Passive Optical Networks in Particle Physics Experiments

24th November, PH-ESE Seminar

Work conducted by PH-ESE-BE-OPTO Team Members

Outline

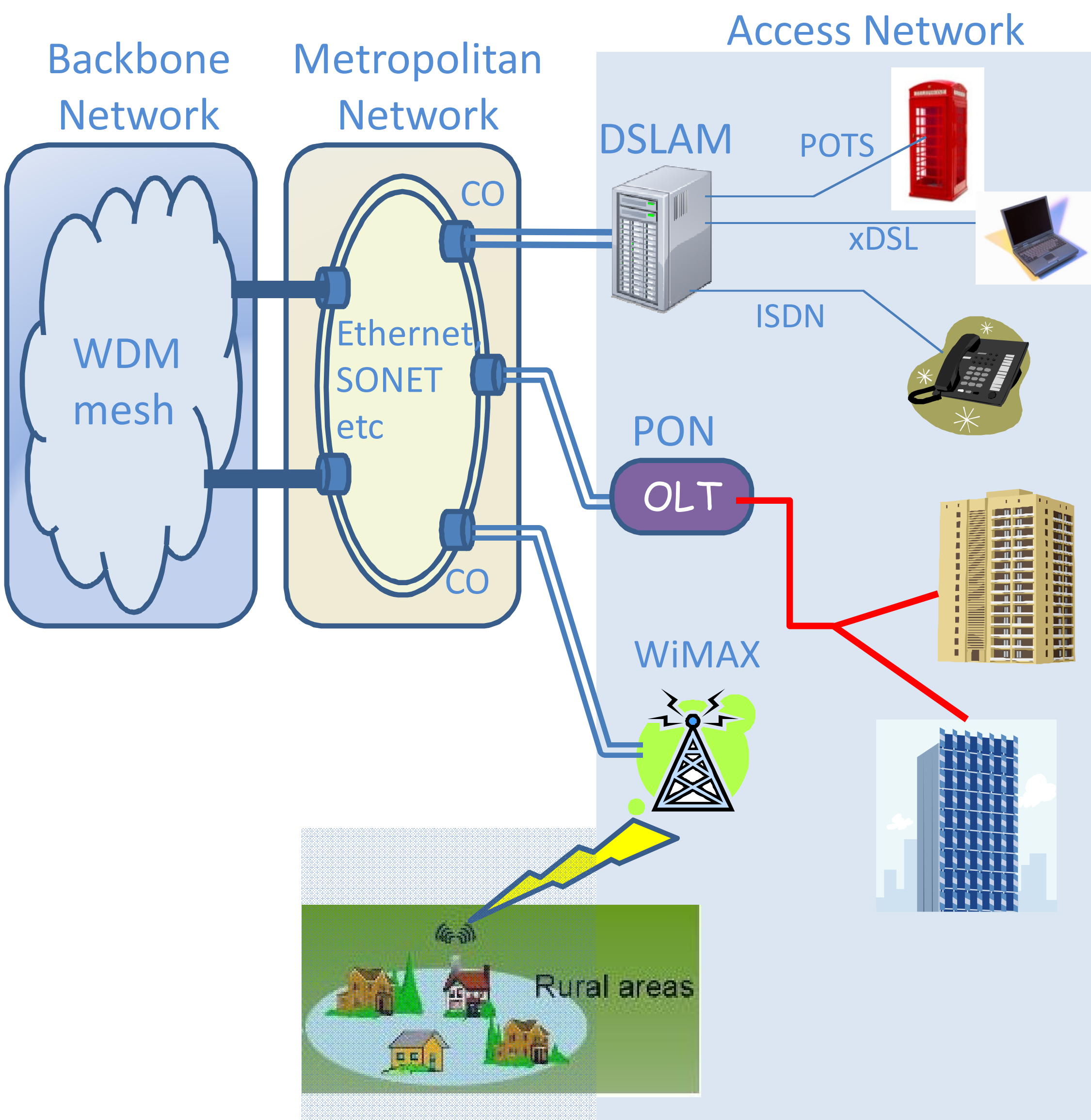
- Commercial PON technologies
- PONs in Timing Systems for HEP
- Future PONs and their implications in Timing Systems

Commercial PON technologies

- PON definition
- Motivation for current work
- PON Protocols
- PON Transceivers
- Optical Components

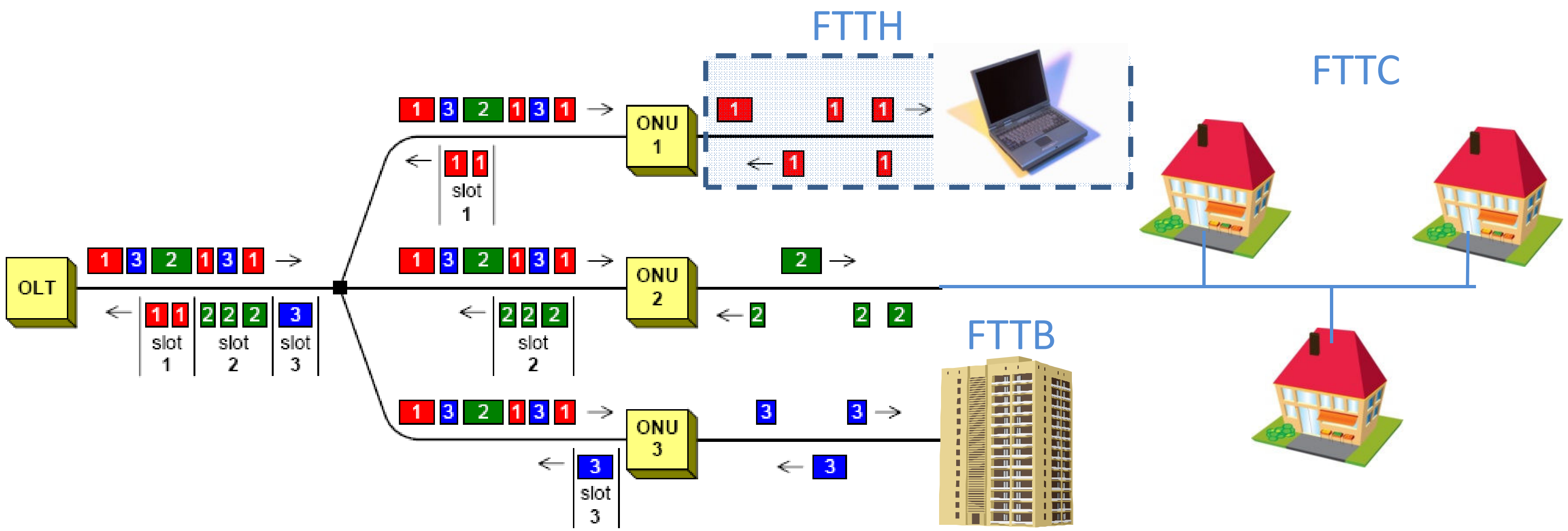
PONs in Access Networks

- Access Networks are the last segment connection from COs (central offices) to customers
- They are also called first-last mile networks
- Examples of access networks are:
  - ISDN
  - xDSL
  - WiMAX
  - and most recently PONs…



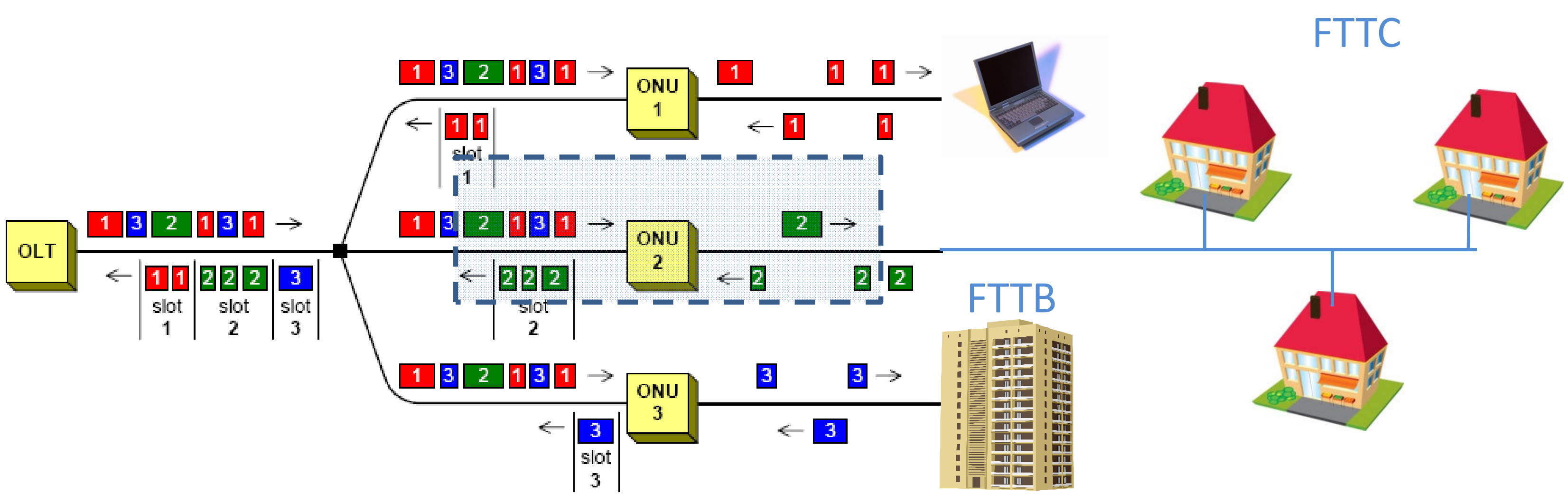
What is a PON?

- PON is a Point-to-MultiPoint (PMP) optical network with no active elements in the signal's path from the source to the destination
- Data are exchanged between a central node, the Optical Line Terminal (OLT), and a number of end terminals, the Optical Network Units (ONUs)
- A long feeder fiber delivers the data close to the ONUs before signal is split by means of an optical splitter and secondary fibers
- According to where ONUs are placed we have different PON versions namely FTTH, FFTC, FFTB etc



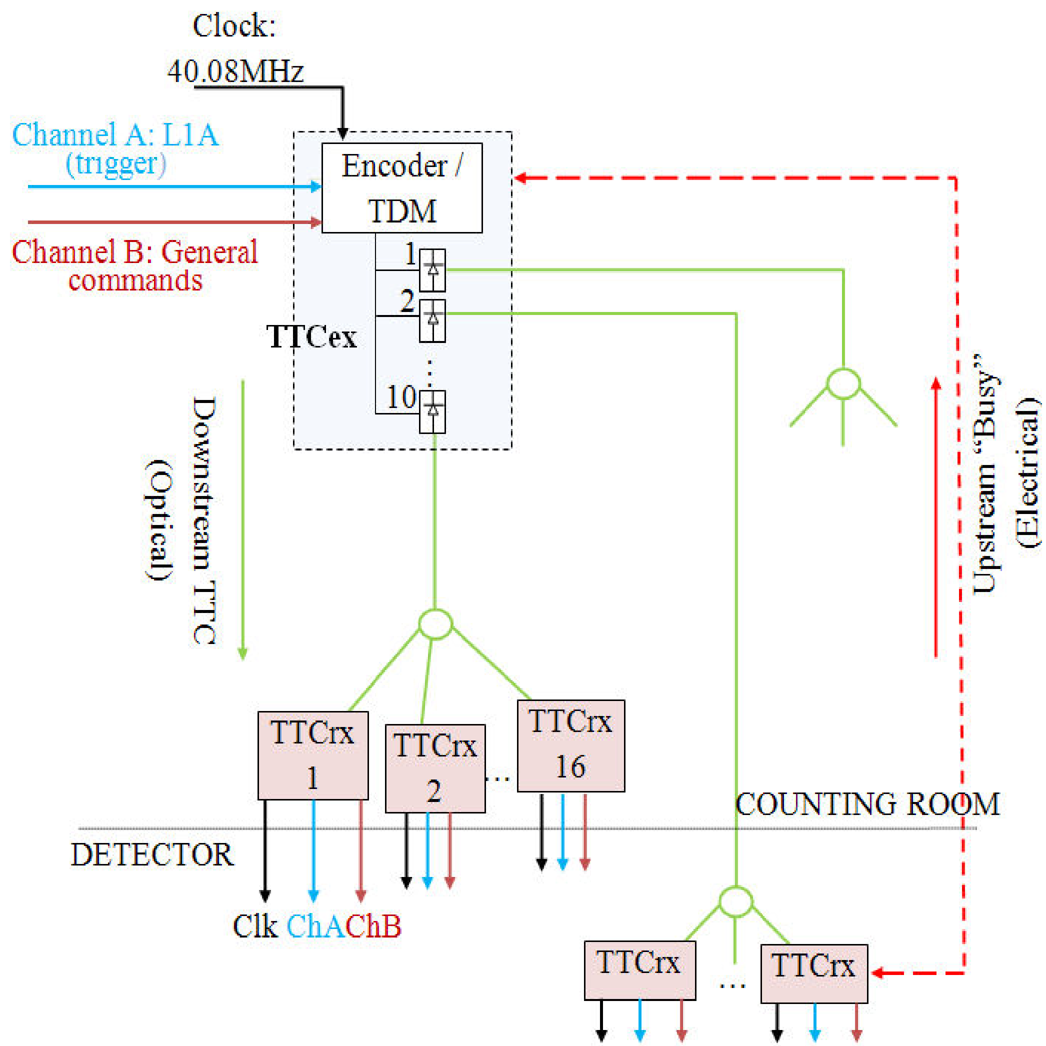
General PON Considerations

- In the downstream direction (OLT→ONUs) PON is a broadcast network
- ONUs are filtering out data not addressed to them
- In the upstream direction (ONUs→OLT) however a number of customers share the same transmission medium and some channel arbitration mechanism should exist to avoid collisions and to distribute bandwidth fairly among ONUs
- TDM is the preferred multiplexing scheme in first generation PONs as it is very cost effective. Dynamic Bandwidth Allocation Algorithms are employed for fairness. All intelingence is built in the OLTs
- Upstream transmission is of burst mode type



Motivation

- There are currently P2P and P2MP optical links in LHC
- P2P links are used in DAQ due to high bandwidth demands
- P2MP links are used to transmit timing information
- Current TTC system is unidirectional (optically)
- A slow electrical feedback is used to communicate the status of the subdetectors back to the TCS
- It would be beneficial to replace this electrical link with a higher bit rate, "real" time optical link



System Requirements

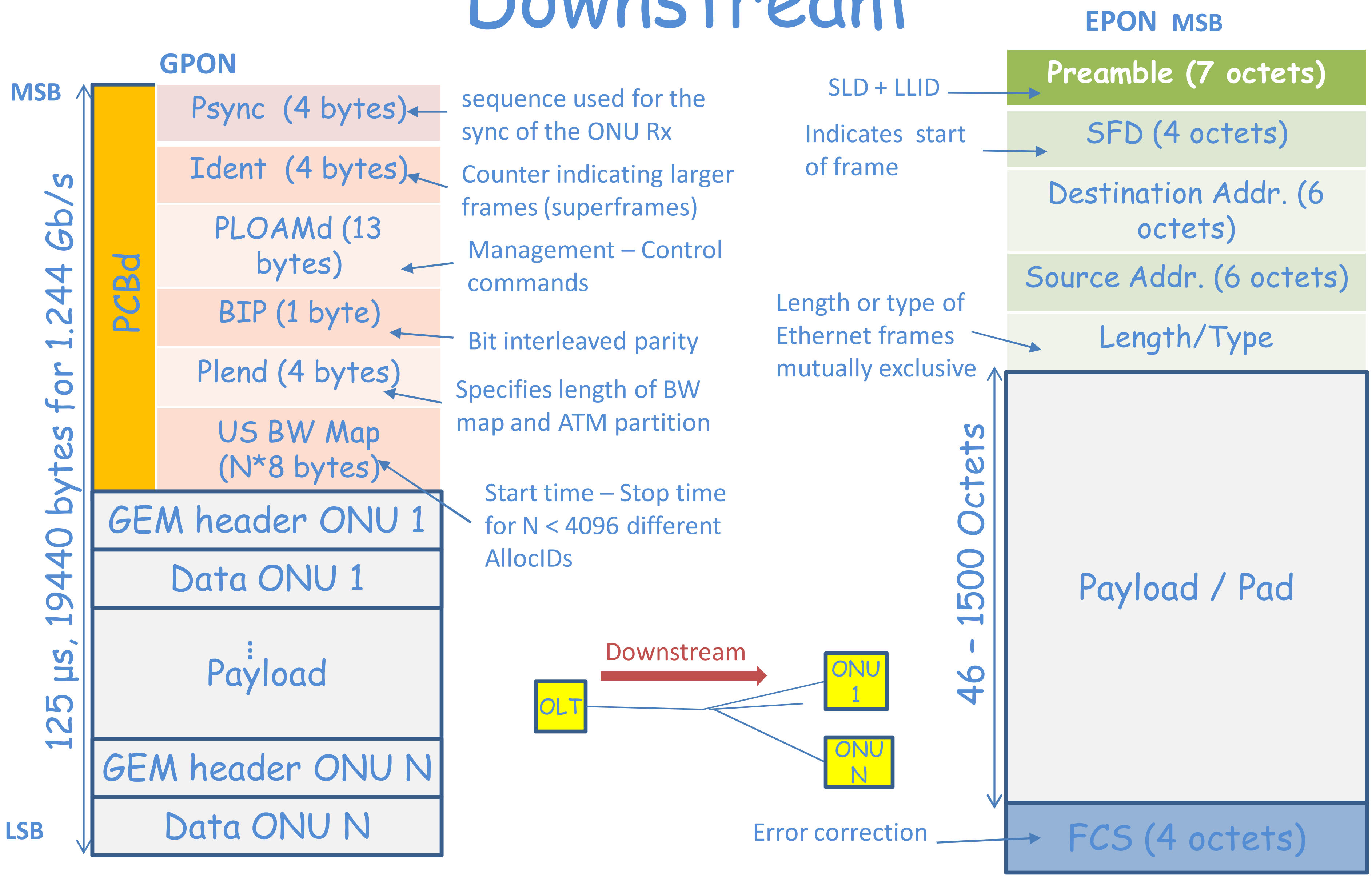
- System has to be able to deliver **synchronous** triggers and commands continuously
- **Latency has to be fixed** at both transmitting and receiving ends
- Recovered clocks have to be of **low jitter**
- System must provide with the flexibility of both individually addressing or broadcasting to slave nodes
- Slaves have to be able to respond in short time

TDMA PON Protocols

- Ethernet PON (E-PON) established by IEEE. Work started in 2001, completed in 2005. IEEE 802.3-2005
- Supports Ethernet frames
- Giga-bit PON (GPON) established by ITU. Work started in 2001 completed in 2004. ITU G.984
- Supports mixed ATM and Ethernet frames through generic encapsulation method (ITU G.7041)
- >95% of LAN data are of Ethernet type but the battle is still on…

Standard	EPON	GPON
Framing	Ethernet	GEM
Max. BW	1 Gb/s	2.48 Gb/s
Splitting ratio	16	64
Avg. BW / user	60 Mb/s	40 Mb/s
Max. Reach	20 km	20 km

GPON and EPON Frames Downstream

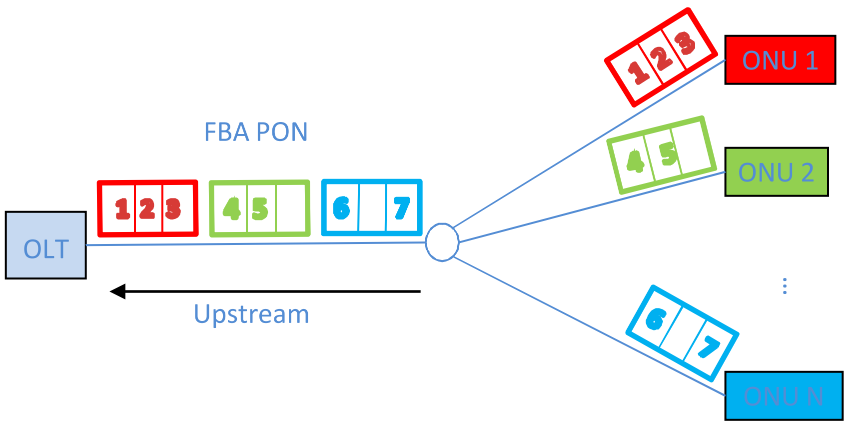


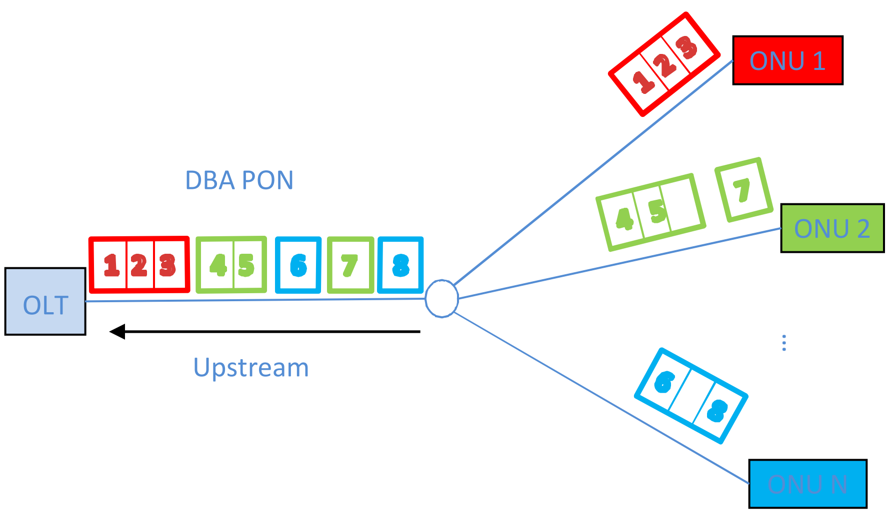
Bandwidth Allocation Schemes

- BW allocation schemes are not part of protocols
- However, both EPONs and GPONs provide with the necessary information for any allocation algorithm to be implemented
- Two main bw allocation schemes:

A. Fixed/Static Bandwidth Allocation (FBA)

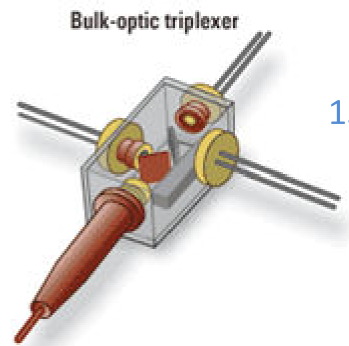
B. Dynamic Bandwidth Allocation (DBA)

