OFDMA PHY for EPoC: a Baseline Proposal

Andrea Garavaglia and
Christian Pietsch – Qualcomm

Supported by

- Jorge Salinger (Comcast)
- Rick Li (Cortina)
- Lup Ng (Cortina)

Outline

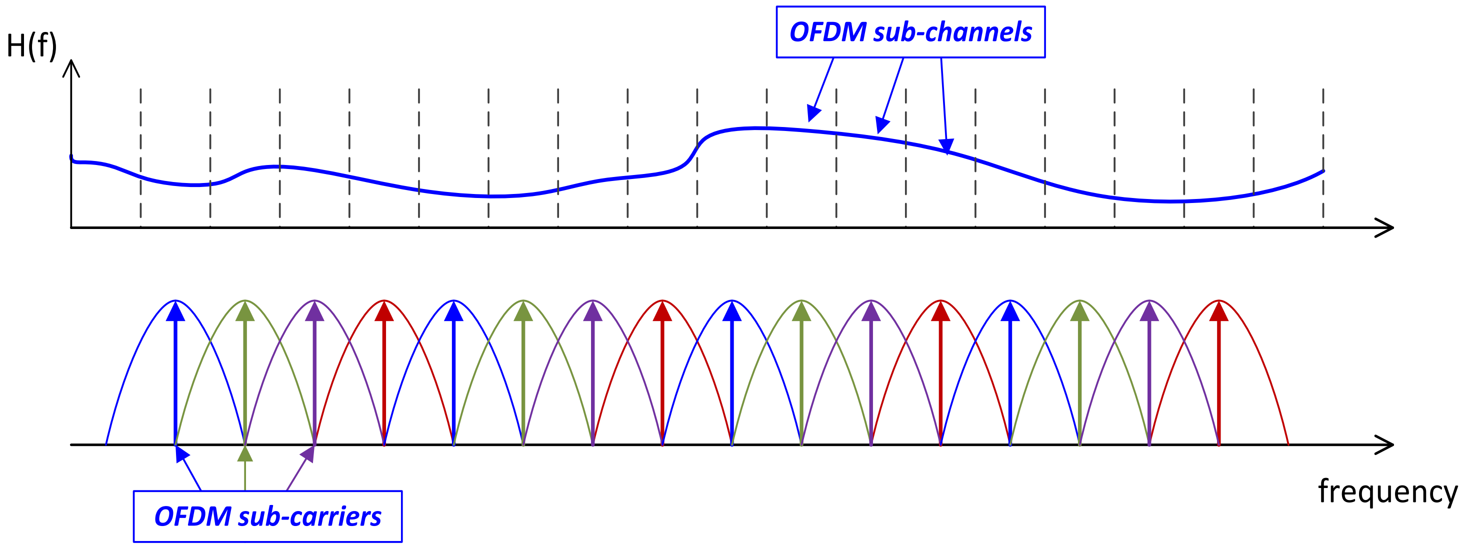
- OFDM: motivation and background
  - OFDM key strengths
  - How does OFDM work
- OFDM for EPoC PHY - numerology
  - Cyclic Prefix selection
  - Carrier spacing and symbol duration
  - Robustness against impairments
- OFDMA
  - OFDMA versus TDMA
  - Flavors of OFDMA: Downstream and Upstream
- Summary

OFDM – Motivation

- OFDM is widely deployed by latest communication systems, e.g.:
  - DVB-T, DVB-T2, DVB-C2
  - LTE
  - Wireless LAN (IEEE 802.11): a, g, n, ac
- **Key advantages:**
  - Efficient ways to cope with channel impairments, like for example:
    - Time dispersive channels
    - Narrowband interference
    - Frequency selective channel
    - Resilience to burst noise
  - No inter OFDM symbol interference due to cyclic prefix
  - Reasonable computational complexity
  - Less sensitive to time synchronization than a single carrier scheme
  - Coexistence with legacy services while maintaining high spectral efficiency
    - Fine frequency granularity due to subcarriers
    - Easily adapted to available bandwidth

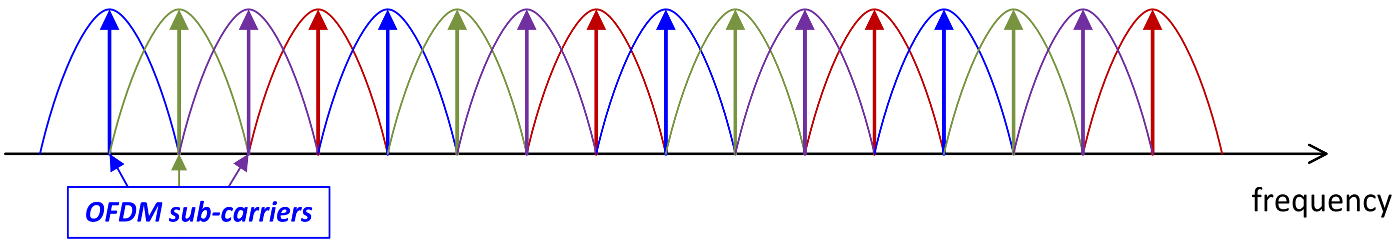
OFDM – Orthogonal Frequency Division Multiplexing

- **<u>OFDM</u>** is a special scheme for multi-carrier transmission for which the available spectrum is divided into narrowband orthogonal sub-channels each with flat spectral characteristics and each used for transmission of a subcarrier
  - A high data rate stream is converted into *M* parallel low data rate streams, each modulating one subcarrier in the frequency domain
  - A high spectral efficiency is achieved while allowing for a low-complex implementation since subcarrier separation is simple due their orthogonality

