Fronthaul Bandwidth Analysis and Latency Constraint Considerations

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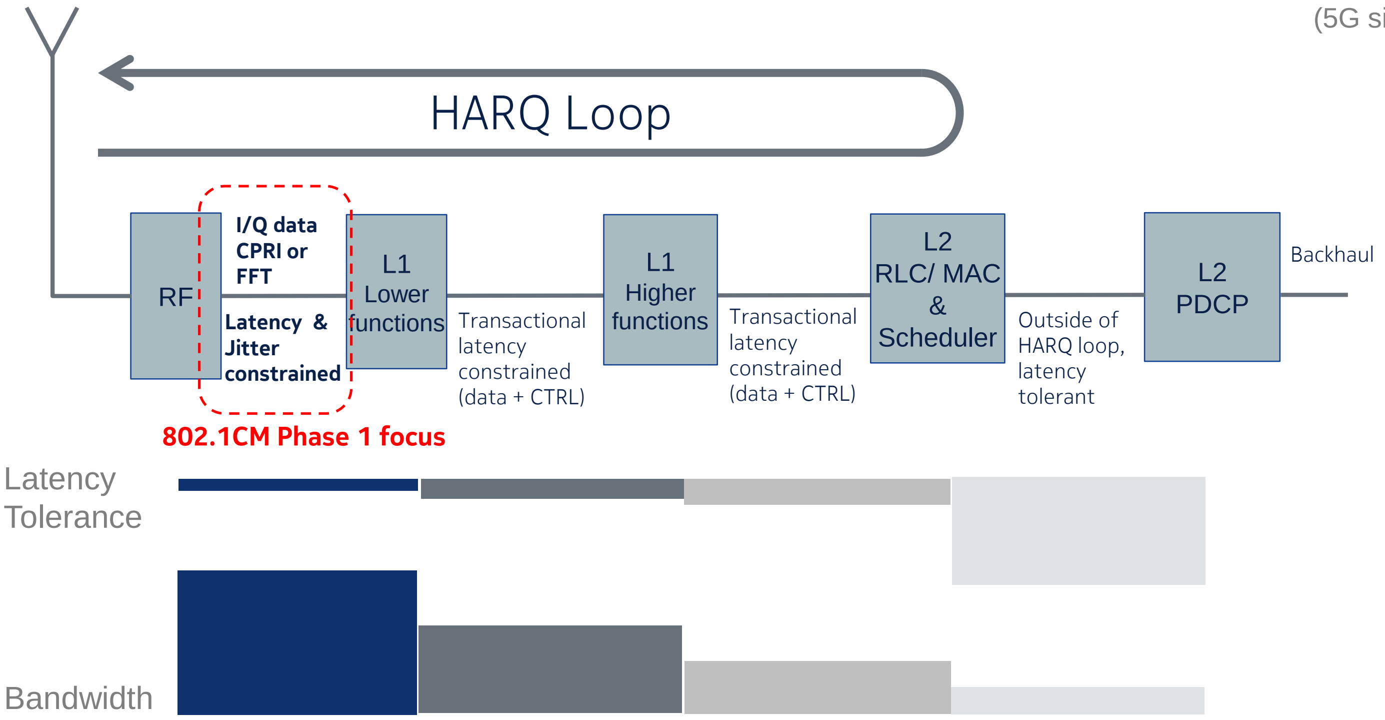
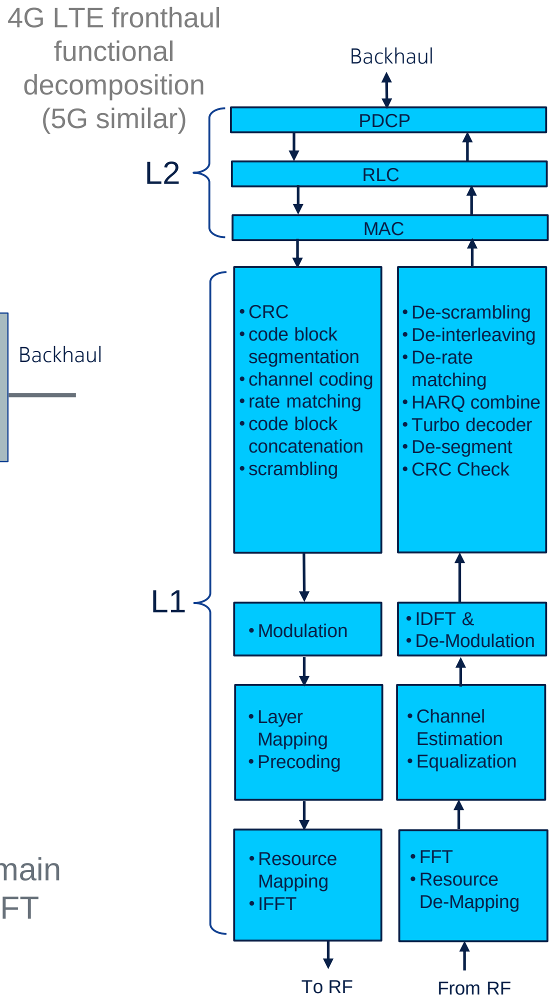
Frontthaul Functional Options Overview



