OFDM Numerology

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Outline

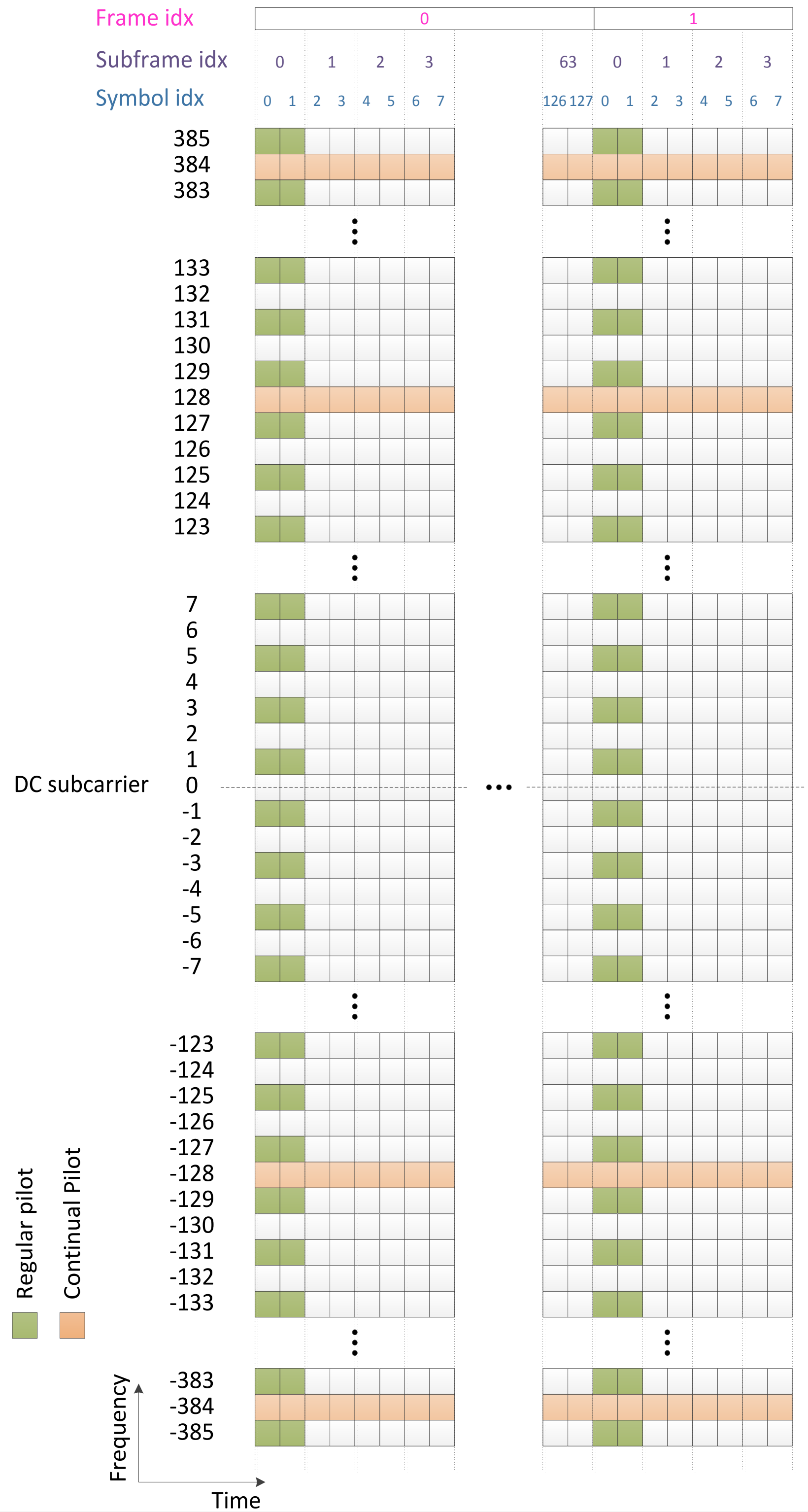
- Downstream Numerology Overview
- Frame Structure and Pilot Structure
- CP Impact Analysis
- Modulation and FEC Proposal
- Time Domain Interleaving

Downstream Numerology Overview

- OFDM numerology
  - Subcarrier spacing: 50 kHz and 25 kHz
  - FFT sizes: 4096 and 8192 with sampling frequency of 204.8 MHz
    - 3800 or 7600 available subcarrier in 190 MHz of OFDM block
  - Cyclic prefix: configurable: 1.25 μs, 2.5 μs, 3.75 μs, and 5 μs
  - Constellation size: Odd and even constellations from 256QAM to 4096QAM
- Frame structure
  - A frame consists of 128 (4k FFT) and 64 (8k FFT) subframes
  - A subframe consists of 2 OFDM symbols
- Pilots
  - Regular pilots only in subframe 0; used for full blown channel estimation
  - Continual pilots in all subframes; used for tracking
  - Pilot overhead: 1-2% based on FFT size
- 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

