OFDM Numerology

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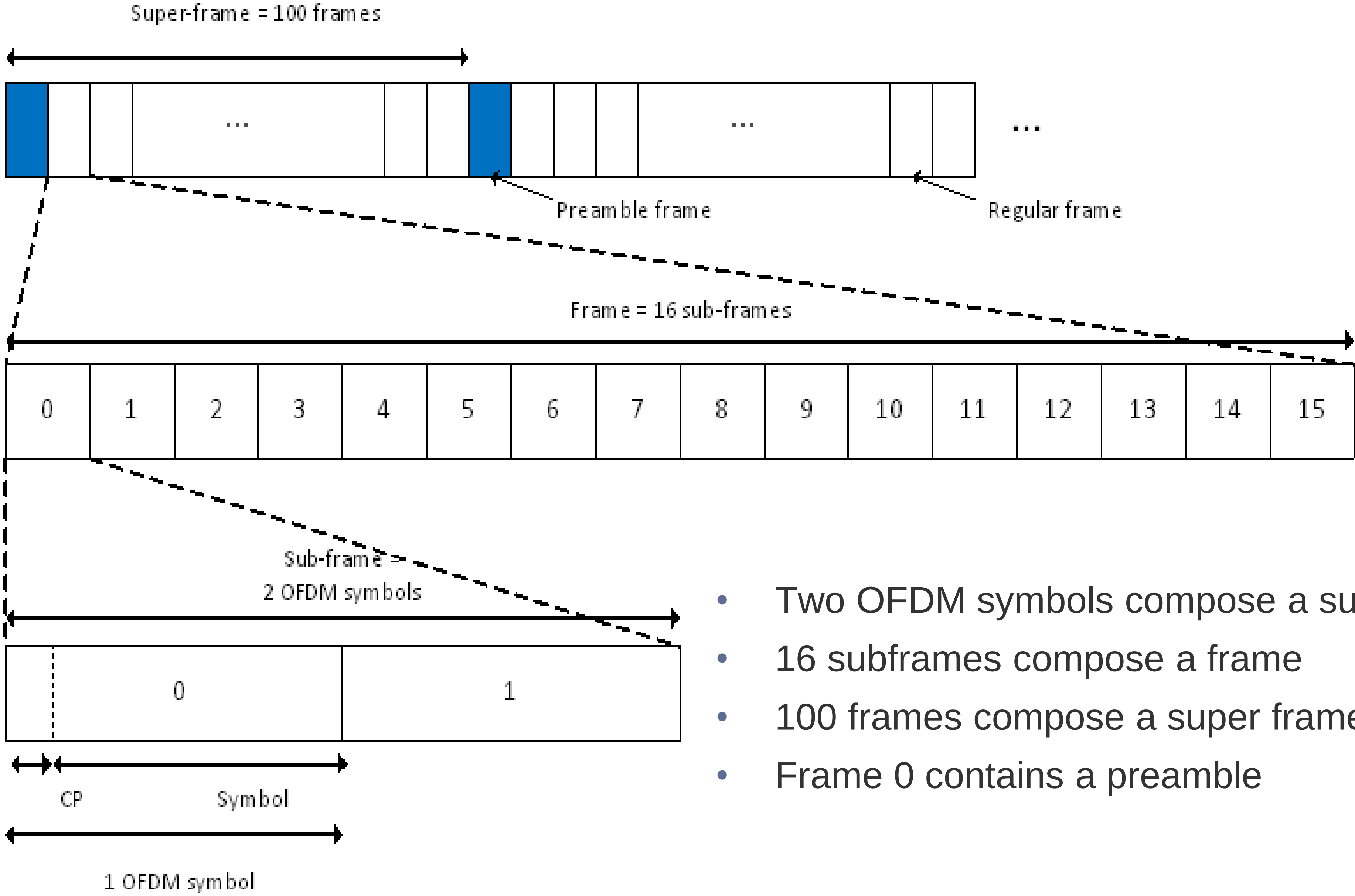
Outline

- Downstream Numerology Overview
- Frame Structure and Pilot Structure
- CP Impact Analysis
- FEC Proposal
- Time Domain Interleaving

Downstream Numerology Overview

- OFDM Numerology
  - Subcarrier spacing 12.5 kHz
  - FFT size = 16384 with sampling frequency of 204.8 MHz
    - 15200 available subcarrier in 190 MHz of OFDM block
  - Cyclic prefix: configurable size between 1.25 μs and 5 μs
  - Constellation size: Even constellations from 256QAM to 4096QAM
- Pilots
  - 1 pilot symbol every 64 subcarrier in each OFDM symbol
  - Pilots spread over a frame of 32 OFDM symbols
  - Pilot overhead is 1/64
- Interleaving
  - Time domain interleaving is configurable: different levels or none
  - Frequency domain interleaving
    - Across code blocks within one OFDM symbol
    - Each code block sees similar SNR conditions

