OFDM Capacity Optimization

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OFDM Optimization – Channel Configuration And Profile Selection

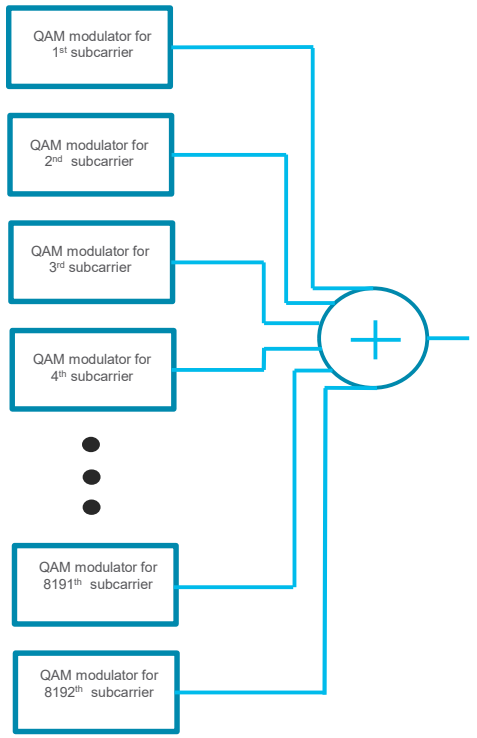
- Orthogonal frequency division multiplexing (OFDM) channel capacity can be greatly impacted by configuration choices due to high physical layer (PHY) overhead
- OFDM PHY is most impacted by subcarrier spacing and cyclic prefix with next codeword pointer and roll-off also contributing overhead
- Multiple data profiles with different modulation orders allow an OFDM channel to run at different speeds for different modems
- Overly conservative profile selection thresholds can cause the CMTS to use lower order modulation profiles reducing channel capacity

Minimizing OFDM PHY Overhead

- 25 kHz subcarrier spacing has less overhead than 50 kHz
- Lower cyclic prefix has less overhead than higher values
- Next codeword pointer modulation set to 64-QAM (maximum) will use fewer subcarriers for overhead compared to QPSK or 16-QAM
- Higher roll-off period results in smaller guard bands which allows more subcarriers for data (guard band can also be configured with guard band override command)

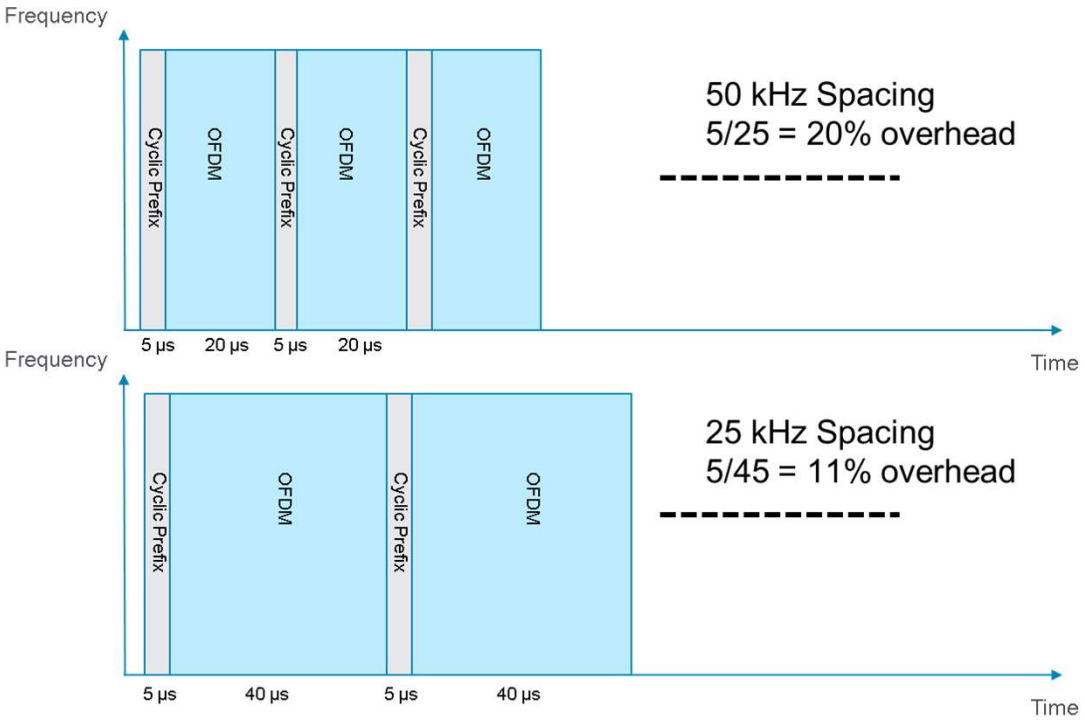
FFT Combines Many Subcarriers To One Composite Signal

