Modulation Formats Which Approach the Shannon Limit

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Symbols and Acronyms

EDFA: Erbium doped fibre amplifier
WDM: Wavelength division multiplexing
FEC: Forward error correction
C+L: Particular amplification wavelengths
PDH: Plesiochronous Digital Hierarchy
SDH: Synchronous Digital Hierarchy
IP: Internet Protocol
QAM: Quadrature Amplitude Modulation
SSB: Single side band
ASK: Amplitude shift Keying
PSK: Phase shift keying
m: number of constellation points
BER: Bit error ratio
LDPC: Low Density Parity Check
OSNR: Optical signal to noise ratio
ASE: Amplified spontaneous emission
DSP: Digital signal processing
DFB: Distributed feedback laser
MZM: Mach Zehnder modulator
RZ: Return to Zero
DPSK: Differential PSK
CS: Carrier suppressed
Pol: Polaraisation
OFDM: Orthogonal frequency domain multiplexing
CoWDM: Coherent WDM
ASIC: Application specific integrated circuit

C: Channel capacity
B: Channel bandwidth
N_0: Noise spectral density
P_b: Bit energy
snr: Signal to noise ratio
Q(x): Q function for a Gaussian random variable
E_s: Energy value to quantify size of a constellation
E_b: Mean energy of a symbol
e_i: Complex field value
λ: Wavelength
c: Speed of light
N_{amps}: Number of amplifiers
G: Amplifier gain
n_{sp}: Spontaneous emission factor
h: Plank’s constant
v: Frequency
D: Dispersion
γ: Nonlinear coefficient
L_{eff}: Effective length

A small selection of related sessions

	Short Courses	Workshops	Tutorials	Sessions/Invited Speakers
Communication Theory			Digital Coherent Receivers.	Franceschini
FEC				Kschischang
Non-linear effects	Modeling & Design	Electronic Signal Processing and the Design of Optical Transport Systems	Capacity Limits of Fibers. Impact and Mitigation of Non-Linear Effects.	Nakazawa, Bigo, Fuerst, Shieh, Sun, Sakamoto, Sano, George
Modulation formats	WDM in Long-Haul Modulation Format	Single-Carrier Versus Multiple-Carrier Modulation Formats for WDM Systems		
New Technologies	Photonic ICs Electronic Circuits	100Gbit/s for $100	Photonic Crystal Fibers.	Prevost, Brès, Krauss, Kaneko, Klamkin, Morse, Hauske, Yoo, Clarke,
	Reinforce	Consolidate	Build on	Highlight

Introduction

- Trends in optical communication
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  - Generic communication theory
  - Forward Error Correction Codes
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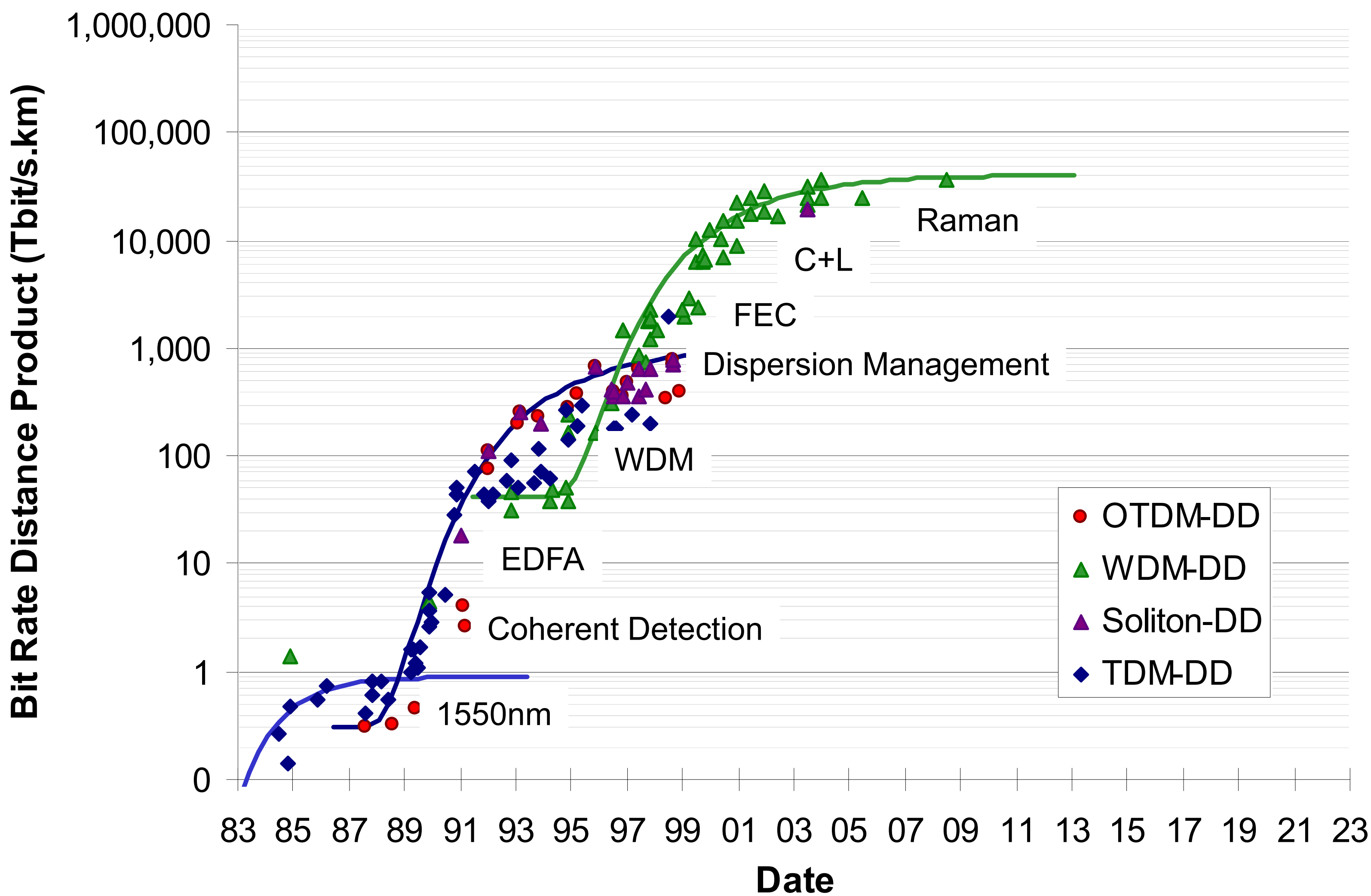
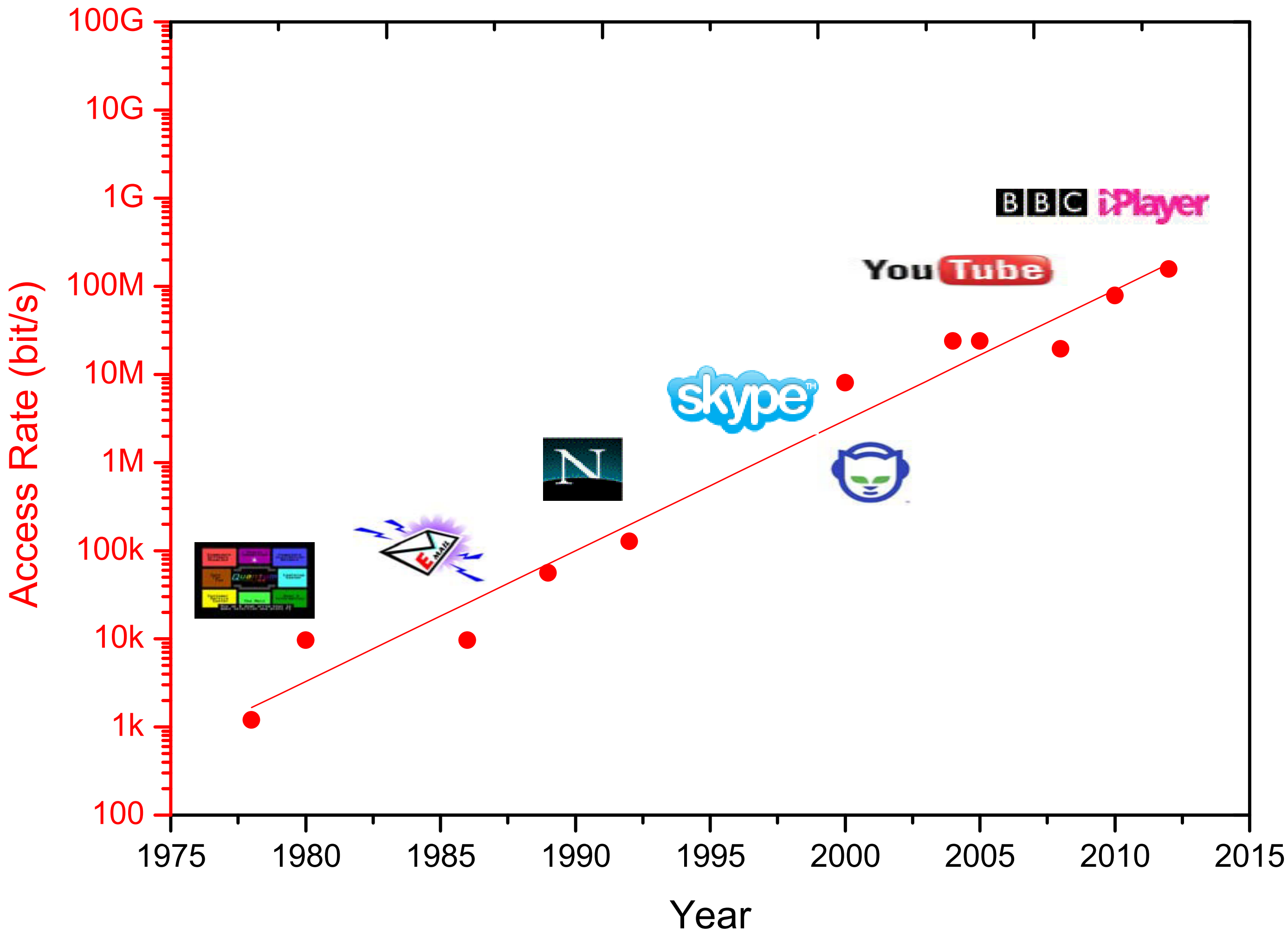
  - Capacity limit for non-linear systems
  - Multi-level modulation formats
  - Breaking the current limit

Maximum capacity (research)

