Baseline Proposal for EPoC PHY Layer

IEEE 802.3bn EPoC - September 2012

AVI KLIGER, BROADCOM
LEO MONTREUIL, BROADCOM
ED BOYD, BROADCOM

NOTE

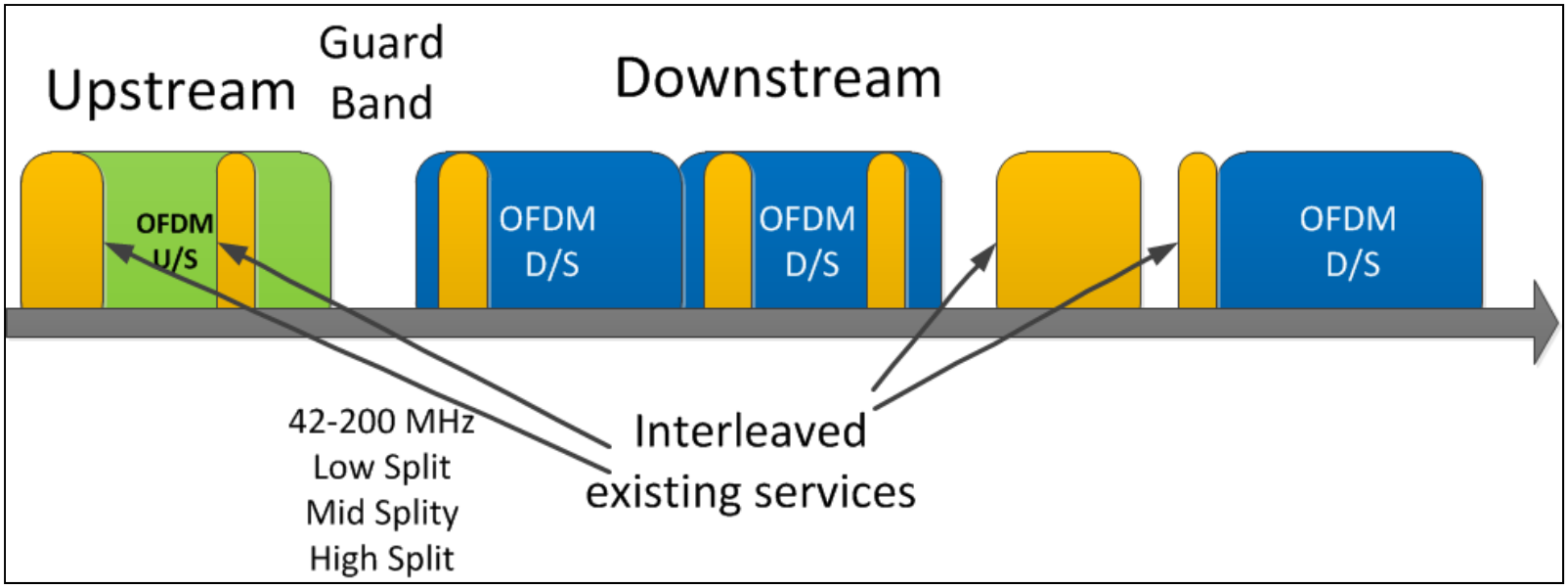
- This presentation includes results based on an in-house Channel Models
- When an approved Task Force Channel Model is available, this presentation will be updated.
- The results are expected to be similar

OFDM parameters are based on a companion contribution: "Symbol size considerations for OFDM EPoC PHY", September 2012, Geneva

Considerations for EPOC PHY Proposal

- Support Ethernet / EPON MAC
  - Comply with EPON protocol, no required changes to existing standards / devices
    - EPoC PHY connects “seamlessly” to an EPON MAC
  - Latency and delay jitter comply with Ethernet/EPON MAC requirements
- Throughput
  - Upto 5 Gbps in the downstream and 1Gbps in the upstream
  - Objective: downstream MAC/PHY Rate of 1 Gbps in a 120 MHz bandwidth
- Co-existence with existing services
  - Frequency agile
  - Allow interleaving of EPoC and existing services is the same frequency band
- Optimize network capacity
- Minimize complexity
- Robustness to interference
  - Micro-reflections, Burst noise
  - Adaptive to loop conditions

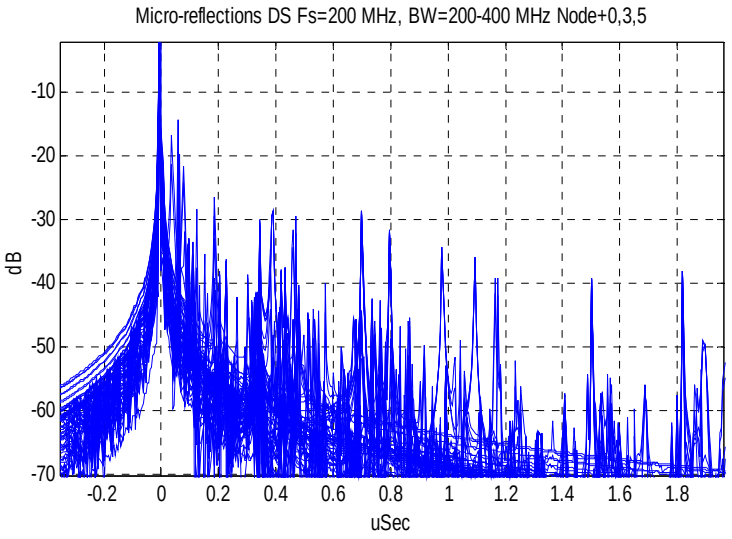
FDD Frequency Usage: Upstream Below Downstream

