EPoC Performance Model Delay and Efficiency

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Scope

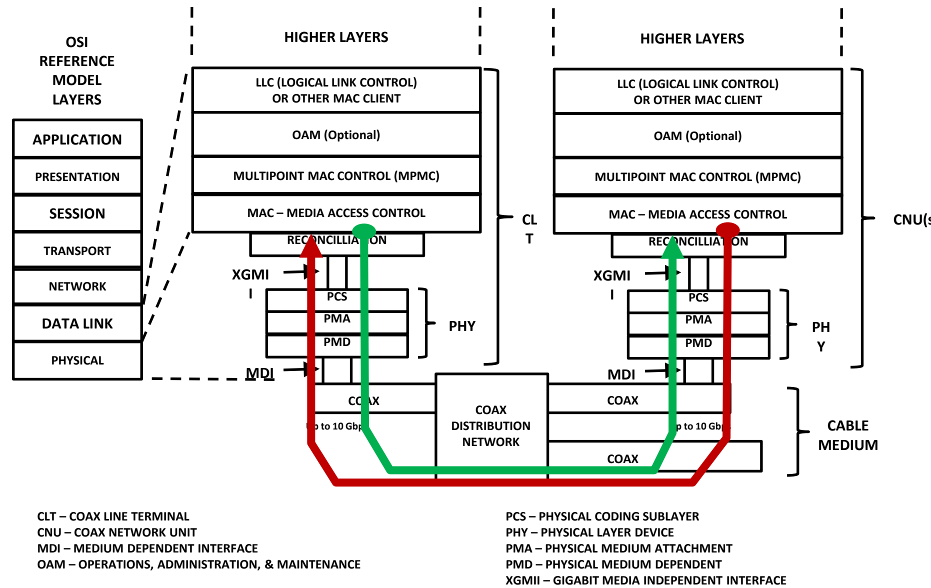
- The EPoC performance model aim at providing a spreadsheet to play with tradeoff between delay and efficiency of EPoC systems, in order to have a common base for discussion/understanding
- The tool **does not intend** to provide a mean for detailed verification of the state diagrams and standards, for which more detailed modeling and simulations will be needed based on experience in EPON
- Input values are parameterized so that different solutions/option could be considered when evaluating delay and efficiency of certain proposal
- The focus of the EPoC performance model is primarily on the coax PHY and also includes additional impact due to MPCP/MAC layer
  - For additional optical backhaul connection only a input field will be provided

MAC Performance Model - Summary

- Focus on delay but also consider efficiency
  - For both delay and efficiency, two components: PHY and MAC
  - Look at worst case in supported multi-user scenarios
    - This also includes the case of single user in the system using up to 1 Gb/s
  - Efficiency: need to know how much efficiency is consumed by overhead due e.g. guard interval, guard bands, etc. – focus on relative figures and efficiency on the coax side – how the trade-off affects delay vs. efficiency
- Improve the model with further details
  - Consider symbol duration
  - Consider preamble presence/duration
  - Split propagation time (cable length) from switching time
    - – Transmit/receive sharing PHY and influence on the switching time
  - Number of simultaneous transmitters
- Important question is: does the absolute numbers meet the delay/jitter requirements?

Delay Model – Latency and Jitter

- The delay model is meant to firstly characterize latency and jitter of the coax portion of the plants, with focus on the PHY and considering as reference points the interfaces between MAC and PHY (see figure)
- Optical part could be considered as well, OCU can be modeled with simple configurable delay (see next slide)

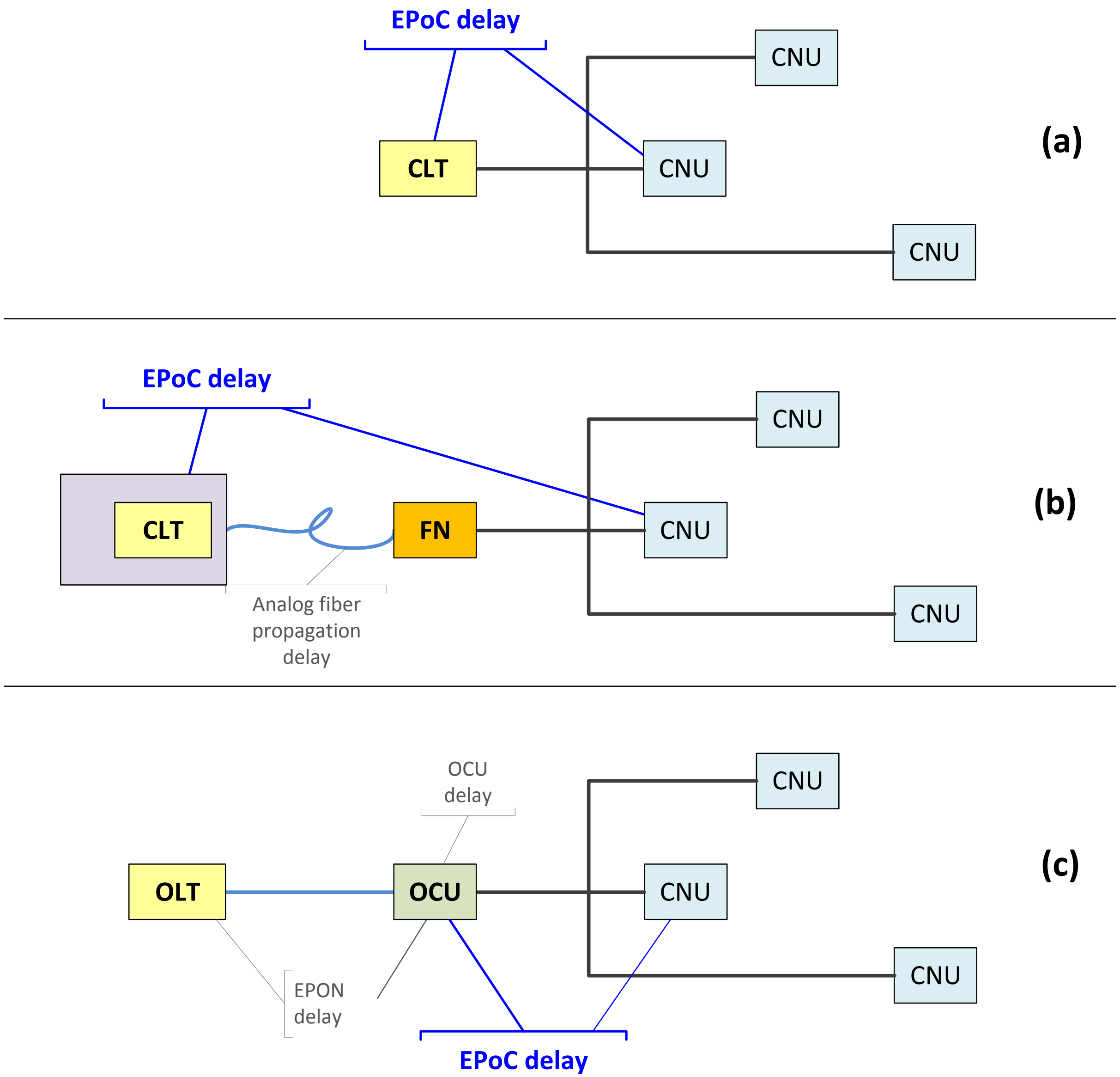


- In addition, implications at MAC layer are considered, whereby the overall delay and jitter are generally represented as a function of PHY and MAC:

delay = function(PHY, MAC) and jitter = function(PHY, MAC)

  - The PHY components consider the delay due to processing at the transmitter and receiver sides (e.g. symbol processing, interleavers, etc.), possible guard intervals and preambles, the number of transmitters and min/max burst sizes
    - Propagation delay is treated separately and linked to the cable length
  - The MPCP/MAC components considers the additional delay due to the resource allocation and depends primarily on scheduling/ polling cycles, the number of transmitters and min/max burst sizes, report cycle

Delay Model – Reference Scenarios



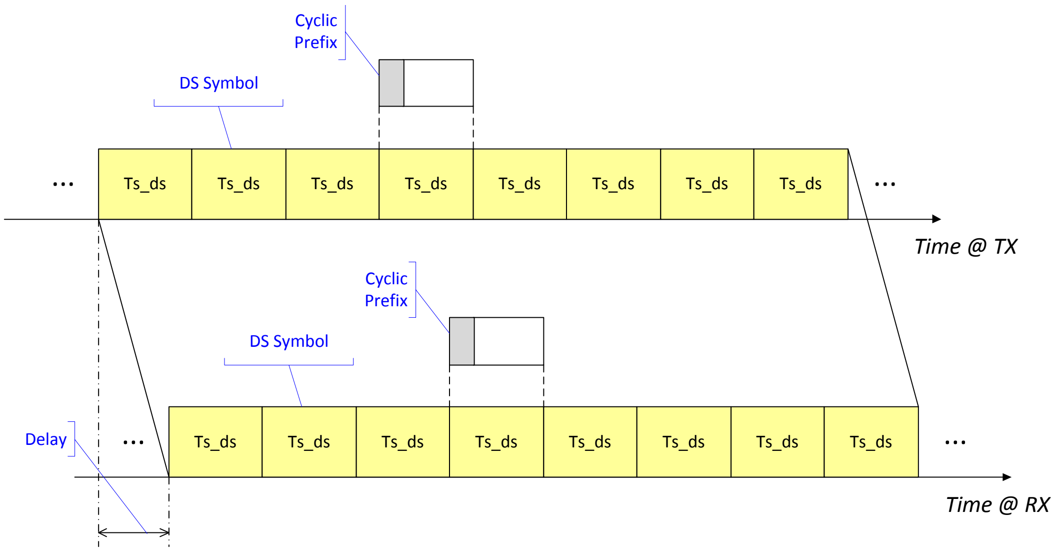
The EPoC performance model is focus on the **EPoC part**, for which a detailed model will be developed to characterize delay and efficiency tradeoffs.

