Modulation Nonlinearity and Mitigation Technique in Multiband Radio-over-Fiber Systems

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Outline

- Introduction
- Experimental setup and theoretical analysis
- Modulation nonlinearity
  - Intra-band I/Q cross-modulation
    - 16QAM
  - Inter-band cross-modulation
    - OOK+OOK
  - Both intra- and inter-band cross-modulation
    - 16QAM+16QAM
- Nonlinearity mitigation: pre-compensation
  - Intra-band
  - Inter-band

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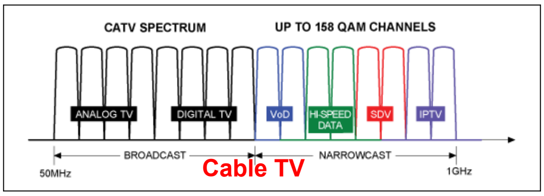
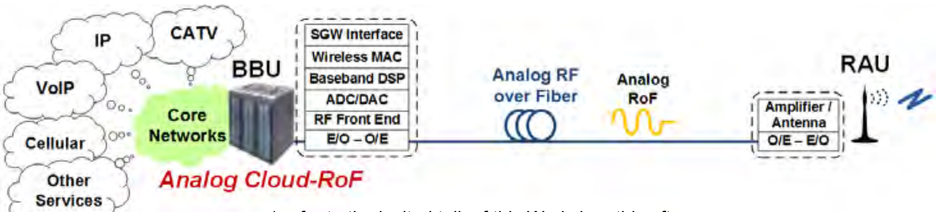
Examples of Multiband RoF Systems

(a) Cable TV System using HFC Access Technology



(b) Multiband Cloud Radio Access Networks (C-RAN)



* refer to the invited talk of this Workshop this afternoon

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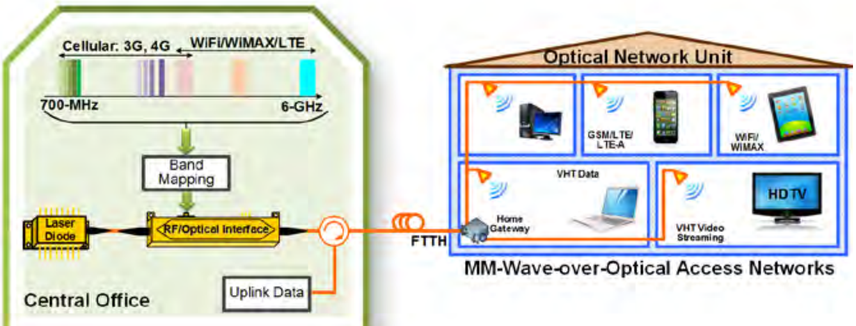
Indoor Multiband Radio-over-Fiber Systems



Indoor MM-wave Access Systems

- Pros/cons of multiband analog RoF
  - ☺ Subcarrier multiplexing (SCM) to carry multi-service to multi-users
  - ☺ Capable of direct up-converting legacy wireless services to millimeter wave (mm-wave)
  - ☺ Transparent, compatible and convergent with existing wireless infrastructure
  - ☹Modulation nonlinearity between multiple bands
  - ☹Especially for applications with large number of channels, e.g., CATV, mobile backhaul

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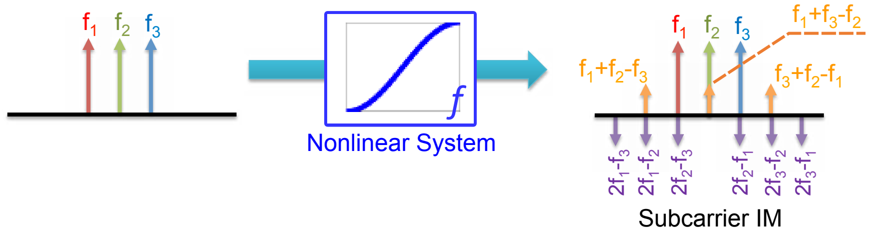
Introduction