- For 25 kHz spacing have 8192 subcarriers (have 4096 for 50 kHz)
- Fast Fourier Transform (FFT) functions on chips are used to provide the *equivalent* of 8192 individual QAM modulators summed together – one transmitter
- One composite signal with symbol duration of 40 µs (1/25 kHz) or 20 µs (1/50 kHz)
- Seems like capacity should be the same for either option – 2 times the subcarriers at half the rate = half the subcarriers at 2 times the rate



Cyclic Prefix Can Create High Overhead

- Cyclic prefix is time period between successive OFDM symbols used to minimize intersymbol interference caused by micro-reflections
- Valid range for cyclic prefix is 192 to 1024 samples (204.8 MHz sampling rate – 0.9387 µs to 5 µs)
- Cyclic prefix overhead is almost twice as high with 50 kHz spacing compared to 25 kHz due to symbol duration differences
- Cyclic prefix values above 512 have shown minimal benefits and just creates more overhead



Next Codeword Pointer Message

- The next codeword pointer (NCP) is used to indicate when one codeword ends and another one starts within an OFDM symbol
- The number of NCP messages per symbol can vary
- Valid options for NCP modulation are QPSK, 16-QAM and 64-QAM
- OFDM downstreams should have no issues supporting 64-QAM
- Using lower modulation orders for NCP requires more subcarriers for overhead instead of data
- Increasing NCP modulation order can increase the channel capacity by 5 – 20 Mbps.

Roll-off Values Can Determine Guard bands

- By default, the guard band (taper region) for each band edge will be determined by roll-off setting
- The higher the roll-off period, the smaller the required guard band in frequency
- 25 kHz has lower guard band requirements than 50 kHz
- Guard band override allows users to override default behavior (1 MHz on each edge recommended)
- Lower guard bands allows more data subcarriers
- Roll-off must be less than cyclic prefix

FFT	Roll-Off Period (Nrp)	Taper Region (MHz)
4096	64	3.575
	128	1.875
	192	1.325
	256	0.975
8192	64	3.3375
	128	1.7125
	192	1.1625
	256	0.9875[1]

[1]The taper region of 0.9875 MHz is in accordance with the requirement for a minimum taper region of 1 MHz minus half subcarrier spacing. Achieving up to approximately 0.5 dB impact to the noise power in the adjacent spurious emissions integration region would allow a taper region of 0.8625 MHz, if the specification did not mandate the minimum taper region to be larger than this.

Table 75 - CMTS Proposed Configuration Parameters

OFDM Speeds Based On Configurations

- The large number of configuration options make for complicated channel speed formulas - this is what spread sheets are made for!
- User enters configuration options
- Spread sheet provides estimate of channel speed minus PHY overhead (rates displayed on traffic generators)

