NiCT *EXAT2008*

Optical Orthogonal Frequency Division Multiplexing: the story so far....

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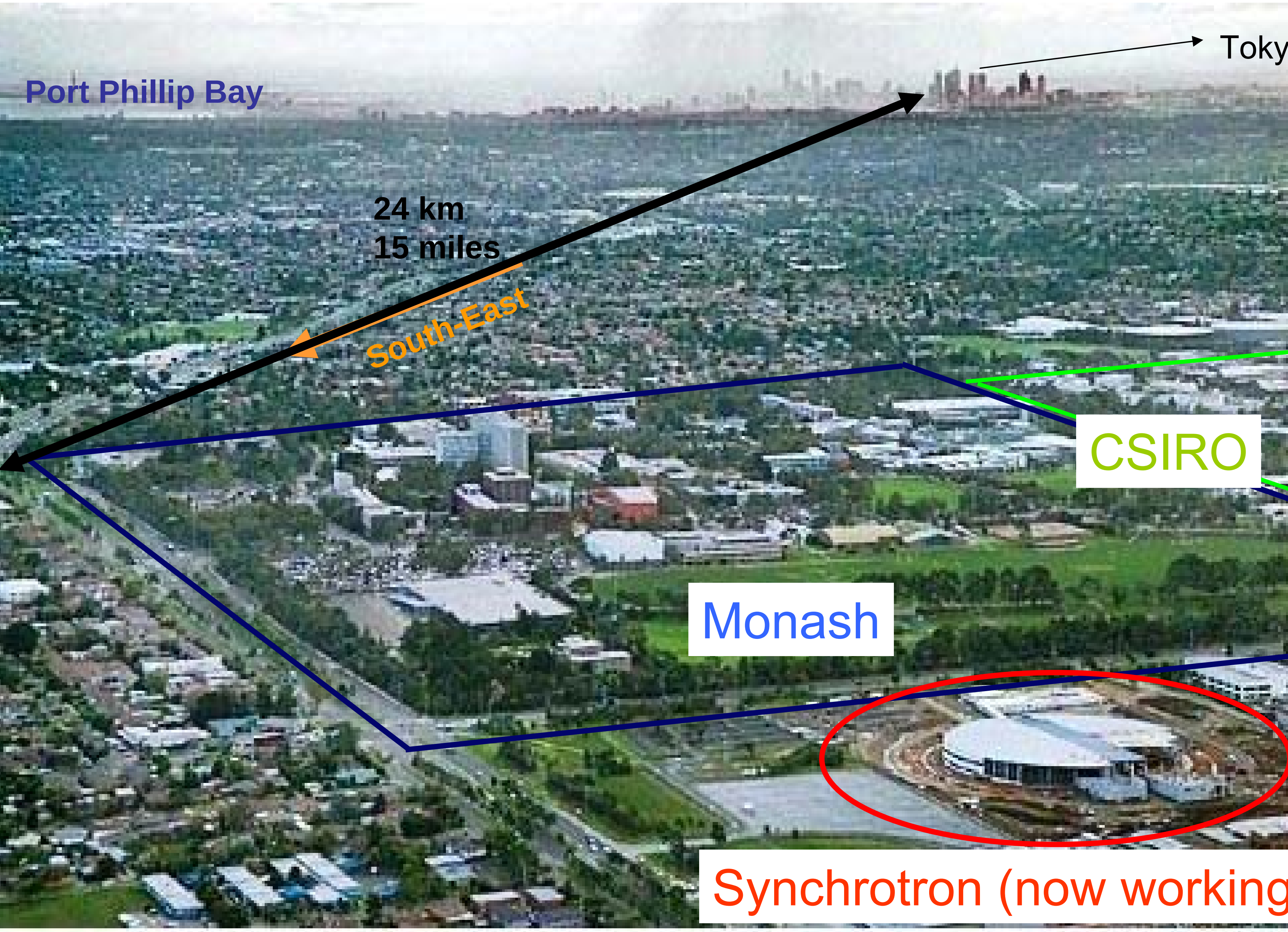
Abstract

OFDM is well known to provide significant benefits to wireless transmission, but has only recently been accepted into the optical communications community.

Over the last 2 years many different optical OFDM schemes have been proposed, simulated and demonstrated experimentally; O-OFDM is now seen as a potential 100 Gbit/s technology, providing high spectral efficiency and in-built dispersion and nonlinearity compensation.

This talk will cover the background to optical OFDM, some of the issues that at first made it unattractive, and the solutions to these issues proposed by various groups.



Toky

Port Phillip Bay

24 km
15 miles

South-East

CSIRO

Monash

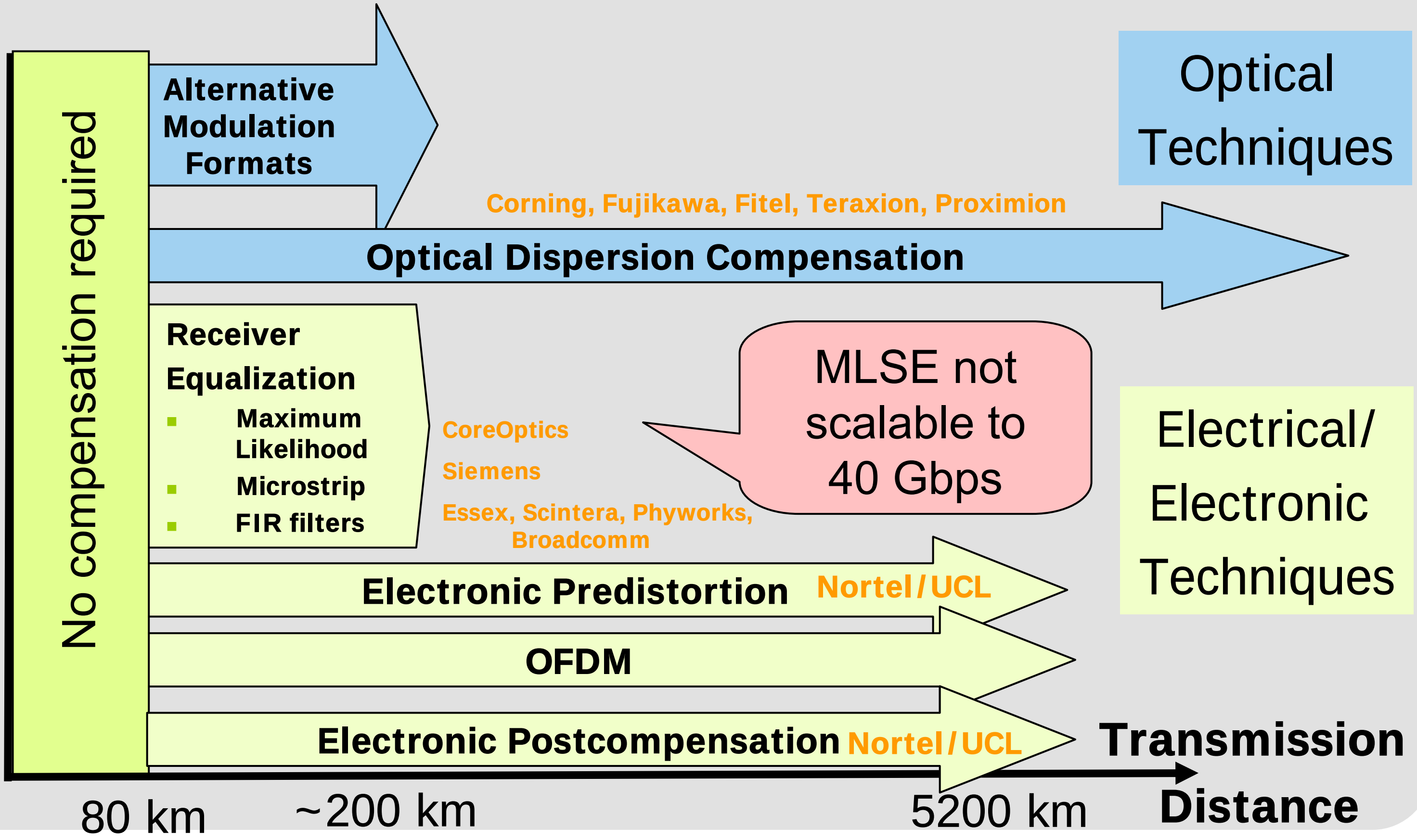
Synchrotron (now working

Summary

- Electronic Dispersion Compensation
- Flavors of Orthogonal Frequency Division Multiplexing
- Principle of OFDM
- OFDM for Long-Haul
- Experimental Results
  - 10 Gbit/s 4-QAM RF Unconverted
  - 20 Gbit/s Direct Digital Synthesis
  - 24 Gbit/s Colorless transmitter (2008 design)
- Nonlinearity Effects and Compensation
- Scaling to higher bit rates
- Conclusions

The Dispersion Limit

10 Gbit/s/wavelength

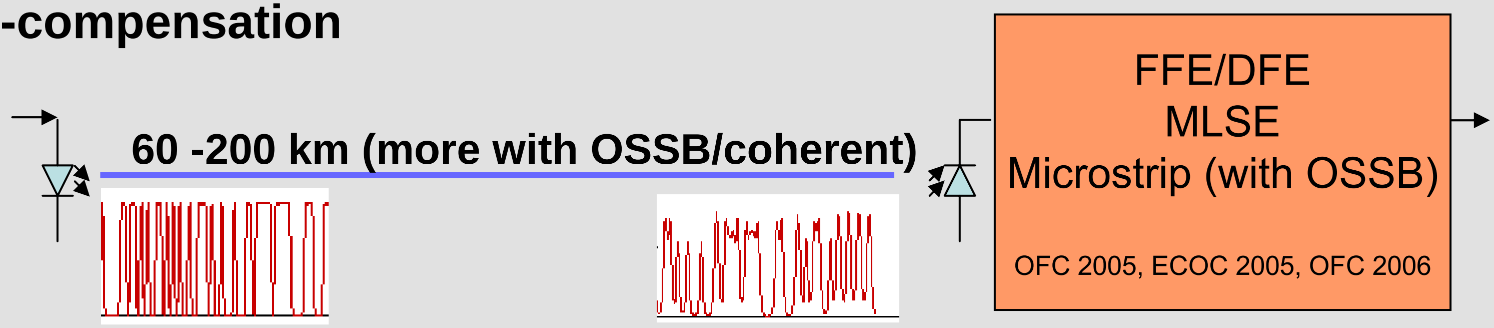


Electronic Dispersion Compensation (EDC)

- Replaces optics with electronics
  - CMOS is cheap and gets better by the year
  - Software/Firmware is easily upgradable
- Advantages
  - Complexity at the ends of a link (edges of a network)
  - “Plug and Play” – reduced link engineering
  - Reduces outside plant (amplifiers and dispersion compensators)
  - Could support rapidly changing network topologies
  - Reduces the risk that a network wont work
  - No clock recovery issues
  - Efficient numerical computation, even at 40 Gbps
  - Identifies causes of degradation (self monitoring)

Two Common Types of EDC

Post-compensation



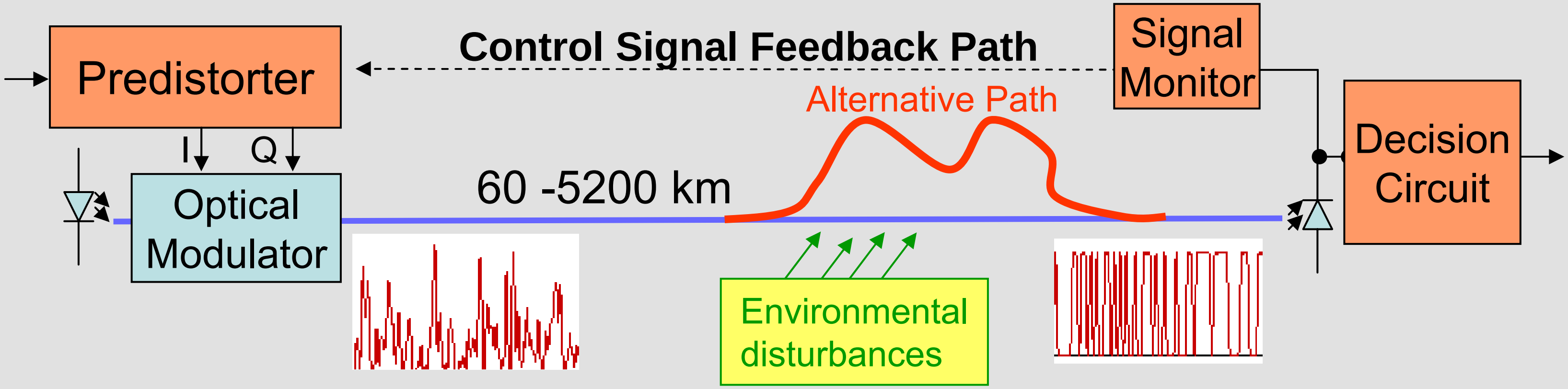
60 -200 km (more with OSSB/coherent)

FFE/DFE
MLSE
Microstrip (with OSSB)

OFC 2005, ECOC 2005, OFC 2006

(now with coherent receivers)

Pre-compensation D. McGhan *et al.* OFC2005.



Predistorter

I Q

Optical Modulator

Control Signal Feedback Path

Signal Monitor

Alternative Path

60 -5200 km

Environmental disturbances

Decision Circuit

OFDM does not require a feedback path!

OFDM

Introduction to Theory

For an up-to-date list of publications, type “Arthur Lowery” into Google

Orthogonal Frequency Division Multiplexing

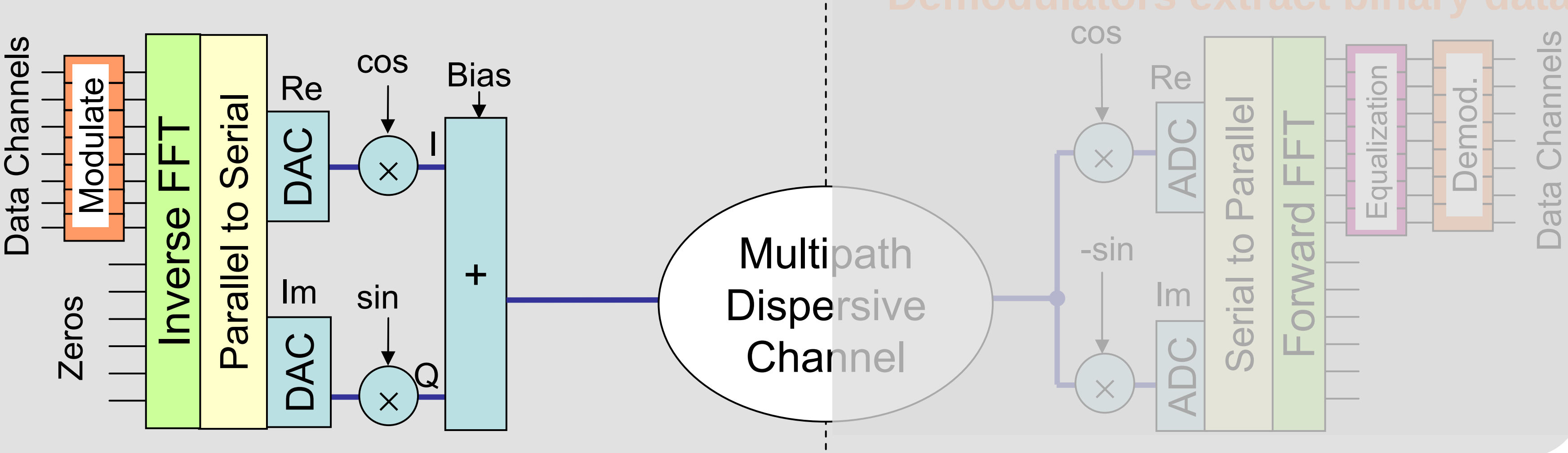
- Uses many narrow-bandwidth channels
  - Each is tolerant to dispersion (almost infinite dispersion limit)
  - Generated using an inverse Fast Fourier Transform
  - Separated using a Fast Fourier Transform
- Used for digital broadcasting, wireless, next generation mobile, ADSL
  - Already accepted as the best solution for radio channels
- Scalable to high bit rates (Processing ≈ $n\log_2 n$)

Typical OFDM System: Transmitter

Generates high numbers of subcarriers each carrying one QAM symbol

- Modulators take parallel channels
- IFFT generates OFDM waveform
  - zeros give polynomial interpolation
- DACs and I-Q modulators create real-valued waveform (OFDM band)

- I-Q demodulators and ADCs create complex waveform
- FFT separates subcarriers
- Equalizer corrects phase & amplitude
- Demodulators extract binary data



