DOCSIS 3.0 Upstream: Technology, RF Variables & Case Studies

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Agenda

• DOCSIS 3.0 A-TDMA
  – Return Path Readiness
    • QAM, SNR, MER and Margin
    • Optical Links
    • Spectrum Fidelity
    • Frequency Response Distortion
  – Combined Impairment Testing & Analysis
  – Summary

• Example Plant Assessments
  – RF Upstream System Characterization
  – Upstream Spectrum: Snapshots & Indicators

• DOCSIS 3.0 S-CDMA - Introduction
DOCSIS 3.0 – What’s New

• NOT New
  – 64-QAM is a DOCSIS 2.0-specified upstream modulation
  – 5.12 Msps (6.4 MHz) is a DOCSIS 2.0-specified upstream symbol rate
  – S-CDMA is a DOCSIS 2.0-specified format
  – Support for advanced equalization (Pre-EQ) - DOCSIS 2.0 requirement

• IS New
  – Channel Bonding
    • Downstream
    • Upstream
  – Others that are don’t care for the plant
    • IPv6
    • Enhanced Multicast with QoS
    • Enhanced Security
    • Network Mgmt (IPDR)
DOCSIS 3.0 – Channel Bonding

• Channel bonding is logical (two phy channels tied together at data link layer)
  – Increases peak rate, but not upstream channel capacity

• Possible physical layer impact is associated with the use of new spectrum
  – New spectrum is not always clean
  – Increased sensitivity of higher order modulations

• Moving to wideband (6.4 MHz) single channel has similar constraints as bonding – deploying new spectrum
  – Choice of center frequency and fidelity

• More channels means understanding and applying return path laser transmitter loading principles
Enabling DOCSIS 2.0 & 3.0: Return Path Readiness
MER & Margin – What’s the 64-QAM Effect?

• 64-QAM consumes ~6-7 dB of return path margin beyond 16-QAM
  – This amount of margin might not be available “alarm-free”
  – If available, what’s left requires more careful attention to maintain fidelity
  – Smaller dB’s or accuracy, alignment, calibration, make a difference

• Consider a functioning, practical return delivering a 31 dB MER
  – Post-EQ MER threshold limits of approx 21/24/28 dB support 16/32/64 QAM
  – For fixed BW and level, assuming an uncorrected QAM error rate of 1e-8
    • That's ~ 17 dB of margin for QPSK
    • That's ~ 10 dB of margin for 16-QAM
    • That’s ~ 7 dB of margin for 32-QAM
    • That's ~ 3 dB of margin for 64-QAM
  – 3 dB is a small margin
    • Below the level of alignment accuracy that can often be guaranteed
    • Below plant-wide changes that can take place slowly over time and temperature
    • Below common MER variations observed on working channels due to dynamics of noise and interference
    • ⇒ Margin this small requires more attention to plant setup & maintenance
MER & SNR – Understanding the Difference

• What the CMTS reports as SNR is in fact MER – i.e. all impairments are included
  – SNR in communications literature often refers only to the noise floor
  – MER thresholds for error rate are thus always approximations
  – Post-EQ MER includes all impairments, but evaluated after CMTS receiver processing has worked to repair any distortion imposed
  – The difference between SNR & MER did not used to matter very much because of margin and band of operation

• Facts of MER life
  – It is impossible to extract from an MER alone the breakdown of the contributing impairments
    • Constellation plot has clues
  – MER is an averaging measurement, and impulsive events are thus not typically reflected in a way representative of their impact
  – There IS NOT a unique relationship between MER and bit or symbol error rate – the same MER can result in different error rates
Return Path Variables

• Plant variables impacting the move to higher order modulations and higher symbol rates
  
  – Link SNR and dynamic range
    • Primarily driven by the optical link
    • Includes return path setup and maintenance practices
      • Proper return laser power loading and HE levels
      • Forward path isolation

  – Spectrum Fidelity – Ingress and impulse degrading available SNR
    • Primarily due to in-home disturbances, typically < 20 MHz
    • In-band interference on DOCSIS channel
    • Out-of-band or wideband impulse impacting laser loading
    • 64-QAM more sensitive

  – Choice of carrier frequency and bandwidth sensitive to cascade depth
    • Impinging on diplexer roll-off
    • Combined frequency response distortions a threat for 64-QAM
    • Wideband channels (6.4 MHz) increase likelihood
Available SNR – Dynamic Range vs Laser Type

QAM sensitivity to loading varies with laser type

Noise Power Ratio (NPR)
- Approximates a full QAM load
- Link SNR & dynamic range
- Operating point headroom

