Feasibility of TDD in EPoC

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Feasibility of TDD in EPoC

Part 1: Introduction and Disclaimers

Agenda

- **Part 1:** Introduction and Disclaimer (Jorge Salinger)
- **Part 2:** Motivation for TDD (Jorge Salinger)
- **Part 3:** Feasibility of a Single PHY for TDD and FDD
  - PHY Sublayer Analysis (Hesham ElBakoury)
  - Details on PCS Sublayer (Nicola Varanese)
- **Part 4:** TDD efficiency and delay considerations (David Barr and Christian Pietsch)
- **Part 5:** Summary and Conclusions (Juan Montojo)

Disclaimers

The intent of this presentation is

1. to prove the feasibility of introducing a TDD mode of operation within the 802.3 protocol stack → <u>This presentation does not include any technical proposal</u>
2. to show that both a TDD and a FDD mode can be supported by a <u>single PHY</u>
3. to analyse the performance achievable with TDD and to prove that TDD operation does not entail any degradation of packet delay jitter
4. there are a number of topics which the TF will be addressed, but are not addressed in this presentation. These include, but are not limited to: Fragmentation, Initialization, PMA Analysis, etc.

High Level FDD/TDD Comparison

- FDD/TDD: differences
  - TDD implies discontinuous (bursty) transmission and reception → **Addressed in this deck**
  - TDD operation entails additional delays → **Addressed in this deck**
- FDD/TDD: common issues
  - Supporting a wide variety of semi-static PHY configurations
    - US/DS carrier frequency (Low Band / High Band) → **Addressed in this deck**
    - US/DS bandwidth (e.g., different number of subcarriers for US/DS)
    - US/DS split (i.e., % of time for US or DS)
  - Supporting adaptive modulation and FEC (dynamically changing in time). → **Not** addressed in this deck (but not precluded by our analysis and applicable for FDD and TDD)

Feasibility of TDD in EPoC

Part 2: Motivation for TDD

Why is TDD better for some key MSO scenarios?

- Currently available DS spectrum in 750 MHz cable networks is completely filled (~65% of all systems)
- Currently available US spectrum in most cable networks (all HFC capacities) mostly filled already (DOCSIS and legacy OOB), and remainder will be used by most MSOs
- Upgrades not likely soon, but if implemented most US will be used for DOCSIS and little DS will become available (if any) for most MSOs
- Capacity on unused high portion of spectrum (>750 MHz) is plentiful, but is only available as a passive overlay of cable network without the need for a rebuild
  - In this portion of spectrum FDD would be possible but difficult to use, while TDD would be more advantageous, easier to use, and would provide more flexibility
- It's all about spectrum: where to place EPoC
  - Most MSOs wanting for deploy EPoC immediately will need to use high spectrum, for which TDD is a better choice

Assignment and participants of TDD team

- Request from Ed Mallette et. al. in Minneapolis
- Additional questions/comments from various sources
  - Feasibility of a Single PHY for TDD and FDD
  - TDD efficiency and delay considerations
  - Cost implications of TDD
  - Impact of TDD on standard and equipment availability
- A team of participants with interest in TDD got together on weekly meetings (and more frequent at times) between Minneapolis and San Diego to address questions and comments
- List of participants in the team included
  - Qualcomm, Entropic, Cortina, ZTE, Cisco, Huawei, ALU, Comcast, BHN, TWC Rogers Communications, and CableLabs
- Motivation of participants for TDD:
  - MSO: avoid diplex, flexibility of US:DS ratio, higher US and DS, symmetrical services, etc.
  - Vendors: develop what customers need and can use ASAP
  - No intent to delay; actually goal is to accelerate

Timeline objectives

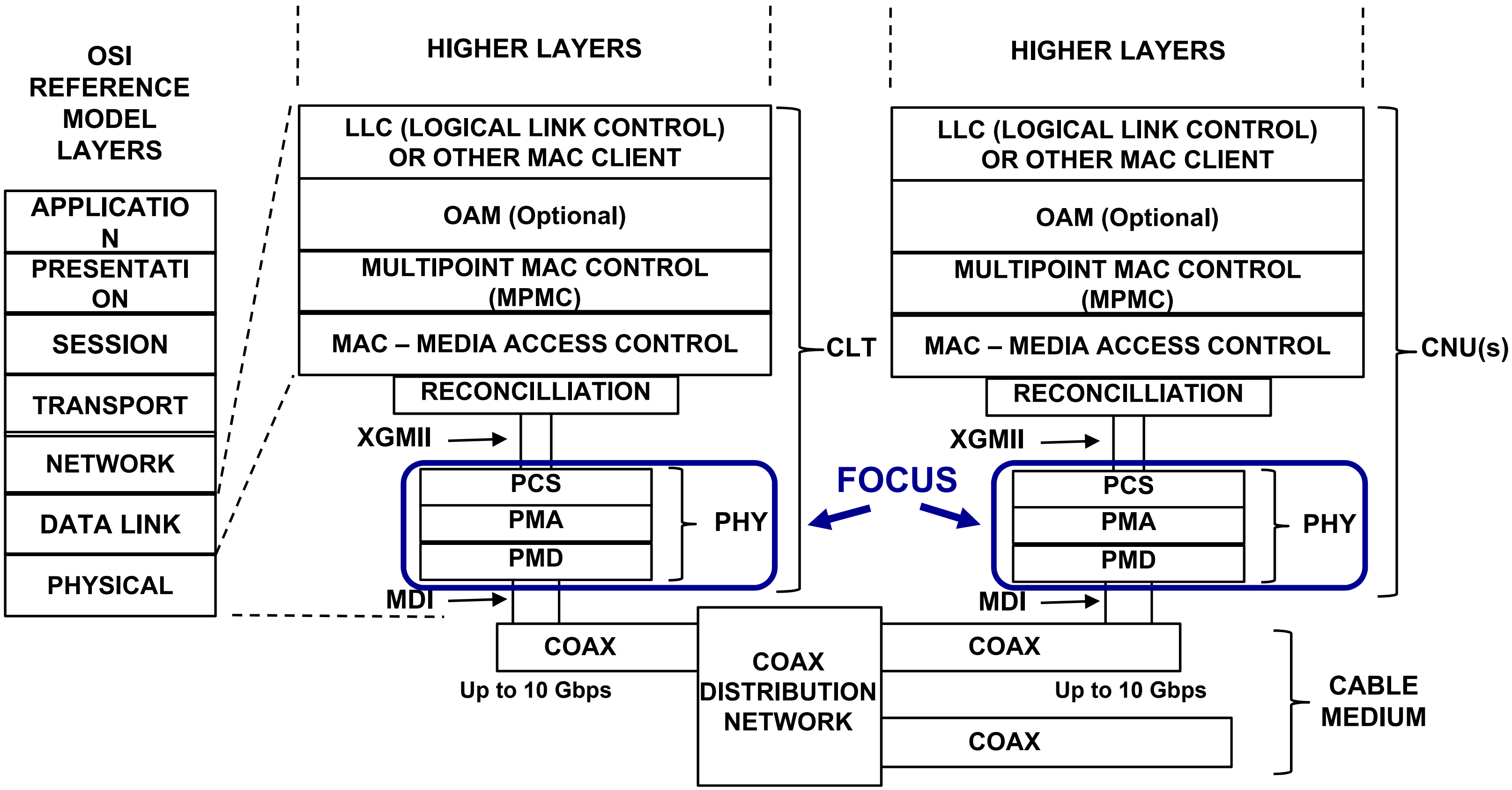
- Complete standard by end of 2013 with both FDD and TDD
  - Complete specs for system and product requirements by end of 2013 (outside IEEE)
  - Hope to see vendor products by 2014 for deployment
- Vendors and MSOs see EPoC as common goal and need ASAP

Feasibility of TDD in EPoC

Part 3: Feasibility of a Single PHY for FDD and TDD

PHY Sublayer Analysis

EPoC PHY Sub-layers



CLT – COAX LINE TERMINAL
CNU – COAX NETWORK UNIT
MDI – MEDIUM DEPENDENT INTERFACE
OAM – OPERATIONS, ADMINISTRATION, & MAINTENANCE

PCS – PHYSICAL CODING SUBLAYER
PHY – PHYSICAL LAYER DEVICE
PMA – PHYSICAL MEDIUM ATTACHMENT
PMD – PHYSICAL MEDIUM DEPENDENT
XGMII – GIGABIT MEDIA INDEPENDENT INTERFACE

Definition of a single PHY

- A single PHY uses the same PMD, PMA, and PCS.
- Requirement for EPoC: supporting different PHY configurations
  - Different carrier frequencies (Low Band / High Band)
  - Different US/DS bandwidths (e.g., different number of subcarriers)
  - Different US/DS split (i.e., % of time for US or DS)
- Common technology choice for each PHY sub-layer for both FDD and TDD
  - Ex: same modulation, FEC
  - Same parameter set for FDD and TDD (e.g. In OFDM, the number of subcarriers, number of pilots, etc.)
- No significant additional complexity for supporting both FDD and TDD

Goal is to show that using the same PMD, PMA, and PCS we can support <u>both TDD and FDD with a single PHY</u>.

PMD Analysis /1

- Signal processing for downstream and upstream is the same for both TDD and FDD.
  - Same symbol duration.
  - Same modulation.
  - For example, in case of OFDM, same subcarrier spacing and cyclic prefix duration, or other parameters in case of other modulation schemes.
- Main differences are in the Analog Front-End (AFE), but details about AFE architecture are not specified in the standard
- FDD and TDD use a common set of AFE parameters and there are some parameter that are specific to FDD and/or TDD

> - Frequency arrangement for US/DS
> - Transmission window and time allocation for US/DS (i.e., % of time for US or DS)

PMD Analysis /2

AFE parameter Configuration:

- Informing CNUs about AFE parameters
  - E.g., OAM message → **Common for FDD and TDD**
- Instructing PHY about AFE parameters
  - E.g., extension of the MDIO interface → **Common for FDD and TDD**

PMA Analysis

- PMA takes care of mapping the incoming bit stream from PCS into transmission symbols, and vice versa.
  - PMA needs to know the modulation order
  - PMA is made aware of this via, e.g., MDIO
- PMA is the same for both FDD and TDD

PCS Analysis

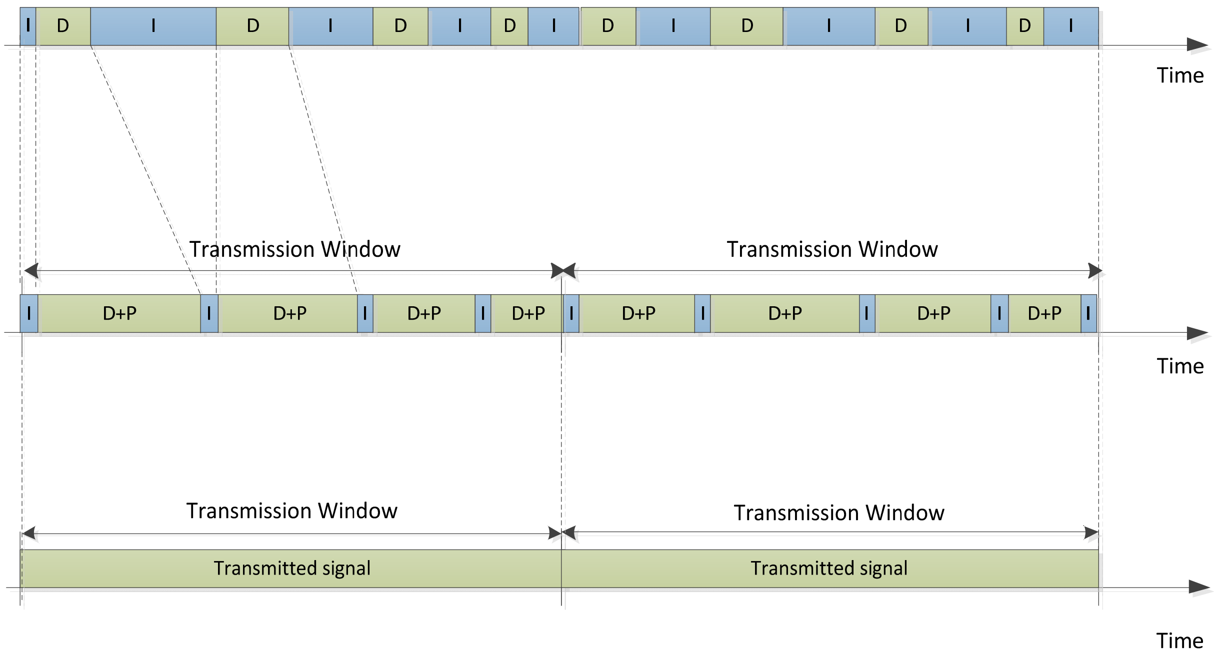
- All PCS functionalities present in today's EPON are the same for the EPOC PHY for TDD and FDD
  - Idle insertion/deletion
  - Scrambling
  - FEC: Stream-based or block-based, but the same for both FDD and TDD
- Requirements
  - Support different PHY rates with a fixed MAC rate
  - Support both FDD and TDD with a full-duplex fixed-rate MAC
- Address both requirements with a single solution in PCS
  - Detail description in the next section