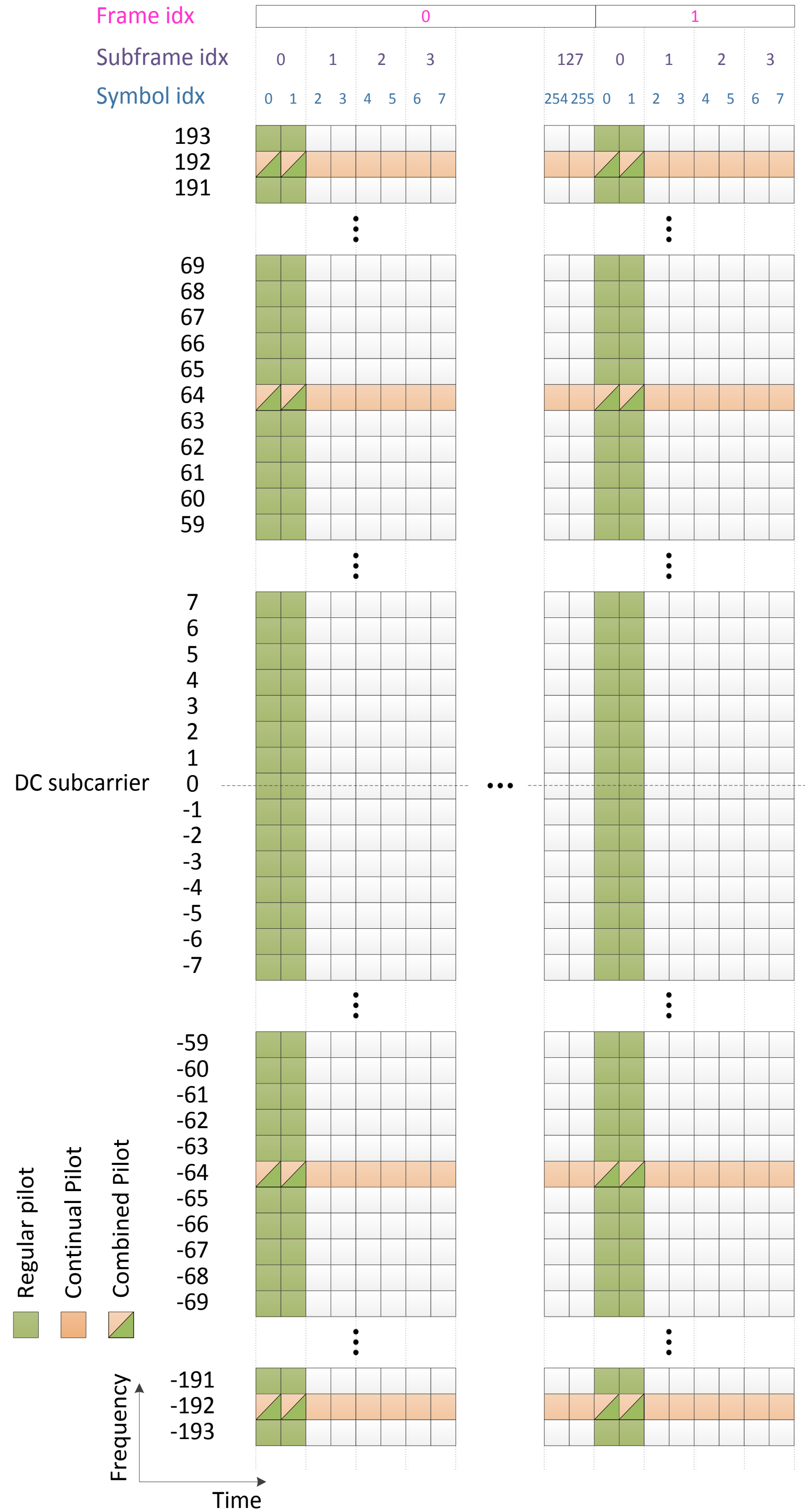
Pilot Structure: 25 kHz Spacing

- Symmetric pilots around center subcarrier
- Regular pilot symbols:
  - One pilot symbol on every second subcarrier
  - Two consecutive OFDM symbols with regular pilots. These two symbols define subframe 0.
  - Repetition of regular pilots every 64 subframes
  - Used to obtain a reliable one shot estimate of the channel response
- Continual pilots:
  - One pilot symbol on every 256 subcarriers
  - Used to track/update the channel estimate that was obtained from the regular pilots until a new full blown channel estimate becomes available
- Pilot overhead:
  - Regular pilots: 1/128
  - Continual pilots: 1/256
  - Combined pilot overhead: 3/256 = 1.17%



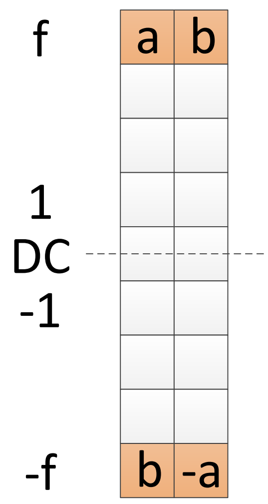
Pilot Structure: 50 kHz Spacing

- Symmetric pilots around center subcarrier
- Regular pilot symbols:
  - One pilot symbol on every subcarrier
  - Two consecutive OFDM symbols with regular pilots. These two symbols define subframe 0.
  - Repetition of regular pilots every 128 subframes
  - Used to obtain a reliable one shot estimate of the channel response
- Continual pilots:
  - One pilot symbol on every 128 subcarriers
  - Used to track/update the channel estimate that was obtained from the regular pilots until a new full blown channel estimate becomes available
- Pilot overhead:
  - Regular pilots: 1/128
  - Continual pilots: 1/128
  - Combined pilot overhead: 1/64 = 1.56%



Pilot Structure (Details)

- Subframe pilot structure:
  - The pilots are all symmetric with respect to the center frequency (DC), i.e. if there is a pilot on frequency f there is also a pilot on frequency –f
  - If the pilot symbol is ‘a’ at frequency f and ‘b’ at frequency –f in the first OFDM symbol of the subframe the second OFDM symbol of the subframe carries pilot symbol ‘b’ at frequency f and ‘-a’ at frequency –f.
  - This pilot structure provides excellent properties to estimate impairments like carrier frequency offset, phase noise, sampling frequency offset, and IQ mismatch



- Regular pilot density in subframe 0:
  - With a maximal delay spread of about 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

