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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

5G small cell backhaul/midhaul over TDM-PON

ITU-T G-series Recommendations – Supplement 75

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Supplement 75 to ITU-T G-series Recommendations

5G small cell backhaul/midhaul over TDM-PON

Summary

Supplement 75 to the ITU-T G-series Recommendations enumerates the various requirements arising from IMT-2020/5G small cell systems, concentrating on the backhaul and radio access point (RAP) midhaul portions of the network and comparing them with capabilities of the current and future time-division multiplexing-passive optical network (TDM-PON), such as 10-gigabit-capable symmetrical passive optical network (XGS-PON) defined in Recommendation [ITU-T G.9807.1] and 50G TDM-PON defined in the ITU-T G.9804.x series. Application scenarios and related requirements are also suggested as guidance.

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* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

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Supplement 75 to ITU-T G-series Recommendations

5G small cell backhaul/midhaul over TDM-PON

1 Scope

This Supplement studies the best application scenario of TDM-PON in 5G small cell backhaul and midhaul, and researches and determines related technical requirements.

NOTE – Annex A of [b-3GPP TR 38.801] on "Transport network and RAN internal functional split" considers functional split Options1-8. Because the split is an internal splitting within 5G RAN, it is not about the backhaul [b-3GPP TR 38.801] F1 interface (CU to DU split), which is defined as midhaul [b-3GPP TS 38.470]. Concurrent support for RAN deployment scenarios is outlined in [b-ITU-T GSTP-TN5G]. The definition of ITU-T is also used in O-RAN. In this Supplement, the focus is on midhaul and backhaul over the time-division-multiplexing passive optical network (TDM-PON). The fronthaul over TDM-PON is studied in other Supplements.

2 References

None.

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following terms defined elsewhere:

3.1.1 eLTE eNB [b-3GPP TR 38.801]: The eLTE eNB is the evolution of eNB that supports connectivity to EPC and next generation core (NGC).

3.1.2 evolved Packet Core [b-3GPP TR 21.905]: Is a framework for an evolution or migration of the 3GPP system to a higher-data-rate, lower-latency, packet-optimized system that supports, multiple RATs.

3.1.3 F1 [b-3GPP TR 38.472]: Interface between a gNB-CU and a gNB-DU, providing an interconnection point between the gNB-CU and the gNB-DU.

3.1.4 F1-C [b-3GPP TR 38.472]: Reference point for the control plane protocol between gNB-CU and gNB-DU.

3.1.5 F1-U [b-3GPP TR 38.472]: Reference point for the user plane protocol between gNB-CU and gNB-DU.

3.1.6 gNB [b-3GPP TR 38.801]: A node which supports the NR as well as connectivity to NGC.

3.1.7 new radio access network (RAN) [b-3GPP TR23.799]: A radio access network which supports either NR or E-UTRA or both, interfacing with the NGC.

3.1.8 new radio [b-3GPP TR 21.905]: Fifth generation radio access technology.

3.1.9 next generation core (NGC) [b-3GPP TR23.799]: A core network specified in the present Recommendation that connects to a NextGen access network.

3.1.10 NG-U [b-3GPP TR23.799]: A user plane interface used on the NG3 reference points between new RAN and NGC.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

None.

4 Abbreviations and acronyms

10 GEPON	10 Gbit/s Ethernet Passive Optical Network
3D	3 Dimensional
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	Fifth Generation Core network
ACK	Acknowledgment
AES	Advanced Encryption Standard
AI	Artificial Intelligence
AN	Access Network
API	Application Platform Interface
AR	Augmented Reality
BAP	Backhaul Adaptation Protocol
BBU	Baseband Unit
BH	Backhaul
BRAS	Broadband Remote Access Server
BS	Base Station
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CBRS	Citizen Broadband Radio Service
CC	Component Carrier
CDF	Cumulative Distribution Function
CEN	Carrier Ethernet Network
CHLI	Consecutive High Loss Intervals
CN	Core Network
CO	Central Office
CoMP	Coordinated Multiple Points
CP	Control Plane
CPRI	Common Public Radio Interface
CPU	Central Processing Unit
C-RAN	Centralized RAN
CRC	Cyclic Redundancy Check
CT	Channel Termination
cTE	constant Time Error
CU	Central Unit

DAS	Distributed Antenna System
DAW	Dedicated Activation Wavelength
DBA	Dynamic Bandwidth Allocation
DBRu	Dynamic Bandwidth Report, Upstream
DC	Dual Connection
DCN	Data Centre Network
DF	Distribution Fibre
DIS	Digital Indoor System
DL	Down Link
DOW	Drift Of Window
D-RAN	Distributed RAN
DSP	Digital Signal Processing
dTE_H	high-frequency sub-band of the dynamic TE
dTE_L	low-frequency sub-band of the dynamic TE
DU	Distributed Unit
E2E	End-to-End
eCPRI	evolved Common Public Radio Interface
EEC	Ethernet Equipment Clock
eEEC	enhanced synchronous Ethernet Equipment Clock
eMBB	enhanced Mobile Broadband
EMS	Element Management System
eNB	evolved NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
EqD	Equalization Delay
ESMC	Ethernet Synchronization Message Channel
ESP	Encapsulating Security Payload
E-UTRA	Evolved-UMTS Terrestrial Radio Access
EVC	Ethernet Virtual Circuit
F1AP	F1 Application Protocol
F1-C	F1 Control plane interface
F1-U	F1 User plane interface
FANS	Fixed Access Network Sharing
FAPI	Functional Application Platform Interface
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FF	Feeder Fibre

FFT	Fast Fourier Transform
FH	Fronthaul
FISR	Fault Isolation and Service Restoration
FIT	Failures in Time
FPGA	Field Programmable Gate Array
FS	Framing Sublayer
FTS	Full Timing Support
FTTB	Fibre To The Block
FTTH	Fibre to the Home
FTTx	Fibre to the *x*
GE	Gigabit Ethernet
GEM	GPON Encapsulation Mode
GNSS	Global Navigation Satellite System
GPON	Gigabit-capable Passive Optical Network
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSM	Global System for Mobile communications
GSMA	Global System for Mobile Communications Association
GSO	Geostationary Satellite Orbit
GTP-U	GPRS Tunnel Protocol for the User plane
HARQ	Hybrid Automatic Repeat request
HEO	Highly inclined Elliptical Orbit
HLI	High Loss Interval
HLS	High Layer Split
HMD	Head-Mounted Display
HRM	Hypothetical Reference Model
IAB	Integrated Access and Backhaul
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
IPRAN	IP Radio Access Network
IPSec	Internet Protocol Security
IWF	Interworking Function
JT	Joint Transmission
KPI	Key Performance Indicator
LAN	Local Area Network
LDPC	Low Density Parity Check

LEO	Low-Earth Orbit
LLS	Low-Layer Split
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MEC	Multiaccess Edge Computing
MEF	Metro Ethernet Forum
MH	Midhaul
MIC	Message Integrity Checks
MIMO	Multiple Input Multiple Output
MLSE	Maximum Likelihood Sequence Estimation
MME	Mobility Management Entity
mMIMO	massive Multiple Input Multiple Output
mmW	millimetre Wave
MNO	Mobile Network Operator
MPM	Multi-Passive-Optical-Network Module
MT	Mobile Termination
MTBF	Mean Time Between Failures
MTIE	Maximum Time Interval Error
MTP	Motion To Photon
MTTR	Mean Time To Repair
MU-MIMO	Multiuser Multiple Input Multiple Output
NACK	Non-Acknowledgement
NAS	Non-Access-Stratum
NE	Network Element
nFAPI	network Functional Application Platform Interface
NFV	Network Function Virtualization
NGC	Next Generation Core
NGMN	Next Generation Mobile Networks
NG-PON2	40-Gigabit-capable Passive Optical Network
NIC	Network Interface Card
NR	New Radio
NSA	Non-Standalone
OAM	Operation Administration and Maintenance
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing

OLT	Optical Line Termination
OMCI	Optical network termination Management and Control Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
O-RAN	Open-Radio Access Network
OSS	Operation Support Systems
OTA	Over-The-Air
P2MP	Point to MultiPoint
P2P	Point-to-Point
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PHY	Physical Layer
PNF	Physical Network Function
PoE	Power over Ethernet
PON	Passive Optical Network
PPP	Point-to-Point Protocol
pRRU	pico Remote Radio Unit
PRTC	Primary Reference Telecom Clock
PTN	Packet Transport Networking
PTP	Precision Timing Protocol
QL	Quality Level
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAP	Radio Access Point
RAT	Radio Access Technology
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
rHUB	remote HUB
RIB	Radiated Interface Boundary
RLC	Radio Link Control
ROW	Rights of Way
RRC	Radio Resource Control
RRH	Remote Radio Head
RRU	Remote Radio Unit
RS	Reed Solomon

RTD	Round-Trip Delay
RTT	Round-Trip Time
RU	Radio Unit
SA	Standalone
SC	Small Cell
SCF	Small Cell Forum
SCG	Secondary Cell Group
SCS	Subcarrier Spacing
SCTP	Stream Control Transmission Protocol
SDAN	Software-Defined Access Network
SDAP	Service Data Adaptation Protocol
SDH	Synchronous Digital Hierarchy
SDN	Software-Defined Networks
SDU	Service Data Unit
SEC	SDH Equipment Clock
SGSN	Serving GPRS Support Node
SI	Study Item
SLA	Service Level Agreement
SoC	System on Chip
SOHO	Small Office / Home Office
SON	Self-Optimizing Network
SR	Service Router
SR-DBA	Status Reporting Dynamic Bandwidth Allocation
SRG	Shared Risk Group
SU-MIMO	Single-User Multiple Input Multiple Output
SWO	Switchover
SyncE	Synchronous Ethernet
TAB	Transceiver Array Boundary
TAE	Time Alignment Error
T-BC	Telecom Boundary Clock
TC	Transmission Convergence
TCO	Total Cost of Ownership
T-CONT	Transmission Container
TCP	Transmission Control Protocol
TDD	Time-Division Duplex
TDEV	Time Deviation
TDM	Time-Division Multiplexing

TDMA	Time-Division Multiple Access
TDM-PON	Time-Division Multiplexing-Passive Optical Network
TE	Time Error
TEID	Tunnel End point Identifier
T-GM	Telecom Grand Master
TN	Transport Network
ToD	Time-of-Day
TRxP	Transmission Reception Points
T-TSC	Telecom Time Slave Clock
TWDM	Time and Wavelength Division Multiplexing
TX	Transmitter
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UE	User Equipment
UL	Up Link
UMa	Urban Macro cell
UMTS	Universal Mobile Telecommunication System
UNI	User Network Interface
UP	User Plane
URLLC	Ultra Reliable Low-Latency Communication
UTC	Universal Time Coordinate
UTM	UAV-Traffic Management
vAN	virtual Access Node
VLAN	Virtual Local Area Network
VNF	Virtual Network Function
VNO	Virtual Network Operator
VR	Virtual Reality
WDM	Wavelength Division Multiplexing
XG-PON	10-Gigabit-capable Passive Optical Network
XGS-PON	10-Gigabit-capable Symmetric Passive Optical Network

5 Conventions

None.

6 Review of 5G small cell systems

6.1 Types of small cell

6.1.1 Background of the 3G/4G era

In [b-ITU-R M.1035] for IMT-2000, i.e., 3G, the cell layers can be put into four categories: mega (satellite) cells, macro cells, micro cells and pico cells. The cell types used for different IMT-2000 services are the decision of the operator. However, the size of the cells is related to radio range, and thus some requirements are placed on the design of the radio interface(s). Some typical cell parameters for these cell types are shown in Table 1 [b-ITU-R M.1035].

Table 1 – Example of typical cell type parameters [b-ITU-R M.1035]

Cell type	Mega cell	Macro cell	Micro cell	Pico cell
Cell radius	100–500 km	≤35 km	≤1 km	≤50 m
Installation	LEO/HEO/GSO	top of building/tower, etc.	lamp post/ building wall	inside building
Terminal speed	–	≤500 km/h	≤100 km/h	≤10 km/h
NOTE – Low-earth orbit (LEO): A circular or elliptical orbit of about 700 to 3 000 km altitude above the Earth's surface. Highly inclined elliptical orbit (HEO): An elliptical orbit most typically with a perigee of 500 km or more and an apogee of 50 000 km or less altitude above the Earth's surface with an inclination angle greater than 40° from the equatorial plane. Geostationary satellite orbit (GSO): The orbit of a geosynchronous satellite whose circular and direct orbit lies in the plane of the Earth's equator.				

In the 4G era, there are usually 4 methods for classifying small cells (SCs):

1) Method 1: According to the combination of the baseband and radio frequency, SCs can be divided into integrated SC and micro remote radio unit (RRU).
   - Integrated SC: This mainly refers to the device containing the baseband and radio frequency unit, which has the main function of the base station and can be directly connected to the core network.
   - Micro RRU is also called distributed SC. The integrated SC is directly connected to the core network, while the micro RRU is connected to the baseband unit (BBU)[b-CCSA SR208].
2) Method 2: According to the transmission power level, long term evolution (LTE) SCs are generally divided into:
   - Watt level, power range is 1–10 w, and typical value is 5 w.
   - Milliwatt level, power range is 100–500 mw, and typical value is 100 mw [b-CCSA SR208].
3) Method 3: According to the coverage scenario, SCs can be divided into outdoor SCs and indoor SCs. Based on Method 1, indoor SCs can be further divided into indoor integrated SCs and indoor distributed SCs [b-CCSA SR208].
4) Method 4: According to the relevant definition and classification in 3GPP and whether baseband and radio frequency are co-located, SCs are divided into the following four types: integrated SCs, micro RRUs, integrated pico cells and pico RRUs [b-CCSA 2014B3]. Among them, the integrated SC and micro RRU should meet the requirements of medium range base station (BS) in 3GPP, and the integrated pico cell and pico RRU should meet the requirements of the local area BS in 3GPP [b-CCSA 2014B3].

In [b-3GPP TS 36.104], there are four BS classes as follows:

- Wide area BSs are characterized by requirements derived from macro cell scenarios with a BS to user equipment (UE) minimum coupling loss equal to 70 dB.
- Medium range BSs are characterized by requirements derived from micro cell scenarios with a BS to UE minimum coupling loss equal to 53 dB.
- Local area BSs are characterized by requirements derived from pico cell scenarios with a BS to UE minimum coupling loss equal to 45 dB.
- Home BSs are characterized by requirements derived from femto cell scenarios as shown in Table 2 [b-3GPP TS 36.104].

The rated output power, $P_{rated,c}$, of the BS shall be as specified in [b-3GPP TS 36.104].

Table 2 – Base Station rated output power [b-3GPP TS 36.104]

BS class	$P_{rated,c}$
Wide area BS	(Note)
Medium range BS	< + 38 dBm
Local area BS	< + 24 dBm
Home BS	< + 20 dBm (for one transmit antenna port) < + 17 dBm (for two transmit antenna ports) < + 14 dBm (for four transmit antenna ports) < + 11 dBm (for eight transmit antenna ports)
NOTE 1 – There is no upper limit for the rated output power of the wide area BS. NOTE 2 – This is Table 6.2-1 of [b-3GPP TS 36.104].	

6.1.2 Types of small cell in the 5G era

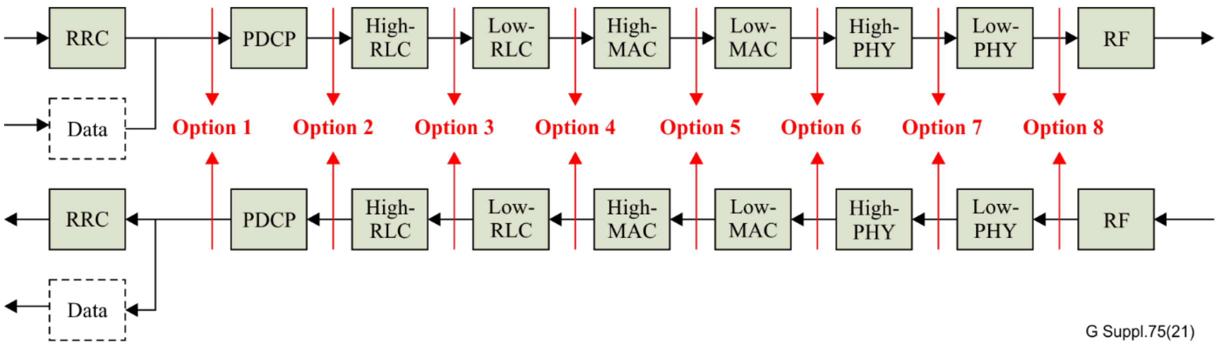


Figure 1 – Function split between central and distributed unit [b-3GPP TR 38.801]

As shown in Figure 1, from the protocol split option of the radio access network (RAN) defined by [b-3GPP TR 38.801], Option 2 has been selected as the BS split named the F1 interface. The remaining splitting methods are basically manufacturer-defined. Option 2 is basically the higher layer split interface between the central unit (CU) and the distributed unit (DU). The lower layer split point between the DU and radio unit (RU) can be Option 6 (medium access control (MAC) / physical layer (PHY) split)/Option 7/Option 8 (common public radio interface (CPRI)). Option 6 and Option 7 are often referred to as the evolved common public radio interface (eCPRI), and Option 7 includes sub-Options 7.1, 7.2 and 7.3.

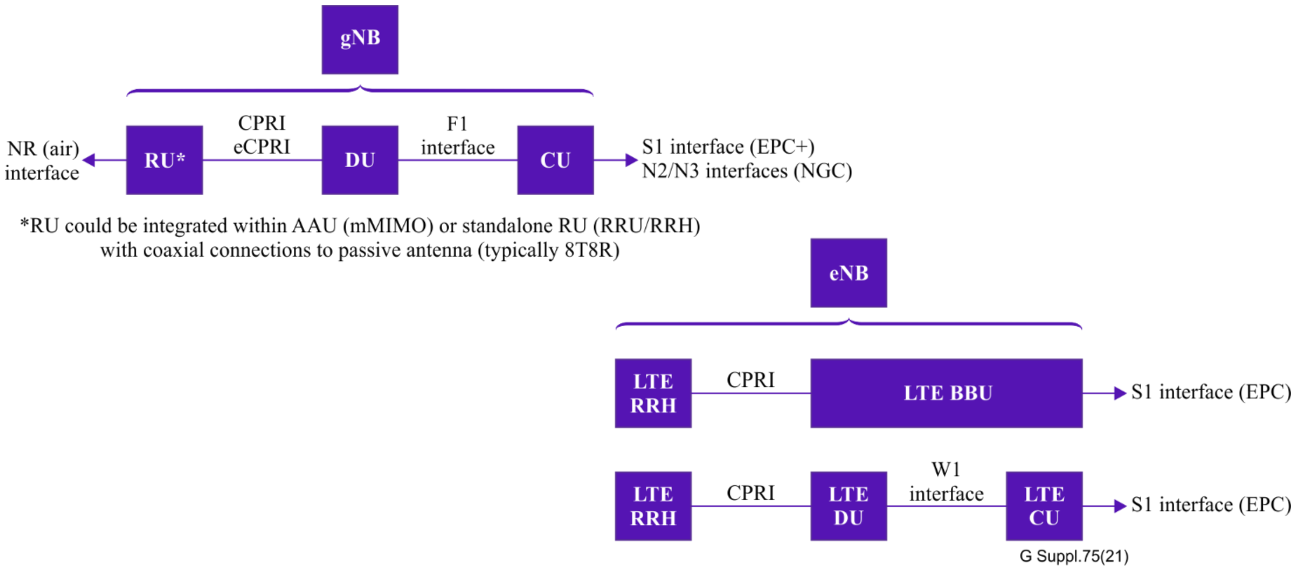


Figure 2 – 4G/5G RAN and interfaces

Figure 2 shows 4g/5g RAN and interfaces.

According to [b-SCF238], SCF's work on common interfaces, at system-on-chip level functional application platform interface (FAPI) and 5G FAPI) and system level network FAPI (nFAPI) is the effort to define common framework within which many designs and suppliers can innovate and interwork. These interfaces and SCF's Split 6 architecture is particularly strongly supported among operators or other organizations which are planning to deploy SCs in enterprise and industrial environments. In the indoor enterprise setting, 48% of operators or other organizations plan to support Option 6 for the split between radio units, distributed units and centralized units in disaggregated networks. There was also significant support in private industrial and campus networks [b-SCF238]; see also Figure 3.

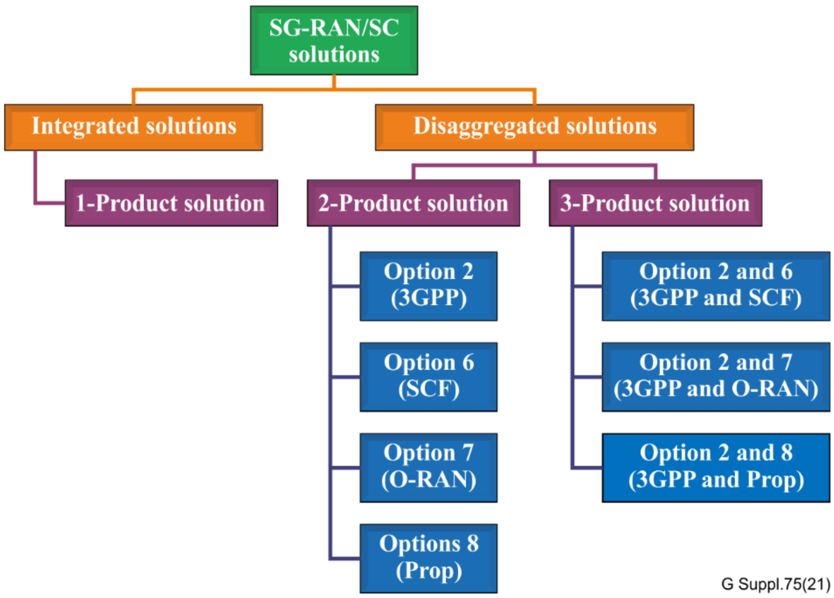


Figure 3 – The Small Cell Forum's view of commercially viable 5G small cell network solutions [b-SCF238]

Based on the split options, the following types of 5G RAN or cells exist:

- Integrated cell (i.e., all-in-one);

• Two-unit disaggregated RAN with split Option 2;
• Two-unit disaggregated RAN with Small Cell Forum (SCF) split Option 6;
• Two-unit disaggregated RAN with O-RAN split Option 7.2x;
• Two-unit disaggregated RAN with split Option 8;
• Three-unit disaggregated RAN with SCF split Options 2/6;
• Three-unit disaggregated RAN with O-RAN split Option 2/7x;
• Three-unit disaggregated RAN with split Option 2/8 [b-SCF238].

According to [b-3GPP TS 38.104], base stations can be divided into four types i.e., 1-C, 1-H, 1-O, and 2-O. Among them, 1 and 2 refer to FR1 and FR2, respectively; C is the antenna connector; H is the TAB connector. O defines over-the-air (OTA) requirements at the radiated interface boundary (RIB) interface. This division will be instrumental for analysing synchronization (time alignment errors).

As shown in Figures 4 and 5, for BS type 1-C, the requirements are applied at the BS antenna connector (port A) for a single transmitter or receiver with a full complement of transceivers for the configuration in normal operating conditions. If any external apparatus such as an amplifier, a filter or the combination of such devices is used, requirements apply at the far end antenna connector (port B) [b-3GPP TS 38.104].

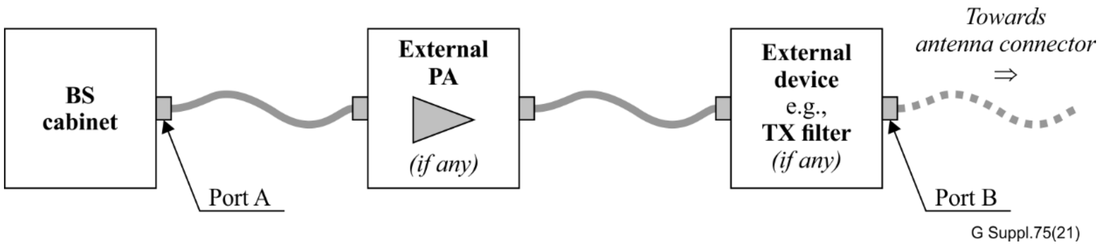


Figure 4 – BS type 1-C transmitter interface [b-3GPP TS 38.104]

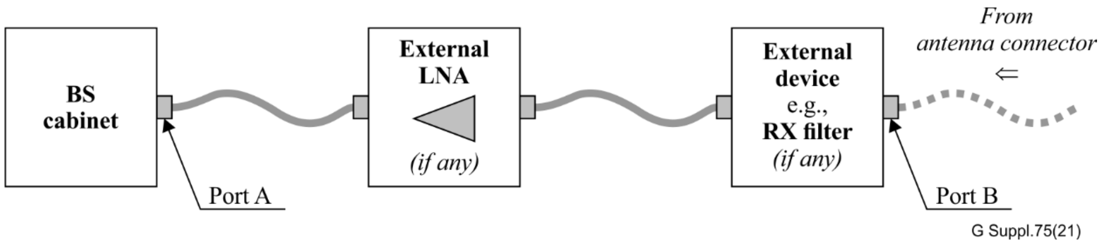


Figure 5 – BS type 1-C receiver interface [b-3GPP TS 38.104]

According to the minimum distance away from the ground (UE to BS) of 35/5/2 meters for BS types 1-O and 2-O, and minimum coupling loss of 70/53/45 dB for BS types 1-C and 1-H, the BS is divided into three classes, wide area/medium range/local area base station, which are characterized by requirements derived from the scenarios named macro cell, micro cell and pico cell [b-3GPP TS 38.104]. The minimum distance away from the ground between the BS and the UE is defined for 1-O, 2-O type base stations. Coupling loss is defined for BS type 1-H and 1-C. At present, there are no BS type 1-O or BS type 2-O of SCs, and the SCs can be considered BS type 1-C. The rated carrier output power of the BS type 1-C shall be as specified in Table 3.

Table 3 – BS type 1-C rated output power limits for BS classes

BS class	$P_{rated,c,AC}$
Wide area BS	(Note 1)
Medium range BS	≤ 38 dBm
Local area BS	≤ 24 dBm
NOTE 1 – There is no upper limit for the $P_{rated,c,AC}$ rated output power of the wide area BS. NOTE 2 – This is Table 6.2.1-1 of [b-3GPP TS 38.104].	