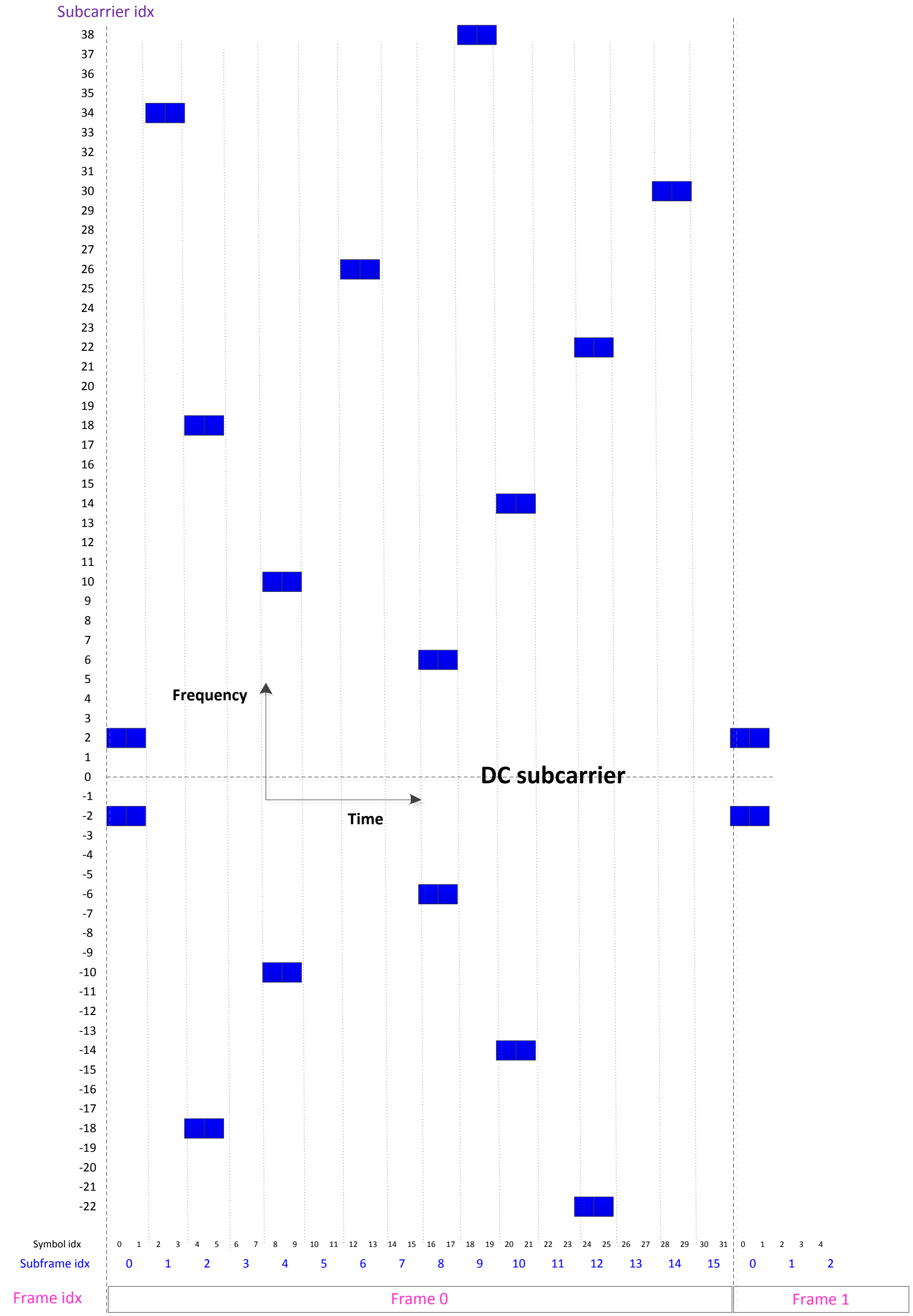
Frame Structure



- Two OFDM symbols compose a subframe
- 16 subframes compose a frame
- 100 frames compose a super frame
- Frame 0 contains a preamble

Pilot Structure (Details)

- 1 pilot subcarrier every 64 subcarriers in each OFDM symbol (except around center frequency)
- Same pilot locations on two consecutive OFDM symbols (defining a subframe)
- Pilot positions symmetric with respect to center carrier frequency (DC subcarrier in baseband)
- Staggered in frequency over time to yield a regular pilot pattern with 1 pilot every 4 subcarriers
    - 32 OFDM symbols compose a frame
    - Effectively, OFDM symbols with 16 different pilot positions
    - Single channel estimate every 32 OFDM symbols (i.e. one per frame)
- No need for additional pilots



Pilot Structure (Details)

- Staggered Pilots:
  - Reduces pilot overhead to 1/64 = 1.56%
- Same Pilot position in a subframe:
  - Enables continuous tracking of phase noise and carrier frequency offset
- Symmetric pilots round carrier frequency:
  - Enables correction of Tx IQ mismatch and RX IQ mismatch correction
- Effective pilot pattern with pilots on every fourth subcarrier:
  - With a maximal CP length (delay spread) of 4us, the minimal coherence bandwidth is 250kHz
  - 5 pilots in the coherence bandwidth (i.e. with 50 kHz spacing) is a reasonable choice