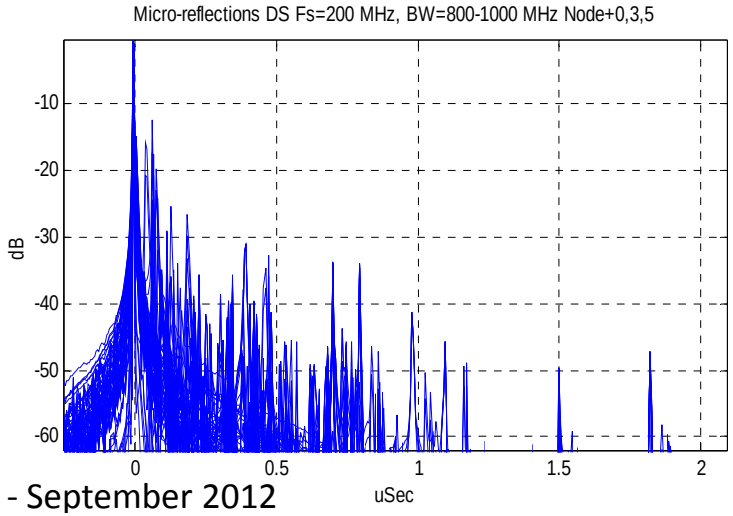


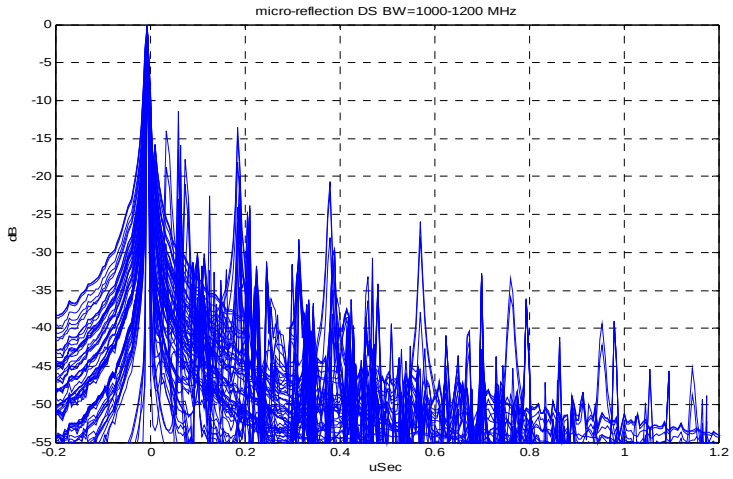
- Downstream signal
  - Subcarrier spacing of 50 KHz, aggregated number of sub-carriers is 16384 to cover 800 MHz between 200-1150 MHz
  - Subcarriers divided into four OFDM blocks each of about 200 MHz
    - All synchronize to same clock
    - Each band can be interleaved with other services by turning off sub-carriers
- Upstream RF band is located below downstream RF band
  - Subcarrier spacing of 50 KHz, a single 200 MHz block is required

Loop Impulse responses - Downstream

- Aggregated impulse responses over about 70 simulated channels
- Node+0, Node+3 and Node+5 topologies
- Examples: 200 MHz bands at 200-400 and 1000-1200 MHz
- Simulated loops to be used to assess required guard interval

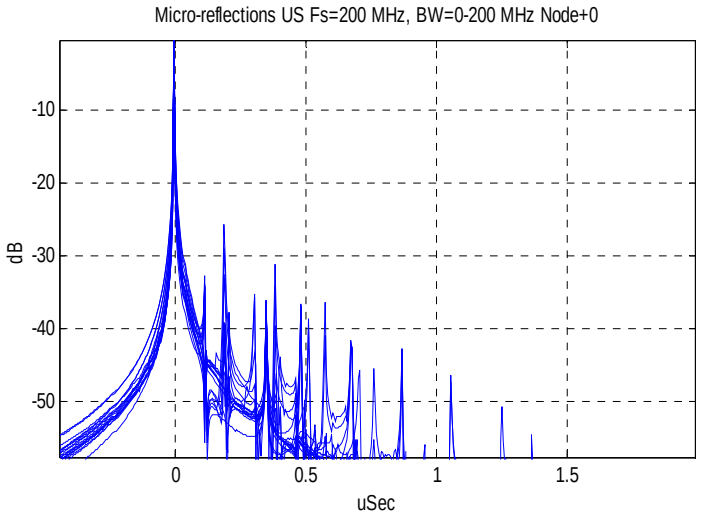


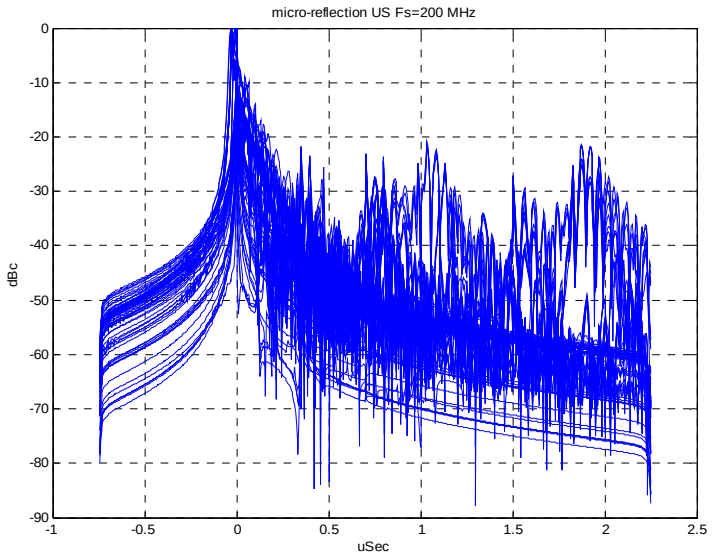




Loop Impulse responses - Upstream

- Upper figure shows micro-reflections for the Node+0 only loops
- Lower figure shows micro-reflections simulated for Node+0, Node+3 and Node+5 loops
- Micro-reflections larger and longer in spread than in the downstream
  - Some very long (Node_5 case)
- Expected as micro-reflections are attenuated slower at lower frequencies.
- Require larger CP sizes





Reference Clock and Synchronization

- Clock reference
  - Generated in the CLT PHY
- CLT OFDM Sampling frequency
  - Downstream transmission of the CLT PHY uses the reference clock to generate the OFDM sampling clock
  - In the CLT the sampling frequency in the downstream transmitter and upstream receiver must be derived from the same clock
- CLT Carrier frequency
  - In the CLT the carrier frequency in the downstream transmitter and upstream receiver must be derived from the same clock
- CNUs acquire the clock reference from the downstream signal
  - CNUs transmit their OFDMA signal using the acquired sampling frequency and carrier frequency.