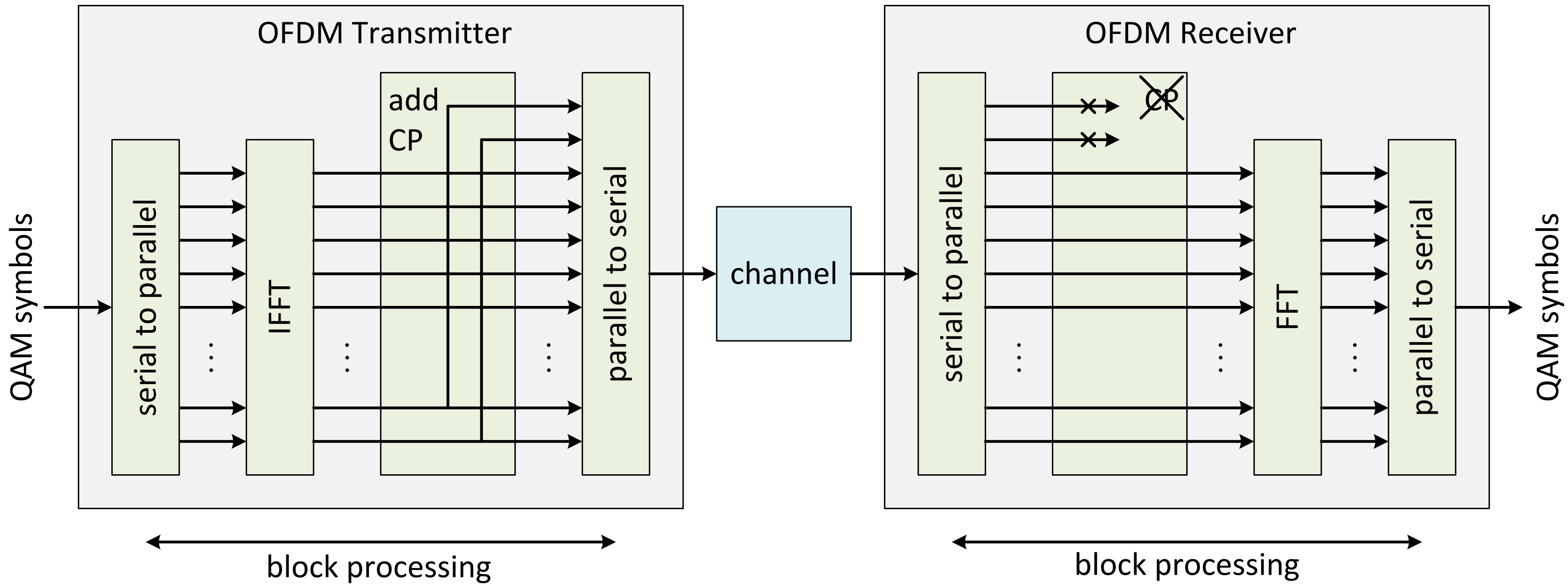


OFDM – How It Works

- OFDM relies on frequency domain processing:
  - QAM modulated symbols are placed on each subcarrier in the frequency domain
  - QAM symbols are received on each subcarrier in the frequency domain
- A frequency selective channel is converted into frequency flat sub-channels:
  - Different sub-channels may observe different channel conditions
  - Modulation order may be adjusted according to SNR on sub-channels
- The OFDM symbol duration is much longer than the channel delay spread:
  - A requirement for frequency flat sub-channels
  - Inter OFDM symbol interference is eliminated at marginal costs
- The subcarriers are orthogonal:
  - No interference between subcarriers,
    i.e. the QAM symbols on the subcarriers may be detected independently



OFDM – Block Diagram and Block Processing



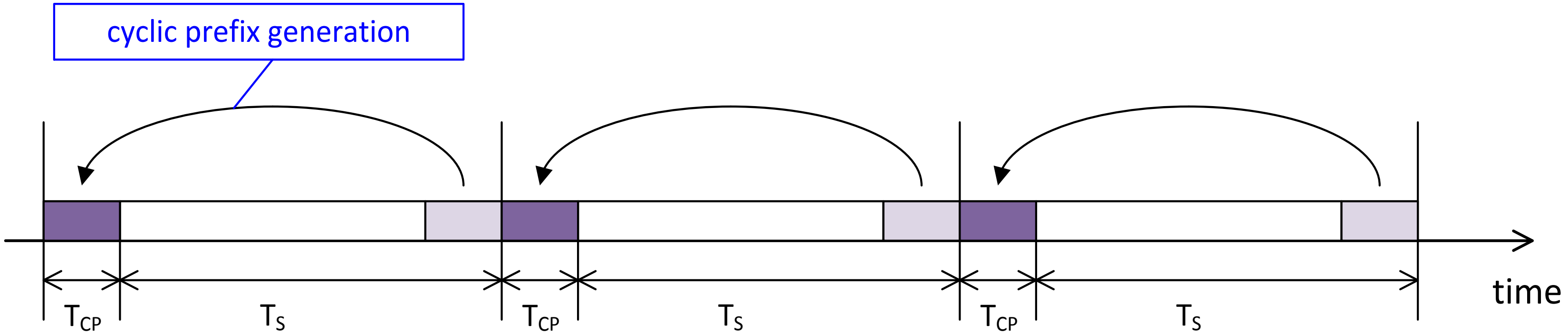
- Block processing at the transmitter:
  - QAM symbols for all subcarriers are gathered prior to IFFT
  - IFFT is carried out jointly for all QAM symbols dedicated to an OFDM symbol
- Block processing at the receiver:
  - An entire OFDM symbol has to be received before processing can start
  - All QAM symbols become available at the same time after the FFT
- MAC layer does not need to be aware of OFDM PHY layer block processing

OFDM for EPoC PHY – Possible Numerology

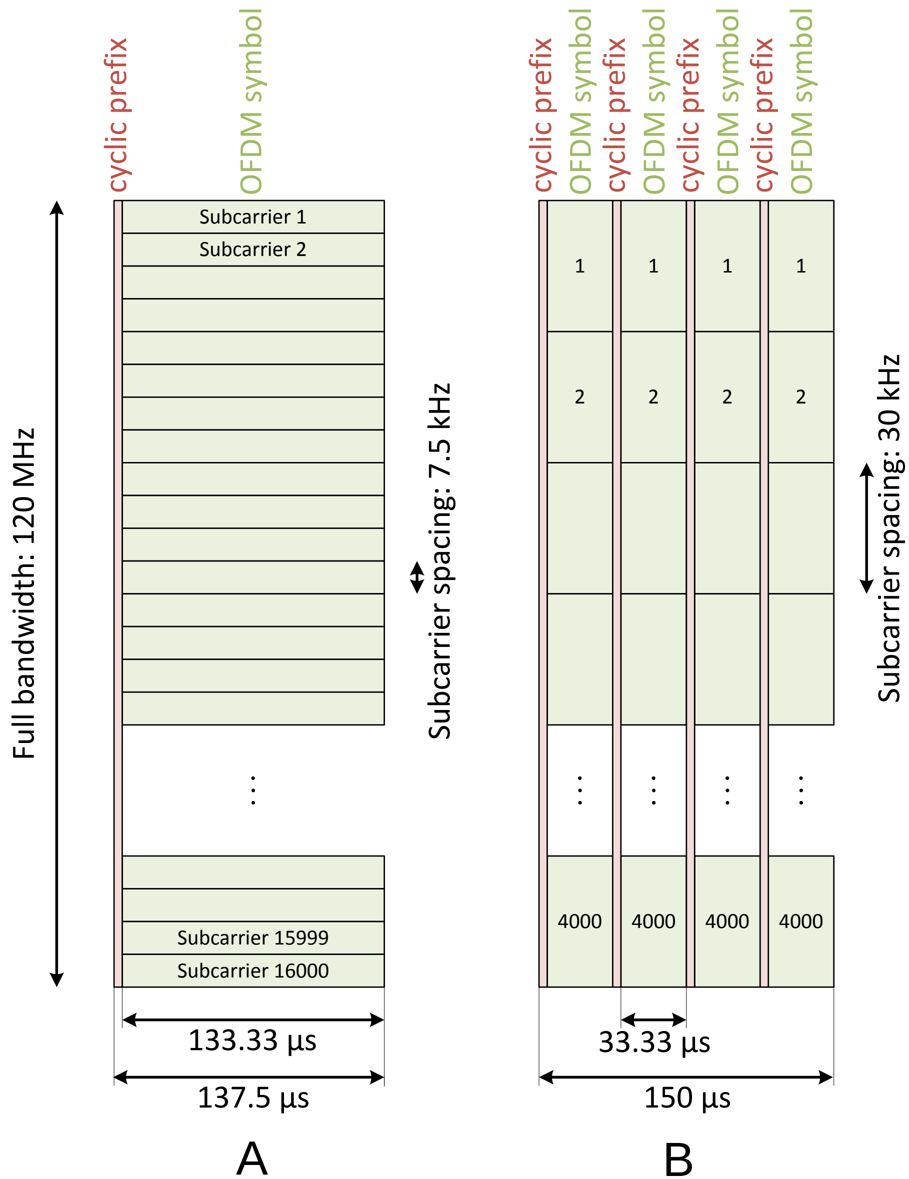
PHY Parameter	Value	Comments
Bandwidth	120 MHz	• Target Bandwidth
Subcarrier Spacing (f_{Δ})	7.5 kHz	• Enable low-cost implementation while incurring low CP overhead • OFDM symbol duration = 1/subcarrier spacing
Cyclic Prefix Duration (T_{CP})	~1 µs or ~4 µs	• Sufficient to cover cable plant micro-reflections (reflections > -40dB) • Possible to support multiple CP durations for different deployments
QAM Modulation Orders Supported	16-QAM 64-QAM 256-QAM 1024-QAM 4096-QAM	• Support a range of modulation orders from 16-QAM up to 4096 QAM • Selection of specific QAM-order depends on SNR achievable in the plant • Different QAM-order may be used on downstream and upstream • Different QAM-order could be possible to/from different CNUs

