Baseline Proposal for EPoC PHY Layer

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NOTE

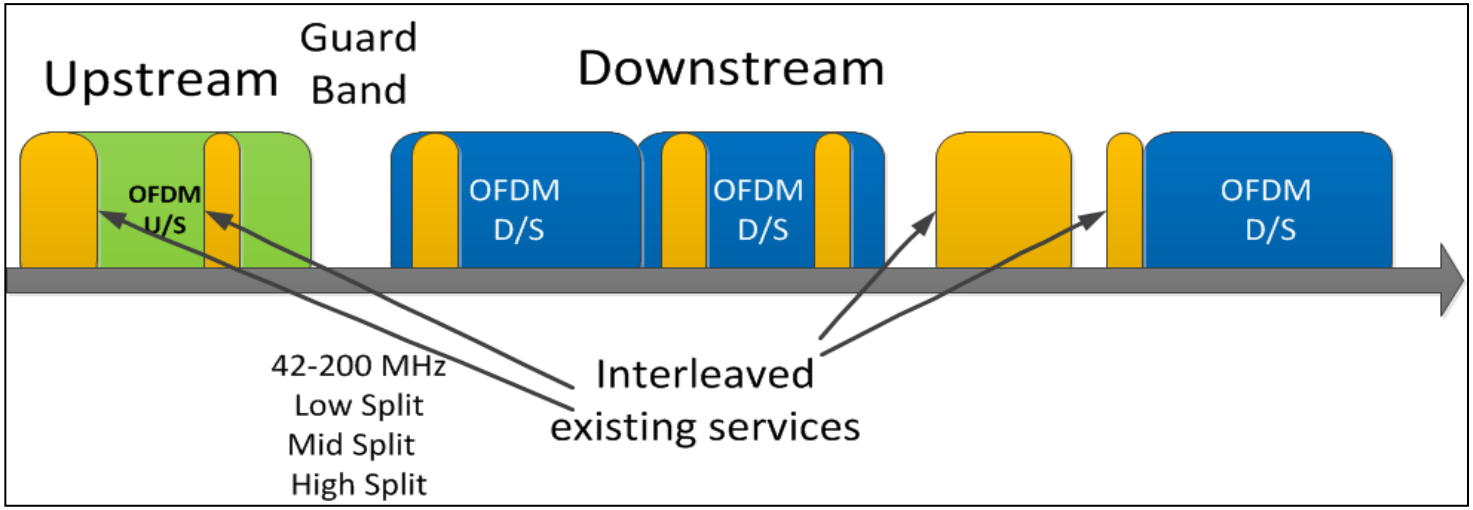
- This presentation includes results based on an in-house Channel Models
- When an approved Task Force Channel Model is available, this presentation will be updated.
- The results are expected to be similar

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
  - Minimize latency and delay jitter to comply with Ethernet/EPON MAC requirements
- Throughput
  - Up to 5 Gbps in the downstream and 1Gbps in the upstream
- 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

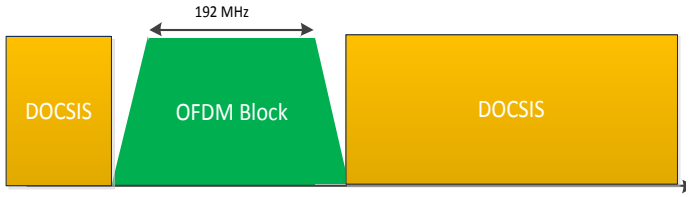
FDD Frequency Usage
Upstream Below Downstream



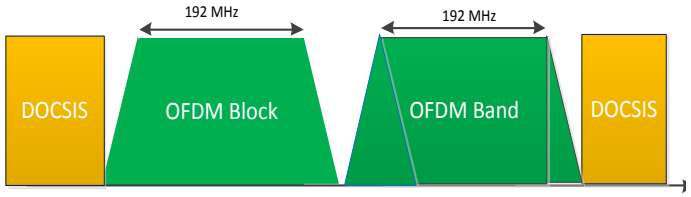
- Downstream signal
  - Subcarrier spacing of 50 KHz, aggregated number of sub-carriers is 16384 to cover 800 MHz between 200-1150 MHz
  - Subcarriers divided into four OFDM blocks each of about 200 MHz
    - All synchronize to same clock
    - Each block can be interleaved with other services by turning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