Downstream Signal Overview: OFDM Parameters

- Continuous Broadcast transmission over one or more OFDM blocks
  - Synchronized transmission over blocks and all subcarriers
- Each OFDM band has the following characteristics
  - Sub-carrier spacing is 50 KHz
  - FFT size of 4096 with sampling frequency of 204.8 MHz
  - 3840 available sub-carriers in a 192 MHz IFDM block
  - Configurable Cyclic Prefix size between 1 to 3.5 uSec
  - Configurable window shaping, one window value per CP size
  - Constellation size: odd and even constellations from QAM256 to QAM4096
    - May vary per sub-carrier to accommodate for variable SNR

Downstream Signal Overview: OFDM Parameters

- Pilots
  - Staggered rotated pilots over all sub-carriers for channel estimation
  - 32 pilots in each OFDM symbol (1/128 of the subcarriers)
  - A single Channel Estimation iteration every 128 OFDM symbols (~2.6 mSec)
  - No need for interpolation
- Continuous pilots
  - Requirement for continuous pilots for frequency synchronization is to be discuss
  - If required then 32 pilots should be used for both staggered and continuous pilots

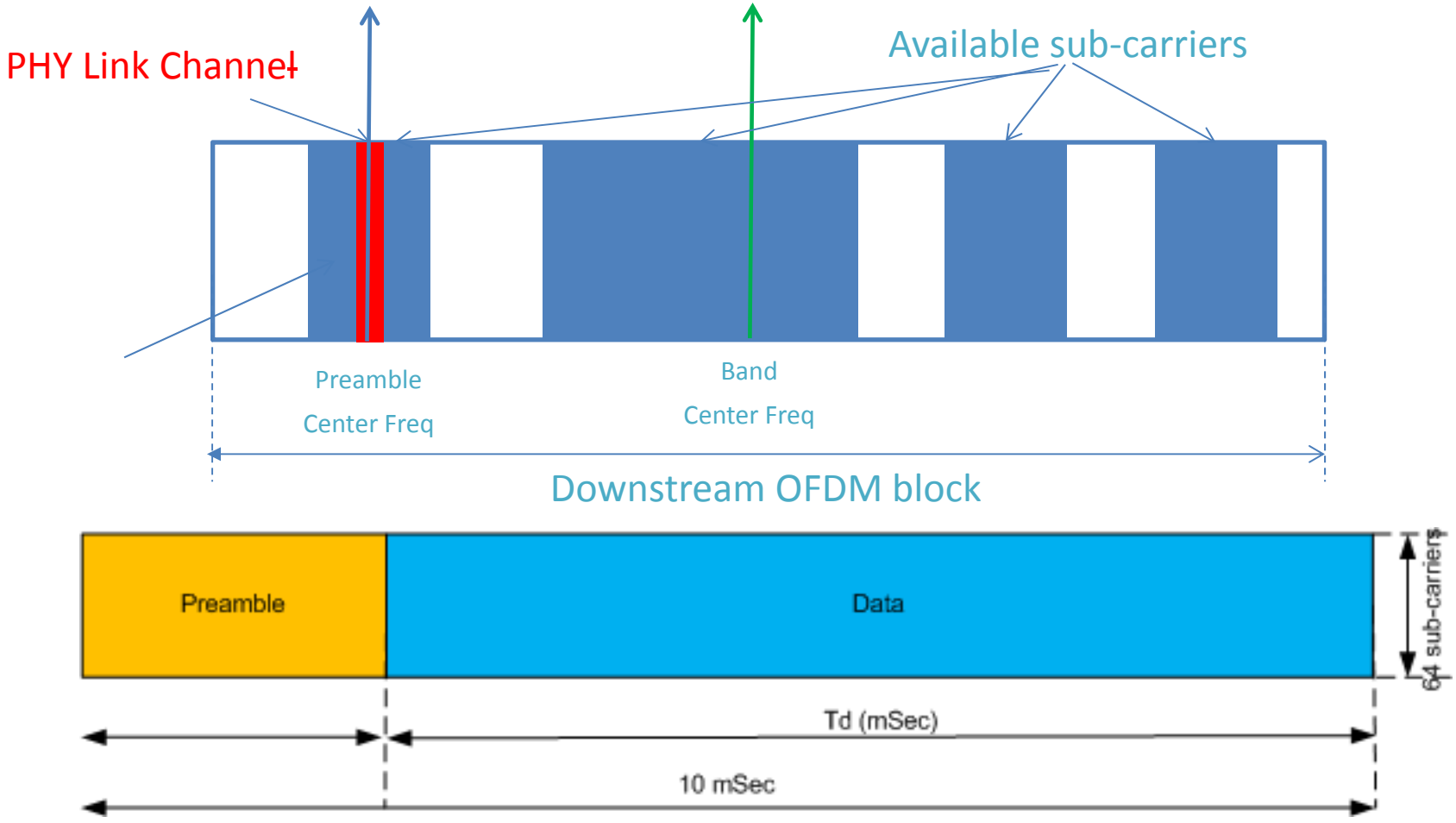
Downstream Signal Overview: FEC and Interleaving

- Forward Error Correction code
  - Partially coded 12K LDPC code
  - Code rate: 90%
  - Shortening to achieve 0.5 bit granularity with step size of 1.5 dB
  - Details and performance are presented in a companion contribution "Forward Error Correction Proposal for EPoC PHY Layer, September 2012"
  - At Frame Error Rate of interest (1e-6) performs better than 16K DVB-C2 FEC
- Interleaving – (optional , may be modified according to channel model)
  - Time domain Convolutional interleaver
    - Optional to protect against burst noises in the downstream
    - About 300 uSec depth is required to support -20dB bursts of 20uSec in duration
  - Frequency domain interleaver