Noise Power Ratio (NPR) = Signal-to-(Noise Plus Distortion) Ratio
9 dB Optical Link (25 km/15 mi)

Total Power, all Signals 5-42 MHz

Low Headroom or dynamic range means sensitivity to other link variables (analog return paths)
Spectrum Fidelity – Now More Critical

- Impulsive interference > signal power
- Laser loading concern – clipping and headroom for new carriers
- Limitations of band usage for adding new carriers

- Impulsive noise into DOCSIS band @ ~ -15 dBc pk
- 16-QAM supported but FEC probably working hard
  - Insufficient for 64-QAM
- Energy is wideband – issue for any new carriers for single or bonded channels

Characteristics typ of approx 15-20% of nodes in any large HE
Impulse Noise Spectrum – A Closer Look

Impulse Noise – Typical < 20 MHz Signature and Burst
Impulse Noise – MER Perspective

**MER versus Time**

> 8 dB Range
> QAM Order (6 dB min from 16-QAM to 64-QAM)

**Equalizer (Channel Freq Response vs Time)**
Spectrum Fidelity – Clean....Except

High narrowband static interference - 9.6 MHz, 11.9 MHz, 13.8 MHz

High narrowband interference coupled with low freq impulse
What’s the 6.4 MHz BW Effect? (or 5.12 Msps)

• The D3.0 Equalizer is a fixed “24-Tap” structure designed in part to “undo” plant reflections
  – One Tap = One QAM Symbol period in time (5.12 Msps period is approx 195 nsec)
  – Total time spanned by 24 taps for 5.12 Msps is less than 5 usec

• As symbol rate increases, Equalizer time spanned decreases
  – The 5.12 Msps (6.4 MHz) span is one-half that of 2.56 Msps (3.2 MHz), i.e. it handles reflections closer in time only (and distance) by factor of 2

• At 5.12 Msps, time span can be shorter than some practical plant reflections, and thus they are not equalized

• This unmitigated reflection energy contributes directly as interference that degrades MER – with 64-QAM most at risk

• A reflection long enough in time and yet large enough in amplitude to cause degradation is atypical, but it has been observed in the field
  – Multi-building MDUs can be prone to these conditions

• When reflections combine with Group Delay Variation (choice of center frequency), Equalizer can be overwhelmed in broader range of cases
The 6.4 MHz Effect – A Closer Look

Impulse Responses vs. DOCSIS Mask @ 5.12 Msps

"Ideal" Channel Impulse Response

Response of Different Upstream Paths from Each CM
The 6.4 MHz Effect – A Closer Look

Impulse Responses vs. DOCSIS Mask @ 5.12 Msps

Common “Linear” Distortions

-60 -55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0

Magnitude (dB)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

TAP Location

Micro-reflections

CM 1-6

DOCSIS Assumptions

- Represents Group Delay Variation
- Micro-reflections

Micro-reflection Time Span approx 3 usec
DOCSIS 2.0 Transmit Pre-Equalization
Maximum Correctable Micro-Reflection
16 MHz CF, 64-QAM, 6.4 MHz, 5.12 Msym/sec

**Single Dominant Micro-reflection Only**

<table>
<thead>
<tr>
<th>DOCSIS 1.0 Req’t</th>
<th>Simulated D2.0 Pre-Eq Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16-QAM</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
</tr>
<tr>
<td>&lt; .5 usec</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>-4</td>
</tr>
<tr>
<td>.5-1.5 usec</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>-6</td>
</tr>
<tr>
<td>&gt;1.5 usec</td>
<td>-30</td>
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<tr>
<td></td>
<td>-13</td>
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</table>

*Equalizer mitigation limits within 2 dB*
Combined Impairment Characterization: Packet Error Rate (PER) vs. Ingress + Impulse Interference
New and Improved Performance Metrics

- Wideband 64-QAM is the end of the “free margin” era of DOCSIS
- Wideband 64-QAM requires more of the return plant for high performance
- There is less performance margin as a result
- There is less room for error with the various contributions
- There is a need to understand the multiple potential contributors to performance degradation
- The MER metric is itself limited in information conveyed
- It is desirable to find other metrics of performance from available information, such as FEC statistics from the CMTS
- End-user performance is tied to packet error rate (PER)
- There is thus strong interest in understanding the correlation between PER and available FEC statistics

Refer to full analysis and results in SCTE Expo 2009 Paper: "Characterizing and Aligning the HFC Return Path for Successful DOCSIS 3.0 Rollouts"