Coexistence and PHY Bonding Options

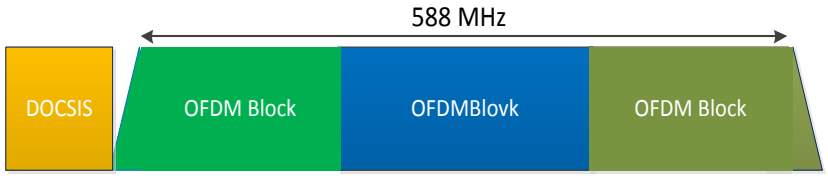
- A single 192 MHZ OFDM block
  - Guard-band are required on each side



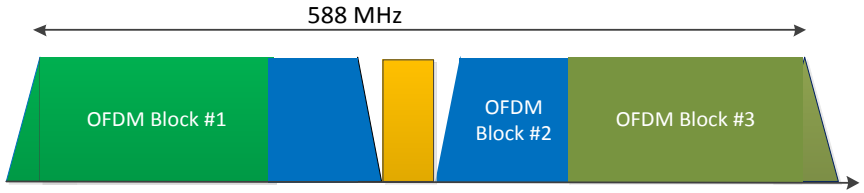
- Separated OFDM block
  - With guard bands between contiguous blocks



- Multiple contiguous OFDM bands
  - No guard band between OFDM blocks

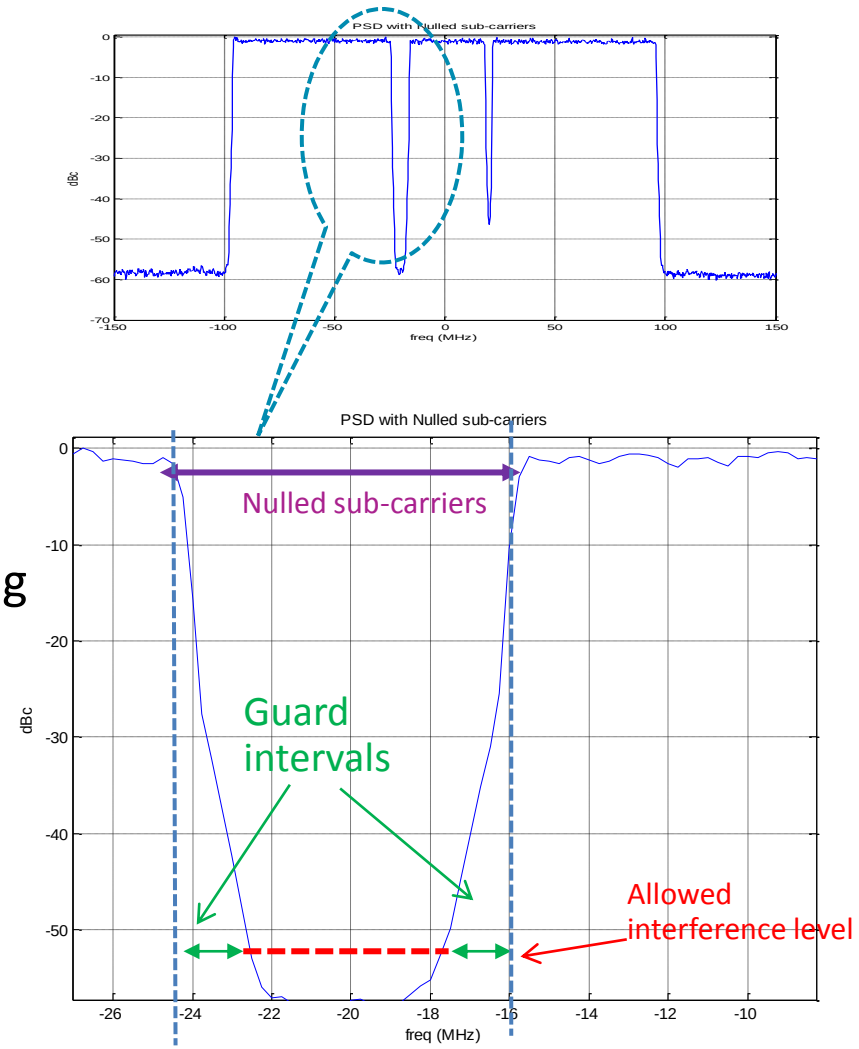


- Multiple OFDM band with legacy block interleaved



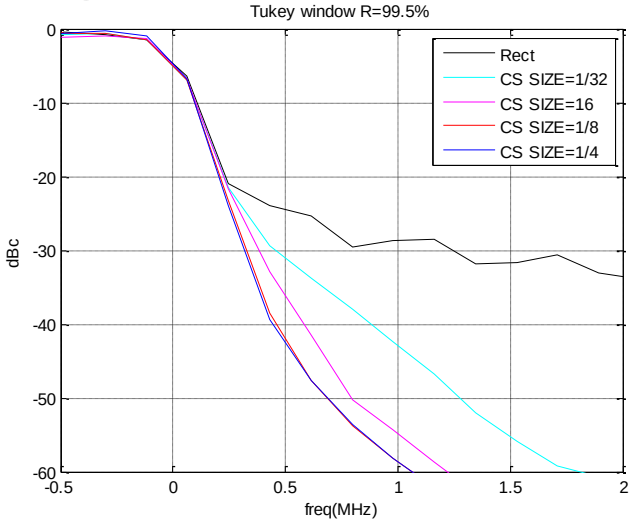