- Modulation nonlinearity
  - Frequency domain: subcarrier intermodulation (IM) to generate unwanted frequency components
    - Has been extensively investigated
    - Frequency dependent
    - High-order harmonics (2f, 3f, …)
    - Sum/difference frequencies:
      - Composite triple beat (CTB, $f_1 \pm f_2 \pm f_3$)
      - Two-tone third-order intermodulation (IM3, $2f_1 \pm f_2$)



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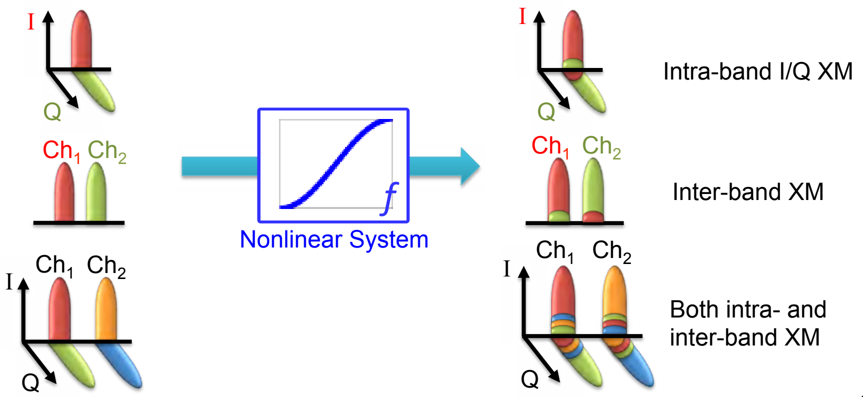
Introduction

- Modulation nonlinearity
  - Time domain: data pattern cross-modulation (XM) between different channels
    - Not reported in the field so far
    - Pattern dependent
    - Intra-band: between I/Q channels of a vector signal (e.g. QAM)
    - Inter-band: between two or more data channels at different carrier frequencies



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- Introduction
- **Experimental setup and theoretical analysis**
- **Modulation nonlinearity**
  - **Intra-band I/Q cross-modulation**
    - **16QAM**
  - **Inter-band cross-modulation**
    - **OOK+OOK**
  - **Both intra- and inter-band cross-modulation**
    - **16QAM+16QAM**
- **Nonlinearity mitigation: pre-compensation**
  - **Intra-band**
  - **Inter-band**

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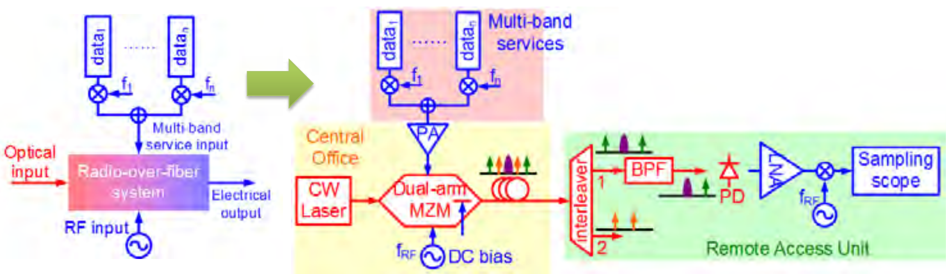
Experimental Setup



- Dual-arm MZM
  - Upper-arm: multi-band data modulated onto optical central carrier
  - Lower-arm: driven by pure RF to generate multiple sidebands
- Interleaver
  - Separate odd/even sidebands
  - 0^{th} and $\pm 2^{nd}$ sidebands beat in PD to up-convert data to RF band
  - Pure $\pm 1^{st}$ RF sidebands are reserved for uplink