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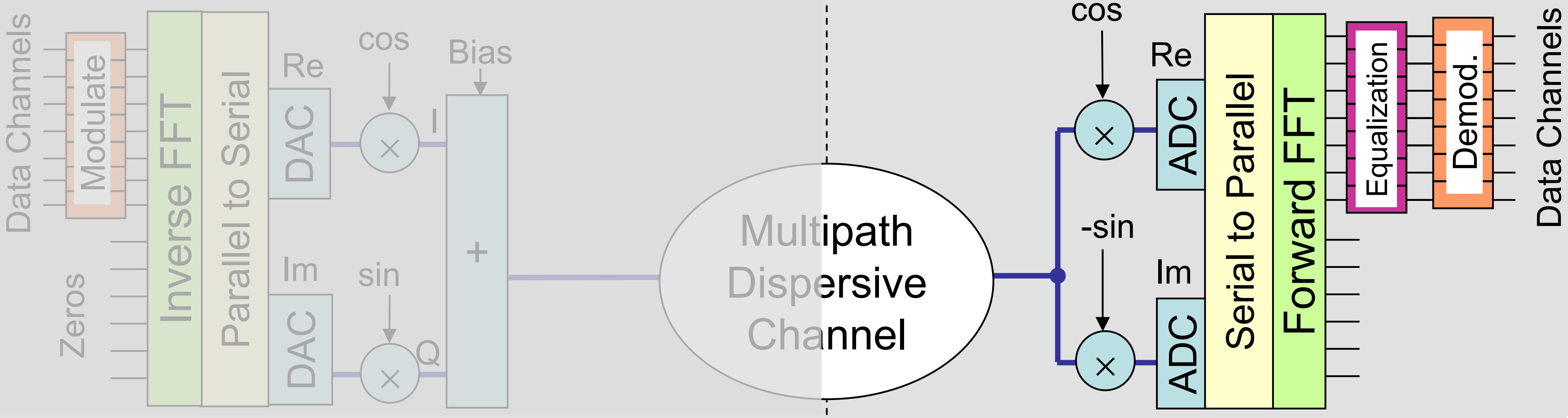
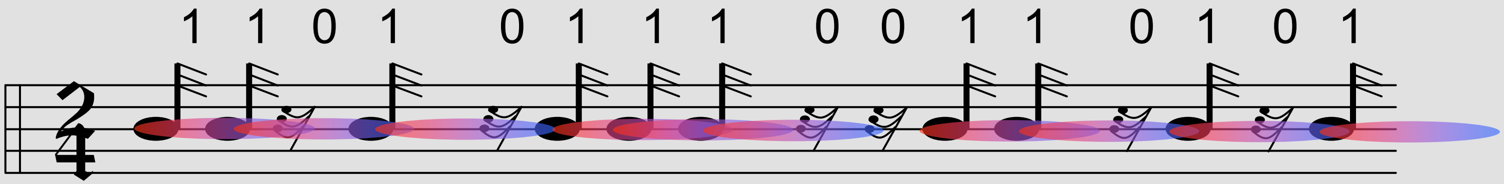
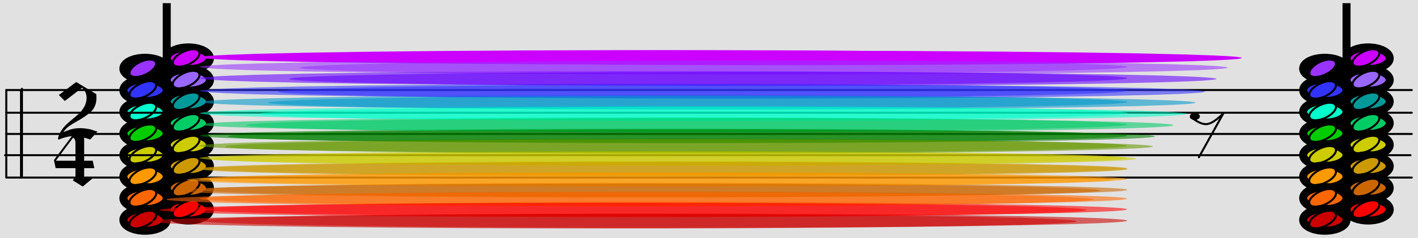


Principle of OFDM – Music Analogy

- Conventional systems transmit on a single frequency, using a ‘beat’ for a ‘1’ and a space for a ‘0’.
- Dispersion causes their energy to spreads into adjacent beats.

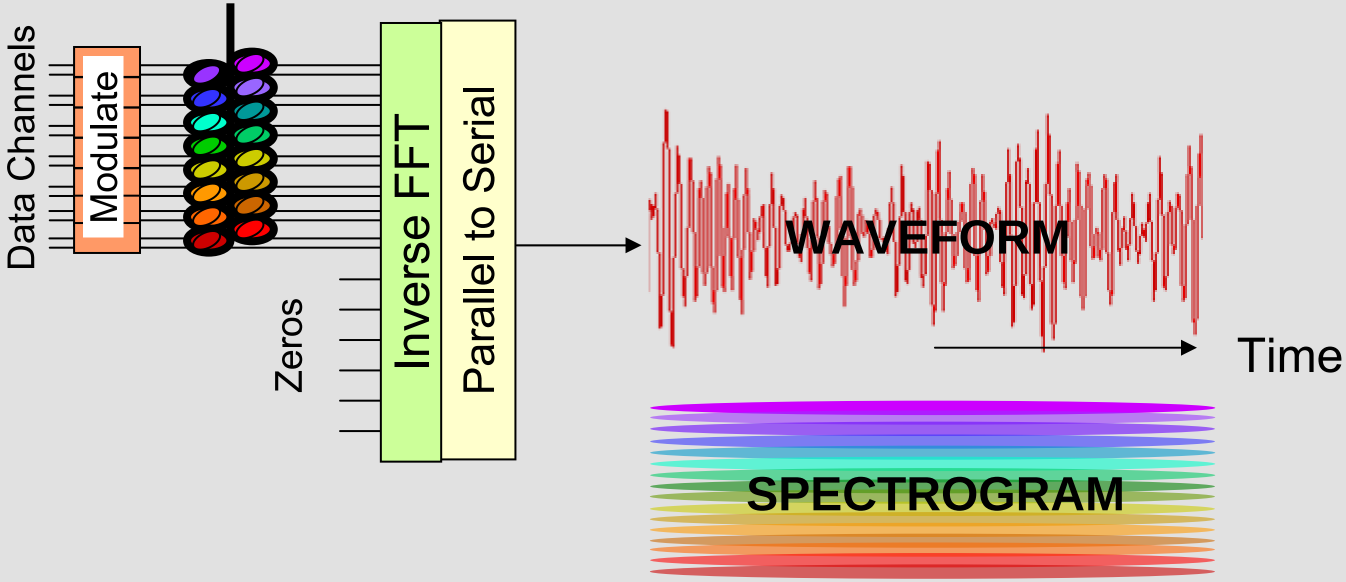


- OFDM transmits many parallel frequencies (*notes*) simultaneously (a musical chord), held for a long time
- The information is in the complexity of the ‘chord’
- Dispersion can be handled by Guard bands or Cyclic Prefixes



Generating the Subcarriers (Transmitter)

- An Inverse Fast Fourier Transform is an easy way to generate the waveform from a superposition of subcarriers



Data Channels

Modulate

Zeros

Inverse FFT

Parallel to Serial

WAVEFORM

Time

SPECTROGRAM

- Usually QAM modulation is used to set the phase and amplitude of each subcarrier
- The iFFT can be stuffed with zeros to give a higher sample rate (better defined spectrum with aliasing away from main band)

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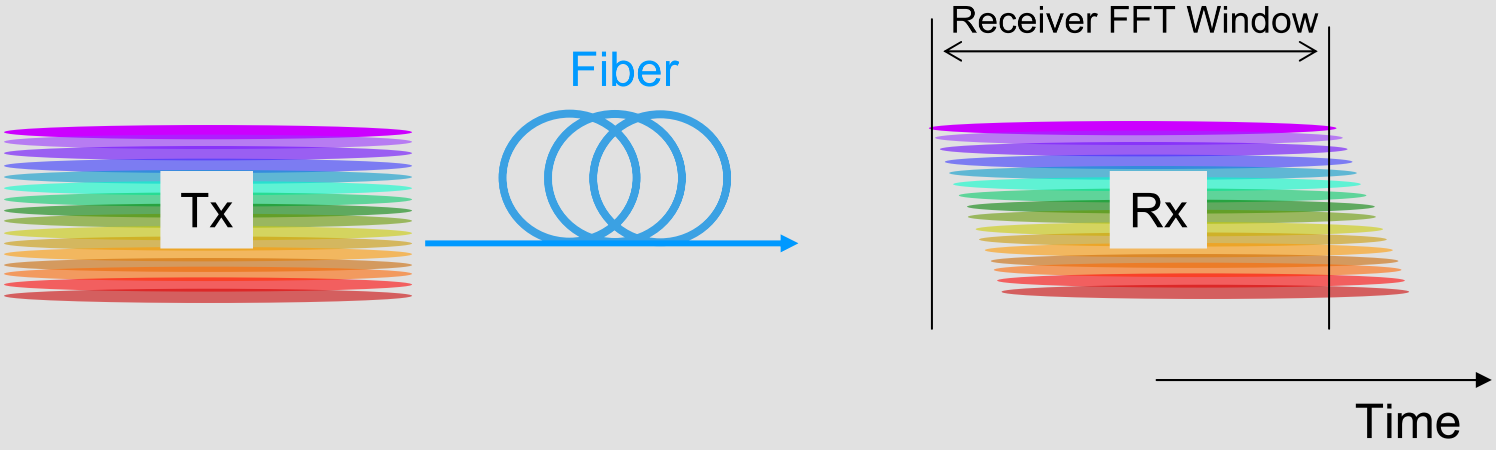
OFDM

Equalising Dispersion

Dispersion 1

Dispersion delays redder subcarriers compared with bluer subcarriers

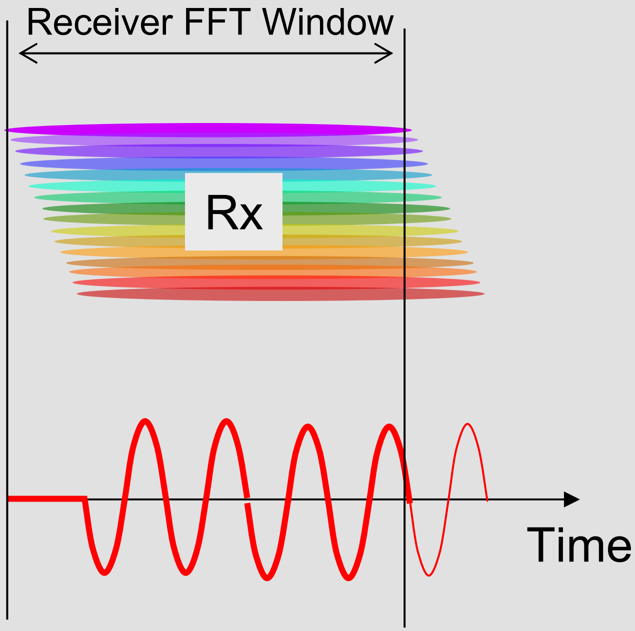
- consider the reddest subcarrier shifted out of the receiver FFT window…



Dispersion 2

Dispersion delays redder subcarriers compared with bluer subcarriers

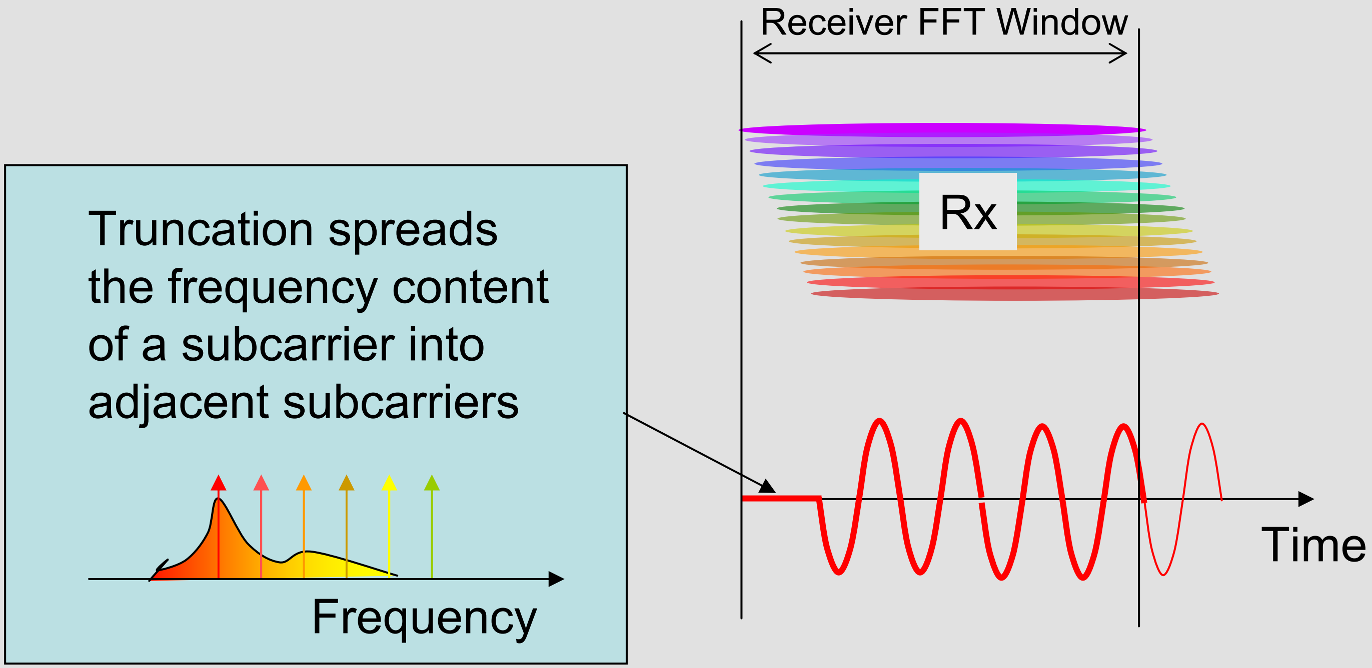
- consider the reddest subcarrier shifted out of the receiver FFT window…



Dispersion 3

Dispersion delays redder subcarriers compared with bluer subcarriers

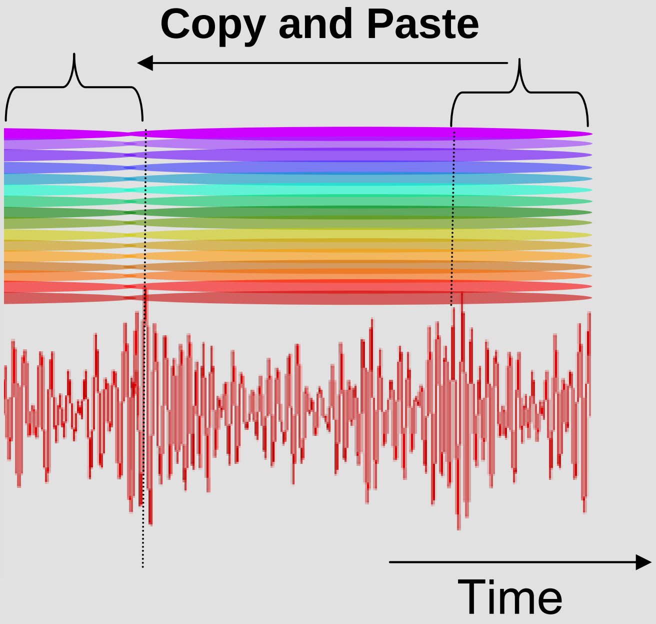
- consider the reddest subcarrier shifted out of the receiver FFT window…



Truncation spreads the frequency content of a subcarrier into adjacent subcarriers

Cyclic Prefix 1

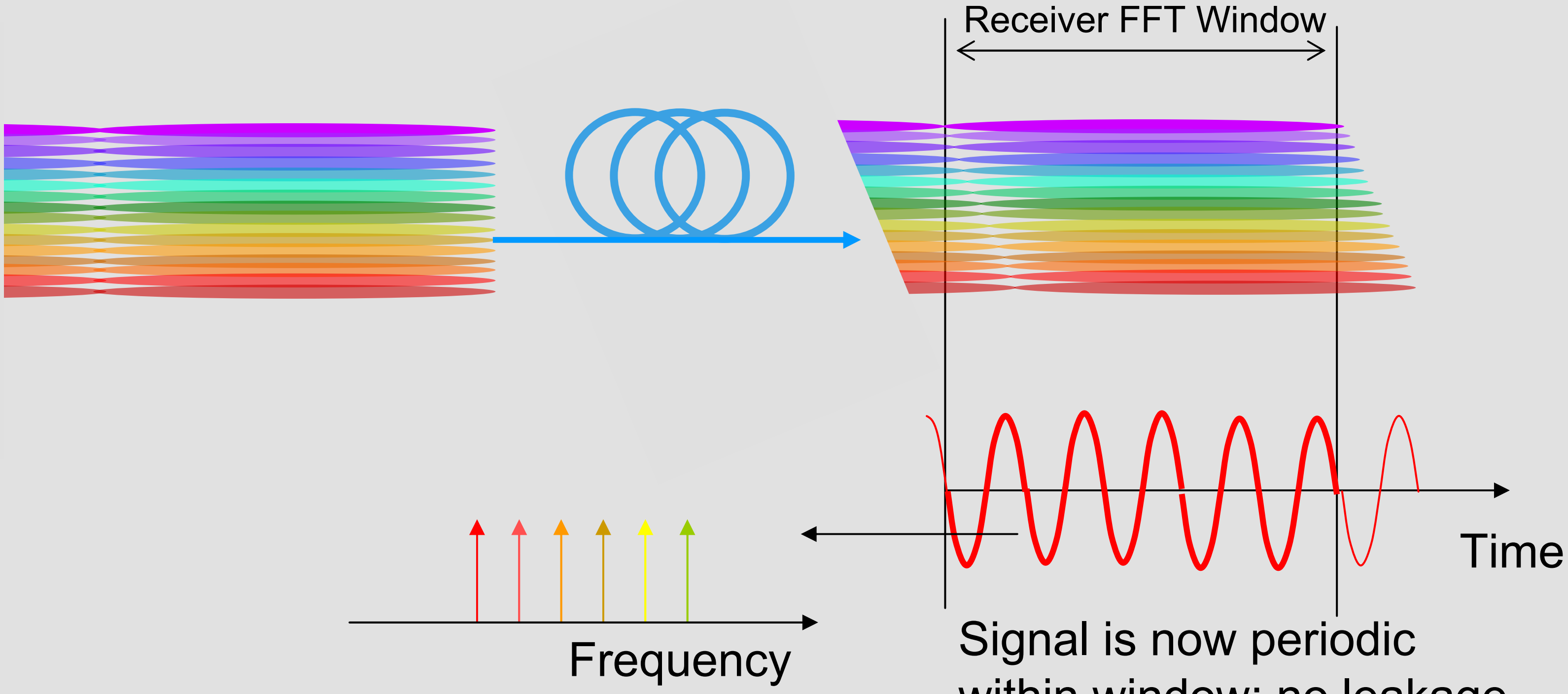
To cope with dispersion delaying each signal differently, **a cyclic prefix** is added to the signal before transmission



The duration of the prefix is equal to the differential delay across the signal's bandwidth. This is a small fraction of the length of the OFDM symbol.

