# *Performance Analysis of SCM Optical Transmission Link for Fiber-to-the-Home*

**EECS891**

***Anthony Leung***

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# Introduction: FTTH & WDM-PON

**Increasing Data Services Requirements**

- Continued increasing data bandwidth demand
- DSL & Cable Modem unlikely to meet longer term needs

**Cost Improvements**

- Cost of optoelectronic equipment continues to decline
- Reduced maintenance costs

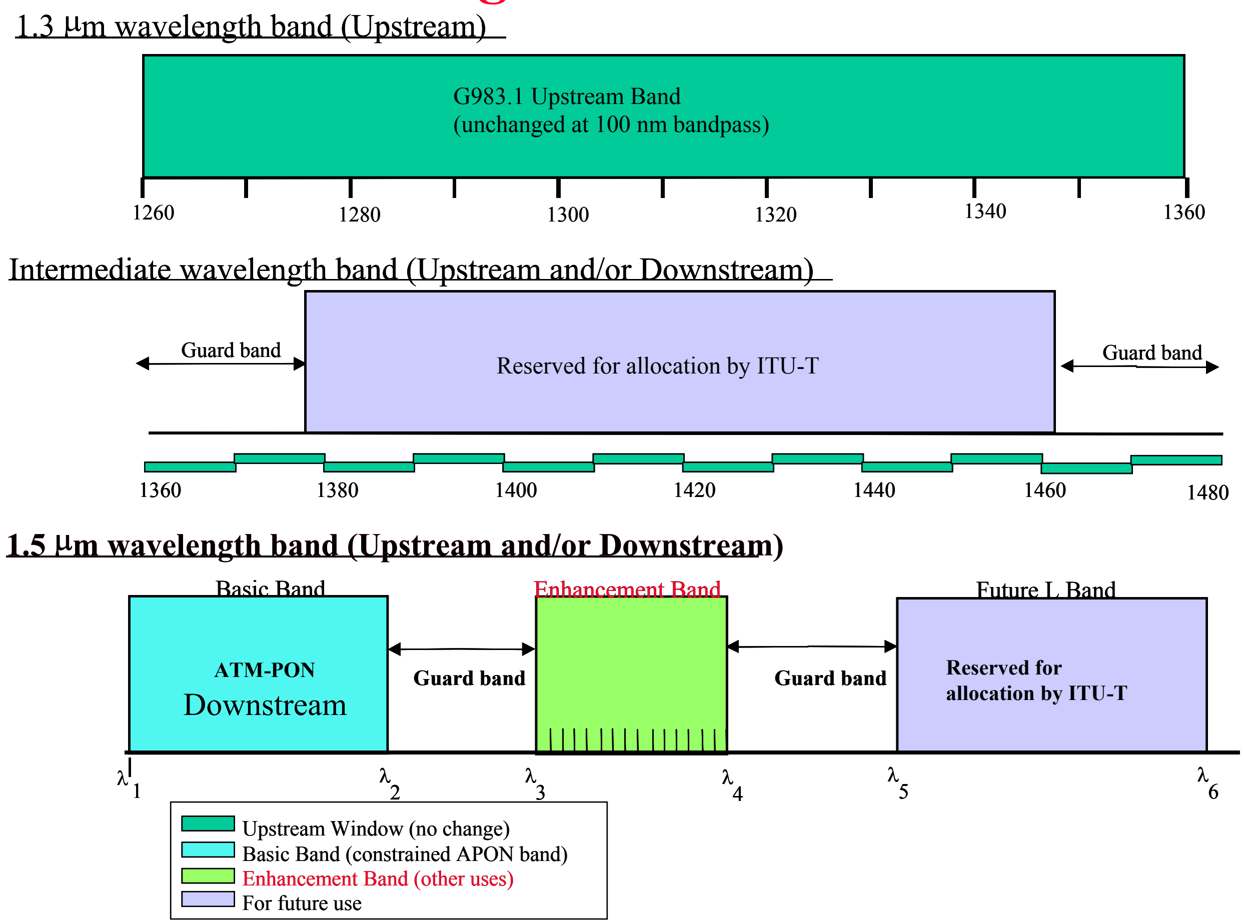
**Competition**

- Entertainment Video Overlay

**Technology Improvements**

- Future Access Network "One for All" Architecture

# ITU-T G.983.3 Wavelength Allocation Standard




**ITU-T G.983.3 standard for Enhancement Band**

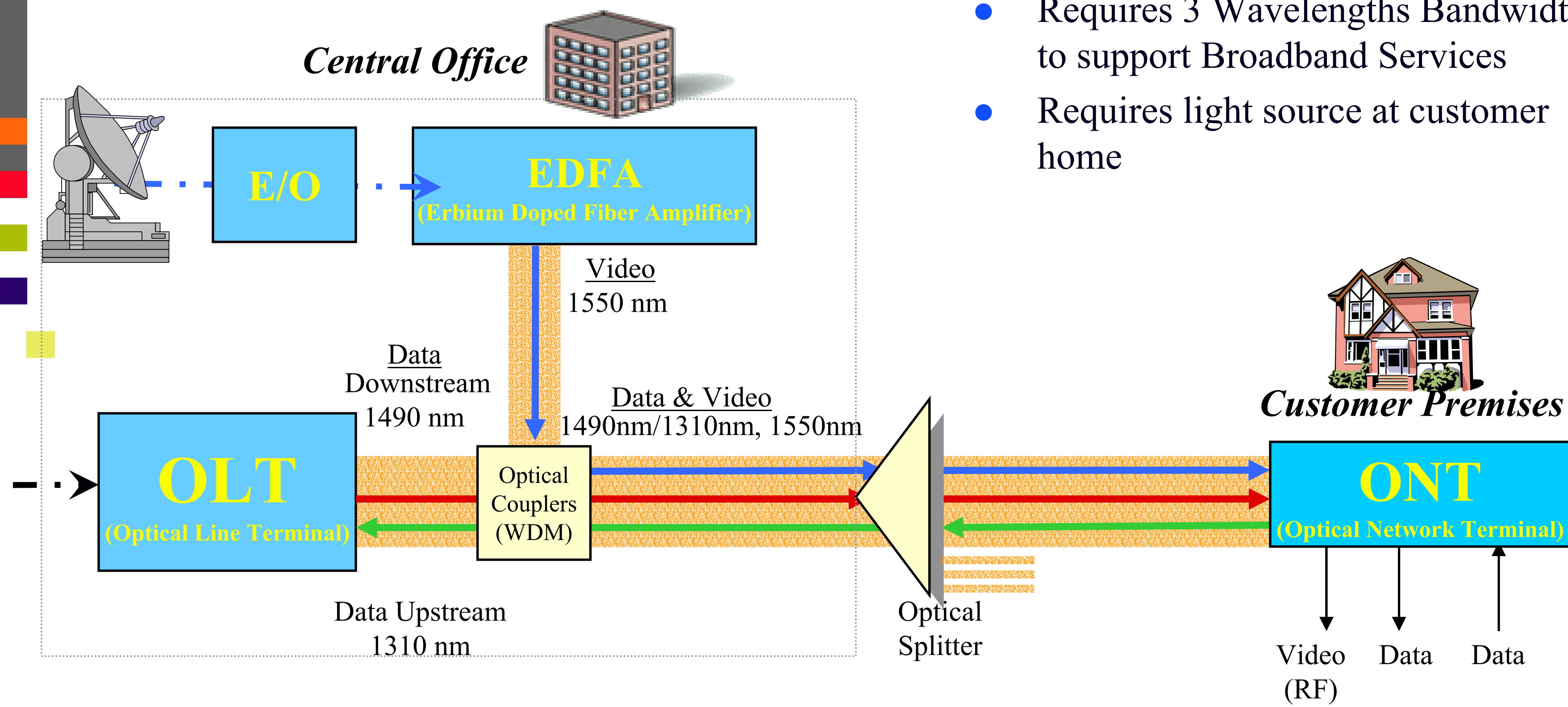
- **1.5µm wavelength Enhancement band (Upstream and /or Downstream)**
- **Application options at Enhancement Band (1539nm to 1560nm) are:**

  **1) Additional Digital Service Uses**

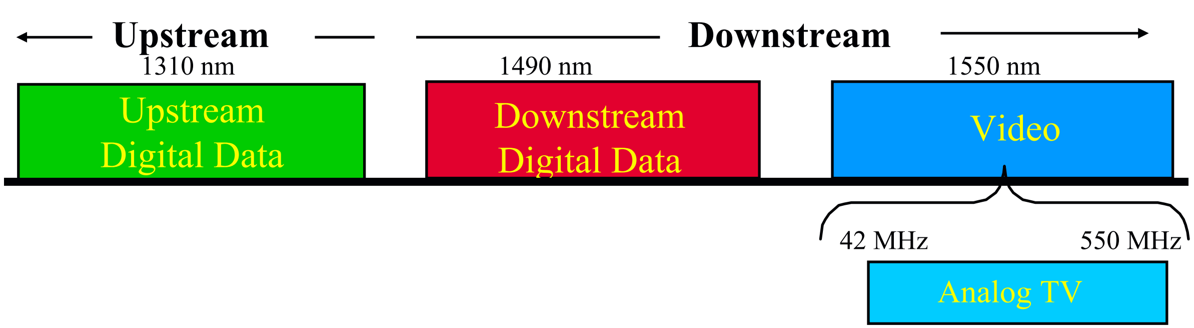
  **2) Video Distribution Service**

# *WDM-PON Network Architecture*

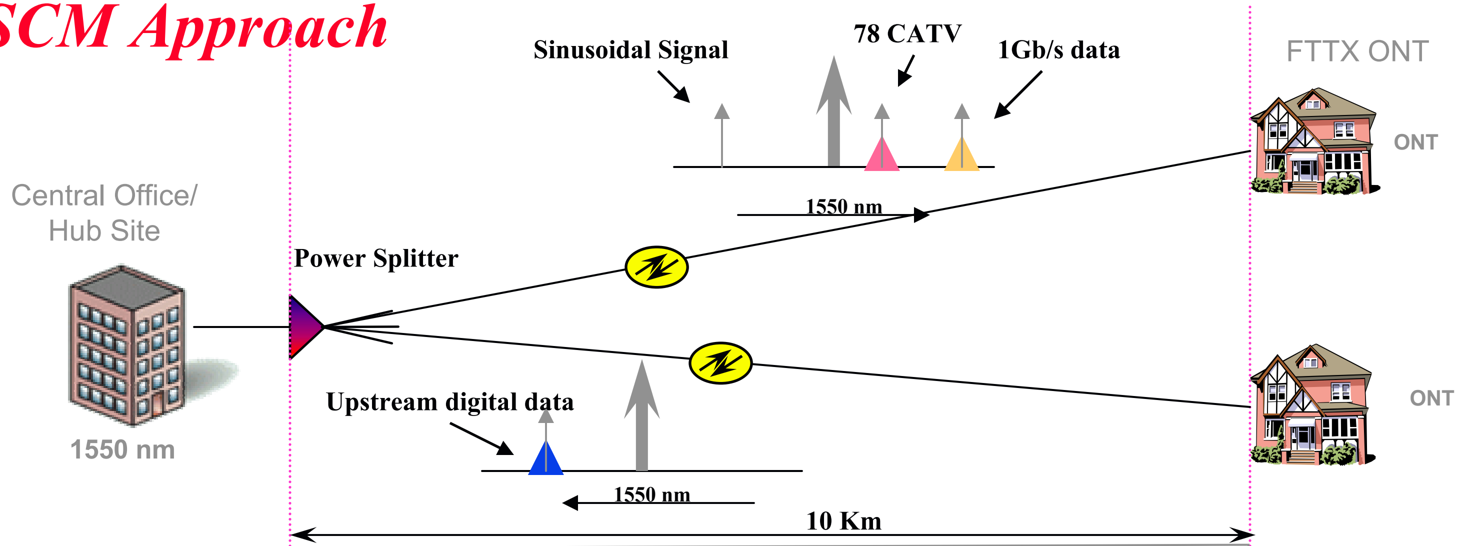
- Requires 3 Wavelengths Bandwidth to support Broadband Services
- Requires light source at customer home




## Bandwidths & Services



# SCM Approach




**Downstream**
**Data at lower sideband of optical carrier (1550nm)**
**Video at lower sideband of optical carrier (1550nm)**
**Optical subcarrier at upper sideband of optical carrier (1550nm)**
**Upstream**
**Data at upper sideband of optical carrier (1550nm)**

Use Microwave double side band technology

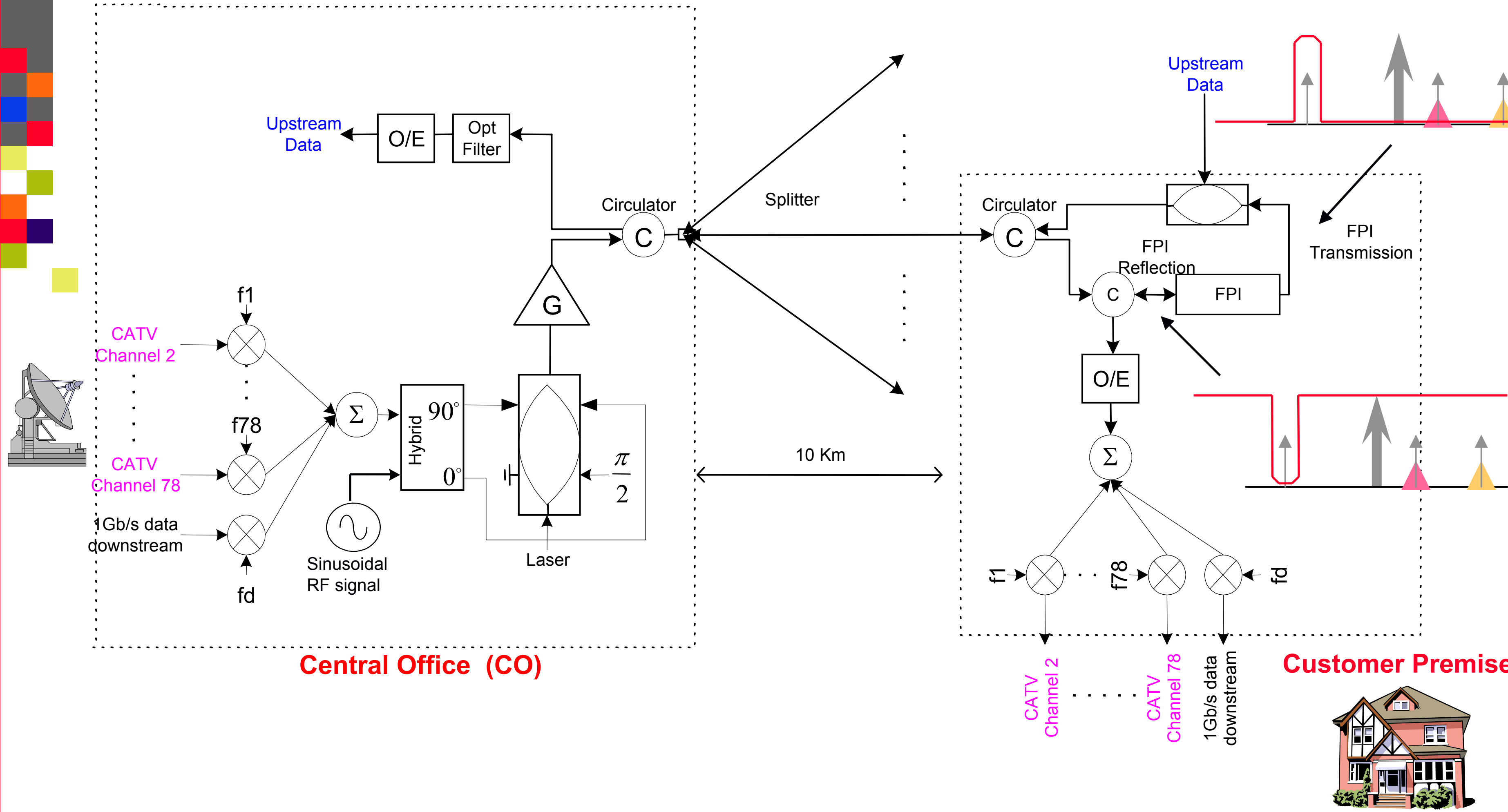
- Optical modulated 78 CATV channel & 1 Gb/s digital data at the lower side band of optical carrier.
- At the same time, Optical modulated a sinusoidal RF signal at the upper side band of optical carrier and deliver from CO to Customer, this optical RF signal is used as optical light source for upstream data transmission. Therefore, no laser source requires at customer side.