Coexistence: Sub-carrier Nulling and Shaping

- Co-existence with legacy services
- Reduce interference to/from narrow band signals
- Any sub-carrier 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

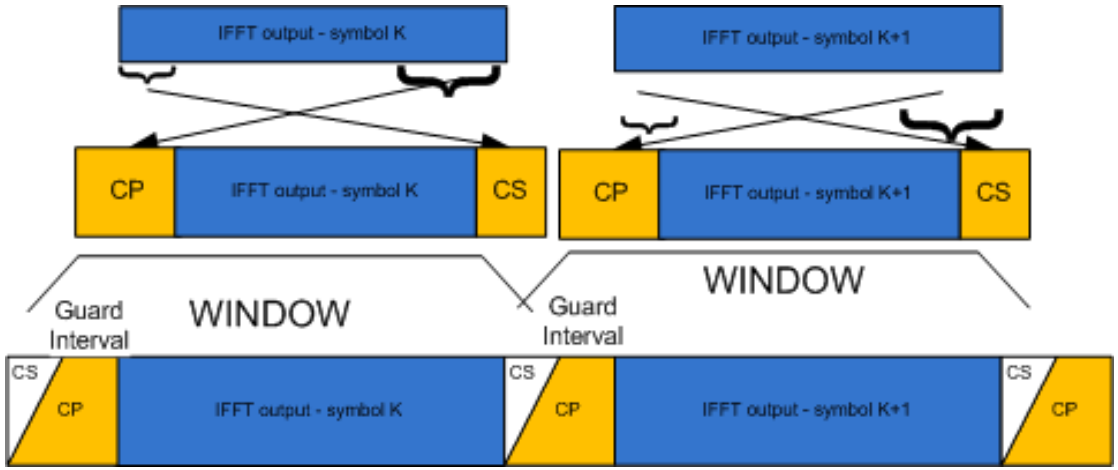


Interleaving with other services: Window Shaping

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



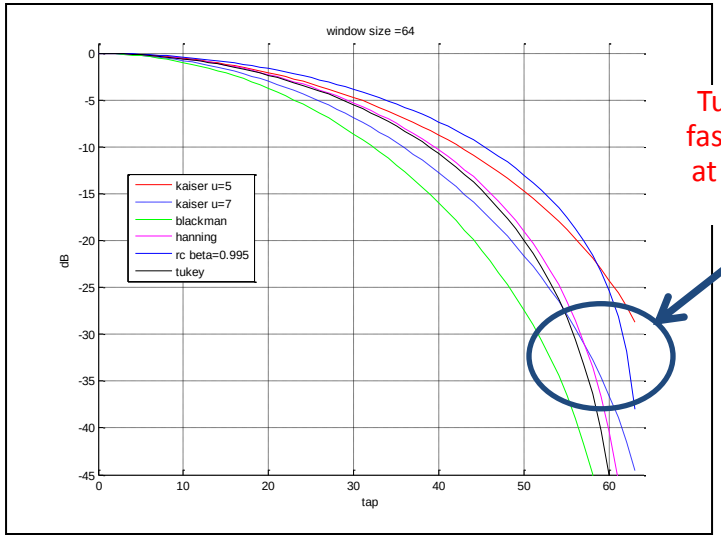
- **Simple implementation: overlap and add in the time domain**



