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1024 to 4096 Reasons for Using D3.1 over RFoG

Unleashing Fiber Capacity by Jointly Optimizing D3.1 and RFoG Parameters

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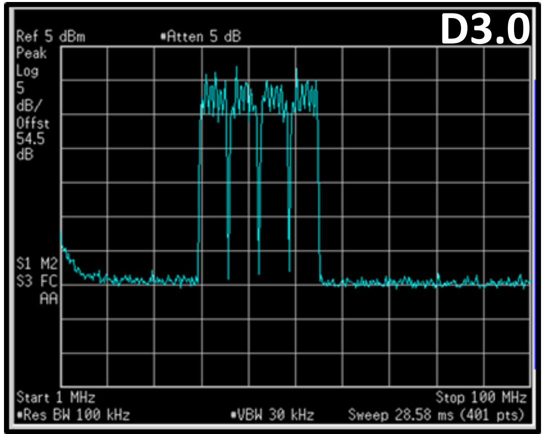
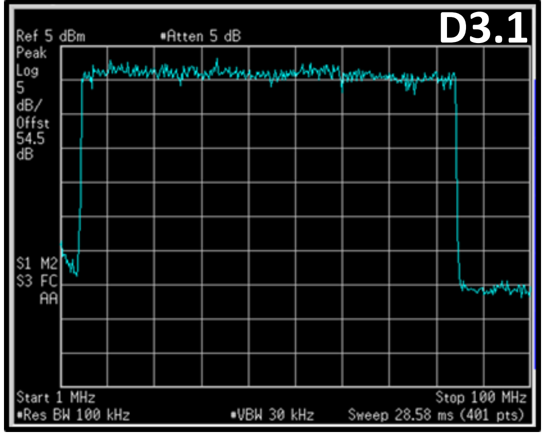
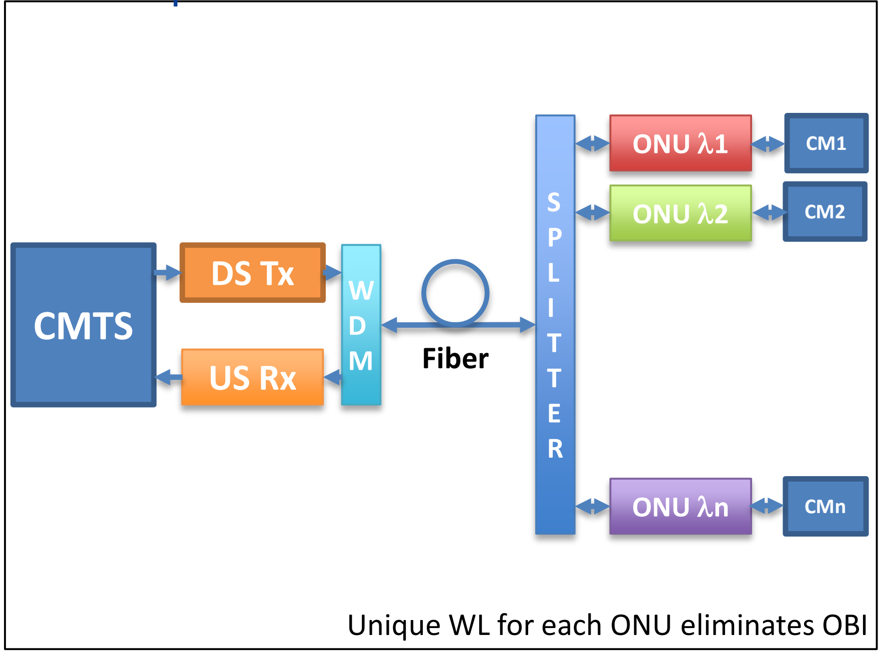
- D3.1 and RFoG: Need for OBI Elimination
  - Wavelength Selective ONU Option
  - Multi Diode Receiver Option
- D3.1 US and DS Numerology
  - The Mini-slot, Frame Size
  - Cyclic Prefix, Rolloff Period
- D2.0, D3.0, D3.1 and SCTE IPS 174
  - CP and Laser Turn On time
  - Mini-Slot and Laser Turn On RF
- Single ONU Simulated D3.1 Tests
  - Dizzying array of D3.1 Options
  - CLGD-FSW Tests
- Multi-CM/ONU CMTS System Tests
  - Test Configuration, System Sims
  - Measured Results
- Discussion
  - Dynamic Range
  - Dynamic Sliver
- Conclusions



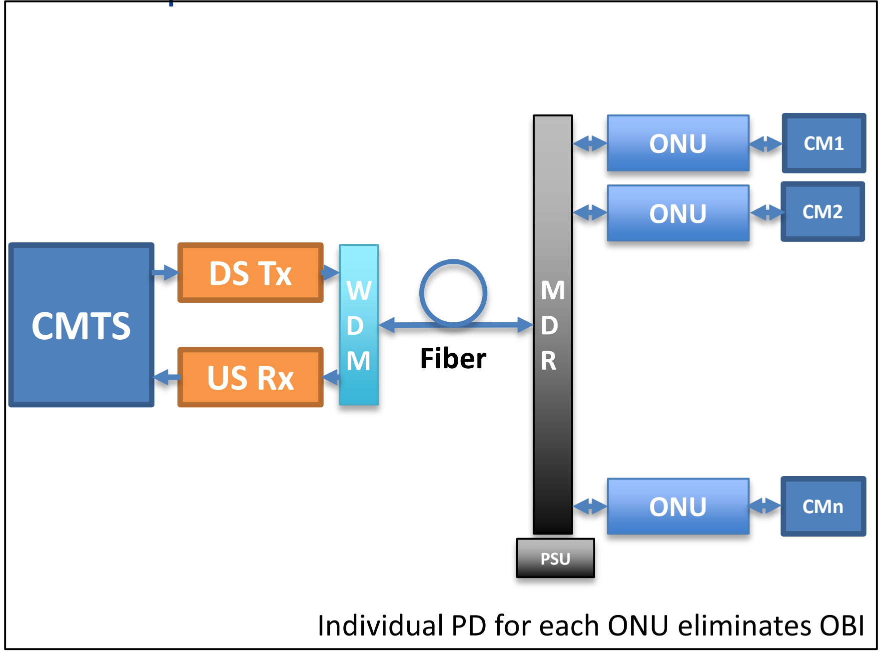


OBI and RFoG

WSO Option for OBI elimination



MDR Option for OBI elimination



D3.1 allows significantly higher number of CMs to transmit simultaneously
Thus OBI elimination is an urgent matter in the D3.1 over RFoG environment