ReDeSign Channel Models Case 1 and Case 2

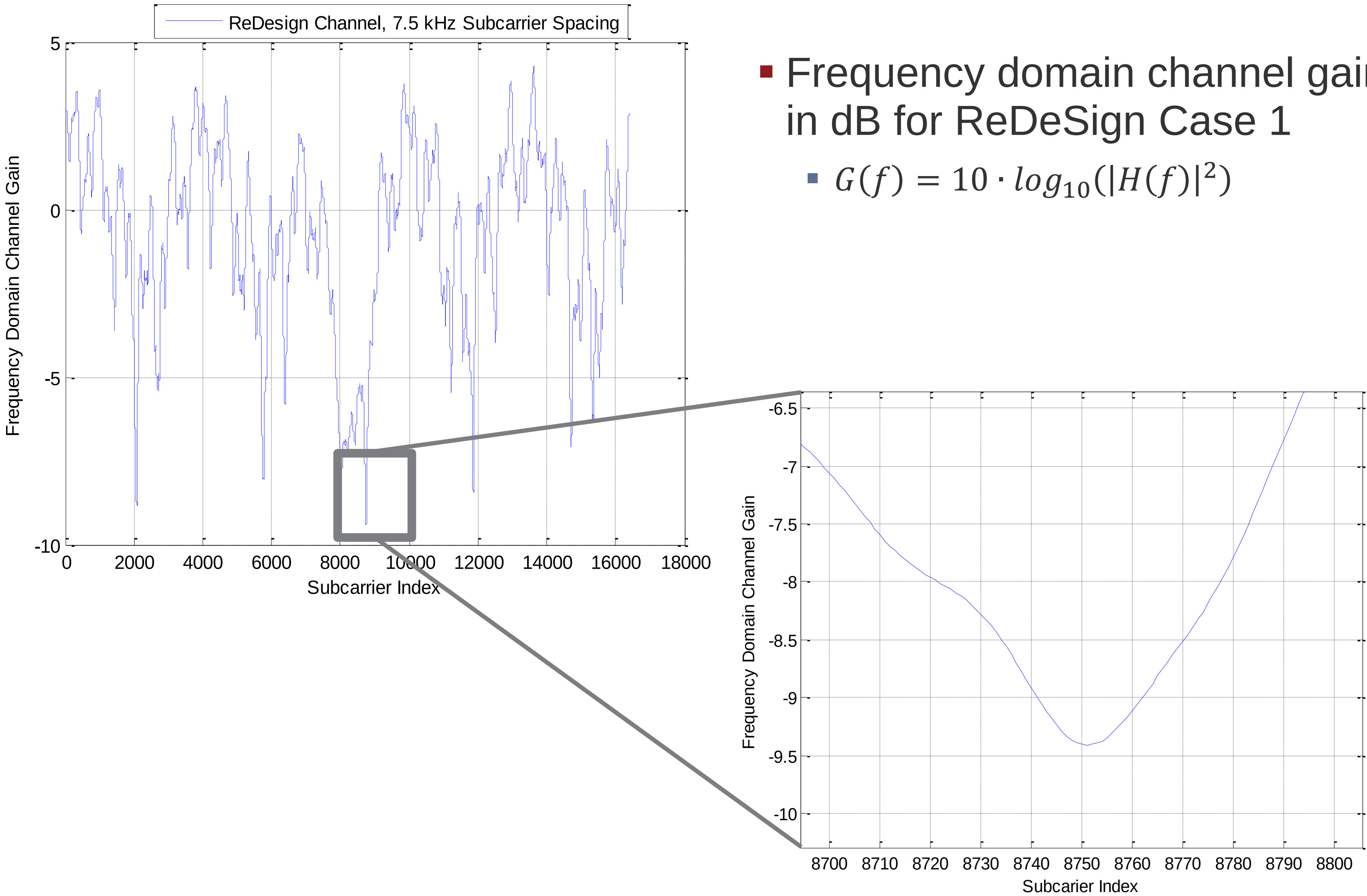
- ReDeSign Channel Model Case 1

	Power	Delay	Phase
	[dB]	[ns]	[rad]
Case 1	-11	38	0,95
	-14	181	1,67
	-17	427	0,26
	-23	809	1,20
	-32	1633	1,12
	-40	3708	0,81

- ReDeSign Channel Model Case 2

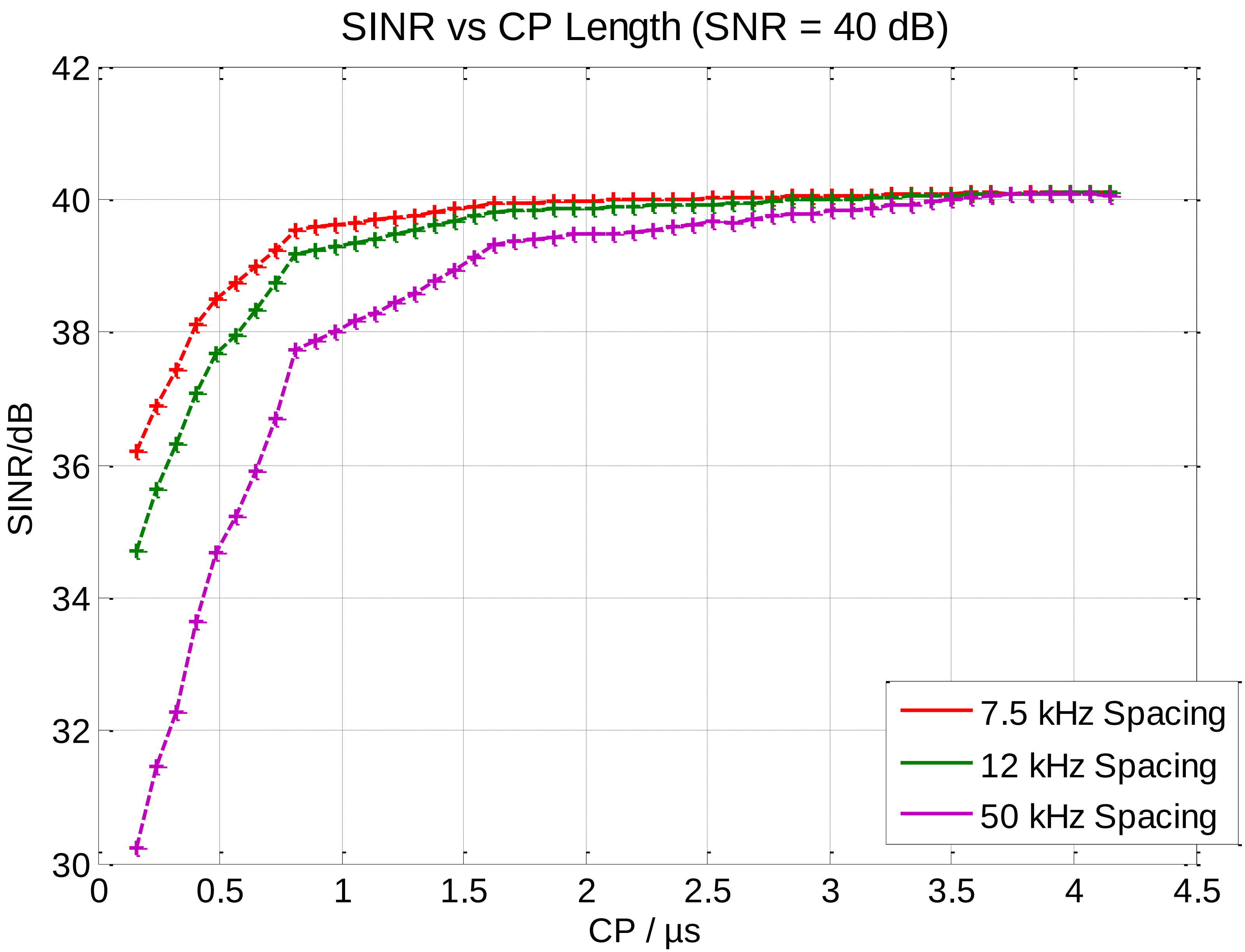
	Power	Delay	Phase
	[dB]	[ns]	[rad]
Case 2	-11	162	0,95
	-14	419	1,67
	-17	773	0,26
	-23	1191	1,20
	-32	2067	1,12
	-40	13792	0,81

