1G (1980s)
- 2.4 Kbps speed
- Voice
- Analog signal

2G (1990s)
- 114 Kbps speed
- Voice, higher coverage
- GSM/CDMA

2.5G
- GPRS/EDGE

3G (2000s)
- 11 Kbps speed
- Voice, SMS, Email, Web
- UMTS/EVO
- Up to 2Mbps
- Large emails
- 11s MP3 download

3.5G
- HSPA+
- Up to 10Mbps
- Smart Phones take off

4G LTE (2010s)
- 110Mbps
- HD Video, Mobile TV, Enhanced security & mobility

4.5G (2016)
- LTE_A
- ~300Mbps
- Carrier Aggregation

1G to 4G timeline:
- 1G (1980s)
- 2G (1990s)
- 2.5G
- 3G (2000s)
- 3.5G
- 4G LTE (2010s)
- 4.5G (2016)
2G/GSM

BTS

A-bis

BSC

A-Int

MSC

PSTN

2.5G/GPRS

BTS

Gb

SGSN

Gn

GGSN

3G/3.5G

nodeB

Iub

RNC

IuPS

IuCS

Gi
NEF: Network Exposure Function
NRF: Network Repository Function
PCF: Policy Control Function
UDM: Unified Data Management
AF: Application Function
AUSF: Authentication Server Function
AMF: Access & Mobility Management Function
SMF: Session Management Function
NWDAF: Network Data Analytics Function
UE: User Equipment
RAN: Radio Access Network
UPF: User Plane Function
DN: Data Network
QoS flow handling

QoS Flows

Radio Bearers

F1/W1 Split 2

RLC Channels

Logical Channels

Split 6

Transport Channels

Scheduling/Priority Handling

Multiplex, UE₁

HARQ

HARQ

Rate matching => scrambling

Split 7-3

Modulation => layer mapping

Split 7-2

BF Precode (DL)/Equalisation (UL) => RE-mapping

Split 7-1

IFFT => CP addition => D/A conversion => Analog BF

Split 8

CC₁

CCₙ

CC₁

SDAP

QoS flow handling

PDCP

ROHC

ROHC

Security

Security

RLC

Seg, ARQ

Seg, ARQ

MAC

Multiplex, UE₁

HARQ

HARQ

PHY

Scheduling/Priority Handling

F1-C

F1-U

DU

RU

CU
Projected cash flow with forecast benefit of softwarization and RAN disaggregation to reduce CAPEX & OPEX.

Key economic indicators (bubble volume = data/month)

<table>
<thead>
<tr>
<th>Year</th>
<th>Revenue ($Tn)</th>
<th>Global Cash Flow ($Tn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2000</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>2005</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>2010</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>2015</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>2020</td>
<td>1.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

- **Global cash flow**
- **Revenue (no softwareization)**
- **Revenue (with softwareization)**
π/2-BPSK  QPSK  16QAM

64QAM  256QAM
1 FRAME (10 ms) 10 sub-frames

Sub-FRAME (1 ms) → ←

1 slot per subframe

2 slots per subframe

4 slots per subframe

14 symbols per slot

Symbol

Subcarriers

15 KHz subcarrier spacing (SCS)

66.67 μs symbol duration

Numerology $\mu = 0$

Normal CP

15 KHz subcarrier spacing (SCS)

66.67 μs symbol duration

Symbol

Subcarriers

30 KHz subcarrier spacing (SCS)

33.33 μs symbol duration

Numerology $\mu = 1$

Normal CP

30 KHz subcarrier spacing (SCS)

33.33 μs symbol duration

Symbol

Subcarriers

60 KHz subcarrier spacing (SCS)

16.67 μs symbol duration

Numerology $\mu = 2$

Normal CP

60 KHz subcarrier spacing (SCS)

16.67 μs symbol duration
Sub-FRAME (1 ms)  

1 FRAME (10 ms) 10 sub-frames

4 slots per subframe

16 slots per subframe

8 slots per subframe

12 symbols per slot

14 symbols per slot

14 symbols per slot

Numerology $\mu = 2$
Extended CP
60 KHz subcarrier spacing (SCS)
16.67 $\mu$s symbol duration

Numerology $\mu = 3$
Normal CP
120 KHz subcarrier spacing (SCS)
8.33 $\mu$s symbol duration

Numerology $\mu = 4$
Normal CP
240 KHz subcarrier spacing (SCS)
4.16 $\mu$s symbol duration
Numerology 1
30 KHz subcarrier spacing

