5G Public Private Partnership

Test, Measurement and KPIs Validation Working Group

Whitepaper

Beyond 5G/6G KPI Measurement

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Executive Summary

We are at the start of the 6G research era, where both academia and industries are actively investigating new promising use cases and technologies intended for 6G. To steer research towards 6G vision, one of the very first and important steps is to identify the relevant KPIs based on the envisioned 6G use cases. The B5G and 6G KPIs and target values have been identified in the previous white paper "Beyond 5G/6G KPIs and Target Values" [1], which are collected from 5G PPP phase III research projects with focus on projects of the ICT-52. The KPIs are either evolved from previous generation KPIs or are new deriving from new B5G/6G use cases and 6G features/ capabilities/ network targets. The main objective of this document is to present a view of which KPIs have been measured in which ICT-52 projects and how it is measured.

This paper provides an overview of the Beyond 5G and 6G KPIs that are evaluated in the ICT-52 projects, based on the received input from the corresponding projects. Apart from that, a detailed description of the KPIs target values and the measurement methodologies used in the corresponding ICT-52 projects is presented. It shall be noted that currently measurement methodologies are defined for the majority of beyond 5G/ 6G KPIs identified in [1]. In the next period, TMV will follow up on the measurement methodologies for the beyond 5G/ 6G KPIs that are not presented in this document.

As 6G research moves forward in the context of 6G SNS R&I Work Programme, the definition of new KPIs as well as new testing and measurement methodologies in the context of SNS 6G research projects, will be incorporated in the next phases of the TMV work.

1. Introduction

Today, with 5G networks being widely rolled out in various deployment environments, with various configurations, for serving various public and vertical sector needs, being used in the context of various scenarios and use cases, research and innovation activities move forward to defining the next, the 6th generation of systems. While deployed 5G networks are still under evaluation to prove their capabilities and potential in commercial, operational environments, the requirements and KPIs are being discussed for 6G systems, in order to properly steer the 6G research and innovation activities. To this end, besides having clearly defined KPIs it is vital to identify at early stages methodologies and tools to evaluate these KPIs even at early research stages, so that the 6G technologies can be properly validated.

Research on beyond 5G/ 6G technologies is the focus of the closing call of 5G PPP phase III Programme, the ICT-52 call, with the relevant projects paving the way for 6G technologies and primitive/ prototype elements. This work comes along with the early definition of beyond 5G/6G use cases and the definition of relevant KPIs.

This white paper is the continuation of the 5G-PPP TMV Working Group white paper entitled «Beyond 5G/6G KPIs and Target Values» [1]. The latter provided an early analysis of possible Beyond 5G/6G KPIs based on current work and perspectives from ICT-52 projects, seeking to understand the level to which existing definitions in standard documents will apply to 6G and to identify, at early stages, gaps and new candidate KPIs for being standardized for 6G systems. The intention of this white paper is to provide an analysis of the nature of the beyond 5G/6G KPIs identified in [1] by further elaborating on the feasibility of these KPIs to be measured, on the methods and tools to be used for their evaluation, and on identifying challenges encountered, gaps identified and research steps to be followed on the measurement and evaluation methodologies to be used in the 6G era.

With the early analysis of the beyond 5G/ 6G KPIs measurement and evaluation methods and tools, the 5GPPP TMV group is progressing the discussion on KPIs and validation, aiming to deliver a solid baseline for the forthcoming discussions to take place in the corresponding SNS JU WG.

1.1. ICT-52 Projects Overview

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

HEXA-X [2] is the flagship project for 6G vision and intelligent fabric of technology enablers. 6G BRAINS [3], AI@EDGE [4], and DAEMON [5] are related to Artificial Intelligence solutions, while DEDICAT 6G [6] and REINDEER [7] address smart connectivity approaches. RISE-6G [8] vision capitalizes on the latest advances in Reconfigurable Intelligent Surfaces (RIS) technologies and the design of the RIS-enabled wireless environment as a service, while TeraFlow [9] targets cloud-native SDN controllers. MARSAL [10] is related to network orchestration, while B5G-OPEN [11] targets an integrated packet-optical transport architecture based on MultiBand (MB) optical transmission.