At present, the SC architecture introduced in the industry mainly has three types: one is an integrated type; another has integrated DU only; and the last is a distributed type. The integrated type integrates the baseband and radio frequency parts, and mainly is implemented by a system on chip (SoC). L2 and L3 are also processed within the same hardware, so this architecture has no split CU and split DU. The radio access points are RU and DU combined with a split option to have the CU function as a centralized (and/or virtualized component). The Figure 6 provides clarification [b-Sutton]

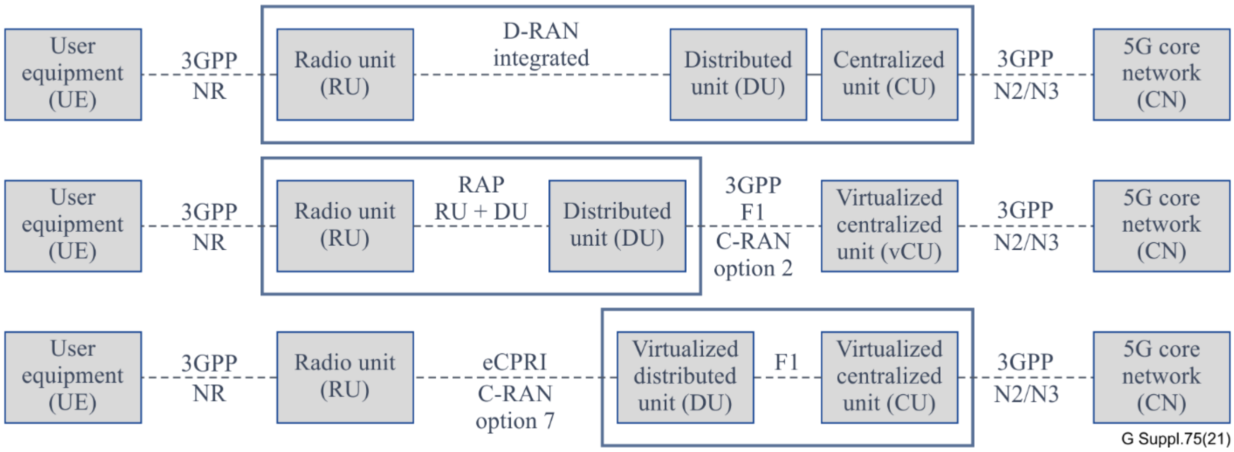


Figure 6 – Suggested picture for clarification [b-Sutton]

The integrated type can be divided into indoor and outdoor sub-types. The indoor integrated type is generally light-like, and the outdoor integrated type is generally pole-like. An integrated SC generally has an embedded high-gain directional antenna, which is particularly advantageous for street coverage.

At present, the typical power range value of integrated type 5G SCs is 500 mw, which is divided into two types, i.e., 2*250 mw and 4*125 mw.

The distributed type can also be divided into indoor and outdoor sub-types (Table 4). The indoor distributed type SC is split into BBU + remote hub (rHUB) + pico remote radio (pRRU) by Option 8 or Option 7, which is called as 5G digital indoor system (DIS). The BBU of 5G DIS is an integrated CU+DU. When Option 8, i.e., CPRI, is the transport protocol between the BBU and pRRU, the pRRU only has radiofrequency (RF) and antenna. When Option 7-2, i.e., eCPRI, is the transport protocol between BBU and pRRU, the pRRU has low PHY, RF and antenna. Clause 10.1 discusses 5G DIS and bearer technology. Fronthaul links are not considered in this Supplement.

The outdoor distributed SC is also called micro RRU. Compared with an integrated SC, a micro RRU can share a BBU with the macro station, which has more advantages in software capability evolution, function expansion, cell division and the macro-micro intensive collaboration network model.

Table 4 – Suggested overview table

Baseband function integration	RU (low PHY only) (fronthaul transport)	RU+DU (midhaul transport)	RU+DU+CU (backhaul transport)
Indoor	pRRU	LAN link cells	All-in-One pico Femto cell
Outdoor	Micro RRU	Radio Access Point (RAP)	'pole mount' micro/ pico cell

Only mid- and backhaul SCs are further considered in this Supplement.

Supporting or not supporting mmW, the number of antennas and frequency bandwidth (e.g., 100 MHz, 200 MHz or more) will make a big difference in the bearing requirements of SCs. In practice, the above technical specifics of the BS station are also often used in defining types.

6.1.3 Technical comparison between small cells and macro stations

A SC is a cellular BS that transmits and receives 3GPP-defined RF signals with small power and small form factor. In most cases, it serves a small coverage area.

A 5G NR SC is one or multiple network units which fulfil the 3GPP TS 38 series NG-RAN (new radio – radio access network) gNB specification. The division method for types of SC by split option(s) is shown in clause 6.1.2.

Different types of SCs will support a variety of frequency bands as defined by 3GPP, which are divided into the FR1 (Sub-6 GHz) and FR2 (mmW) bands. Depending on deployment, these may be either licensed (for example, to a mobile network operator (MNO)), shared (as in the citizen broadband radio service (CBRS) spectrum in the United States of America) or unlicensed (as in the 2.4 and 5 GHz bands used by Wi-Fi networks) [b-SCF238].

SCs would generally exclude massive (m) multiple input multiple output (MIMO), where there are more than 16TX and 16RX co-located RF channels or transceiver units (TRXUs). Larger configurations such as 32TX and 32RX TRXUs are more suitable for macro cells. Beamforming and hybrid beamforming are relevant particularly to FR2 SCs. Multiuser (MU) MIMO and single-user (SU) MIMO are also relevant to SCs [b-SCF238].

Considering key issues for physical design and hardware architecture, Table 5 compares SCs and macro cells.

Table 5 – Comparing small cell and macro cell key issues for physical design and hardware architecture [b-NGMN BH REQ]

Key issues	SC backhaul requirements	Macro cell backhaul requirements	Resulting solution benefits
Equipment form factor and weight	Small in size, "one box" architecture (all outdoor). Minimum number of physical ports. Unobtrusive appearance, "street furniture camouflage". Optional SC integration, functional independence of RAN and backhaul.	In many cases macro deployment is "out of sight" and less restricted in space. A requirement for support of legacy backhaul encourages split-mount modular architecture and high densities of physical interfaces.	Reduces the space used. Minimizes the overhead of civil works permissions and site engineering. Reduces installation costs and rentals. Avoids negative public reaction.

Table 5 – Comparing small cell and macro cell key issues for physical design and hardware architecture [b-NGMN BH REQ]

Key issues	SC backhaul requirements	Macro cell backhaul requirements	Resulting solution benefits
Power supply and consumption	Mains power supply. Support for power over Ethernet. Low power consumption, a fraction of what is required for the SC.	"Classic" telecommunication captive office specification for DC power. Performance and cooling needs requires higher power consumption.	Enables the deployment at the street level and minimizes the cost and complexity of the power supply.
Installation procedures	Lightweight equipment, easily mounted. Single technician's task, fast procedures with little or no site preparation. Ideally one site visit for RAN and backhaul.	Fully controlled and regulated site acquisition and engineering, less pressure for "instant roll-out".	Reduces the cost of installation and improves the speed of deployment.
Commissioning procedures	"Plug and play" with minimum training. Automated provisioning.	Fewer installations, traditionally performed by highly skilled "Telco grade" technicians.	Reduces the cost of installation and improves the speed of deployment.
Reliability and maintenance	Resistant to shocks and vibrations. Highly reliable in all weather conditions. Easily replaced (maintains configurations).	Secured site environment allows a greater degree of protection against environmental conditions.	Reliability and easy replacement lower the cost of operations.
Green credentials	Goes above and beyond all commonly accepted standards on the use of materials.	The same.	Essential for corporate social responsibility.
Safe-to-touch	Safety consideration on an unauthorized person's (general public) contact with the SC equipment.	Normally located at restricted access area General telecommunication equipment's safety requirements.	Reduces risks of injury or damage to persons and/or things.
Risk of physical access	Protection from any types of intervention such as weather and malicious attacks.	Normally located in a restricted access area. General telecommunication equipment's safety requirements.	Improves operational reliability and reduces any physical damage.

With technology trends in SCs such as combing with virtualization, expansion into high frequency bands and white-box hardware design, many new characteristics of SCs will emerge in the future, so these comparisons need continuous attention and research.

The main special technical difficulties on bearing midhaul and backhaul of 5G SC such as some types of SCs combining with mmW or some types of new services need more study.

6.2 Small cell architecture

6.2.1 Requirements on the physical design of small cells and backhaul units

Physical design is likely to be a key differentiator between SC solutions as it impacts the range of locations suitable for deployment and its cost. The aspects of the physical design for the SC and associated backhaul unit include size, weight, connectivity, power, appearance, environmental, backhaul/RAN integration, reliability, and installation and commissioning. With perhaps the exception of the environmental protection, requirements are all the more challenging for SCs than for macro cells.

Varying degrees of integration between SC and backhaul unit are possible which impacts factors such as ease of deployment, size, security and flexibility, as illustrated by the following examples:

- Fully integrated modules: Backhaul function integrated into RAN node with a dedicated backhaul card (or vice versa). Full integration reduces vulnerability to tampering, reduces size and potentially eases deployment. Flexibility in selecting best in class RAN or backhaul units is compromised.
- Two separate modules within a single enclosure: Connections for data and power within a single physical enclosure so that the interconnections between the two are protected from the outside and it can be seen as a single volume.
- Completely separated modules: Seen as two boxes from the outside, and interconnections between the two have to be protected both from weather and malicious interventions [b-NGMN BH REQ].

6.2.2 Key trends on small cell form factors and architecture

In the 5G era, SCs will be deployed in a far wider range of scenarios (for example, driven by the release of new spectra in the Sub-6 GHz and mmW ranges), and the form factors and architectures will be extremely varied.

For 5G, the introduction of virtualized, disaggregated networks means that some SCs will consist of two or three elements, while others will still be all-in-one. The 5G SC product's form factor, power, size, interfaces and specification will vary according to the use case and deployment scenario.

Three key trends are driving the unprecedented diversification of SC form factors and architectures:

- Cellular technology is moving beyond generic mobile broadband services and is starting to be adopted for many different purposes, by a wide range of enterprises, industries and government agencies. Different environments and use cases have very different performance and form factor requirements, from a huge, distributed radio system for a large campus to an almost invisible unit embedded in a pavement for a smart traffic application. A diversity of spectrum bands, including shared spectrum, will also be in play.
- The virtualization of the mobile networks is driving the adoption of disaggregated, multivendor architectures in which radio units are separated from virtualized baseband units. This can be done in several different ways according to the needs of the use case.
- The roll-out of 5G will drive further proliferation of SC designs because it will push the densification and scale of deployment to new levels. 5G will often be deployed in relatively high frequency bands, which lend themselves to SCs, and it will be implemented as a ubiquitous network designed to support every kind of user, location and application [b-SCF238].

6.2.3 Functional architecture corresponding to different 5G RAN architectures

The functional architecture of the SC is directly related to the type division of the SC, that is, the split option(s) and integrated degrees for CU, DU and RU. Clause 6.1 describes the different split options in detail.

Split Option 2 is referred to as a high layer split (HLS) option, whereas split Options 6, 7 and 8 are low layer split (LLS) options. Under each solution, the split of the functional architecture is shown as follows.

1) 3GPP Split Option-2 solution

- CU: The gNB-CU includes the service data adaption protocol (SDAP), packet data convergence protocol (PDCP) and the radio resource control (RRC) protocol.
- DU: The gNB-DU(s) includes radio link control (RLC), MAC, PHY, baseband and RF processing. The SCF (FAPI) PHY application platform interface (API) should be used to interface the software stack to the PHY hardware, which comes from different vendors [b-SCF222].

2) O-RAN Split Option-7.2x solutions

- O-CU: The central unit includes the SDAP, PDCP and RRC protocols.
- O-DU: The distribution unit includes the RLC, MAC and high-PHY protocols.

The SCF FAPI PHY API should be used to interface the software stack to the PHY hardware, which comes from different vendors [b-SCF222].

- O-RU: The radio unit includes low-PHY (fast Fourier transform (FFT) / inverse fast Fourier transform (IFFT)), baseband and RF processing.

3) SCF Split Option-6 solutions

- S-CU: The central unit includes the SDAP, PDCP and RRC protocols.
- S-DU: The distributed unit includes RLC and MAC.
- S-RU: The radio unit includes PHY, baseband and RF processing.

4) Proprietary Split Option-8 solutions

- CU: The central unit includes the SDAP, PDCP and RRC protocols.
- BBU: The distributed unit includes the RLC, MAC and PHY protocols. The SCF FAPI PHY API should be used to interface the software stack to the PHY hardware, which comes from different vendors [b-SCF222].
- Remote radio head (RRH): The RRH only includes RF processing.

6.2.4 Main product architecture solutions in the industry chain

This sub-clause mainly focuses on the product architecture of 5G SCs.

From the perspective of the development of the industry chain, one is an end-to-end (E2E) solution mainly based on an x86 processor and field programmable gate array (FPGA), and the other is an ARM-architecture-based SoC solution. Some manufacturers can provide a low power consumption SoC+FPGA solution.

The first type is taken as an example, because the evolution of 5G wireless access networks is gradually moving towards virtualization, and manufacturers have introduced the architecture of the x86-processor-based solution. The RF front end solution is the manufacturer's FPGA + third-party radio frequency integrated circuit (RFIC), and the DU and CU are developed and implemented based on the general x86 platform. Through serial x86 processors, different types of processors can be adapted to BSs of different sizes. It should be noted that the CU and DU in the current SC product solution have not yet been separated. The current implementation is mainly CPU processing L2/L3 (L1), and FPGA processing (L1/low PHY).

In the architecture of the x86 processor solution, L1 software and L2/L3 can be provided by different vendors. This solution focuses on the C-RAN model and is also suitable for integration with multiaccess edge computing (MEC) and other services. This architecture is more in line with the O-RAN architecture.

Comparing different solutions, the following questions are suggested to be continually studied. The first is that the SCs are usually used to cover indoor or outdoor point-like areas, so there is a need for more study on the performance of the centralized deployment of CU and/or DU baseband processes of the disaggregated 5G gNB and on the impact of coordination among these SCs. The second is that when SCs are used for private network services, which usually have strict requirements on delay, the separated architecture increases the transmission delay. The third is the complexity of the E2E system.

In the 5G era, in order to reduce cost, some operators are promoting white-boxing of SC products, especially RU or integrated RU+DU.

6.2.5 Analysing some types of small cell combining with mmW

Some types of SC can support the FR2, i.e., mmW.

Compared with FR1, mmW has the following advantages:

1) Higher frequency band, and abundant frequency resources can provide sufficient large bandwidth.
2) Easy to combine beamforming technology.
3) Very low latency can be expected.
4) It is easier to implement dense cell deployment.
5) It is expected to achieve centimetre-level high-precision positioning.
6) The equipment is highly integrated and easy to install.

At the same time, mmW also faces the following challenges:

1) The propagation and penetration loss is large, resulting in a small coverage distance.
2) Mobility management is more difficult.
3) Product realization is more complicated.
4) The demand for coexistence with medium and low frequency poses challenges to the compatibility of terminal antennas.
5) Differences in network requirements of various services [b-GSMA mmW WP] [b-CU mmW WP] [b-FuTURE mmW WP].

In the future, SC with mmW will mainly have the following characteristics.

Firstly, due to the increase in spectrum bandwidth, the fronthaul interface will move up to reduce the demand for fronthaul bandwidth;

Secondly, both the size of the antenna and the coverage area of mmW are further reduced than sub-6G, so the probability of line of sight (LOS) scenarios is improved. Due to the short wavelength of mmW, mMIMO technology can realize the design of large scale antenna arrays at the BS. mmW applications combined with beamforming can effectively increase antenna gain.

Thirdly, the beamforming method is different from the traditional method: it adopts adaptive digital-analogue hybrid beamforming;

Fourthly, the frame structure is different from FR1 (i.e., sub-6G): the mainstream subframe carrier interval is 120 kHz and the time slot is 0.125 ms.

Due to their spectral characteristics, i.e., LOS transmission, SCs with mmW can use wireless spectrum resources more accurately and efficiently. The smaller of the SCs will require and bring a greater number for deployment, finally providing better coverage quality and a faster rate. At the same time, it needs to be noted that when the coverage density of a BS is large, the interference is also large, and the subscriber's rate may not be continuously increased.

Compared with the traditional frequency band dub-6G, the mmW has another feature, that the physical size of the antenna can be relatively small. This is because the physical size of the antenna is proportional to the wavelength of the band. It is convenient to equip the BS equipment with an mmW antenna array to realize various MIMO technologies. It should be noted that UE supporting mmW still uses the traditional four antennas, and there is no array antenna.

High-order MIMO is on the BS side, which improves the capacity of the system, not the single subscriber's rate. The increase of single subscriber's rate mainly comes from the increase of bandwidth and higher order modulation and demodulation.

The current antenna technology needs to be studied continuously.

The mmW is seriously affected by atmospheric absorption and rain fading as well as LOS propagation characteristics, resulting in a very large attenuation of mmW in the air. This feature also means that mmW technology is not suitable for use in UE outdoors or in locations far away from the BS.

6.3 Siting challenges and recommended solutions for small cell

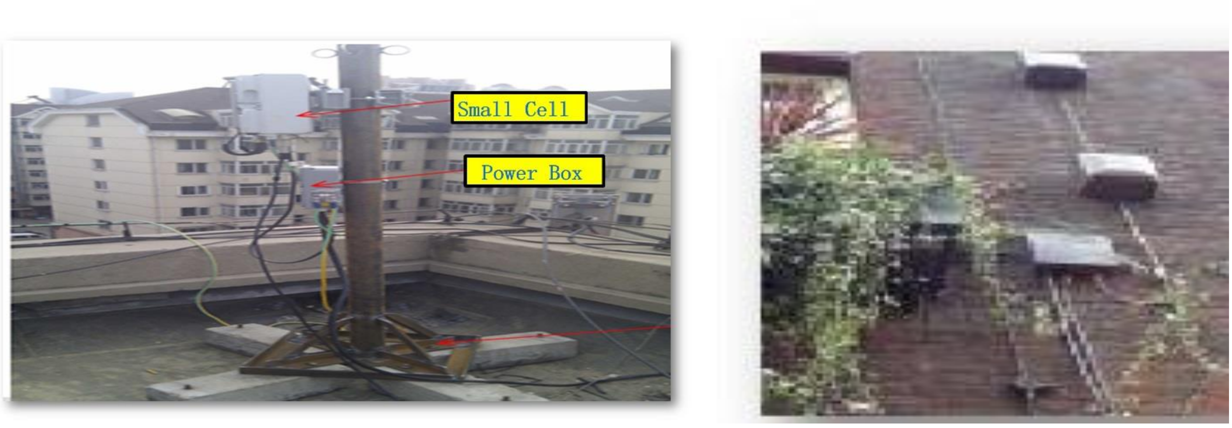


Figure 7 – Schematic diagram of small cell installation

The installation environment of SC is complex, including multiple installation methods such as hanging poles, wall hanging, ceiling and embedded, which bring great challenges to the backhaul network, site acquisition, power acquisition and maintenance. See also Figure 7.

Achieving massive densification requires a new approach to SC deployments, from site acquisition to RF planning, integration with existing infrastructure, installation and network optimization.

6.3.1 Challenges

Some of the key challenges are outlined as follows; most are based on [b-SCF195].

6.3.1.1 Site acquisition and approval

Generally, MNOs have teams of site acquisition personnel that are given search areas or search rings that have been provided by RF engineers who design the wireless network. As networks densify, the search areas are shrinking and becoming more specific. Any location found within this area, if it meets the height requirement on the search area request, should be a viable candidate for the RF engineer to evaluate. The site acquisition team will often be required to submit multiple candidates for the RF engineers to review [b-SCF195].

For traditional BSs, this approval can take several months and involve obtaining regulatory approvals from several government agencies.

6.3.1.2 New site types

Densification involves identifying new site solutions such as pre-approved telegraph poles, lamp posts, securing lower radiation heights on roof tops or traditional cell towers. The goal is to minimize zoning review and regulatory approval timelines, but these new site types still need to be included in the regulatory framework in many cases [b-SCF195].

6.3.1.3 Power issues

As well as increased numbers of sites and backhaul connections, densification introduces far more places where grid power must be available. That gives rise to several issues:

- Cost: the cost of connecting a SC may not be significantly less than connecting a macro tower.
- Space constraints: there may not be room for a dedicated power source on a site such as a lamp post [b-SCF195].

6.3.1.4 Installation

Installation locations for urban SCs are typically determined during the RF planning and design phase. When selecting the appropriate locations, the following considerations should also be taken into account:

- Power source availability;
- Backhaul connectivity options;
- Special environmental conditions;
- Local zoning requirements [b-SCF195].

6.3.2 Planning and design processes

The planning and design processes required to deploy an enterprise SC network are shown and described in Figure 8 [b-SCF079].

Figure 8 – Planning and design processes [b-SCF079]

6.3.3 Recommendations

In 2018, SCF and 5G Americas issued a list of recommendations to ease the process of approvals and deployment for SCs [b-SCF195]. These are summarized in Table 6.

Table 6 – Summary of recommended solutions to facilitate small cell siting (i.e., Figure 15 in [b-SCF195])

Key challenge	SCF recommended solutions
Streamlining the regulatory approval for SC equipment	Standard industry classifications of equipment with common documentation of compliance and conformity to be used when defining related policies; some of these classes can be exempt from the approval process or subject to a light regulatory regime.
Scaling the planning application process to support large numbers of cells	Common rules on which equipment classes can be exempt or subject to fast track approval; batch process for groups of cells, to decrease the approval time and reduce the workload of local administrations.

Table 6 – Summary of recommended solutions to facilitate small cell siting (i.e., Figure 15 in [b-SCF195])

Key challenge	SCF recommended solutions
Securing sufficient suitable sites with power and backhaul	Simplified common frameworks to ease the opening of access to street furniture and other existing assets. Census of available assets per municipality. Open access to administrative buildings.
Cost of installation	Adopt simplified rules of installation that would enable non-skilled workers to deploy (based on classes of equipment and complexity of installation). Reduce administrative charges (e.g., installation, operation, periodical revision taxes).
Radiofrequency compliance	Follow international recommendations for installation classes and provide information.
Administrative complexity	Single executive to coordinate all approvals (e.g., in a smart city programme). Streamlined paperwork and filing to minimize the approval processes and reduce the workload of the administration.

A more detailed set of recommendations for best practice are summarized as wireless deployment and rights of way (ROW), wireline advocacy, one-touch make-ready and national database [b-SCF195].

Deployment processes must be streamlined too, which includes how new form factors could simplify deployment, a best-case deployment process for SCs, addressing the power issue, environment and aesthetics [b-SCF195].

Table 7 summarizes the key challenges for deploying a commercially viable dense network, and their suggested solutions.

Table 7 – Key challenges of dense deployment, and recommended solutions (i.e., Table 3-1 in [b-SCF192])

Challenge	Solution
TCO and cost of capacity	Advanced capacity planning, spectral efficiencies, shared or neutral host networks, automation/SON.
Coverage and QoS	Flexible standards and regulations to cover non-traditional cell sites (e.g., rural, street furniture, underground car parks).
Backhaul and power	Standardized frameworks agreements with fibre or copper owners; mixed toolkit of backhaul and power options.
Pre-deployment: site acquisition and equipment approval	Common rules on which equipment classes can be exempt or subject to fast track approval; a batch process for groups of cells; new BS design.
Deployment and maintenance processes for large scale	Create simplified common frameworks for access to sites; simplify installation procedures; automate maintenance; site sharing.

6.3.4 Backhaul considerations in planning and design for siting

For geographical design purposes, several backhaul-related considerations should be taken into account:

- Existing places where operators have already deployed network infrastructure should be considered. These places are normally more accessible for the installation of new equipment, while also making it easier to support operations.

- Consideration of different types of wireless backhaul options: Different frequency bands; LOS or non-LOS; point-to-point (P2P) or point-to-multipoint (P2MP).
- Consideration of different types of wired backhaul options (fibre, copper, cable).
- Bandwidth requirements, initially and over the expected life of the SC. The expected bandwidth growth may dictate what type of medium should be deployed (e.g., copper may be initially sufficient but fibre may provide the necessary bandwidth evolution needs).
- Packet-based. For the backhaul link is IP-based, ensure that it can provide the appropriate level of synchronization. The level and type of synchronization required depends as much on the cell location as it does on the technology used. For example, SCs in a dense enterprise environment are provided to enhance capacity and therefore may utilize full coordination techniques such as coordinated multiple points (CoMP), which would dictate what level of frequency, time and phase synchronization is required [b-SCF079].

6.4 Comparison of indoor coverage capabilities between macro station and small cell

With the development of mobile Internet communication technology and subscriber's requirements, more and more mobile services take place indoors. Especially in the 5G era, more than 85% of services will take place in indoor scenes, and the importance of 5G indoor coverage gradually becomes prominent.

For cellular mobile communication networks, an outdoor macro BS is the main means to achieve the coverage of a region. However, since the mobile service is mainly indoor, there will be a loss of wireless signal when spreading from the outdoor to the indoor. In order to ensure the quality of the mobile service via a signal which reaches the indoors, the number of BSs can be increased. The method of reducing the distance between BSs reduces the loss of signal in outdoor transmission. Secondly, the construction of DISs directly solves the indoor coverage challenge. However, DISs can only guarantee indoor coverage in some buildings. In general, an outdoor BS is more effective in providing macroscopic coverage. Therefore, study on indoor deep coverage by outdoor signals is very important [b-Zhang].

Indoor coverage by outdoor signal means the signal by outdoor macro BSs through wireless signal penetration to indoor coverage. Its advantage is lower capital expenditure (CAPEX) because there is no need for indoor coverage construction. Its disadvantage is poor coverage effect. Due to the high frequency band used and large penetration loss, it is difficult to reach a higher level in indoor signal intensity, resulting in insufficient deep coverage, poor service experience, i.e., in the quality of experience (QoE) provided within the coverage range and other problems. However, in outdoor coverage, if the transmission power is increased by considering the influence of the penetration loss, it will cause interference to the neighbouring cell.

The calculation of penetration loss has been mentioned in [b-Zhang] [b-Zhou] [b-Lv] and [b-3GPP TR 38.901]. As shown in Figure 9 and Table 8, the penetration loss of the same material increases with the increase of frequency, and objects of different materials have different penetration losses in the same frequency band. Objects of different materials have different degrees of variation in penetration loss caused by the same variation in frequency bands. The different thickness of the same material also has an impact on the value of the penetration loss.

