms.
Other remarks	Decomposition of Latency according to 5GPPP needs to be taken into account [1][3].

KPI name (project)	**E2E Application Latency - for Video processing services**
Projects	DEDICAT-6G, AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	DEDICAT-6G: Calculation of time difference between camera capture and appearance in video playback. AI@EDGE: Latency induced in system during processing of video resources.
Standard definition	n/a
Target value (project)	DEDICAT-6G: E2E 200ms at application level AI@EDGE: <100ms

Other remarks	n/a

KPI name (project)	**Mission critical QoS of services - latency related**
Projects	DEDICAT-6G
3GPP Rel. 18 docs	ETSI TS 122 179 in 2020 related to 3GPP MCX[7]
Project definition	The quality and availability of the Intelligent Distributed Coverage Extension brought by DEDICAT-6G shall not be regressed accordingly to the standard released by the ETSI in the Technical Specification 122,179 in 2020 related to 3GPP MCX[7].
Standard definition	The MC Audio Functional Component shall address the 4 main indicators defined in the standard: Provide MC-PTT access time less than 300 ms for 95% of all requests; The End-to-End MC-PTT access time less than 1000 ms for all MCX mobile application under the same network coverage; The mouth-to-ear latency less than 300 ms for 95% of all voice bursts; The maximum late call entry time shall be 150 ms for 95% of all late call request. The indicators related to IP and data transmissions (MC Data or MC Video Functional Components shall be as following): The End-to-End Delay which is the time required for IP packets to be transmitted shall be less than 10 ms; The User Data Rate shall be 100 Mbps in downlink and 50 Mbps in uplink;
Target value (project)	DEDICAT-6G poses the same target values as in the standard definition in the above KPIs. In addition, the Reliability indicator of the DEDICAT-6G shall be at least 99.999% of success for the transmission of a packet of 32 bytes within 1ms.
Other remarks	n/a

KPI name (project)	**Sensor to Vehicle Latency**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	From sensor detection to Vehicle, including sensor fusion on edge. Compute time passed between packets send from Edge Network to Vehicles and vice versa. The goal is to recreate the network-level data exchange required to build a cooperative perception between emulated vehicles and a virtual human-driven vehicle.
Standard definition	n/a
Target value (project)	Not provided by project.

Other remarks	Evaluation of the C-V2X simulation environment using 5G network emulators, driving simulators, network simulators.

KPI name (project)	**Runtime Delay**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	The time needed for MEAO to perform any LCM (Life Cycle Management) operations, i.e., while an application instance is running (e.g., scaling, termination, heal, etc.)
Standard definition	n/a
Target value (project)	Achieve runtime delay in the proximity of at most 650 ms
Other remarks	In the 5G Core, multiple operations and applications run at any instance. So in the context of the system’s automation, the delay of LCM operations must be as low as possible.

3.2 Capacity

The “Capacity” KPIs category refers to metrics that are used to evaluate the amount of network resources provided to end-users. The relevant KPIs summarising the ICT-52 project views are as follows:

KPI name (project)	**User Data Rate**
Projects	6G BRAINS, REINDEER, TeraFlow, DEDICAT-6G, AI@EDGE
3GPP Rel. 18 docs	Use-case specific, e.g., 3GPP TS 22.261[23].
Project definition	Projects use standard definition, see ITU-R M.2410-0 (11/2017)[4] below.
Standard definition	From ITU-R M.2410-0(11/2017)[4]. Report: user experienced data rate is the minimum data rate required to achieve a sufficient quality experience, with the exception of scenario for broadcast like services where the given value is the maximum that is needed.
Target value (project)	6G BRAINS: Max. 100Mbps REINDEER: "Virtual reality home gaming (150 Mbps) Location-based information transfer (10 Mbps) Position tracking of robots and UVs (Up to 10 Mbps)

	Augmented reality for professional applications (45 Mbps – 3Gbps depending on if video streams are compressed/uncompressed) Augmented reality for sport events (5 Mbps) MARSAL: Smart contracts' throughput Hexa-X: based on use cases [10] DEDICAT-6G: Peak data rate in bit/s: 20 Gbit/s (DL); 10 Gbit/s (UL), Minimum user data rate (5th percentile) in bit/s: 100 Mbit/s (DL); 50 Mbit/s (UL). AI@EDGE: Possibly minimum 15Mbps (4k streaming requirements)
Other remarks	Should be achieved with: 5th percentile of Shannon's capacity with respect to UE with lowest 5th percentile"

KPI name (project)	**Network Capacity**
Projects	DAEMON, REINDEER, DEDICAT-6G
3GPP Rel. 18 docs	n/a
Project definition	Project uses standard definition, see ITU-R M.2410-0 (11/2017)[4] below.
Standard definition	ITU-R M.2410-0 Report (2017)[4]: Area traffic capacity is the total traffic throughput served per geographic area (in Mbit/s/m2). The throughput is the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time. This can be derived for a particular use case (or deployment scenario) of one frequency band and one TRxP layer, based on the achievable average spectral efficiency, network deployment (e.g. TRxP (site) density) and bandwidth. Let W denote the channel bandwidth and ρ the TRxP density (TRxP/m2). The area traffic capacity Carea is related to average spectral efficiency SEavg through equation. Carea = ρ × W × SEavg In case bandwidth is aggregated across multiple bands, the area traffic capacity will be summed over the bands. This requirement is defined for the purpose of evaluation in the related eMBB test environment. The conditions for evaluation including supportable bandwidth are described in Report ITU R M.2412-0[4] for the test environment. NGMN Recommendations (2016)[2]: NGMN, defines this KPI similarly with ITU, but details two different conditions: Full buffer: Total traffic throughput served per geographic area (in Mbit/s/m2). The computation of this metric is based on full buffer traffic.