The case of EPoC deployed with analog fiber and CLT in headend can be easily considered adding analog fiber delay as function of the optical fiber length.

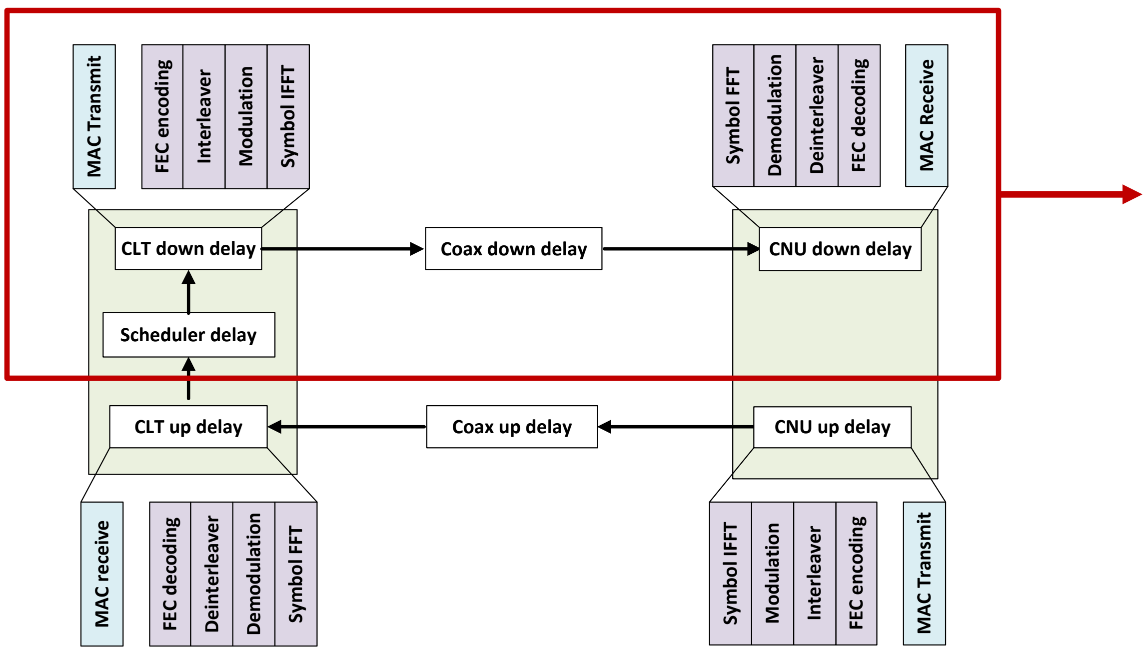
Similarly, the case of EPON with digital fiber can be easily considered adding EPON delay and OCU delay terms.

Note: no detailed model for EPON or HFC will be developed, only input cells are provided

Delay Model – PHY for FDD downstream



In case of FDD downstream there is a continuous transmission consisting in a sequence of DS symbols



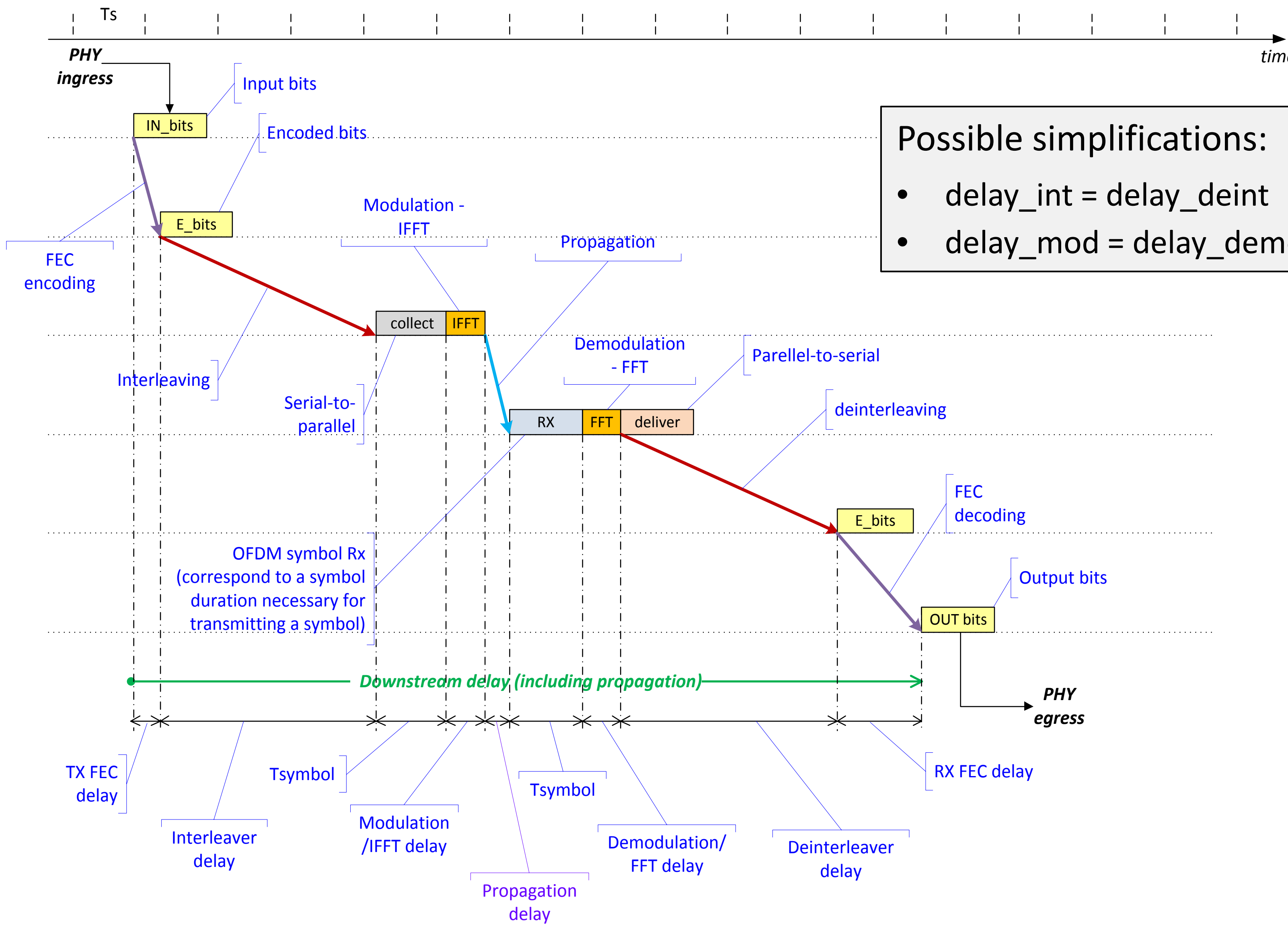
Generally speaking the PHY needs to perform operations for:

- FEC encoding/decoding
- Interleaving/de-interleaving
- Modulation/demodulation
- Symbol IFFT/FFT

Some of the operations are block-level processing related to symbol duration – some may not be present

See next slide for details

Delay Model – PHY for FDD downstream (cont.)

