PHY Link Channel

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Definition of PHY Link Channel (PLC)

- Downstream:
  - PLC broadcasts information necessary to enable the operation of the PHY layer (e.g., proper demodulation and decoding of data)
  - PLC conveys CNU-specific information (supported MCS in US, power control commands, timing advance commands)
- Upstream:
  - PLC collects CNU-specific information (e.g., supported MCS in DS)
  - PLC transmission allows estimation of supported MCS in US (sounding), power control, timing advance commands
- In order to ensure **scalability**, each PHY channel (192MHz) has its own, dedicated PLC
- The standard will **not** mandate to place PLC in a specific frequency location (e.g., around DC subcarrier)
- PLC does **not** convey MAC Control information (GATE/REPORT messages)

Requirements for PHY Link Channel

- Must be detectable by any new CNU trying to join the network
- Center frequency of PLC is not necessarily the same as center frequency of the corresponding OFDM Channel
- CNU doesn’t need any information on OFDM channel frequency usage, FFT size and CP size, except for a raster of the PLC center frequencies
- PLC is **transparent to upper layers**
  - No additional buffering requirements
  - No additional jitter and latency

Downstream PLC

Purpose of PLC

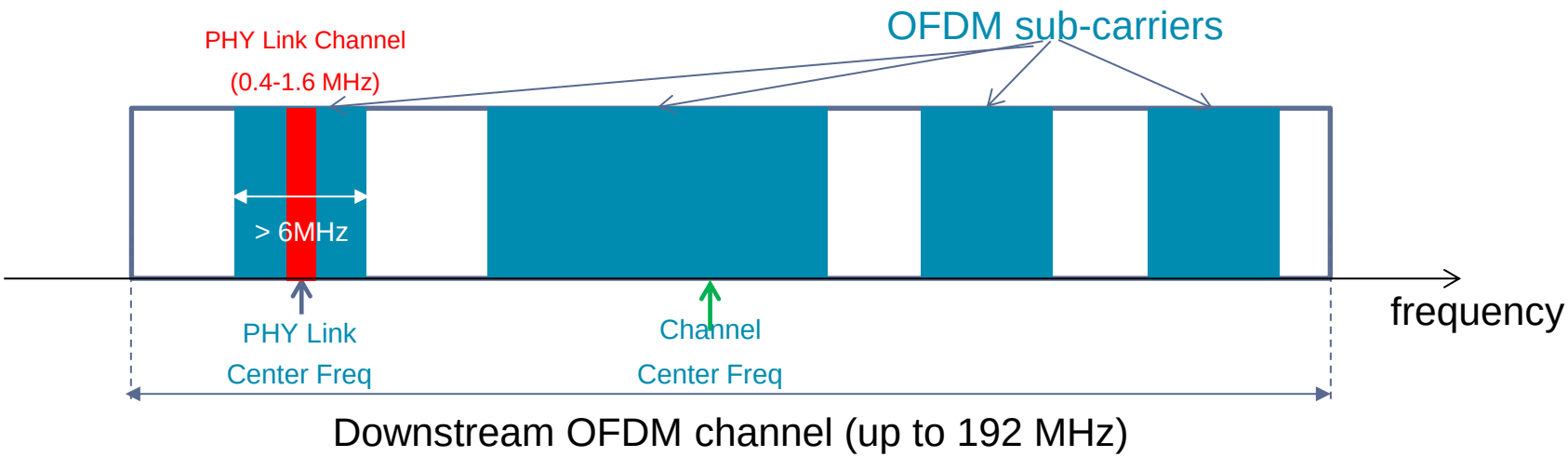
- Example to information carried by the PLC Data:
  - OFDM channel ID
  - DS Bandwidth (Number of available sub-carriers in this OFDM channel)
  - Exclusion bands, e.g.,
    - Start frequency of each EB
    - Stop frequency of each EB
  - DS Continuous Pilots locations
  - Information regarding PHY frame structure
    - TDD split in terms of US/DS OFDM symbols and guard interval
    - FDD US information: carrier frequency, number of available subcarriers
  - Frequency Interleaving pattern (logical to physical subcarrier mapping)
  - Time Interleaving depth for DS
  - Active profiles (active MCS's)
  - **Timing advance information for specific CNU(s)**
  - **Assignment of specific CNU(s) to a given DS/US profile**
  - **Power control information for specific CNU(s)**

Broadcast Message

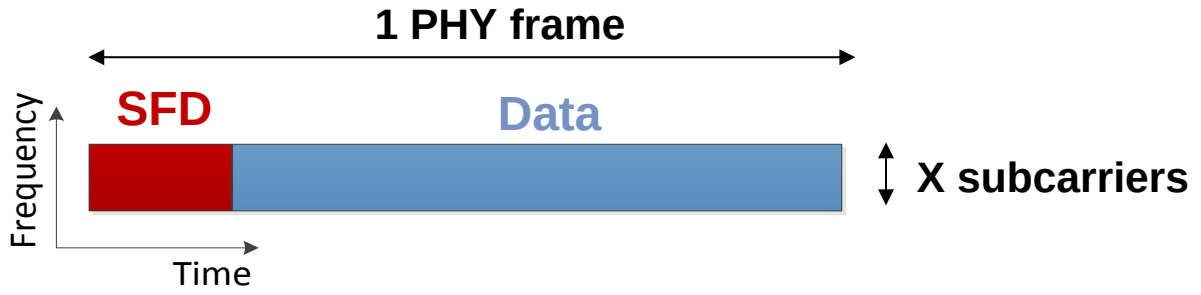
Message for a specific CNU

PLC Structure /1

- QAM16 constellation for data
  - ~12 dB more robustness to AWGN than QAM256 to protect against bad SNR with a simple error correction code
- Forward Error Correction code
  - Provides more robustness against channel notches and noise bursts
  - Short code to reduce latency and complexity
- Center frequency is located at one of today's DOCSIS center frequencies (as determined by EIA or other channel plan in use by operator)