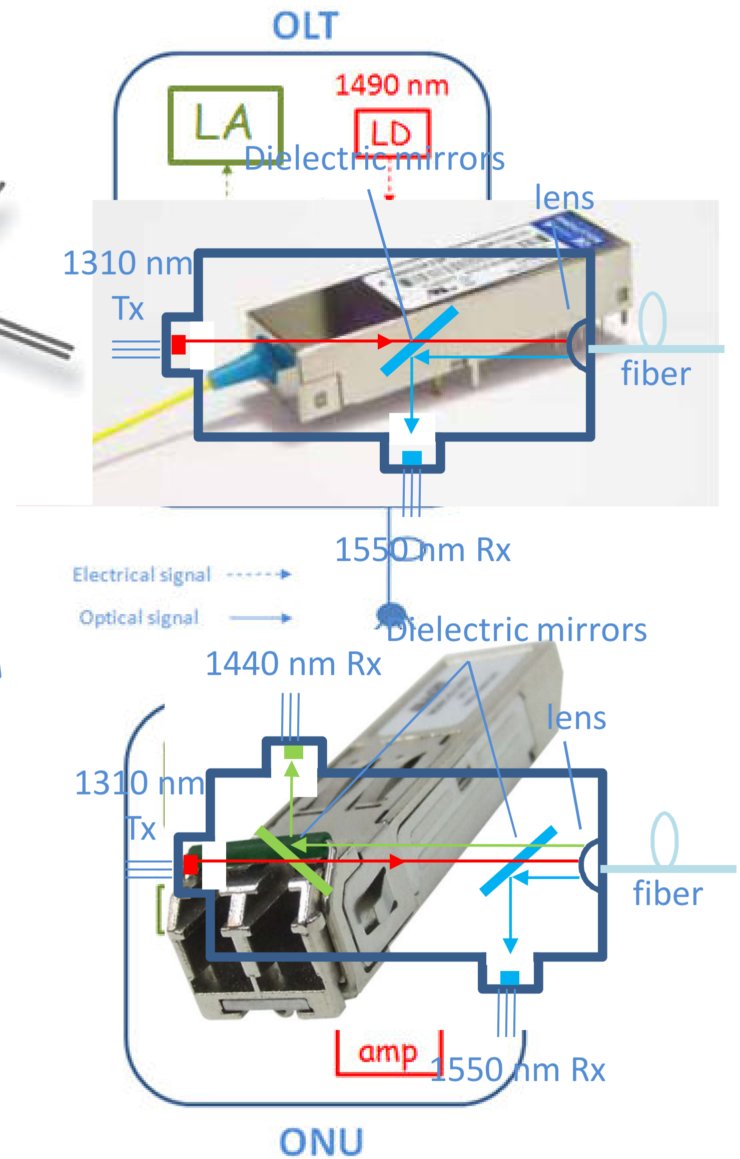




PON Transceivers

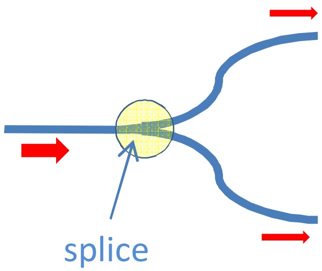
- Burst mode laser drivers at Slave (ONU)
- FP lasers and PIN diodes for efficiency
- Burst mode RXs at OLTs
- APDs for high sensitivity and DFB lasers
- WDM filters for upstream-downstream multiplexing into one fiber
- Bulk-Optic subassembly packaging method
- Cost: ~900$/OLT cost ONU ~90$/ONU. Gigabit Ethernet TRXs $100 SM

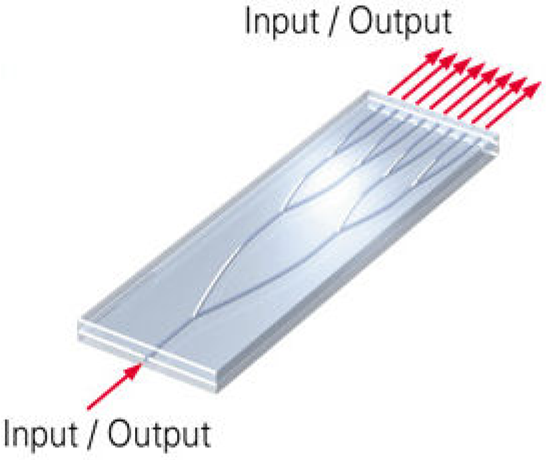




Optical Components: Splitter

- Two types of splitters are found
1) Traditional bi-conic fused silica splitter
2) Photonic Lightwave Circuit (PLC) splitter
- PLC has the advantage of smaller footprint
- Better alignment with in/out coupled fibers
- Uniform splitting ratio
- Better scalability
- Temperature stability





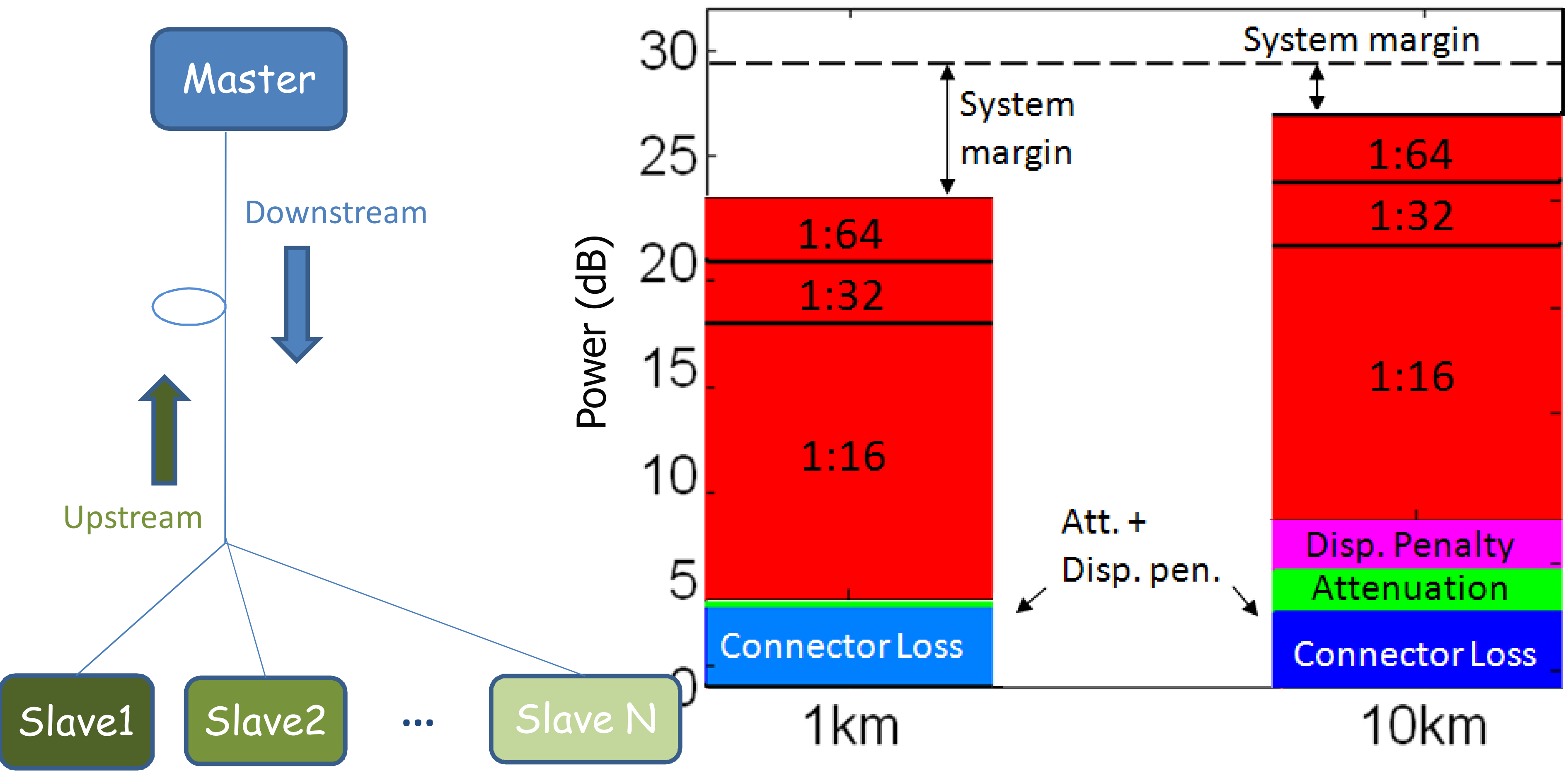
PON Demonstrator for TTC Applications

- PON system specifications
- Protocol in the Upstream/Downstream
- Transceiver Design on Virtex 5 FPGA

System Specifications

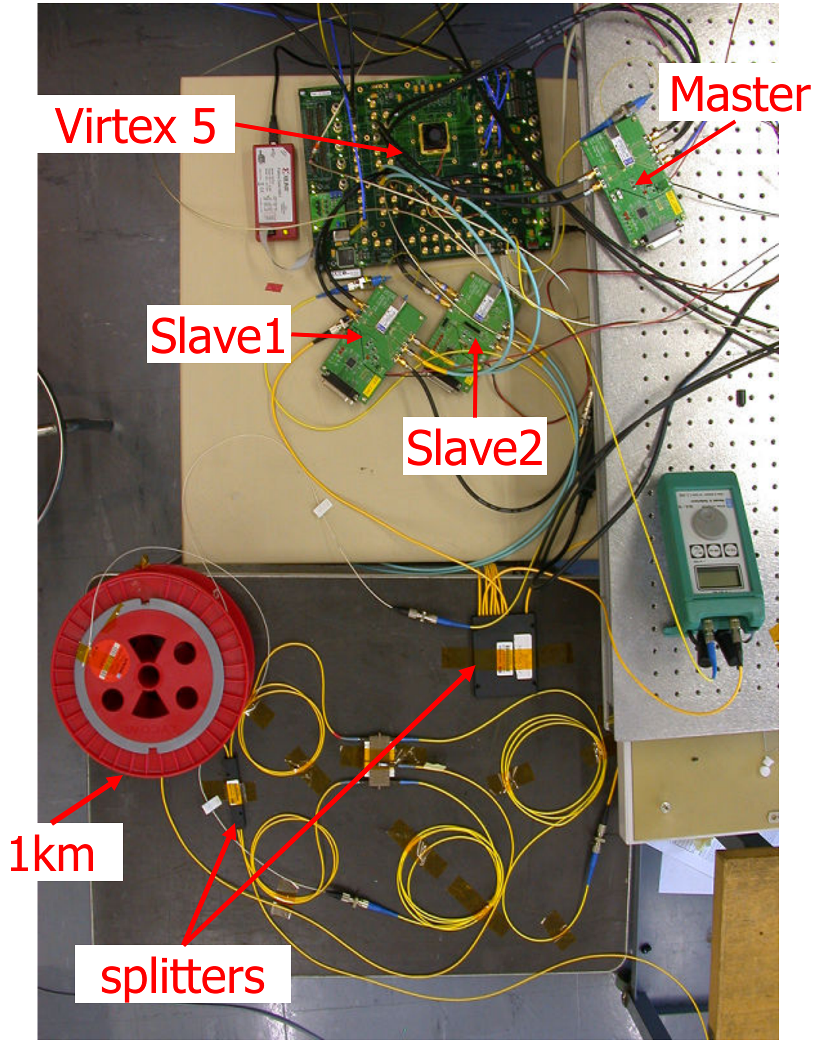
Property (General)	PON Demonstrator
Clock rate	40 MHz (ie LHC clock rate 40.08MHz)
Max distance	Up to 1000m
Encoding | Target BER	NRZ 8b/10b | $<10^{-12}$
Splitting ratio	1:64
Frame Format	Commands + Trigger
BW Allocation Algorithm	Fixed BW
Property (Down|Up)	**PON Demonstrator**
Bit rate	1.6 Gb/s | 800 Mb/s
Latency	Fixed and Deterministic| To be determined
Received clock jitter	Able to drive a high-speed SERDES

System Power Budget



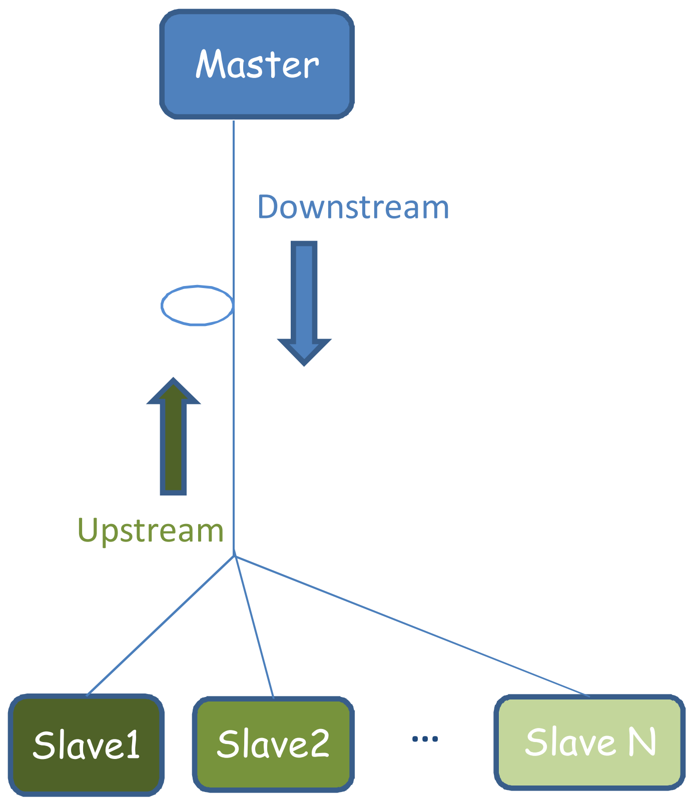
PON Demonstrator

- Our system is designed to support 64 slave nodes
- Only 2 slave nodes are used in the first demonstration due to one FPGA platform and number of evaluation board available
- However, all features of a PON can be demonstrated with this system
- Both master and slaves are implemented on the same Virtex 5 platform
- Both physical layer and medium access algorithm have been implemented



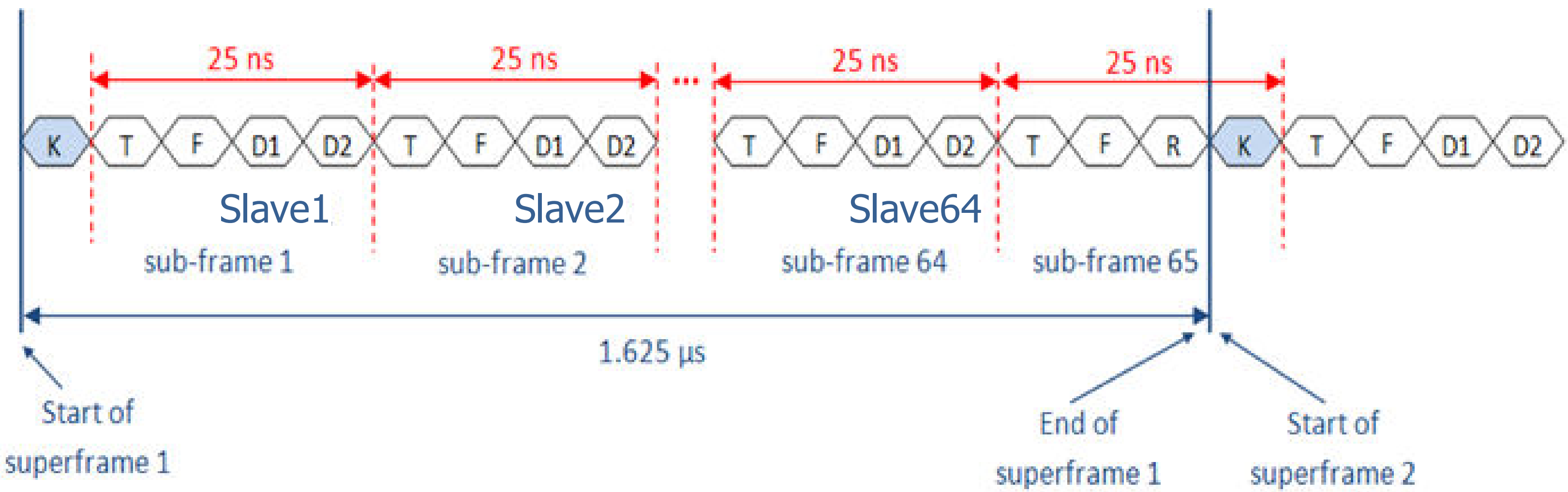
PON Demonstrator for TTC Applications

- Protocol in the Downstream/Upstream



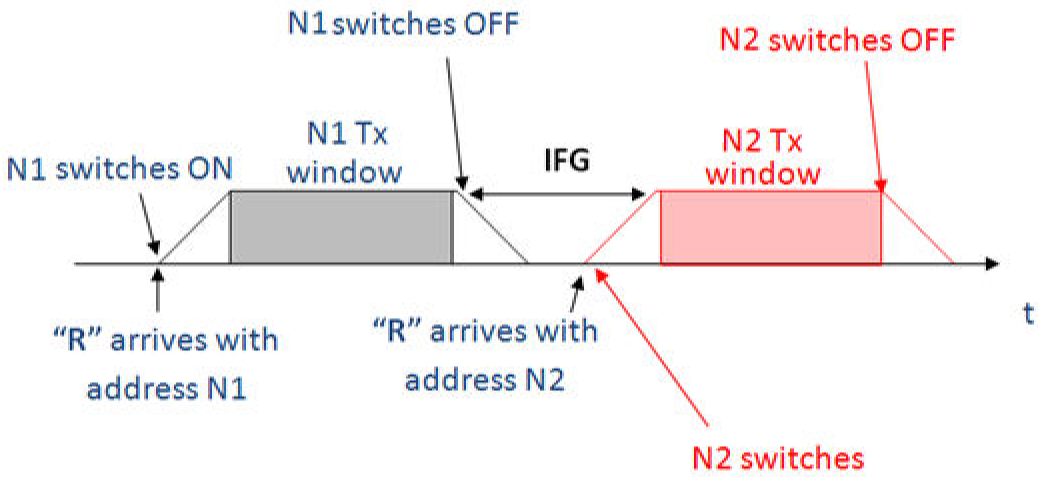
Downstream Frame

- Synchronous transmission of super-frames with a period of 1625ns = 65*25ns at 1.6Gbit/s
- Comma, “K”, character for frame alignment and for sync
- T character carries trigger info. “F” for trigger protection or other functions
- D1 and D2 carry broadcast or individually addressed information depending on the first bit of the D1 byte.
- “R” field contains the address of the next ONU to transmit
- 590.8 Mb/s are available for data downstream

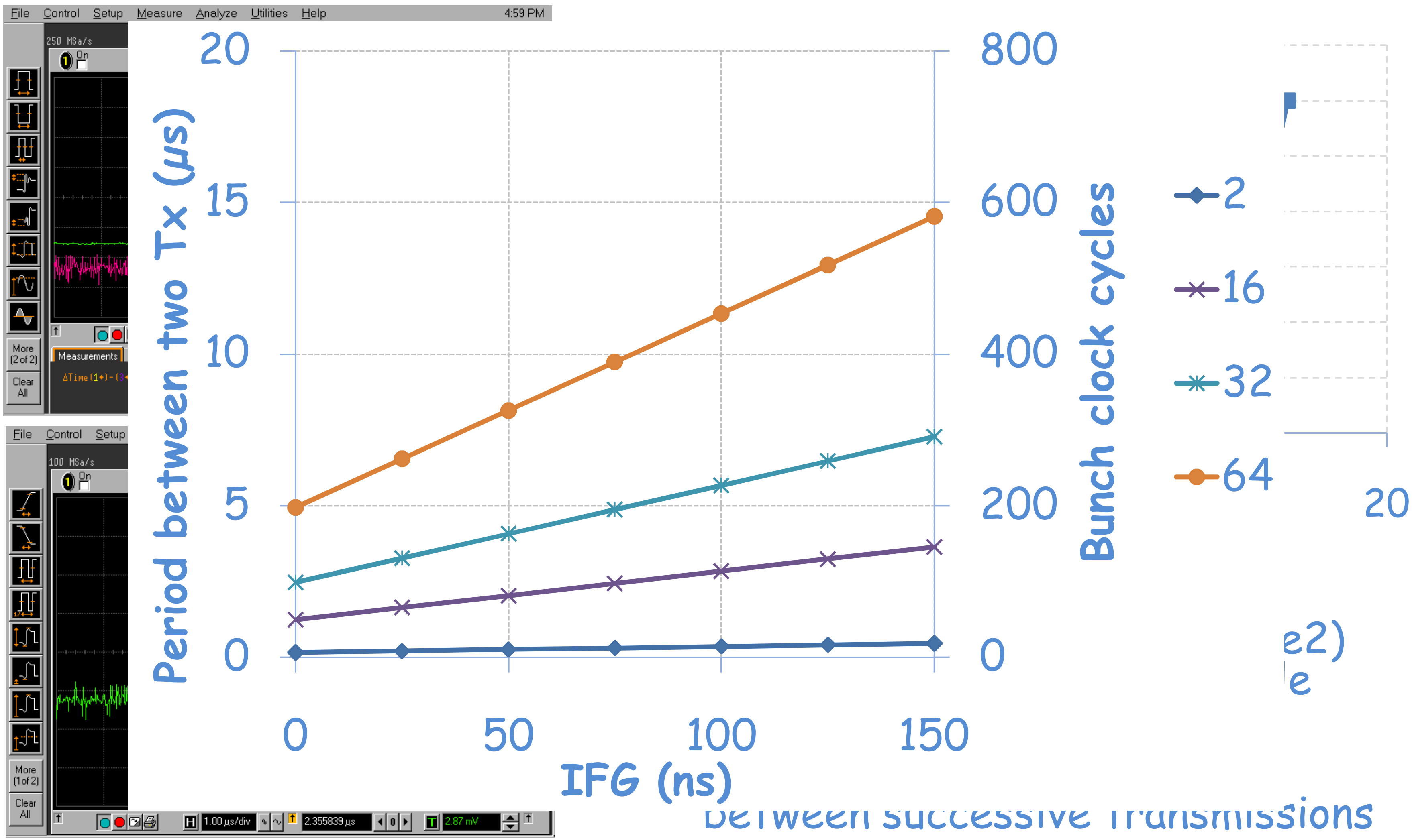


Upstream Frame

- Slave N1 receives an R character with its address and switches its laser ON
- IFG between successive emissions allows to master receiver to adapt to different bursts
- Channel arbitration is a logic built-in at the OLT
- Total BW 800Mb/s, 7.7 Mb/s are available per Slave node for pure data