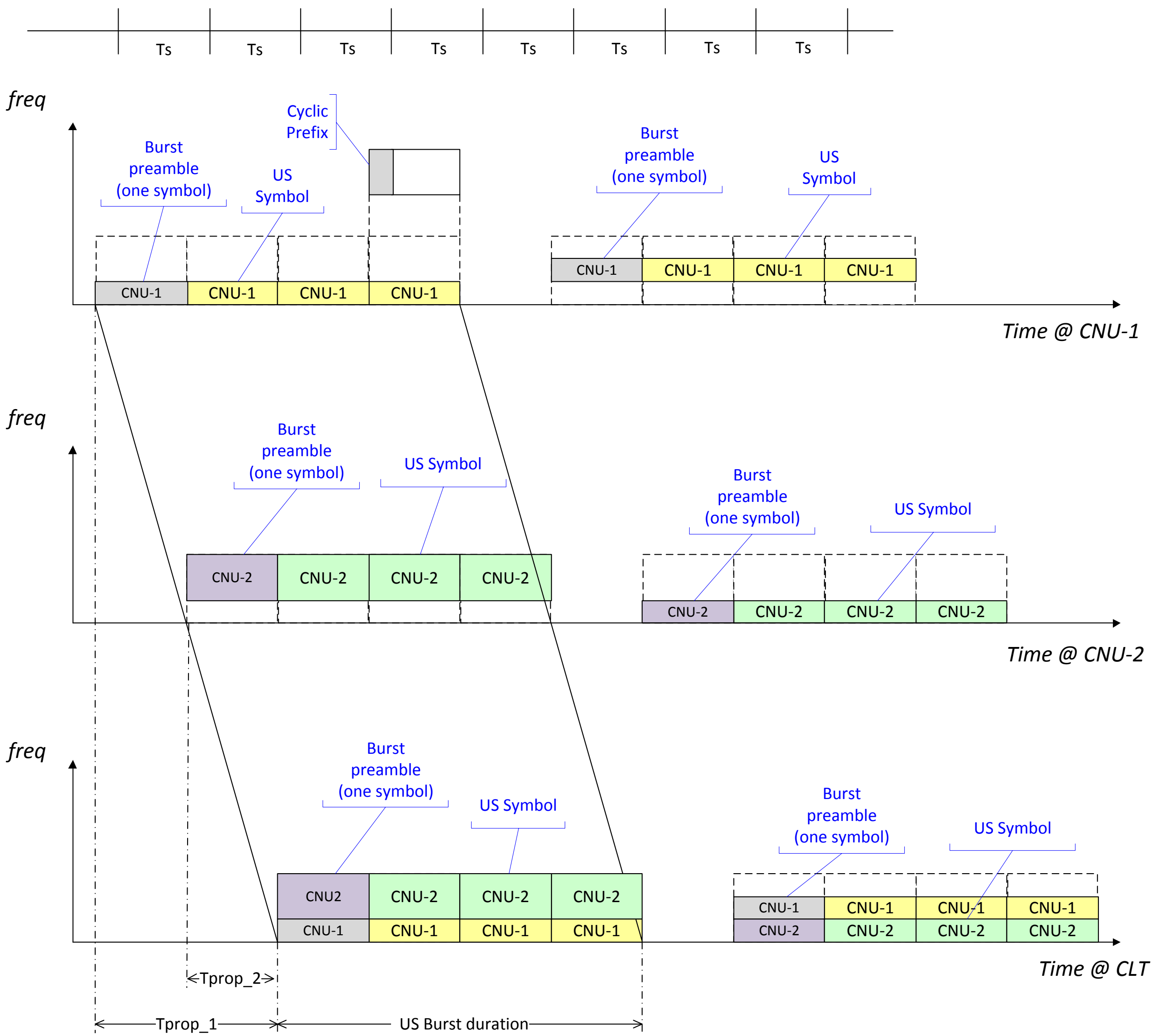


Possible simplifications:

- delay_int = delay_deint
- delay_mod = delay_demod

Note: Propagation delay depends on the cable plant and can vary significantly – this is just an example.

Delay Model – PHY for FDD upstream

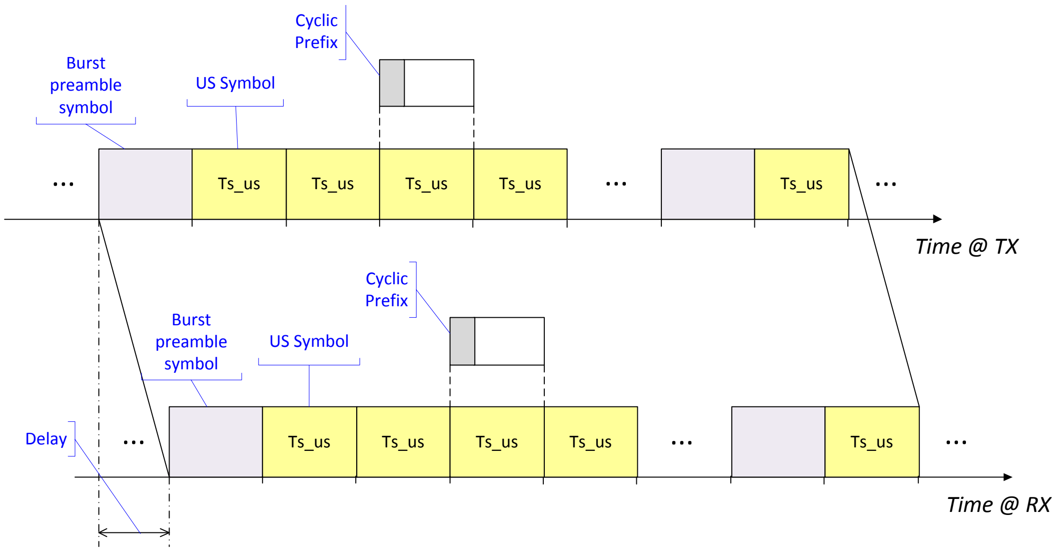


In case of FDD upstream there is a burst transmission consisting in a sequence of upstream symbols

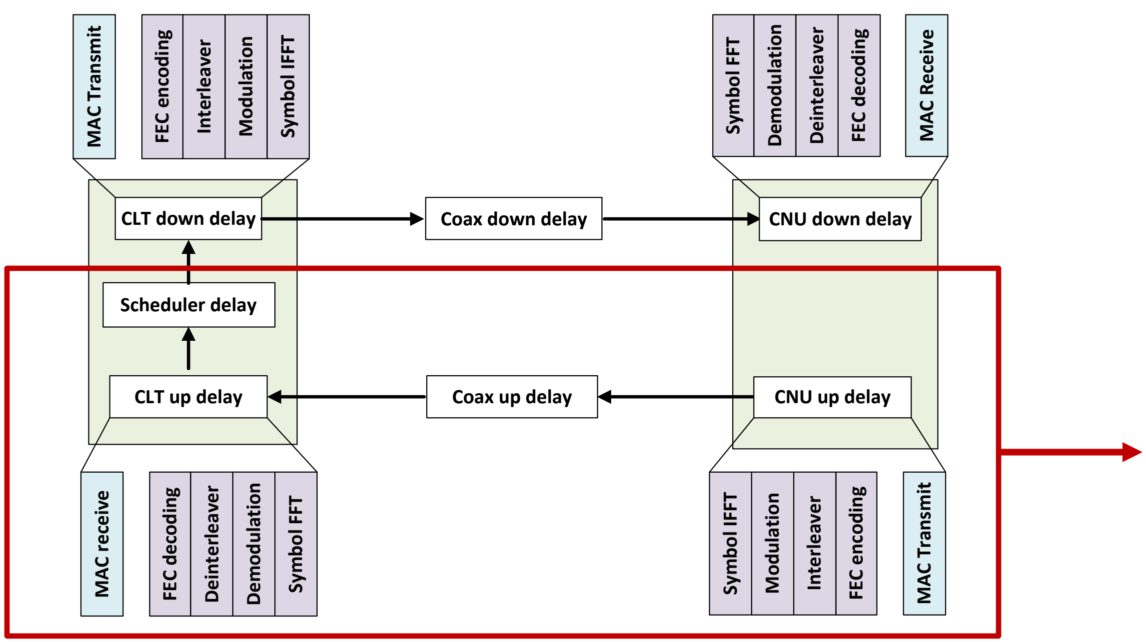
- The transmit sequence could include a burst preamble (of Np*symbol duration)
- Different CNUs are time-aligned via RTT compensation
- Concurrent transmission could be enabled in the frequency domain

<u>Note</u>: the burst preamble at the start of each US transmission could be included to help with clock alignment in US and with channel estimate, depending on the particular solution whether needed or not.

Delay Model – PHY for FDD upstream (cont.)



In case of FDD upstream there is a burst transmission consisting in a sequence of US symbols and potentially starting with a burst preamble (of Np*symbol duration)