# *Project Goal*

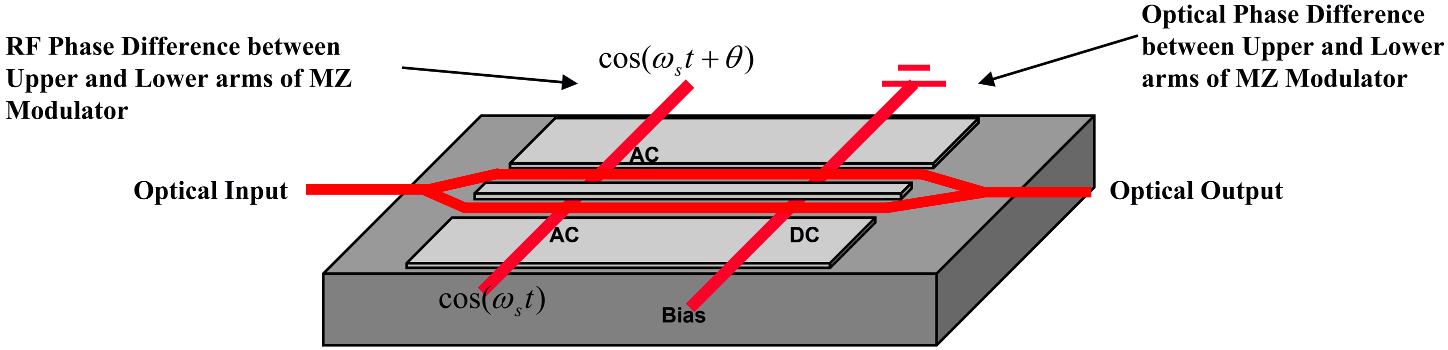
- Examine Physical Transmission Performance Using SCM Approach transmitting 78 CATV channel and 1Gb/s digital channel from CO to Customer Premises
  - Analyze 78 Analog CATV Carrier-to-Noise Ratio (CNR) Performance
  - Analyze 1Gb/s Digital Channel Q-Value Performance
  - Analyze the fiber crosstalk in SCM Network
    - Stimulated Raman Scattering (SRS)
    - Cross Phase Modulation (XPM)
    - Four wave Mixing (FWM)
  - Evaluated the Overall Transmission Performance due to fiber crosstalk

This project is the first time to demonstrate for this comprehensive analysis using microwave double side band technology for FTTH application

# SCM Network Architecture

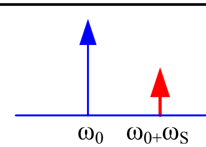
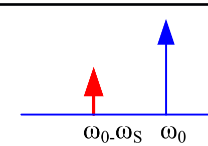
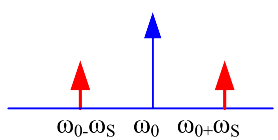
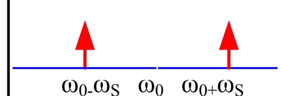
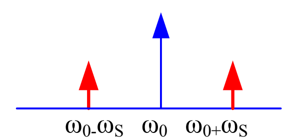
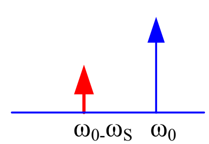
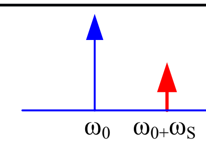


# *Optical Modulation & MZ Modulator*

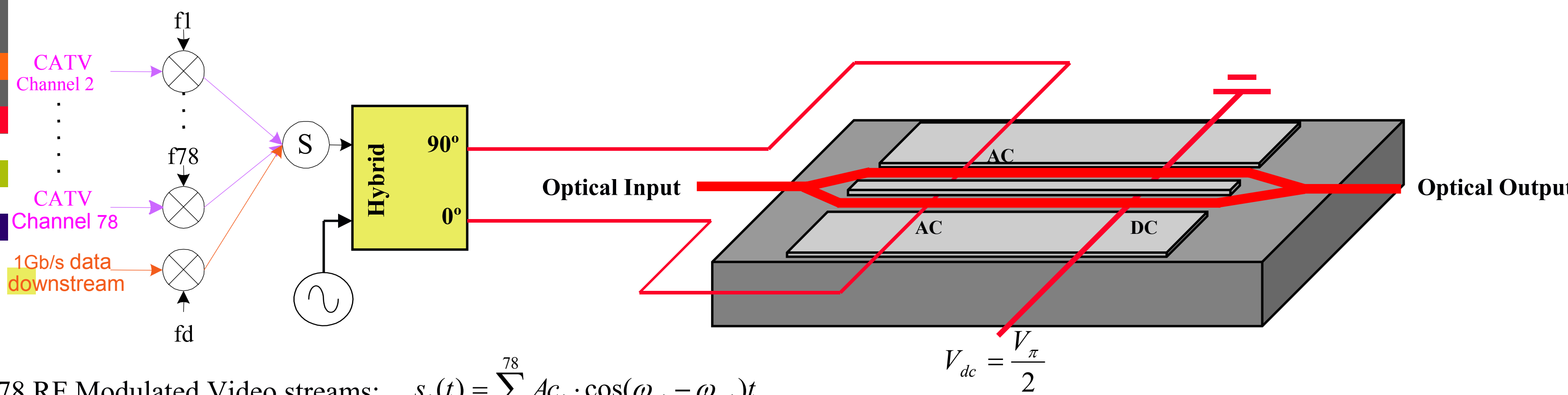



**Optical Output**

$$E_o(t) = \frac{A}{2}\left\{\cos\left[\omega_c t + \frac{V_{dc}}{V_\pi}\pi + \frac{V_{ac}}{V_\pi}\pi\cos\omega_i t\right] + \cos\left[\omega_c t + \frac{V_{ac}}{V_\pi}\pi\cos(\omega_i t + \theta)\right]\right\} \quad [1]$$

| | Optical Δψ = $-\frac{\pi}{2}$ | Optical Δψ = $\pi$ | Optical Δψ = $\frac{\pi}{2}$ |
|---|---|---|---|
| RF Δθ = $-\frac{\pi}{2}$ |  | |  |
| RF Δθ = $\pi$ |  |  |  |
| RF Δθ = $\frac{\pi}{2}$ |  | |  |

# *Optical Single Side Band Modulation*




78 RF Modulated Video streams: $s_i(t) = \sum_{i=1}^{78} Ac_i \cdot \cos(\omega_{ci} - \omega_{mi})t$

Downstream digital RF Channel: $s_d(t) = x(t) \cdot \cos(\omega_d t)$

Upstream RF Channel: $s_u(t) = \cos(\omega_u t)$

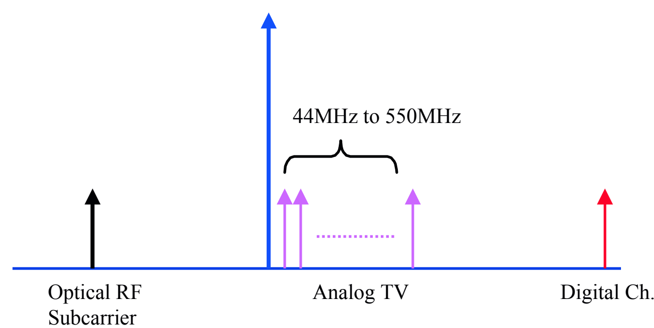
**Optical Output**

$$E(t) = \frac{E_i}{2}\left\{J_0(\frac{\pi A}{V_\pi})[\cos(\omega_c t) - \sin(\omega_c t)]\right\}$$

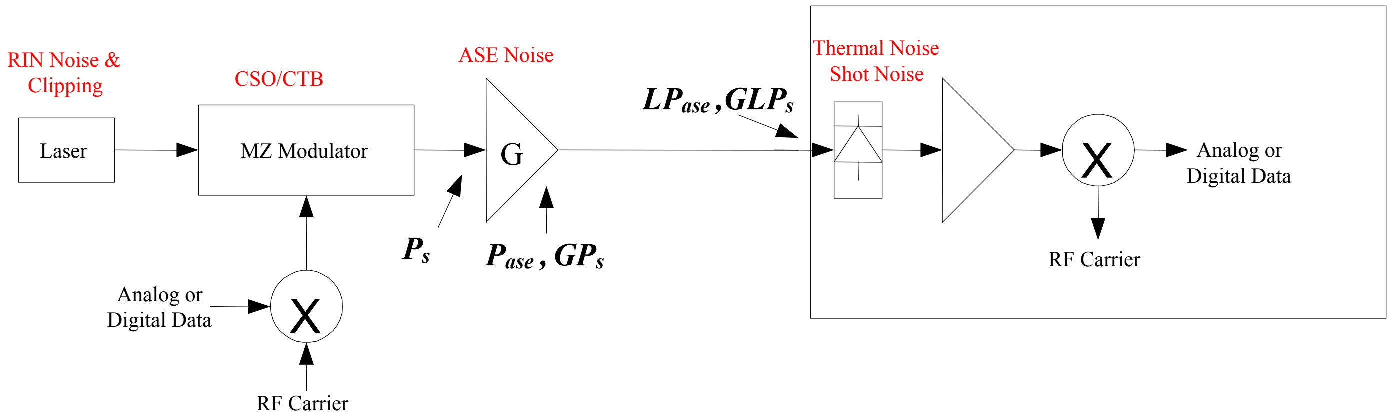
$$-E_i\left\{J_1(\frac{\pi A}{V_\pi})\cos(\omega_c + \sum_{i=1}^{78}(\omega_i - \omega_m))t\right\}$$

$$-E_i\left\{J_1(\frac{\pi A}{V_\pi})x(t)\cos(\omega_c + \omega_d)t\right\}$$

$$-E_i\left\{J_1(\frac{\pi A}{V_\pi})\cos(\omega_c - \omega_u)t\right\}$$



# *Noise Contributions in Optical Transmission*




- Thermal Noise: Noise is generated in resistive elements (Photo-detector)
- Shot Noise: Noise is generated when an optical signal is incident on the photo-detector
- RIN Noise: Noise is generated by spontaneous emission with the laser source
- Booster Amplifier Noise: Noise generated by Amplifier
- Clipping: It set the fundamental limitation on how much the laser can be clipped for composite input signal
- Intermodulation Distortion: Composite second order (CSO) & Composite Triple Beat (CTB) generated by Conventional MZ Modulator

Thermal Noise Limited → Shot Noise Limited → RIN Noise Limited → ASE Noise Limited

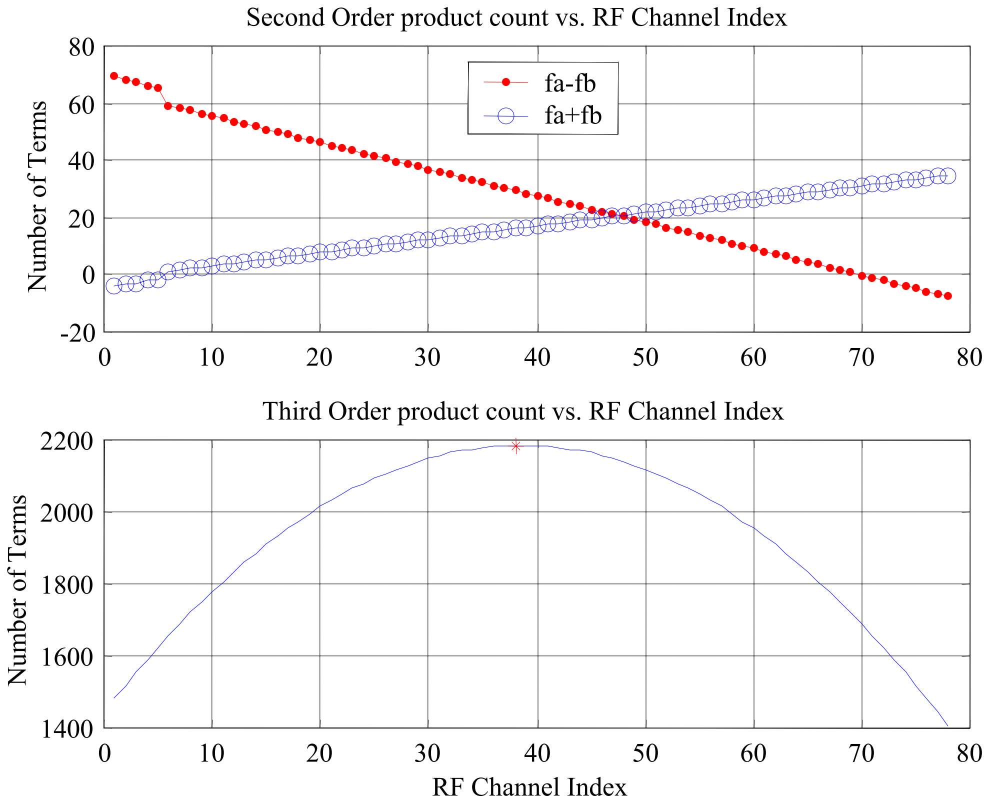
Optical Receiver Power Increase →

# *Nonlinear Distortions (CSO, CTB) of Convention MZ Modulator*

- Transfer function of MZ modulator is a sine wave-like function of input voltage

$$P_s = P_o \cdot \cos^2 \left[ \frac{\frac{\pi V(t)}{V_\pi} - \theta}{2} \right] = \frac{P_o}{2} + \frac{P_o}{2} \cos\left(\frac{\pi V(t)}{V_\pi} - \theta\right)$$

- **Composite Second Order (CSO)** **: Max 79 CSO Distortion terms fall at RF channel 1**
- **Composite Triple Beat (CTB)** **: Max 2185 CTB distortion terms fall at RF channel 38**