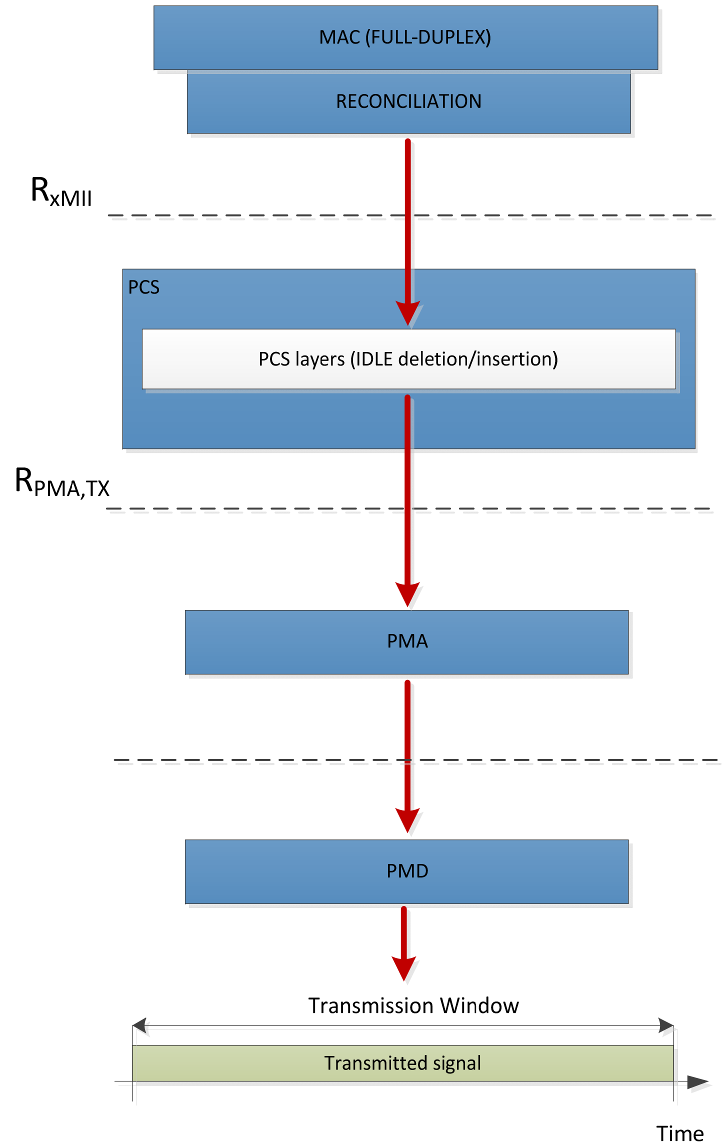
Details on PCS Sublayer

Assumptions

- The *information rate* supported by the PHY is known by MPCP
  - Depends on modulation order and FEC (assumed not to change dynamically in time)
- The Media-Independent Interface between MAC and PHY (xMII) runs at a fixed rate R_{xMII}
- The PMA input bit rate (coded bits / second) for transmission is $R_{PMA,TX}$
- The PMA layer does not change the bit rate (coded bits / second)

FDD Stack Operation during Transmission





<u>Legend :</u>

D = Data bits (Ethernet frame)

I = Idle characters

P = Parity bits from FEC

By transmission, we cover DS operation for the CLT and US operation for the CNU

Details on Stack Operation

- Operation:
  - The upper sub-layers of the PCS layer:
    1. Performs idle deletion in order to leave space for parity bits introduced by FEC (this operation does not change the bit rate)
    2. Re-times the bit-stream in order to match the PMA transmission bit-rate $R_{PMA,TX}$
  - This operation is analogous to 10G-EPON PCS operation (FEC and 66/64b encoding require idle deletion and re-timing of the bit-stream)
    - Details of PCS operation will be specified by the 802.3bn Task Force
    - The representation of Data, Parity and Idle characters in the previous slide is only exemplary
- Example computation of bit rates
  - OFDM symbol duration: 100us
  - Number of subcarriers available for Tx: 12000 (120 MHz bandwidth)
  - Maximum modulation order: 1024-QAM (10 bits)

→ $R_{PMA,TX}$ = 1.2 Gbps (for 10G-EPON, $R_{PMA,TX}$ = 10.3125 Gbps)

→ $R_{PMA,TX} \neq R_{XGMII}$ = 10 Gbps

Considerations

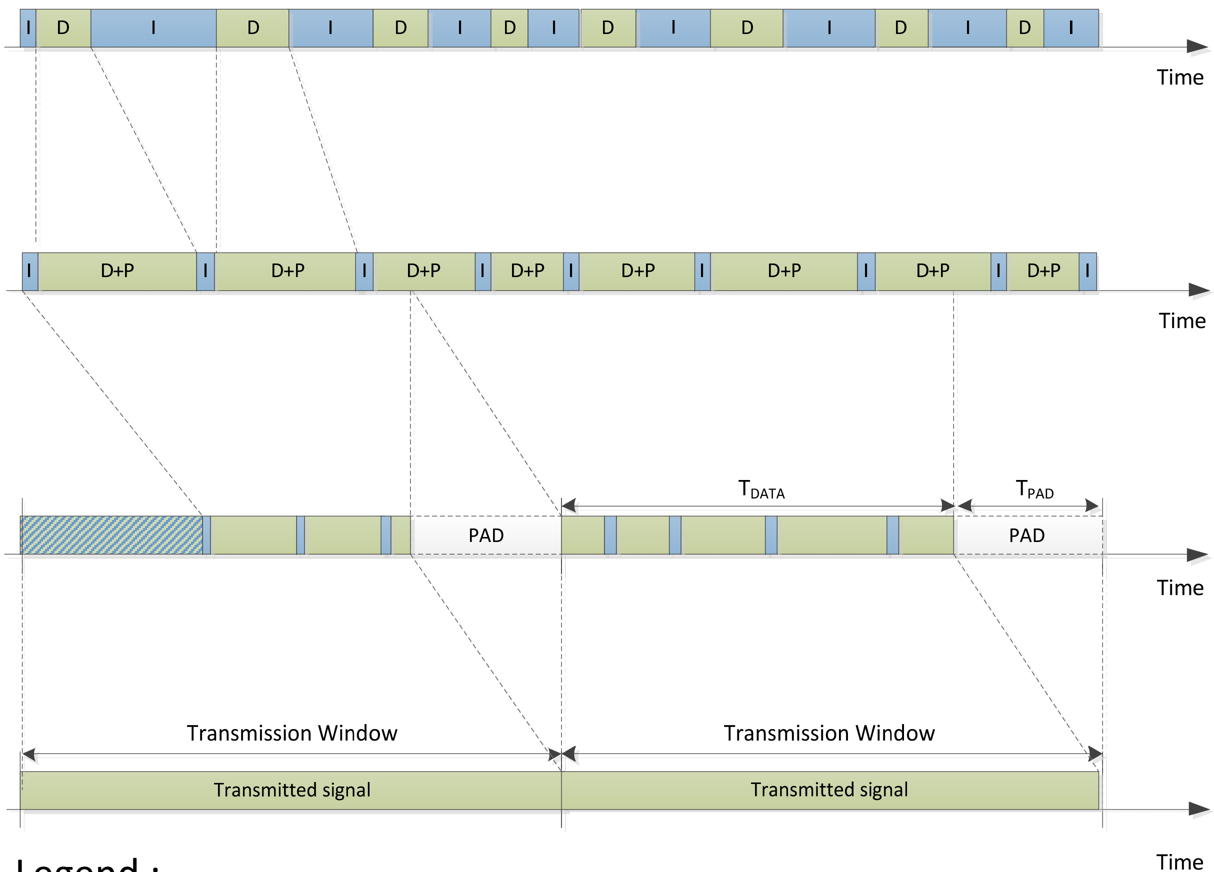
- The PMA rate can be different in the transmit and the receive direction
  - Example computation of bit-rates, FDD with asymmetric bandwidth allocation:
    - OFDM symbol duration: 100us
    - Number of subcarriers available for Tx: 10000 (100 MHz bandwidth)
    - Number of subcarriers available for Rx: 2500 (25 MHz bandwidth)
    - Maximum modulation order: 1024-QAM (10 bits)

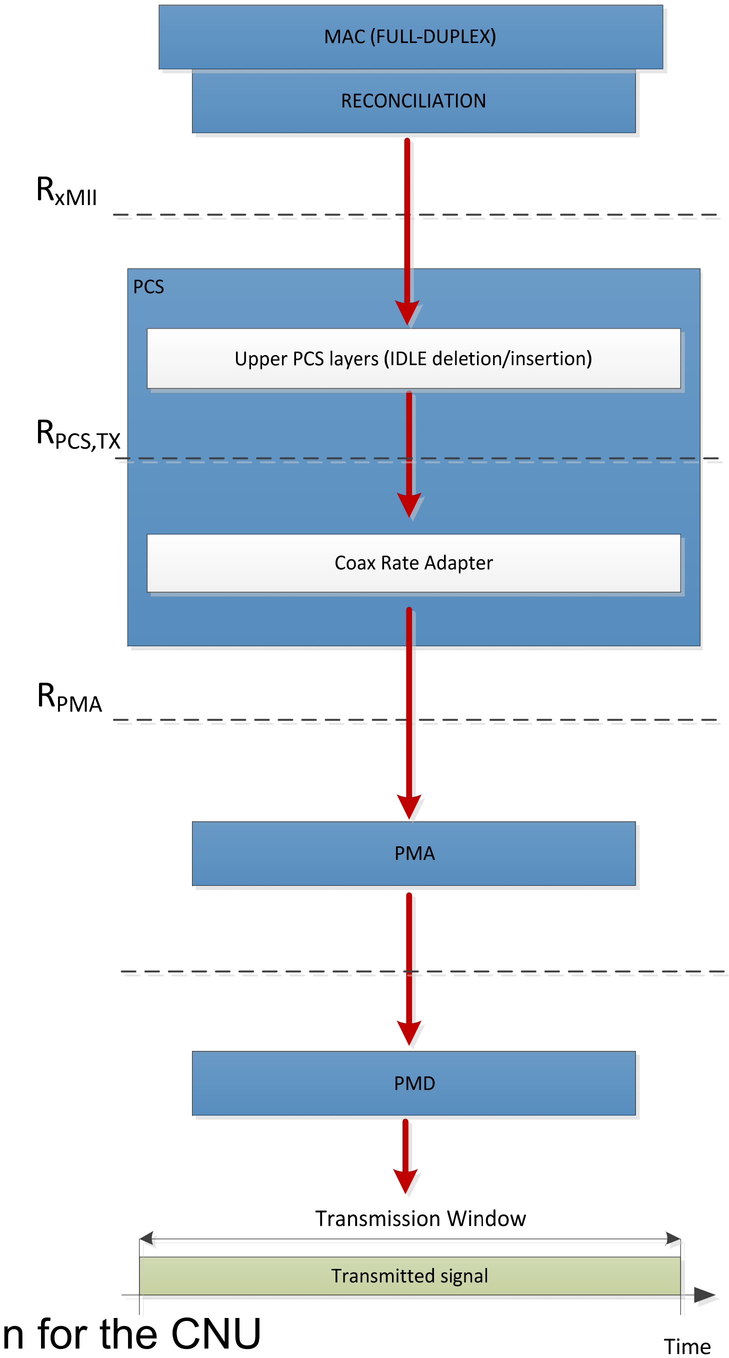
    → $\mathbf{R_{PMA,TX} = 1.0}$ **Gbps**