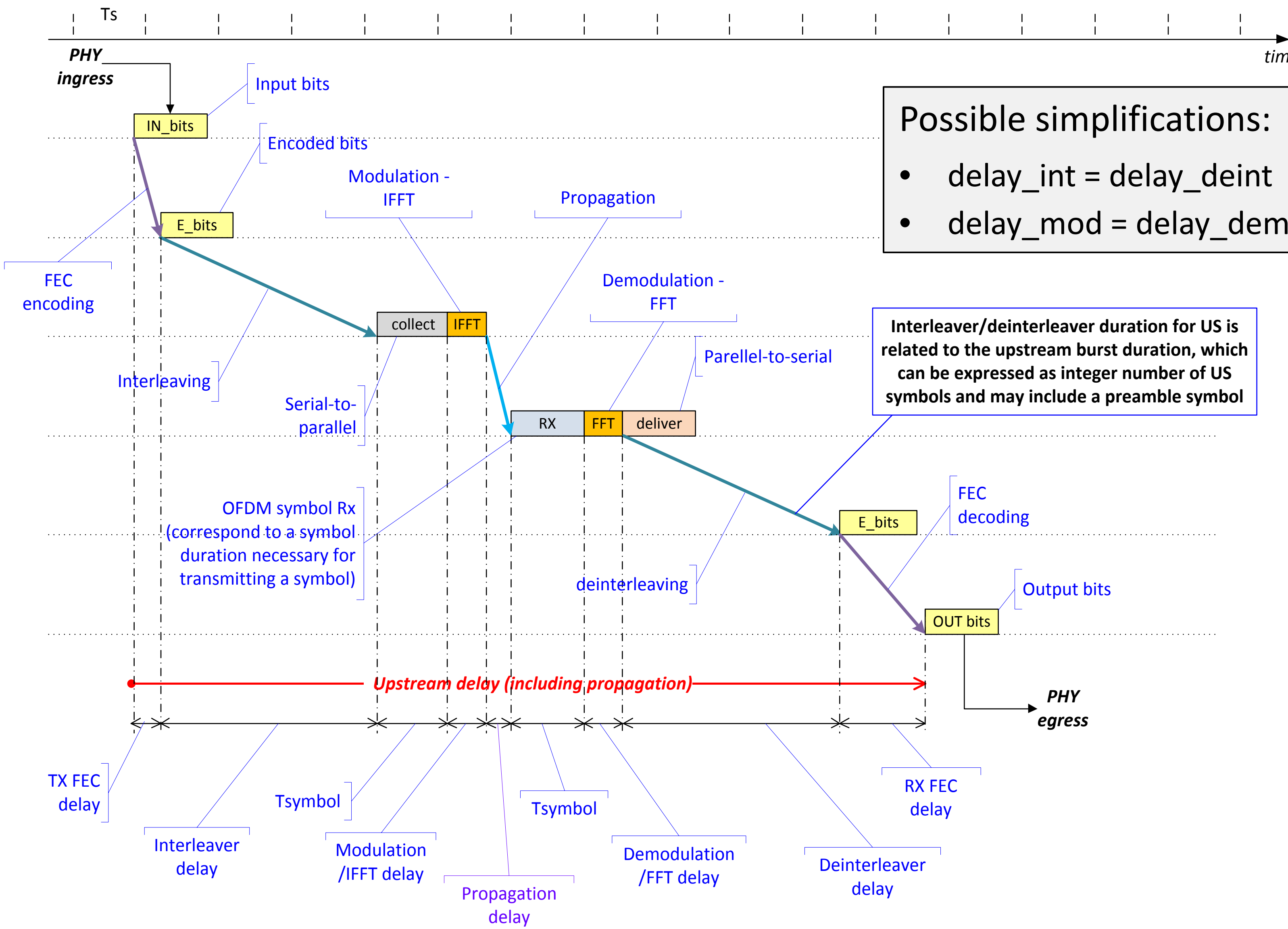
Generally speaking the PHY needs to perform operations for:

- FEC encoding/decoding
- Interleaving/de-interleaving
- Modulation/demodulation
- Symbol IFFT/FFT

Some of the operations are block-level processing related to symbol duration – some may not be present

See next slide for details

Delay Model – PHY for FDD upstream (cont.)



Possible simplifications:

- delay_int = delay_deint
- delay_mod = delay_demod

Note: Propagation delay depends on the cable plant and can vary significantly – this is just an example.

Delay Model – PHY for FDD summary

In case of FDD, the delay model results in the following terms:

$$PHY\_delay_{FDD\_DS} = T_{enc} + (2/n)*T_{FDD\_DS\_Int} + 2*T_{DS\_symb} + 2*T_{mod\_FFT} + T_{dec}$$

$$PHY\_delay_{FDD\_US} = T_{enc} + (2/n)*T_{FDD\_US\_Int} + 2*T_{US\_symb} + 2*T_{mod\_FFT} + T_{dec}$$

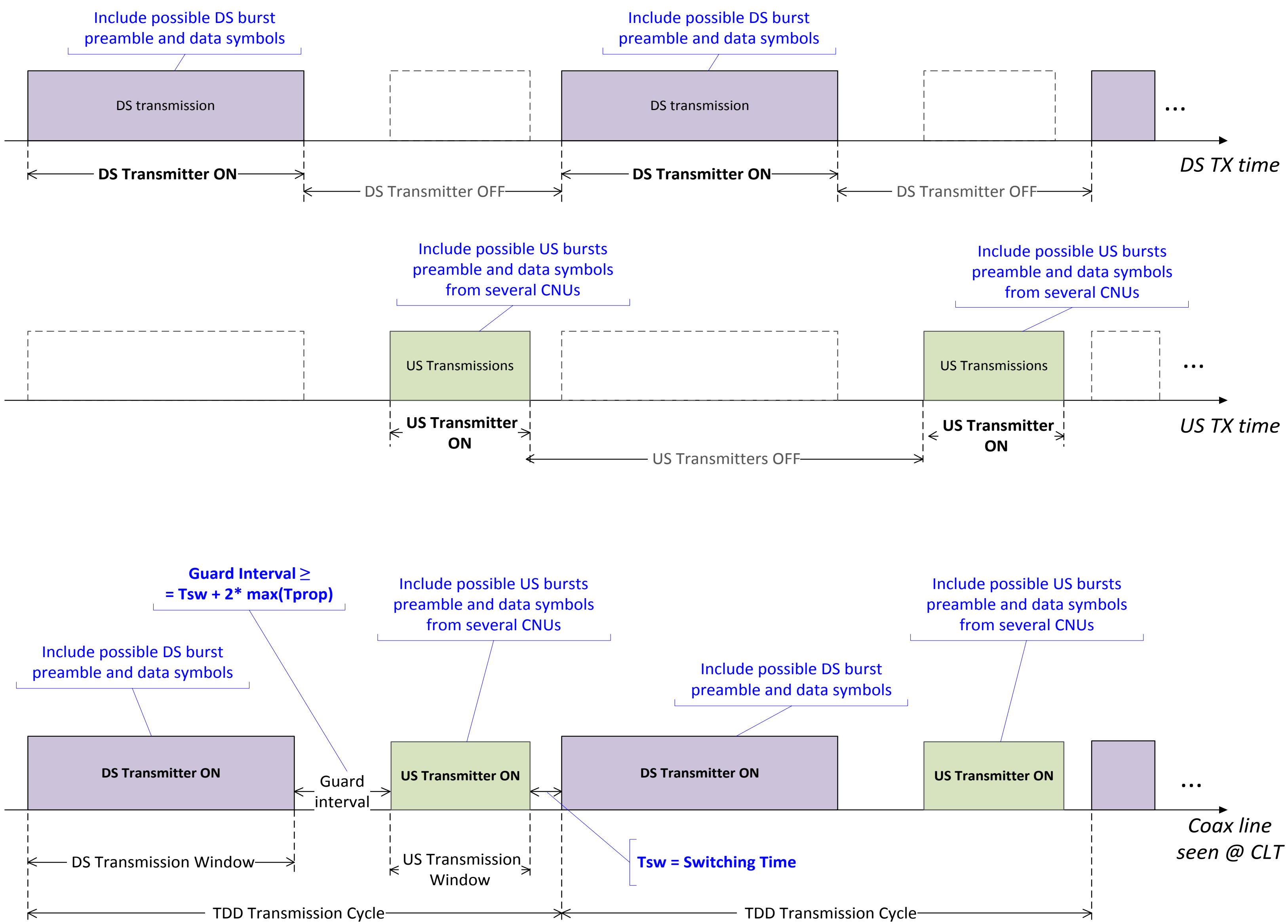
$T_{propagation\_oneway} = L_{cable} / (0.87*c)$ where *c* is the speed of light in vacuum

n = 1 for block interleaver and n = 2 for convolutional interleaver of same size

Note: The following assumption and considerations holds

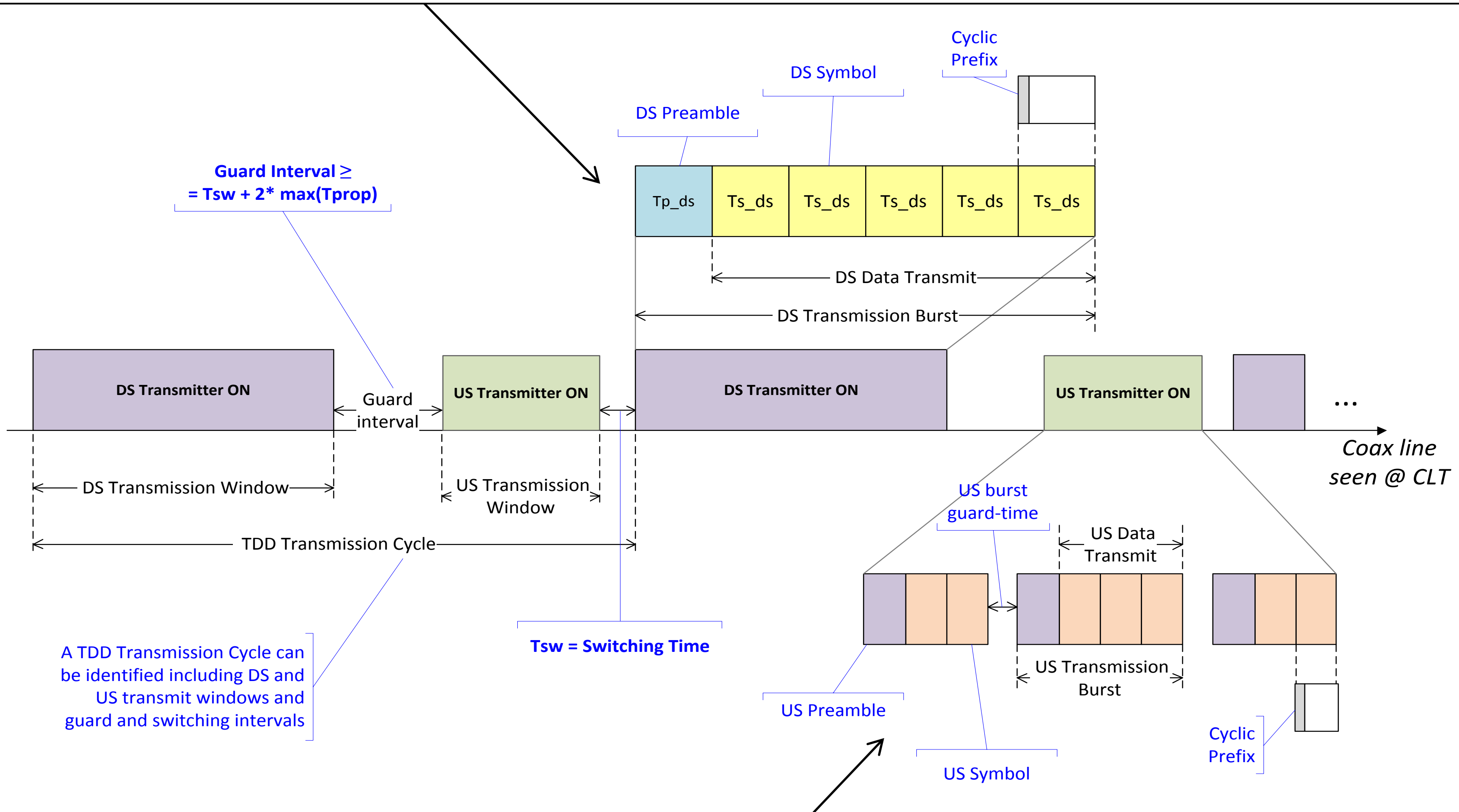
- Delay of interleaver and deinterleaver in one direction are the same
- Delay for modulation/IFFT and demodution/FFT are the same
- Encoder/decoder are the same for DS and US
- Modulation/demodulation are the same for DS and US
- Different symbol duration for DS and US are possible
- Different interleavers for DS and US are possible
    - interleaver length is related to burst noise characteristics and in case of US the transmission burst may be equal or a multiple of the interleaver length
    - US interleaver from multiple CNUs may be inefficient against burst noise