Upstream frame (2)



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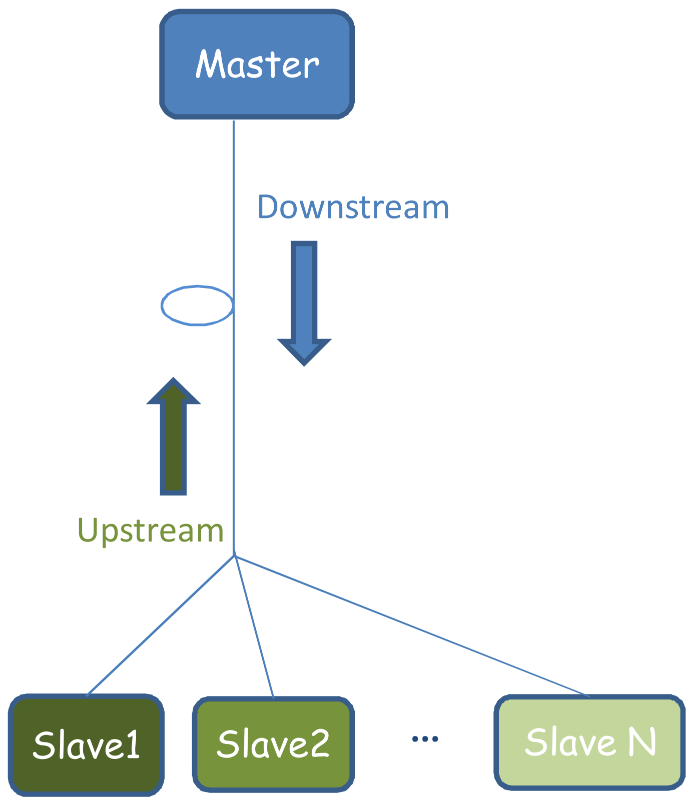
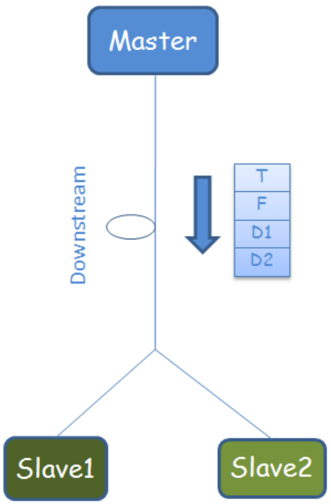
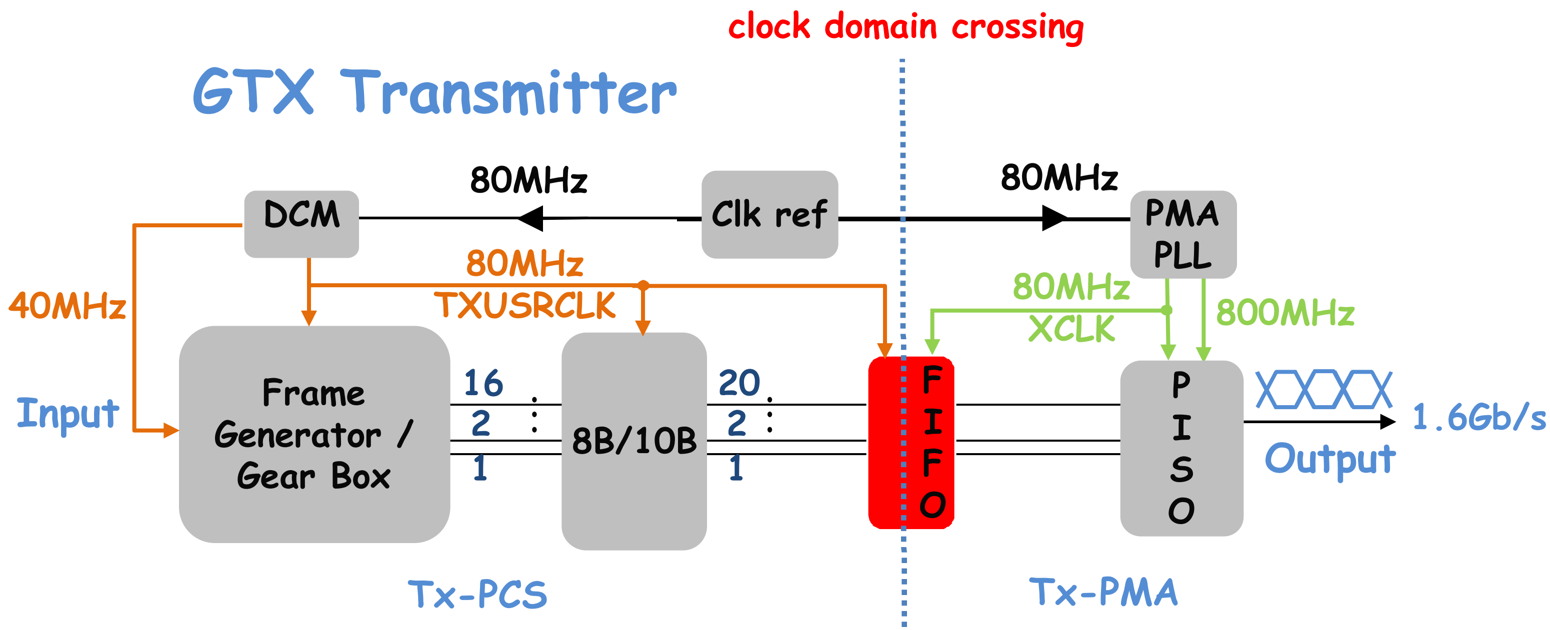
PON Demonstrator for TTC Applications

- Master/Slave Transceiver Design on FPGA



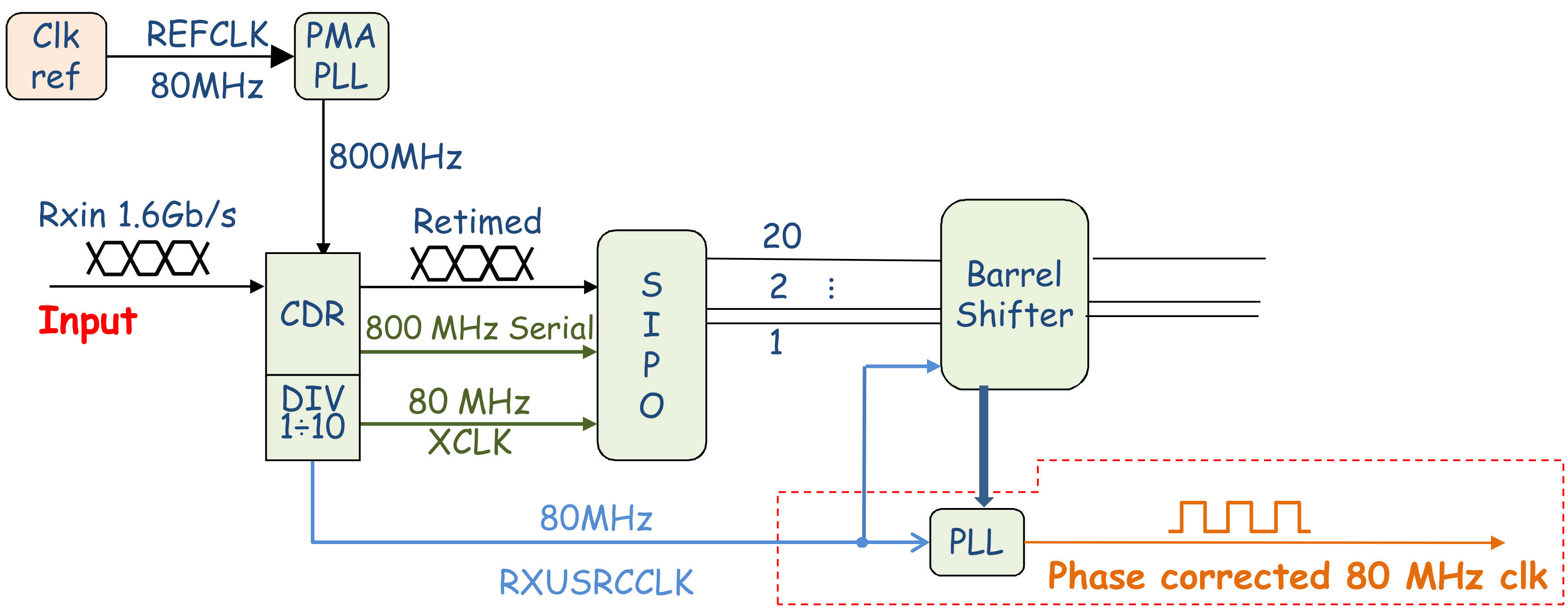
Master Transmitter

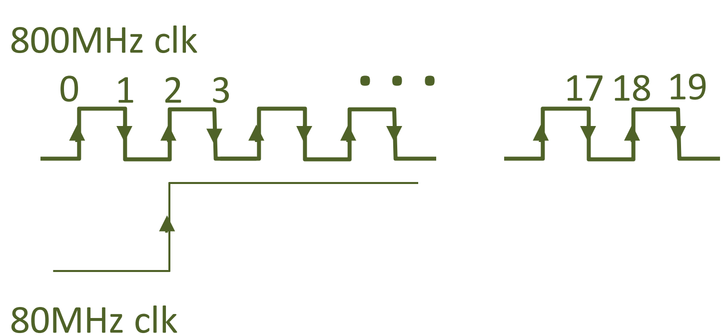




- Latency issues at the Tx arise at clock domain crossing points
- It is particularly important to bypass any elastic buffers in the data path
- In GTX Tx this is achieved by advanced mode which forces PMA PLL to phase align XCLK and RXUSRCLK clocks

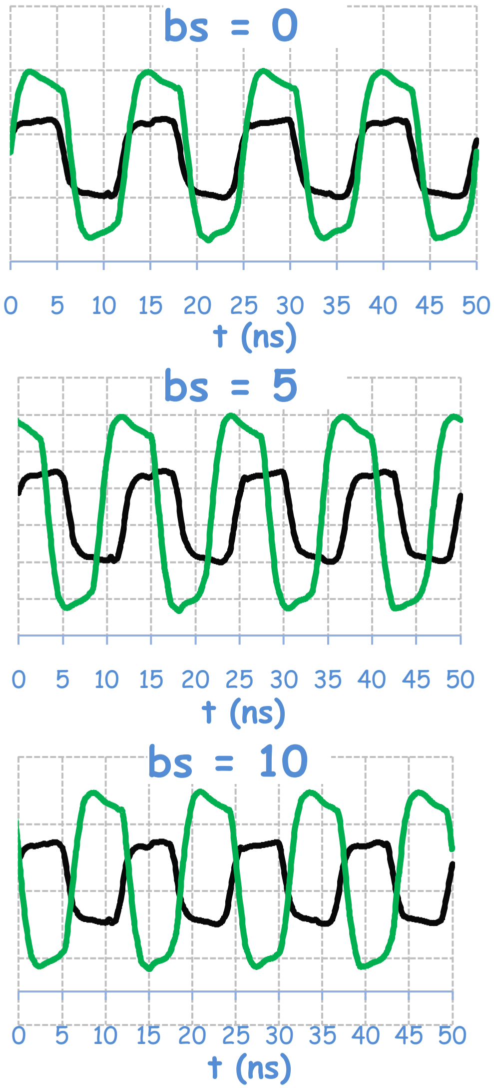
Slave Receiver

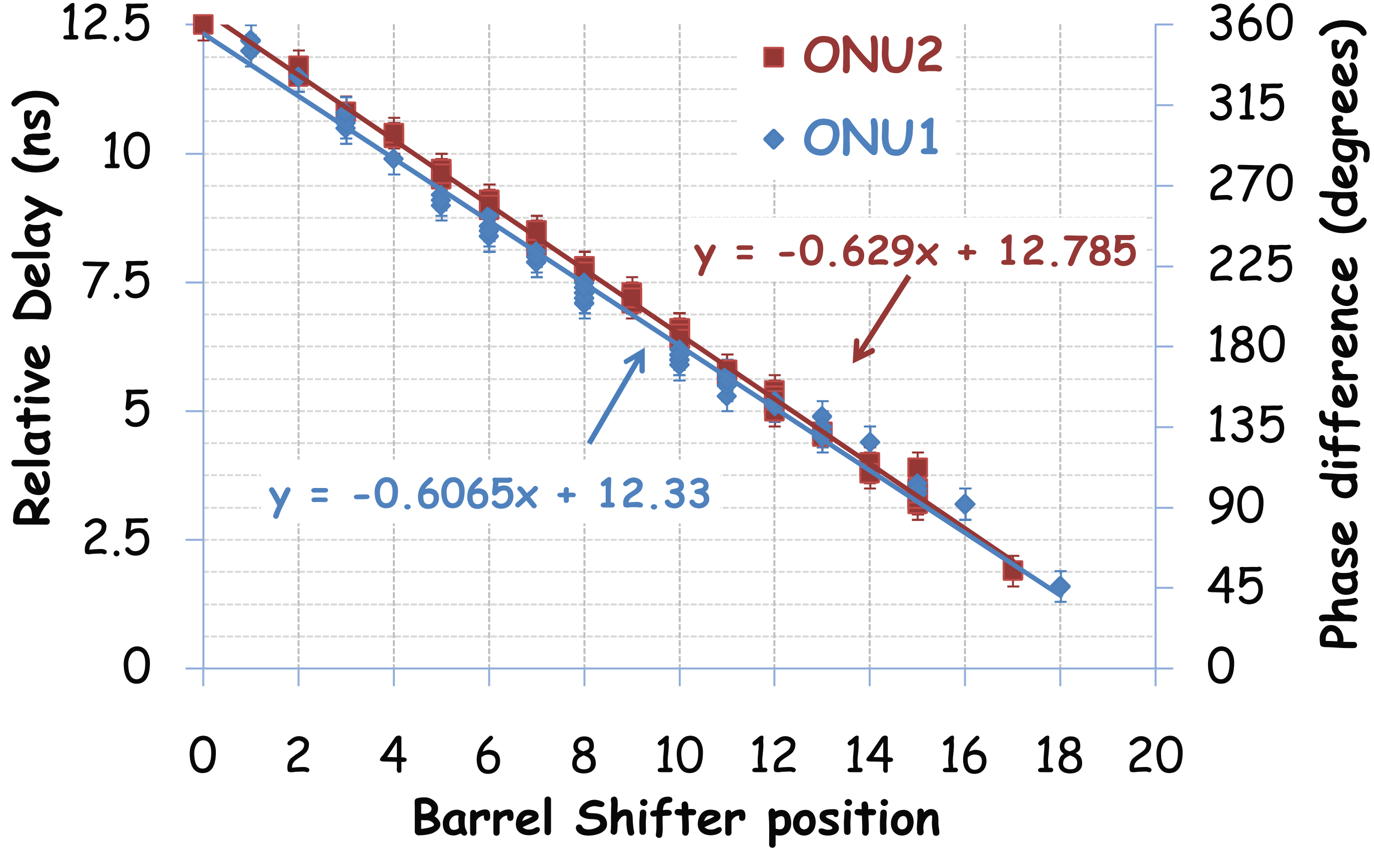




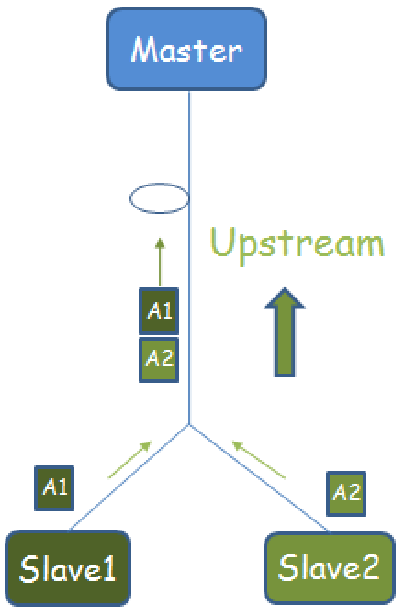
- 80 MHz parallel clk can lock on any of the 20 first edges of the 800 MHz serial clk
- That affects the order with which parallel data are exiting the SIPO
- By fitting "K" characters into the frame and identifying them in a Barrel shifter we can predict the starting point of the XCLK