OFDM Downstream			
Size of channels (MHz) - 24-192 MHz[1]	192	192	MHz
FFT size (4K or 8K FFT)	4096	8192	subcarriers
Subcarrier spacing	50	25	kHz
Cyclic prefix (Ncp)	512	512	samples[2]
Roll-off (Nrp) - must be less than Ncp	256	256	samples[2]
Ncp overhead	11%	6%	
Guard band override (leave blank if not used)[3]	1	1	MHz
Guard band on upper and lower edge (MHz)[4]	1.000	1.000	MHz
Number of active subcarriers	3800	7600	subcarriers
PLC overhead (number of subcarriers)	8	16	subcarriers
Continuous Pilot Scaling (48 - 120 subcarriers)	48	48	subcarriers
Continuous Pilots (include pilots for PLC)	56	56	subcarriers
Scattered Pilots (estimate)	29	59	subcarriers
Num of NCP - must be >0 (estimate)	4	4	
QAM order of NCP (QPSK, 16QAM, 64QAM)	6	6	bits / sym
NCP overhead (including CRC)	40	40	subcarriers
FEC overhead	12%	12%	8/9 code
Data QAM order (bits per symbol)	12	12	bits / sym
Data Rate (Mbps)	**1716**	**1841**	**Mbps**
Overhead % based on active subcarriers	24.73%	19.27%	

Conservative OFDM Channel Configuration

- Cyclic prefix at maximum
- 50 kHz subcarrier spacing
- Only single profile limiting channel to 256-QAM

```
cable downstream ofdm-chan-profile 10
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 50KHZ
  profile-control modulation-default 256-QAM     (1024 Mbps)
  profile-ncp modulation-default 16-QAM
```

- Used guard band override at 1 MHz and NCP modulation of 16-QAM for all examples to minimize variables

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP messages per symbol

Popular OFDM Channel Configuration

- Cyclic prefix at maximum
- 50 kHz subcarrier spacing
- Multiple profiles allow to allow some modems to run higher order modulations

```
cable downstream ofdm-chan-profile 10
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 50KHZ
  profile-control modulation-default 256-QAM     (1024 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM     (1280 Mbps)
  profile-data 2 modulation-default 2048-QAM     (1408 Mbps)
  profile-data 3 modulation-default 4096-QAM     (1536 Mbps)
```

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP messages per symbol

Change Profile To 25 kHz Subcarrier

```
cable downstream ofdm-chan-profile 10
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 50KHZ
  profile-control modulation-default 256-QAM (1024 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1280 Mbps)
  profile-data 2 modulation-default 2048-QAM (1408 Mbps)
  profile-data 3 modulation-default 4096-QAM (1536 Mbps)
```

```
cable downstream ofdm-chan-profile 20
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 25KHZ
  profile-control modulation-default 256-QAM (1156 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1445 Mbps)
  profile-data 2 modulation-default 2048-QAM (1589 Mbps)
  profile-data 3 modulation-default 4096-QAM (1734 Mbps)
```

- Change subcarrier spacing from 50 kHz to 25 kHz
- Increase channel capacity by ~13%

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP messages per symbol

Change Profile To 512 Cyclic Prefix And 25 kHz Subcarrier

```
cable downstream ofdm-chan-profile 10
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 50KHZ
  profile-control modulation-default 256-QAM (1024 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1280 Mbps)
  profile-data 2 modulation-default 2048-QAM (1408 Mbps)
  profile-data 3 modulation-default 4096-QAM (1536 Mbps)
```

```
cable downstream ofdm-chan-profile 21
  cyclic-prefix 512
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 25KHZ
  profile-control modulation-default 256-QAM (1224 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1530 Mbps)
  profile-data 2 modulation-default 2048-QAM (1683 Mbps)
  profile-data 3 modulation-default 4096-QAM (1836 Mbps)
```

- Change subcarrier spacing from 50 kHz to 25 kHz
- Reduce cyclic prefix from 1024 to 512
- Increase channel capacity by ~20%

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP messages per symbol

Configuration Impact On Channel Capacity

192 MHz OFDM with 1MHz guard bands	50 kHz			25 kHz		
	Cyclic Prefix 1024	Cyclic Prefix 512	Cyclic Prefix 256	Cyclic Prefix 1024	Cyclic Prefix 512	Cyclic Prefix 256
256-QAM	1024 Mbps	1138 Mbps	1205 Mbps	1156 Mbps	1224 Mbps	1261 Mbps
1024-QAM	1280 Mbps	1422 Mbps	1506 Mbps	1445 Mbps	1530 Mbps	1576 Mbps
2048-QAM	1408 Mbps	1565 Mbps	1657 Mbps	1589 Mbps	1683 Mbps	1734 Mbps
4096-QAM	1536 Mbps	1707 Mbps	1807 Mbps	1734 Mbps	1836 Mbps	1891 Mbps