	Non full buffer: Total traffic throughput served per geographic area (in Mbit/s/m2). Both the user experienced data rate and the area traffic capacity need to be evaluated at the same time using the same traffic model.
Target value (project)	DAEMON: 100% Enhancement compared to 5G REINDEER: Virtual reality home gaming, position tracking of robots, and UBs and Location-based information transfer (50 Mbps/m2); Augmented Reality for Professional Applications, Human and robot co-working in industrial environments (4.5-5 Mbps/m2) Tracking of goods and real-time inventory – Enable evolution of logistics and real-time information on the status of each single item of the supply chain. (10 Mbps/m2 for warehouses, 100 Mbps/m2 for hospitals); Real-time digital twins in manufacturing (20 Mbps / m2) Augmented reality for sport events (10Mbps/m2). Analytical study for evaluation DEDICAT-6G: Area traffic capacity in Mbit/s/m2: 10 Mbit/s/m2 (DL) (Bandwidth: 100MHz)
Other remarks	n/a

KPI name (project)	**User Density – Connection Density**
Projects	6G BRAINS
3GPP Rel. 18 docs	n/a
Project definition	Calculate the number of devices that meet the data rate and reliability requirements in a specific area.
Standard definition	User Density is also known as Connection Density: A number of definitions have been provided by standardisation organisations as follows: • ITU-R M.2410-0 Report (2017)[4]: Connection density is the total number of devices fulfilling a specific quality of service (QoS) per unit area (per km2). Target QoS to be defined as delivery of a message of a certain size within a certain time and with a certain success probability. The target value of this KPI for 5G networks is 1 000 000 devices per km^2. • NGMN Recommendations (2016)[2]: Same definition as ITU, with the remarks that QoS definition should take into account the amount of data generated within a time t_gen that can be sent or received within a given time, t_sendrx, with x% probability. "

Target value (project)	0.33-3 per m2
Other remarks	lower than the 5G target of 1/m2 in 5G

3.3 Packet Loss

“Packet Loss” related KPIs are used for evaluating the packet transmission success rate of a system to transmit defined amount of traffic within a predetermined time. The relevant KPIs defined in ICT-52 projects are summarised in the following table.

KPI name (project)	**Packet Error Rate @ network layer**
Projects	6G BRAINS
3GPP Rel. 18 docs	n/a
Project definition	Packet error rate within latency requirements (with target latency).
Standard definition	ITU-R M.2410-0 (11/2017)[4]: Reliability relates to the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability. Reliability is the success probability of transmitting a layer 2/3 packet within a required maximum time, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface at a certain channel quality. This requirement is defined for the purpose of evaluation in the URLLC usage scenario. The minimum requirement for the reliability is 1-10-5 success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-URLLC test environment, assuming small application data (e.g. 20 bytes application data + protocol overhead). Proponents are encouraged to consider larger packet sizes, e.g. layer 2 PDU size of up to 100 bytes.
Target value (project)	E2E reliability of up to 10^{-7} to maintain close synchronisation at E2E, per link reliability of around 10^{-9}, Measured on Network Layer
Other remarks	Data packets captured with Profitap[14] and calculate reliability using block error rate for both DL and UL

KPI name (project)	**Layer2/3 packet transmission success rate**

Projects	DAEMON
3GPP Rel. 18 docs	n/a
Project definition	Data transmission success probability to send a given amount of traffic within a predetermined time duration.
Standard definition	Project uses standard definition, see ITU-R M.2410-0 (11/2017)[4]
Target value (project)	Five 9's, measured at Layer 2/3 over the radio interface until the Linux container on the edge node.
Other remarks	The success probability of transmitting a layer 2/3 packet within a required maximum time at a certain channel quality.

KPI name (project)	**Packet Loss Rate**
Projects	TeraFlow
3GPP Rel. 18 docs	n/a
Project definition	The ratio of packets dropped to packets transmitted between two endpoints over a period of time.
Standard definition	Reliability is Maximum tolerable packet loss rate at the application layer within the maximum tolerable end-to-end latency for that application.
Target value (project)	Not defined
Other remarks	Use cloud-native distributed architectures. SDN Control Layer with NFV-based functions, dedicated Monitoring component using ECA-based policy management and KPOI templates for services and devices.

KPI name (project)	**Frame Loss**
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	The forwarding rate of interface under 100% of load for various frame lengths of the Transport Network Equipment (TNE).
Standard definition	n/a
Target value (project)	Measured using a traffic generator and analyser (Ethernet).

Other remarks	Different traffic configurations for backhaul, midhaul and fronthaul.

KPI name (project)	**Signal Packet Loss**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	Define the percentage of packets dropped during a wireless E2E exchange of data.
Standard definition	n/a
Target value (project)	Not defined.
Other remarks	The goal is to measure the reliability of a communication system in regards to information loss during broadcast. Direct E2E links in Edge Computing Systems, eNBs, ground stations etc.

KPI name (project)	**Service Recovery Time**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	Average time for restoring internet services in-flight. Focused on UEs connected to in-flight network.
Standard definition	n/a
Target value (project)	$\leq$ 180 s
Other remarks	n/a

3.4 Compute

The "Compute" KPIs family comprises a number of newly defined KPIs, not considered in previous generation networks. This reveals the increasing importance and role of computing resources in implementation, usage and performance of 6G services. The relevant KPIs defined are summarised in the following table.

KPI name (project)	**Edge computational resource usage**

Projects	DAEMON
3GPP Rel. 18 docs	n/a
Project definition	Reduction in computational resources (%) before/after the application of the solution
Standard definition	n/a
Target value (project)	Target: 40%. Current results of the DAEMON partners show that by applying intelligent radio and CPU scheduling in O-RAN architectures, one can reduce the computation resources required by virtualized base stations by up to 20% with minimal impact on performance. The improved NI design developed by DAEMON shall advance those techniques from multiple perspectives as outlined in Objectives 1-3, hence making a 40% reduction target viable.
Other remarks	• Reduction of computing resources with edge solutions • Multi-timescale Edge resource management • Edge computing for energy consumption

KPI name (project)	**Operation expenditure @edge**
Projects	DAEMON
3GPP Rel. 18 docs	n/a
Project definition	Reduction in OPEX (%) before/after the application of the solution
Standard definition	n/a
Target value (project)	Target: 60%. Preliminary studies of the DAEMON partner demonstrate how AI models trained with customized loss functions that reflect monetary costs can avoid Service-Level Agreement (SLA) violations and reduce Operation Expenditure (OPEX) by up to 40%. While these figures refer to local solutions, the structured coordination of NI instances enabled by the DAEMON architecture will allow targeting further cost savings of up to 60%.
Other remarks	• Edge orchestration • Kubernetes cluster and virtualized RAN deployment on the edge node • Reduced OPEX via resource savings