Delay Model – PHY for TDD



Delay Model – PHY for TDD (cont.)

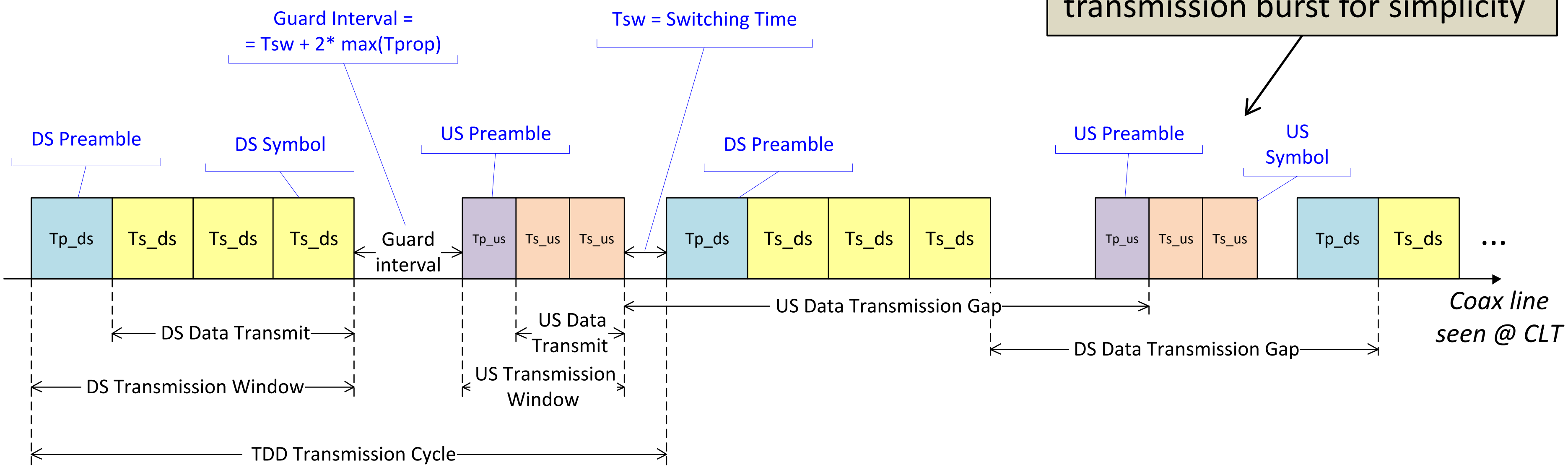
DS transmission occurs in the DS transmission window and generically consist in a sequence of data symbols (during DS data transmit time) preceded by a possible DS preamble.



US transmission occurs in the US transmission window and consist in a sequence of US transmit bursts, each of them including data symbols (US data transmit) and preceded by a possible US preamble.

Delay Model – PHY for TDD (cont.)

Example referring to single US transmission burst for simplicity



TDD Transmission Cycle $= T_{DS\_TXwin} + [\ 2*T_{SW} + 2*\max(T_{prop})\ ] + T_{US\_TXwin}$

$= T_{DS\_TXdata} + T_{DS\_TXgap}$

$= T_{US\_TXdata} + T_{US\_TXgap}$

For multiple bursts, the sum including burst guard-times shall be considered

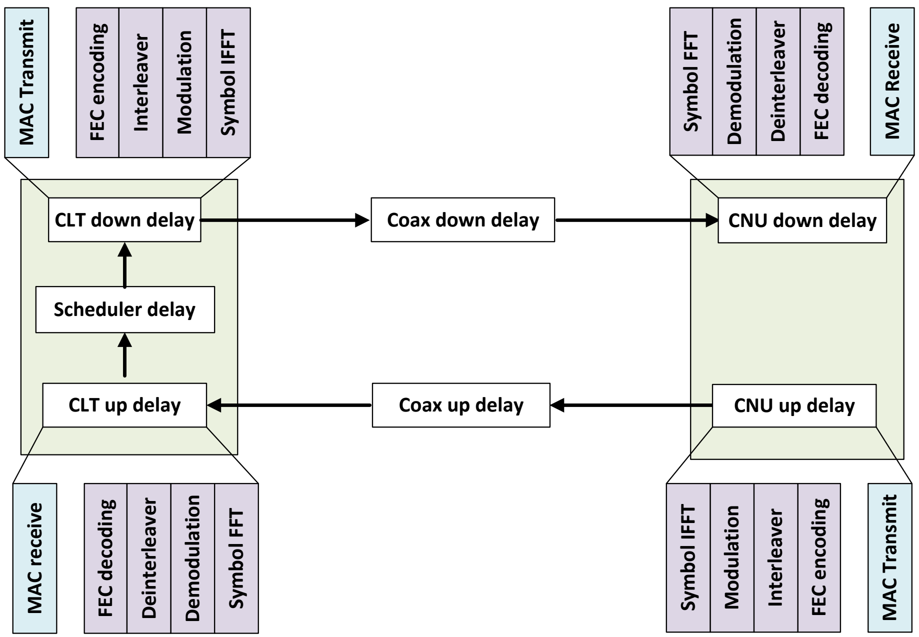
$T_{DS\_TXwin} = T_{DS\_TXdata} + T_{DS\_preamble}$ and $T_{US\_TXwin} = T_{US\_TXdata} + T_{US\_preamble}$

$T_{DS\_TXgap} = T_{US\_TXwin} + T_{DS\_preamble} + [\ 2*T_{SW} + 2*\max(T_{prop})\ ]$

$T_{US\_TXgap} = T_{DS\_TXwin} + T_{US\_preamble} + [\ 2*T_{SW} + 2*\max(T_{prop})\ ]$

Note: coax line is idle during this time

Delay Model – PHY for TDD (cont.)



