Proposal of a transmission structure for GEPOF technical feasibility

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Disclaimer

- This presentation does not provide a complete list of requirements for a Gigabit Ethernet POF PHY, but only the necessary that motivates the development of a transmission structure

Motivation and objectives

Motivation

- GEPOF PHY will have to be defined to fullfil with special requirements imposed by operation and environmental specifications of the automotive applications (see [2]):
  - Clock frequency deviation: +/- 200 ppm (aging and temperature)
  - Max. wake time (from power off to Gigabit link ready): 100 ms
  - Operation temperature range: -40 to 95ºC
- In [4] it was shown that the characteristics of the optical transmitter present a deep dependency with temperature:
  - The coupled optical power is expected to change about 5 dBo between -40ºC and +95ºC
  - The impulse response and specially the harmonic distortion (to be compensated by the PHY) are also deeply affected by the temperature
- In [3] is explained that the TIA circuit needs to implement an Automatic Gain Control (AGC) based on trans-impedance control to avoid saturations and optimize the noise figure as a function of the optical power coupled to photodiode.
  - Therefore, variations on temperature are going to produce variations of TIA response, since it closely depends on the trans-impedance

Motivation

- Crystal oscillator frequency drift:
    - We can expect 5 ppm/ºC in the worst case temperature point for a low cost crystal oscillator
    - Let's assume cold start of a car from -40ºC and the ECU where the PHY is integrated achieves an inner ambient temperature of 40ºC in 1 minute aided by the heating system
    - Frequency drift = 5·80/60 = ~7 ppm/s, where the PHY has to operate with BER < 10^{-12} and without loosing the link
- Mechanical vibrations:
    - The optical inline connectors and headers are going to experience vibrations transmitted by the engine and the wheels that are rolling on the road
    - Relevant power spectral density is between 5 and 200 Hz
    - Optical coupling between elements are going to experience insertion losses as a function of time, doing variable the optical power coupled to photodiode
    - Time variant optical power is going to produce variable channel impulse response observed by the GEPOF PHY receiver:
        - Typically the TIA AGC is faster than 200 Hz, therefore the trans-impedance is going to change in time as a function of vibrations, causing linear time variant channel response
        - Algorithms like ADC AGC, timing recovery, channel estimation and equalization should be designed to cope with this variable channel

Motivation

- Summarizing, in some maner we can consider the communication channel is a mobile (vs. static) channel
- These special requirements have to be taken in consideration in the PCS and PMA definitions to make easier the life of PHY companies and make technically feasible the PHY implementation

Objectives

- The main objective of this presentation is to propose a transmission structure which could be a baseline for a PCS and a PMA definitions
- The proposed transmission structure has to fullfil the following objectives:
  - To make feasible the implementation of very short and deterministic link establishment
  - To make feasible the implementation of fast, robust and deterministic timing recovery
  - To make feasible the implementation of robust and deterministic adaptive channel equalization
  - The make feasible a robust and deterministic the communication between link partners for adaptive THP coefficients, link status advertisement, capabilities announcement, fast link startup, etc.

Transmission structure

Transmission structure: introduction

- The proposed transmission structure defines how the data are transmitted over the physical medium, including:
  - Time ordering
  - Different parts:
    - **Pilots** for timing recovery and channel estimation and equalization
    - **Header** for signaling and negotiation
    - **Payload** encoded data (i.e. Ethernet frames from GMII)
  - Power scaling to each part, in such a way the transmission is optimum according to the physical medium constraints

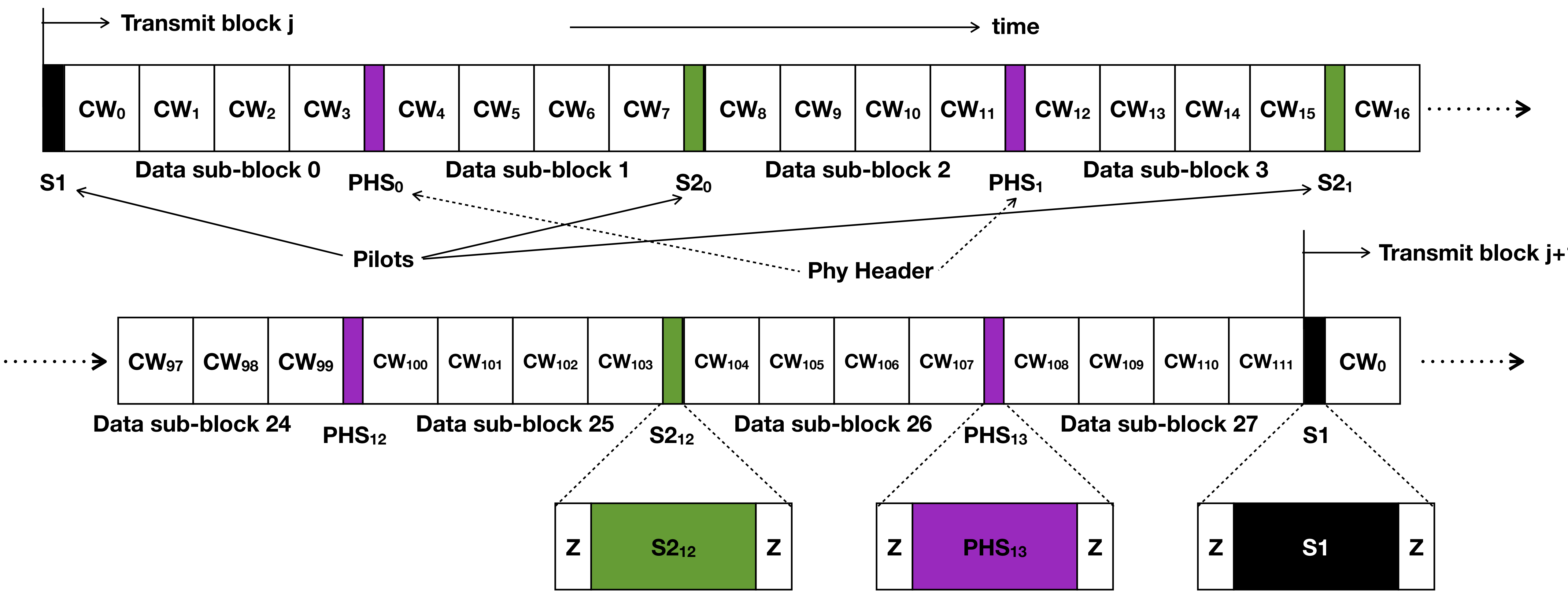
- Two different modes of operation are going to be proposed:
  - **Normal mode**: where the transmission structure is active all the time, and idle information is sent in payload data sections when no user data is available to transmit from GMII.
  - **Low-Power Idle mode**: where the payload data is only active when user data is available from GMII. In this mode of operation the transmission and therefore synchronously the reception may be switched off for reducing the power consumption (this is related to 802.3az - Energy Efficient Ethernet).