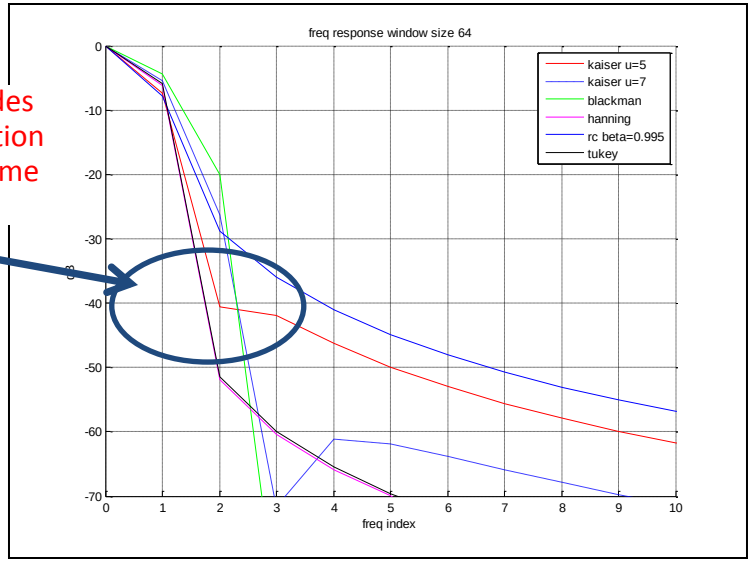
- Ref: "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform", FREDRIC J. HARRIS, PROCEEDINGS OF THE IEEE, JANUARY 1978,

Window Selection

- Choose a window type with
  - narrow frequency response at the required leakage attenuation
  - short time duration at the required ISI
  - Example: 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



Downstream Signal Overview: OFDM Parameters

- Continuous Broadcast transmission over one or more OFDM blocks
  - Synchronized transmission over blocks and all subcarriers
- Each OFDM block 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 OFDM block
  - Configurable Cyclic Prefix size between 1 to 3.5 uSec
  - Configurable window shaping, one window size 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
Pilots

- 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 discussed
  - If required then 32 pilots should be used for both staggered and continuous pilots

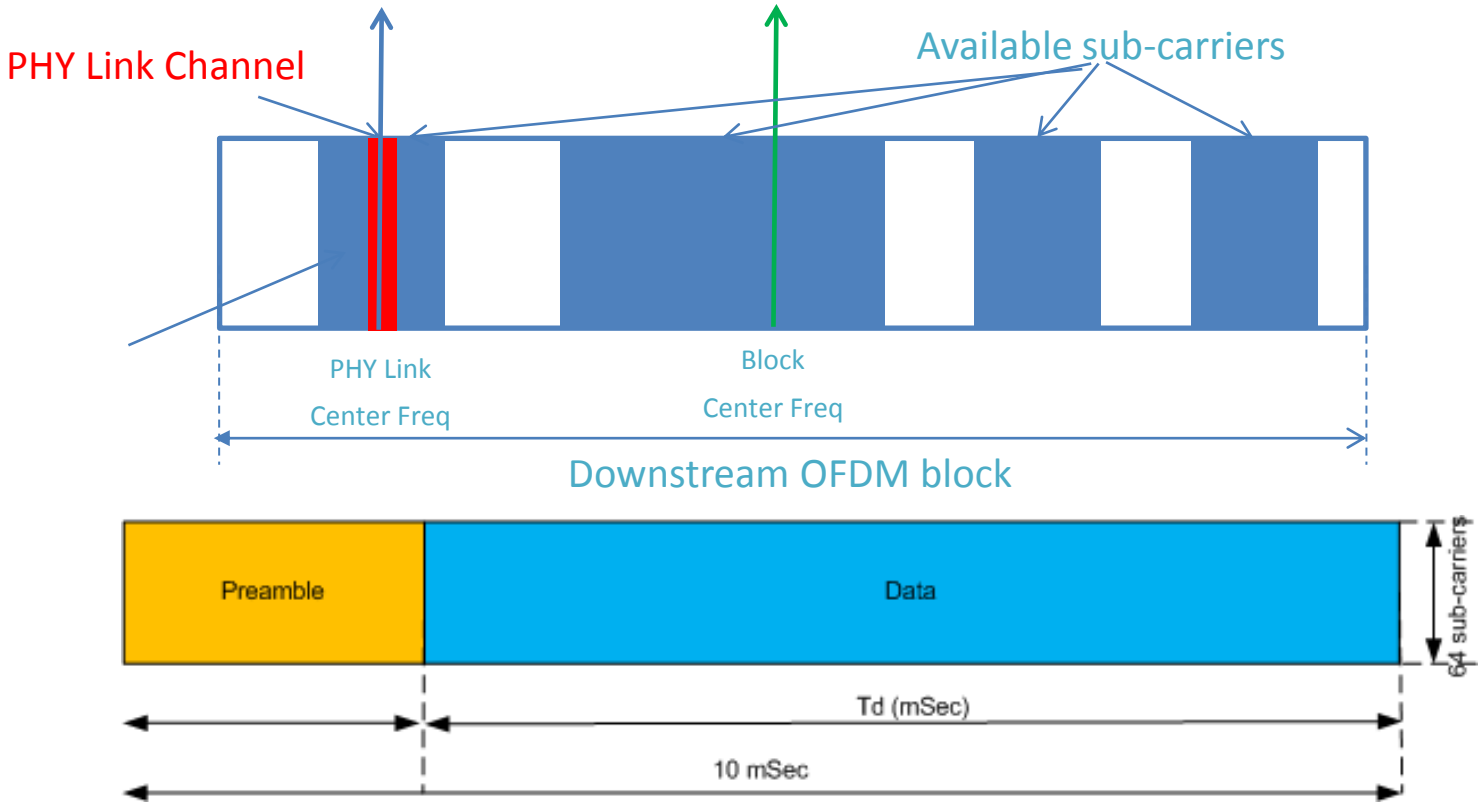
Downstream Signal Overview: FEC and Interleaving