Frequency Domain Channel Gain for ReDeSign

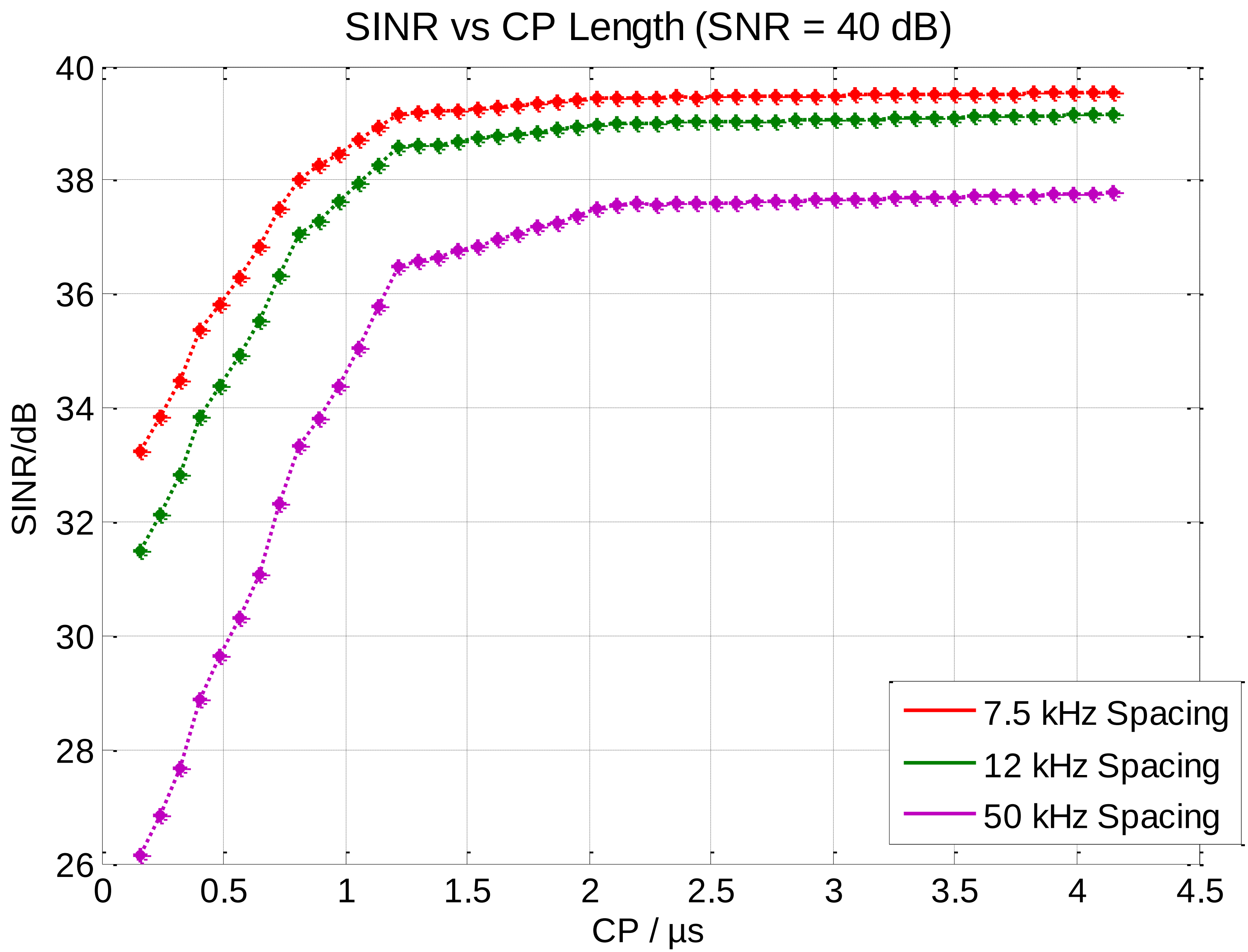


- Frequency domain channel gain in dB for ReDeSign Case 1
  - $G(f) = 10 \cdot log_{10}(|H(f)|^2)$