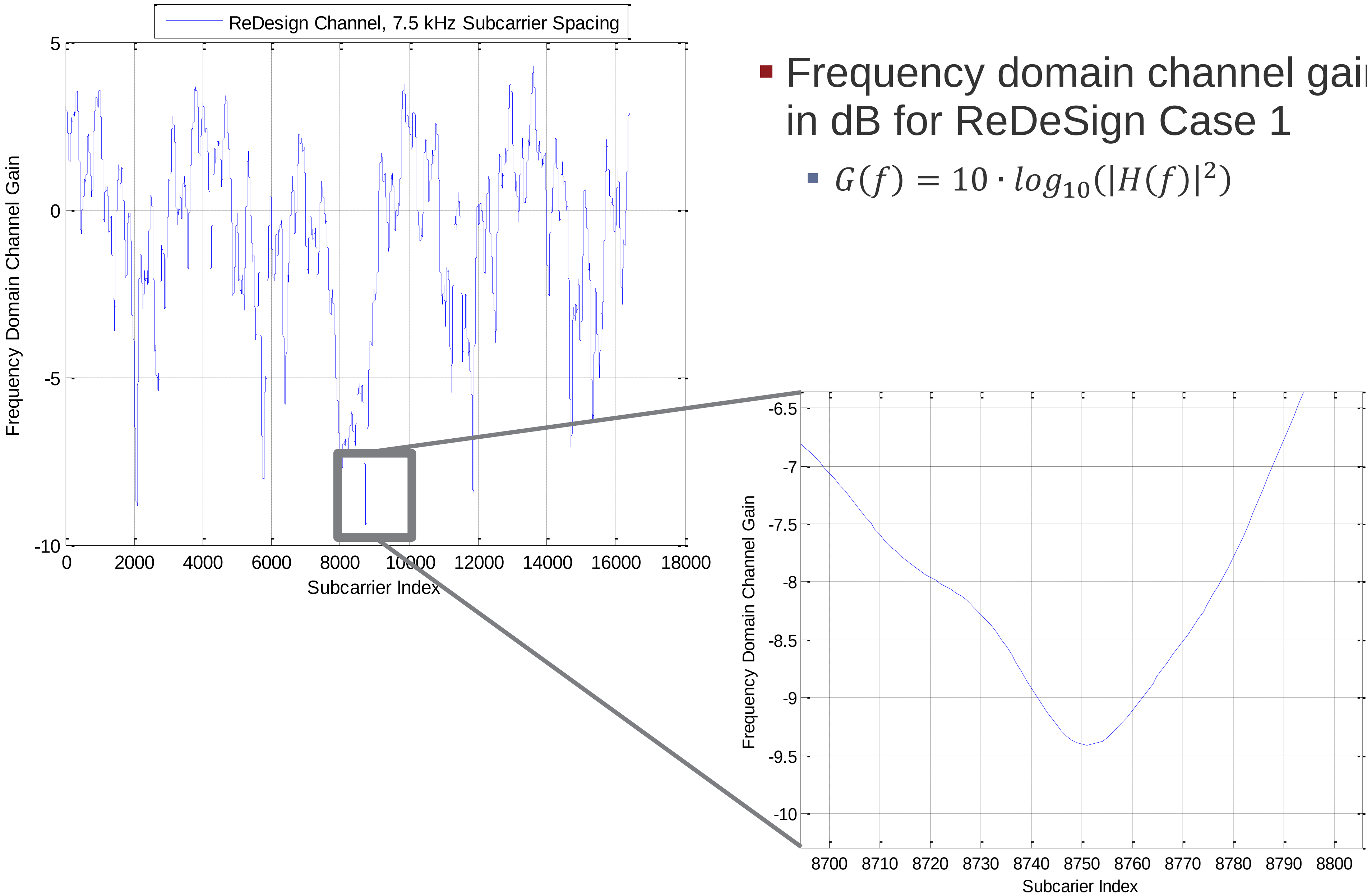
- ReDeSign Channel Model Case 1

	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

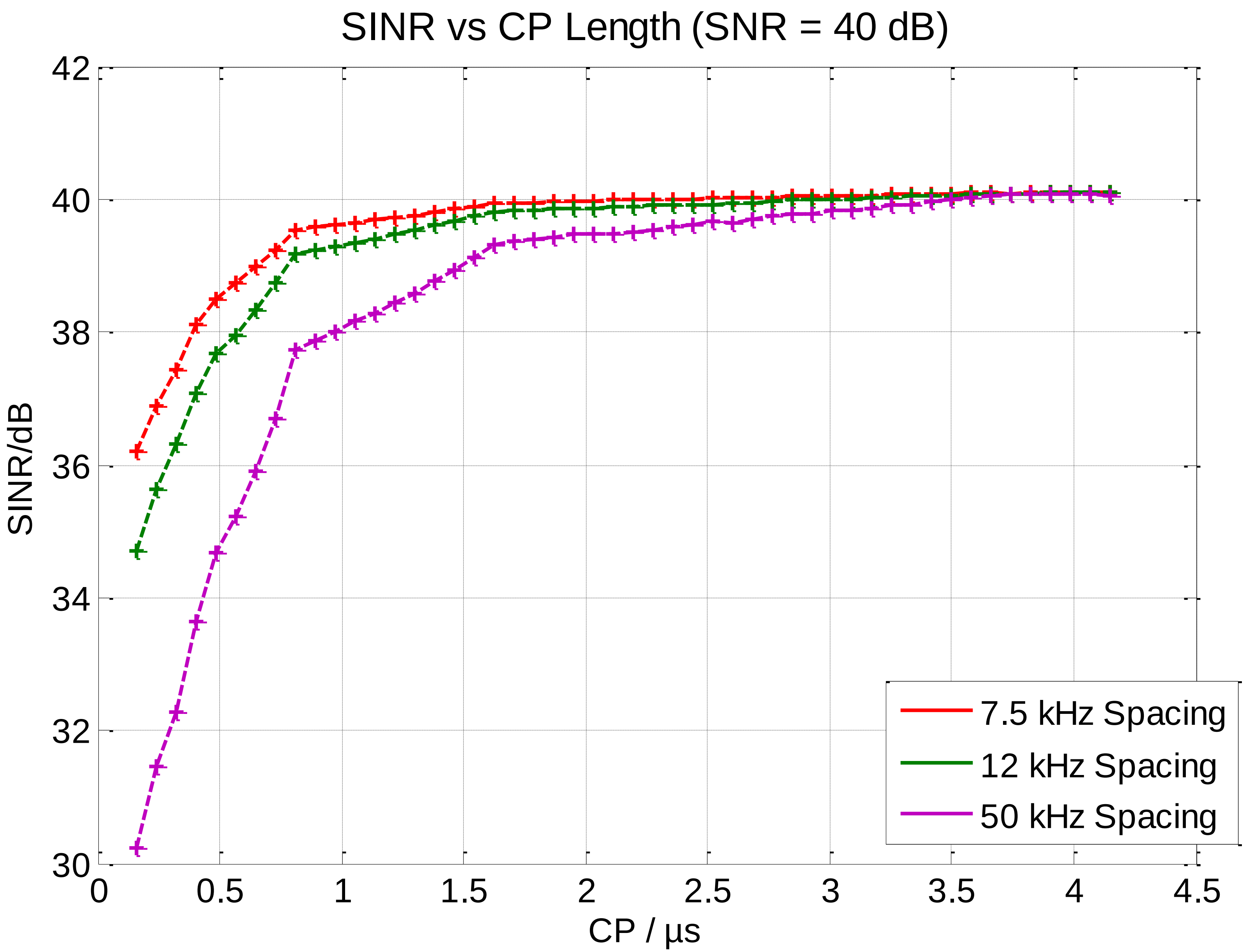
	Power	Delay	Phase
	[dB]	[ns]	[rad]
Case 2	-11	162	0,95
	-14	419	1,67
	-17	773	0,26
	-23	1191	1,20
	-32	2067	1,12
	-40	13792	0,81