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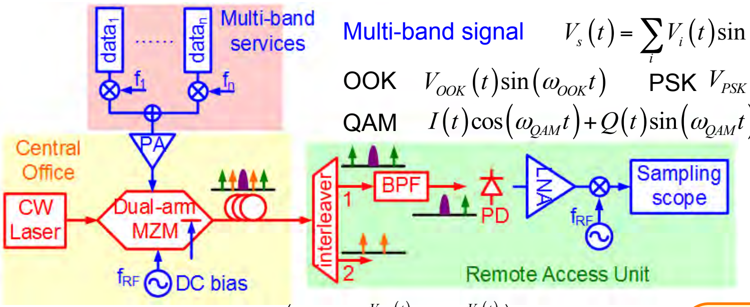
Experimental Setup



Multi-band signal $V_s(t)=\sum_i V_i(t)\sin(\omega_i t+\varphi_i)$

OOK $V_{OOK}(t)\sin(\omega_{OOK}t)$ PSK $V_{PSK}\sin[\omega_{PSK}t+\varphi(t)]$

QAM $I(t)\cos(\omega_{QAM}t)+Q(t)\sin(\omega_{QAM}t)$

Transfer function $T=\frac{1}{2}\left(e^{j\phi_{DC}}e^{j\frac{\pi V_{RF}(t)}{V_\pi}}+e^{j\frac{\pi V_s(t)}{V_\pi}}\right)$

After beating in PD $I_{ph}\propto\cos(2\omega_{RF}t)\left[DC\ const.+\sin\left(\frac{\pi V_s(t)}{V_\pi}\right)\right]$

Nonlinearity

For best linearity set DC bias $\phi_{DC}=\frac{\pi V_{DC}}{V_\pi}=\frac{\pi}{2},\ V_{DC}=\frac{V_\pi}{2}$

- Nonlinearity comes from the **sinusoidal transfer function** of the O/E interface of the optical modulator
- Not only for dual-arm MZM, but also apply to other modulators (IM, PM)

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Theoretical Analysis Results

