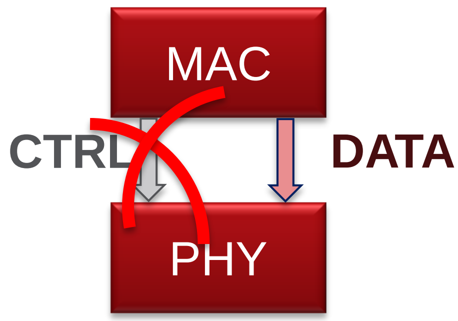
Burst Markers for EPoC Burst Mode

Nicola Varanese, Hendrik Schoeneich, Juan Montojo

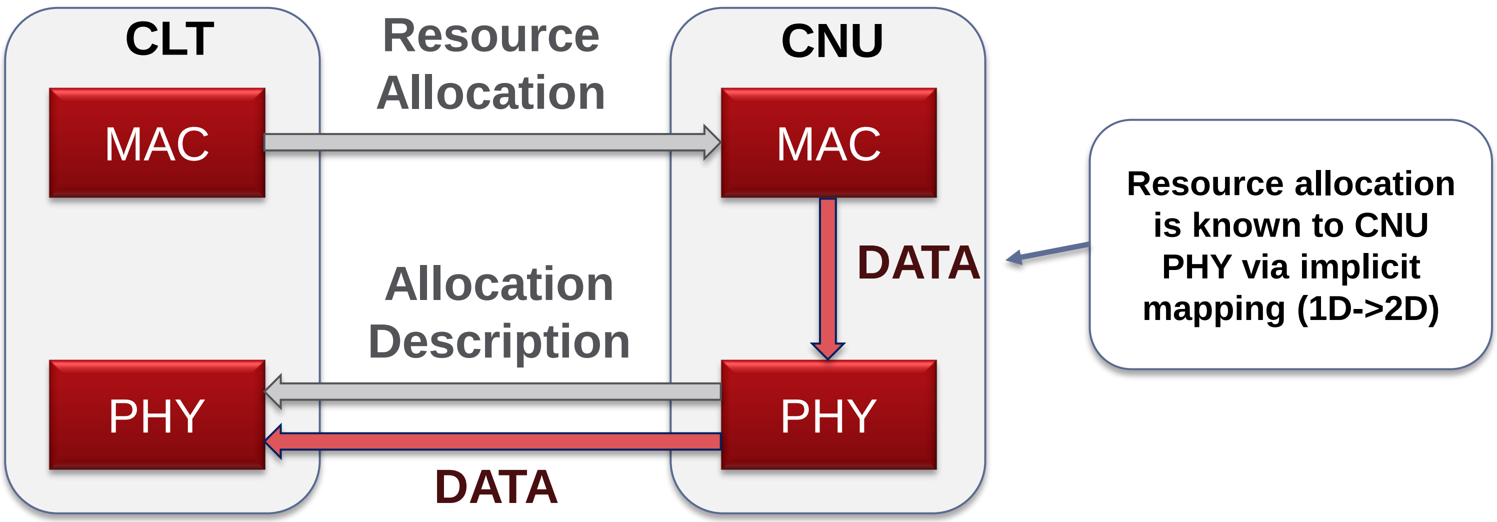
Qualcomm

Motivation

- In EPoC burst mode, a particular transmission (for a single CNU and/or profile) occupies a subset of the available PHY resources
  - MAC Ctrl determines resource allocation
  - PHY needs to be informed about resource allocation in order to perform transmission and reception operations correctly
- The 802.3 standard protocol architecture does not define any explicit way of passing control information between MAC and PHY entities

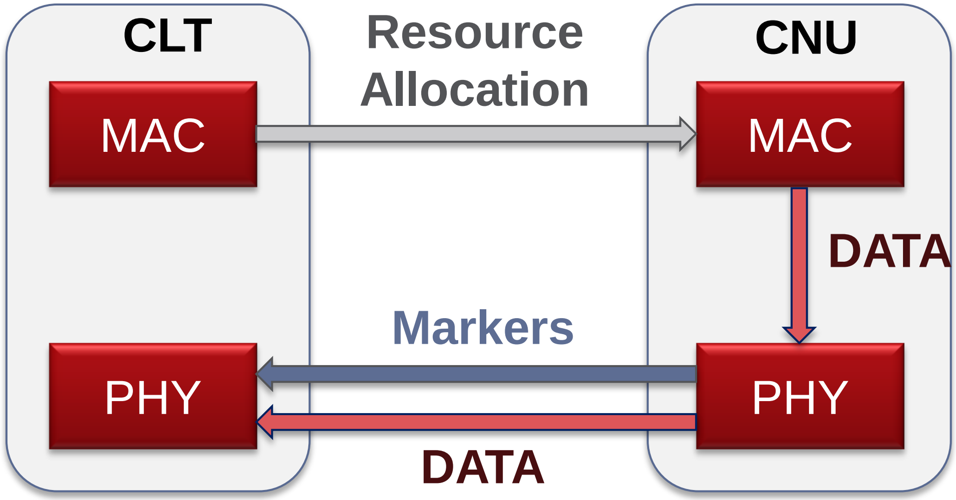


- PHY layer is unaware of any scheduling decision taken at the MAC layer
  - In particular, for US resource allocation:

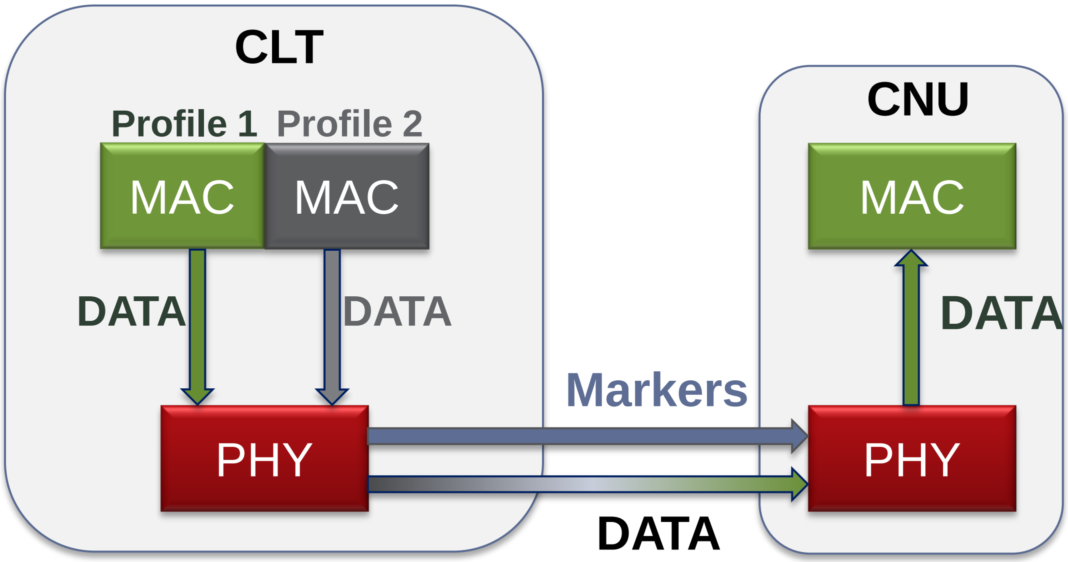


Motivation

- The allocation description will not be conveyed to the CLT PHY via a dedicated control channel
- Start/end of PHY bursts need to be delimited via burst-specific markers



- In downstream, a common control channel could be feasible
- However, it is desirable to use markers for DS as well for simplicity reasons
  - Nice-to-have symmetric burst mode for both US and DS
  - However, differences do exist between US and DS
  - These discrepancies are covered in this contribution



Definition of Burst Markers

- A marker is a known sequence of modulated symbols (in frequency domain)
- Markers share the same resources as regular data symbols
  - No dedicated control channel
  - Markers do not overwrite pilots and vice-versa
- A specific marker is defined for each possible active profile
  - E.g., assuming the use of a ternary alphabet for the markers

Profile	Marker (8 symbols)
0	{+1, 0,-1,-1, 0, 0,+1,+1}
1	{ 0,-1, 0, 0,+1,+1, 0, 0}

- Markers play the role of burst preamble and postamble (where needed)
  - The same marker delimits the start and the end of a burst
- Start-of-burst for a given profile is signaled by detection of corresponding marker
- Do we need additional, FEC protected information ? **No.**
  - The only additional information we need is the length of the burst
  - If needed, end-of-burst can be signaled by an additional postamble marker
  - Overall reliability bottleneck is the detection of the start-of-burst marker. If marker detection is reliable enough, we do not need anything else.

Upstream Transmission

Upstream Burst Markers

Features specific to Upstream transmission:

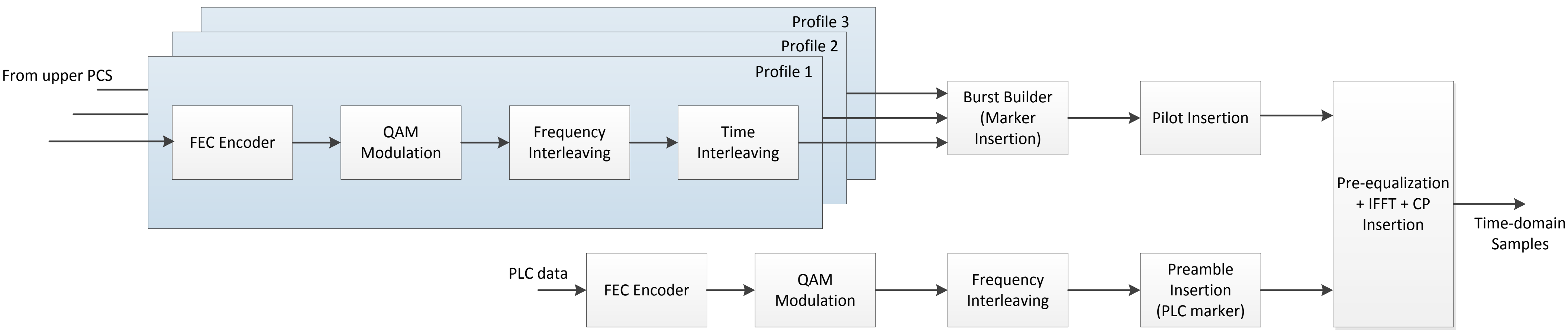
- Each CNU performs pre-equalization
  - Channel is pre-compensated at transmitter’s side (to some extent)
- Each burst is interleaved in Time and Frequency independently
  - Different bursts correspond to independent grants
- Time/Frequency resources are divided into Resource Blocks (RB)
  - A particular grant spans an integer number of RBs
- Association of pilot tones to a specific burst is unknown until the burst start/end have been detected
- Transmissions from different CNUs do not follow back-to-back

  → Need for markers:

  1) At the start of each burst
  2) At the end of each burst

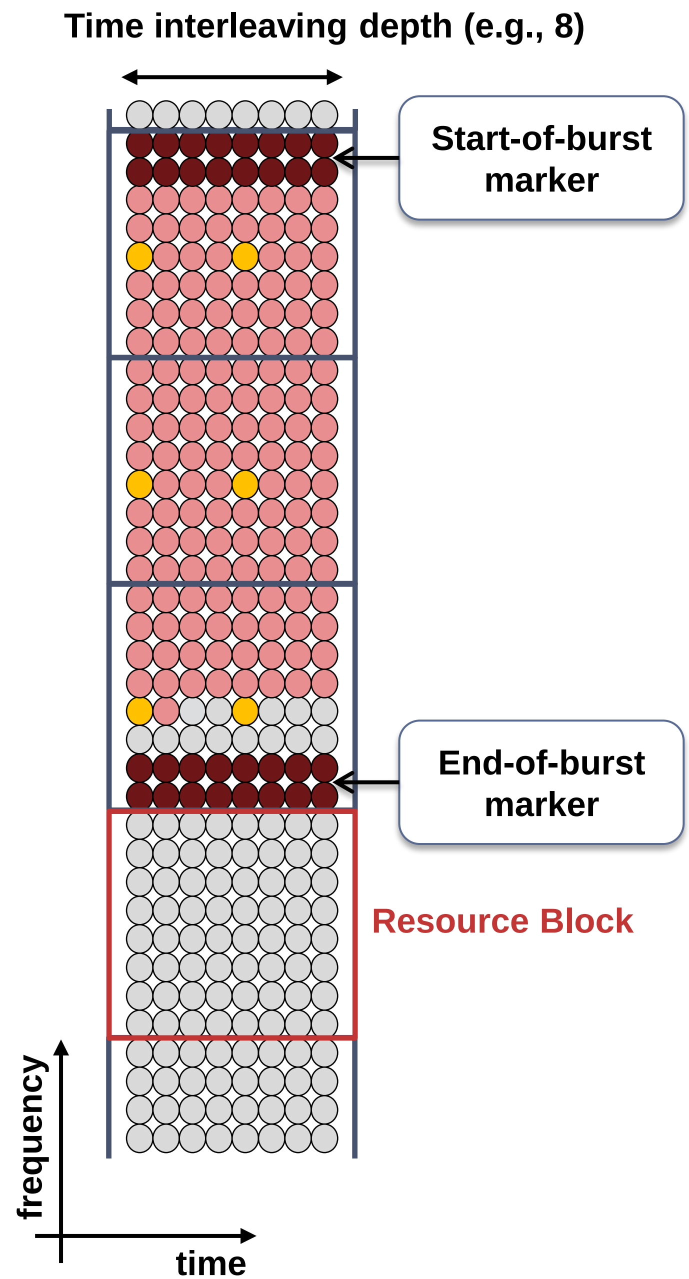
Upstream Transmitter Processing

- Frequency and Time interleaving are performed separately for each burst
- Burst builder inserts markers and assembles OFDM symbols, possibly from multiple bursts
- Pilots are inserted after marker insertion and burst construction
  - Pilot symbols do not depend on the specific profile or CNU
  - Pilot scrambling sequence depends only on frequency resources occupied by bursts being transmitted by this CNU



Upstream Receiver Processing

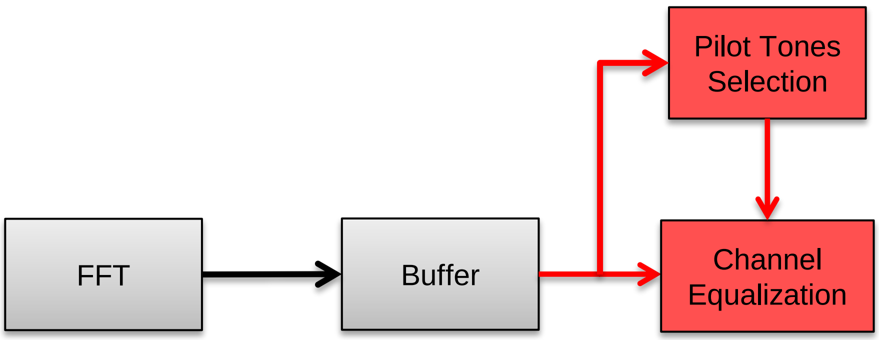
- The output of the FFT is buffered in blocks equal to the time interleaving depth
- Each burst occupies an integer number of RBs
- The marker for the specific burst profile is placed at the start of the first RB and at the end of the last occupied RB. In this example:
  - ● is a marker symbol (e.g., {-1, 0,+1})
  - ● is a data symbol (e.g., 1024QAM)
  - ● is a pilot symbol (e.g., QPSK)
  - ○ is an unused resource element
- As a general rule, markers do not overwrite pilots, i.e., they share resources with data symbols
- Markers and pilots are independent and are located at predictable locations



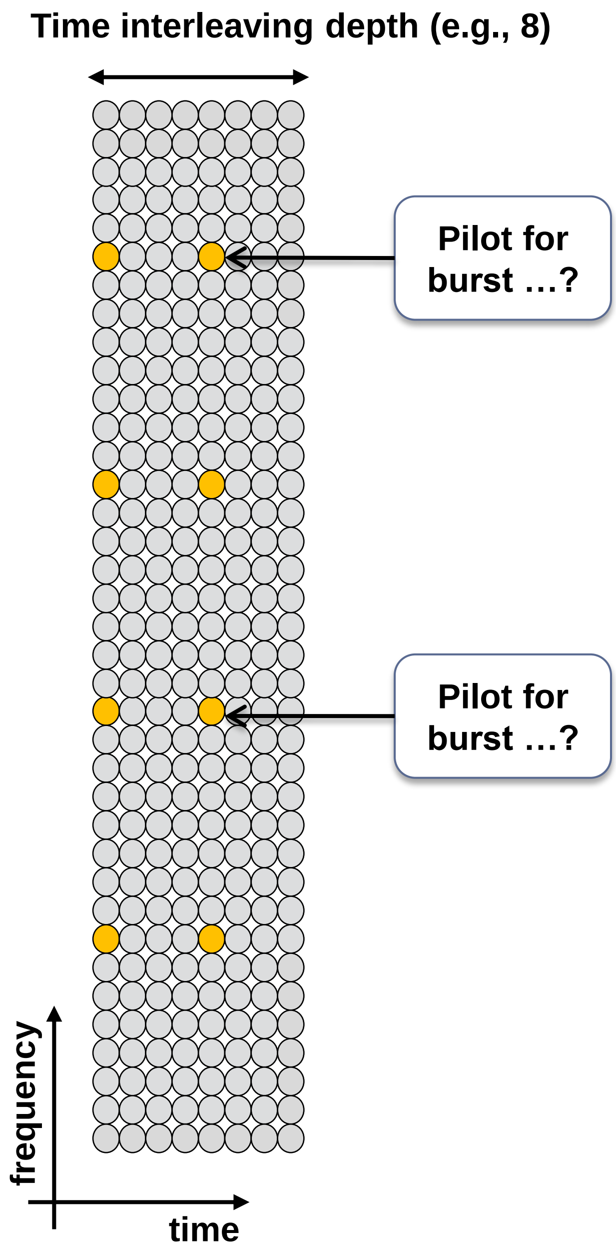
The receiver will look first for pilots or markers ?

Upstream Receiver Processing

- Pilot position is known
  → Can equalization occur prior to marker detection ?

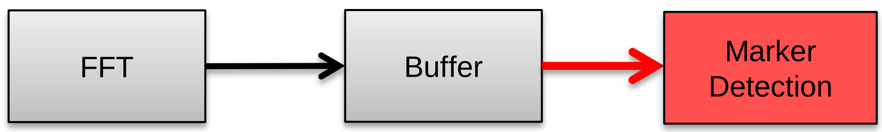


- **No**, since we do not know which burst each pilot is associated with
  - Still, we could perform some sort of very rough equalization on a per-RB basis to better condition the marker search problem
  - However, channel estimation needs to be then repeated for each burst anyways, if we do not want to experience severe performance degradation on data decoding due to raw channel estimates



Upstream Receiver Processing

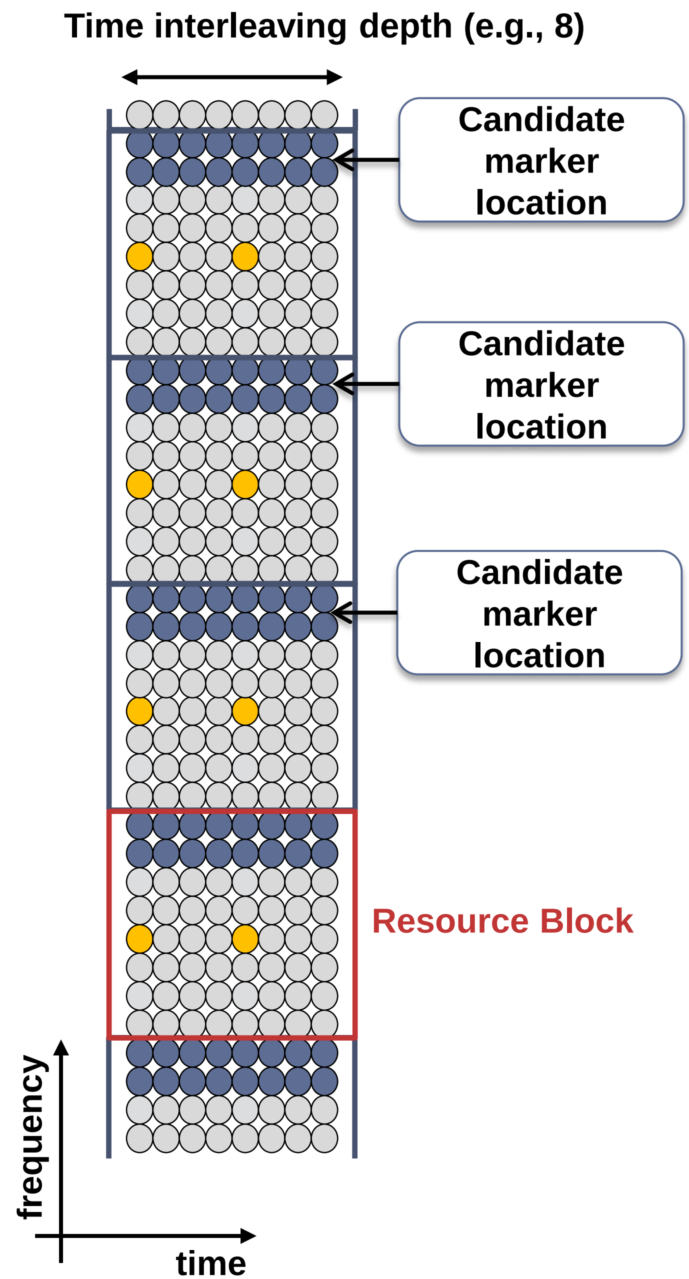
- Marker detection follows FFT and buffering



- Marker searcher scans all **candidate marker locations**

- Marker detection needs to be resilient to residual channel distortion (not pre-equalized)
  - Phase may change in time (CNU LO instability)
  - Channel response may change in frequency (e.g., RF front-end response varies with temperature)

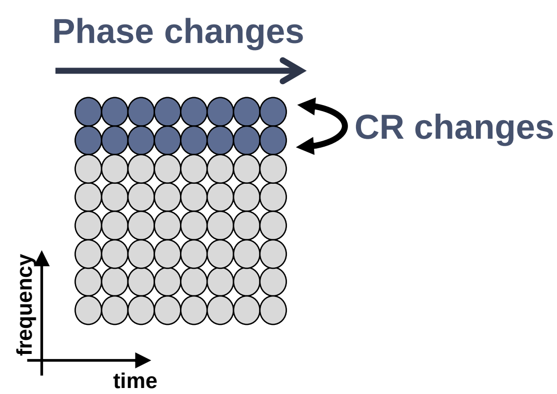
- Design criteria:
  1) How many symbols should a marker comprise ?
  2) How to place the markers within a **RB** ?