Cyclic Prefix 2

- The cyclic prefix ensures identical signals are shifted into the FFT window, as are shifted out



Signal is now periodic within window: no leakage

Equalization 1

- In 4-QAM, data is encoded onto the phase
- A symbol will be received without error if it falls in the correct quadrant in phase space

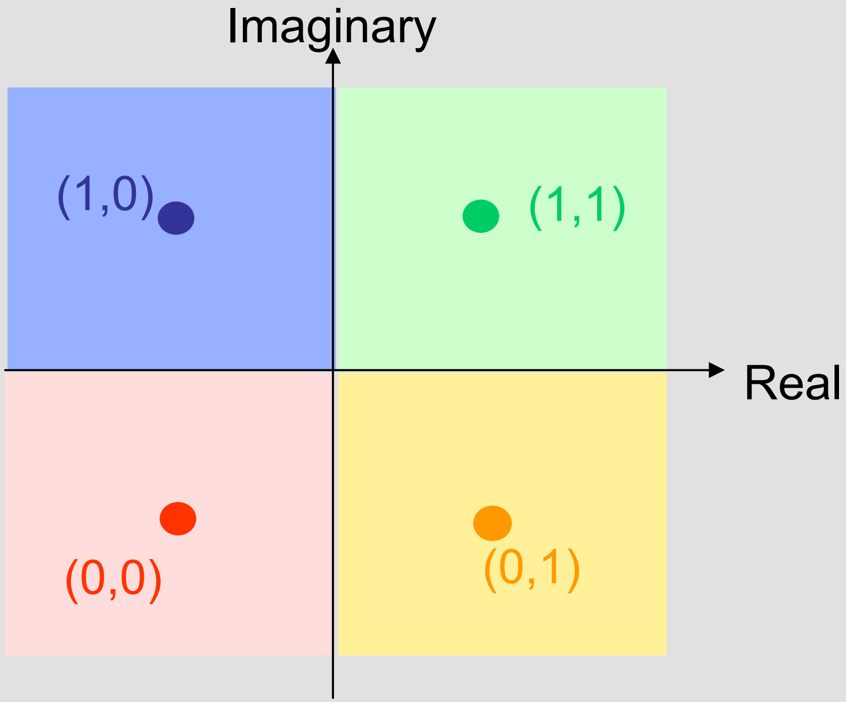
Transmitted Symbols

● (1,1)

● (1,0)

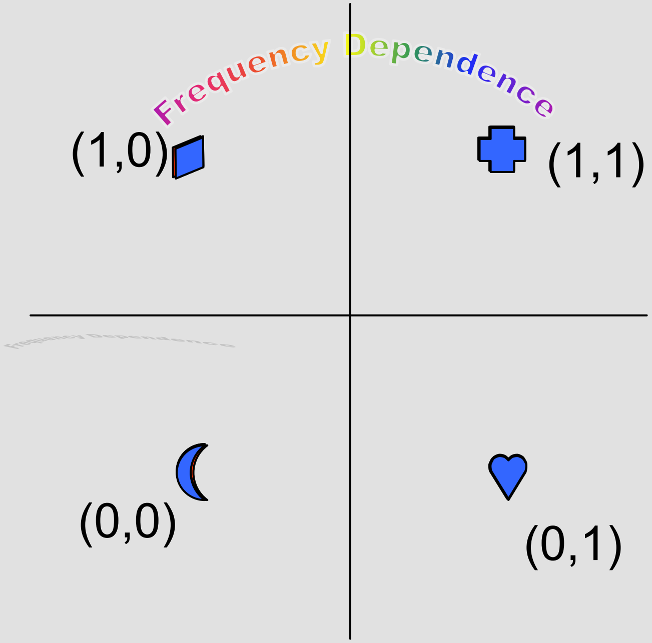
● (0,0)

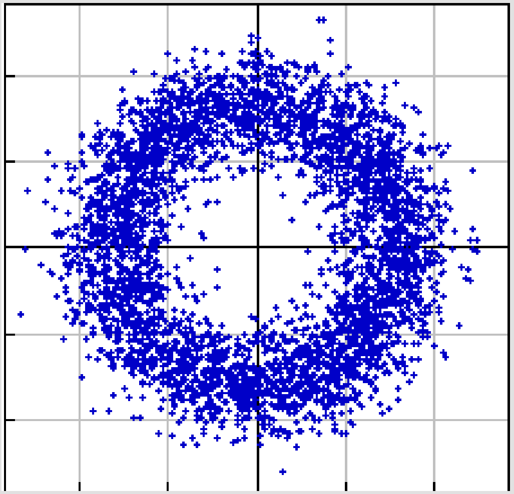
● (0,1)



Equalization 2

- Dispersion shifts the phases of the subcarriers dependent on their frequency
- A >45-degree phase shift causes an error

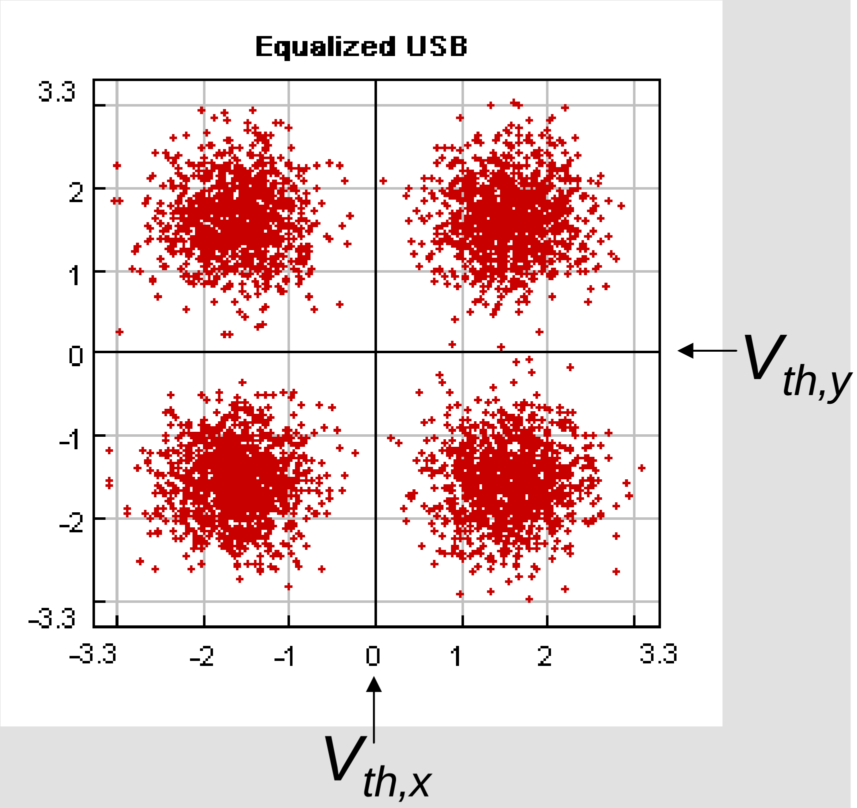




Noise also spreads the positions of symbols

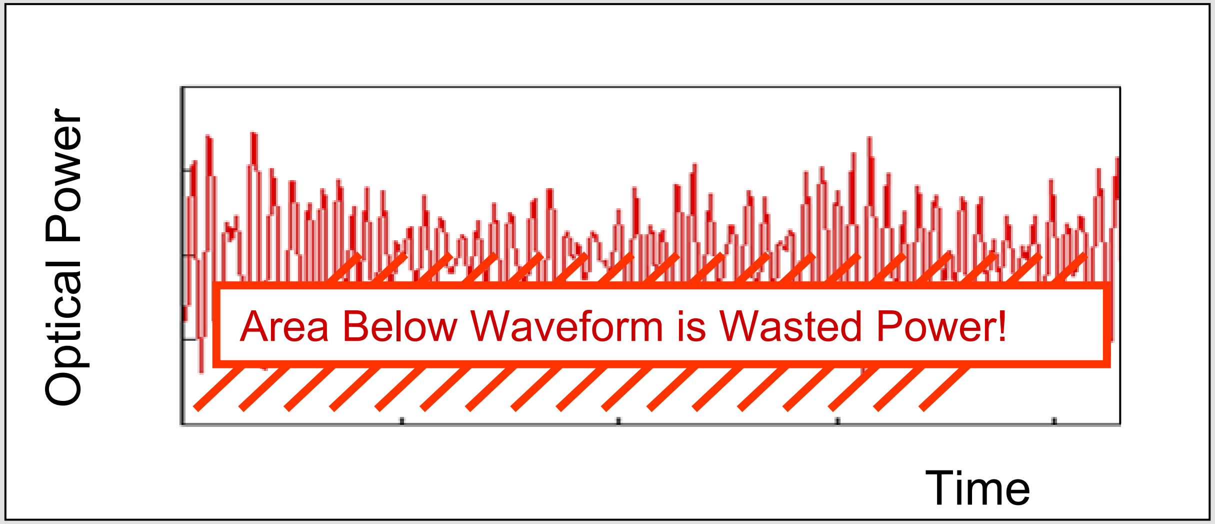
Equalization 3

- Equalization ‘unwinds’ the phase distortion, placing the received symbols in the correct quadrants
  - noise and FWM will cause errors
- Equalization relies on training symbols or pilot tones within a symbol
  - this causes an overhead, reducing data rate
- Coherent systems require frequent equalization because of the evolving relative phases of the transmitter oscillator and local oscillator



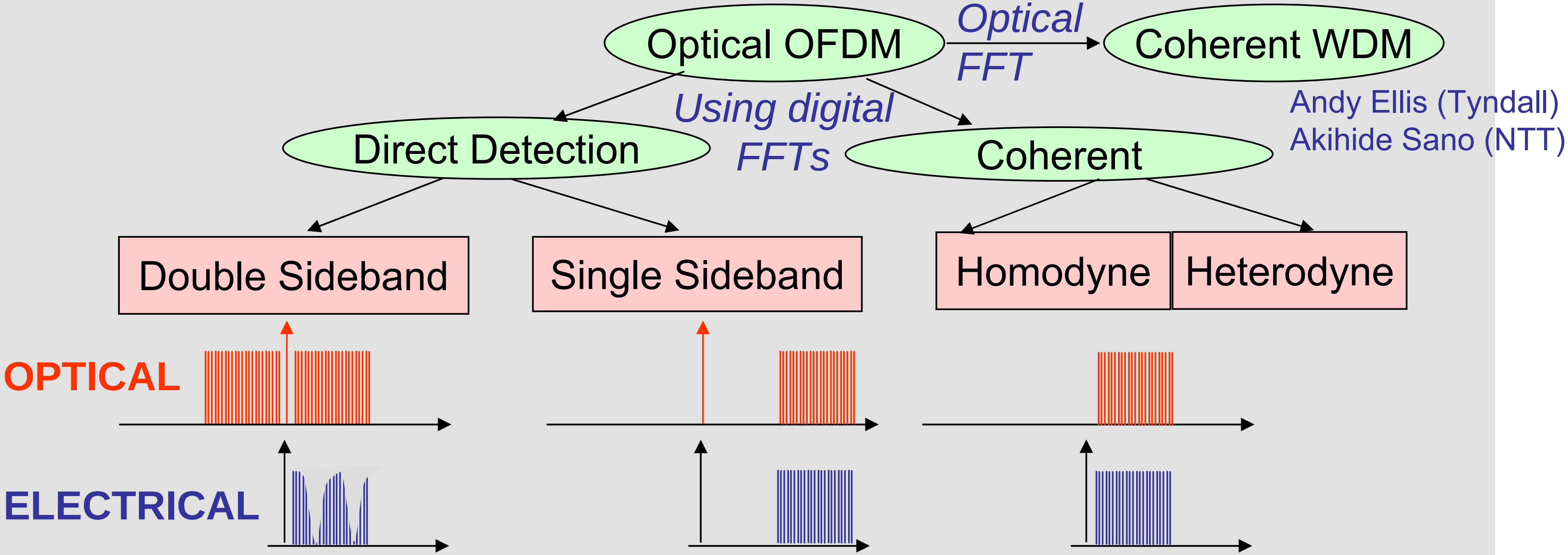
OFDM for Optical - Issues

- Bipolar Signal - requires high bias – high mean power



- Requires Optical Single Sideband Transmission
  - To remove nulls in the baseband (RF) response
- Sensitive to optical fiber nonlinearities
- Sensitive to intermodulation distortion (e.g. square-law detection)

Flavors of OFDM



Intensity Modulated

UCL, Leeds, Bangor,

Clipped

Armstrong: El.Letts 2006, Globecom 2006

Suppressed carrier

Guard band

Lowery & Armstrong Optics Express, Dec 2005, PD: OFC 2006/ OFC2007

Hewitt OFC2007

Direct IQ Modulation

RF Homodyne

Sheih *et al.* Electronics Letters Apr. 2006

ECOC 2006, OFC 2007

Jansen PD: OFC2007

Our Solution at Monash

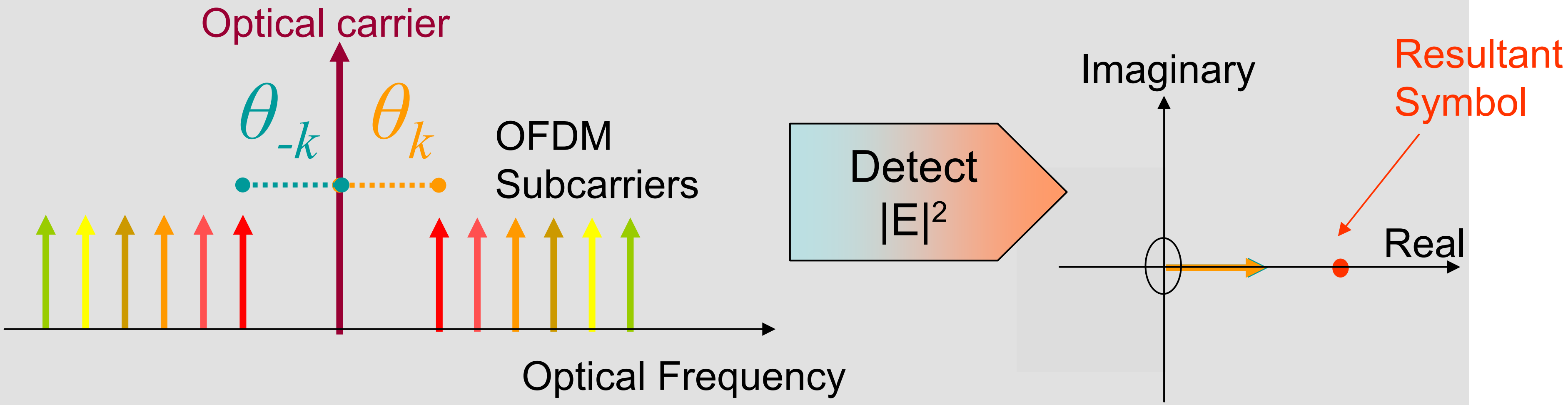
- Direct-Detection
- Single-Sideband
- Carrier Suppression
- Guard-band

With:

- Nonlinearity pre- and post- compensation
- Carrier Boost

Details in J. Lightwave Technology, Jan 2008
(Schmidt, Lowery, Armstrong)

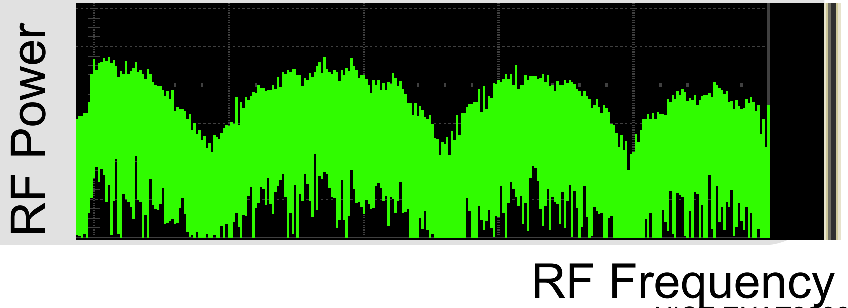
Why Optical Single Sideband? (1)



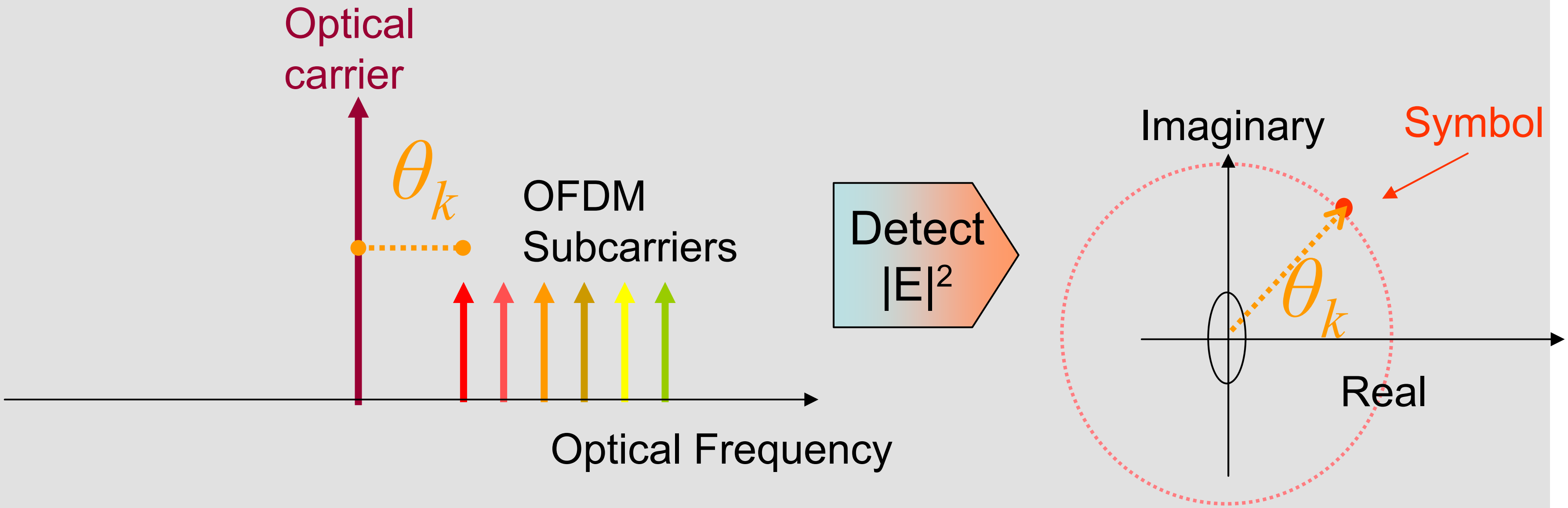
1) Consider the phase shifts of the upper and lower sidebands due to dispersion (relative to the carrier)

2) Symbol always lies on the real axis.