Transmission structure: introduction

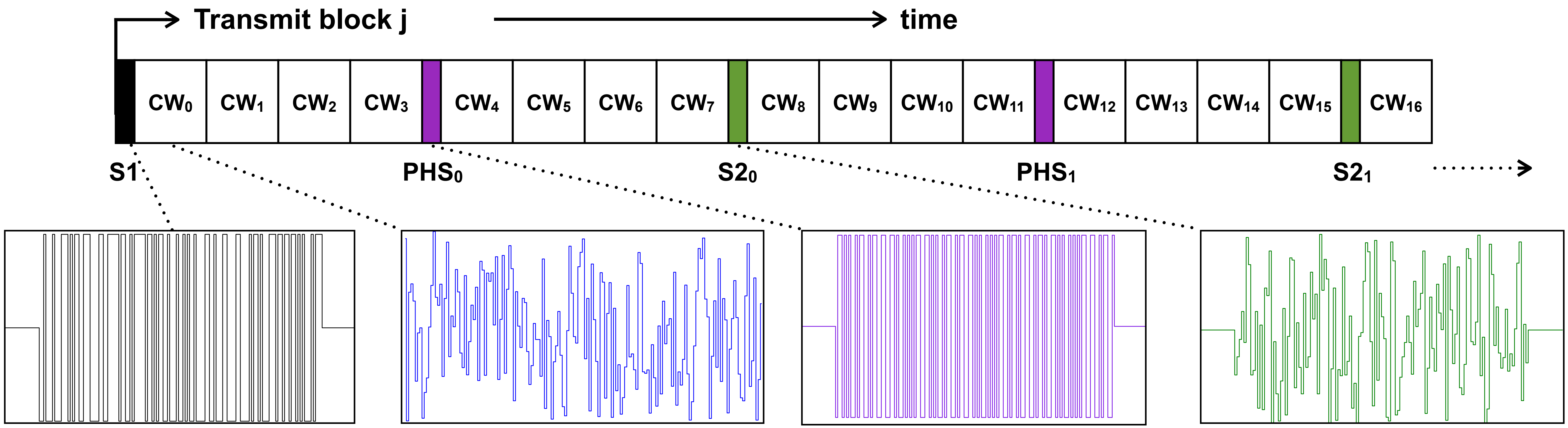
- The transmission structure is designed attending to following key points:
  - Bandwidth limitations and transmission characteristics of all the elements that compose the channel (i.e. opto-electronics, POF, optics, etc.)
  - Noise sources in channel
  - Both spectrally efficient coded modulation schemes and Tomlinson-Harashima Precoding are needed to meet link budget requirements (see [1])
  - In order to use high spectrally efficient modulation schemes, in [4] is argued that compensation of non-linear response caused by the optoelectronics is necessary
  - Symbol synchronization and low jitter timing recovery: symbol identification among all the transmitted ones, and what is the optimal sampling phase
  - Robust logic sub-channel used for adaptive configuration, so that the system is able to dynamically adapt the precoding coefficients, advertise the link status, negotiate physical transmission capabilities during the link startup, etc.

Transmission structure: general architecture

- The transmission structure comprises:
  - **Pilots**: for symbol synchronization, timing recovery, non-linear channel estimation and equalization adaptation.
  - **Physical header**: for link startup, capabilities negotiation, user data synchronization, adaptive precoding
  - **Payload data blocks**, which include high coding gain forward error correction (FEC), high spectral efficiency modulation and precoding.