Bands	Scalar / Vector	Format	Signal $V_s(t)$	Ch.	Modulation index	Output	Intra-band I/Q XM	Inter-band XM	Distortion	Constellation / Eye diagram
Single-band	Vector	QAM	$I(t)\cos(\omega_1 t)+Q(t)\sin(\omega_1 t)$	I	$m_I(t)=\frac{\pi I(t)}{V_\pi}$	$J_1(m_I)[J_0(m_Q)+J_2(m_Q)]$	Yes	N/A	Constellation compression	
				Q	$m_Q(t)=\frac{\pi Q(t)}{V_\pi}$	$J_1(m_Q)[J_0(m_I)+J_2(m_I)]$				
		PSK	$V_1\sin[\omega_1 t+\varphi_1(t)]$	PSK1	$m_1=\frac{\pi V_1}{V_\pi}=const.$	$J_1(m_1)\sin[\omega_1 t+\varphi_1(t)]$	No	N/A	No	
Two-band	Scalar + Scalar	OOK + OOK	$V_1(t)\sin(\omega_1 t)+V_2(t)\sin(\omega_2 t)$	OOK1	$m_1(t)=\frac{\pi V_1(t)}{V_\pi}$	$J_0(m_2)J_1(m_1)$	N/A	Yes	Eye-diagram suppression	
				OOK2	$m_2(t)=\frac{\pi V_2(t)}{V_\pi}$	$J_0(m_1)J_1(m_2)$				
	Vector + Scalar	QAM + OOK	$I(t)\cos(\omega_1 t)+Q(t)\sin(\omega_1 t)+V_2(t)\sin(\omega_2 t)$	I	$m_I(t)=\frac{\pi I(t)}{V_\pi}$	$J_0(m_2)J_1(m_I)[J_0(m_Q)+J_2(m_Q)]$	Yes	Yes	Constellation compression + scaling	
				Q	$m_Q(t)=\frac{\pi Q(t)}{V_\pi}$	$J_0(m_2)J_1(m_Q)[J_0(m_I)+J_2(m_I)]$				
				OOK2	$m_2(t)=\frac{\pi V_2(t)}{V_\pi}$	$[J_0(m_I)J_0(m_Q)-2J_2(m_I)J_2(m_Q)]J_1(m_2)$	N/A	Yes	Eye-diagram suppression	
	Vector + Vector	QAM + QAM	$I_1(t)\cos(\omega_1 t)+Q_1(t)\sin(\omega_1 t)+I_2(t)\cos(\omega_2 t)+Q_2(t)\sin(\omega_2 t)$	I1	$m_{I1}(t)=\frac{\pi I_1(t)}{V_\pi}$	$[J_0(m_{I2})J_0(m_{Q2})-2J_2(m_{I2})J_2(m_{Q2})]\times J_1(m_{I1})[J_0(m_{Q1})+J_2(m_{Q1})]$	Yes	Yes	Constellation compression + scaling	
				Q1	$m_{Q1}(t)=\frac{\pi Q_1(t)}{V_\pi}$	$[J_0(m_{I2})J_0(m_{Q2})-2J_2(m_{I2})J_2(m_{Q2})]\times J_1(m_{Q1})[J_0(m_{I1})+J_2(m_{I1})]$				
				I2	$m_{I2}(t)=\frac{\pi I_2(t)}{V_\pi}$	$[J_0(m_{I1})J_0(m_{Q1})-2J_2(m_{I1})J_2(m_{Q1})]\times J_1(m_{I2})[J_0(m_{Q2})+J_2(m_{Q2})]$	Yes	Yes		
				Q2	$m_{Q2}(t)=\frac{\pi Q_2(t)}{V_\pi}$	$[J_0(m_{I1})J_0(m_{Q1})-2J_2(m_{I1})J_2(m_{Q1})]\times J_1(m_{Q2})[J_0(m_{I2})+J_2(m_{I2})]$				
		PSK + PSK	$V_1\sin[\omega_1 t+\varphi_1(t)]+V_2\sin[\omega_2 t+\varphi_2(t)]$	PSK1	$m_1=\frac{\pi V_1}{V_\pi}=const.$	$J_0(m_2)J_1(m_1)\sin[\omega_1 t+\varphi_1(t)]$	No	Small	No	
				PSK2	$m_2=\frac{\pi V_2}{V_\pi}=const.$	$J_0(m_1)J_1(m_2)\sin[\omega_2 t+\varphi_2(t)]$	No	Small		

* intra-band XM * inter-band XM

- QAM signals suffer from both intra- and inter-band XM
- PSK signals has intrinsic resistence to intra-band I/Q XM and inter-band XM to other channels
- Scalar signals only suffer from inter-band XM
- All intra/inter-band XMs induce radical distortion to constellations, no phase rotation induced

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- **Nonlinearity mitigation: pre-compensation**
  - Intra-band
  - Inter-band

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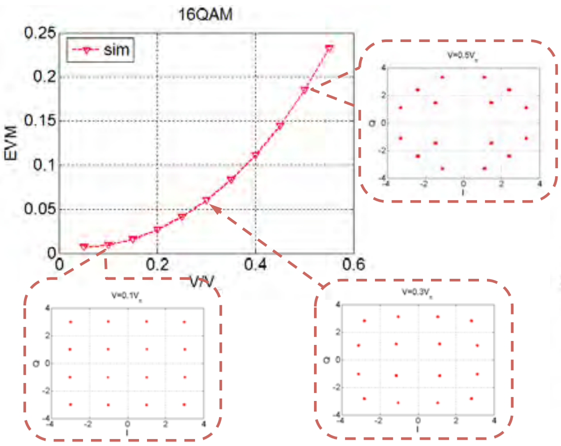
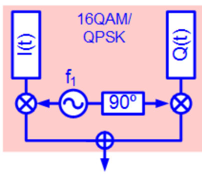
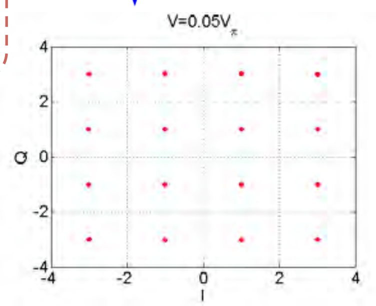
Intra-band I/Q XM: 16QAM