D3.1 Numerology Summarized

D3.1 DS Numerology

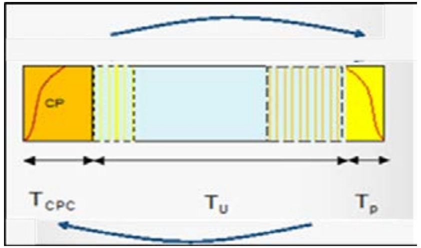
D3.1 Downstream Parameters Summarized (from CM-SP-PHYv3.1)		
Mode	4k	8k
Channel BWs	24MHz to 192MHz	
Subcarrier spacing	50kHz	25kHz
Symbol duration	20us	40us
Cyclic Prefix	0.9375, 1.25, 2.5, 3.75, 5us	
Rolloff Period	0, 0.3125, 6.25, 0.9375, 1.25us	
OFDM Constellation	CNR AWGN 1GHz	CNR AWGN 1-1.2GHz
4096	41.0	41.5
2048	37.0	37.5
1024	34.0	34.0
512	30.5	30.5
256	27.0	27.0
128	24.0	24.0
64	21.0	21.0
16	15.0	15.0

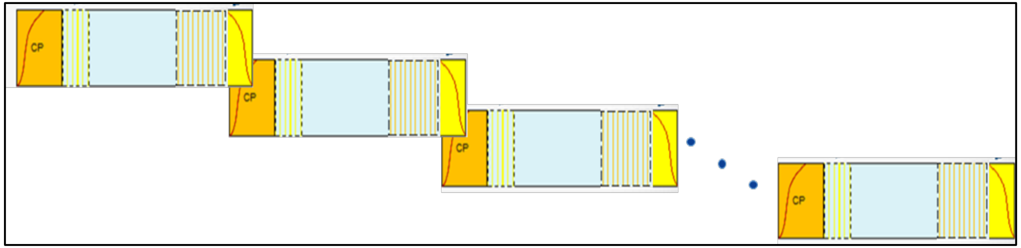
D3.1 US Numerology

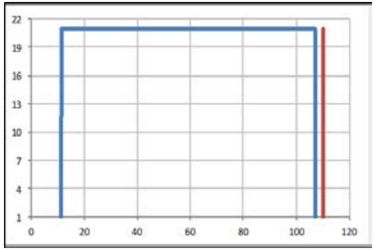
D3.1 Upstream Parameters Summarized (from CM-SP-PHYv3.1)		
Mode	2k	4k
Channel BWs	10MHz-96MHz	6.4MHz - 96MHz
Subcarrier spacing	50kHz	25kHz
Symbol duration	20us	40us
Cyclic Prefix	0.9375, 1.25, 1.5625, 1.875, 2.1875, 2.5, 2.8125, 3.125, 3.75, 5.0, 6.25 us	
Rolloff Period	0, 0.3125, 0.625, 0.9375, 1.25, 1.5625, 1.875, 2.1875 us	
OFDMA Constellation	CNR AWGN	
4096	43.0	
2048	39.0	
1024	35.5	
512	32.5	
256	29.0	
128	26.0	
64	23.0	
32	20.0	
16	17.0	
8	14.0	
QPSK	11.0	

- D3.1 presents a vast array of choices, multiple CP, RP and Symbol sizes
- Improved SNR results in higher Capacity

D3.1: Symbol, Frame and the Mini-Slot







- D3.1 Upstream in the Time Domain
  - Symbol Size can be 20us or 40us, multiple Symbols join to form a frame
  - Each Symbol has multiple CP and RP options, CP helps with micro-reflections in the typical HFC plant, RP shapes the Symbol
  - In an RFoG System, CP must be chosen to accommodate ONU Laser Turn-On time

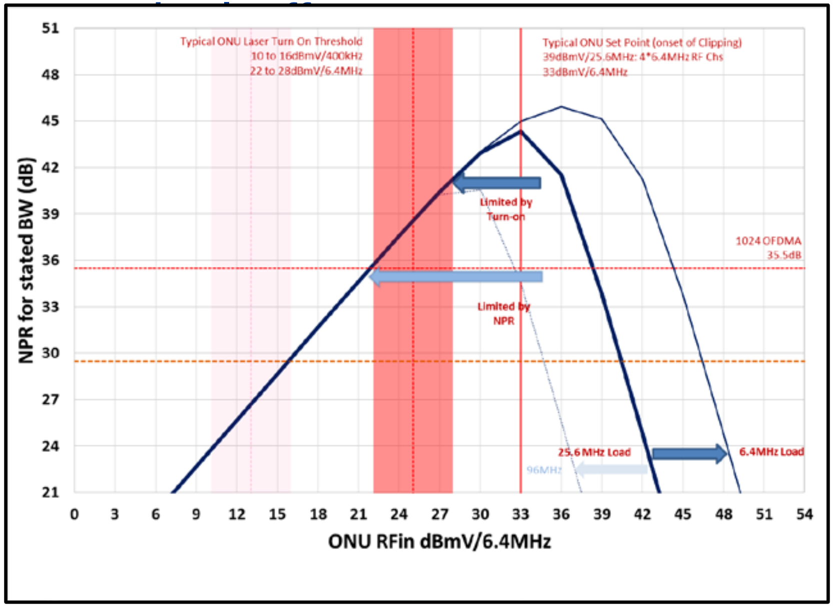
- D3.1 Upstream in the Frequency domain
  - Encompassed Spectrum may range from 6.4MHz to 96MHz
  - But can transmit in as little as 400kHz of mini-slot size
  - A very wide range of RF input can be present at the ONU

The 400 kHz mini-slot in frequency domain along with consecutive set of symbols that comprise a Frame, in time domain, form a well-defined unit that carries data in D3.1