3) Phase shifts of $(n+1)\pi/2$ null the subcarrier power.



Why Optical Single Sideband? (2)



Optical carrier

θ_k

OFDM Subcarriers

Optical Frequency

Detect $|E|^2$

Imaginary

Symbol

θ_k

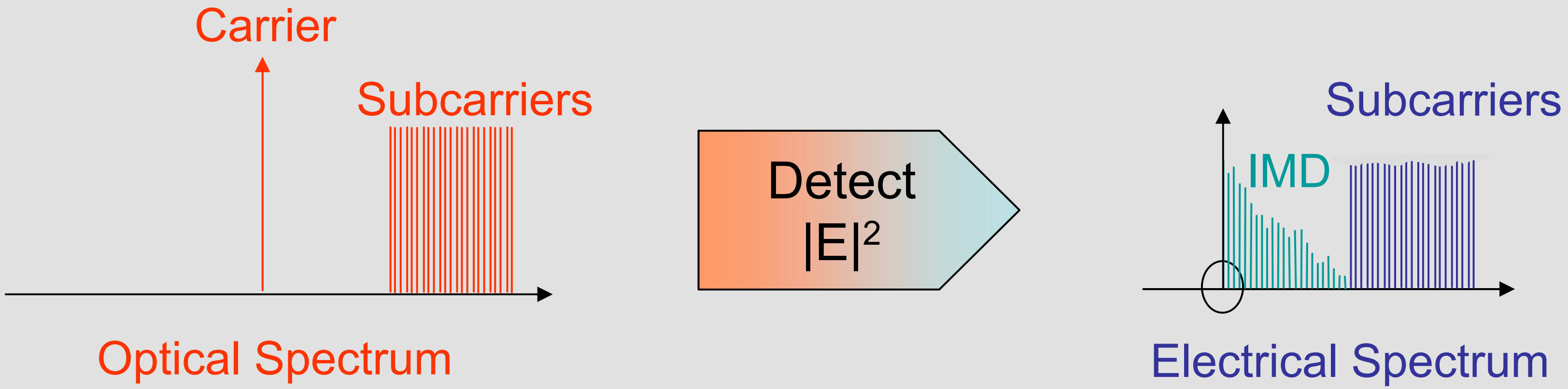
Real

With Optical Single Sideband, there is only one photodetection component at each electrical frequency, so there is no nulling at certain frequencies.

The phase shift θ_k due to dispersion can be equalised in the electrical domain.

Why Frequency Band Offset?

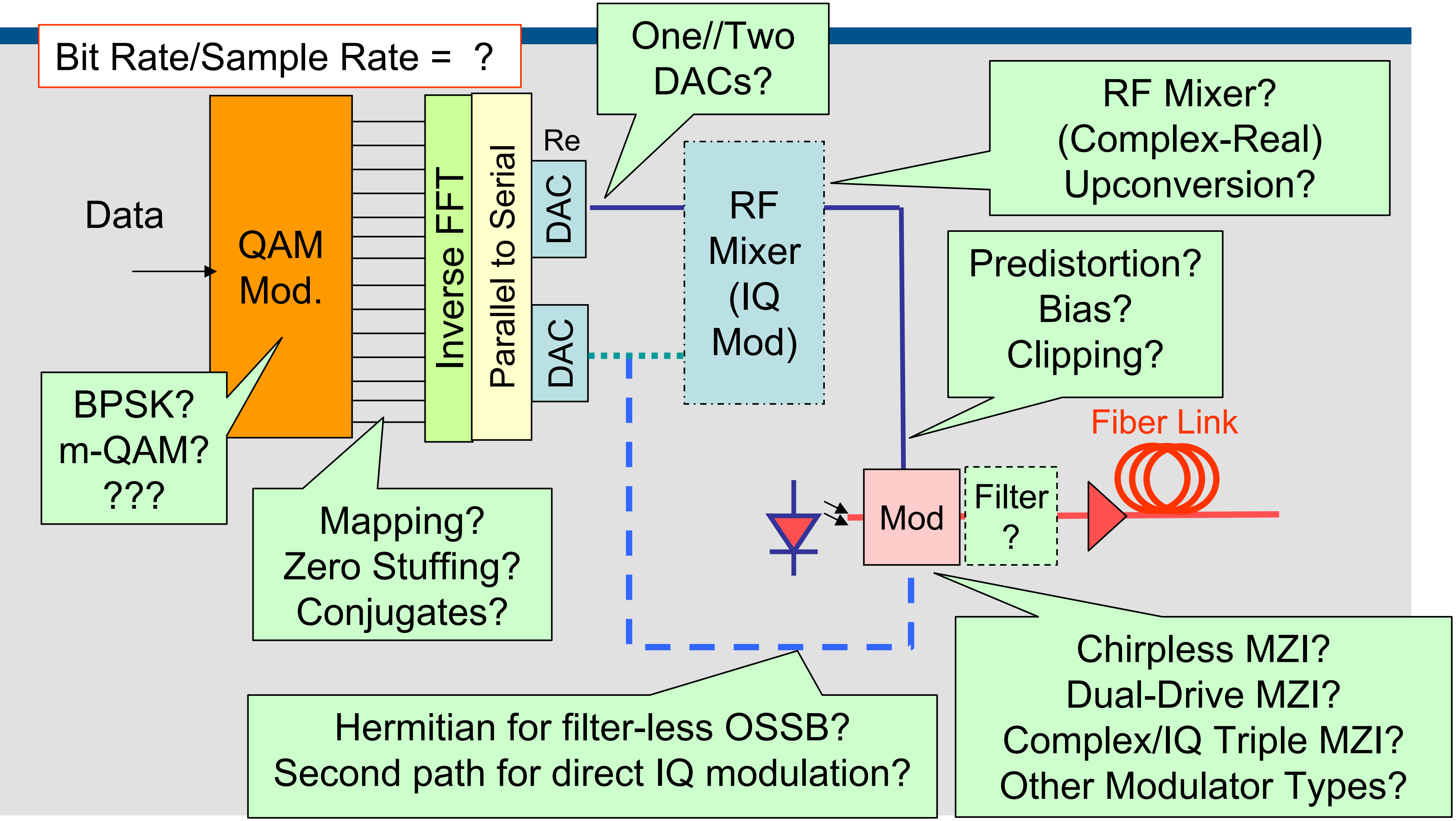
- Intermodulation distortion
  - Distortion due to *subcarrier* × *subcarrier* mixing
  - Signal due to *subcarrier* × *carrier* mixing



- Offsetting the subcarriers from the carrier means the distortion products will mainly fall outside OFDM band
  - Allows a highly-suppressed carrier

Transmitter and Receiver Options

Transmitter Choices



Bit Rate/Sample Rate = ?

One//Two DACs?

RF Mixer? (Complex-Real) Upconversion?

Predistortion?
Bias?
Clipping?

BPSK?
m-QAM?
???

Mapping?
Zero Stuffing?
Conjugates?

Hermitian for filter-less OSSB?
Second path for direct IQ modulation?

Chirpless MZI?
Dual-Drive MZI?
Complex/IQ Triple MZI?
Other Modulator Types?

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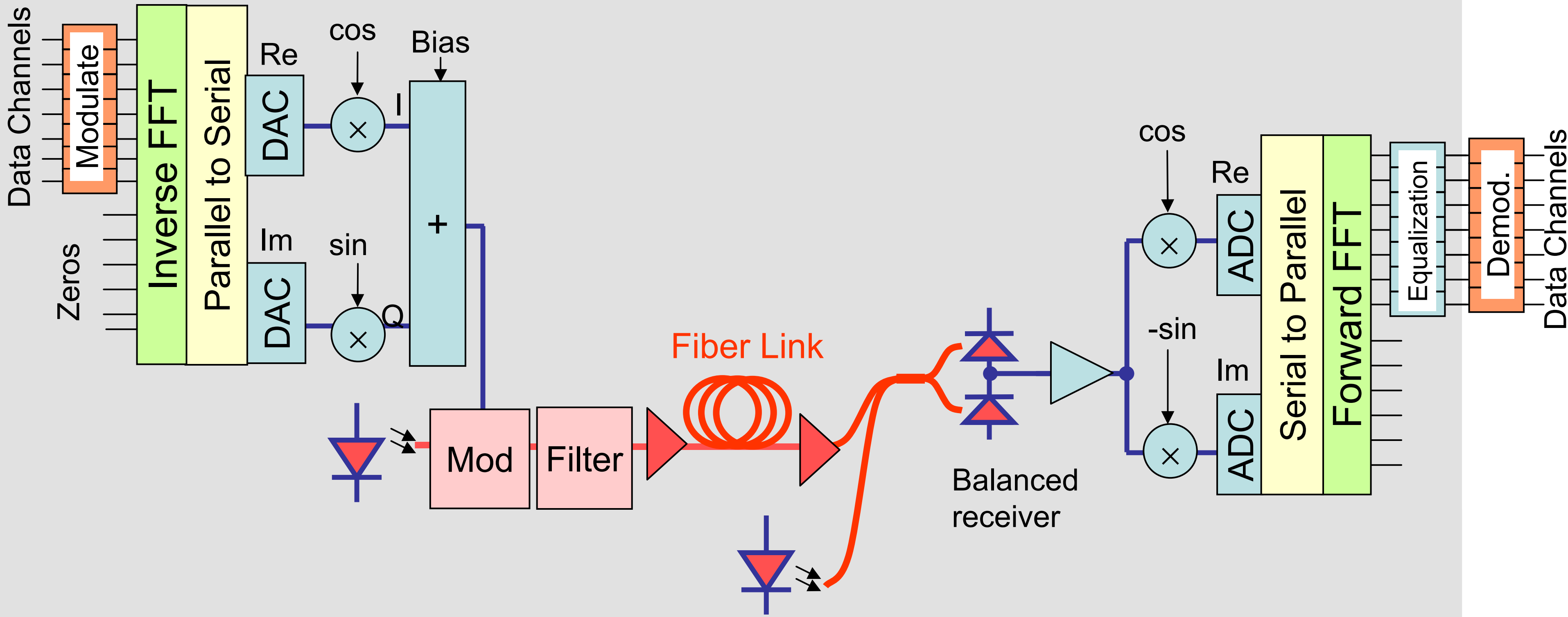
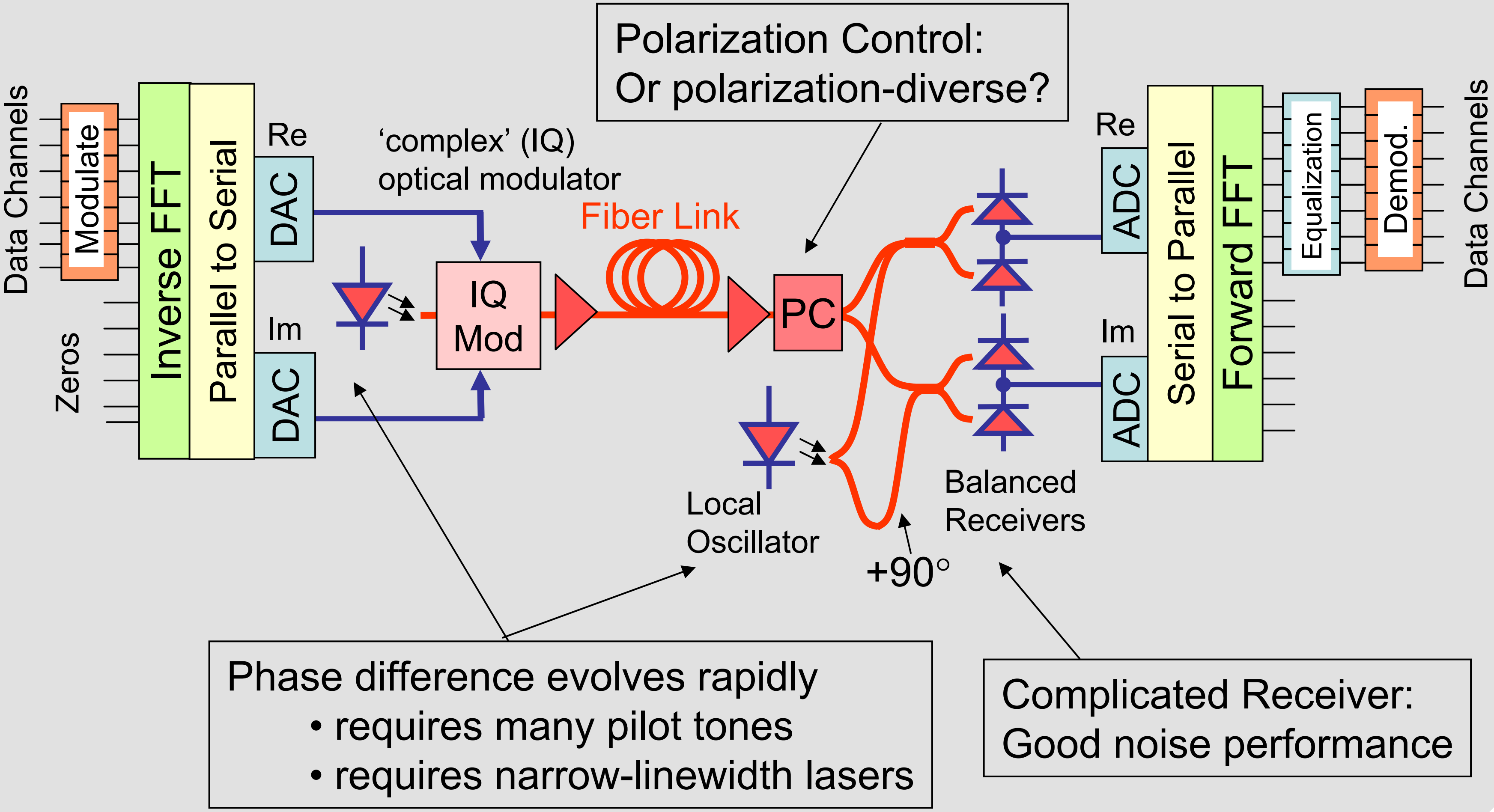
Coherent System
(RF upconversion, Heterodyne receiver)



Coherent System (direct IQ modulation and homodyne detection)



Polarization Control:
Or polarization-diverse?