- 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 (1/2)

- 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 , 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

PHY Link Channel (2/2)

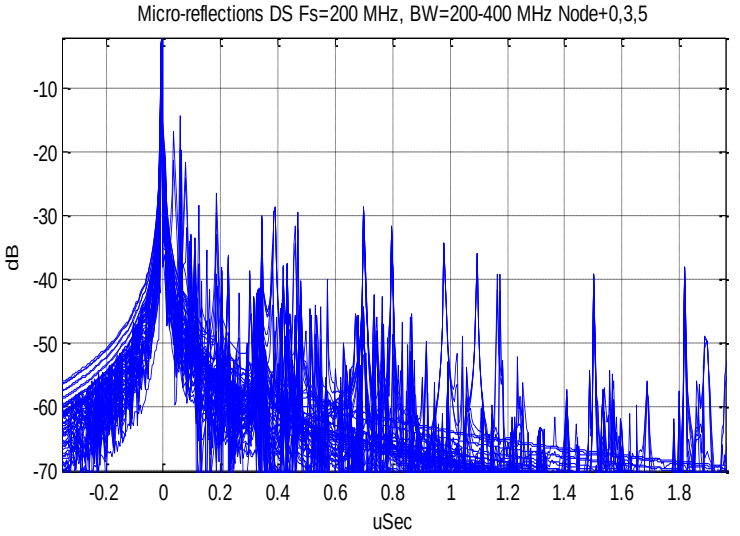


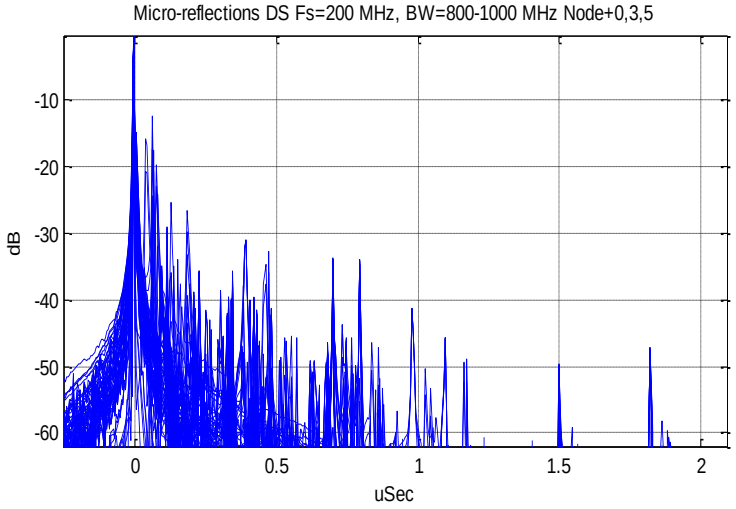
- 32 sub-carriers its own FEC
- Robust mode
- Aligned to a 6/8 MHz legacy channel