- Theoretical results





- Single-band vector signal



- Constellation squeezed into a circle

- V ↑ → I/Q cross-modulation ↑ → constellation distortion ↑ → EVM ↑
- Outer points in constellation have larger I/Q amplitudes, also suffer more severe I/Q cross-modulation than inner points

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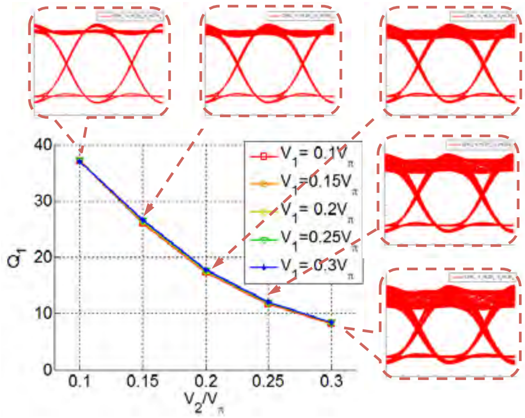
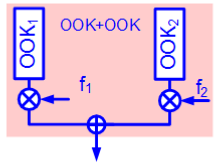
Inter-band XM: OOK+OOK

- Theoretical results





- Two-band scalar signals

- Due to the lack of noise, Q_1 not dependent on V_1
- 5 curves for $0.1 < V_1/V_\pi < 0.3$ overlap

- As driving voltage of OOK_2 increases, $V_2\uparrow$
  - Eye diagram of Ch1 degrades
  - Q-factor of OOK_1 reduces, $Q_1\downarrow$

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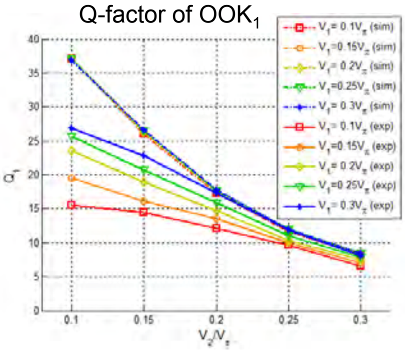
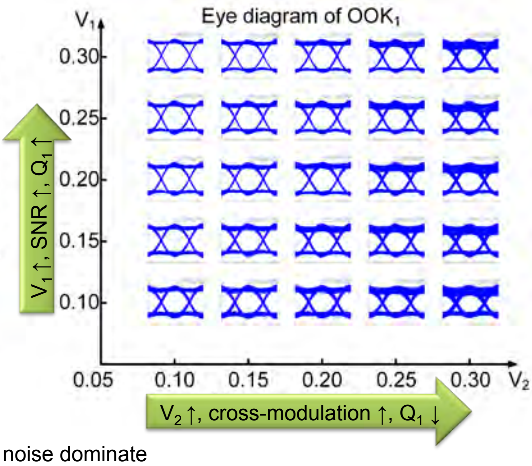
Inter-band XM: OOK+OOK

- Experimental results

Q-factor of OOK_1





- Small V_2
  - Weak inter-band cross-modulation, noise dominate
  - Experimental Q_1 deviates from theoretical limit
- Large V_2
  - Cross-modulation dominate, experimental Q_1 approaches theoretical limit