Frequency Domain Channel Gain for ReDeSign

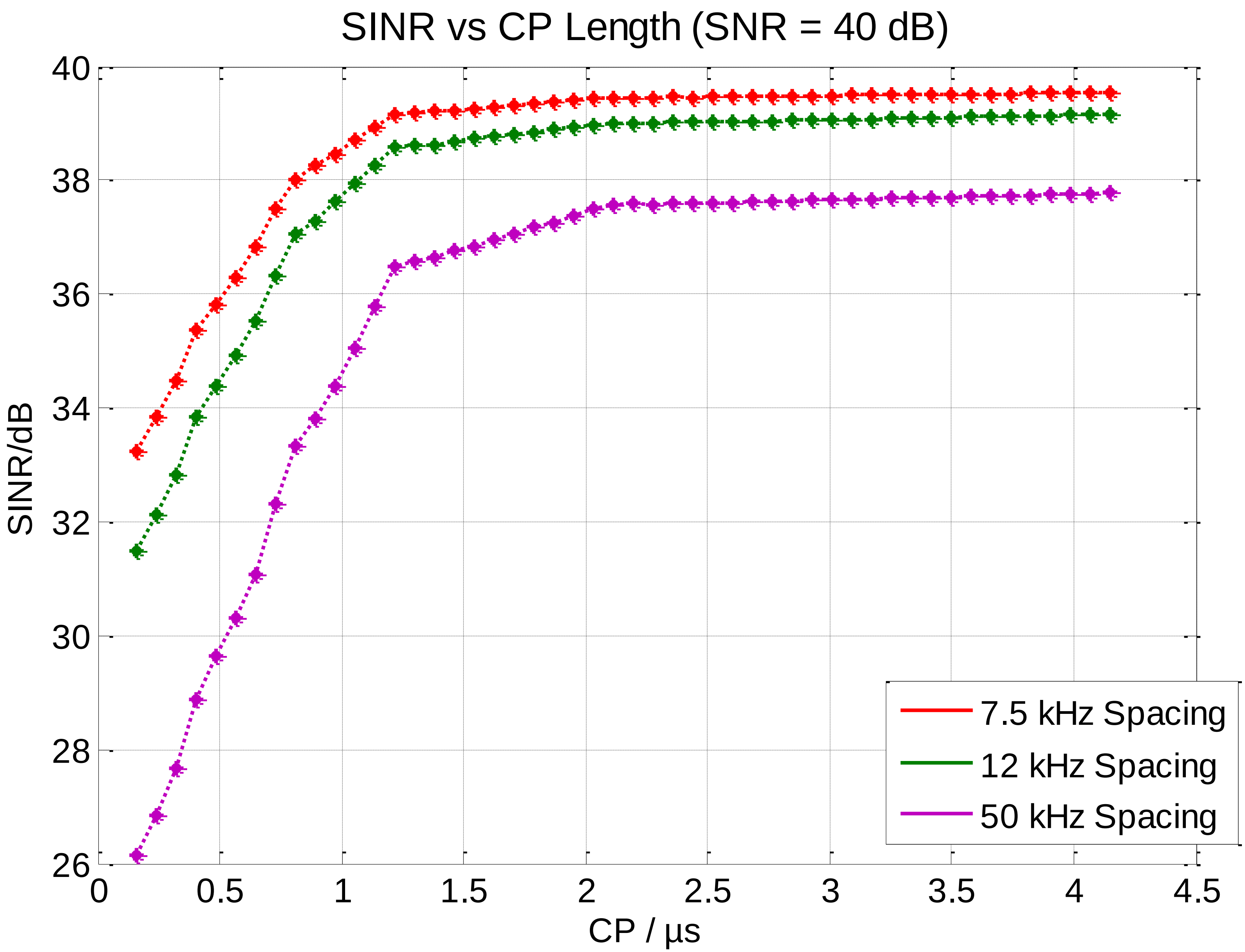


- Frequency domain channel gain in dB for ReDeSign Case 1
  - $G(f) = 10 \cdot log_{10}(|H(f)|^2)$