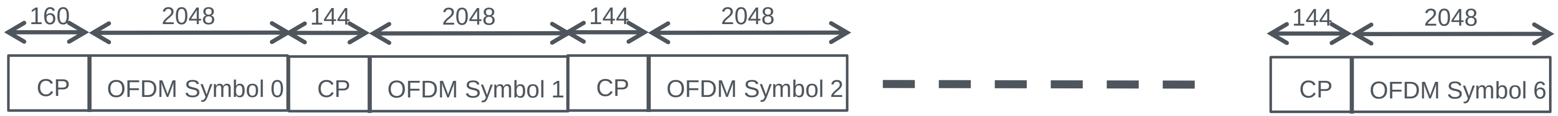


For real-time splits (within HARQ), CPRI provides a continuous stream of time-domain quantized in-phase (I) and quadrature (Q) data of the baseband signal and FFT/IFFT interface provides a continuous stream of frequency-domain I/Q data. These two interfaces are latency and jitter constrained and bandwidth hungry.

CPRI & CPRI Compressed

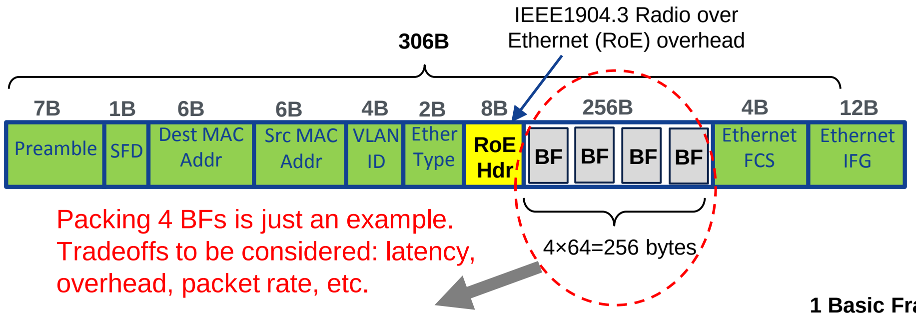
LTE Channel Bandwidth	1.4	3	5	10	15	20	(MHz)
Sample rate	1.92	3.84	7.68	15.36	23.04	30.72	(M samples/s)
Normal cyclic prefix	7 OFDM symbols (1st symbol contains longer prefix)						
First symbol	138	276	552	1104	1656	2208	samples
Other symbols	137	274	548	1096	1644	2192	samples