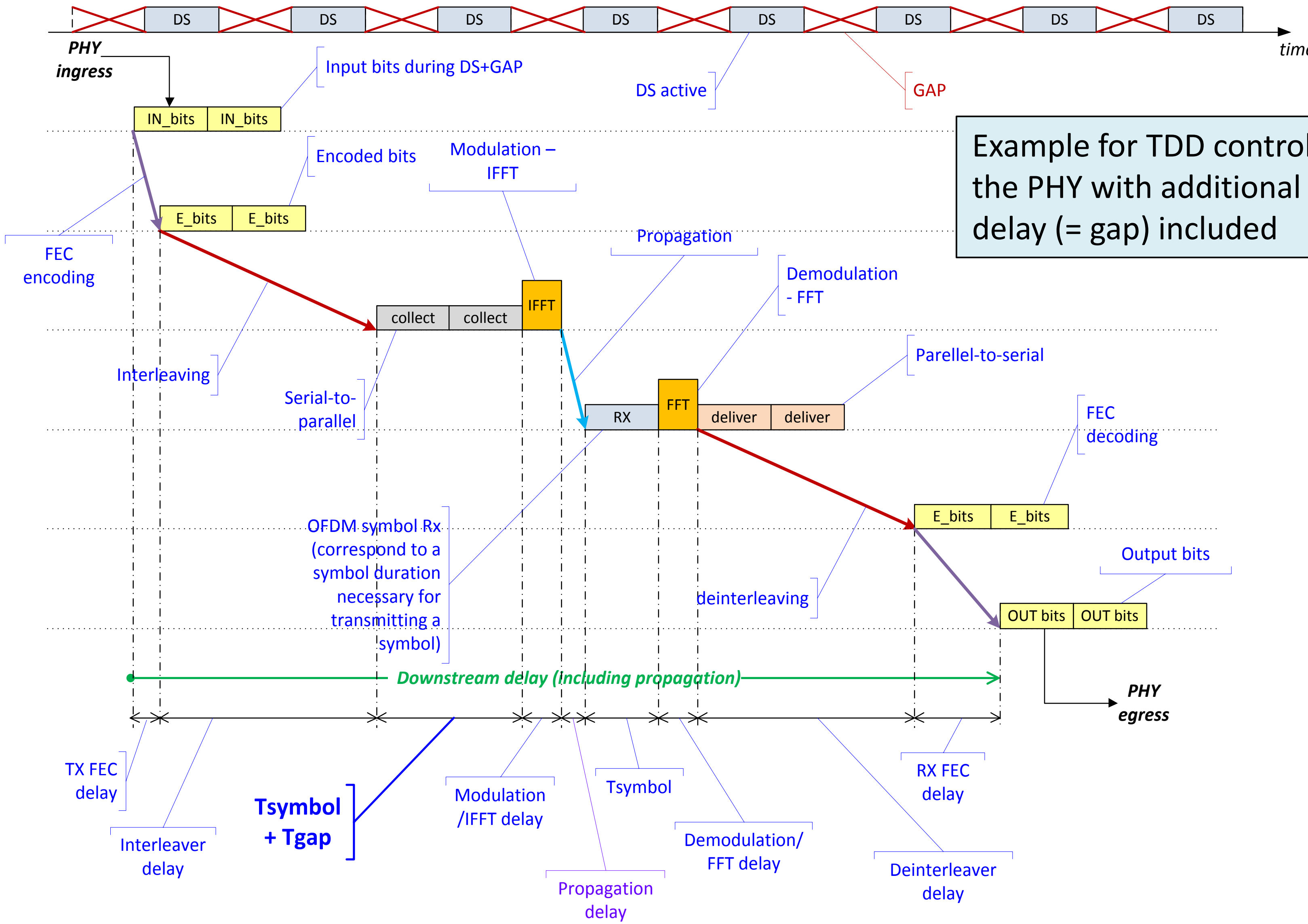
Also in case of TDD the PHY needs to perform operations for:

- FEC encoding/decoding
- Interleaving/de-interleaving
- Modulation/demodulation
- Symbol IFFT/FFT

➢ The same analysis as for FDD can be reused, with the inclusion of the DS and US data transmission gaps

- In case TDD is controlled at the PHY, data are collected over all time and transmitted during the DS transmission window and the average rate is matched over a TDD cycle)
  - In this case an additional PHY delay term accounting for the transmit gap is added
  - An example is included in the next slide
- In case TDD is controlled at the MPCP, data are both collected and transmitted only over the DS transmission window and the average rate is matched over a TDD cycle)
  - In this case there is no additional delay at the PHY and an additional (jitter) term accounting for the transmit gap shall be included in the MAC/MPCP part – see MAC/MPCP implications

Delay Model – PHY for TDD downstream example



Example for TDD controlled in the PHY with additional PHY delay (= gap) included

Note: Propagation delay depends on the cable plant and can vary significantly – this is just an example.

Delay Model – PHY for TDD summary

In case of TDD, the delay model results in the following terms:

$$PHY\_delay_{TDD\_DS} = T_{enc} + (2/n)*T_{TDD\_DS\_Int} + 2*T_{DS\_symb} + 2*T_{mod\_FFT} + T_{dec} + q*T_{DS\_Txgap}$$

$$PHY\_delay_{TDD\_US} = T_{enc} + (2/n)*T_{TDD\_US\_Int} + 2*T_{US\_symb} + 2*T_{mod\_FFT} + T_{dec} + q*T_{US\_Txgap}$$

$T_{propagation\_oneway} = L_{cable} / (0.87*c)$ where *c* is the speed of light in vacuum

n = 1 for block interleaver and n = 2 for convolutional interleaver of same size

q = 1 for TDD control in PHY and q = 0 for TDD control in MPCP

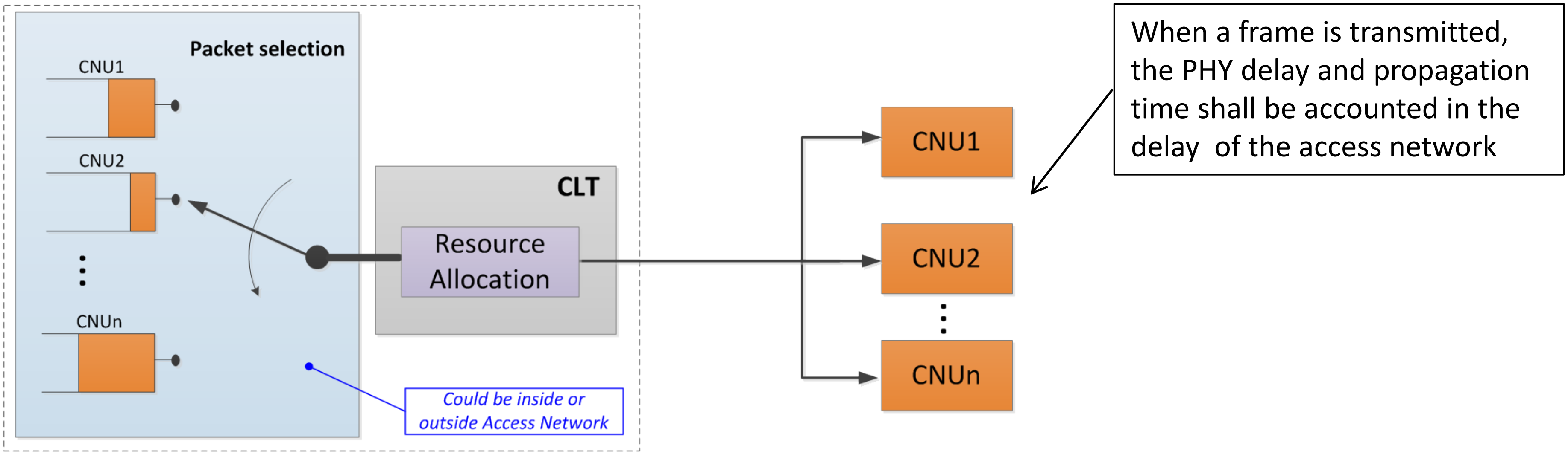
Note: The following assumption and considerations holds

- Delay of interleaver and deinterleaver in one direction are the same
- Delay for modulation/IFFT and demodulation/FFT are the same
- Encoder/decoder are the same for DS and US
- Modulation/demodulation are the same for DS and US
- Different symbol duration for DS and US are possible
- Different interleavers for DS and US are possible
- Different DS/US transmission gaps are possible, either via fixed configuration or variable in time between a minimum (at least one data symbol when transmitting) and maximum value (e.g. to meet delay/jitter requirements)

Delay Model – MAC/MPCP implications

- For simplicity, assumption is that each user has the same traffic profile and it is treated the same, with assigned resources in round-robin fashion
  - This is reasonable starting point, further refinement may be considered later
- Latency and jitter due to the MAC/MPCP components includes:
  - DS scheduler cycle and resource allocation
  - US polling cycle and resource allocation
  - Report cycle (in relation with RTT)
  - Number of transmitters and min/max burst sizes
  - TDD control (in case done at MPCP level)
- The same components also affect efficiency of the system
  - These aspects will also be considered during the further analysis

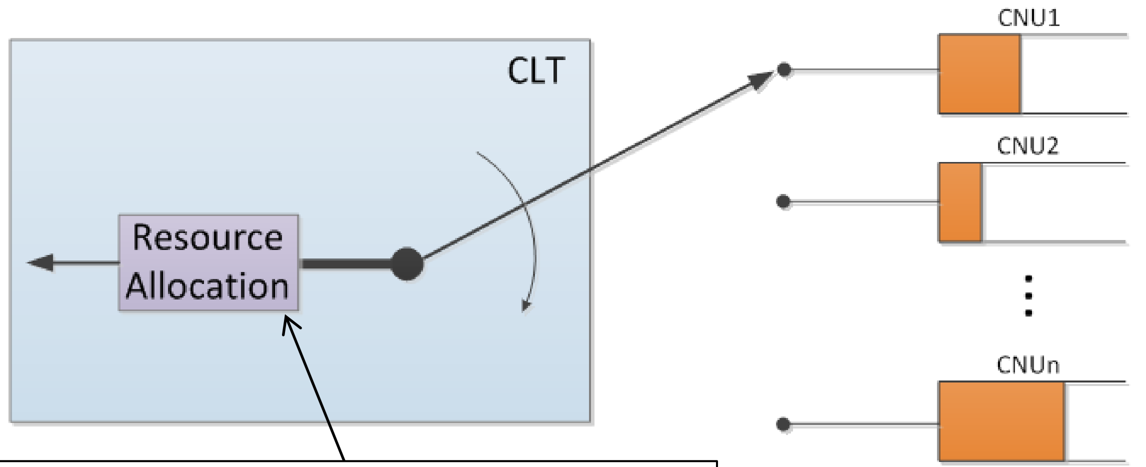
Delay Model – DS resource allocation



- Traffic switching and scheduling would result in additional end to end delay for data to be selected by the scheduler for transmission – this may happen inside or outside the AN domain
- This delay at system level is outside the scope of the present exercise – it could be included in further study during the Task Force activity in case needed

No implication needs to be considered for DS scheduling, as it is assumed that DS traffic shaping and aggregation (scheduling) considered outside the access network

Delay Model – US resource allocation



US scheduler resource allocation: fresh queue status is reported once at each polling cycle

The PHY delay and propagation time shall be accounted in the delay each time REPORT/GATE messages or data are transmitted

Compared to DS, GATE/REPORT messages need to be added in US

The implication of the US resource allocation at MPCP level results in additional delay for status REPORT, for GATE assignment and for user data transmission:

- **REPORT**: CNUs reports are collected in a round robin fashion during a polling cycle, so a REPORT will take between (PHY_delay_US) and (PHY_delay_US + $T_{polling\_cycle}$)
- **GATE**: resource allocation are typically matching received reports and takes a (PHY_delay_DS + MAC_ProcDel) time to reach CNUs after reports is received and CLT has reacted to it (this is accounted in the MAC processing delay)

Delay Model – US resource allocation (cont.)