SINR at Demodulator Output – ReDeSign Case 1



SINR at Demodulator Output – ReDeSign Case 2

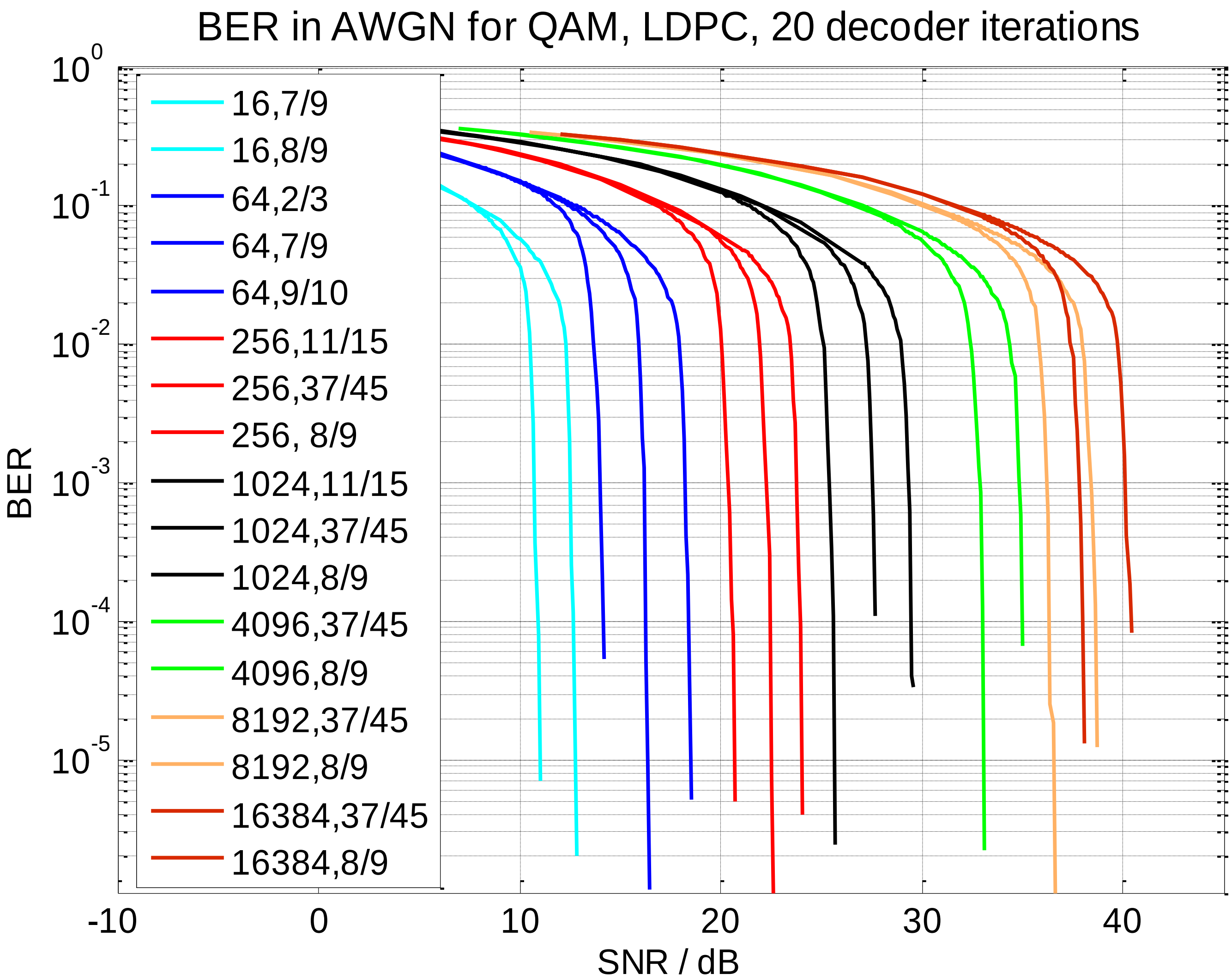


Forward Error Correction

- Downstream proposal: DVB-C2 LDPC codes
  - Common MCS per group of users enables the aggregation of Ethernet frames dedicated to multiple users of such a group into a single code word. (equivalent to multiple profiles approach)
  - It is anticipated that longer codes are more efficient when users are grouped
  - Applying the LDPC DVB-C2 codes is the preferred approach since they are well known and fully specified
    - Final decision will depend on the channel model

- Upstream proposal: IEEE 802.11n LDPC codes
  - The IEEE LDPC codes support short code word lengths that fit well with OFDMA
  - Analysis for AWGN and time dispersive channels has shown that performance is superior compared to RS codes of similar length
  - Code word lengths are optimized for Ethernet frame lengths