-Dr. R Howald, Phillip Chang, et al
**Laboratory Test Conditions**

**Plant**
- 20 km DFB link
- N+6 cascade
- 36.5 DOCSIS carrier frequency
- 40+ DOCSIS 2.0 modems (various)

**Data**
- 64-QAM/16-QAM @ 5.12 Msps
- Maximum FEC: K=219, T=16
- No Interleaving
- Ingress Canceller ON
- Pre-Equalization ON
- 1518-byte packets

**Additive Noise & Interference**

- **AWGN Noise**
  - SNR = 35 dB
  - SNR = 27 dB

- **Static Ingress**
  - Single CW Carrier @ -10 dBC
  - Three CW Carriers uniformly spread @ -15 / -20 / -25 dBC
  - Single FM Carrier @ -10 dBC
  - Three FM Carriers uniformly spread @ -15 / -20 / -25 dBC

- **Impulse Noise**
  - 4 usec AWGN pulse @ 100 Hz
    - -10 dBC and -5 dBC
  - 10 usec AWGN pulse @ 1 kHz
    - -10 dBC and -15 dBC
### Sampling of Lab Test Results

#### 16-QAM vs 64-QAM: Impulse + Ingress Thresholds

<table>
<thead>
<tr>
<th>1518-Byte Packets</th>
<th>Impulse (dBc-pk) - Gated AWGN @ 10 MHz BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Floor = 35 dB</td>
<td></td>
</tr>
<tr>
<td>10 usec @ 1 kHz</td>
<td></td>
</tr>
<tr>
<td>Ingress (dBc)</td>
<td>UCER/CCER PER</td>
</tr>
<tr>
<td>CW Interference</td>
<td>16-QAM</td>
</tr>
<tr>
<td>1x @ -10 dBc</td>
<td>0.055 / 0</td>
</tr>
<tr>
<td>3x @ -15 dBc/tone</td>
<td>0.07 / 0.007</td>
</tr>
<tr>
<td>FM Modulated (20 kHz BW)</td>
<td></td>
</tr>
<tr>
<td>1x @ -10 dBc</td>
<td>0.17 / 0.017</td>
</tr>
<tr>
<td>3x @ -15 dBc/tone</td>
<td>0.2 / 0.02</td>
</tr>
<tr>
<td>Noise Floor = 27 dB</td>
<td></td>
</tr>
<tr>
<td>Ingress (dBc)</td>
<td>UCER/CCER PER</td>
</tr>
<tr>
<td>CW Interference</td>
<td>16-QAM</td>
</tr>
<tr>
<td>1x @ -10 dBc</td>
<td>0.3 / 0.001</td>
</tr>
<tr>
<td>3x @ -15 dBc/tone</td>
<td>0.5 / 0</td>
</tr>
</tbody>
</table>

- FEC is always working hard for AWGN = 27 dB – a 64-QAM margin issue
- Modulated ingress is noticeably worse on error rate performance vs CW
- MER is not very informative under these relatively harsh impairments
- Impulse noise can dominate PER, overwhelm FEC and be invisible to MER
- Without impulse, the ingress canceller is excellent at mitigating interference
Sampling of Lab Test Results - PER

Packet Error Rate vs Uncorrectable Codewords

• CMTS reports FEC statistics, while PER is what the service QoE is tied to
• Above charts estimates a quantifiable correlation between uncorrectable codeword errors and PER for this set of conditions
• There is an expected correlation between UCER and PER
• Apparent knee in the degradation curve of packet delivery as the uncorrectable codewords reach approximately 1e-3
**DOCSIS 3.0 A-TDMA: Summary**

- **Early DOCSIS**
  - Very robust modulations – GONE
  - Low bandwidth – GONE
  - Anywhere in the spectrum – GONE
  - All the laser load you needed – GONE

- **For wideband 64-QAM every dB will matter more**
  - Most of current link margin to 16-QAM gets removed
  - DFBs can restore some margin being lost
  - Upstream alignment & maintenance practices have added importance
  - Become accustomed to looking at acceptable margins differently

- **Spectrum**
  - Wideband QAM, micro-reflections, and cascade effects constrain location of channels
  - Combined freq response distortions can overwhelm the equalizer
  - Typical upstream fidelity not suited to instant 64-QAM success for 100% of footprint
  - S-CDMA allows use of full band - need A-TDMA and S-CDMA to optimize upstream

- **MER is an insufficient and non-unique predictor of performance**
  - Hidden by the large margins available to date inherent in 16-QAM
  - Does not capture impulse noise in particular in a way representative of impact
  - Combined impairment effects and less available margin require additional metrics