    → $\mathbf{R_{PMA,RX} = 0.25}$ **Gbps**

We introduce a Coax Rate Adapter at the PCS to cope with asymmetric DS/US bandwidth (FDD) and DS/US time split (TDD)

FDD Stack Operation during Transmission





Legend :

D = Data bits (Ethernet frame)

I = Idle characters

P = Parity bits from FEC

$$R_{PCS,TX} = R_{PMA} \times \frac{T_{DATA}}{T_{DATA} + T_{PAD}}$$

By transmission, we cover DS operation for the CLT and US operation for the CNU

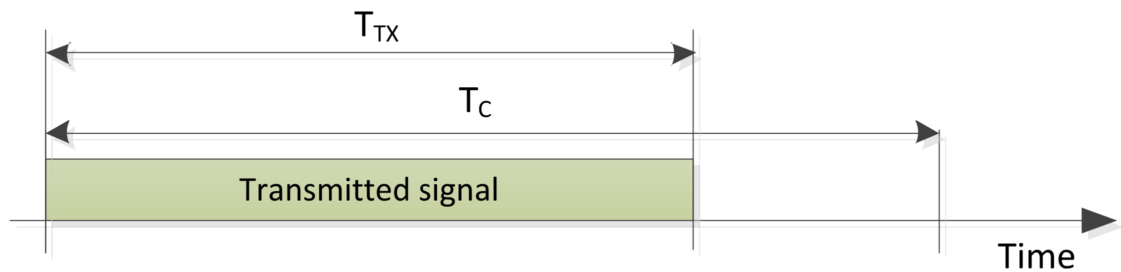
Details on FDD Stack Operation

- Operation:
  - The upper sub-layers of the PCS layer:
    1. Performs idle deletion in order to leave space for parity bits introduced by FEC (this operation does not change the bit rate)
    2. Re-times the bit-stream in order to match the bit-rate $R_{PCS,TX}$
  - The Coax Rate Adapter:
    1. Divides the incoming bitstream in slices according to the transmission window size
    2. Re-times each slice with the PMA rate $R_{PMA} > R_{PCS,TX}$
    3. Pads with zero symbols the portion of the transmission window left empty
  - The PMA layer converts the received slice into a physical signal spanning the whole transmission window
  - Example computation of T_{DATA}/T_{PAD}:
    - **R_{PMA} = 1.2 Gbps**
    - **$R_{PCS,TX}$ = 1.0 Gbps**

$$\Rightarrow \quad T_{PAD} = \frac{R_{PMA} - R_{PCS,TX}}{R_{PMA}} = \frac{1}{6} T_{DATA}$$

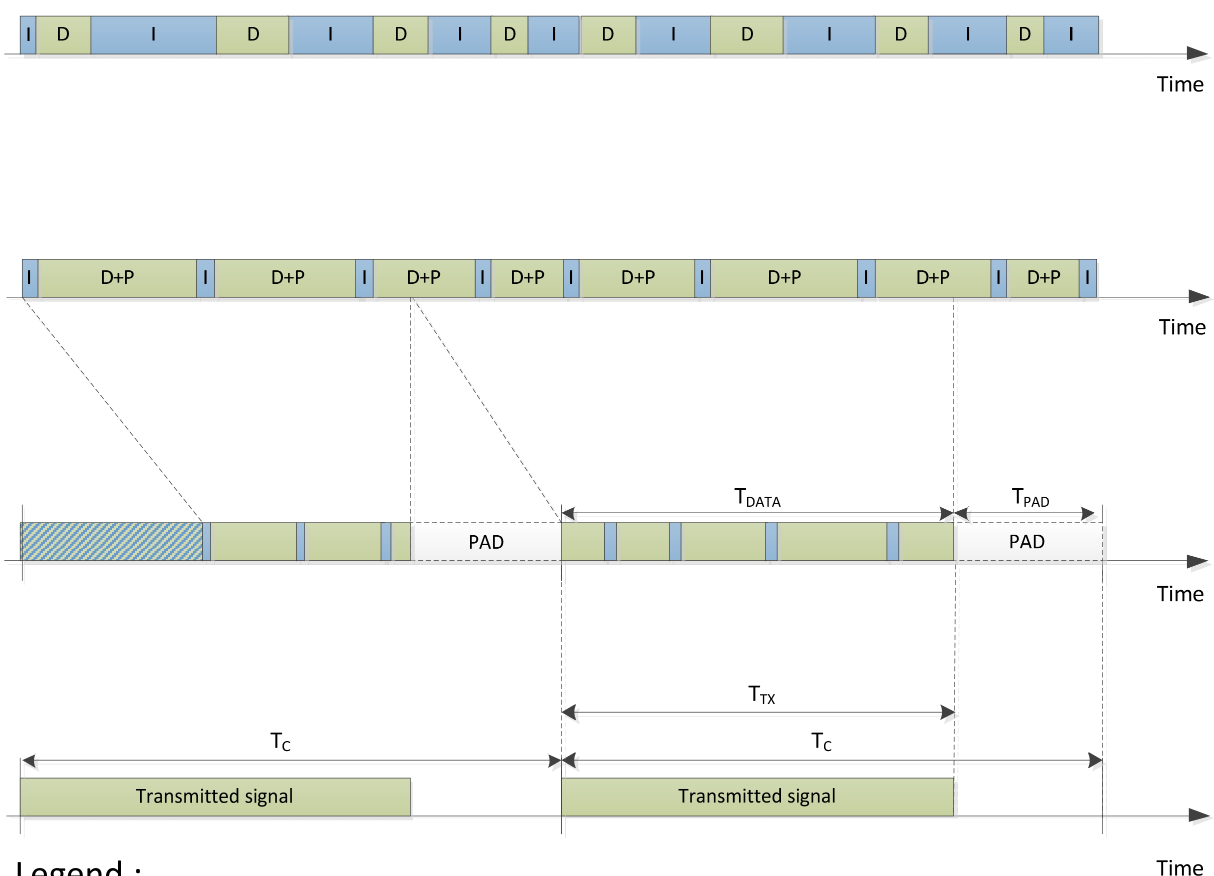
Value of Coax Rate Adapter for TDD PHY Operation

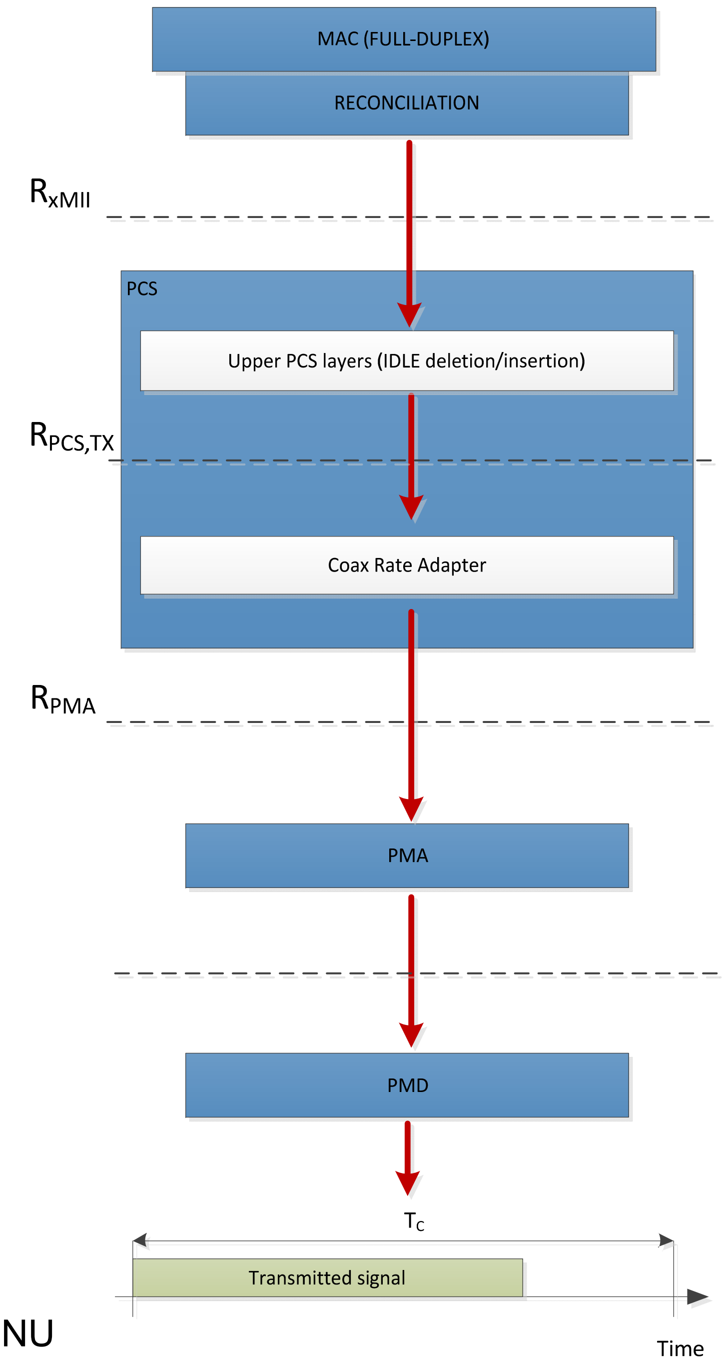
- The PMA rate can be different in the transmit and the receive direction
  - Example computation of bit-rates, TDD with a given US/DS split:
    – OFDM symbol duration: 100us
    – Number of subcarriers available: 12000 (120 MHz bandwidth – same for US and DS)
    – Maximum modulation order: 1024-QAM (10 bits)
    → $\mathbf{R_{PMA} = 1.2}$ **Gbps**
    → $\mathbf{R_{PCS,TX} = R_{PMA} \times T_{TX} / T_C}$



- The Coax Rate Adapter can be employed as is in order to match PCS with a PMA/PMD operating in TDD mode
  - TDD operation entails a proper configuration of the PMA and PMD layers

TDD Stack Operation during Transmission





Legend :

D = Data bits (Ethernet frame)