Further information on the ICT-52 projects is summarized in Annex A.

2. KPI Measurements Provided by ICT-52 Projects

The available B5G and 6G KPIs and the corresponding target values have been defined in the previous version of the white paper "Beyond 5G/6G KPIs and Target Values" [1]. This section presents an overview of which KPIs have been measured in different ICT-52 projects, as well as the detailed description of how the target KPI is measured in each ICT-52 project. The information provided in this section is based on the aggregation of the received responses from the ICT-52 projects.

2.1. Information Collection Process for B5G/6G KPI Evaluation

The definition of B5G and 6G KPIs together with the target value from 5G PPP ICT-52 projects have been presented in [1], including both the well-known standard network KPIs (adjusted for beyond 5G/6G systems) as well as new KPIs specific for B5G and 6G systems. The collected KPIs are then grouped into different KPI categories such as capacity, latency, packet Loss, compute, energy, security, localization, and service related.

In order to get an overview of the target values and the measurement methodologies for the KPIs defined in [1], an information collection template as presented in Table 1 was sent out to all the ICT-52 projects. After receiving the feedback from the requested projects, information about which specific KPIs have been evaluated in each ICT-52 project has been extracted and is described in the following section.

Table 1. Information collection template for KPI measurement methodology

KPI family	This field includes a mapping of the specific KPI to main KPI categories such as capacity, latency, packet Loss, compute, energy, security, localization, and service related
KPI name	In this field the KPI is named in a short and understandable way.
How is it measured? (method/tool)	In this field information is provided regarding the tool that has been used to collect the measurements, and the methodology – including the filtering, averaging, post processing of the measurements – that was used to extract the value of the KPI.
What is the target value of the KPI?	In this field the target value of the KPI is defined.
Is the measurement method/tool able to cope with the target value?	This field includes information on the challenges related to the capability of the method or the tool to measure and evaluate the target KPI. Restrictions of the tool, ambiguities inserted by the measurement process etc. are collected at this point.
Any research ongoing on the new measurement method? How/What?	This field aims to collect insights on further advancements, innovations, research related to the measurement methods applicable to (standard and new) beyond 5G/6G KPIs.

2.2. Overview of B5G/6G KPIs Evaluation in ICT-52 projects

The TMV WG has received responses from 6 out of 10 of the ICT-52 projects. With the aggregation of the received information, an overview table of which beyond 5G/6G KPIs have been evaluated in which ICT-52 projects are summarized in Table 2. In practice, Table 2 enlists all the beyond 5G/6G KPIs that have been identified by ICT-52 projects in [1]. As observed, currently, the details related to KPI measurement and evaluation are not available for the complete list of the KPIs given the fact that ICT-52 projects are still in progress.

In general, it can be seen that most of the defined beyond 5G/5G KPIs in [1] have been evaluated in different ICT-52 projects, depending on the scope of the projects, the definition of the addressed scenarios and use cases, and the nature of the applications/services.

Table 2. Mapping of beyond 5G/6G KPIs evaluated in ICT-52 projects

KPI / Project		DAEMON	MARSAL	TERAFLOW	DEDICAT6G	REINDEER	B5G-OPEN
Capacity	Peak Data Rate		x				
	User Experienced Data Rate				x	x	x
	Network Capacity						
	Service Bandwidth						x
	Area Traffic Capacity					x	
	Connection Density						
Latency	User Plane Latency		x				x
	Control Plane Latency						x
	E2E Service Latency	x			x		
	New Latency contribution components	x					
	E2E Application Latency – for Video processing services				x		
	Mission critical QoS of services – latency related				x		
	Runtime Delay			x			
	Service Setup Delay			x			x
	Slice Setup Delay			x			
Packet Loss	Packet Error Rate						
	Layer2/3 packet transmission success rate						
	Packet Loss Rate		x				
	Frame Loss						
	Signal Packet Loss						
Compute	Edge computational resource usage	x	x				
	Operation expenditure @edge	x					
	Delta in network management decision	x					
	Availability						
	Resource utilization		x		x		
	Computing resource utilization						
Energy	Network Energy efficiency				x		x
	Device Energy Efficiency				x		x
	Reduced energy consumption			x			
	VNF Energy consumption reduction	x					