Slot 0 (14 symbols)  Slot 1 (14 symbols)  Slot 18 (14 symbols)  Slot 19 (14 symbols)

Subframe 0 (1 ms)  Subframe 9 (1 ms)

Frame (10 ms)
Complex radio channel
Radio channel
Transmitter

Receiver

Radio channel
Radio channel
Radio channel
Channel State Indicator-Reference Signal (CSI-RS) on 32 ports

Channel Quality Indicator (CQI)
Rank Indicator (RI)
Precoding Matrix Indicator (PMI)

Channel State Indicator-Reference Signal (CSI-RS) on 8 ports each

Synchronization Signal Block (SSB)
Channel Quality Indicator (CQI)
Rank Indicator (RI)
Precoding Matrix Indicator (PMI)

Channel State Indicator-Reference Signal Resource Indicator (CRI)
Channel State Indicator-Reference Signal (CSI-RS) on 32 ports

Channel Quality Indicator (CQI)
Rank Indicator (RI)
Sounding Reference Indicator (SRS)

Synchronization Signal Block (SSB)
Channel Quality Indicator (CQI)
Rank Indicator (RI)
Sounding Reference Indicator (SRS)
Channel State Indicator-Reference Signal Resource Indicator (CRI)
CRAN (BBU Hotel)

4G/LTE 4.5G/LTE_A

Small cells

eNB

CPRI

S1-U

S1-MME

MME

SGW

Fronthaul

Backhaul

4G/LTE
<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Division Multiplex</td>
<td>Electrical Transmission</td>
</tr>
<tr>
<td>Electrical Transmission</td>
<td>Optical Transmission</td>
</tr>
<tr>
<td>IQ Data</td>
<td>Vendor Specific</td>
</tr>
<tr>
<td>Control &amp; Management Plane</td>
<td>HDLC</td>
</tr>
<tr>
<td>SYNC</td>
<td>L1 Inband Protocol</td>
</tr>
</tbody>
</table>
Sync byte K28.5

CW130 contains: RAI, SDI, LOS, LOF

1 hyperframe (66.67 µs)

1 basic frame

Index of control word
X=0

Index of subchannel
Ns=0

Index of control word within subchannel
Xs=0
Physical Layer based synchronization network

A: PRC, EEC, SSU OR SEC network limits

Packet master clock

B: PEC-M output packet network limits

C: PEC-S-F input packet network limits

End application clock

D: PEC-S-F output network limits (deployment case 2)

E: End application requirements (e.g., frequency accuracy)
Packet slave clock (PEC-S) - CUT

Ideal input packet timing signal (no PDV)

Packet master clock (PEC-M)

Output physical clock within certain performance limits

FR
Packet Network

Reference

Packet Master Clock

Packet Slave Clock

Packet Slave Clock

Packet Slave Clock

Packet Network
Deployment Case 1

Network time reference (e.g., GNSS engine)

A → PRTC → T-GM → Packet network → T-BC → T-TSC → End application

Deployment Case 2

Network time reference (e.g., GNSS engine)

A → PRTC → T-GM → Packet network → T-BC → T-TSC → End application

Time clock
A B C D E

PRTC, PRC → T-GM → Partial Timing Support Packet Network → T-BC → T-TSC-A

Local Time Ref (e.g. GNSS)

A'
CU/DU RU

Option 1  Option 2  Option 3  Option 4  Option 5  Option 6  Option 7  Option 8

RRC  PDCP  High RLC  Low RLC  High MAC  Low MAC  High PHY  Low PHY

RF  Downlink  Uplink  eCPRI
eCPRI Radio Equipment Control (eREC)

- User Plane
  - SAP_U
- Sync
  - SAP_S
- Control & Mgmt
  - SAP_CM

Standard Protocols

Transport Network Layer

eCPRI specific

Transport Network
5G RU

4G RRU

CPRI
eCPRI

5G RU

RoE

CPRI
eCPRI

4G BBU

5G CU+DU

RoE

Ethernet/WDM
4G PS Only (LTE-SAE)

4G Cellular IoT Core CIoT Service Gateway Node

Control User Plane Separation CUPS

Connected to Base Station
NF_A (Consumer) → Request → NF_B (Producer) → Response → NF_A (Consumer)

NF_A (Consumer) ← Subscribe ← NF_B (Producer) ← Notify ← NF_A (Consumer)

3GPP TS 23.501
R15

- JSON
- HTTP/2
- TLS
- TCP
- IP
- L2

R16 (under consideration)