I = Idle characters

P = Parity bits from FEC

$$R_{PCS,TX} = R_{PMA} \times \frac{T_{DATA}}{T_{DATA} + T_{PAD}}$$

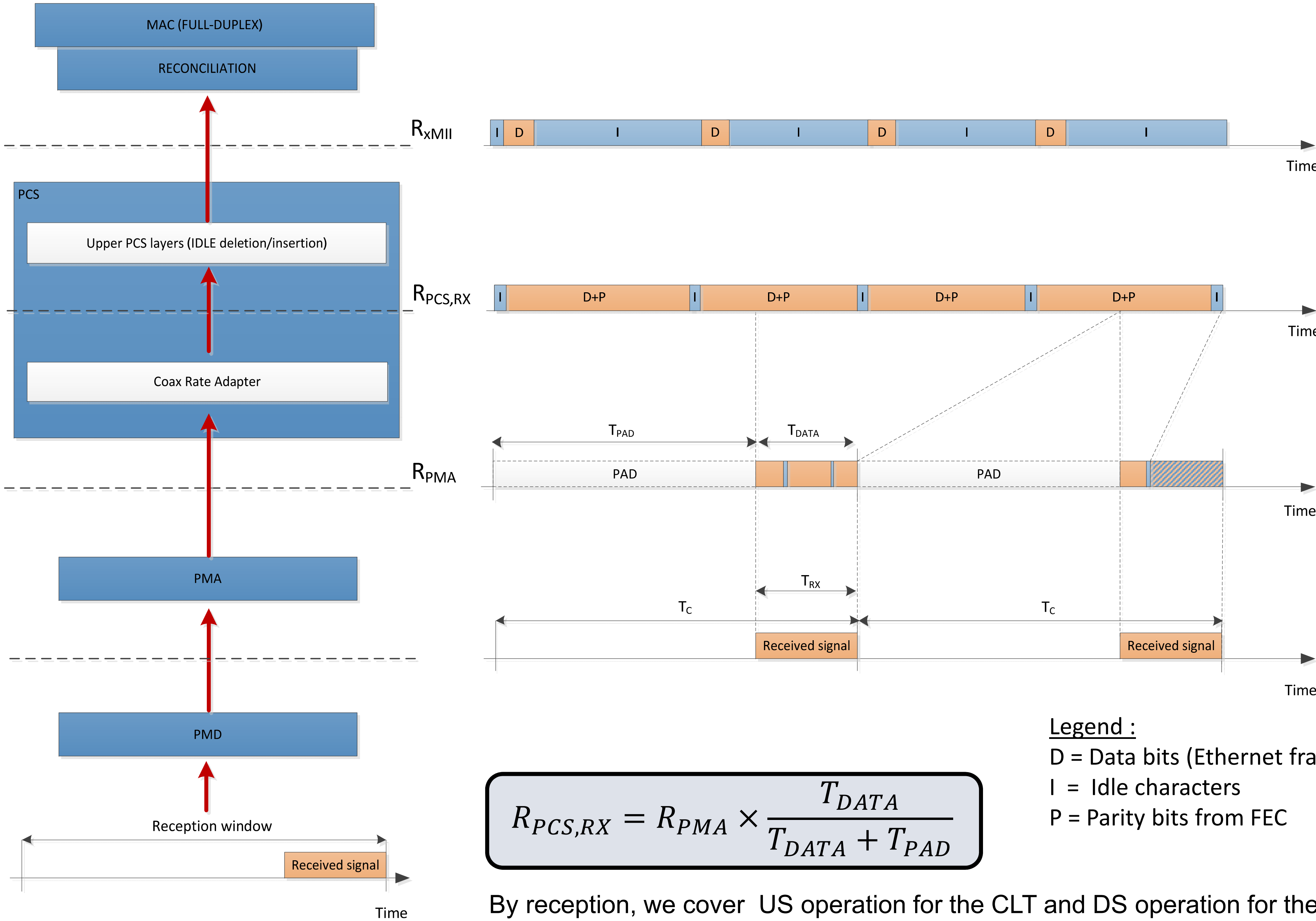
By transmission, we cover DS operation for the CLT and US operation for the CNU

Details on TDD Stack Operation

- Operation: **SAME AS FDD**
  - The upper sub-layers of the PCS layer:
    1. Performs idle deletion in order to leave space for parity bits introduced by FEC (this operation does not change the bit rate)
    2. Re-times the bit-stream in order to match the bit-rate $R_{PCS,TX}$
  - The Coax Rate Adapter:
    1. Divides the incoming bitstream in slices according to the transmission window size
    2. Re-times each slice with the PMA rate $R_{PMA} > R_{PCS,TX}$
    3. Pads with zero symbols the portion of the transmission window left empty
  - The PMA layer converts the received slice into a physical signal spanning only the transmission window
  - T_{DATA} and T_{PAD} determined by T_{TX} and T_C

$$\boxed{R_{PCS,TX} = R_{PMA} \times \frac{T_{TX}}{T_C}}$$

TDD Stack Operation during Reception



$$R_{PCS,RX} = R_{PMA} \times \frac{T_{DATA}}{T_{DATA} + T_{PAD}}$$

Legend :

D = Data bits (Ethernet frame)

I = Idle characters

P = Parity bits from FEC

By reception, we cover US operation for the CLT and DS operation for the CNU

Details on TDD Stack Operation

- Operation:
  - During the reception slot, the PMA layer converts the received signal into a bitstream at rate R_{PMA} , filling with PAD symbols the remaining part of the reception window
  - T_{DATA} and T_{PAD} determined by T_{RX} and T_C

$$\boxed{R_{PCS,RX} = R_{PMA} \times \frac{T_{RX}}{T_C}}$$

- During the reception slot, the TDD adapter reproduces the incoming bit stream from PMA at the reception bit rate $R_{PCS,RX}$ (smaller than R_{PMA}).
  - PAD bits are discarded

SAME AS FDD

- The upper sub-layers of the PCS layer:
  - Perform idle insertion in order to adapt the PCS reception bit-rate $R_{PCS,RX}$ to the xMII rate R_{xMII}
  - fill spaces left empty by parity bits removed by FEC (this operation does not change the bit rate)

Considerations on Coax Rate Adapter /1

- Common block for TDD and FDD
- Allows the use of bi-directional, fixed-rate interface between PCS and PMA layers
- Confines rate adaptation functionalities in the PCS layer
  - Rate adaptation depends only on AFE parameters
    - US/DS bandwidth (e.g., different number of subcarriers)
    - Transmission window duration and US/DS split (i.e., % of time for US or DS)
  - Fully transparent to MAC → MAC is full-duplex

Considerations on Coax Rate Adapter /2

- Blocks in PCS other than Coax Rate Adapter are the same for TDD and FDD
  - Idle insertion/deletion
  - Scrambling
  - FEC: Stream-based or block-based, but the same for both FDD and TDD

- PMA/PMD layers take care of synchronization procedures
  - CNU performs frame synchronization with respect to the CLT
  - Synchronization reference signals are the same for both FDD and TDD (details will be discussed in TF)

Feasibility of TDD in EPoC

Part 4: TDD Efficiency and Delay Considerations

Background

- Questions have arisen about EPoC performance
  - even though such questions should be more properly aimed at the Task Force
    - » e.g., there are no proposals the Study Group can consider
  - about Latency in particular
    - and applicability to Business Services, such as MEF-23.1
  - about Latency and Jitter in TDD more particularly
    - many assume that Latency of FDD Repeater media conversion is acceptable
    - many assume that Latency of TDD must be worse
      - » How much worse?
      - » Does Latency growth become unacceptable as more CNUs are added?

Efficiency Ratios and Latency Growth with TDD

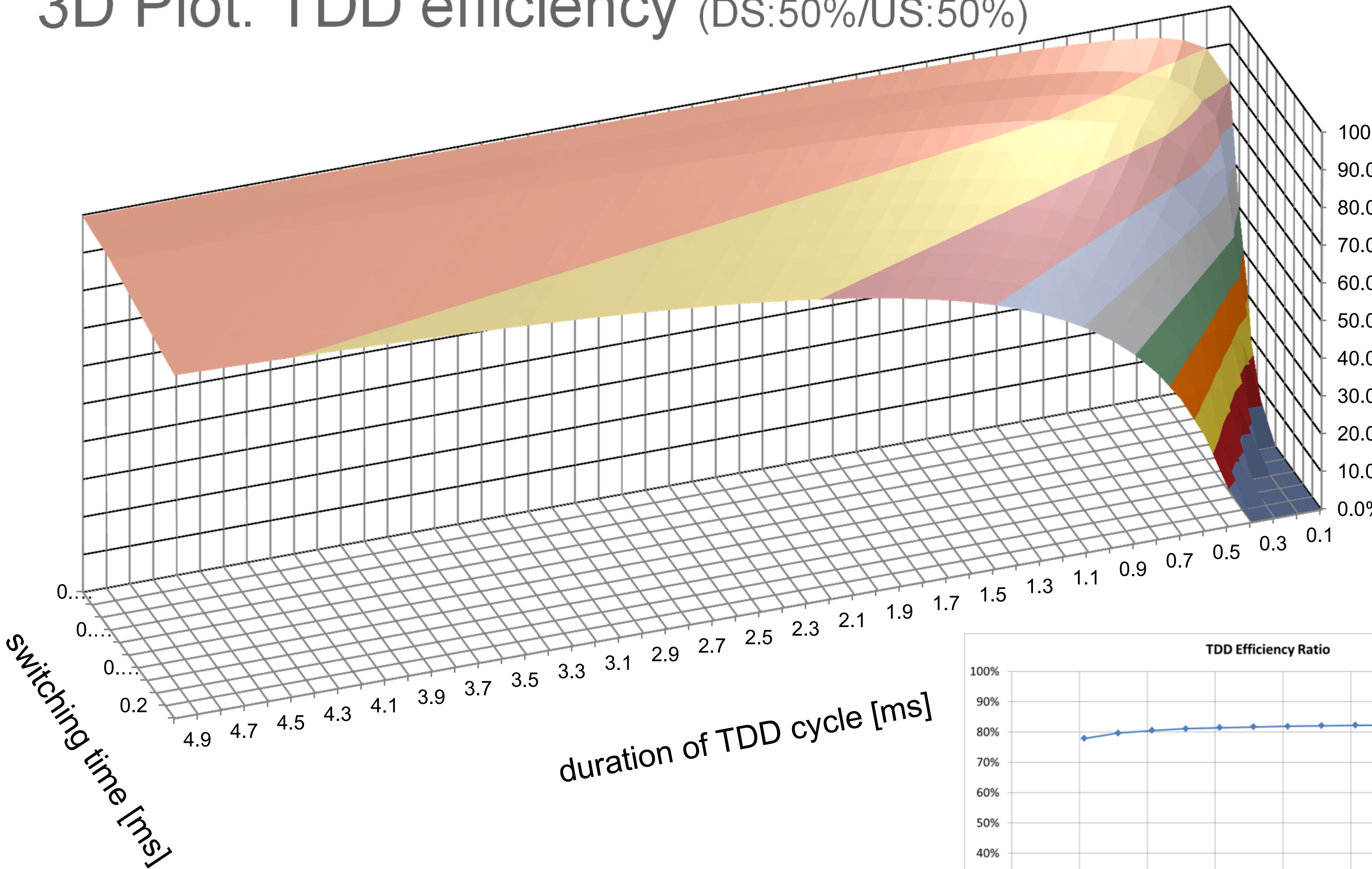
- The Efficiency Ratio is the indication of how much bandwidth is usable for a particular deployment
  - Accounting for guard frequency and guard time as needed for a give access technology
  - For FDD the Efficiency Ratio depends on the required frequency guard
  - For TDD the Efficiency Ratio varies with:
    - Switching rate between US and DS transmissions
    - Maximal cable length (Round Trip Time)
    - Split between US and DS
- Does Latency growth become unacceptable as more CNUs are added?
  - Is it worse with TDD?
    - This concern seems to be motivated by anecdotes about other MAC/PHYs
      - 802.11 using CSMA/CA MAC, EoCs in China using TDMA MACs
  - Latency growth versus # CPEs is a Layer-2 issue
    - whereas EPoC will be a PHY-Layer Spec
  - EPoC must reuse the Ethernet MAC (as is)
    - it is what it is, for better or for worse
    - latency growth, if any, will be identical for both TDD & FDD