Security	Anomaly detection precision	x					
	Security conformance						
	Tenant data privacy		x				
Localization	Localization accuracy				x		
	Direction and orientation accuracy						
	Localization related delays						
	Localization (error) integrity						
Service	Service availability				x		x
	Service reliability				x		
	Service safety, integrity, maintainability						x
	CAPEX & OPEX reduction			x			x

2.3. B5G/6G KPIs Evaluation Insights in ICT-52 Projects

This section provides further details on the evaluation (target values and measurement methodology) of the KPIs addressed by the corresponding ICT-52 projects (i.e., the KPIs that are marked with ‘x’ in Table 2). It shall be noted that all KPIs enlisted in the following sections are measured at the corresponding ICT-52 projects. The KPI definitions in the case of Capacity-related KPIs are based on Standard specific definitions or are project-defined. In all other cases the KPI definitions are project-defined, adhering to standards’ definitions as indicated in [1].

2.3.1. Capacity KPIs

The capacity related KPIs that have been evaluated in ICT-52 projects are listed in Table 3 and Table 4, which include peak date rate, user experienced data rate, area traffic capacity, service bandwidth, line capacity and multiband optical components capacity. The last two KPIs are specific to fiber networks. The capacity related KPIs are one of the most important KPIs in each generation of the communication system, therefore most of the capacity related KPIs have been covered in various ICT-52 projects, except for "Connection Density", which is a project defined KPI in 6G BRAINS [1]. As no feedback has yet been received from the 6G BRAINS project, thus the measurement information related to this specific KPI is missing. From Table 3 and Table 4, it is shown that the target value for the capacity of B5G/6G systems is generally 10 to 100 times higher than 5G systems.

Table 3. B5G/6G Capacity-related KPIs evaluated in ICT-52 projects

KPI Family	**Capacity**			
KPI Name	Peak Data Rate	Line Capacity	MultiBand Optical Components Capacity	Area Traffic Capacity
KPI Source	Standard Definitions	Project	Project	Standard Definitions
Projects	MARSAL	B5G-OPEN	B5G-OPEN	REINDEER
How is it measured?	Measured on the UL on a FR2 frequency band. The KPI value is evaluated by capturing traffic and post processing. The traffic is generated using the tool Iperf.	Spectrum capacity: Fiber Spectrum (1260nm – 1625nm); C = ~4 THz; C+L = ~11 THz; S+C+L = ~21 THz; O+E+S+C+L = ~53 THz; Fiber spectrum bands where optical channels can be allocated anywhere in the network optical layer Line capacity: Total fiber transmission capacity in a transmission system (min. 20 km)	Spectrum capacity: Fiber Spectrum (1260nm – 1625nm); C = ~4 THz; C+L = ~11 THz; S+C+L = ~21 THz; O+E+S+C+L = ~53 THz; Fiber spectrum bands where optical channels can be allocated anywhere in the network optical layer Line capacity: Total fiber transmission capacity in a transmission system (min. 20 km) Node capacity: Total maximum throughput of a network node including the Add/Drop traffic	The channel sounder developed, namely a RadioWeaves' testbed, is used for synchronized high-quality wireless propagation channel measurements at FR1 bands between distributed radio units (i.e., D-MIMO access point) and several distributed UEs. Channel sounder measurements are post-processed offline (using suitable interference suppression method such as zero-forcing combining) to emulate dedicated interference-free link(s) towards each user. The ergodic Shannon's capacity is computed per one of such users' link, which approximates the average spectral efficiency average as per eq. (6) in the whitepaper. Note: computation of Shannon's capacity also requires Tx and Rx received noise power spectral density values (which can be taken from he identified use cases).
Target Value	10 Gbit/s	100x with respect to NG-PON2	Switching Matrix, Add/Drop, Amplifier, Transceiver with own KPIs	100Mpbs for indoor hospital deployments as in [12]
Is the target value met?	The handset is capable of generating traffic using the indicated software tool.	Testing and validation are ongoing.	Testing and validation are ongoing.	The channel sounder is able to perform high-quality link measurements with enough accuracy to predict large KPIs target values. Based on the identified use cases, the target value can be met. Testing and measurement are still ongoing.