PHY Link Channel

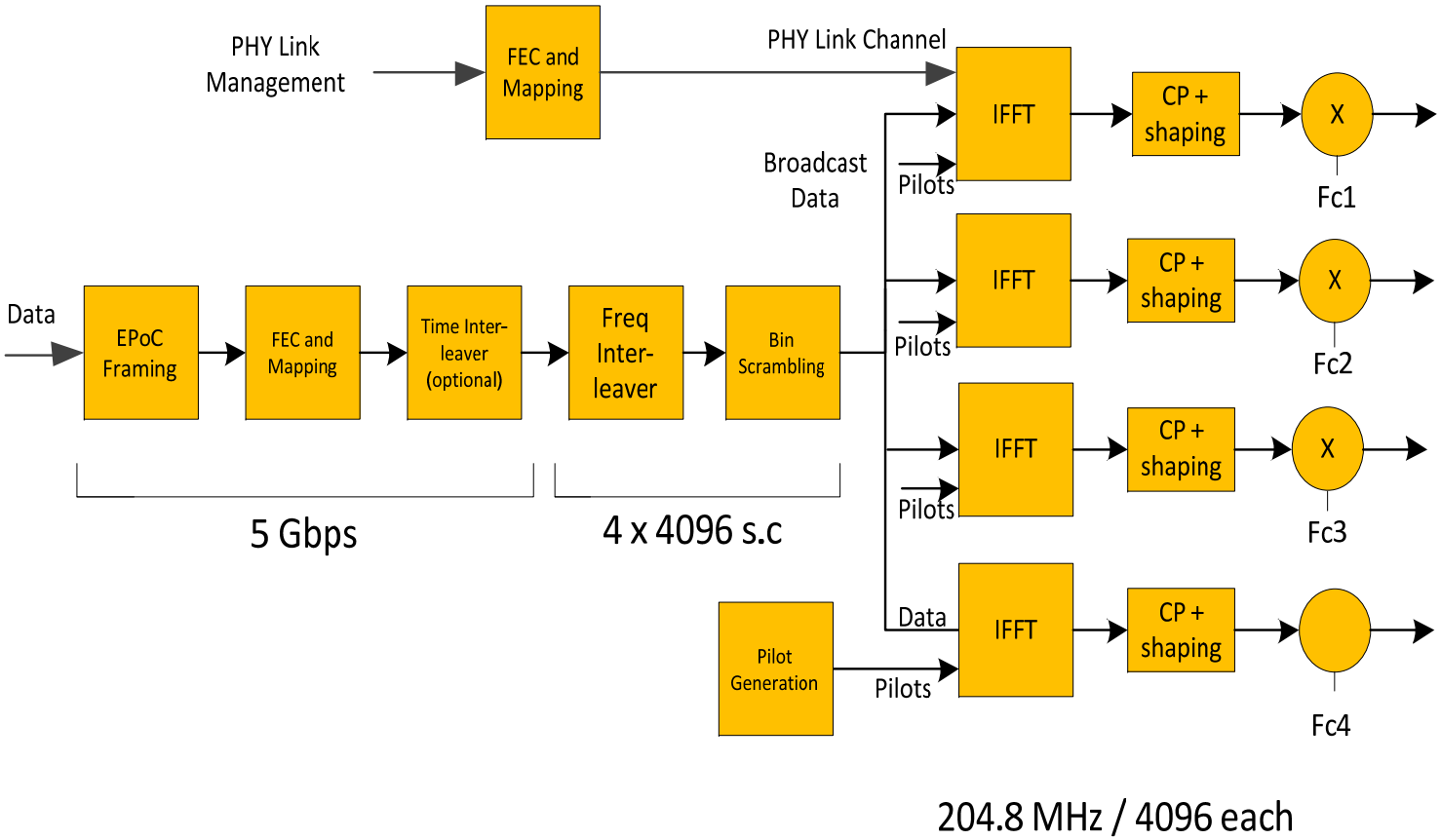
- Runs in parallel to data on separated and dedicated sub-carriers
  - Isolate PHY Link management from upper layers
  - Enable PHY Link information transfer without halting data transmission
- PHY Link information
  - Preamble and profile information required for new nodes to join the network
  - After synchronization PHY Link information on transmission characteristics can be acquired for full sync with the downstream signal
  - For existing nodes to sync and update on transmission profiles
    - PHY configuration such as bit Loading of carriers, frequency mapping, FEC, CP size, upstream symbol size, upstream time offset, power level, upstream block size, interleaver pointer, TDD duty cycle control, etc.
  - PHY control such as power save protocol and wake on LAN
- Uses 32 sub-carriers
  - Aligned to a 6/8 MHz legacy channel
  - Own FEC encoder

PHY LINK Channel (2)



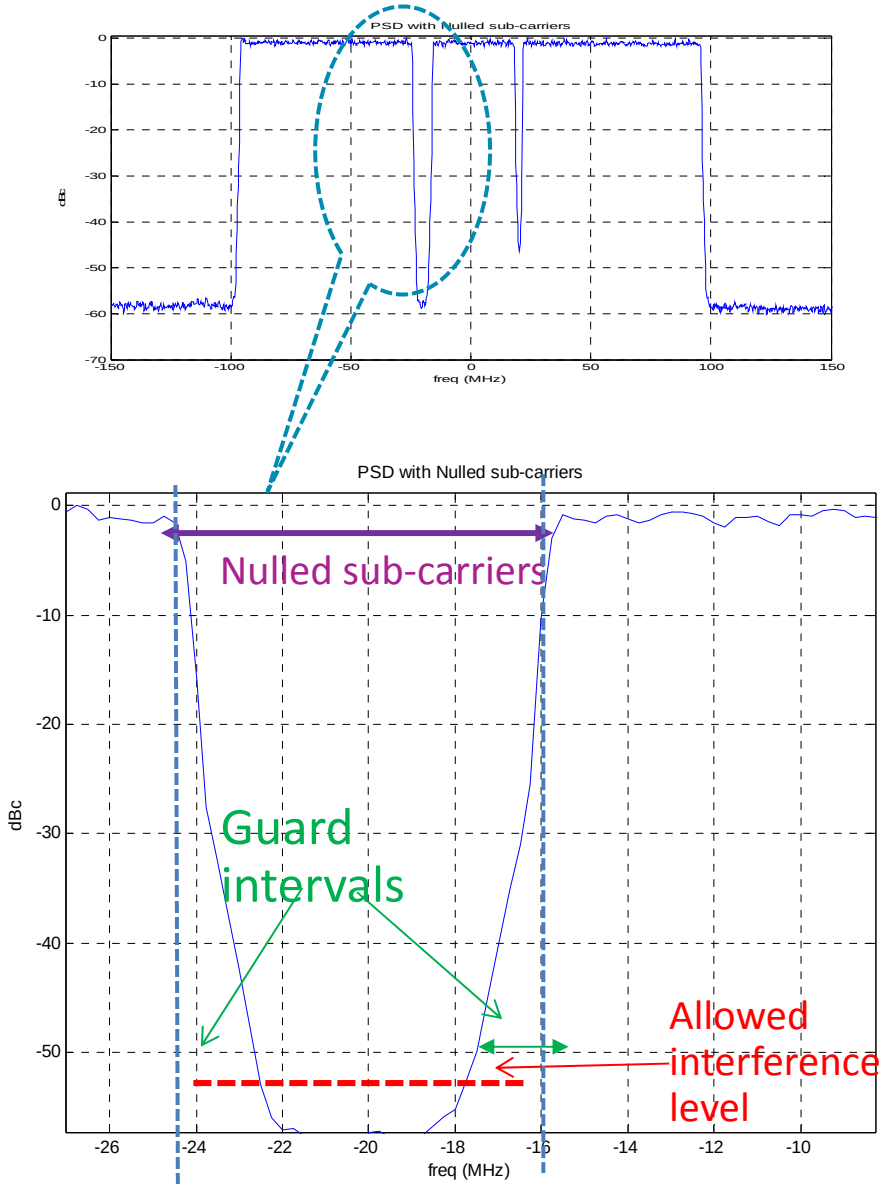
- PHY Link Frame consists of Preamble follows by a block of data
- Preamble can be transmitted every 10 mSec