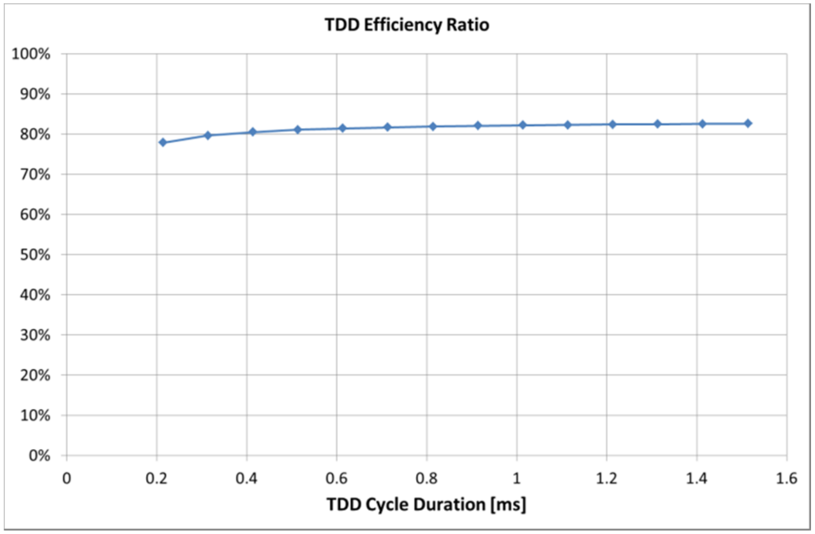
Excel Sheet for TDD Delay and Efficiency Ratio

- Based on the feasibility study, we assume:
  - MAC is not aware of TDD operation (PHY layer only approach)
  - MAC/PHY interface operates at constant rate in full duplex mode

- There is a posted Excel spreadsheet that allows to calculate the incremental delay incurred by TDD operation for different spectrum use cases. In addition, efficiency ratios for TDD and FDD are stated to allow for the comparison between TDD and FDD efficiency
  - Note: this spreadsheet can be used to compute the efficiency ratio and incremental delay incurred by TDD operation

3D Plot: TDD efficiency (DS:50%/US:50%)

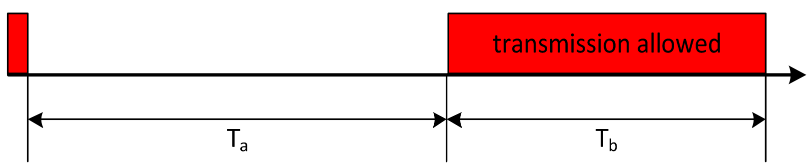




2D plot assumes a Guard Interval of 14 μs

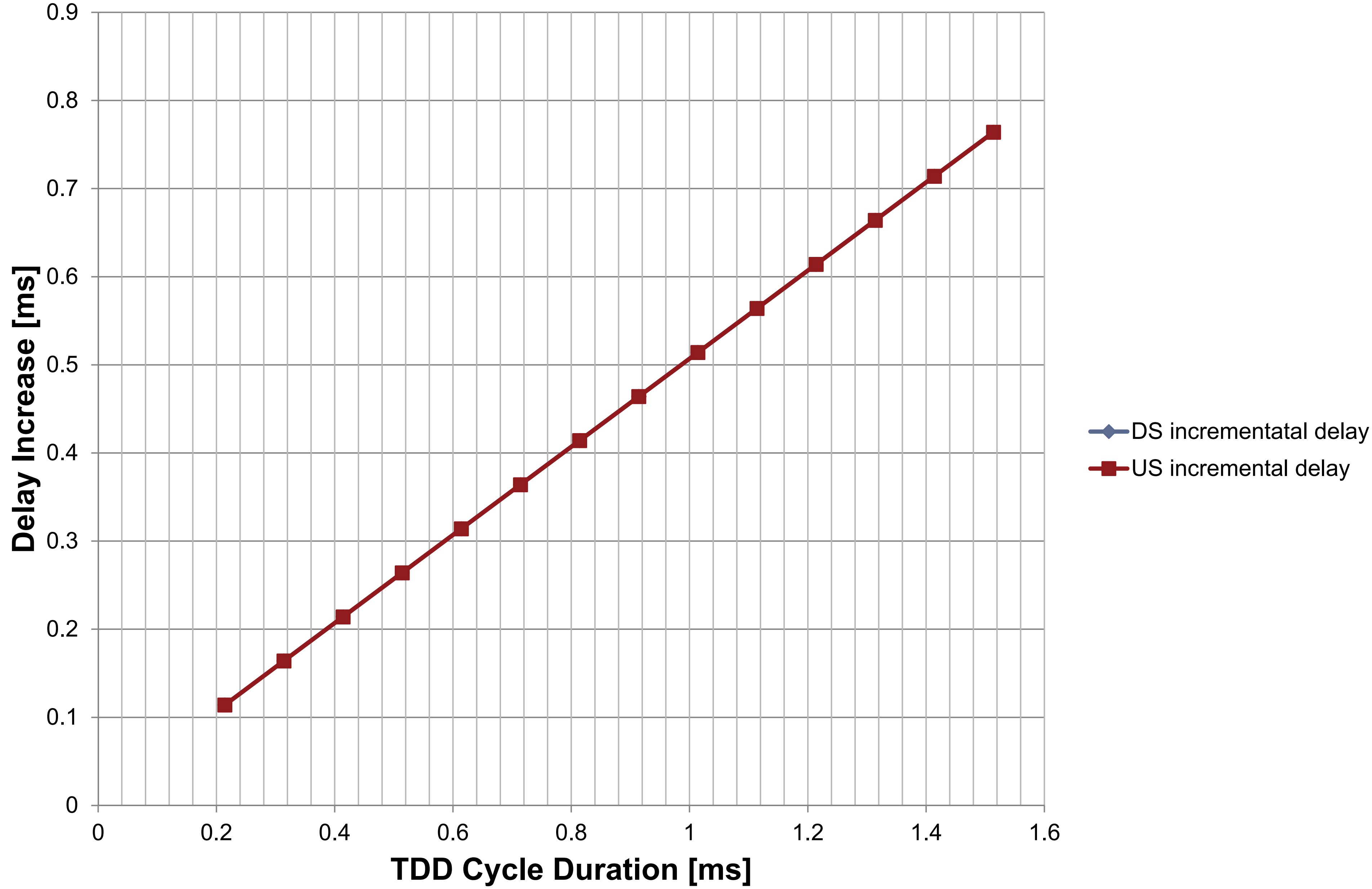
TDD Delay Consideration

- The incremental downstream delay between FDD and TDD is a function of the US time window duration and the guard time:
  - Ranges from 0 to the sum of the US time window duration and guard time
- This additional delay can be chosen to constitute
  - A fixed delay with no jitter opting to incur the max delay increase
    - This is the delay shown in the spreadsheet, in the delay computations of this deck and represented by T_a in figure below
  - A variable delay with jitter from 0 to the max additional delay



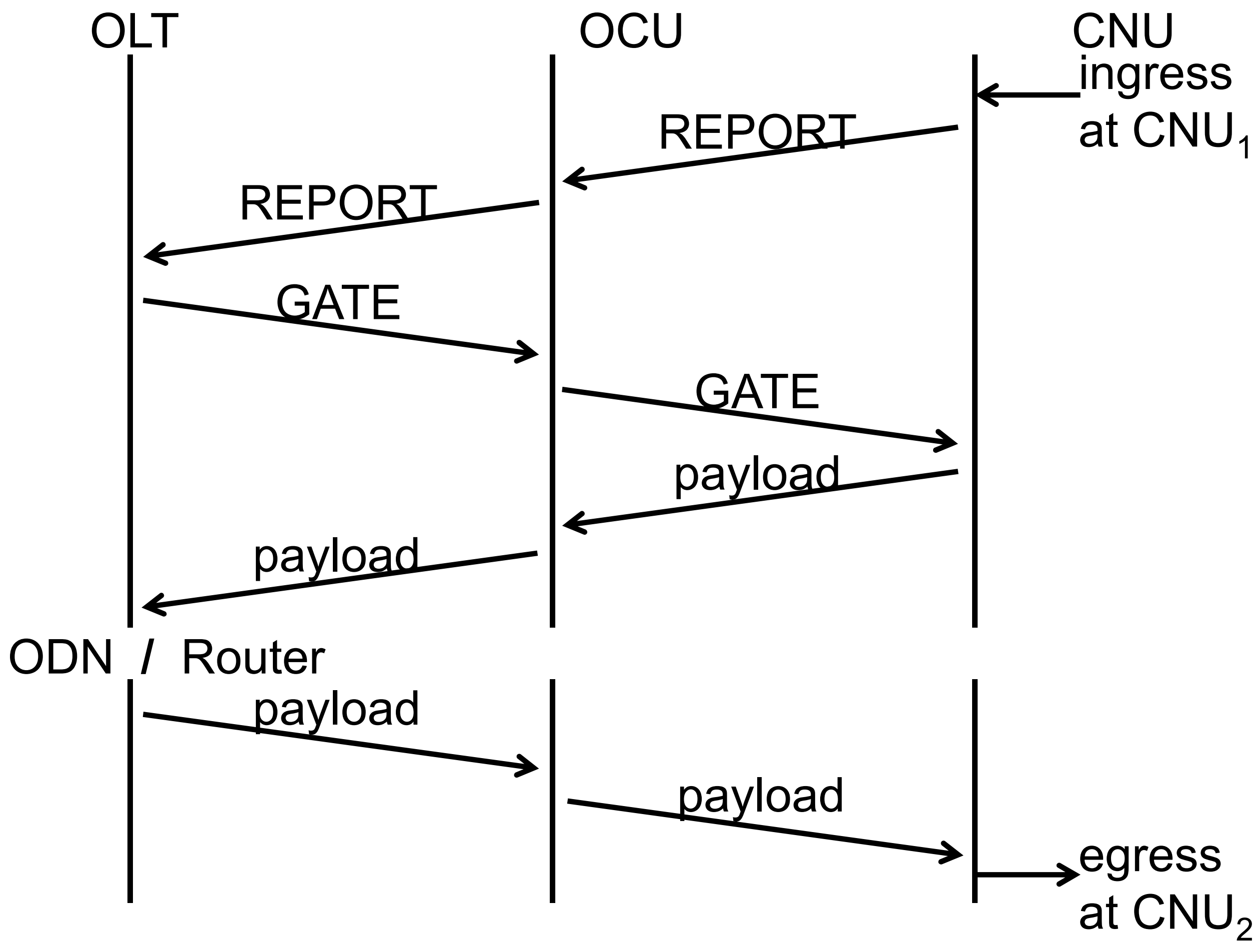
- Therefore, one can operate TDD **without incremental jitter**
  - Incremental delays of 0.5 ms or less still enable efficient operation modes
- For the Upstream, the delay is dominated by the DBA cycle as in FDD

Plot: Delay Increase Due to TDD (DS:50%/US:50%)