Phase difference evolves rapidly
- requires many pilot tones
- requires narrow-linewidth lasers

Complicated Receiver:
Good noise performance

Experimental Results

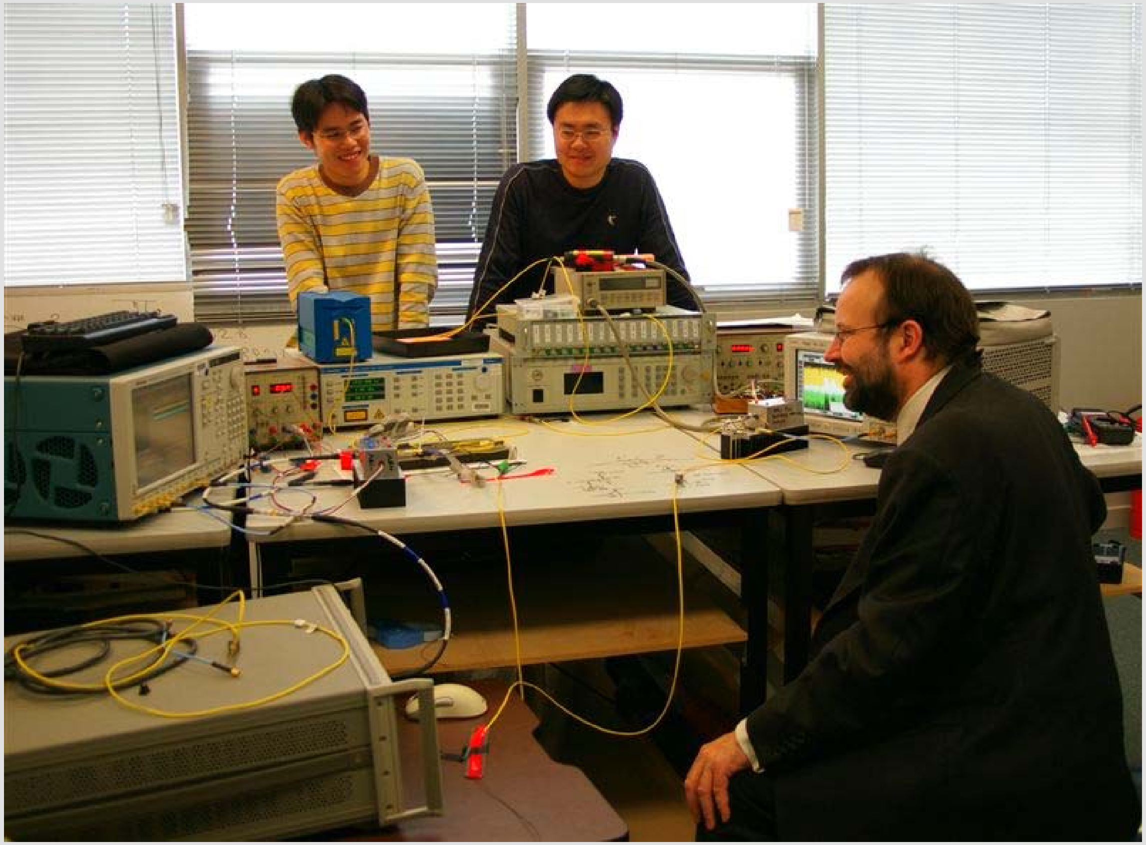
From Monash University

Our Experimental Results (OFC2007 Post Deadline)

Rate	QAM	Length	Comments	BER
20 Gbit/s	16 QAM	320 km	Single DAC OSSB using filter	2.5e-3
12 Gbit/s	32 QAM	400 km	Dual DAC Colorless OSSB Transmitter	3e-4
10 Gbit/s	4 QAM	400 km	Dual DAC RF Up-converter plus filter	1e-4

Details in our OFC 2007 Post-Deadline paper (schmidt, Lowery, Armstrong)

Transmitter and Receiver



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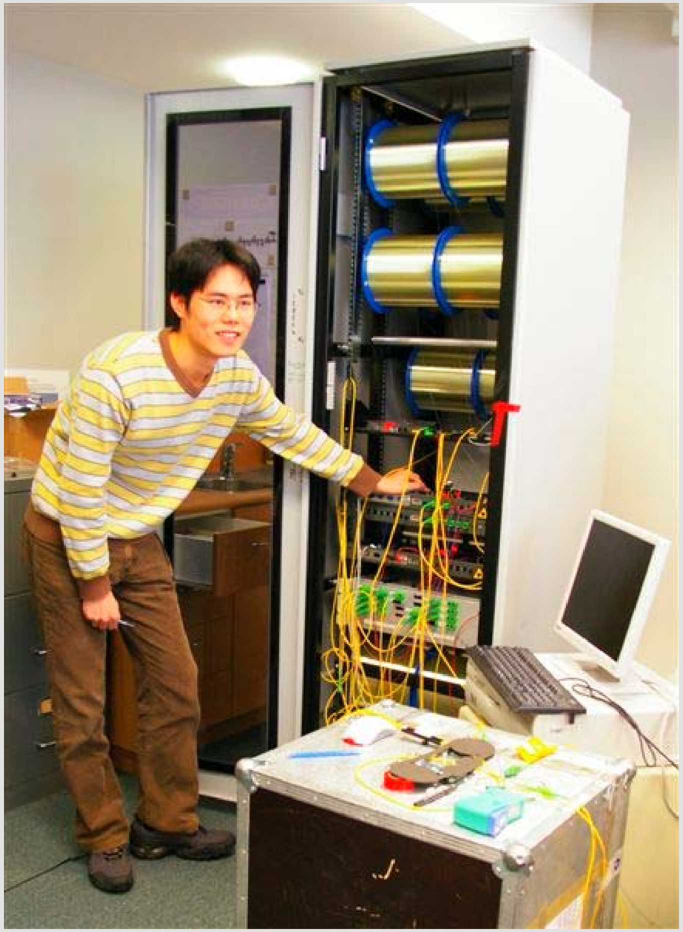
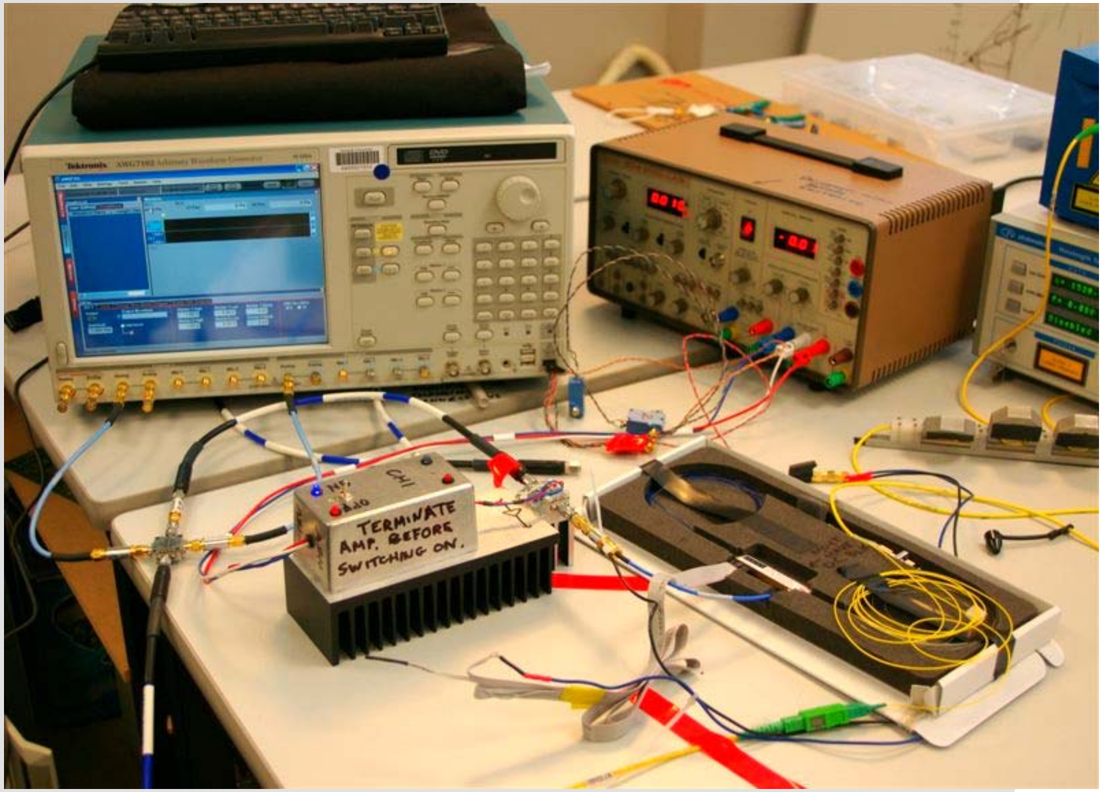
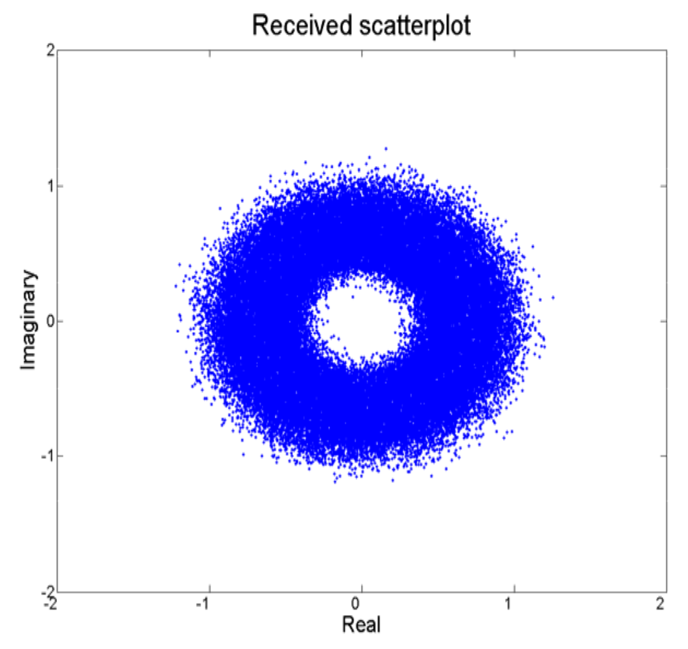
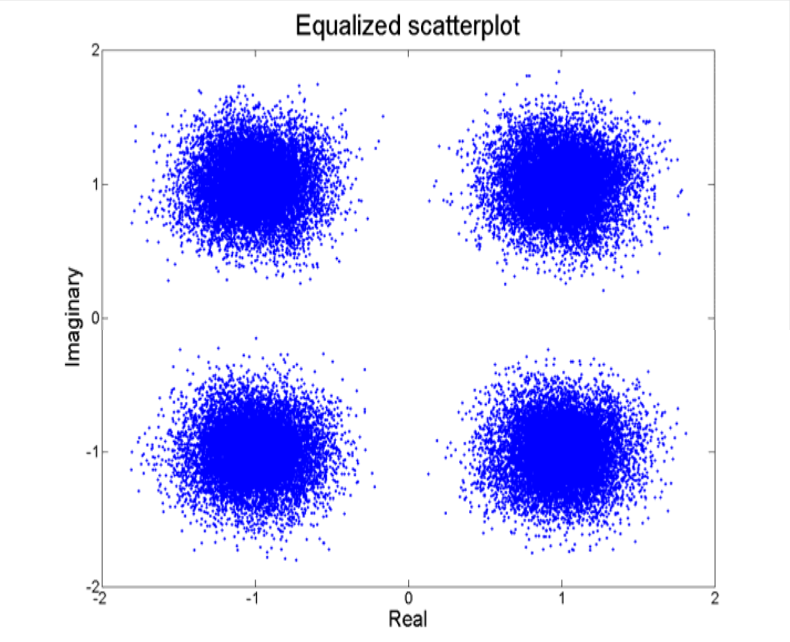
Optical Link and Transmitter





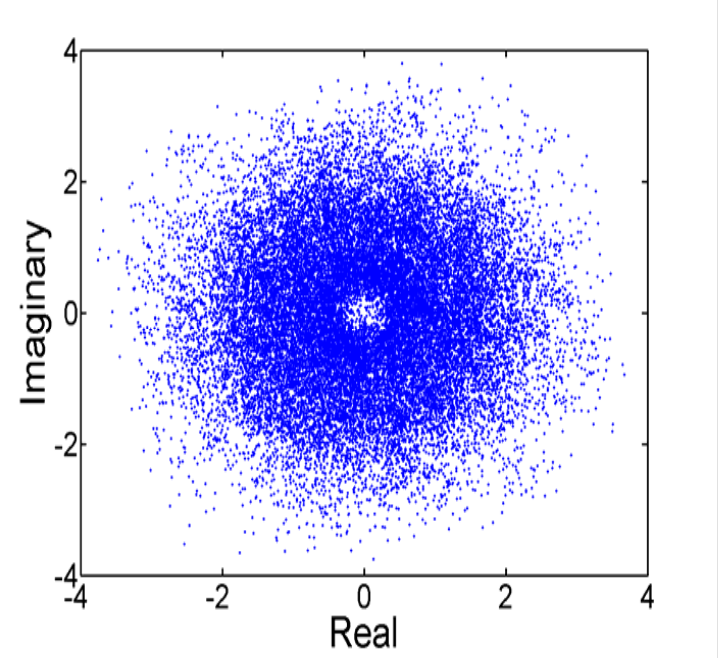
10 Gbit/s Using RF Mixers (400 km)

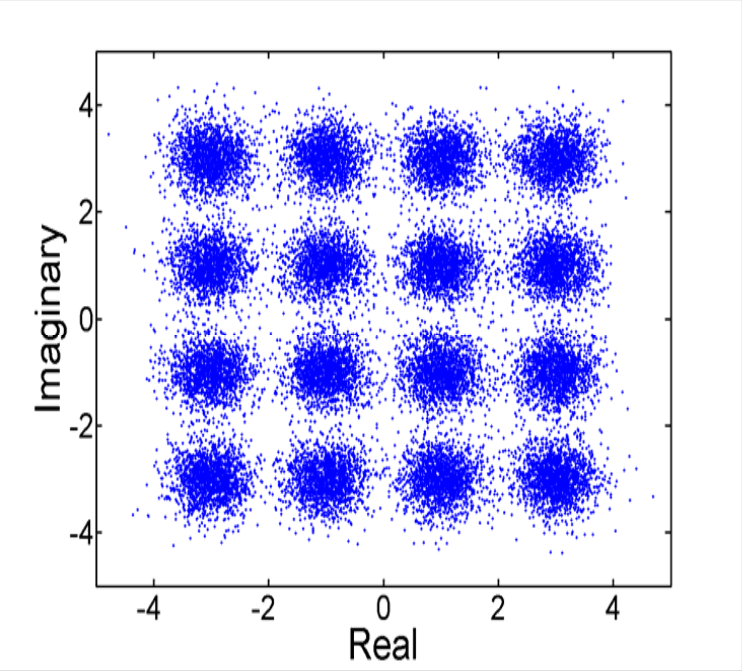




- 400km
- BER < 10^{-5}

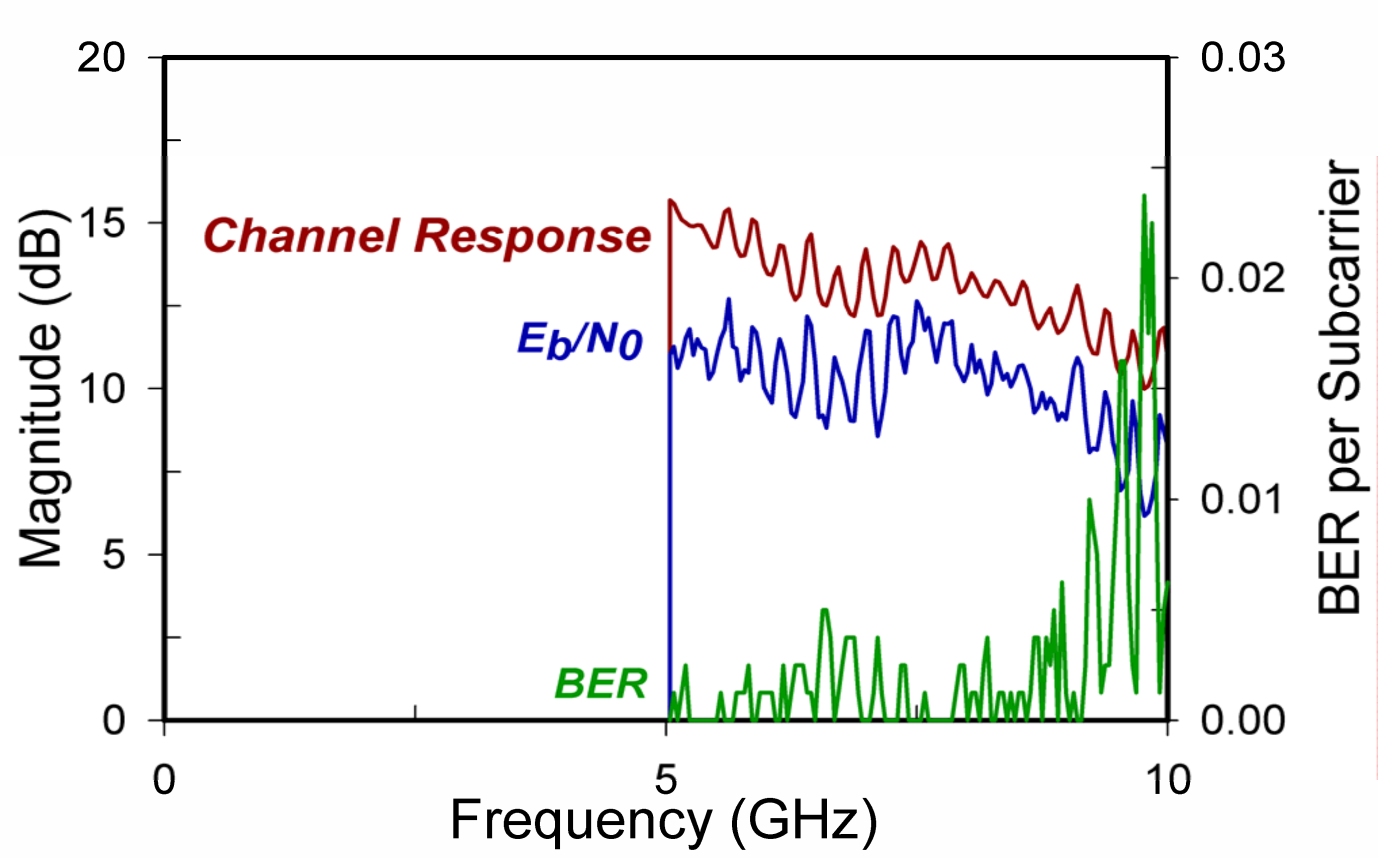
20 Gbit/s Using Direct Digital Conversion