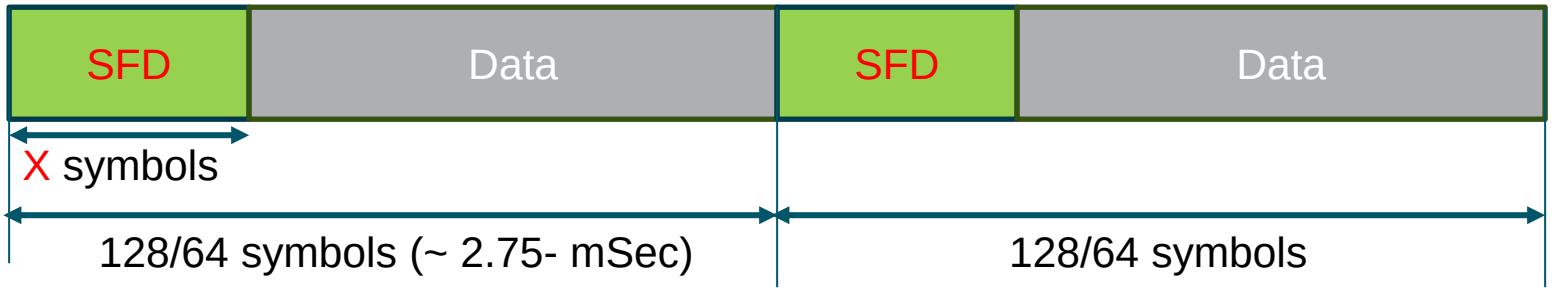
PLC Structure /2



- PLC includes Start-of-Frame Delimiter (SFD) for FEC word alignment
- PLC SFD and Data are repeated every PHY frame (corresponds to pilot repetition period)
- Uses **dedicated subcarriers**
  - **8, 16, 32 subcarriers for 4k FFT size**
  - **16, 32, 64 subcarriers for 8k FFT size**
- **Reducing** the number of subcarriers for PLC Data
  - Time interleaving gains against burst noise (FEC codeword is spread over multiple symbols)
  - Small overhead even if very few resources are available
- **Increasing** the number of subcarriers for PLC Data
  - Frequency interleaving gains against channel notches
  - Negligible overhead if available bandwidth is larger than 24MHz

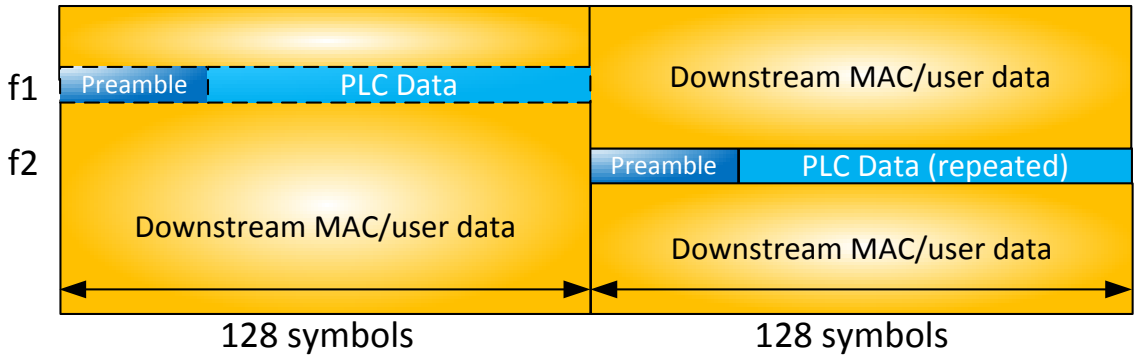
Start-of-Frame Delimiter (SFD)

- Sent only on the subcarriers dedicated to the PLC
- Enables alignment to PLC FEC codeword and aids the detection of the PLC
- Consists of a BPSK PN sequence in frequency
- Eight symbol SFD gives excellent robustness at bad SNR
- SFD is repeated every 128 (4k FFT) or 64 (8k FFT) OFDM symbols for FDD, 256 or 128 OFDM symbols for TDD
  - This gives a SFD interval of ~2.75 mSec with CP=1.5uS in the FDD case
  - Could use a different number of symbols, but fixed in the spec
  - Trade-off between resources employed for SFD and PLC data throughput
  - For FDD, it could be aligned with rotating pilot cycle so that pilots do not interrupt SFD



PLC Robustness Against Burst Events and Ingress

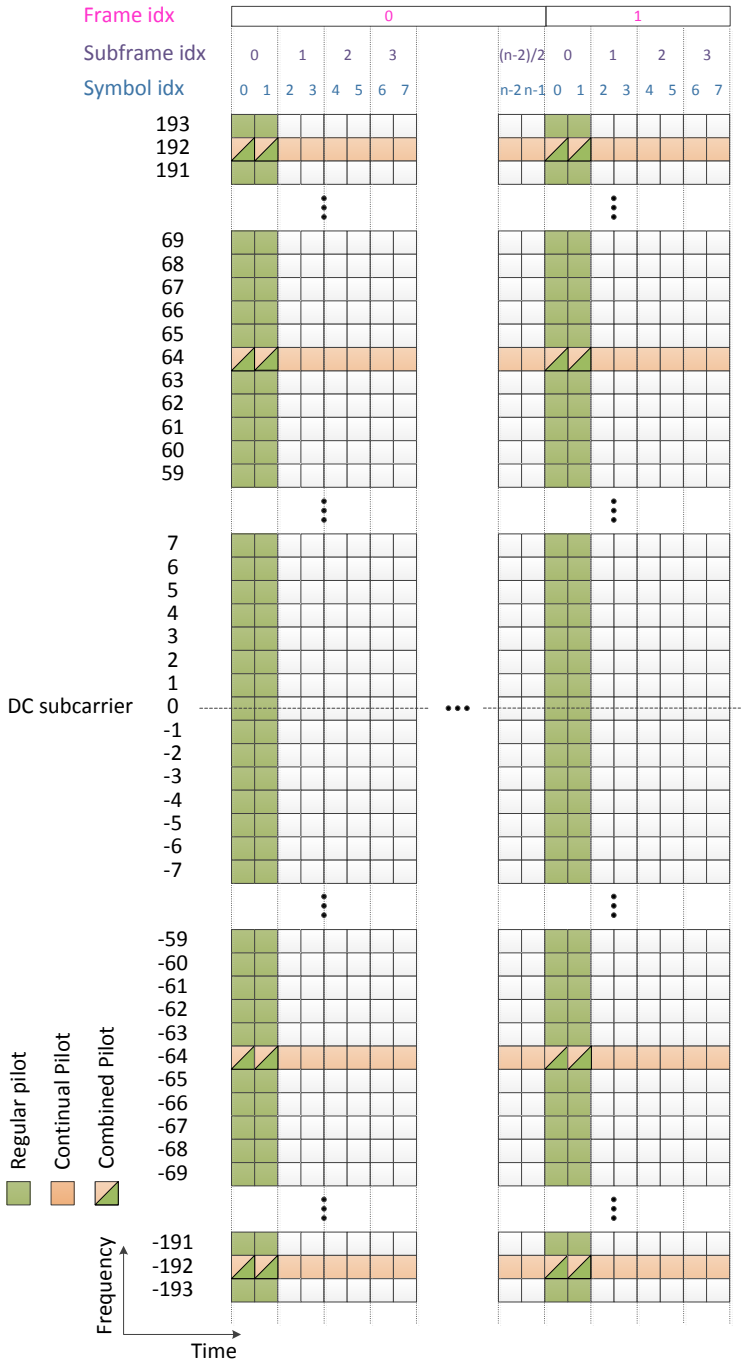
- Consider Forward Error Correction code to improve robustness
  - Trade code performance (code rate) with latency to determine FEC
  - Is robustness against burst noise is required?
  - A burst event will only affect one to two OFDM symbols
    - FEC can readily be designed to correct for this
- Ingress, narrowband notches, etc.:
  - Ingress is often predictable; locate channel where ingressors are not expected
    - CLT is capable of moving the PLC channel if required
  - For narrowband notches (possibly seen by certain modems due to local micro-reflections), coded QAM 16 constellation gives an additional 12 dB or more robustness (compared to QAM 256 or higher)
- With multiple OFDM channels use a PLC on each channel
  - Increase robustness
  - Expedite detection
  - If this is not adequate, PLC can be duplicated at two different frequencies
  - Or, the channel could alternate between two different frequencies, with the same information being sent on both