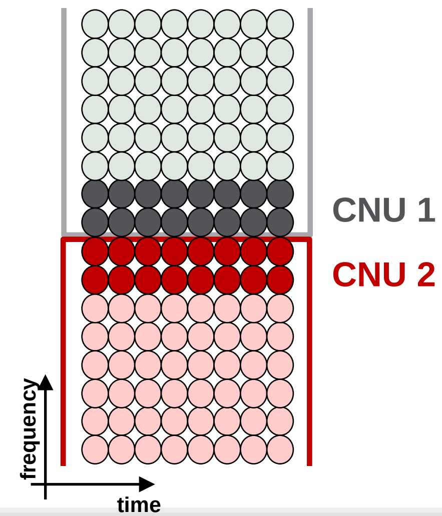


Marker Design Criteria

1) How many modulated symbols should a marker comprise ?
   - The statistical properties of marker detection depend mainly from this number
   - It should be the same number for any possible interleaver depth and RB size
   - Numbers that seem to be reasonable are **[16, 32] modulated symbols**

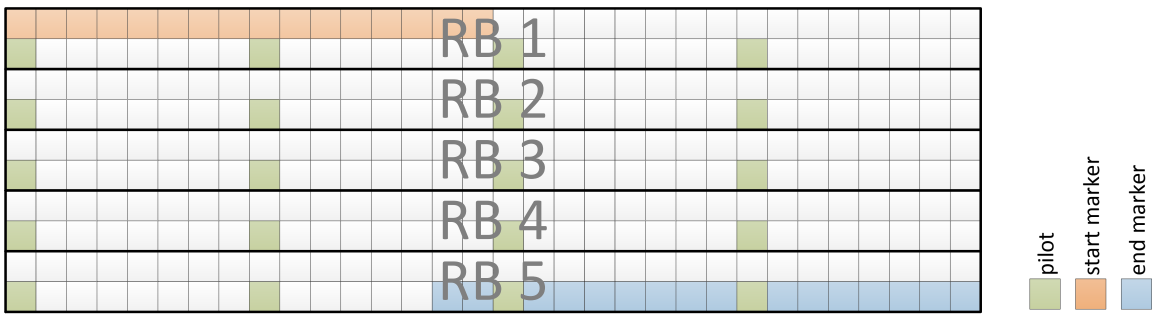
2) Horizontal placement
   - Minimizes distortion due to Channel Response changes
   - Phase changes can be countered by employing, e.g., differential modulation techniques
   - Markers can be used as edge continual pilots
     - » No need to extrapolate the channel estimate at the edges of a grant
     - » Time/phase tracking capabilities

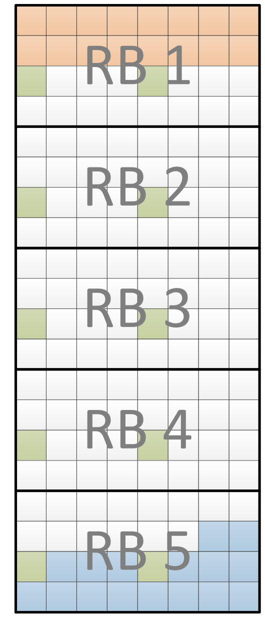




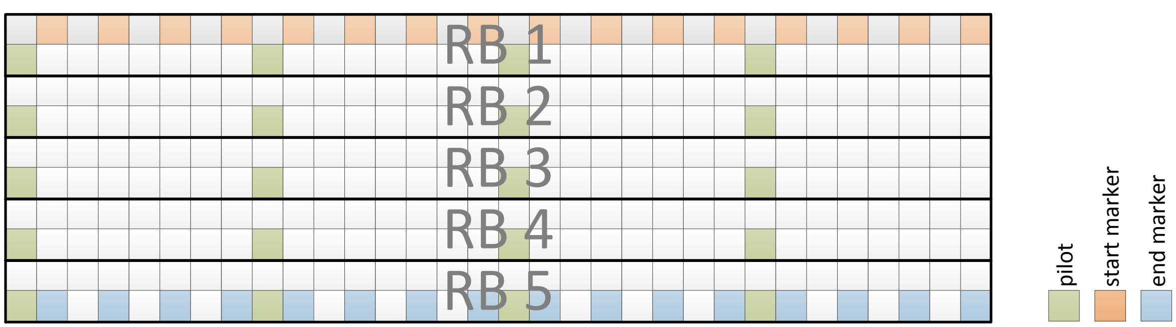
Combining Markers with Pilots

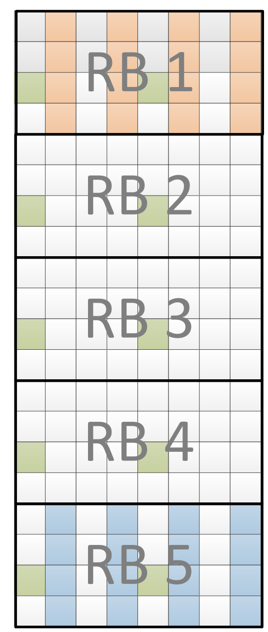
- General rule: markers do not overwrite pilots
- In order to avoid asymmetric marker placement with some RB configurations, e.g.,





- Marker symbols can be interleaved with data symbols at the start/end of the burst, e.g.,

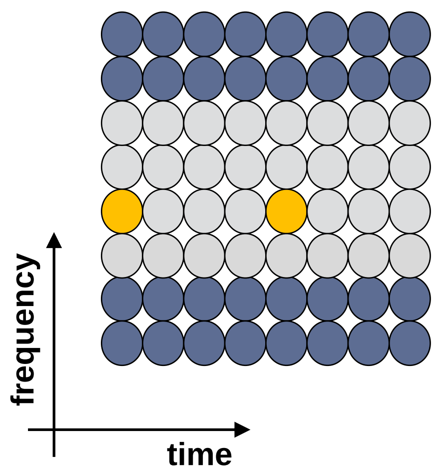




Impact of Markers on Upper Layers

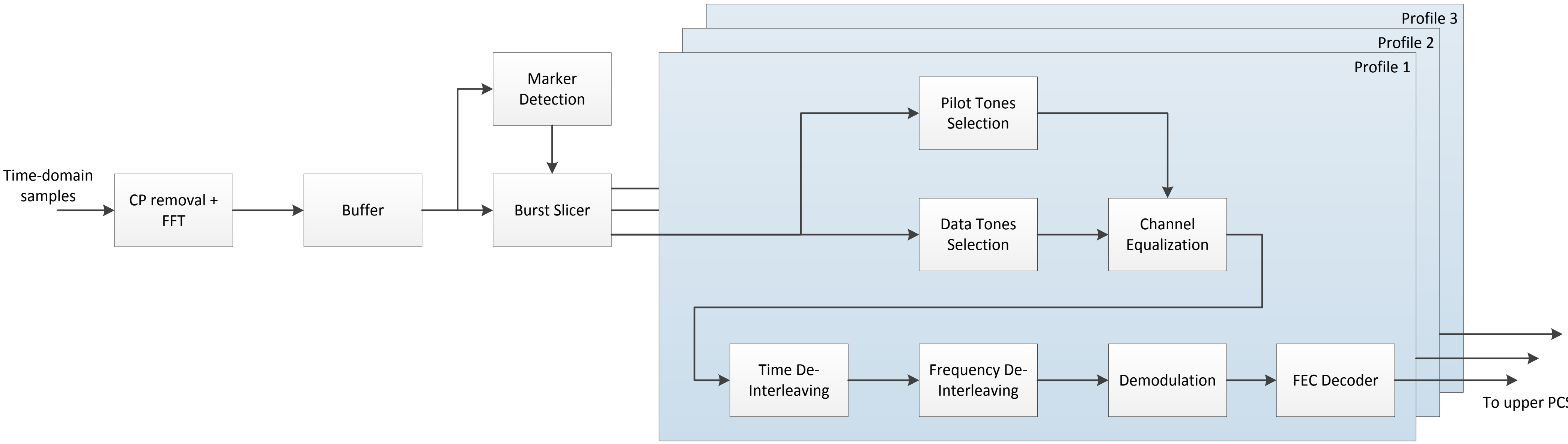
- Markers are a constant overhead for every burst in terms of integer resource elements
  - They will always occupy the same number of modulated symbols (resource elements)
  - Similar overhead as laser on/off burst overhead in EPON

- Marker overhead influences the minimum PHY burst size
  - E.g., a single 8x8 RB (or smaller) is not able to carry a 64 Bytes frame, even with the highest modulation



Overall Upstream Receiver Processing

- Marker search is performed right after FFT (possibly jointly with buffering of incoming samples)
- Channel estimation and equalization, Frequency and Time de-interleaving are performed separately for each burst, after burst slicing has occurred