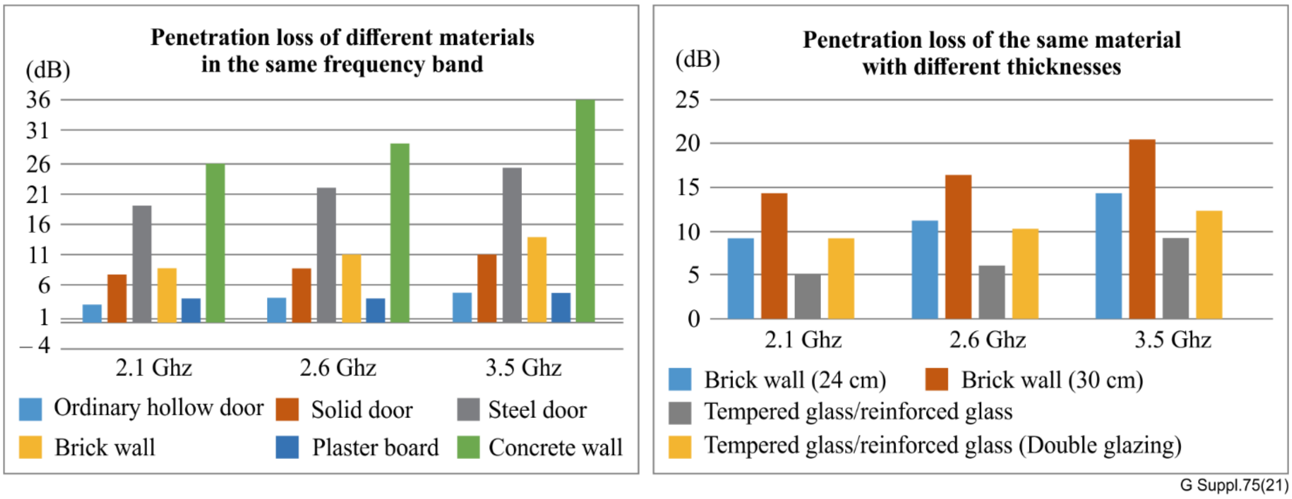


Figure 9 – The penetration loss of wireless signals corresponding to different materials/thicknesses

Table 8 – Test data of penetration loss of building materials in different frequency bands [b-ZTE WP]

Building penetration loss(dB)	1800/2100 MHz	2600 MHz	3500 MHz
Brick wall	10-15	11-18	12-20
Concrete wall	20-30	22-32	25-35
Plaster wall	8-12	9-14	10-15
Ordinary glass wall	2-5	4-6	5-8
Thin wooden door	3-5	5-7	5-8

The content of this clause is a comparison around sub-6 GHz (i.e., FR1) for 5G NR between macro cells outdoor with SCs indoor. The mmW (i.e., FR2) are unlikely to have an outdoor macro cell deployment as penetration loss is too high. Hence mmW (i.e., FR2) SCs (SC) can be outdoor-SC or indoor-SC and no mmW macro cell deployments are expected. The detail of penetration loss of 5G mmW is given in clause 10.5.

6.5 Application scenarios for small cell

Compared with macro stations, SCs can be easier to camouflage and hide due to their lighter weight and smaller size. They are more suitable for deployment in sensitive areas.

SCs are mainly used to supplement not-spots and hot-spots.

The main application scenarios of SCs are in densely populated areas, covering peripheral communications that cannot be reached by macro base stations. SCs are not only much smaller than macro base stations in size, but also have reduced power consumption.

Different types of SCs will support a variety of frequency bands as defined by 3GPP, which are divided into the FR1 (sub-6 GHz) and FR2 (mmW) bands. Depending on deployment, these may be either licensed (for example to an MNO), or shared (such as in the CBRS spectrum in the USA) or unlicensed (such as the 2.4 and 5 GHz bands used by Wi-Fi networks) [b-SCF238].

Based on [b-SCF238], SCF market analysis has categorized 5G SC environments to meet 5G use cases as follows:

- Residential (or small office / home office (SOHO)): Indoor deployment.

- Indoor enterprise: Office spaces, commercial real estate, hotels, healthcare, etc. This can be further broken down into small, medium and large enterprise.
- Private industrial: Indoor/outdoor private networks to support enterprise and industrial applications [b-SCF235].
- Campus environments: Indoor and outdoor venues, manufacturing complexes, educational institutions and stadiums.
- Outdoor dense urban public.
- Outdoor rural public.

Table 9 provides the key characteristics of these deployment scenarios:

Table 9 – Key characteristics of deployment scenarios [b-SCF238]

Deployment scenario	Key characteristics
Indoor residential (or SOHO)	Single SC Very low cost Low power consumption and power rating Lowest size/volume Low mobility Low user count (capacity) Low throughput self-backhaul Plug and play customer install
Indoor enterprise (small, medium, large)	SC network Varying cost: low to medium cost Low-high eMBB capacity Radio unit low size/volume Backhaul 100 (small) – 3000 Mbit/s (large) Copper (small) / fibre fronthaul infrastructure Low power consumption and power rating Potentially neutral host and edge computing [b-SCF234] Customer install (small) to professional install (large)
Private industrial: Indoor/outdoor [b-SCF235]	High capacity (eMBB and mMTC) Copper/fibre fronthaul infrastructure Use cases may drive high reliability / low latency (ultra reliable low-latency communication (URLLC) [b-SCF199], Industry 4.0, edge computing [b-SCF234] and potentially high security Licensed, unlicensed or shared spectrum (CBRS) MNO/neutral host/third-party network providers
Campus: Indoor/outdoor environments	High capacity eMBB Copper/fibre fronthaul infrastructure Professional install
Dense urban: Outdoor dense urban public network	High capacity eMBB Professional install (MNO)
Rural public: Outdoor networks	High mobility High coverage (higher power rating) Potentially non-ideal front/backhaul

6.6 Summary

This clause is a simple review of 5G SC systems, which includes types, architecture, siting challenges and recommended solutions, and application scenarios. Comparison of indoor coverage capabilities between macro station and SC was also introduced.

7 Requirements for small cell backhaul and radio access point midhaul

NOTE – Work in O-RAN WG9 and MEF related to this topic should continue to be followed and studied.

7.1 Capacity

The characteristics of the midhaul F1 interface are similar to those of backhaul. In consequence, the same methodology can be used for capacity provisioning. A widely used methodology for 4G/LTE to dimension the backhaul capacity is described by NGMN Alliance [b-NGMN LTE BH]. It evaluates provisioning of 'last mile' backhaul based on the busy time mean and peak backhaul traffic for single cell and tri-cell eNBs. These figures can be extrapolated to provision backhaul capacity in the 'aggregation' part of the transport network based on traffic area capacity in the aggregation area covered by a TDM-PON optical distribution network (ODN).

7.1.1 Estimation model and calculation method for single base station

As shown in Figure 10, from [b-NGMN LTE BH] (clause 3), backhaul traffic comprises a number of components in addition to the user plane traffic.

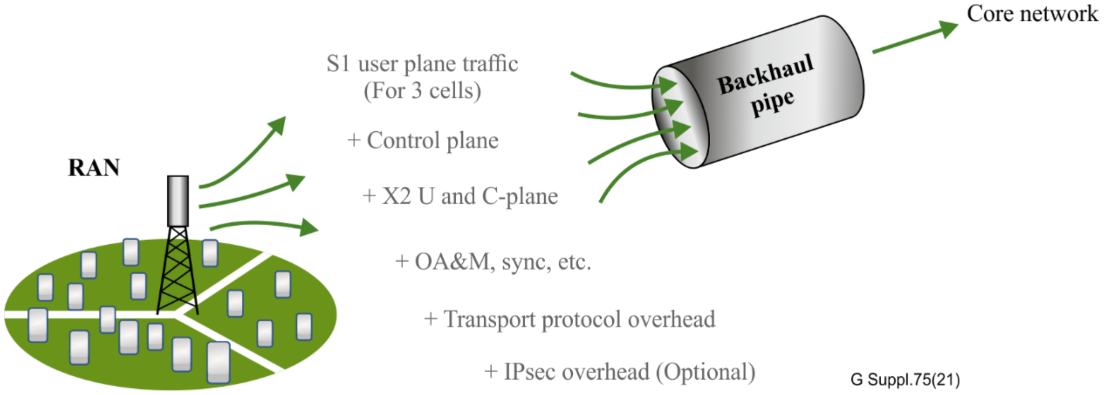


Figure 10 – Components of backhaul traffic [b-NGMN LTE BH]

The optimized backhaul group agreed on the following assumptions:

- X2 traffic: It was agreed to use 4% as a cautious average of these figures.
- Control plane, operation, administration and maintenance (OAM) and synchronization signalling: Compared with associated user plane traffic, these can be ignored.
- Transport protocol overhead: 10% is used to represent the general case.
- IPSec: The NGMN backhaul group assume IPSec Encapsulating Security Payload (ESP) adds an additional 14% on top of the transport protocol overhead (making 25% in total).

In [b-NGMN LTE BH] (clause 4.1), two options are provided in terms of formulas.

The lower bound assumes peaks are uncorrelated but that the busy time mean applies to all cells simultaneously. The provisioning for N eNBs is therefore the larger of the single cell peak or N * the busy time mean, thus:

$$\text{Lower provisioning bound for } N \text{ cells} = \text{Max (peak, } N * \text{busy time mean)} \quad (1)$$

This method can be called the "lower assume method".

A yet more conservative approach would be to assume that while one cell is peaking, the others are generating traffic at the mean busy time rate, thus:

$$\text{Conservative lower bound for } N \text{ cells} = \text{Max}(\text{peak} + (N - 1) * \text{busy time mean}, N * \text{busy time mean}) \quad (2)$$

This method can be called the "conservative assume method" [b-NGMN LTE BH].

The above guidelines and other white papers from NGMN are widely accepted by the mobile community as a capacity design guideline [b-NGMN BH REQ] [b-NGMN E2E ARC]. The open question is, however, whether these guidelines can be applied to 5G NR.

Based on [b-IMT-2020 B REQ], with some revising work such as adding the "lower assume method", Table 10 provides some methods, assumptions and values for the estimation of the capacity requirement.

Table 10 – Evaluation method and assumption parameter model of single station [b-IMT-2020 B REQ]

Parameter	5G in low frequency	5G in high frequency
Spectrum resources	3.4~3.5 GHz,100 MHz bandwidth	Higher than 28GHz, 800 MHz bandwidth
BS configuration	3 Cells, 64T64R (NOTE – macro station) 8 'logical' layers (NOTE – Number of MIMO layer)	3 Cells, 4T4R (NOTE – SC with mmW)
Spectrum efficiency	Peak 40 bit/s/Hz, mean 7.8 bit/s/Hz	Peak 15 bit/s/Hz, mean 2.6 bit/s/Hz
Other parameter	10% framing overhead, 5% Xn traffic, 1:3 TDD UL/DL	10% framing overhead, 1:3 TDD UL/DL
Peak bandwidth of single cell a	100 MHz * 40 bit/s/Hz * 1.1 * 0.75 = 3.3 Gbit/s	800 MHz * 15 bit/s/Hz * 1.1 * 0.75 = 9.9 Gbit/s
Mean bandwidth of single cell b	100 MHz * 7.8 bit/s/Hz * 1.1 * 0.75 * 1.05 = 0.675 Gbit/s (Xn traffic mainly occurs in the average scenario)	800 MHz * 2.6 bit/s/Hz * 1.1 * 0.75 = 1.716 Gbit/s (high frequency stations are mainly used for no-spots and hot-spots; Xn traffic has only been counted into low-frequency stations)
Peak bandwidth of single station in the "conservative assume method" c	3.3 + (3 − 1) * 0.675 = 4.65 Gbit/s	9.9 + (3 − 1) * 1.716 = 13.33 Gbit/s
Peak bandwidth of single station in the "lower assume method" d	3.3 Gbit/s	9.9 Gbit/s
Mean bandwidth of single station e	0.675 * 3 = 2.03 Gbit/s	1.716 * 3 = 5.15 Gbit/s

a) Bandwidth of single cell = spectrum width * spectrum efficiency * (1 + framing overhead) * TDD DL ratio.
b) Bandwidth of single cell = spectrum width * spectrum efficiency * (1 + framing overhead) * TDD DL ratio * (1 + Xn).
c) Peak bandwidth of single station in the "conservative assume method" = peak bandwidth of single cell * 1 + mean bandwidth of single cell * (N − 1).
d) Peak bandwidth of single station in the "lower assume method" = peak bandwidth of single cell.
e) Mean bandwidth of single station = mean bandwidth of single cell * N.

NOTE 1 – In method from NGMN for LTE, 4% is used as a cautious average for X2 traffic.

NOTE 2 – Line "base station configuration" is for both 'cases' a 3 cell BS, although this may represent a typical macro station with lower frequency, the higher frequencies and/or SCs may be single (omnidirectional or 180°) cell per BS. Thus, an example is also need to show single cell/sector BS on high frequency. The spectrum efficiency and capacity of the single (omnidirectional or 180°) cell need further research.

NOTE 3 – Spectrum efficiency

It can be seen from Table 10 that spectrum efficiency is a key parameter when estimating capacity requirements. The spectrum efficiency is related to many factors, and it needs to be fully studied when calculating and selecting [b-ITU-R SM.1046-3].

NOTE 4 – Integrated 4G+5G bearer scenario

In the initial stage of 5G construction, the bearer network may carry 4G and 5G BSs at the same time. At this time, the calculation model and formula are the same. Note the difference in spectrum efficiency of 4G BSs. Some papers mention that the average bandwidth of 4G BSs is 0.15 Gbit/s and the peak bandwidth is 0.9 Gbit/s. Further research is needed.

In the fronthaul (FH)/midhaul (MH)/backhaul (BH) segment, the ratio of uplink (UL)/ downlink (DL) traffic have different specialties. In the FH segment, there is a large amount of traffic for signalling, so the traffic of the UL are nearer to the traffic of the DL. Different passive optical networks (PONs) have different UL/DL capabilities:

- XGS-PON, 10 GEPON (symmetrical) and [b-ITU-T G.9804.x] (50G UL/50G DL, under study) are 1:1;
- 10 GEPON (asymmetric) is near 1:10;
- XG-PON and [b-ITU-T G.9804.x] (12.5G UL/50G DL) are near 1:4;
- [b-ITU-T G.9804.x] (25G UL/50G DL) is near 1:2.

The real measured ratio of UL/DL traffic can decide whether the XG-PON can be used for the MH/BH segment. Measuring, monitoring and statistics on UL/DL traffic are needed.

In the future, if a more suitable ratio based on real measured value exists, it can be used in the estimation method in this clause.

During calculation and estimation of the upstream bandwidth, the following two formulas shown in Table 10 can be used:

- For peak bandwidth of single cell:

  Bandwidth of single cell = spectrum width * spectrum efficiency * (1 + framing overhead) * time division duplex (TDD) DL ratio.
- For mean bandwidth of single cell:

  Bandwidth of single cell = spectrum width * spectrum efficiency * (1 + framing overhead) * TDD DL ratio * (1 + Xn).

When calculating the UL:

1) "Spectrum width" is the same as the DL.
2) "Spectrum efficiency": Numbers of UL/DL antennas and streams (i.e., MIMO layers) are listed as follows:
   - For macro BS with 64T64R, the DL streams are generally 16, and the UL are streams generally 8;
   - For SC with 4T4R, the maximum DL streams are generally 4, and the UL streams are generally 2;
   - For SC with 2T2R, the DL streams are generally 2, and the UL streams are generally 2.
3) The TDD DL ratio should be changed to the TDD UL ratio.

4) For "framing overhead" there is a need to find authoritative parameters or test.

5) "Xn" there is a need to find authoritative parameters or test.

7.1.2 Simulation and model for area traffic capacity

7.1.2.1 Definitions from [b-ITU-R M.2410-0]

Peak spectral efficiency: The maximum data rate under ideal conditions normalized 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).

The 5G-NR max spectral efficiency is calculated by 3GPP as 7.4036 bit/s/Hz for the maximum MCS defined in 5G NR. This is an MCS 27 from Table 5.1.3.1-2 in [b-3GPP TS 38.214], which uses a 256QAM constellation, that is, modulation order $Q_m = 8$ and a coding rate $R_{max} = 948/1024 = 0.925$.

Peak data rate: The maximum achievable data rate under ideal conditions of peak spectral efficiency (in bit/s), which is the received data bits assuming error-free conditions assignable to a single 5G NR SC, 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).

The peak traffic requirements scale linearly with carrier bandwidth and layer of transmission reception points (TRxP) referred to as 'MIMO layers'. mMIMO allows more antennas to support multiple data streams and beamforming. In FR1 (450 MHz to 6 GHz), 5G allows bandwidths from 5 MHz to 100 MHz. In FR2 (24.25–52.6 GHz), 5G offers values from 50 MHz to 400 MHz. We can consider typical bandwidth in the 5G system up to 100 MHz in FR1 and 400 MHz in FR2.

User experienced data rate: The 5^{th} percentile user spectral efficiency is the 5% point of the cumulative distribution function (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 service data units (SDUs) delivered to Layer 3, over a certain period of time, divided by the channel bandwidth, and is measured in bit/s/Hz.

Average spectral efficiency: this aggregates the throughput of all users (the number of correctly received bits, i.e., the number of bits contained in data of backhaul packets are 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 MIMO layers and is measured in bit/s/Hz/'MIMO Layer'. SDU means the user information or service information that is in the data section of a Layer 2 frame (such as a backhaul packet). This information is itself framed bytes according to a Layer 3 protocol (such as IP). The SDU is therefore the information used as frames for the Layer 3 processing. The remainder of the Layer 2 frame is considered Layer 2 specific overhead bytes.

Area traffic capacity: 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.

Let W denote the channel bandwidth and ρ the MIMO layer. The area traffic capacity C_{area} is related to average spectral efficiency SE_{avg} through Equation (3).

$$C_{area} = \rho * W * SE_{avg} \quad (3)$$

Transport overhead: The backhaul N3 and midhaul F1 user planes use GTP-U [b-3GPP TS.29.281] to transport SDU (IPv4, IPv6, IPv4v6, Ethernet or unstructured). An overhead of 11–30% may therefore be added depending on the structure and frame size mix. For the TDM-PON transport described further in contribution, an Ethernet transport with VLANs, with commonly used imix: 7 packets of 64 Bytes, 4 packets of 598 Bytes and 1 packet of 1522 Bytes is expected to be the common deployment option. A 20% transport overhead is therefore considered on top of the area traffic capacity (C_{area} * 1.2) for both the backhaul and midhaul cases.

7.1.2.2 Simulation and model for area traffic capacity

At the ITU-T SG15/Q2 meeting in Dusseldorf, October 2019, the following simulation model was presented by Nokia Bell Labs [b-ITU-T D071]. The NGMN Alliance has published dimensioning guidelines for the aggregated backhaul capacity in LTE networks based on the results of a numerical analysis, assuming statistical traffic of user data [b-NGMN LTE BH]. In a Nokia Bell Labs paper [b-Bidkar], a detailed xHaul traffic analysis (C_{area}) is performed using system level radio simulations as specified by 3GPP [b-3GPP TR 36.814] yet using a 5G-NR numerology [b-3GPP TS 38.104] to obtain a better understanding of the statistical traffic requirements for midhaul. The urban macro cell (UMa) scenario from [b-3GPP TR 36.814] with a 3D channel model is used for these simulations with an 5G NR FR1 (Sub-6GHz) – frequency division duplex (FDD), 100 MHz, 30 kHz SCS, 4 × 4 MIMO radio configuration. For this UMa simulation environment, a regular hexagonal layout is used. Each site has three sectors. For UMa, the gNB is located at 25 m height and the inter-site distance is 500 m. The theoretically calculated peak traffic requirements assuming perfect channel conditions for a single SC of this configuration at the F1 interface is approximately 1.94 Gbit/s (excluding overhead).

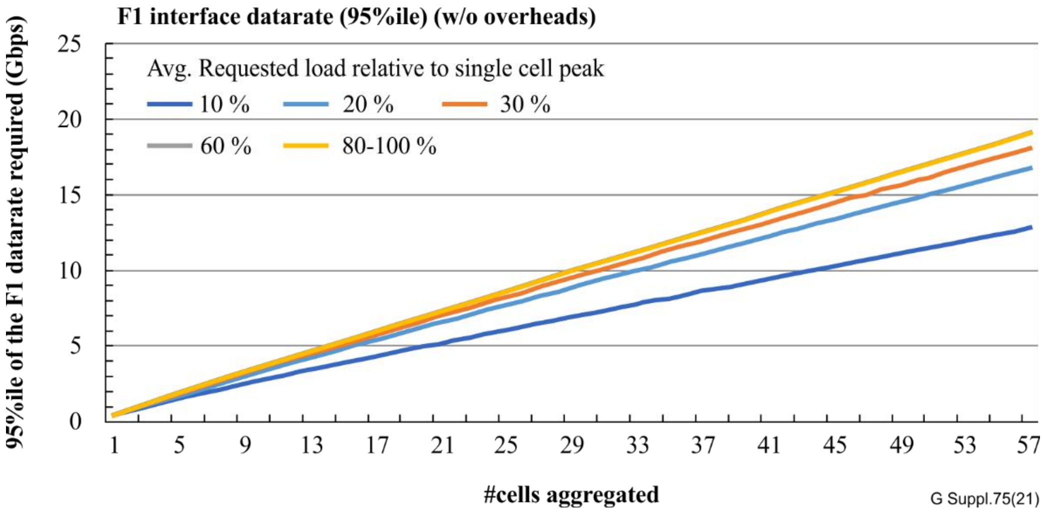


Figure 11 – F1 midhaul area traffic capacity simulation based on 5G NR (3GPP 3D-UMa)

Figure 11 shows midhaul F1 area traffic capacity (C_{area}) requirements as a function of the number of aggregated SCs (cell = sector for multisector macro cell-sites) for the considered radio configuration. The F1 area traffic requirement increases linearly for a given requested load as the area (i.e., the number of aggregated cells) increases. This is due to similar channel conditions and user traffic requirements for each cell due to the homogeneous cellular network simulation scenario.

7.2 Latency

The requirements for latency (delay) (see Figure 12) can be represented by Equation (4).

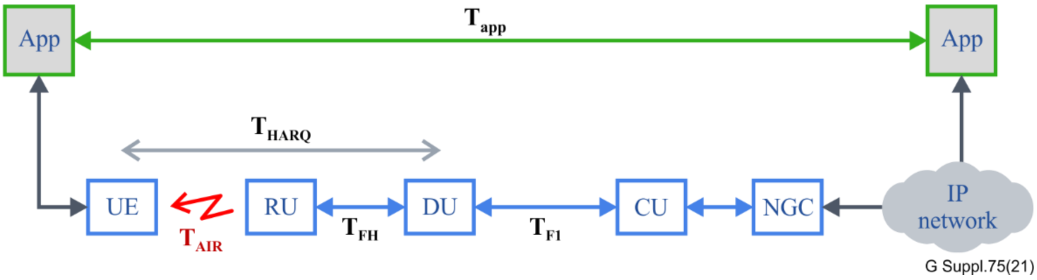


Figure 12 – Requirements for latency (delay)

$$T_{app} = T_{UE} + T_{AIR} + T_{RU} + T_{FH} + T_{DU} + T_{F1} + T_{CU} + T_{BH} + T_{NGC} + T_{SRV} \quad (4)$$

with

$$T_{HARQ} <= T_{UE} + T_{AIR} + T_{RU} + T_{FH} + T_{DU} \quad (5)$$

The definitions are as follows. There are two different latency requirements that need to be investigated: scheduling latency and application latency.

Scheduling latencies: Scheduling latency is the time that a system is unproductive because of scheduling tasks. For scheduling latency, the following has to be considered per 'system': (T_{UE} – User Equipment; T_{AIR} – radio spectrum; T_{RU} – RU; T_{FH} – FH transport; T_{DU} – DU (baseband functions); T_{F1} – MH transport; T_{CU} – CU (baseband functions); T_{BH} – BH transport; T_{NGC} – core functions; T_{SRV} – application functions).

Latency at air interface (T_{air}) is defined as $t_4 - t_3$ for UL and $t_{12} - t_{11}$ for DL. This is the packet transmission time between RU and UE and is mainly due to physical layer communication (spectrum in the air). Air environment time to transmit and propagation delay also contribute. Radio transmissions over the air interface often occur in a harsh wireless environment. Wireless signals are easily degraded due to path loss and interference, and transmission errors are far more likely at the cell edge. Propagation delay depends on obstacles (building, trees, hills, etc.) to propagation and the total distance travelled by the RF signal.

The processing time at gNB elements (baseband processes), T_{RU}, T_{DU} and T_{CU}, and at the UE, T_{UE}, is the processing delay that involves channel coding, rate matching, scrambling, cyclic redundancy check (CRC) attachment, precoding, modulation mapper, layer mapper, resource element mapper, and OFDM signal generation. On the other hand, UL processing at UE involves CRC attachment, code block segmentation, code block concatenation, channel coding, rate matching, data and control multiplexing, and channel interleaver.

The transport system delay (T_{FH}, T_{F1} or T_{BH}) comprises the propagation delay or "time-of-flight" of signals through (typically) a fibre optic cable (so the delay can be known from the fibre length) added to the signal traversal latency through any packet switches in that transport network (packet processing delay).

T_{BH}: latency of the BH transport. For a BH (5G NR N2/N3 interface), the latency constraints for propagation plus packet processing originate from the transmission control protocol (TCP) slow start and require 8 ms RTT.

T_{F1}: latency of the MH transport. The latency constraints for the F1 interface [b-3GPP TS 38.47x] are the same as for the BH interface in [b-3GPP TR 38.801] Option 2: 1.5-10 msec. F1 latency furthermore depends on the applicability of the CoMP functionality to a great extent, which conditions the type of CoMP processing that can be applied and the associated performance [b-3GPP

TS 38.47x]. The deployment of CoMP sets some constraints on the MH when a distant radio access point (RAP) is coordinated. Simulation on the X2 interface [b-3GPP TR 25.912] [b-Artuso] has shown the impact of latency on CoMP efficiency or loss due to the latency as compared with the maximum achievable gain of CoMP in the ideal case with no latency. Therefore, values of the MH network latency below 1 ms ensure a gain above 120% that is progressively reduced to ~25% when the latency reaches 5 ms. Higher values of the latency (10 ms and 20 ms) impact drastically the performances of CoMP joint transmission (JT) leading to a loss of the system throughput compared with the case without cooperation. Hence F1 interface with a latency below 5 ms, ideally below 1.5 ms, is specified.