- JSON
- HTTP/3
- QUIC
- IP
- L2

3GPP TR 29.893
Classic

Service Based
1. Initial UE Message

2. [Optional] UE Context transfer, identification, authentication and security procedures

3a. UDM selection

3b. Nudm_SDM_Get (Slice Selection Subscription Data)

3c. Nudm_SDM_Get response

4a. Nnssf_NSSelection_Get

4b. Nnssf_NSSelection_Get response

3GPP TS 23.502 Figure 4.2.2.3-1
<table>
<thead>
<tr>
<th>Bits</th>
<th>Number of Octets</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>PDU Type (=0)</td>
</tr>
<tr>
<td>PPP</td>
<td>RQI</td>
</tr>
<tr>
<td>PPI</td>
<td>Spare</td>
</tr>
<tr>
<td>Padding</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bits</th>
<th>Number of Octets</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>PDU Type (=1)</td>
</tr>
<tr>
<td>Spare</td>
<td>QoS Flow Identifier</td>
</tr>
<tr>
<td>Padding</td>
<td></td>
</tr>
</tbody>
</table>
NSSAI

S-NSSAI #1
S-NSSAI #n

UE

RAN

AMF

HSS

NRF

Retrieves NFs from NS-ID

Enquiry NSSF for (S)-NSSAI – NS-ID mapping(**)

AMF selection function based on TempID or NSSAI

NSSAI

NRF

Slice specific network functions

SMF #1

UPF#1

SMF #n

UPF#n
MEC Application (VNF)

Virtualization Infrastructure (e.g. NFVI)

MEC Application (VNF)

MEC Application (VNF)

Virtualization Infrastructure Manager (e.g. VIM)

MEC Platform (MEP) (VNF)

MEC Platform (MEP) (VNF)

MEC System Level Management: Operations Support System (OSS) & MEC Orchestrator (MEO)
MEC Application (VNF)

MEC Service

Service Registry

Traffic Rules Control

DNS Handling

MEC Platform (MEP) (VNF)

Mp1 {mp1} API
MEC Service
- e.g. Location
MEC Service
- e.g. RNIS

Service Registry
- Traffic Rules Control
- DNS Handling

MEC Platform (MEP) (VNF)

MEC Application A (Service Consuming & Producing) (VNF)

{3rd Party Dev} API

MEC Application B (Service Consuming) (VNF)

{3rd Party Dev} MEC API, e.g. RNI

MEC Application C (Service Producing) (VNF)

MEC Application D (VNF)

{ls} MEC API

{rni} MEC API

MEC Service
- e.g. Location

MEC Service
- e.g. RNIS

{3rd Party Dev} MEC API, e.g. RNI
New Service Idea → Available

Telco Operators

New Service Idea → Demand → Deploy → Sell

Equipment Vendors

New Service Idea → Demand → Drive → Implement

Critical mass of supporters

SDOs

New Service Idea → Standardize → Implement

2-6 Years

OTT Provider Cycle

New Service Idea → Available

New Service Idea → Develop → Deploy → Publish

2-6 Months
19% Energy and Utilities
18% Manufacturing
13% Public Safety
12% Healthcare
10% Public Transport
9% Media and Entertainment
8% Automotive
6% Financial Services
4% Retail
1% Agriculture
eDRX Cycle
(N hyper-frames of 10.24s)

Paging Window
(~1.28s Cycle)

RX/TX
Short Idle Window so Device is Reachable
ManagedElement
  +-ENodeBFunction
  +-NblotCell
  ceLevelNumber = 1 \{1,2,3\}
    1 = CE_level1
    2 = CE_level2
    3 = CE_level3
  cmcIndex = 0 \{0,1,2\}
    0 = CMC Index 0
    1 = CMC Index 1
    2 = CMC Index 2

<table>
<thead>
<tr>
<th>Channel (carrying)</th>
<th>Maximum Number of Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMC Index 0</td>
</tr>
<tr>
<td>NPDSCH (NB-SIB1)</td>
<td>4</td>
</tr>
<tr>
<td>NPDCCH</td>
<td>2</td>
</tr>
<tr>
<td>NPUSCH (ACK/NACK)</td>
<td>2</td>
</tr>
<tr>
<td>NPRACH (preamble)</td>
<td>2</td>
</tr>
</tbody>
</table>
Multiple IoT Data Transfer Methods