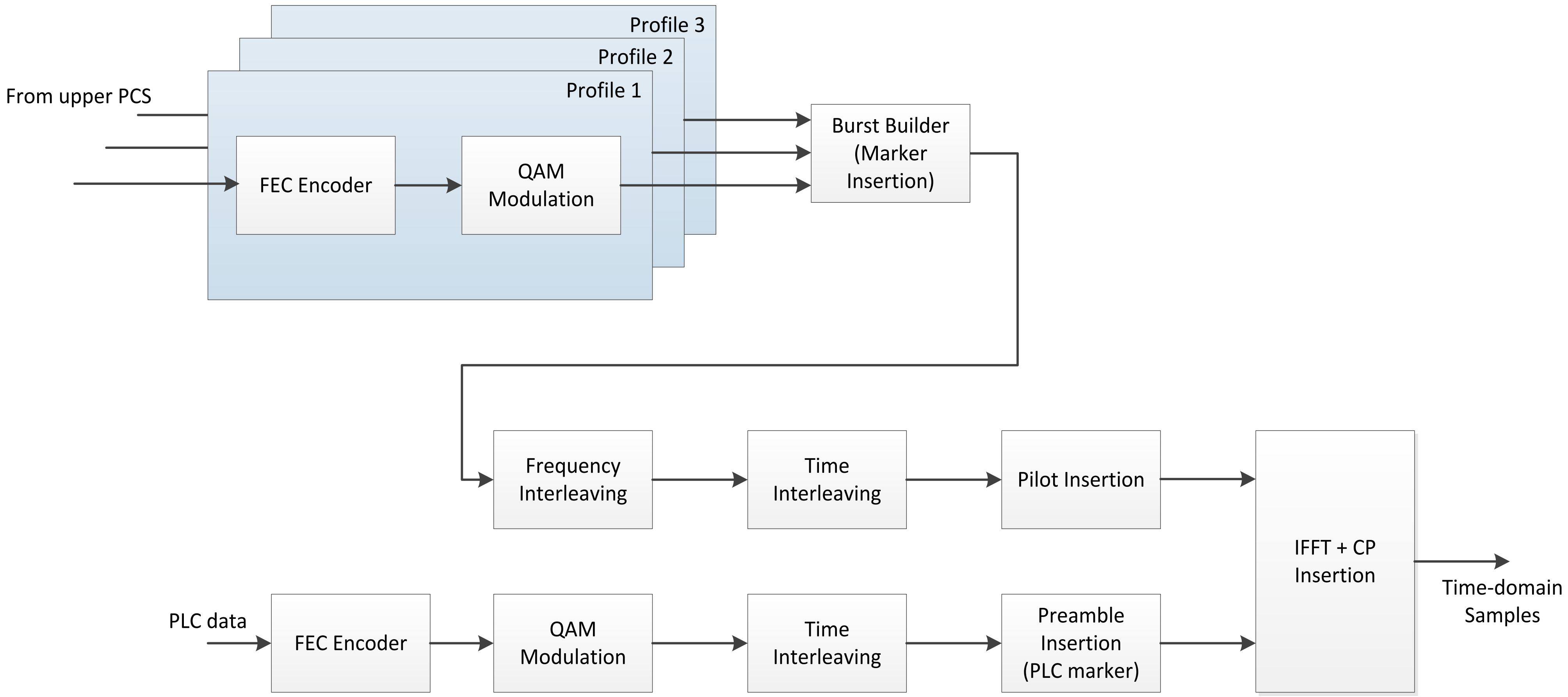
Downstream Transmission

Downstream Burst Markers

- In the DS case, transmission is continuous.
  - One profile follows the previous back-to-back (no notion of Resource Block)
  - Only a single start marker for each profile is needed
- EPoC DS is a system with a single transmitter
  - Pilot positions are known to CNUs
  - The channel response is estimated over the full bandwidth by each CNU using all available pilots in order to achieve the largest possible processing gain
  - This implies that channel equalization is performed before marker detection
    - Channel distortion is (ideally) immaterial to marker detection
- Marker detection comes after frequency and time de-interleaving (see following slides)
  - Modulated symbols from multiple profiles are spread across entire frequency band and multiple OFDM symbols
  - Time and frequency interleaving are common for all profiles

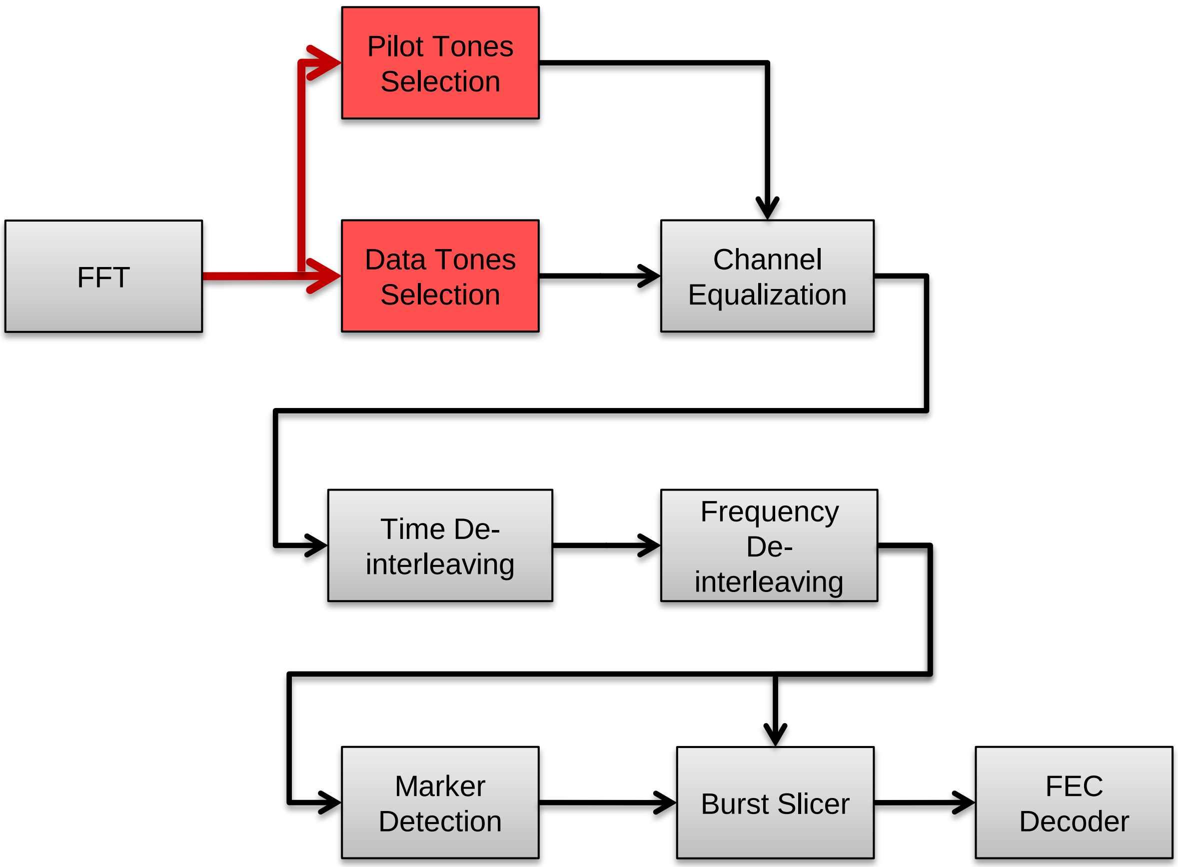
Downstream Transmitter Processing

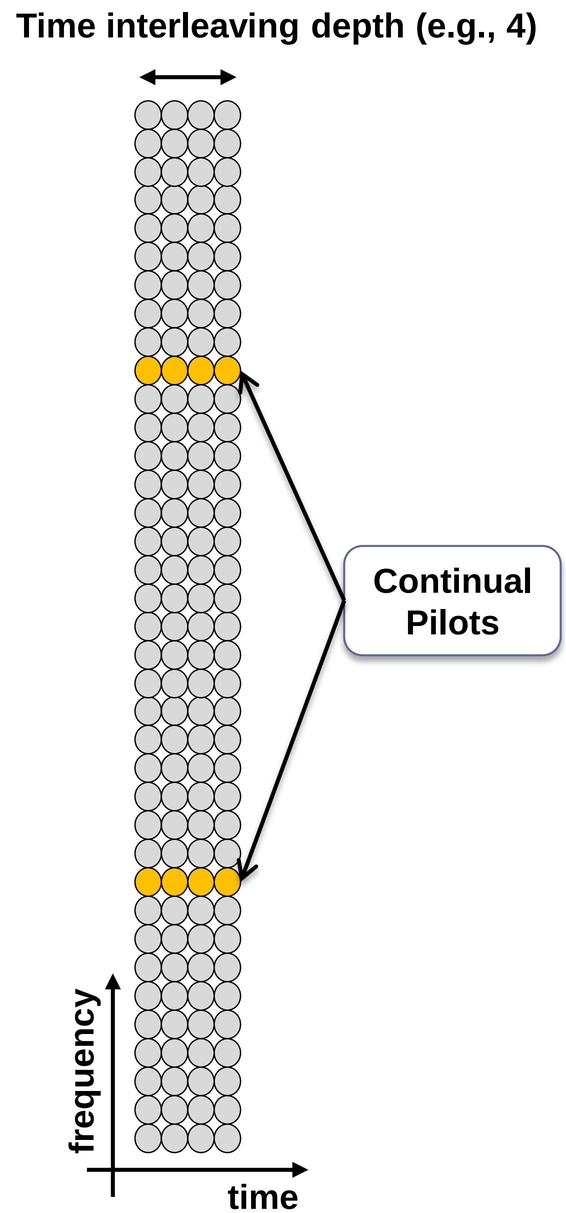
- Frequency and Time interleaving are performed over the continual modulated symbol stream coming from the Burst Builder
- Spreading each profile over a wider frequency range improves the effectiveness of interleaving and overall PHY performance



Downstream Receiver Processing

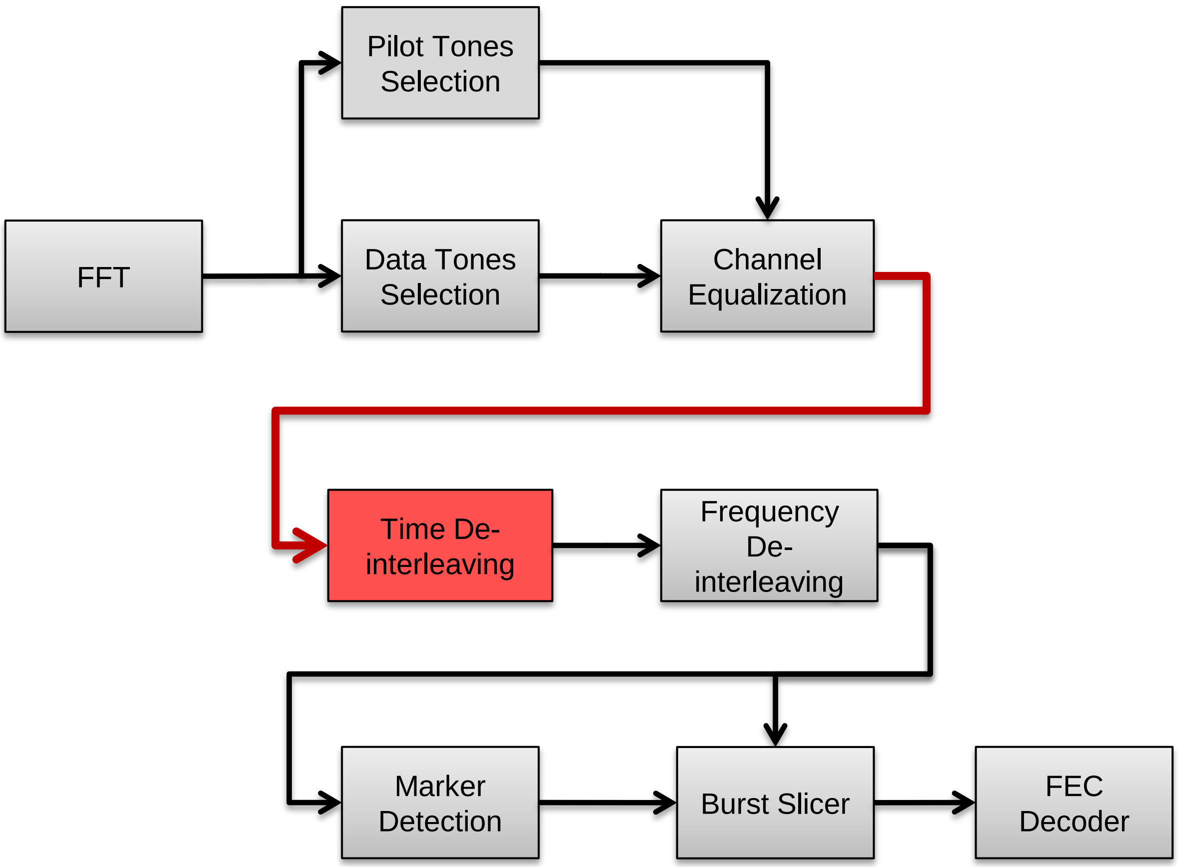
- Pilot tones (regular and continual) are selected from FFT output for channel estimation/tracking (here only continual pilots are shown)
- Data (and marker) symbols undergo channel equalization