Transmission structure: normal mode



Pilot S1:
✦Block/symbol synchronization
✦Timing recovery

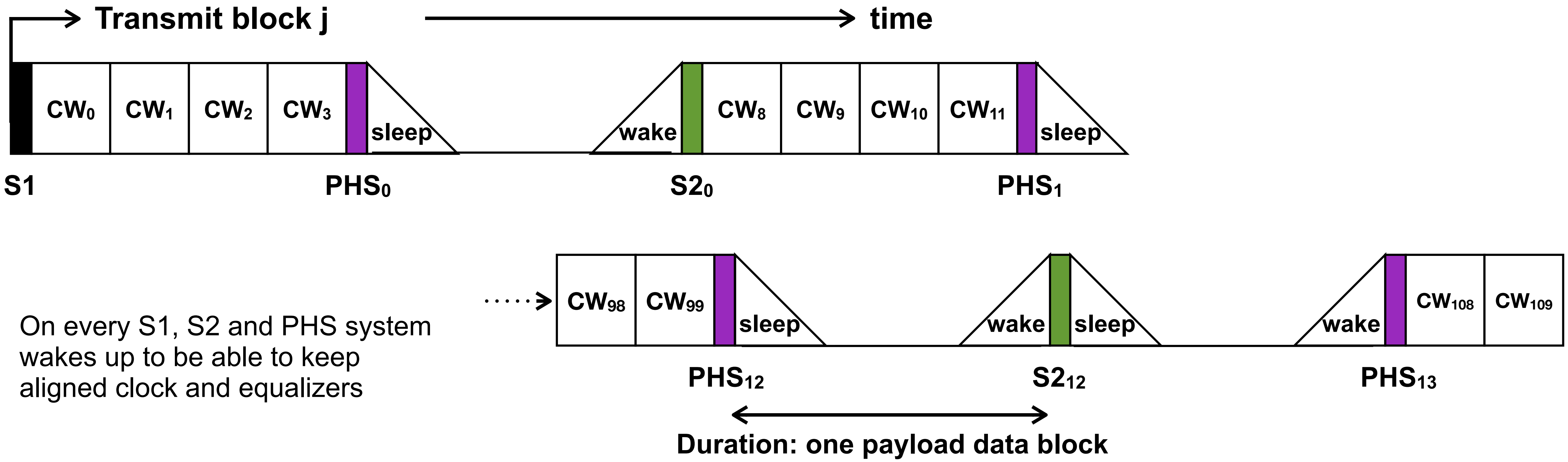
Payload: e.g. Adaptive THP - MLCC
✦Encapsulated Ethernet frames from GMII

Phy Header:
✦Link startup
✦THP negotiation
✦Decapsulation synchronization

Pilot S2:
✦Non linear channel estimation
✦Equalizer adaptation
✦Timing recovery

- Continuous transmission, independently of user data is available to transmit. The payload data blocks are filled with idle information
- The receiver can easily track changes of the receive signal (i.e. baseline wander, attenuation variations, clock frequency drift, channel response variations, etc) using the pilots as well as the other parts of the structure

Transmission structure: LPI mode



On every S1, S2 and PHS system wakes up to be able to keep aligned clock and equalizers

- Physical header is used by both link partners to agree the use of LPI mode during the startup
- All the pilot and header sub-blocks are transmitted, but the transmission can be stopped during the payload sub-blocks. Therefore the receiver is able to use the pilots for:
  - Transmit block synchronization
  - Timing recovery
  - Channel estimation and equalization adaptation
  - Adaptive TH precoding
- The LPI mode always affects complete payload sub-blocks, so it is not possible to stop or restart the transmission in the middle of a payload sub-block.
- The power saving shall depend on the percentage of time required to sleep and wake up the system compared with the payload sub-block length (sleep and wake up time of optoelectronics < 100 ns)

Transmission structure: main properties

- Periodic structure:
  - This allows deterministic implementation
  - Special slots of time are reserved for each kind of signals required to implement tasks of PMA receive function (timing recovery, equalization, frame alignment, etc)
  - Adaptive equalization and timing recovery does not depend on traffic load ➤ the system is able to keep aligned with the link partner
- Data aided adaptive channel equalization and timing recovery
  - Pilot signals apriori known by the receiver are used to greatly help the link startup and channel variations tracking
  - Very fast and robust timing recovery can be implemented theoretically without clock frequency deviation limits
  - Non-linear adaptive filtering (i.e. Volterra truncated series) algorithms are very difficult to implement based on blind decisions
  - Non-linear adaptive filtering algorithms require multilevel signal input to channel to be able to excite all the channel non-linearities
- Additional latency is added to Ethernet frames due to S1, S2 and PHS. As will be seen, it is ~0.5 us, which is much lower than latency added by FEC

Transmission structure: pilots (pilot S1)

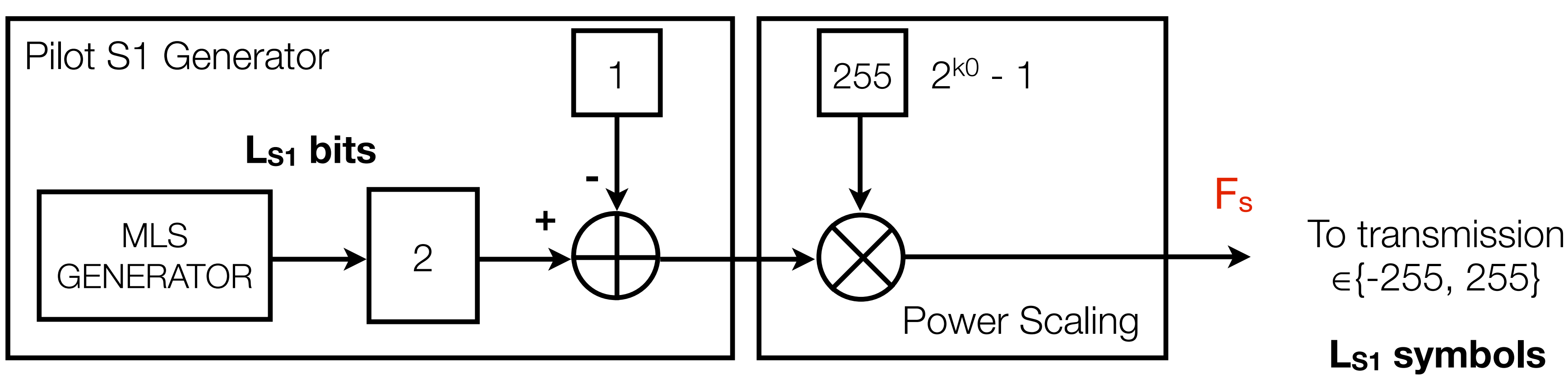
- Transmitted at the beginning of the transmission structure
- Designed for symbol synchronization, so that the receiver easily detects the beginning of transmit block
- The pilot S1 consists of a pseudo-random sequence of 2-PAM symbols.
- The sequence is large enough for low variance detection
- 2-PAM is simple and, because the information is a priori known by receiver, the receiver is able to implement data-aided algorithms for detection, e.g. cross correlation that may be implemented with simple tree of adders.
- Pilots S1 may also be used for timing recovery, allowing to search for the optimum sampling point. E.g. Mueller-Müller's clock recovery algorithms that run at symbol rate.