Downstream Transmitter Block Diagram



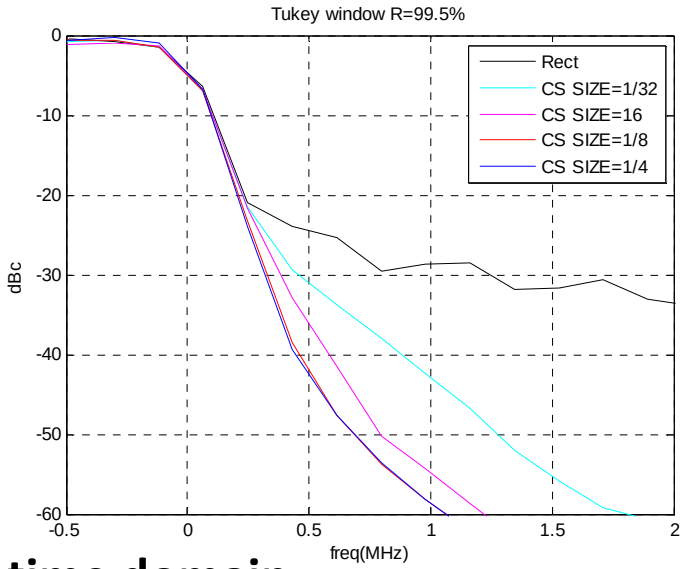
Sub-carrier Nulling and Window shaping

- Co-existence with legacy services
- Reduce interference to/from narrow band signals
- Any sub-carriers and any number of sub-carriers can be nulled
- To exist with legacy services use granularity of 6/8 MHz
- Lower granularity for coexisting/avoiding interference with narrowband signals
- Need to allow guard band to avoid leakage
- Window shaping is a low-complexity efficient method to reduce leakage into nulled sub-carriers

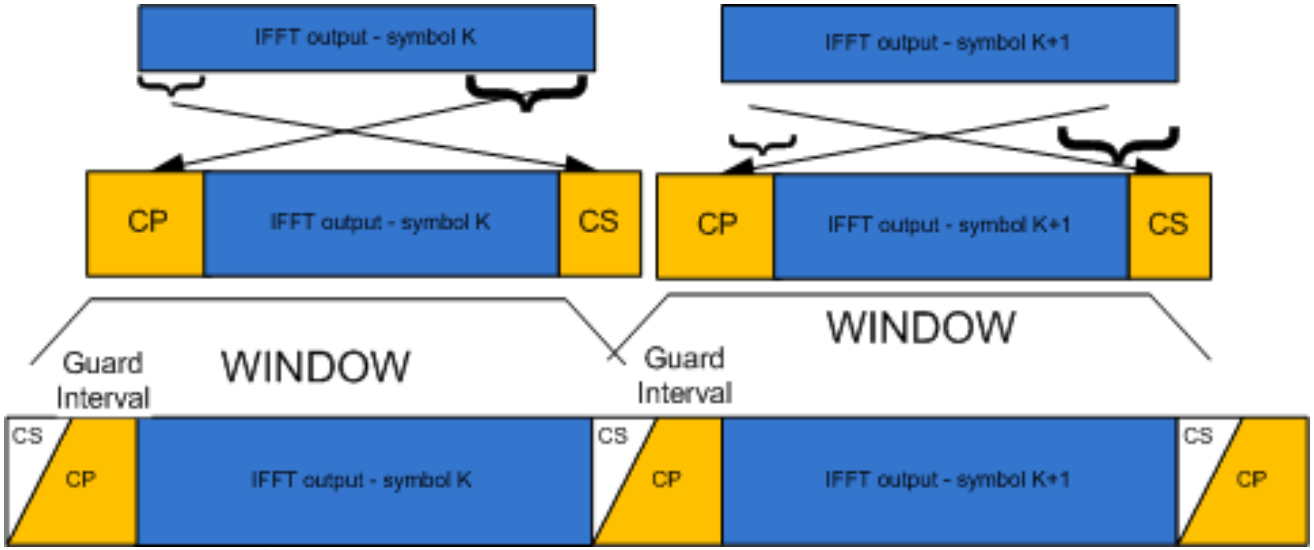


Interleaving with other services: Window Shaping

- Windowing [1] in time domain improves resolution in frequency domain
- Reduce out-of-band leakage
- Reduce leakage into nulled sub-carriers



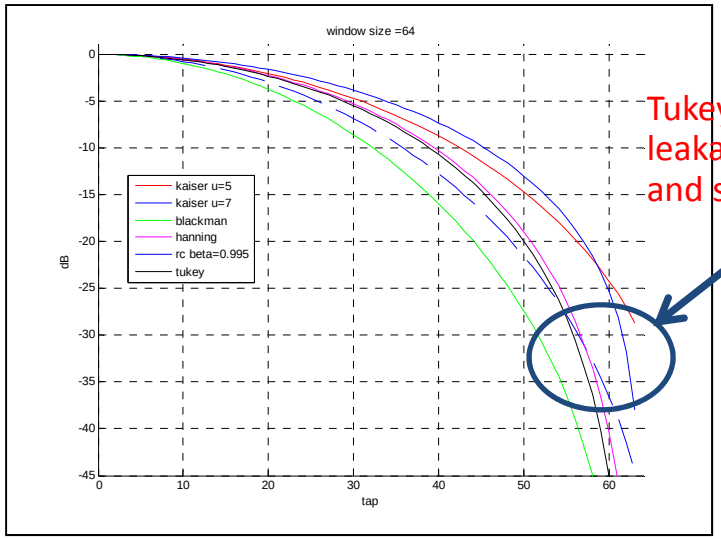
- **Simple implementation: overlap and add in the time domain**