SINR at Demodulator Output – ReDeSign Case 1



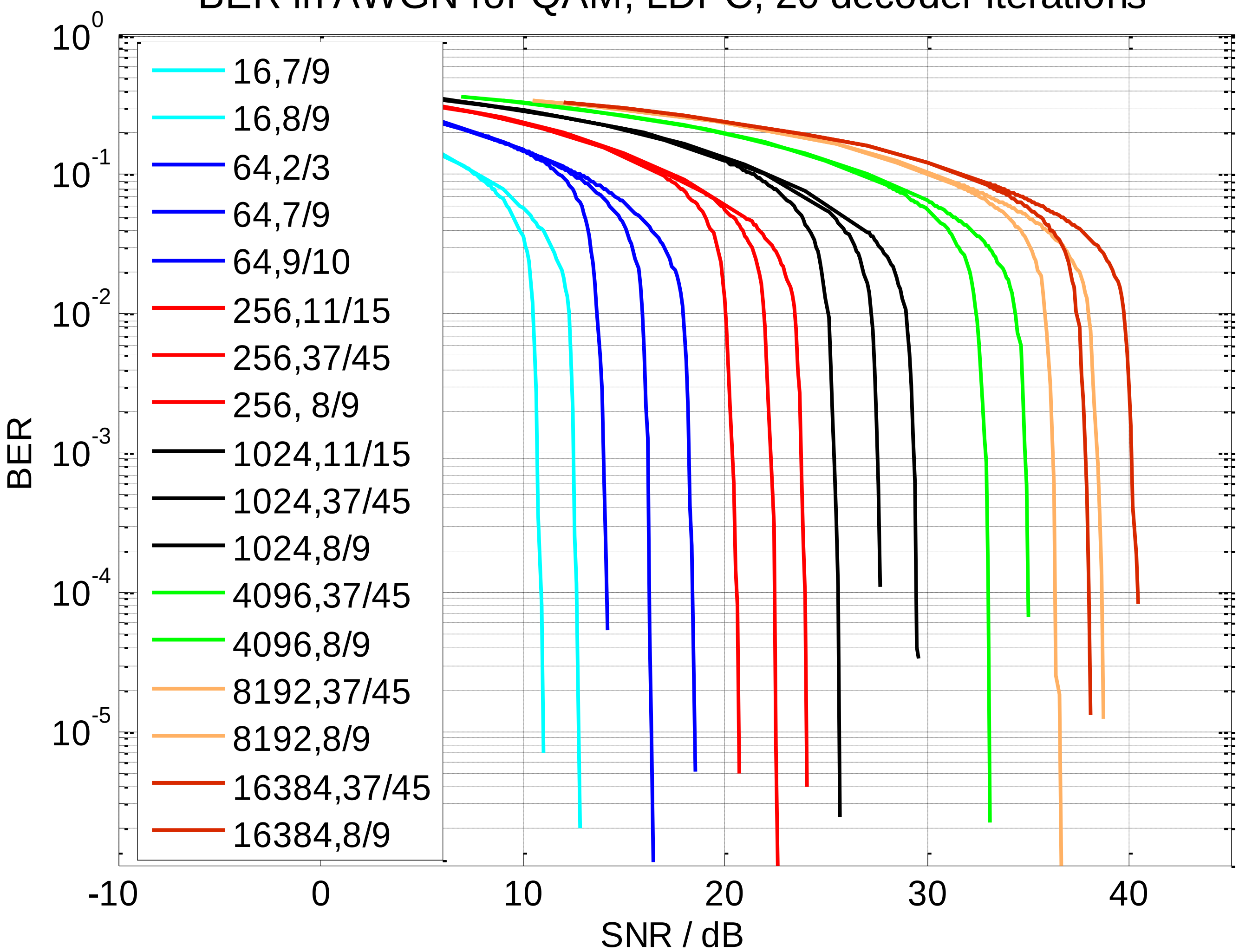
SINR at Demodulator Output – ReDeSign Case 2



Modulation and Forward Error Correction

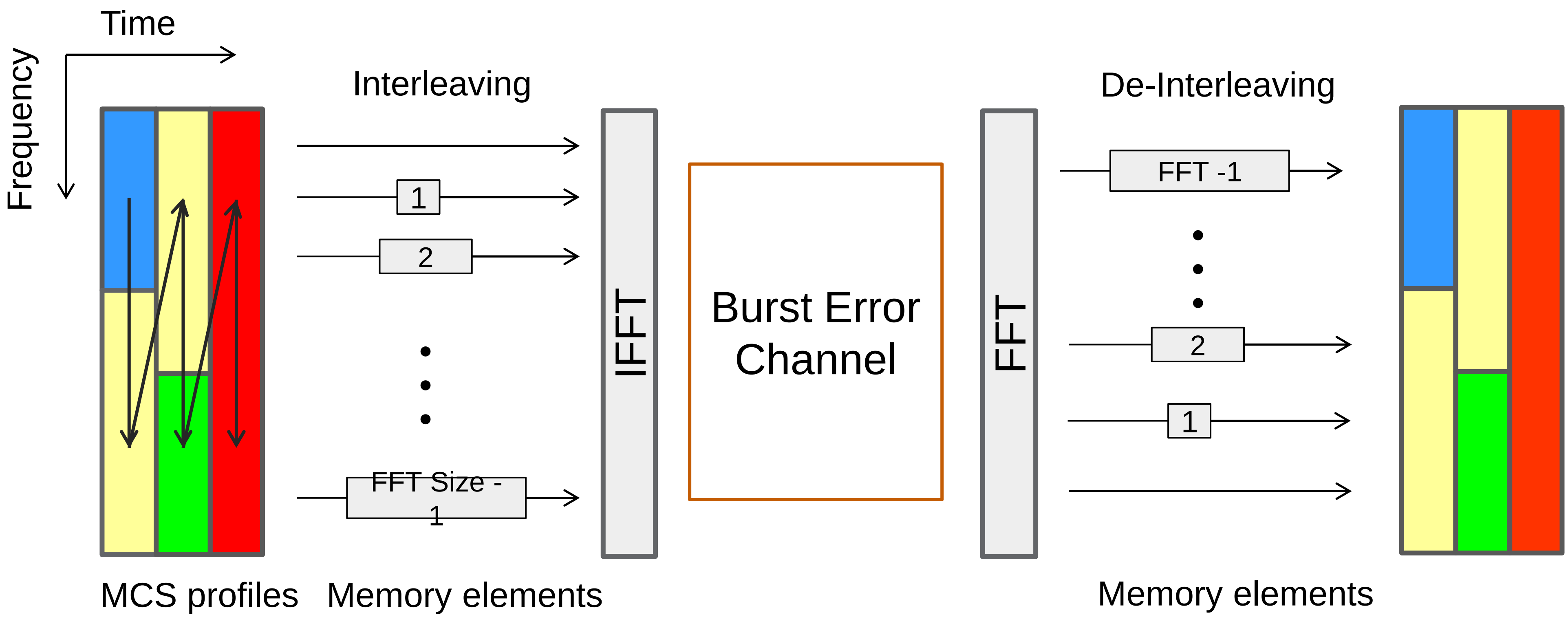
- QAM Modulation
  - Preferred modulation alphabets are (16QAM), (32QAM), (64QAM), (128QAM), 256QAM, 512QAM, 1024QAM, 2048QAM, and 4096QAM
- Downstream proposal: DVB-C2 codes
  - Common MCS per group of users enables the aggregation of Ethernet frames dedicated to multiple users of such a group into a single code word. (equivalent to multiple profiles approach)
  - It is anticipated that longer codes are more efficient when users are grouped
  - Applying the DVB-C2 LDPC and BCH codes is the preferred approach since they are well known and fully specified
- 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