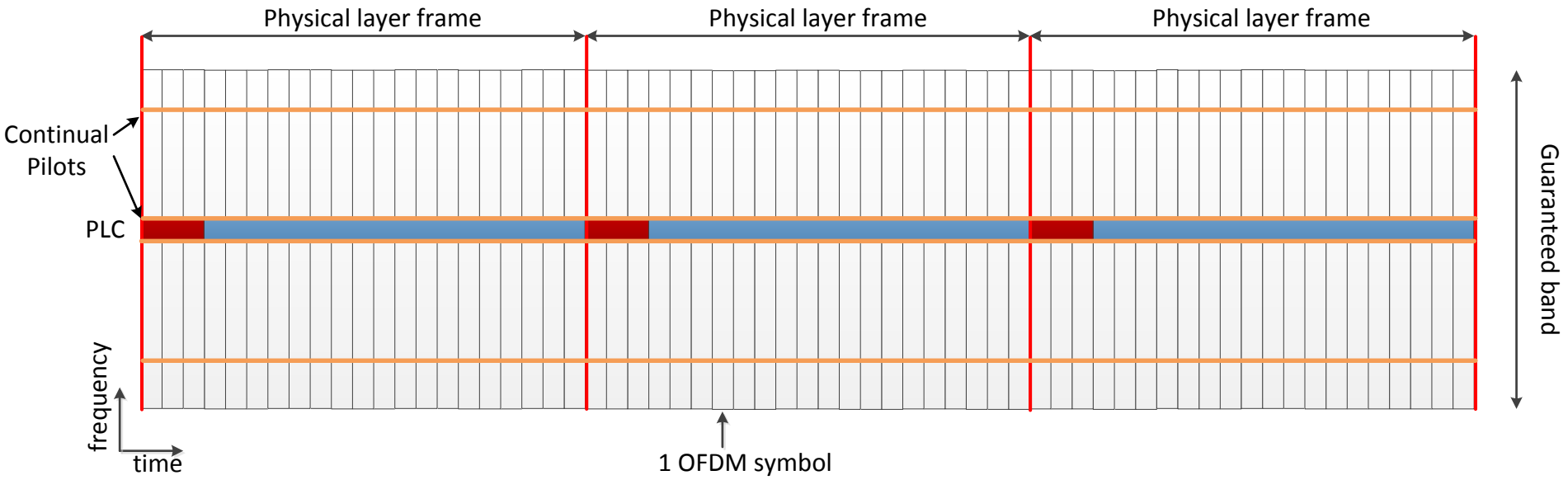
Proposed PHY Frame Structure

- **Regular pilot symbols** (this example shows the TDD configuration)

- **Continual pilot symbols**:
  - Present on every OFDM symbol (just like PLC)
  - With 50kHz spacing, continual pilot symbols occur every 128 subcarriers (i.e., at the borders of legacy 6MHz channels)
  - **Not** transmitted within exclusion bands
  - **Additional continual pilots** can be used as edge pilots at the borders of each exclusion band (configured via PLC)
  - Used to track channel variations (e.g., phase tracking), improve channel estimate and **locate the PLC (searcher algorithm)**

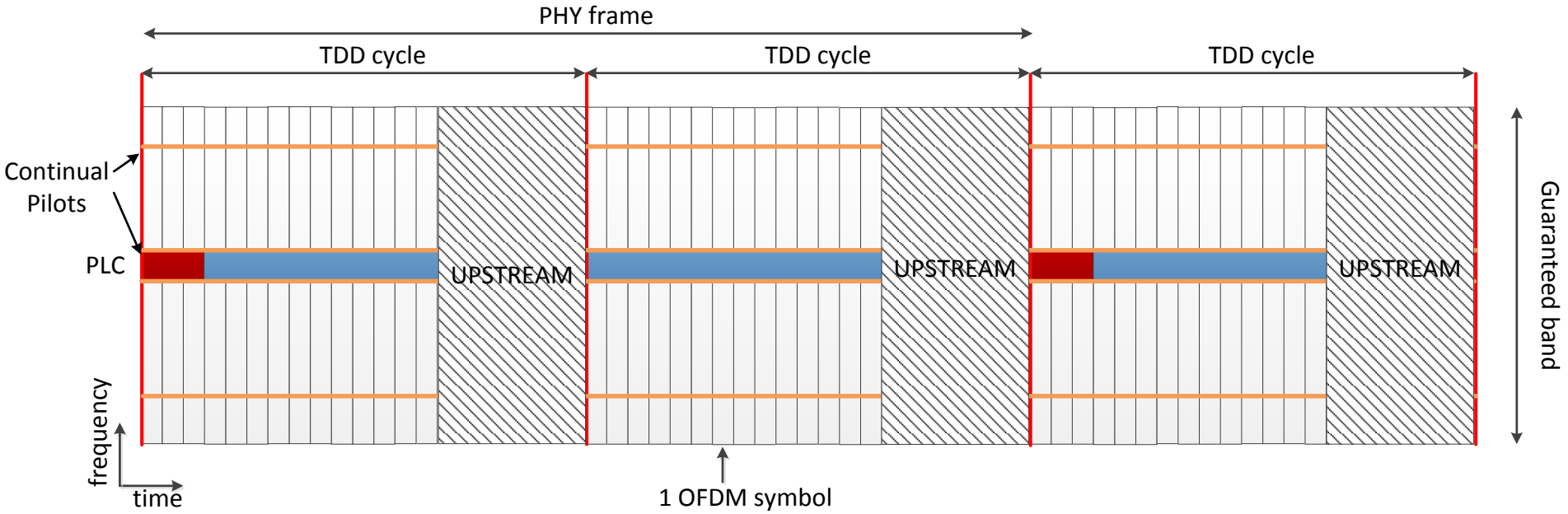


Resources Reserved for PLC



- The standard will define the notion of **minimum guaranteed continuous band**
  - No exclusion bands and nulled subcarriers are allowed within at least a portion of the channel as wide as this minimum band
  - Possible values: **6MHz, 12MHz, 24 MHz**
- PLC is placed at the center of such a band
- **Additional continual pilots** are placed within such a band, **symmetrically** with respect to the PLC (see figure)
- **Searcher algorithm** is based on the continual pilots related to the PLC