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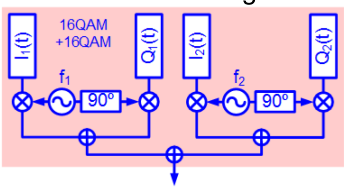
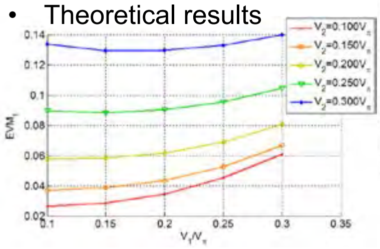
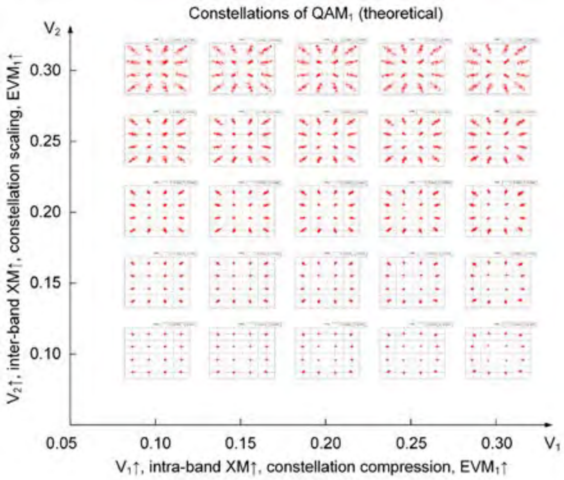
Intra- and Inter-band XM: 16QAM+16QAM

Two-Band vector signals



- Theoretical results





- Two-dimension nonlinearity: intra- and inter-band XM
  - V_1↑, constellation compression due to intra-band I/Q XM, EVM_1↑
  - V_2↑, constellation scaling due to inter-band XM from QAM_2, EVM_1↑

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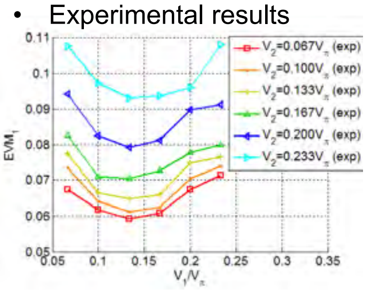
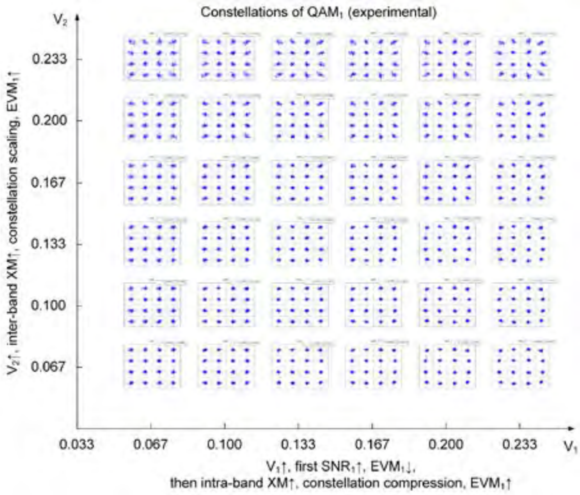
Intra- and Inter-band XM: 16QAM+16QAM

- Experimental results





- Two-dimension nonlinearity: intra- and inter-band XM
- Discrepancy from theory for small V_1 due to noise

- V_1↑, first EVM_1 ↓ as SNR ↑, then EVM_1 ↑ due to intra-band I/Q XM
- V_2↑, EVM_1↑ due to inter-band XM from QAM_2
- Horizontal: constellation first become clearer, then compressed due to intra-band XM
- Vertical: constellation scaled due to inter-band XM