T_{HARQ}: latency requirements of hybrid automatic repeat request (HARQ) loop radio access. TDD LTE HARQ ACK/NACK timing is specified by a predefined table. Therefore, in TDD NR, HARQ acknowledgement (ACK)/non-acknowledgement (NACK) timing is fully configurable for a specific physical downlink shared channel (PDSCH) by specifying the parameter K1. As of [b-3GPP TS 38.331], the maximum K1 value is 15.

However, as T_{HARQ} (as shown in Equation (5)) is outside the BH and MH range, this is not further considered in this Supplement.

T_{FH}: is the latency of the LLS FH transport. It is defined in eCPRI and [b-O-RAN CUS] as T12 (downstream) and T34 (upstream) – see Figure 13 [b-O-RAN CUS]. Annex B of [b-O-RAN CUS] describes in detail how the HARQ loop is decomposed in the *Txx* timings of the drawing.

Figure 13 shows a definition of reference points for delay management [b-O-RAN CUS].

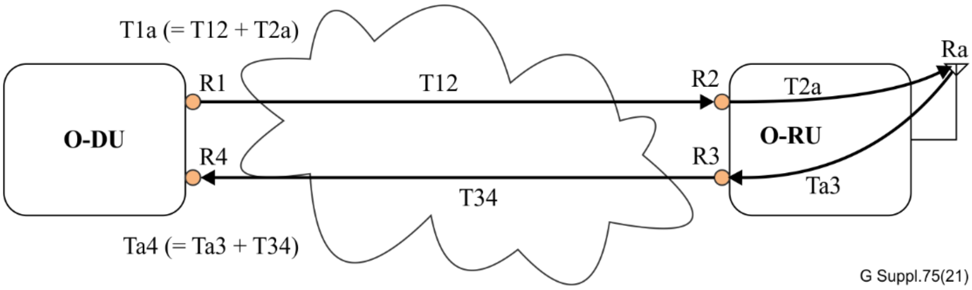
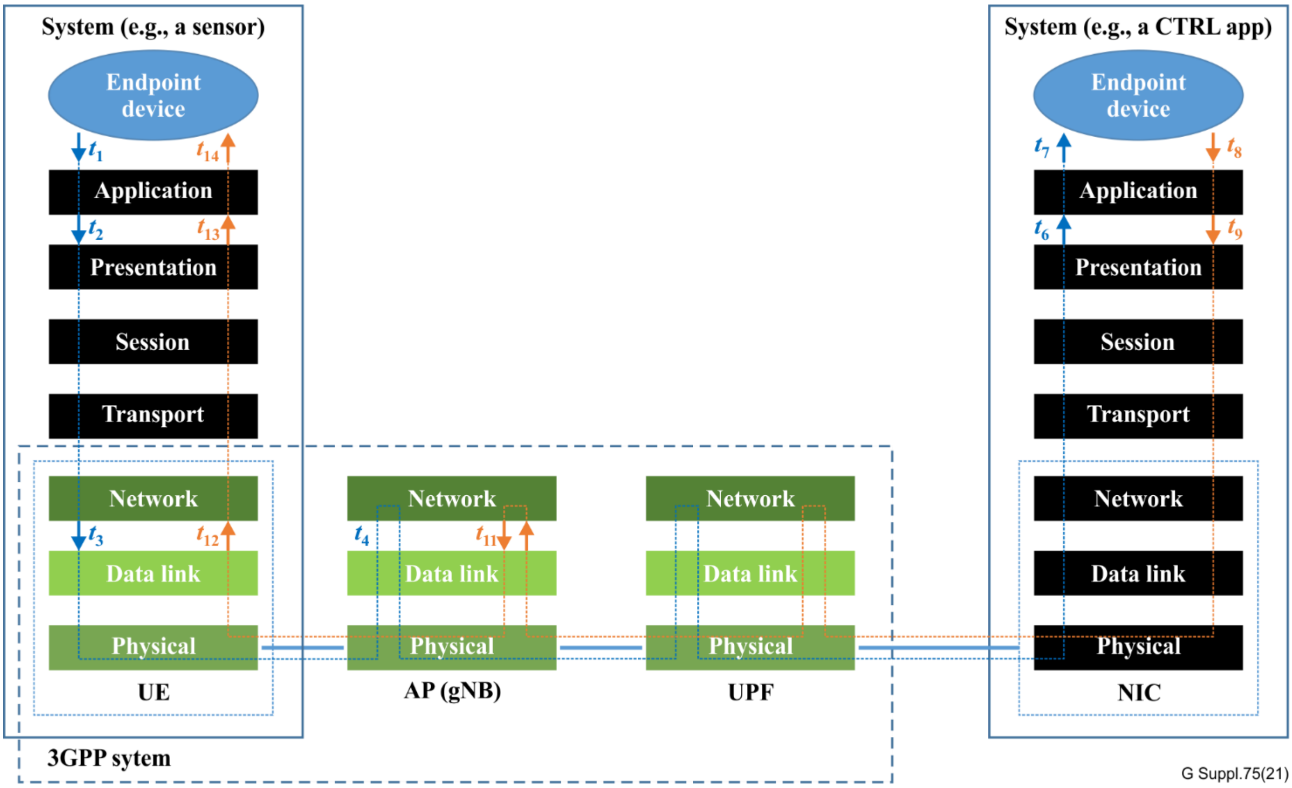


Figure 13 – Definition of reference points for delay management (i.e., Figure B-1 in [b-O-RAN CUS])

However, as T_{FH} is fronthaul, it is not further considered in this Supplement.

T_{NGC} is the processing time taken by the 5G next generation core (NGC) network. It is contributed by various core network entities such as the mobility management entity (MME), the serving GPRS support node (SGSN), and software- defined networks (SDNs) / network function virtualization (NFV). The processing steps of the core network include non-access-stratum (NAS) security, evolved packet system (EPS) bearer control, idle state mobility handling, mobility anchoring, UE IP address allocation and packet filtering.

Application latency (T_{app}): Application latency is defined E2E as the time it takes to transfer a given piece of information from a source end point device to a destination end point device, measured at the application service access points, from the moment it is transmitted by the source end point device to the moment it is successfully received at the destination end point device. In Figure 14 [b-NGMN Verticals], t_1–t_7 and t_8–t_{14} are E2E latency.



NOTE – t_5 would be the latency of the blue line within the user plane function (UPF) and t_{10} would be the latency of the orange line, as within the access point (AP) (gNB).

Figure 14 – Reference points of latency definition (i.e., Figure 2 in [b-NGMN Verticals])

Application latencies (T_{app}) for 5G NR SCs. 3GPP has classified 5G use cases into three categories: eMBB, mMTC and URLLC. Vertical industry use cases have been studied by various standards development organizations and industry consortia. However, there is no clear cut to which category a use case belongs to. There are use cases, for example, requiring both eMBB and URLLC. Table 11 [b-NGMN Verticals] provides T_{app} E2E latency (or round-trip time (RTT)) for vertical URLLC services.

Table 11 – Illustration of dimensioning of latency application [b-NGMN Verticals]

Use case group	Use case example	E2e latency	Jitter	Round trip time	E2e reliability	Network reliability	User experienced throughput	Network throughput	Availa-bility	Time synchronous accuracy	Device/ connection density
AR/VR	Augmented worker	10 ms			99.999 9%						
	VR view broadcast			<20 ms	99.999%		40–700 Mbit/s				3 000/km^2
Tactile interaction	Cloud gaming	<7 ms (uplink)			99.999%		1 Gbit/s				3 000/km^2
Energy	Differential protection	<15 ms	<160 µs		99.999%		2.4 Mbit/s			10 µs	10-100/km^2
	FISR	<25 ms					10 Mbit/s				10/km^2
	Fault location identification	140 ms	2 ms		99.999 9%		100 Mbit/s			5 µs	10/km^2
	Fault mngmnt in distr. power generation	<30 ms				0.999 99	1 Mbit/s		99.999%		<2 000/km^2
Factory of the future	Advanced industrial robotics	<2 ms		<30 ms task planner; <1–5 ms robot ctrl	99.999 9% to 99.999 999%						

Table 11 – Illustration of dimensioning of latency application [b-NGMN Verticals]

Use case group	Use case example	E2e latency	Jitter	Round trip time	E2e reliability	Network reliability	User experienced throughput	Network throughput	Availa-bility	Time synchronous accuracy	Device/ connection density
	AGV control	5 ms			99.999%		100 kbit/s (DL) 3–8 Mbit/s uplink				
	Robot tooling	1 ms robotic motion ctrl; 1–10 ms machine ctrl	<50%		99.999 9%						
UAV	UTM connectivity				99.999%		<128 bit/s				
	Cmnd & Ctrl	<100 ms			99.999%						
	Payload	Application dependent									
Position measurement delivery	for AR in smart factory	<15 ms							99.9%		
	for inbound logistics in manufacturing	<10 ms							99.9%		

For example, VR services [b-NGMN Verticals] is category 2 (1–10 ms) and is further split by IETF in [b-IETF TS AR&VR].

AR/VR developers generally agree that motion to photon (MTP) latency becomes imperceptible below about 20 ms [b-IETF TS AR&VR] (see Figure 15). Latency greater than 20 ms not only degrades the visual experience, but also tends to result in virtual reality sickness. Also known as cybersickness, this can cause symptoms similar to motion sickness or simulator sickness, such as general discomfort, headache, nausea, vomiting and disorientation. The best localized AR/VR systems have significantly improved the speed of sensor detection, display refresh and GPU processing in their head-mounted displays (HMDs) to bring MTP latency below 20 ms for localized AR/VR. However, network-based AR/VR research has just started. In this case, the E2E round-trip delay needs to be within 20 ms as shown in Figure 15.

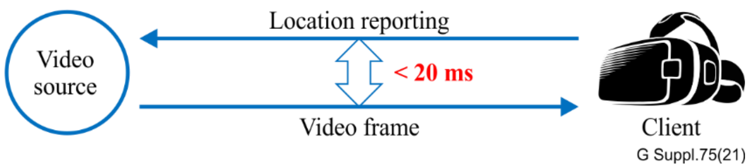


Figure 15 – MTP RTT or 2 × T_{app} [b-IETF TS AR&VR]

This T_{app} budget will be consumed by the sum of all propagation delay, switching delay and queuing delay ($T_{UE} + T_{AIR} + T_{RU} + T_{FH} + T_{DU} + T_{F1} + T_{CU} + T_{BH} + T_{NGC} + T_{SRV}$). The total delay budget for a network device ($T_{FH} + T_{F1} + T_{BH}$) will be low single digit ms, i.e., the accumulated maximum delay (round trip) allowed for all network devices is about 2 to 4 ms. This is equivalent to 1 to 2 ms delay in one direction for all network devices on the path for this application.

7.3 Time and frequency synchronization

Air interface frequency error

The BH and MH transport network (TN) shall ensure all SCs meeting a ±50 ppb air interface frequency error requirement. [b-3GPP TS 38.104] (for 5G NR) specifies ±50 ppb as the short-term average error in 1 ms duration applicable to both 4G LTE and 5G NR technologies. Within this BH and MH TN, all network element (NE) supporting synchronous Ethernet (SyncE) transport across the network shall comply with input and output jitter and wander requirements specified in [b-ITU-T G.8262] (for Ethernet equipment clock (EEC)).

Fronthaul interfaces (defined by [b-IEEE 802.1CM]) require the SyncE clock specification, to comply with [b-ITU-T G.8262.1] (for enhanced EEC (eEEC)). The use of eEECs is recommended as they provide less generated noise in normal operation and during network rearrangements, allowing a larger number of hops while meeting a given time error budget (see clause 7.3). However, FH is not further considered in this Supplement.

Air interface maximum time error

Many of the commercial 5G networks going live around the world today use TDD. TDD radio frames inherently require time and phase alignment between radio BSs, to prevent interferences and related loss of traffic. Time synchronization is also required in FDD networks when different radio coordination features are used. As specified in [b-ITU-T G.8271], time error requirement for fundamental NR TDD is 1.5 µs for 5G NR TDD and including synchronous dual connectivity and intraband non-contiguous and interband carrier aggregation, with or MIMO or transmit (TX) diversity [b-Ruffini]. These features and related timing requirements are applicable within a single operator network, and as a result, control of the relative time error between antennas used by the feature is sufficient. In cases where the TDD-unicast area is not isolated, the 3GPP has specified that traceability to a standard timing reference (universal time coordinate (UTC)) is required. This prevents interference between different networks using adjacent frequency bands or between national borders, because it enables the phase alignment of the radio frames generated by different networks with overlapping areas.

While the introduction of 5G did not cause any fundamental change to radio network synchronization requirements versus 4G TDD, some applications may put more stringent local accuracy requirements on the synchronization of the 5G nodes. Examples can be found in [b-Ruffini]. Various applications, however, including location based services and some coordination features, may be handled at a different level of accuracy for a cluster of 5G NR RUs. The performance requirements of some of these features are under study. For information purposes only, values between 500 ns and 1.5 µs have been mentioned for some features. Depending on the final specifications developed by 3GPP, it is possible to classify this additional level of accuracy for a cluster into a further three sub-classes which are listed in Table 12. Considering FR1 applications only, the time error requirement at least meets 260 ns as a maximum relative time error requirement. In 3GPP terminology this is equivalent to time alignment error (TAE).

Table 12 – Time and phase requirements for cluster-based synchronization (Data copied from [b-ITU-T G.8271])

Level of accuracy	Maximum relative time error requirements	Typical applications (for information)
4A	3 µs	5G NR intraband non-contiguous (FR1 only) and interband carrier aggregation; with or without MIMO or TX diversity.
6A	260 ns	5G NR intraband contiguous (FR1 only) and intraband non-contiguous (FR2 only) carrier aggregation, with or without MIMO or TX diversity.
6B	130 ns	5G NR (FR2) intraband contiguous carrier aggregation, with or without MIMO or TX diversity.
The maximum relative time error requirements represent the largest timing difference measured between any two elements of the cluster. See Appendix VII of [b-ITU-T G.8271.1] for an illustration of how requirements are specified in a cluster.		

Figure 16 shows the reference points to define the network time error |TE| vs air interface time alignment error |TAE| and the concept of relative vs absolute.

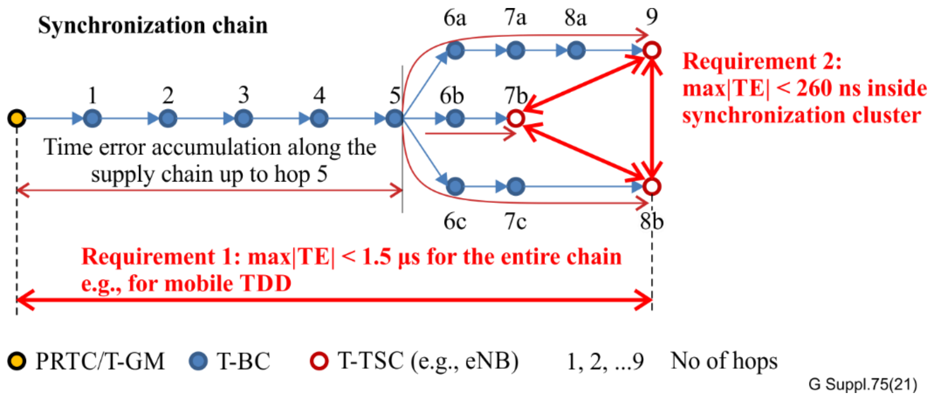


Figure 16 – Illustration of relative time error

Each network element in a TN clock chain generates time error (including constant time error (cTE) and dynamic dTE_H, dTE_L), which will accumulate through the entire clock chain and be present at the SC, as described in [b-ITU-T G.8271.1] Appendix IV. SC filtering is needed to filter the accumulated dynamic time error and reduce the frequency error down to an acceptable level.

This full timing support (FTS) with accuracy requirements for TN are specified in the time and phase synchronization aspects of packet networks [b-ITU-T G.8271], the network limits for time synchronization in packet networks [b-ITU-T G.8271.1] and the timing characteristics of clocks, [b-ITU-T G.8273.2], [b-ITU-T G.8273.3]. The precision timing protocol (PTP) clock specification, profile of [b-IEEE 1588v2] is set in [b-ITU-T G.8275.1].

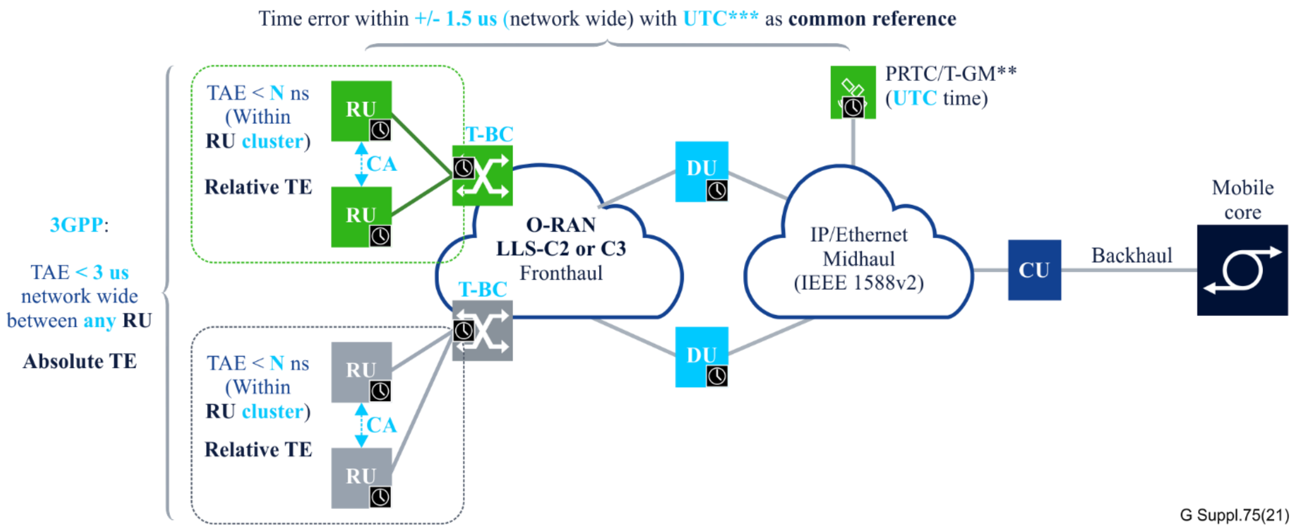
The BH and MH TN shall ensure SCs meeting level 4A of accuracy that can be achieved with an FTS network based on a Class B telecom boundary clock (T-BC).

For FH [b-ITU-T G.8271.1] Appendix V and Appendix XII, the following is considered in these appendices:

- **Intrastation synchronization**. This concerns accuracy levels 4A, 6A and 6B in Table 12 (with particular focus on 6B being the one with the most stringent requirements).
- **Interstation synchronization**. This concerns the levels of accuracy 4A and 6A.

Where: intrastation, (i.e., synchronization distributed within a building from a common co-located clock via a logical star topology), and interstation, (i.e., synchronization from a remote master via a chain of cascaded clocks). In this Supplement we consider the networked (transportable) use case of interstation synchronization only. This corresponds to the clock model and synchronization topology of O-RAN with network timing distribution configurations; these are C2 and C3. O-RAN LLS specification Annex H [b-O-RAN CUS] analyses the possible frequency and time error budgets for the LLS C2 and C3 architectures. This will require a limited [b-ITU-T G.8271] FTS network with T-BC Class C nodes. However, FH is not further considered in this Supplement.

The time and phase requirements (TAE) are summarized in Figure 17.



* 3GPP TDD RAN sync/time requirements are independent from the actual RAN design options (e.g., O-RAN, Cloud RAN, D-RAN, etc.), therefore mandatory and to be met by all RAN architectures.

** PRTC/T-GM (primary reference telecom clock/telecom grand master) can be located at different points in the network (e.g., at CU, DU), aka as PTP Master.

*** UTC – universal time coordinate is the primary time standard by which the world regulates clocks and time; 3GPP requires UTC to be the common time reference for MNO.

Figure 17 – Timing relationships and synchronization clusters

Synchronization OAM requirements

For frequency synchronization, the monitoring functions include frequency offset monitoring of the selected reference source, frequency offset monitoring of reference sources in the priority list and clock pull-in, hold-in range notice, etc.

For time synchronization, the monitoring functions include PTP time offset monitoring, PTP delay monitoring, PTP time offset accumulation monitoring, etc.

7.4 High availability

Increasing reliability in 5G NR opens up potentially lucrative new business opportunities for the industry, arising from new applications such as mission critical applications (see URLLC definitions in [b-3GPP TS 22.261]) that simply will not work properly if reliability is too low. Reliability creates confidence in users that they can depend on communications even in life-threatening situations. An MNO has therefore reliability performance targets that it measures for its RN. One of these can be resiliency and this is often a function of the handoff between the multiple RAN BSs. An MNO might use the fact that there are multiple RAN BSs available for UE to stay connected – this is categorized as ***radio resiliency***. While the details of radio resiliency are out of scope for this Supplement, the MNO might leverage features of TN resiliency or RAN redundancy to improve its overall radio resiliency performance.

The BH and BH TN shall – according to [b-MEF 22.3] clause 10 – be resilient to failures that affect the user network interface (UNI) or the connection (Ethernet virtual circuit (EVC)) with limits on the duration of short-term disruptions and to apply constraints such as diversity.

The resiliency performance attributes defined in [b-MEF 22.3] are high loss interval (HLI) and consecutive high loss intervals (CHLI) in addition to an availability objective for a given EVC. The NGMN Alliance identifies a service continuity time (in clause 5.2.1 of [b-NGMN OBH REQ]) for a mobile user equipment to disconnect and specifies a range of 500 ms to 2 s. This includes both the radio link to the user and mobile BH segments. The duration of any disruption as seen by a RAN can be smaller than the CHLI for a given service if the transport domain or the RAN domain have mechanisms to recover faster from such disruptions. Such mechanisms can help in achieving a target of 50 ms to 250 ms switching time to an alternate core (in BH) or edge (in MH) site as recommended by the NGMN Alliance.

TN must deliver high availability. This can be achieved by pooling a number of transport resources (both transport elements/nodes and physical cable routes) and using either active/active load balancing to ensure no interruption in service should one or more resources fail or even active/stand-by with fast switchover protocols. The failed resource can be left to recover while the other resources continue to function.

During fault conditions in the TN, a TN operator can maintain service performance for an EVC using multiple Ethernet layer connections. The availability performance of the EVC is improved if there is at least one connection within the CEN that is fault-free to support the EVC. This is much more likely if the connections supporting an EVC have diversity constraint with different shared risk groups (SRGs). An SRG is a set of NE and can also include fibre links, which are collectively impacted by a specific fault or fault type. The TN operator is responsible to minimize the short-term disruptions for the EVC with mechanisms to recover from high loss events by selecting a diverse connection. The duration of such short-term disruptions, if any, is reported with HLI, CHLI and TN availability in the service level agreement (SLA). This is categorized as ***TN resiliency*** in this Supplement.

In [b-3GPP TS 22.261], Annex F describes the relation of reliability and communication service availability. Reliability in the context of network layer packet transmissions is a percentage value of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of sent network layer packets. In other words TN availability is part of the reliability as defined by [b-3GPP TS 22.261]; see Table 13.

Table 13 –Example of relationship between reliability (as defined in [b-3GPP TS 22.261]) and communication service availability when the survival time is equal to the transfer interval

Communication service availability	Reliability (as defined in [b-3GPP TS 22.261]) 1 – p
99.999 9 %	99.9 %
99.999 999 %	99.99 %
99.999 999 99 %	99.999 %
99.999 999 999 9 %	99.999 9 %
99.999 999 999 999 %	99.999 99 %

Achieving at least five 9 s TN availability seems mandatory. The 3GPP specification [b-3GPP TS 22.104] for cyberphysical control applications lists currently "Communication service availability" with a maximum of 99.999 999 99 %, which correspond to a five 9s TN availability. It is noted that these 3GPP specifications are a work in progress and the final reliability parameters remain therefore for further study.

7.5 Security

Some radio deployments will utilize security mechanisms [b-MEF 22.3], such as IP Security (IPSec) ([b-IETF RFC 4301]), which is optional in 3GPP specifications, when the mobile BH connectivity to RAN BS (such as 5G SCs) is through untrusted domains. In a BH topology the security gateway will typically be located on the same site as the network controller. The mobile BH connectivity across a TN might be mostly of the E2E tunnel type when IPSec is used between a RAN BS and core with a centralized security gateway architecture. In 5G NR, E-Line is likely to be used when IPSec mechanisms are used to transit through untrusted TN domains with centralized security gateways. E-Line can be used to support both N2/N3; Xn (BH) and F1 (MH) traffic.

The use of MACSec security in FH is out of the scope of this Supplement.

7.6 Service slicing

Radio network architecture has been traditionally built around a specific use case. For example, GSM was built primarily for voice and LTE for mobile data. The 5G NR RN will be designed to be flexible enough for an operator to create an instance of an entire network virtually, that is, a customized network for each diverse use case. Different customized virtual networks will exist simultaneously and without interfering with each other. For example, a customized virtual network for ultra-low-latency autonomous vehicle control can coexist with a customized virtual network for 3D video/4K screen viewing, which requires extremely high throughput.

The virtualization [b-ETSI NFV-INF] of system resources, consists of network, computing, and storage, together with programmability, through the adoption of software-defined networking that embodies a separation of the control plane and user plane. The composability of virtualized functions facilitates a dynamic, on-demand configuration, and instantiation of logical networks through the enabling construct of network slicing, which is a pivotal ingredient of system-wide virtualization. The separation of the control plane and the user plane, the shared network data layer, and the use of stateless functions in the network, together with heterogeneity and disaggregation of the radio access network, facilitate customizable levels of flexibility and granularity in a virtualized context.

The GSMA definition of network slicing is the following [b-GSMA NS] "From a mobile operator's point of view, a network slice is an independent E2E logical network that runs on a shared physical infrastructure, capable of providing a negotiated service quality. The technology enabling network slicing is transparent to business customers. A network slice could span across multiple parts of the network (e.g., terminal, radio access network RAN, Core Network (CN) and transport network (TN)) and could also be deployed across multiple operators. A network slice comprises dedicated and/or shared resources, e.g., in terms of processing power, storage, and bandwidth and has isolation from the other network slices." Using slicing, it is possible to provide logical networks with different characteristics towards different use cases and/or different customers.