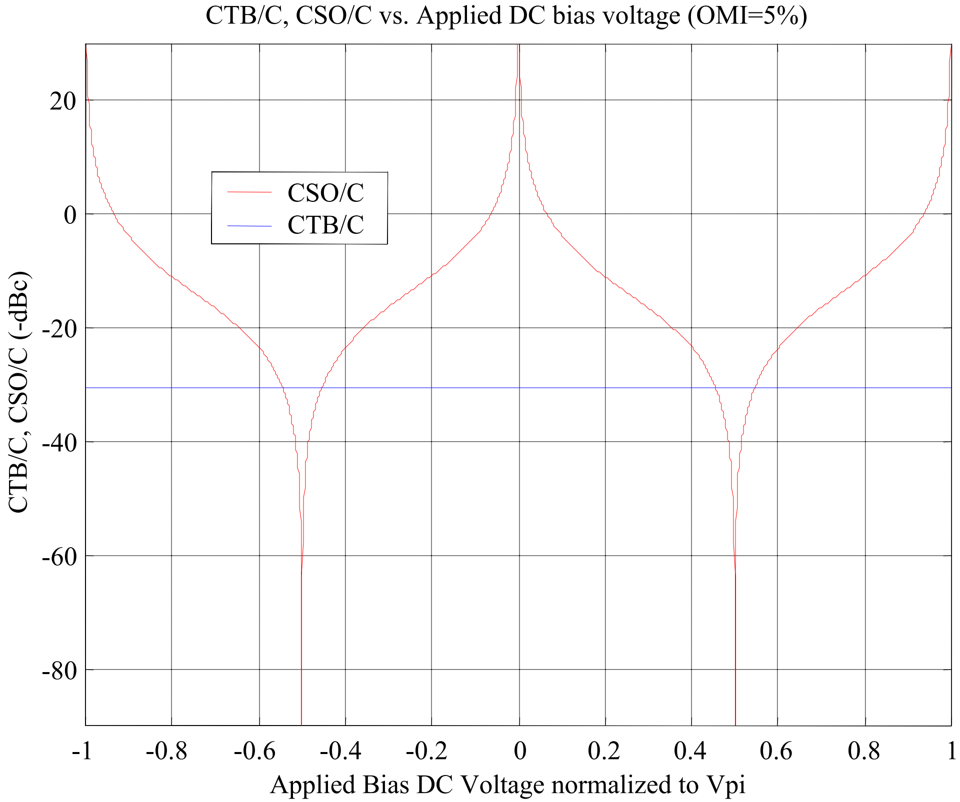
# Nonlinear Distortions (CSO, CTB) of Convention MZ Modulator

Power ratio of CSO/C

$$\frac{CSO}{C}=\left\{\frac{2[J_1(\frac{\pi A}{V_\pi})]^2[J_0(\frac{\pi A}{V_\pi})]^{N-2}}{2J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1}}\right\}^2 N_{CSO}\cdot\left\{\frac{\cos(\frac{\pi}{V_\pi}V_{dc})}{\sin(\frac{\pi}{V_\pi}V_{dc})}\right\}^2$$

Power ratio of CTB/C

$$\frac{CTB}{C}=\left\{\frac{2[J_1(\frac{\pi A}{V_\pi})]^3[J_0(\frac{\pi A}{V_\pi})]^{N-3}}{2J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1}}\right\}^2 N_{CTB}\cdot\left\{\frac{\sin(\frac{\pi}{V_\pi}V_{dc})}{\sin(\frac{\pi}{V_\pi}V_{dc})}\right\}^2$$




- CSO Cancelled when Applied DC Voltage bias at ±0.5Vπ ,±1.5Vπ,… (Q-point)
- CTB independent of Applied DC Voltage
- CSO is negligible

# *Transmission Standard & Device Parameter Values*

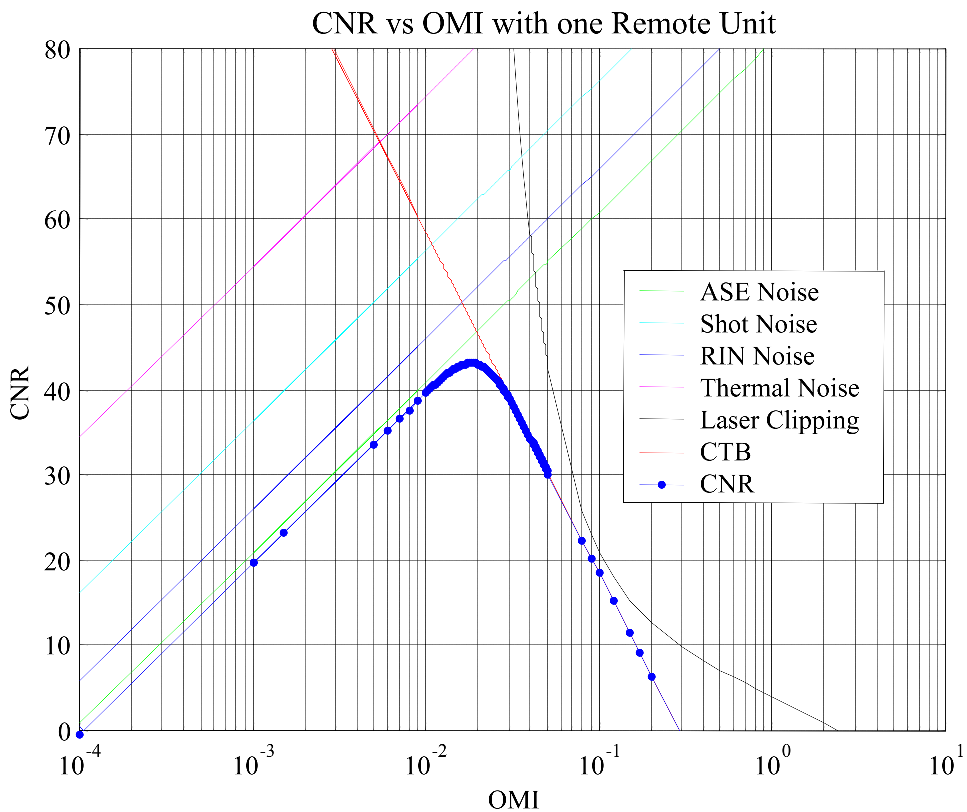
| Parameter | FCC Requirement | Typical Value | Project Target |
|---|---|---|---|
| CATV Carrier/Noise | > 43dB [Section 76.605 (a) (7)] | 48dB +/- 2dB | 50dB |
| CATV CSO | > 51dBc [Section 76.605 (a) (8)] | -53dBc +/- 2dB | -60dBc |
| CATV CTB | > 51dBc [Section 76.605 (a) (8)] | -53dBc +/- 2dB | -60dBc |
| Digital Q-Value | 6 | 6 | 6 |

| Laser | MZ Modulator | Booster Amplifier | Photodiode |
|---|---|---|---|
| Power = 6, 8 &10dBm | Loss=5dB | Input Power -1, 1 & 3dBm | Responsivity = 0.8, 0.9A/W |
| Wavelength = 1550nm | Bandwidth = 20GHz | Output Power = 17dBm | BW = 6MHz (CATV) |
| RIN=-155, -160dB/Hz | | Noise Figure = 5dB | BW = 0.75GHz (Digital) |
| | | nsp = 1.5849 | T=300K, Kb=1.38e-23 |
| | | Coupling and Isolator loss = 2dB | Resistance = 1000 ohms |

# CATV CNR Analysis using Conventional MZ Modulator

$$CNR_{total}^{-1} = CNR_{RIN}^{-1} + CNR_{Thermal}^{-1} + CNR_{shot}^{-1} + CNR_{ASE}^{-1} + CNR_{Clipping}^{-1} + CNR_{CTB}^{-1}$$

$$CNR_{total}^{-1} = [\frac{m^2 I_p^2}{2RIN \cdot I_p^2 B}]^{-1} + [\frac{m^2 I_p^2}{\frac{8KTB}{R}}]^{-1} + [\frac{m^2 I_p^2}{4qI_p B}]^{-1} + [\frac{m^2 I_s}{8hfn_{sp}RB}]^{-1} + [\frac{\sqrt{2\pi}(1+6\mu^2)e^{\frac{1}{2\mu^2}}}{\mu^3}]^{-1} + [\frac{16}{m^4 \cdot N_{ctb}}]^{-1}$$




**Parameter Values**

- Optical Power budget : 1 end Users
- RIN=-155dB/Hz
- -1dBm input at Booster Amplifier
- R=0.8 A/W

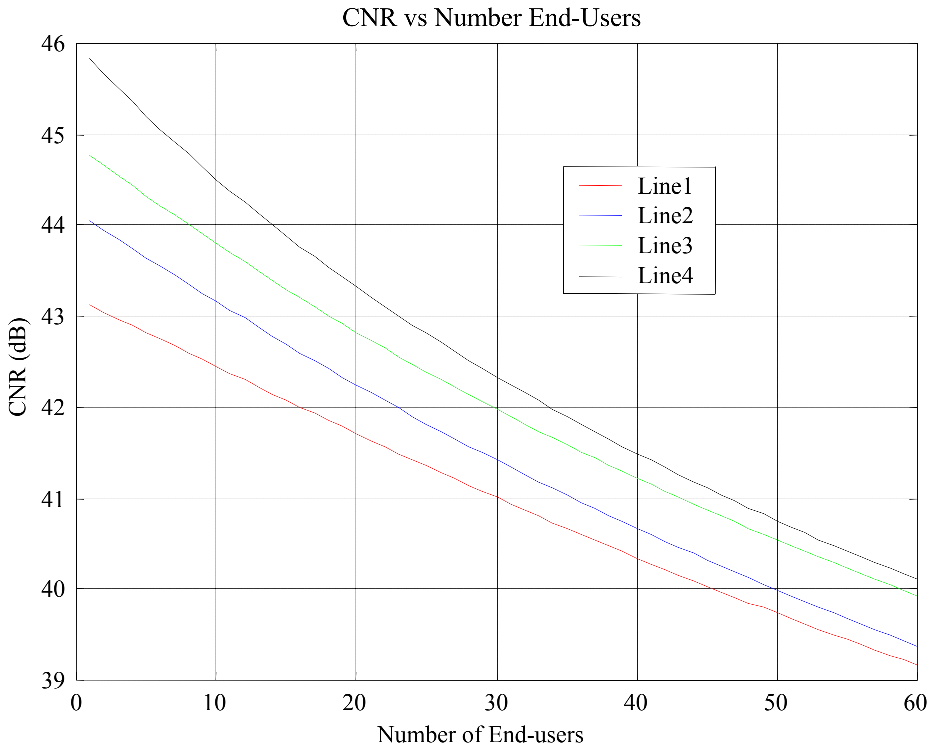
- CNR=43.1dB (Maximum)
  C/CTB = 47dB
  OMI = 1.84%
- Disregarding CTB term for the moment:
  1) CNR increases to 50dB, as OMI increases to 3.4% OMI.

  2) As OMI continues to increase, Clipping becomes dominant

  3) Optimized OMI from 3% to 5% range

# *Scalability of SCM network using Conventional MZ Modulator*

| Parameters | Line 1 | Line 2 | Line 3 | Line 4 |
|---|---|---|---|---|
| Input power at Booster Amplifier | -1dBm | 1dBm | 1dBm | 3dBm |
| Laser RIN | -155dB/Hz | -155dB/Hz | -160dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.8 A/W | 0.8 A/W | 0.9A/W | 0.9 A/W |
| Fiber distance | 10km | 10km | 10km | 10km |

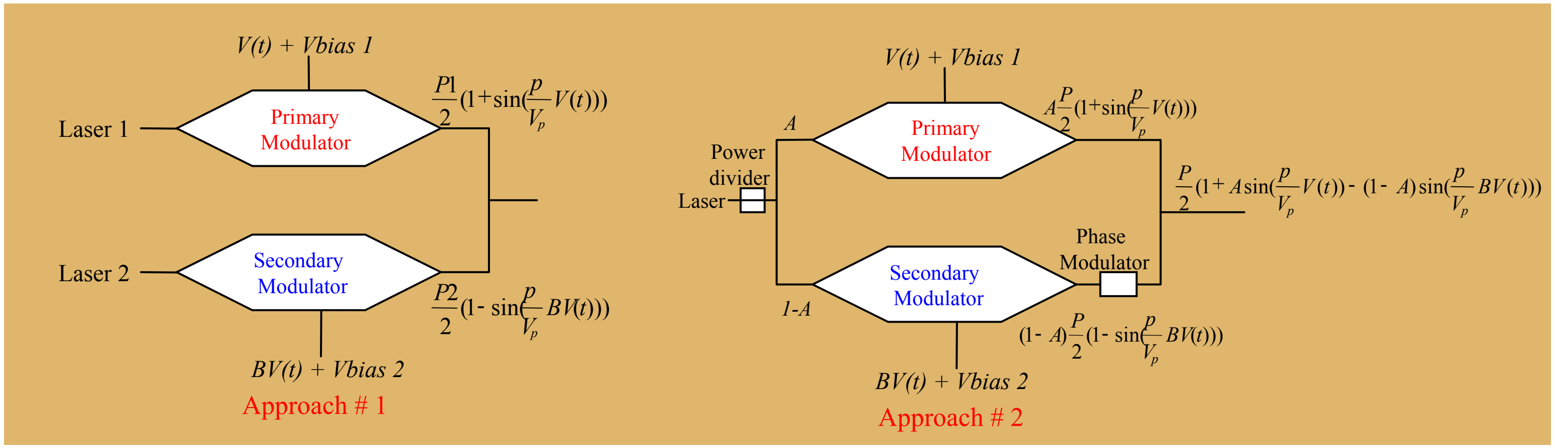



Increase SCM Network Scalability

- Improved ASE Noise
- Improved Laser RIN Noise
- Improved Receiver Noise

- The "SCM/WDM-PON" network scalability can not be improved further as the third order nonlinear distortion (CTB) severe limit overall CNR performance
- It cannot implement in practical CATV network without reduced CTB noise

# Dual Parallel Linearized External Modulators




- Primary Modulator bias at Q-point ($V_{dc} = 0.5V_\pi$)
- Secondary Modulator bias at Q-point 180º from the point chosen for the primary modulator ($V_{dc} = 1.5V_\pi$)
- Apply higher RF driver power and less Optical power to secondary modulator. This result higher OMI and higher distortion.  CTB created in secondary modulator can be made to cancel the distortion products from the primary modulator [2]

A = Optical Power Ratio

B = RF Power Ratio

Transfer Function of DPMZ

$$\frac{P_{out}}{P_{in}} = A\cos^2\left[\frac{\frac{\pi V(t)}{V_\pi}-\frac{\pi}{2}}{2}\right] + (1-A)\cos^2\left[\frac{B\frac{\pi V(t)}{V_\pi}-\frac{3\pi}{2}}{2}\right] = \frac{1}{2}\left(1+A\sin\frac{\pi V(t)}{V_\pi}-(1-A)\sin\frac{B\pi V(t)}{V_\pi}\right)$$