RFoG: SCTE IPS 174 Standard and D3.1 Upstream

SCTE IPS 174

Simplified Summary of RFoG SCTE IPS 174	
ONU DS WL Range	1540-1565 nm
ONU US WL Ranges	1610+/-10 nm
ONU Laser Power on	3+/-1.5 dBm
ONU Laser Power off	<-30 dBm
ONU Laser Turn-On time	<1.3 us
ONU Laser Turn-Off time	<1.6 us
ONU Laser Turn-On RF	+7 to +16 dBmV
ONU Laser Turn-Off RF	+1 to -8 dBmV
OMI at Total Power	35% +/-3dB @39dBmV
Nominal RF Input Level/6.4MHz	33 dBmV (17.5% OMI)
Nominal Number of RF Channels	4
OBI Elimination Options	None as currently written



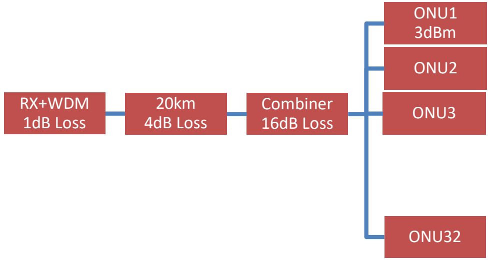
ONU can require up to 16dBmV/400kHz to turn on the ONU Laser in Burst Mode

Maximum single D3.1 Encompassed Spectrum can be up to 96MHz

Overall Dynamic Range limited by ONU Laser Turn-on and Encompassed Spectrum - not just available SNR

DYNAMIC RANGES: RECEIVER, RF and NPR

Optical RX Dynamic Range



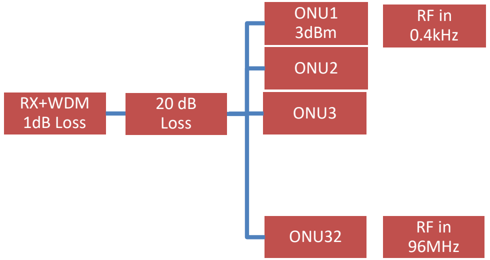
RFoG Loss	22dB
ONUs ON	P(dBm) in Rx
1	-19
4	-13
16	-7
32	-4

The Rx must work from -3 to -19dBm

High Saturation + High Sensitivity

D3.0 had only 4 ONUs that could turn on simultaneously

D3.1 RF Dynamic Range



RF nom	OMI nom	MHz
33	17.5%	6.4
RF(MHz)	RF(dBmV)	OMI(%)
0.4	21	4%
1.6	27	9%
6.4	33	18%
25.6	39	35%
48	42	48%
96	45	68%

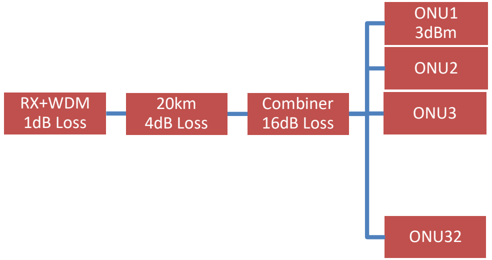
Max Tx Static Range: 24dB

RF in Low: The ONU will not turn on

RF in High: The ONU will clip

D3.0 needed only 6dB of Range

NPR Dynamic Range

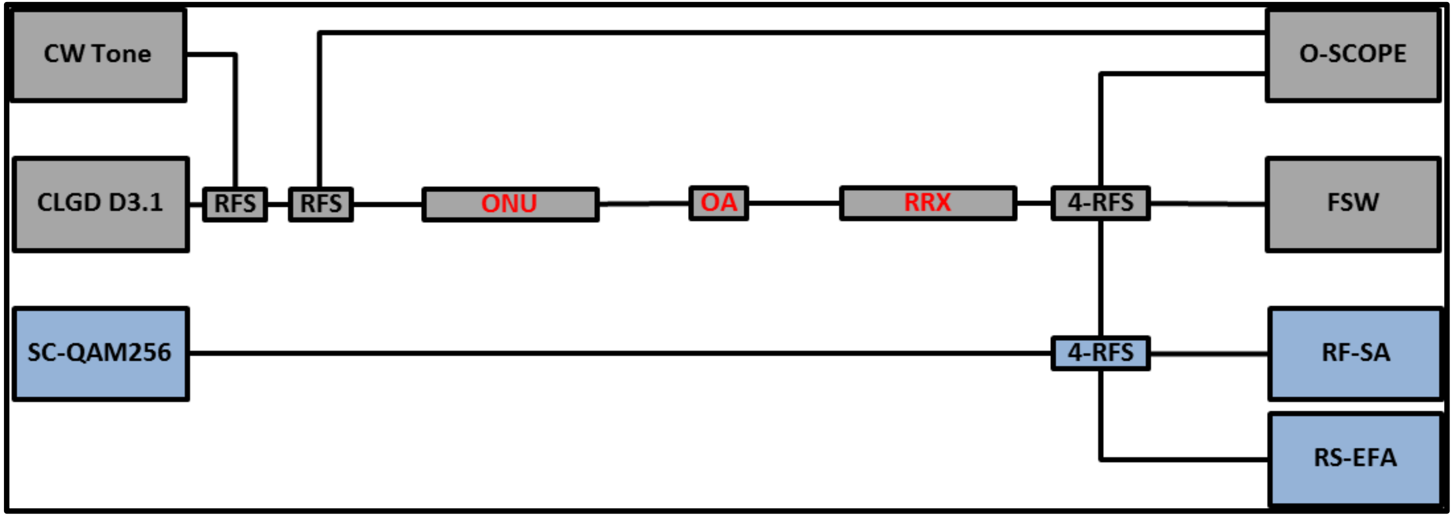


RFoG Loss	22dB	WSO Option
ONUs ON	P(dBm) Total	Est NPR(dB)
1	-19	44
4	-13	41
16	-7	38
32	-4	35

In Burst Mode, if only one ONU is On, the SNR is adequate, but if all 32 ONUs are ON, then even in BTM, the SNR can suffer

In Continuous Mode, the SNR is as above, but there is no impact due to laser turn-on clipping, collateral clipping and the selection of low CP values