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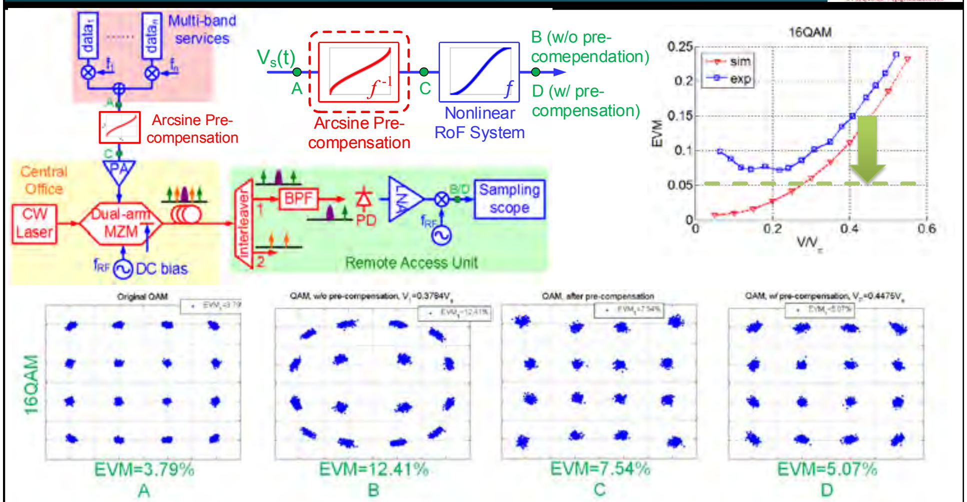
Mitigate Intra-band XM



- **B:** 16QAM suffers from intra-band I/Q XM, constellation compression
- **C:** arcsine pre-compensation stretches the constellation
- **D:** constellation compression effect is canceled
- EVM reduced to ~5%, approaching noise limit

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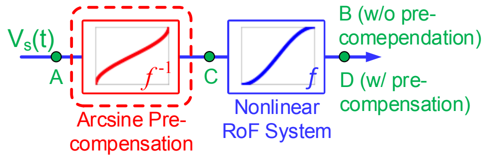
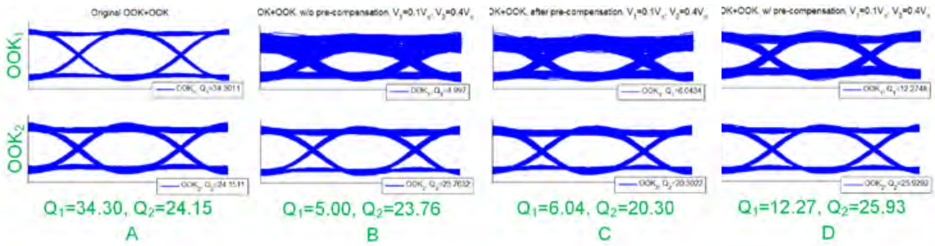
Mitigate Inter-band XM



- Cancel inter-band between two OOK signals



- **A:** $V_1=0.1V_\pi$, $V_2=0.4V_\pi$
- **B:** Eye openning of OOK_1 suppressed by inter-band XM from OOK_2, Q_1=4.997
- **C:** Pre-compensation also induces XM (Q_1=6.04), but in an opposite way
- **D:** Inter-band XM canceled, and Q factors improved (Q_1=12.27)

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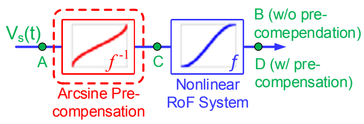
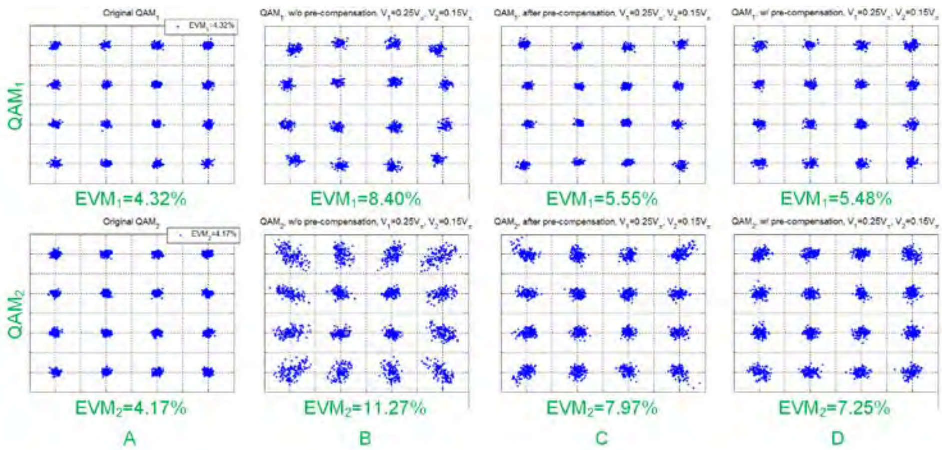
Mitigate Both Intra- and Inter-band XM



