IEEE
Future Networks

Optical Transport Networks

Reza Vaez-Ghaemi, Ph.D.
February 2020
What is 5G?

- eMBB: much higher bandwidth
- uRLLC: extremely low latency
- mMTC: very large number of low power end points
Definition Backhaul, Fronthaul, CRAN

Cell Site

Core Site

Central Site

MACROCELL

SMALL CELLS

Centralized/Cloud RAN

FTTA (Fiber to the Antenna)

RRU (Radio Radio Unit)

BBU (Baseband Unit)

Fronthaul

Backhaul

BSC/RNC SGW/MME

Mobile Switching Center

BSC/RNC SGW/MME

Mobile Switching Center

BSC/RNC SGW/MME

Mobile Switching Center
CPRI Specification

- 4G Fronthaul Uses Common Public Radio Interface (CPRI)
- CPRI protocol defines the layer 1 and elements of layer 2
  - Sync
  - Alarms
  - Encoding

<table>
<thead>
<tr>
<th>Option</th>
<th>Rates (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>614.4</td>
</tr>
<tr>
<td>2</td>
<td>1228.8</td>
</tr>
<tr>
<td>3</td>
<td>2457.6</td>
</tr>
<tr>
<td>4</td>
<td>3072.0</td>
</tr>
<tr>
<td>5</td>
<td>4915.2</td>
</tr>
<tr>
<td>6</td>
<td>6144.0</td>
</tr>
<tr>
<td>7A</td>
<td>8110.1</td>
</tr>
<tr>
<td>7</td>
<td>9830.4</td>
</tr>
<tr>
<td>8</td>
<td>10137.0</td>
</tr>
<tr>
<td>9</td>
<td>12165.1</td>
</tr>
<tr>
<td>10</td>
<td>24330.2</td>
</tr>
</tbody>
</table>
4G Fronthaul Challenge

- CPRI Technology can be scaled up to a certain level with WDM and OTN
- Bandwidth requirements increase with number of antennas and signal bandwidth
- CPRI may not meet the requirements of massive MIMO applications

<table>
<thead>
<tr>
<th>Antenna</th>
<th>10 MHz</th>
<th>20 MHz</th>
<th>100 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.49 Gbps</td>
<td>0.98 Gbps</td>
<td>4.9 Gbps</td>
</tr>
<tr>
<td>2</td>
<td>0.98 Gbps</td>
<td>1.96 Gbps</td>
<td>9.8 Gbps</td>
</tr>
<tr>
<td>4</td>
<td>1.96 Gbps</td>
<td>3.92 Gbps</td>
<td>19.6 Gbps</td>
</tr>
<tr>
<td>64</td>
<td>31.36 Gbps</td>
<td>62.72 Gbps</td>
<td>313.6 Gbps</td>
</tr>
</tbody>
</table>

Source: China Mobile
Functional Split Options

- Solving the bandwidth problem of 4G requires redistribution of functions between BBU and RRH
- Backhaul network interfaces with BBU (S1) which holds most functions from RRC to PHY
- RRH hosts the RF functions
Evolving xhaul Networks

Today:
- Backhaul
  - S1/Ethernet

Tomorrow:
- Backhaul
  - eS1/Ethernet

- CU
  - vCU

- Midhaul
  - F1
    - NGFI-II

- Fronthaul
  - DU
    - O-DU/
    - vDU
  - eCPRI
    - NGFI-I

- RU/
  - O-RU

NGFI: IEEE 1914.1
eCPRI Physical layer

- eCPRI does not mandate any physical layer
- Ethernet PHY and OTN can be valid options
- Most volumes are expected to be Ethernet
- eCPRI physical line rates from 10G to 100G
- 25/40GE starting to show up in vendor and SP designs