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP (16-QAM) messages per symbol

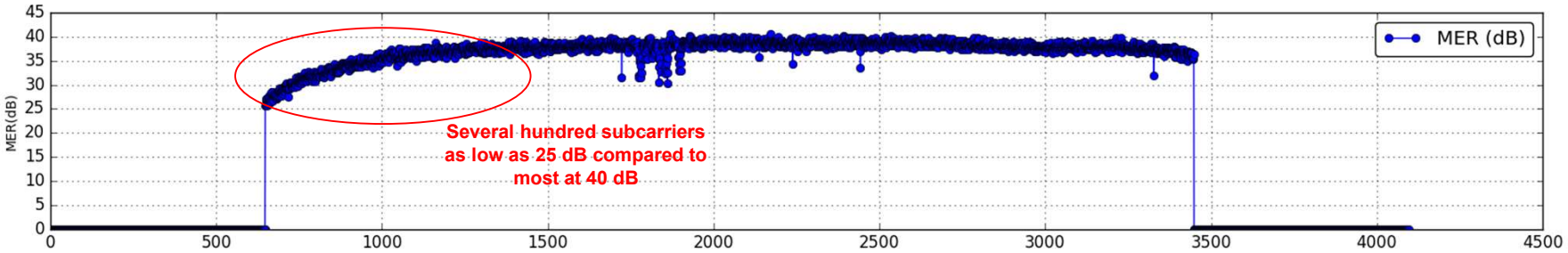
- Changing NCP modulation from 16-QAM to 64-QAM will add 5 - 10 Mbps
- A cyclic prefix of 192 samples will have ~2% less overhead than 256 samples but could reduce RxMER values at band edges in some plants

Cyclic Prefix Impact On RxMER

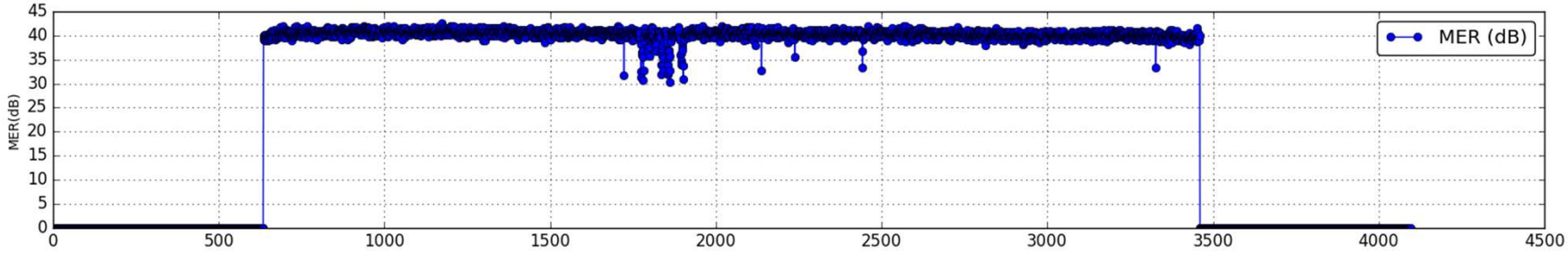
- Receive modulation error ratio (RxMER) is best indicator of modem performance
- Modems use scattered pilots which move throughout spectrum over time to measure RxMER for each subcarrier (will use preamble for RxMER values in physical layer link channel – PLC)
- CMTS polls modem with OFDM profile test (OPT) to get RxMER for each subcarriers
- Management tools can graph RxMER by polling modem directly or getting RxMER data from cBR-8 output (“show cable modem <mac> prof-mgmt downstream verbose”)
- Python or other scripting tools can also provide graph output