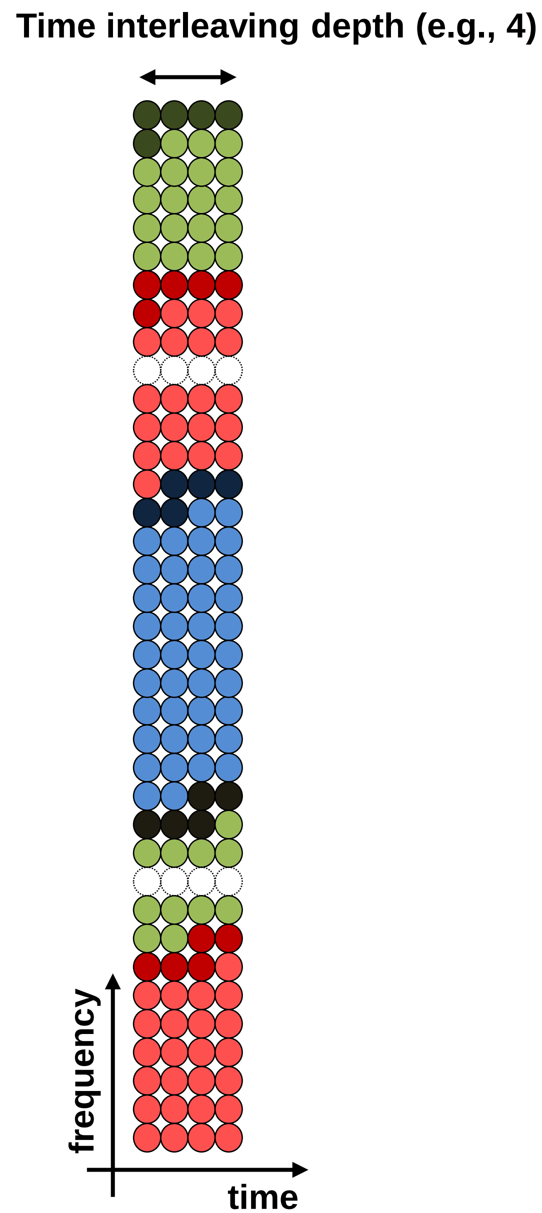




Downstream Receiver Processing

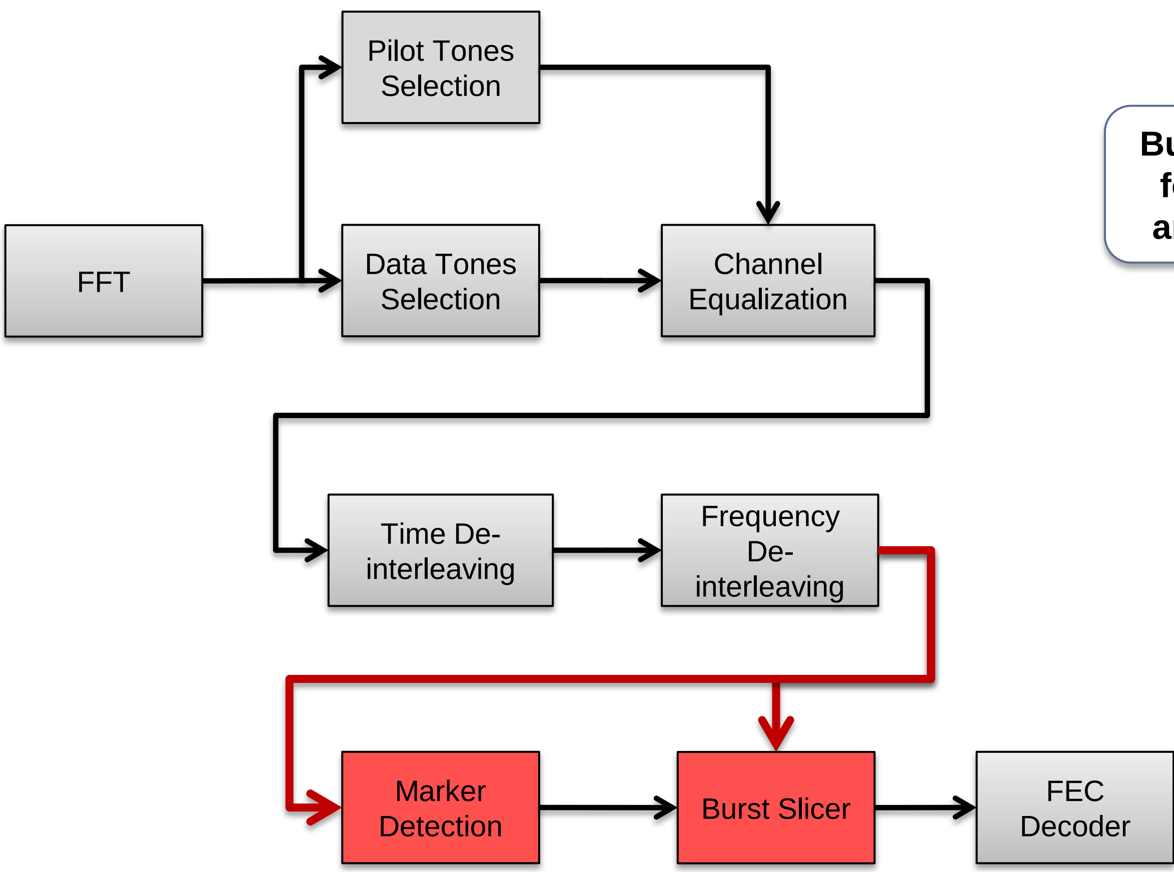
- Time and Frequency de-interleaving is a reordering operation applied to modulated symbols (in this figure frequency interleaving is neglected for simplicity)
- In DS we have no notion of Resource Blocks: Markers are not aligned to a specific time/frequency grid

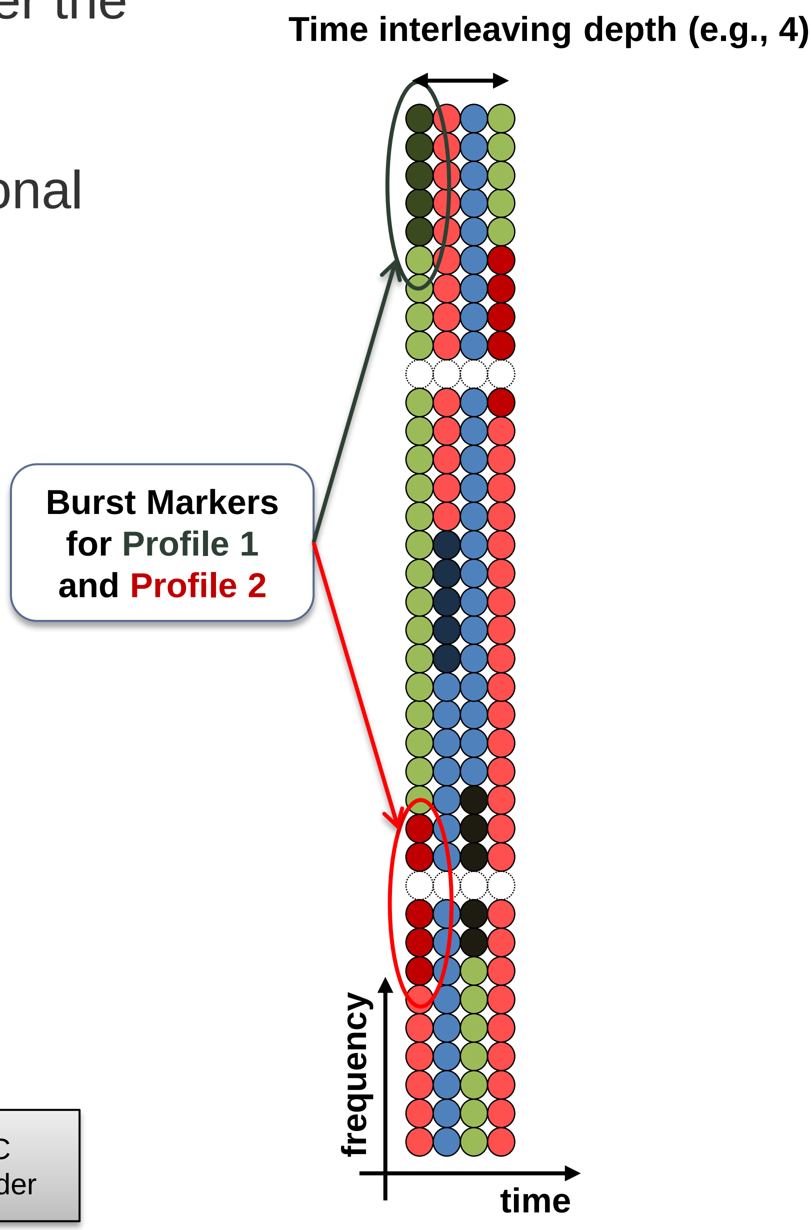




Downstream Receiver Processing

- Markers detection is a running correlation over the stream of re-ordered modulated symbols
- Marker detection does not require any additional buffering