Transmission structure: pilots (pilot S1)

- The power scaling of pilot S1 is chosen such that the transmission of this sub-block uses the full range of the light emitter device, having max SNR in the receiver
- The pilot S1 is prepended and appended by zero valued symbol sequences
  - Zero valued symbols are transformed into average optical power at the LED output
- The length of each zero valued symbol sequence is selected to be able to contain the complete channel impulse response (the most representative taps).
- The zero sequences are inserted before and after 2-PAM symbols to both, avoid the ISI caused by previous payload data sub-block over the pilot S1, and to avoid ISI of pilot S1 over the next precoded payload data sub-block
- 2-PAM scheme is robust enough for symbol synchronization and timing recovery over non-linear channels, but it is not suitable for channel estimation and equalization.

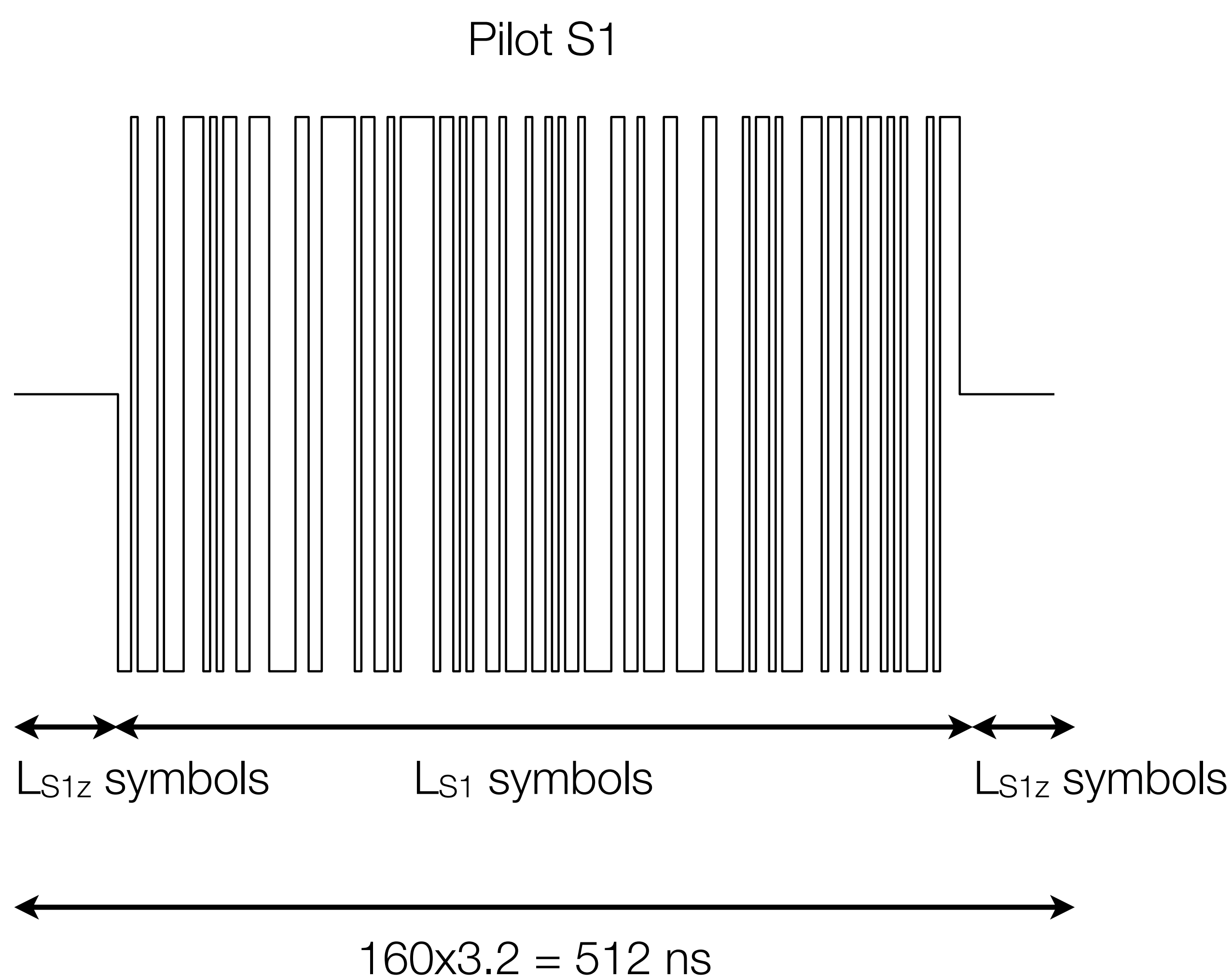
Transmission structure: pilots (pilot S1)

- Possible generation of pilot S1:
  - A binary Maximum Length Sequence (MLS) generator is used to generate a binary pseudo-random sequence of L_{S1} bits length.
  - After this, it is 2-PAM modulated.
  - A power scale factor is applied before to transmit S1 to the channel
    - The power scale factor is relative to the factors applied to the other parts of the structure
    - Let define integer k_0 as the maximum 2^{k0}-PAM constellation that system manages in payload data sub-block and/or pilot S2.
    - k_0 is used to define the scaling factor for all the parts composing the transmission structure.
    - k_0 is high enough to allow fine resolution defining scaling factors.
    - The constellations of all the parts are normalized to the arbitrary range $[-2^{k0}, 2^{k0})$ after scaling.
    - In figure, e.g. $k_0 = 8$.
    - In figure, F_S is the symbol rate.