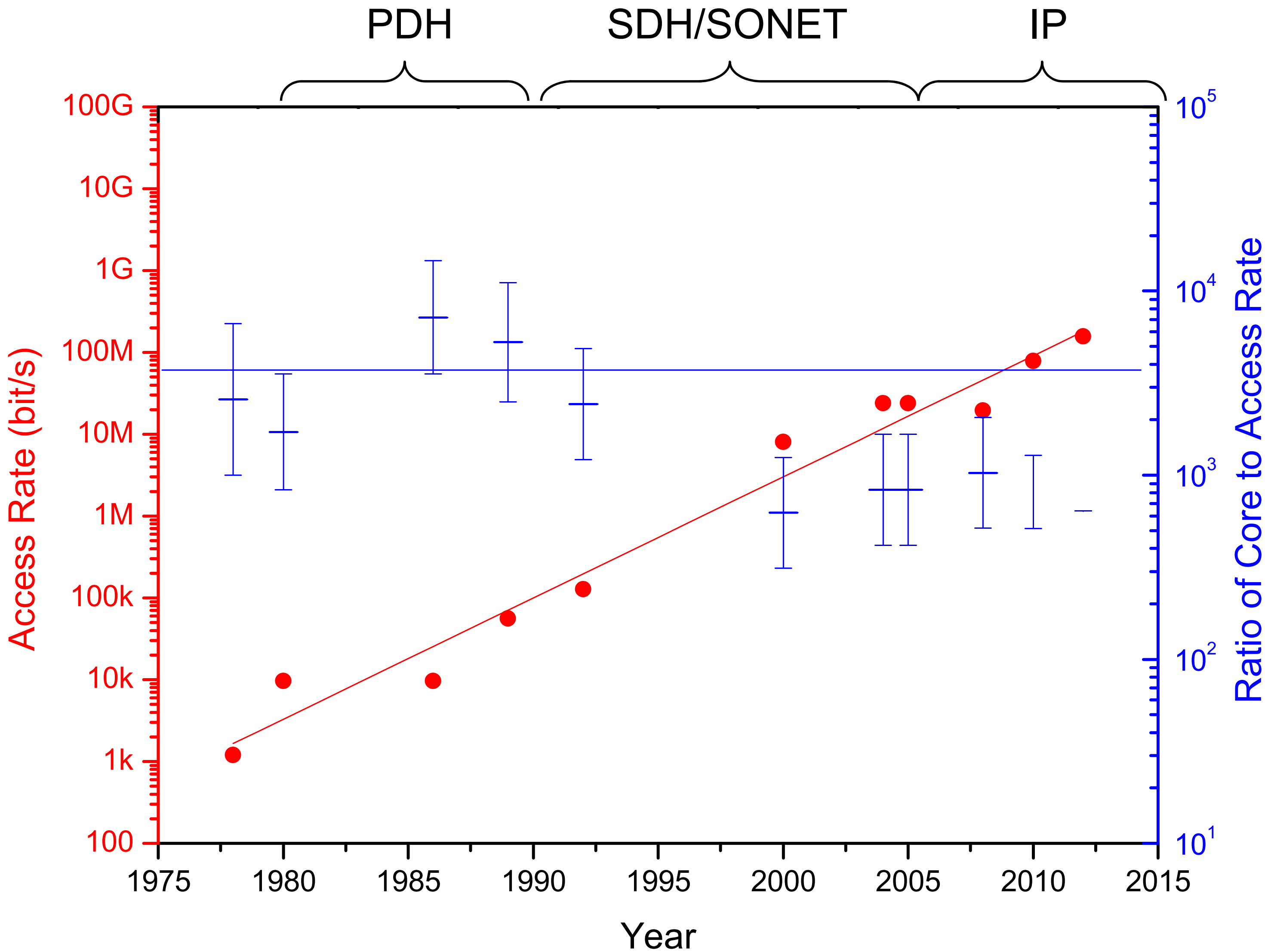


User Demand

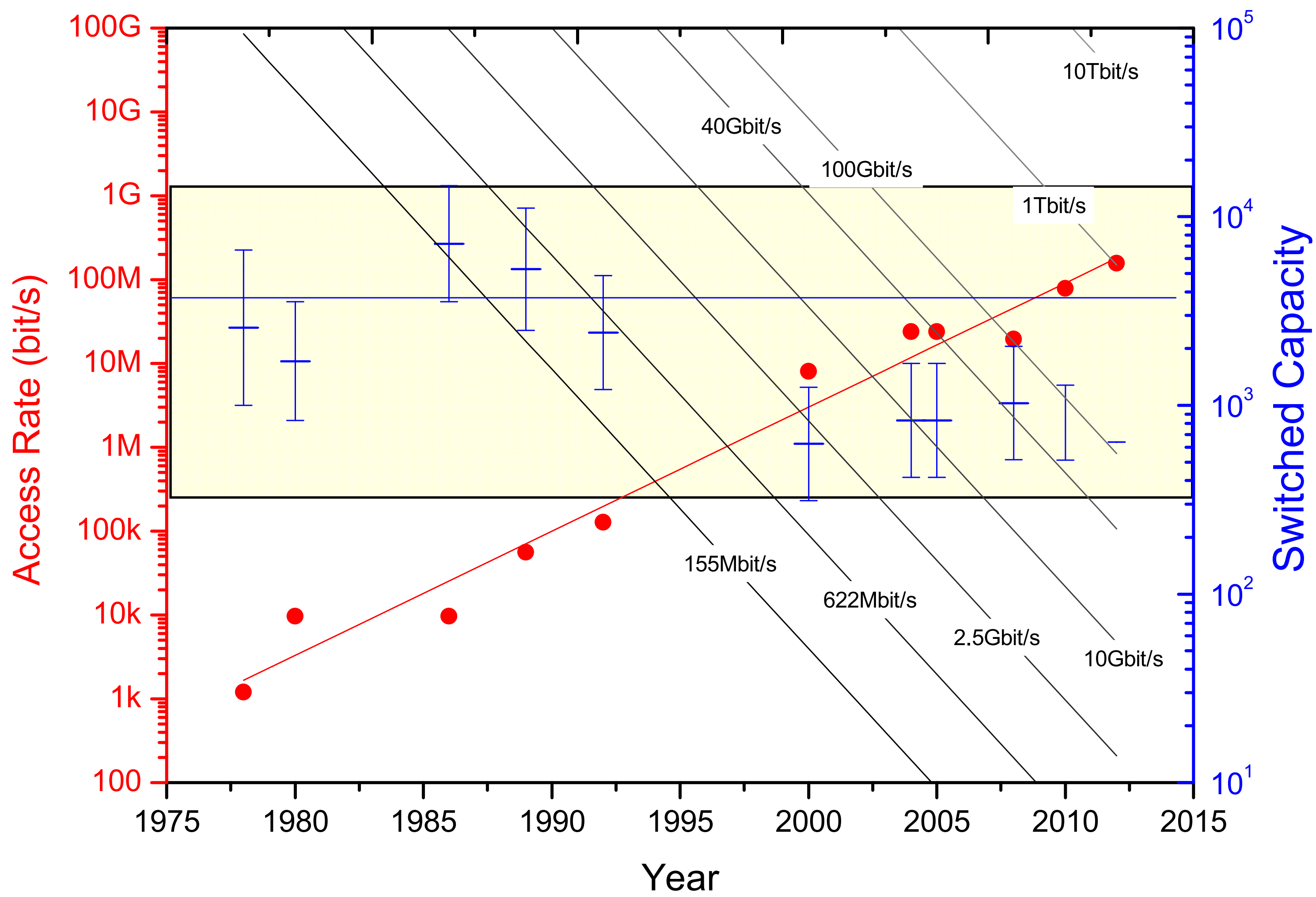


Access Rate (bit/s)
100G
10G
1G
100M
10M
1M
100k
10k
1k
100
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
BBC iPlayer
YouTube
skype
N

Network Architecture



Switching Capacities



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Shannon Limit

- Shannon's Second Theorem – The Noisy Channel Coding Theorem
  - C.E.Shannon, "A Mathematical Theory of Communication", Bell Syst. Tech. J., **27**, pp379-423 & pp623-656
  - "Reliable communication over a discrete memory-less channel is possible if the communication rate R satisfies R < C, where C is the channel capacity. At rates higher than the capacity, reliable communication is impossible."

$$\begin{aligned} C/B &= \iint p_{Y,X}(y,x) \log_2 \frac{p_{Y,X}(y,x)}{p_Y(y) p_X(x)} \, dy \, dx \\ &= -\int p_Y(y) \log_2 p_Y(y) \, dy + \iint p_{Y,X}(y,x) \log_2 p_{Y|X}(y|x) \, dy \, dx \\ &= H(Y) - H(Y|X) \,, \end{aligned}$$

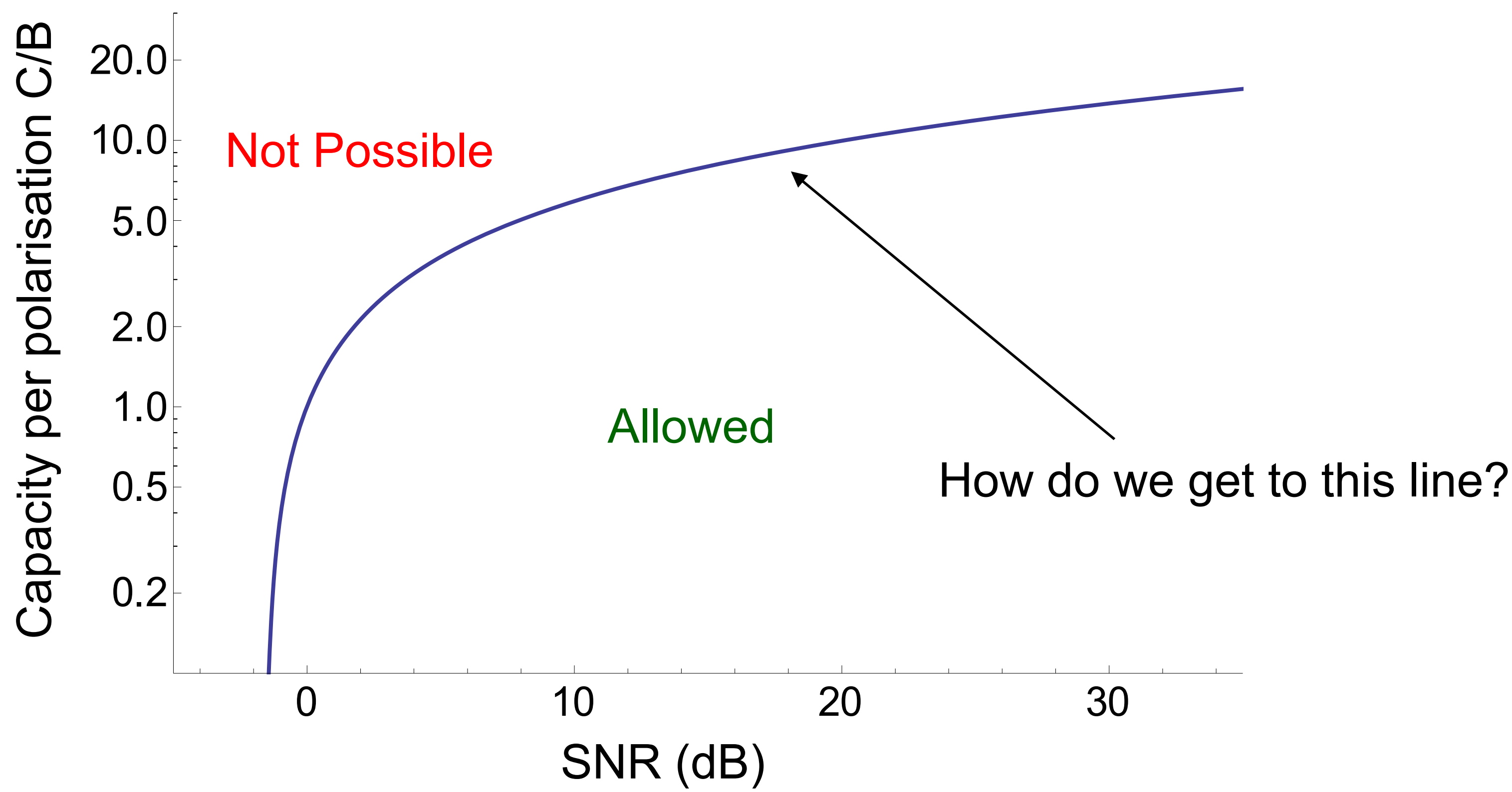
$$C = B.\log_2\left(1 + \frac{P}{N_o B}\right)$$

  - At infinite bandwidth

$$C_\infty = \frac{P}{N_o} \log_2 e$$

Information Spectral Density

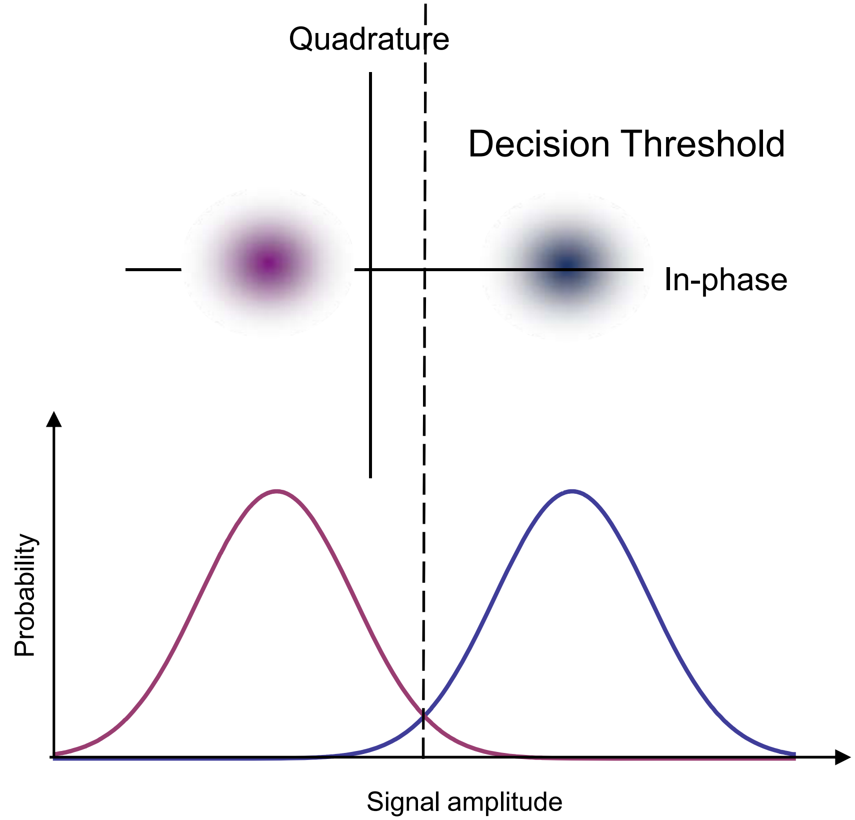
Information Spectral Density of ideal memory-less AWGN channel



Calculation of required SNR

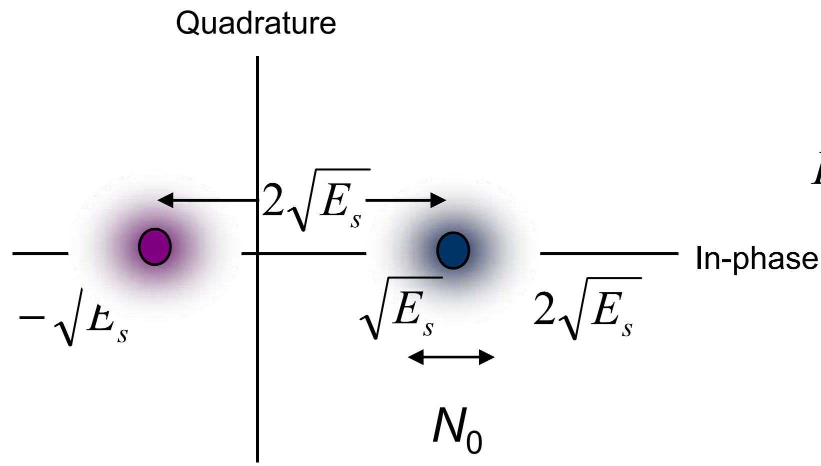
- Linear (coherent) detection
- Hard decision
- Assume memory-less AWGN channel
- Signal-independent noise
  - Thermal noise, local oscillator shot noise limited system
- Calculate probability that each bit “escapes”

Calculation of required SNR 1: Bit Error Rate



$$P_e = \frac{Q\left(\frac{|e_1 - e_2|}{2}\sqrt{\frac{2}{N_0}}\right)}{2} + \frac{Q\left(\frac{|e_1 - e_2|}{2}\sqrt{\frac{2}{N_0}}\right)}{2} = Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)$$