SINGLE CM/ONU TESTS



- The SC-QAM256 when added Post RRX will provide
  - A reliable always-on constellation for performance assessments of MER and BER
- Traditional RF spectrum analyzer will provide
  - Readings of RF spectrum in Max/Min Hold position, and MER and BER of SC-QAM256
- View of the FSW will provide a measure of the US MER
  - Varying CP and measuring MER provides the relationship between ONU Laser turn-On and the CP Value needed for reliable operation of D3.1

THE DIZZYING CHOICES IN D3.1

Arbitrary Waveform Filename	QAM Modulation	Encompassed Spectrum (MHz)	FFT Size	CP Value (us)	RP Value (us)	File Created
DS3_1 US Case #1	1024					X
DS3_1 US Case #2	2048	34	4K	0.9375	0.3125	X
DS3_1 US Case #3	4096					X
DS3_1 US Case #4	1024					X
DS3_1 US Case #5	2048	34	2K	0.9375	0.3125	X
DS3_1 US Case #6	4096					X
DS3_1 US Case #7	1024					X
DS3_1 US Case #8	2048	34	4K	0.9375	0.625	X
DS3_1 US Case #9	4096					X
DS3_1 US Case #10	1024					X
DS3_1 US Case #11	2048	34	2K	0.9375	0.625	X
DS3_1 US Case #12	4096					X
DS3_1 US Case #13	1024					X
DS3_1 US Case #14	2048	34	4K	6.25	0.3125	X
DS3_1 US Case #15	4096					X
DS3_1 US Case #16	1024					X
DS3_1 US Case #17	2048	34	2K	6.25	0.3125	X
DS3_1 US Case #18	4096					X
DS3_1 US Case #19	1024					X
DS3_1 US Case #20	2048	34	4K	6.25	2.1875	X
DS3_1 US Case #21	4096					X
DS3_1 US Case #22	1024					X
DS3_1 US Case #23	2048	34	2K	6.25	2.1875	X
DS3_1 US Case #24	4096					X
DS3_1 US Case #25	1024					X
DS3_1 US Case #26	2048	34	4K	1.5625	0.3125	X
DS3_1 US Case #27	4096					X
DS3_1 US Case #28	1024					X
DS3_1 US Case #29	2048	34	2K	1.5625	0.3125	X
DS3_1 US Case #30	4096					X
DS3_1 US Case #31	1024					X
DS3_1 US Case #32	2048	34	4K	1.5625	1.25	X
DS3_1 US Case #33	4096					X
DS3_1 US Case #34	1024					X
DS3_1 US Case #35	2048	34	2K	1.5625	1.25	X
DS3_1 US Case #36	4096					X
DS3_1 US Case #37	1024					X
DS3_1 US Case #38	2048	34	4K	3.125	0.3125	X
DS3_1 US Case #39	4096					X
DS3_1 US Case #40	1024					X
DS3_1 US Case #41	2048	34	2K	3.125	0.3125	X
DS3_1 US Case #42	4096					X
DS3_1 US Case #43	1024					X
DS3_1 US Case #44	2048	34	4K	3.125	2.1875	X
DS3_1 US Case #45	4096					X
DS3_1 US Case #46	1024					X
DS3_1 US Case #47	2048	34	2K	3.125	2.1875	X
DS3_1 US Case #48	4096					X

Sample 48 CLGD ARB Files with varied parameters

Individual D3.1 Parameters

- Modulation Formats
  - 1024, 2048, 4096 OFDMA
- Encompassed Spectrum
  - 34MHz
- FFT Size
  - 2K, 4K
- Cyclic Prefix
  - 0.9375us, 1.5625us, 3.125us, 6.25us
- Roll-off Period
  - 0.3125us, 0.625us, 1.25us, 2.185us

Individual ONU Parameters

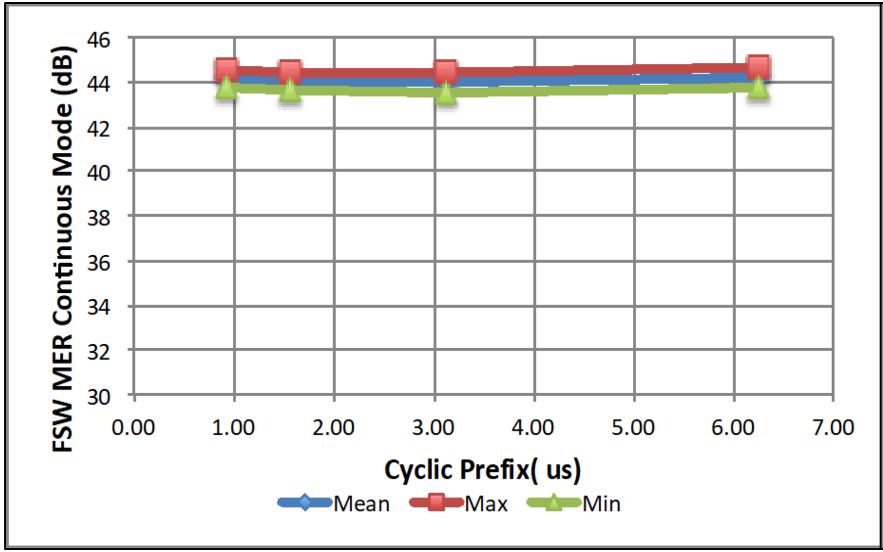
- *Laser Turn-on times*
- *Laser Turn-on threshold*
- *Burst/Continuous Modes*