Primary Modulator Transfer Function

Secondary Modulator Transfer Function

# Dual Parallel Linearized External Modulators

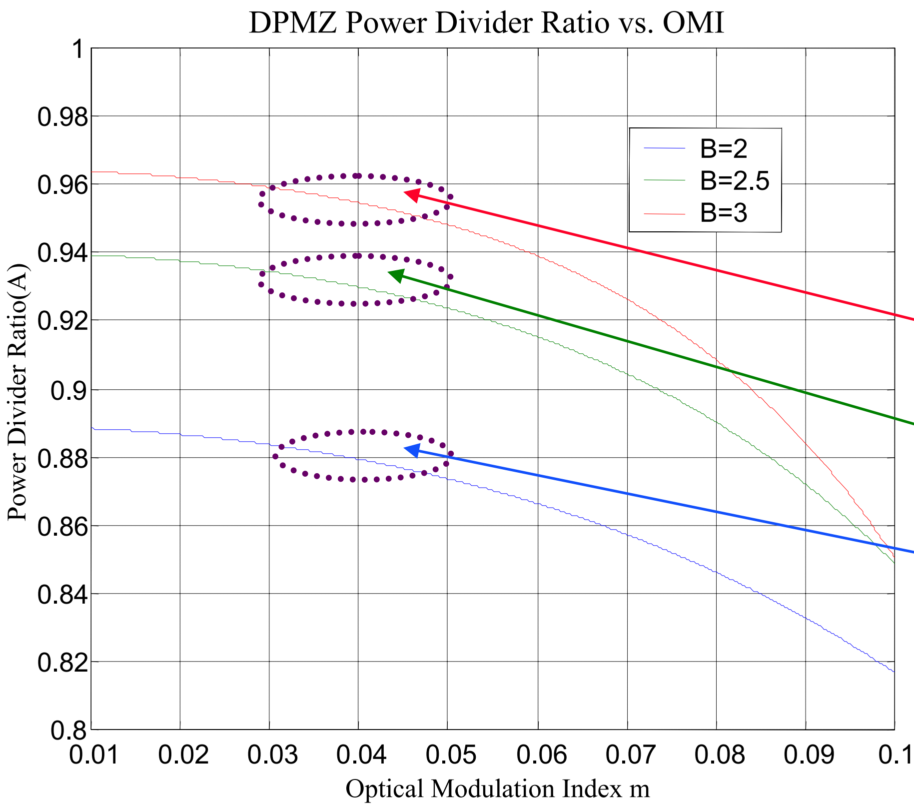
- Amplitude of Fundamental carrier with frequency $\omega_k$

$$\frac{P_{\omega_k}}{P_{in}} = AJ_1\left(\frac{\pi A}{V_\pi}\right)J_0\left(\frac{\pi A}{V_\pi}\right)^{N-1} - (1-A)J_1\left(B\frac{\pi A}{V_\pi}\right)J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-1}$$

- Amplitude of third order distortion component of the frequency $\omega_i+\omega_j+\omega_k$

$$\frac{P_{\omega_k+\omega_j+\omega_k}}{P_{in}} = AJ_1\left(\frac{\pi A}{V_\pi}\right)^3 J_0\left(\frac{\pi A}{V_\pi}\right)^{N-3} - (1-A)J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3}$$

$$A = \frac{J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3}}{J_1\left(\frac{\pi A}{V_\pi}\right)^3 J_0\left(\frac{\pi A}{V_\pi}\right)^{N-3} + J_1\left(B\frac{\pi A}{V_\pi}\right)^3 J_0\left(B\frac{\pi A}{V_\pi}\right)^{N-3}}$$



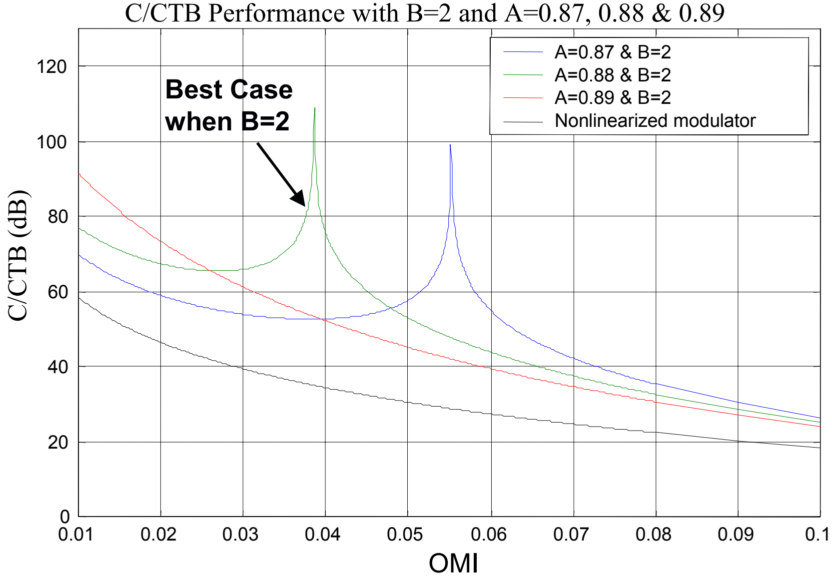

The optimize value of OMI is from 3% to 5%, Laser clipping becomes dominant as OMI increases to 5%

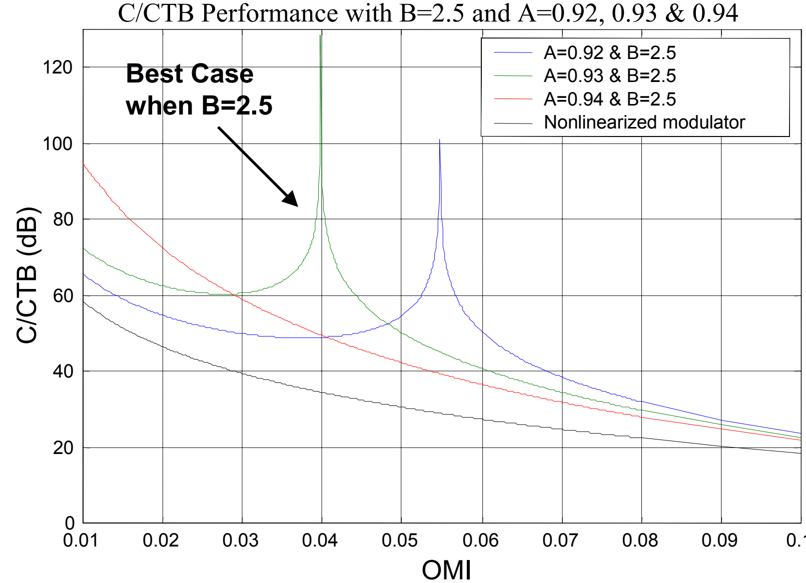
B = 3, A =0.94 to 0.97

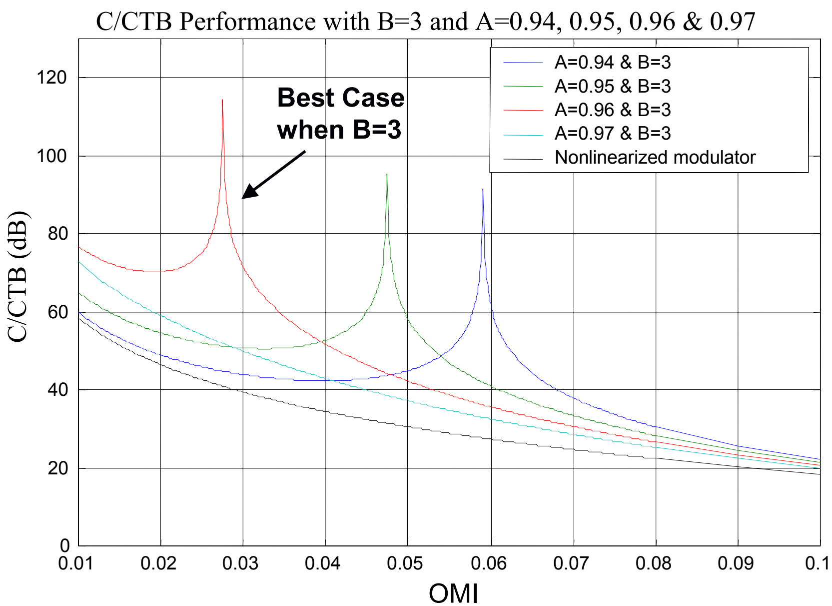
B = 2.5, A =0.92 to 0.94

B = 2, A =0.87 to 0.89

# *DPMZ*



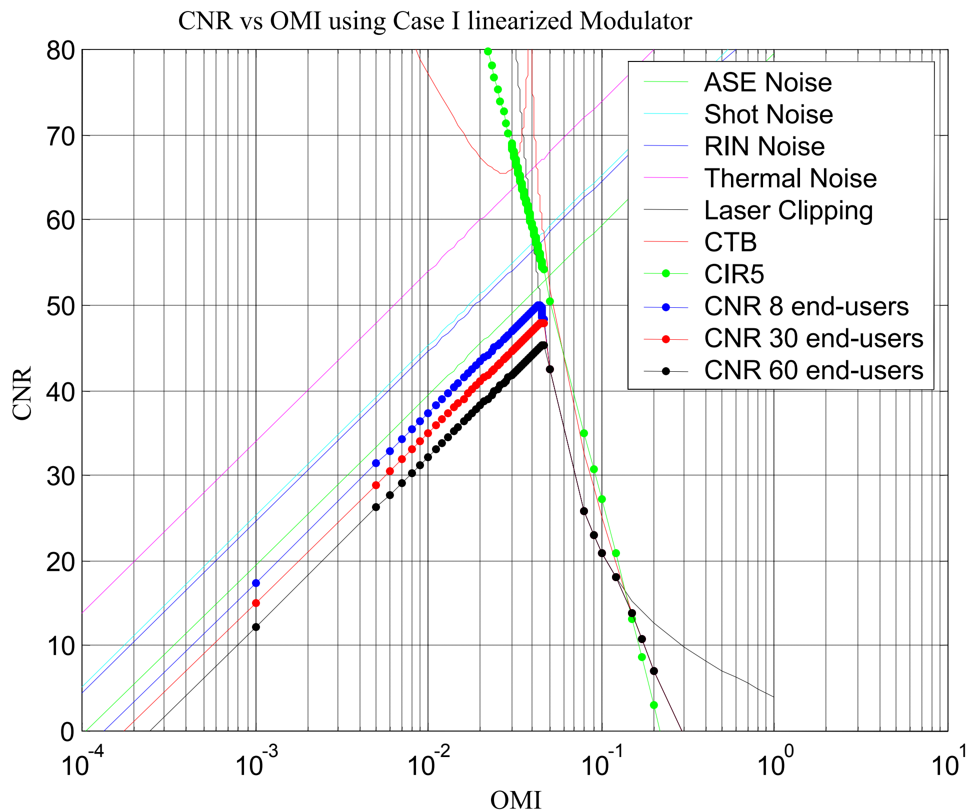




**Case I:** A=0.88, B=2, OMI = (1% - 4.5%), CTB/C > 60 dB

**Case II:** A=0.93, B=2.5, OMI = (1% - 4.4%), CTB/C > 60 dB

**Case III:** A=0.96, B=3, OMI = (1% - 3.4%), CTB/C > 60 dB

# *CATV CNR Analysis Using Linearized MZ Modulator*




**Parameter Values**

Linear Modulator

- A = 2 & B = 0.88

Optical Power budget

- 8 Customers
- 30 Customers
- 60 Customers

RIN=-155dB/Hz

-1dBm input at Booster Amplifier

R=0.8 A/W

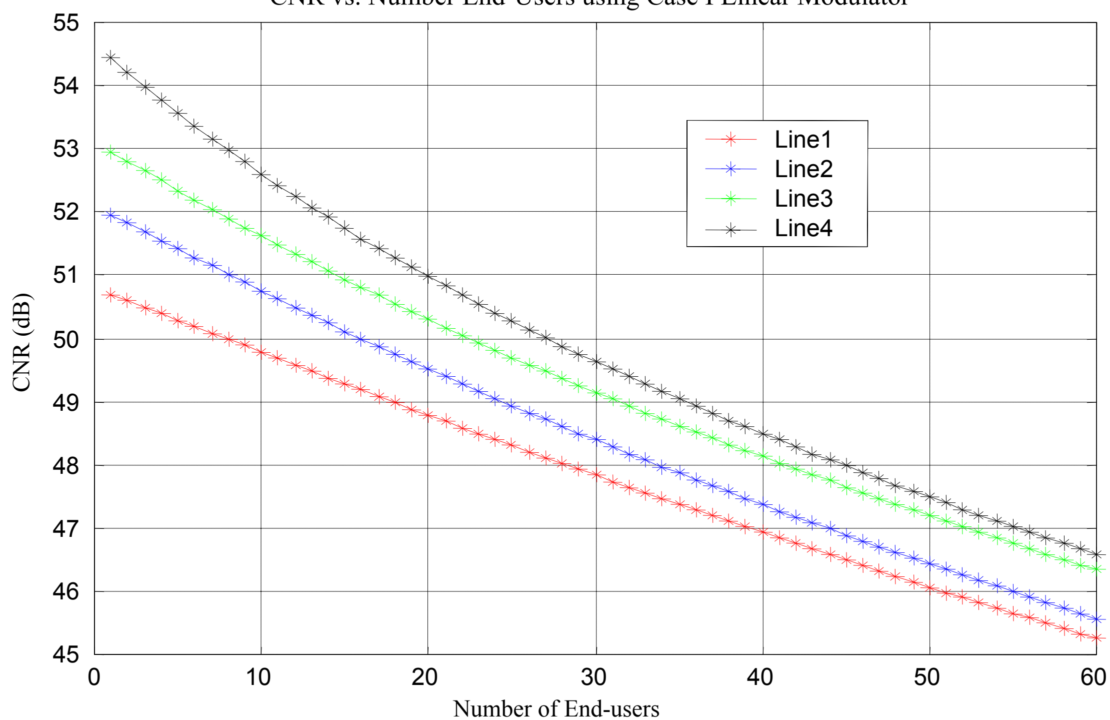
Results

- Optical Power Budget = 8 Customers
- CNR=50dB
- C/CTB = 60.5dBc
  OMI = 4.48%

# *Scalability of SCM Externally M0odulated Optical Link Using DPZM*

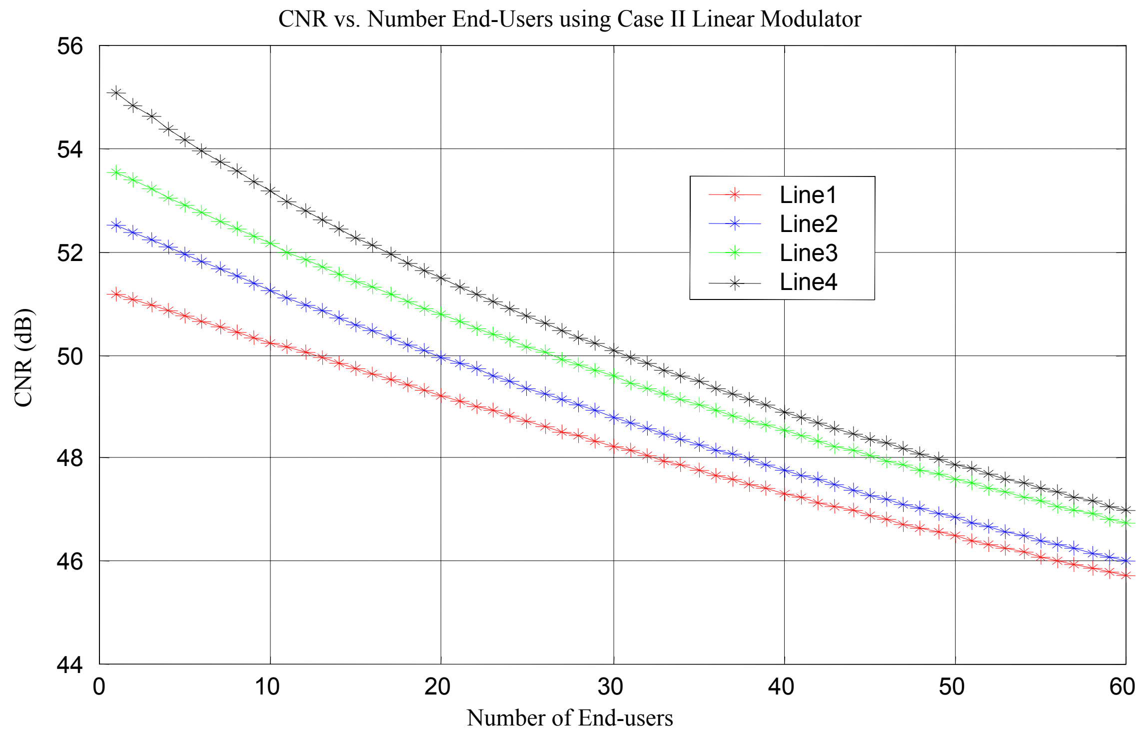
| PARAMETERS | Line 1 | Line 2 | Line 3 | Line 4 |
|---|---|---|---|---|
| **Case I : MZ Modulator** | A=0.88 & B=2 | A=0.88 & B=2 | A=0.88 & B=2 | A=0.88 & B=2 |
| Input power at Booster Amplifier | -1dBm | 1dBm | 1dBm | 3dBm |
| Laser RIN | -155dB/Hz | -155dB/Hz | -1 60dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.8 A/W | 0.8 A/W | 0.9A/W | 0.9 A/W |
| Fiber distance | 10km | 10km | 10km | 10km |
| **RESULTS** | | | | |
| No. of End -Users > 50dB CNR | **8** | **15** | **22** | **27** |
| CNR per Channel | 50 dB | 50.1163 dB | 50.0553dB | 50.0079 dB |
| C/CTB per Channel | 60.4695 dB | 60.6555 dB | 60.65dB | 60.655dB |
| OMI per Channel | 4.48 % | 4.47 % | 4.47 % | 4.47% |
| Receiver Optical Power per RF Channel | -13.647dBm | -16.37dBm | -18dBm | -18.9dBm |