Calculation of required SNR
1: Signal to Noise Ratio



$$P_e = Q\left(\frac{2\sqrt{E_s}}{\sqrt{2N_0}}\right)$$

$$snr = \frac{E_b}{N_0}$$

PSK or bi-polar ASK

$$E_b = \frac{E_s}{2} + \frac{E_s}{2} = E_s$$

$$P_e = Q\left(\sqrt{2 \cdot snr}\right)$$

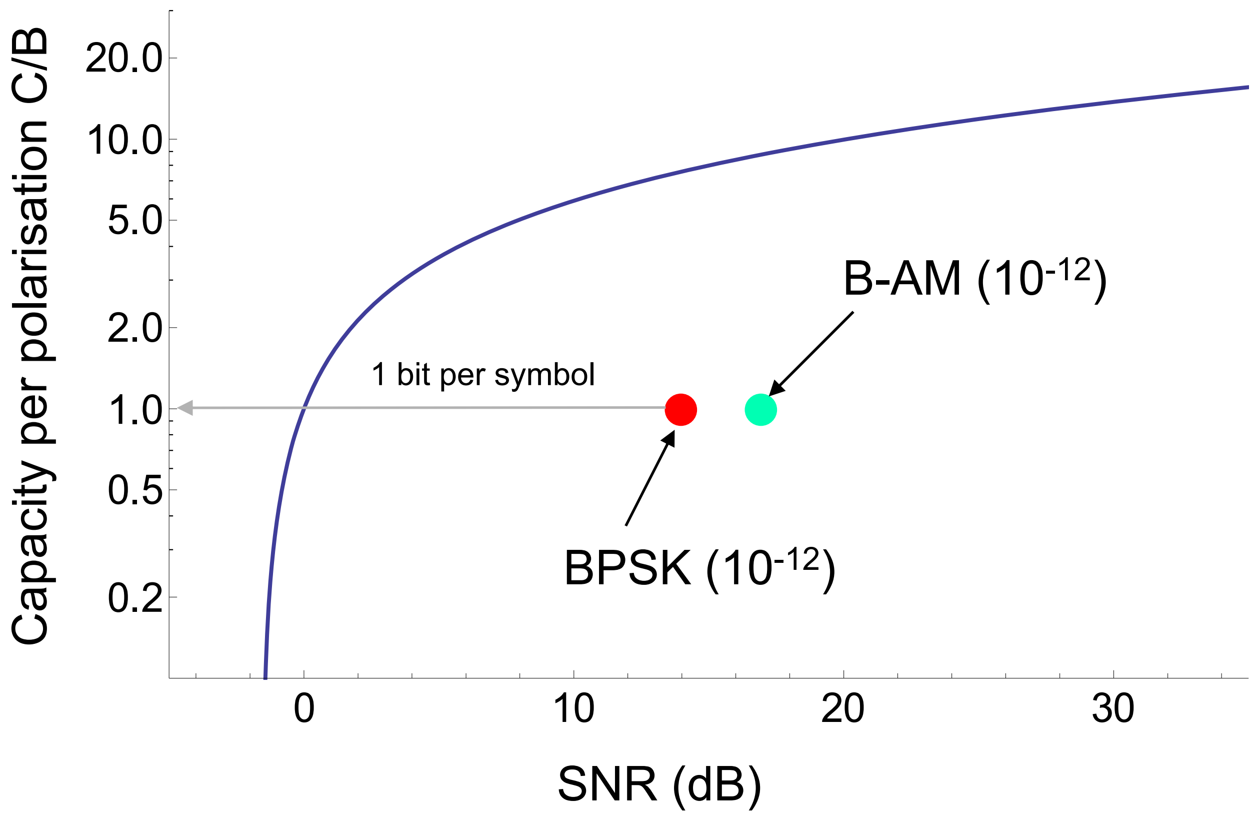
AM or uni-polar ASK

$$E_b = \frac{0}{2} + \frac{4E_s}{2} = 2E_s$$

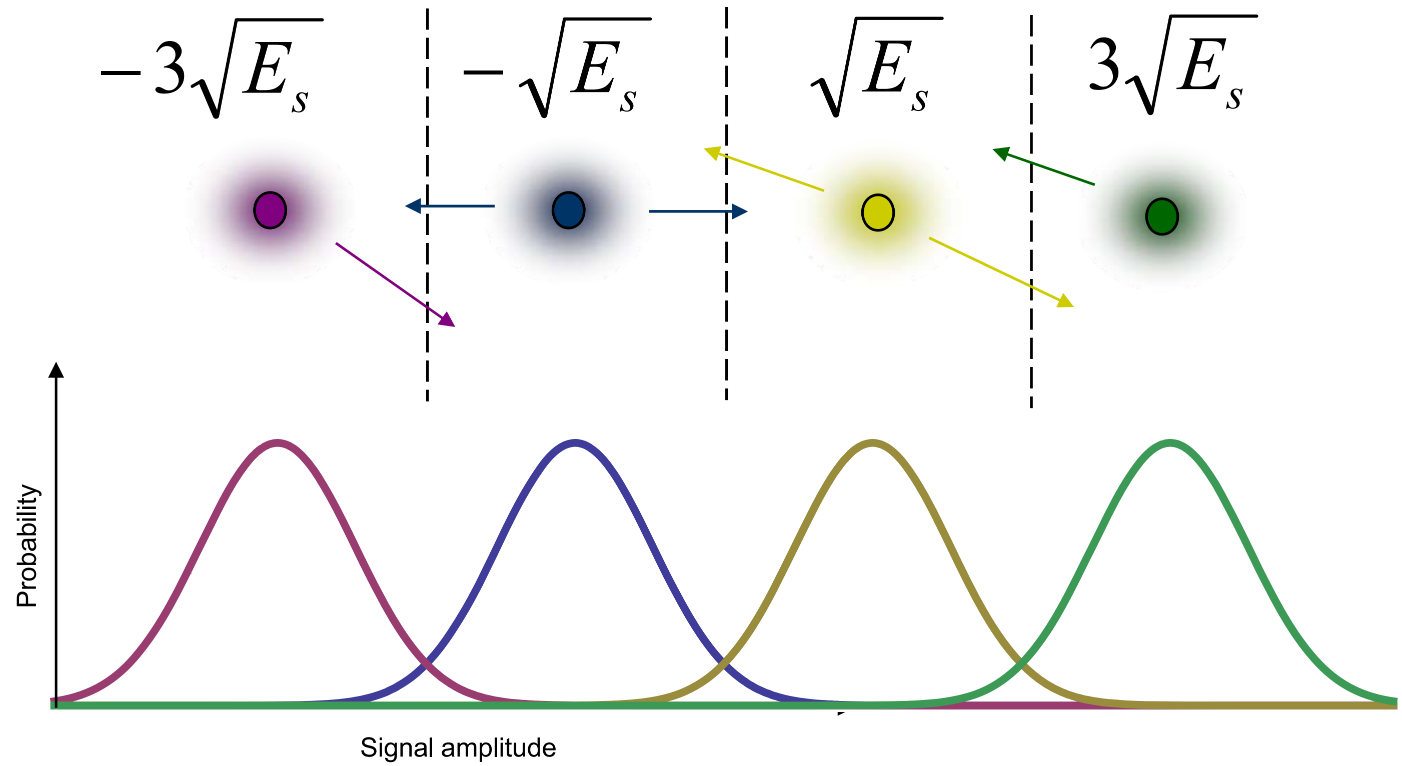
$$P_e = Q\left(\sqrt{snr}\right)$$

Information Spectral Density

Information Spectral Density of ideal memory-less AWGN channel

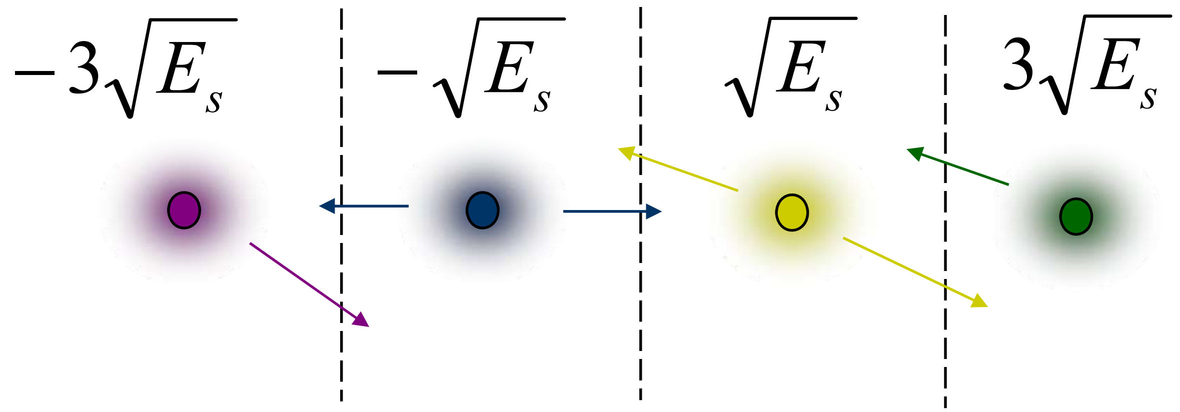


Extending to higher order modulation



$$P_e = \frac{Q\left(\frac{|e_1-e_2|}{\sqrt{2N_0}}\right)}{4} + 2\,\frac{Q\left(\frac{|e_1-e_2|}{\sqrt{2N_0}}\right)}{4} + 2\,\frac{Q\left(\frac{|e_1-e_2|}{\sqrt{2N_0}}\right)}{4} + \frac{Q\left(\frac{|e_1-e_2|}{\sqrt{2N_0}}\right)}{4} = \frac{3}{2}\,Q\left(\frac{|e_1-e_2|}{\sqrt{2N_0}}\right)$$

Extending to higher order modulation

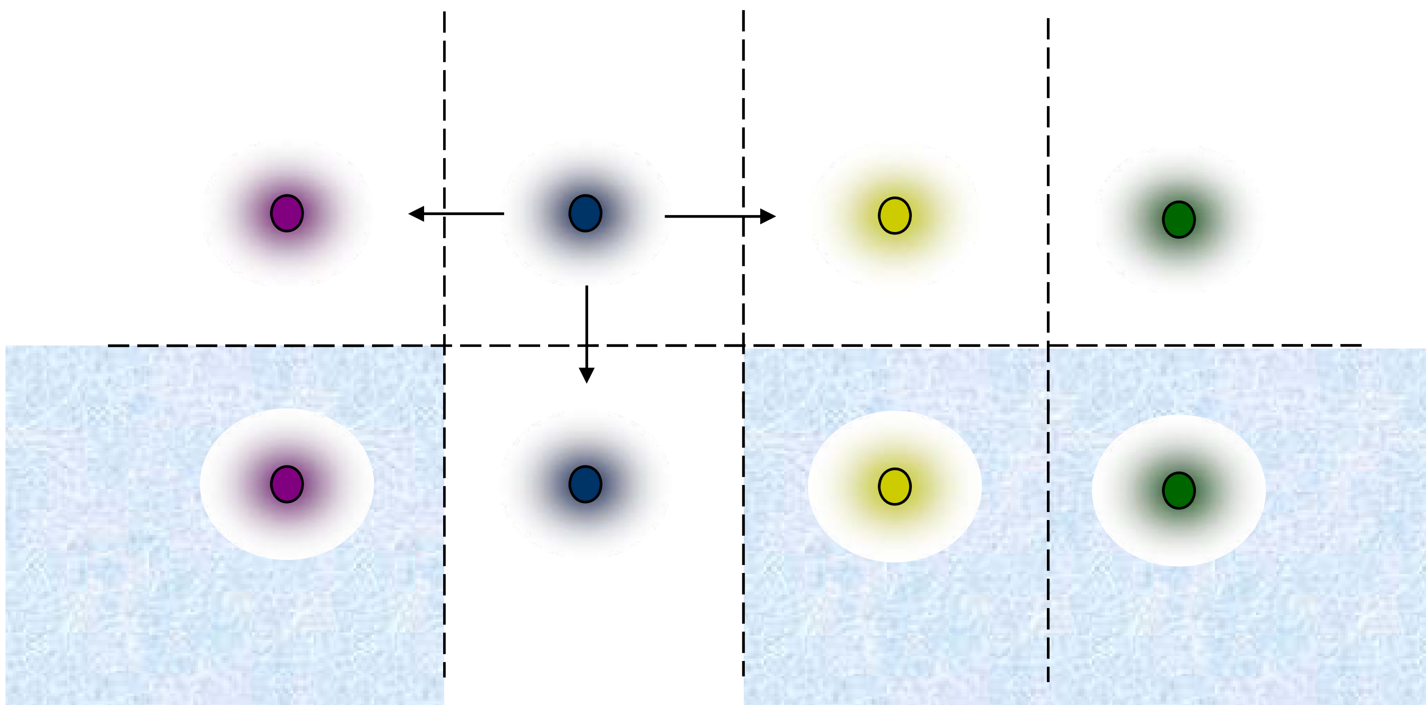


Probability

$$E_b = \frac{9}{4}E_s + \frac{1}{4}E_s + \frac{1}{4}E_s + \frac{9}{4}E_s = 5E_s$$

$$P_e = \frac{Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)}{4} + 2\,\frac{Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)}{4} + 2\,\frac{Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)}{4} + \frac{Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)}{4} = \frac{3}{2}Q\left(\frac{|e_1 - e_2|}{\sqrt{2N_0}}\right)$$

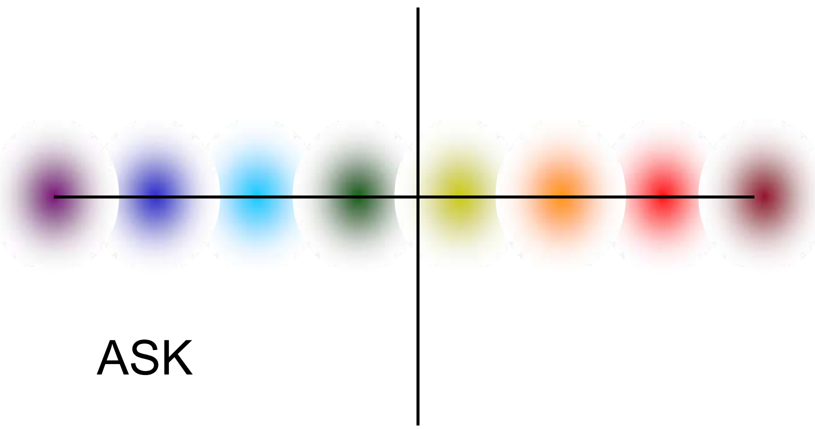
Extending to higher order modulation

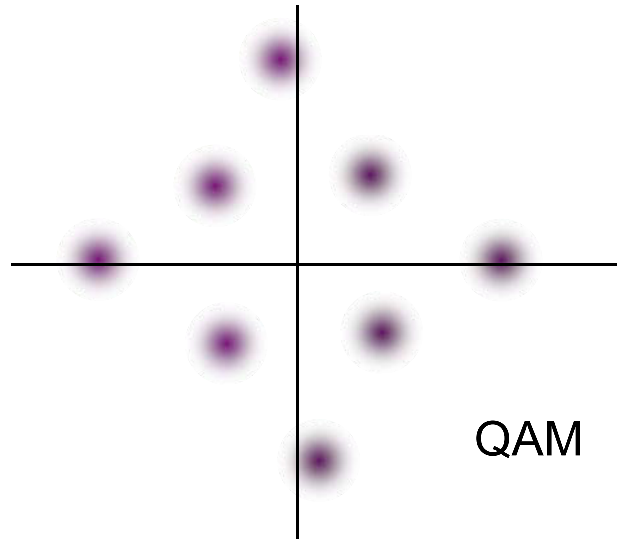


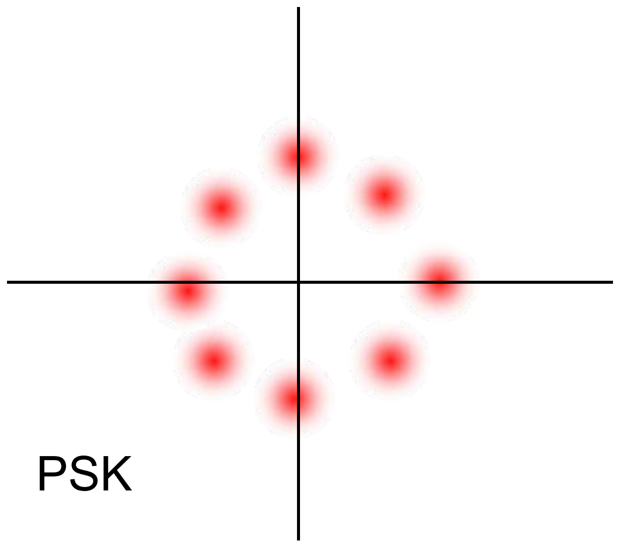
Calculating modulation scheme performance

1. Calculate minimum distance (e_1-e_2, $2\sqrt{E_s}$)
2. Determine symbol noise level (N_o)
3. Calculate BER using symbol probability and effective number of boundaries
4. Calculate energy per bit E_b as a function of E_s
5. Substitute E_b for E_s and snr for E_b/N_0 to give BER as a function of snr
6. Calculate ISD from number of levels and symbol probability