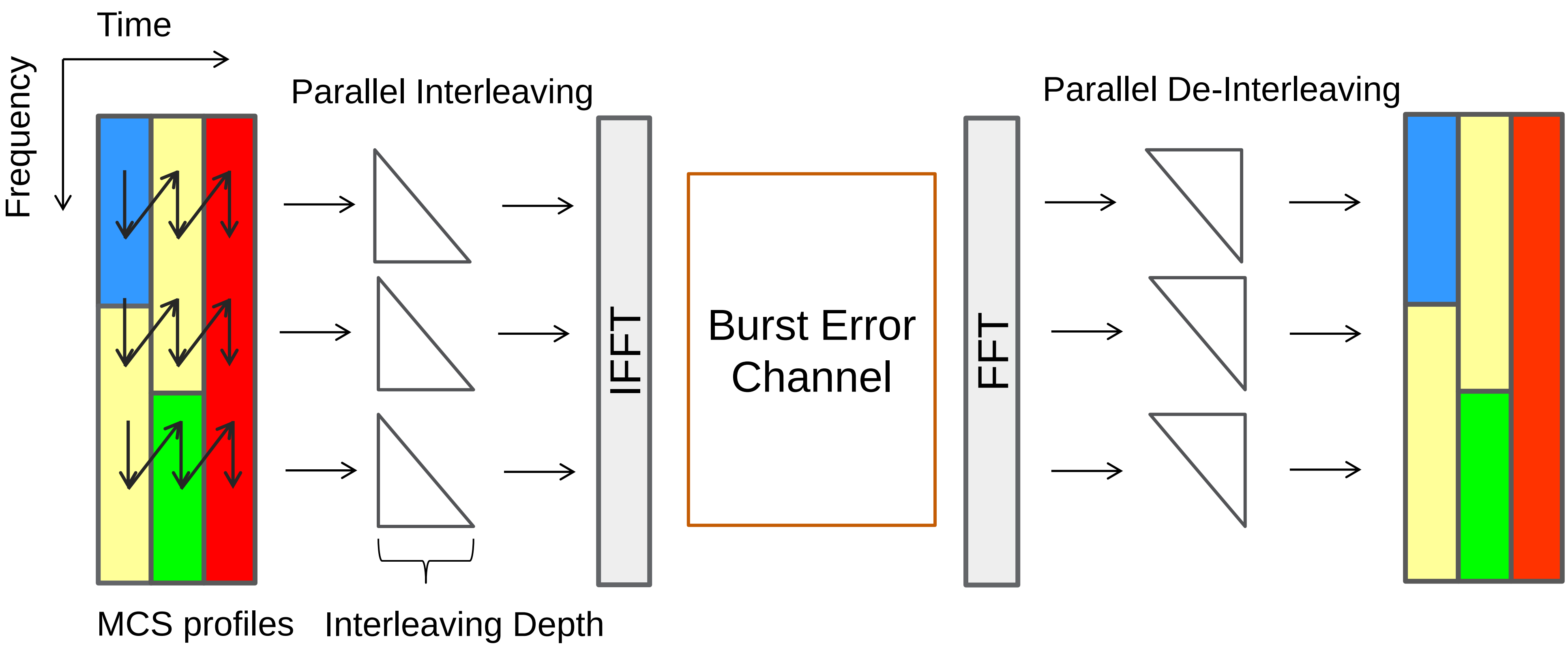
- Code word length 16200 bits w/o outer BCH code
- Gray mapping in I and Q
- Floating point LLR
- Note:
  8192 QAM is plotted for information. There is little benefit of using 8192 QAM over 4096 QAM and 16384 QAM