CNR vs. Number End-Users using Case I Linear Modulator



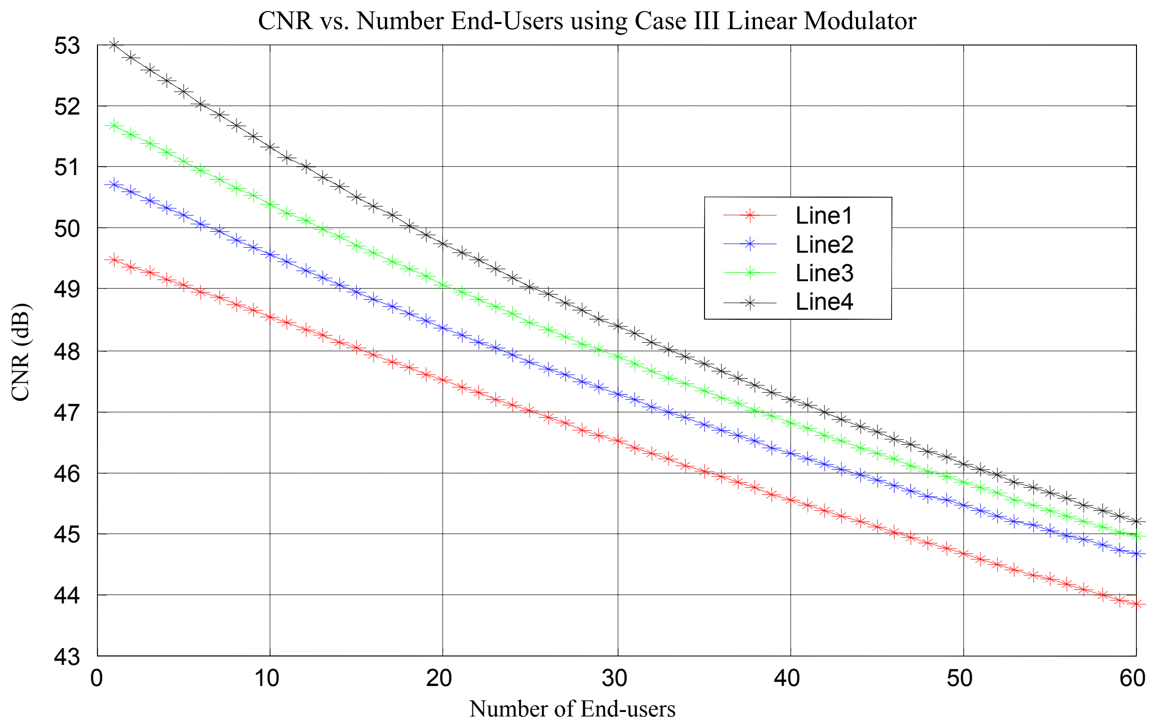
# Scalability of SCM Externally Modulated Optical Link Using DPZM

| PARAMETERS | Line 1 | Line 2 | Line 3 | Line 4 |
|---|---|---|---|---|
| **Case II: MZ Modulator** | A=0.93 & B=2.5 | A=0.93 & B=2.5 | A=0.93 & B=2.5 | A=0.93 & B=2.5 |
| Input power at Booster Amplifier | -1dBm | 1dBm | 1dBm | 3dBm |
| Laser RIN | -155dB/Hz | -155dB/Hz | -160dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.8 A/W | 0.8 A/W | 0.9A/W | 0.9 A/W |
| Fiber distance | 10km | 10km | 10km | 10km |
| **RESULTS** | | | | |
| No. of End -Users > 50dB CNR | **12** | **19** | **26** | **30** |
| CNR per Channel | 50.036 dB | 50.085 dB | 50.043dB | 50.08 dB |
| C/CTB per Channel | 61.9 dB | 61.89dB | 61.89dB | 61.89dB |
| OMI per Channel | 4.34 % | 4.34 % | 4.34 % | 4.34% |
| Receiver Optical Power per RF Ch | -14.8dBm | -16.8dBm | -18.1dBm | -18.8dBm |



# Scalability of SCM Externally Modulated Optical Link Using DPZM

| Parameters | Line 1 | Line 2 | Line 3 | Line 4 |
|---|---|---|---|---|
| **Case III: MZ Modulator** | A=0.96 & B=3 | A=0.96 & B=3 | A=0.96 & B=3 | A=0.96 & B=3 |
| Input power at Booster Amplifier | -1dBm | 1dBm | 1dBm | 3dBm |
| Laser RIN | -155dB/Hz | -155dB/Hz | -160dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.8 A/W | 0.8 A/W | 0.9A/W | 0.9 A/W |
| Fiber distance | 10km | 10km | 10km | 10km |
| **RESULTS** | | | | |
| No. of End -Users > 50dB CNR | **0** | **6** | **12** | **18** |
| CNR per Channel | 49.47 dB | 50.062 dB | 50.1182dB | 50.05 dB |
| C/CTB per Channel | 60.0191 dB | 60.0191dB | 60.0191dB | 60.0191dB |
| OMI per Channel | 3.43 % | 3.43 % | 3.43 % | 3.43% |
| Receiver Optical Power per RF Channel | -4.6dBm | -12.38dBm | -15.9dBm | -17.6dBm |



# *Digital Data Q-Value Analysis*

$$I_p = I \cdot \{\left[2AJ_1(\frac{\pi V}{V_\pi})J_0(\frac{\pi V}{V_\pi})^{N-1} \cdot x(t) \cdot \cos(\omega_d)t\right] - \left[2(1-A)J_1(B\frac{\pi V}{V_\pi})J_0(B\frac{\pi V}{V_\pi})^{N-1} \cdot x(t) \cdot \cos(\omega_d)t\right]\}$$

$$Q_{BPSK} = \frac{I_P(1) - I_P(-1)}{\sigma(1) + \sigma(-1)} = \frac{2 \cdot I \cdot \{\left[2A(\frac{m}{2})e^{-m^2N/4}\right] - \left[2(1-A)(\frac{Bm}{2})e^{-B^2m^2N/4}\right]\}}{2(\sigma_{Shot} + \sigma_{RIN} + \sigma_{Thermal} + \sigma_{ASE})}$$

$$Q_{QPSK} = \frac{I_P(\frac{1}{\sqrt{2}}) - I_P(-\frac{1}{\sqrt{2}})}{\sigma(\frac{1}{\sqrt{2}}) + \sigma(-\frac{1}{\sqrt{2}})} = \frac{I \cdot \{\left[2A(\frac{m}{2})e^{-m^2N/4}\right] - \left[2(1-A)(\frac{Bm}{2})e^{-B^2m^2N/4}\right]\}}{\sqrt{2} \cdot (\sigma_{Shot} + \sigma_{RIN} + \sigma_{Thermal} + \sigma_{ASE})}$$

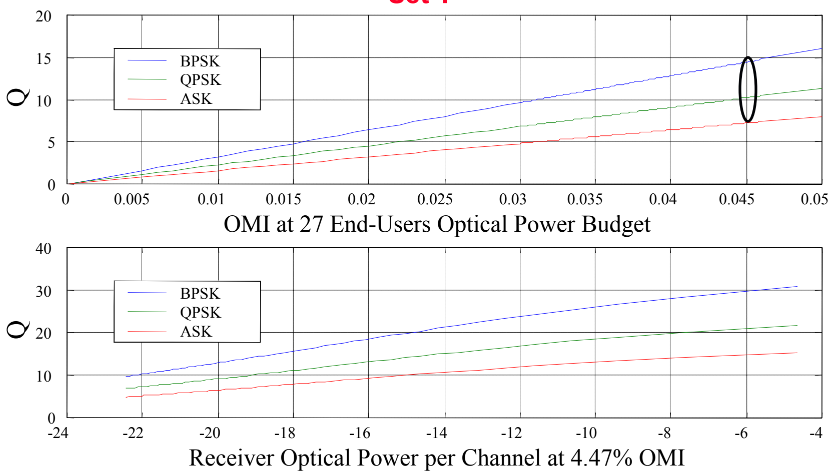
$$Q_{ASK} = \frac{I_P(1) - I_P(0)}{\sigma(1) + \sigma(0)} = \frac{I \cdot \{\left[2A(\frac{m}{2})e^{-m^2N/4}\right] - \left[2(1-A)(\frac{Bm}{2})e^{-B^2m^2N/4}\right]\}}{2(\sigma_{Shot} + \sigma_{RIN} + \sigma_{Thermal} + \sigma_{ASE})}$$

| **Parameter** | **Set 1** | **Set 2** | **Set 3** |
|---|---|---|---|
| **Linear MZ Modulator** | A=0.88 & B=2 | A=0.93 & B=2.5 | A=0.96 & B=3 |
| Input power at Booster Amplifier | 3dBm | 3dBm | 3dBm |
| Laser RIN | -160dB/Hz | -160dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.9 A/W | 0.9 A/W | 0.9A/W |
| Fiber distance | 10km | 10km | 10km |
| No. of End-Users | 27 | 30 | 18 |
| OMI / Channel | 4.47% | 4.34% | 3.43% |
| Receiver Optical Channel Power | -18.9dBm | -18.8dBm | -17.6dBm |

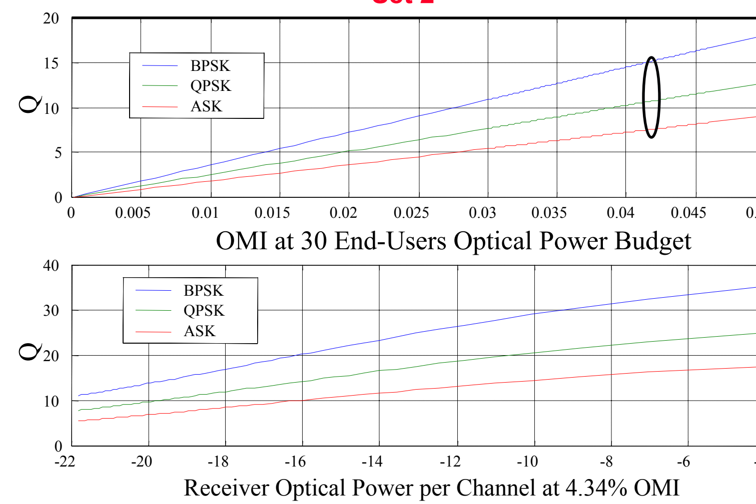
# *Digital Data Q-Value Analysis*

| RESULTS | Set 1 | Set 2 | Set 3 |
|---|---|---|---|
| BPSK Q-Value | 14.3 | 15.7 | 16.9 |
| QPSK Q-Value | 10.1 | 11 | 11.9 |
| ASK Q-Value | 7.2 | 7.8 | 8.4 |

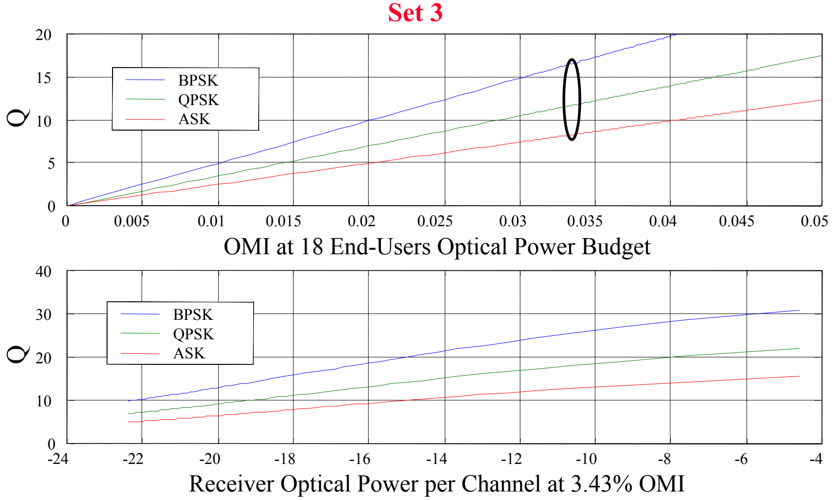
**Set 1**




**Set 2**




**Set 3**




1) **The Requirements of Digital is more relax compared to Analog channel.**

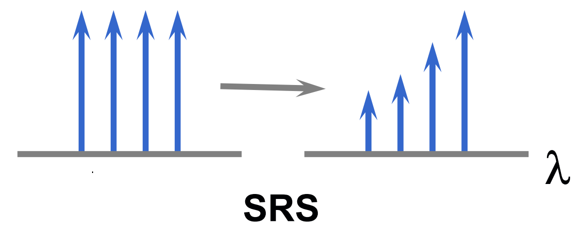
2) **High Optical Power Transmission in SCM Network**

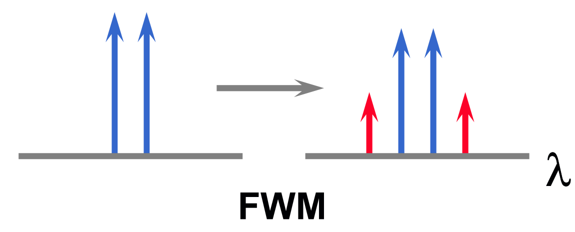
3) **Q-Value continues to increase as optical power increase**