OFDM – Cyclic Prefix (CP)

- The CP plays an integral role in the construction of the OFDM signal:
  - It acts as a guard period and thus eliminates inter OFDM symbol interference
  - It guarantees orthogonality between subcarriers of the OFDM symbol for time dispersive channels
- The length of the CP must be at least as long as the channel delay spread
- It is constructed by adding a copy of the last time domain samples of the OFDM symbol to the beginning of the OFDM symbol, see diagram below
- An overhead incurs due to the CP: $\frac{T_{CP}}{T_{CP}+T_S}$
  - Longer OFDM symbols cause less overhead due to the CP



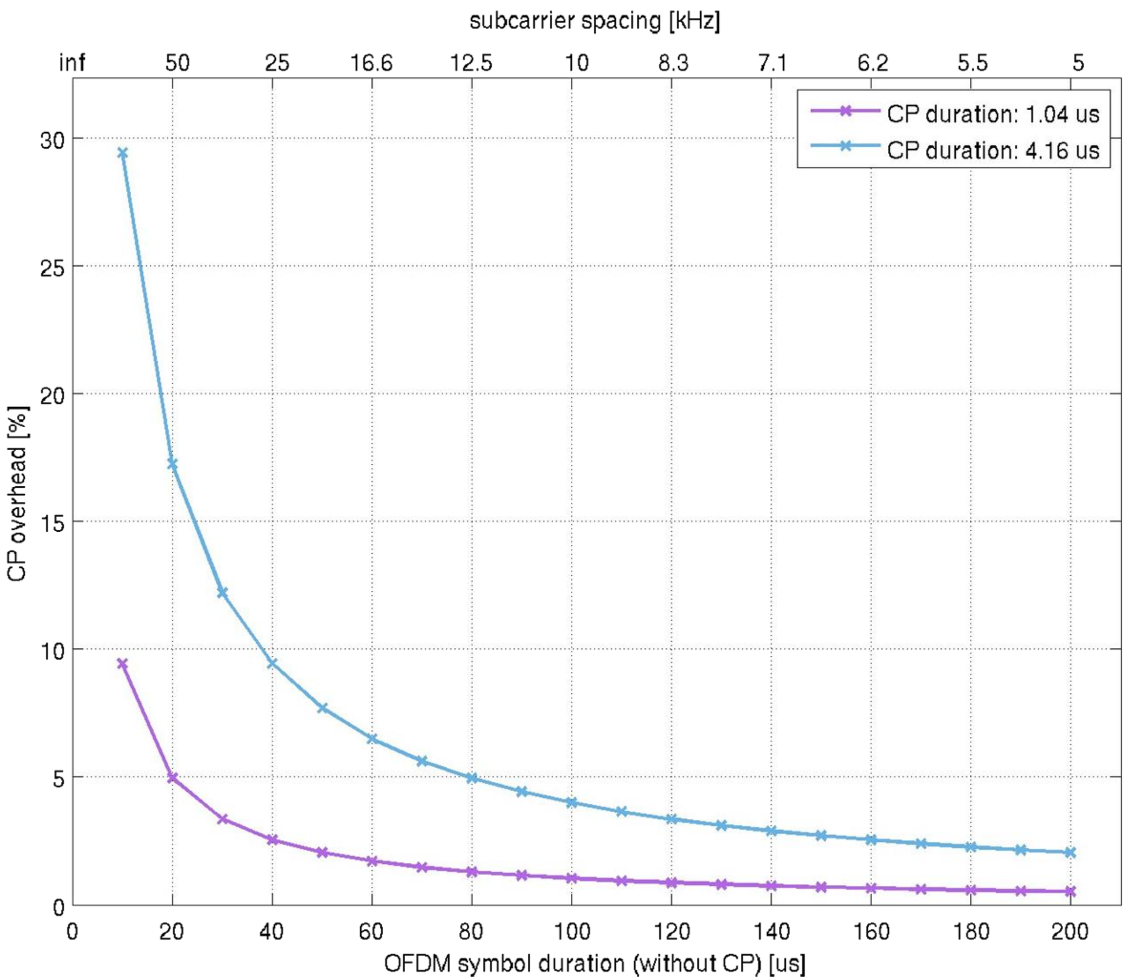
OFDM Symbol Duration – Subcarrier Spacing (I)



- Relationship: $f_\Delta = 1/T_s$
  - OFDM symbol duration: T_s
  - Subcarrier spacing: f_Δ (or sub-channel width)
- Example: Two configurations:
  - A: $T_s = 133.33\ \mu s$
  - B: $T_s = 33.33\ \mu s$
  - CP duration: $T_{CP} = 4.16\ \mu s$
- Configuration B requires 4 OFDM symbols to transmit the same amount of data as configuration A
- Example CP overhead:
  - A: $\frac{4.16\mu s}{137.5\mu s} = 3\%$
  - B: $\frac{4.16\mu s}{33.33\mu s} = 12.5\%$
  - B has $\frac{(150-137.5)\mu s}{137.5\mu s} = 9\%$ more CP overhead than A