BER Curves for DVB-C2 LDPC Code – Example



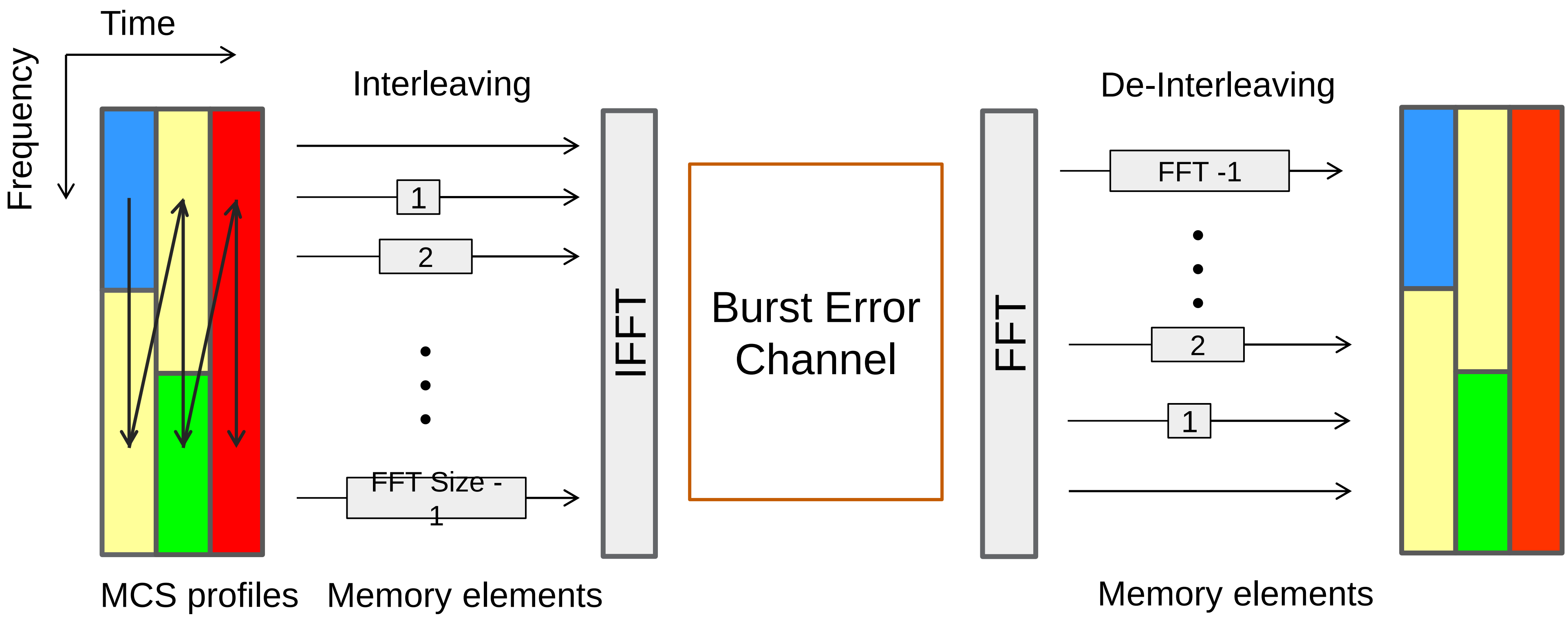
- Code word length 16200 bits w/o outer BCH code
- Gray mapping in I and Q
- Floating point LLR
- Note:
  8192 QAM is plotted for information. There is little benefit of using 8192 QAM over 4096 QAM and 16384 QAM

QAM Modulation and Outer Coding Proposal

- Downstream QAM Modulation
  - Preferred modulation alphabets are (16QAM), (64QAM), 256QAM, 1024QAM, and 4096QAM
  - Usage of odd modulation orders (32QAM), (128QAM), 512QAM, and 2048QAM is not preferred since it complicates processing like LLR computation. Similar performance can be achieved by choosing even modulation orders and appropriate coding rates.

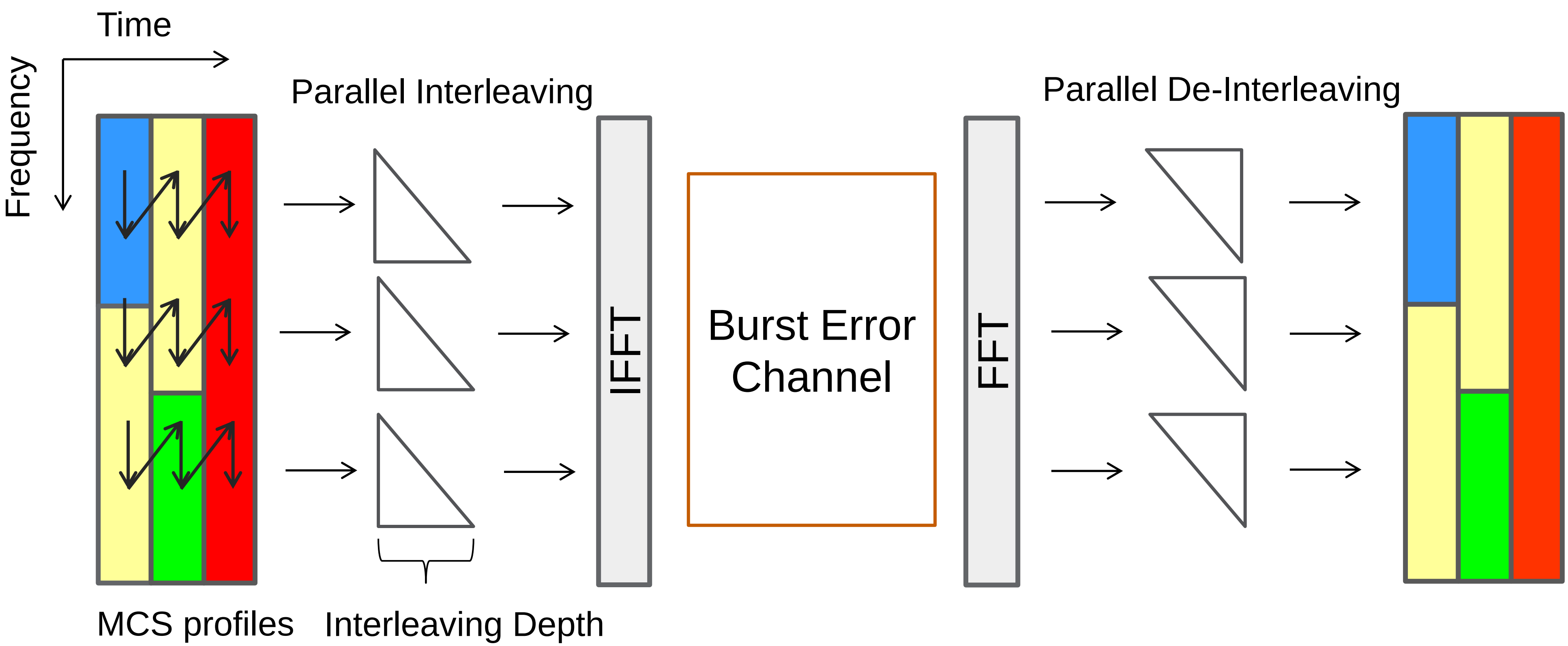
- Downstream Outer Coding
  - Preference is not applying an outer BCH code
  - This proposal may be revised of performance needs for an outer code are shown
    - Performance to be verified in time dispersive channels, burst noise, etc.