- Samples per slot (7 symbols) = 2208 x 1 + 2192 x 6 = 15360
- Samples per LTE frame (10ms) = 15360 x 2 x 10 = 307200 per 10ms or 30.72 MHz
- Each sample is 16 bits I + 16 bits Q = 32 bits (including CPRI control overhead)
- Each AxC CPRI BW = 307200 x 32 / 10ms = 983.04 Mbps (AxC: Antenna-Carrier)
- 2x2 MIMO with 2Tx/2Rx = 983.04 x 2 = 1966.08 Mbps or 1.966 Gbps
- In an example CPRI compressed scheme, the 20MHz channel sample rate can be down-sampled from 30.72MHz to 23.04MHz
  - Each sample is now 9 bits I + 9 bits Q = 18 bits (caveat: the bit-width per I or Q sample of 9 bits is a design parameter)
  - Each AxC CPRI BW = 23.04 x 18 = 414.72 Mbps
  - 2x2 MIMO with 2Tx/2Rx antennas = 414.72 x 2 = 829.44 Mbps



CPRI over Ethernet (Structure Agnostic)

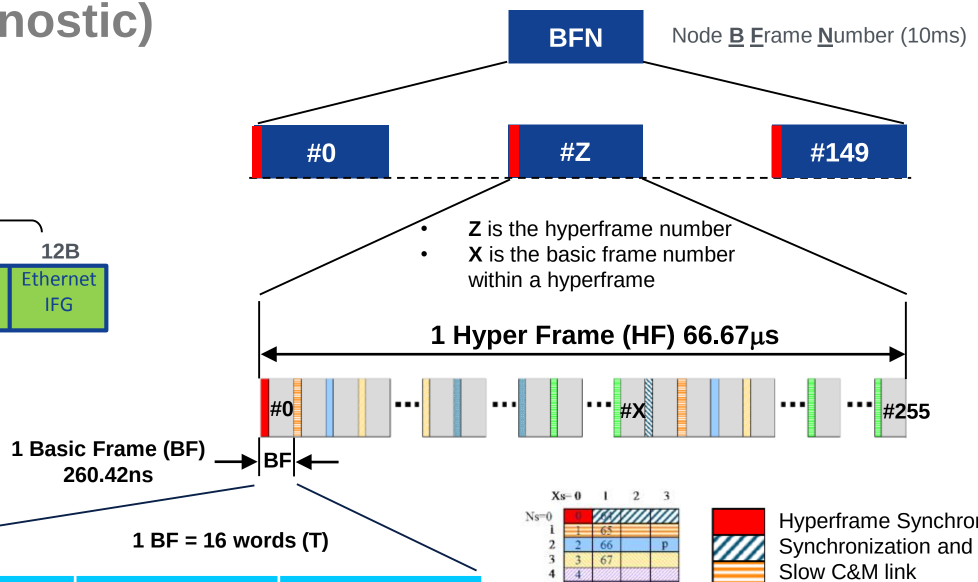
Ethernet frame structure



Packing 4 BFs is just an example. Tradeoffs to be considered: latency, overhead, packet rate, etc.

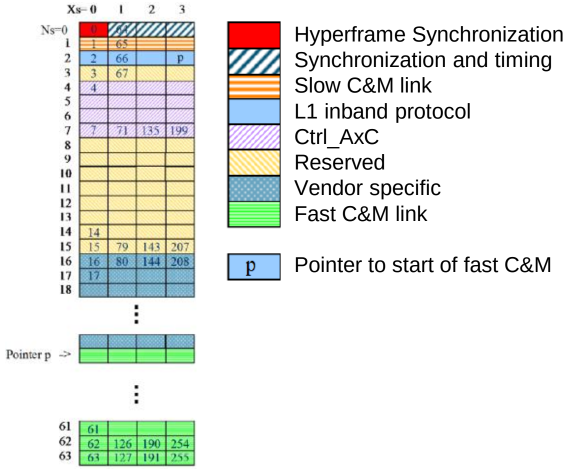
CPRI over Ethernet (structure agnostic) rate = 306 bytes over 4 CPRI BFs time = 2350.08Mbps