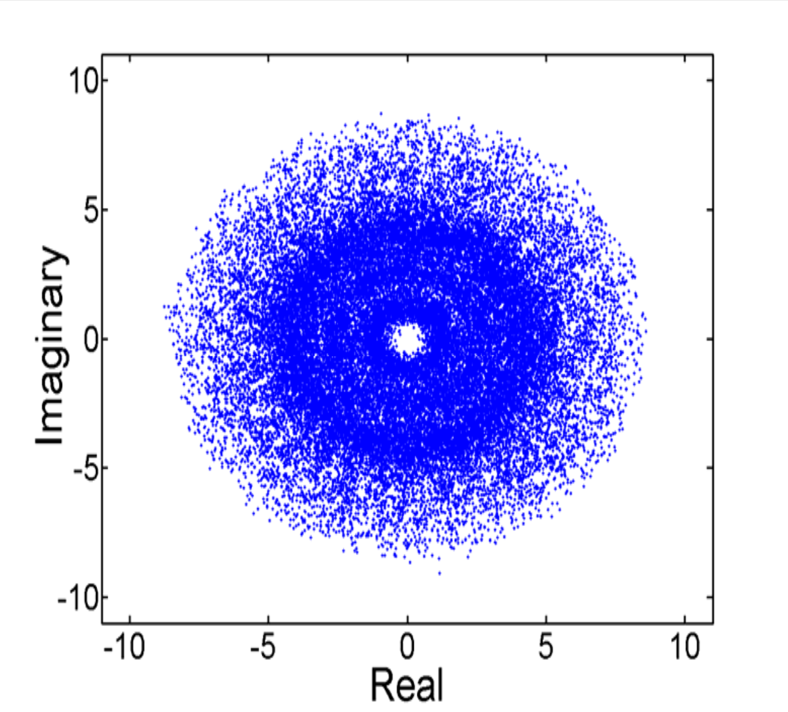
- 320 km
- BER = 2.5×10^{-3}

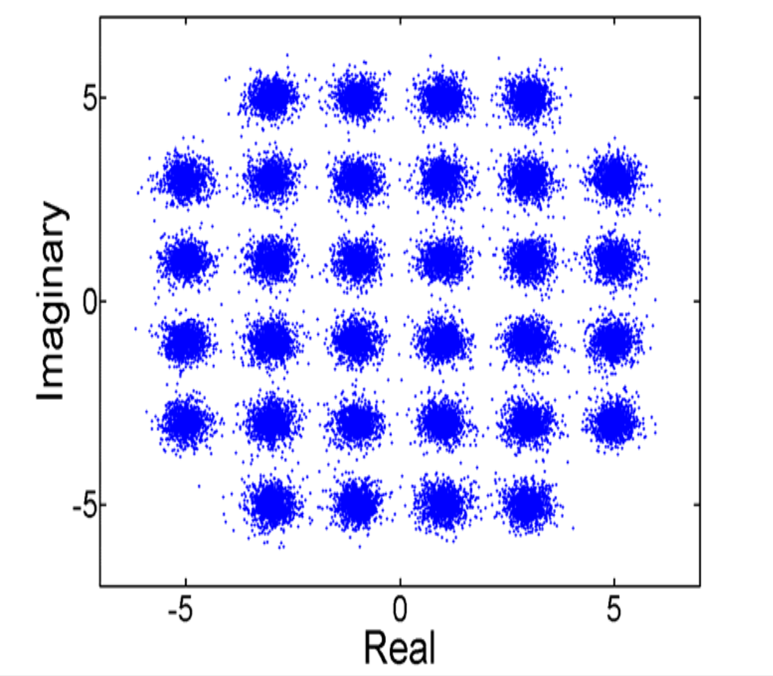
20 Gbit/s Using Direct Digital Conversion



Channel response is a result of electrical and optical components.

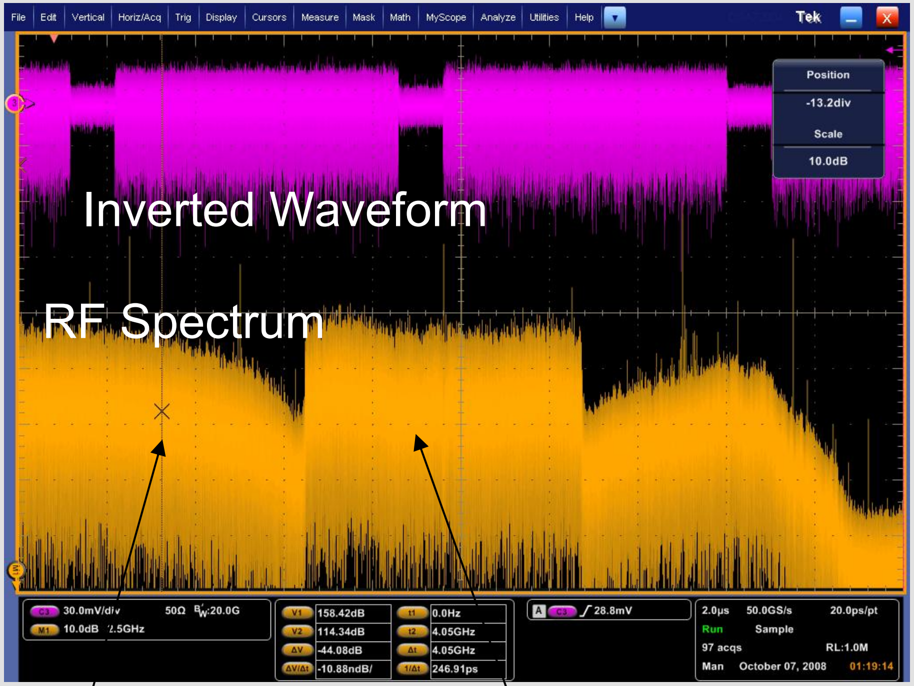
12 Gbit/s Using Colorless Transmitter (2006)





- 400km
- BER = 3×10^{-4} for 184,000 bits

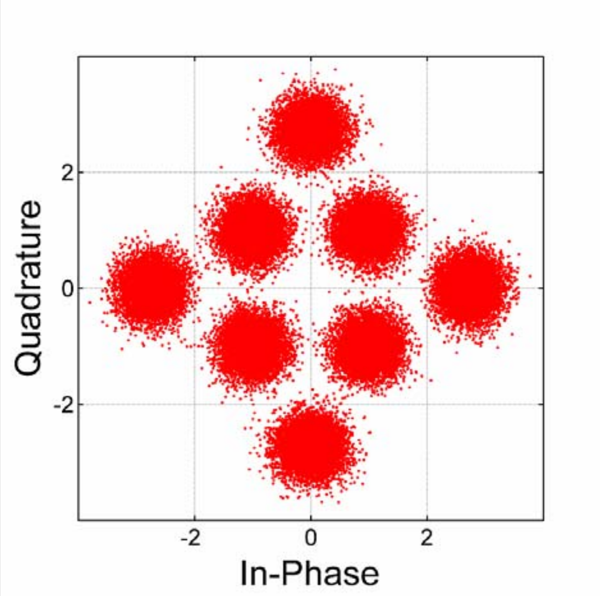
24 Gbit/s Using Modified Colorless Transmitter (using only10 GS/s DACs)



```
C3  30.0mV/div     50Ω  BW:20.0G      V1    158.42dB    t1   0.0Hz       A  C3  ∫ 28.8mV     2.0μs   50.0GS/s     20.0ps/pt
M1  10.0dB  2.5GHz                    V2    114.34dB    t2   4.05GHz                         Run     Sample
                                      ΔV    -44.08dB    Δt   4.05GHz                         97 acqs              RL:1.0M
                                      ΔV/Δt -10.88ndB/  1/Δt 246.91ps                        Man     October 07, 2008  01:19:14
```

Signal × Signal

Signal × Carrier



BER of 2×10^{-4}
(800 km, 40-GHz ASE filter)

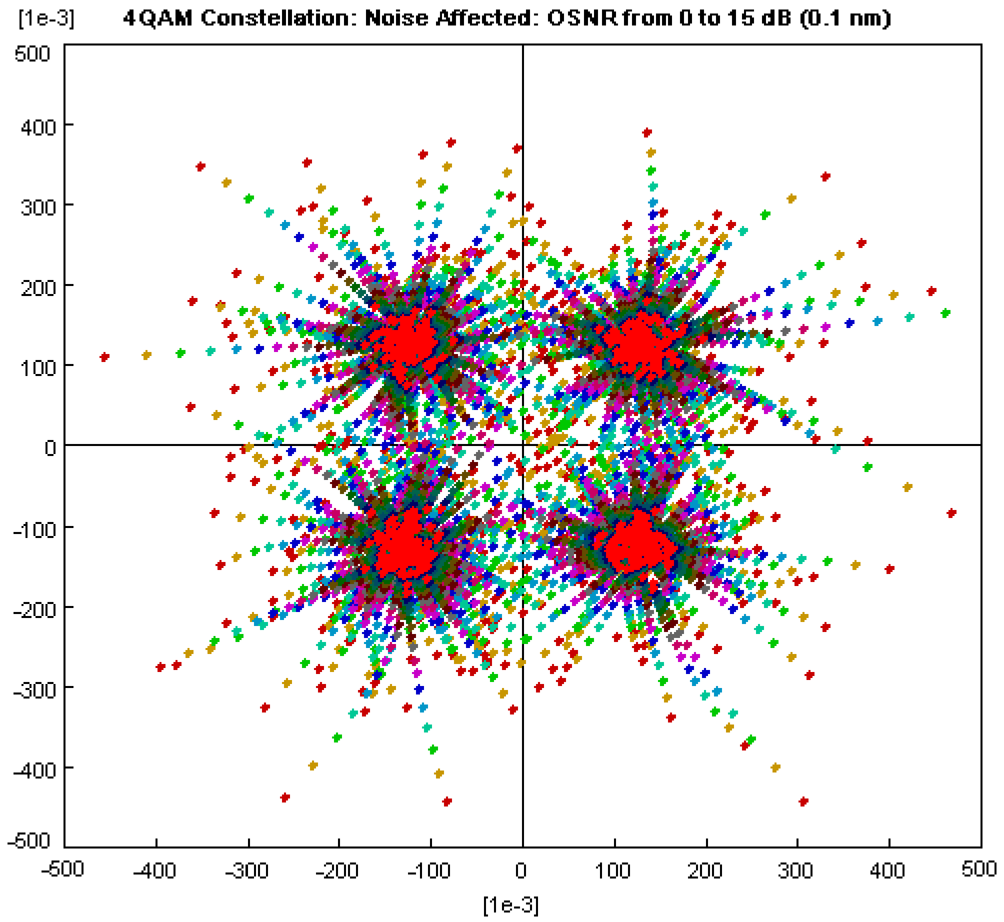
Thanks to Brendon Schmidt and Liang Du

Impairments

Amplified Spontaneous Emission

Effect of Amplifier Noise (ASE)

- ASE causes bivariate Gaussian spreading of points
- This is a sweep of OSNR from 0 dB to 15 dB.
- The same random sequence is used for each noise level – radial spreading
- Bright Red is 15 dB OSNR



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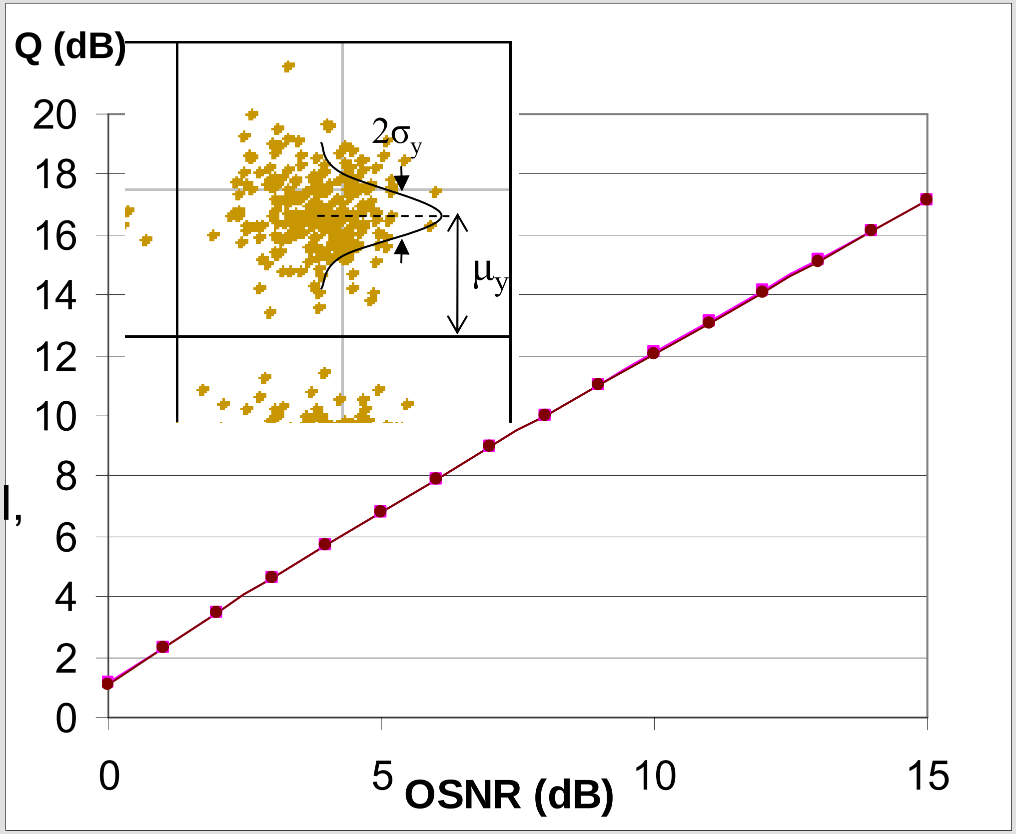
Q versus OSNR

- $Q_{dB} = 20.\log_{10}q$
- $q = \sigma_x/\mu_x = \sigma_y/\mu_y$

For 4-QAM
optimum filtering
ASE dominated,
modulator biased at quad. or null,
Pcarrier= Psideband