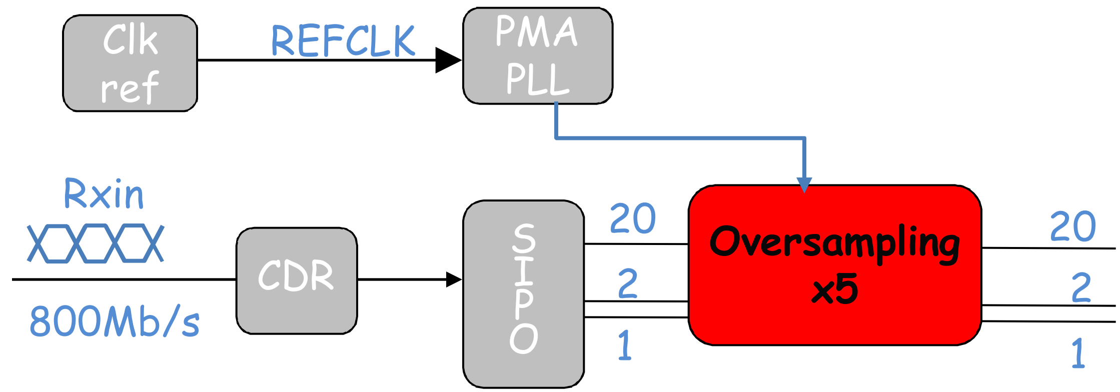
Slave Rx Latency, Barrel Shifter

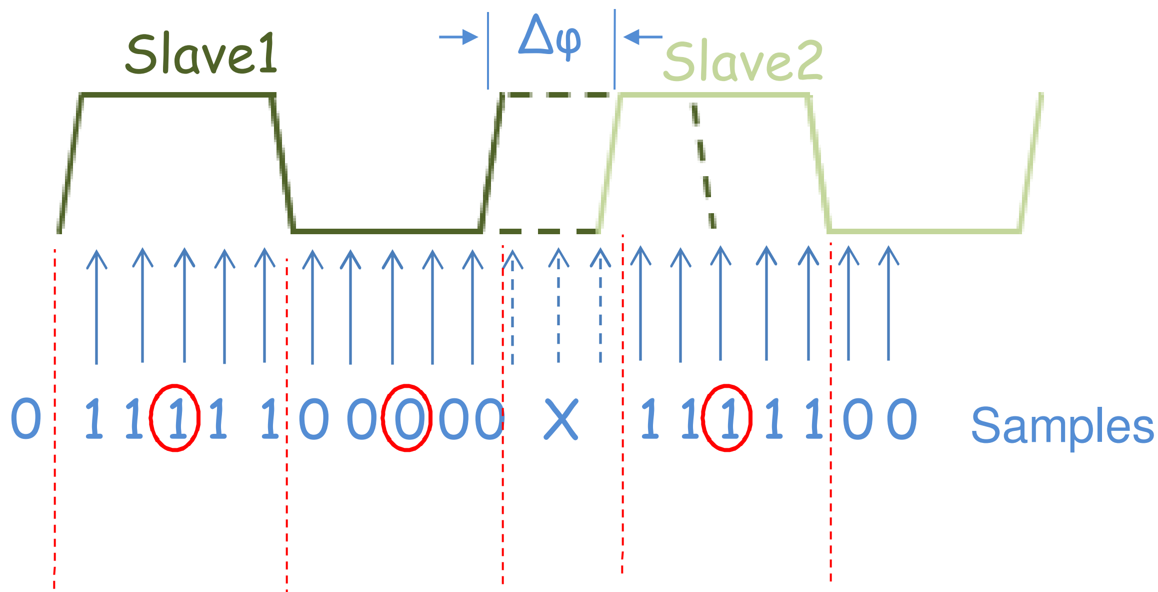




OLT Burst Mode Receiver





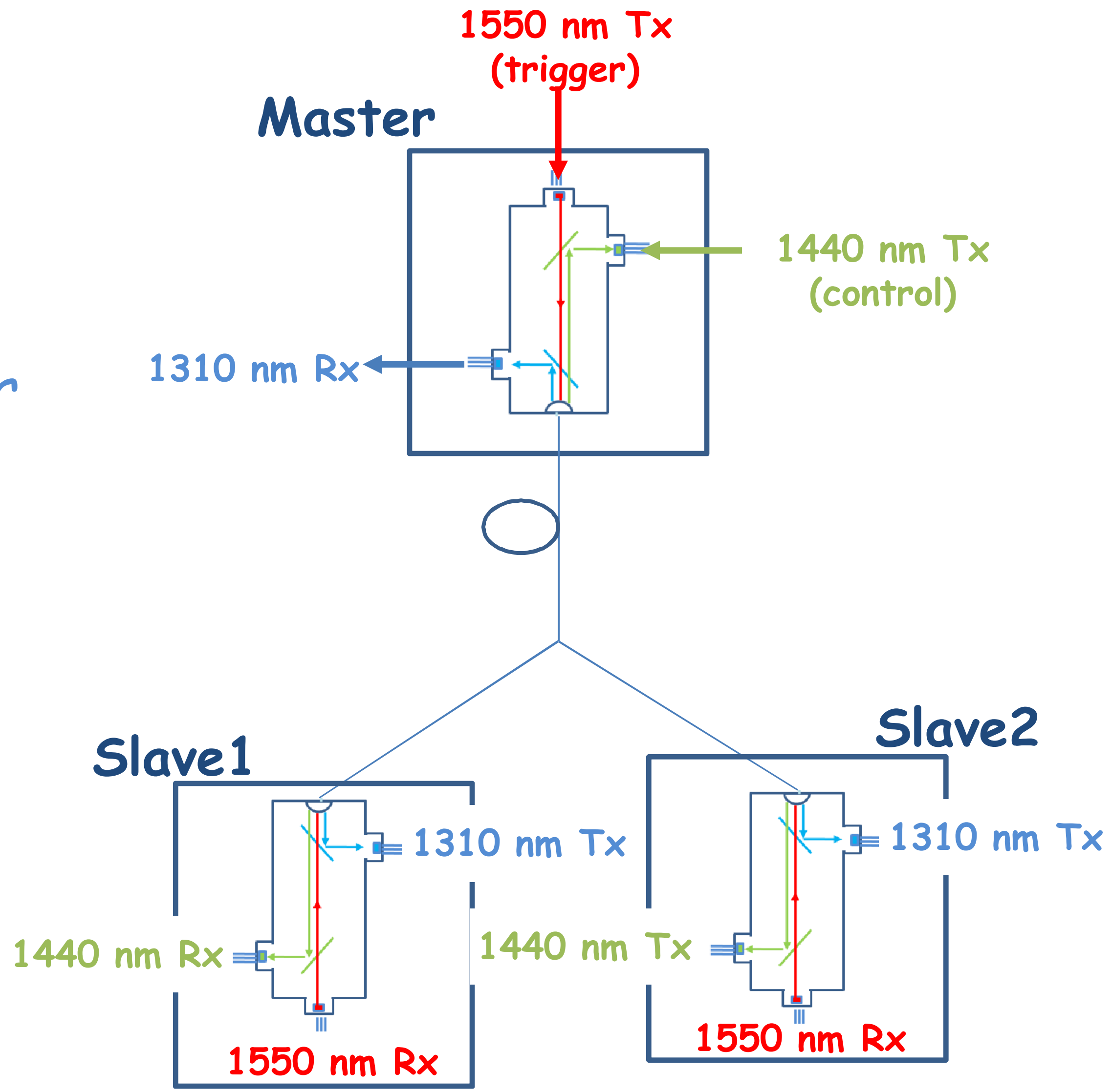


Future PON

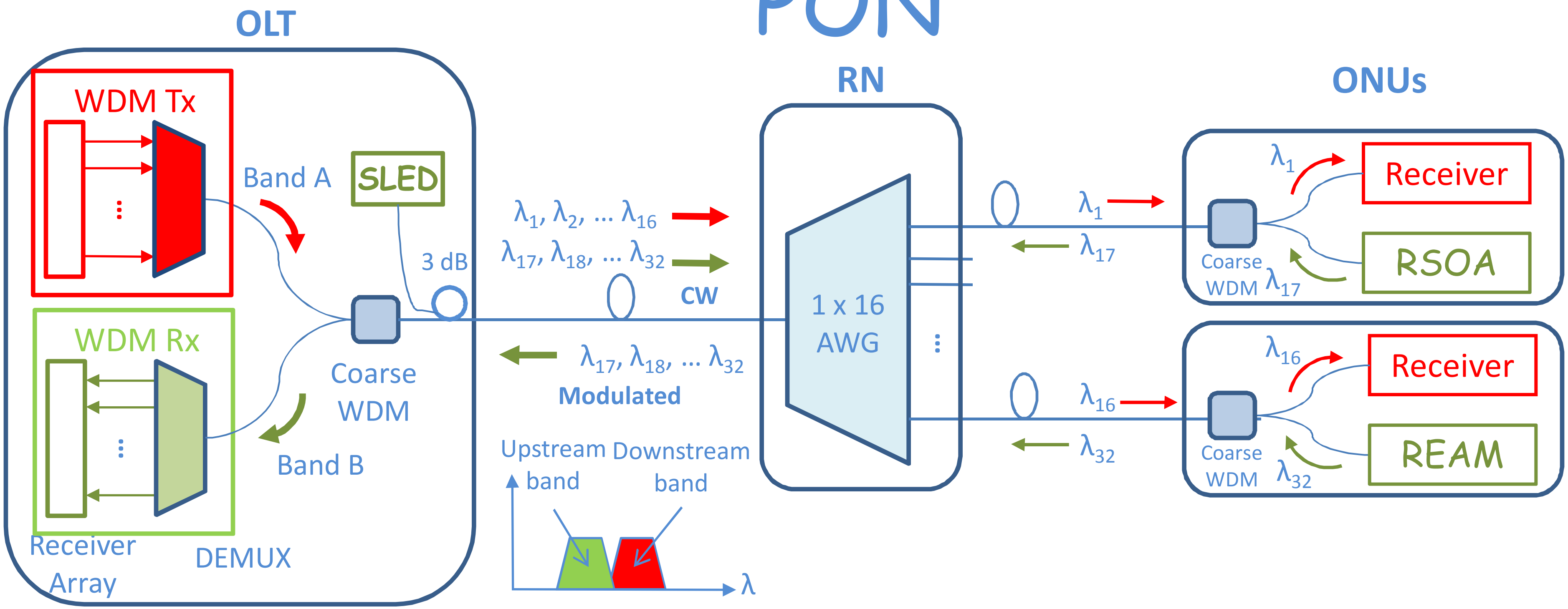
- Tri-band PONs
- WDM PONs

Tri-Band PONs

- Tri-band PON transceivers utilize 1440nm band
- They can be used in our context to separate the trigger from the control information
- That can simplify protocols of communication and complexity at the OLT



Wavelength Division Multiplexing PON



- In a WDM PON scenario each channel (or channel group) is assigned one wavelength upstream and one downstream for communication with OLT
- Benefits are higher bandwidth per channel, loss is independent from splitting ratio, less complicated scheduling algorithm at OLT, easy expansion, better delivery of services
- Main disadvantage is the need for expensive WDM components such as AWGs, filters, tunable lasers / laser arrays / laser per ONU, broadband receivers etc
- “Colorless” WDM PONs are developed to tackle cost issues

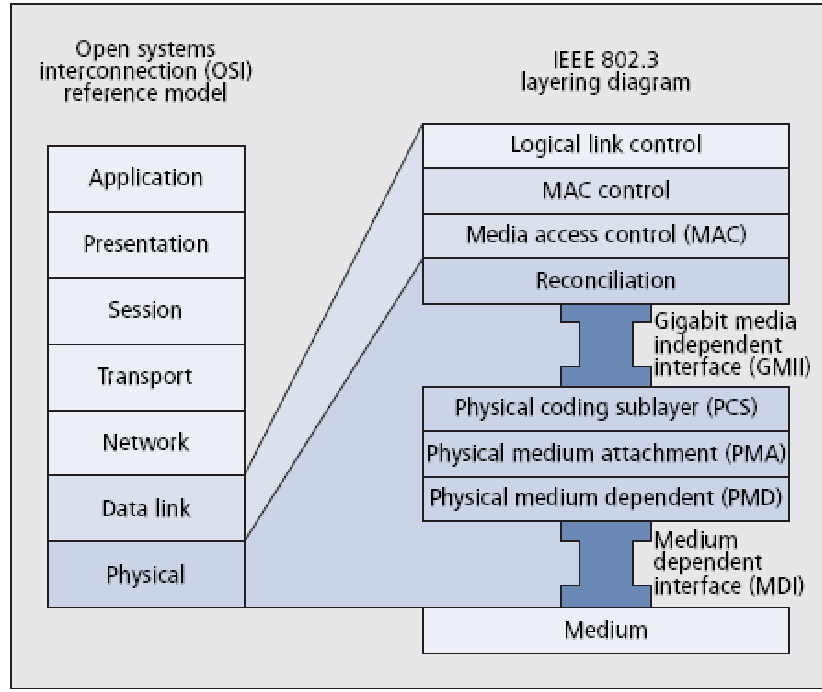
Summary

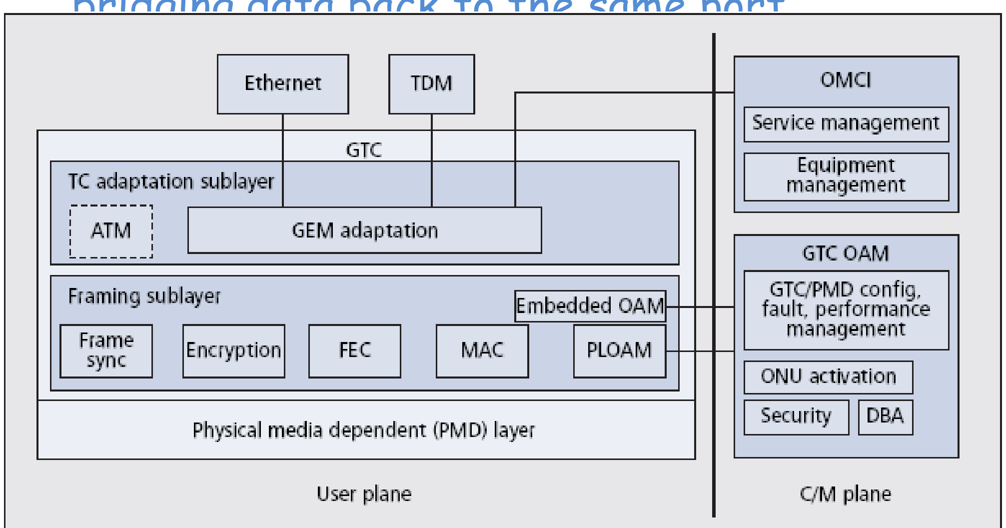
- A passive optical network for timing distribution applications has been successfully demonstrated
- In the downstream direction were trigger is transmitted, deterministic latency has been achieved
- A burst mode receiver was implemented in the upstream

Questions?

PONs in OSI Architecture

- PONs reside in the last two layers in the OSI architecture namely
- Data link layer which is responsible for the access to the medium and for error correction
- Physical layer which is responsible for transmitting and receiving the information
- In GPON terminology the two layers are called: G-Transmission Convergence (GTC) and Physical Media Dependent (PMD)
- EPON modifies MAC layer to allow for bridging data back to the same port





DBA Algorithms

- Requirements for DBA:

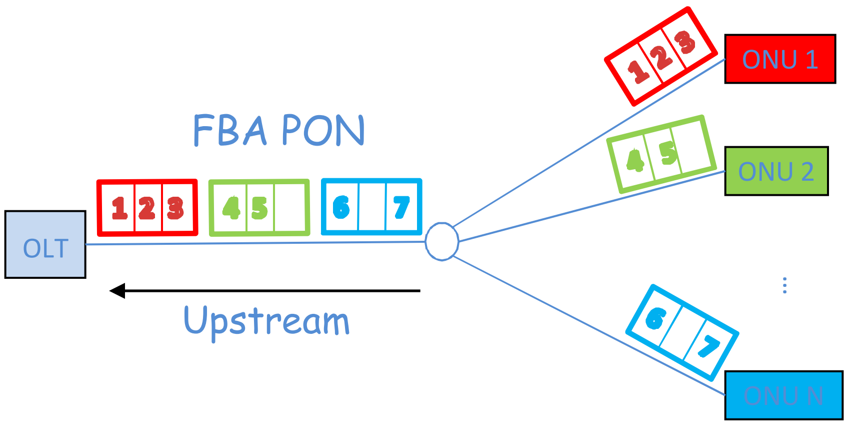
a) **Fairness**: Allocates the bw between users fairly
b) **Low delay**: Minimize latency (<1.5 ms for voice channels)
c) **High efficiency**: Can increase the efficiency of the bw (throughput) and increase peak rate

- Fair Queuing Scheduling
- Interleaved Polling with Adaptive Cycle Time (IPACT)

i. Fixed Service
ii. Limited Service
iii. Constant Credit Service
iv. Linear Credit Service
v. Elastic Service

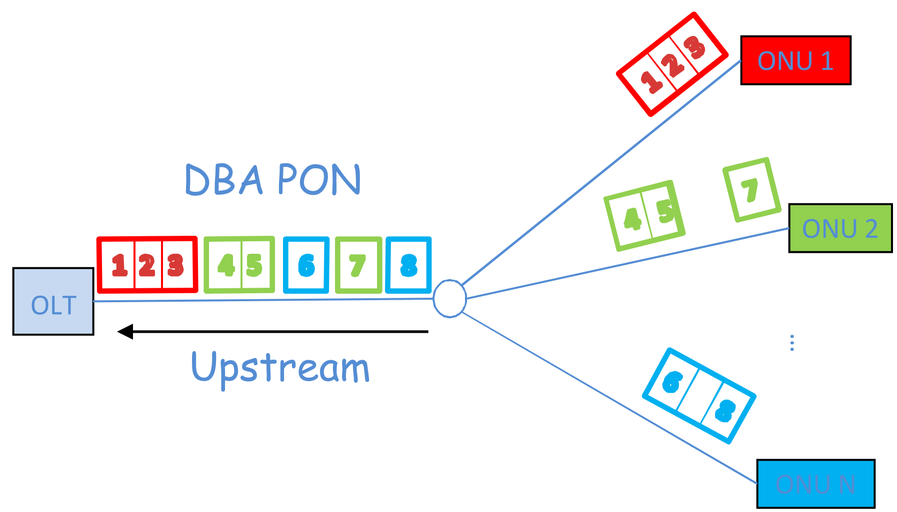
- Deficit Round-Robin Scheduling
- DBA using Multiple Queue Report Set
- etc ..

FBA - DBA Comparison



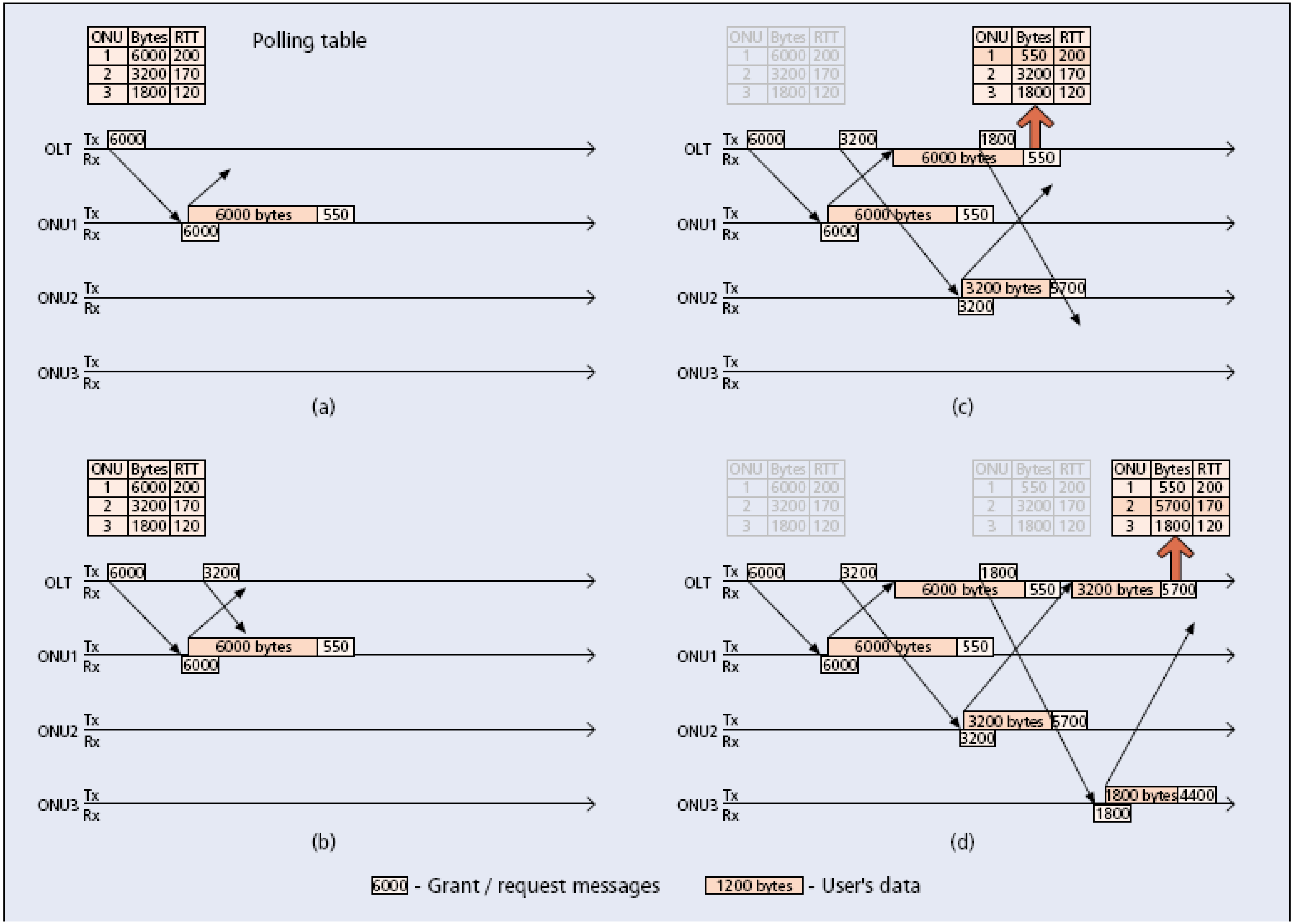
- FBA algorithm is easy to implement
- However, unused bw is wasted
- FBA is not frequently encountered

- DBA can result in high bw utilization efficiency
- It can also run efficiently different classes of service
- However, efficiency is traded with higher complexity at the scheduler

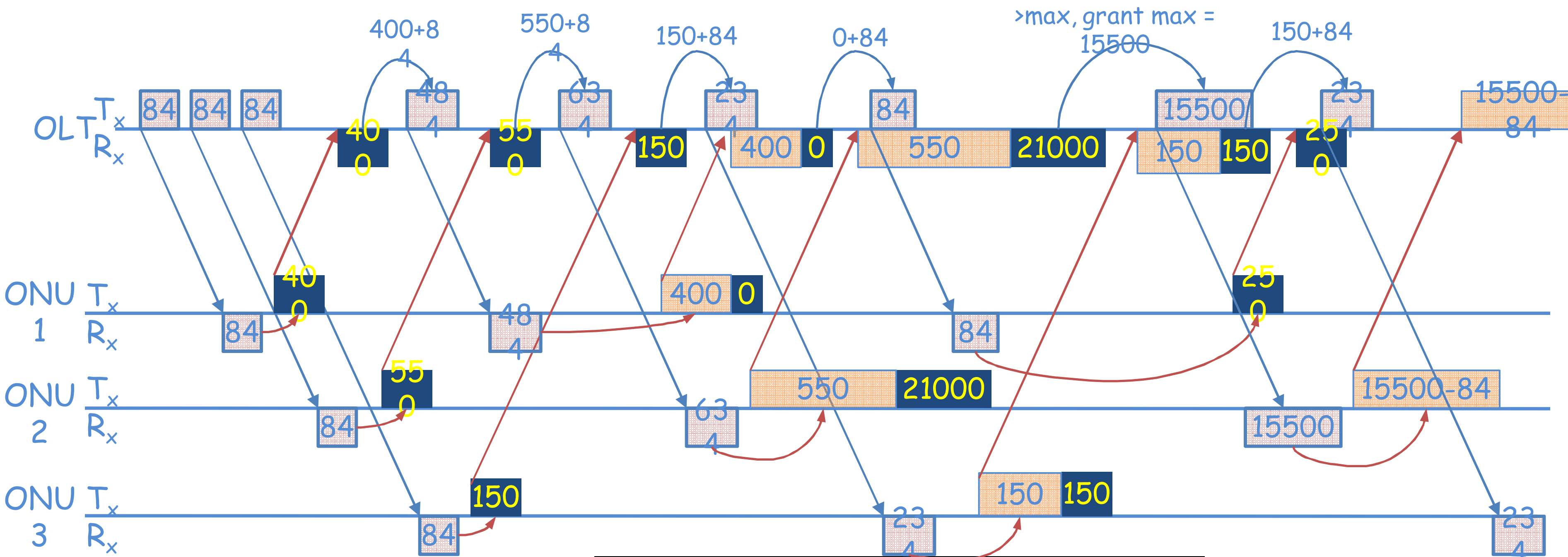


IPACT Scheduling

- ONUs are addressed sequentially in a round robin fashion
- In the Simplest IPACT implementation each ONU is granted all requested bw



Limited Service IPACT

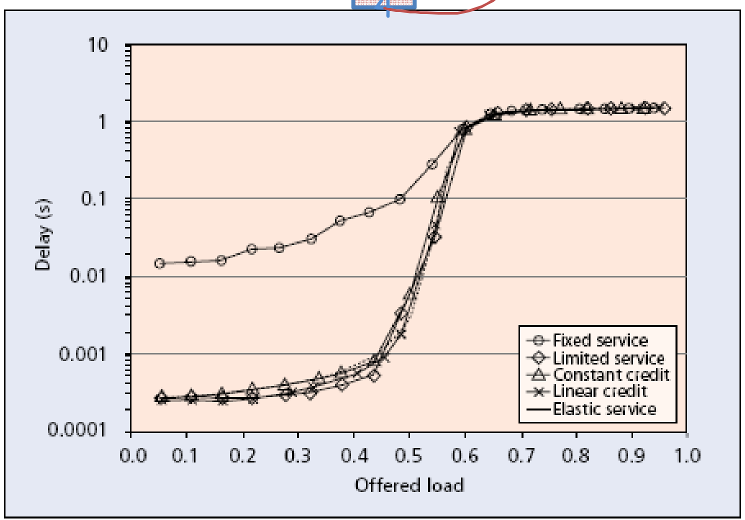


GRANT frame with grant length = 84

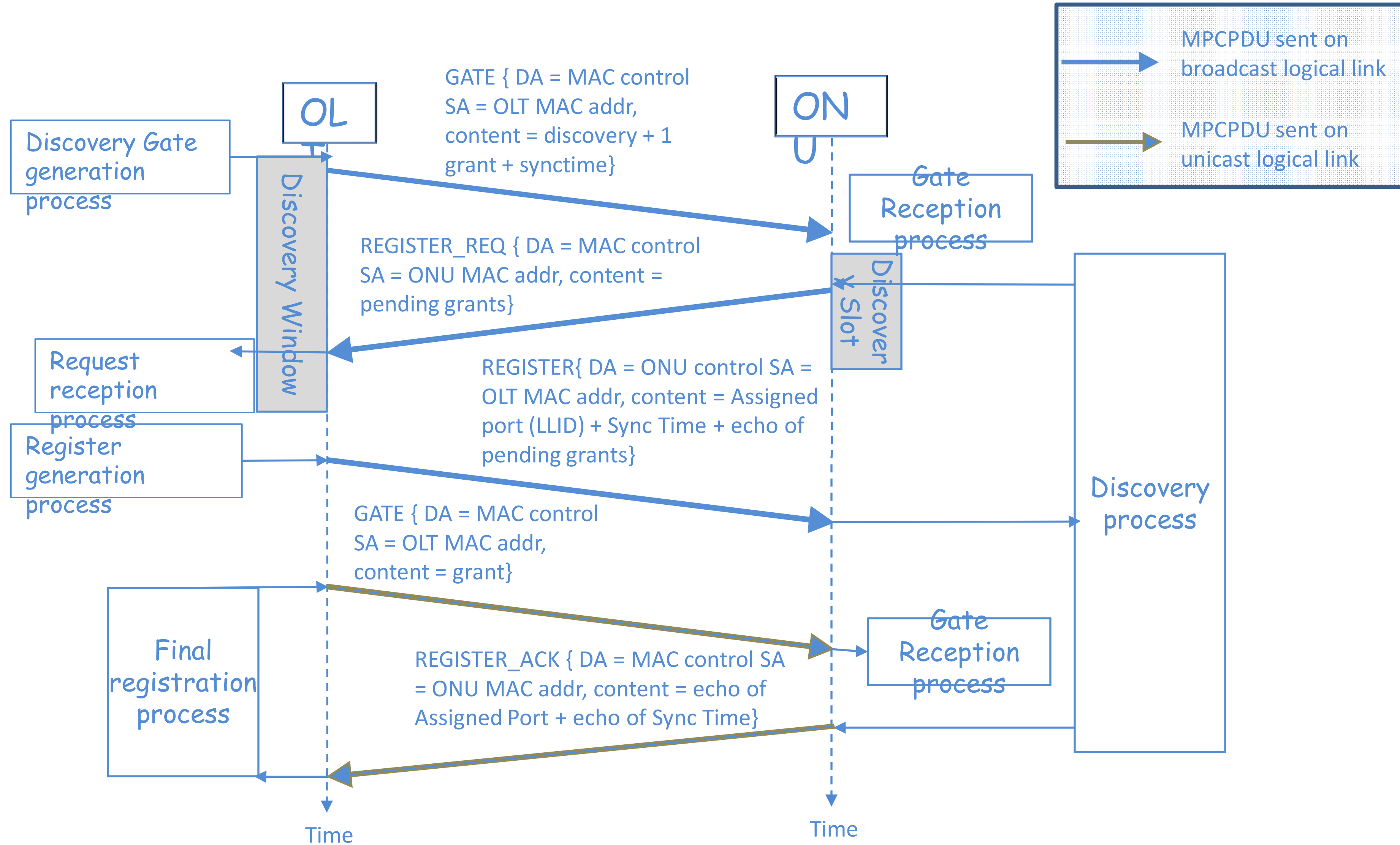
REPORT frame reporting queue of 400

300 byte of Ethernet data including overheads

- At light loads all alternative scheduling schemes easily outperform fixed service in terms of delay
- As network load increases delay for all scheduling schemes converges to fixed service