CPRI frame structure



CPRI line bit rate (Mbps) including 8b/10b line coding	Length of word T (bit)	BF size in bytes
614.4	T=8	16
1228.8	T=16	32
2457.6	T=32	64
3072.0	T=40	80
4915.2	T=64	128
6144.0	T=80	160
9830.4	T=128	256

After removing line coding overhead, this rate supports 1966.08Mbps rate for the LTE 20MHz 2x2 MIMO configuration



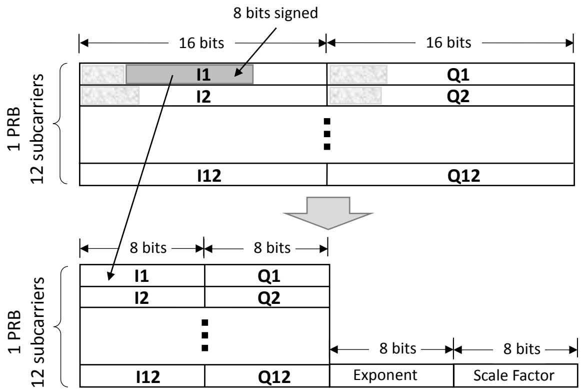
FFT

- Data Subcarriers per symbol (20MHz): 1200 for 100 PRBs (Physical Resource Blocks)
- bits per I or Q sample: 16 bits
- I/Q bits per symbol = 1200 x 16 x 2 = 38400 bits (or 4800 bytes)
- Uncompressed I/Q bit rate per AxC = 38400 / (0.001/14) = 537.6Mbps (14 symbols per 1ms TTI in LTE)
- 2 antennas: 1075.2Mbps
    - Add Ethernet and single VLAN = 1187.2Mbps

- FFT fronthaul interface throughput applies to both DL and UL, except in the UL, we need to consider PRACH (Physical Random Access Channel) traffic that carries random access preambles used for initiation of random access procedure
    - PRACH preamble uses subcarrier spacing of 1.25 kHz instead of 15 kHz and occupies 6 PRBs
    - Only 840 subcarriers from the 6 PRBs need to be considered in the UL FFT BW
    - Each PRACH subcarrier carries 16 bits I and 16 bits Q and all PRACH subcarriers are transported over 1 TTI (1ms)
    - PRACH therefore consumes 26.9Mbps raw bandwidth. The PRACH bandwidth in the UL becomes 29.7Mbps per AxC, or 59.4Mbps for 2x2 MIMO configuration after adding Ethernet encapsulation overhead.
- With PRACH, the UL FFT interface bandwidth for 2x2 MIMO configuration is then 1246.6Mbps, while the DL remains at 1187.2Mbps

FFT Compressed (20MHz with reduced bit-width per I or Q sample)

- UL (8 bits per I or Q sample)
  - (8 bits I + 8 bits Q) x 12 subcarriers per PRB = 24 bytes of I/Q per PRB. 1 byte exponent per PRB + 1 byte scale factor per PRB = 26 bytes per PRB
  - For 100 PRBs, it is 26x100=2600 bytes per symbol. 2600x8/(0.001/14)=291.2Mbps
    - No overhead: 291.2 Mbps
    - Add Ethernet + single VLAN: 323.68 Mbps
  - Uplink PRACH compressed BW
    - PRACH compressed BW can be calculated similarly to be14.6Mbps.
    - Adding Ethernet encapsulation overhead the PRACH compressed bandwidth becomes 16.2Mbps per AxC.
  - Total UL FFT compressed BW with 2x2 MIMO = 679.8Mbps



- DL (10 bits per I or Q sample to support 256QAM in the DL)
  - (10 bits I + 10 bits Q) x 12 subcarriers per PRB = 30 bytes of I/Q per PRB. 1 byte exponent per PRB + 1 byte scale factor per PRB = 32 bytes per PRB in DL L1' FFT 10 bits compression scheme. For 100 PRBs, it is 32x100=3200 bytes per symbol. 3200x8/(0.001/14)=358.4Mbps per AxC, or 716.8Mbps for 2 antennas. Add Ethernet + single VLAN: 793.4 Mbps.