Overhead due to Cyclic Prefix

Overhead due to cyclic prefix: $\frac{T_{CP}}{T_{CP}+T_S}$



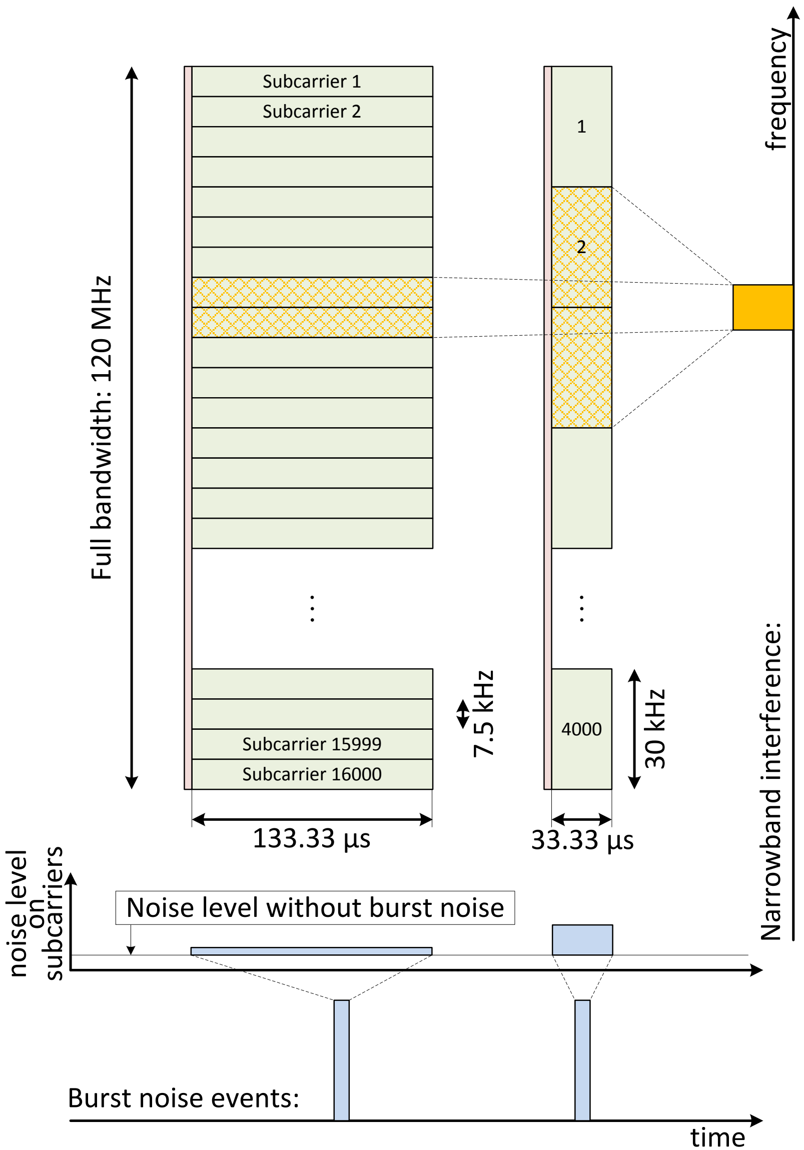
- The CP duration must be larger than the maximum channel delay spread (and any additional delay spread added due to filtering and inaccurate synchronization), but only a little larger than this to minimize overhead
- Hence, given a certain cable plant that is known to cause a certain maximal delay spread, the optimal CP length is predefined.
- The parameter of choice is the OFDM symbol duration, which then influences CP overhead. To minimize overhead it is essential that

$$T_{CP} \ll T_S$$

OFDM Symbol Duration – Pros/Cons

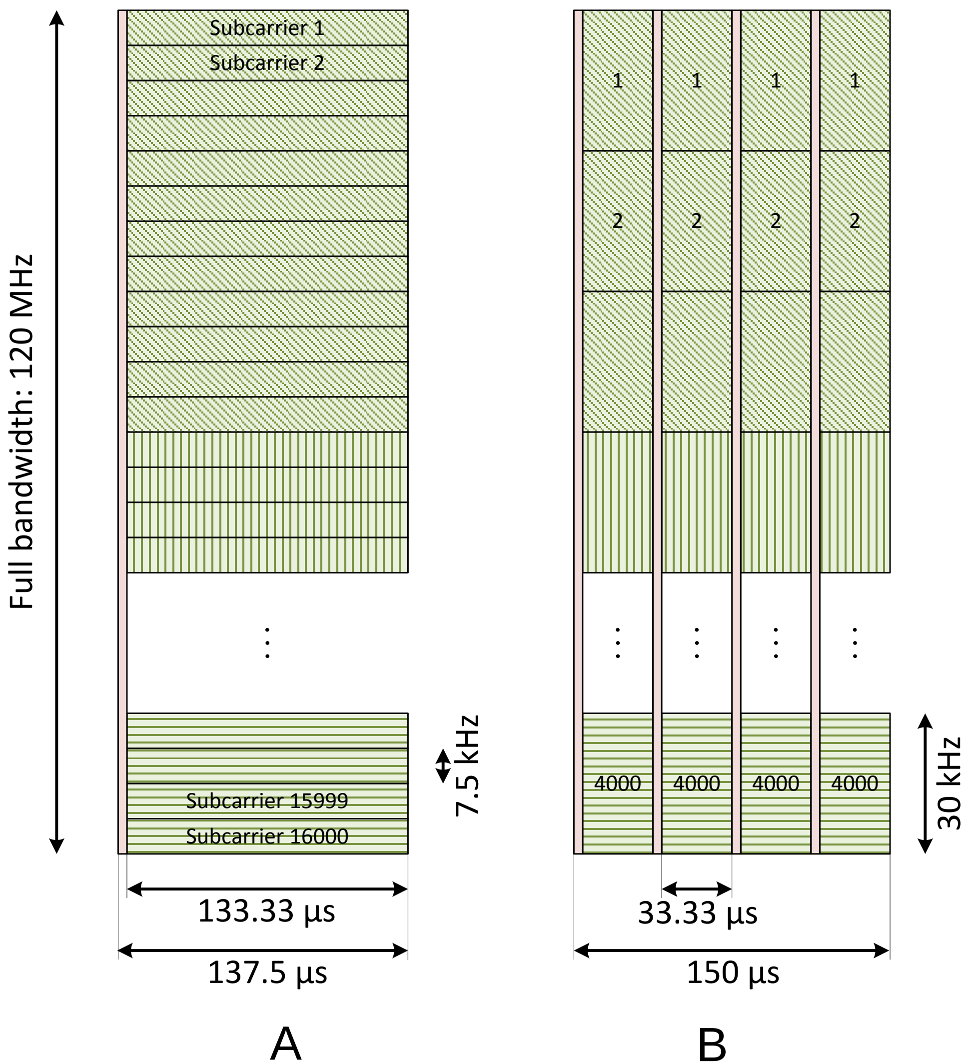
Feature	Pros	Cons
Long OFDM symbols	- More robust against burst noise (no additional interleaving needed) - Less CP overhead	- May impact the end-to-end delay for cases where no interleaver would be required
Small subcarrier spacing	- Finer granularity for counteracting narrowband interference (e.g. notching of single subcarriers)	- Larger FFT size needed for a given spectrum - Higher frequency accuracy required
Short OFDM symbols	- Could achieve a smaller end-to-end delay for cases where no interleaver is required	- Less robust against burst noise, requires interleaver - High CP overhead, impacting overall spectral efficiency
Large subcarrier spacing	- Reduced FFT size sufficient - Reduced frequency accuracy	- Difficult or inefficient counteracting of narrow-band interference