According to NGNM; one of the key design choices [b-NGMN NET CUS] when realizing an application (5G service as in URLLC) in a cloud native fashion is the separation of packet routeing, application monitoring and analytics, and service orchestration from the actual application, whose sole objective must focus on processing incoming requests and returning a response. However, how an application – which is decomposed into a set of functions realized as microservices – is initially orchestrated and lifecycle managed at run time must not become part of the application. This allows a truly cloud native realization of the application where testing, staging and production environments can use the same code base without any modifications.

The BH and BH TN shall be a network slice subnet for connectivity as defined in [b-3GPP TS 28.530] (see Figure 18). The TN supporting connectivity facilitates the communication between core and RAN network functions. The network slice combines network slice RAN subnet with network slice core subnet and corresponding TN connectivity.

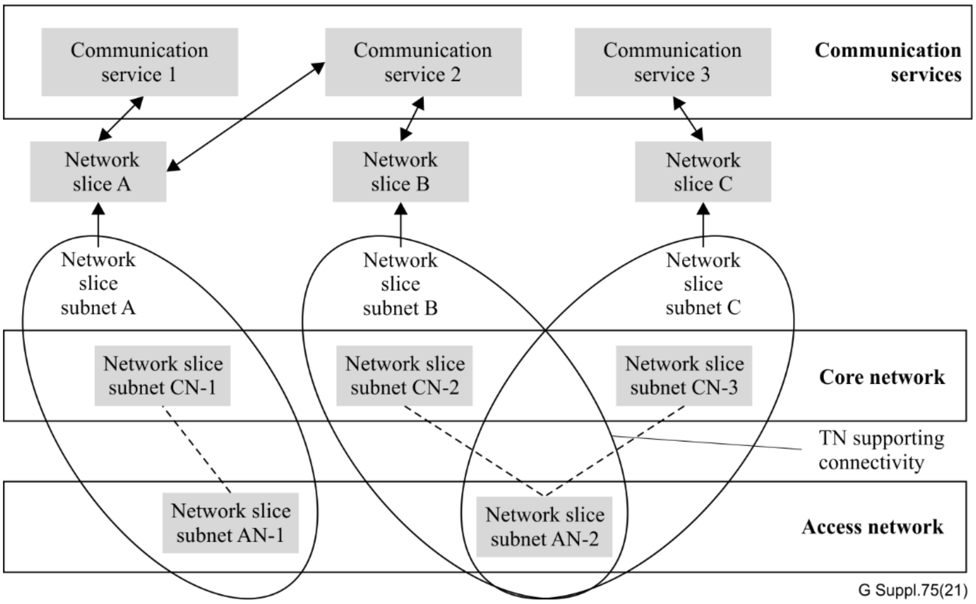


Figure 18 – A variety of communication services provided by multiple network slices[b-3GPP TS 28.530]

7.7 Transport management

The 5G system consists of a 5G access network (AN), 5G CN and UE; see [b-3GPP TS 28.530]. The 5G system is expected to be able to provide optimized support for a variety of different communication services, different traffic loads, and different end user communities. The next generation 3GPP management system is expected to support the management of the 3GPP 5G system and 3GPP legacy systems. The 3GPP management system directly manages 3GPP managed network components (e.g., 5G RAN, 5G CN). For non-3GPP domains (e.g., DCN, TN), the 3GPP management system needs to coordinate with the corresponding management systems of the non-3GPP domains.

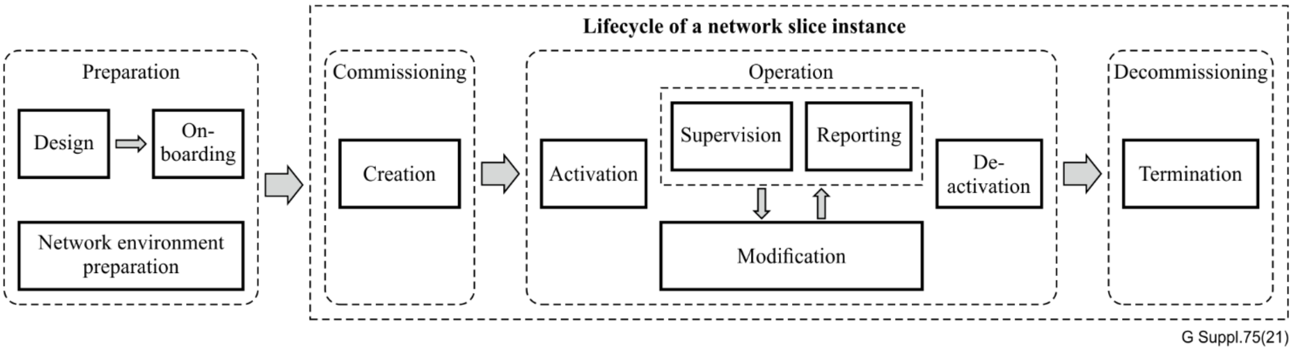


Figure 19 – Management aspects of network slicing [b-3GPP TS 28.530]

Each phase, described in subsequent clauses, defines high level tasks and should include appropriate verification of the output of each task. See also Figure 19.

- Preparation. The preparation phase includes network slice design, network slice capacity planning, on-boarding and evaluation of the network functions, preparing the network environment and other necessary preparations required to be done before the creation of a NetworkSlice instance.
- Commissioning. NetworkSlice instance provisioning in the commissioning phase includes creation of the NetworkSlice instance. The creation of a NetworkSlice instance can include creation and/or modification of the NetworkSlice instance constituents.

- Operation. The Operation phase includes the activation, supervision, performance reporting (e.g., for KPI monitoring), resource capacity planning, modification and de-activation of a NetworkSlice instance.
- Decommissioning. NetworkSlice instance provisioning in the decommissioning phase includes decommissioning of non-shared constituents if required and removing the NetworkSlice instance specific configuration from the shared constituents. After the decommissioning phase, the NetworkSlice instance is terminated and does not exist anymore.

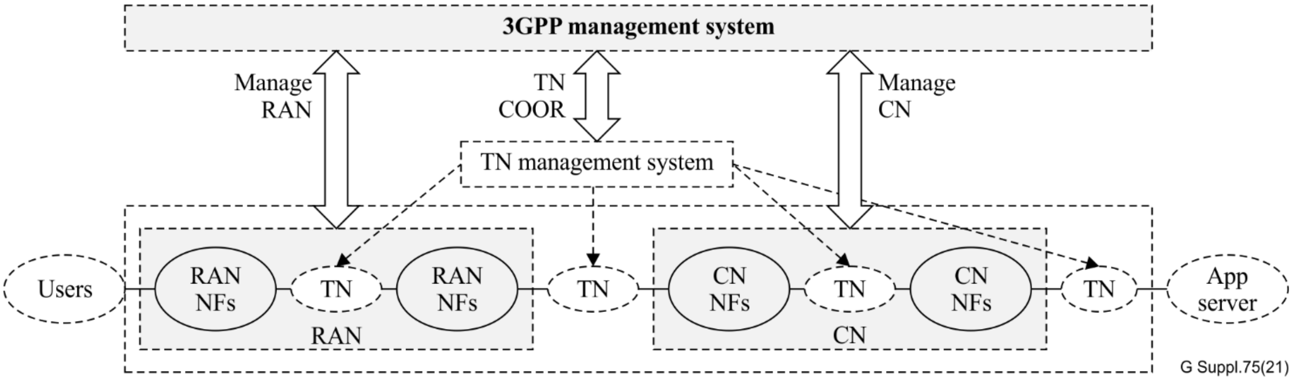


Figure 20 – Example of coordination between 3GPP and TN management systems [b-3GPP TS 28.530]

When providing an end-to-end communication service, the network may use non-3GPP parts (e.g., data centre network (DCN), TN) in addition to the network components defined in 3GPP. Therefore, in order to ensure the performance of a communication service according to the business requirements, the 3GPP management system has to coordinate with the management systems of the non-3GPP parts when preparing a network slice for this service (see Figure 20). This coordination may include obtaining capabilities of the non-3GPP parts and providing the slice specific requirements and other requirements on the non-3GPP parts. The BH and MH TN domain management shall therefore receive the derived requirements for the TN domain. The coordination may also include related management data exchange between those management systems and the 3GPP management system.

7.8 Difference between requirement for backhaul and midhaul

7.8.1 Split option of protocol stack

In this Supplement we refer to MH for 5G SCs as the Option 2 split. The Option 2 has been adopted for the F1interface [b-3GPP TS38.47x] and V1 interface ([b-3GPP TR 37.876]) as defined in the conventions of clause 5.

The detailed description of Split Options 2 (PDCP/RLC split) and justification are shown as follows (see also clause 11.1.2 in [b-3GPP TR.38801]).

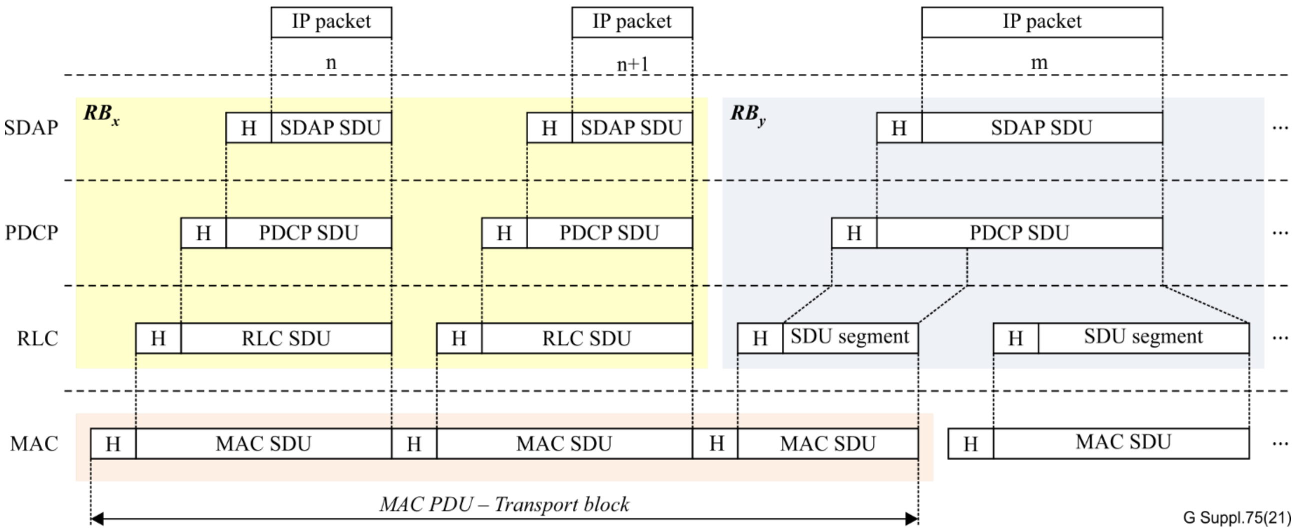
Option 2 may be a base on an X2-like design (X2 is the interface between two connected eNBs) due to similarity on the U-plane but some functionality may be different, e.g., C-plane since some new procedures may be needed.

Option 2-1 Split U-plane only (3C-like split) (3C is PDCP-RLC split standardized for LTE dual connectivity).

Option 2-2: In this split option, RRC, PDCP are in the CU. The RLC, MAC, physical layer and RF are in the DU. In addition, this option can be achieved by separating the RRC and PDCP for the control plane (CP) stack and the PDCP for the user plane (UP) stack into different central entities.

Both BH and MH are packet data and have no fixed length. Take Option 2 as MH and Option 1 as BH (Option 1 is different with BH only in RRC signalling), and the capacity increase of the two is less than 1%.

In [b-3GPP TS 38.300] (clause 6.6), an example of the Layer 2 data flow is depicted as shown in Figure 21 (i.e., Figure 6.6-1 in [b-3GPP TS 38.300]), where a transport block is generated by MAC by concatenating two RLC PDUs from RB_x and one RLC PDU from RB_y. The two RLC PDUs from RB_x each correspond to one IP packet (n and $n + 1$) while the RLC PDU from RB_y is a segment of an IP packet (m).



NOTE – H depicts the headers and subheaders.

Figure 21 – Data flow example (Figure 6.6-1 in [b-3GPP TS 38.300])

7.8.2 Transport network and RAN internal functional split

This clause is same as Annex A in [b-3GPP TR 38.801].

Based on the above analysis, it can be seen that compared with BH, the Option 1 capacity increases the frame header overhead related to RRC signalling, but usually the amount of overhead is extremely small. Because it is a non-fixed-length packet, there is only a statistical ratio, and the Option 1 traffic growth ratio is about less than 5% compared with the BH.

Compared with Option 1, Option 2 increases the overhead of the PDCP frame header. According to Table A-1 in [b-3GPP TR 38.801], the growth ratio is about less than 1%.

The calculation method for the capacity requirement of BH is shown in clause 7.1.

Some important study conclusions have already been shown in [b-ITU-T G. Suppl.66] as follows:

- From a transport bandwidth perspective, the most important characteristic of the higher layer split Options 1–7 is the fact that the amount of data to be transported scales with the user traffic on the air interface. Hence the transport at these split points can benefit from statistical multiplexing gains in aggregating network architectures.
- Increases by less than one percent for split Option 2 (F1 interface) as compared with Option 1 (BH).

Based on [b-3GPP TS 38.47x], some important points of the F1 interface should be noted as follows:

1) From a logical standpoint, the F1 is a P2P interface between the endpoints. A logical P2P interface (for example, the E-line EVC as described below) should be feasible even in the absence of a physical direct connection between the endpoints.

NOTE – These remarks "(for example the E-line EVC as described below)"are also applicable for N2/N3 interface for BH. Hence, we may want to add that these observations are valid for "5G SC BH and MH".

2) For the F1 data transport,

- The transport layer for data streams over F1 is an IP-based transport. Figure 22 shows the transport protocol stacks over F1.

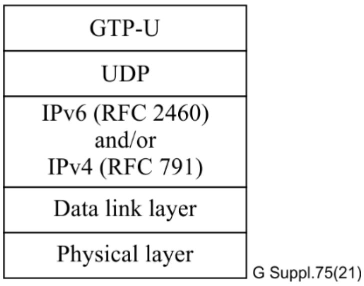


Figure 22 – Transport network layer over F1

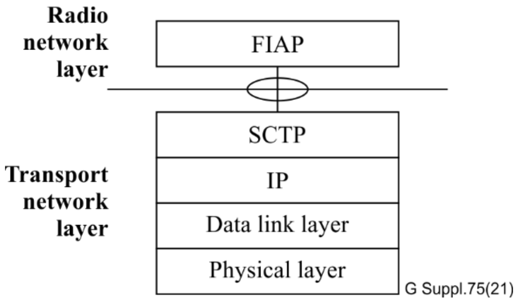


Figure 23 – F1-C signalling bearer

- Figure 22 is Figure 5.1 in [b-3GPP TS 38.474], and Figure 23 is Figure 4.1-1 in [b-3GPP TS 38.472]. The GTP-U ([b-3GPP TS 29.281]) protocol over UDP over IP shall be supported as the transport for data streams on the F1 interface. The data link layer is as specified in clause 4 in [b-3GPP TS38.474].
- The transport bearer is identified by the GTP-U TEID [b-3GPP TS 29.281] and the IP address (source TEID, destination TEID, source IP address, and destination IP address).

3) For the F1 signalling transport,

- Function and protocol stack of F1-C signalling bearer. The protocol stack for F1-C signalling bearer is shown in Figure 23 [b-3GPP TS 38.472] and details on each protocol are described below. The TN layer is based on IP transport, comprising stream control transmission protocol (SCTP) on top of IP.
- Data link layer. The support of any suitable data link layer protocol, e.g., PPP, Ethernet, etc., shall not be prevented.
- IP layer. The gNB-CU and gNB-DU shall support IPv6 [b-IETF RFC 8200] (i.e., reference [2] in [b-3GPP TS 38.472]) and/or IPv4 [b-IETF RFC 791] (i.e., reference [3] in [b-3GPP TS 38.472]). The IP layer of F1-C only supports P2P transmission for delivering F1 application protocol (F1AP) messages. The gNB-CU and gNB-DU shall support the Diffserv Code Point marking as described in [b-IETF RFC 2474] (reference [4] in [b-3GPP TS38.472]).

7.8.3 Other requirements

Requirements on latency, time and frequency synchronization, availability, security, service slicing and transport management can be seen in clause 7.2 to clause 7.7.

7.9 Summary

This clause is focused on requirements for SC BH and RAP MH. It includes capacity, latency, time and frequency synchronization, high availability, security, service slicing, transport management, and difference between requirement for BH and MH. The technologies on 5G SC are now developing, so further study will be needed in the future.

8 Comparison between backhaul requirements and PON capabilities

8.1 Capacity

Unlike direct fibre P2P or wavelength division multiplexing (WDM) technologies, packet transport networking (PTN) employs packet multiplexing methods to share multiple connections over the same network. TDM-PON is one such widely used fibre access technology that provides a cost-efficient solution for a P2MP aggregation network architecture. And depending on the split ratio (e.g., 1:32 or 1:64), it allows for very high-density deployments (e.g., fibre to the home (FTTH)) which can be leveraged by operators to densify their cellular networks using 5G-NR SCs. Even though the traffic scales linearly with the number of aggregated cells due to the homogeneity of the simulation scenario, there is temporal randomness within the xHaul traffic at every cell. The temporal randomness in the xHaul traffic can be exploited efficiently in the TDM-PON which can adapt its dynamic bandwidth allocation at ms scales. Considering the overall traffic capacity requirements and the temporal randomness in the traffic at each cell, a high speed TDM-PON can be efficiently used to aggregate multiple radio cells. Since a typical PON serving area spans 1 km^2, it can cover a reasonable number of cells depending on the inter-cell distances.

Figure 24 shows the high layer split architecture for F1 MH.

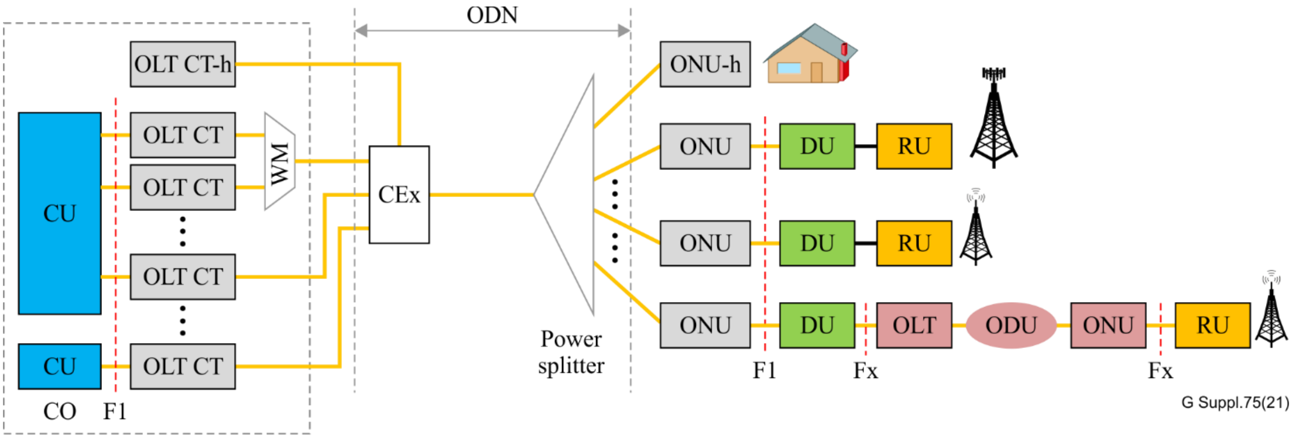


Figure 24 – F1 midhaul: high layer split architecture [b-ITU-T G. Suppl.66] (Figure 9-2)

The results of the MH traffic calculations [b-Bidkar] in clause 7.1 are now followed by an analysis of the number of xHaul connections that can be aggregated using a high speed TDM-PON. In this clause, we analyse the number of F1 midhaul connections from our simulation scenario, which can be aggregated on a single TDM-PON. We consider a 10G XGS-PON [b-ITU-T G.9807.1] or the TWDM-PON [b-ITU-T G.989] as an example with an effective downstream throughput of 8.3 Gbit/s considering forward error correction (FEC) and the most significant TC layer protocol overheads of TDM-PON.

Calculations of the effective throughput of XGS-PON [b-ITU-T G.9807.1] are illustrated in Table 14.

Table 14 – Simplified XGS-PON TC-level U/S throughput

Line rate	9.95328	Gbit/s
Nominal FEC factor for RS (216,248)	0.871	
Burst mode overhead: "worst-case" (Table B.III.2 in [b-ITU-T G.9807.1])	1024	bytes
Including framing sublayer (FS) header (4 bytes) and trailer (4 bytes)	1032	bytes
=> Overhead per burst	0.829	µs
#ONUs	32	
#T-CONTs per optical network unit (ONU)	1	
T_{jt} [b-ITU-T G.989.3] of T-CONTs	1	µs
=> No. bursts per PON frame (125 µs)	4	
Available throughput at TC layer (NOTE – Not counting other overheads such as optical network termination management and control interface (OMCI)	8.439	Gbit/s
Average Ethernet frame size: Assuming the frame size in BH and MH reflects the user's application frame size. Commonly used IP mix (imix), assuming 1 VLAN tag: 7 frames of 64 Bytes, 4 frames of 598 Bytes, 1 frame of 1522 Bytes	364	Bytes
GEM header (per Ethernet frame)	8	Bytes
Available throughput at Ethernet layer (including GEM header encapsulation overhead)	8.257	Gbit/s

In a homogenous radio deployment where all cells in our simulation scenario are of the same type and for the F1 MH interface, 10G TDM-PON can support up 24 cells with F1 interface (without overhead of 20% as specified above).

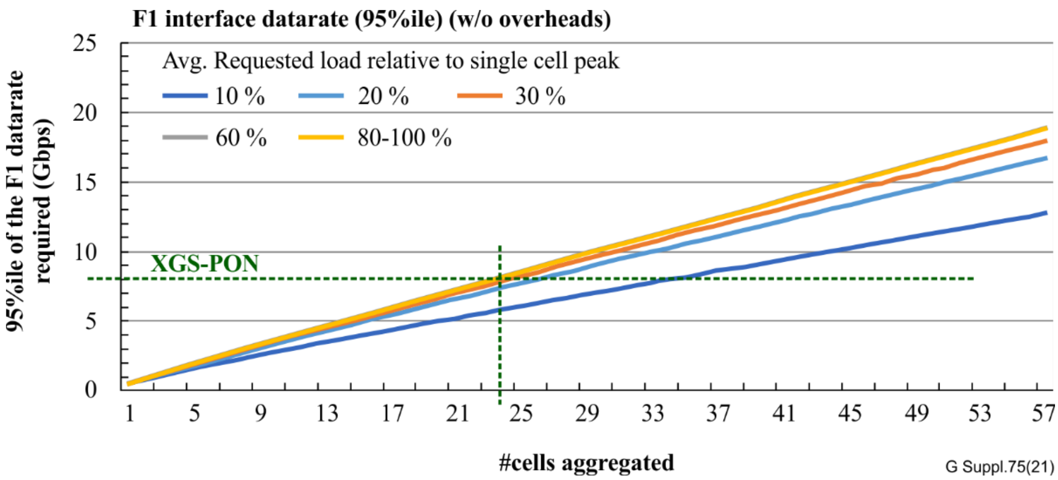


Figure 25 – F1 midhaul area traffic capacity with 10G TDM-PON

Figure 25 shows the maximum number of F1 interface cells that can be aggregated on a 10G TDM-PON for a certain load condition. The points under the line graph depict all feasible combinations of aggregated cells with F1 interface of this 5G NR FR1 100 MHz, 4 × 4 MIMO radio configuration.

To extrapolate for other radio configurations, it is assumed that area traffic capacity scales linearly with carrier bandwidth and MIMO layers from the 20 optical network units (ONUs) on XSG-PON (100 MHz-4 layers with 20% overhead).

- Component carrier (CC) bandwidth from 50MHz to 800 MHz.
- Number *N* of transmission layers (defined by MIMO) from 1 to 16.

Table 15 – Maximum number of ONU with midhaul in a dedicated 10G TDM-PON (3D-UMa radio 5G NR)

	***N* layers**	**1**	**2**	**4**	**8**	**16**
CC (MHz)						
50		160	80	40	20	10
100		80	40	20	10	5
200		40	20	10	5	3
400		20	10	5	3	
800		10	5	3		
	Number of ONU on a single ODN with F1 traffic over 10G TDM-PON.					

For future higher speed TDM-PON [b-ITU-T G.9804.x], Table 15 can be scaled using the throughput calculation for a higher speed PON solution.

For TDM-PON the delay contributions to be additionally considered are in upstream.

8.2 Latency

Unlike 'ideal transport', which is direct fibre P2P or WDM technologies with almost only fibre propagation delay as a factor, TDM-PON is PTN, which introduces on top of the propagation delay also switching delay and queuing delay in both the upstream and downstream directions. All these delays depend on the packet statistics (e.g., distribution of sizes and interarrival times), bit rates and/or on transmission frame size, and can reach up to low single digit milliseconds. However, if special precautions are taken, they can be substantially reduced.

A simplified example of TC-level latency is shown in Table 16.

Table 16 – Simplified TC-level latency example

Propagation delay per km	5	µs
Packet networking induced delays (upstream and downstream)		
– Framing	0.2	µs
– Scrambling	negligible nanosecond range	
– FEC 10 Gbit/s Reed Solomon (RS) 25 Gbit/s low density parity check (LDPC) 50 Gbit/s LDPC	 ~1 ~10 ~5	µs µs µs
– Digital signal processing (DSP)	Negligible, ~1	µs

Table 16 – Simplified TC-level latency example

– Store & forward processing for 1500/9000 Byte 10 Gbit/s 25 Gbit/s 50 Gbit/s	 1.2/7.2 0.5/2.9 0.25/1.45	μs μs μs
– Bit interleaving (50 G downstream only – when it is on)	~2	μs
Upstream only		
– Ranging quiet window	Up to 250	μs
– Interburst delay	Up to 125	μs
– Segment buffering	Up to 125	μs
– Max delay for dynamic bandwidth allocation (DBA) cycle (two extremities)	Up to 1500	μs
Maximum extra delay one-way upstream	Up to 2	ms

For TDM-PON the delay contributions to be considered are therefore both in downstream and in upstream (such as those described [b-Pfeiffer] which is focused on considerations on transport latency in PON):

1) Propagation delay, scaling as ~5 μs/km for standard optical fibres and for all wavelengths (negligible spectral variation for typical PON ODN distances). It must be noted that in TDM-PON all ONUs are virtually located at the same distance as a result of the ONU's individually assigned equalization delay.