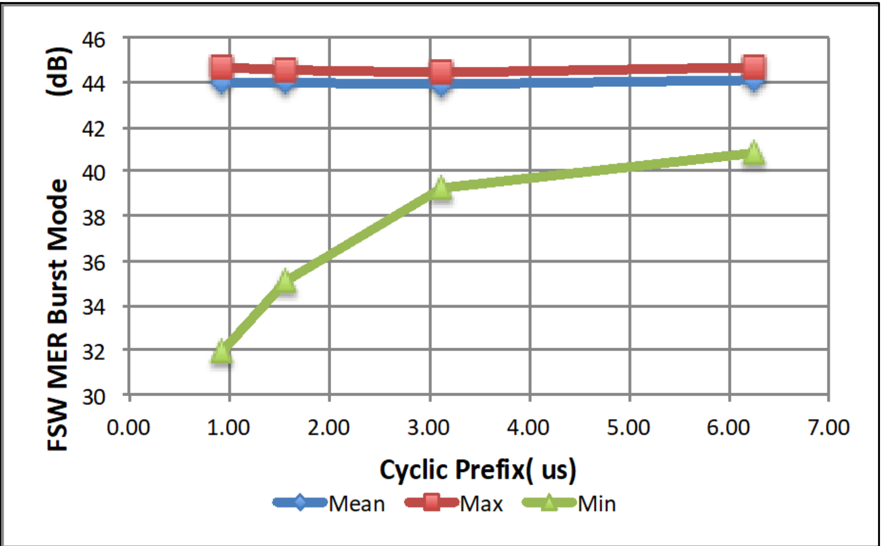
Varying individual parameters enables us to understand effects of each parameter on performance

CLGD+FSW Tests: Sample results (1024QAM, 2K FFT, 0.3125uS RP, SCTE IPS 174 COMPLIANT ONU)

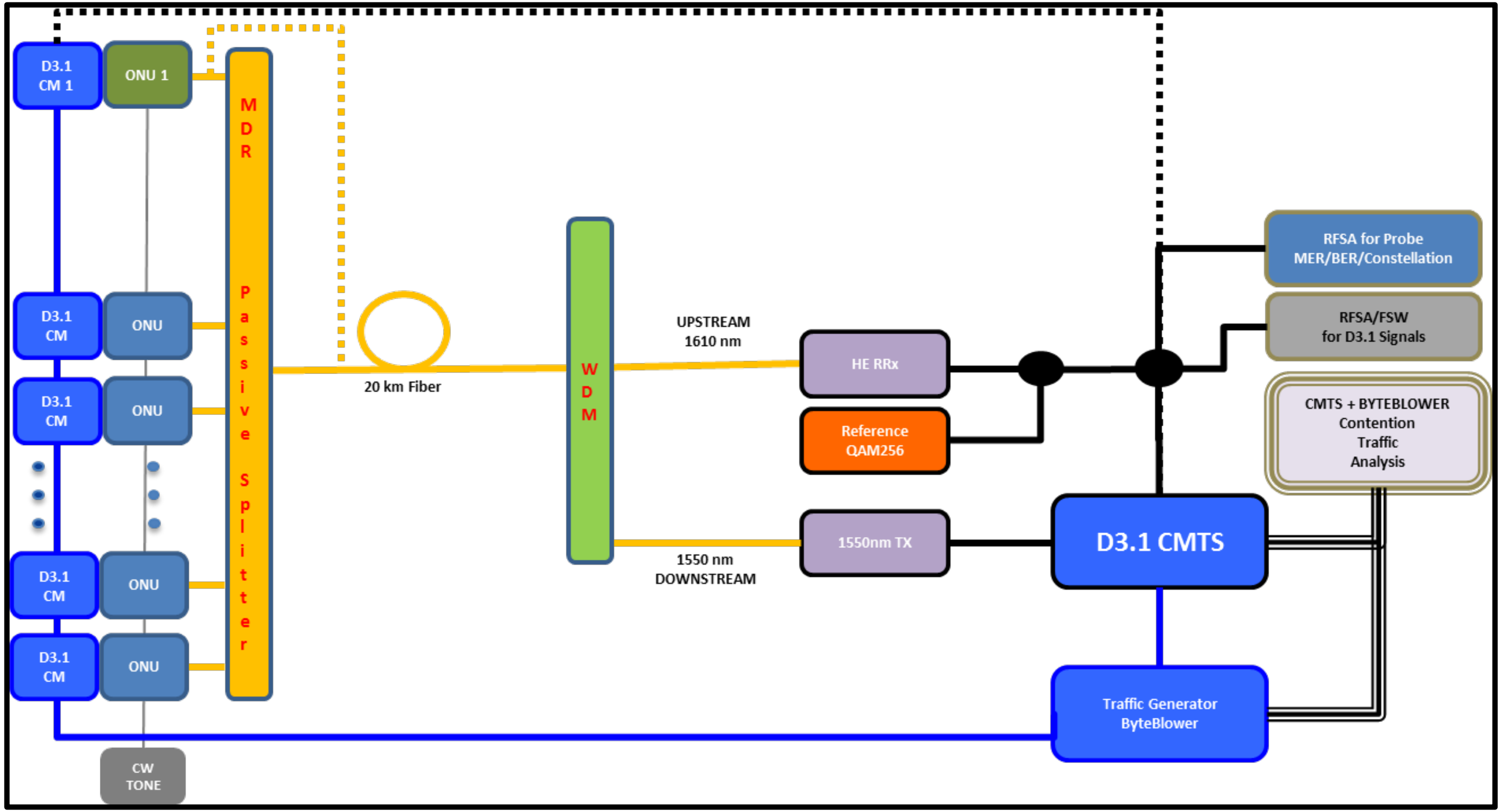
27dBmV/35MHz	MER Continuous Mode ONU			MER Burst Mode ONU (1.3us)		
CP	Mean	Max	Min	**Mean**	**Max**	**Min**
0.9375	44.2	44.5	43.8	**44.0**	**44.6**	**31.9**
1.5625	44.0	44.4	43.6	**44.0**	**44.5**	**35.1**
3.1250	44.0	44.4	43.5	**43.9**	**44.4**	**39.2**
6.2500	44.2	44.6	43.8	**44.1**	**44.6**	**40.8**

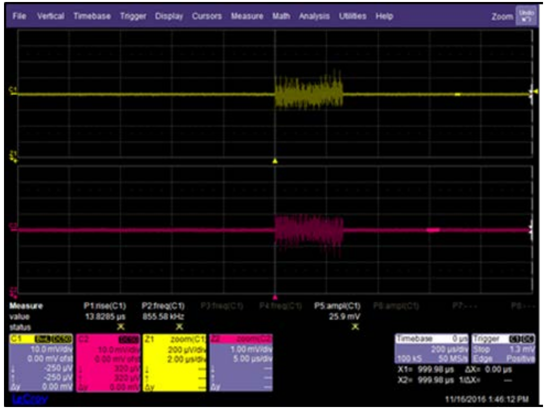
Rolloff Parameter does not affect performance significantly
CP must exceed the Laser Turn-on time for adequate performance, Continuous Mode performance impervious to CP values