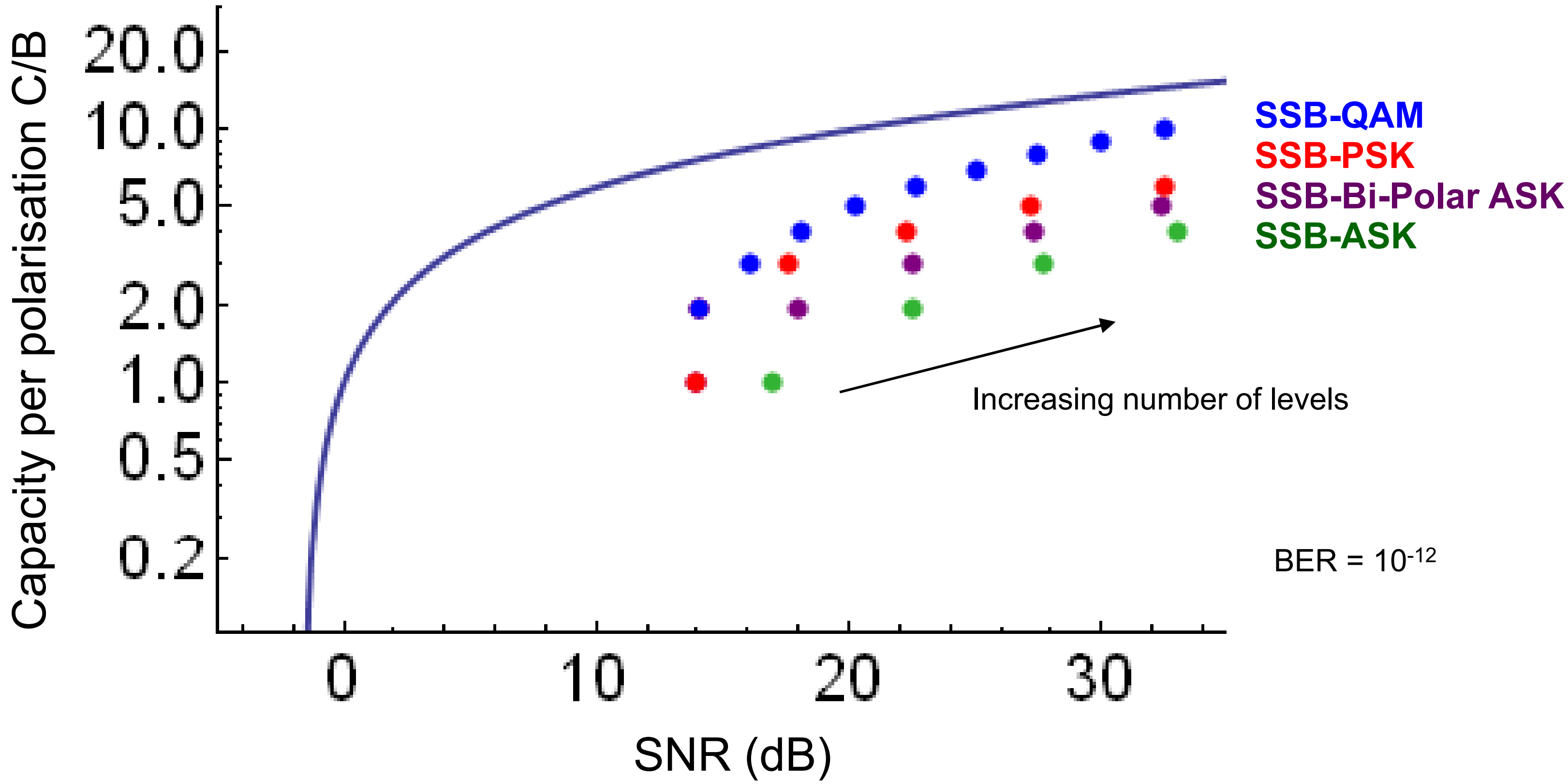
Signal Constellations





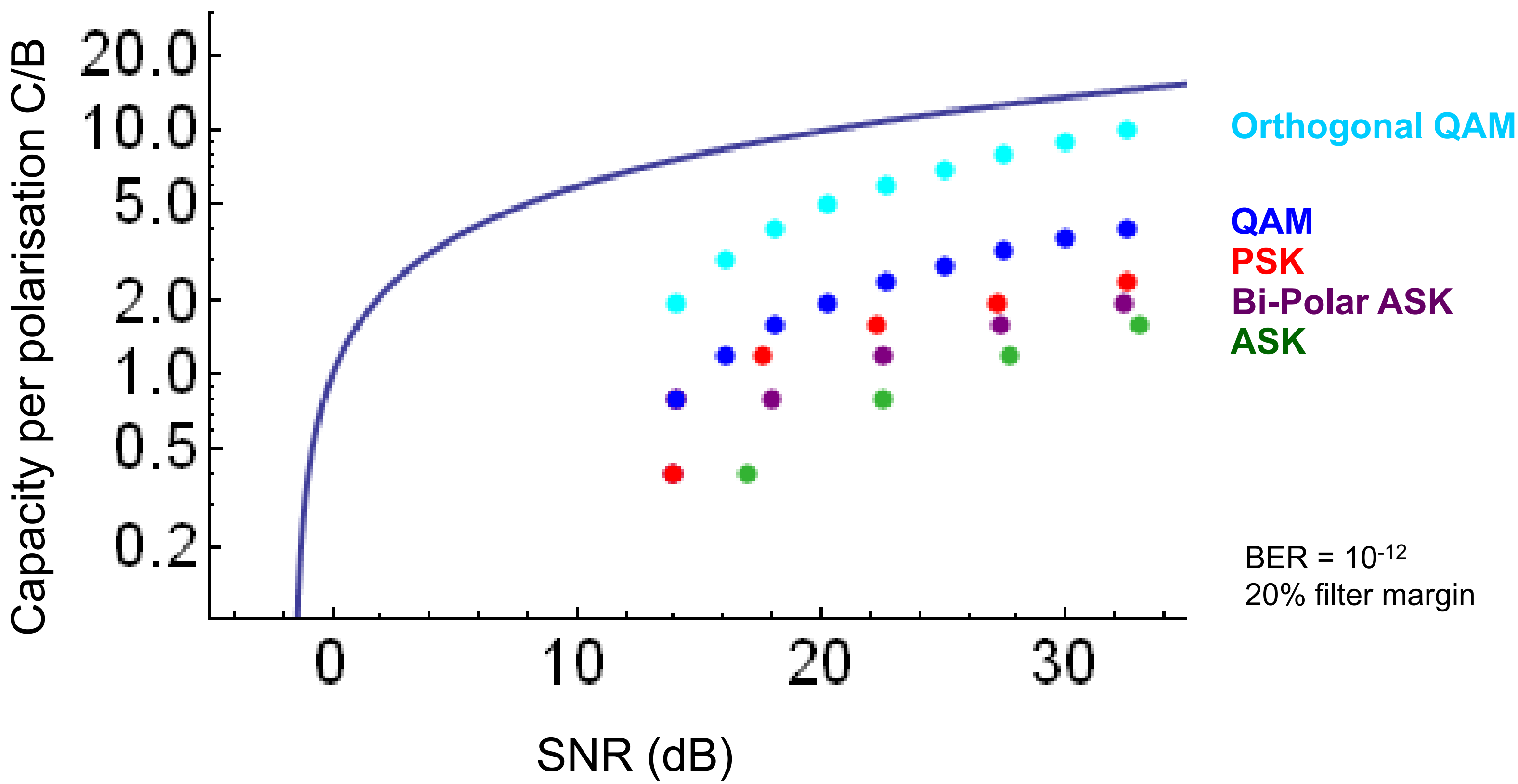


Information Spectral Density of common multi-level modulation formats



Impact of Optical Demultiplexing and Practical Optical Modulation

20% Guard Band for Filtering
Double Side Band Modulation for ASK and PSK



Fundamental limits[1]

- Unconstrained modulation (amplitude + phase) with direct detection

$$\frac{C}{B} \cong \log_2(1 + snr)$$

- Phase modulation with coherent detection

$$\frac{C}{B} \cong \frac{1}{2}\log_2(snr) + 1.1$$

- Unconstrained modulation (amplitude + phase) with coherent detection

$$\frac{C}{B} \cong \frac{1}{2}\log_2(snr) - 1.0$$

1: J.M.Kahn, K-P.Ho, JQE **10** 2 pp259 (2004)

Fundamental Limits[2]

Definition

$$Q(x) \equiv \frac{1}{2} Erfc\left(\frac{x}{\sqrt{2}}\right)$$

Bi-polar ASK

$$P_e = 2\frac{m-1}{m} Q\left(\sqrt{\frac{6.\log_2(m)}{m^2-1} snr}\right)$$

Uni-polar ASK

$$P_e = 2\frac{m-1}{m} Q\left(\sqrt{\frac{6\log_2(m)}{m^2-1} snr.p_r(m)}\right), p_r(m) = \frac{\sum_{i=1}^{m/2} (2.i-1)^2}{2\sum_{i=1}^{m} (i-1)^2}$$

PSK (low BER)

$$P_e \approx \begin{cases} Q\left(\sqrt{2snr}\right) & m = 2 \\ Q\left(\sqrt{2snr}\right)\left\{1 - \frac{1}{2} Q\left(\sqrt{2snr}\right)\right\} & m = 4 \\ \frac{2}{\log_2(m)} Q\left(\sqrt{2snr.\log_2(m)} Sin\left(\frac{\pi}{m}\right)\right) & otherwise \end{cases}$$

1: J.G.Proakis, Digital Communications (4th Edition) McGraw-Hill (2000)

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12. J.M.Kahn, K-P.Ho, JQE **10** 2 pp259- (2004)
13. K.P.Ho, PTL, **17** pp858- (2005)
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15. E.Ip et.al., Optics Express, **16** 2 pp753- (2008)

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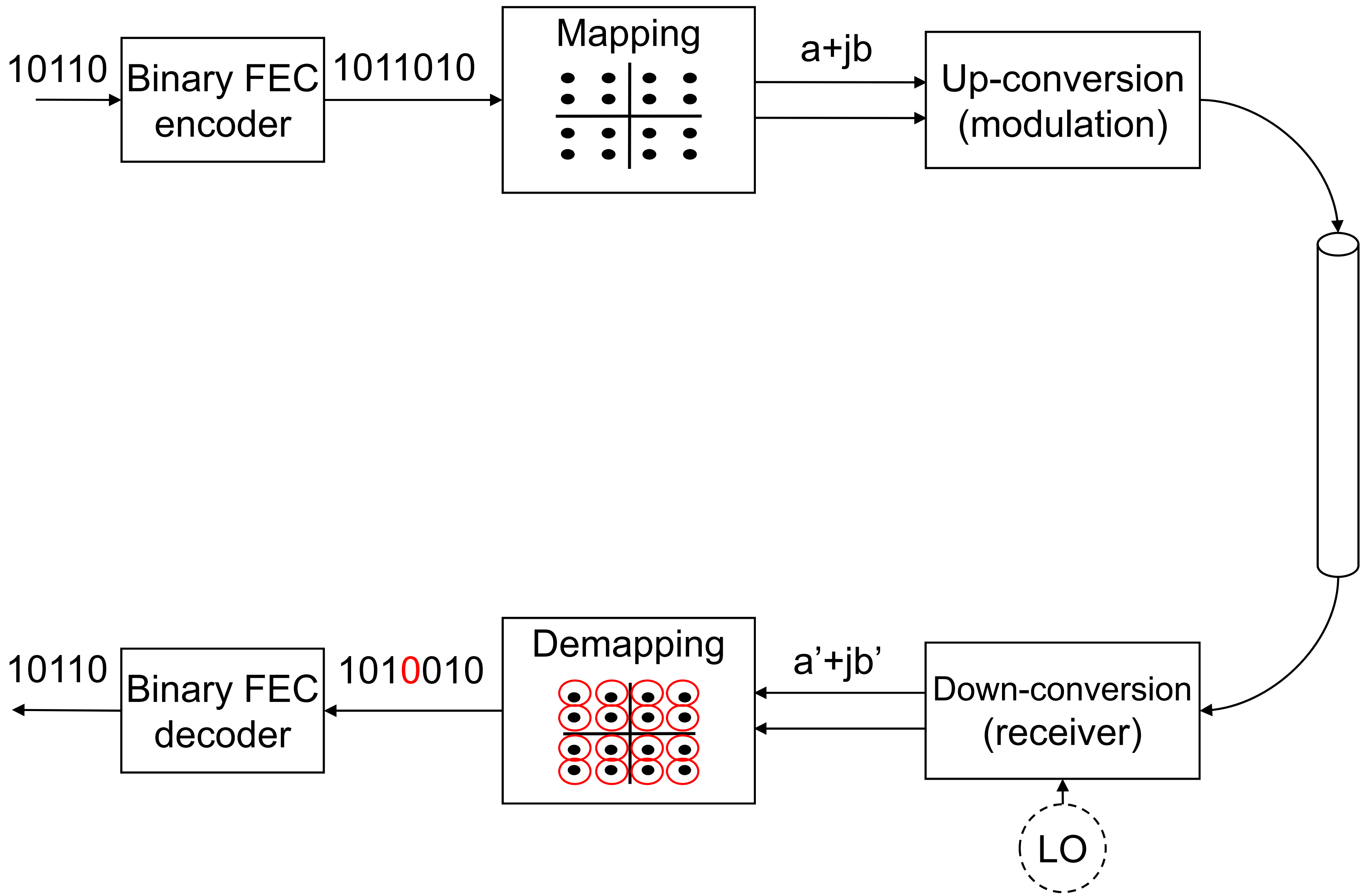
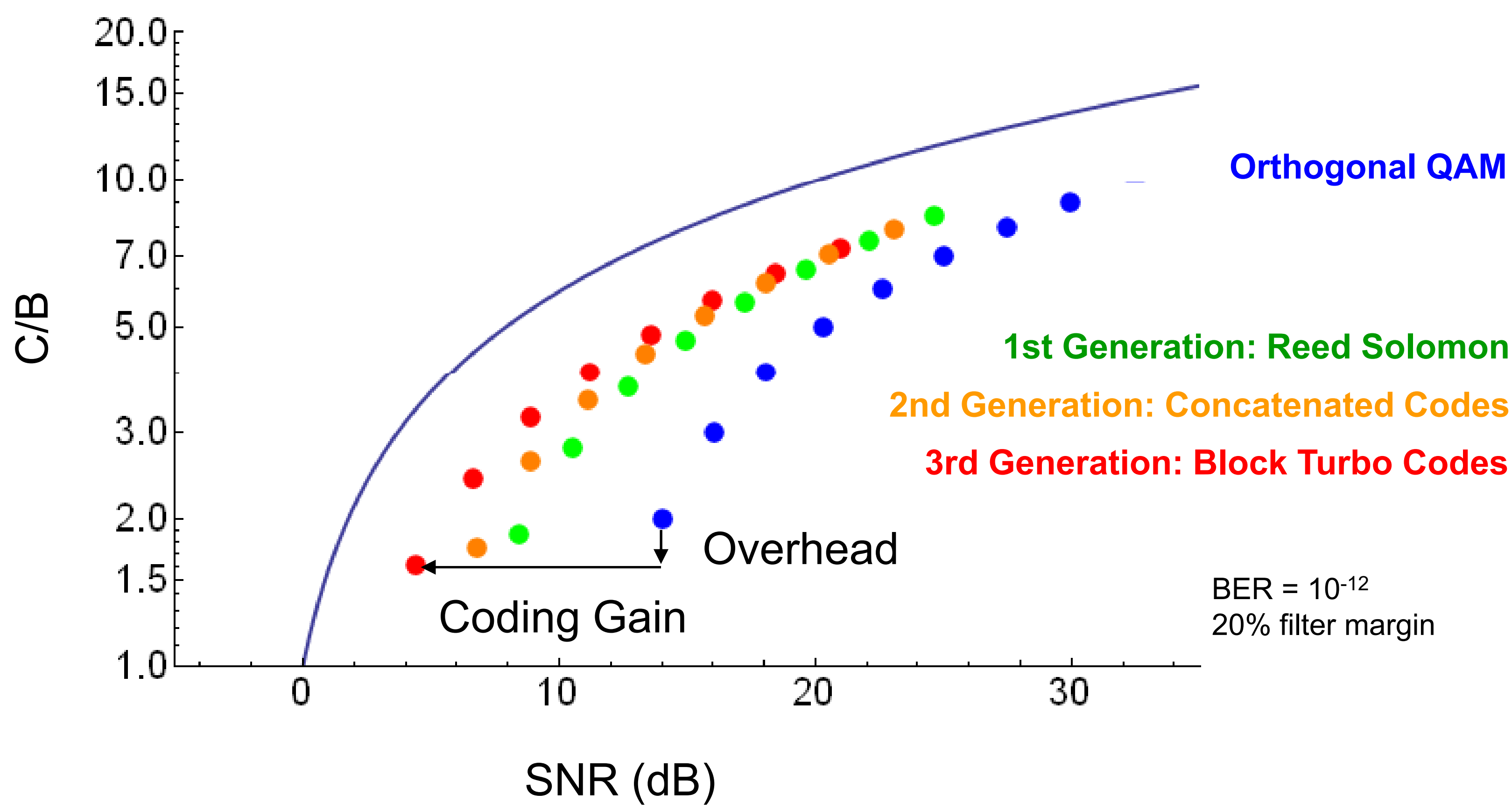
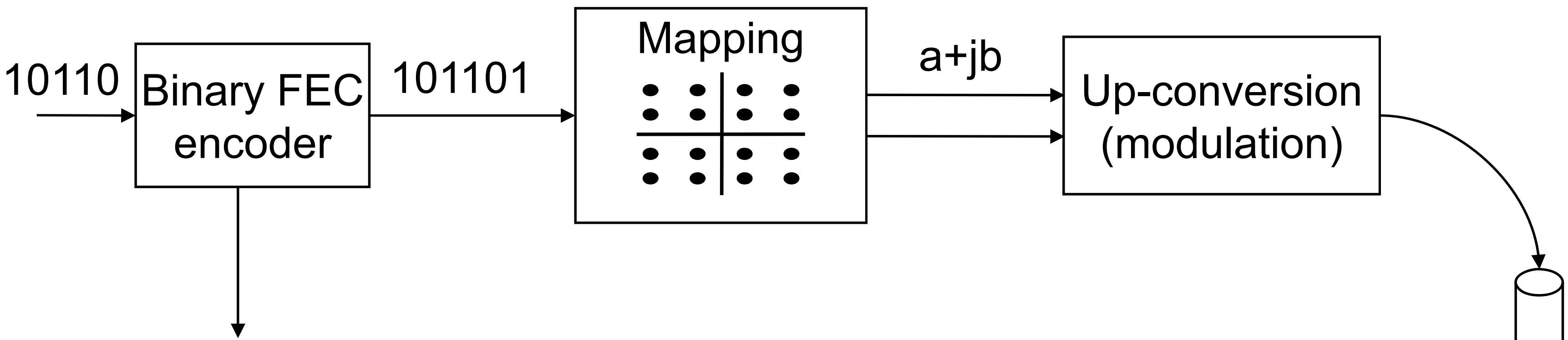
Error Correction Codes
Current Status