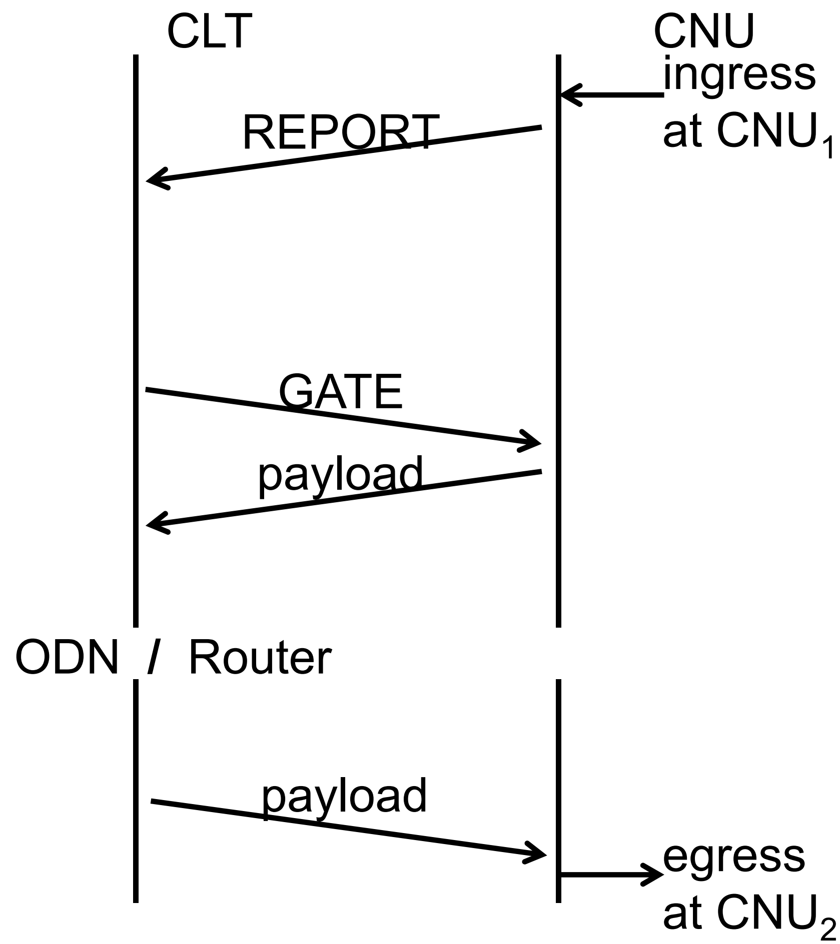
This plot assumes a Guard Interval of 14 µs

MEF End-to-End through PHY Repeaters



- MEF end-to-end includes 2× { US traversal + DS traversal } through OCUs
  - this is true for either FDD or TDD Repeater
  - only difference in Latency is delay through Coax/OCUs
  - Thus, only need to evaluate difference in Latency
    - any additional delay of TDD compared to FDD

MEF End-to-End through CLTs



- MEF end-to-end includes 2× { US coax + DS coax } through CLTs
  - again, this is true for either FDD or TDD CLTs
  - only difference in Latency is delay over coax (FDD vs. TDD)
  - Thus, only need to evaluate difference in Latency
    - any additional delay of TDD compared to FDD

Observations and Conclusions

- MEF End-to-End uses 4 traversals through TDD Repeater OCU
  - ½ TDD Cycle worst-case per traversal
  - Total = 2× TDD Cycles additional delay
- How long is a TDD Cycle (how short can it be)?
  - Guard Period overhead for switching Downstream ←→ Upstream
    - » 2× 7μs IFGs (inter-frame guard interval) plus one DS preamble
      - see SG contributions from May
  - TDD Cycles of a few hundred microseconds are reasonable (e.g. 300μs)

<u>Conclusions:</u>

- Thus, OCU conversion between FDD on fiber to/from TDD on coax
  - roughly ~**600μs** total additional delay (compared to FDD)
    - can be reduced to zero via optimized OLT/CLT scheduling (vendor-specific)
  - i.e., End-to-End (CNU_1 → CNU_2)
- Conclusion: TDD additional delay constitutes a small % of the delay budget even for MEF-23.1 requirement
  - MEF-23.1 High specifies **10ms** (99.9%) maximum Latency
  - We do not have any incremental symbol jitter from TDD operation

Complexity (Relative Cost): FDD vs. TDD

- TDD transceiver may operate at twice the channel-width as FDD transceivers
    - » given the same total US+DS spectral allocation
  - – Thus, TDD's peak datarate is double that of FDD
    - » this capacity to dispatch traffic at double the peak throughput is beneficial
    - » and it's available for either downstream or upstream traffic as needed
  - – Some have tried to mis-characterize this useful capability as a demerit
    - » claiming higher system & CPE costs
  - – However, FDD requires ***two*** PHY implementations (1 each for US and DS)
    - » whereas TDD requires only one transceiver
    - » so those claims are unfounded

Feasibility of TDD in EPoC

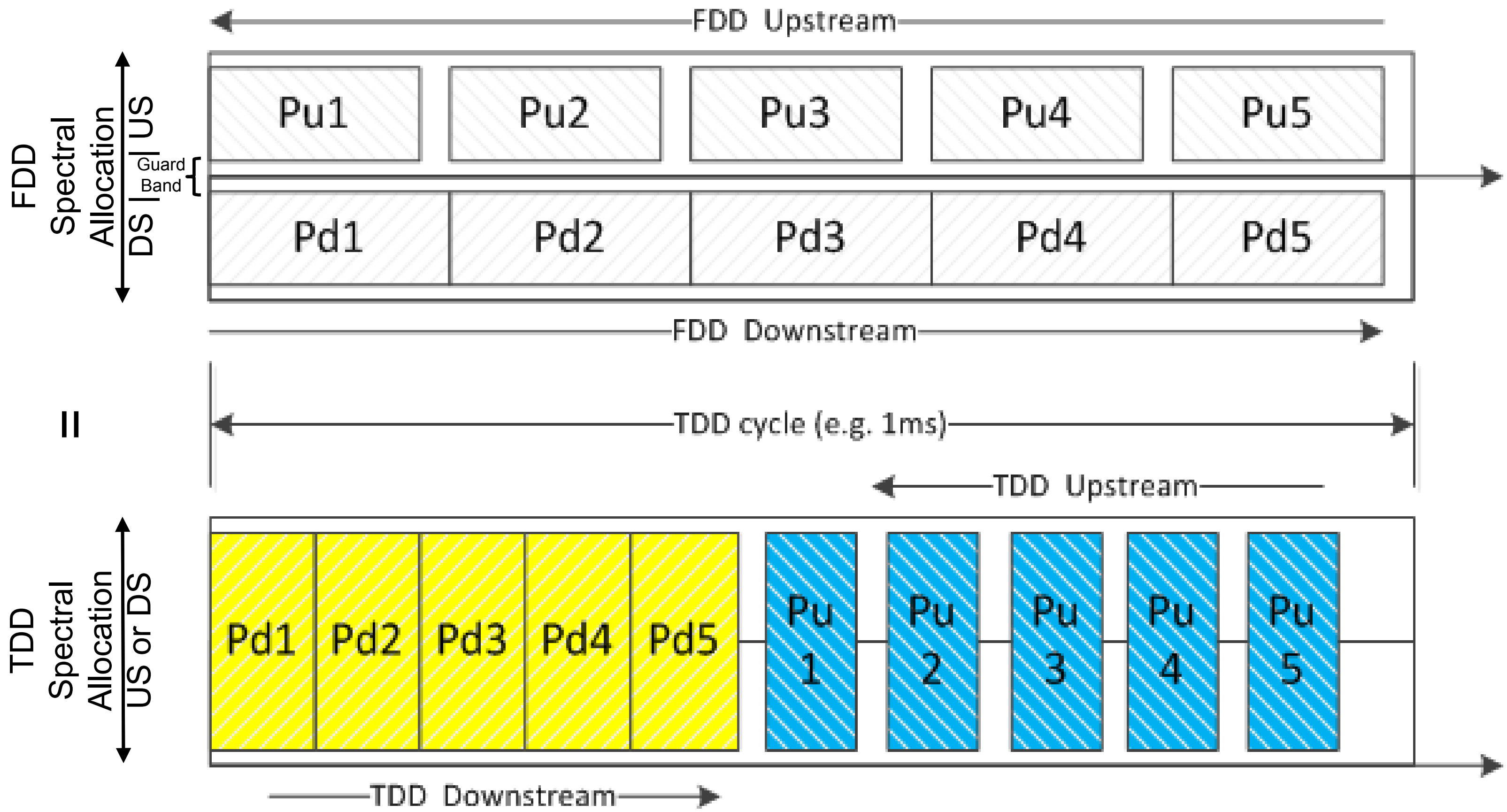
Part 5: Summary and Conclusions

Summary and Conclusions

- Demonstrated feasibility of supporting both FDD and TDD in a single PHY
  - No changes to the MAC Layer are required to support TDD
  - PCS, PMA and PMD sublayers the same for both FDD and TDD
  - Include Coax Rate Adapter which addresses two design goals
    - Support multiple PHY configurations (different US/DS bandwidths and time splits)
    - Same functionality for FDD and TDD
- TDD provides high throughput efficiency
- TDD increases end-to-end latency by a small value (~600 µs) relative to FDD, given the proper selection of the TDD cycle and guard interval
- TDD can be designed so that there is no increase in delay jitter
- There are resources in the Study Group/Task Force who are dedicated to developing TDD text for standard
  - Inclusion of TDD will not delay the completion of the standard

Backup

Review of FDD vs. TDD

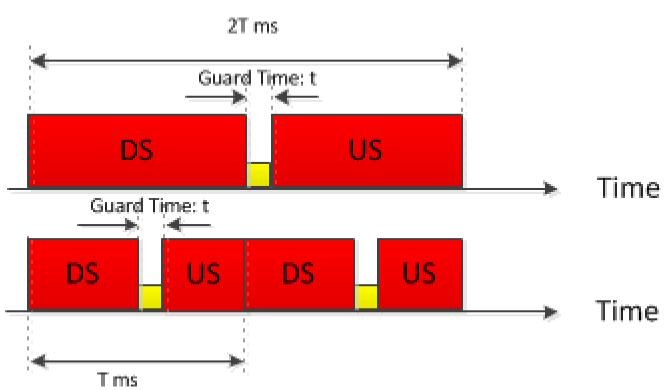


Depicts symmetric US/DS (and same total US+DS spectral allocation for both FDD & TDD)

- <u>Observations:</u>
  - Latency averaged over all payloads is ~same for FDD & TDD
    - » FDD upstream latency is ¼ TDD cycle shorter
    - » TDD downstream latency is ¼ TDD cycle shorter
  - FDD & TDD are ~equally efficient, as long as US & DS are fully occupied

FDD versus TDD – Delay and Efficiency Tradeoff

- In FDD packets can be transmitted at all times
- In TDD packets can only be transmitted when the US/DS configuration allows it
  - This entails an intrinsic increase in latency for TDD systems that is controllable by design
- This increase is a function of the US/DS configuration period
  - T: reference time interval