TDD-specific Aspects



- SFD and PLC data repeated every 256 OFDM symbols (TDD DS PHY frame duration)
- PLC provides information on
  - TDD cycle duration and DS/US split (i.e., DS and US time-slot duration)
  - TDD guard interval duration
- SFD located at the start of DS time-slot
  - As for FDD, PLC enables PHY frame synchronization and alignment to the TDD DS/US cycle

Initial Acquisition Sequence

- Scan designated channel plan (6 MHz or 8 MHz) looking for continual pilots and/or PLC SFD
  - The sequence below is an example and is implementation dependent
  1. Find FFT size and CP size using correlation
  2. Find FFT boundaries
  3. Find fractional frequency offset
  4. Find continual pilots (and integer frequency offset)
  5. Find SFD (Preamble)
  6. Estimate channel using SFD

  All should be accomplished in a single Preamble period on the average
- Begin receiving PLC
- Decode PLC to find messages describing OFDM channel parameters (center frequency, available sub-carriers, FEC/Interleaving pointers, profile, pilots …)
- Start Admission process and Ranging
- Begin receiving Data

Detection of the Downstream PLC –1

Simulation Setup /1

- Searcher outcome:
  - OFDM symbol boundary estimate
  - Carrier Frequency Offset estimate
- Carrier Frequency Offset (CFO)
  - Fractional CFO
  - Integer CFO (alignment to PLC subcarriers)

$$CFO = k\Delta_{SC} + \delta$$

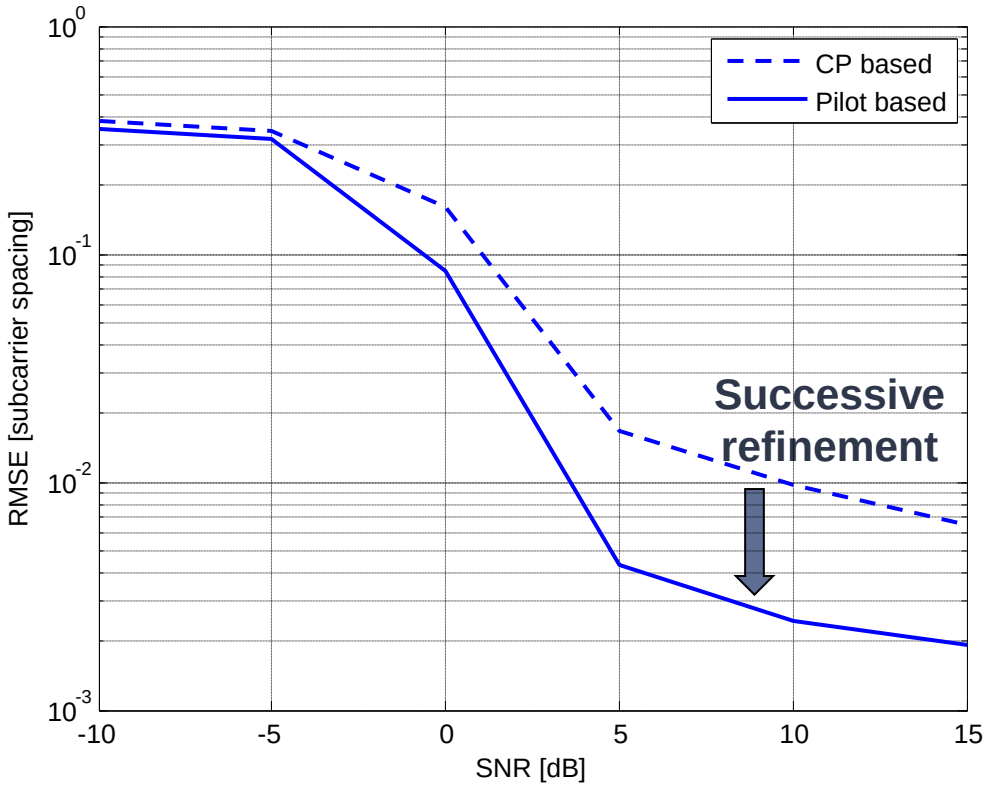
- Searcher operation:
  - Searcher processes **12 consecutive symbols**
  - **Time domain processing**
    - Perform OFDM symbol boundary search
    - Perform fractional CFO estimation and correction
  - **Frequency domain processing**
    - Search for continual pilots (integer CFO estimation)
    - Re-estimate fractional CFO

Simulation Setup /2

- Minimum guaranteed continuous band of 25.6MHz
- 4k FFT size (50kHz subcarrier spacing)
  - 512 subcarriers
- **4 continual pilots** available for acquisition (1 every 128 subcarriers)
- +4.76dB pilot boost
- ReDeSign Channel Model 2
  - Unrealistic according to some: >12dB dynamic range within 6MHz
- Sampling frequency offset: 80ppm
- Integer CFO k : 10
- Fractional CFO δ : 0.26 x 50kHz
- Total CFO : 513kHz