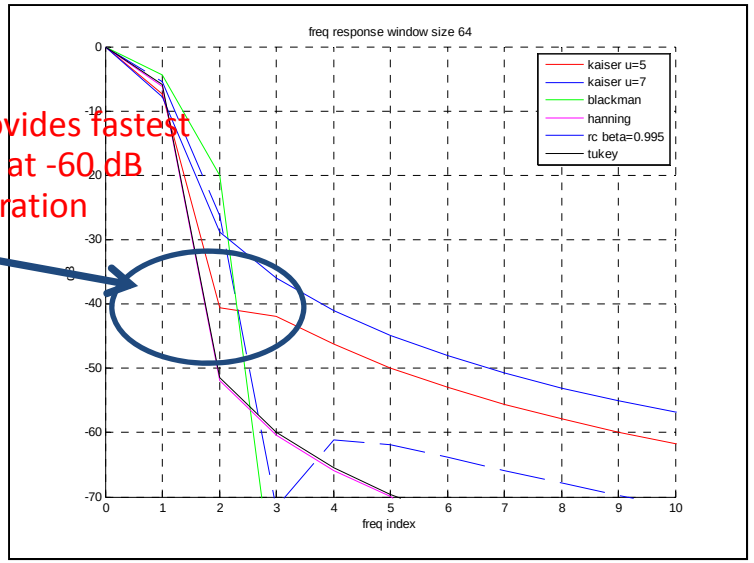
- Ref: "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform", FREDRIC J. HARRIS, PROCEEDINGS OF THE IEEE, JANUARY 1978,

Window selection

- Choose a window type with
  - narrow frequency response at the required leakage attenuation
  - short time duration at the required ISI
  - Require leakage of -55 dBc and ISI of -40 dBc
- Time and frequency responses for several windows are depicted below
- Tukey window is selected for reduction of leakage to -50 to -60 dBc with the lowest number of turned off sub-carriers and with relatively short time duration at -40 dB (for lower time overhead)
- Allowed leakage into adjacent services need to be determined by the group

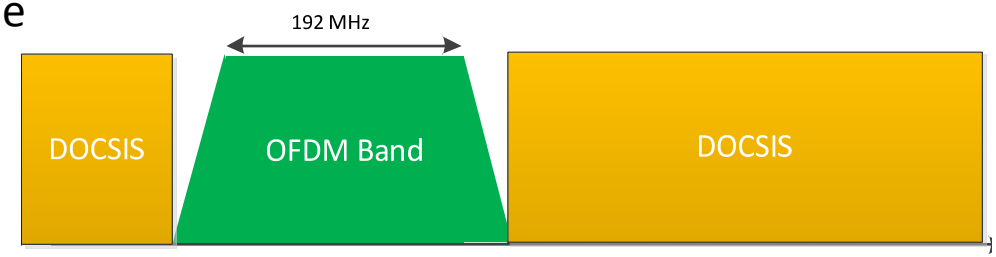


Tukey window provides fastest leakage reduction at -60 dB and short time duration

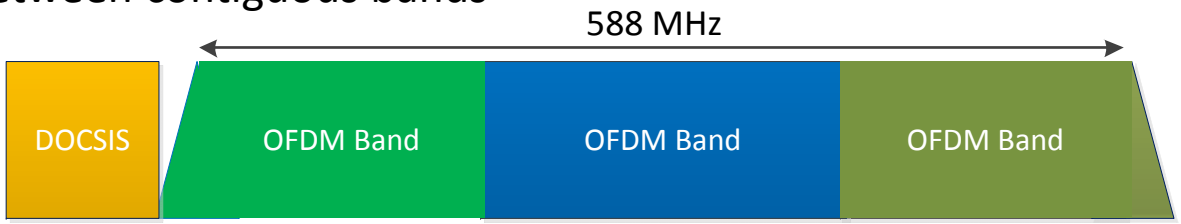


Coexistence and PHY Bonding Options

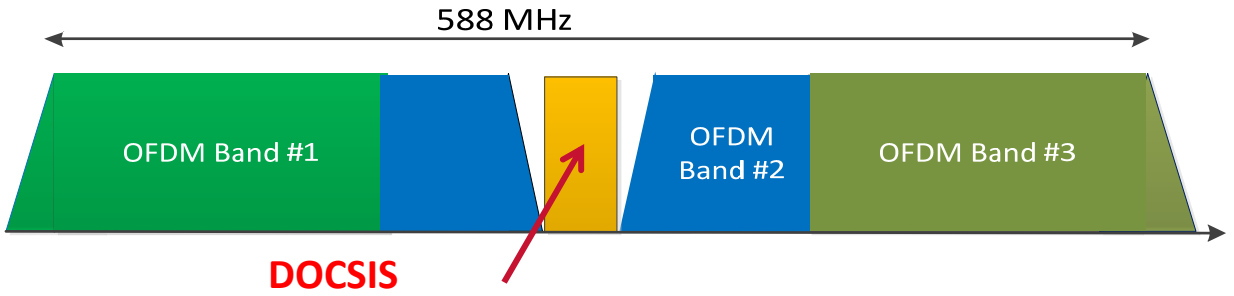
- A single 192 MHZ OFDM band
  - Guard-band are required on each side



- Three contiguous OFDM Bands
  - No need for guard bands between contiguous bands