New ONU Registration EPON



Ranging/Synchronization in GPON

$$RTT = 2Tpd + Ts + T_iO1 + T_iO2 + T_iS1 + T_iS2 + EqD$$

$$Ts + T_iO1 + T_iO2 + T_iS1 + T_iS2 < 50\ \mu s$$

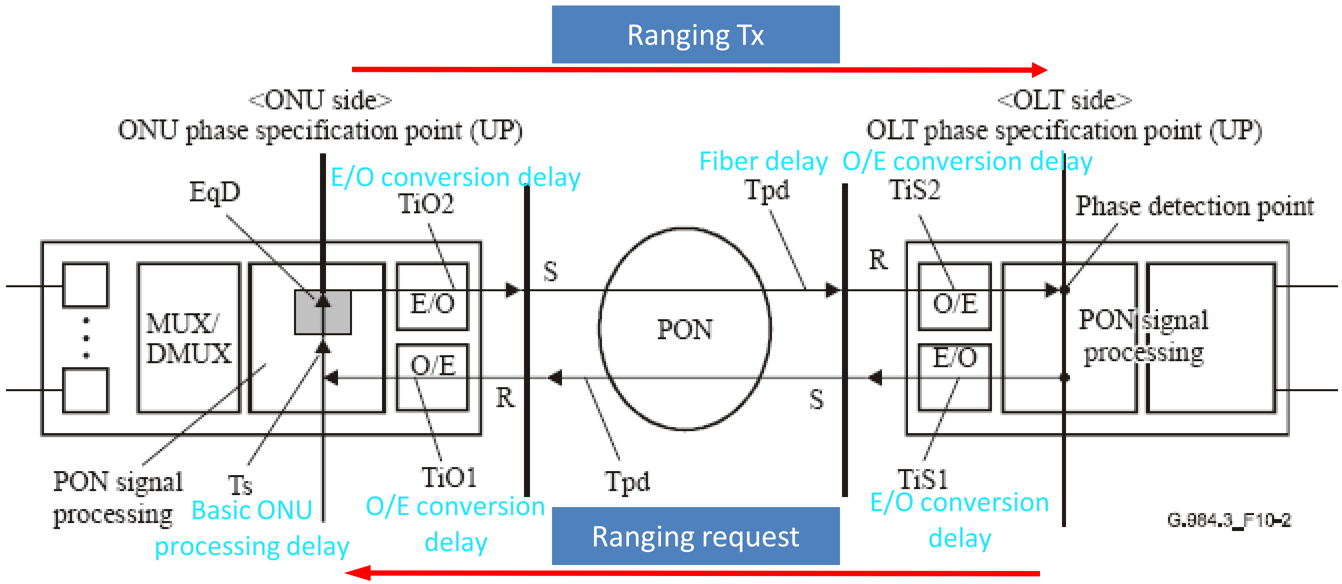


Figure 10-2/G.984.3 – Configuration of the phase delay points

- GPON implements an alternative equalization scheme
- A variable delay EqD is introduced at the ONU
- EqD has the objective to male all ONUs appear equidistant from OLT
- Phase of signal is measured from first bit transmitted from OLT to last bit received by ONU
- Every time ONU transmits RTT is compared to expected value and EqD is updated

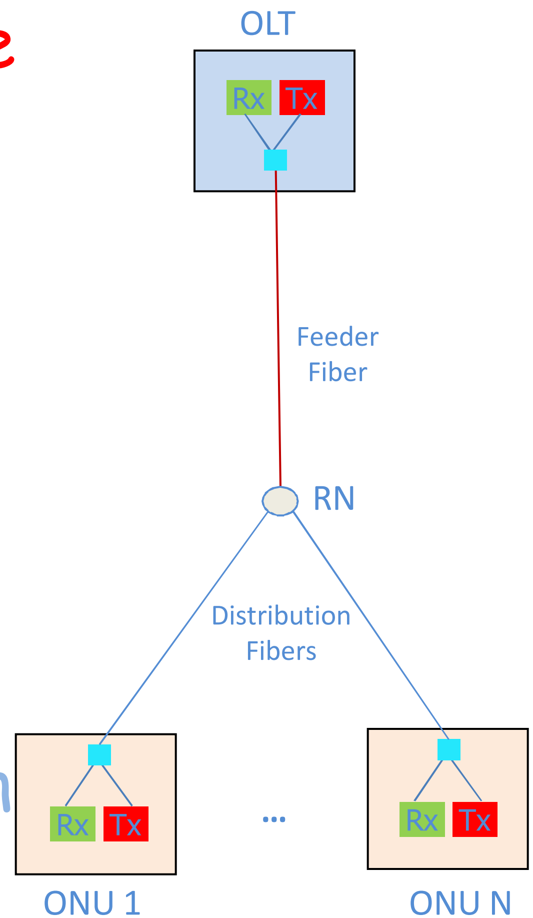
PON Protection

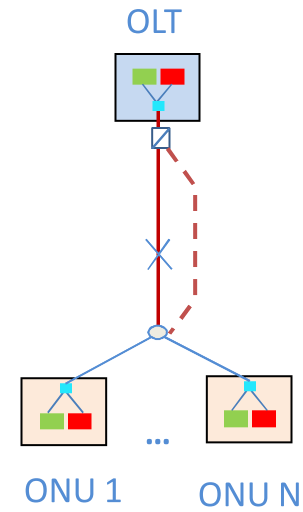
- Resources that require protection:

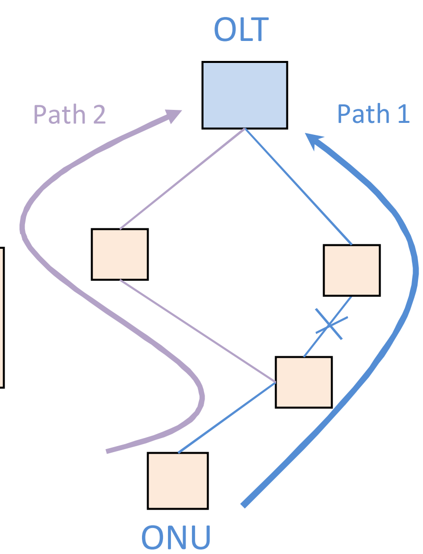
1) Feeder fiber
2) Distribution Fiber
3) OLT Transceiver
4) ONU Transceiver
5) RN (Splitter / WDM Demux)

- Protection Schemes

a) Preplanned Protection
b) Dynamic Restoration







Protection Schemes

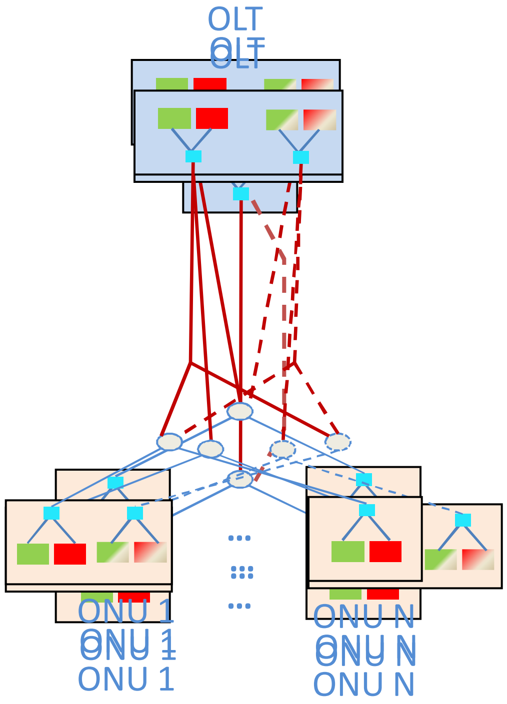
- ITU-T G.983.1 GPON Protocol specifies four protection architectures for PONs

a) Simple feeder fiber architecture

b) Feeder+OLT transceiver

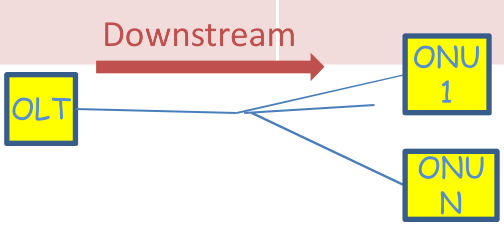
c) Feeder+Distribution+OLT+ONU Transceivers

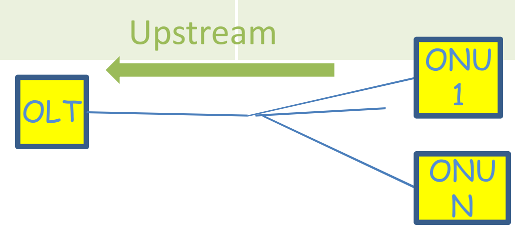
d) Hybrid protection



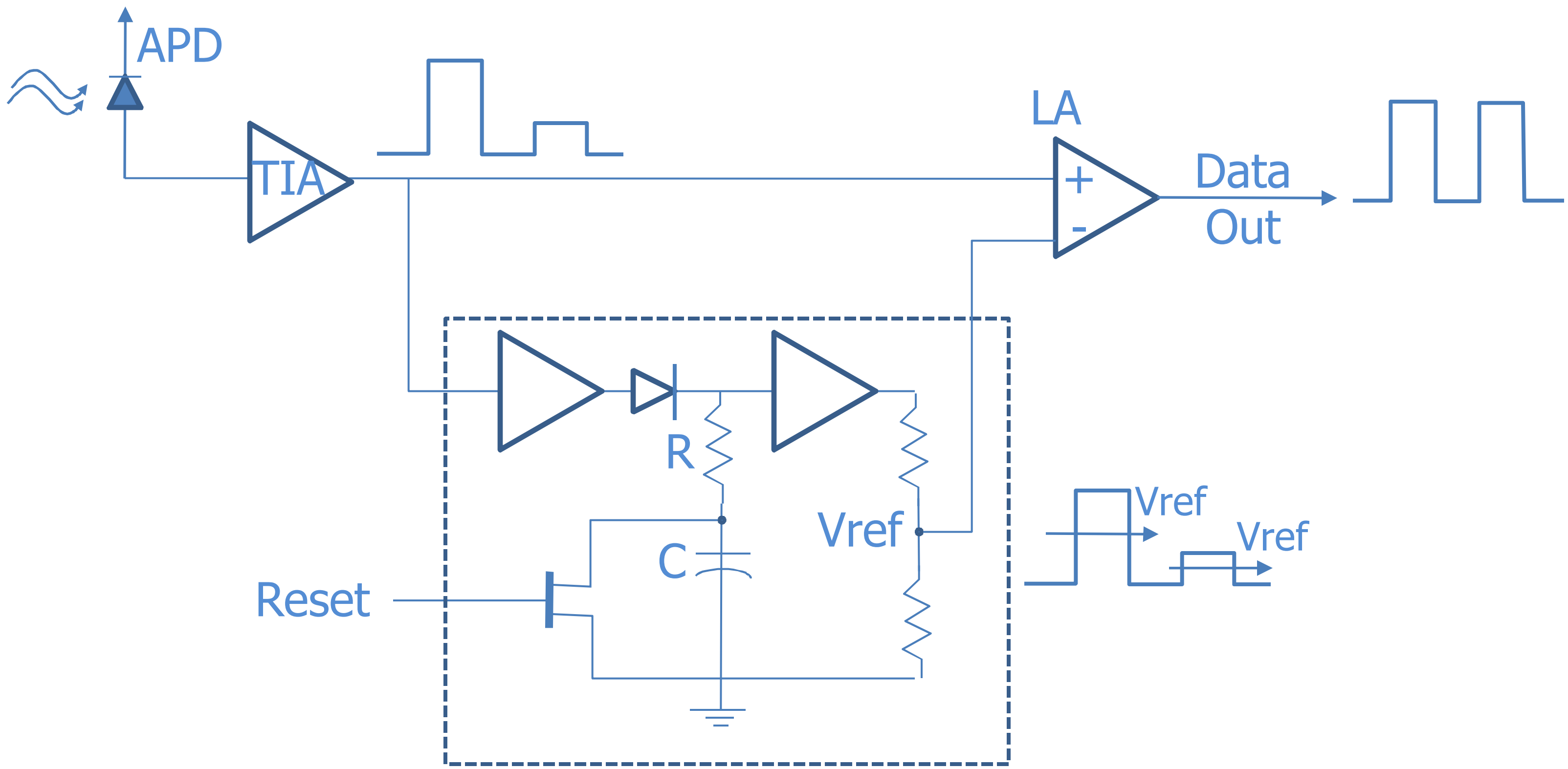
EPON vs GPON Physical Layer

	UNIT	Downstream (GPON)	Downstream (EPON)	Upstream (GPON)	Upstream (EPON)
Bit-rate	Gb/s	1.244/2.48	1	1.244/2.48	1
Wavelength (SF)	nm	1480-1500	1480-1500	1260-1360	1260-1360
Mean Tx Power Min	dBm	-4 A/+1 B/ +5 C	-7	-3 A/ -2 B/ +2 C	-4
Mean Tx Power MAX	dBm	+1 A/ +6 B/ +9 C	2	+2 A/ +3 B/ +7 C	-1
Splitting Ratio		<64	<32	—	—
Max reach	Km	20	20	—	—
Line coding	-	NRZ	NRZ	NRZ	NRZ
Rx Sensitivity	dBm	-25 A/ -25 B/ -26 C	-27	-24 A/ -28 B/ -29 C	-24
Tx On-Off (1 Gbps)	ns	—	—	13	512
Clock recovery /AGC (1 Gbps)	ns	—	—	36	<400



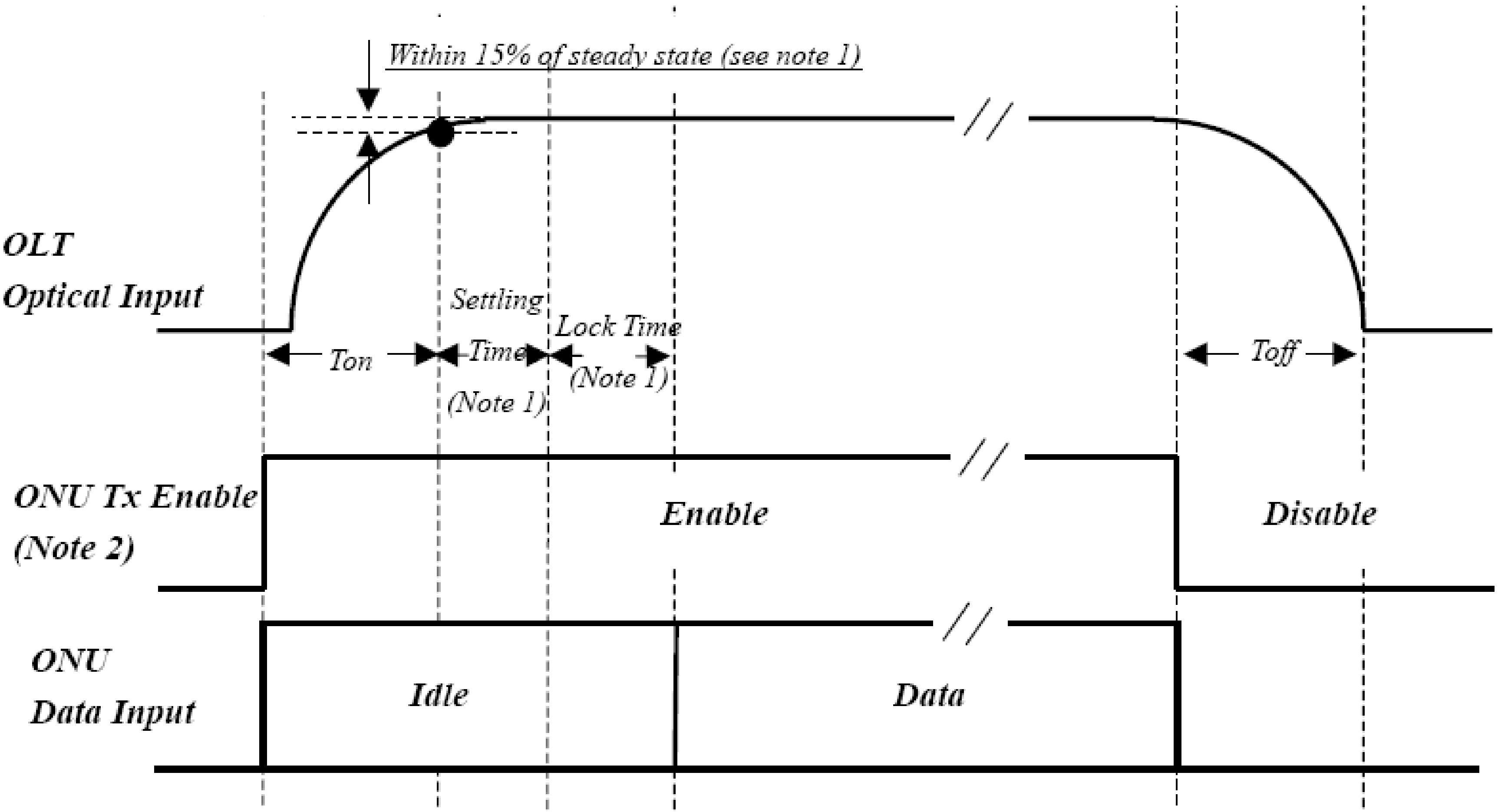


Burst Mode Rx Decision Threshold set



Peak Detection Circuit

P2MP Timing Parameters

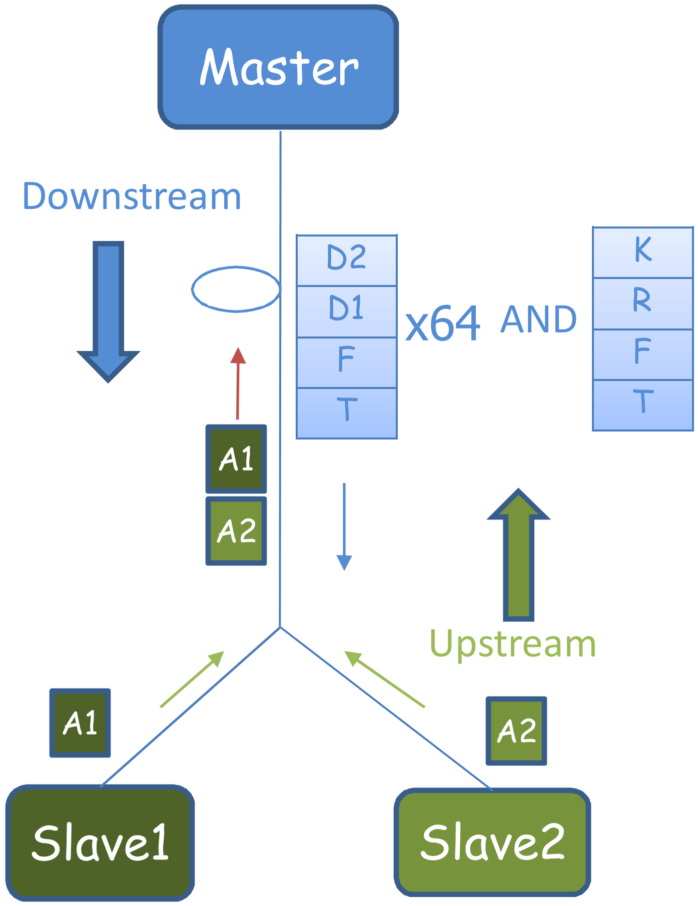


Note 1. Sync time is 520ns (Receiver settling time + CDR lock time).

Note 2. Tx Enable is the control signal of optical ON/OFF to ONU.