Transmission structure: pilots (pilot S1)

- Preferred design for Gigabit over POF:
  - Length of the zero symbols sequences composing pilot S1: L_{S1z} = 16 symbols @ 312.5 MSps
  - Length of 2-PAM symbols sequence composing pilot S1: L_{S1} = 128 symbols @ 312.5 MSps



Transmission structure: pilots (pilot S2)

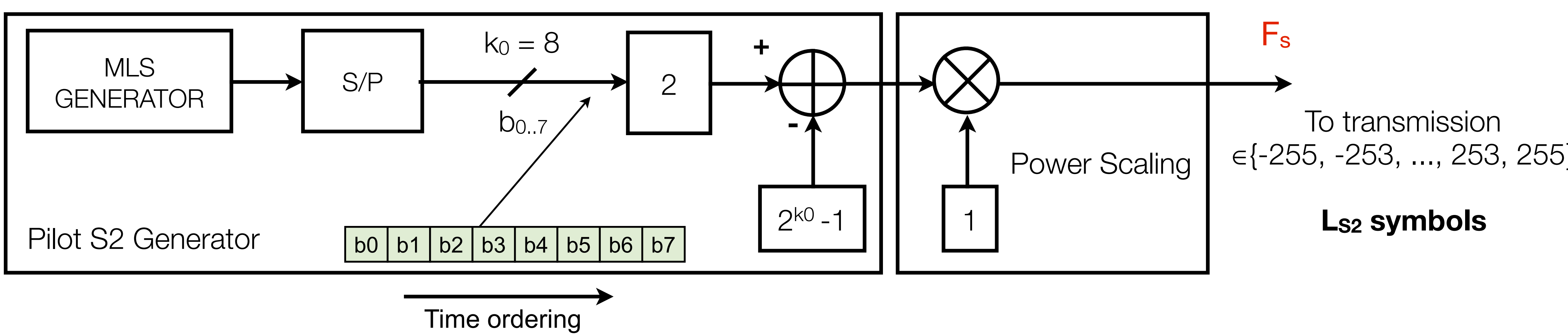
- S2 consists of a sequence of M-PAM symbols.
- Because the channel is not linear, more than 2 levels are needed to excite and extract all the information of the channel response
- Because the pilot S2 is known a priori by the receiver, it may be able to implement data-aided estimation algorithms for non-linear channel estimation, e.g. RLS estimation based on truncated Volterra series, where e.g. DC, 1st order, 2nd order and 3rd order responses may be estimated
- The Volterra based response may be used in the receiver to linearize the channel response to improve the reliability of the data detection.
- Pilot S2 may also be used for equalization adaptation, i.e. estimation of feedforward equalizer and TH precoding coefficients.

Transmission structure: pilots (pilot S2)

- Because data-aided algorithms for channel estimation and equalization require of relatively long training sequences for good convergence, the pilot S2 is not transmitted in a whole, but it is split in several chunks, such that:
    - The latency of the user data transmission is reduced
    - The length of each S2 chunk is equal to S1
    - The time separation between S2 chunks ($S2_x$ in figure) and S1 is the same, therefore pilot S2 may be used together with S1 for timing recovery, since they represent a time base.
    - In other words, the S1 and $S2_x$ sequences are periodic with a priori known frequency.
- Each S2 chunk is prepended and appended by zero sequences to avoid ISI issues.
    - Please note that the payload data sub-blocks are precoded (post-cursor inter-symbol interference is eliminated in TH precoder), but in the receiver the non-precoded parts S1, S2 and PHS produce post-cursor interference.
- The power scaling of pilot S2 is such that the extreme values of M-PAM modulation (i.e. M-1 and -M+1, for {-M+1, -M+3, … , M-3, M-1}) takes the extremes of light emitter device

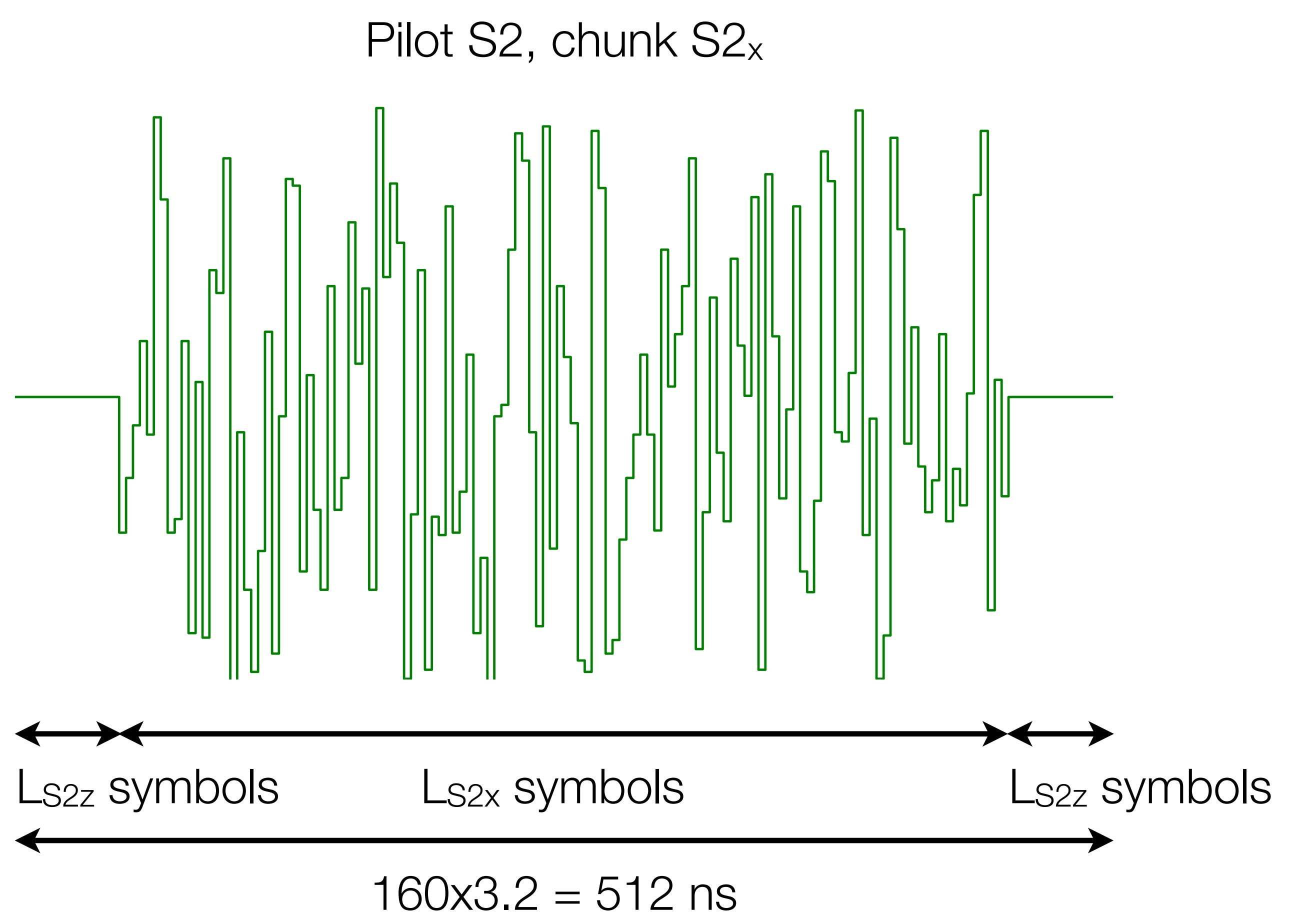
Transmission structure: pilots (pilot S2)