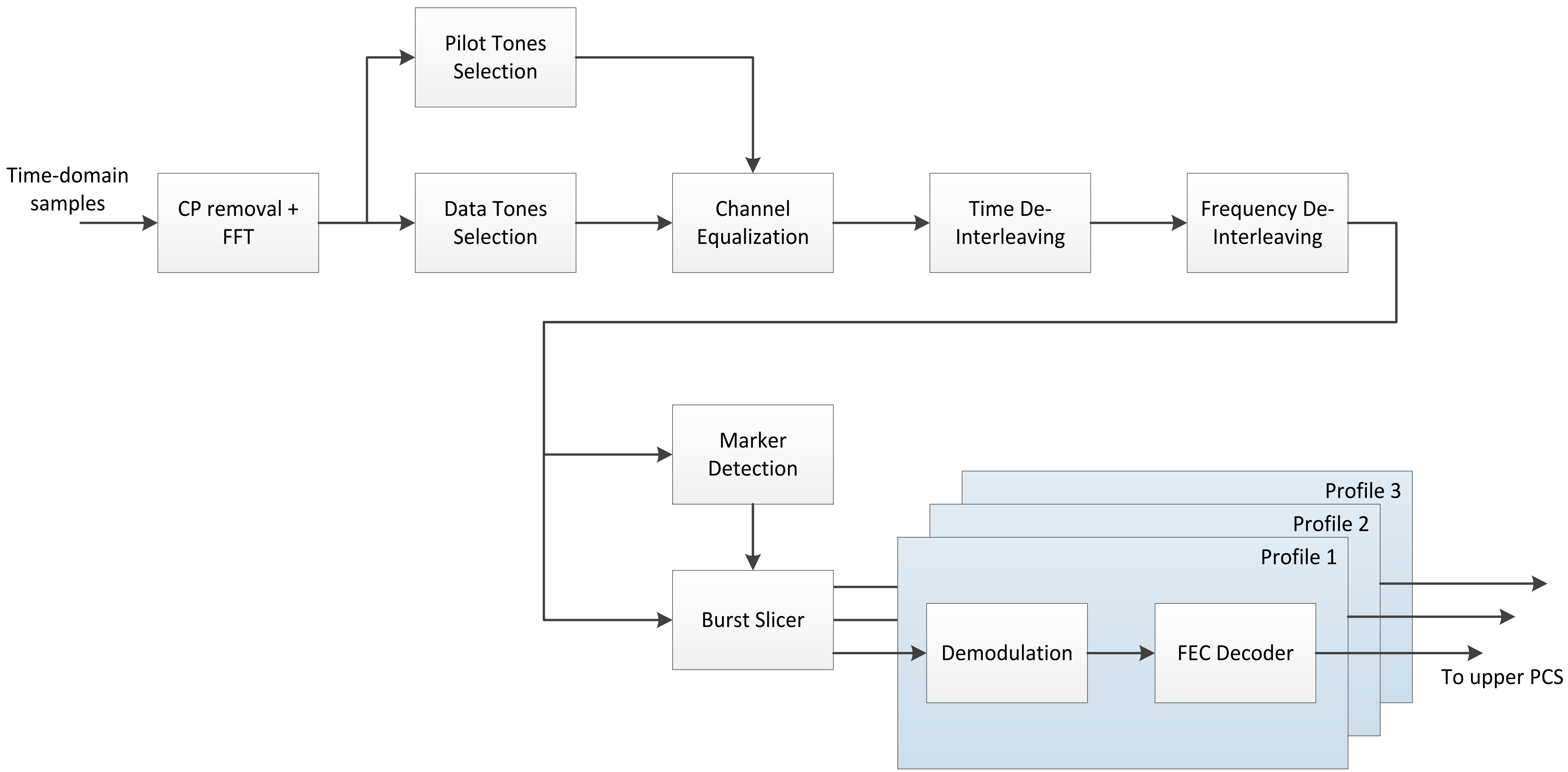




Overall Downstream Receiver Processing

- Channel estimation and equalization, Frequency and Time de-interleaving are performed after the FFT and are burst-agnostic

- Marker search is performed last, before demodulation and FEC decoding



Marker Sequence Design

Marker Sequence Design

- There are N_m valid marker sequences of length L_m

$$\boldsymbol{m_i} = [m_i[0] \quad \cdots \quad m_i[l] \quad \cdots \quad m_i[L_m - 1]], 0 \le i < N_m$$

- All sequences are pairwise uncorrelated and with unit amplitude (the latter is not necessarily needed but simplifies the description)

$$\sum_{l=0}^{L_m} m_i[l] \cdot m_j^*[l] = \sum_{l=0}^{L_m} e^{j(\mu_i[l] - \mu_j[l])} = \begin{cases} L_m, i = j \\ 0, i \ne j \end{cases}$$

- The marker sequences are Hadamard sequences
- In DS the transmit sequence is the marker sequence itself

$$\boldsymbol{s}_{\mathrm{DS}} = \boldsymbol{m_i}$$

- In US the phases of the marker sequence define the phase change of the transmit sequence

$$\boldsymbol{s}_{\mathrm{US}} = \left[p \cdot e^{j\mu_i[0]} \quad s_{\mathrm{US}}[0] \cdot e^{j\mu_i[1]} \quad s_{\mathrm{US}}[1] \cdot e^{j\mu_i[2]} \quad \cdots \quad s_{\mathrm{US}}[L_m - 2] \cdot e^{j\mu_i[L_m - 1]}\right]$$

- US reference phase is given
  - by the first regular pilot in the first OFDM symbol of the grant for the start marker
  - By the last regular pilot in the first OFDM symbol of the grant for the end marker

Marker Detector

- In DS the marker detector correlates the equalized received samples with the marker sequences directly
- In US the correlation with marker sequences is done after derotation of the FFT output, i.e., before channel estimation at the receiver

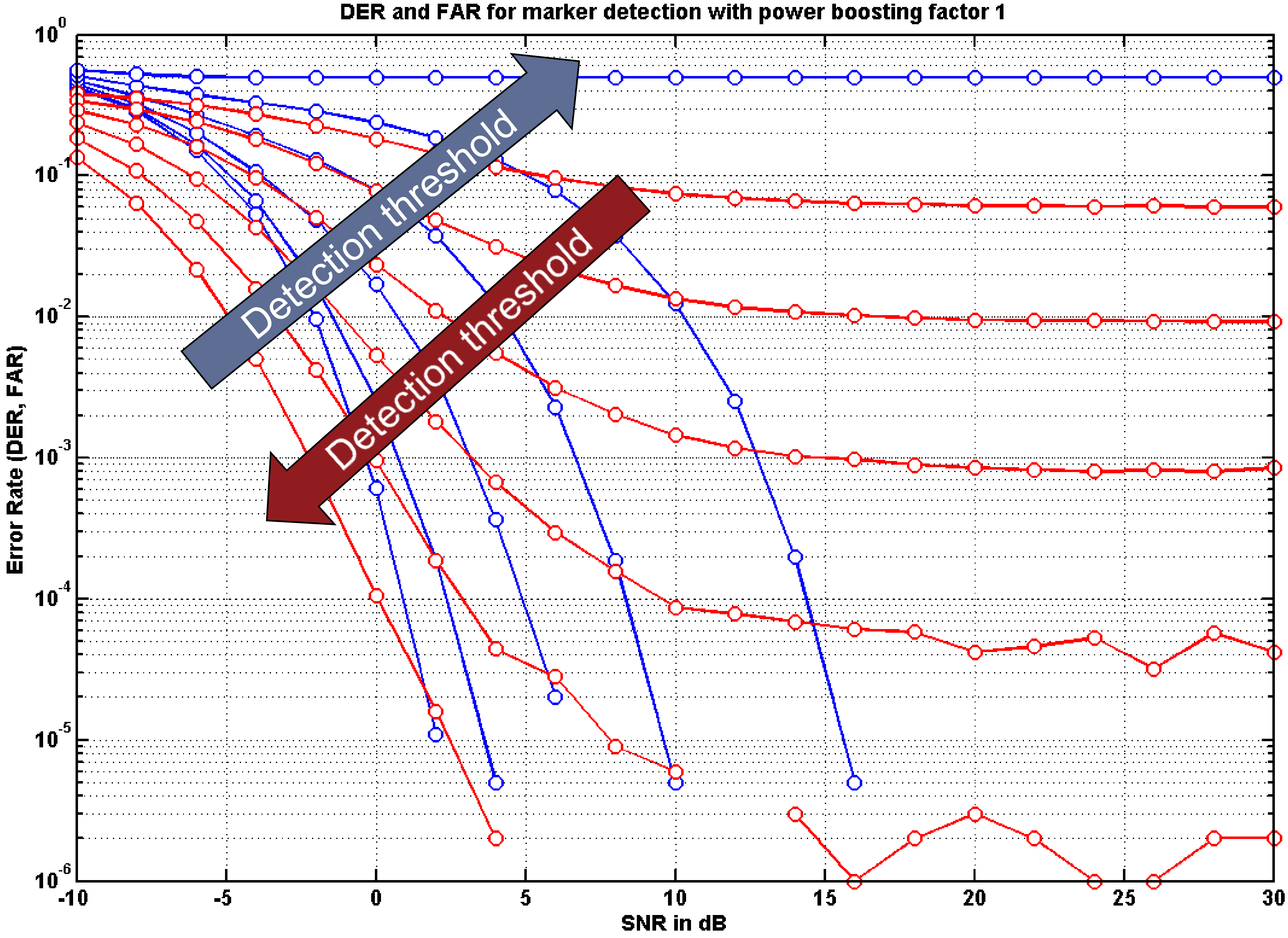
$$\begin{bmatrix} \frac{s_{\mathrm{US}}[0] \cdot p^*}{|p|^2} & s_{\mathrm{US}}[1] \cdot s_{\mathrm{US}}^*[0] & \cdots & s_{\mathrm{US}}[L_m - 2] \cdot s_{\mathrm{US}}^*[L_m - 3] & s_{\mathrm{US}}[L_m - 1] \cdot s_{\mathrm{US}}^*[L_m - 2] \end{bmatrix}$$

- The correlation detector decides in favor of the marker sequence with highest correlation
- One additional hypothesis of having no marker sequence is taken into account by introducing a detection threshold