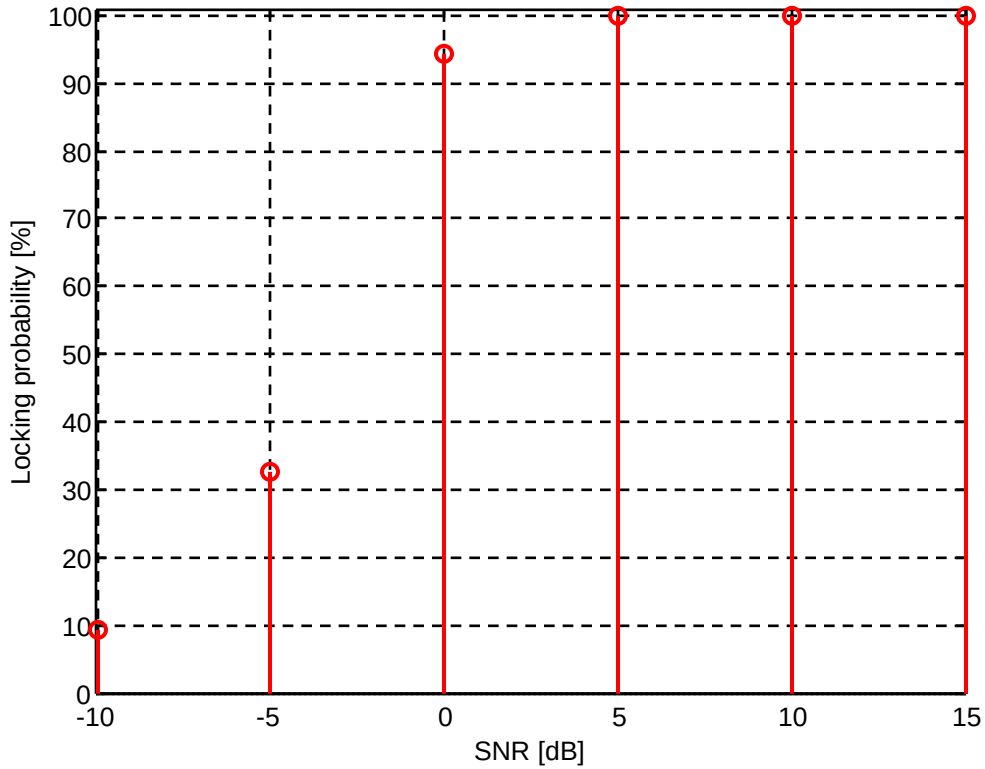
Simulation Results /1

- Fractional CFO estimation
  - **Time domain**
    - CP-based fractional CFO estimation
  - **Frequency domain**
    - Pilot-based fractional CFO estimation (refinement of CP-based estimate):



Simulation Results /2

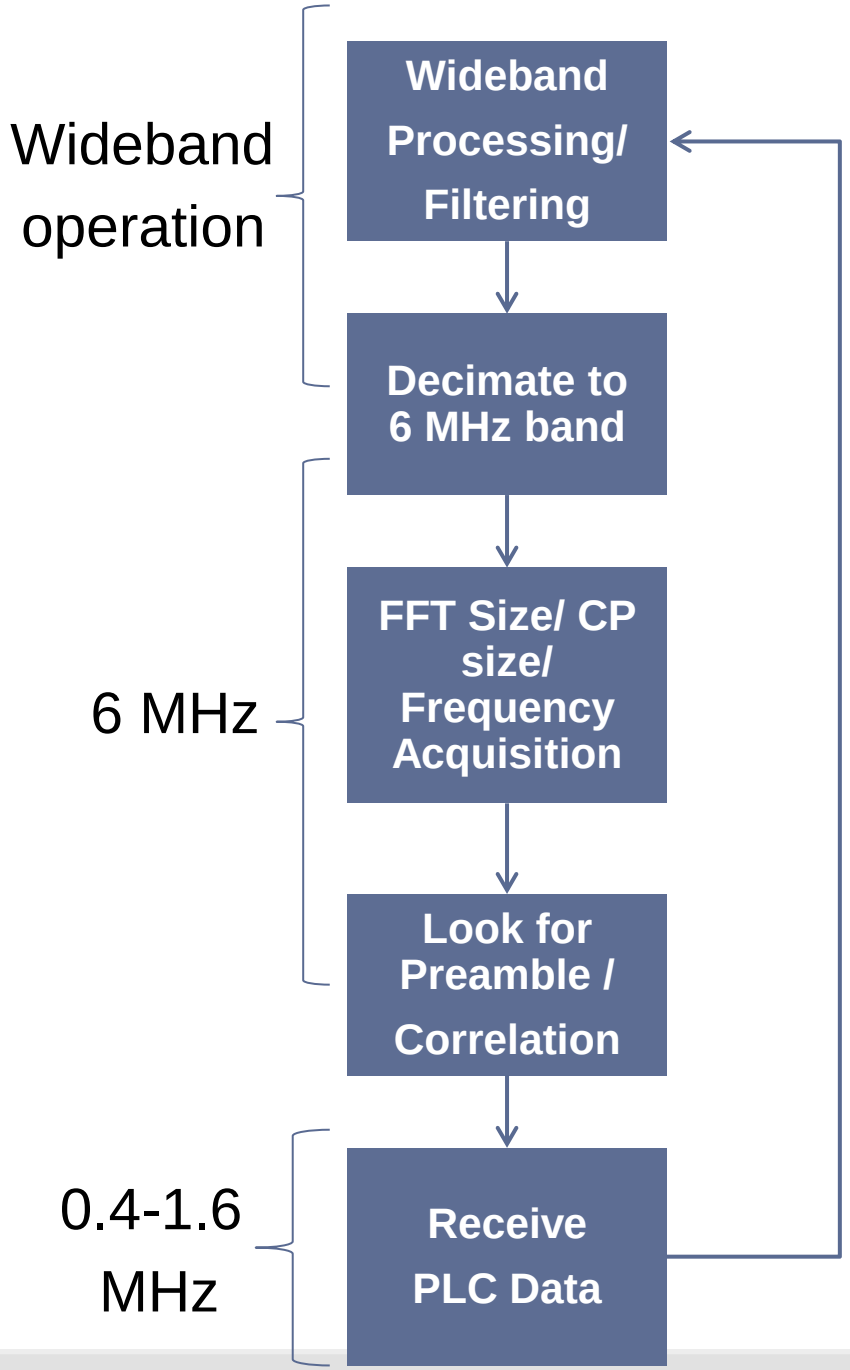
- Integer CFO estimation (subcarrier index alignment)
  - **Frequency domain**
    - Search for continual pilots (integer CFO estimation)
- Success probability:



Detection of the Downstream PLC – 2

PLC receiver tasks at Initialization

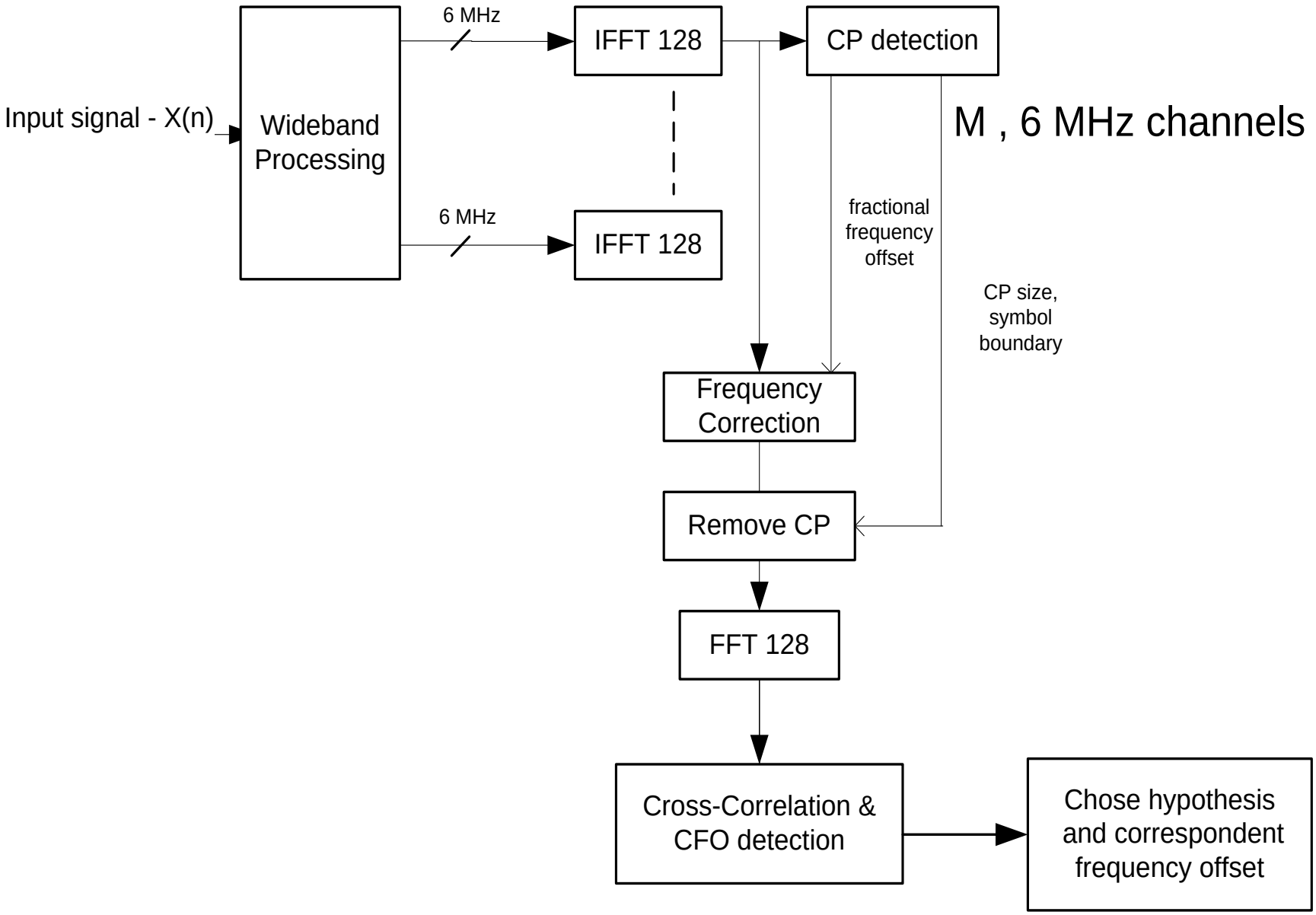
- Wideband processing and decimation
  - Divide the full-band into M 6 MHz signals around Center frequency raster
  - Look for FFT size/ CP size among hypothesis crossing a threshold
  - Recover timing and frequency
  - Find FFT boundary
- Using best CP size look for Preamble
- Preamble search can done serially or in parallel on multi 6 MHz bands
  - Trade complexity and acquisition time
- Preamble detector a very simple 8-tap 1-bit Correlator
- For fast detection use M such Correlators



Preamble Acquisition Time

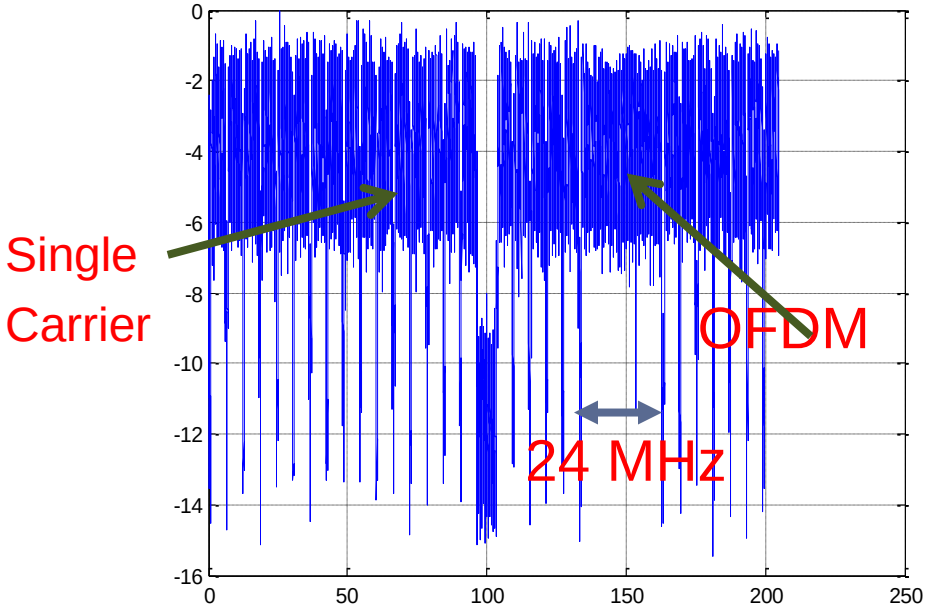
- Preamble every 64/128 symbols (2.75 mSec)
- Scan 150 frequencies
- CP / FFT detection takes
  - 64 uSec to detect the CP/FFT
  - 10 hypothesis done serially < 25 mSec
  - Search time depends on OFDM band
- Serial Preamble detection
  - Worst case Preamble detection time ~ 0.5 Sec (150*2.75)
- Parallel Preamble detection (e.g. M=32)
  - Worst case Preamble detection time ~ 15.5 mSec