- **<u>Data</u>**: the distributed GATE messages will have to sort out contention among CNU transmissions, which will also be done in a round robin fashion during a defined period of time (scheduling cycle) - data transmission will take between (PHY_delay_US) and (PHY_delay_US + T_{sched_cycle})

- **<u>By summing up all the components</u>**:
  - *min(delay) = 2*PHY_delay_US + PHY_delay_DS +* MAC_ProcDel
  - *max(delay) = 2*PHY_delay_US + PHY_delay_DS +* MAC_ProcDel + *($T_{polling\_cycle}$ + T_{sched_cycle})*
    - ➢ *Jitter = max(delay) – min(delay) = $T_{polling\_cycle}$ + T_{sched_cycle}*

- *The implications due to MPCP results in an added jitter component*
  - *Typically best performance are achieved when the queue polling cycle and the US scheduling cycle are equally long*
  - *So for simplicity, it can be assumed that the polling cycle and the contention cycle have the same duration T_{sched_cycle} and therefore Jitter = 2* T_{sched_cycle}*

Delay Model – Scheduler/Polling cycles duration

- The duration of the DS scheduler cycle and of the US polling cycle is generally configurable in the system and is in the order of few ms and can be captured as in the following in the final spreadsheet for convenience

- For FDD, the duration could be expressed in integer number of symbols:

$$T_{sched\_cycle} = N_{DS\_cycle} * T_{DS\_symb} \quad \sim \quad T_{polling\_cycle} = N_{US\_cycle} * T_{US\_symb}$$

- For TDD, the duration of a scheduling cycle and of the polling cycle could be expressed in terms of integer number of *TDD Transmission Cycles*
  - The TDD Transmission Cycle includes a number of DS symbols, a number of US symbols and the TDD guard intervals to change between DS and US
  - See slide 14 for details and definition of TDD Transmission Cycle

$$T_{sched\_cycle} = N_{DS\_TDD} * T_{TDD\_TXcycle} \quad \sim \quad T_{polling\_cycle} = N_{US\_TDD} * T_{TDD\_TXcycle}$$

Delay Model – Queue Status Report

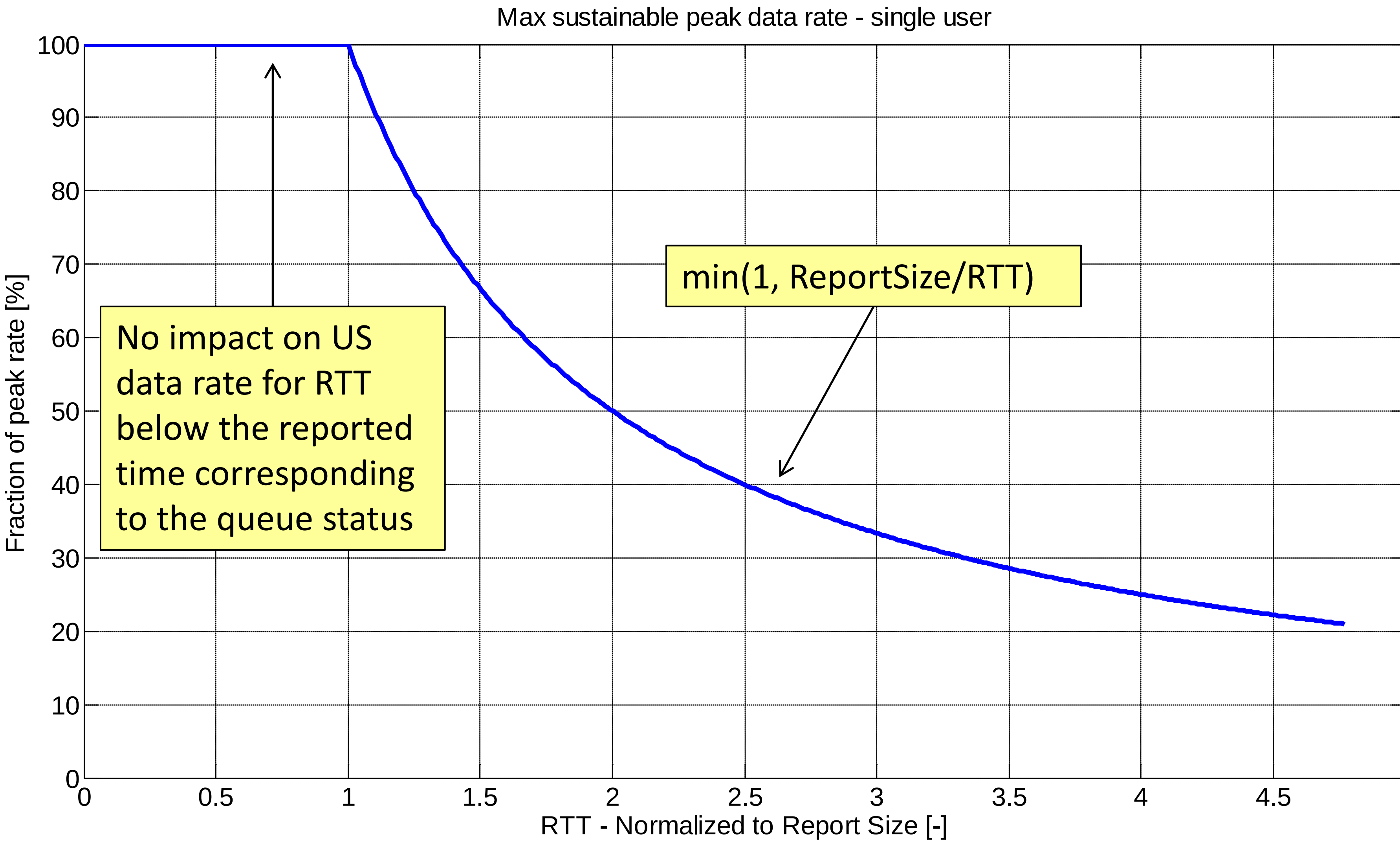
- The US data rate of a single user (LLID) in the system is limited by the RTT and maximum report size, as upstream resource are usually allocated reflecting the CNU need

- Based on the current mechanisms:
  - At most a number of time quanta (TQ) equal to the maximum contained in a report messages can be granted for new data over a round trip time (RTT)
  - In case the RTT exceeds the maximum number of reported TQ, a loss in the sustainable data rate for that user (LLID) is experienced (see next slide)
    - Current maximum size of reported queue length for one LLID (*report size*) is ~1.05 ms

- In case needed, solutions to overcome this possible problem are considered outside the scope of the present exercise

  - A point is added to slide 30, for future work

Delay Model – Queue Status Report (cont.)



Delay Model – Number of transmitters

- Another aspect for performance model is related to how many CNUs are sharing resources allocated during certain point of time – generally N ≥ 1 CNUs can be considered and the following can be observed:
  - The PHY delay for transmitted data is not affected by N (same delay for the transmitted data if one or more CNU transmits or receives)
  - As far as MPCP implications, the number of simultaneous transmitters can influence the duration of the polling and scheduling cycle but does not change the principle described in slides 19-21
    - If a total of M CNUs are active in the system and N ≤ M of them can be served simultaneously, the polling/scheduling cycle can be shorten by a factor N, which improves the jitter observed at each CLT/CNU connection
    - Applicable to both DS and US

Conclusion on delay

- no effect on the PHY delay due to number of transmitters,
- potential reduction of the jitter by a factor N = number of transmitters

Delay Model – Number of transmitters (cont.)

- If N CNUs can be served in the same symbol or burst of symbols, the minimal amount of data that can be carried will scale down of a factor *N*
  - If *N* is small, there is a potential loss of efficiency as a single user may not have enough amount of data to fully use the allocated bandwidth
  - This can be expressed as related to the symbol duration and the data rate:
    - min(allocation_symbol) = dataRate * T_{symbol} / N
    - min(allocation_burst) = dataRate * T_{burst} / N = dataRate * (n_s *T_{symbol}) / N

      where n_s is the number of symbols in the considered burst
  - On the other hand, if *N* is high, there may be issues due to spurious emissions in upstream
    - This pose an upper limit to what values of *N* can be used in practice
    - Typically *N* can range between 16 (easy) and 128 (very tough) units, further investigation may be needed (see slide 30)

Delay Model – Number of transmitters (cont.)