# *Fiber Nonlinearities (From Linear to Non-linear Propagation)*

Types of Fiber Nonlinearities

- Stimulated Scattering
  - Raman (SRS)
- Nonlinear index (Kerr Effect)
  - Cross-phase modulation (XPM)
  - Four-wave mixing (FWM)

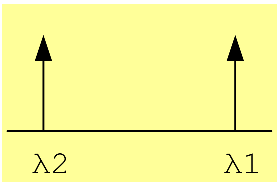


# *Stimulated Raman Scattering (SRS) Frequency Response Concept in WDM Network [3]*

Use coupled propagation equations to solve for SRS Crosstalk level

$$\frac{\partial I_1}{\partial z} + \frac{1}{v_1}\frac{\partial I_1}{\partial t} = (gI_2 - \alpha)I_1 \qquad \frac{\partial I_2}{\partial z} + \frac{1}{v_2}\frac{\partial I_2}{\partial t} = (-gI_1 - \alpha)I_2$$

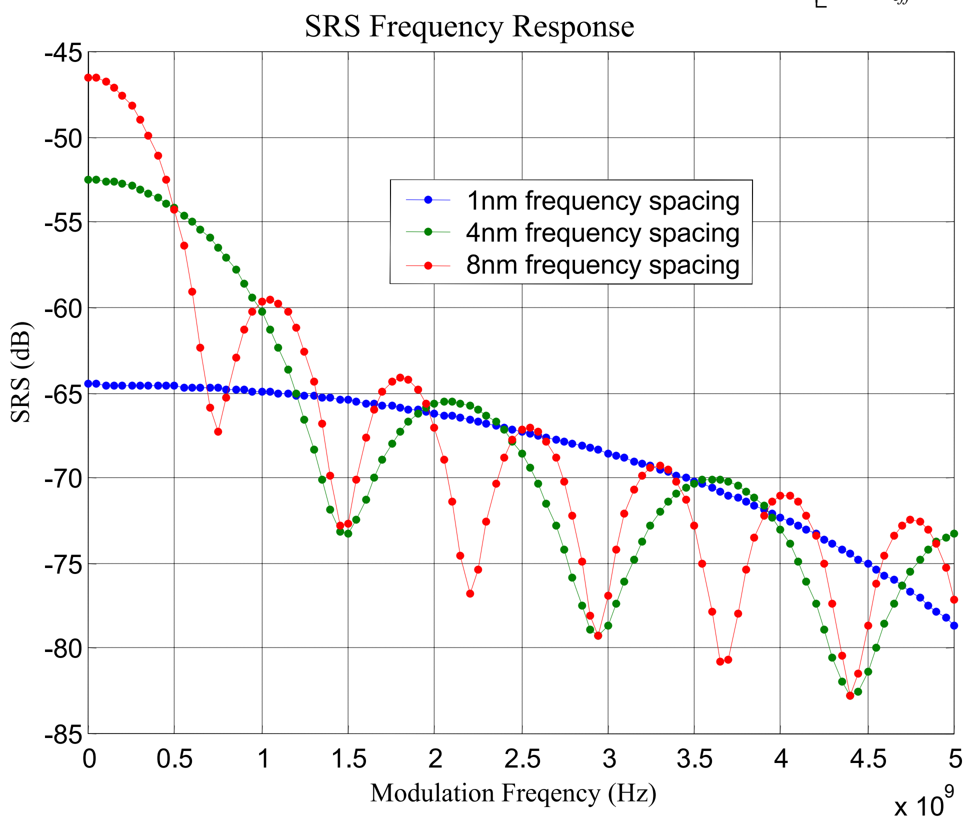



Optical Carrier power after fiber loss

Interaction between the optical carriers, results in optical dc power gain or loss

$$P_2(0,\mu_2) \approx P_2(0,\mu_2)e^{-\alpha z}\left[1 - \frac{g}{A_{eff}}\int_0^z P_1(0,\mu_2 + d_{12}z')e^{-\alpha z'}dz'\right] = P_o e^{-\alpha z}\left\{1 - \frac{g}{A_{eff}}P_o\left|\frac{1-e^{-\alpha z}}{\alpha}\right|\right\}$$

$$P_1(0,\mu_1) \approx P_1(0,\mu_1)e^{-\alpha z}\left[1 + \frac{g}{A_{eff}}\int_0^z P_2(0,\mu_1 + d_{12}z')e^{-\alpha z'}dz'\right] = P_o e^{-\alpha z}\left\{1 + \frac{g}{A_{eff}}P_o\left|\frac{1-e^{-\alpha z}}{\alpha}\right|\right\}$$

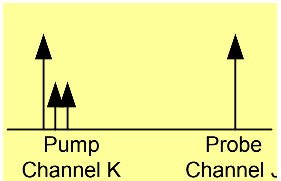



**Parameter Values**

- SM fiber, Slope of Raman Gain = 5e-15m/W/THz
- 10dBm optical power entering fiber
- 10km fiber length
- Dispersion = 17ps/nm/km

- Transfer Function of SRS has a low pass filter characteristic
- SRS increases, as the Frequency Spacing between two channel increases.
- SRS is dominant at high frequency spacing and at small modulation frequency

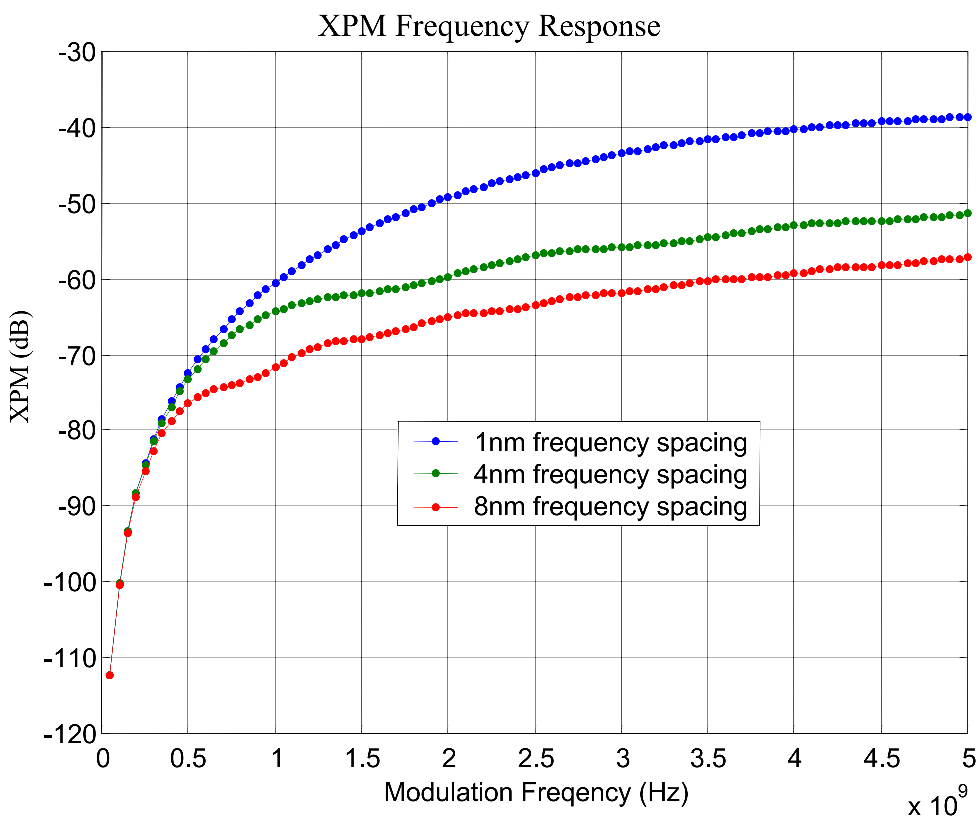
# *Cross Phase Modulation (XPM) Frequency Response Concept in WDM Network [4]*




Fiber Dispersion results in convert Phase Modulation to Intensity Modulation

$$\frac{\partial A_j(t,z)}{\partial z} + \frac{\alpha}{2}A_j(t,z) + \frac{1}{\nu_j}\frac{\partial A_j(t,z)}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A_j(t,z)}{\partial^2 t} = i\gamma_j[2P_k(t-d_{jk}z,z)]A_j(t,z)$$

Fiber Loss    Linear Phase Delay    Phase Modulation in the channel J induced by channel k

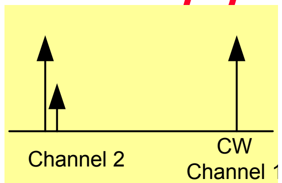



**Parameter Values**

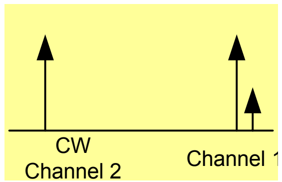
- 10dBm optical power entering fiber
- 10km fiber length
- Dispersion = 17ps/nm/km

- XPM transfer function has a high pass filter characteristic
- XPM increases, as the Frequency Spacing between two channel decreases.
- XPM is dominant at small frequency spacing and at large modulation frequency

# *Constructive & Destructive SRS+XPM Frequency Response Concept in WDM Network [3]*

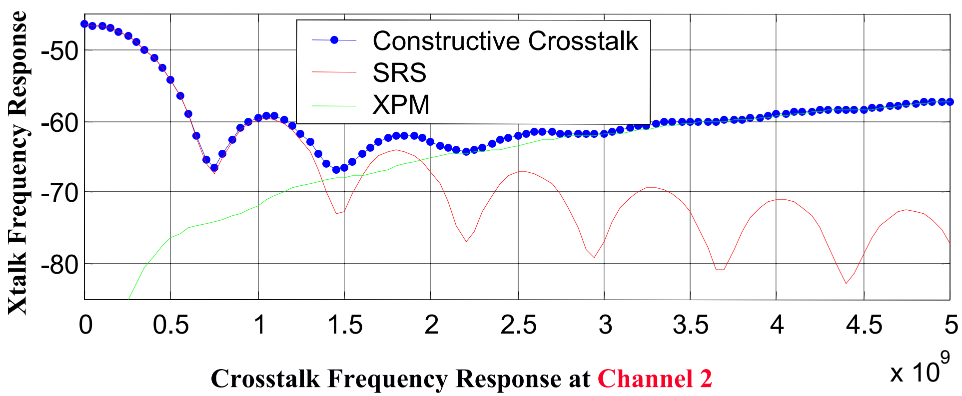



- Crosstalk at Channel 1 (Constructive)
- Power gain through SRS Interaction
- XPM crosstalk at Channel 1

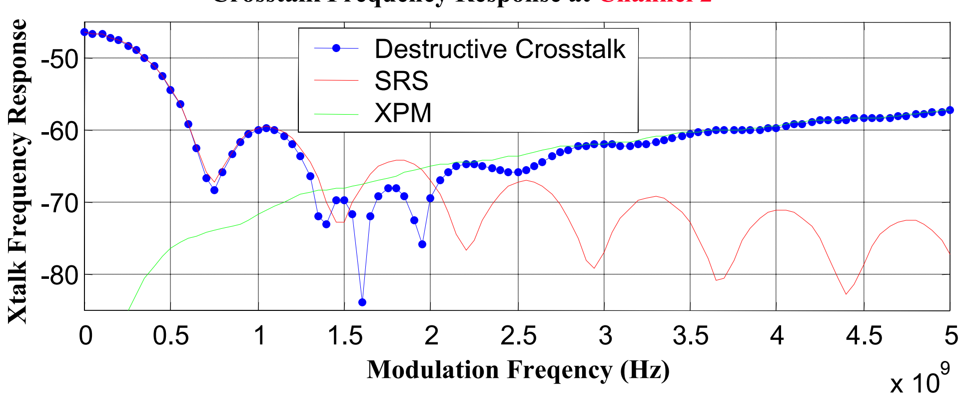



- Crosstalk at Channel 2 (Destructive)
- Power depletion through SRS Interaction
- XPM crosstalk at Channel 2

**Crosstalk Frequency Response at Channel 1**




**Crosstalk Frequency Response at Channel 2**

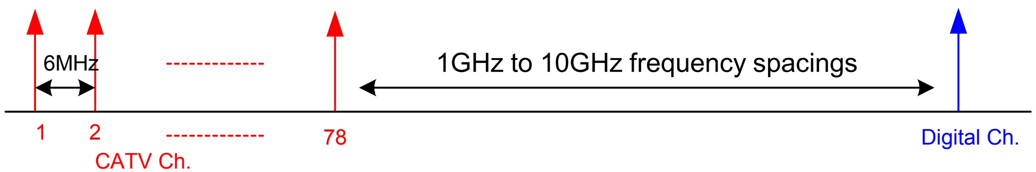


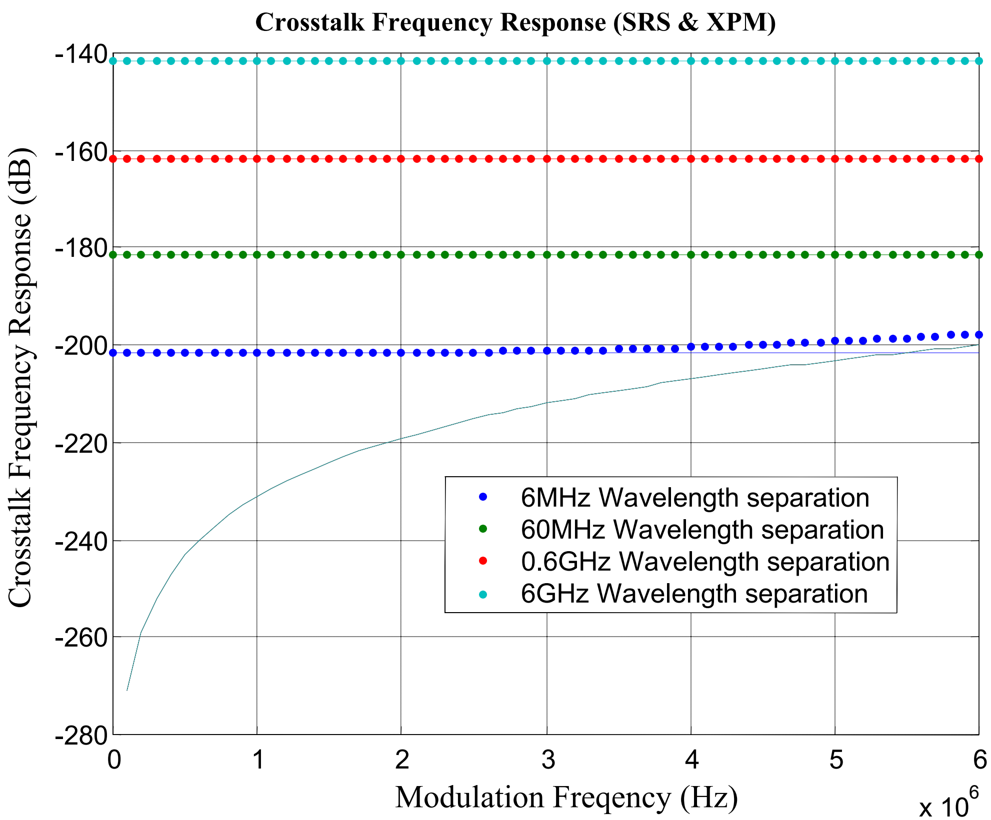

**Parameter Values**

- 10dBm optical power entering fiber
- 10km fiber length
- 17ps/nm/km Dispersion
- 0.8 nm Frequency spacing