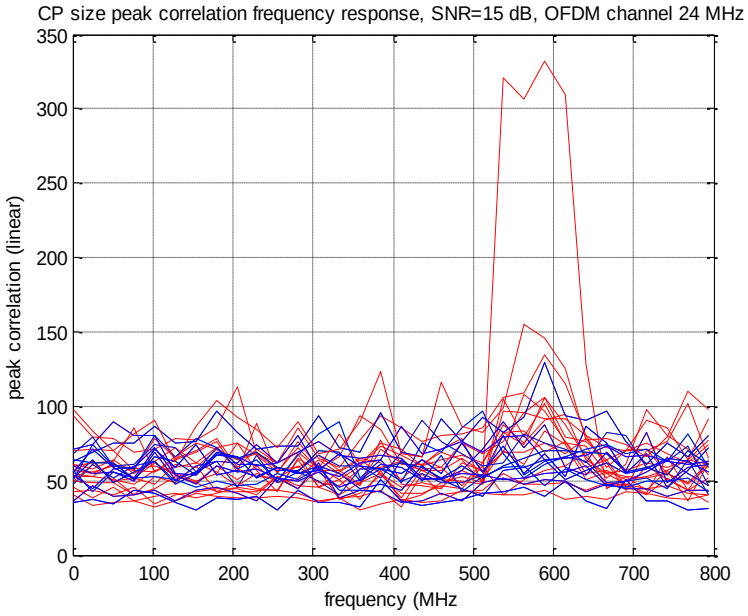
CP size, Frequency and PLC detection scheme

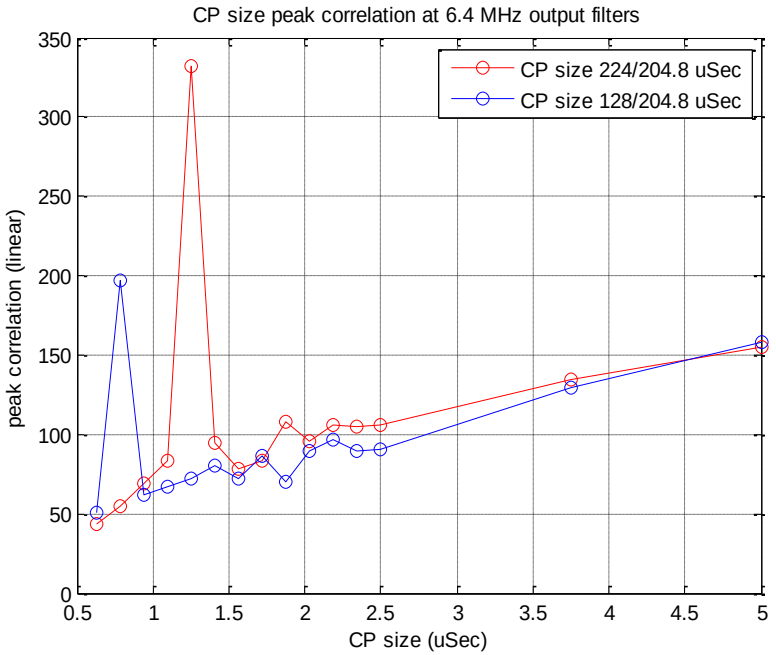


CP Size Recovery with LEAGACY Services (1)

- 192 MHz band with 24 MHz OFDM and rest is single carrier signals
- CP resolution is 32/204.8 = 0.16 uSec
- SNR = 15 dB
- Carrier and sampling frequency offsets: 170 ppm
- Actual CP sizes of 0.625 uSec and 1.09 uSec
- FFT Size = 4K
- TX window included