KPI name (project)	**Delta in network management decision**
Projects	DAEMON

3GPP Rel. 18 docs	n/a
Project definition	Performance gap between the actual decision performance and optimum performance
Standard definition	n/a
Target value (project)	Target: 1%. DAEMON will ensure that decisions on network resource and function allocation occurring at periodicities of hours will perform very close (99%) to optimum oracles. This will ensure that such decisions are precise enough to assist constructively faster NI, which use such longer timescale decisions (e.g. policies) as input.
Other remarks	• Network resource and function allocation at periodicities of hours, with minimal overhead (<1%) • Run with Linux containers running on edge nodes

KPI name (project)	**Availability**
Projects	TeraFlow
3GPP Rel. 18 docs	n/a
Project definition	No definition provided by the project
Standard definition	ISO/IEC 27000 (2014)[16] definition: The property of being accessible and usable upon demand by an authorized entity
Target value (project)	No target value provided, but it can be calculated using the following formula: Availability = (1 – (MTTR/MTBF)) x 100%, where MTTR is the mean time to repair, and MTBF is the mean time between failures
Other remarks	• Measures the ratio of uptime to the sum of uptime and downtime, where uptime is the time the network slice is available • Use cloud-native distributed architectures

KPI name (project)	**Resource utilization**
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	The resource utilization in terms of computing, storage, and networking, of the hosts and data-centres across the network domains.
Standard definition	n/a

Target value (project)	No target value provided
Other remarks	• Resource utilization in terms of computing, storage, and networking, of the hosts and datacentres across the network domains. • Avoid the overall network underutilization of available resources while diminishing overutilization of certain hosts.

KPI name (project)	**Scale-out latency**
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	The time it takes from submitting the order of creating (or scaling-out) a containerized function to the actual deployment of such function.
Standard definition	n/a
Target value (project)	No target value provided
Other remarks	• Scale-out latency and related resource utilization. • Investigate how to achieve optimal latency budgets through the MEC orchestrator (MEO) to derive the optimal placement of the containerized application functions at the Radio Edge or Regional Edge data-centres.

KPI name (project)	**Computing resource utilization**
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	The percentage of the available processing and storage Virtual Elastic resources that are consumed by MEC applications
Standard definition	n/a
Target value (project)	No target value provided
Other remarks	• Increased compute resource utilization via load balancing • Measured as the amount of system CPU and storage consumed relative to the maximum resources of the Virtual Elastic infrastructure resource pool

3.5 Energy

Energy Efficiency has always been a critical performance indicator of a system, thus relevant KPIs have been defined from previous networks generations. These definitions in some cases need to be/ are repurposed to provide KPIs which are measurable in the B5G/ 6G network implementations / technologies/ network architecture segments. The relevant KPIs considered by ICT-52 projects are summarised in the following tables.

KPI name (project)	**Network Energy efficiency**
Projects	DEDICAT-6G
3GPP Rel. 18 docs	Network energy efficiency: • ITU-R M2410-0[4] • 3GPP TR 21.866[18] • RP-213554: Study on network energy savings for NR[15]
Project definition	Decreased energy consumption (incl. communication and computation) in order to increase the operation lifetime of a mobile station or server
Standard definition	Network energy efficiency is the capability of a RIT/SRIT to minimize the radio access network energy consumption in relation to the traffic capacity provided. Energy efficiency of the network can relate to the support for the following two aspects: a) Efficient data transmission in a loaded case; b) Low energy consumption when there is no data.
Target value (project)	A factor of 10. Investigate how the energy consumption in edge devices and potentially in the system overall can be reduced through dynamic intelligence distribution
Other remarks	Measured as relative value

KPI name (project)	**Device Energy Efficiency**
Projects	DEDICAT-6G
3GPP Rel. 18 docs	Network energy efficiency: • ITU-R M2410-0[4] • 3GPP TR 21.866[18] • RP-213554: Study on network energy savings for NR[15]
Project definition	Comparison of the battery level measures with and without the use of intelligence distribution mechanisms for certain services/applications.

Standard definition	Device energy efficiency is the capability of the RIT/SRIT to minimize the power consumed by the device modem in relation to the traffic characteristics. Energy efficiency of the device can relate to the support for the following two aspects: a) Efficient data transmission in a loaded case; b) Low energy consumption when there is no data.
Target value (project)	n/a
Other remarks	Measured as relative value

KPI name (project)	**VNF Energy consumption reduction**
Projects	DAEMON
3GPP Rel. 18 docs	Network energy efficiency: • 3GPP TR 21.866[18] • RP-213554: Study on network energy savings for NR[15] Energy efficiency in NFV • ETSI EN 303 471 (2019-01)[8]
Project definition	Reduction in VNF energy consumption (%) before/after the application of the solution
Standard definition	The data volume transferred to and from the NFVI per unit of energy consumed by the NFVI. The data volume is defined by the arithmetic sum of Layer 2 payload content of the number of successfully transmitted and received bits.
Target value (project)	DAEMON 50%: DAEMON aims at saving of up to 25% of energy costs thanks to a NI-assisted VNF placement based on energy considerations. Furthermore, additional 25% savings will be allowed by NI-assisted VNFs that can adapt their energy footprint to the context of the location where they are running
Other remarks	Measured as relative value

3.6 Security

This KPI family covers KPIs related to security, anomaly detection and privacy. Historically security in systems have often been an afterthought which has been added and checked after the main functional development have taken place. But even when security have been included and planned from the beginning, vulnerabilities are still discovered later due to the complexity of the systems. This makes the definition of security related KPIs at an early stage vital. The relevant KPIs considered by the ICT-52 projects are summarized in the following tables.

KPI name (project)	**Anomaly detection precision**
Projects	DAEMON
3GPP Rel. 18 docs	n/a
Project definition	Precision-recall area under curve (AUC) with at least minimum scoring in precision and recall
Standard definition	n/a
Target value (project)	Target: >0.85. DAEMON will target a 0.9 precision-recall area under curve (AUC) with at least 85% scoring in both precision and recall.
Other remarks	The KPI evaluates the capability of the applied anomaly detection method, which means that the KPI is independent of which anomaly detection method is applied. It would be good to have the description of this KPI extended with more details on the anomaly detection method and an example of this.