Narrowband Interference and Burst Noise



- Narrowband Interference:
  - Affects a only few subcarriers
  - Modulation order can be reduced on these subcarriers or affected subcarriers can be easily blanked
  - A smaller subcarrier spacing provides higher granularity
- Burst noise:
  - Typical burst noise duration: 10 µs
  - Burst noise affects all subcarriers
  - Burst noise increases noise level on the subcarriers
  - The longer the OFDM symbol duration the lower the increase of noise level
  - Two alternatives for coping with burst noise: - long OFDM symbols
    - interleaving (see next slide)

OFDM Symbols Duration and Interleaving



- Each shaded area corresponds to a separate interleaving block or FEC block
- For a certain level of resilience against burst noise, the data has to be spread across a certain period of time (e.g. 133 µs)
- Interleaving across multiple OFDM symbols is required for short OFDM symbols (B)
- With long OFDM symbols no inter OFDM symbol interleaving is needed (A)
- The delay due to processing is similar for both alternatives

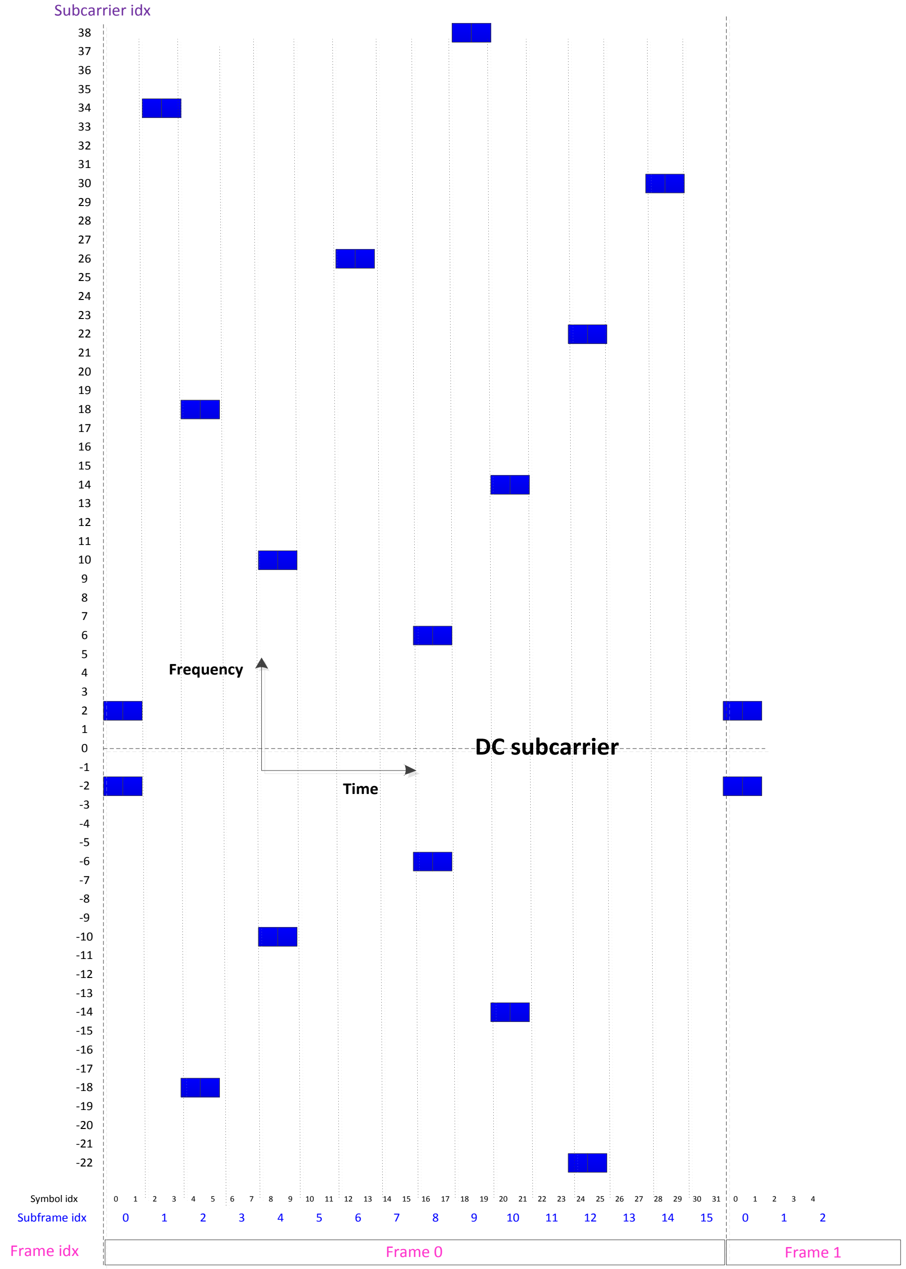
OFDM for EPoC PHY – Robustness

Distortion	Robustness
Linear Distortion (Micro-reflections)	• OFDM cyclic prefix (CP) addresses all linear distortions up to the length of the CP – past the CP micro-reflection power shall be low
Time-variant Channels	• To provide robustness against time-variant channels, channel coding is employed together with OFDM • A Forward Error Correction (FEC) scheme is included for that • Different coding rate could be used to better adjust to frequency channel conditions while maximizing the system capacity
Impulse Noise	• Burst noise lowers the SNR of affected OFDM symbol(s), but if the noise burst is significantly shorter than the OFDM symbol period, the degradation is small and no further interleaver is needed • Additionally FEC coding provides degradation margin

Narrowband Interference	• Narrowband interference may cause low SNR on some subcarriers:
	    • This can be addressed by adaptive modulation which does not use the same QAM-order on each subcarrier
	    • Alternatively, receiver may ignore information on certain low SNR subcarriers – no information sent on those sub-carriers

Pilot Symbols – Example

- At the receiver side, it is necessary for demodulation to estimate the channel
- For that, symbols known in advance to the receiver (called pilots) should be included into the data stream
  - Certain subcarriers are used by pilots and reduce the spectral efficiency
- The number of required pilots depends on the frequency and time variability of the channel impulse response
  - Pilots should be staggered in time and frequency
  - Pilot structure is a design criterion