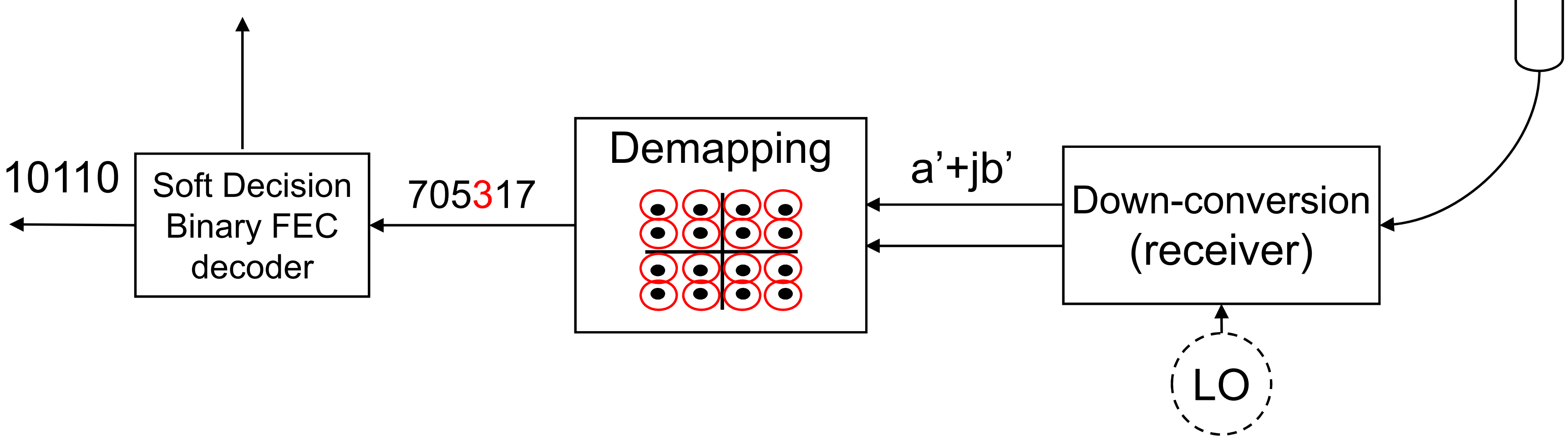
Forward Error Correction



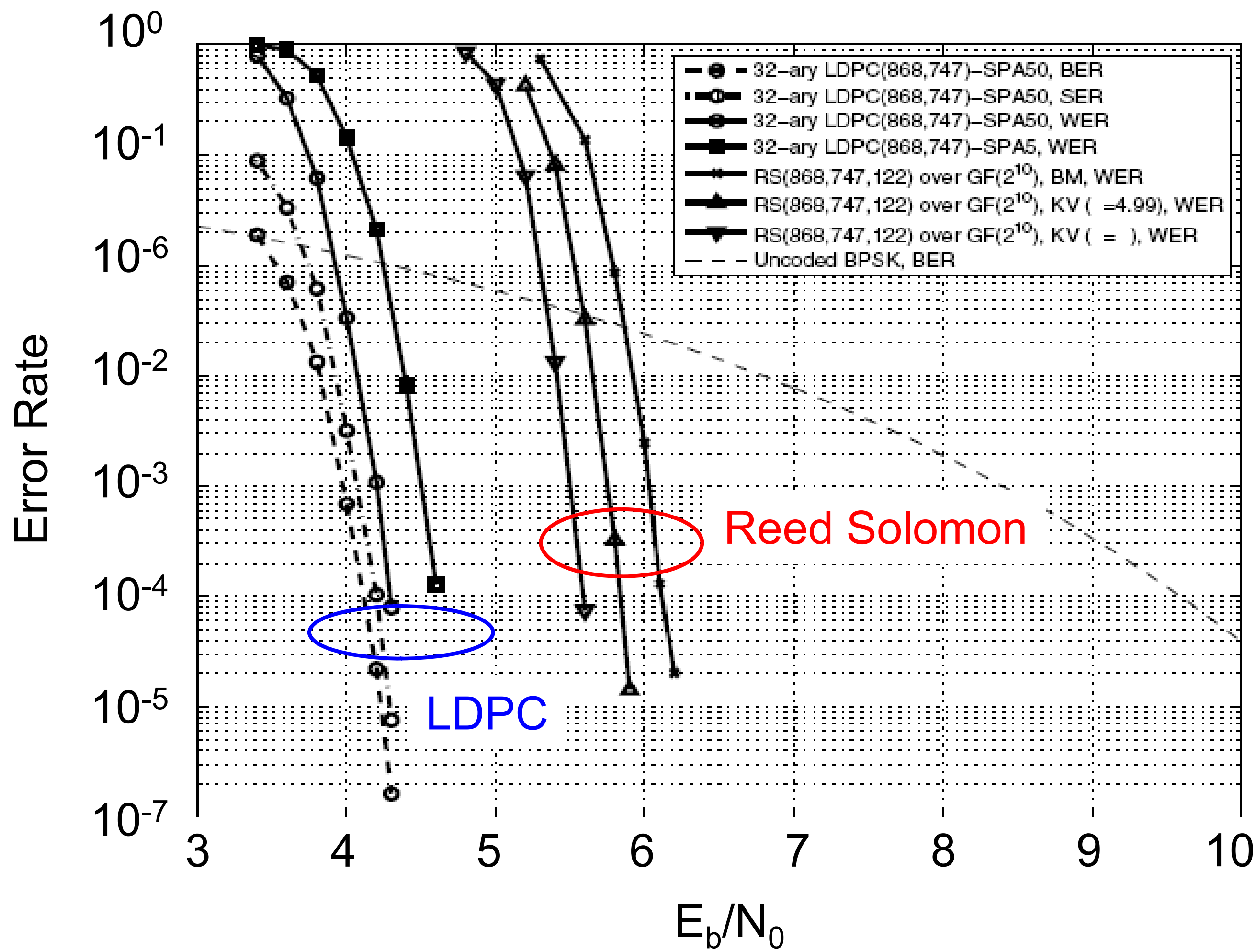
Error Correction Codes
Soft decision decoding



- Eg Low Density Parity Check (LDPC) Codes
  - Within 0.005 of Shannon limit (100% overhead)

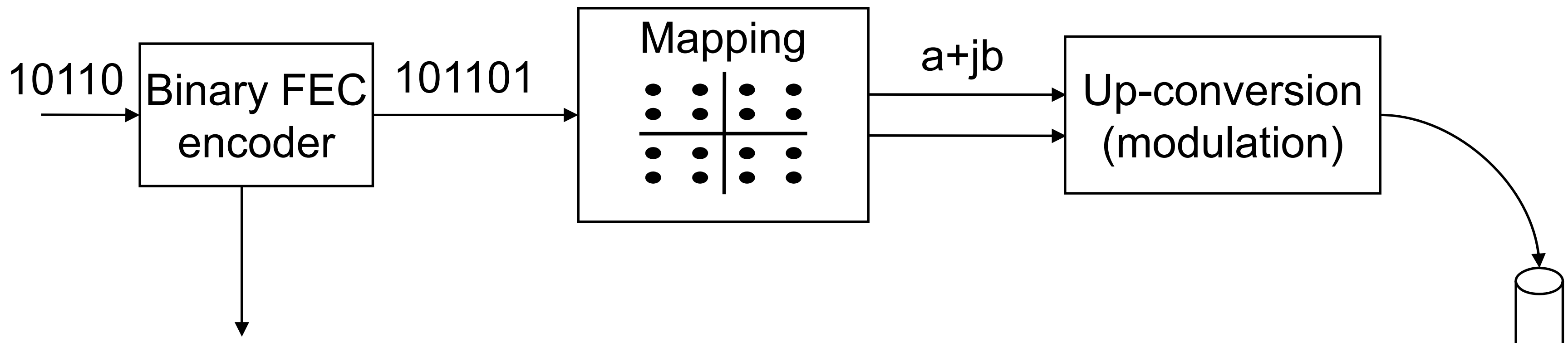


Performance of RS & LDPC codes[1]

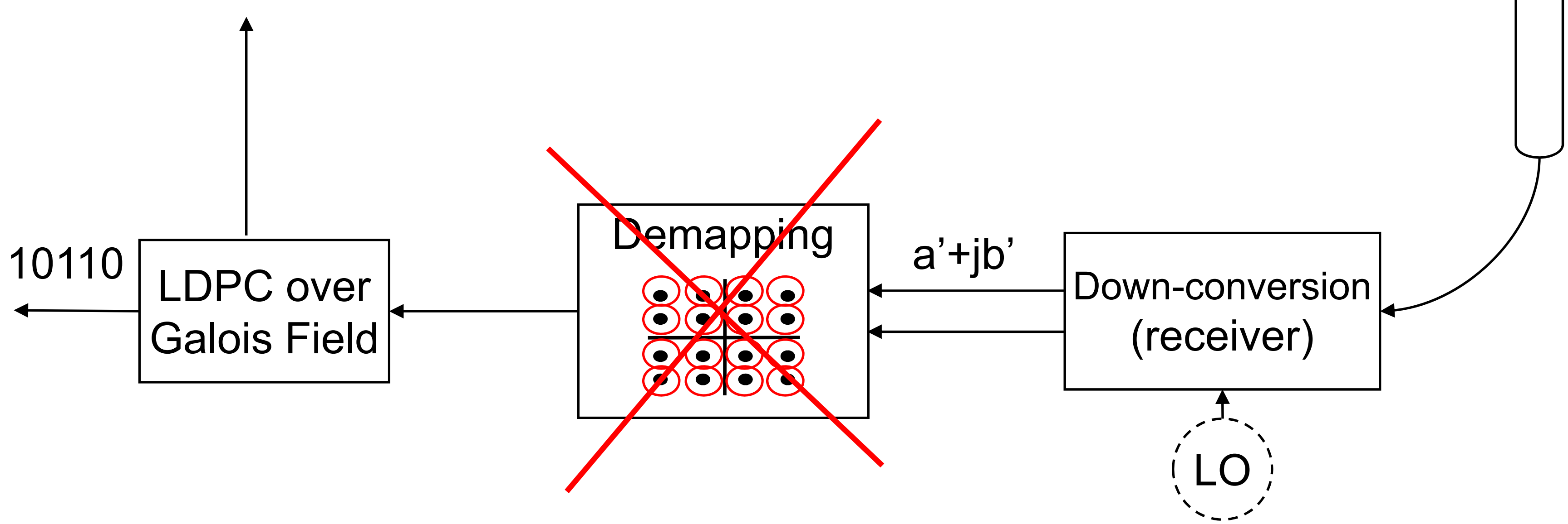


1: B.Zhou, et.al., Information theory and Applications Workshop, 2008

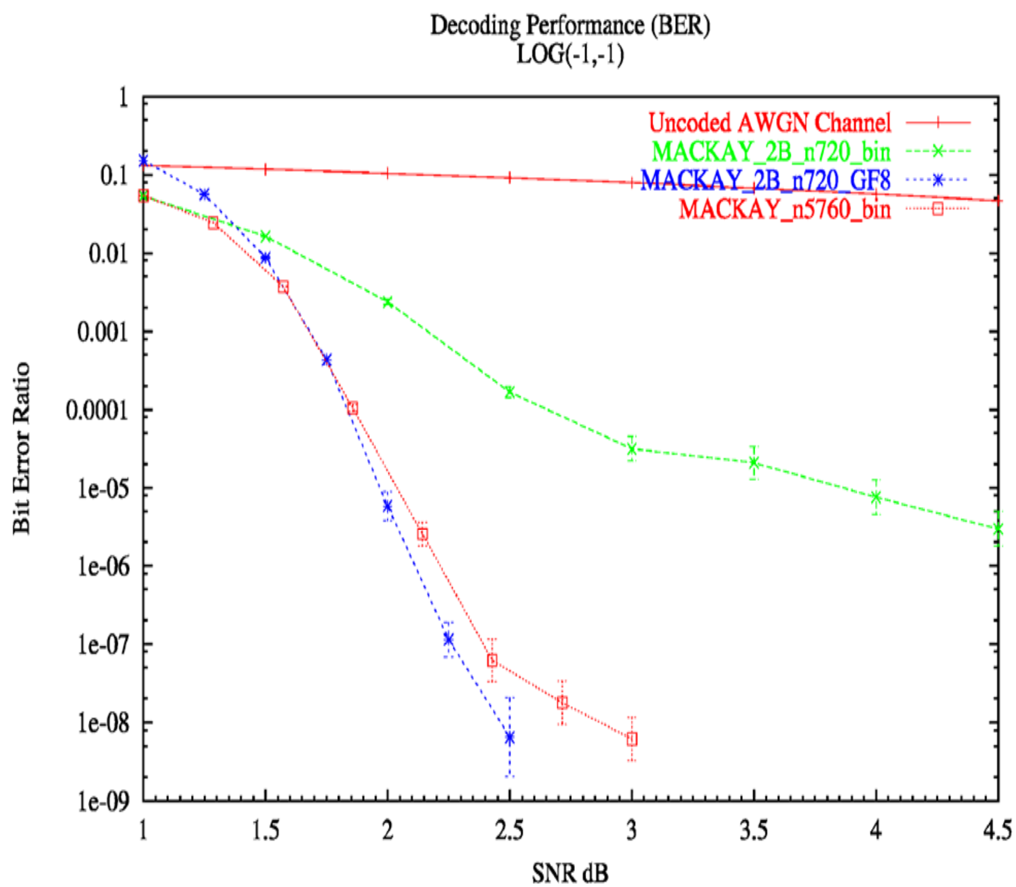
Error Correction Codes
Current Status



- Multi-level (c.f. binary) coded LDPC
- Additional refinements for soft decision based systems



Short LDPC codes over GF(q)[1]



- LDPC over GF(q) easily outperform same length binary codes (length n=720)
- Moreover they perform as well as much longer binary codes (n=5760)

1: C.Spagnol Ph.D. Thesis: Aspects of LDPC codes for hardware implementation

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Signal to Noise Ratio in Optical Systems[1]

- Capacity limits expressed in terms of $SNR = E_b/N_0$
- Convert to optical signal to noise ratio $OSNR = P_s/P_n$

$$OSNR = \frac{E_b}{N_0}\frac{R.\lambda^2}{2.\Delta\lambda.c} \qquad SNR_{dB} = OSNR_{dB} + 4_{dB}\Big|_{10.6Gbit/s,1550nm,0.1nm}$$