KPI name (project)	**Security conformance**
Projects	TeraFlow
3GPP Rel. 18 docs	3GPP TR 33.916[19], 3GPP TR 33.818[20]
Project definition	Conformance to security constraints. Network slice controller authentication. Date integrity of a network slice.
Standard definition	Security Assurance Methodology (SECAM) Security Assurance Specifications (SCAS)[17]
Target value (project)	Note that the use of security or the violation of this SLO is not directly observable by the network slice consumer and cannot be measured as a quantifiable metric.
Other remarks	KPI monitored using ECA-based policy management.

KPI name (project)	**Tenant data privacy**
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	Amount of confidential information shared between the tenants and the infrastructure owner, needed to optimize performance of whole system.

Standard definition	n/a
Target value (project)	Not provided by project
Other remarks	A measure of how well telemetry from a tenant is anonymized when applying privacy preserving function developed within project. Description mention how performance is expected to drop when privacy is improved/strengthened - but is yet to defined what performance is referred to and how the level of privacy measured (between transferred data and raw data).

3.7 Channel

The Channel KPI family cover KPIs related to the physical channel such as spectral efficiency, SINR, channel estimation efficiency and energy efficiency. These are typically know from previous generation communication systems, but with the increased complexity in the physical channel, and the advent of including AI and ML in the mix, evaluating the KPIs in the new setting becomes more relevant than ever. The relevant KPIs considered by ICT-52 projects are summarised in the following tables.

KPI name (project)	**Spectral Efficiency**
Projects	RISE-6G
3GPP Rel. 18 docs	New SI/WI: Network Energy Savings: definition of an evaluation methodology and KPIs (i.e. system-level network energy consumption and energy savings gains, as well as assessing/balancing impact to network and user performance (e.g. spectral efficiency, capacity, UPT, latency, handover performance, call drop rate, initial access performance, SLA assurance related KPIs), energy efficiency.
Project definition	Reliably transmitted rate of information. SE = log2(1+SINR) Measured at the UE in the physical layer through RSSI[12].
Standard definition	ITU-R M.2410-0 (11/2017)[4] Average spectral efficiency is the aggregate throughput of all users (the number of correctly received bits, i.e. the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time) divided by the channel bandwidth of a specific band divided by the number of TRxPs and is measured in bit/s/Hz/TRxP.
Target value (project)	Planned to boost by a factor of 10 with the RIS optimisation, measured in bits/s/Hz
Other remarks	n/a

KPI name (project)	**Communication reliability (SINR)**

Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	The set of UEs where the received signal SINR is greater than defined level t, measured for DL and UL, could be also defined as percentage of decoded packets (outage probability), also Reliability of the RIS control channel (capability to adapt)[12].
Standard definition	The one minus the outage probability referring to the SINR metric
Target value (project)	RIS-enabled systems enlarge coverage area where SINR is above target value t.
Other remarks	Availability is the percentage of time/area where the target SINR is met, RSSI measurements used for calculation.

KPI name (project)	**Channel estimation accuracy**
Projects	RISE-6G
3GPP Rel. 18 docs	Common KPI in various PHY-Layer releases.
Project definition	Estimation of the end-to-end channel matrix with Normalized Mean Squared Error (NMSE) metric to assess the performance of the channel estimation process, Frobenius norm used[12].
Standard definition	The difference between the actual channels and its estimation.
Target value (project)	Depends on the application and on the operating SNR.
Other remarks	Estimated at UE in the physical layer using pilot signals. Will be evaluated by simulations where the channel is known.

KPI name (project)	**Energy efficiency**
Projects	RISE-6G
3GPP Rel. 18 docs	3GPP TR 21.866[18]
Project definition	Energy Efficiency (EE) is defined as the ratio of the sum data spectral efficiency and the total power consumption at the DL for proving the target service[12].
Standard definition	Similar to the project’s definition.

Target value (project)	Usage of RIS should boost a service EE. Also, beamforming optimisation is considered. Initial measurements without RIS (M1) and the second measurement with the presence of RIS (M2), gain will be calculated in dB G(dB)=10*log10(M2/M1). Several dBs gain expected
Other remarks	Planned to be measured in indoor environment.

KPI name (project)	**Secrecy spectral efficiency (SSE)**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	Secrecy Spectral Efficiency (SSE) is given by SSE = max(0, R1-RN1) where R1 = log2(1+SINR1) and RN1 = log2(1+SINRN1) expressing the legitimate receiver's and eavesdropper's rate, measured in bits/s/Hz [12].
Standard definition	n/a
Target value (project)	When difference R1-RN1 is less than 0 no secrecy rate is achievable. RIS can offer boosting to SSE.
Other remarks	Estimated at UE in the physical layer using pilot signals. Will be evaluated by simulations where the channel is known.

KPI name (project)	**Spectral Efficiency** (Per user spectral efficiency, System spectral efficiency)
Projects	MARSAL
3GPP Rel. 18 docs	n/a
Project definition	The spectral efficiency can be measured as the information rate that can be transmitted over given physical resource blocks of the considered cell-free mMIMO networks at the radio edge.
Standard definition	n/a
Target value (project)	The spectral efficiency can be measured as the information rate that can be transmitted over given physical resource blocks for both uplink and downlink directions, measured in bits/s/Hz.
Other remarks	Cell Free mMIMO networks, Precoding optimisation, and radio resource allocation.

3.8 Electromagnetic Field (EMF)

A long-established aspect of mobile networks that has always been addressed is the Electromagnetic Field (EMF) exposure of the involved people in the scenario and in particular the evaluation and measure of dosimetric quantities. A number of KPIs addressing this aspect from various levels/ points are defined by ICT-52 projects, and are summarised in the tables below.