OFDM for EPoC PHY – DVB-C2 – LTE

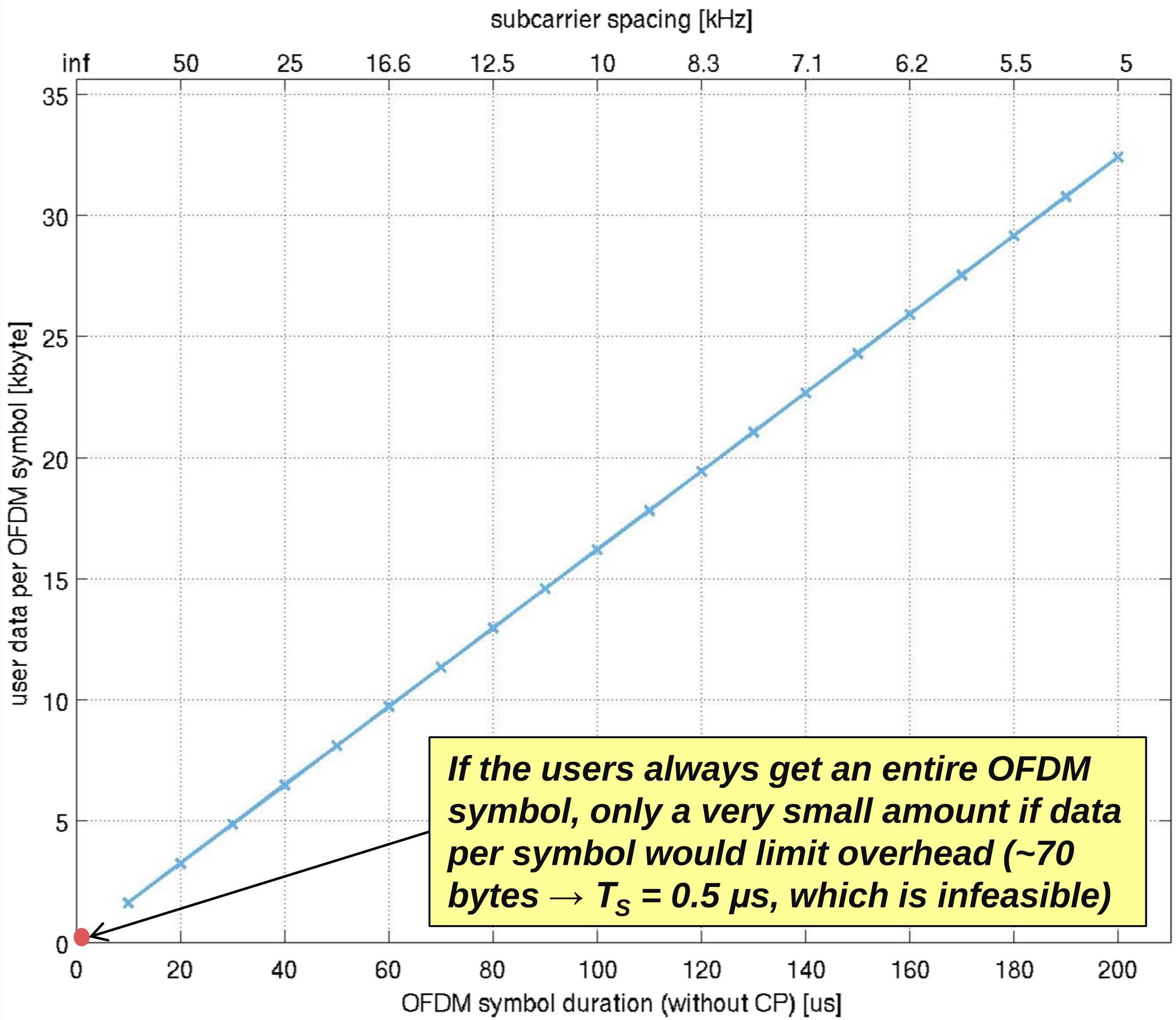
	EPoC example	DVB-C2 (Europe)	LTE
Bandwidth span (digital bandwidth)	120 MHz	8 MHz	20 MHz
Symbol duration	133.33 µs	448.03µs	66.67µs
Subcarrier spacing	7.50 kHz	2.232kHz	15kHz
CP duration (typically used)	4.17 µs	7.00µs	4.76µs
CP overhead	3.03%	1.54%	6.66%
FFT size	16384	4096	2048
Highest modulation order	4096 QAM	4096 QAM	64 QAM
Highest code rate	0.9	0.9	0.9
Maximum payload per OFDM symbol	24576 bytes	67205 bytes	9000 bytes

Baseline Proposal #1

- Adopt OFDM as the basis for the EPoC PHY

  - Moved by:
  - Seconded by:
  - Technical motion (>=75%)
  - Yes / No / Abstain

How much user data does one OFDM symbol carry?



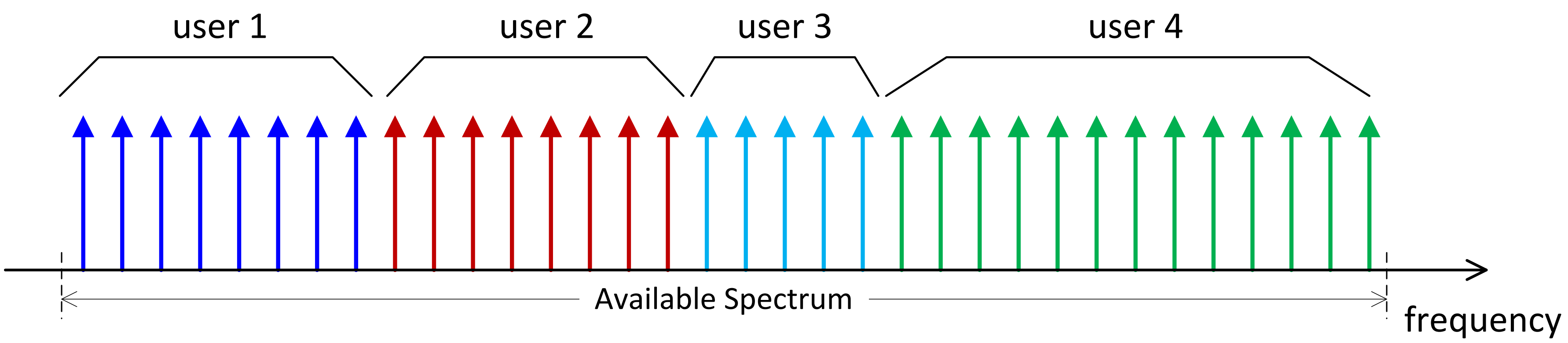
Assumptions:
- 120 MHz bandwidth
- up to 4096 QAM
- include pilot/guard tones

- Typical amount of user data per OFDM symbol ~3000-25000 bytes
- But the smallest grant size should be in the range of 64 bytes to minimize overhead
- A better resource granularity is needed

OFDMA is the answer

OFDMA – Orthogonal Frequency Division Multiple Access

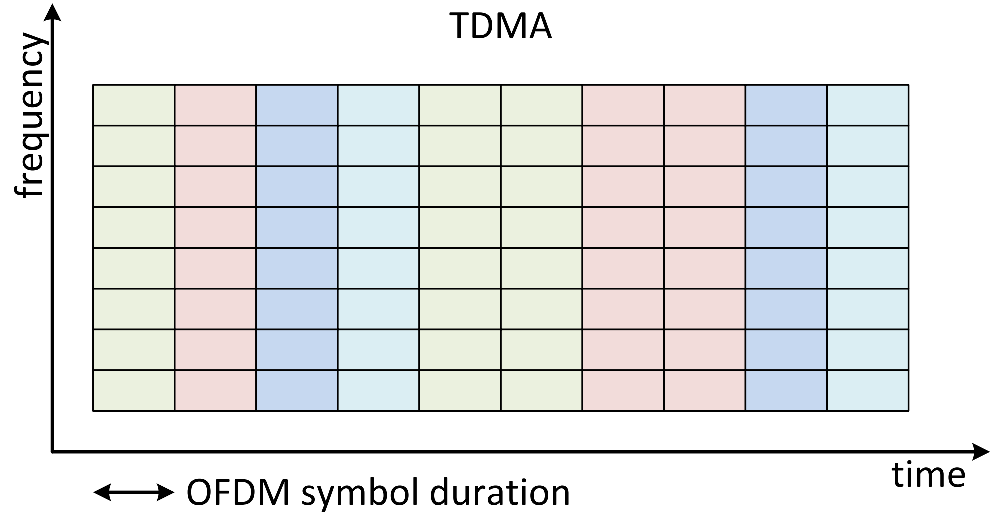
- **<u>OFDMA</u>** is an access technique for OFDM to effectively achieve multi-user communication systems for which subcarriers are distributed to different users at a given point of time
- While with TDMA all the subcarriers are assigned to the same user at a given time, with OFDMA groups of subcarriers are allocated to different users in the same symbol – see below
  - Typically a contiguous group of sub-carrier is allocated to one user
  - The same principle can apply for both downstream and upstream