Direct Convolutional Time Interleaving



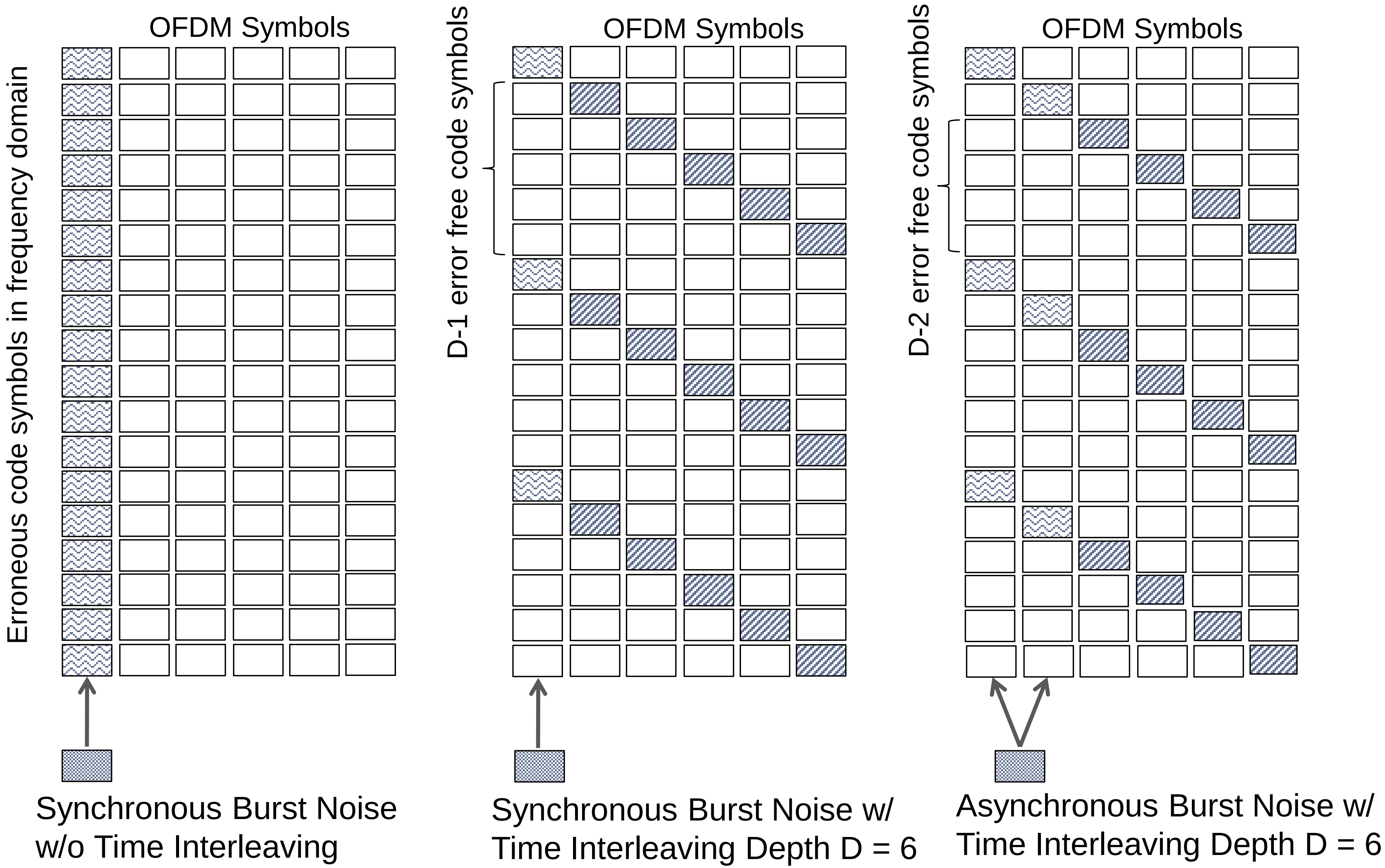
- Convolutional interleaving is applied at subcarrier level
- Convolutional interleaving delays each subcarrier in time
- For a time-invariant channel, interleaving across MCS profiles is possible
- But: Delay and memory consumption are excessive for direct interleaving
  - Required number of memory elements: 16k · (16k – 1) / 2 = 131064k