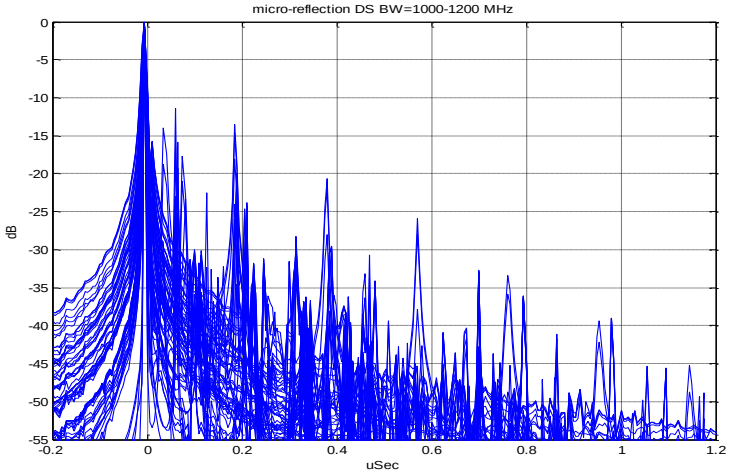
- Preamble followed by a block of data
- Can be transmitted every 10 mSec

Channel Model, ISI and CP Size
Loop Impulse responses - Downstream

- Based on in house data and simulations
- Aggregated impulse responses of ~70 simulated channels
- Node+0, Node+3 and Node+5 topologies
- Examples: 200 MHz blocks at 200-400, 800-1000MHz 1000-1200 MHz
- Simulated loops used to assess required guard intervals



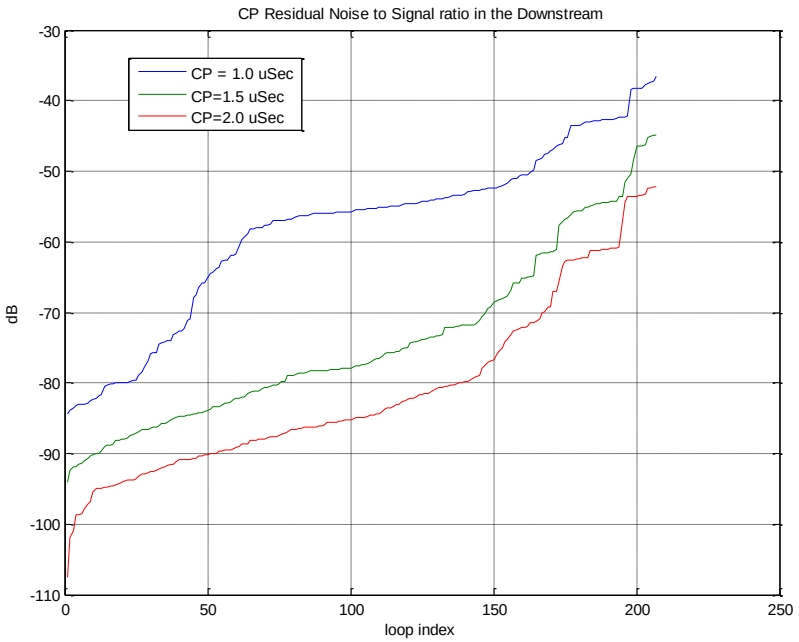




Simulated CP size and ISI- Downstream

- Based on simulated loops
- Show residual echo with CP size per loop
  - Require ISI of ≤ -45 dB
  - Support QAM1024 with 37 dB SNR
  - With/without Tukey window
- Configurable CP between 1-2.5 uSec
  - A single Window size per CP size

CP Residual noise to signal ratio



- 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 (Mbps)	Relative
PHY Rate per 200 MHz available BW (Mbps)	1623	100.00%
Used sub-carriers per 200 MHz (1 interl)	1596	98.31%
Used sub-carriers per 200 MHz (2 interl)	1568	96.61%
Used sub-carriers per 200 MHz (4 interl)	1513	93.22%