2) The switching/forwarding and queuing delays in packet switches, depending on the switch technology and architecture (cut-through vs store-and-forward), and on the total traffic load of the switch during operation, accounting typically for single digit μs delays.

   - Transmission protocol induced delays for encapsulation, coding, mapping, FEC and other digital signal processing (DSP) functions, e.g., for mitigating signal distortions from bandwidth-limited transmission. In 10 Gbit/s and higher PON systems the related latencies remain in the sub-μs range, unless complex DSP algorithms come into play, such as low density parity check (LDPC) for FEC or maximum likelihood sequence estimation (MLSE) for dispersion compensation, where latencies can reach into the lower μs range.
   - Buffer delays introduced when accounting for burstiness of data transmission, for packet fragmentation, line rate conversion and framing mismatches at transitions between segments [b-Pfeiffer].

For TDM-PON, the delay contributions to be additionally considered are in upstream:

1) The insertion of quiet windows in TDM-PON for allowing new ONUs to join the network, ONU activation and ranging. In the most general case, where the fibre distance of the ONU from the OLT is not known, this delay can be as large as a few 100 μs.

2) The buffer delay in ONU related to the burstiness of PON upstream traffic. This interburst delay between two frames of a single ONU could be almost a full frame length (125 μs). While such buffering is inevitable in real networks, the buffer depth should still be kept small, in combination with low jitter node designs.

3) The conventional processes for dynamic bandwidth assignment (DBA) can give rise to additional packet delays. Each T-CONT has three bandwidth parameters:

- Fixed-bandwidth that is always granted, even when not demanded.
- Assured-bandwidth that is guaranteed to be granted whenever demanded.
- Best-effort-bandwidth that is only granted when demanded and when bandwidth is available [b-Pfeiffer].

The T-CONT contains the dynamic bandwidth report, upstream (DBRu)-enable, which is used for the status reporting dynamic bandwidth allocation (SR-DBA). The SR-DBA decreases the bandwidth ramp-up time (as illustrated in Figure 26) compared with a traffic monitoring version of the DBA that does not use DBRu.

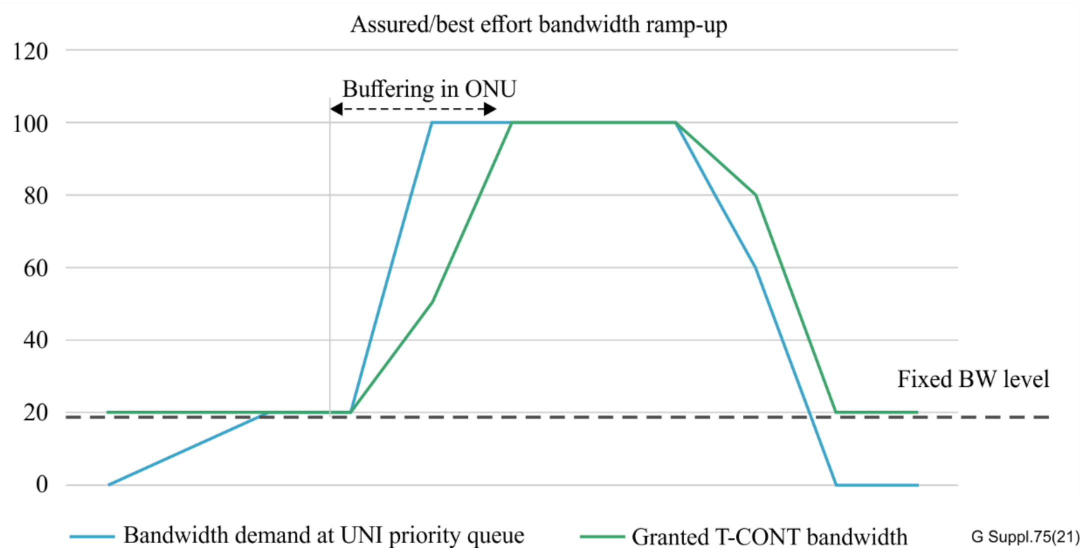


Figure 26 – Example of assured/best-effort bandwidth ramp-up

Considering the T_{F1} requirements as described above for 5G networks, it can be concluded that TDM-PONs are configurable to support BH and MH latency requirements.

8.3 Time and frequency synchronization

Synchronization model over TDM-PON: definition

In this Supplement we study packet-based methods with timing support of intermediate nodes and not the alternative of a distributed primary reference time clock (PRTC) approach, implementing a global navigation satellite system (GNSS) receiver in the end application (a global positioning system (GPS) receiver, for example). The hypothetical reference model (HRM) we study is therefore a network reference model with access clause based on a TDM-PON as a P2MP shared media technology. In the scope of [b-ITU-T G.8271.1], it is indicated that the recommendation covers the case of FTS to the protocol level and that the physical layer is Ethernet. The transport clause of the network shall have both SyncE and PTP in use for time transfer; the access technology shall use a native access clock and shall regenerate PTP across reference point C (see Figure 27) towards the packet slave clock.

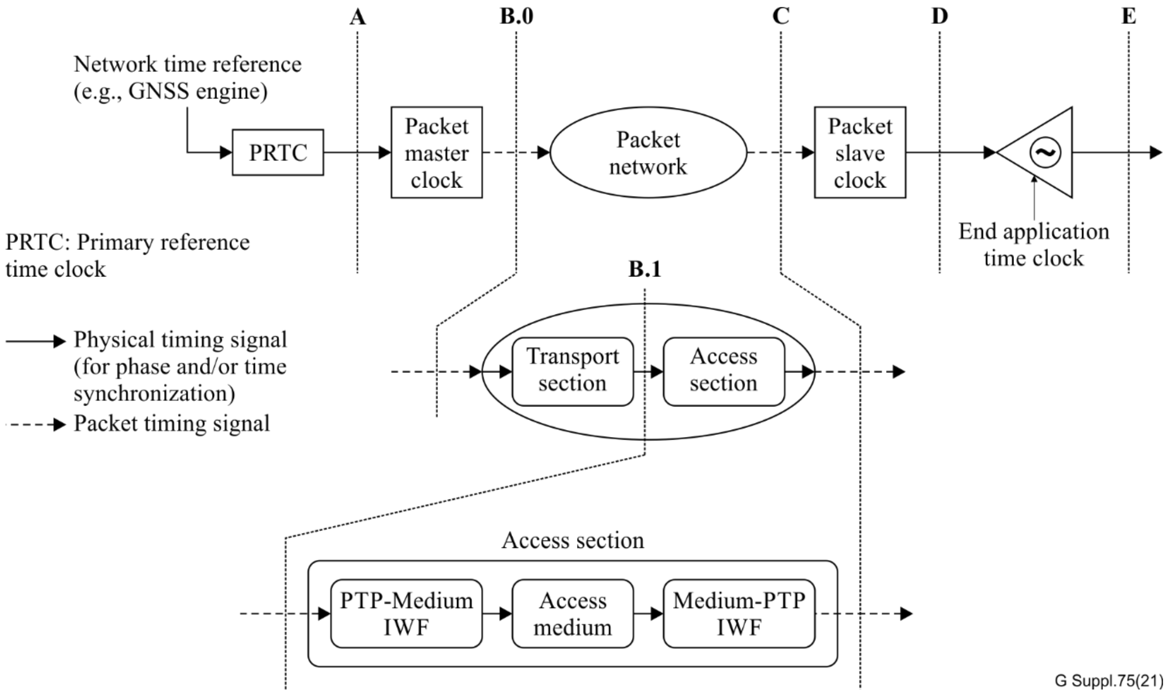


Figure 27 – Network reference model with access clause

The transport clause in HRM 2 consists of a network chain comprising full timing aware [b-ITU-T G.8273.2] T-BCs using PTP and SyncE. The most likely deployment scenario for these access technologies will be at the edge of a network where that network complies with HRM2 and uses both PTP and SyncE. In fact, HRM2 explicitly indicates the analysis has been completed with use of a SyncE network of Option 1 EECs.

Figure 28 shows models for budgeting in a chain of xPon devices [b-ITU-T G.8271.1].

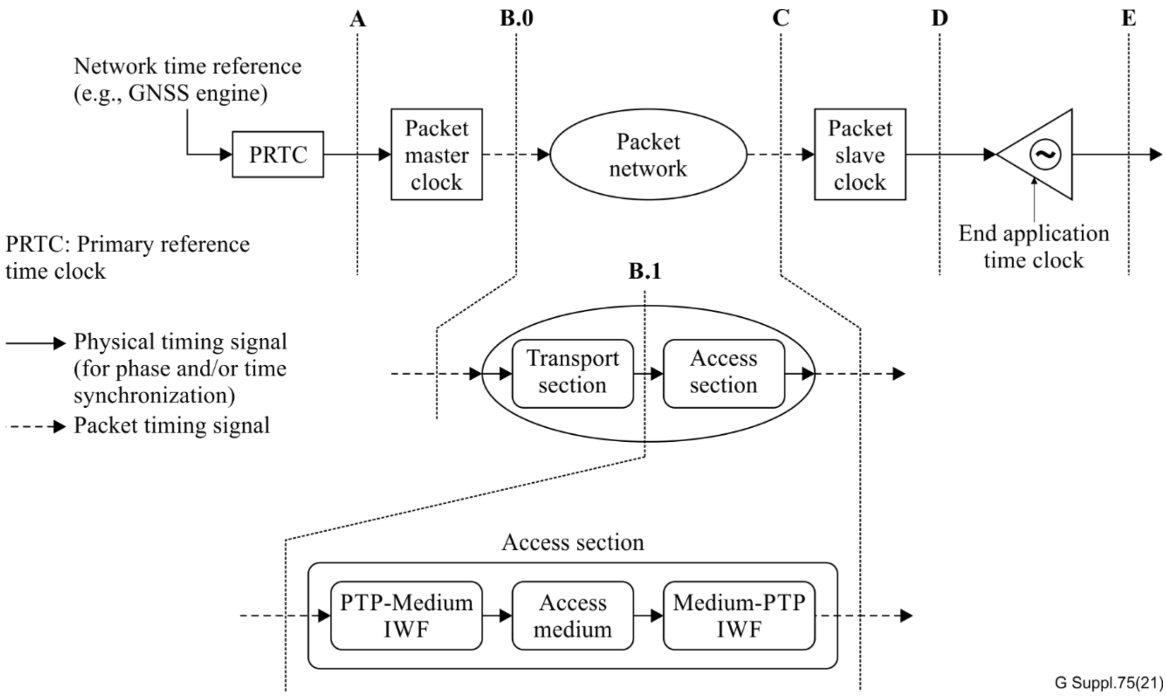


Figure 28 – Models for budgeting in a chain of xPON devices per Appendix IX in [b-ITU-T G.8271.1]

Regarding the TDM-PON access clause, there may also be T-BCs, and in this case, they are connected to and from native access clocks. These native access clocks provide the direct connection to the (PON P2MP fibre) medium. Essentially, the T-BC and TDM-PON native access clock provides an interworking function (IWF) that converts between Ethernet carrying PTP and the access medium. The TDM-PON access clause will have a time error that is a combination of the constant and dynamic components of the medium as well as contribution from the clocks in the access clause. To meet the time error requirement, the time error budget for TDM-PON should be specified. A combination of OLT and ONU can be treated as 2 T-BCs in a PTP chain. Since the native access media systems have this Layer 1 frequency distribution that differs from pure EEC clocks, it is desirable to provide some discussion of the implications of this to the delivery of time. Because TDM-PON IWF specifies explicitly a mechanism that does not allow for an independent transfer of an arbitrary frequency reference and a time reference, both parameters must be phase locked.

The PON-specific time-of-day (ToD) distribution method was first introduced in 2009 as a part of [b-ITU-T G.984.3 Amd2] and subsequently reproduced, mutatis mutandis, in clause 10.4.6 of [b-ITU-T G.984.3], clause 13.2 of [b-ITU-T G.987.3], clause 13.2 of [b-ITU-T G.989.3] and clause C.13.2 of [b-ITU-T G.9807.1]. These clauses of "Time-of-day distribution over PON" specify an IWF for the native access clock of a TDM-PON. This IWF provides the information required to achieve ToD synchronization between a reference clock at the OLT and a local clock at the ONU. With this IWF the OLT sends ToD to ONU via a Unicast OLT-G OMCI message. ToD information is a unicast message to transfer phase sync from OLT to ONU, which has been defined in the OLT-G OMCI message in [b-ITU-T G.988]. The 14 byte ToD attribute comprises two fields: the first field (4 bytes) is the sequence number of the specified GEM superframe. A certain downstream frame is identified by the value of its superframe counter (*N*). The second field (10 bytes) is TstampN using the timestamp format (UTC) of clause 5.3.3 of [b-IEEE 1588v2]. The ONU uses this ToD message (*N*, TstampN) value pair to obtain accurate time synchronization with OLT. The OLT informs the ONU of ToD when a certain downstream frame would arrive at a hypothetical ONU with zero equalization delay and zero ONU response time. TstampN refers to the exact ToD at which the first bit of downstream frame *N* arrives at a hypothetical ONU. The content of ToD (*N*, TstampN) is same for all ONUs since TstampN refers to the exact ToD at which the first bit of downstream frame *N* arrives at a hypothetical ONU that has an EqD of zero and a response time of zero. The arrival of the signal at the ONU is defined to be the instant at which the optical signal crosses the optical connector or splice that is the boundary between the ODN and the ONU.

Synchronization model over TDM-PON: performance

5G BH and MH proposes timing synchronization for FTS and [b-ITU-T G.8273.2] contains explicitly defined requirements for a T-BC Class B, including a pair of media converter T-BC, such as OLT/ONU.

Table 17 gives a noise generation estimation for a pair of media converters.

Table 17 – Noise generation estimation for a pair of media converters (data copied from [b-ITU-T G.8273.2] Annex V)

	Based on Class A T-BC		Based on Class B T-BC		Based on Class C TBC	
	Single T-BC	Pair of media converters	Single T-BC	Pair of media converters	Single T-BC	Pair of media converters
cTE (ns)	±50	±100	±20	±40	±10	±20
dTE_L MTIE (ns)	40	60	40	60	10	15
dTE_L TDEV (ns)	4	6	4	6	2	3
dTE_H (peak-to-peak, ns)	70	70	70	70	For further study	For further study
max|TE| (ns)	100	160	70	100	30	45

The T-BC classification of a TDM-PON depends entirely on the accuracy (max |TE|) of the IWF. In all above mentioned TDM-PON specifications, an informative Appendix is provided which contains the error analysis of the method in the respective system context. The accuracy of the IWF used in a TDM-PON can be broken down as described below and in Equations (6) to (8).

Fibre propagation delay: Derives from the refractive index difference (Equation (6)) as a function of wavelength, to bind the index difference for the wavelength bands for the practical fibres characterized by the range of zero-dispersion wavelength. It then obtains the optimal correction factor to be applied to the ratio of refractive indices $n_{dn} /(n_{dn} + n_{up})$, and establishes the bound on the ToD inaccuracy associated with that ratio.

$$\Delta_{OLT} = Teqd \frac{n_{\mathrm{dn}}}{n_{up} + n_{dn}} \tag{6}$$

A maximum estimate of the index correction factor is an estimated value of 0.5 or an error of around 60 ns over 200 µs XGS-PON (20 km). It should be noted that different fibres may exhibit different absolute refractive indices.

It has been observed [b-ITU-T SG15-C-1096] that this approach with a correction factor is too generic for the current best practice of using a set of fixed wavelength pairs and, therefore, can be substantially improved given that the relative dispersion between upstream wavelength and downstream wavelength is very well specified and controlled. For example, the mentioned contribution states that for all four TWDM channel pairs in NG-PON2, the optimal correction factor can be set to 0.500059, leading to an error of at most 0.000003, which corresponds to a timing inaccuracy of ±0.6 ns. In Equation (7) the presently recommended correction factor is used.

$$\frac{n_{dn}}{n_{up} + n_{dn}} \approx 0.500061 \tag{7}$$

The error does not exceed 0.000004, which corresponds to a timing inaccuracy of ±0.8 ns. Similar optimal correction factors can be found for other TDM-PON wavelength pairs, substantially reducing this propagation delay inaccuracy to low single digit ns.

Equalization delay accuracy: The arrival phase of the ONU transmission may drift due to ageing, temperature changes and other factors. In those cases, the equalization delay is recalculated and adjusted from the drift of the upstream transmission. This in-service equalization delay adjustment allows small corrections to be made without having to re-range the ONU. The accuracy of equalization delay is determined by a drift of window (DOW) threshold. This DOW establishes the safe bounds within which the transmission drift is considered acceptable and does not require any mitigating action. For current TDM-PON, this DOW is approximately ±3 ns.

Internal timing corrections: Both the OLT and ONU are responsible for compensating for their internal delays from wherever the logical computations and/or event triggers occur to the optical interfaces, which are used as reference points for standardization purposes. In the PON system, the TDMA requirements imply that these internal delays are stable at least over each ranging lifecycle to the accuracy specified (see DOW above). The stability and predictability of PON equipment over longer time periods is not specified. However, one can expect the cycle-to-cycle variability to be contained within the bounds of ±64 bits at 10 Gbit/s, which corresponds to two uncontrolled serializer-deserializer delays in the downstream link. In this case, the resulting timing uncertainty is approximately 6.5 ns. Finally, the ToD distribution method uses TstampN, a 10-byte timestamp format (UTC), which is limited in precision to 1 ns. Therefore, each timestamp calculation in the standard format based on precise measurements introduces a rounding error that may reach ±0.5 ns. The time calculations which are local to the OLT or ONU can in principle be performed in higher precision and, therefore, do not necessarily introduce a rounding error.

In summary, it can be estimated that with ToD distribution function of TDM-PON as IWF in an HRM, the max |TE| can be below 45 ns (as shown in Table 17 for Class C pair of media converters)

$$\text{Max absolute time error} = <4 \text{ ns (prop noise)} + <3 \text{ ns (EqD – DOW)} + < 6.5 \text{ ns (Internal corrections)} =< 14 \text{ ns Time error for the IWF in TDM-PON} \quad (8)$$

The actual implementations that do not allow for the independent transfer of an arbitrary frequency reference and time reference: both parameters must be phase locked. The locking allows for transfer of time noise components in the range 0–10 Hz as required by [b-ITU-T G.8273.2], while using an [b-ITU-T G.8271] Annex A compliant V.11 interface for time distribution via a 1 pps clock, and time update rates below 20/s on the native medium itself. The message frequency recommended in the TDM-PON is at least once every 24 hours. [b-ITU-T G.987.3], [b-ITU-T G.9807.1] and [b-ITU-T G.989.3] recommend the selected PHY frame be within a 10 s window of the current time. The ONU is expected to complete clock synchronization within 10 s of communication of the (*N*, TstampN) value pair via OMCI. The ONU frequency reference is phase locked to the PTP time reference from the native media to PTP IWF, not directly to a frequency generated by the originating PR(T)C. As a consequence, the noise transfer functions as specified by [b-ITU-T G.813], [b-ITU-T G.8262] and [b-ITU-T G.8262.1] for the physical layer frequency reference across the SEC/EEC clock of a network node do not apply for a native media clause, consisting of a network side termination (GPON OLT) and a subscriber side termination (GPON ONU), when connected to an HRM-2 type packet network. This is means the L1 frequency presented out of the native access media to PTP media converter shall have long term traceability to the PRTC, rather than to the frequency reference that generates the SyncE input to the PTP to the native access media converter. The QL value used in the ESMC transmitted out of the native access media to the PTP device should indicate the frequency traceability based on the PTP source using the mapping defined in Annex F of [b-ITU-T G.8275.2].

From the above IWF accuracy it can be concluded that TDM-PONs that are compliant with the ITU-T ToD distribution function can be made compliant to [b-ITU-T G.8273.2] T-BC Class B as pair of media converters. As a consequence, TDM-PON can be used as TN for BH and MH SCs meeting level 4A of accuracy that can be achieved with an FTS network based on Class B T-BC.

Synchronization OAM in TDM-PON

Higher accuracy synchronization needs more complete performance monitoring functions. [b-ITU-T G.Suppl. 68] specifies the time and frequency monitoring functions as in clause 7.2 and clause 9.2.

Which of the monitoring functions can be and shall be used for TDM-PON synchronization needs further study.

8.4 High availability

Mobile BH, as well as high-density residential services, justifies the addition of PON redundancy and protection switching. In this Supplement, we study TN resiliency with TDM-PON-based protection methods. [b-ITU-T G.984.1] outlines several topologies for achieving redundancy; these have been named Type A, Type B, Type C and Type D. The [b-ITU-T G.987.x] series, [b-ITU-T G.989.x] series and [b-ITU-T G.9807.1] describe the 10-gigabit-capable passive optical network (XG-PON), the 40-gigabit-capable passive optical network (NG-PON2) and the 10-gigabit-capable symmetric passive optical network (XGS-PON) systems. Each of these further describe protection aspects of those systems. Compared with metro and backbone transport networks, access networks are very cost sensitive because only a few end points need to share all the costs associated with the protection. Currently there is a lack of deployment of PON protection systems, largely because of cost considerations. Building redundancy into PON will make it more expensive. Any protection architecture should minimize additional cost of protection and at the same time improve TN resiliency to an acceptable level.

There have been several reports on failure rates and time to repair for TDM-PON components. Failure rates differ widely and depend on geography, environment, assumptions and component design, at a minimum. The failure of some TN elements has more impact on services than others. For example, ONU failure or distribution fibre cuts affects only one RAN element. But a failure of OLT or feeder fibre can shut down the entire PON. Mean time to repair (MTTR) will also be different for different network elements. The deployment and operational situation is very different operator by operator or area by area: the probability of fibre cuts is very different between underground and aerial, for example, and the situation of the underground space is also very different case by case.

Unavailability is defined as the probability that the equipment, service or fibre is unavailable at any time and can be defined mathematically as in Equation (9).

$$\text{Network unavailability due to a component failure} = \text{FIT} \times \text{MTTR} \times 10^{-9} \qquad (9)$$

Another measure of failure rates is the mean time between failures (MTBF). This is the average time between failures for an MTBF (h) = 10^9/FIT.

The allowed unavailability times are generally intended to be reserved for outages of an unplanned nature. There is hence a correlation between TN availability requirements and protection switching speed goals. This switchover (SWO) corresponds to the HLI and CHLI in the TN resilience definition. The use case of planned PON upgrades requires subsecond and even 50 ms to 120 ms switching times. [b-ITU-T G. Suppl. 51] provides methods that are recommended for adding redundancy and increasing the reliability of PON networks that can be used to calculate the TN availability.

The [b-ITU-T G.Suppl. 51] availability formula for the overall access part of the TN availability is shown in Equation (10).

$$A = 1 - \left(\frac{\text{MTTR}_{\text{OLT}}}{\text{MTBF}_{\text{OLT}}+\text{MTTR}_{\text{OLT}}} + \frac{\text{MTTR}_{\text{ONU}}}{\text{MTBF}_{\text{ONU}}+\text{MTTR}_{\text{ONU}}} + \frac{\text{MTTR}_{\text{FF}}}{\text{MTBF}_{\text{FF}}+\text{MTTR}_{\text{FF}}} + \frac{\text{MTTR}_{\text{DF}}}{\text{MTBF}_{\text{DF}}+\text{MTTR}_{\text{DF}}}\right) \qquad (10)$$

FF = Feeder Fibre

DF = Distribution Fibre

The MTTR in the denominators is negligible compared with the MTBF, therefore, for an unprotected TDM-PON (FIT and MTTR parameters per [b-ITU-T G.Suppl.51]), Equation (11) applies.

$$A=1-\left(\frac{4}{400\,000}+\frac{24}{3\,900\,000}+\frac{24}{278\,000}+\frac{24}{2\,500\,000}\right)=99.988\% \qquad (11)$$

This is only one example; the fibre reliability in many cases is better than that used here and availability would improve accordingly. However, achieving five 9 s is very unlikely in an unprotected configuration. Using the same assumptions [b-ITU-T G. Suppl. 51] as with the unprotected PON but changing the MTTR from 4 h for the OLT and 24 h for the feeder fibre to 60 s (0.017 h) gives 50 ms recovery speed.

$$A=1-\left(\frac{1.4\times10^{-8}}{400\,000}+\frac{24}{3\,900\,000}+\frac{1.4\times10^{-8}}{278\,000}+\frac{24}{2\,500\,000}\right)=99.998424\% \quad (12)$$

It should be noted that Type B can almost meet five 9 s of availability. The dominant sources of unavailability are on the unprotected parts of the network, the drop fibre and the ONU. If the MTTR of these were improved, five 9 s could be met.

Regarding ranging after switchover, in a case of limited re-ranging, the fewer ONUs that require it, the more switchover time is saved. The key is to keep the number of re-ranged ONUs as small as possible. Fortunately, Type B protection has its own features for facilitating the minimum number: only the feeder fibre clause is protected. As a result, in timing relationships, the only difference between the working path and backup path is the possibly different RTDs caused by the possibly different lengths of the two trunk fibres. Therefore, it can easily be observed that the differences between the pre-switchover transmission time and the post-switchover transmission time are the same for all ONUs in the same system. It makes sense that the OLT obtains this "common transmission time difference" by just re-ranging any one of the connected ONUs, instead of completing a ranging process for every ONU. Then all the other EqDs can be updated by a simple calculation based on this information.

NOTE – On the pre-ranging/equalization features, precalculated zero distance EqD via alternative wavelengths (in TWDM-PON) can be seen in dedicated activation wavelength (DAW) contributions and [b-ITU-T G.989.3]. They show alternative ranging options on alternative wavelength.

Given other sources of availability outside the access network, to reliably achieve five 9 s, the Type C architecture could be examined. Type C protection allows for five 9 s of availability with a slow switching speed of 1 min (including full ranging). Building Type C redundancy into PON, based on the full-duplex of both distribution and ONU resource group, will make it much more expensive than Type B. It can be questionable if this additional cost of protection for Type C would be needed for bringing TN resiliency to an acceptable level considering the radio resiliency discussed in the requirements clause above.

Conclusion: TDM-PON protection can provide TN resiliency for BH and MH in 5G NR. In particular, the details of automatic protection switching in Type B has been more fully worked out to match 5G NR SCs.