Direct Convolutional Time Interleaving



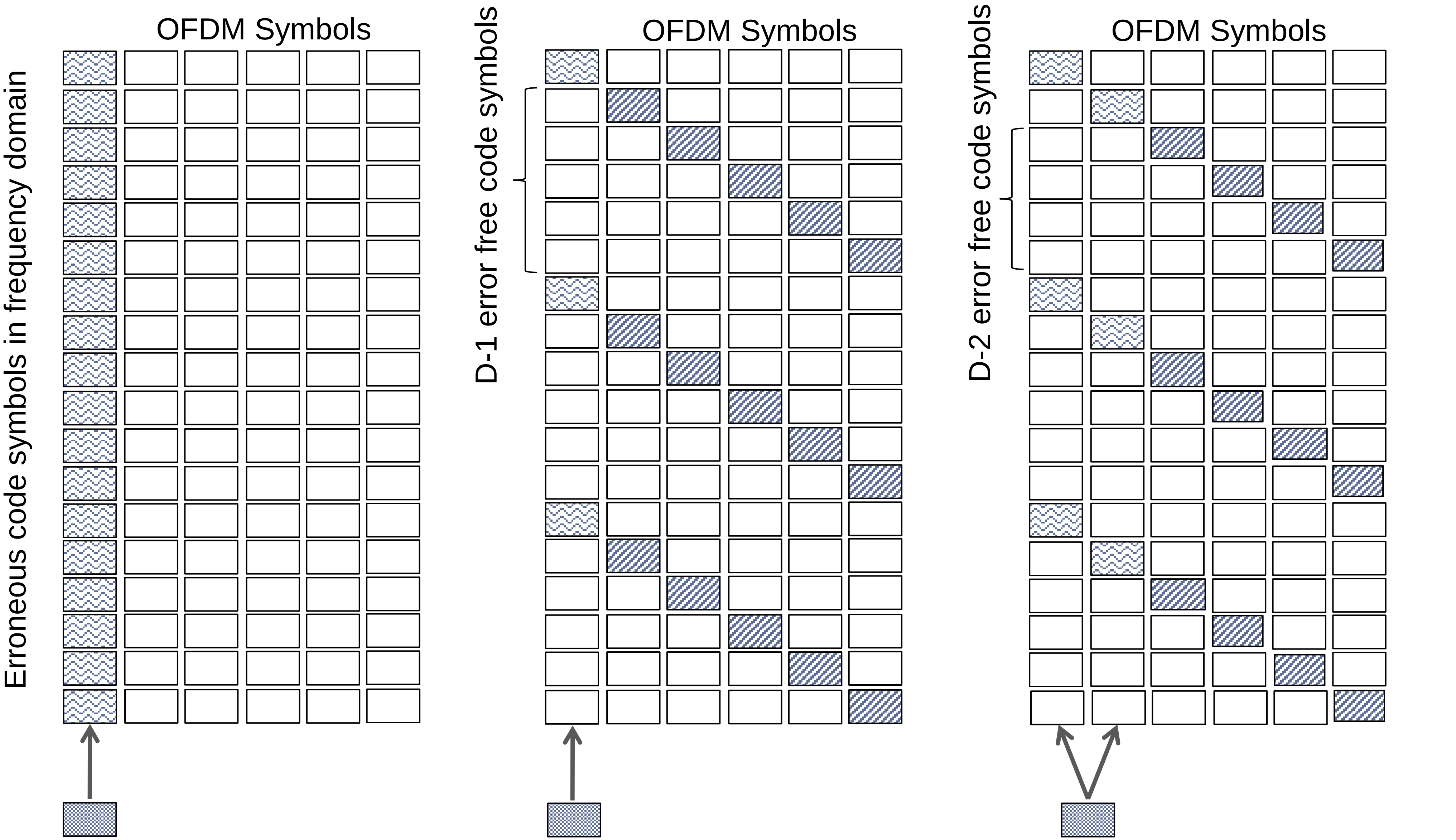
- Convolutional interleaving is applied at subcarrier level
- Convolutional interleaving delays each subcarrier in time
- For a time-invariant channel, interleaving across MCS profiles is possible
- But: Delay and memory consumption are excessive for direct interleaving
  - Required number of memory elements: 4k · (4k – 1) / 2 = 8386560

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 4k FFT, 4k/16 parallel interleavers are required
  - Required number of memory elements: 256 · 16 · (16 – 1) / 2 = 30720