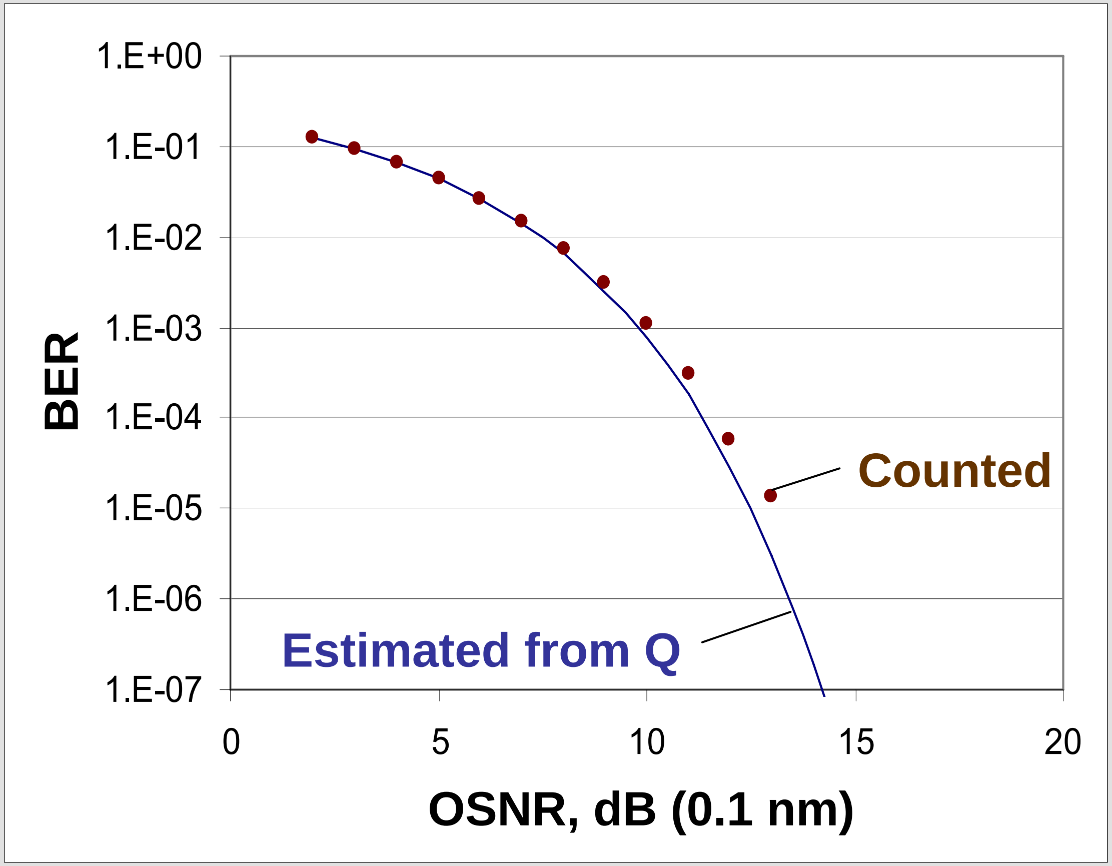
QdB = 1.0615 OSNR + 1.4032 dB

$R^2 = 0.9994$

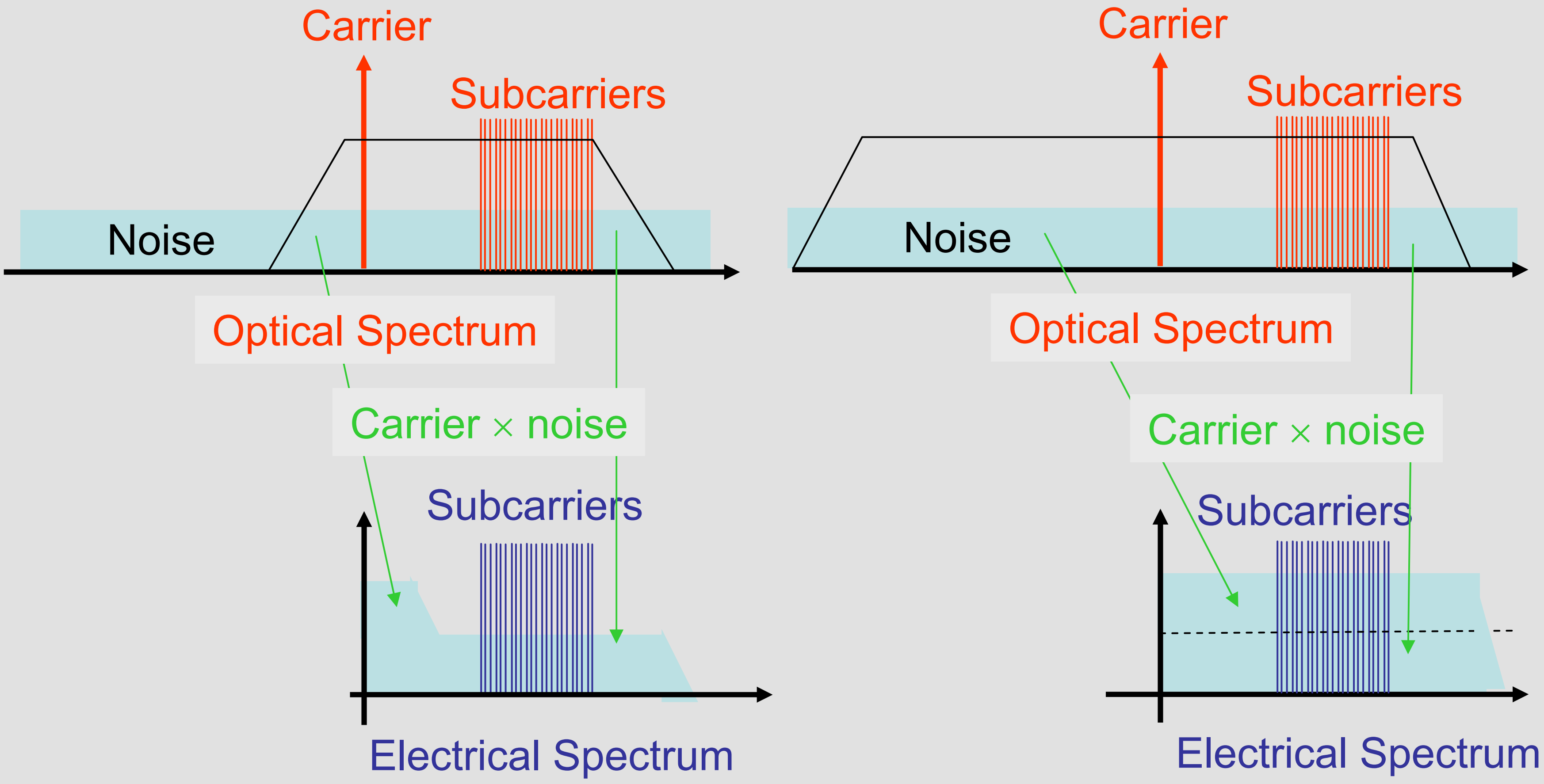


BER versus OSNR

- BER(estimate) =½erfc($q/\sqrt{2}$)
- erfc is Excel definition
- 10 dB OSNR gives 0.001 BER



Effect of Filter Bandwidth: noise from image



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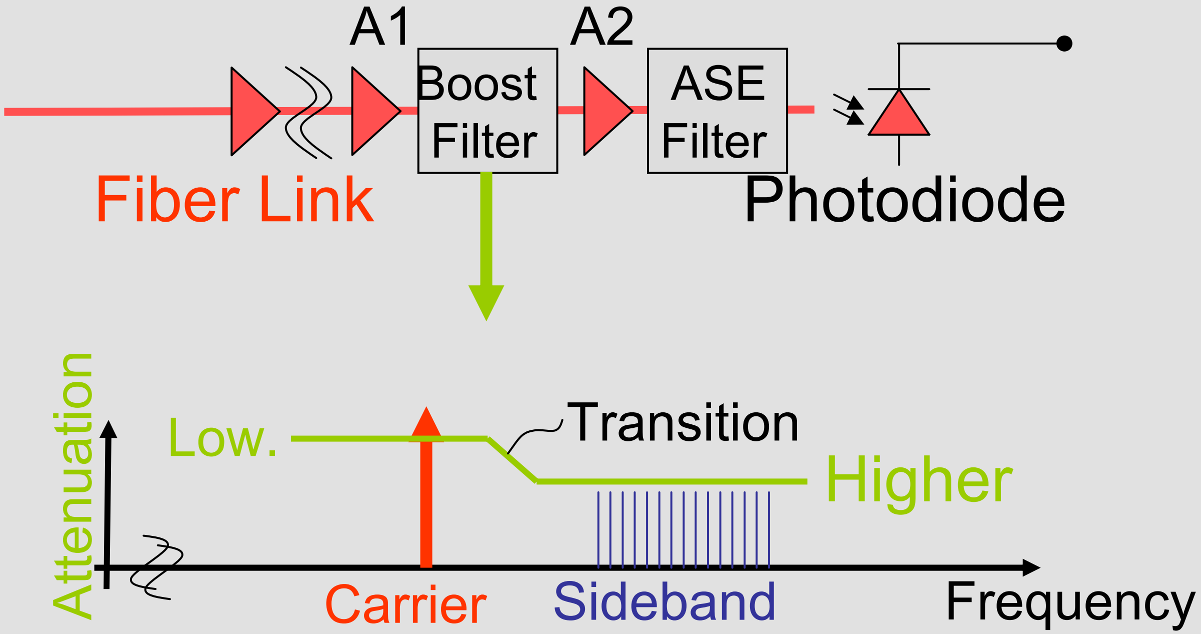
A. J. Lowery, "Amplified-spontaneous noise limit of optical OFDM lightwave systems," Opt. Express **16**, 860-865 (2008) http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-2-860

Carrier Boost in DD-OOFDM

One way of obtaining good performance is a **strong local oscillator** (compared with the signal):

suppresses: *Signal* ×*Signal*, *Signal* ×*ASE*, *ASE* ×*ASE*,

- so why not **boost** the carrier to mimic a strong local oscillator?

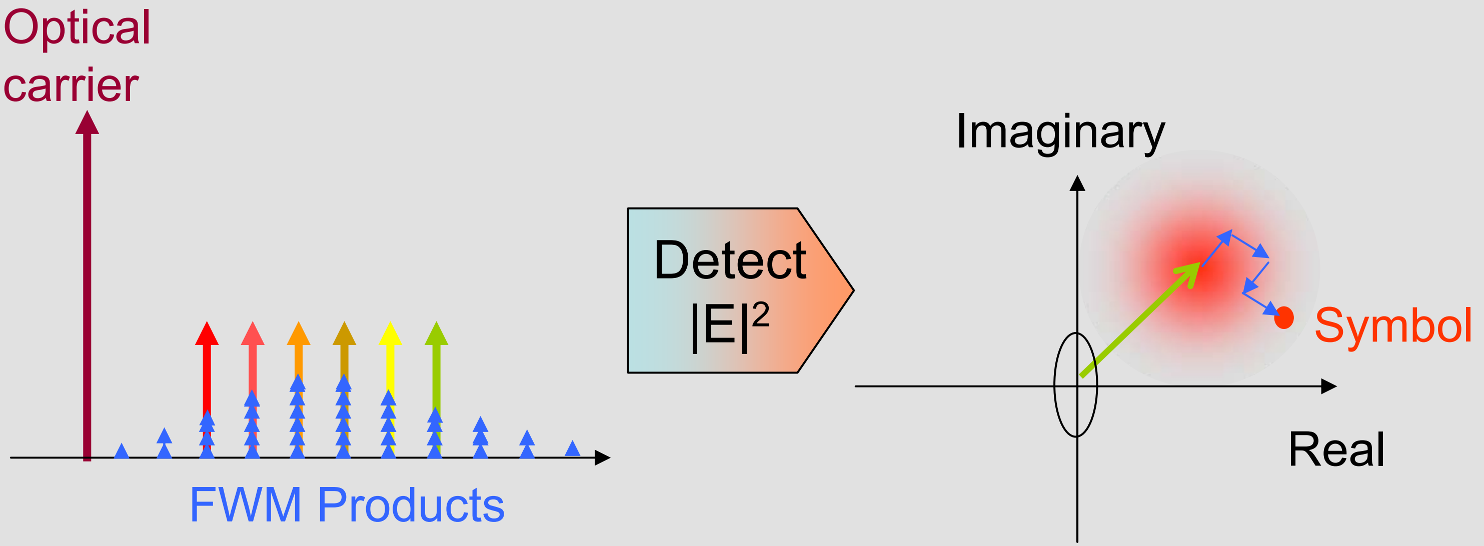


A. J. Lowery, "Improving sensitivity and spectral efficiency in direct-detection OFDM lightwave systems,"
Optical Fiber Telecommunications (OFC 2008), San Diego, paper OMM4

Impairments

Nonlinearity

Effects of Nonlinearity – Theory



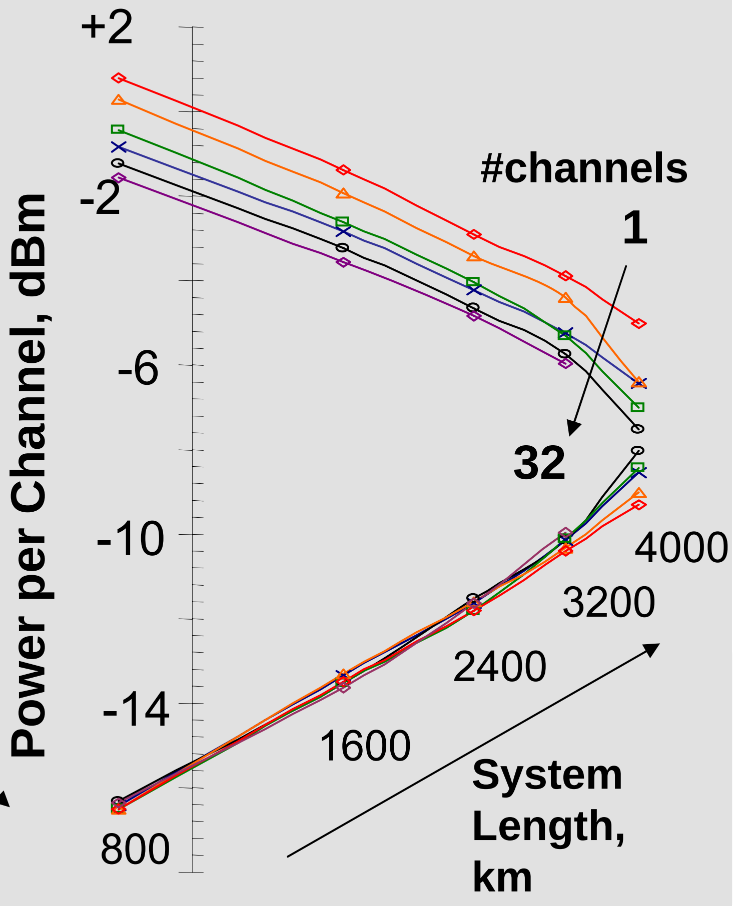
Close carriers mean strong FWM products (no ‘walk-off’)

FWM products have random, but distinct, phases. They add as a random walk to the **signal vector**, causing a **Gaussian spread**.

The FWM degradation is independent of the number of carriers.

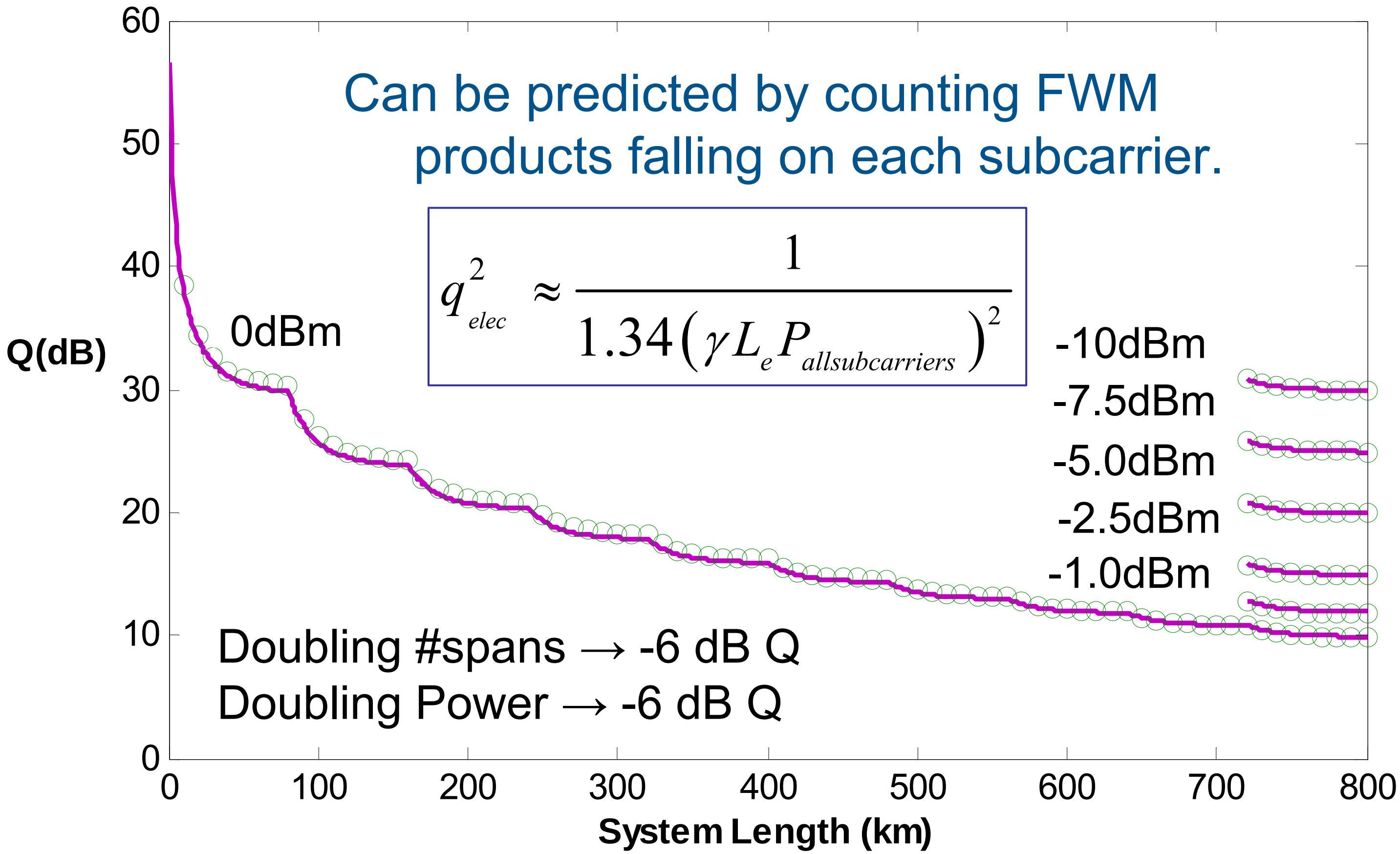
Effects of Nonlinearity – 80 km spans WDM

- Lines for Q = 11.4 dB
- Nonlinearity affects max. power
  - Depends on channel count
- Noise affects min power
  - “58 equation”
- 5 dB decrease in margin per doubling of length



Lowery, Du, Armstrong: OFC 2006
(and JLT Jan 2007 for WDM)

Effects of Nonlinearity – Q limit with multiple 80 km spans WDM (coherent)



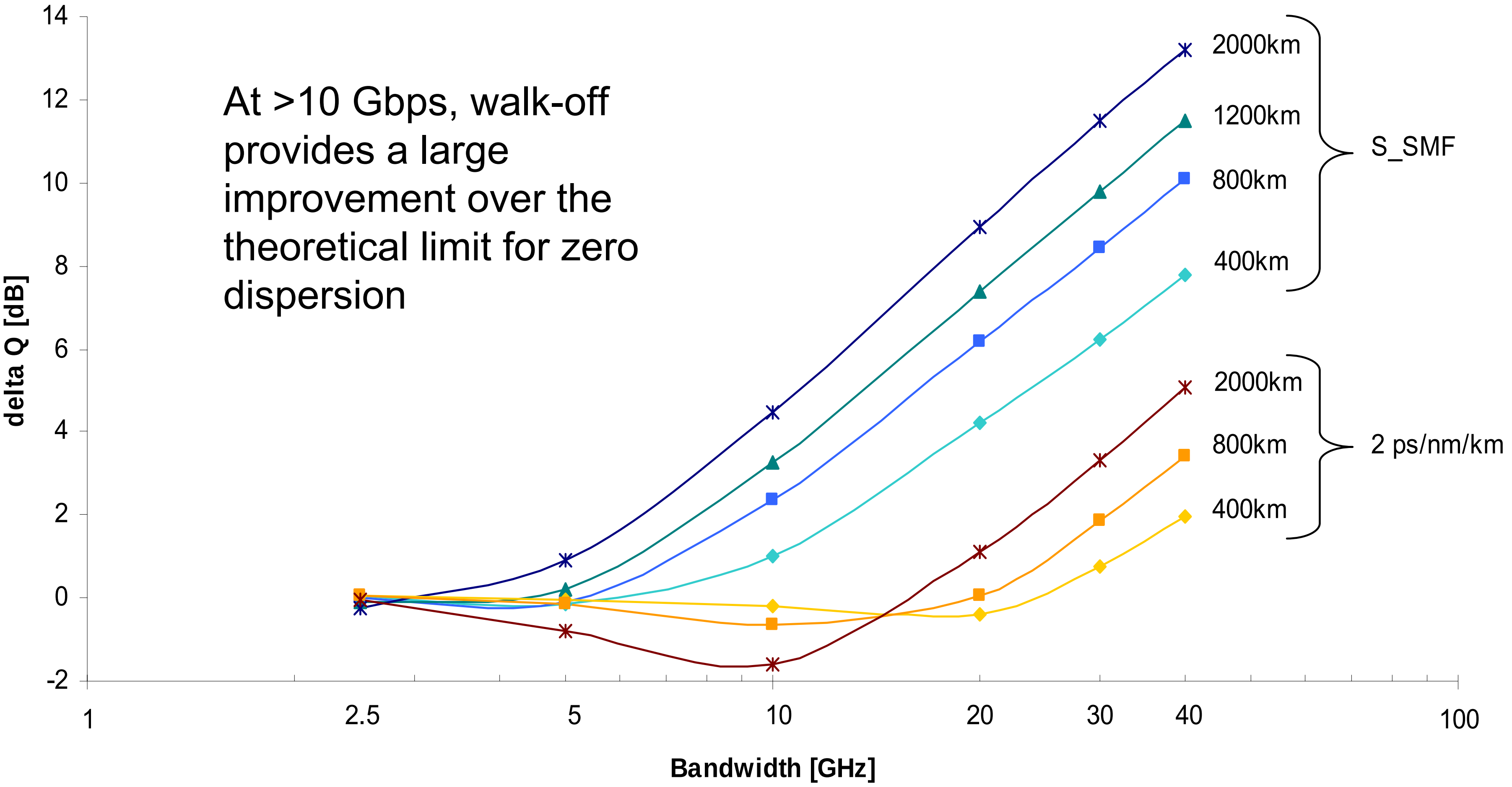
Can be predicted by counting FWM products falling on each subcarrier.