KPI name (project)	**Self EMF exposure**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	For the uplink communication direction, S-EMFEU = R_UL/X_I, where R_UL is the data rate that is transmitted by the considered user in the uplink direction and X_I is the EMF to which the same considered user is exposed. Note that the considered user can be seen as an uplink “intended” user[12].
Standard definition	IEC 62209-1/2[28] (Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices - Human models, instrumentation and procedures)
Target value (project)	A first measurement of the metric will be performed in the absence of the reconfigurable intelligent surfaces RIS(s): M1. A second measurement will be performed in the presence of RIS(s): M2. We expect to observe a gain G=10*log10(M2/M1) of several dBs.
Other remarks	In connection with these measurements should also be considered the limits set by EU and national agencies

KPI name (project)	**Inter EMF exposure**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	For the downlink communication direction, I-MFEU is defined as I-EMFEU = R^DL/X^NI, where R^DL is the data rate that is delivered to the intended user and X^NI is the EMF to which the non-intended user is exposed. When considering multiple non-intended users, X^NI is the EMF of the most exposed one[12].
Standard definition	IEC 62232[9] (Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure)

Target value (project)	A first measurement of the metric will be performed in the absence of the RIS(s): M1. A second measurement will be performed in the presence of RIS(s): M2. We expect to observe a gain G=10*log10(M2/M1) of several dBs.
Other remarks	In connection with these measurements should also be considered the limits set by EU and national agencies

3.9 Localisation

The Localisation KPI family contains KPIs related to accuracy, delay and error of localisation and direction. This is an added service provided by the communication network besides its core functionalities, that are provided to the users and devices connected to the network. The relevant KPIs considered by ICT-52 projects are summarised in the following tables.

KPI name (project)	**Localisation accuracy**
Projects	6G BRAINS, RISE-6G
3GPP Rel. 18 docs	TS 22.261 V18.5.0 (2021-12)[23] TS 23.271 (Rel. 17)[21] / TS 22.071 (Rel. 16)[22]
Project definition	The localization accuracy describes the distribution of the localization error. The location error is a 3D random variable, comprising horizontal (XY) and vertical (Z) errors. Common statistics can be computed based on the 3D error or 2D error and include the Mean Square Error (MSE), the Root MSE (RMSE), the 99% localization error in meters (i.e., the error value such that 99% of the localization errors have smaller magnitude).
Standard definition	Accuracy is the difference between actual location and estimated location. Note: this KPI may refer to the horizontal only or the 3D location (including the vertical location)
Target value (project)	6G BRAINS 1 mm to 1 cm RISE-6G 1 cm to 10 cm[12]
Other remarks	• Measured as an absolute value • Relate to service • Already in 5G and 5G Enhanced

KPI name (project)	**Direction/Orientation accuracy**

Projects	6G BRAINS, Hexa-X
3GPP Rel. 18 docs	3GPP TS 22.804[25], 3GPP TS 22.855[26]
Project definition	Direction accuracy. Definition in D2.1/6G-BRAINS[11] Orientation accuracy [°]. Accuracy of the estimated direction of UE: roll, pitch, yaw[10]. Angular resolution [°] Required minimum distinguishable angle between two objects (orientation)[10].
Standard definition	n/a
Target value (project)	1° direction accuracy (6G-BRAINS)
Other remarks	n/a

KPI name (project)	**Localisation related delays**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	First-time-to-fix: time until the system provides the first location estimate; Localization latency: time between a positioning request and the position being available; Update rate: time between successive position estimates[12].
Standard definition	n/a
Target value (project)	not provided
Other remarks	n/a

KPI name (project)	**Localisation (error) integrity**
Projects	RISE-6G
3GPP Rel. 18 docs	n/a
Project definition	Relevant localization integrity metrics are[12]: • Reliability: measured by mean-time between failures (MTBF) or duration of the time the service is available; • Availability: fraction of the time the service is available.

Standard definition	n/a
Target value (project)	not provided
Other remarks	n/a

3.10 Service Availability and Reliability

This KPI family cover KPIs related to service availability and reliability. New generations of communication networks become more integrated with the services using the communication networks, as opposed to simply providing end-to-end connectivity between services and users. The relevant KPIs considered by ICT-52 projects are summarised in the following tables.

KPI name (project)	**Service availability**
Projects	Hexa-X
3GPP Rel. 18 docs	3GPPP TS 22.261[23]
Project definition	Percentage of time during which QoS targets are met and service is offered during operation.
Standard definition	Use-case specific, e.g., 3GPP TS 22.261[23] for communication service availability; c.f. references in D1.3 for each use case
Target value (project)	Relative ratio, e.g., 99,999% of operation time QoS targets are met
Other remarks	For communication service: Network nodes (virtual NFs + hardware functions). For AI/Computation and Localization/sensing: depending on service realization (e.g., MEC nodes, AI/ML Agents)

KPI name (project)	**Service reliability**
Projects	Hexa-X
3GPP Rel. 18 docs	3GPP TS 22.261[23], 3GPP TS 22.104[24]
Project definition	Percentage of amount of sent packets delivered within QoS constraints by communication service. Ability of communication service to perform as required for a given time interval. Percentage of AI inference/decisioning requests that are fulfilled within the agreed QoS targets by AI Agents. Percentage of Localization/Sensing requests that are fulfilled within the agreed QoS targets by localization/sensing service.
Standard definition	Use-case specific; c.f. references in Hexa-X D1.3[10] for each use case

Target value (project)	Relative ratio, e.g., 99,999% of packets are transmitted
Other remarks	For communication service: Network nodes (virtual NFs + hardware functions). For AI/Computation and Localization/sensing: depending on service realization (e.g., MEC nodes, AI/ML Agents)

KPI name (project)	**Service safety, integrity, maintainability**
Projects	Hexa-X
3GPP Rel. 18 docs	n/a
Project definition	Reference to applicable standards and regulations in the domain; functional requirements, if available.
Standard definition	Use-case specific; c.f. references in Hexa-X D1.3[10] for each use case
Target value (project)	Not provided
Other remarks	KPI evaluating whole system setup

KPI name (project)	**Vehicle density**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	Measurement of vehicle positions and velocities and statistical evaluation of the in-out vehicle flow.
Standard definition	n/a
Target value (project)	Not provided
Other remarks	The goal is to determine the maximum number of vehicles inside a network instance that can be served by the system.