Parallel Convolutional Interleaving Structure

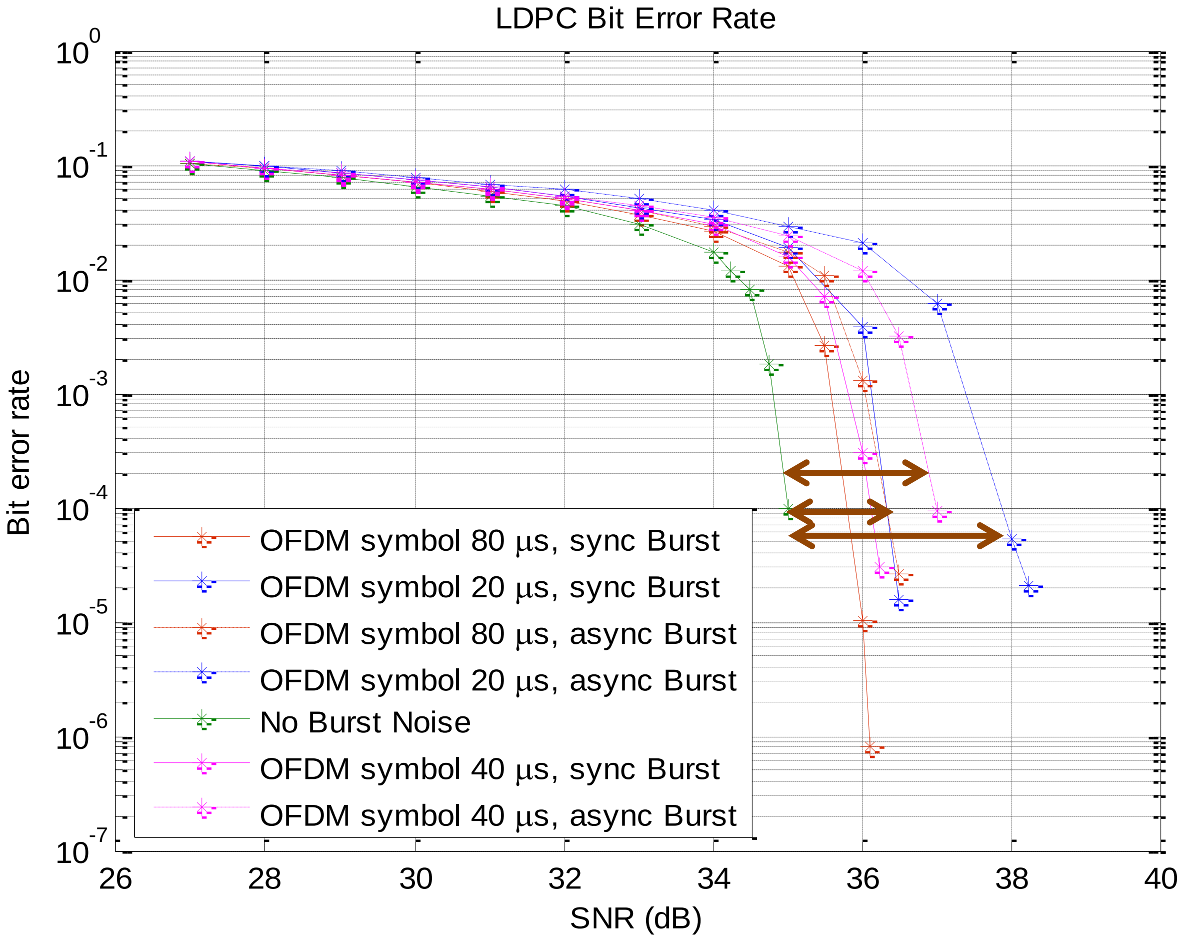


Synchronous Burst Noise w/o Time Interleaving

Synchronous Burst Noise w/ Time Interleaving Depth D = 6

Asynchronous Burst Noise w/ Time Interleaving Depth D = 6

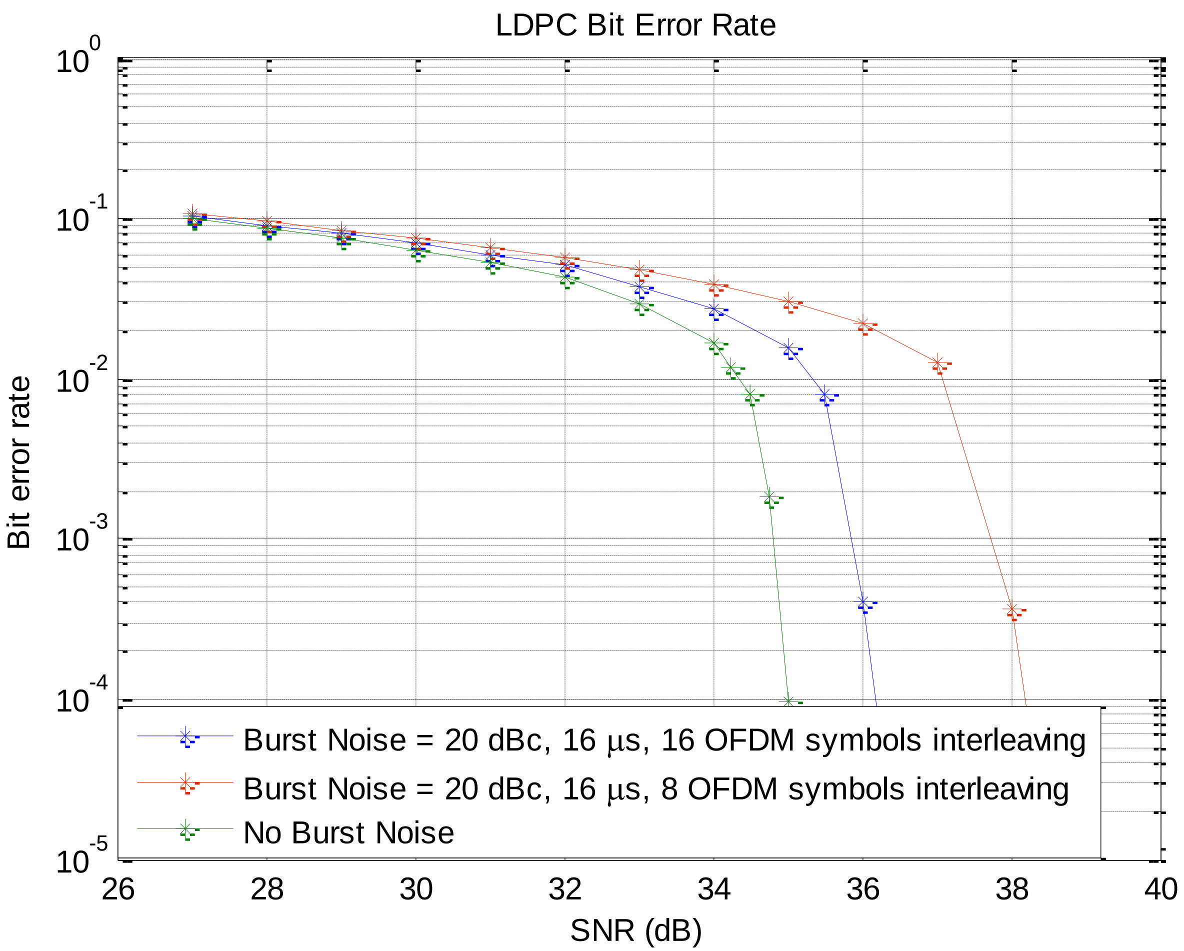
Performance when Asynchronous Burst Noise is Present



- 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

Comparison Interleaver Depth 8 and 16



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

- Interleaving across 16 symbols performs 2dB better than interleaving across 8 OFDM symbols when moderate burst noise is present
- Interleaving across very few symbols shows little benefits

Conclusions

- A frame structure was proposed with 1-2% 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 longer OFDM symbol for optimum performance
- The DVB-C2 codes should be used in downstream direction
  - Main advantage is that they are fully specified and field-proven
- The need for time interleaving depends on the burst model and details are for further study
  - Required interleaver depth depends on the burst noise model and the OFDM symbol duration
  - Longer OFDM symbols provide better protection against burst noise than shorter OFDM symbols

thank you