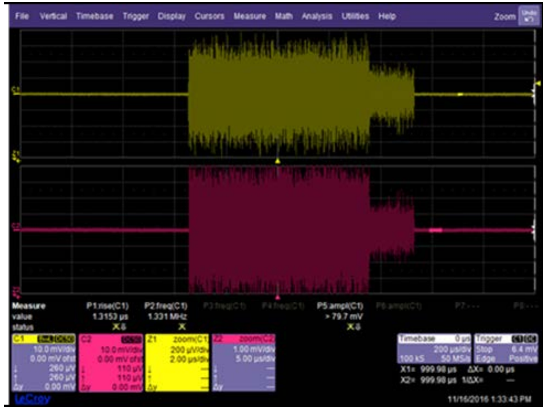




Multi-CM/ONU D3.1 Test Setup





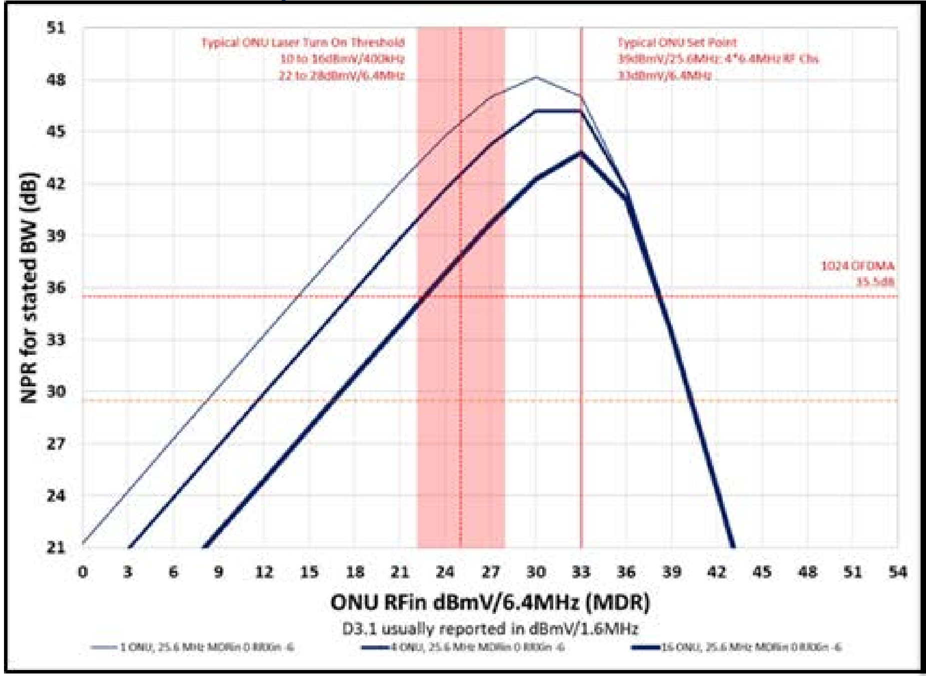


Ranging, Registering and Signaling

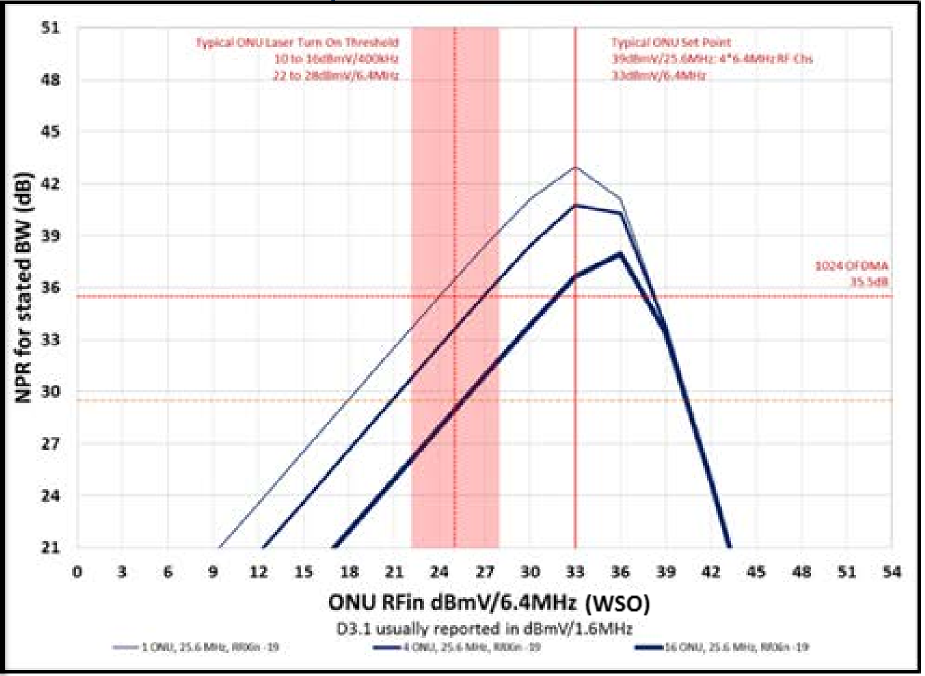
- D3.0 range and register signals are of a lower modulation format and require a lower MER than the data signals themselves
- For D3.1 to complete range and register, adequate MER must be established using the same modulation profile as the data signals
    - Therefore, it is critical that the system robustly support the required MER before the CMs are set to range and register
- D3.1 Range and Register signals use the 400kHz mini-slot
    - RF levels into the ONU must feature an RF level which is high enough within 400 kHz to trigger the ONU laser on for successful range and registering
- Range and register signals are sent periodically in addition to station maintenance,
    - Therefore the MER of the system must be maintained to prevent time out conditions
- Larger bursts of traffic generally use larger numbers of available mini-slots in the Frequency Domain before using additional Frames in the Time Domain