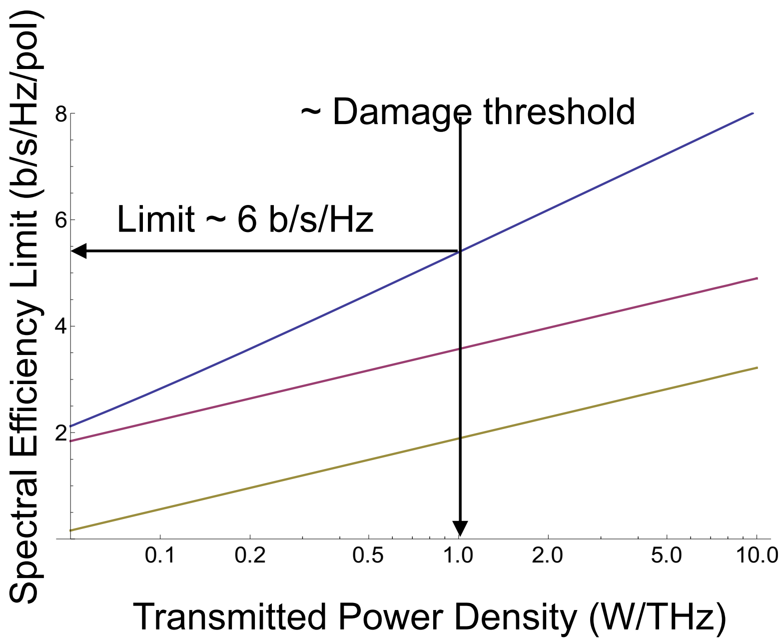
- Noise accumulation well known

$$P_{N/polarisation} = N_{amps}.(G-1).n_{sp}.h.\nu.\Delta\nu$$

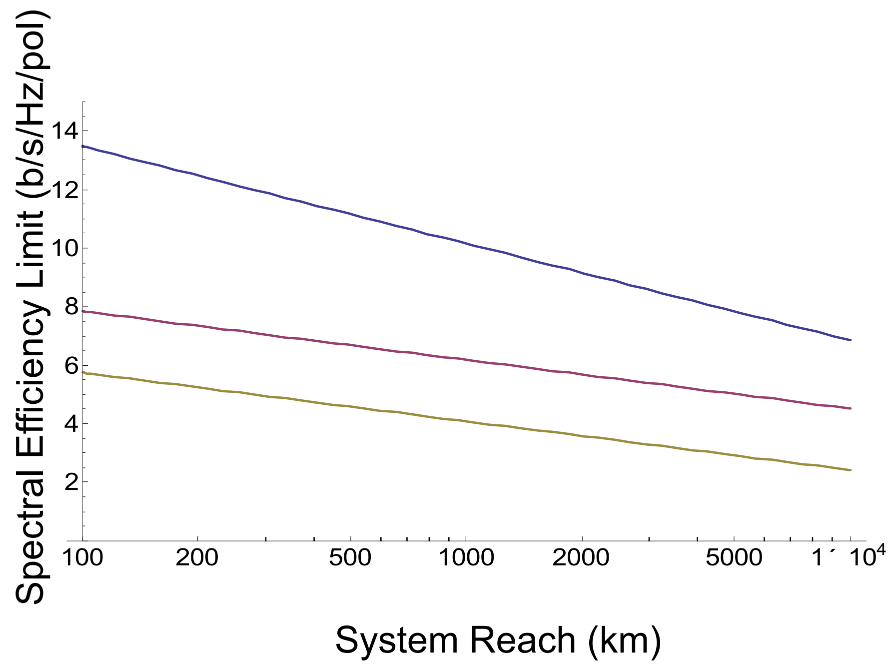
Add input insertion loss to gain

1: J.M.Kahn, K-P Ho, JQE **10** 2, pp259 (2004)

Capacity limit for a 2,000km optical system



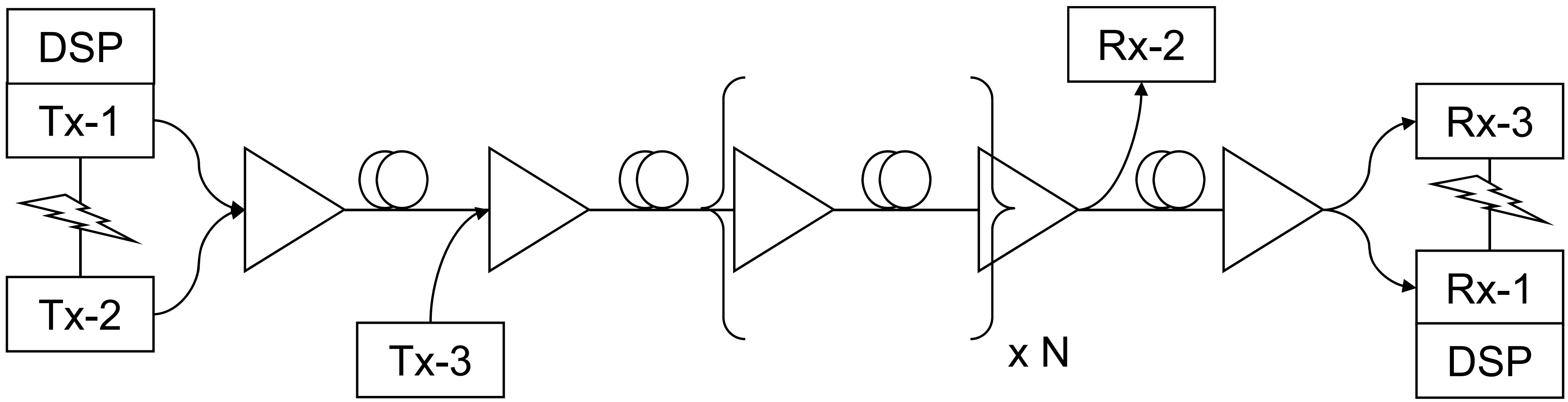
2000km, 80km spacing, 4.5dB noise figure, 20% guard bands, 50GHz channel spacing



80km spacing, 4.5dB noise figure, 1dB input loss, 500mW over C band, 50GHz channel spacing

But optical communication links are characterised by a *distributed* nonlinear response

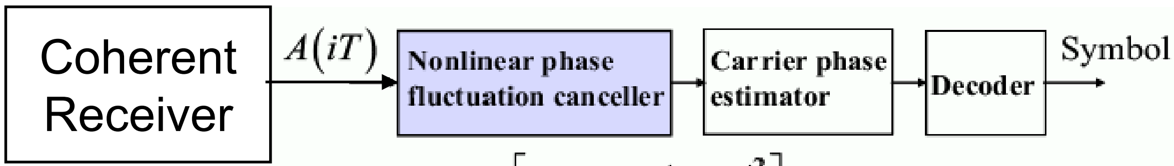
Origin of fundamental capacity limit for optical fibres[1,2,3]



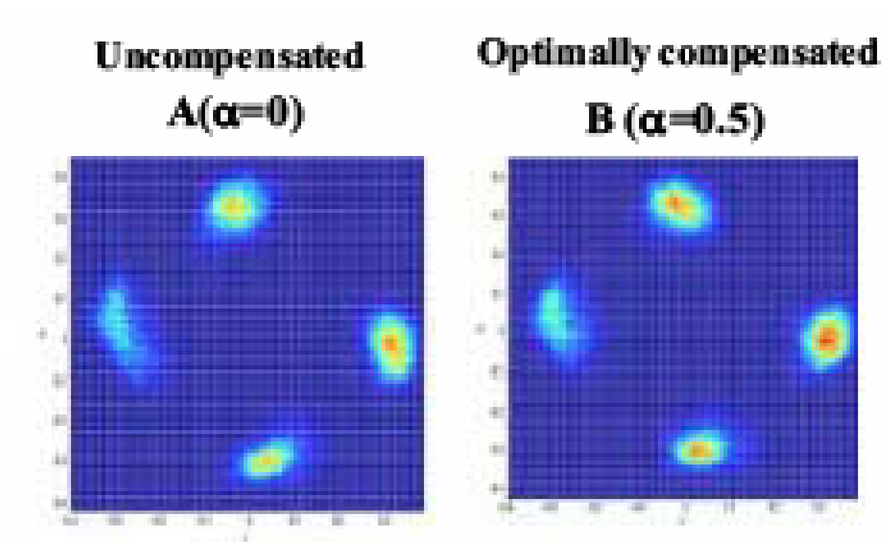
- Per channel DSP
  - Dispersion (Chromatic + Polarisation)
  - Coherent Detection
  - Self Phase Modulation Correction[3]
    - But not non-linear mixing between signal & ASE (early dispersion maps)
- Multiple transmitters
  - Don’t actually communicate
  - Are not always co-located
- Inter channel nonlinearity gives the fundamental limit

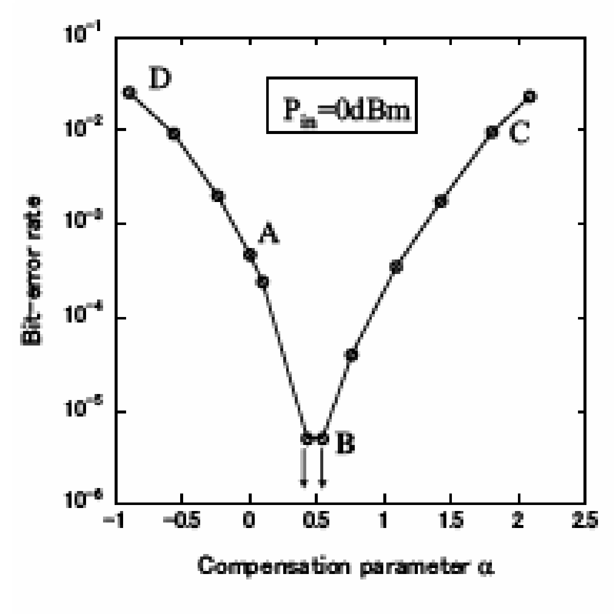
1: P.P.Mitra, J.B.Stark, Nature, **411**, pp1027, (2001)
2: L.G.L.Wegener et.al., Physica D, **189**, pp81, (2004)
3: R-J, Essiambre et.al., ECOC 2008, We1E1(2008)

Example of simple receiver based nonlinearity compensation.



$$A_c(iT) = A(iT)\exp\left[j\alpha m(\gamma\ell)_{eff} \left|A(iT)\right|^2 \right]$$

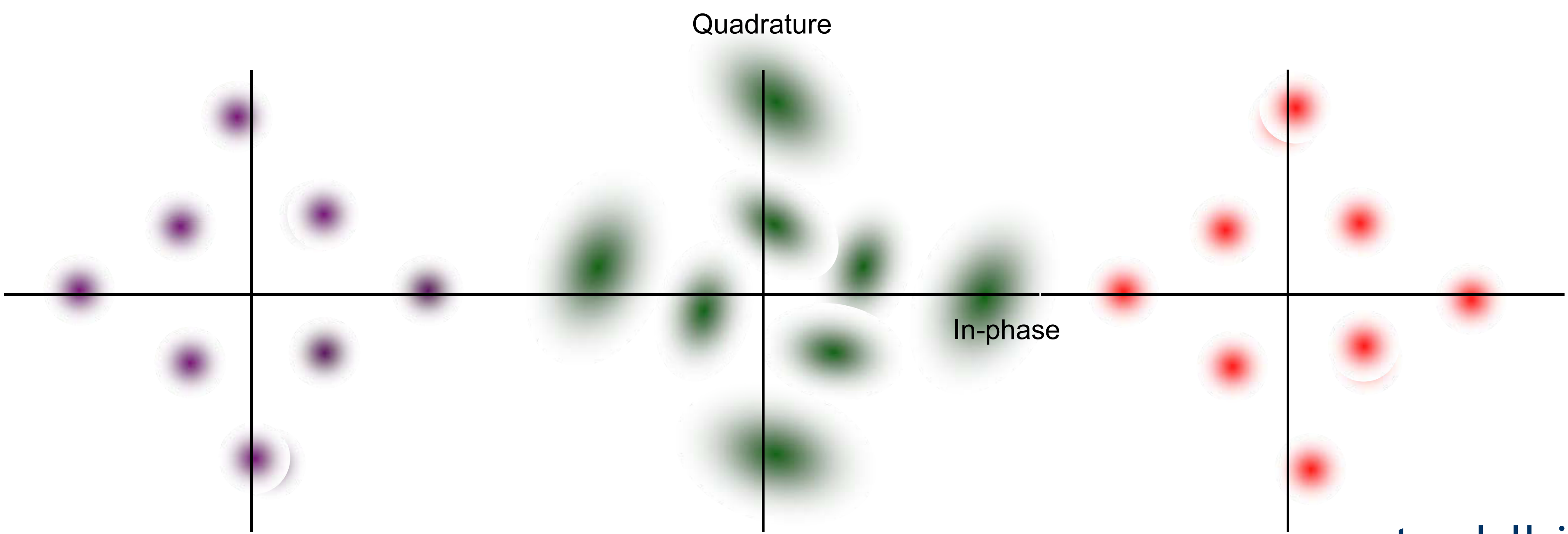




K.Kikuchi, Optics Express, **16** 2 pp889- (2008)

Cross phase modulation

- Signal processing to mitigate SPM
- Dispersion management to reduce signal –ASE interaction
- All other channels act as noise sources to wavelength of interest
- Appropriate Dispersion Map
  - High local dispersion to degrade phase matching
  - Dispersion management to control PAP
  - Sufficient residual dispersion per span
  - Dispersion map is key



Impact of cross phase modulation

- Random walk process
  - Sub-linear accumulation with number of amplifiers
- Depends on dispersion map
- Proportional to fibre non-linearity and effective length

$$I_{XPM} = \sqrt{\frac{B.D.\Delta\lambda}{2.\gamma^2 \ln\left(\frac{N_a}{2}\right) L_{eff}}}$$

- Adds noise to the signal

$$P_N \Rightarrow P_N + P_{XPM} = P_N + \left(1 - e^{-\frac{P_S}{I_{XPM}}}\right) P_s$$

- Leaches power from the signal

$$P_S \Rightarrow P_s e^{-\frac{P_S}{I_{XPM}}}$$

1: P.P.Mitra, J.B.Stark, Nature, **411**, pp1027, (2001)

Four Wave Mixing[1]

- Similar treatment to XPM
- Is dominant for PSK with certain dispersion maps (constant intensity)

$$I_{XPM} = \sqrt{\frac{B.D.\Delta\lambda}{2.\gamma^2 \ln\left(\frac{N_a}{2}\right) L_{eff}}}$$