Table 3: Common Ethernet interface types for the given use cases

<table>
<thead>
<tr>
<th>Use case</th>
<th>Standard / Interface Type</th>
<th>#Lanes</th>
<th>Signal Rate per Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>10GBASE-SR/LR/ER ([5], clause 52)</td>
<td>1</td>
<td>10G</td>
</tr>
<tr>
<td></td>
<td>10GBASE-LRM ([5], clause 68)</td>
<td>1</td>
<td>10G</td>
</tr>
<tr>
<td></td>
<td>25GBASE-SR ([6])</td>
<td>1</td>
<td>25G</td>
</tr>
<tr>
<td></td>
<td>40GBASE-SR4 LR4/ER4 ([5], clauses 86/87)</td>
<td>4</td>
<td>10G</td>
</tr>
<tr>
<td></td>
<td>100GBASE-SR10 ([5], clause 86)</td>
<td>10</td>
<td>10G</td>
</tr>
<tr>
<td></td>
<td>100GBASE-SR4/LR4/ER4 ([5], clauses 95/88)</td>
<td>4</td>
<td>25G</td>
</tr>
</tbody>
</table>
eCPRI Transport Requirements

- Latency and Packet Loss Ratio
- Different SLA’s for user plane and C&M
- Different classes for User Plane (normal and slow) and C&M (fast and normal)

<table>
<thead>
<tr>
<th>CoS Name</th>
<th>Example use</th>
<th>One way maximum packet delay</th>
<th>One-way Packet Loss Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>User Plane</td>
<td>100 μs</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Medium</td>
<td>User Plane (slow), C&amp;M Plane (fast)</td>
<td>1 ms</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Low</td>
<td>C&amp;M Plane</td>
<td>100 ms</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>
IEEE 802.1cm: Timing Sensitive Networks

- IEEE 802.1cm describes fronthaul and synchronization requirements
- Verification of latency and frame loss ratio essential for fronthaul traffic
- It defines features and options for two classes of fronthaul traffic
  - Class 1: CPRI (Split option 8) IEEE 802.1cm

<table>
<thead>
<tr>
<th>Flow</th>
<th>Latency</th>
<th>Frame Loss Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>IQ</td>
<td>100 µs</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>C&amp;M</td>
<td>No requirement</td>
<td>10^{-6}</td>
</tr>
</tbody>
</table>

- Class 2: eCPRI (Split option 7)
  - Requirements for split options E, I_D, II_D, and I_U (eCPRI Transport Networks)

<table>
<thead>
<tr>
<th>CoS Name</th>
<th>Flow</th>
<th>Latency</th>
<th>Frame Loss Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>User Plane (fast)</td>
<td>Table below</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>Medium</td>
<td>User Plane (slow) and, C&amp;M Plane (fast)</td>
<td>1 ms</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>Low</td>
<td>C&amp;M</td>
<td>100 ms</td>
<td>10^{-6}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow</th>
<th>Latency</th>
<th>Use case</th>
</tr>
</thead>
<tbody>
<tr>
<td>High25</td>
<td>25 µs</td>
<td>Ultra-low latency</td>
</tr>
<tr>
<td>High100</td>
<td>100 µs</td>
<td>E-UTRA and NR</td>
</tr>
<tr>
<td>High200</td>
<td>200 µs</td>
<td>For installation up to 40 km</td>
</tr>
<tr>
<td>High500</td>
<td>500 µs</td>
<td>Large latency installations</td>
</tr>
</tbody>
</table>
xHAUL Transport Network Technologies

- **Backhaul and Midhaul**
  - Bandwidth -> Big Pipes
  - WDM, PON or switched/routed network
  - FlexE in future

- **Fronthaul:**
  - Latency/jitter -> Delay sensitive
  - Initial deployments: Dark fiber and WDM
  - Future: NG-PON and TSN/FlexE
WDM Technologies

- Wideband WDM channels spaced ~100 nm apart
- CWDM channels are spaced 20 nm apart
- DWDM channels are spaced ~0.4 to 0.8 nm apart
- DWDM enables a much higher density, therefore a better usage of the fiber
- Characterize the wavelengths and respective attenuation level

2 Wideband WDM Channels  18 CWDM Channels  96+ DWDM Channels
PON in xhaul networks

- PON networks can be planned for different use cases in access networks:
  - Convergence vs. wireless only:
    - Legacy TDM PON with overlay WDM for converged fixed/wireless networks
    - Dedicated PON for (only) wireless networks
  - Lower layer split (fronthaul/Fx) vs. higher layer split (midhaul/F1) vs. mixed fronthaul/midhaul

BTN: Backhaul Transport Network
TDM PON in fronthaul (latency sensitive) networks

- TDM PON: challenge: upstream latency in several ms range!
- Need to reduce upstream latency:
  - Differentiated services: prioritize fronthaul traffic above all others
  - Dynamic Bandwidth Allocation (DBA): considers dynamic upstream traffic and buffer status
  - Cooperative DBA: OLT and DU/CU coordinate to determine the optimal upstream bandwidth
(T)WDM PON in fronthaul (latency sensitive) networks

- WDM PON
  - Path loss: fiber + mux/demux + connectors
  - Link distance: mostly below 10 km
  - Delay: fiber transmission + WDM processing
  - Separate links for data, management, and synchronization (SyncE/PTP)
  - Bidirectional optics preferred for saving fiber and operational/fiber management costs.