- SRS dominant for small modulated frequency or large wavelength separation
- XPM is dominant for large modulated frequency or small wavelength separation
- In between we must consider whether the Channel suffered by SRS is going through power gain or depletion

# *SRS+XPM crosstalk in SCM Externally Modulated Network*

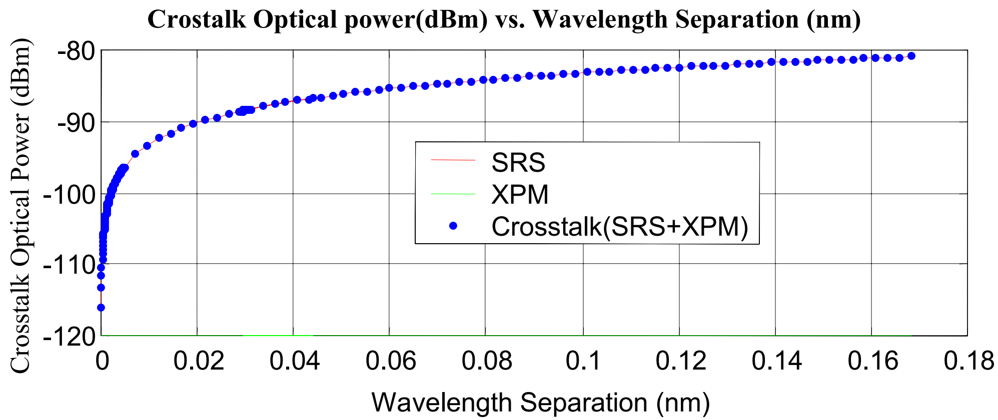


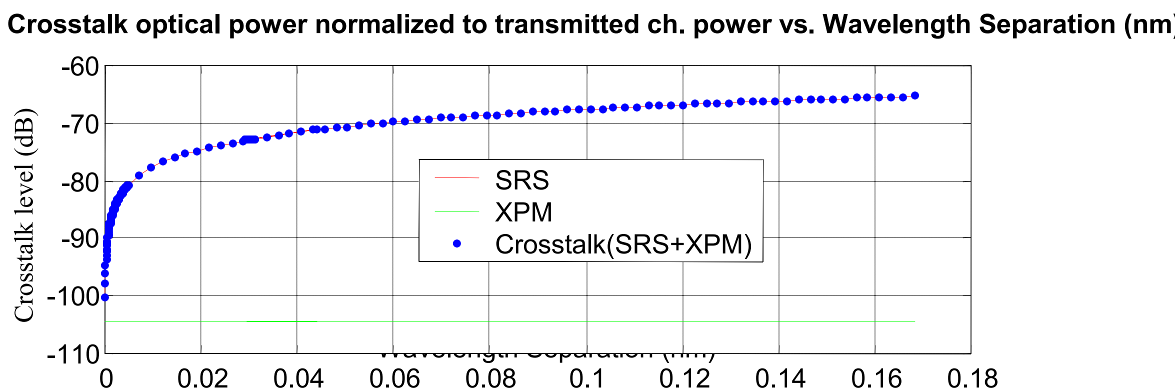




**Parameter Values**

- Optical Power Budget = 30 End-Users
- -15.6dBm optical channel power entering fiber
- 10km fiber length, 0.22dB/km
- 5e-15m/W/THz SRS Gain Slope
- 17ps/nm/km Dispersion

# *SRS+XPM Crosstalk in SCM Externally Modulated Network*

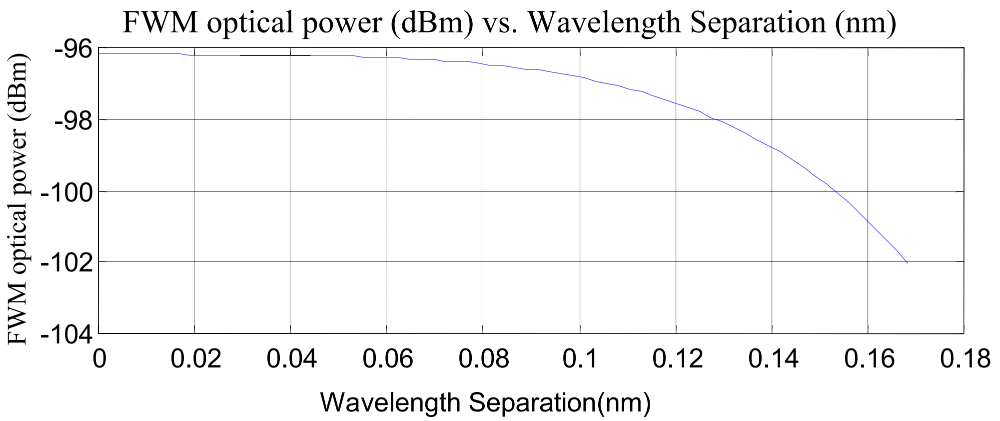


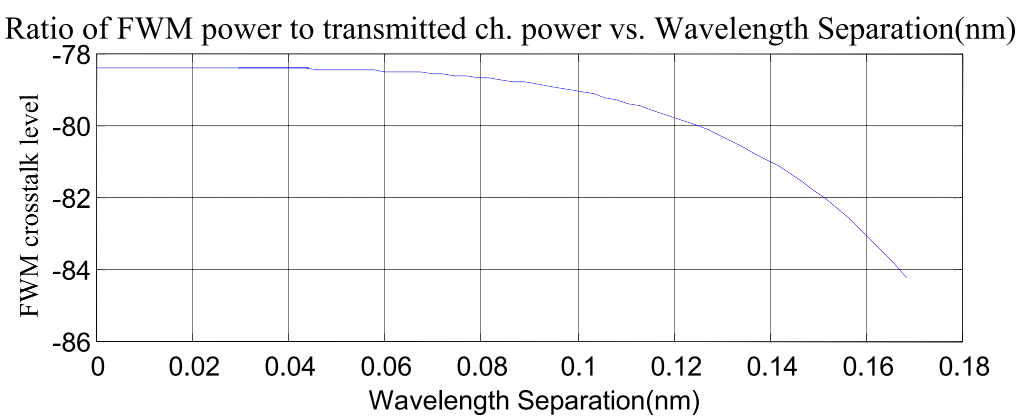




- SRS is the dominant crosstalk compared to XPM
- Overall result, SRS & XPM crosstalk shows very minimal impact between two subcarrier under same wavelength

# *Four-Wave Mixing*

$$P_{ijk}(L) = \frac{1024\pi^6}{n^4\lambda^2c^2}(DX_{1111})^2(\frac{P_iP_jP_k}{A_{eff}{}^2})L_{eff}{}^2\eta$$

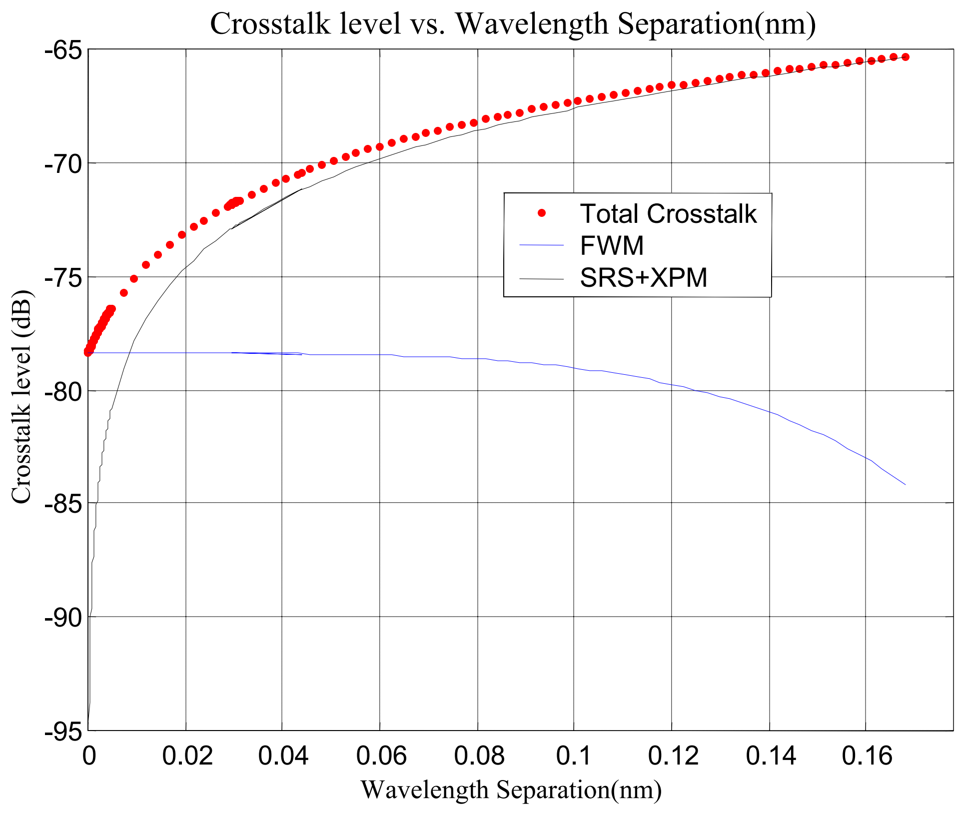



**Parameter Values**

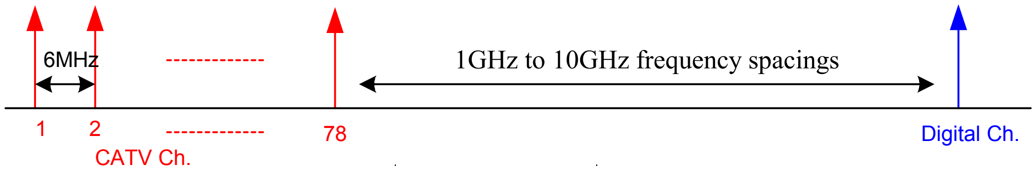
- Optical Power Budget = 30 End Users
- -15.6dBm optical channel power entering fiber
- 10km SM standard fiber
- 17ps/nm/km Dispersion
- D=6 (None of Frequencies are the same)

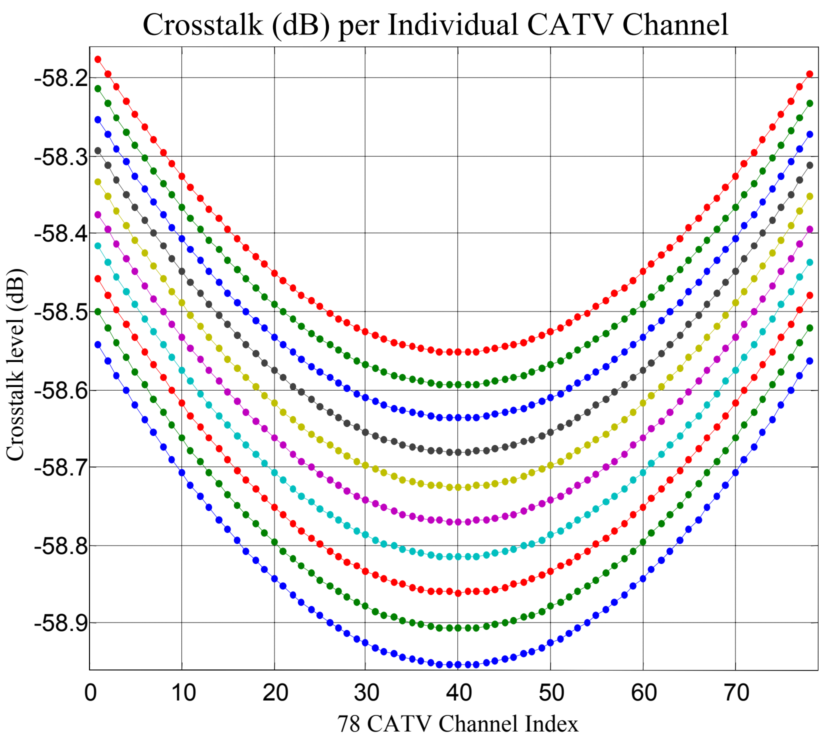
# *Total Crosstalk in SCM Externally Modulated Network*

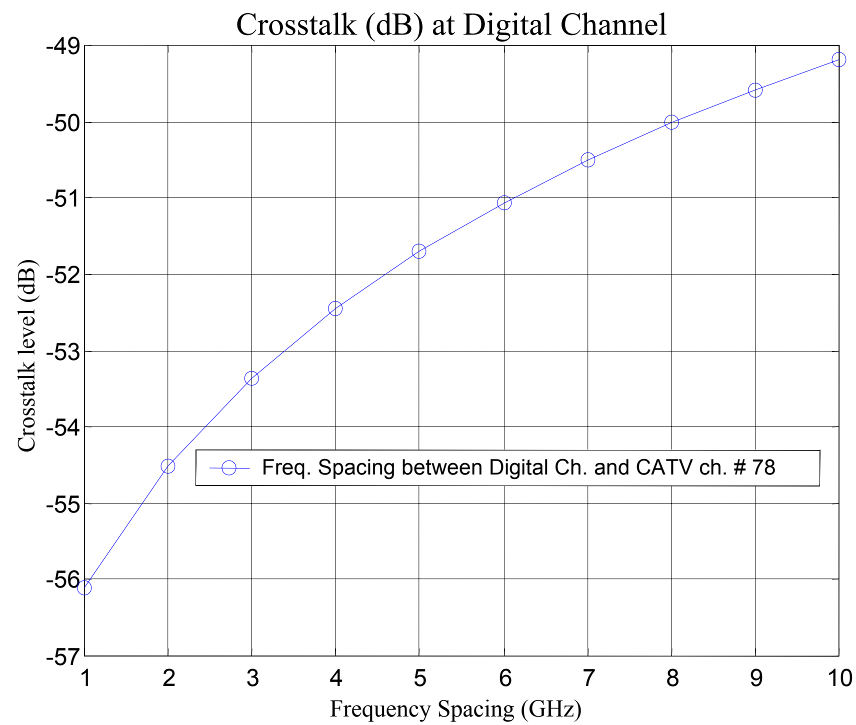



- FWM is the major source of nonlinear crosstalk in SCM optical systems with extremely narrow spacing between RF channels
- SRS becomes dominant as channel spacing increases

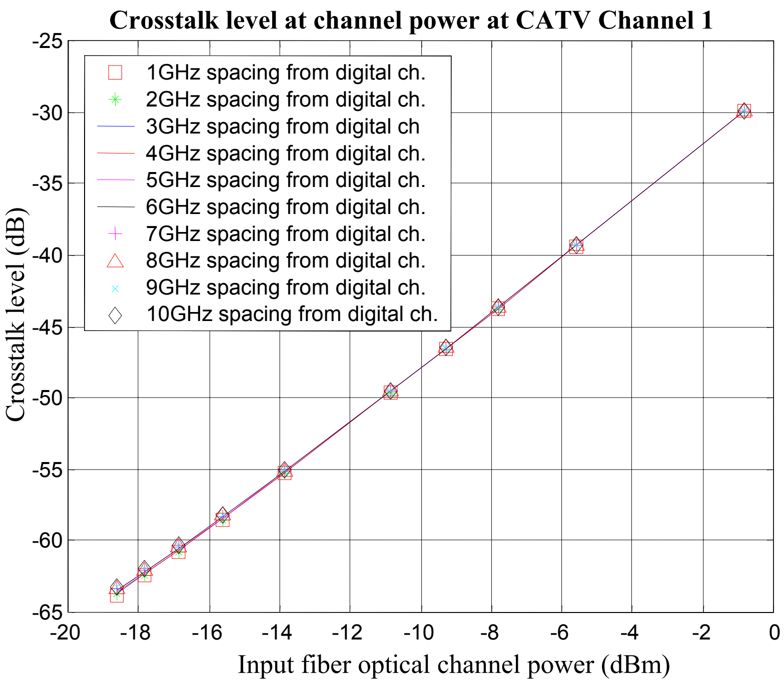
# *Total Crosstalk in SCM Externally Modulated Network*