- The upstream efficiency can be computed as the ratio between the actual allocation and the potential full allocation in case of no loss:

$$US\_efficiency = \frac{actual\_Capacity}{full\_Capacity} = \frac{full\_Capacity - Losses}{full\_Capacity}$$

- As first approximation to assess the efficiency loss, the probability of data amount or frame size needs to be considered and compared with the minimal allocation size
  - efficiency loss only happens when the *min(allocation) > available_data*
  - The loss is directly proportional to the difference between the two terms

$$Losses = \sum_{x_i < A_{min}} p(x_i) \cdot (A_{min} - x_i)$$

where A_{min} is the minimal allocation possible, x_i is the size of available data (e.g. 64 bytes) and $p(x_i)$ is the discrete probability density of having data of size x_i

- More investigation may be needed to refine the model, so it has not been included for now included in the spreadsheet

Delay Model – TDD Control in MPCP

- In case TDD control is implemented at MPCP level, when a transmission occurs (either DS or US), the PHY delay is not affected and the model in slide 17 can be used directly for that
- However the implication on the delay from MAC/MPCP depends on the time a packet arrives compared to when the coax cable will be available for transmission in that direction:
  - The minimal added delay is zero (packet arrives during transmit window)
  - The maximum added delay is as long as the transmit gap (packet arrives immediately after the transmit window is over)

  - min(delay_DS) = PHY_delay_DS
  - max(delay_DS) = PHY_delay_DS + T_{DS_Txgap}

  - min(delay_US) = PHY_delay_US
  - max(delay_US) = PHY_delay_US + T_{US_Txgap}

Jitter_DS = T_{DS_Txgap} and Jitter_US = T_{US_Txgap}

Summary

- In this presentation the key principles and the details of the EPoC Performance Model are illustrated, with focus on delay and efficiency.
- The model provides a toolbox to discuss and compare performance of EPoC at high level, and has been developed in a fully parameterized way:
  - PHY delay models for downstream and upstream
  - PHY delay models for FDD and TDD modes of operations
  - Implications due to MAC/MPCP for delay and efficiency
- The outcome of the model is a excel spreadsheet where the model components are implemented, to be used for comparison and tradeoff analysis, thus achieving a common base for discussion/understanding
  - The tool **does not intend** to provide a mean for detailed verification of the state diagrams and standards, for which more detailed modeling and simulations will be needed based on experience in EPON
- Additional activities for future work are captured in the next slide

Future Work

Different questions have been identified during the development of the model, which would need to be sorted out by the task force – they are listed here.

- For the case of TDD, few points may need to be investigated further
  - Fixed vs. variable TDD transmission cycle and/or DS/US transmit window
  - Ranging in case of TDD (for US transmit time alignment)
  - Discovery window for TDD (for registration)
    - When US is not yet ranged like for registration, needs to ensure it does not hit the DS window (this is in particular relevant for the TDD control done in PHY)
  - Handling of frames at burst end for TDD
- In case of scenario (c), it remains open how to consider the disparity of data rate between fiber and coax - is this part of the scope?
- The upstream data rate limitation due to LLID queue status report may need to be further investigated
- The number of concurrent transmitters in upstream for tolerable spurious emissions may need further investigation

Spreadsheet – Input parameters (screenshot - partial)

Input Parameters	Value	Unit	Comment
FEC Encoding Time	10	us	
FEC Decoding Time	30	us	
FDD DS Interleaving Time	200	us	Set to 0 in case of no interleaver
FDD DS Interleaving Type	2	-	1 = block interleaver; 2 = convolutional interleaver
FDD US Interleaving Time	200	us	Set to 0 in case of no interleaver
FDD US Interleaving Type	1	-	1 = block interleaver; 2 = convolutional interleaver
TDD DS Interleaving Time	200	us	Set to 0 in case of no interleaver
TDD DS Interleaving Type	1	-	1 = block interleaver; 2 = convolutional interleaver
TDD US Interleaving Time	200	us	Set to 0 in case of no interleaver
TDD US Interleaving Type	1	-	1 = block interleaver; 2 = convolutional interleaver
DS Symbol duration	50	us	
US Symbol duration	50	us	
Modulation and FFT Time	10	us	
MAC Processing Delay	40	us	
TDD Control Type	0	-	1 = PHY control; 0 = MPCP control
Cable length - type 1	100	m	715QR, 540QR, 550, or 500 Rigid Trunk
Cable length - type 2	100	m	RG11 feeder coax
Cable length - type 3	100	m	RG6 drop coax
Cable phase velocity - type 1	261000000	m/s	715QR, 540QR, 550, or 500 Rigid Trunk
Cable phase velocity - type 2	261000000	m/s	RG11 feeder coax
Cable phase velocity - type 3	261000000	m/s	RG6 drop coax
Fiber length	1000	m	
Fiber phase velocity	200000000	m/s	Speed of light in the fiber
Optical Transmission Type	0	-	1 = digital EPON; 0 = analog fiber

Spreadsheet – Output quantities (screenshot)

Intermediate quantities	Value	Unit	Output quantities	Value	Unit
FDD PHY Delay for DS	360.00	us	**FDD minimal DS delay**	**360.00**	**us**
FDD PHY Delay for US	560.00	us	**FDD maximal DS delay**	**360.00**	**us**
			FDD DS delay variation (jitter)	**0.00**	**us**
TDD PHY Delay for DS	560.00	us			
TDD PHY Delay for US	560.00	us	**FDD minimal US delay**	**1520.00**	**us**
			FDD maximal US delay	**3520.00**	**us**
Cable propagation time	1.15	us	**FDD US delay variation (jitter)**	**2000.00**	**us**
Fiber propagation time	5.00	us	**FDD RTT**	**922.30**	**us**
FDD Polling Cycle	1000.00	us	**TDD minimal DS delay**	**560.00**	**us**
FDD Scheduling Cycle	1000.00	us	**TDD maximal DS delay**	**792.30**	**us**
			TDD DS delay variation (jitter)	**232.30**	**us**
TDD Polling Cycle	864.60	us			
TDD Scheduling Cycle	864.60	us	**TDD minimal US delay**	**560.00**	**us**
			TDD maximal US delay	**792.30**	**us**
FDD US burst length	200.00	us	**TDD US delay variation (jitter)**	**232.30**	**us**
TDD US burst length	200.00	us	**TDD RTT**	**1122.30**	**us**
TDD DS burst length	200.00	us			
			FDD Fraction of peak rate	**100.00**	**%**
TDD DS Gap length	232.30	us	**TDD Fraction of peak rate**	**93.43**	**%**
TDD US Gap length	232.30	us			
TDD Guard Interval DS -> US	17.30	us			
TDD Guard Interval US -> DS	15.00	us			
TDD Transmission Cycle	432.30	us			
Reported queue length	1048.58	us			

Backup Material

Delay Model – Q&A to the group @ 27-July-2012

Q1: First priority should be the worst case within a reasonable scenario (e.g. multiple users in a system, taking the worst case in there): is any need to also consider typical case? If yes, what could be a definition of such typical case?

***A1**: The conclusion is to have worst case in realistic multi-user scenario and exclude corner cases – can be seen as typical scenario, 99%-tile. Still some open points:*

(1) Max 1 Gb/s BW PAR Objective: to an individual CNU? Or to multiple CNUs on a coax segment? If multiple CNUs, max to an individual CNU?

(2) Consider max optical distance on HFC network – inputs needed, specification states at least 10-20 km of fibers needs to be supported in EPON, depending on scenario (clause 56.1.3)

Q2: The main objective is to analyze the delay in the PHY -> proposed reference points are from (a) packet leaves the MAC and enter the PHY in the transmitter to (b) packets leaves the PHY and is delivered to the MAC in the receiver. Once the PHY delay is modeled, the implication that this has on the MAC are also considered so that the overall delay = f(PHY, MAC) is modeled and compared with the requirements

***A2**: Proposed reference points and way forward are fine for the exercise. Agreed to start with coax PHY delay components and then implications and highlight transmit/receive sides separately*

Q3: It is proposed to focus on coax part: like to hear opinion about including also the optical part and the OCU later on or not

***A3**: Will start with coax modeling, and consider adding the optical part later. OCU model may be reduced to a simple delay component to play with.*

Q4: For simplicity we are planning to do the analysis for a system with equal traffic distribution. Like to hear if that is sufficient or other traffic profile should be selected.

***A4**: Equal traffic (all users treated the same) is good place to start with, will include a variable number of transmitters in the model. Later additional cases may be added and consider asymmetric traffic.*

Delay Model – Q&A to the group @ 13-August-2012

Q5: Is 1 Gb/s PAR objective to individual CNU or on coax line at CLT output?

A5*:** ***The conclusion is that the 1 Gb/s refers to the line rate and it shall be supported in case of multiple and also of single CNU – the case of single user consuming entire line is a valid one to be supported

Q6: Shall the model with OCU in slide 5 be kept or removed?

A6*:** ***It is kept and meant to just add a place-holder field in the final spreadsheet where people interested can include delay numbers modeling the fiber length and the EPON/OCU delay