I/Q bit-width 8 bits UL and 10 bits DL here is just an example and the actual bit-width needs to be determined carefully by simulation and empirical studies.

Frontthaul Bandwidth Summary and Scaled to 5G

4G LTE 2x2 MIMO, 20MHz

Numbers in **Mbps**	CPRI	CPRI over Ethernet	CPRI Compressed	FFT	FFT Compressed
DL	1966.1	2350.1	829.4	1187.2	793.4
DL BW gain factor	1x	0.84x	2.4x	1.7x	2.5x (10bit)
UL	1966.1	2350.1	829.4	1246.6	679.8
UL BW gain factor	1x	0.84x	2.4x	1.6x	2.9x (8bit)

DL: 40x, 320x

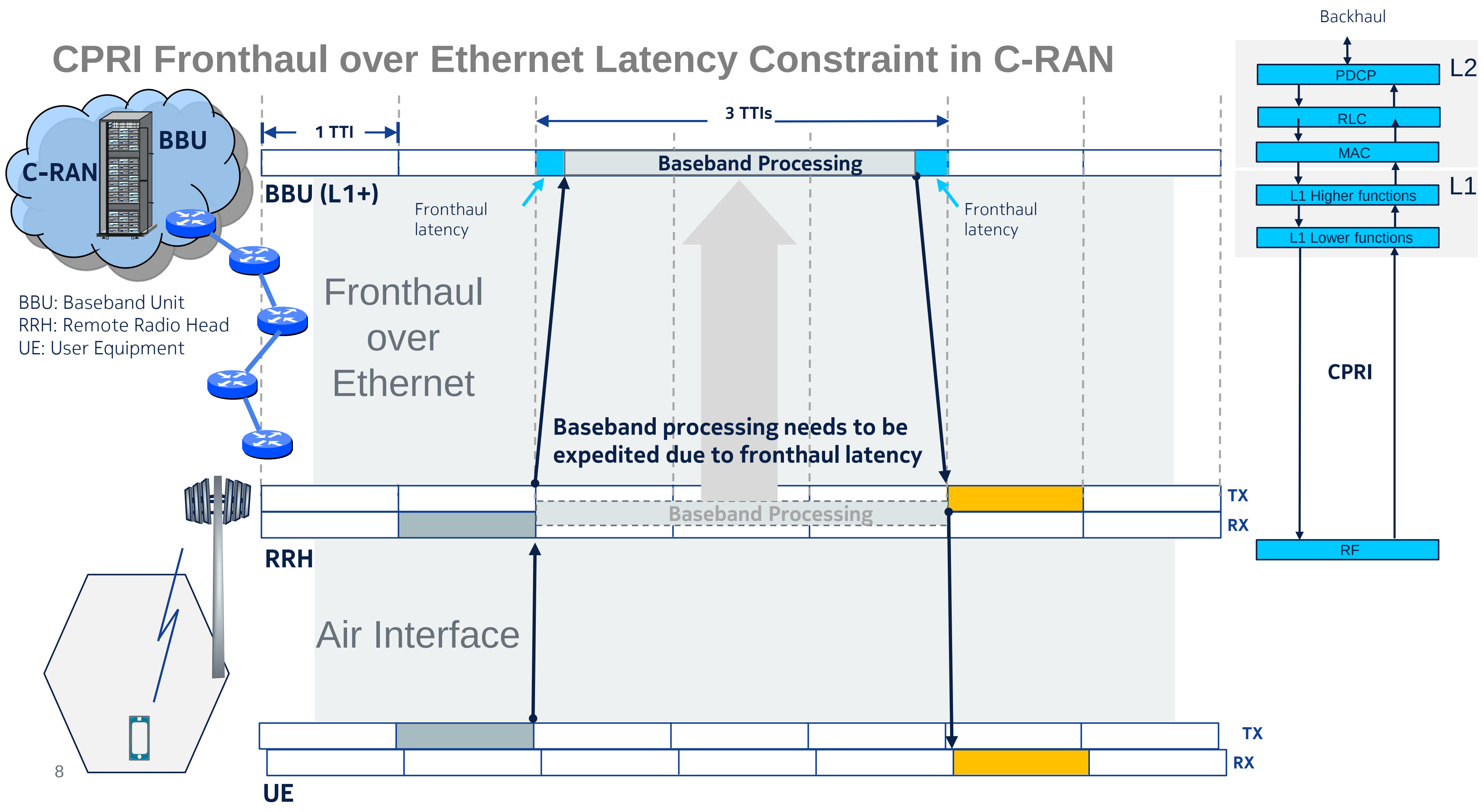
UL: 20x, 320x

5G Network with Massive MIMO with 64Tx/8 layers, 64Rx/4 layer, 200MHz

Numbers in **Gbps**	CPRI	CPRI over Ethernet	CPRI Compressed	FFT	FFT Compressed
DL (Hybrid Beamforming)	78.6	94.0	33.2	47.5	31.7
UL (Hybrid Beamforming)	39.3	47.0	16.6	24.9	13.6
DL (Digital Beamforming)	629.1	752.0	265.4	379.9	253.9
UL (Digital Beamforming)	629.1	752.0	265.4	398.9	217.5

- 5G: Massive MIMO with 64Tx/8 layers, 64Rx/4 layer, 200MHz
  - Hybrid Beamforming (consists of analog RF beamforming using phase shifters and baseband digital beamforming of dimension the same as no. of layers)
    - 5G DL Scaling Factor: 40x (10x BW increase from 20MHz to 200MHz, 4x layer increase from 2 layers to 8 layers)
    - 5G UL Scaling Factor: 20x (10x BW increase from 20MHz to 200MHz, 2x layer increase from 2 layers to 4 layers)
  - Digital Beamforming (done at the baseband and one dedicated fronthaul connection per antenna)