PON Protocol

- Synchronous delivery of a periodic trigger with clock rate 25ns, **(T)** field
- F field to protect the trigger field, **(F)** field
- Broadcast commands to ONUs, **(D1)** and **(D2)** fields
- Individually addressing of ONUs, **(D1)** and **(D2)** fields
- Arbitration of upstream channel to avoid collisions due to simultaneous transmissions from multiple ONUs, **(R)** field

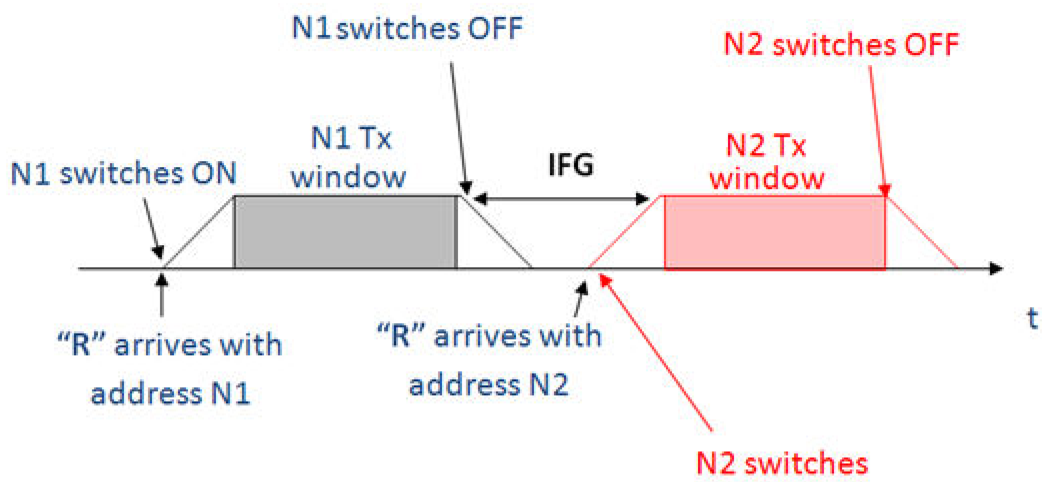


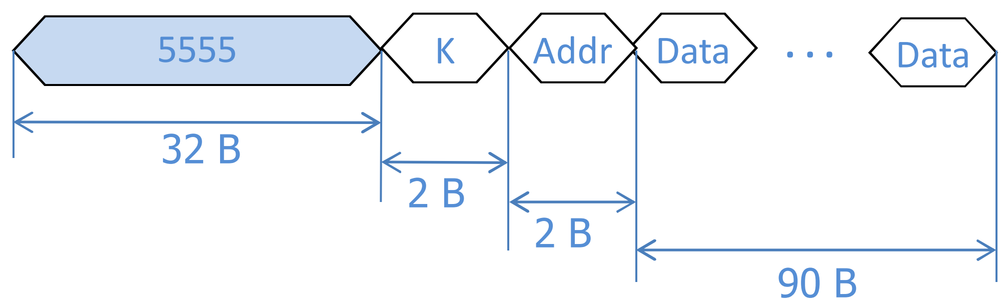
Protocol Properties

- No destination addresses are required to be transmitted
- Easy resynchronization in case of loss of sync
- Simple algorithm for accessing the upstream channel
- Downstream available BW: 9.23 Mb/s/ONU
- Upstream available BW: 7.66 Mb/s/ONU

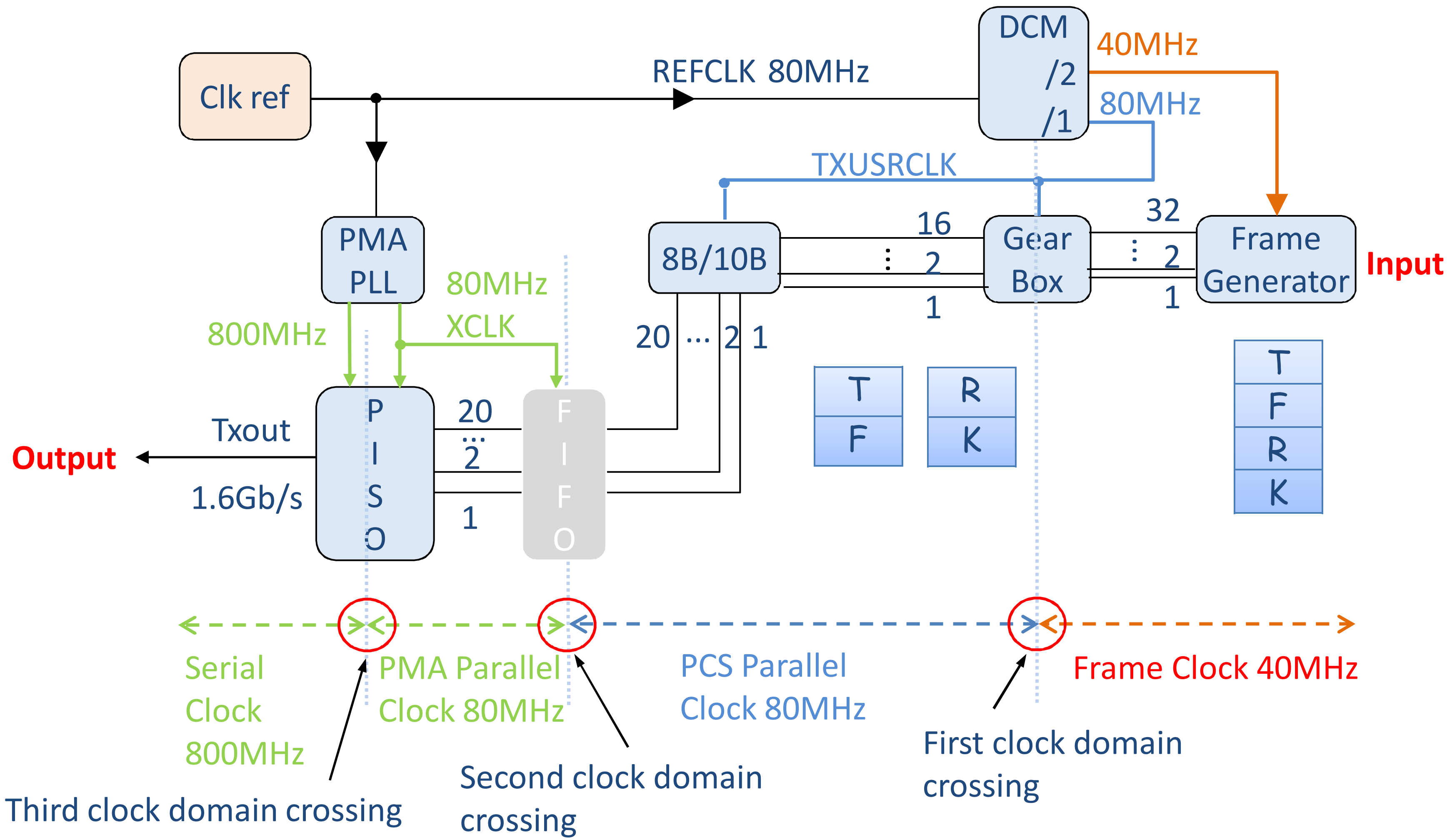
Upstream Frame

- Slave N1 receives an R character with its address and switches its laser ON
- IFG between successive emissions allows receiver to adopt between bursts
- Upstream contains 32 bytes of <5555> for CDR followed by two SFD, <D555>, bytes for frame alignment
- A 2 byte address field and data are following
- Channel arbitration is a logic built-in at the OLT
- Total BW 800Mb/s, 7.7 Mb/s are available per Slave node for pure data

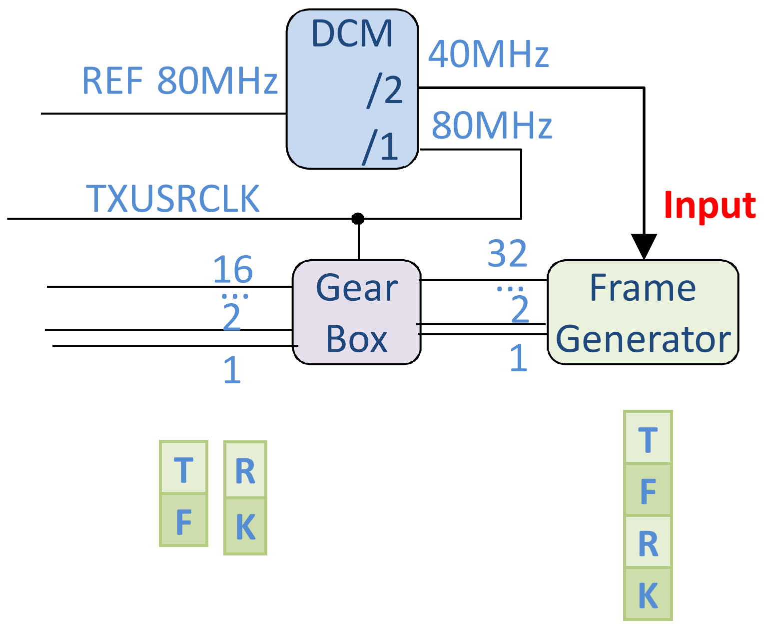


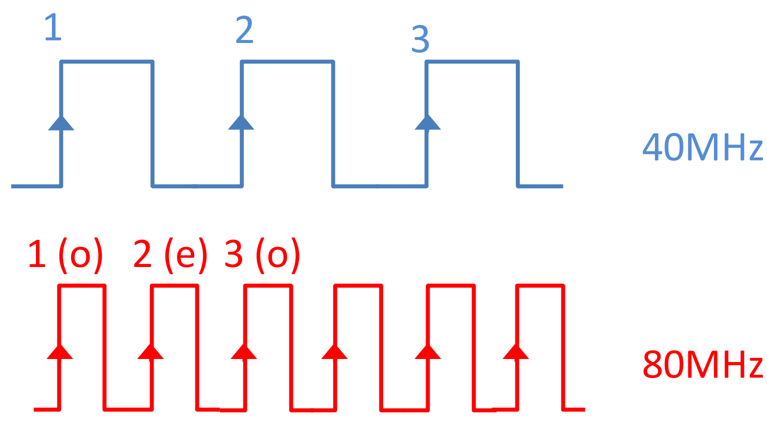


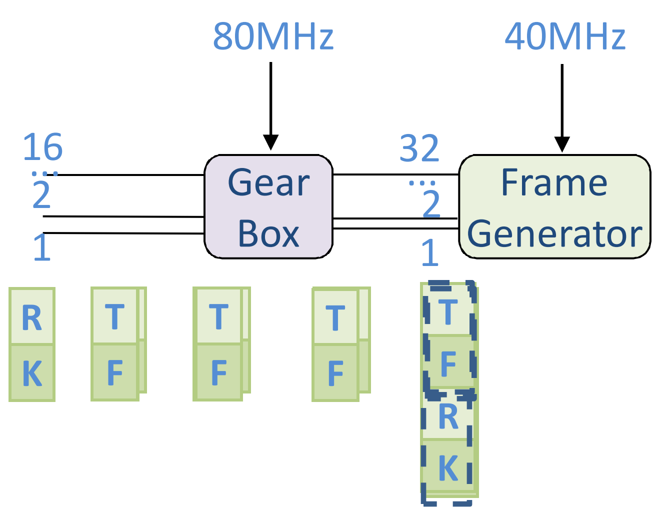
Master Transmitter



OLT Tx - Gear Box







BW Downstream

- To calculate the BW assigned to each ONU we need:

A) To exclude the trigger, “F” field and “K” and “R” characters 590.76 Mb/s is available for data to all ONUs

B) To exclude BW assigned to 8b/10b encoding

- The usable minimum downstream BW is 9.23Mb/s/ONU (for 64ONUs @ 1.6Gb/s)

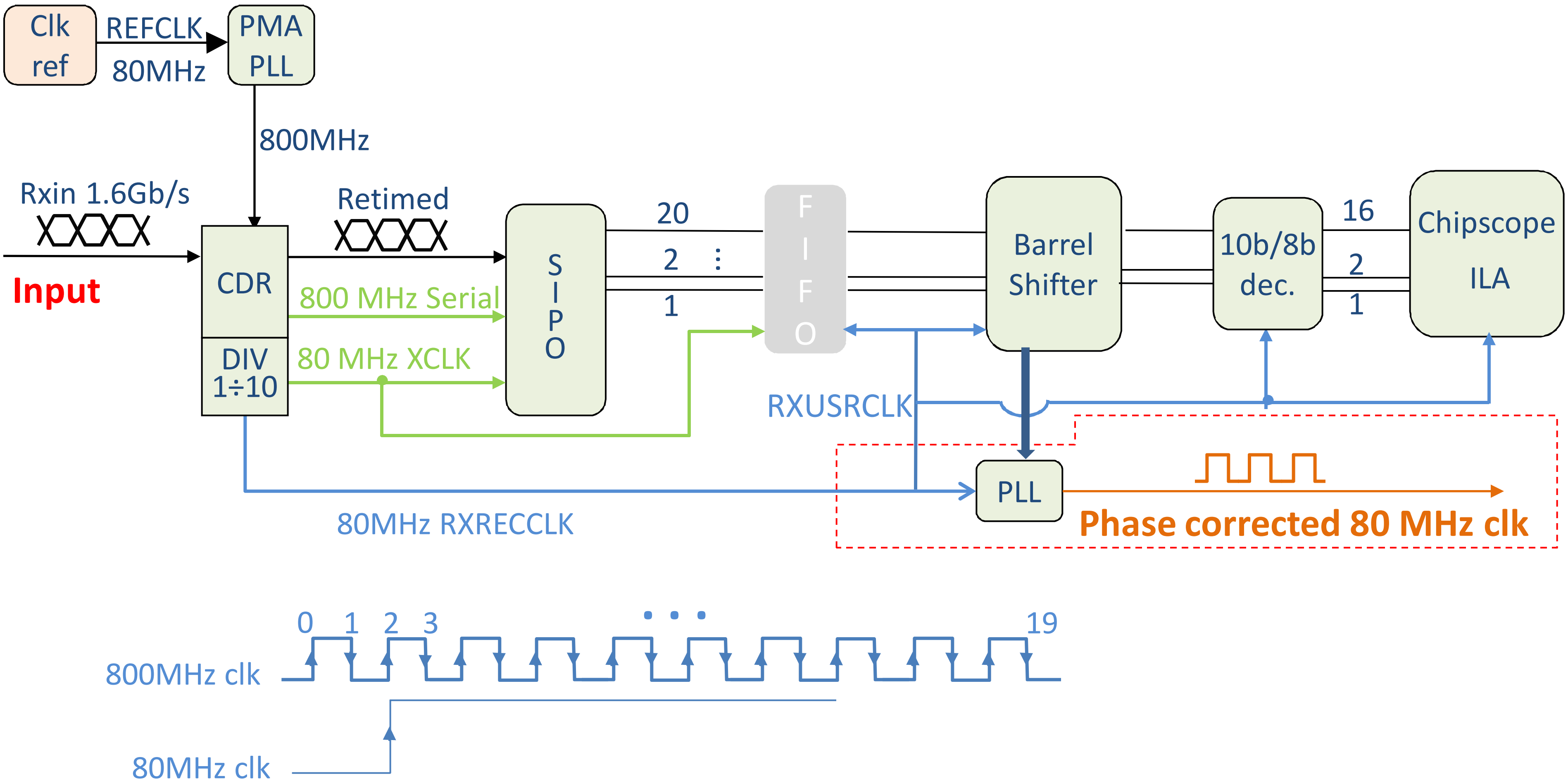
OLT Tx Characteristics

3. Transmitter Specifications (Vcc = 3.13V to 3.47V)

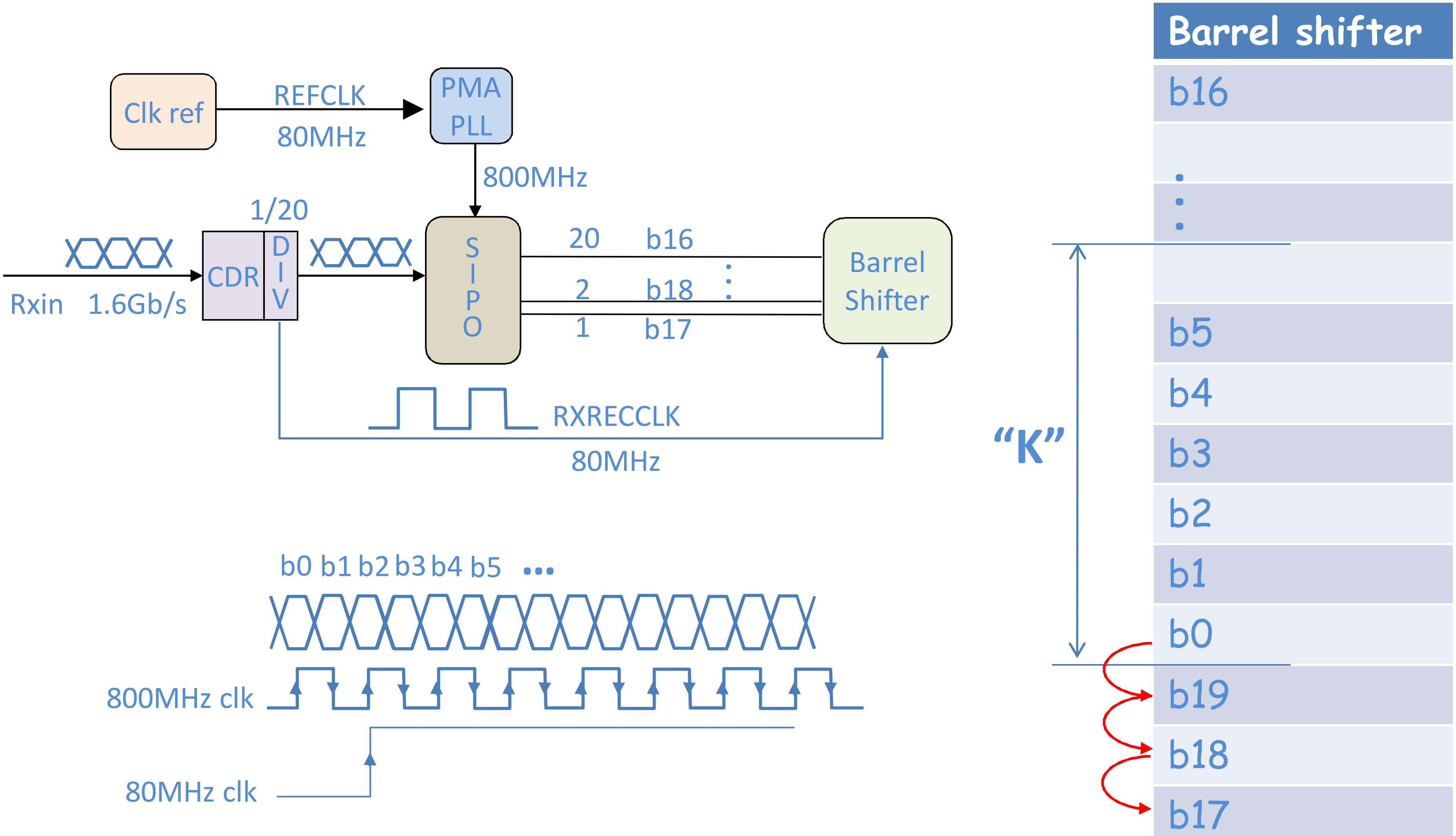
Parameter••	Symbol••	Min.••	Typ.••	Max.••	Unit••	Remark••
Electrical Characteristics						
Differential Input Voltage	Vin	0.4	-	1.6	Vp-p	LVPECL
Common-mode Input Voltage••	Vcm••	TBD		TBD	V••	LVPECL
Singled-ended Tx shutdown••	V_{SHDN}••	2.0	-	-	V••	LVTTL
Singled-ended Tx turn on••	V_{SHDN}••	-	-	0.8	V••	LVTTL
Tx Alarm High (Tx fail)••	Vtxf••	2.4	-	-	V••	LVTTL
Tx Alarm Low (Tx normal)••	Vtxf••	-	-	0.4	V••	LVTTL
Optical Characteristics						
Optical Output Power (E.O.L)••	Pout••	3.5	-	8	dBm••	-
Optical Output Power with TX	Pout off••	-	-	-39	dBm••	-
Optical Extinction Ratio••	ER••	9	-	-	dB••	-
Transmitter Eye Mask	-••	Refer to Fig. 1			-••	-••
Optical Wavelength••	• ••	1480	-	1500	nm••	-
Relative Intensity Noise	$RIN_{15}OMA$••	-••	-••	-115••	dB/Hz••	-••
Spectral Width (rms)	Δλ	-	-	0.44	nm	-
Side Mode Suppression Ratio••	SMSR••	30	-	-	dB••	-
Optical Return Loss Tolerance••	Torl••	-	-	15	dB••	-
Optical Return Loss of ODN••	-••	20	-	-	dB••	-
Transmitter Reflectance	Rt••	-	-	-10	dB••	-
Dispersion Penalty [1]	DP	-	-	2.3	dB	-

Note1. Measured with 2^7-1 PRBS at $1x10^{-12}$ BER and 9 dB extinction ratio and the decision timing offset should be a minimum of

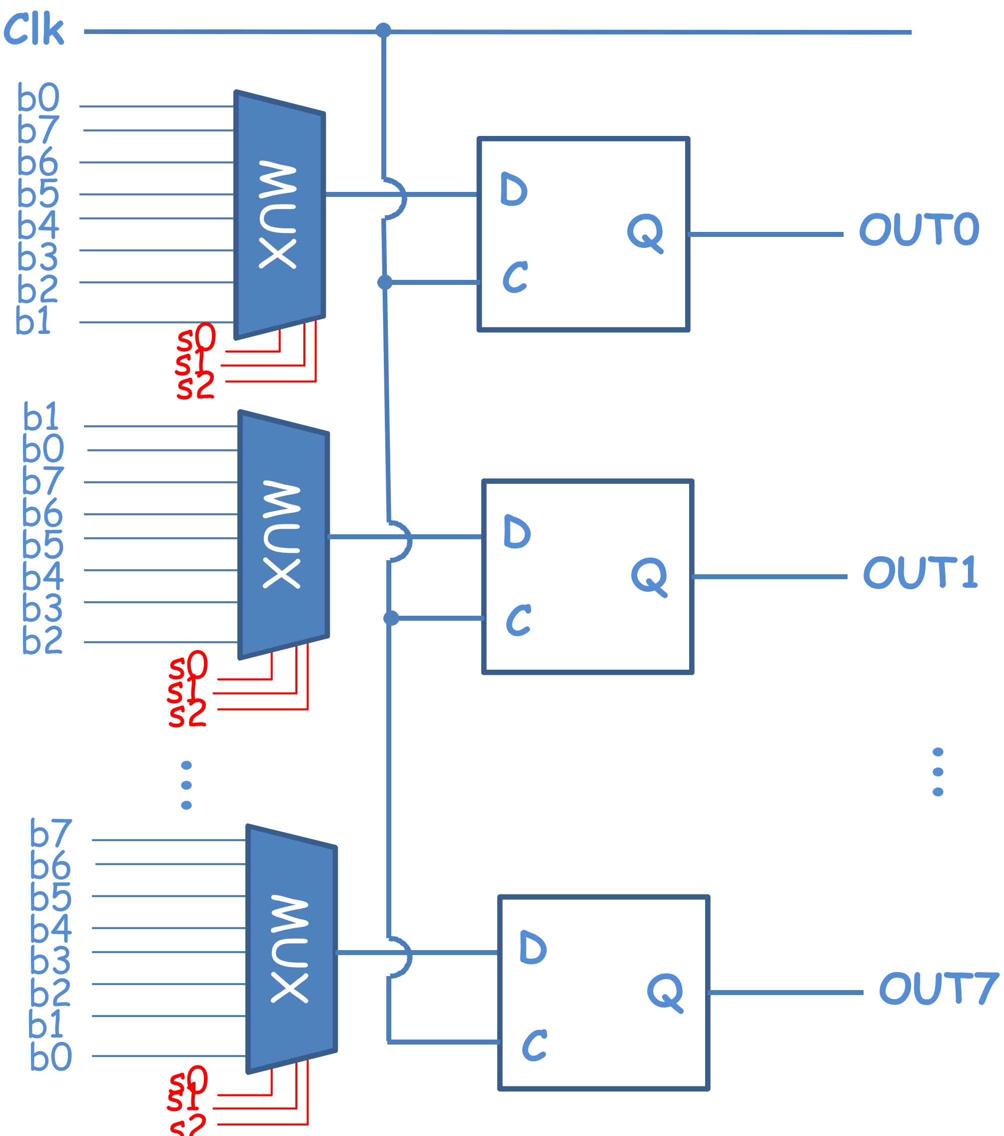
Slave Receiver



Barrel Shifter



Barrel Shifter



S2	S1	S0	O7	O6	O5	O4	O3	O2	O1	O0
0	0	0	b7	b6	b5	b4	b3	b2	b1	b0
0	0	1	b6	b5	b4	b3	b2	b1	b0	b7
0	1	0	b5	b4	b3	b2	b1	b0	b7	b6
0	1	1	b4	b3	b2	b1	b0	b7	b6	b5
1	0	0	b3	b2	b1	b0	b7	b6	b5	b4
1	0	1	b2	b1	b0	b7	b6	b5	b4	b3
1	1	0	b1	b0	b7	b6	b5	b4	b3	b2
1	1	1	b0	b7	b6	b5	b4	b3	b2	b1