- Possible generation of pilot S2:
  - A binary MLS generator is used to generate a binary pseudo-random sequence of $k_0 \cdot L_{S2}$ bits length.
  - After this, the MLS output is 2^{k0}-PAM modulated:
    - The bits are grouped in k_0 bits chunks (serial to parallel transform) to form a sequence of unsigned integer numbers.
    - After this, the sequence of k_0 integrer numbers are multiplied by 2 and added to $(-2^{k0}+1)$ to form the zero mean 2^{k0}-PAM symbols belonging to the set {-M+1, -M+3, …, M-3, M-1}.
  - A power scale factor is applied before transmission to the channel
    - The power scale factor is relative to the factors applied to the other parts of the structure
    - According to the previous definition (see pilot S1), the scaling factor for S2 is 1.
    - In figure it is provided an example for $k_0 = 8$.
    - After the sequence of L_{S2} M-PAM symbols was generated, the sequence is divided in chunks of $L_{S2x} = L_{S1}$ symbols, and sequence of $L_{S2z} = L_{S1z}$ zero symbols are prepended and appended to each chunk.



Transmission structure: pilots (pilot S2)

- Preferred design for Gigabit over POF:
  - Length of the zero symbols sequences composing pilot S2: $L_{S2z} = L_{S1z} = 16$ symbols @ 312.5 MSps
  - Length of M-PAM symbols sequence composing pilot S2: $L_{S2} = 1664$ symbols @ 312.5 MSps
  - Length of each M-PAM symbols sequence chunk composing pilot S2: $L_{S2x} = L_{S1} = 128$ symbols @ 312.5 MSps
  - Number of $S2_x$ chunks in a transmit block: 13; considering pilot S1, the total number of pilot sections in a transmit block is 14.
  - Number of levels of M-PAM: 256



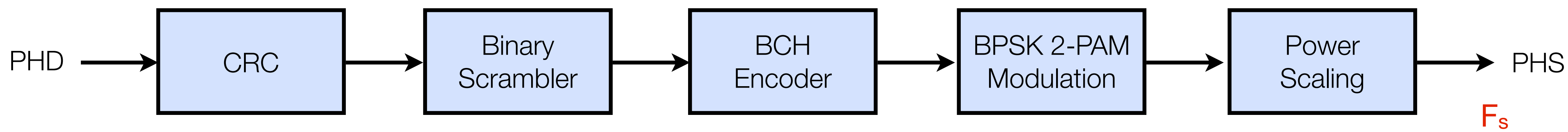
Transmission structure: physical header

- Logic data communication sub-channel used for:
  - Adaptive configuration, so the system is able to dynamically adapt a set of THP coefficients
  - Advertise the link status,
  - Negotiate physical transmission capabilities, etc.
  - Link startup

- Designed to be decoded by the receiver in a more robust way than the payload data sub-blocks:
  - The binary information carried by the physical header (called PHD - Physical Header Data) is scrambled and encoded with a FEC before modulation
  - The FEC is designed according to the error correction capability provided by the FEC used in payload data, such that the error probability of PHD decoding is always lower.
  - Cyclic Redundancy Check (CRC) is added before FEC for error detection capabilities; the receiver is able to know with high probability the PHD was corrupted.