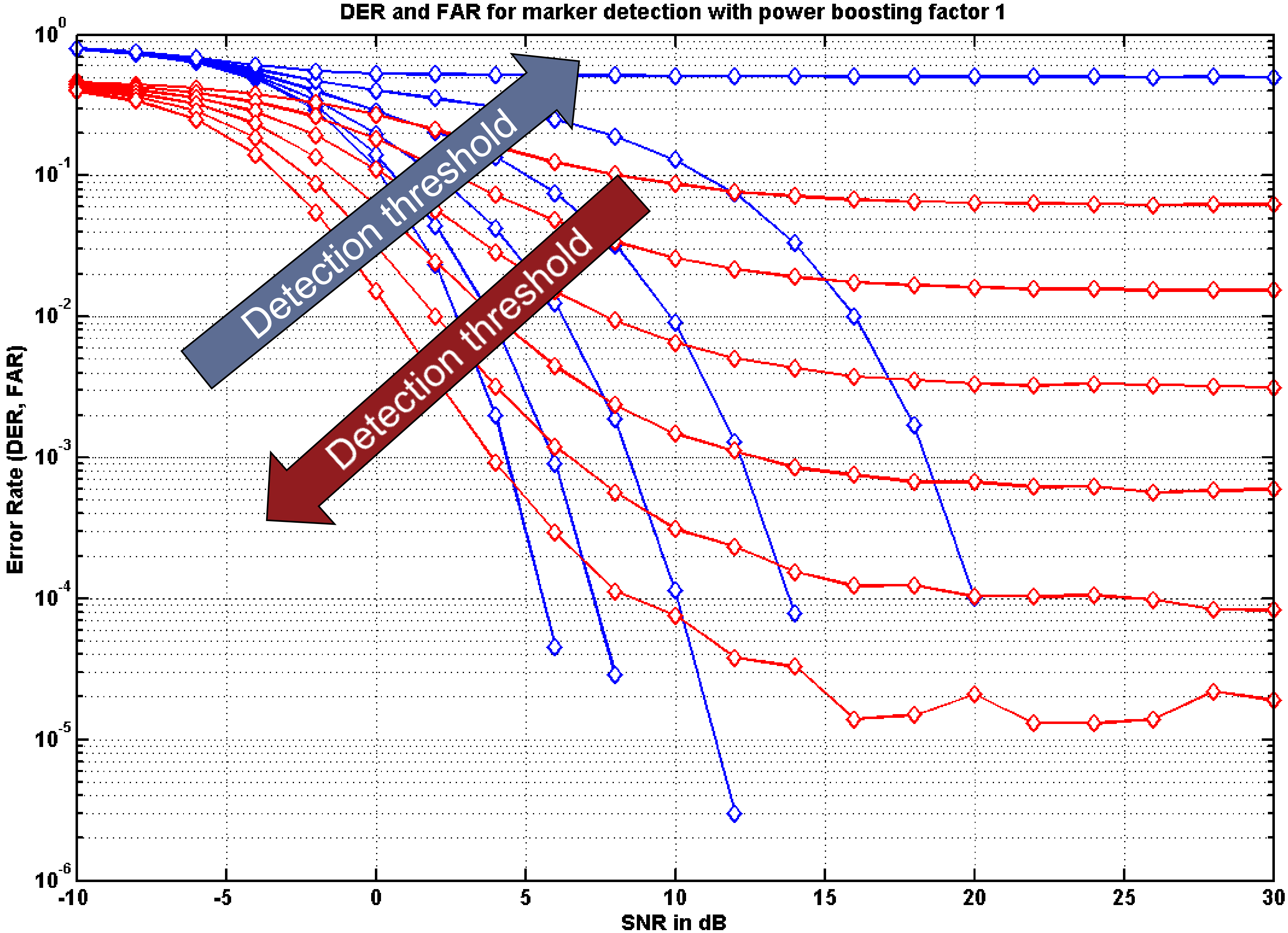
Numerical Results

- Marker sequence length $L_m = 16$
- Regular pilots and marker sequences are assumed to use the same power boosting factor
- Four valid marker hypotheses are assumed, each using a distinct Hadamard sequence
- The detection threshold is varied
- The SNR is valid for the marker sequence, this is not to be mixed up with the data SNR
- Error types
  - *Detection Error Rate (DER)*: One marker sequence is transmitted, the DER shows the relative number of events that this sequence is not detected
  - *False Alarm Rate (FAR)*: No marker sequence is transmitted, the FAR shows the relative number of events that a marker sequence is detected

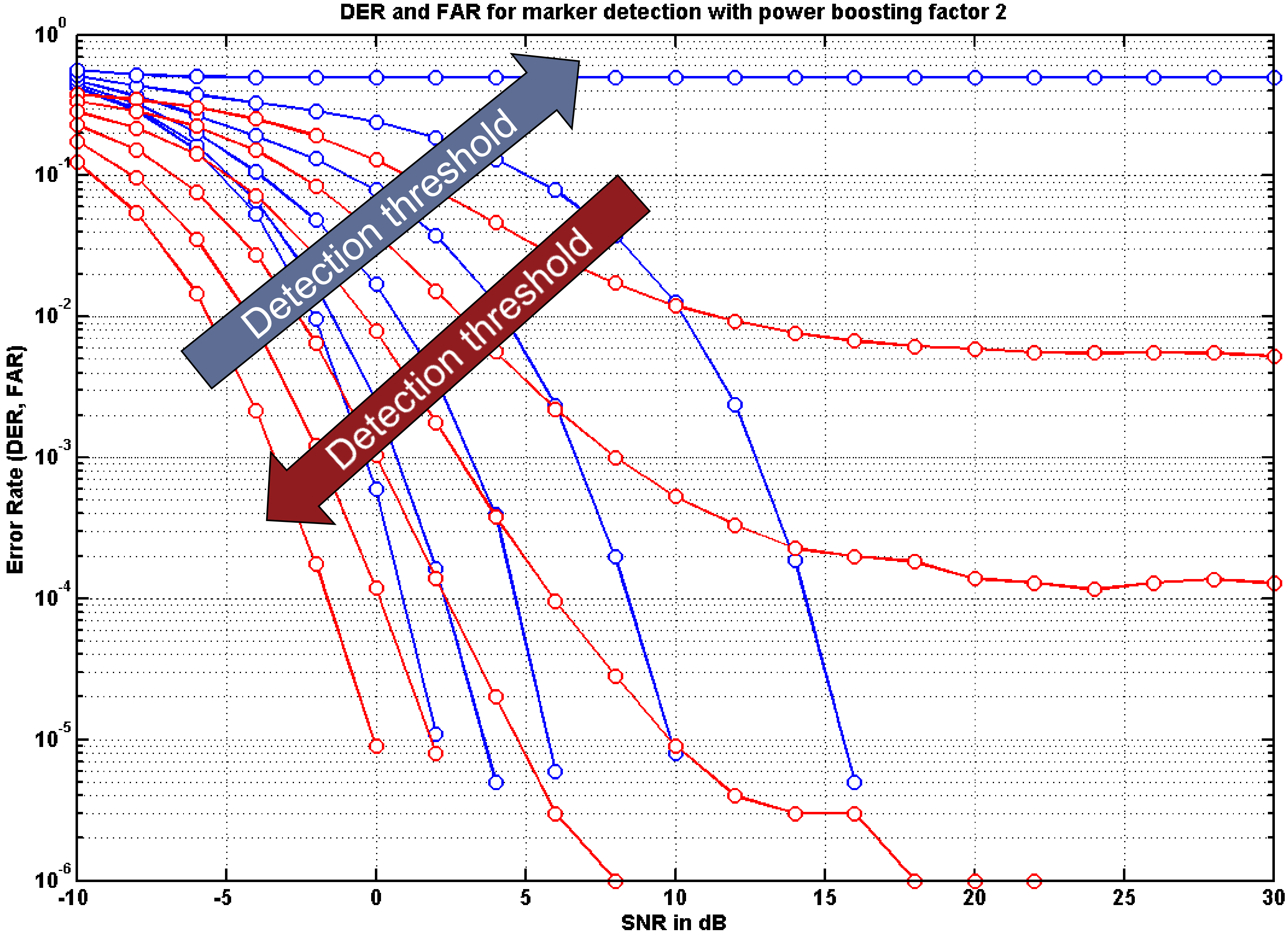
DS w/o power boosting



US w/o power boosting



DS, power boosting 3dB



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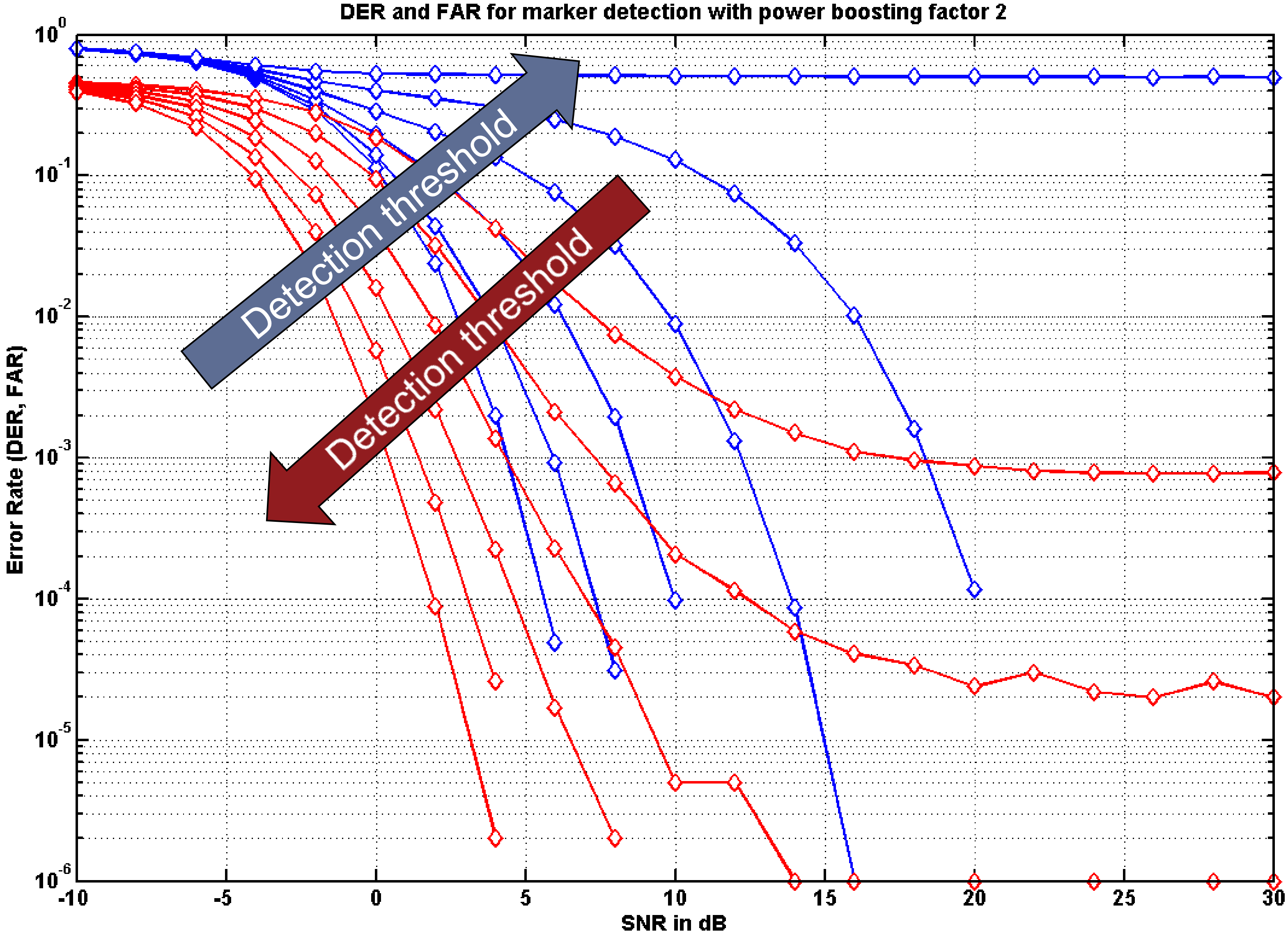