A: $V_1=0.25V_\pi$, $V_2=0.15V_\pi$
B: QAM_1 suffers from intra-band XM (constellation compression)
QAM_2 suffers from inter-band XM (constellation scaling)
C: Constellations stretched
D: Pre-compensation cancels both intra- and inter-band XM



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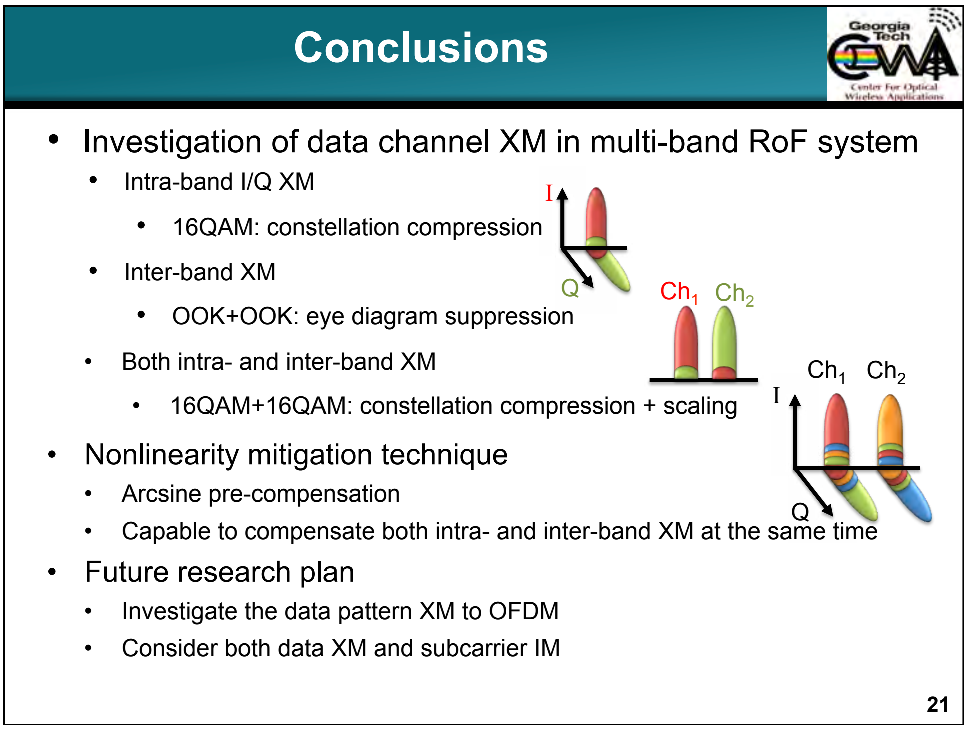
Conclusions
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• Investigation of data channel XM in multi-band RoF system
• Intra-band I/Q XM
• 16QAM: constellation compression
• Inter-band XM
• OOK+OOK: eye diagram suppression
• Both intra- and inter-band XM
• 16QAM+16QAM: constellation compression + scaling
I
Q
Ch_1 Ch_2
I
Q
Ch_1 Ch_2
• Nonlinearity mitigation technique
• Arcsine pre-compensation
• Capable to compensate both intra- and inter-band XM at the same time
• Future research plan
• Investigate the data pattern XM to OFDM
• Consider both data XM and subcarrier IM
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Thank You!
Q & A
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