KPI name (project)	**System memory load**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a

Project definition	Average memory usage during orchestration operations (i.e., processing orchestration requests in Mobile Edge Application Orchestrator - MEAO). Measured for the whole orchestration platform, or for the specific orchestration or management entity (e.g., NFV, MEAO, Edge Controller, etc.).
Standard definition	n/a
Target value (project)	Not provided
Other remarks	Measuring software and Hardware components involved in the deployment of MEC systems

KPI name (project)	**Runtime Delay**
Projects	AI@EDGE
3GPP Rel. 18 docs	n/a
Project definition	The time needed for MEAO to perform any LCM (Life Cycle Management) operations, i.e., while an application instance is running (e.g., scaling, termination, heal, etc.)
Standard definition	n/a
Target value (project)	Achieve runtime delay in the proximity of at most 650 ms
Other remarks	The goal is to automate the process of handling LCM operations between MEC applications with a low cost in time delay

KPI name (project)	**Service reliability**
Projects	DEDICAT-6G
3GPP Rel. 18 docs	n/a
Project definition	Service reliability can be defined as the success probability of transmitting a layer 2/3 packet within a maximum latency required by the targeted service (ITU-R M.2410[4]). With the use of intelligence distribution mechanisms this should either improve or at least remain the same as the baseline.
Standard definition	ITU-R M.2410-0 (11/2017)[4] Reliability relates to the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability.

Target value (project)	Not defined.
Other remarks	Measurements will be collected at the application layer. Packets that arrive delayed or erroneous are considered as lost packets.

4 Conclusion

The motivation for this white paper was to provide an initial analysis of KPIs for B5G and 6G systems. This view allows to understand what definitions are available to be inherited from previous generations, and which KPIs are new and need to be defined based on current research activities. It was motivated that defining KPIs early on in the B5G and 6G system development is critical to ensure the measurability of performance and advances of the system. KPIs need to be defined in terms of metrics, target values and how to measure them. This paper takes the initial step in gaining an overview of KPIs based on active B5G and 6G research projects under the ICT-52 call. The KPIs are collected from the projects based on current work on use cases and network functionalities to ensure the current relevance.

The approach presented in this paper analyses the current view of the KPIs by clustering them according to KPI family and relate them to available standardization documents. The clustering yielded 10 KPI families which further help analyse the KPIs and identify relevant existing standards. This approach takes input from the ICT-52 projects which ensures that the KPIs are relevant to scenarios being researched, but also limits the space covered by KPIs to topics covered by the ICT-52 projects.

For each of the KPIs it was identified where there is overlap between KPIs from ICT-52 projects and standard network KPI definitions. This indicate which KPIs will be evolved from previous definitions in terms of new target values or measurement approaches, or which KPIs will be defined as new KPIs.

The ICT-52 projects provided information about context of the KPIs, project definition, target values and other notes, depending on availability in the projects. This means that the input is limited by the state of progress in the projects where some KPIs are well defined while others mostly only have preliminary descriptions. This highlights the need for further iterations of this paper as the ICT-52 projects progress. This will also open the possibility to include inputs from other B5G and 6G research projects as they commence.

In the end this white paper provides in no way a final image of KPIs defined for B5G and 6G systems, but rather initiates the iterative process for providing overview of B5G and 6G KPIs and measurement approaches. The critical point is that the process is iterative and should as such be repeated periodically as the research projects and innovations evolve.

5 Next steps

As mentioned in the conclusion the work presented in this paper is to be seen as the beginning of an iterative process for collecting and defining KPIs in terms of applicability, domain, target values and measurement methods. The is envisioned to be collected continuously from ICT-52 projects as they evolve but also to collect KPI definitions from other B5G and 6G research projects as they commence and evolve, e.g. from the SNS call[13].

A next step for this work is to further develop the definition of the KPIs into formalized descriptions, which should be done in sync with standardisation bodies. This will also include fixing target values for KPIs which will become more clear as the B5G and 6G visions evolve and mature.

As the KPI definitions evolve the KPI families and the mapping of KPIs to these will also evolve. The KPI families defined and utilized in this work are used as a tool to help the analysis process of KPIs, but also to better understand the KPIs in their context.

Another important point to cover in the next steps is to look into how to measure the KPIs. For previously defined KPIs there are typically well-defined measurement approaches but for new KPIs this might not be fully defined, or maybe even not at all. Defining how to measure KPIs is a natural step in the definition work, but depending on the KPI, its context and its definition the measurement approach might be more or less straightforward forward. In some cases there might exist measurement methods that can be utilized while in other cases the methods must be defined from scratch.

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Abbreviations and acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
5G IA	5G Infrastructure Association
5G PPP	5G Public Private Partnership
6G	6th Generation
B5G	Beyond 5G
CDF	Cumulative Distribution Function
E2E	End-to-End
eMBB	Enhanced Mobile Broadband
EMF	Electric and Magnetic Fields
ICT-52	5G-PPP ICT-52-2020
ITE	Information Technology Equipment
KPI	Key Performance Indicator
KPI	Key Performance Indicator
LCM	Life Cycle Management
LMLC	Low mobility large cell
MEAO	Mobile Edge Application Orchestrator
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
mMIMO	Massive MIMO
mMTC	Massive Machine Type Communications
NFV	Network Functions Virtualisation
NFVI	Network Function Virtualization Infrastructure
NI	Network Intelligence
NTE	Network Telecommunications Equipment
NTE	Network Telecommunications Equipment
OPEX	Operational Expense
PDU	Protocol Data Unit
QoE	Quality of Experience
QoS	Quality of service
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RIT	Radio Interface Technology

SCAS	Security Assurance Specifications
SDU	Service Data Unit
SECAM	Security Assurance Methodology
SINR	Signal to Interference & Noice Ratio
SLO	Service Level Objective
SRIT	Set of Radio Interface Technologies
T&M	Test and Measurement
TRxP	Transmission Reception Point
URLLC	Ultra-Reliable and Low-Latency Communications
V2X	Vehicle to X
VNF	Virtualized Network Function

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Annex A ICT-52 Project Descriptions

6G BRAINS aims to bring AI-driven multi-agent Deep Reinforcement learning (DRL) to perform resource allocation over and beyond massive machine-type communications with new spectrum links including THz and optical wireless communications (OWC) to enhance the performance with regard to capacity, reliability and latency for future industrial networks.