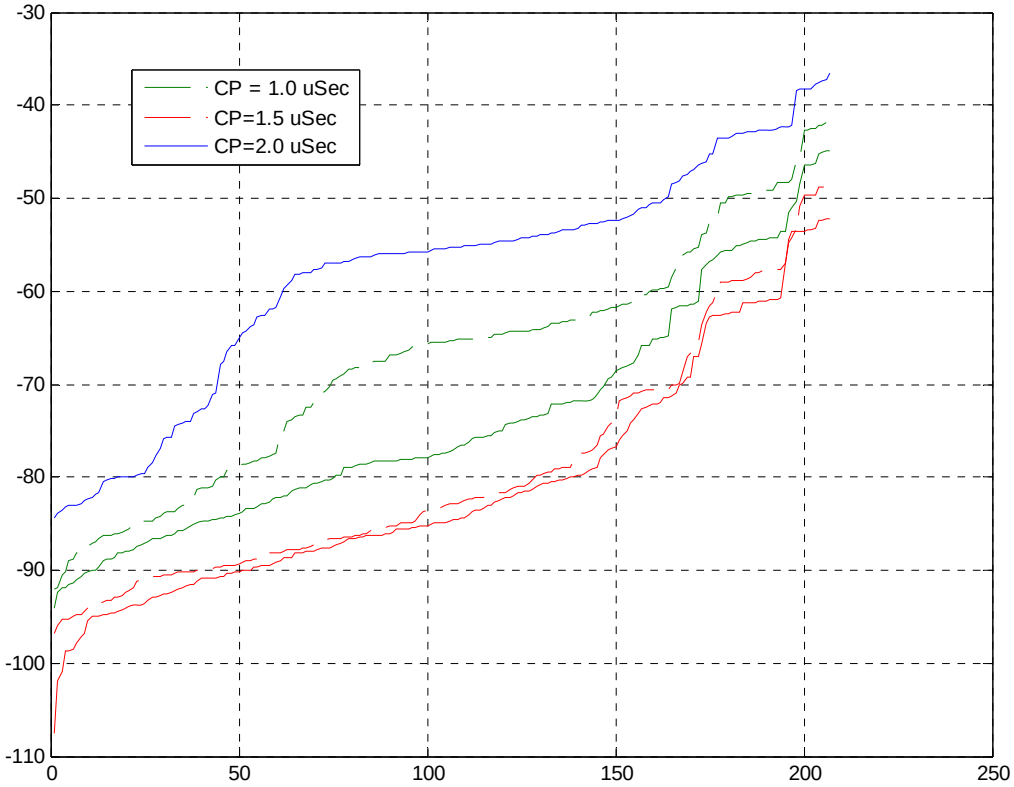


- Multiple OFDM band with legacy block interleaved



Simulated CP size and ISI- Downstream

- The simulated loops were used to assess required CP size per loop and with different window sizes
  - Require ISI of ≤ -45 dBc
    - To support QAM1024
  - Tukey window is used, sizes are relative to 4096 FFT size
- CP sizes per loop are depicted, sorted by size
- Use four configurable CP sizes between 1.0 uSec and 2.5 uSec
- CP size is configurable
  - A single Window size per CP size



- Solid line – without windowing
- Dashed line – with windowing

Downstream OFDM Parameters and Data Rates

- Data rates (QAM1024, 1.0 uSec guard interval)
  - 1650 Mbps on 192 MHz RF spectrum
  - 5000 Mbps on 588 MHz RF spectrum
- OFDM parameters for a single 192 MHz block

CP size (uSec)	**0.94**	**1.56**	**2.03**
Sampling frequency (MHz)	204.8	204.8	204.8
FFT Size	4096	4096	4096
Subcarrier spacing (KHz)	50.00	50.00	50.00
Symbol size (uSec)	20.94	21.56	22.03
CP size (samples)	192	320	416
Window shaping (samples)	128	192	256
Numer of Pilots	32	32	32
Numbe of subcarrier for PHY lonk channel	32	32	32
Available subcarriers	3840	3840	3840
Nulled subcarriers per interleaved block	64	56	48
Used sub-carriers per 600 MHz (three blocks)	12032	12032	12032
Used sub-carriers per 200 MHz (one block)	3776	3776	3776
Code Rate	90%	90%	90%
Actual OFDM RF Bandwidth (MHz)	192.0	192.0	192.0
Num of bits / sub carriers	10	10	10
PHY Rate per 192 MHz available BW (Mbps)	**1623**	**1576**	**1543**
PHY Rate with 588 MHz available BW (Mbps)	**5172**	**5022**	**4915**

Data Rates when Interleaving with Legacy

- 1024 QAM 1uSec guard interval

	Rate	Relative
PHY Rate per 200 MHz available BW (Mbps)	1651	100.0%
Used sub-carriers per 200 MHz (1 interl)	1624	98.3%
Used sub-carriers per 200 MHz (2 interl)	1596	96.7%
Used sub-carriers per 200 MHz (4 interl)	1541	93.3%

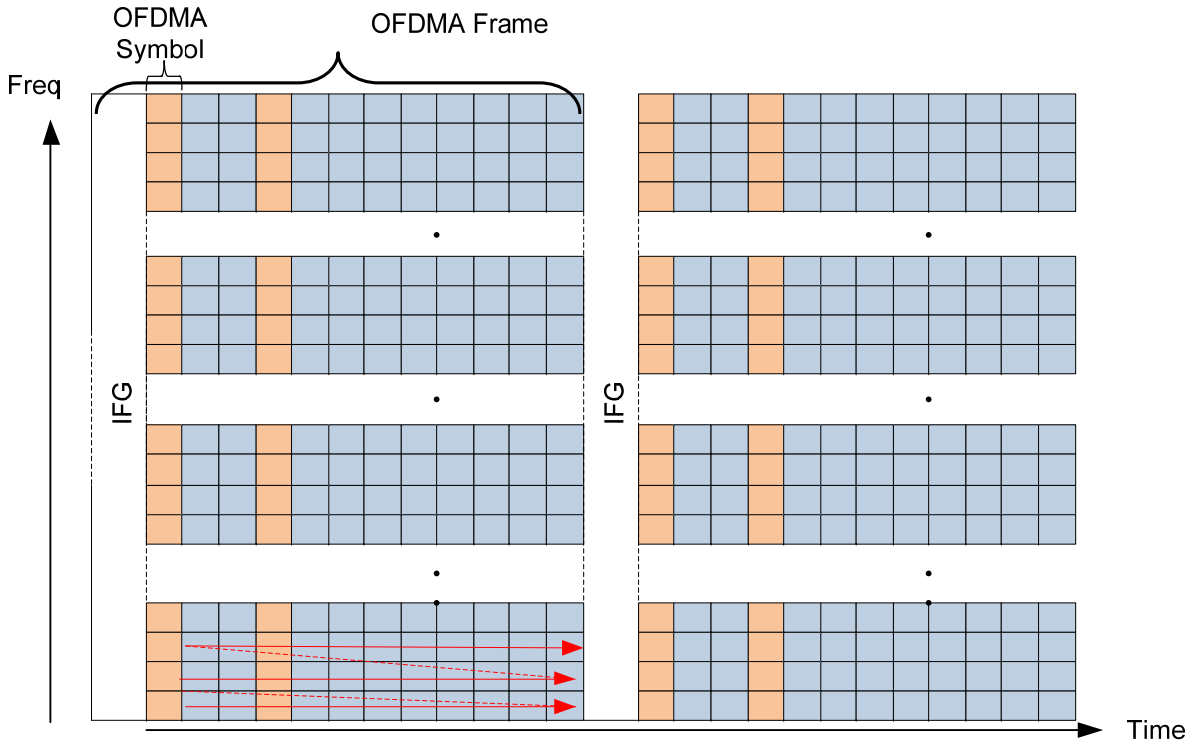
Upstream Signal Overview : OFDM Parameters

- Burst OFDMA transmissions
- OFDMA characteristics -
  - Sub-carrier spacing: 50 KHz
  - FFT size of 4096 is used with sampling frequency of 204.8 MHz
    - 3840 sub-carriers in a 192 MHz EPoC band
  - Four configurable Cyclic Prefix sizes between 1 to 3.5 uSec
  - Configurable window shaping
  - Constellation size: Odd and even constellations from QPSK to QAM4096
  - Adaptive per sub-carrier to accommodate variable SNR
- SYNC symbols for Channel Estimation per OFDMA burst
  - Retrain on channel to be insensitive to cable changes
- Pre-equalization