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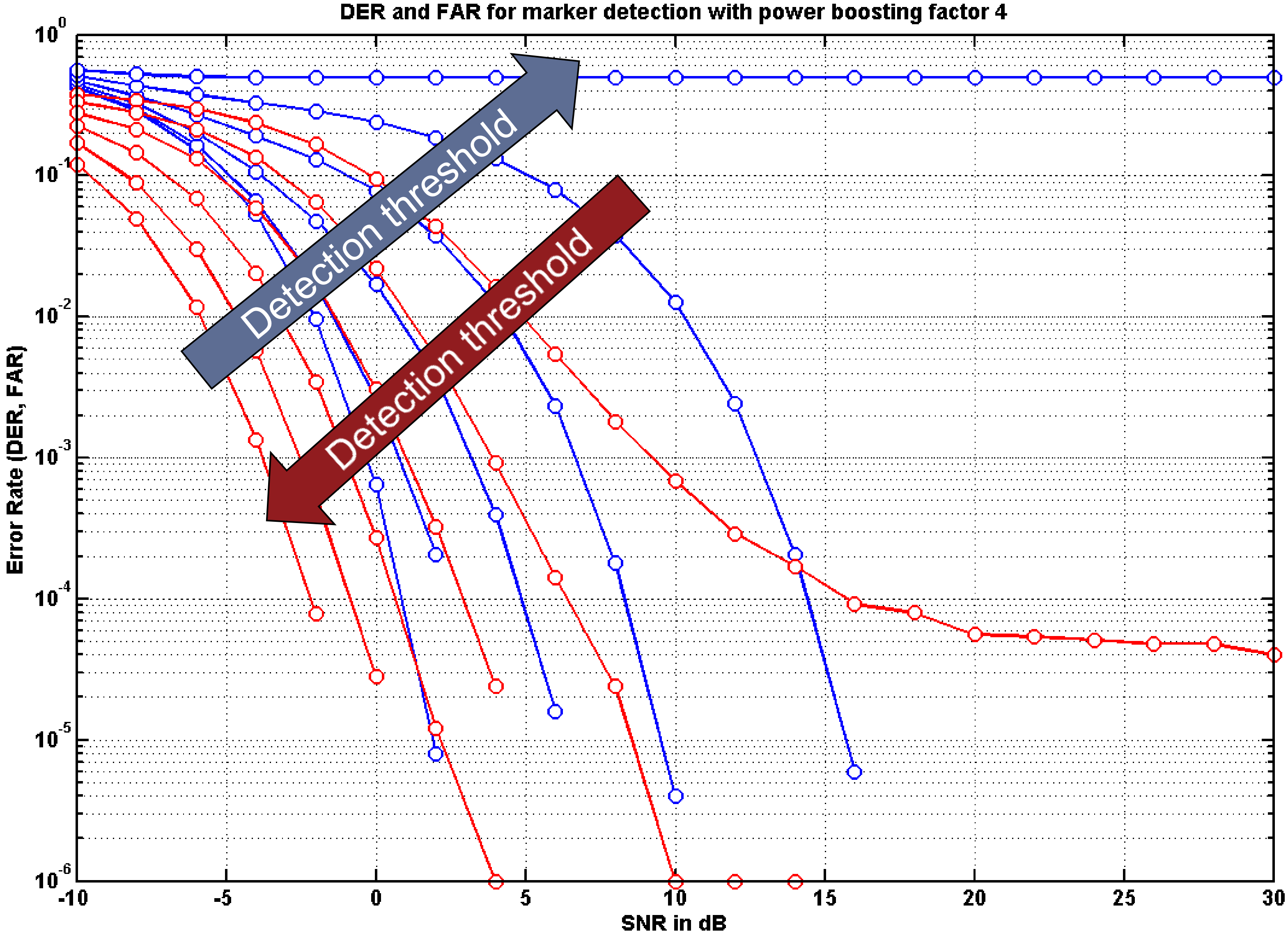
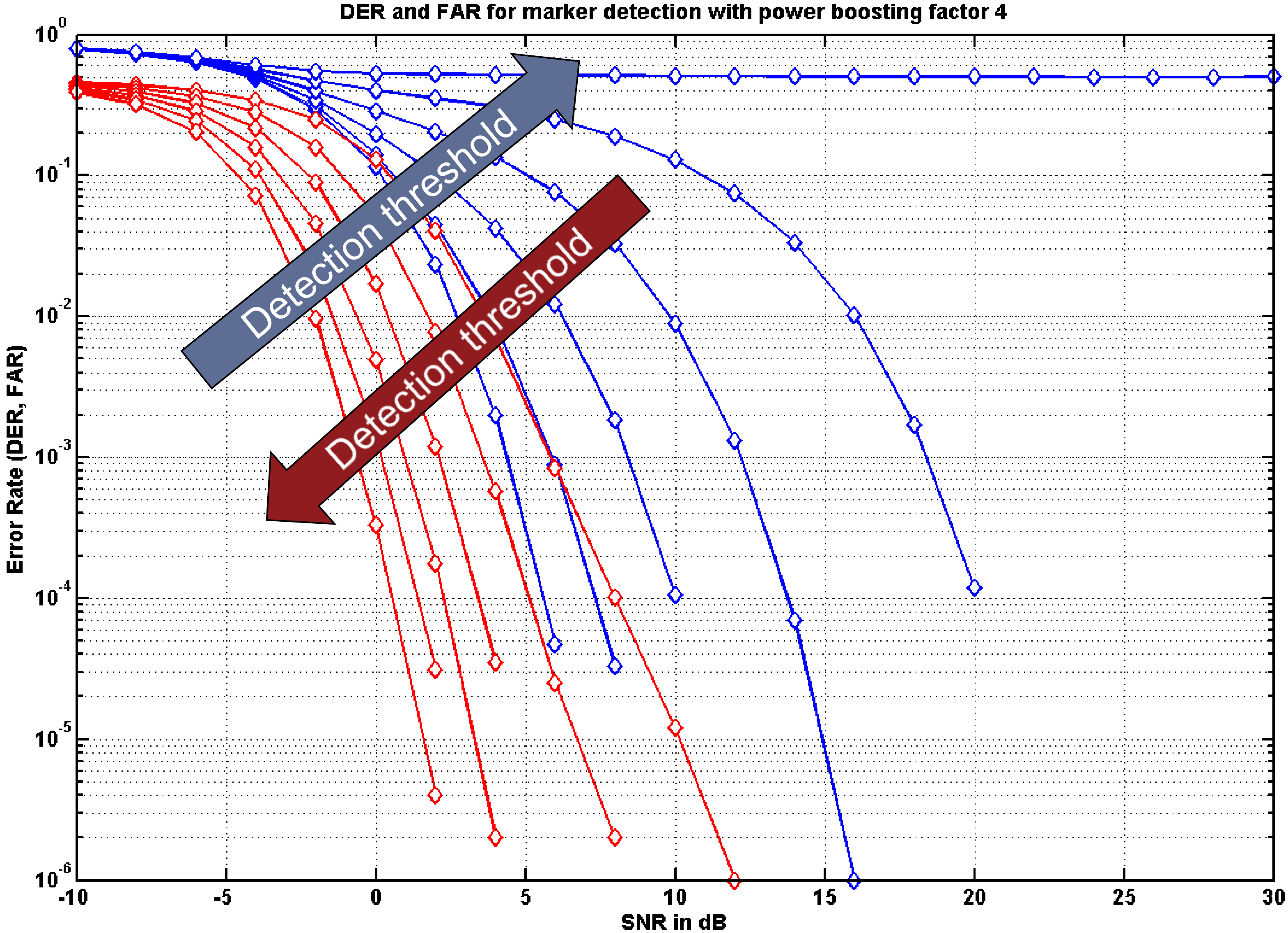


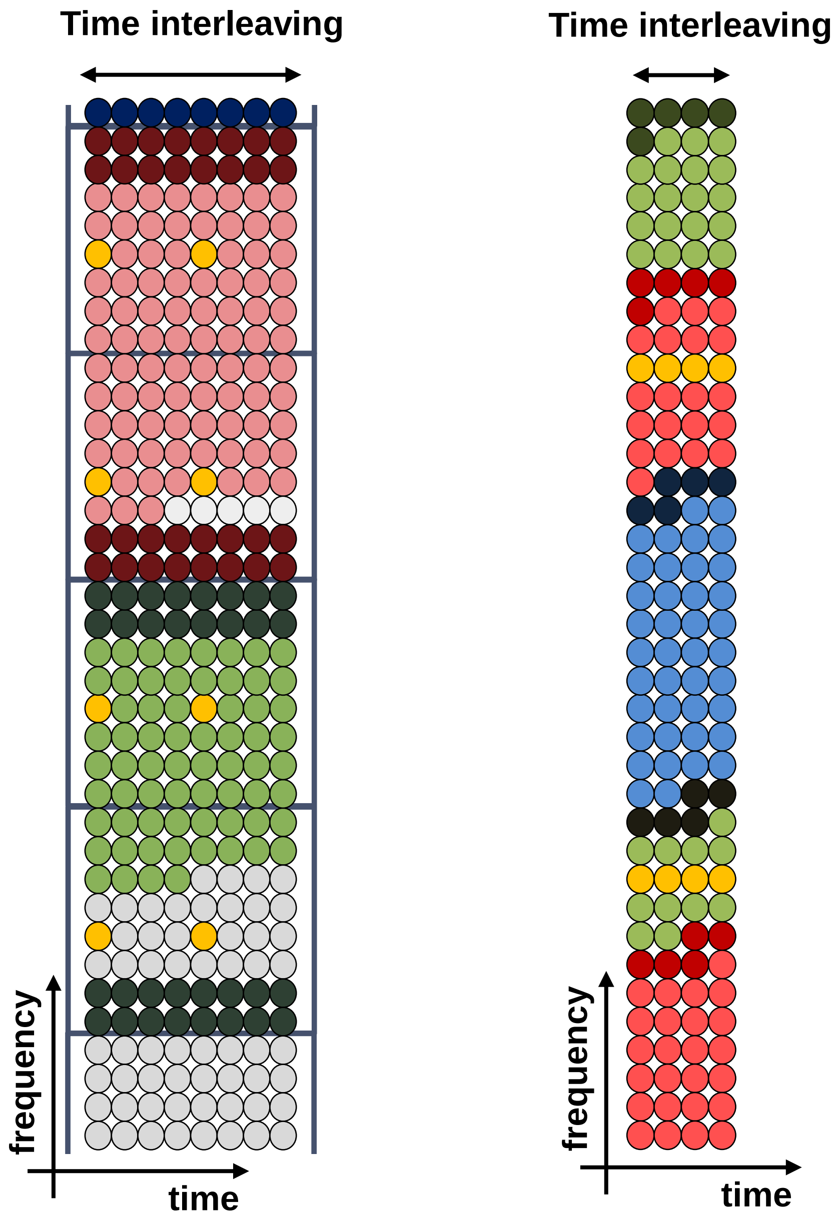
US, power boosting 6dB



Conclusions

Final Considerations

- The figure represents how the stream of modulated symbols will look like in US (left) and DS (right)
- Differences:
  - In US bursts are aligned to RBs. In DS bursts follow each other back-to-back
  - In US there is need for two markers, one at the start and one at the end of the burst, respectively.
- Impact on transceiver architecture
  - Marker detector
  - Burst builder/slicer



thank you