The project proposes a novel comprehensive cross-layer DRL driven resource allocation solution to support the massive connections over device-to-device (D2D) assisted highly dynamic cell-free network enabled by Sub-6 GHz/mmWave/THz/OWC and high resolution 3D Simultaneous Localization and Mapping (SLAM) of up to 1 mm accuracy.

The enabling technologies in 6G BRAINS focus on four major aspects including disruptive new spectral links, highly dynamic D2D cell-free network modelling, intelligent end-to-end network architecture integrating the multi-agent DRL scheme and AI-enhanced high-resolution 3D SLAM data fusion.

The developed technologies will be widely applicable to various vertical sectors such as Industry 4.0, intelligent transportation, eHealth, etc.

Website: 6g-brains.eu

Artificial Intelligence has become a major innovative force and it is one of the pillars of the fourth industrial revolution. This trend has been acknowledged also by the European Commission that has already pointed out how high-performance, intelligent, and secure networks are fundamental for the development and evolution of the multi-service Next Generation Internet (NGI). While great progress has been done during the last years with respect to the accuracy and performance of AI-enabled platforms, their integration in potentially autonomous decision-making systems or even critical infrastructures requires end-to-end quality assurance.

AI@EDGE addresses the challenges harnessing the concept of "reusable, secure, and trustworthy AI for network automation". In AI@EDGE European industries, academics and innovative SMEs commit to achieve an EU-wide impact on industry-relevant aspects of the AI-for-networks and networks-for-AI paradigms in beyond 5G systems. Cooperative perception for vehicular networks, secure, multi-stakeholder AI for IIoT, aerial infrastructure inspections, and in-flight entertainment are the uses cases targeted by AI@EDGE to maximise the commercial, societal, and environmental impact. To achieve the goal, AI@EDGE targets significant breakthroughs in two fields: (i) general-purpose frameworks for closed-loop network automation capable of supporting flexible and programmable pipelines for the creation, utilization, and adaptation of the secure, reusable, and trustworthy AI/ML models; and (ii) converged connect-compute platform for creating and managing resilient, elastic, and secure end-to-end slices capable of supporting a diverse range of AI-enabled network applications.

Website: aiatedge.eu

The success of Beyond 5G (B5G) systems will largely depend on the quality of the Network Intelligence (NI) that will fully automate network management. Artificial Intelligence (AI) models are commonly regarded as the cornerstone for NI design; indeed, AI models have proven extremely successful at solving hard problems that require inferring complex relationships from entangled and massive (e.g., traffic) data. However, AI is not the best solution for every NI task; and, when it is, the dominating trend of plugging 'vanilla' AI into network controllers and orchestrators is not a sensible choice.

Departing from the current hype around AI, DAEMON will set forth a pragmatic approach to NI design. The project will carry out a systematic analysis of which NI tasks are appropriately solved with AI models, providing a solid set of guidelines for the use of machine learning in network functions. For those problems where AI is a suitable tool, DAEMON will design tailored AI models that respond to the specific needs of network functions, taking advantage of the most recent advances in machine learning. Building on these models, DAEMON will design an end-to-end NI-native architecture for B5G that fully coordinates NI-assisted functionalities.

Website: h2020daemon.eu

In future 6G wireless networks, it is imperative to support more dynamic resourcing and connectivity to improve adaptability, performance, and trustworthiness in the presence of emerging human-centric services with heterogeneous computation needs. DEDICAT6 aims to develop a smart connectivity platform using artificial intelligence and blockchain techniques that will enable 6G networks to combine the existing communication infrastructure with novel distribution of intelligence (data, computation, and storage) at the edge to allow not only flexible, but also energy efficient realisation of the envisaged real-time experience. DEDICAT 6G takes the next vital step beyond 5G by addressing techniques for achieving and maintaining an efficient dynamic connectivity and intelligent placement of computation in the mobile network. In addition, the project targets the design and development of mechanisms for dynamic coverage extension through the exploitation of novel terminals and mobile client nodes, e.g., smart connected cars, robots, and drones. DEDICAT also addresses security, privacy, and trust assurance especially for mobile edge services and enablers for novel interaction between humans and digital systems. The aim is to achieve (i) more efficient use of resources; (ii) reduction of latency, response time, and energy consumption; (iii) reduction of operational and capital expenditures; and (iv) reinforcement of security, privacy, and trust. DEDICAT 6G will focus on four use cases: Smart warehousing, Enhance experiences, Public Safety and Smart Highway. The use cases will pilot the developed solutions via simulations and demonstrations in laboratory environments, and larger field evaluations exploiting various assets and testing facilities. The results are expected to show significant improvements in terms of intelligent network load balancing and resource allocation, extended connectivity, enhanced security, privacy and trust and human-machine interactions.

Website: dedicat6g.eu

A flagship for 6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds

2030 and beyond, Europe and the world will face opportunities and challenges of growth and sustainability of tremendous magnitude; proactively tackling the issues of green deal efficiency, digital inclusion and assurance of health and safety in a post-pandemic world will be key. A powerful vision is needed to connect the physical, digital, and human worlds, firmly anchored in future wireless technology and architectural research. The Hexa-X vision calls for an x-enabler fabric of connected intelligence, networks of networks, sustainability, global service coverage, extreme experience, and trustworthiness.

Wireless technologies are of critical relevance for our society and economy today; their importance for growth will continue to steadily increase with 5G and its evolution, enabling new ecosystems and services motivated by strongly growing traffic and trillions of devices. The ambition of the Hexa-X project includes developing key technology enablers in the areas of:

- fundamentally new radio access technologies at high frequencies and high-resolution localization and sensing;
- connected intelligence through AI-driven air interface and governance for future networks, and
- 6G architectural enablers for network disaggregation and dynamic dependability.

Website: hexa-x.eu

MARSAL targets the development and evaluation of a complete framework for the management and orchestration of network resources in 5G and beyond, by utilizing a converged optical-wireless network infrastructure in the access and fronthaul/midhaul segments.