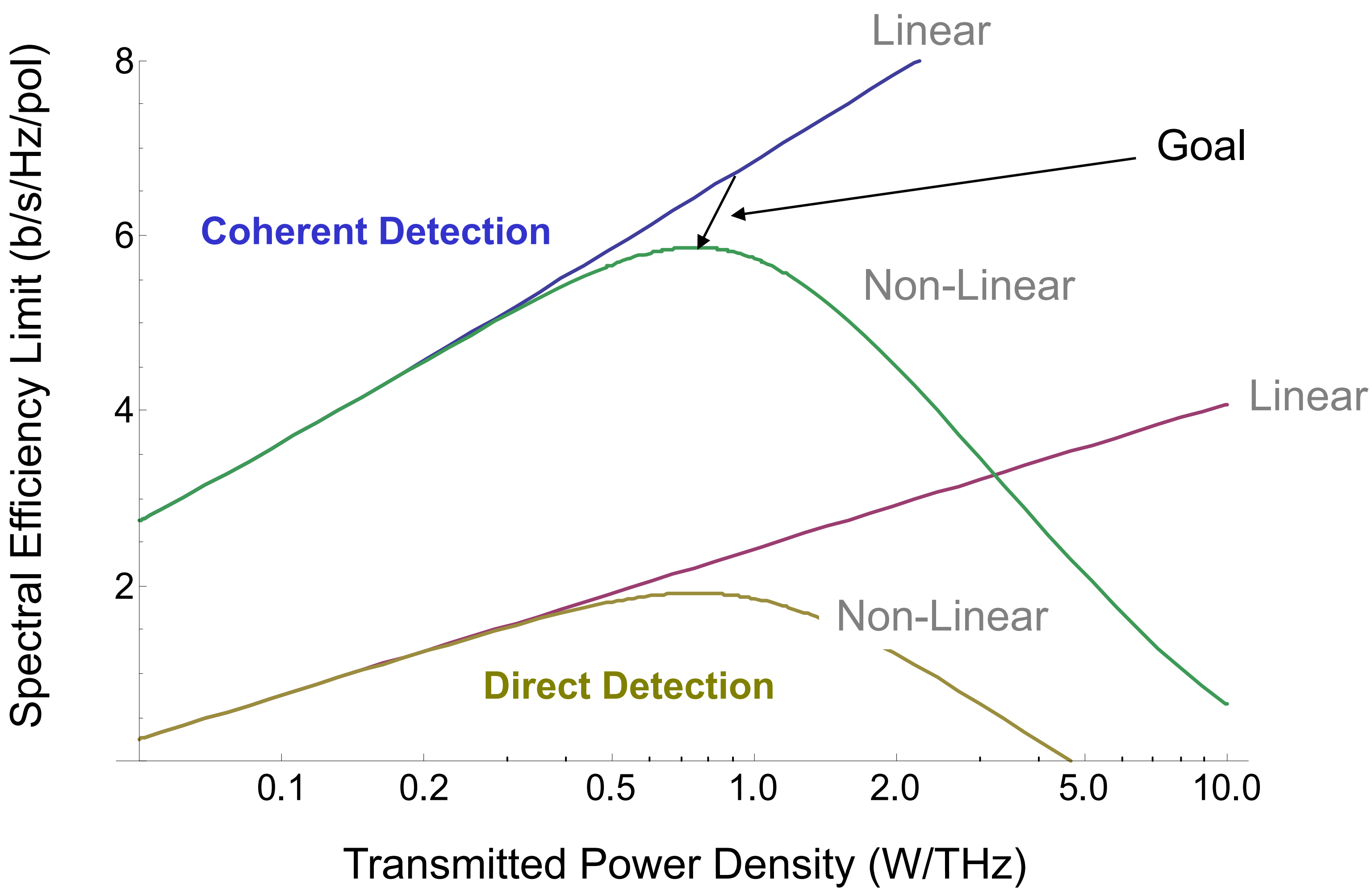
$$\frac{1}{I_{FWM}} = N_A \sum_{p,q\neq 0}^{|p+q|<\frac{n_c-1}{2}} \frac{\gamma^2 D_{pq}^2}{\alpha^2 + \left(2\pi\lambda^2 D\Delta f^2 q.p/c\right)^2}$$

$$D_{pq} = \begin{matrix} 1, p = q \\ 2, p \neq q \end{matrix}$$

- XPM typically dominates and is considered hereafter.

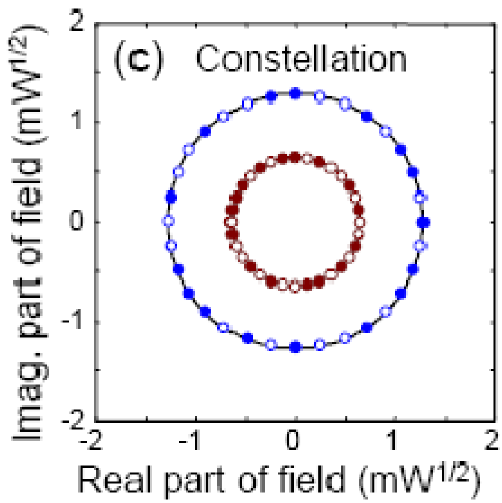
1: J.M.Kahn, K-P Ho, JQE **10** 2, pp259 (2004)

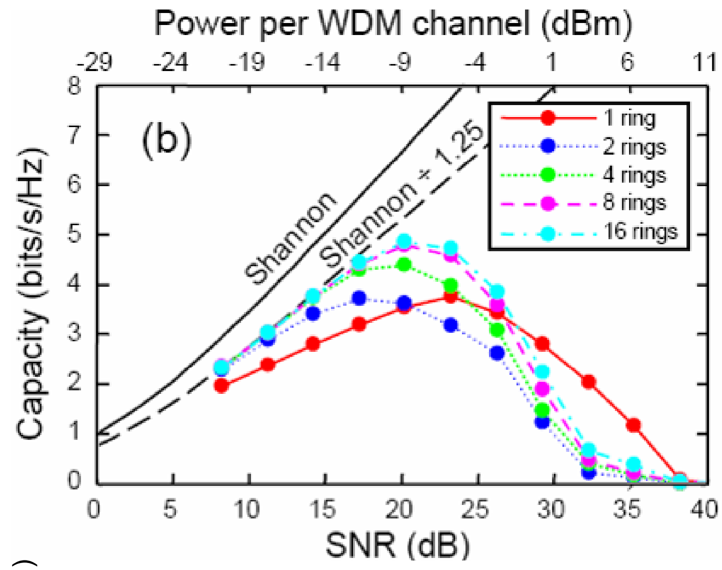
Capacity limit with non-linear transmission

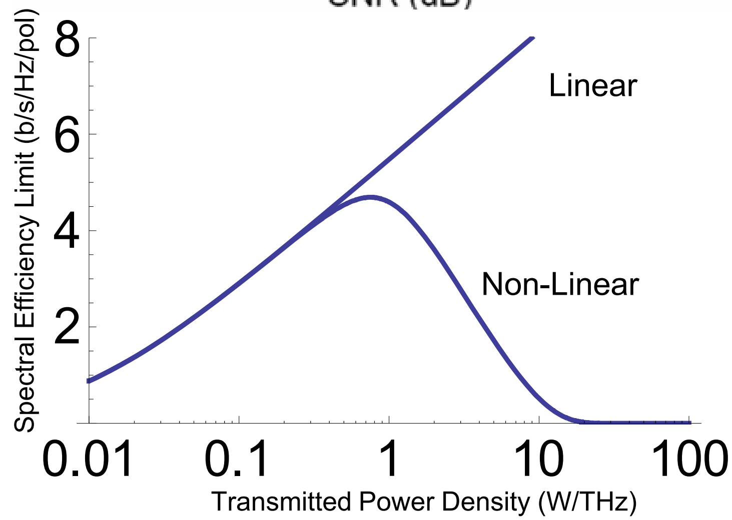


2000km, 80km spacing, 4.5dB noise figure, 50 GHz channels at 50 baud

Numerical simulations







R-J Essiambre et.al., OFC2008 paper OTuE1 (2008)

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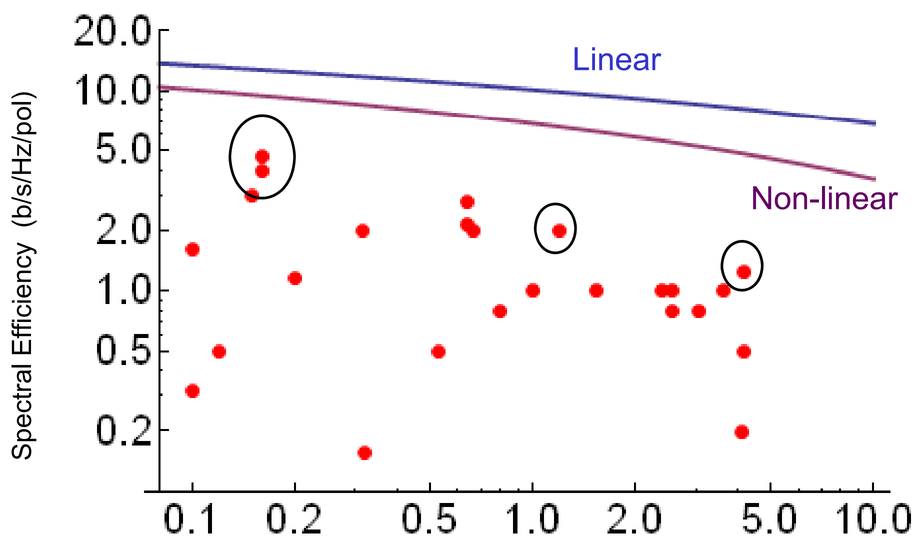
Introduction

- Trends in optical communication
- Shannon limit
  - Generic communication theory
  - Forward Error Correction Codes
- Optical Systems
  - Capacity limit for non-linear systems
  - Multi-level modulation formats
  - Breaking the current limit

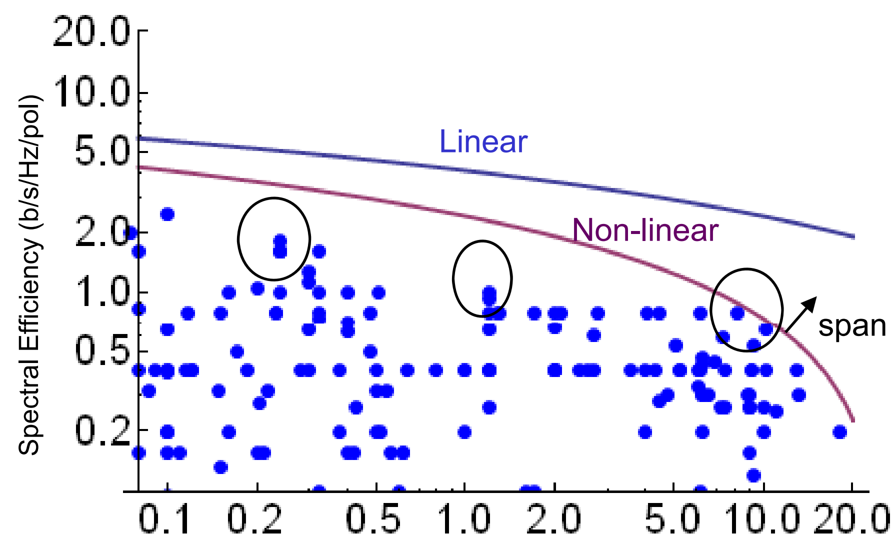
Progress towards the capacity limit

Coherent Detection



Transmission distance (Mm)

Direct Detection



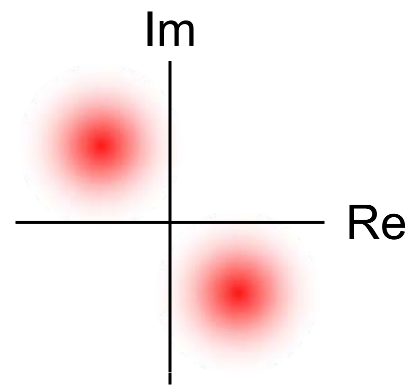
Transmission distance (Mm)

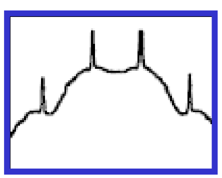
Solid lines calculated for; 80km spacing, 4.5dB noise figure, 50 GHz channels at 50 Gbaud, Optimum power
Dots plotted for notable experimental results, **per polarisation**

Direct Detection 1: Filtered CS-RZ DPSK[2]

8,000km 0.8 b/s/Hz

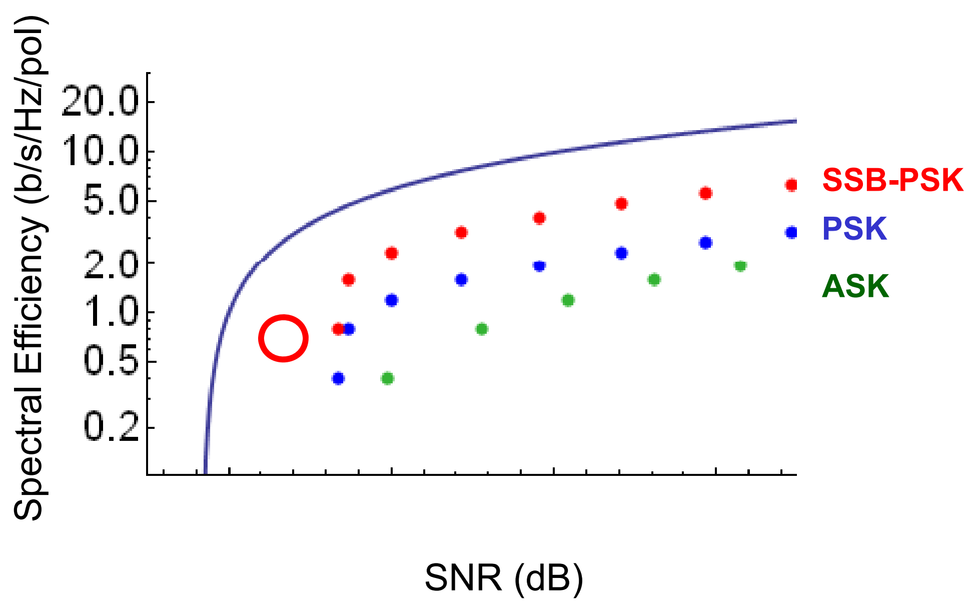
- Long Haul Transmission (mitigate non-linearity)
  - RZ format
  - dispersion management
- For spectral efficiency
  - DPSK for sensitivity benefit
  - Pre-filtering for SSB
  - FEC





(a)

Fig. 2 Optical spectra of (a)standard, (b)symmetrically filtered and (c)asymmetrically filtered CS-RZ signals

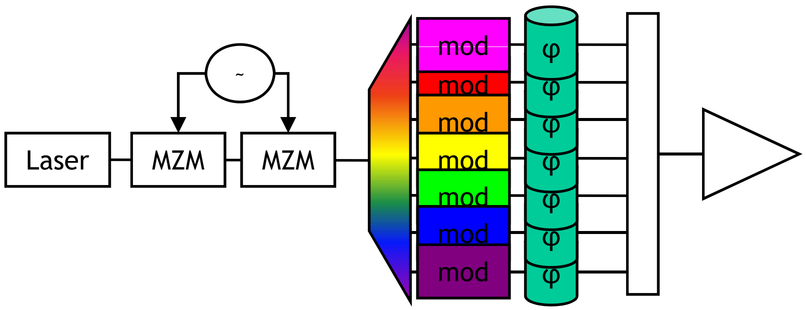


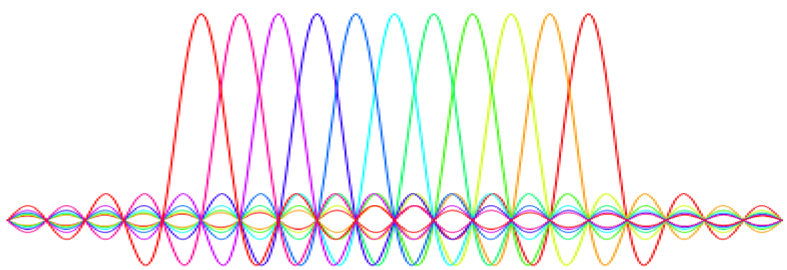
1: I.Morita, N.Edagawa, ECOC 2003, PDP page 60 (2003)

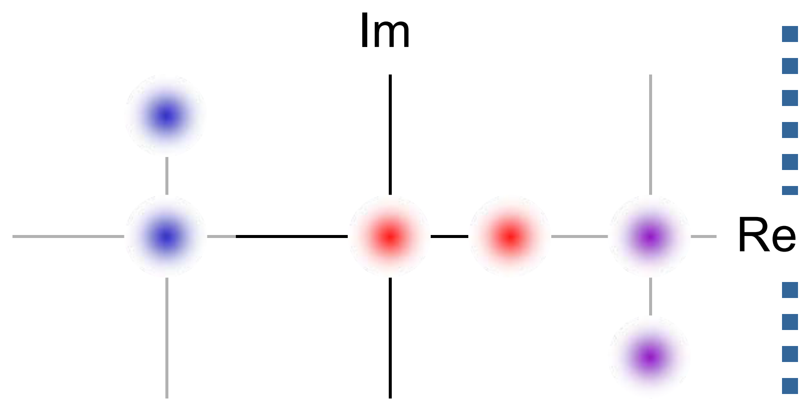
Direct Detection 2: Coherent WDM[1]