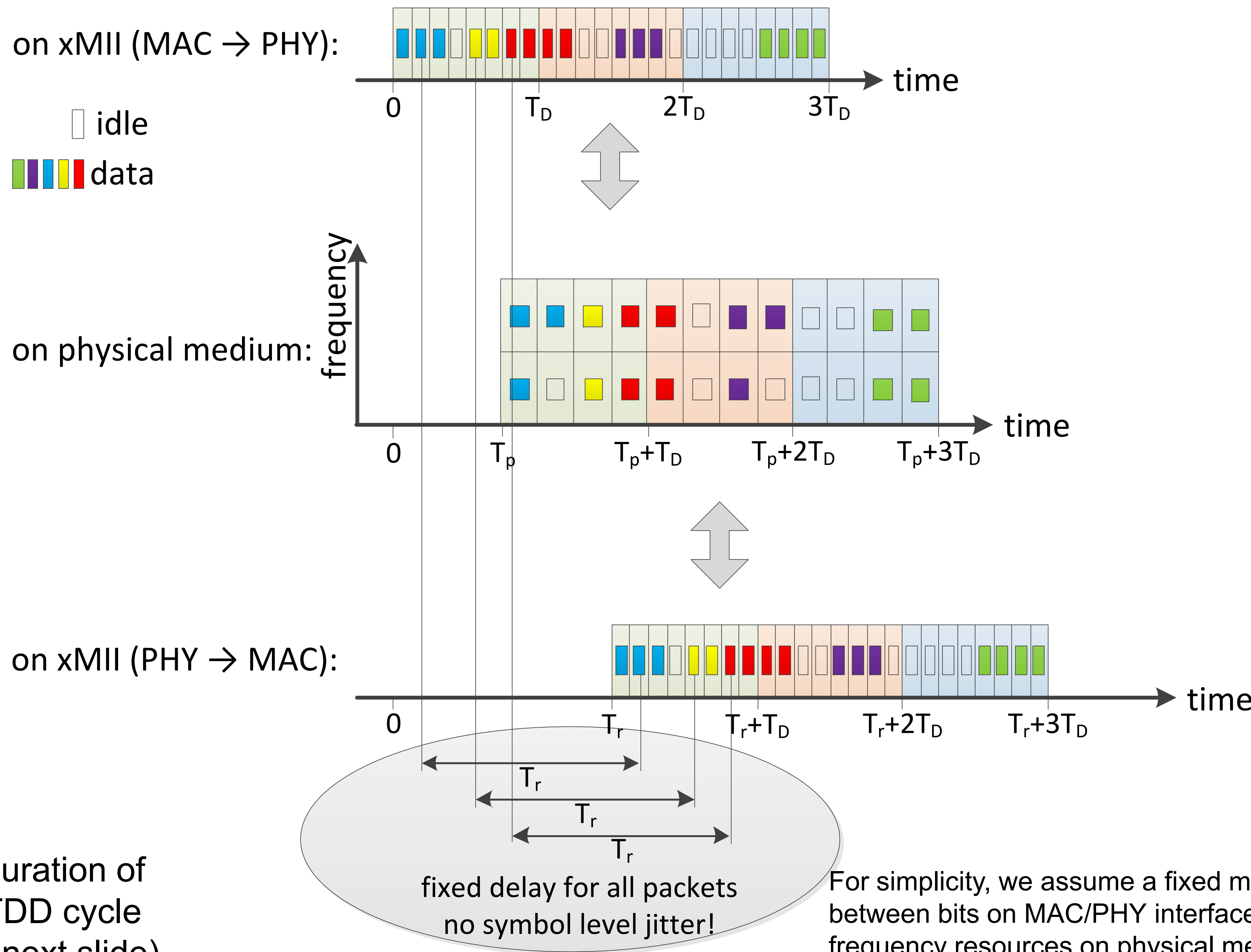


DS/US period = 2T → Max increase in latency: 2T/2 = T ms

DS/US period = T → Max increase in latency: T/2 ms

- The US/DS configuration period can be chosen to fit a particular delay requirement
  - Longer US/DS configuration periods entail lower switch time overhead but higher increase in latency (and vice versa)

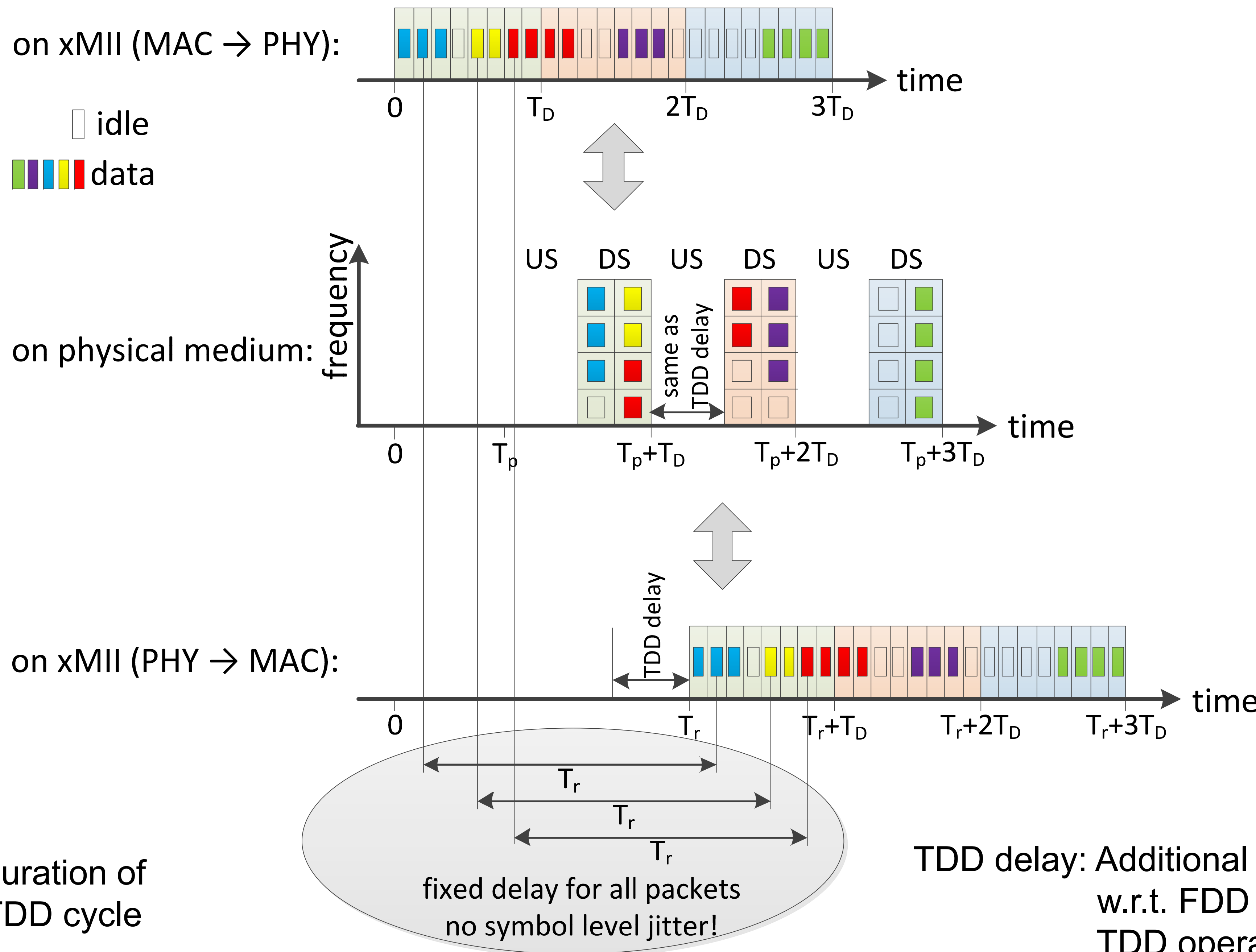
FDD – **Fixed Delay** (Reference, Downstream)



T_D: duration of TDD cycle (see next slide)

For simplicity, we assume a fixed mapping between bits on MAC/PHY interface and time frequency resources on physical medium

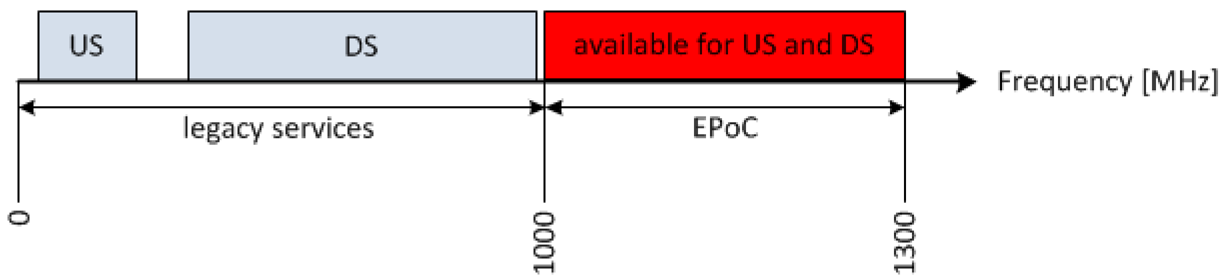
TDD – **Still Fixed Delay** (Downstream)



T_D: duration of TDD cycle

TDD delay: Additional delay w.r.t. FDD due to TDD operation

Assumptions for Spectrum Usage



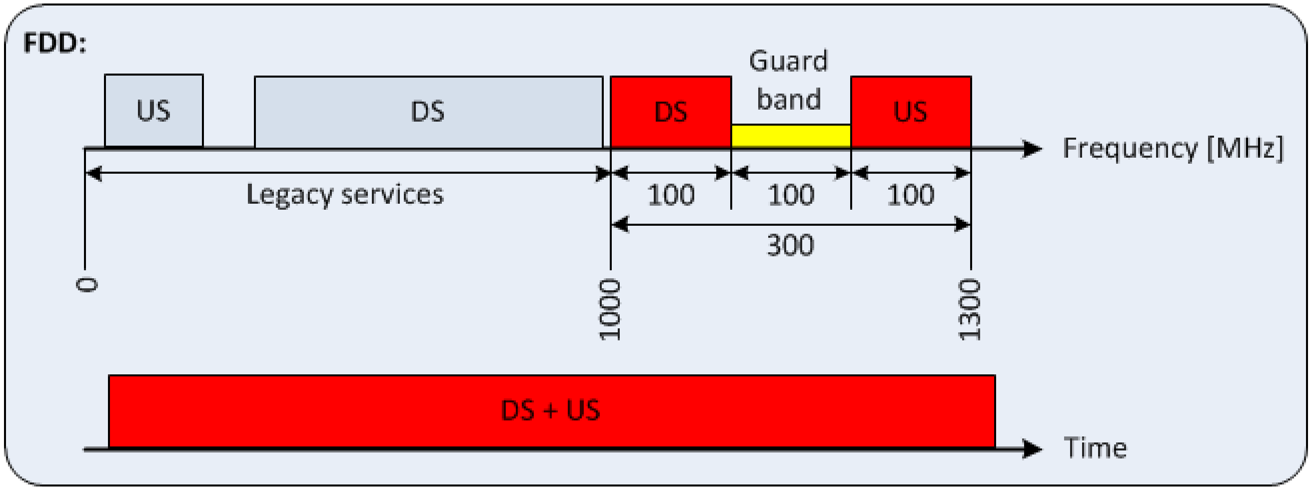
Example:
- Carrier frequency: 1.15 GHz
- Bandwidth: 300 MHz

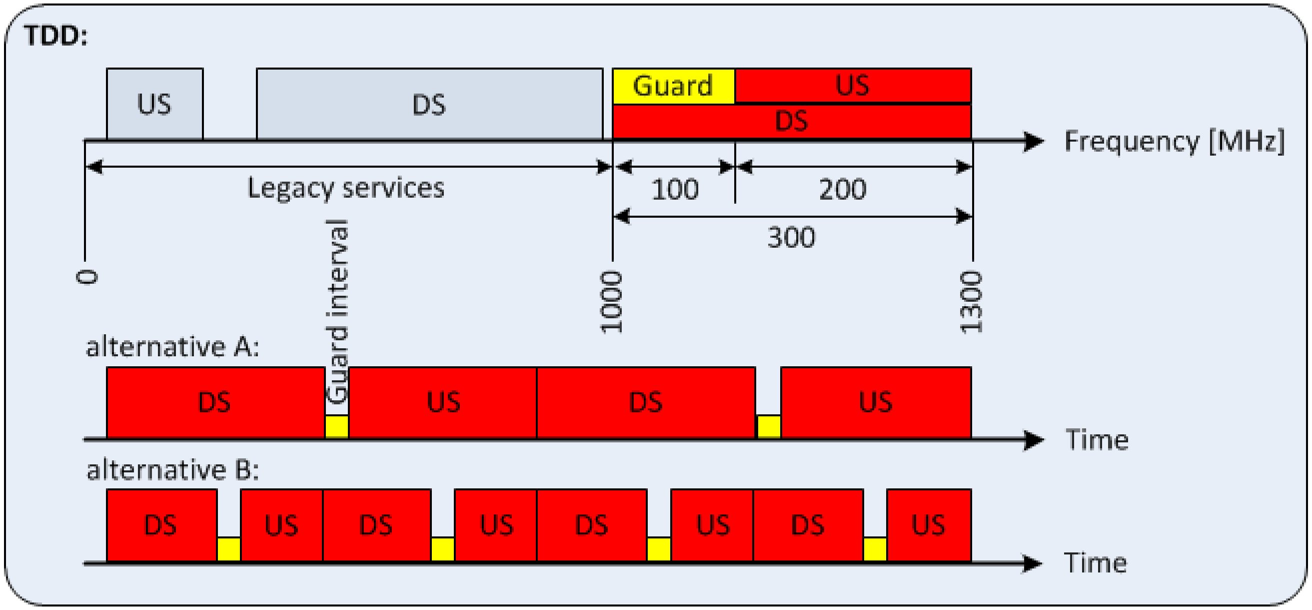
- Legacy services (e.g. below 1 GHz):
  - Upstream (US) in low frequencies (e.g. 5 MHz – 65 MHz)
  - Downstream (DS) in high frequencies (e.g. 85 MHz – 1 GHz)
- Spectrum for EPoC available above currently used spectrum
  - e.g. 1 GHz – 1.3 GHz
    - Used for US and DS transmissions
      - FDD or TDD, both are viable options
  - Must not cause harmful interference to legacy services:
    - EPoC spectrum is well separated from legacy US spectrum:
      - No interference to legacy US expected
    - EPoC spectrum is close to legacy DS spectrum
      - Interference of EPoC signal to legacy DS must be minimized by design