- **UE:**
  - S1-MME
  - S1-MME {NAS (Encrypted Small Data)}

- **C-SGN:**
  - S1-MME

- **SCEF:**
  - PtP IP Tunnel for Non-IP Data

- **SMSC/IWMSC:**
  - SMS

- **AS:**
  - Interworking with IoT Platform

- **New Elements & Interfaces:**
  - non-IP data
1. MO/MT Data Transport in Control Plane CIoT EPS Optimization

UE in ECM_CONNECTED

2. Control Plane Service Request (w/ active flag)

3. S1-AP: UL NAS Transport (Control Plane Service Request w/ active flag)

MME establishes S1-U bear(s)

4. Release Access Bearers

5. Release Access Bearers Response

6. S1-AP: Init. Context Setup Request (Service Accepted)

7. Radio Bears Setup

8. Uplink Data


10. Modify Bearer Request

11. Modify Bearer Response
0. UE is ECM Idle

1. RRC Connection establishment or RRC early data request (NAS Data PDU with EBI)

1b. Retrieve UE context

2. S1S1-AP Initial UE Message (NAS Data PDU with EBI)

3. Check Integrity and decrypts data

4. Modify Bearer Request

5. Modify Bearer Request

6. Modify Bearer Response

7. Modify Bearer Response

8. Uplink Data

9. Downlink Data

10. Data encryption and integrity protection

11. Downlink S1-AP msg

11. S1-AP UE context release command

12a. RRC DL Message (NAS Data PDU with EBI)

12a. RRC Early Data Complete (NAS Data PDU with EBI)

13. NAS Delivery notification

14. No further activity detected

15. S1 release procedure (see clause 5.3.5)
0. UE is ECM Idle

1. Downlink Data

2. Downlink Data Notification

3. Paging

4. Paging

5. RRC Connection establishment (NAS Data Service request)

6. S1-AP UE Message (NAS Service Request)

7. Modify Bearer Request

8. Modify Bearer Request

9. Modify Bearer Response

10. Modify Bearer Response

11. Downlink Data

12. Data encryption and integrity protection

13. Downlink S1-AP Message (NAS DATA PDU with EBI)

14. RRC DL Message (NAS PDU with Data)

15. RRC UL Message (NAS PDU with Data)

16. UL S1-AP Message (NAS DATA PDU with EBI)

17. Check Integrity and decrypts data

18. Uplink Data

19. No further activity detected

20. S1 release procedure
1. MO non-IP Data

2. NIDD Submit Request

3. NIDD Request

4. NIDD Submit Response
1. NIDD Submit Request

2. Authorization and load control

3. NIDD Submit Request

4. NIDD Submit Response

5. NIDD Submit Response

6. NIDD Submit Indication

8. NIDD Delivery

9. NIDD Submit Response

9. NIDD Submit Response
<table>
<thead>
<tr>
<th>Category</th>
<th>Application Example</th>
<th>Availability</th>
<th>UL Bandwidth &amp; Data Size</th>
<th>DL Data Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Delay Sensitivity</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive Car</td>
<td>HIGH 99.9%</td>
<td>HIGH 10Mbps</td>
<td>HIGH 200bytes</td>
<td>HIGH 20bytes</td>
<td>HIGH Continuous</td>
<td>LOW</td>
<td>HIGH 1ms</td>
<td>NORMAL</td>
</tr>
<tr>
<td>Industrial Control</td>
<td>Switch on/off, device triggered to send</td>
<td>HIGH 99.999%</td>
<td>HIGH 50Mbps 0-20bytes</td>
<td>HIGH 20bytes</td>
<td>MED 1 day (40%) 2hrs (40%) 1 hour (15%) 30mins (5%)</td>
<td>LOW</td>
<td>HIGH 1ms</td>
<td>DEEP</td>
</tr>
<tr>
<td>Utilities/ Meters</td>
<td>Smart Water Meter</td>
<td>LOW 99%</td>
<td>LOW 50kbps 20bytes with cut off of 200 bytes</td>
<td>LOW 50% of UL data size</td>
<td>MED 1 day (40%) 2hrs (40%) 1 hour (15%) 30mins (5%)</td>
<td>LOW</td>
<td>HIGH 5sec</td>
<td>DEEP</td>
</tr>
<tr>
<td>Security</td>
<td>Smoke alarm detectors, power failure notification, tamper notifications</td>
<td>HIGH 99.9%</td>
<td>LOW 50kbps 20bytes</td>
<td>LOW 0 ACK payload size is assumed to be 0bytes</td>
<td>LOW Every few months, Every Year</td>
<td>LOW</td>
<td>MED 1sec</td>
<td>DEEP</td>
</tr>
</tbody>
</table>