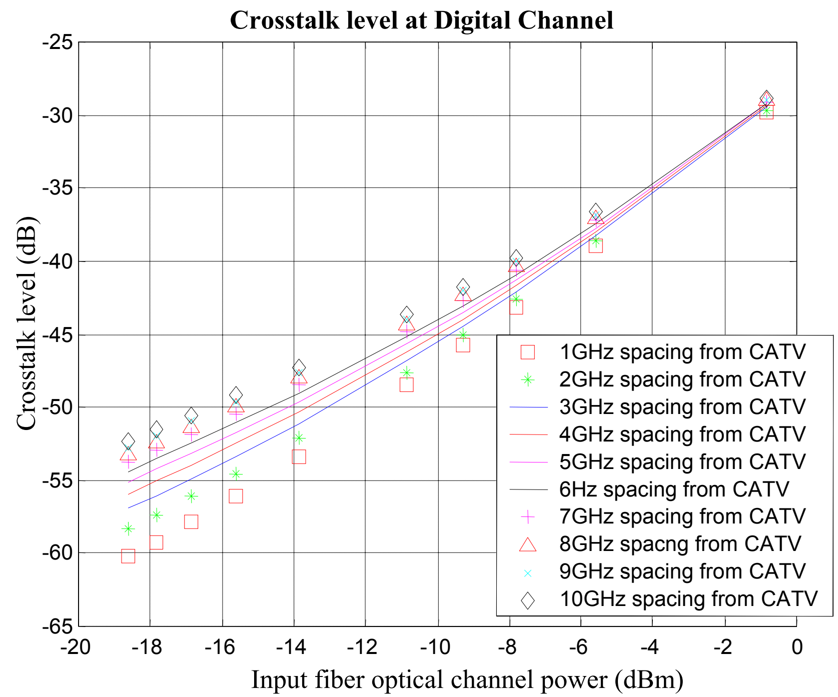


# *Total Crosstalk in SCM Externally Modulated Network*



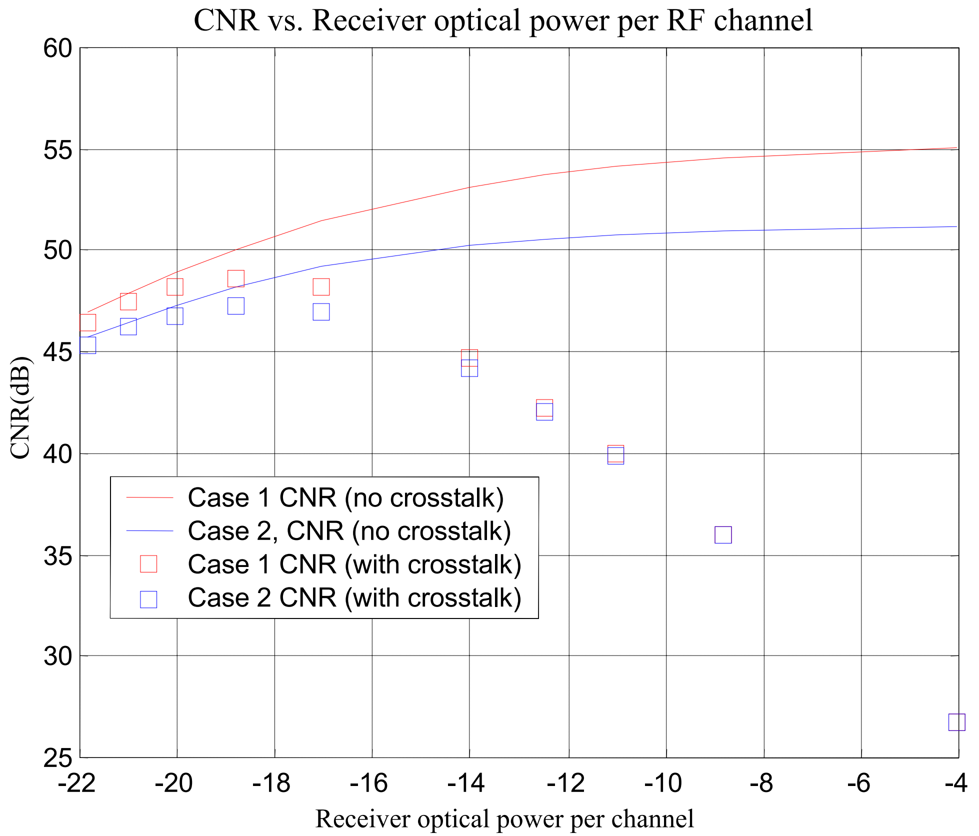




- The CATV Crosstalk level remains constant as power increases because FWM is the dominant Crosstalk at narrow channel spacing

- It demonstrates that as optical power increases, FWM becomes the dominant crosstalk in SCM externally modulated Network

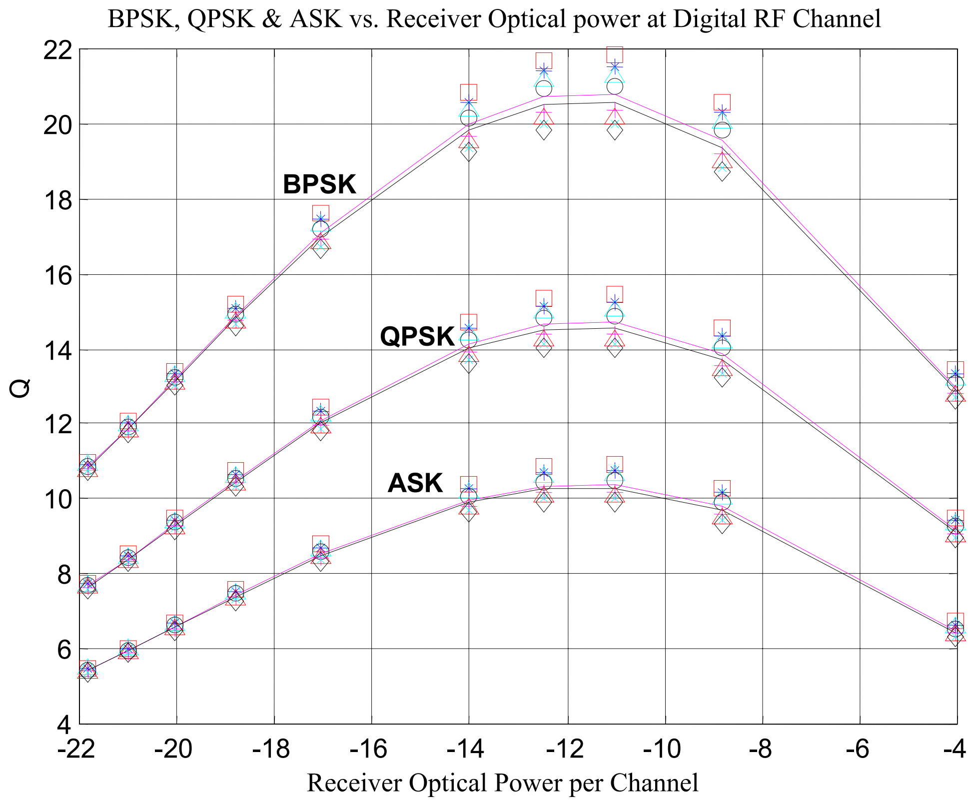
# *Signal-crosstalk Noise in SCM Transmission Performance for CATV*

| PARAMETERS | Case 1 | Case 2 |
|---|---|---|
| **Linearized MZ Modulator** | A=0.93 & B=2.5 | A=0.93 & B=2.5 |
| Input power at Booster Amplifier | -1dBm | 3dBm |
| Laser RIN | -155dB/Hz | -160dB/Hz |
| Photodiode Responsivity | 0.8 A/W | 0.9 A/W |
| Fiber distance | 10km | 10km |
| OMI | 4.343% | 4.343% |

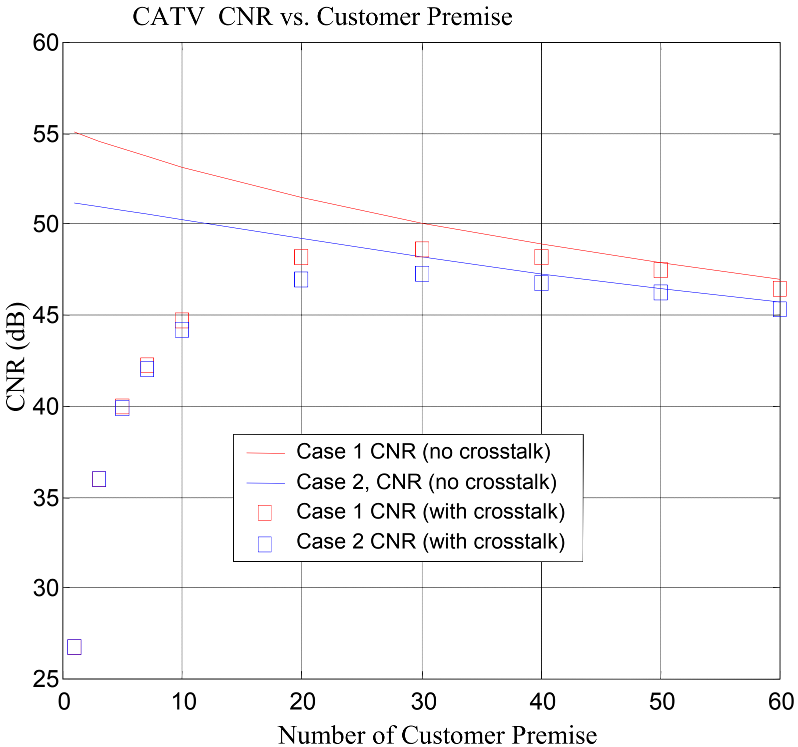


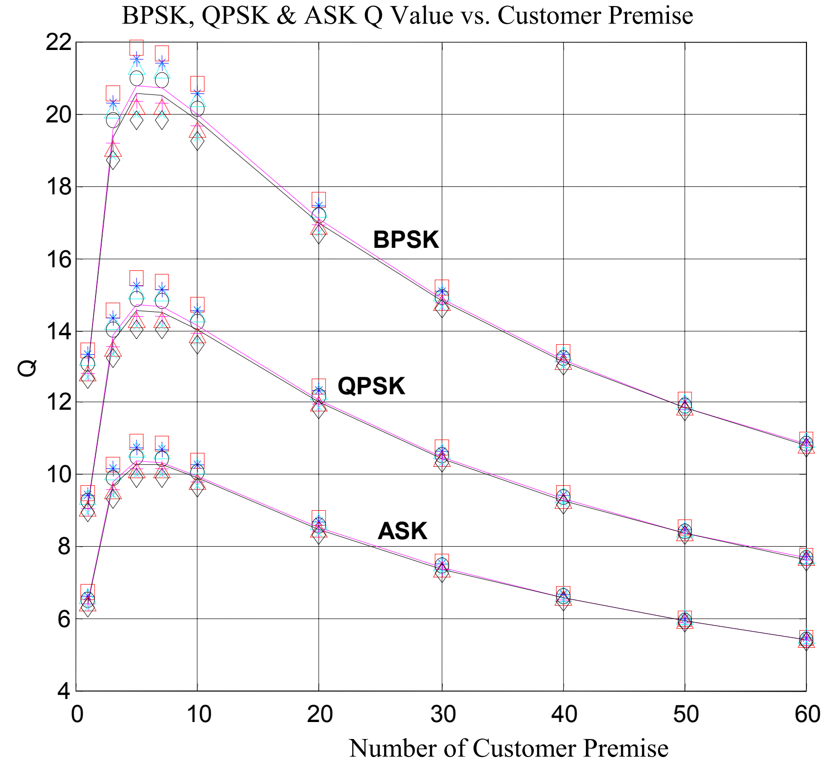
# *Signal-crosstalk Noise in SCM Transmission Performance for Digital Data*

| PARAMETERS | |
|---|---|
| **Linearized MZ Modulator** | A=0.93 & B=2.5 |
| Input power at Booster Amplifier | 3dBm |
| Laser RIN | -160dB/Hz |
| Photodiode Responsivity | 0.9 A/W |
| Fiber distance | 10km |
| OMI | 4.343% |



# *Conclusion*




- **Transmission Quality**
  - Optimizing the Receiver Optical Power per RF Channel = **-17dBm to -20dBm**
  - CATV CNR in the range of **48dB to 48.5dB**
  - Digital BPSK Q = **13 to 17**
  - Digital QPSK Q = **9 to 12**
  - Digital ASK Q = **6 to 8**
- **Network Scalability**
  - Number of Customers premises = **20 to 40**

# *Future Work*

- Analyze the uplink transmission performance and the impact of optical crosstalk under bi-directional fiber transmission.
- Analyze uplink multiple access method such as Time Division Multiple Access (TDMA), Subcarrier Multiple Access (SCMA) and their efficiencies.
- Because Narrow-band optical filter is relative expensive compared to wide-band optical filter, further study in separate upper and lower side-band of optical carrier at end-user is suggested.
- The even-order distortion produced by a MZ modulator can be cancelled using OSSB Modulation.  CSO is also affected by various phenomena such as chirp, fiber chromatic dispersion and polarization-mod dispersion (PMD), self-phase modulation (SPM) as well as gain-tilt of optical amplifiers.  Future study in CSO distortion in SCM externally modulated optical network is suggested.

# *Acknowledgements & Questions*

Many Thanks to:

- Dr. Hui for his guidance throughout this project
- Dr. Frost and Dr. Saiedian for their service on the project committee

Questions?

# *References cited in this presentation:*


- [1] R. Hui, B. Zhu, R. Huang, C. Allen, K. Demarest, D. Richards, "Subcarrier Multiplexing for High-speed Optical Transmission," *Journal of Lightwave Technology, vol. 20, no. 3, March 2002*

- [2] J. Brooks, G. Maurer, R. Becker, "Implementation and Evaluation of a Dual Parallel Linearization System for AM-SCM Video Transmission," *Journal of Lightwave Technology, vol. 11, no. 1, January 1993.*

- [3] M Phillips & D. Ott, "Crosstalk Due to Optical Fiber Nonlinearities in WDM CATV Lightwave Systems," *Journal of Lightwave Technology, vol 17, no. 10, Oct. 1999.*

- [4] R. Hui, Y. Wang, K. Demarest, C. Allen, "Frequency Response of Cross-Phase Modulation in Multispan WDM Optical Fiber Systems," *IEEE Photonics Technology letters, vol 10, no. 9, September, 1998*