Parallel Convolutional Time Interleaving

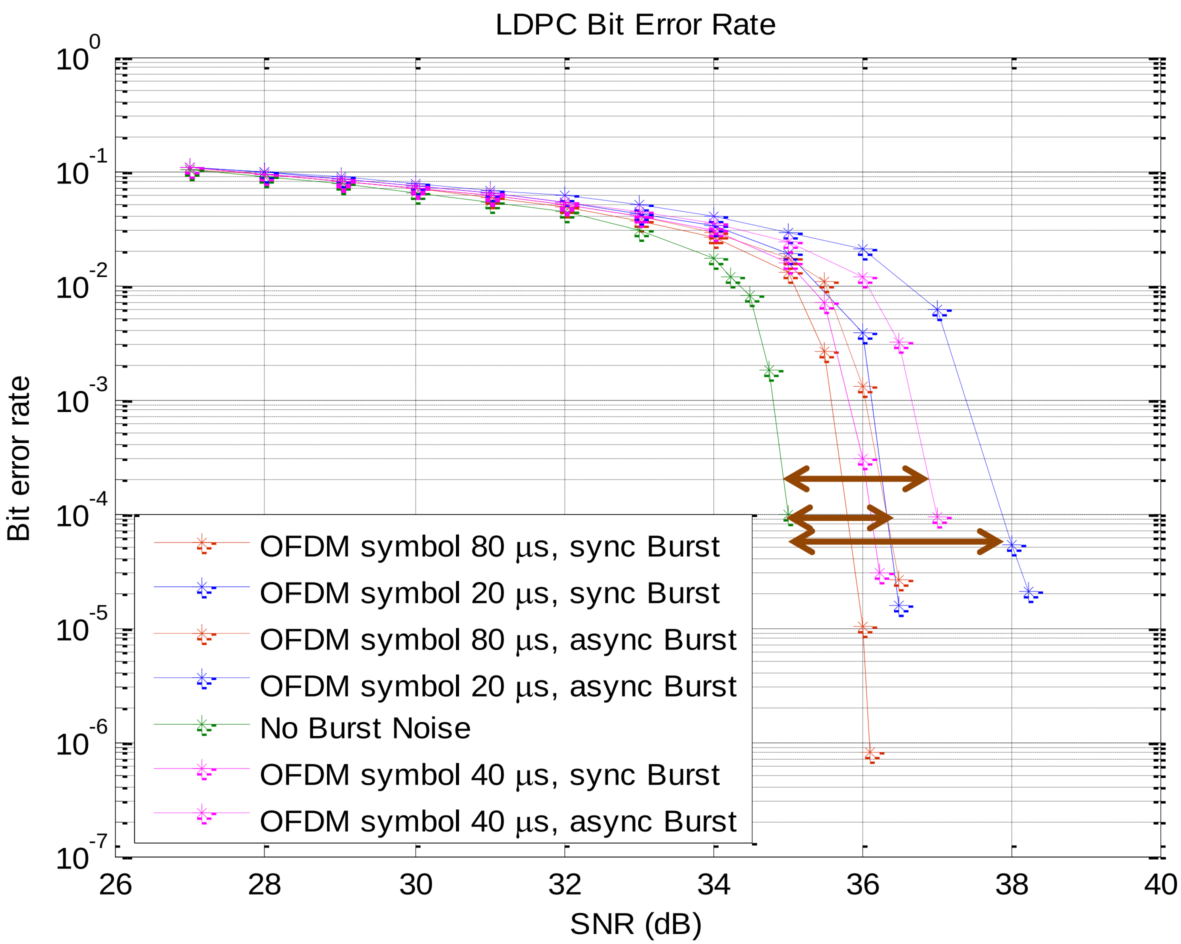


- Interleaver depth depends on the burst noise model
  - Interleaver depth is expected to be at most 16 OFDM symbols (similar to DVB-C2)
- For a 16k FFT, 16k/16 parallel interleavers are required
  - Required number of memory elements: 1025 · 16 · (16 – 1) / 2 = 120k

Parallel Convolutional Interleaving Structure



Performance when Asynchronous Burst Noise is Present



- Data Rate
  - 4096QAM
  - DVB-C2 LDPC code
    - Code length n = 16200 bits
    - Code rate R = 8/9, 20 Iterations
- OFDM Symbol Duration
  - 20, 40, 80 µs
- AWGN Channel Model
- Interleaver depth D = 16
- Burst Noise Assumptions
  - CIR = 20 dBc, duration = 20 µs
  - Gaussian distributed
  - Synchronous and symmetrically asynchronous to OFDM symbols

Loss ~ 1.2 dB for interleaver depth D = 16 and 80 µs OFDM symbol
Loss ~ 1.9 dB for interleaver depth D = 16 and 40 µs OFDM symbol
Loss ~ 2.9 dB for interleaver depth D = 16 and 20 µs OFDM symbol

Conclusions

- A frame structure was proposed with 1.6% pilot overhead
  - Pilot density supports channels with up to 4 μs delay spread
  - Pilot pattern allows for estimation of phase noise and I/Q imbalance
- The impact of CP length has been analyzed for ReDeSign channels
  - ReDeSign like channels require CP durations of almost 4 μs and long OFDM symbol for optimum performance
  - OFDM symbol duration of 80 μs is required for channels with long delay spread
- The DVB-C2 LDPC codes should be used in downstream
  - Main advantage is that they are fully specified and field-proven
- The need for time interleaving depends on the burst model and is for further study
  - Required interleaver depth depends on burst noise model and OFDM symbol duration
  - Longer OFDM symbols provide better protection against burst noise than shorter symbols

thank you