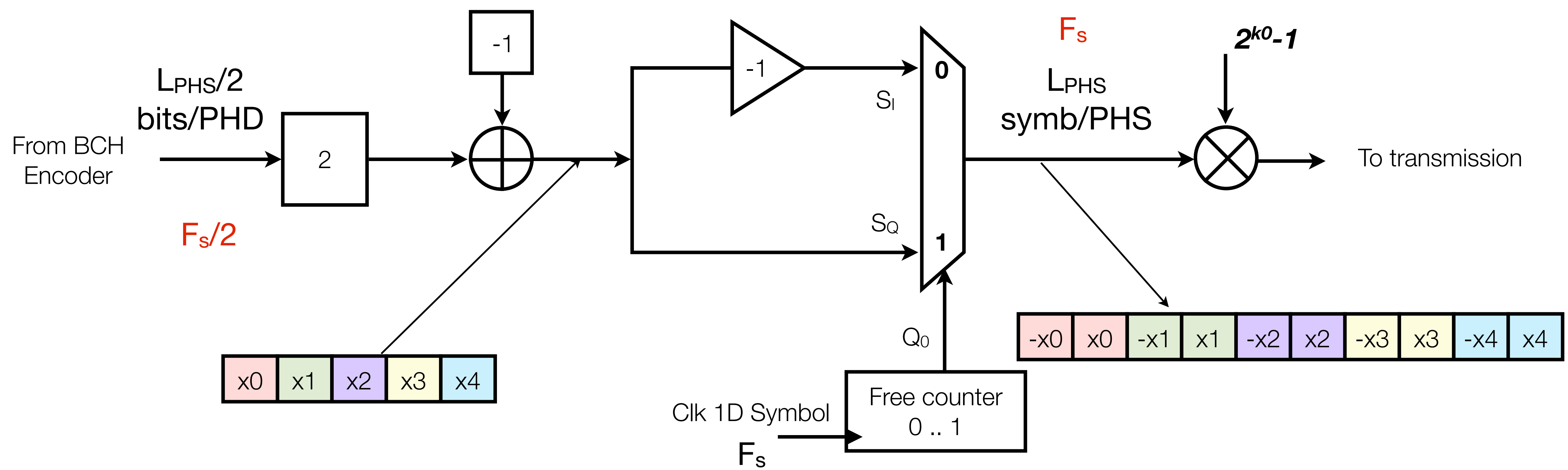
Transmission structure: physical header

- In [5] a FEC based on MLCC is proposed that is feasible for the payload data sub-blocks
- According to that scheme, a suitable PHD encoding is provided in next figure.
  - Binary BCH code is also employed as FEC for PHD encoding



Transmission structure: physical header

- Physical Header Subframe (PHS) is obtained after CRC, binary scrambling, BCH encoding and modulation
- The way the PHS is encoded is independent to THP state used for payload data sub-blocks. This allows PHD reception from power on reset, to start the negotiation of precoding coefficients, capabilities negotiation, etc.
- Robust PHS modulation based in 2D BPSK 2-PAM:
  - A BPSK 2-PAM (0.5 bits/dim) modulation is proposed.
  - It is not TH precoded.
  - It is boosted ~6 dB respect to user data (see power scaling for payload data block)
  - This special kind of 2D modulation used over a 1D channel allows a very low cost implementation of VA-MLSE (capacity approaching) for optical equalization of PHS