FDD/TDD Spectrum Usage (Example: 300 MHz spectrum above 1 GHz)

Basic assumptions:

- FDD:
  - Guard band between DS and US spectrum (here: 100MHz / 1.15GHz = 8.7%)
  - Concurrent DS and US transmissions
  - US spectrum above DS spectrum to avoid the need of another guard band
- TDD:
  - Guard band only needed for US transmission; FDD US and TDD US require the same BW for the guard band
  - Guard intervals required when switching between DS and US transmissions
  - Tradeoff between overhead and latency (see alternatives A and B)





FDD / TDD Efficiency Ratios (Example: 300 MHz spectrum above 1 GHz)

- Efficiency Ratio α:
  - FDD:
    - 200 MHz out of 300 MHz are used
  - TDD: (β: loss due to guard time interval)
    - Guard interval every:
      - » TDD 1: DS/US period = 0.7 ms (short),
      - » TDD 2: DS/US period = 2 ms (long)
    - Guard time = 2*20 μs + 15 μs = 70 μs
      - » Hardware switching time: 15 μs
      - » Maximum propagation delay on cable (max 5.2 km of cable): 20 μs
    - US uses only 200 MHz out of 300 MHz
    - Assume equal time allocation to US and DS

α_{FDD} = 200 MHz / 300 MHz = 0.667 = 66.7%

β_1 = (0.7 ms – 70 μs) / 0.7 ms = 0.9

β_2 = (2 ms – 70 μs) / 2 ms = 0.965

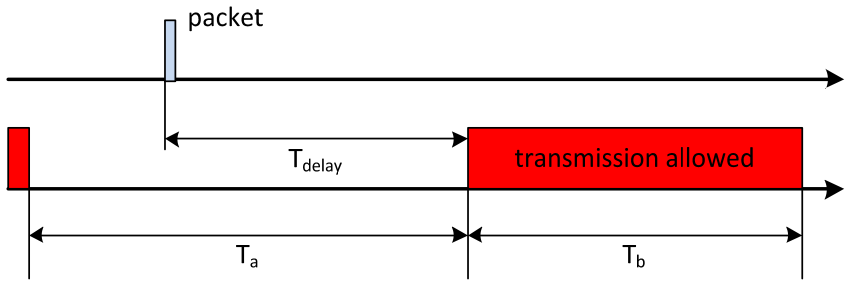
$\alpha_{TDD\ 1} = \beta_1 (1 + 200 / 300)/2$ = 0.75 = 75%

$\alpha_{TDD\ 2} = \beta_2 (1 + 200 / MHz)/2$ = 0.804 = 80.4%

Efficiency ratio higher for TDD than for FDD

Delay and Jitter Calculations

- Latency increase for TDD vs. FDD
  - Delay increase: T_a
    - TDD 1: Increase in latency: 0.42 ms
    - TDD 2: Increase in latency: 1.07 ms



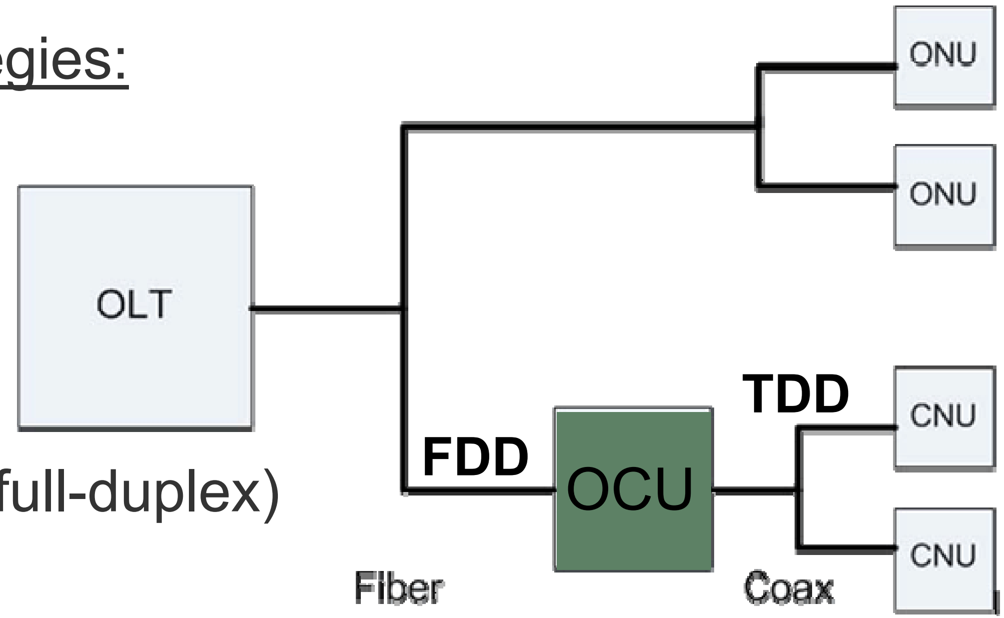
- No increase of jitter (all packets will have maximal delay)

Latency increase for TDD can be bounded by proper selection of system parameters

Repeater in TDD Mode

<u>OCU transposes two duplexing strategies:</u>

- FDD Full-Duplex on the fiber side
- TDD Half-Duplex on the coax side
  - while retaining the flexibility of TDD



- FDD channels are always available (full-duplex)
  - available to some CNU (not any CNU)
    - » each CNU still needs to wait for its turn
- TDD channels are not always available (half-duplex)
  - async traffic needs to wait for upstream or downstream phase
    - » 1/8th TDD Cycle on average at PHY
    - » ½ TDD Cycle worst-case at PHY
  - but this delay is mitigated
    - » TDD dispatches pending traffic twice as quickly as FDD

Repeater in TDD Mode

- FDD channels are always available (full-duplex)
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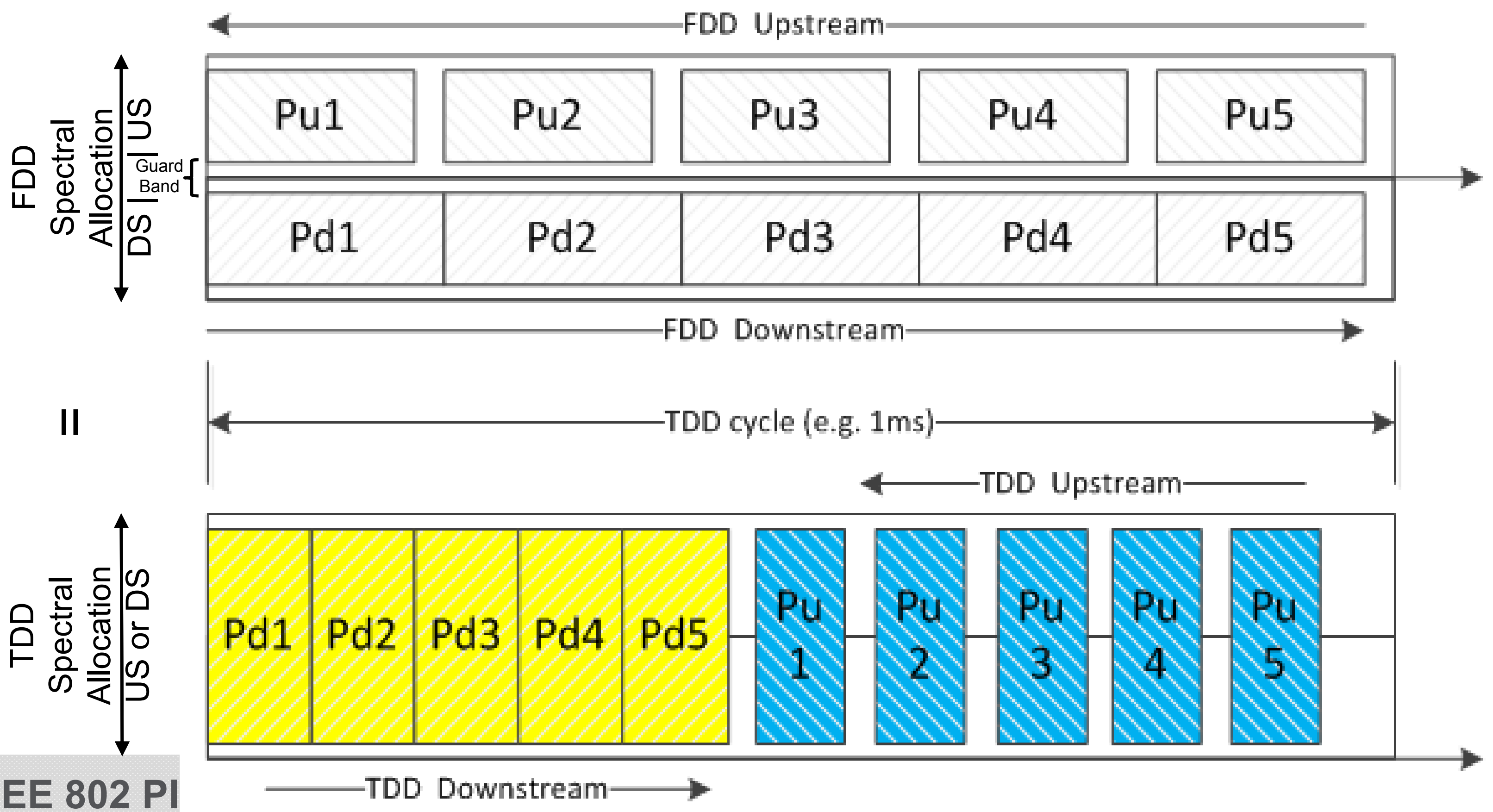

MEF 23.1

MEF CoS Parameter Objectives (CPOs)

(PT1, e.g., Metro)

Description (MEF Example Suggested Applications)	MEF CoS	CIR-only	MFD (ms)	FDR (ms)	FLR (ratio)	FD (ms)	IFDV (ms)
			MEF CPOs (PT1)				
Sync, Voice, Near-RT	H	FALSE	7	5	1.E-04	10	3
Control/Signaling, Data	M	FALSE	13	10	1.E-04	20	8
Data, Background	L	FALSE	28	16	1.E-03	37	14

- Where:
  - FD: Frame Delay, the maximum latency end-to-end;
  - MFD: Mean Frame Delay;
  - FDR: Frame Delay Range (between the min to max at 95% percentile);
  - IFDV: Inter-frame Delay Variation (related to FDR but not identical)
  - FLR: Frame Loss Rate.
- MEF has mathematical definitions for all these terms
- MEF lists requirements per considered applications
  - e.g., delay & throughput