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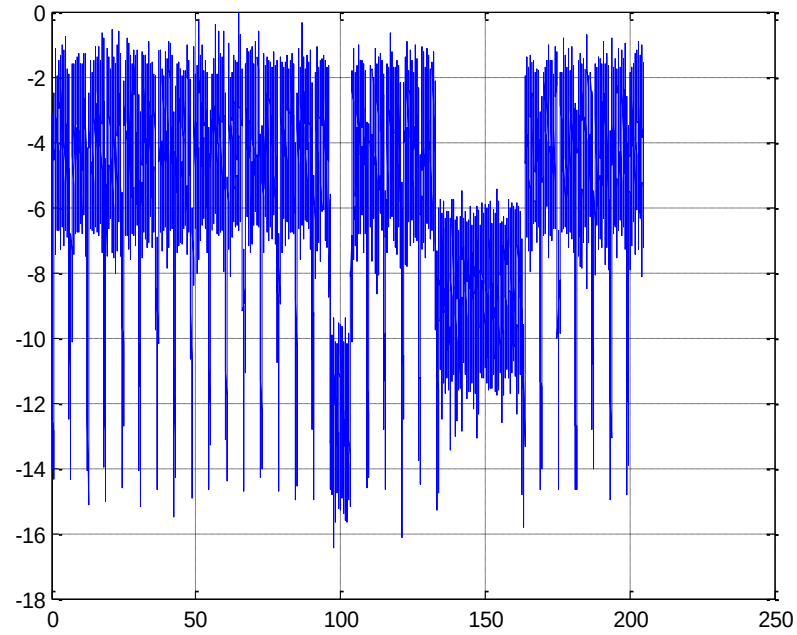
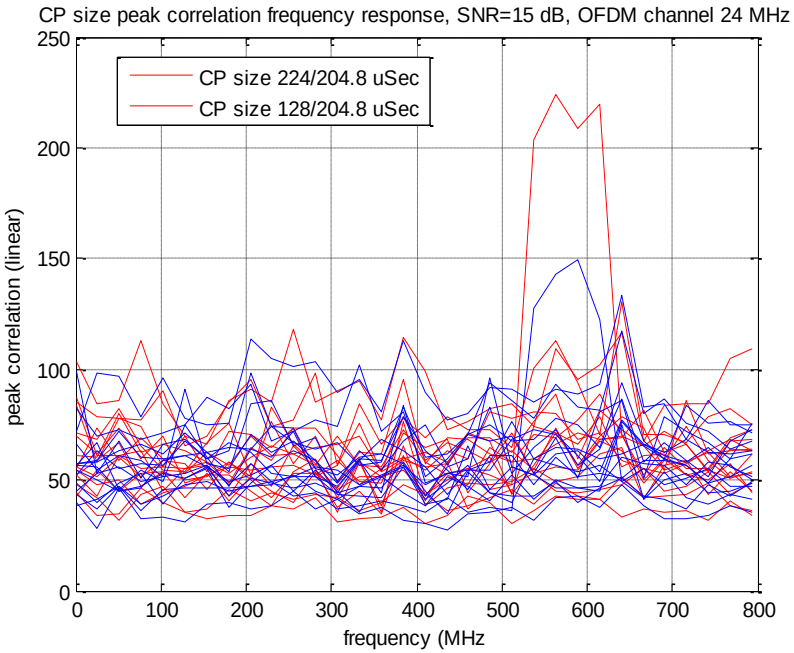
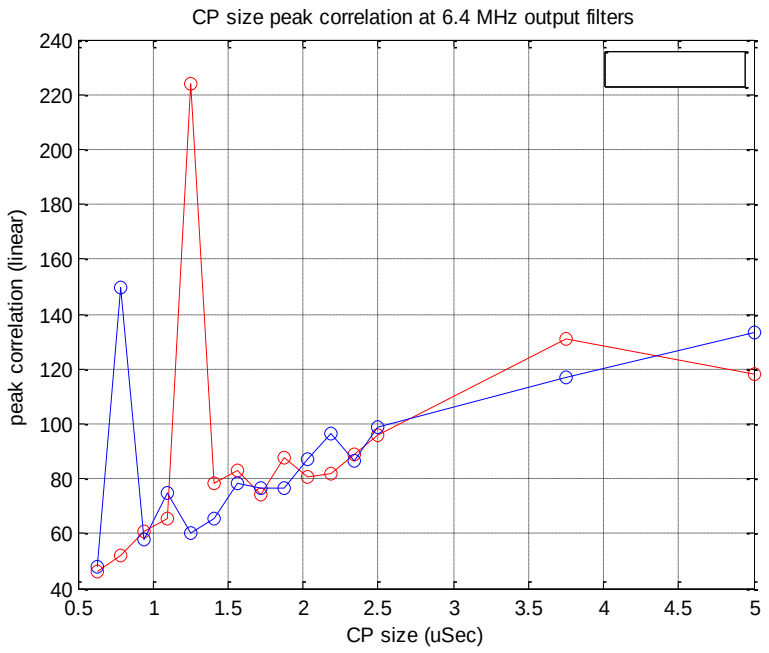
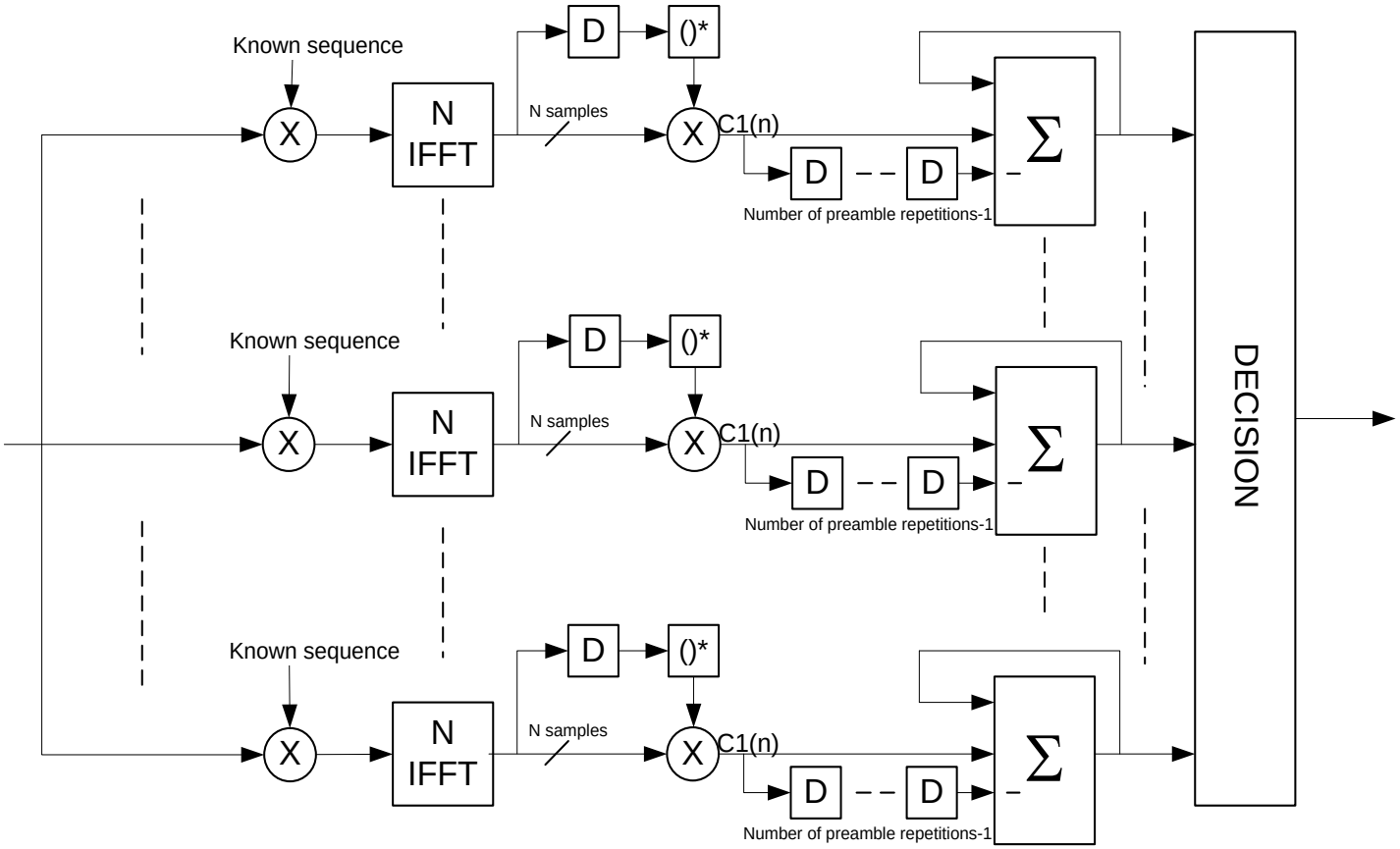






Cross correlation and CFO detection



- N = Preamble length (8,16,32)
- Correlator has N “multipliers by 1 bit
- The Small FFT and Correlator blocks allow to use parallel data to expedite acquisition time

SFD Detection Performance

- SFD detection performance
  - SFD is a repetition of a PN sequence in the frequency domain
  - Detection probability vs. SNR with different numbers of symbols and sub-carriers were simulated
  - Results depicted in table below

Number of symbols with 99.9% Preambles detection

Num of sub carriers	Numer of symbols		
	SNR = 10 dB	SNR = 15 dB	SNR = 25 dB
32	4	4	4
16	6	4	4
8	8	6	4

Final Proposal

Proposal for PLC

- In order to ensure **scalability**, each PHY channel (192MHz) has its own, dedicated PLC
- The standard will **not** mandate to place PLC in a specific frequency location (e.g., around DC subcarrier)
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