OFDMA vs. TDMA – Achieving Better Granularity

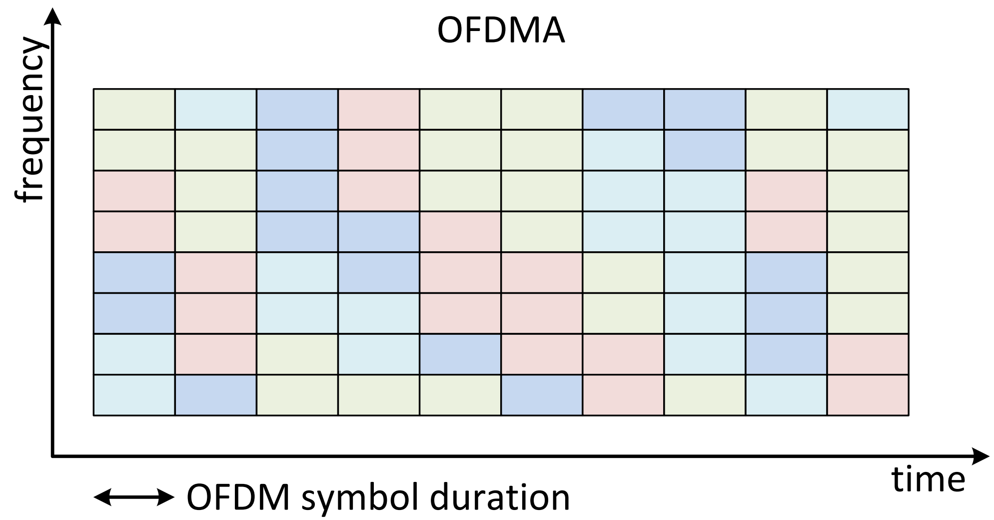
OFDM with TDMA

- A user gets the entire OFDM symbol
- If the user has less data to transmit the remaining resources in the OFDM symbol are wasted – large overhead



OFDM with OFDMA

- Multiple users share a single OFDM symbol
- Each user can get an amount of resources tailored to the real need, thus minimizing overheads

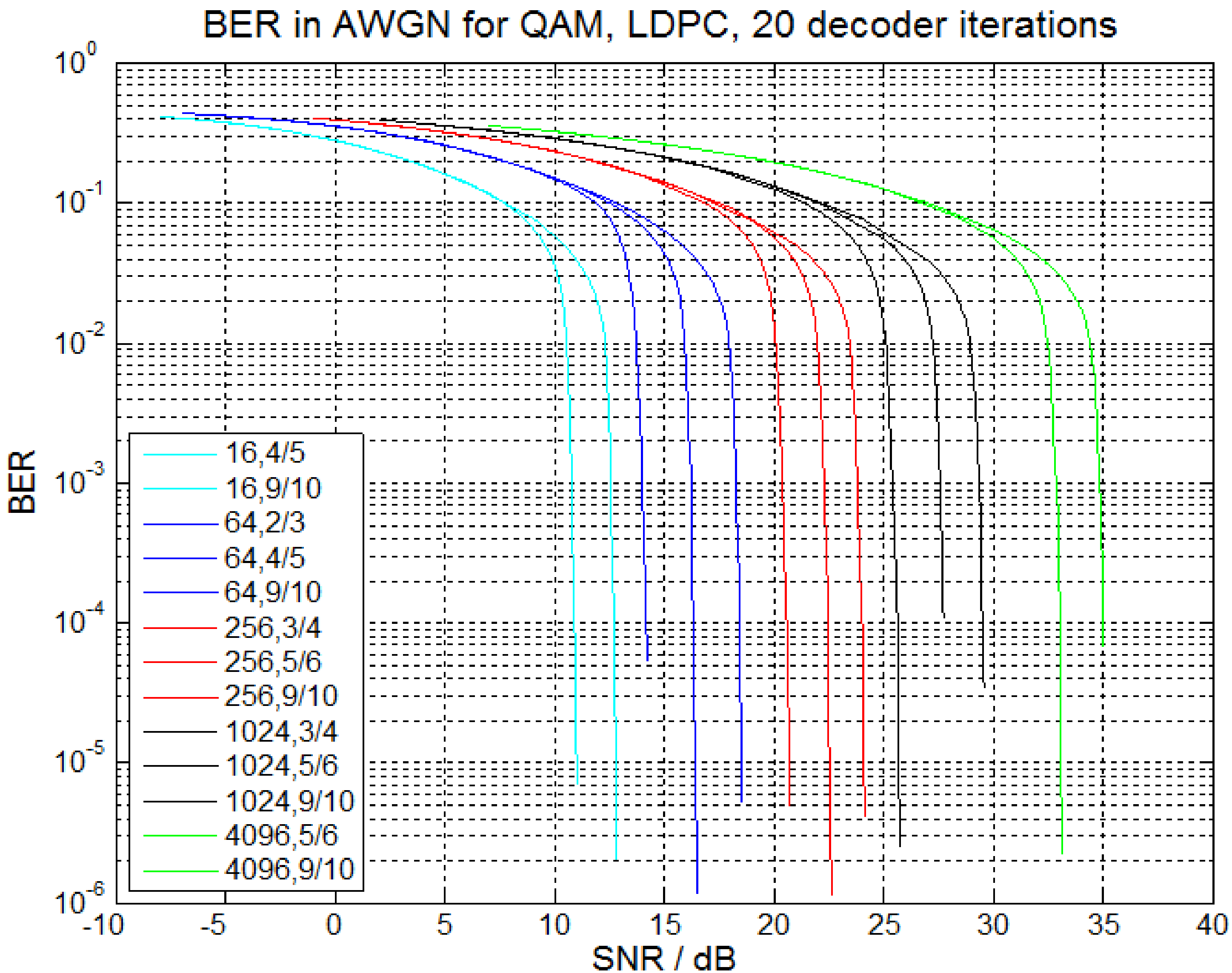


Note: Each color represents a different user

OFDMA and MCS – Further Granularity Refinement

- **Modulation and Coding Scheme** (MCS) describes the combination of modulation order (16-QAM, 64-QAM, etc.) and coding rate which is use to encore and map information bits into OFDM subcarriers in OFDMA
  - The modulation order determines how many bits can be carried by an OFDM tone – the bits include both information bits and parity bits
    - Example: 4096 QAM translates in 12 bits/symbol or 12 bits/sub-carrier
  - The coding rate determines how many parity bits are added to a given set of information bits and it is typically expressed as ratio between information bits and overall number of bits after encoding
    - Example: coding rate 9/10 means 9 information bits encoded in 10 bits
- The selection of the appropriate MCS is related to the Signal-to-Noise Ratio (SNR) which is perceived over a certain link and frequency spectrum
  - The higher the SNR, the higher can be the modulation order and the coding rate, as less protection is needed to carry the same information
  - In the next slide an example of mapping between SNR and MCS is given