$$q_{elec}^{2} \approx \frac{1}{1.34\left(\gamma L_{e} P_{allsubcarriers}\right)^{2}}$$

Doubling #spans → -6 dB Q
Doubling Power → -6 dB Q

Lowery, Wang, Premaratne: Optics Express, 2007

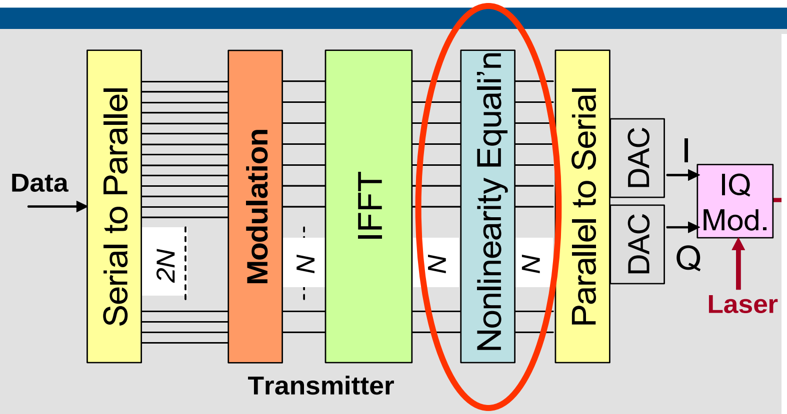
Effect of Dispersion on Nonlinearity



At >10 Gbps, walk-off provides a large improvement over the theoretical limit for zero dispersion

Du and Lowery, In press, Optics Express, 2008

Nonlinearity Compensation

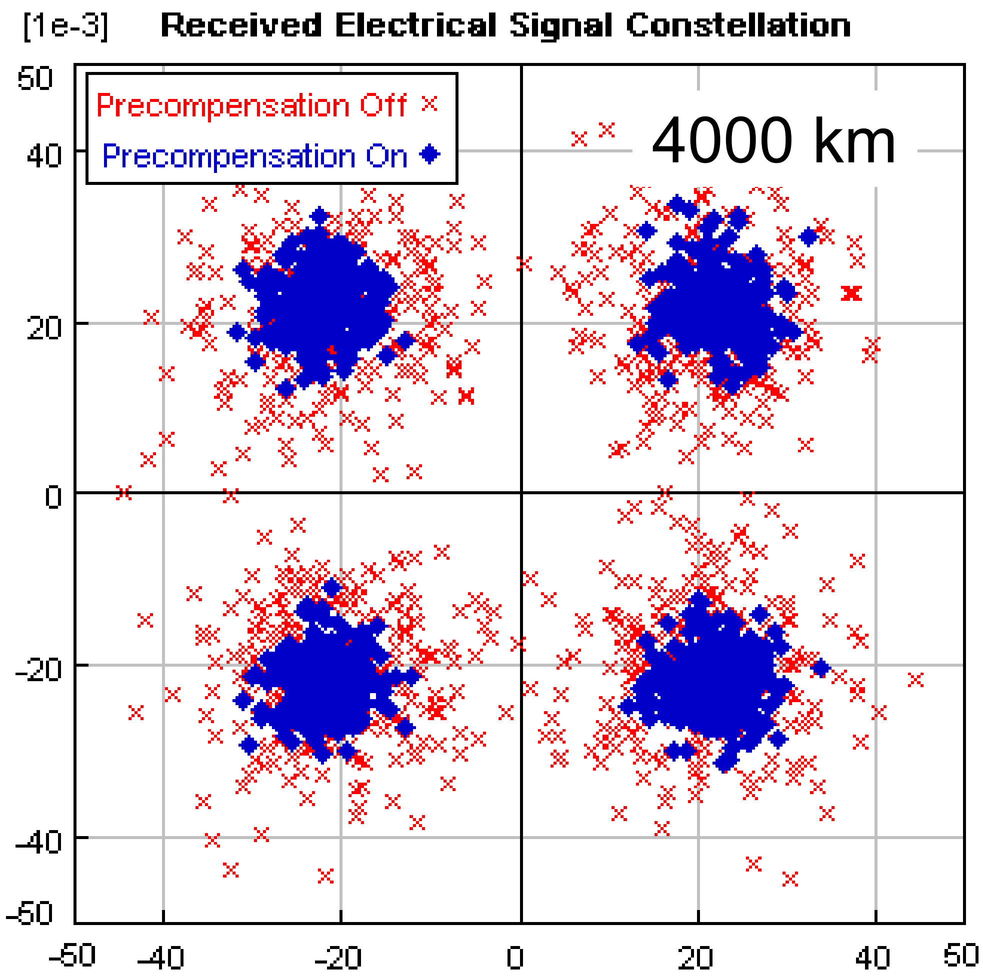


Nonlinearity (*t*)

Very simple implementation:

$$\theta(t) = P(t).sL_{eff}.2\pi n_2 /(\lambda_0 A_{eff})$$

Increase in *Q* is > 7 dB!



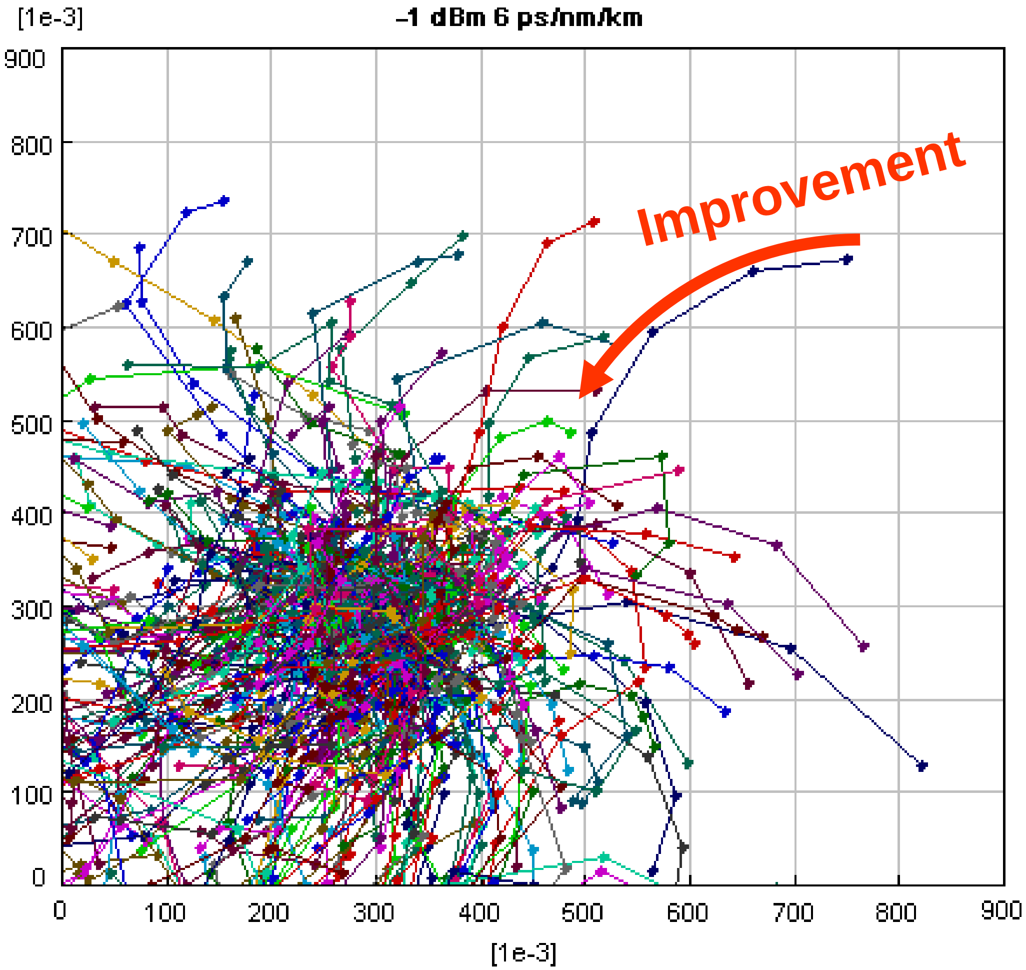
A J Lowery: Photonics Technology Letters, pp. 1556-1558 (2007)

Nonlinearity Compensation

- Nonlinearity compensation pulls-in outlying points of each subcarrier

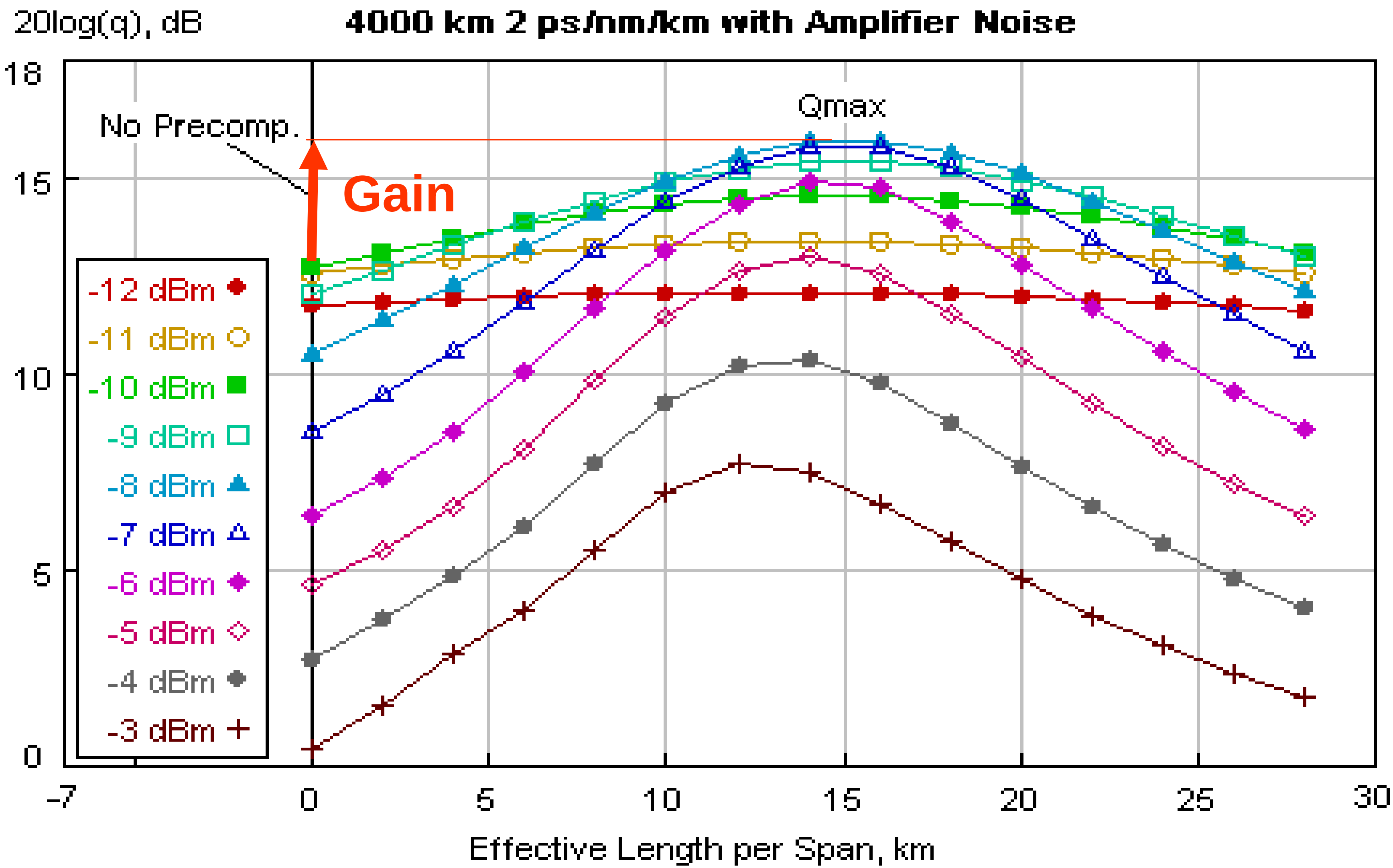
- Walk off means the improvement is limited

  - But it is still useful!



MONASH University

Nonlinearity Compensation



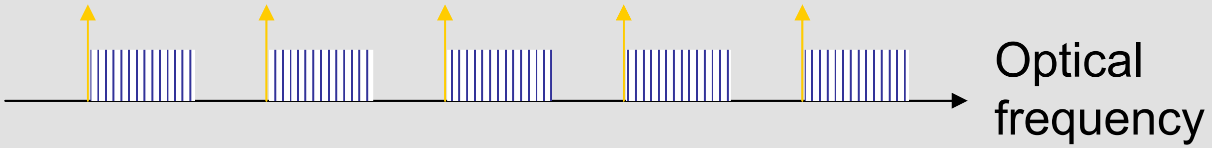
Scaling OFDM to higher bit rates

- OFDM is numerically efficient
  - for 1000 km of fiber at 10 Gbit/s, MLSE requires 370× more than OFDM
  - And fewer than Pre/Post compensation (few times)

Henning Bülow: OMG5, OFC 2007

100G Systems Demonstrations

- Sander Jansen *et al.*
  - Uses dual-polarization transmission with electronic PMD compensation
  - Subcarriers contain a pilot tone to allow phase noise to be compensated in the RF domain
- William Shieh *et al.*
  - Uses an optical comb source
  - Same OFDM spectrum modulated onto each line of the comb
  - No phase noise compensation



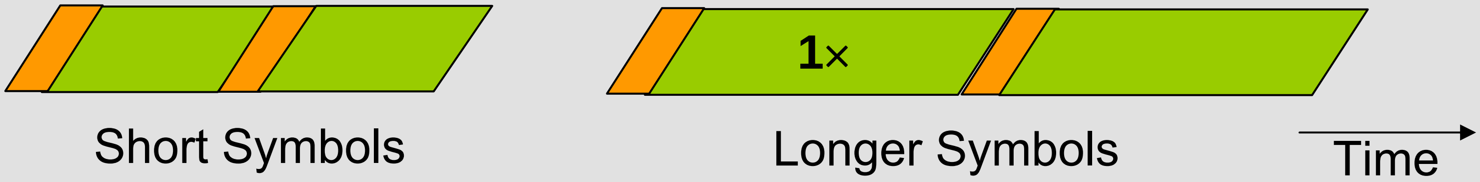
See OFC 2008 Postdeadlines

Efficiency and scaling to higher bit rates

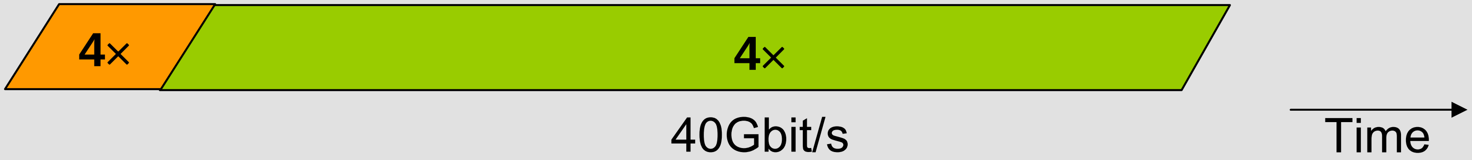
- OFDM is Scalable to higher bit rates
  - Processing complexity is prop. to $5N.\log_2(N) + k.N$
  - With 4096 symbols, 40 Gbps requires 24× more processing per OFDM Symbol
  - But we have N× more time to do it
    - (4096 OFDM symbol covers 4 × more time at 40 Gbps)
  - So computation speed requirement is only 6× that of 10 Gbit/s

Scaling to higher bit rates: Overhead

- Longer symbols (*N*) add a proportionally shorter cyclic prefix – a lower overhead



- For 10% overhead at 4000 km,10 Gbps, *N*=256
  - Increases to *N*=4096 at 40 Gbps (because of higher bandwidth of the optical signal and the higher bit rate, hence symbol rate)



Conclusions

- Orthogonal Frequency Division Multiplexing offers advantages for long-haul dispersion compensation:
  - No reverse feedback path
    - Responds to rapid fluctuations
  - Signal can be dropped at any point
  - Timing synchronization easy (no clock recovery)
  - Slower DACs and ADCs, especially if RF subcarrier is used
  - Self-monitoring
  - Compensates for electrical and optical channel imperfections

- We have shown 20 Gbit/s (all digital), 24 Gbit/s (colorless, all-digital) and 10 Gbit/s (RF mixers)

- More scalable than MLSE (and starts from a better base)
  - only 6× more processing for 40 Gbps

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