8.5 Security

PON networks use multiple security features to:

- Isolate traffic for each user
- Encrypt data traffic
- Prevent unauthorized devices being connected
- Validate control messages

These security features rely on the packet structure used in PON data transmission. Each packet of data is comprised of the payload (the user information being transmitted) and a header comprising information about the transmission (such as its length, origin and destination) and security information (encryption keys, timeslot codes, etc.)

TDM-PON has a P2MP architecture, where one fibre is split to serve multiple end points or users. The current TDM-PON standards have put a lot of effort in defining the features that will ensure the security of data transferred over a PON.

In the downstream direction the OLT sends traffic towards all ONUs; while an ONU will receive data packets for all end points/users, it is only able to take in those packets in a matching identifier in the GEM. A malicious ONU on the network will not have been provisioned with a recognized GEM identifier and, therefore, is unable to take in any packets.

In the upstream direction (from the RAN base station to the CN), an ONU sends the traffic only in one direction-to the OLT. Each ONU transmits directly to the OLT in assigned timeslots. The signal is not reflected back into the network, for example from splitters or OLTs, because these devices are designed and manufactured to reflect almost no light. So, it is not possible for traffic sent by one ONU to be intercepted by another ONU. If a malicious ONU is somehow inserted in the network without triggering an alarm, it will still not be recognized in the OLT's provisioning database and will not be granted timeslots to send its data.

In order to interfere with traffic on a PON a malicious user would need to interfere with the physical nature of a fibre optic network. Any device introduced on the network needs a physical connection, which will disrupt signals in the network and should trigger an alarm.

The current PON systems, including GPON, XG-PON, XGS-PON, etc., have been widely deployed and take an advanced encryption standard (AES-128) as their sole encryption algorithm to guarantee the security of communication. AES is one of the block ciphers which is standardized in the international encryption algorithms [b-ISO/IEC 18033-3]. These common block ciphers operate a block of plaintext with a defined length, i.e., 128 bit, to yield a block of cipher text with the same length. All packets coming from or to an ONU are encrypted with the key, which is only known by that ONU and the OLT. Encryption keys are generated by each ONU and sent upstream to the OLT. They are periodically refreshed (e.g., hourly, daily) depending on the network configuration. As previously mentioned, traffic is not mirrored back into the network, so other ONUs cannot intercept the keys (also, the encryption keys are themselves encrypted when sent). Encryption is applied to both the data payload and the GEM payload, providing an additional level of security, so GEM frames cannot be read even if intercepted.

Message integrity checks (MIC) are used by OLT and ONUs to verify that the downstream and upstream control messages come from a legitimate source and that they have not been tampered with. In downstream, a MIC is generated and inserted by the OLT when a message is transmitted and checked by the ONU when received. In upstream, a MIC is generated and inserted by the ONU when the message is transmitted and checked by the OLT when received. For every ONU there is a dedicated set of keys used to generate the MIC. These MIC keys are calculated by the OLT and ONU independently, based on information bidirectionally exchanged during the ONU activation process, such as the ONU serial number and registration ID. Hence, only the OLT and the ONU have all the information needed to generate and validate the MIC for control messages related to that ONU. MICs are executed in the control layer and are a protection against a malicious user trying to disrupt a network, rather than steal data from it.

Conclusion: TDM-PON is considered an untrusted TN. BH and MH IPSec tunnels can be transported over TDM-PON. Additional encryption of PON is providing additional level (hop-by-hop) of security an MIC.

8.6 Sharing access domain

Reference is made to [b-ITU-T SG15-C-2862] for all requirements for slicing in TDM-PON based access.

The required TN connectivity subslice domain could be implemented in a TDM-PON virtual access node (vAN) of a virtual slice as defined in [b-BBF TR-370] fixed access network sharing (FANS). FANS is a resource sharing approach that allows the exposure of a broader set of access functions to virtual network operators (VNOs). In the vAN model of TDM-PON, network slicing is performed in both the management and data planes. In that virtual (fibre) access domain, each VNO controls virtual access nodes (vANs) as well as potentially other L2 virtualized functions in the data plane via the brokerage and mediation of the centralized management system. The SDN-based FANS model leverages on the so called software-defined access network (SDAN) to deliver network automation, interface programmability, FANS service flexibility and agility, and separation of virtual domains.

Conclusion: the slicing solutions in TDM-PON (under study) as well as the concept of FANS shall deliver the subslice functionality required by 5G NR service slicing.

8.7 Access domain management

The SDN infrastructure consists of a resource controller and various PON equipment such as a TDM-PON. The SDN infrastructure has functions supporting the monitoring and controlling of the PON equipment.

Management aspects of the SDN controller are as follows:

- Management aspects for the SDN controller are described in [b-BBF OB-BAA].
- An element management system (EMS) needs to send and receive management signals for interactions with the OSS.

Conclusion: to support the requirements of a TN domain, TDM-PON management shall include next to the EMS also an SDN control function integrated to the TN management system per [b-BBF OB-BAA].

8.8 Summary

This clause is focused on comparisons between BH/MH requirements and PON capabilities. It includes capacity, latency, time and frequency synchronization, high availability, security, sharing access domain and access domain management. The technologies around both PON and 5G SC are developing, so further study will be needed in the future.

9 Suggested application scenario and requirement

Table 18 analyses the main features of segments in 5G RAN and applicable bearer technologies, including the integrated CU+DU+RU SC.

Table 18 – Comparisons between all segments in 5G RAN

Segment	Reach	Bandwidth	Latency	Topology	Applicable technology	Remark
5G DIS (BBU-rHUB）	Almost ⩾2 Km.	25G eCPRI. 4G is CPRI (10-157.3G).		Parallel P2Ps	Fibre	Usually in the same building
5G DIS (rHUB-pRRU）	PoE ⩾ 0.1km; Hybrid fibre ⩾ 0.2 km; can be extended by cascading.	4G pRRU is GE port. 5G pRRU 6-8G(100MHz,4T4R,8B10B/64B66B,3.2:1/4:1).		Parallel P2Ps	CAT6A+PoE, or hybrid fibre.	Usually on the same floor in a building
BH of 5G DIS (BBU-CO side)	BBU is now the same as in macro cell, but differences may arise in the future					
BH of SC	20 km	Related to the number of subscribers and the actual traffic; see clause 7	See clause 7	Star	High speed PON such as 10G/50G TDM-PON	Integrated CU+DU+RU. May be integrated CU+DU or DU+RU.

Table 18 – Comparisons between all segments in 5G RAN

Segment	Reach	Bandwidth	Latency	Topology	Applicable technology	Remark
MH of SC	The requirement of latency should be met	Calculation method is shown in Table A-1 and A-2 in [b-3GPP TR 38.801]; it is about 1% difference between MH and BH via estimation.	[1.5-10 ms]	Logical P2P or Star (one DU only can be connected to one CU)	Support UDP/IP. MH can be bear via cable-connected (parallel P2Ps), when CU and DU are located in same room. High speed PON such as 10 G/50 G TDM-PON.	Separated CU. For integrated CU+DU, there is no MH.
BH of macro cell	<40 km	About 2G per gNB (avg. value). about 6G per gNB (peak. value)	>4 ms	Mainly ring	IP (such as IPRAN+ IPRAN)	Scale of BBU (or DU, or integrated CU+DU) Pooling is the key. It needs many 10GE or higher rate ports.
MH of macro cell	The requirement of latency should be met	Calculation method is shown in Table A-1 and A-2 in [b-3GPP TR 38.801]; it is about 1% difference between MH and BH via estimation.	[1.5-10 ms]	Logical P2P or star (one DU only can be connected to one CU)	Support UDP/IP. MH can be bear via cable-connected (parallel P2Ps), when CU and DU located in same room.	Separated CU. For integrated CU+DU, there is no MH.
FH of macro cell	D-RAN <300 m C-RAN <10/20 km. Large/small concentrations are different.	Primary *n**3*25G (eCPRI), sometimes this is 10 GE.	100 µs	D-RAN is P2P. C-RAN mostly is star.	Fibre, WDM with 25G per wavelength.	

NOTE – "BH of macro cell" means classic D-RAN macro-sites. The latency of the BH > 4 ms but can be lower in case of specific application latencies.

9.1 Topology

TDM-PON should use the same ODN resources as FTTH in the MH/BH of the SC, so the star topology is still the main one.

MH is logic P2P and Star (parallel P2Ps). One DU only can be connected to one CU. The BH is a TCP/IP network, which supports multiple flexible topologies such as mesh, ring network, etc., and can cover multiple network deployments of operators.

PON usually is star topology. This Supplement uses the same ODN resources as for the FTTH scenario. Regional/geographical differences for this Supplement over ODN may be limited.

9.2 Use cases

This clause refers to the work done for 3G and 4G SCs as described in clause 10.2.

SC's large scale deployment requires the existing network to have abundant mobile BH resources. At the same time, the BH bearer network is required to have high network bandwidth, reliability, clock time synchronization capabilities and flexible power supply capabilities. In order to ensure network revenue, mobile operators need to consider choosing a cost-effective, flexible and reliable technology to carry the BH of SCs.

The deployment of SCs is more geographically intensive than for the existing macro BSs, it is not feasible to use traditional backhaul platforms, and it also brings great challenges to the bandwidth requirements of UL ports. On the other hand, the area that needs to be covered is highly consistent with the FTT*x* network that has been deployed on a large scale. The use of FTT*x* can flexibly and quickly provide the on-demand deployment of SCs, which has significant advantages, such as fast return on investment, low deployment cost and fewer load-bearing resources.

It should be noted that in the future, SCs will become more multimode, intelligent and integrated, which will bring about a diversification of equipment forms, capabilities and MH/BH bearer requirements. The FTT*x* access network has a smooth evolution capability and a series of ONU products in various forms, which can be used to flexibly meet the needs of SCs. Flexible deployment of PON equipment according to different scenarios, unified management with different role permissions and different regions and E2E visual interfaces can meet the indoor and outdoor application scenarios of SCs well. During bearing, it can meet the indicator requirements of delay, QoS, clock synchronization and power supply.

9.3 Network resource sharing

With the gradual development of 5G construction, the density of physical BSs and the number of fibre connections built per km^2 will increase significantly, while the number of FTT*x* users and the number of fibre connections will also increase. In order to maximize cost control, full use of the existing FTT*x* optical fibre infrastructure should be made, including telecommunications room cabinets, pipe holes, poles, ODN, optical cables, optical fibres, etc., to achieve the sharing of the basic resources of the fixed network and mobile networks. The following benefits are expected:

- Good scalability: With the increase in the number of 5G subscribers, the application of new services and the increase in traffic consumption, the capacity demand of 5G RAN will continue to grow, and FTT*x* has good long-term evolution and upgrade capabilities. New low-latency technologies suitable for the 5G bearer are also being continuously upgraded.
- Great QoS: FTT*x* has high QoS capabilities, so can well support the triple services i.e., voice, data and video, and can better support 5G services. TDM-PON can realize flexible statistical multiplexing and DBA functions and can make full use of system bandwidth.
- Convenient and efficient deployment for synchronization: 5G requires that the bearer network must support time and frequency synchronization, and PON has the characteristics of flexible adaptation.

In the 5G era, deployment mainly adopts C-RAN architecture with centralized deployment of DUs. For fixed network access, the distances separately between the DU pool to users and telecommunications room of access network to users are basically the same. In some areas with great telecommunications room, it is possible to achieve common siting and resource sharing for fixed network and mobile network, which can effectively reduce CAPEX. The present telecommunications room, power supply, air-conditioning/conditioner, transmission equipment and other resources of the fixed network can be shared, which is also convenient for the centralized management of equipment.

C-RAN with central DUs means FH transport in dense area over some network. This may be out of the scope of this Supplement. The main focus should be on full D-RAN with CU+DU+RU SC or a distributed DU (RU+DU SC) with F1 interface which is defined as 'MH'.

Building a shared network infrastructure is an confirmed practice of MNOs. This kind of mobile network infrastructure sharing has many forms. For SC networks, infrastructure sharing is even more critical, because it requires high-density network deployment and wider and more diverse deployment scenarios. In the future application of PON bearing 5G SCs, sharing can be realized by using PON network slicing, through PON's SDAN and NFV technology. The realization of network slicing is E2E, where each slice (for example, allocated by each MNO) can have its own network architecture, engineering mechanism and network bearer. Network slicing realizes the virtualization and dynamic allocation of most network access and service resources (for connection, computing or storage), and supports on-demand, flexible, pay-as-you-go cloud services. The network slicing method realizes sharing and is more scalable, small unit owners can accommodate more tenants and new users, and the type of service provision can also include 5G vertical industries. See also Figure 29.

SCF also specifies the multivendor standardized interface (network functional application platform interface (nFAPI)) in the SC physical network function (PNF) and virtual network function (VNF) interface, which decouples the deployment of the SC physical hardware PNF and VNF. In a typical imagined sharing scenario, the controller can belong to the host of the PON OLT resource clause [b-SCF500].

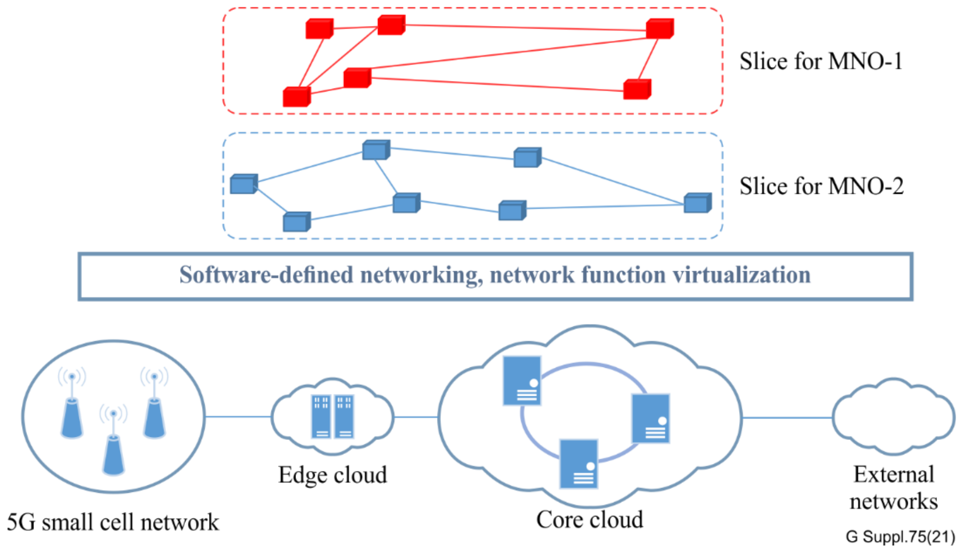


Figure 29 – Example conceptualization of network slicing for small cell sharing (i.e., Figure 23 in [b-SCF500])

9.4 Fibre usage

The amount of optical fibre used includes (under the condition of protection/unprotection): the length of the feeder fibre, the length of the distribution fibre, the total length of the optical fibre and whether it conforms to the optical cable structure and direction.

For TDM-PON bearing SCs,

– The number of feeder fibres = the number of SCs * average bandwidth of the SC interface (or peak bandwidth?)/single PON port capacity.

– The number of distribution fibres is the number of SCs.

– The topology of PON is usually star. This Supplement can use the same line requirements (route, fibre core and fibre cable, etc.) and utilization calculation method as FTTH. Mathematical formulas used to describe the model and calculation examples can be further studied.

9.5 Summary

SCs are characterized by small coverage, high BS density and small BH bandwidth. Therefore, PON bearers can be given priority for their BH services. Since the number of user accesses of each BS is different, the bandwidth requirements may vary greatly. The UNI port of the ONU that connects to the integrated SC should have a large capacity (e.g., ≥10 Gbit/s) to adapt to the flexible bandwidth requirements. PON has the advantages of abundant fibre resources and P2MP, which can save feeder fibre.

In current 10G TDM-PON even with multi-PON module (MPM) modules and future higher speed TDM-PON, the PON port capacity is greatly extended, and its capacity can bear more MH/BH of SCs.

10 Other topics

10.1 5G DIS and bearer technology

At present, the main features of the new DIS are list as follows:

- Firstly, it supports the 5G frequency bands (including FR1 and FR2), which solves the physical limitations of traditional passive DAS and the system complexity of active DAS.
- Secondly, it uses BBU directly connected to RRH. The signals under multiple pRRUs under same single cell are directly superimposed and transmitted back to the BBU for processing.
- The third is to support MIMO multichannel evolution.
- The fourth is to realize visual OAM.
- The fifth is to support 5G multiservice development.

The split-baseband solutions is described in clause 6.1, which includes Option 8 (CPRI), Option 7 (eCPRI) and even Option 2 (F1). The pRRU could also be 'RAP' i.e., with real-time baseband functions integrated later.

The new DIS only needs to deploy active antenna head-end equipment, using Ethernet cable or optical/electrical hybrid cable as the transmission media and power supply line at the same time. The installation is very convenient, and deployment is quick. These above features can meet the requirements of 5G indoor networks.

Compared with the earlier DAS system, the current new DIS has begun to evolve to a flatter, simpler and more flexible architecture.

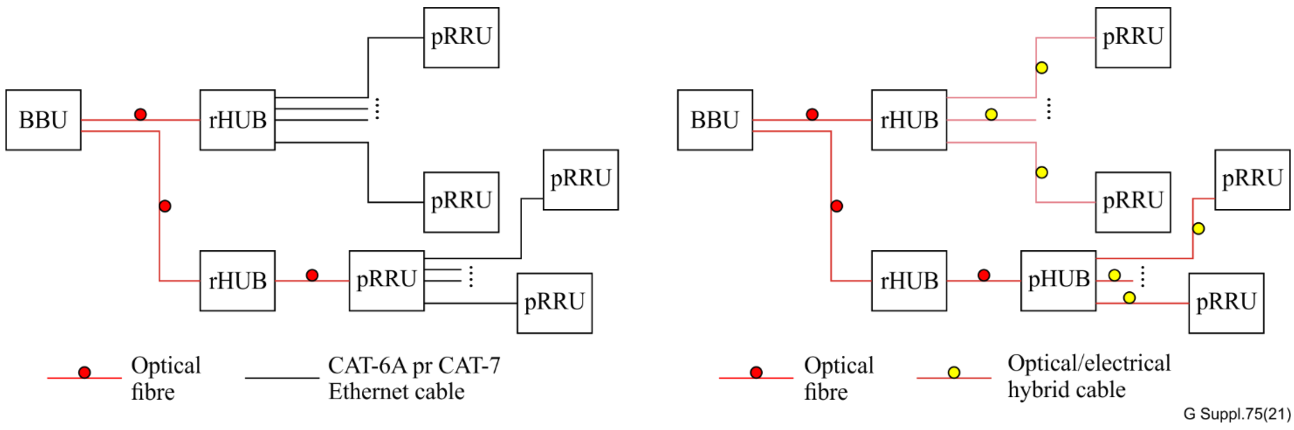


Figure 30 – BBU (DU) + rHUB + pRRU Architecture

Indoor coverage in 5G can be considered a specific application scenario for 5G small and micro cells. It adopts BBU (DU) + rHUB + pRRU architecture, can support optical and electrical hybrid transmission, supports the 5G 3.4-3.6 GHz frequency band and will expand to support the mmW frequency band in the future.

As shown in Figure 30, between rHUB and pRRU, a 10 Gbit/s optical/electrical hybrid cable or CAT6A Ethernet cable with PoE is used. BBU (DU) and rHUB are connected by optical fibre, using a 10G/25G/40G optical interface (currently mainly a 25G optical interface), and the interface is CPRI or eCPRI protocol. The rHUB uses an AC power supply. Usually, one rHUB connects 8 pRRUs. The pRRU can also be connected to several external antennas.

It should be noted that the optical fibre connection between rHUB and BBU can have multiple levels (such as 4 levels) cascade, and currently it is mainly 2 levels cascade. The rHUB to BBU in eCPRI could be transported over a switched network. This FH link is excluded from this Supplement. Alternatively, if rHUB integrated the DU function of gNB, this transport can converge with production and/or office LAN. The latter would map to the passive optical LAN where TDM-PON can be used. In this case BH or MH is used, and this would fit the domain described in this Supplement.

The equipment specifications of the DIS have the following requirements.

Based on the CCSA standard [b-CCSA DIS], there are three types i.e., A1, A2 and A3 for BBU. The Type A1 BBU should support 12 or more 4T4R cells with 100 MHz bandwidth. The Type A2 BBU should support at least 4 or more 4T4R cells with 100 MHz bandwidth. The Type A3 BBU should support at least 4 or more 2T2R cells with 100 MHz bandwidth. The rate of each optical interface between BBU and rHUB is not less than 10 GE. BBU and rHUB are connected by optical fibre, and the extended distance is not less than 2 km. The topology among BBU and rHUBs is a star connection. The Type A1 BBU supports 6 or more rHUBs. The Type A2 and A3 BBU support 4 or more rHUBs [b-CCSA DIS].

The rHUB should have at least 8 Ethernet ports no less than 10GE, or 8 optical ports no less than 10 GE for connecting to pRRU. The pRRU has at least one electrical/optical interface with 10 GE or above rate. When pRRU adopts PoE/(optical/electrical hybrid cable) power supply, the extended distance is not less than 100/200 m. The rHUB supports star connection with the pRRUs [b-CCSA DIS]. This rHUB to pRRU is a FH connection that is outside the scope of this Supplement.

The Type A1 BBU should support no less than 48 pRRUs connected through the rHUB, and optional 96 pRRUs. The Type A2 and A3 BBU should support no less than 32 pRRUs, optional 64 pRRUs [b-CCSA DIS].

The Ethernet cables widely used in the market are CAT5E, CAT6, CAT6A and CAT7. CAT5E Ethernet cable is used in Gigabit Ethernet, the transmission distance can reach 100 m, and it can support a 1000 Mbit/s transmission speed. The transmission distance of CAT5E Ethernet cable and CAT6A Ethernet cable are both 100 m. CAT6/CAT6A Ethernet cable can provide up to 10 Gbit/s transmission speed in 250 MHz bandwidth. In 10 GBASE-T application, the maximum transmission distance of CAT6/CAT6A Ethernet cable can reach 37/55 m. The CAT6A Ethernet cable can be used in ordinary 5G indoor scenarios, and PoE power supply is used for pRRU.

Optical/electrical hybrid cable integrates optical fibre and power transmission copper wire, which can solve the problems of broadband access, power supply and signal transmission. It can be used in high-end 5G indoor scenarios.

Facing 5G evolution, the indoor network architecture needs to have the ability to quickly introduce 5G NR evolution and enable new 5G mobile services by quickly superimposing 5G NR modules to form converged LTE+5G NR networks within a period of time, so it can provide high QoE to subscribers the same as via a 5G networks. However, traditional RF cables and indoor coupling devices do not support new 5G NR frequency bands, such as C-band and mmW bands, and need to be redeployed. The cost of redeploying all new RF cables indoors is very high. There is even no space in some places so new cable is unable to be deployed. The construction of DIS is geared towards 5G evolution, and it is necessary to strive to realize the target of "no need to change cables or increase end points" of DIS, reduce costs on construction and renovation, and can introduce 5G as needed. Therefore, operators need to deploy large bandwidth, lightweight indoor transmission, such as Ethernet cables, optical fibres and optical/electrical hybrid cables, to replace bulky RF cables and avoid repeated investment in the future.

For the Ethernet cable architecture, a CAT6A Ethernet cable needs to be pre-deployed for superimposing 5G modules, or CAT6A is currently connected to an integrated 3G+4G pRRU, and it will be replaced with an integrated 3G+4G+5G pRRU in the future.

For the evolution of the optical fibre architecture, a 5G pRRU can be cascaded through a CAT6A Ethernet cable at the integrated 3G+4G pRRU connected by the optical/electrical hybrid cable, or it can be replaced with an integrated 3G+4G+5G pRRU.

Since the DIS system uses the same BBU equipment as the macro base station, its backhaul bearer is the same as that of the macro base station.

A preliminary analysis of the possible application scenarios of PON in the DIS bearer is as follows:

First, when the capacity of the BBU is small, the BBU and the DIS are deployed in the same building, and there is a P2MP star topology between the CN and the BBU. Currently fibre to the block (FTTB), 10G TDM-PON can be used as BH, between core and BBU, Higher speed PON [b-ITU-T G.9804.x] can be used for future expansion. If the BBU and the rHUB are deployed in the same building or are relatively close, the cables that meet certain requirements can be used between the BBU and rHUB, rHUB and pRRU, respectively, so there is no application scenarios for PON. This depends on the location of the DU. If the DU (split out the BBU from the CU) is at the rHUB, a MH link can be used and the same remark as FTTB applies and can be covered with this Supplement.

Secondly, when the BBU has a large capacity or may share a rack with the BBU of a macro base station, or the BBU is installed in a central office room, so the BBU and the rHUB are far away from each other and are star topology. Due to the bandwidth and latency requirements between BBU and rHUBs, various WDM technologies with 10G/25G interface can be used to bear the FH between BBU and rHUBs.

10.2 Research on PON bearing small cell in 3G and 4G eras

For 3G and 4G, many studies and tests have been carried out on PON bearing SC BH service, and there are many related publications [b-Yang] [b-Wang-1] [b-Liu-1] [b-Lin] [b-Wang-2]. This clause summarizes and analyses them for reference in the 5G era. IPRAN technology was used as a comparison example during analysis.

10.2.1 Technical advantages

10.2.1.1 Improve network performance

The target area for deep coverage (residential area, commercial area) is also a focus area for broadband users, and broadband resources are abundant, which are convenient for providing BH networks for LTE SC. Using PON to bear SC BH services can give full play to the network efficiency of the existing ODN, access network points and other infrastructure resources in the FTTH network construction, and effectively increase the actual port occupation ratio.

10.2.1.2 Save fibre resources

Compared with the traditional P2P topology networking, the PON system adopts a P2MP topology structure, which is consistent with the scattered and unpredictable SC structure. The optical splitting for PON access method can save at least 80% of the feeder fibre and 50% of the distribution fibre. The higher the density of the SC, the greater the amount of feeder fibre saved.

10.2.1.3 Simple and fast deployment

FTTH ODN splitting points are located in residential areas, buildings, streets and villages. Broadband networks are in these places and can be accessed by simply laying indoor wiring optical cables.

10.2.1.4 Ultra-high bandwidth access

Through the deployment of 10G PON, FTTH can flexibly provide 100 Mbit/s, 1 Gbit/s and 10 Gbit/s access capabilities to meet the bandwidth requirements of BSs.