Cyclic Prefix Impact On RxMER

144 MHz OFDM channel 756 MHz – 900 MHz



50 kHz subcarriers, **cyclic prefix 192 / roll-off 128**
Channel speed 1362 Mbps @ 4096-QAM (1248 Mbps @ 2048-QAM)



50 kHz subcarriers, **cyclic prefix 256 / roll-off 192**
Channel speed 1352 Mbps @ 4096-QAM

Note: guard bands in example based on roll-off not on configured size

Observe Impact Of Cyclic Prefix Changes

- Can display OFDM data profile in use by each modem before and after changes (can grep to limit output to channel under test)

```
cbr8#show cable modem phy ofdm-profile downstream
MAC Address    I/F           Chan          DCID  Curr  Recm  Dwngd  Unfit
4800.33ef.3bf6 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
4800.33ef.0d22 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
a08e.7869.fd9e C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
4800.33ef.3cd6 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
909d.7d2e.9241 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
5009.591e.50d9 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
d4b9.2f6e.9344 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
6477.7d90.4466 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
6477.7d90.4300 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
909d.7d2e.8ff5 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
b0da.f912.340d C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
6477.7d90.3f24 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
6477.7d90.3c8a C6/0/4/UB     Do6/0/4:158   159   2     2     1      N/A
4065.a3ff.f4c9 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
d43f.cbe1.8311 C6/0/4/UB     Do6/0/4:158   159   3     3     2      N/A
```

CMTS Selects OFDM Profiles For Modems

- Modem comes online and locks on profiles (3 data + control profile)
- CMTS polls modem with OFDM profile test (OPT) to get RxMER for all subcarriers
- CMTS runs RxMER data through profile selection thresholds to determine best profile to use for each modem
- CMTS periodically polls modem for RxMER information and adjust profiles as needed
- If modem sees uncorrectable codeword (cw) errors above threshold for a profile, it sends CM-STATUS event type 16 message (DS OFDM profile failure) so CMTS can adjust profile
- This process is now referred to as “internal profile management applications (PMA)”

OFDM Profile Selection Process On cBR-8

- Look at RxMER value for each subcarrier (in ¼ dB increments)
- Can exclude a percentage of subcarriers from calculations as outliers (2% by default) but all data subcarriers will be used to carry traffic
- Compare RxMER value for all remaining subcarriers against thresholds
- If RxMER from one subcarrier is below the threshold required to run a particular profile, that profile will not be selected
- cBR-8 considers both default and mixed modulation profiles so is aware of subcarrier location relative to configured profile
- cBR-8 begins transmitting to modem using selected profile
- cBR-8 adjust modulation profile based on periodic RxMER data or CM-STATUS messages from modem

Default RxMER Selection Thresholds Are Conservative

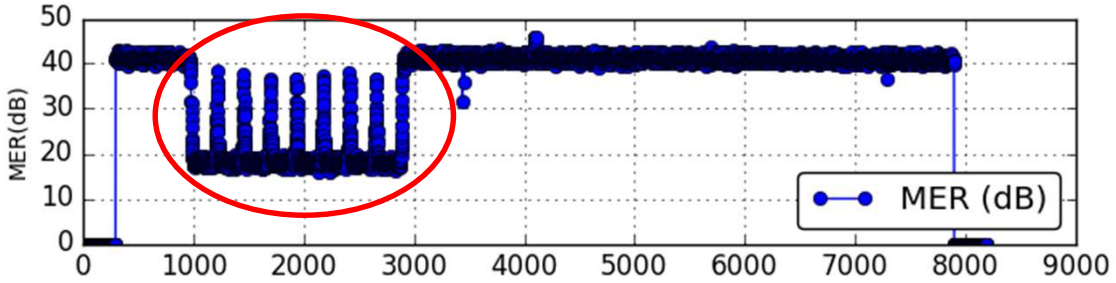
- cBR-8 uses conservative thresholds with ~ 6 dB of margin
- Low density parity check (LDPC) combined with frequency interleaving in D3.1 is very robust to impairments
- D3.1 OFDM can downgrade to lower modulation orders if plant conditions change while D3.0 downstreams can not
- Recommend reducing thresholds by 2 - 3 dB