    - 5G DL Scaling Factor: 320x (10x BW increase from 20MHz to 200MHz, 32x antenna increase from 2 antennas to 64 antennas)
    - 5G UL Scaling Factor: 320x (10x BW increase from 20MHz to 200MHz, 32x antenna increase from 2 antennas to 64 antennas)

CPRI Fronthaul over Ethernet Latency Constraint in C-RAN



Conclusion

- 5G fronthaul will see a huge demand on transport bandwidth to support massive MIMO, higher order of modulation, and large bandwidth
- Compression techniques in the time and frequency domains of I/Q data may help alleviate the bandwidth demand but only to a certain extent; need to consider other fronthaul functional splits that can further reduce the transport bandwidth demand
- Need to be very careful to introduce a new profile in 802.1CM that includes 802.1CB Frame Replication and Elimination for Reliability, as 802.1CB can double or triple or more the fronthaul bandwidth that is already huge in the 5G use cases
- Current 100μs end-to-end latency budget for IQ data between REC and RE in current IEEE 802.1CM draft D0.4 may be significantly limiting the fronthaul physical reach distance
- Ethernet fronthaul latency/jitter (including switching, queueing/scheduling, sync accuracy, etc.) can be a major source of constraint to the baseband processing time
  - Need to balance the complexity and cost of employing TSN features to reduce Ethernet fronthaul latency/jitter
  - Different Ethernet transport profiles are needed for different fronthaul functional splits ➔ there is no one-size-fit-all profile