New measurement method	Research on how to automate the process while enabling dynamic adaptation for different frequencies to ensure high accuracy in the KPI value evaluation.	No	No	Yes, one objective of REINDEER is to develop a testbed that can be used as a measuring tool to prove the RadioWeaves' concept. This includes how to interconnect and exchange data/triggering information across many distributed radio units, setting up the distributed radio units for experiments, etc.

Table 4. B5G/6G User Experienced Data Rate-related KPIs evaluated in ICT-52 projects

KPI Family	**Capacity**		
KPI Name	User Experienced Data Rate	User Data Rate	Service Bandwidth
KPI Source	Standard Definitions	Project	Project
Projects	REINDEER, B5G-OPEN	DEDICAT6G	B5G-OPEN
How is it measured?	REINDEER: The channel sounder developed in the REINDEER project, namely a RadioWeaves' testbed, is used for synchronized high-quality wireless propagation channel measurements at FR1 bands between several distributed radio units (i.e., D-MIMO access points) and several distributed UEs. Channel sounder measurements are post-processed offline (using suitable interference suppression method such as zero-forcing combining) in order to emulate dedicated interference-free link(s) toward each user. The instantaneous Shannon's capacity is computed per such user link, which approximates the spectral efficiency Se_{user} as per eq. (3) in the whitepaper. An empirical cumulative distribution function can be constructed from computing instantaneous Shannon's capacities over the distribution of users. Its 5th percentile can be multiplied by the link's bandwidth in order to obtain an estimate of the User Experienced Data Rate. Note: computation of Shannon's capacity also requires Tx and Rx received noise power spectral density values (which can be taken from the identified use cases).	Different approaches have been used. In one approach throughput has been measured by placing Qosium Probes to video source (smart glasses/smartphone), MEC, and in video client. Qosium Scope can then measure and collect the sent/received throughput from the specific network interface. In another approach, tests have been set up where a known data stream sends data over UDP (e.g., using iperf) from the MAP to the UEs over 5G link. At the UE side, the throughput of the received data streams will be measured at the application over a small time window (e.g., per second).	Port speed: Port line rate per optical carrier in a transmission system (min. 20 km) User data rate (consumer): Residential service peak rate User data rate (business): Business service peak rate
Target Value	REINDEER: 150 Mbps (for virtual reality home gaming as in [12]) B5G-OPEN: Increase of 10× in-service bandwidth with reference to currently deployed C-band transport solutions	• > 5 Mbps per user for the DEDICAT 6G Enhanced Experience use case • > 16 Mbps for the Smart Highway use case	Increase of 10× in-service bandwidth with reference to currently deployed C-band transport solutions.
Is the target value met?	REINDEER: Testing and measurements are ongoing but it should be Yes based on current understanding. B5G-OPEN: Yes	Yes	Testing and validation are ongoing.
New measurement method	REINDEER: Yes, one objective of the REINDEER project itself is to develop a testbed that can be used as a measuring tool to prove the RadioWeaves' concept. This includes how to interconnect and exchanging data/triggering information across many distributed radio units, setting up the distributed radio units for experiments, etc.	No	

2.3.2. Latency KPIs

Latency is a critical parameter for the delivery of 5G and beyond services, thus it is a primary KPI evaluated by projects. Measuring and evaluating end-to-end latency at user plane, for various applications/services provides a direct measure of the end-user perceived performance. At the same time, the disaggregation and distribution of user plane in 5G systems came hand in hand with the elaboration and optimization (separately) of various latency components (i.e., at various 5G network segments and layers). It is foreseeable, that this trend will persist also in 6G networks and will affect the relevant set of KPIs for 6G networks. In this context, all latency related KPIs defined in [1] (evaluating user perceived and system performance) have been covered in various ICT-52 projects and are listed in Table 5 and Table 6. These KPIs include user/control plane latency, E2E service/application latency, runtime delay, service setup delay, slice setup delay, service provisioning time, new latency contribution components, etc. It is shown from Table 5 and Table 6 that the user/control plane latency is usually limited to 1 ms level, the service/slice setup delay is set to be less than 50 ms, while the E2E service/application latency depends on the use case ranging from a few milliseconds to few hundred milliseconds. It shall be noted that a lot of focus is put on latency KPIs referring to the orchestration layer. This indicates the increasing importance of network and service orchestration to be continued in the 6G era.