System NPR Simulations
32 way splitter + 20km link

NPR: MDR Option



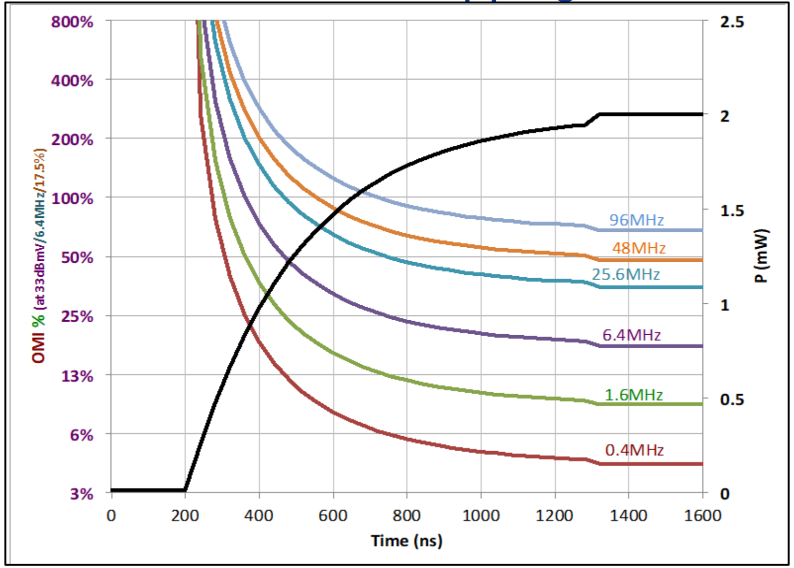
NPR: WSO Option



NPR and the Dynamic Range of the WSO Option is limited by SNR degradation due to multiple simultaneously on ONUs

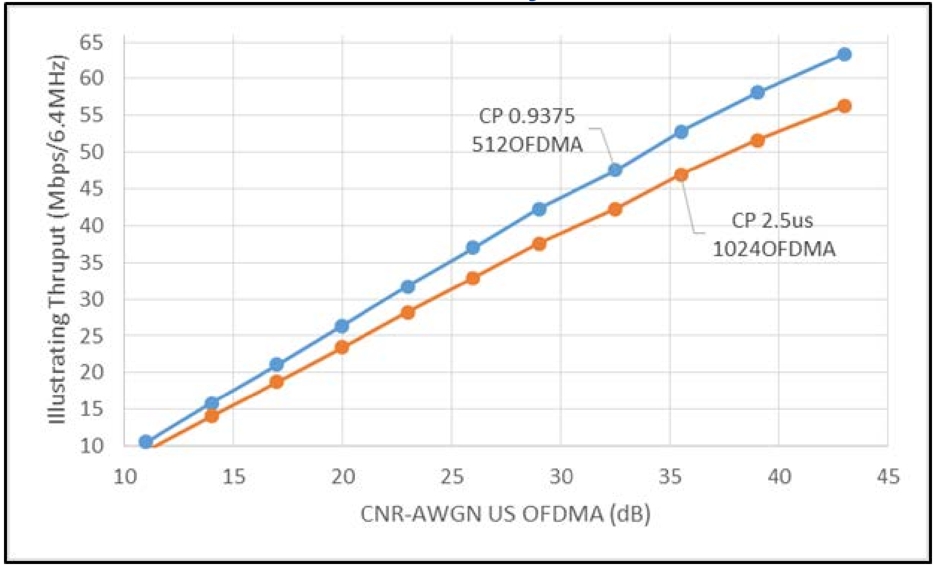
The higher SNR possible in MDR Option may not result in greater NPR Dynamic Range due to the Laser Turn-on Threshold

Self and Collateral Clipping



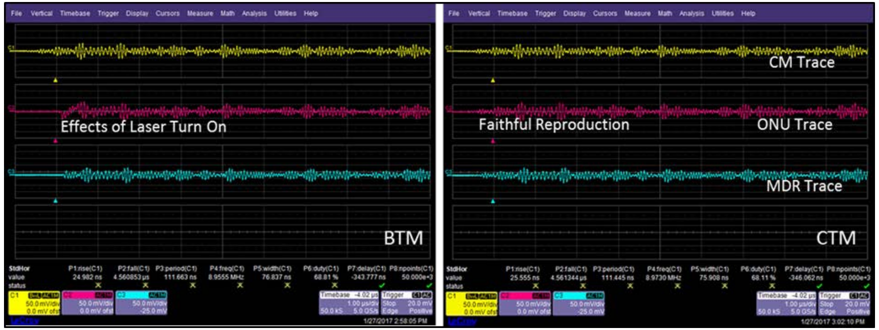
- The ONU Laser experiences a high OMI from initial Turn-On to Maturity
- Laser Clipping occurs, which impacts
  - Current ONU (Self Clipping)
  - Other Transmitting ONUs (Collateral Clipping)

CP choice and Efficiency



- Increasing the CP enables the accommodation of stronger echoes and longer Laser Turn-on, but decreases Efficiency
- A CP increase is an equivalent to a reduction in SNR which is equivalent to a decrease in Capacity
  - 0.9375us to 2.5us CP equivalent to 3dB decrease in SNR, equivalent to a move from 1024OFDMA to 512OFDMA

CTM and BTM in the Time Domain



Time domain Capture of Cable modem output, the ONU Output and the MDR output in the BTM and CTM operations show

- Small delay in the laser turn on can be seen in the BTM operation, no delay seen in CTM operation
- RF level variation in the Turn-On for the BTM operation, no such variation observed in the CTM
- CTM can help avoid Self and Collateral Clipping events

CTM vs. BTM Trade-offs

Effects	ONUs in BTM	ONUs in CTM
Ingress, Noise Funneling Observed	No	Yes
Noise Floor Rise Observed	No	Yes
Laser Turn On Clipping	Yes	No
Collateral Clipping	Yes	No
CP Values Restricted: Laser Turn On Time	Yes	No
Dynamic Range Restricted: Laser Turn On Level	Yes	No

Ingress can be a significant concern

- In the BTM operation Ingress and noise funneling is considerably reduced , but in CTM operation, the issue of Ingress and noise funneling is not addressed
- The CTM operation could enhance efficiency with lower CP values, but the BTM operation would require a minimum CP value to accommodate ONU Laser turn-on
- CTM operation would allow for noise limited operation thereby enhancing Dynamic Ranges and providing flexibility for additional modulation profiles, but BTM is more restricted by the Turn-on level requirement