Upstream Signal : Framing and Interleaving

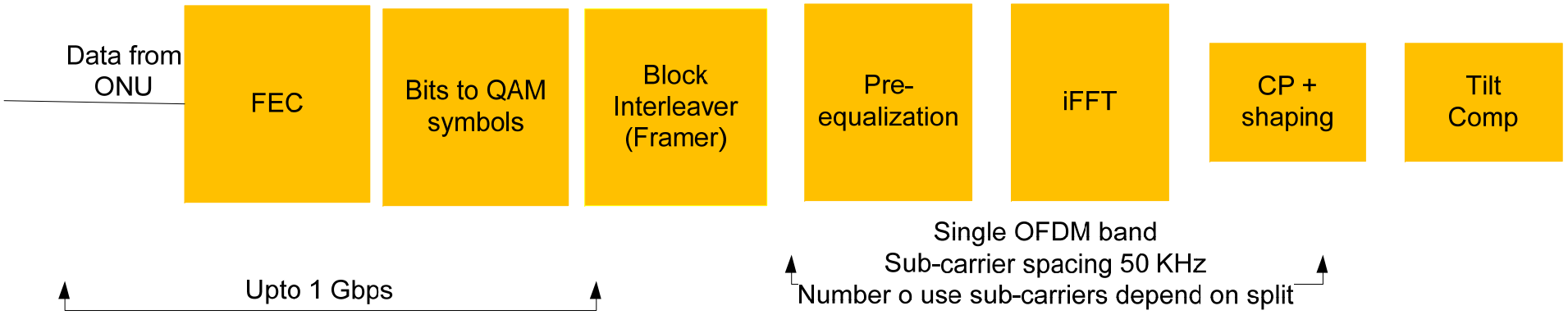
- Interleaving
  - Time domain Block Interleaver aligned to OFDMA framing
- Upstream OFDMA Framing
  - Frame size is about 250 uSec
  - Ten OFDMA symbols per OFDMA Frame, plus two SYNC symbols for channel estimations
  - Inter-frame gap between OFDMA bursts to allow enough time for RF settings
  - Block interleaving is done per OFDMA frames
  - Maximum number of transmitters per frame is 64
- Upstream PHY Link and Discovery
  - Allocated sub-carriers for the ranging and detection of a new CNU by the downstream receiver
  - Uses 32 sub-carriers, Interleaved in the OFDMA frame

Upstream OFDMA Framing



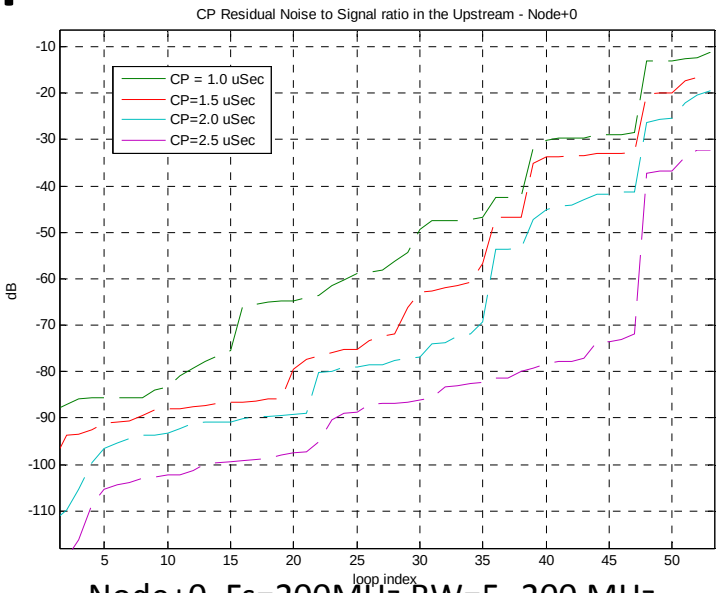
- 2D-to-1D mapping, time domain is mapped into frequency/symbol domain
  - Data is filled subcarrier by subcarrier and transmitted symbol by symbol
  - Minimal slot for transmission are groups of four subcarriers (“Sub Groups”)
- The second SYNC symbol increases robustness against burst noise

Upstream Transmitter Block Diagram

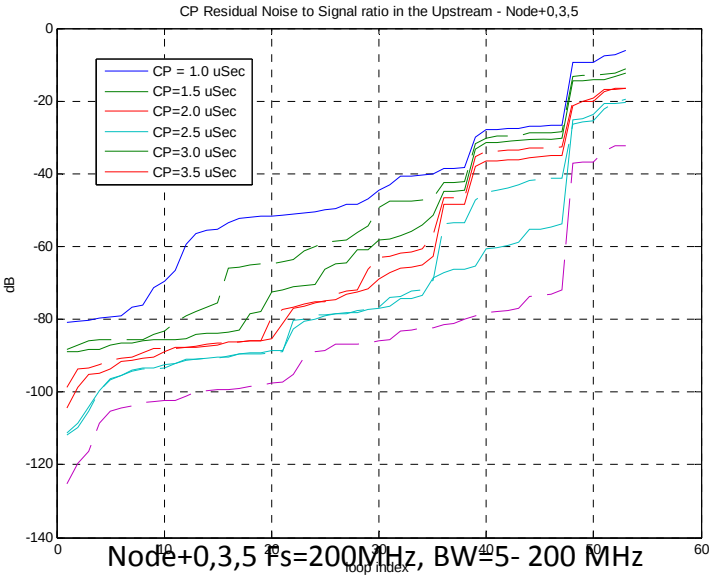


CP size and ISI - Upstream

- Node+0 only loops and Node+0/3/5 loops
- Upstream shows larger CP sizes than downstream in the case of Node+3 and Node+5
- Use four configurable CP sizes for the Upstream
  - Use a single shaping window size per CP size



Node+0, Fs=200MHz BW=5- 200 MHz



Node+0,3,5 Fs=200MHz, BW=5- 200 MHz

Upstream Throughput Performance

- Approx. data rates
- QAM1024 (CP=0.9 uS)
  - Available RF bandwidth: 192 MHz: 1300 Mbps
  - Available RF bandwidth: : 86 MHz: 590 Mbps
  - Available RF bandwidth: : 40 MHz: 260 Mbps
- QAM256 (CP=1.6uS)
  - Available RF bandwidth: : 192 MHz: 1000 Mbps
  - Available RF bandwidth: : 86 MHz: 440 Mbps
  - Available RF bandwidth: : 200 Mbps