Table 5. B5G/6G User Plane Latency-related KPIs evaluated in ICT-52 projects

KPI Family	**Latency – User Plane**			
KPI Name	User Plane Latency	E2E Service Latency	E2E App Latency – for Video processing services	E2E App Latency -Mission critical QoS of services
KPI Source	Standard Definitions	Project	Project	Project
Projects	MARSAL	DAEMON, DEDICAT6G	DEDICAT6G	DEDICAT6G
How is it measured?	Measured between a UE and a containerized application function that may be hosted at the Radio Edge or Regional Edge DC.	DAEMON: Python script is used to analyze the timestamps of UDP packets. The measurement is performed at the end user (i.e., on-board unit in vehicle). DEDICAT6G: Measurements are collected at the application layer by adding timestamps to requests between functional entities/service components of an overall service. Then the difference in time is calculated between the request from one entity (e.g., client) and the response from the other entity (e.g., server). Measurements are also collected e.g., with the use of ping and iPerf.	Service latency can be measured by placing Qosium Probes to video source (smart glasses/smartphone), MEC, and in video client. By doing this, both uplink and downlink network delay can be measured.	Measurements are collected at UE level.
Target Value	1 ms (excluding the RAN latency)	DAEMON: 1 ms DEDICAT6G: The target values are different for various use cases and are within the	< 10 ms	• MC-PTT access time < 300 ms for 95% of all requests; • End-to-End MC-PTT access time < 1000 ms for all MCX apps under the same network coverage;

		range 10 to 200 ms (mostly targeting <100 ms)		• Mouth-to-ear latency <300 ms for 95% of all voice bursts • Max late call entry time shall be 150 ms for 95% of all late call request. • End-to-End Delay shall be <10 ms; • User Data Rate shall be 100 Mbps in downlink and 50 Mbps in uplink • 99.999% of success for the transmission of a packet of 32 bytes within 1ms
Is the target value met?	Yes, when the application function is hosted at the Radio Edge (close to the end user)	Yes	Yes	Yes
New measurement method	No	No	No	No

Table 6. B5G/6G Control and Orchestration Plane Latency-related KPIs evaluated in ICT-52 projects

KPI Family	**Latency – Control Plane and Orchestration Plane**					
KPI Name	Runtime delay	Service setup delay	Slice setup delay	Service provisioning time	New Latency contribution components	Autonomous operation
KPI Source	Project	Project	Project	Project	Project	Project
Projects	TERAFLOW	TERAFLOW	TERAFLOW	B5G-OPEN	DAEMON	B5G-OPEN
How is it measured?	Control plane latency to on-board a new device and upload its configuration.	The required time to setup a new service. It is measured as the time difference between a new service is initiated and the service setup is complete.	Time to setup a new slice. Different messages (slice requests/resource offers) with a specific number of concurrent transactions launched by the program on each trial. Each trial performed 100 times and measured the mean end-to-end latency to complete entire set of transactions in the trial.	Total time to set up application service between UE and VM where the application is hosted	Python script is used to analyze the timestamps of requests/responses logs. The measurement is performed at the Linux container on the edge node.	Network operations: Operation model to maximize the utilization of installed capacity in the network and minimize operational expenditure
Target Value	< 50 ms	< 50 ms	< 50 ms	Multi-technology & multi-vendor specific	1 ms	Switching Matrix, Add/Drop, Amplifier, Transceiver with own KPIs

Is the target value met?	Yes	Yes	Yes	Testing and validation are ongoing	Yes	Testing and validation are ongoing
New measurement method	The current measurement does not consider the necessary time to communicate with the device.	The current measurement is in the control plane only.	No	No	No	No