-> Advances in PON technologies are making them an attractive choice for xhaul networks.
Fronthaul Transport Networks

- Fronthaul Transport Nodes (FTN) carry CPRI and eCPRI traffic
- Initially CPRI and eCPRI carried over separate wavelengths or fiber
- Future: CPRI and eCPRI carried over same wavelength/fiber
  - Necessitates Radio over Ethernet (RoE/IEEE 1914.3) to convert CPRI to Ethernet
Converged Access Switch/Fronthaul Gateway

- Converged access switches bring together CPRI and eCPRI fronthaul:

- CPRI converted to Ethernet (RoE):

- RoE Test applications:
  - Structure agnostic:
    - CPRI sync,
    - bulk BERT (all IQ channels)
  - Structure aware:
    - CPRI sync
    - Channelized BERT (per AxC)
    - Control word transparency (e.g. C&M, VSB)
Converged Access Switch/Fronthaul Gateway

- Low PHY enables connection of CPRI radios to virtualized CU/DU

- Test applications TBD:
  - Provide eCPRI master and slave function
  - Emulate CPRI slave
  - Test Time Domain IQ against Frame Domain IQ
Timing Sensitive Network (TSN) Switch

- TSN switches prioritize express traffic in accordance with respective IEEE standards

- TSN test applications:
  - Emulate express and preemptable traffic
  - Provide different traffic profiles (frame size, burst, …)
  - Measure packet loss, delay and jitter for different type of traffic and profiles
Converged Access Switch/Fronthaul Gateway

- Converged access switches provide T-BC function to deliver strict 5G timing requirements:
  - Synchronization applications:
    - PTP:
      - Emulate PTP master and slave,
      - Perform time error measurements and compare against ITU-T G.827x limits
    - SyncE
      - Emulate SyncE master and slave
      - Measure frequency offset
      - Verify ESMC
FlexE/SPN Technology

- FlexE provides hard separation between different types of services -> SLA’s of each service can be met without impacting the other services (aka Network Slicing)!
- Example:
  - Service 1: eMBB: bandwidth sensitive
  - Service 2: uRLLC: delay sensitive
- Slicing Packet Network (SPN) -> ITU-T G.mtn (Metro Transport Networks)
- Verify bandwidth, latency, jitter for different slices
OTN Technology

- Delivers transparency, extended reach and network management
- Helps aggregate and switch lower rate RU signals
- Not efficient for variable traffic
- OTN B100G -> Flexible OTN (FlexO)
  - G.709.1 FlexO recommendation (2016)
  - Over \( n \times 100 \) Gbps PHYs
  - Signal format \( n \times \text{ODUC} \rightarrow \text{ODUCn} \)
- G.709.25-50 (25 and 50G OTN interfaces)
- Validate FEC, ODU headers (PM/TCM,..), client signal transparency
Converged 4G/5G fronthaul network

- Fronthaul Transport Nodes (FTN) carry CPRI and eCPRI traffic
- Initially CPRI and eCPRI carried over separate wavelengths or fiber
- Future: CPRI and eCPRI carried over same wavelength/fiber

**Test applications:**
- CPRI to CPRI test (bit error, delay)
- eCPRI to eCPRI test
- Synchronization test
Synchronization
5G Synchronization Network

- 5G requires synchronization!
  - GPS might not be viable, since millimeter wave radios need to be close to street level-> poor line of sight in dense/urban areas
  - 5G becomes more dependent on network synchronization

- eCPRI is **not** synchronized (unlike CPRI)
  - PTP/SyncE essential for 5G fronthaul
**eCPRI Synchronization Requirements**