At the network design domain, MARSAL targets the development of novel cell-free based solutions that allows a significant scaling up of the wireless APs in a cost-effective manner by exploiting the application of the distributed cell-free concept and of the serial fronthaul approach, while contributing innovative functionalities to the O-RAN project. In parallel, in the fronthaul/midhaul segments, MARSAL aims to radically increase the flexibility of optical access architectures for Beyond-5G Cell Site connectivity via different levels of fixed-mobile convergence. At the network and service management domain, the design philosophy of MARSAL is to provide a comprehensive framework for the management of the entire set of communication and computational network resources by exploiting novel ML-based algorithms of both edge and midhaul DCs, by incorporating the Virtual Elastic DataCenters/Infrastructures paradigm. Finally, at the network security domain, MARSAL aims to introduce mechanisms that provide privacy and security to application workload and data, targeting to allow applications and users to maintain control over their data when relying on the deployed shared infrastructures, while AI and Blockchain technologies will be developed in order to guarantee a secured multi-tenant slicing environment.

Website: marsalproject.eu

The REINDEER project will develop a new smart connect-compute platform with a capacity that is scalable to quasi-infinite, and that offers perceived zero latency and interaction with an extremely high number of embedded devices. It will thereto develop "RadioWeaves" technology, a new wireless access infrastructure consisting of a fabric of distributed radio, computing, and storage resources. RadioWeaves can be deployed as panels mounted on walls and ceilings. It brings a large number of antennas and intelligence close to devices offering consistently excellent service at minimal transmit power and making very efficient usage of network bandwidth and energy. Technologically, RadioWeaves advance the ideas of large-scale intelligent surfaces and cell-free wireless access, two theoretical concepts that bear great promise to offer capabilities far beyond 5G networks. We will characterize channels based on measurements and develop distributed platform architectures to realize the great potential in actual deployments. We will develop protocols and algorithms to establish novel resilient interactive applications that require 'real-time' and 'real-space' cooperation, for future robotized industrial environments, immersive entertainment, and intuitive care, we will co-design focusing algorithms and protocols for enhanced interaction with many energy-neutral devices. REINDEER will provide experimental proof-of-concept in versatile testbeds. The project runs for 42 months and receives funding from the European Union under grant agreement number 101013425.

Website: reindeer-project.eu

Visions and plans on forthcoming B5G/6G networks have begun, aiming to provide flexible connect-compute technologies to support future innovative services and uses cases. Considering the 2030 horizon, B5G/6G networks are intended to create the basis for human-centred smart societies and vertical industries. To this end, innovation is expected to: (a) support the long-term sustainable transformation of networks into a distributed smart connectivity infrastructure, where new terminal types are embedded in the daily environment; (b) provide the end-to-end connectivity-computation system with the higher flexibility and dynamism needed to accommodate the ever-evolving and heterogeneous nature of future applications, regulations and specific user-/service-/location-based needs.

The RISE-6G vision capitalises on the latest advances on Reconfigurable Intelligent Surfaces (RIS) technology for radio wave propagation control, in order to substantially improve them and, to conceive and implement intelligent, sustainable and dynamically programmable wireless environments that go well beyond the 5G capabilities developed under 3G PPP release 16.

To this end, RISE-6G objectives are to (i) define novel network architectures and operation strategies incorporating multiple RISs; (ii) characterise its fundamental limits capitalizing on our proposed realistic and validated radio wave propagation models; (iii) design solutions to enable online trade between high-capacity connectivity, Energy Efficiency, EMF exposure, and localisation accuracy based on dynamically programmable wireless propagation environments, while accommodating specific legislation and regulation requirements on spectrum use, data protection, and EMF emission; and (iv) prototype-benchmark proposed innovation via two complementary trials with verticals.

RISE-6G project is poised to actively participate in standardisation bodies and bring its technically advanced vision into the planned industrial exploitation. This will secure the European technology leadership, supporting the creation of new European-conceived service and business opportunities in the B5G/6G global race.

Website: rise-6g.eu

TeraFlow will create a new type of secure cloud-native SDN controller that will radically advance the state-of-the-art in beyond 5G networks. This new SDN controller shall be able to integrate with the current NFV and MEC frameworks as well as to provide revolutionary features for both flow management (service layer) and optical/microwave network equipment integration (infrastructure layer), while incorporating security using Machine Learning (ML) and forensic evidence for multi-tenancy based on Distributed Ledgers.

The target pool of stakeholders expands beyond the traditional telecom operators towards edge and hyperscale cloud providers. These actors will be benefited from TeraFlow by a) exploiting a new type of secure SDN controller based on cloud-native solutions while, b) achieving substantial business agility with novel and highly dynamic network services with zero-touch automation features.

Website: teraflow-h2020.eu

B5G-OPEN targets the design, prototyping and demonstration of a novel end-to-end integrated packet-optical transport architecture based on MultiBand (MB) optical transmission and switching networks. MB expands the available capacity of optical fibres, by enabling transmission within S, E, and O bands, in addition to commercial C and/or C+L bands, which translates into a potential 10x capacity increase and low-latency for services beyond 5G.

To realize multiband networks, technology advances are required, both in data, control and management planes. Concerning devices, these include new amplifiers, filterless subsystems, add/drop multiplexers, etc. Such technology advances complement novel packet-optical white boxes using flexible sliceable Bandwidth Variable Transceivers and novel pluggable optics. The availability of MB transmission will also lead to a complete redesign of the end-to-end architecture, removing boundaries between network domains and reducing electronic intermediate terminations.

The control plane will be extended to support multiband elements and a 'domain-less' network architecture. It will rely on physical layer abstraction, new impairment modelling, and pervasive telemetry data collection to feed AI/ML algorithms that will lead to a Zero-Touch networking paradigm including a full featured node operating system for packet-optical whiteboxes.

The results will be shown in two final demonstrations exposing the project benefits from operator and user perspectives. B5G-OPEN will have a clear impact on the society showing the evolution towards a world with increased needs of connectivity and higher capacity in support of new B5G services and new traffic patterns.

The consortium includes partners from 8 countries: three major telecom operators, three vendors, four SMEs and four research centres and academia, combining several years of experience and a successful record in past European projects on related technologies, thus guaranteeing its success

Website: b5g-open.eu