2.3.3. Compute-related KPIs

The compute related KPIs that have been evaluated in ICT-52 projects are listed in Table 7, which includes edge computational resource usage, operation expenditure at edge, resource utilization, and delta in network management decision. These KPIs are normally not considered in previous generation of communication systems but are considered important in evaluating the performance of 6G services. From Table 7 it can be seen that a general requirement for increasing the resource usage or decrease the operation expenditure for 6G services lies in the range between 40% to 60%. Some of the compute related KPIs are relatively easy to measure (e.g., resource usage), while some of the KPIs are not straightforward to get (e.g., OPEX). The collection of measurements to assess these KPIs exploit tools that are inherent or plug-ins of compute virtualization frameworks, and leverage on them to define.

Table 7. B5G/6G Compute-related KPIs evaluated in ICT-52 projects

KPI Family	Compute			
KPI Name	Edge computational resource usage	OPEX @edge	Delta in network management decision	Resource utilization
KPI Source	Project	Project	Project	Project
Projects	MARSAL, DAEMON	DAEMON	DAEMON	MARSAL, DEDICAT6G
How is it measured?	MARSAL: Measured at the Radio Edge and Regional Edge DC in terms of CPU and memory usage. DAEMON: Measured by using the tools of Prometheus and Kubernetes Metrics API(Kubernetes cluster located in a container on the edge node).	The energy consumption of an O-Cloud platform is measured, where one or multiple 5G Distributed Units are virtualized.	Python script is used for the analysis of timestamps in logs of MANO requests/responses. The measurement is located in the Linux container on the edge node.	MARSAL: A mathematical model for the determination of the distribution of the utilized computational resources has been defined. DEDICAT6G: In cases of surge of end users, the ground BS (gBS) capacity may not be sufficient for all users. Mobile Access Points (MAPs) can be deployed for traffic offloading, the effectiveness of offloading in the system will be measured. The performance is compared to the case of not using MAPs. This performance will highly rely on the number of deployed MAPs. Edge offloading performance will be measured with S/W simulation-based patterns, where traffic over MAPs is divided by the total network traffic.
Target Value	MARSAL: 50 % increase in resource usage of the DCs compared to no inter-DC load balancing available	60% reduction	0.01	MARSAL: To guarantee that the connection loss rate is below a predefined threshold. DEDICAT6G: Edge offloading performance is >50%.

	cases. DAEMON: 40% reduction			
Is the target value met?	MARSAL: The resource usage can be measured from 0 to close to 100 %, the target value can be measured by existing tools. DAEMON: Yes, the target value is achievable.	It Is difficult to measure directly.	Yes. It is observed that the decisions on network resource and function allocation, which occur at periodicity of hours, can perform very close to optimum oracles, i.e., 99%.	MARSAL: The derived mathematical model targets to determine the optimum computational capacity values that guarantee that the connection loss rate is below a predefined threshold. DEDICAT6G: Yes
New measurement method	MARSAL: No. The measurement method consists of emulating unbalanced demand in the coverage area of certain Regional Edge nodes and showcase the ability of the MEC system to uniformly re-direct traffic	No	No	MARSAL: Yes, the developed mathematical model is based on stochastic processes, while machine learning is used for the derivation of the state-space probabilitie'' distribution. DEDICAT6G: No

2.3.4. Energy-related KPIs

Energy Efficiency has always been a critical KPI of a system, especially for B5G/6G systems. The energy related KPIs that have been evaluated in ICT-52 projects are listed in Table 8, which includes measuring and optimizing absolute or relative energy efficiency across the various physical and softwarized network segments, namely: network energy efficiency, device energy efficiency, energy consumption reduction compared to existing systems, and VNF energy consumption reduction compared to existing VNFs. All energy related KPIs defined in [1] have been covered in various ICT-52 projects, with a target energy consumption reduction set to 30% to 50%. Existing measuring tools are utilized by the relevant projects.