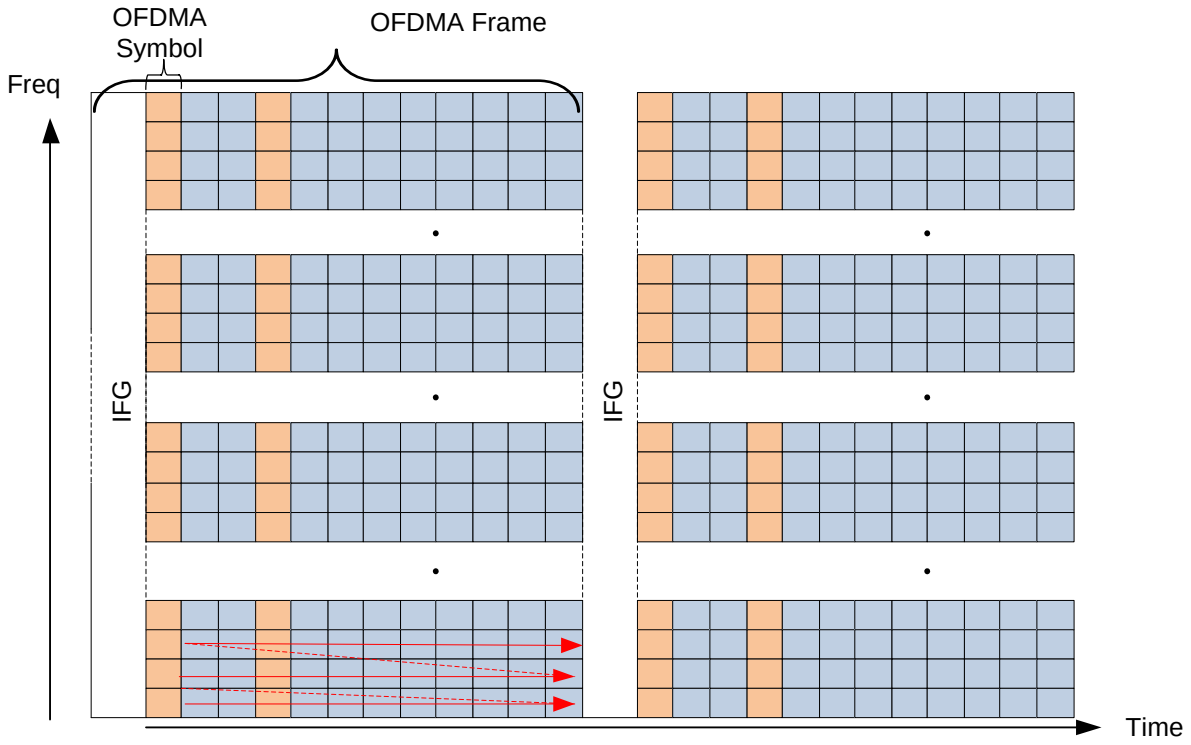
Upstream Signal Overview : OFDM Parameters