BW Upstream

- In our first implementation we give one timeslot of 1625ns to each ONU
- The overhead due to IFG, <5555>, <D555> and address field is 400ns
- That gives a BW utilization (taking into account the 8b/10) of 61.3%
- It corresponds to 7.66Mb/s/ONU (for 64 ONUs @ 800Mb/s)

ONU Rx Characteristics

4. Receiver Specifications (Vcc = 3.135V to 3.465V)

Electrical Characteristics						
Parameter	**Symbol**	**Min.**	**Typ.**	**Max.**	**Unit**	**Remark**
Differential Data Output Swing	Vout	0.4	-	1.6	Vp-p	LVPECL
Data Output Rise/Fall Time	tr/tf	-	-	260	ps	-
Total Generated Receiver Jitter	JRX	-	-	247	ps	-
Optical Characteristics						
Average Rx Sensitivity [1]	RSENS	-	-	-25	dBm	PX-10,PX-20
		-	-	-26.5	dBm	PX-20^{+}
Stressed Rx Sensitivity(@1.25Gb/s)	R_{ST}			TBD	dBm	-
Maximum Input Power (Overload)	Pmax	-3	-	-	dBm	-
Optical Center Wavelength	• є	1480	-	1500	nm	-
SD Assert	SD_A	-	-	-25	dBm	LVTTL, PX-10, PX-20
		-	-	-26.5	dBm	LVTTL, PX-20^{+}
SD De-assert	SD_D	-44	-	-	dBm	LVTTL
SD Hysteresis	-	-	1	-	dB	-
S/X Endurance	-	-	-	-18	dB	1550nm ~ 1560nm
		-	-	4	dB	1625nm ~ 1655nm
Receiver reflectance	Tr	-	-	-12	dB	1480nm ~ 1500nm
		-	-	-20	dB	1550nm ~ 1560nm

Transceivers for PONs

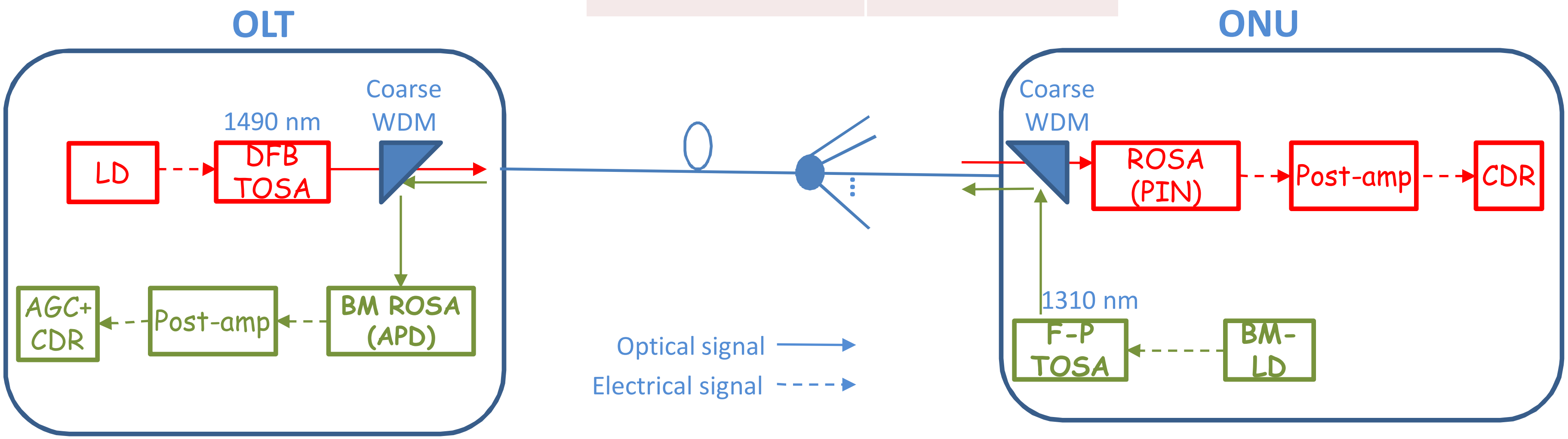
- GPON has far more stringent requirements than EPON
- For this reason GPON components are in general more expensive than EPON
- OLT needs a 1490 nm laser (usually DFB-DBR)
- Burst Mode Receiver
- ONU needs 1310 nm F-P laser with burst mode laser drivers
- PIN diode or APD at 1490 nm

GPON (1.24 Gb/s)

Tx Enable	16 bits (12.9ns)
Tx Disable	16 bits (12.9 ns)
Total (Tg+Tp+Td)	96 bits (77.2 ns)
Guard time Tg	32 bits
Preamble Time Tp	44 bits (35.2 ns)
Delimiter Time Td	20 bits
Rx Dynamic Range	21 dB

EPON

Tx Enable	512 ns
Tx Disable	512 ns
Total (AGC+CDR)	412 ns
Rx Dynamic Range	>21 dB



OLT Rx Characteristics

4. Receiver Specifications (Vcc = 3.13V to 3.47V)

Electrical Characteristics						
Parameter••	**Symbol••**	**Min.••**	**Typ.••**	**Max.••**	**Unit••**	**Remark••**
Differential Data Output Swing••	Vout••	0.4••	-••	1.6••	Vp-p••	LVPECL••
Data Output Rise/Fall Time••	tr/tf••	-••	-••	260••	ps••	-••
Signal Detect (SD) Voltage-Low••	V_{OL}	-••	-••	0.4••	V••	LVTTL••
Signal Detect (SD) Voltage-High••	V_{OH}	2.4••	-••	-••	V••	LVTTL••
Signal Detect (SD) Timing••	T_A	-••	-••	100••	ns••	-
	T_D	-	-	100	ns	-
AGC Reset••	-••	unnecessary••			-••	-••
Optical Characteristics						
Average Rx Sensitivity [1]	RSENSE	-	-	-30	dBm	-
Maximum Input Power (Overload)	Pmax	-8.5	-	-	dBm	-
Optical Center Wavelength••	• ε••	1260••	-••	1360••	nm••	-••
SD Assert	• • • • •••	-	-	-30	dBm	LVTTL
SD De-assert••	SD_D••	-44••	-••	-••	dBm••	LVTTL••
SD Hysteresis••	-••	-	2••	-••	dB••	-••
Receiver Settling Time (including Ton)••	T_rxst••	100	-••	350••	ns••	Refer to Fig. 2 and 3••
Guard Time••	GT••	50	-••	-••	ns••	Refer to Fig. 3••
Dynamic Range (loud/soft ratio)••	DR••	21.5••	-••	-••	dB••	Refer to Fig. 3••
S/X Endurance••	-••	-••	-••	TBD••	dB••	1550nm ~ 1560nm••
		-••	-••	TBD••	dB••	1625nm ~ 1655nm••

Note 1. Measured with PRBS of 2^7-1 at $1x10^{-12}$ BER and 9 dB extinction ratio. Transmitter should be on and driven with by

ONU Tx Characteristics

3. Transmitter Specifications (Vcc = 3.135V to 3.465V)

Electrical Characteristics						
Parameter	**Symbol**	**Min.**	**Typ.**	**Max.**	**Unit**	**Remark**
Input Differential Impedance	Rin	-	100	-	• •	-
Differential Input Voltage	Vin	0.4	-	1.6	Vp-p	LVPECL
Common-mode Input Voltage	Vcm	Vcc-1.49	Vcc-1.32	Vcc-Vin/4	V	LVPECL
Differential Burst Enable	Vben	2.0	-	-	Vp-p	LVTTL
Differential Burst Disable	Vben	-	-	0.8	Vp-p	LVTTL
Rise Time / Fall Time	Tr/Tf	-	-	0.2	ns	20% - 80%
Optical Characteristics						
Optical Output Power	Pout	-0.5	-	4.5	dBm	-
Optical Output Power with TX OFF	Pout_off	-	-	-45	dBm	-
Optical Extinction Ratio	ER	9	-	-	dB	-
Tansmitter Eye Mask Definition	-	Refer to Fig. 2			-	-
Optical Wavelength	• •	1260	-	1360	nm	-
Optical Burst On/Off Time	Ton/Toff	-	-	100	ns	-
Spectral Width (rms or WFHM)	Comply with IEEE 802.3ah PX-10 and PX-20 requirements					Refer to table 1 & Fig 1
Side Mode Suppression Ratio	-	30	-	-	dB	PX-20U, PX-20U^{+}
RIN$_{15}$OMA	-	-	-	-115	dB/Hz	PX-20U, PX-20U^{+}
Optical Return Loss Tolerance	Torl			15	dB	-
Total Jitter	-	-	-	128	ps	-
Transmitter Reflectance @1310nm	Rt	-	-	-6	dB	PX-10
		-	-	-10	dB	PX-20, PX-20^{+}
Dispersion Penalty [1]	DP	-	-	2.8	dB	PX-10
		-	-	1.8	dB	PX-20, PX-20^{+}

Shared PMA PLL

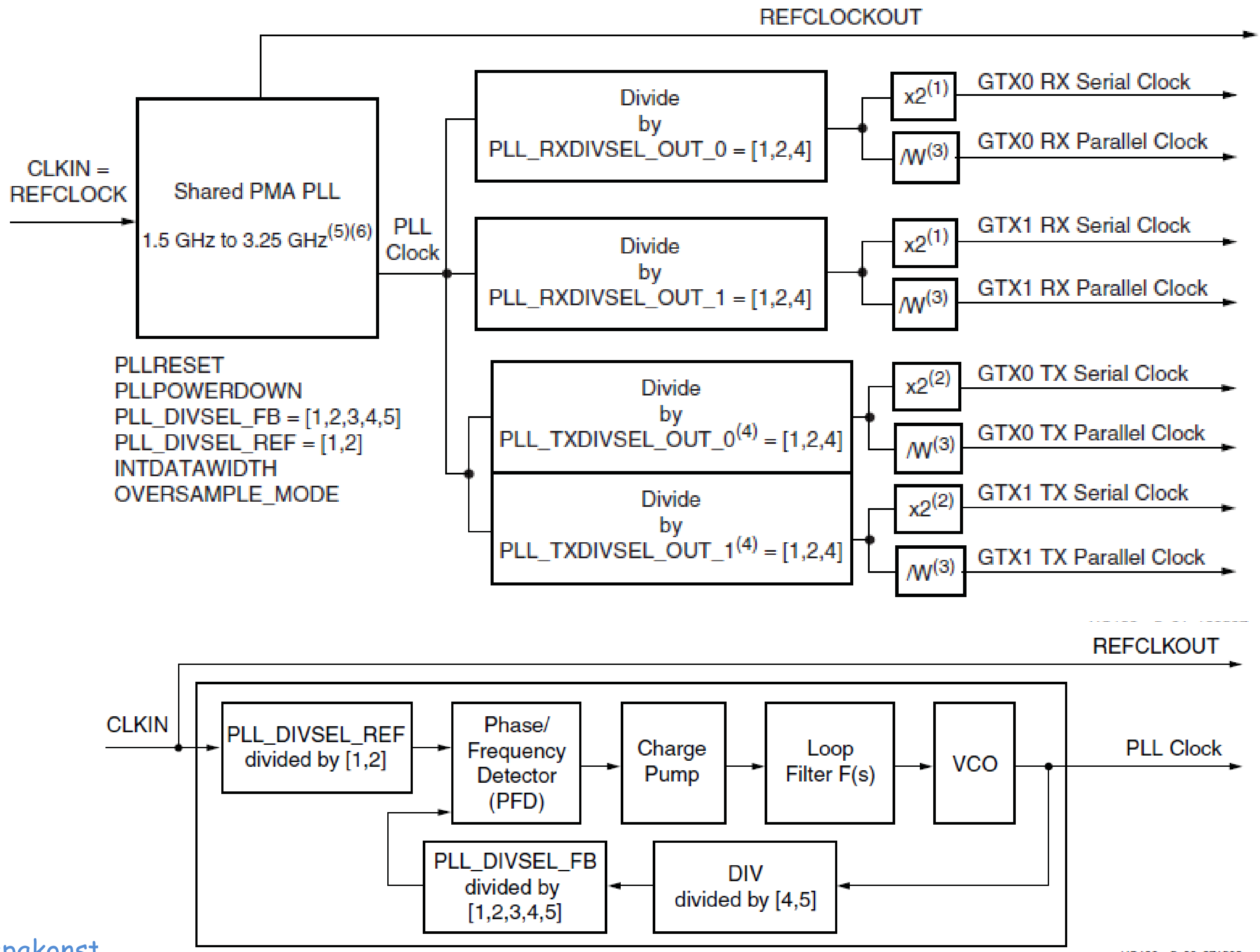
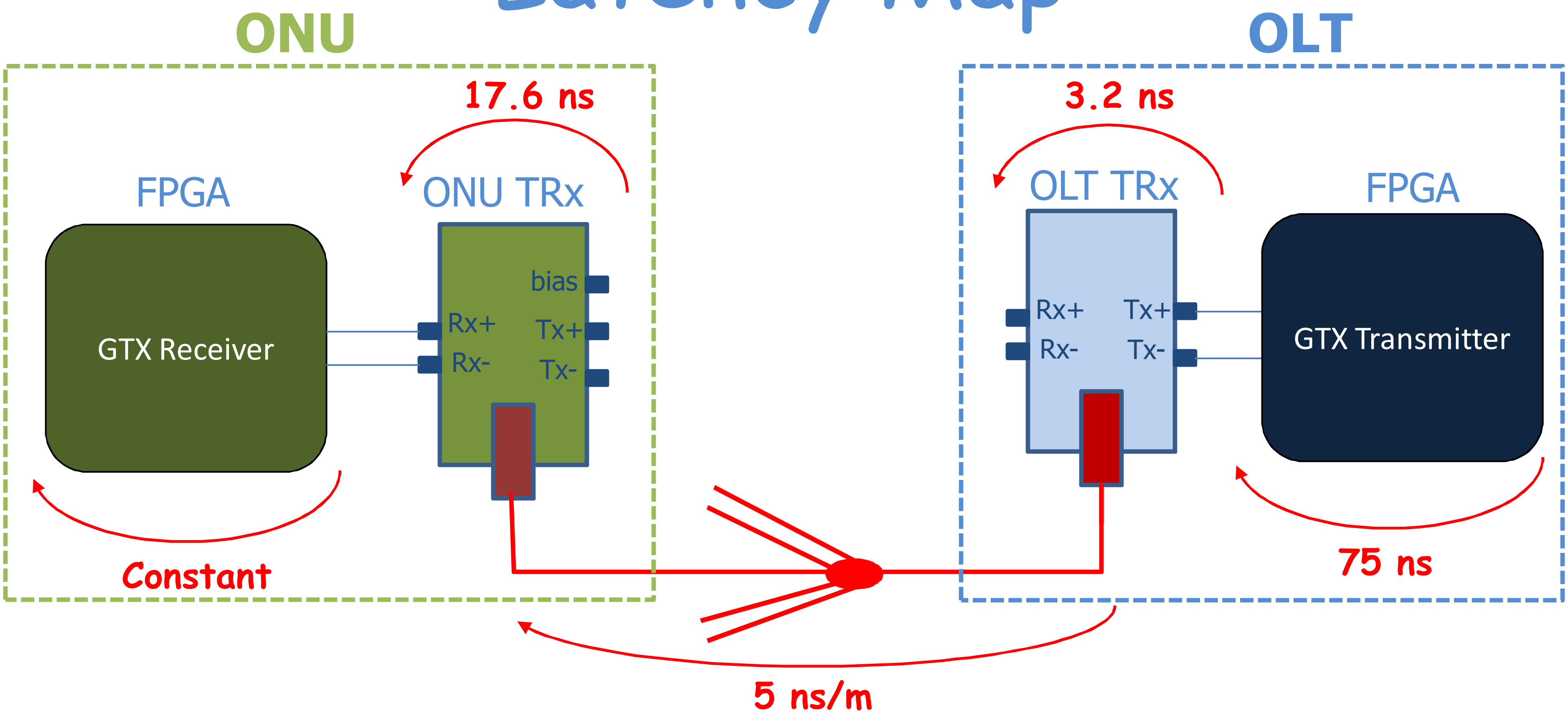


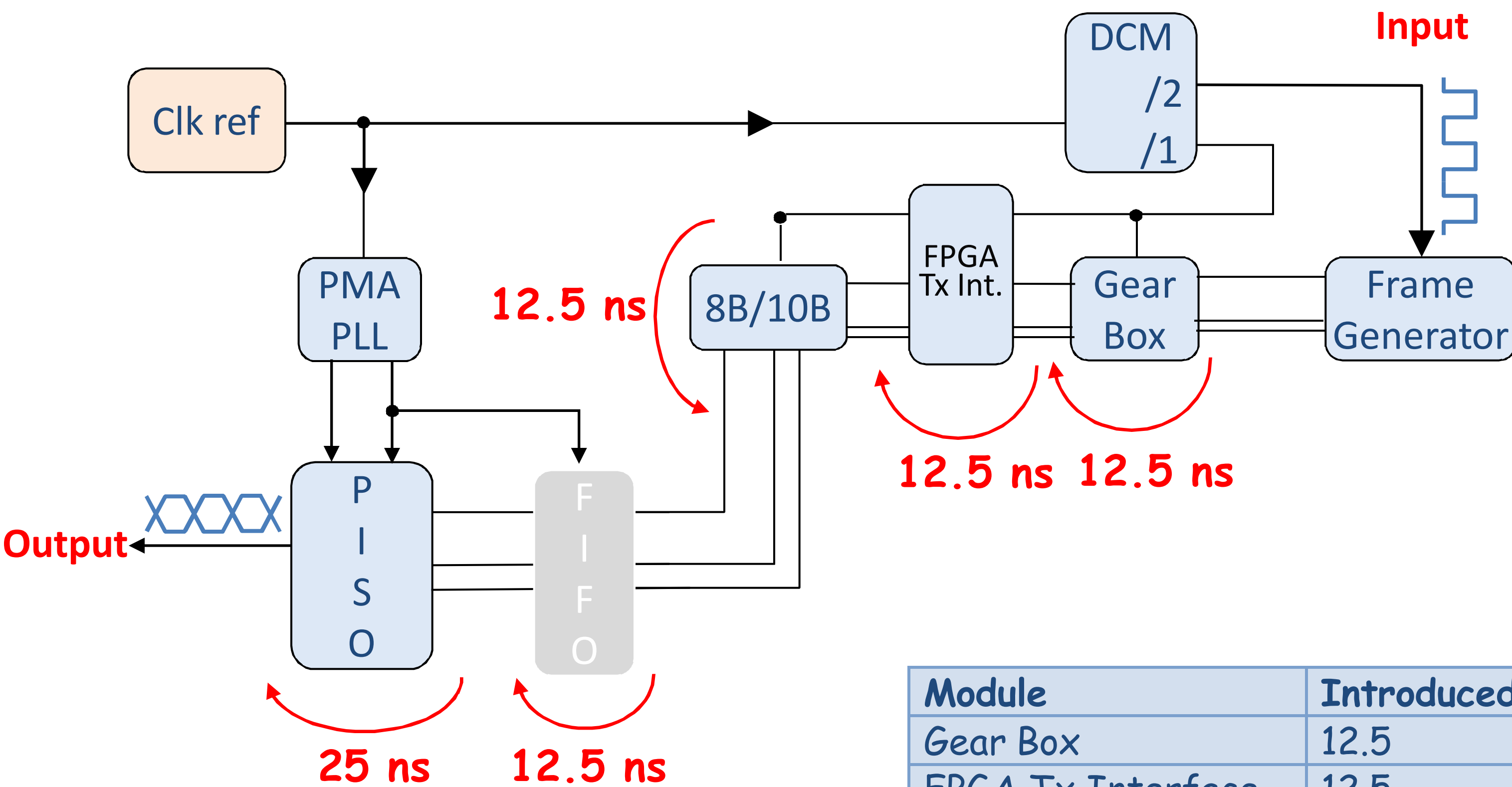
Figure 5-2: **Shared PMA PLL Conceptual View**