Table 8. B5G/6G Energy-related KPIs evaluated in ICT-52 projects

KPI Family	**Energy**			
KPI Name	Network Energy efficiency	Device Energy efficiency	Reduced energy consumption	VNF Energy consumption reduction
KPI Source	Project	Project	Project	Project
Projects	DEDICAT6G	DEDICAT6G	TERAFLOW, B5G-OPEN	DAEMON
How is it measured?	Different methods have been implemented in different use cases. The Carlo Gavazzi energy meters have been placed to the target devices and measurements results have been compared with the baseline values. The battery level of involved mobile nodes (e.g., phones, laptops, robots) is measured with and without the use of DEDICAT 6G mechanisms. The power consumption of involved servers may also be	Different methods have been implemented in different use cases. The Carlo Gavazzi energy meters have been placed to the target devices and measurements results have been compared with the baseline values. The battery level of involved mobile nodes (e.g., phones, laptops, robots) is measured with and without the use of DEDICAT 6G mechanisms. The power consumption of involved servers	TERAFLOW: Reduction of the energy consumption due to multi-layer optimization as compared to the case without multi-layer optimization. Measured in percentage. B5G-OPEN: Relative power consumption reduction in optical transponders per Gb/s with	Measured with PowerTOP (Linux tool) at the Linux container on the edge node.

	measured or at least estimated using various tools, e.g., cheap watt hour meters for on premises servers.	may also be measured or at least estimated using various tools, e.g., cheap watt hour meters for on premises servers.	respect to optical systems in 2020	
Target Value	<10 Mbit/J	<10 Mbit/J	TERAFLOW: 30% to 50% B5G-OPEN: 30% to 50%	50% savings
Is the target value met?	Yes	Yes	TERAFLOW: Yes B5G-OPEN: Testing and validation are ongoing.	Yes
New measurement method	No	No	No	No

2.3.5. Operational KPIs

Although the work performed in the context of R&D projects is usually based on testing environments, thus purposely deployed and operated for the short duration of the project trials and demonstration activities, many projects maintain an outlook to the performance of the proposed solutions in operational environments. These projects attempt to extrapolate insights from the behavior of the network solutions and attempt to assess operational network KPIs, as listed in Table 9. From these KPIs we can distinguish, service availability and reliability KPIs – acknowledging that new extreme use cases are foreseen in B5G/6G systems, will impose very stringent requirements on service availability and reliability-, OPEX/CAPEX and packet loss rates under operational conditions.

Table 9. B5G/6G Network Management -related KPIs evaluated in ICT-52 projects

KPI Family	**Operational Network KPIs**				
KPI Name	Service availability	Service reliability	CAPEX & OPEX reduction	Packet Loss Rate	Network Operations
KPI Source	Project	Project	Project	Project	Project
Projects	DEDICAT6G, B5G-OPEN	DEDICAT6G	TERAFLOW, B5G-OPEN	MARSAL	B5G-OPEN
How is it measured?	DEDICAT6G: Measured as a ratio between up-time and down-time. Dedicated scripts (e.g., Python) used for collecting the up- and down-times, and for calculating the service availability. B5G-OPEN: Operation model to maximize the network utilization and minimize OPEX.	Different methods implemented in different use cases. Packet loss rate at the app layer (delayed or erroneous packets are considered as lost) has been measured. Another method to measure the service reliability is to place the Qosium Probes at video source (smart glasses/smartphone), MEC, and video client. The service reliability can then be monitored and collected using the Qosium packet loss ratio indicator.	TERAFLOW: CAPEX and OPEX reduction, measured in percentage. B5G-OPEN: Based on estimations and analytically.	A mathematical model for the determination of the distribution of the utilized communication resources has been defined, which can be used for the calculation of the connection loss rate.	Operation model to maximize the network utilization and minimize OPEX.

Target Value	DEDICAT6G: >99% B5G-OPEN: > 6x9s.	Reliability >=99.999 Packet loss rate < 10-3	TERAFLOW: n/a B5G-OPEN: CAPEX reduction above 50%	1%	10x monitored data, accuracy (uncertainty <1.5dB)
Is the target value met?	Testing and validation are ongoing.	Yes	TERAFLOW: n/a B5G-OPEN: Analysis is ongoing	The mathematical model targets to determine the optimum radio and FH capacity that guarantee that the connection loss rate is below a predefined threshold.	Testing and validation are ongoing.
New measurement method	No	No	No	Yes, the developed mathematical model is based on stochastic processes, while ML is used for the derivation of the state-space probabilities'' distribution.	