- SLA’s defined in terms of absolute Time Error $|TE|$
- SLA’s derived from Time Alignment Error TAE
- Different categories dependent on wireless service needs

| Category (note 1) | Time error requirements at UNI, $|TE|$ | Typical applications and time alignment error (TAE) requirements at antenna ports of eREs (for information) |
|------------------|--------------------------------------|----------------------------------------------------------------------------------------------------------|
|                  | Case 1 (note 2)                      |                                                                                                          |
|                  | Case 1.1 (note 4)                    |                                                                                                          |
|                  | Case 1.2 (note 5)                    |                                                                                                          |
|                  | Case 2 (note 3)                      |                                                                                                          |
|                  | Typical applications                 |                                                                                                          |
|                  | TAE                                  |                                                                                                          |
| A+               | N.A.                                 | MIMO or TX diversity transmissions, at each carrier frequency                                            |
|                  |                                      | 65 ns (note 6)                                                                                           |
| A                | 20 ns (relative)                     | MIMO or TX diversity transmissions, at each carrier frequency                                            |
|                  | 70 ns (relative)                     | MIMO or TX diversity transmissions, at each carrier frequency                                            |
|                  | 130 ns (note 8)                      | MIMO or TX diversity transmissions, at each carrier frequency                                            |
| B                | 60 ns (relative)                     | Intra-band contiguous carrier aggregation, with or without MIMO or TX diversity                           |
|                  | 70 ns (relative)                     | Intra-band contiguous carrier aggregation, with or without MIMO or TX diversity                           |
|                  | 200 ns (relative)                    | Intra-band non-contiguous carrier aggregation, with or without MIMO or TX diversity, and Inter-band carrier aggregation, with or without MIMO or TX diversity |
|                  |                                      | 260 ns (note 8)                                                                                           |
| C (note 8)       | 1100 ns (absolute)                  | 3GPP LTE TDD                                                                                              |
|                  | 3 us (note 10)                       |                                                                                                          |
Network based synchronization

- PTP/SyncE requires special switch/router function
  - Boundary Clock (T-BC) function ensures proper synchronization

- For the end-to-end network synchronization
  - All T-BC must:
    - Work properly (connect to Grandmaster (T-GM))
    - Deliver minimum delay (time error)
Backhaul Synchronization Test Applications

Time Error measurement at various reference points
- Constant Time Error cTE
- Dynamic Time Error dTE (MTIE/TDEV)
- Maximum Time Error Max |TE|
- Metrics defined in ITU-T G.8271.1 (FTS)/G.8271.2 (PTS/APTS)

PTC: Primary Reference Telecom Clock
GM: Telecom Grand Master
BC: Telecom Boundary Clock
TSC: Telecom Slave Clock

PRTC: Primary Reference Telecom Clock
T-GM: Telecom Grand Master
T-BC: Telecom Boundary Clock
T-TSC: Telecom Slave Clock
Fronthaul Synchronization Test Application

- ORAN Priority: G.8275.1 profile: Time Error measurements at O-RU input
- Second priority G.8275.2 profile
- Absolute TE: against GNSS
- Relative TE: perform Absolute TE at different radios and aggregate
Backup
PHY Split

**MAC**
- Coding
- Rate Matching
- Scrambling
- Modulation
- Layer Mapping
- Pre-Coding
- RE mapping
- Digital BF
- IFFT/CP Add
- D/A
- Analog BF

**RF**
- A/D
- Analog BF

**PHY**
- De-coding
- Rate De-matching
- De-scrambling
- De-modulation
- Est./ Eq. & IDFT
- RE de-mapping
- Digital BF
- FFT/CP Remov.

**Id (eCPRI)**
- Option 6

**IId (eCPRI)**
- Option 7-3 (DL)

**Eu (eCPRI)**
- Option 8

**E (CPRI)**
- Option 7-3 (DL)

**IId (eCPRI)**
- Option 7-2

**Eu (eCPRI)**
- Option 7-2a

**E (CPRI)**
- Option 7-1

**IId (eCPRI)**
- Option 8

**Eu (eCPRI)**
- Option 7-1

**E (CPRI)**
- Option 8

**IId (eCPRI)**
- Option 8

**Eu (eCPRI)**
- Option 8

**E (CPRI)**
- Option 8
PHY Split

- Option 7-3 has the lowest BW requirements
- Option 7-1: simple DU design, joint equalization
- eCPRI specification does not include C&M, OAM, and Sync services