Based on Table 46 in D3.1 PHY Specification

RxMER (in ¼ dB)	RxMER (dB)	QAM	Bit Loading
>60	>15	16	4
>84	>21	64	6
>96	>24	128	7
>108	>27	256	8
>122	>30.5	512	9
>136	>34	1024	10
>148	>37	2048	11
>164	>41	4096	12

Excluded Subcarrier Percentage Conservative

- cBR-8 only excludes 2% of subcarriers from profile selection calculations by default
- LDPC and frequency interleaving are very effective at correcting errors
- Testing has shown that over 25% of channel can see severe impairments without impacting channel performance
- Recommend increasing excluded subcarrier to 10% (excluded subcarriers will still carry data just not impact profile selection)



Modem runs 4096-QAM error free with 48 MHz of 192 MHz channel with RxMER below 20 dB

Adjusted Thresholds Allow High Modulations

- Customers implementing suggested values of 10% excluded subcarriers and 2 – 3 dB reduced RxMER thresholds typically see modems using one to two higher modulation orders
- Normal for over 75% of modems to do 2048-QAM or higher
- Customers staying on default settings usually have most modems at 1024-QAM and less than 10% at 4096-QAM

Change Profile To 25 kHz Subcarrier / 512 Cyclic Prefix With Updated Profile Thresholds

```
cable downstream ofdm-chan-profile 10
  cyclic-prefix 1024
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 50KHZ
  profile-control modulation-default 256-QAM (1024 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1280 Mbps)
  profile-data 2 modulation-default 2048-QAM (1408 Mbps)
  profile-data 3 modulation-default 4096-QAM (1536 Mbps)
```

```
cable downstream ofdm-chan-profile 21
  cyclic-prefix 512
  interleaver-depth 16
  pilot-scaling 48
  roll-off 256
  guardband-override 1000000
  subcarrier-spacing 25KHZ
  profile-control modulation-default 256-QAM (1224 Mbps)
  profile-ncp modulation-default 16-QAM
  profile-data 1 modulation-default 1024-QAM (1530 Mbps)
  profile-data 2 modulation-default 2048-QAM (1683 Mbps)
  profile-data 3 modulation-default 4096-QAM (1836 Mbps)
```

- Change subcarrier spacing from 50 kHz to 25 kHz / reduce cyclic prefix from 1024 to 512
- Adjust profile selection thresholds (modems move from data profile 1 to 3)
- **Increase channel capacity by ~43%**

Speeds are without PHY overhead and assume 192 MHz channel with 4 NCP messages per symbol

Profile Management Applications (PMA)

- Profile management applications (PMA) can now be external to the cBR-8 and use RxMER data and modem cw errors to construct profiles with modulation orders customized to each channel
- Custom OFDM profiles are pushed back from PMA system (up to 7 data profiles per channel on cBR-8)
- PMA may rely on artificial intelligence / machine learning (AI / ML)
- PMA has been able to increase channel capacity when default profile selection thresholds are in use (use 256-QAM as baseline in papers)
- PMA gains are minimal if using suggested profile selection thresholds
- PMA would likely have more benefit in D3.1 upstreams or full duplex DOCSIS (FDX) where shared spectrum can see reduced RxMER

Summary On OFDM Optimization

- Cisco's cBR-8 and cnBR offer full OFDM configuration options - other vendors offer a subset
- Minimize PHY overhead to maximize overall channel capacity and adjust profile selection thresholds to assure modem is using the ideal modulation order
- Operators with multiple CMTS vendors sometimes limit configurations on cBR-8 to achieve uniform configurations across all systems – now you know what capacity hit you are taking
- External PMA may help if your CMTS vendor does not do internal PMA very well or for future FDX – limited gains on a properly configured OFDM channel running on cBR-8 / cnBR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