BER Curves for MCS Selection – Example



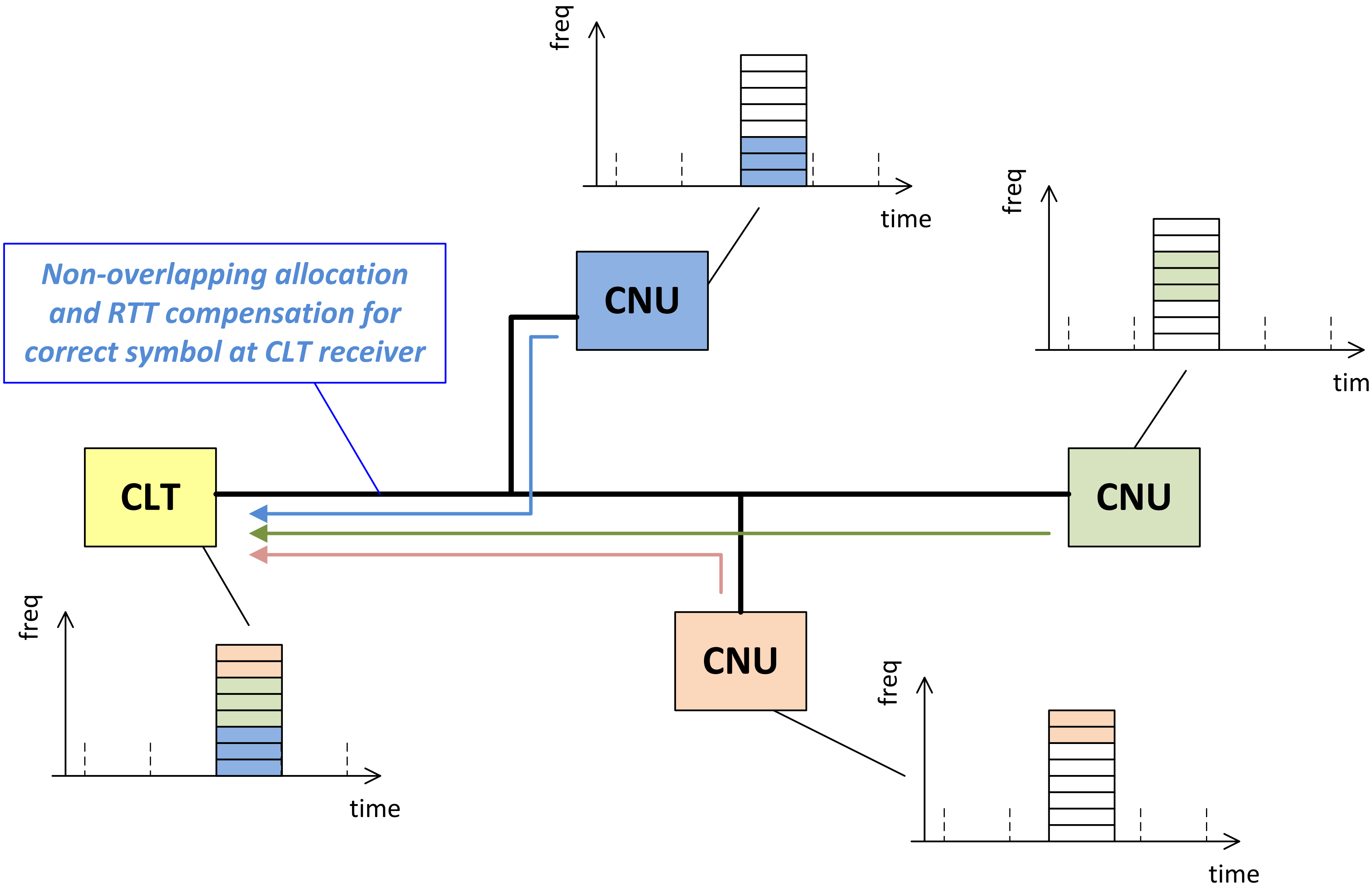
OFDMA in Downstream – Simultaneous Reception

- Multiple users multiplexed in the same OFDM symbol, whereby all CNUs can decode the entire information
  - Same Modulation and Coding Scheme (MCS) used for all users
  - Simpler but less efficient in terms of system performance
- Multiple users multiplexed in the same OFDM symbol, whereby it is only guaranteed that each CNU can decode data dedicated to it
  - User dependent Modulation and Coding Scheme (MCS)
  - Slightly more complex but better system performance
  - Each FEC block can carry data for either a single CNU or for multiple CNUs that support the same MCS

OFDMA in Upstream - Simultaneous Transmissions

- OFDMA supports multiple CNUs transmitting at the same time on different subsets of subcarriers, in a flexible manner
  - This will keep latency small and under control
- The CLT receives an OFDM symbol that is constructed in a distributed fashion by different CNUs
  - Each CNU is allocated a portion of the spectrum with no overlap
  - RTT mechanisms as in EPON ensure time synchronization at CLT
- The maximum number of simultaneously transmitting CNUs depends on the number of LDPC code blocks within a given OFDM symbol
  - Since the capacity of each OFDM symbol is large many CNUs will be able to transmit simultaneously
- In case a single CNU has sufficient data to effectively fill an entire OFDM symbol, it is possible for a single CNU to transmit at a time

OFDMA – Upstream Example



Baseline Proposal #2

- In the upstream each OFDM symbol may contain data from multiple CNUs
  - The precise design solution and related details are for further study

- In the downstream each OFDM symbol may contain data to multiple CNUs
  - The precise design solution and related details are for further study

- Moved by:
- Seconded by:
- Technical motion (>=75%)
- Yes / No / Abstain

Baseline Proposal #3

- The PHY shall support multiple modulation and coding schemes (MCS) to enable adaptation to different channel conditions. Each MCS is defined by a particular modulation order and a coding rate.

- Moved by:
- Seconded by:
- Technical motion (>=75%)
- Yes / No / Abstain

Summary

OFDM Features	Key Benefits
Wideband	• High spectral usage since guard bands are not needed between bonded channels – high spectral efficiency
Flexibility	• Easily adaptable to different spectrum configurations, based on the availability of RF bandwidth • Easily extendable to newly available spectrum
Multicarrier	• Each subcarrier passes through a flat channel so there is no need for equalization at the receiver – low complexity • No inter subcarrier and no inter OFDM symbol interference
Modulation	• High-order QAM – each subcarrier modulated with a high-order QAM leading to very high spectral efficiency • Adaptive modulation according to subcarrier quality • Severely impaired subcarriers can be blanked – avoiding the degradation of the transmission on other subcarriers
OFDMA	• Enables utilization of large bandwidths • Efficient multiuser access technique • Reduces latency of transmission

Thank you