System RF Level Variations

RF Levels dBmV/1.6MHz	MDR System ONU RF in	WSO System ONU RF in
CM-ONU 1	*27.5*	*27.0*
CM-ONU 2	*27.0*	*26.5*
CM-ONU 3	*25.3*	*24.8*
CM-ONU 4	*28.3*	*28.3*
CM-ONU 5	28.3	27.8
CM-ONU 6	27.3	27.3
CM-ONU 7	27.5	27.0
CM-ONU 8	28.0	27.8
CM-ONU 9	27.3	26.8
CM-ONU 10	26.3	25.8
CM-ONU 11	25.3	25.0
CM-ONU 12	26.8	26.3
CM-ONU 13	26.5	26.5
CM-ONU 14	29.0	28.8
CM-ONU 15	23.8	24.0
CM-ONU 16	28.3	28.3
Mean RF	27.0	26.7
Max RF	29.0	28.8
Min RF	23.8	24.0
SD	1.4	1.3
Max-Min	5.3	4.8
Mean RF 4	*27.0*	*26.6*
Max-Min 4	*3.0*	*3.5*

Practical System Limitations

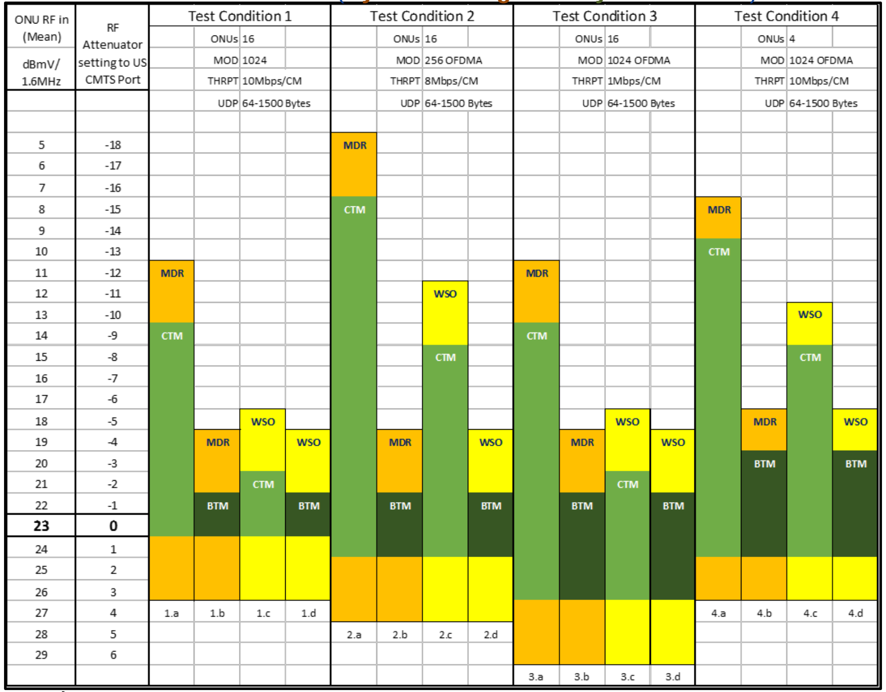
- It is common to experience around 6 dB or more of variation in CM RF input levels across the ONUs
- This is due to
  - ONU unit to unit variations
  - Link variations for individual ONUs to the CMTS
  - Finite resolution of the CMTS long loop AGC
- This variation is further enhanced with
  - Temperature changes
  - Ageing effects
- These variations cause the NPR curves of individual ONUs to be offset horizontally and vertically, and also sometimes shift continually in response to environmental factors
- ***The effective range of operation of the system could be considerably reduced from what would appear to be the dynamic range of an individual ONU***

Measured Results: Dynamic Slivers and Dynamic Ranges

Test Conditions

1. 1024OFDMA with 10Mbps/CM leading to total of 160Mbps traffic for 16 ONUs
   a. MDR with ONUs in CTM operation
   b. MDR with ONUs in BTM operation
   c. WSO with ONUs in CTM operation
   d. WSO with ONUs in BTM operation
2. 256OFDMA with 8Mbps/CM leading to a total of 128Mbps traffic for 16 ONUs
   a. MDR with ONUs in CTM operation
   b. MDR with ONUs in BTM operation
   c. WSO with ONUs in CTM operation
   d. WSO with ONUs in BTM operation
3. 1024OFDMA with 1Mbps/CM to simulate a lightly loaded system for 16 ONUs
   a. MDR with ONUs in CTM operation
   b. MDR with ONUs in BTM operation
   c. WSO with ONUs in CTM operation
   d. WSO with ONUs in BTM operation
4. 1024OFDMA with 10Mbps/CM and 4 ONUs to simulate RFoG system with minimal penetration
   a. MDR with ONUs in CTM operation
   b. MDR with ONUs in BTM operation
   c. WSO with ONUs in CTM operation
   d. WSO with ONUs in BTM operation

Measured Results (Dynamic Range and Dynamic Sliver)



- Reduction in Dynamic Range with multiple ONUs on for both WSO and MDR options
- Without the burden of Laser Turn-on, the Dynamic Range is substantially Increased in CTM operation vs. in the BTM operation
- Move from 1024OFDMA to 256OFDMA helps in the CTM case, but not in the BTM case
- Decrease in the Utilization (Encompassed Spectrum) increases the Dynamic Range due to later onset of Laser Clipping

- D3.1 has many different ‘performance handles’ and calls for the operator to carefully consider tradeoffs to optimize operating conditions for their RFoG networks
- The ability of a significantly higher number of CMs to transmit simultaneously make the matter of OBI elimination a much more urgent matter. Two such, the MDR and WSO options have been evaluated and discussed
- Single ONU tests with the CLGD and FSW helped establish the role of CP and how it affects laser Turn-On requirements
- Multi-CM/ONU tests in a CMTS test bed help establish Dynamic Ranges for various Thruputs and Modes of Operation
- This paper represents a first step towards gaining a complete and full understanding of the implications of supporting D3.1 US capability in existing and to be deployed RFoG Systems … More work to come

THANK YOU!

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