10.2.1.5 QoS support

In terms of QoS, the PON network has a relatively complete VLAN function. Through VLAN multiservice isolation, it realizes service flow classification, priority marking, queue scheduling, buffer management, congestion control and provides virtual private channel for BS BH services.

10.2.2 Technical risks, disadvantages and suggestions

10.2.2.1 Protection capabilities

The PON network is a star network, which does not have the ring protection and switching capabilities of IPRAN and has relatively weak BS protection capabilities. If the Type B or Type C protection mode is adopted, the cost is higher and the port utilization ratio is lower.

The PON UL can be divided into two ways:

Method 1: OLT uplinks to the broadband remote access server (BRAS) / service router (SR). Usually, a single UL to the BRAS/SR cannot provide dual parented node protection. The OLT can improve the protection capability by double-uplinking to the BRAS/SR.

Method 2: Connect the BS service at the OLT directly to the mobile BH bearer network for macro BS (such as IPRAN) to improve reliability. Usually, OLT and IPRAN equipment are in the same telecommunications room. IPRAN has strong protection capabilities due to its network topology and other characteristics.

The topic of protection is also addressed in clauses 7 and 8. The evolutions in TDM-PON will have improvements on protection options with redundancy (geographical) in OLT. In the 5G era, the key point does remain, however, that for these redundancy options "the cost is higher, and the port utilization ratio is lower". However, other backhaul bearing technologies such as IPRAN redundancy options also come with higher cost and lower port utilization. The protection technology of PON is mature; however, the planning and engineering of transport based on PON may require more tests. This clause on protection is related to clause 10.2.3 on deployment strategies.

An important point for SCs is the concept of 'fall back' to other cell coverage in case of failure. TDM-PON may be a good (un)protected solution in cases where the SC layer is complementary to a macro cell layer (see radio resiliency as discussed in clause 7).

10.2.2.2 Rogue ONU

The inherent rogue ONU problem of the GPON network may cause all BSs under the PON port to be offline.

With the mature application of PON technology, there are very few rogue ONUs on the present network. Causes include abnormal ONU optical module components, damage to the optical splitter, and abnormal ONU power module, which will cause long-light emitting, that is, a rogue ONU. The long-light ONU detection function can be turned on to detect continuous light-emitting and can control rogue ONUs. This function can set the time interval for detecting long-light-emitting faults and the shutdown method (automatic shutdown/manual) when long-light-emitting faults are detected in the connected ONU). For special situations such as uncontrolled rogue ONUs, random light emission or the OLT cannot receive any valid information due to a damaged optical module within an ONU, etc., the specific rogue ONU cannot be located, so on-site fibre removal is required.

The risk that one abnormal terminal influencing the central office (CO) side equipment and all other terminals is generic for PON as a technology and all P2MP. It may be referred to the function in the

TDM-PON specifications that addresses 'Rogue ONU' [b-ITU-T G.987.3], [b-ITU-T G.9807.1], [b-ITU-T G.989.3] and [b-ITU-T G.9804.2].

In the 5G era, attention is still being paid to this issue. Related measures need to comprehensively consider cost and protection capabilities. In order to avoid being affected by rogue ONU problems among a large number of FTTH ONUs, the question of whether the BH service should separately occupy the PON port should be considered combing the fault probability and influence on cost.

10.2.2.3 Synchronization

In the 3G and 4G eras, there was a problem that some devices could not support 1588v2 time synchronization.

In the 5G era, the current PON system transmission frequency and clock signal technology are mature. The OLT supports functions such as 1588v2 and SyncE, and can use the PON physical line clock to achieve frequency synchronization. See clauses 7 and 8 for details.

10.2.3 Application deployment strategies in the 3G and 4G eras

- The macro BS is located where network resources are inconvenient or unreachable, such as IPRAN. The area where the macro BS is located has the PON coverage, and the distance from the OLT is less than 20 km. The PON network can bear mobile backhaul services, and it is recommended as a Supplement to other bearer backhaul technologies such as IPRAN. There are certain advantages in terms of cost.
- The following strategies should be comprehensively considered to address issues about cost and protection capabilities: Connecting SCs to the OLT through an independent PON port. In order to facilitate fault location and isolation, the PON board that bears the BH should no longer carry ordinary fixed-line broadband services to avoid the ONT impact of ordinary broadband users. It can be used to bear terminal macro BSs without high importance, or some SCs with fewer users, such as DAS in parking lots.
- The necessity for SCs to have PON interfaces (even ONU capabilities integrated the into optical module) needs to be further studied. It should be noted that this may affect the scalability of the device.

The deployment strategy may be different in 5G cases (especially in densified SCs), yet this very much depends on the operator's strategy. The above deployment strategies should be considered as illustrations of a strategy. It is not mandatory that operators follow these. For instance, the specification in clause 10.2.3.2 to 'no longer carry ordinary fixed-line broadband services' could be different for operators that have evolved automation (e. g. with fixed access networks sharing via virtual slicing) in a 5G context.

10.3 Comparison of integrated access and backhaul (IAB) and PON supporting backhaul for small cell

The 5G network is a super dense network, and it is highly challenging to provide economical, efficient and scalable BH solutions. At present, BH technology is mainly wired technology such as the IP radio access network (IPRAN), PON, etc. In wireless bearer technology for 5G RAN, Sub-6G, mmW and relay will also be used.

One of the most challenging things for 5G deployment would be the fact that the cell coverage is small compared with other legacy technology (e.g., 3G, 4G), especially when mmW (FR2) is used. Therefore, a new technique named integrated access and backhaul (IAB) is added in [b-3GPP TR 38.901]. See also Figure 31. The coverage extension can be supported through IAB. In an area with high traffic, the cost of optical fibre laying can be saved by wireless BH. In mmW deployment scenarios, flexible switching of the BH path can reduce the channel problems caused by channel fading or occlusion.

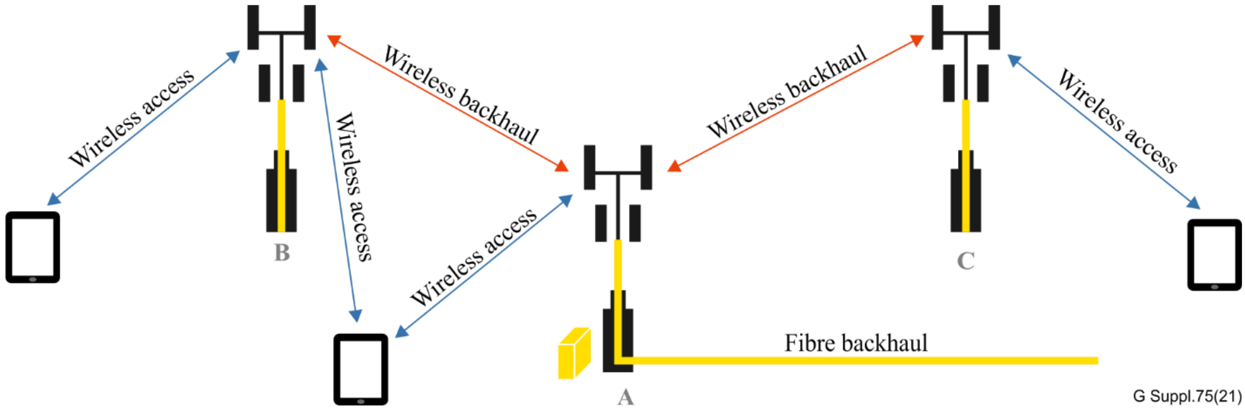


Figure 31 – Schematic diagram of IAB

The technical scheme is as follows:

1) The protocol stack based on L2 architecture. On the original RLC layer, the backhaul adaptation protocol (BAP) adapter sub-layer is defined, which mainly provides routeing, bearing mapping, link control, flow control and other functions.

2) The IAB node provides access service to subordinate UE and BH service to the BS which is its child IAB node. The IAB node is connected to its parent IAB node through a "NR Uu link" and a "MH F1 link". This "NR Uu link" is not as same as the "BH NG-interface link" which is between RAN and 5GC.

The F1 definition of 3GPP for IAB in R16 is as same as in R15. In above paragraph, the F1-interface transports can be defined as the "MH F1 link".

It should be noted that F1 is a logical interface. A logical interface with P2P topology between two nodes can pass through multiple intermediate physical nodes. Both the F1 interface in the IAB node and the NR Uu interface in the IAB node are wireless interfaces through the air channel. This is different from the usual cable connection between the CU and the DU of the 5G macro cell. The physical bearer channels between the FH/MH/BH segments of a 5G macro cell are usually isolated.

3) To support the limited number of hops and limited mobility. Simplified wireless link management and limited switching scenarios can be considered.

In IAB, usually a macro cell works as IAB-donor and one or more SCs (named the IAB-node) is connected wirelessly to the IAB-donor. The IAB node can be considered a relay cell wirelessly connected to a donor. If UE is connected to an IAB node, the communication is relayed to a macro cell via wireless IAB BH and then reaches CN via optical fibre that is connected to the macro cell.

The overall architecture of IAB is shown in Figure 32.

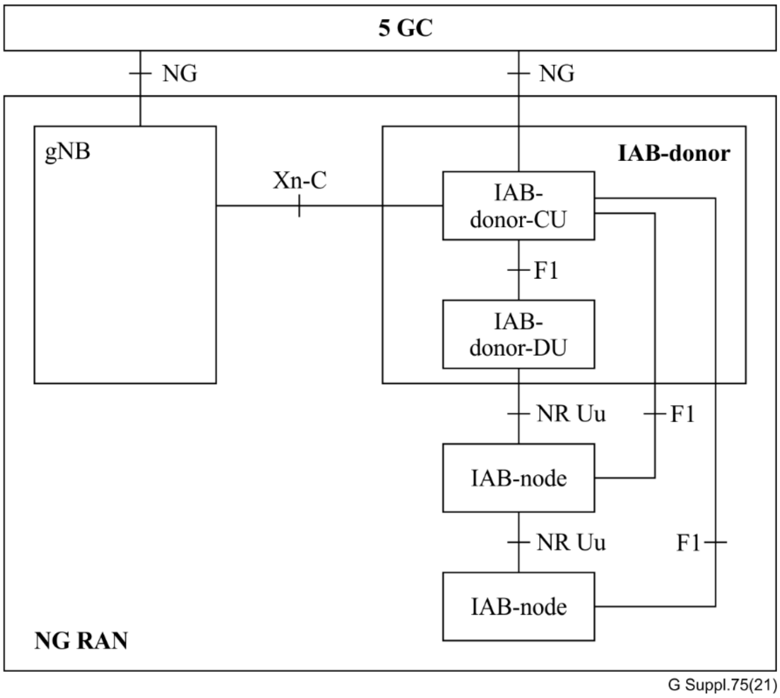


Figure 32 – Overall architecture of IAB [b-3GPP TS 38.401]

The NG-RAN supports IAB by the IAB node wirelessly connecting to the gNB capable of serving the IAB-nodes, named IAB-donor. The IAB-donor consists of an IAB-donor-CU and one or more IAB-donor-DU(s). In a case of separation of gNB-CU-CP and gNB-CU-UP, the IAB-donor may consist of an IAB-donor-CU-CP, multiple IAB-donor-CU-UPs and multiple IAB-donor-DUs. The IAB node connects to an upstream IAB node or an IAB-donor-DU via a subset of the UE functionalities of the NR Uu interface (named the IAB-MT function of the IAB node). The IAB node provides wireless backhaul to the downstream IAB-nodes and UEs via the network functionalities of the NR Uu interface (named the IAB-DU function of the IAB node).

The F1-C traffic between an IAB node and IAB-donor-CU is backhauled via the IAB-donor-DU and the optional intermediate hop IAB node(s). The F1-U traffic between an IAB node and IAB-donor-CU is backhauled via the IAB-donor-DU and the optional intermediate hop IAB node(s).

As mentioned before, the F1 definition of 3GPP for IAB in R16 is as same as in R15. In the above paragraph, the F1-interface transports can be defined as "FH F1 link".

All functions specified for a gNB-DU are equally applicable to an IAB-DU and IAB-donor-DU, unless otherwise stated. All functions specified for a gNB-CU are equally applicable for an IAB-donor-CU, unless otherwise stated. All functions specified for the UE context are equally applicable for managing the context of IAB-MT, unless otherwise stated.

However, it should be noted that unlike the definition of PON backhaul, 'BH' in IAB does not refer to the BH path between 5G RAN and the 5GC. Therefore, there is no contradiction in the use of PON BH technology. It has become an urgent research task to make a comparison between various BH technologies to determine the best application scenario of TDM-PON and make full use of the resources and capabilities of the PON network.

The BH in the IAB node does not refer to the NG-interface between RAN and 5GC but rather to the F1 transport which is named 'MH' (i.e., MH F1 link). The scenario of MH over TDM-PON could therefore also be used to "determine the best application scenario of TDM-PON" in the IAB context. Or vice versa, the RAN capabilities of the IAB networks should be to a large extent identical to a TDM-PON based MH network.

IAB has not been implemented in SC products yet, so the development of technology and products needs to be observed and studied for some time. More research work on the capabilities of IAB and comparison of it with TDM-PON is needed.

The following three IAB network connection topologies were discussed in the IAB SI stage:

- Spanning tree. There is only one wireless relay BH path from each IAB node to the IAB-donor.
- Directed acyclic graph. On the basis of the spanning tree, limited redundant connections between nodes are added, which can avoid the entire data transmission delay caused by a single-point link failure.
- Mesh network. A network connection can be established between any two adjacent nodes. This method is the most flexible but also brings the complexity of network topology management.

The final standard [b-3GPP TR 38.874] has adopted spanning tree and directed acyclic graph.

10.4 4G+5G dual-mode small cell

10.4.1 Architecture from 3GPP

As shown in [b-3GPP TR 38.801] (clause 5.3), in this scenario the NR functionality is co-sited with E-UTRA functionality either as part of the same BS or as multiple BSs at the same site. Co-sited deployment can be applicable in all NR deployment scenarios, e.g., urban macro. In this scenario it is desirable to fully utilize all spectrum resources assigned to both RATs by means of load balancing or connectivity via multiple RATs (e.g., utilizing lower frequencies as coverage layer for users on cell edge). See also Figure 33.

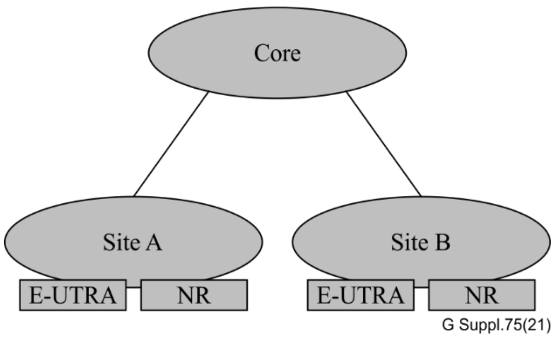


Figure 33 – Co-sited deployment with E-UTRA (Figure 5.3-1 of [b-3GPP TR 38.801])

As shown in [b-3GPP TR 38.801] (clause 10.1), Option 3/3a/3x, 4/4a and 7/7a/7x of the deployment scenarios can be considered tight interworking between NR and E-UTRA.

In order to support the SCG split bearer, another deployment option needs to be supported. In Option 3x shown in Figure 34 (Figure 10.1.2.4.1-1 of [b-3GPP TR 38.801]), the solid line shown between LTE eNB and gNB is used for U-plane data transmission terminated at the gNB, i.e., S1-U data from EPC is split at the gNB.

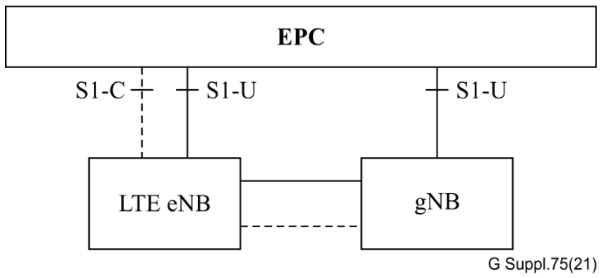


Figure 34 – Option 3x (Figure 10.1.2.4.1-1 of [b-3GPP TR 38.801])

In order to support the SCG split bearer, another deployment option needs to be supported. In Option 7x shown in Figure 35 (Figure 10.1. 4.3-1 of [3GPP TR 38.801]), the solid line shown between eLTE eNB and gNB is used for U-plane data transmission terminated at the gNB, i.e., NG-U data from NGC is split at the gNB.

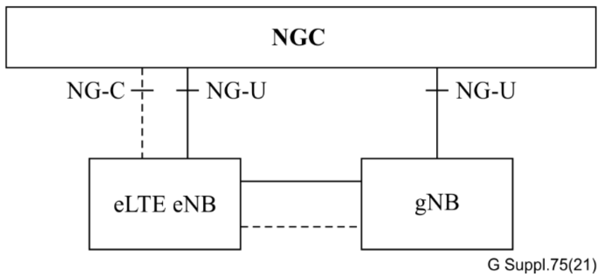


Figure 35 – Option 7x (Figure 10.1. 4.3-1 of [b-3GPP TR 38.801])

10.4.2 BH bearing requirements

How to bear 4G+5G dual-mode SC is also related to the types of ability and deployment with UE and 5GC.

1) UE can be divided into two modes: Only supporting 4G and 4G+5G dual-mode. It should be noted that when the intensity of the 5G signal is weak, the 5G UE may fall back to the 4G network.
2) 4G+5G dual-mode SC is used in scenarios where 4G UE needs to be supported and 5G RAN needs to be deployed. The BS's 4G and 5G BH traffic are directly additive.
3) CN:
   - The backhaul already supports IP technology, so no matter whether the deployment mode of the CN is 5G NSA or 5G SA, it is reachable by IP address;
   - For the co-construction and sharing of multiple operators, the BH signal can be transmitted to the respective CN equipment based on the IP address via a network that supports TCP/IP;
   - Due to the limited processing capability of CN equipment, although the DU can connect with CN by IP address over the BH bearing network, they still need to be deployed in different regions;
   - The processing capability of the CN and how many BSs can be connected need to be continuously studied.

10.5 The developing and analysing of 5G mmW

5G needs to meet the requirements of higher speed and lower latency scenarios and provide support for a variety of new applications. Compared with 4G, 5G can use more spectrum resources for different types of service, including the use of mmW frequency resources to achieve high bandwidth and low delay. The 5G mmW frequency band and the sub-6 GHz band cooperate and complement each other, which is the key to achieve 5G integrity and optimal QoE.

When using carrier aggregation technology combined with advanced antenna design and RF processing technology, it is easier for the 5G mmW network to achieve Gbit/s peak throughput. In addition, the characteristics of the high frequency band and short wavelength of mmW give it spatial advantages in design and deployment, which are more suitable for combining with beamforming technology to enhance performance and reduce interference. Due to the short wavelength, the antenna array of 5G mmW equipment can place more antenna arrays in a space of limited size, especially relevant since the number of antenna arrays of 5G mmW BS can reach 256 or 512 or even more, so more beamforming gain can be obtained both in UL and DL [b-GSMA mmW WP].

The 5G network uses time slots to schedule data. If the length of the time slot is shorter, the delay in the physical layer is smaller. As shown in Table 19, the minimum length of the time slot of NR of the 5G mmW system can be 0.125 ms, which is 1/4 of that in the medium-frequency and low-frequency system. If mini slot scheduling is adopted, the slot delay will be even smaller. Therefore, the 5G mmW system reduces the NR delay compared with the 5G medium-frequency and low-frequency systems, which helps the 5G NR delay to be potentially less than 1 ms and can therefore realize the quality promise of the 5G network to URLLC services such as industrial Internet, AR/VR, cloud gaming and real-time cloud computing. AR/VR services require millisecond-level delays to ensure multisensory coordinated experiences and interaction capabilities. The requirement for low delay of industry Internet was very clear, for example, the requirement of delay of a typical industrial robot network is millisecond-level, and remote real-time control of the product line also needs a millisecond-level delay guarantee. In the industrial visual area that is introducing artificial intelligence (AI), massive computing often needs to be done at some distance, so this also places higher requirement on the time delay of NR [b-GSMA mmW WP].

Table 19 – Different frequency bands of the 5G network corresponding to different time slot intervals [b-GSMA mmW WP]

Frequency band	SCS	Time slot interval
1 GHz	15/30 kHz	1/0.5 ms
1~6 GHz	15/30/60 kHz	1/0.5/0.25 ms
24.25–52.6 GHz	60/120 kHz	0.25/0.125 ms

Compared with the low-frequency and middle-frequency band systems, the 5G mmW system can not only improve the signal gain of the target object through beamforming technology, but also make use of the characteristics of beam orientation to focus the signal energy in a specific direction, so can reduce the interference to other non-target objects, then ensure the communication quality of adjacent links or adjacent cells. Therefore, 5G mmW systems can more easily achieve dense cell deployment. This makes 5G mmW systems ideal for deployment in large venues such as conference rooms, concerts, stadiums, underground railway stations and other densely populated areas.

Compared with sub-6 GHz, the size of 5G mmW components is much smaller, and 5G mmW devices can more easily be miniaturized. When 5G mmW is commercialized on a large scale, the cost of relevant components will be reduced, and it will have more application prospects in professional devices, wearable devices, intelligent components and other fields. In addition, the 5G mmW BS also has the advantages of its small size and being lightweight and easy to install, which is conducive to building a 5G mmW network which is green, efficient and convenient to deploy.

5G mmW also faces the following challenges. 5G mmW has higher frequency bands, high propagation loss, weak diffraction ability and relatively limited coverage, which is the biggest challenge to be faced. In the transmission process of high frequency communication, the path loss is large and the penetration loss from outdoor to indoor is also large. Also, it is seriously influenced by buildings, leaves and rainwater. According to [b-CU mmW WP], the transmission loss of 5G mmW is much higher than that of sub-6 GHz (as shown in Table 20). Meanwhile, bad weather such as rain, snow and fog also have adverse effects on the transmission of mmW. Therefore, the coverage radius of the mmW cell is usually small, and the data transmission for moving UE is prone to be interrupted due to frequent cell switching [b-CU mmW WP][b-FuTURE mmW WP].

Table 20 – Penetration loss of 5G mmW [b-CU mmW WP]

Crown of a tree (*d* = 4 m)	Human body	Load-bearing concrete wall	Wooden door (5 cm)	Ordinary glass door	Body panel of recreational vehicle
20 dB	11–28 dB	Cannot penetrate	6 dB	5 dB	17–23 dB

According to the loss model of the direct path of 0–100 GHz radio waves in urban areas described in [b-3GPP TR38.901], it can be seen that the loss in free space is positively correlated with the carrier frequency. At present, in the mmW band (i.e., the FR2 band which ranges from 24.52 GHz to 52.6 GHz) compared with the 5G sub-6G band, the transmission loss is generally more than 10 dB. With the same transmission power, the theoretical communication coverage of mmW is also far less than that of 5G low-frequency devices. The results of taking 26 GHz and 3.5 GHz as examples to evaluate the difference in transmission loss between the mmW band and the Sub-6G band are shown in Figure 36. It can be seen that the transmission loss of mmW is 17.42 dB, and the theoretical propagation distance will also be significantly reduced.

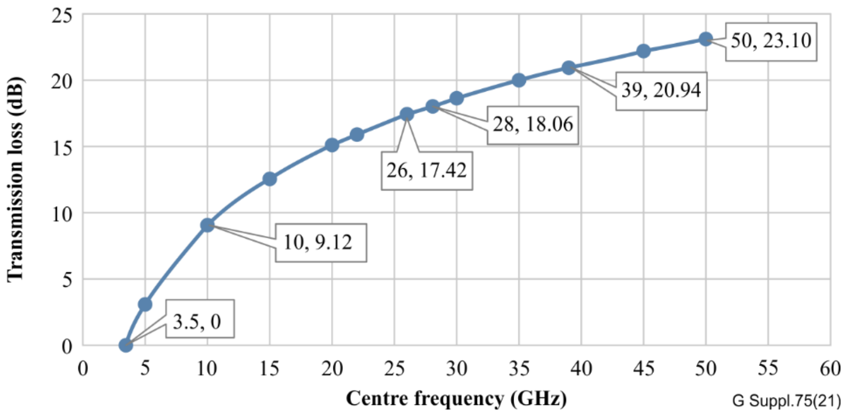


Figure 36 – Transmission loss of different centre frequencies (compared with 3.5GHz) [b-CU mmW WP]

As it is difficult for 5G mmW deployment to achieve continuous and seamless coverage in the short-term, the problems that coexist with sub-6 GHz, especially collaborative network planning, flexible service load sharing, high and low-frequency switching, and interoperability experience, are very important. At present, the mainstream technology routes are dual connection and carrier aggregation (CA). However, due to the hardware differences of communication devices, the timing of mmW and sub-6 GHz carriers is prone to errors, leading to problems in the synchronization of the CA system. Therefore, it is also necessary to optimize the non-synchronous CA system. In addition, the physical limits of the coexistence of different systems, such as space limits and heat dissipation, are also one of the technical challenges of the coexistence of mmW and sub-6 GHz systems.

5G mmW also faces the challenge of mobility management. Due to the characteristics of high frequency signal propagation, the coverage radius of 5G mmW cells is usually small, and the terminal is prone to the interruption of data transmission due to frequent cell handover in the mobile state. In this regard, the 3GPP standard provides two key solutions to this challenge to ensure a seamless QoE.

The first is a variety of flexible and fast cell handover solutions. The second is a fast beam recovery mechanism.

In the future, from the aspects of the service requirements, the emerging industry applications will have a bigger difference in their service requirements, for example, video surveillance and remote surgery need a guaranteed high UL rate, at the same time as 4K/8 K and AR/ VR video require guaranteed high DL rates. If the UL/DL capabilities of NR of 5G mmW technology are imbalanced, so the requirement of flexible deployment cannot be fully met.

The adaptive adjustment scheme of a flexible frame structure can bring three advantages. Firstly, it can be predicted and adjusted according to the long-term service situation of the covered area. The second is to adjust the UL and DL frame structure rapidly according to the emergent situation of 5G industry applications. Thirdly, the application needs of the 5G industry can be met and public network scenarios such as concerts and stadiums that have obvious emerging demand for UL bandwidth can also be effectively faced. Therefore, the flexible frame structure scheme of 5G mmW can cover the changes of various scenarios and various services [b-GSMA mmW WP].

At present, the development of 5G mmW has both opportunities and challenges. The 5G mmW industry will develop along with infrastructure construction in some countries. The industry is also working in the following directions to promote mmW technology and product evolution: commercialization of high frequency devices, improvement of mmW testing schemes and further support for higher frequency bands.

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