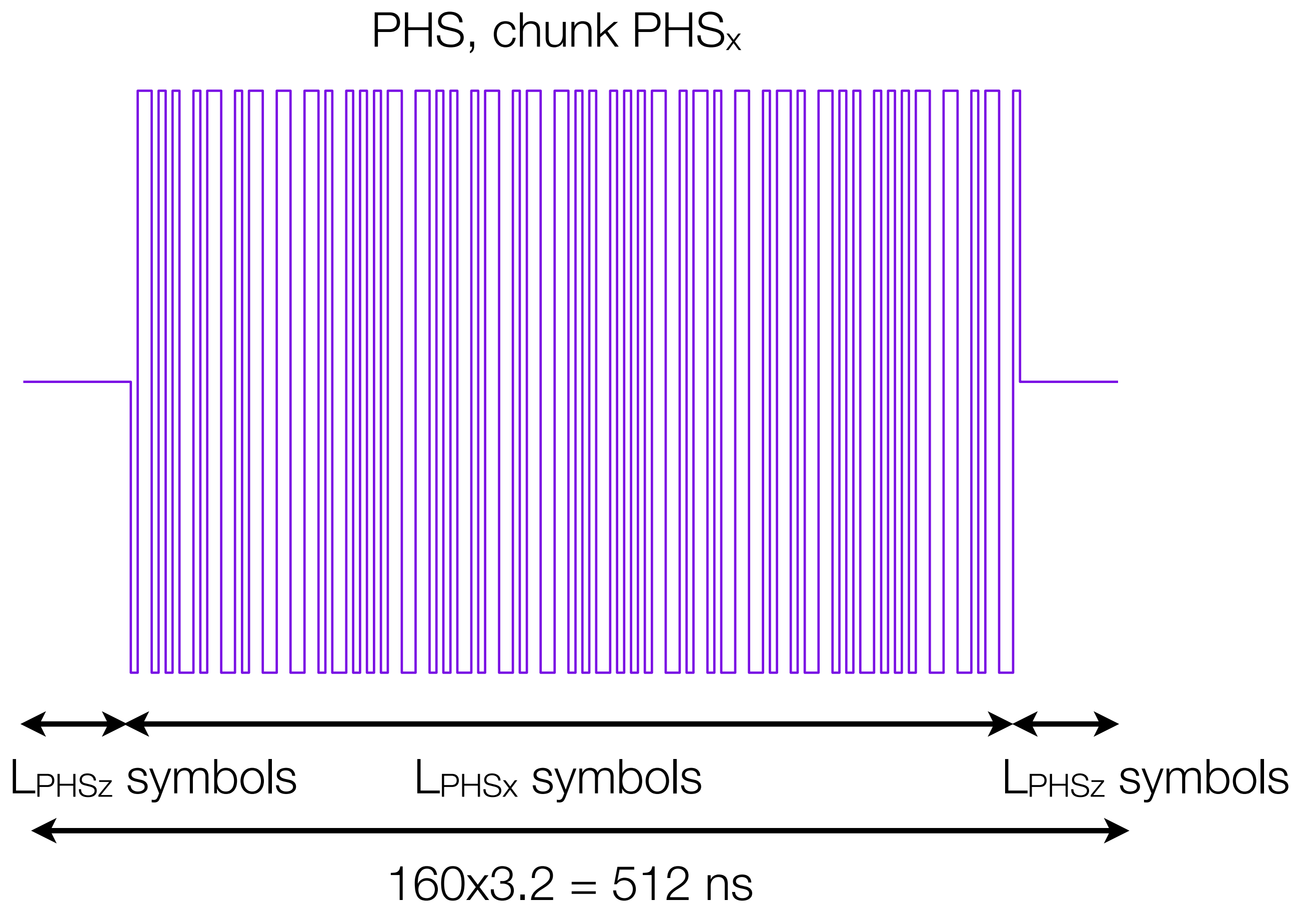


Transmission structure: physical header

- The power scaling of PHS is according to the previous definition of k_0, and it is equal to 2^{k0}-1 (equal to power scaling used for S1)
- The PHS is not transmitted in a whole, but is divided in several chunks (PHS_x), with the same considerations that for S2, and the additional following ones:
  - The time between PHS_x is the same, therefore it may be used together with S1 and S2 for blind timing recovery, since represent time base. The PHS_x sequences are periodic with a priori known frequency.
  - The PHS_X sub-blocks are located in between two consecutive pilot sub-blocks, so the PHS information as well as the pilot estimation capability are uniformly spread along the transmission structure.
- Each PHS_x chunk is prepended and appended by zero sequences to avoid inter-symbol interference issues.

Transmission structure: physical header

- Preferred design for gigabit over POF:
  - Length of the zero symbols sequences composing PHS: $L_{PHSz} = L_{S1z} = 16$ symbols @ 312.5 MSps
  - Length of 2-PAM symbols sequence composing PHS: $L_{PHS} = 1792$ symbols @ 312.5 MSps
  - Length of each 2-PAM symbols sequence chunk composing PHS: $L_{PHSx} = L_{S1} = 128$ symbols @ 312.5 MSps
  - Number of PHS_x chunks in a transmit block: 14



Transmission structure: payload data sub-blocks

- The payload data sub-blocks carry the user data information.
- A feasible encoding technique for data sub-blocks based on MLCC is presented in [5], although it may be different.
- It is advantageous to use block oriented channel coding as in [5] in comparison with convolutional codes, because:
    - The payload data sub-blocks can extend an entire number of code words, so the FEC decoding of each payload data sub-block is independent.
    - The decoding latency is reduced.
    - This is specially useful for the low LPI mode structure, because in other case the decoding latency can be increased in a payload sub-block.
- The payload sub-block length is selected such that the overhead produced by the transmission of pilots and physical header in a transmit block is small.
- The payload sub-blocks are neither prepended nor appended by zero sequences, since these sequences are yet included in S1, S2x and PHSx sub-blocks, able to contain the channel impulse response.

Transmission structure: payload data sub-blocks

- The scaling factor applied to payload sub-blocks depends on the number of levels of the used M-PAM modulation
- The M-PAM modulation takes values of the set {-M+1, -M+3, …, M-3, M-1}.
- Because TH precoding is employed, at the beginning of each payload sub-block (i.e. after either S1, S2x or PHSx sub-blocks are transmitted) the state of feedback filter has to be reset,
  - This is equivalent to all the previous symbols entering the TH precoder were zero.
  - The reason behind this is that the S1, S2 and PHS sub-blocks are not precoded.
- The payload sub-block is also scaled to the arbitrary range $[-2^{k0}, 2^{k0})$. For TH precoded M-PAM and assuming $k_0 = 8$, the scale factor is calculated as:

$$SF_{thp}(k) = \frac{2^{k_0}}{M}$$

M-PAM	$SF_{thp}(k)$
2	***128***
4	***64***
8	***32***
16	***16***
32	***8***

Transmission structure: great numbers

- Preferred design for gigabit over POF:
  - From [ ], spectral efficiency of payload data-block: (1664+1994)/2016+1.5 = 3.3145 b/s/Hz/dim
  - Symbol rate: 312.5 MSps (= 12.5 x 25 = 25/2 x 25)
  - From [ ], FEC code-word length: 2016 symbols
  - Number of code-words composing the payload data sub-block: 4
  - Transmit block length: L_{TB} = (1 + 13 + 14)·(4·2016 + 128 + 16 + 16) = 230272 symbols
  - Transmit block duration: 736.9 us
  - Coarse clock frequency estimation time: ~1.5 ms (2 transmit blocks) from reset
  - Timing recovery lock delay: ~3.7 ms (5 transmit blocks) from reset
  - Margin in time for link establishment: 100 - 3.7 = ~96 ms
    - Channel estimation and first set equalizer coefficients
    - First set THP coefficients interchange between link partners
    - Local and remote receiver status estimation
  - Pilots and PHS overhead: (4·2016 + 128 + 16 +16)/4·2016 = < 2%
  - Raw data rate available for Ethernet frames encoding: ((1664+1994)/2016+1.5) · 312.5 · 8064/(8064 + 160) = 1015.625 Mbps

References

- [1] *Rubén Pérez-Aranda, "Shannon's capacity analysis of GEPOF for technical feasibility assessment", GEPOF SG, Interim Meeting, May 2014*
- [2] *Rubén Pérez-Aranda, "Link budget requirements for Gigabit over POF", GEPOF SG, Interim Meeting, May 2014*
- [3] *Rubén Pérez-Aranda, "Optical receiver characteristics for GEPOF technical feasibility", GEPOF SG, Interim Meeting, May 2014*
- [4] *Rubén Pérez-Aranda, "Optical transmitter characteristics for GEPOF technical feasibility", GEPOF SG, Interim Meeting, May 2014*
- [5] *Rubén Pérez-Aranda, "High spectrally efficient coded modulation schemes for GEPOF technical feasibility", GEPOF SG, Plenary Meeting, July 2014*

Questions?