- 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

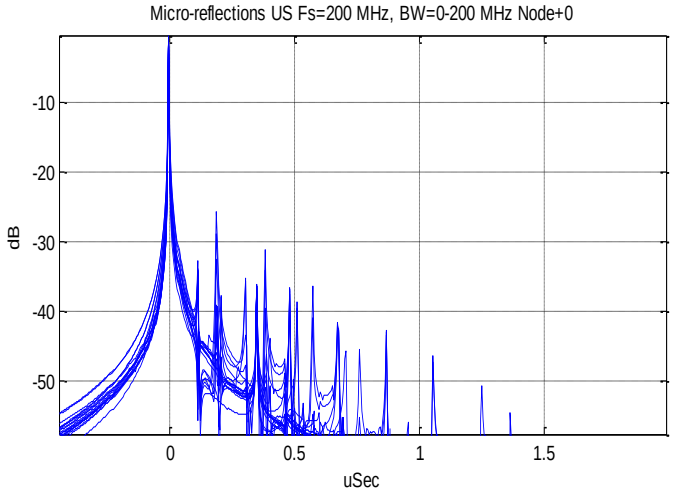
Upstream OFDMA Framing

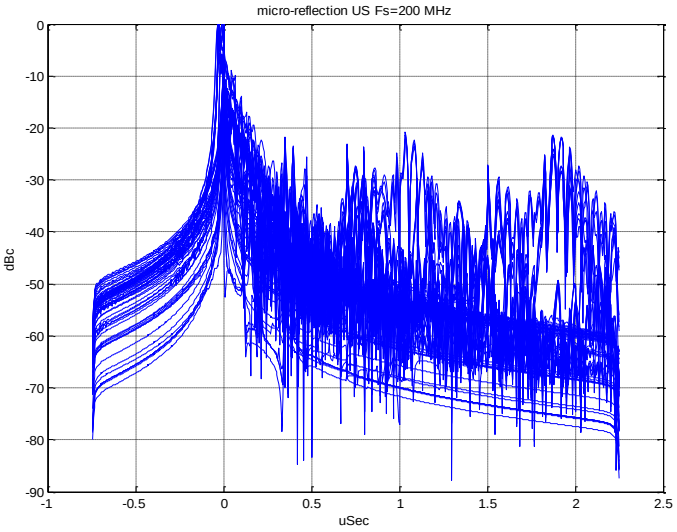


- 2D-to-1D mapping, time domain is mapped into frequency/symbol domain
  - Data is filled subcarrier by subcarrier and transmitted symbol by symbol
  - Minimal slot for transmission are groups of four subcarriers (“Sub Groups”)
- The second SYNC symbol increases robustness against burst noise

Channel Model, ISI and CP Size
Loop Impulse responses - Upstream

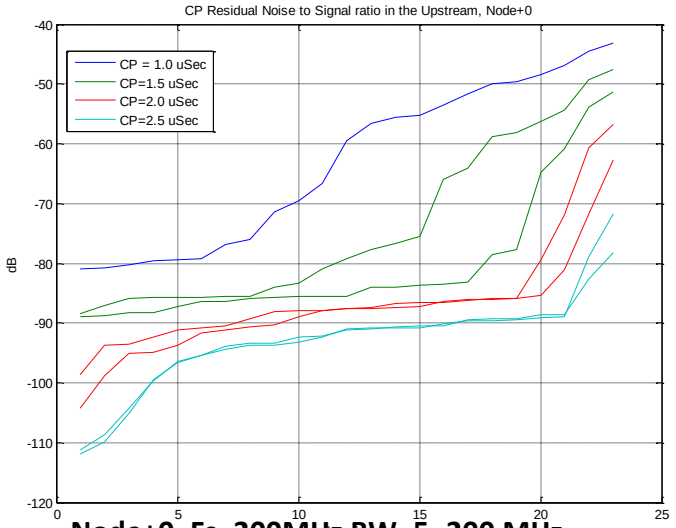
- Upper figure shows micro-reflections for the Node+0 only loops
- Lower figure shows micro-reflections simulated for Node+0, Node+3 and Node+5 loops
- Micro-reflections larger and longer in spread than in the downstream
  - Some very long (Node+5 case)
- Expected as micro-reflections are attenuated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



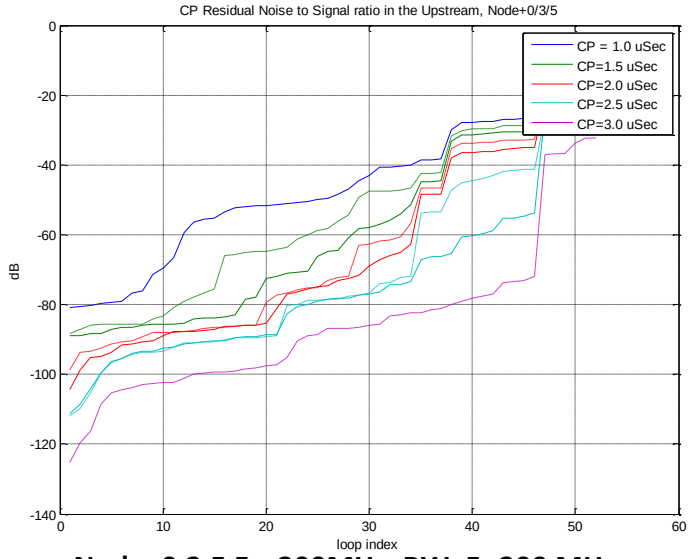


CP size and ISI - Upstream

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



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=0.9uS)
  - 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: : 40 MHz: 200 Mbps