2.3.6. Other KPIs

Last but not least, the late 5GPPP projects can provide useful insights on additional KPIs that will seemingly attract interest in the 6G era. These KPIs refer to aspects of service provisioning that are not critical for 5G services but could be highly critical for the delivery of the advanced 6G services. Some other KPIs that have been evaluated in ICT-52 projects are listed in Table 10. As observed, in the era of high automation in network orchestration and service provisioning, security and privacy aspects are very significant. At the same time, high localization accuracy in the range of cm comes into the foreground to enable advanced 6G services.

Table 10. Other B5G/6G KPIs evaluated in ICT-52 projects

KPI Name	Anomaly detection precision	Tenant data privacy	Localization accuracy
KPI Source	Project	Project	Project
Projects	DAEMON	MARSAL	DEDICAT6G
How is it measured?	The anomaly detection precision/recall is measured from a ticketing system of which the operation teams use. The goal is to design approaches that do at least as good as alarm systems, but overpass them by detecting the issues usually reported via tickets (i.e., issues that alarm systems miss). In fact, what we focus on in terms of performance metrics is accuracy/precision because we want to make sure that we don't flood our engineering teams with false positives.	The similarity of the information transferred with the raw information is measured and analyzed.	It is measured as the difference between the estimated location and the actual location.
Target Value	Detection precision >0.85	n/a	In the range of 10-20 cm
Is the target value met?	The DAEMON project targets a 0.9 precision-recall area under curve (AUC) with at least 85% scoring in both precision and recall.	Yes, the privacy can be adjusted and traded by accuracy.	Yes
New measurement method	No	Yes, different approaches to measure the privacy have been performed by comparing various metrics.	No

3. Conclusions

This paper concludes the effort from the 5GPPP TMV working group around the B5G/6G KPI identification, evaluation and measurements. The paper builds on the previous work of the group on B5G/6G KPI definition and target values [1].

Based on the ICT-52 project survey we conclude that most of the B5G/6G KPIs have been measured in the context of at least one project. Combining the projects' information this paper provides a mapping between the KPIs measured and the ICT-52 projects, which constitutes a useful instrument for the reader to identify the appropriate project to search for more detailed measurement information - in the specific project deliverables and publications.

The high-level evaluation provides insights on how the KPIs were measured but also on whether the target values have been achieved in the corresponding projects. Such type of consolidated information provides good insights on the state of the art and on the challenges to be faced during the evaluation phases as well as on the gaps and needed research on new measurement methods in the 6G era.

A small number of KPIs for which information is not currently available in the context of the corresponding ICT-52 (5GPPP) projects, are expected to be addressed in the next ICT-52 project phases as well as in the context of SNS-JU/6G-IA projects.

The TMV group will continue its activities under the 6G SNS JU program and the 6G-IA association to consolidate views on testing, measurements and validation aspects.

References:

[1] 5G-PPP TMV Working Group white paper: Beyond 5G/6G KPIs and Target Values, Version 1.0, June 2022, https://5g-ppp.eu/wp-content/uploads/2022/06/white_paper_b5g-6g-kpis-camera-ready.pdf, DOI: 10.5281/zenodo.6577506

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Abbreviations and acronyms:

3GPP	3rd Generation Partnership Project
5G	5th Generation
5G PPP	5G Public Private Partnership
6G	6th Generation
B5G	Beyond 5G
BLER	Block Error Rate
CAPEX	Capital Expenditures
E2E	End-to-End
GCF	Global Certification Forum
ICT-52	5G-PPP ICT-52-2020
IoT	Internet of Things
KPI	Key Performance Indicator
MIMO	Multiple Input Multiple Output
NGMN	Next Generation Mobile Networks Alliance
OPEX	Operational Expenditure
QoS	Quality of service
RAT	Radio Access Technology
SUT	System Under Test
T&M	Test and Measurement
UE	User Equipment

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Annex A - ICT-52 Project Descriptions

DAEMON 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

DEDICAT 6G 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 realization 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

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

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 fibers, 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 centers 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