Latency Map



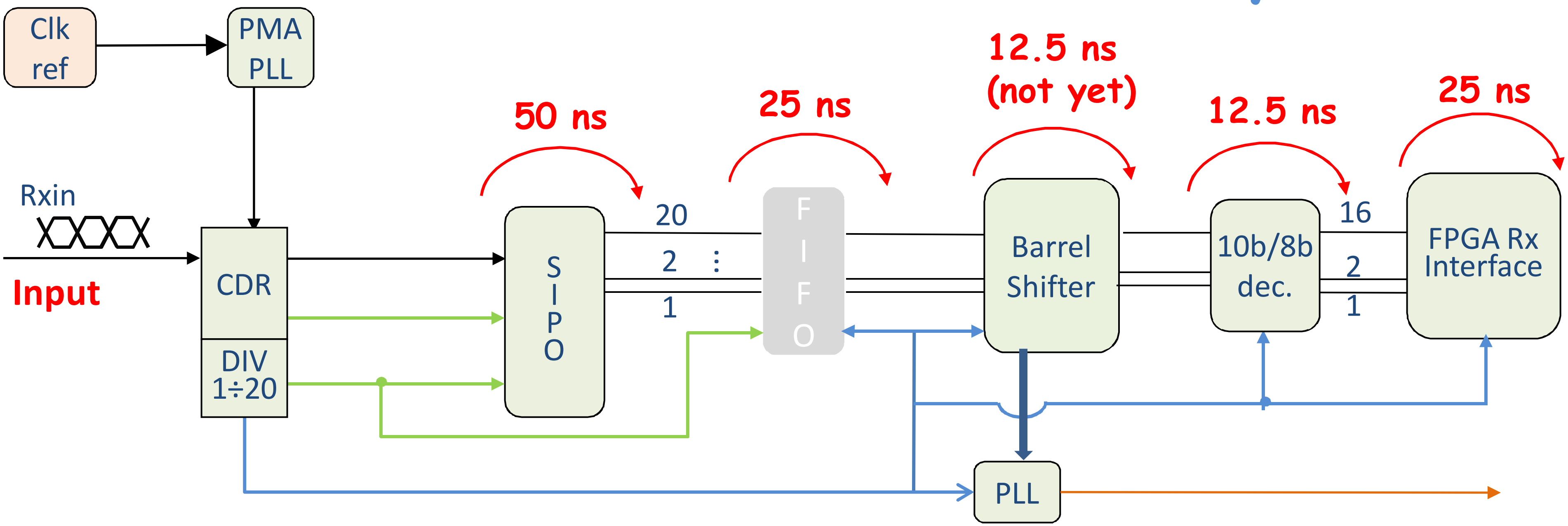
Module	Introduced Latency (ns)
GTX Tx	75
OLT Board	3.2
Fiber	5 ns/m
ONU Board	17.6
GTX Rx	Constant

OLT Tx Latency



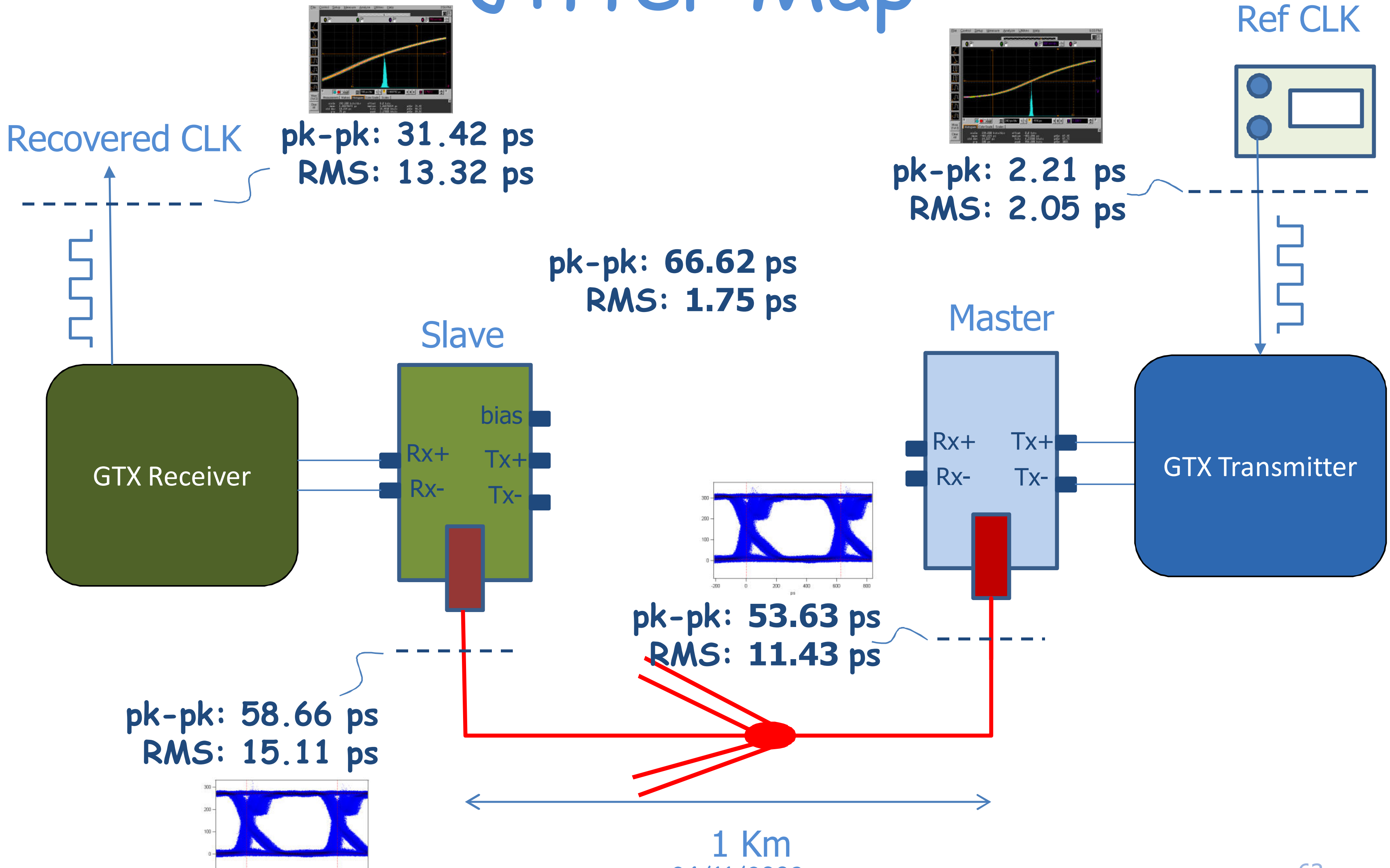
Module	Introduced Latency (ns)
Gear Box	12.5
FPGA Tx Interface	12.5
8b/10b encoder	12.5
FIFO buffer bypass	12.5
PMA+Interface	25
TOTAL	**75**

ONU Rx Total Latency



Module	Introduced Latency (ns)
PMA + Interface	50
buffer bypass	25
Barrel Shifter	12.5
8b/10b decoder	12.5
FPGA Rx Interface	25
TOTAL	**125.5**

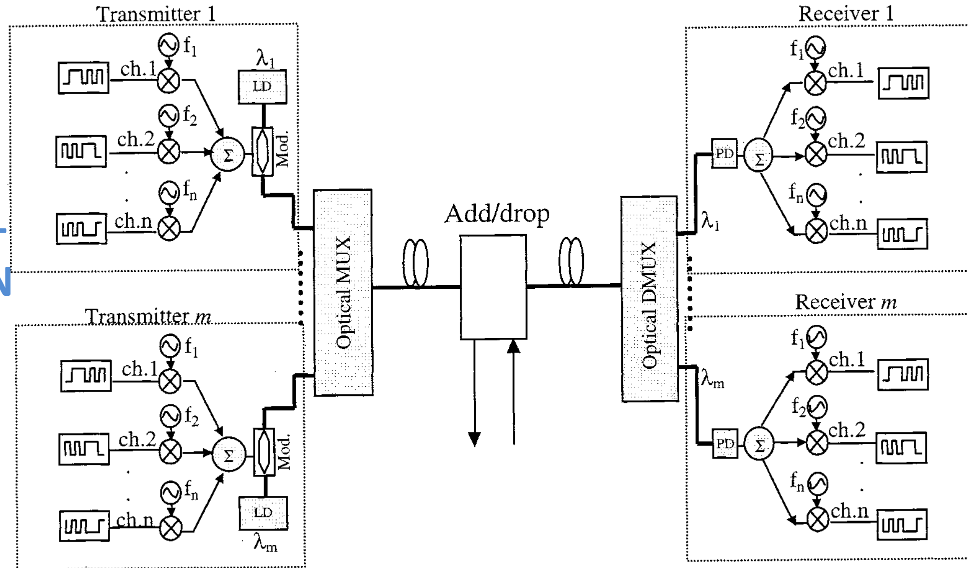
Jitter Map

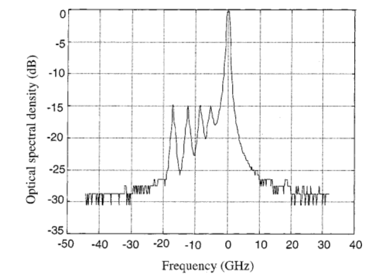


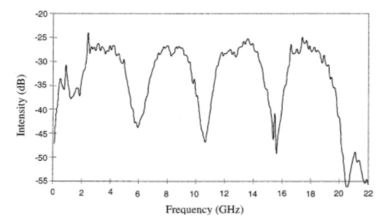
Recovered CLK
pk-pk: 31.42 ps
RMS: 13.32 ps
Ref CLK
pk-pk: 2.21 ps
RMS: 2.05 ps
pk-pk: 66.62 ps
RMS: 1.75 ps
Slave
Master
GTX Receiver
bias
Rx+
Rx-
Tx+
Tx-
Rx+
Rx-
Tx+
Tx-
GTX Transmitter
pk-pk: 53.63 ps
RMS: 11.43 ps
pk-pk: 58.66 ps
RMS: 15.11 ps
1 Km

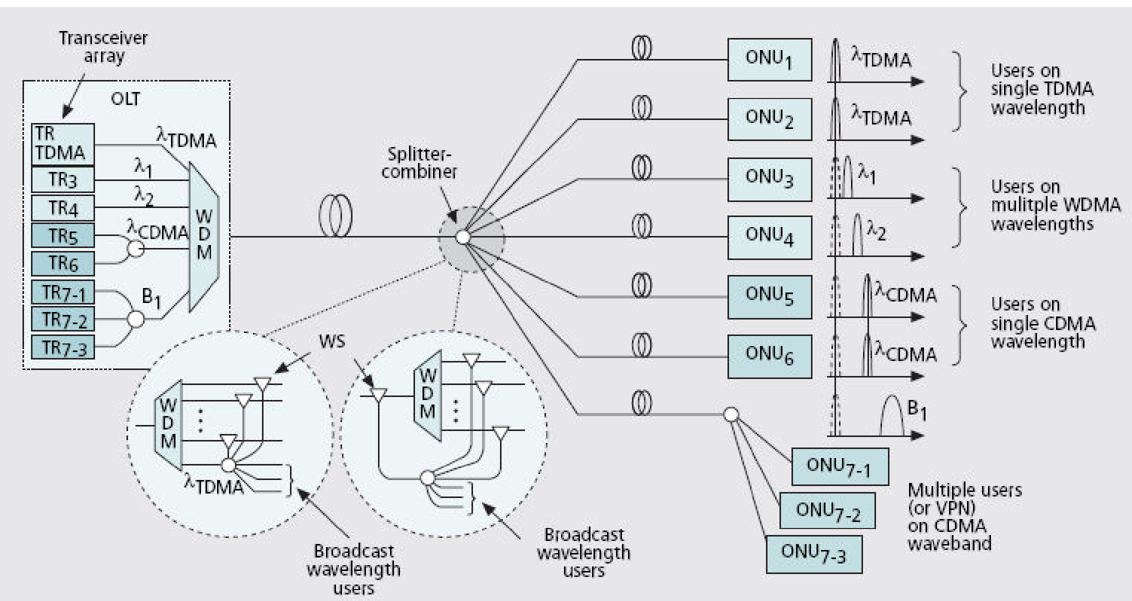
SCM and OCDMA over PONs

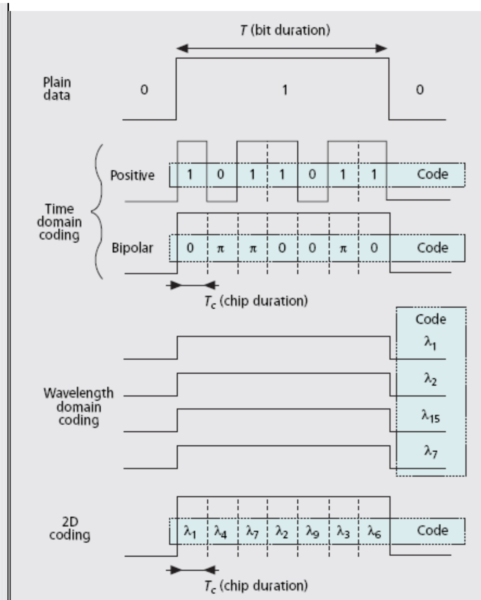
Hybrid WDM-SCM (sub-carrier modulation) PON





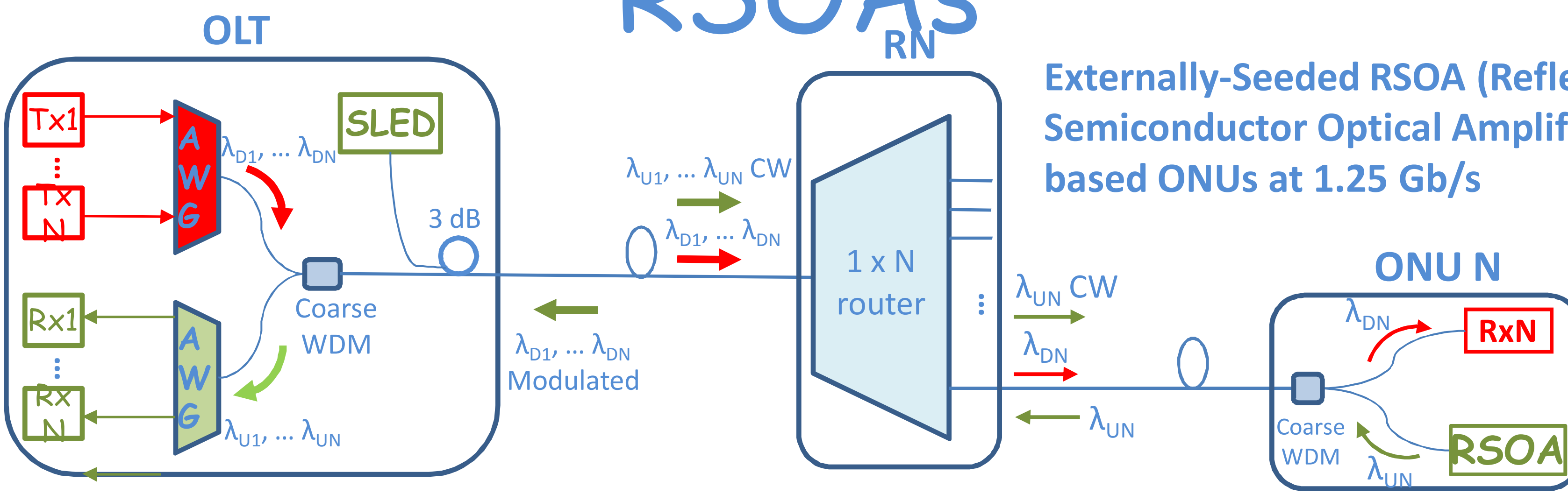




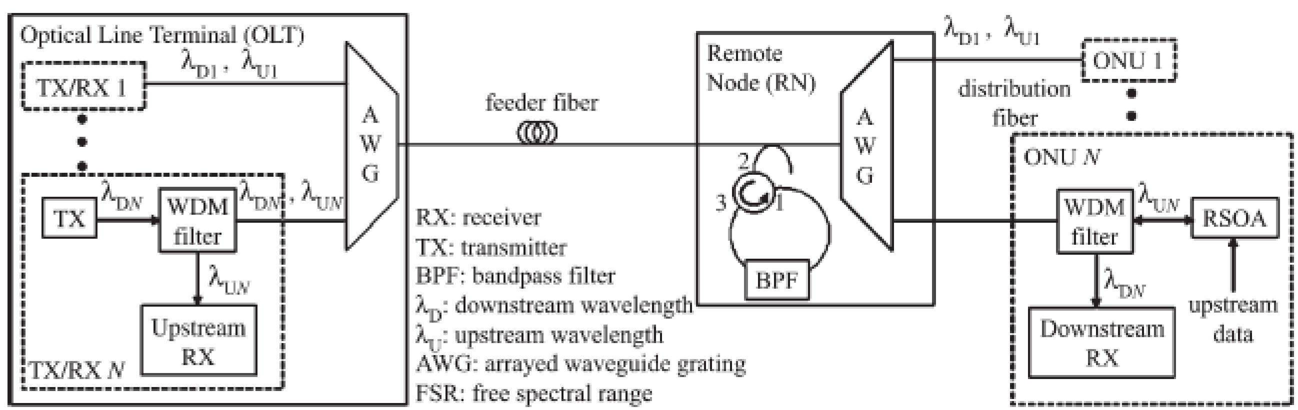


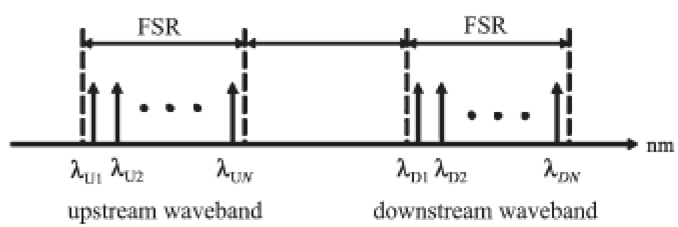
Migration scenario with OCDMA (Optical Code Division Multiplexing Access)

Colorless ONUs based on RSOAs



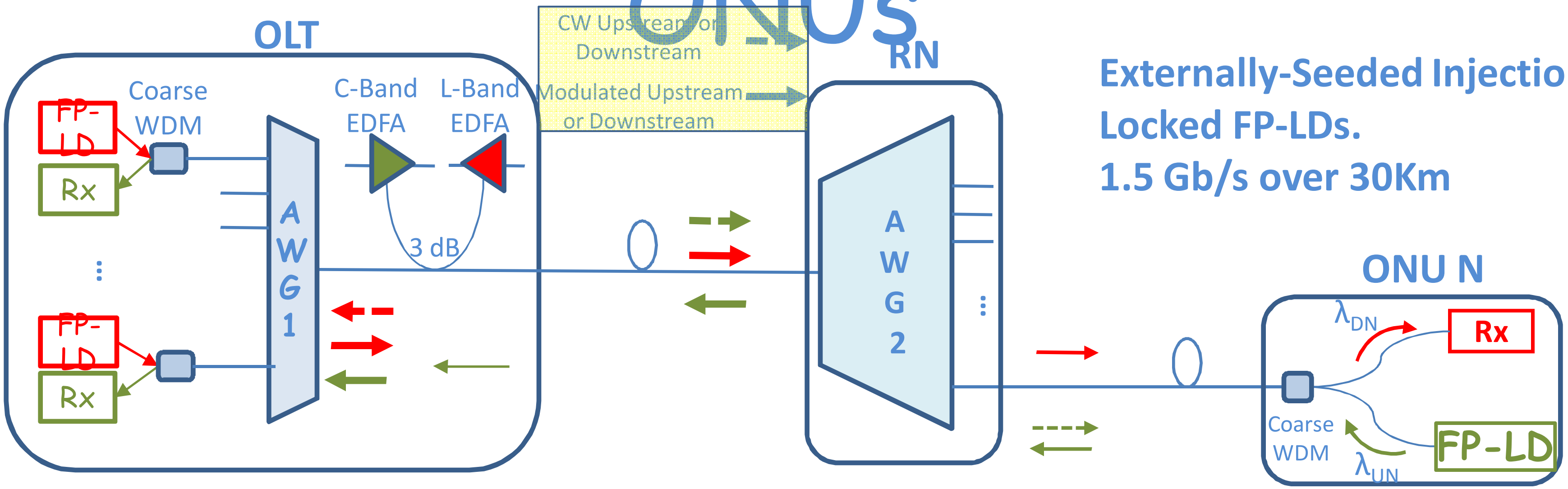
Externally-Seeded RSOA (Reflective Semiconductor Optical Amplifier) based ONUs at 1.25 Gb/s



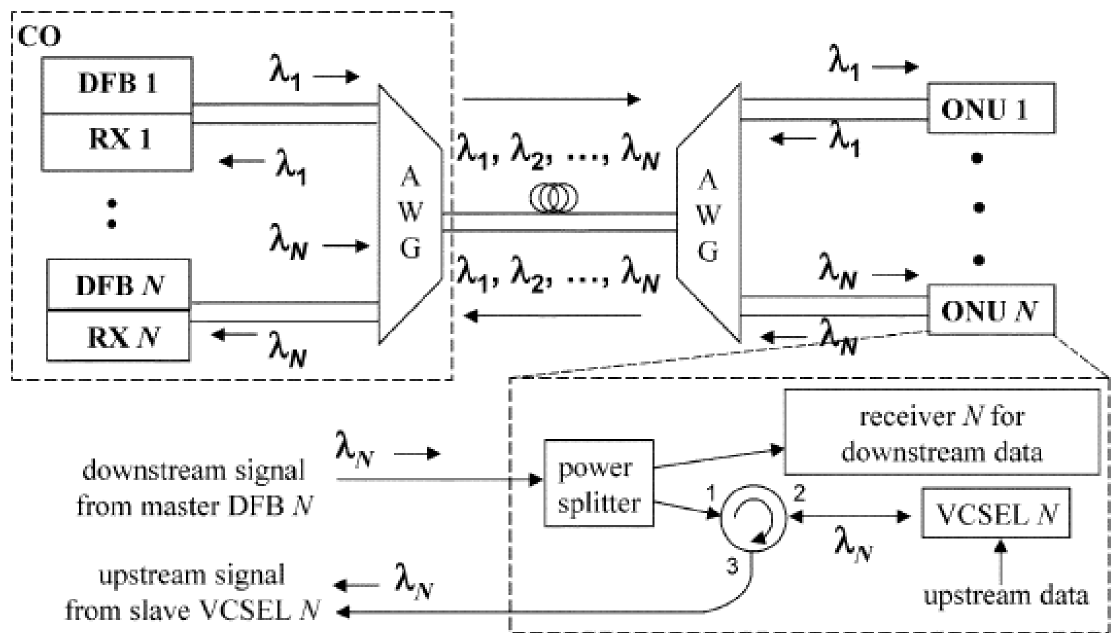


Self-Seeded (Reflective Semiconductor Optical Amplifier) RSOA based ONUs at 1.25 Gb/s

Optically Injection Locked ONUs



Externally-Seeded Injection Locked FP-LDs.
1.5 Gb/s over 30Km



DFB seeded Injection Locked VCSELs, 1550 nm
2.5 Gb/s over 25 Km