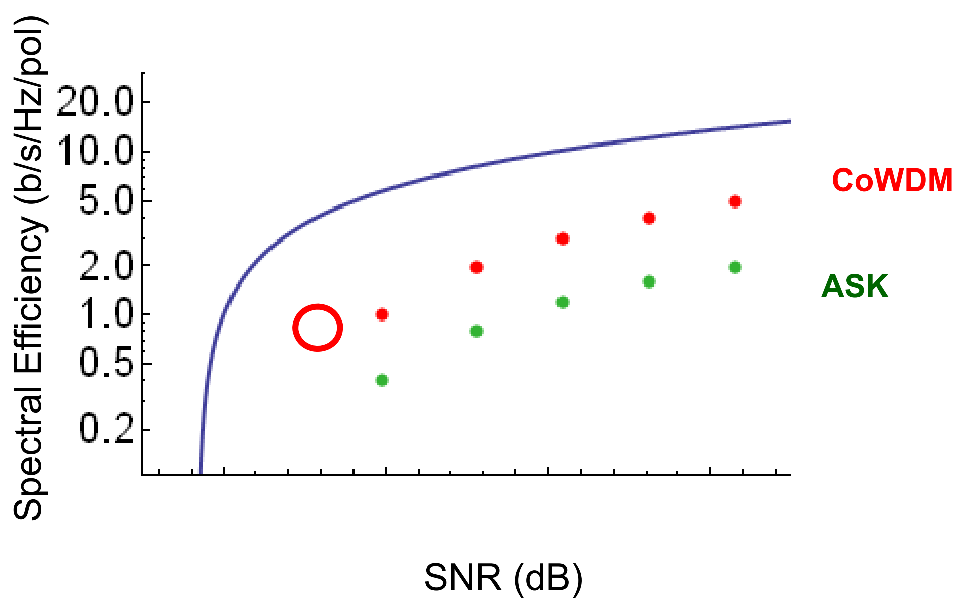
1,200km 1 b/s/Hz

- High Capacity Transmission
  - Low symbol rate (impairments)
- For spectral efficiency
  - Orthogonal Carriers
  - FEC







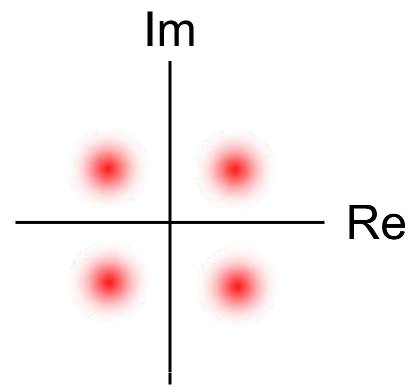


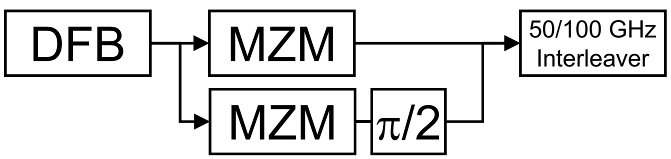
1: T. Healy, et.al., ECOC'07, Mo1.3.5 (2007).

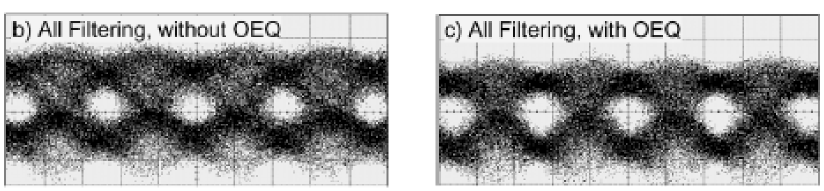
Direct Detection 3: PM-QPSK[1]

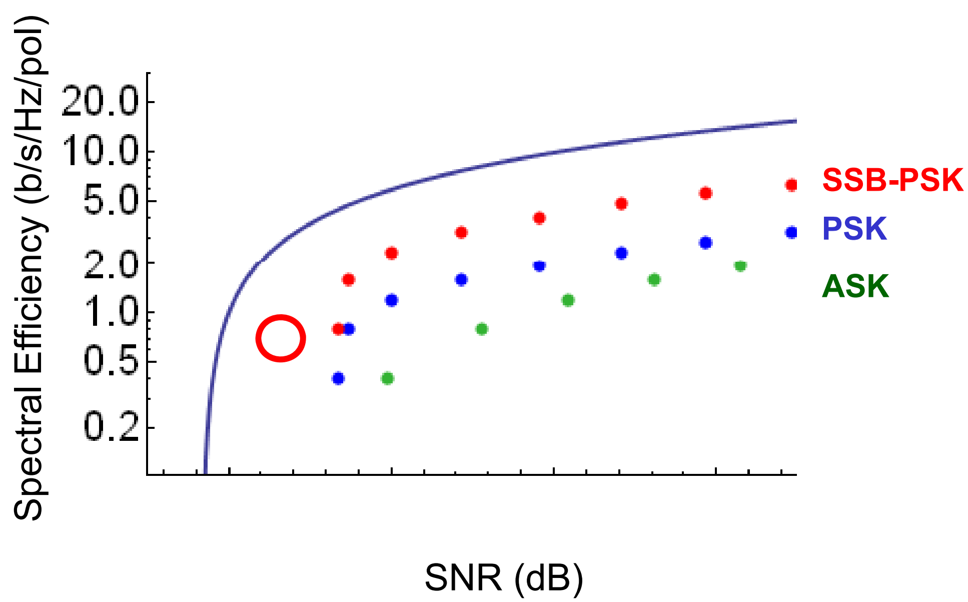
240km 1.6 b/s/Hz/pol

- For spectral efficiency
  - RZ DPSK for sensitivity benefit
  - Pre-filtering to approach SSB
  - DQPSK for enhanced efficiency
  - Optical equaliser
  - FEC







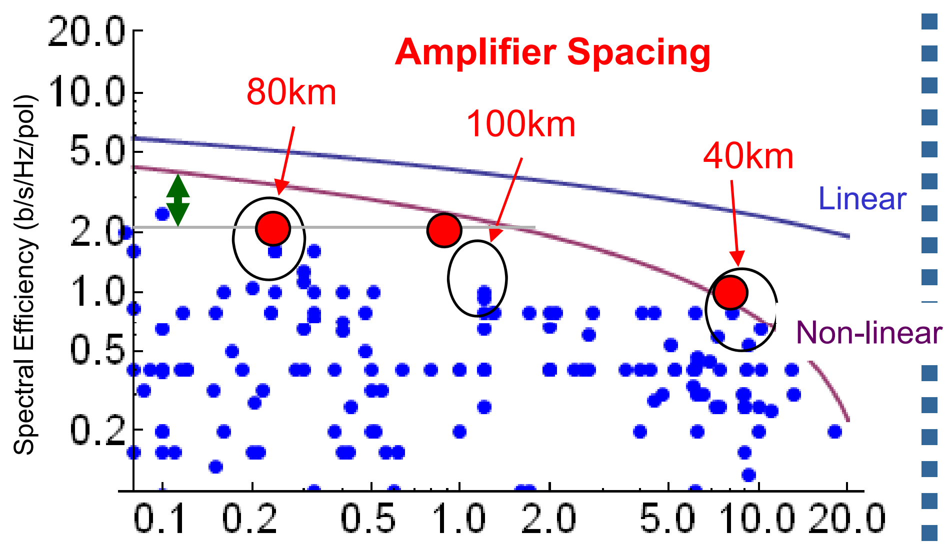


1: A.H.Gnauck, OFC 2007, PDP19 (2007)

Direct Detection Modulation formats

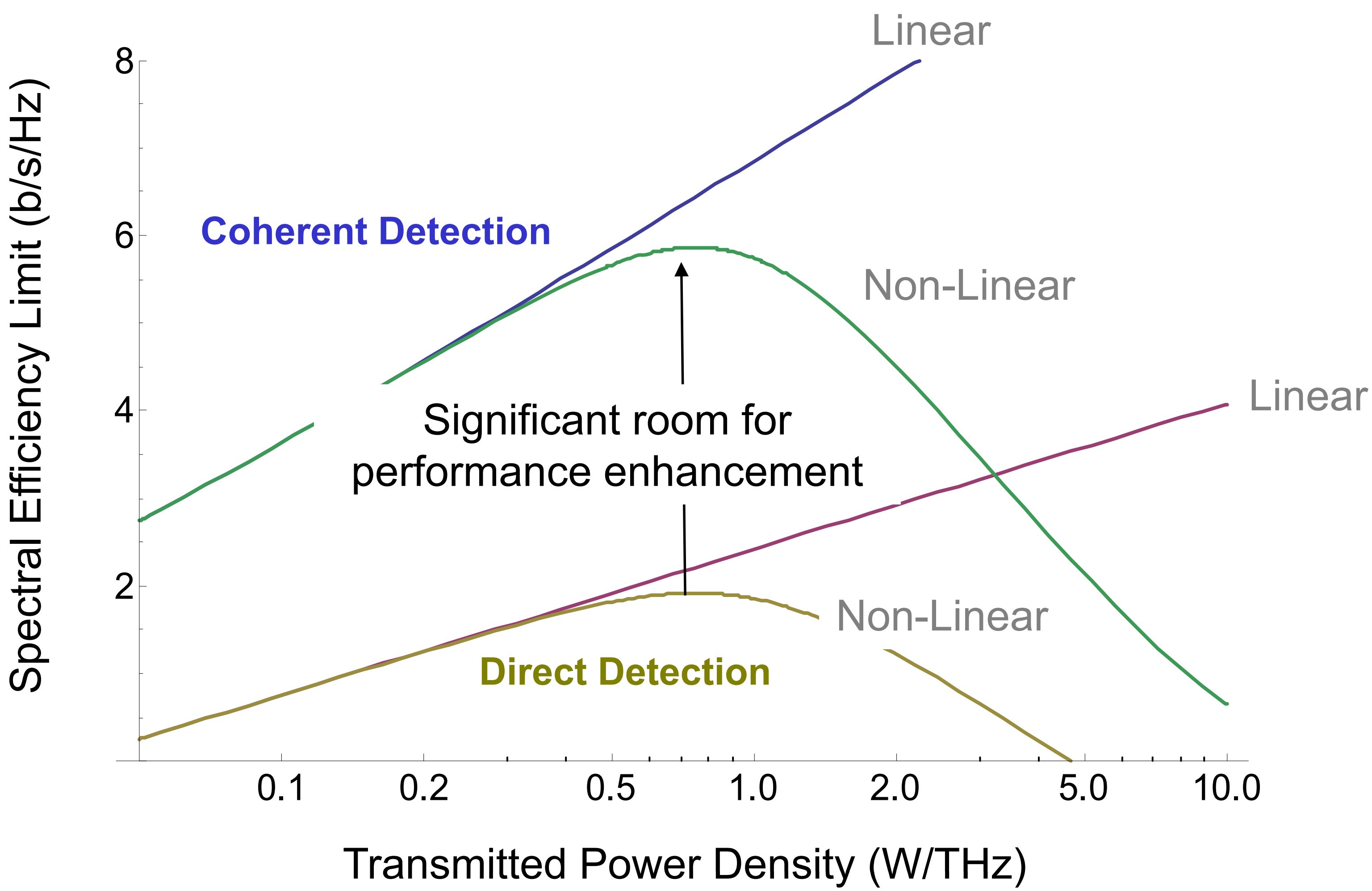
- When amplifier spacing taken into account
  - All three results ~ x2 from the limit
  - Independent of
    - Bi-polar / Uni-polar modulation
    - Single or dual quadrature
    - Polarisation multiplexing
- **Key features**
  - FEC
  - Techniques approaching SSB
    - 80% there using RZ pre-filtering
    - 100% there using Coherent WDM
- **Promising approach**
  - FEC
  - Polarisation multiplexed (x2)
  - Dual Quadrature (x2)
  - Coherent WDM (x2)
- **Little scope beyond ~2 b/s/Hz/pol**

Direct Detection



Transmission distance (Mm)

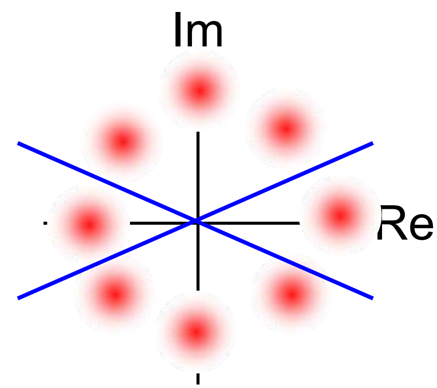
Coherent Detection

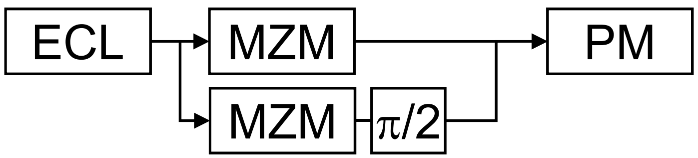


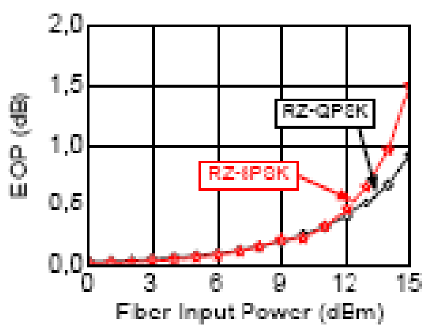
2000km, 80km spacing, 4.5dB noise figure, 50 GHz channels at 50 Gbaud

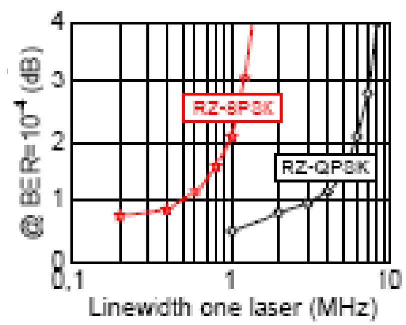
Coherent Detection 1: PSK
1,200km 3 b/s/Hz

- Long Distance High Data Rate
  - Constant Intensity Format
  - Increased constellation size
  - Narrow Line-width Laser
  - FEC

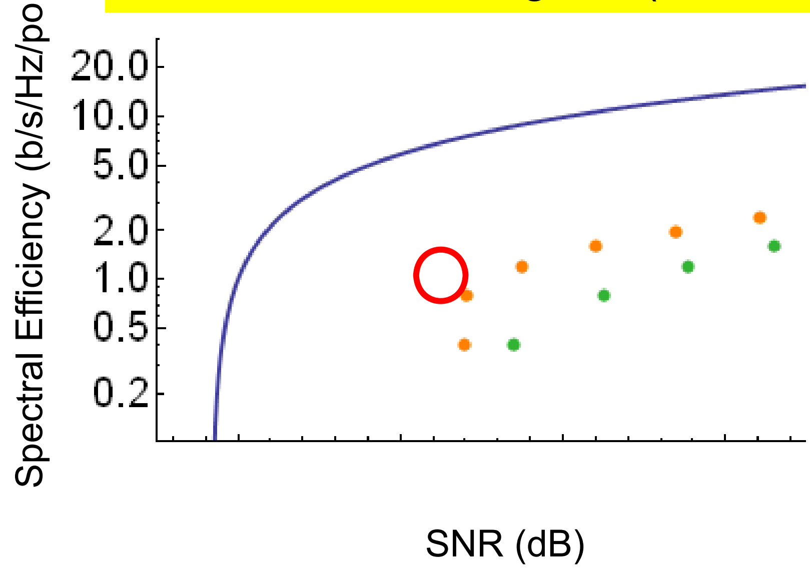








Axes to add and legend (all slides)



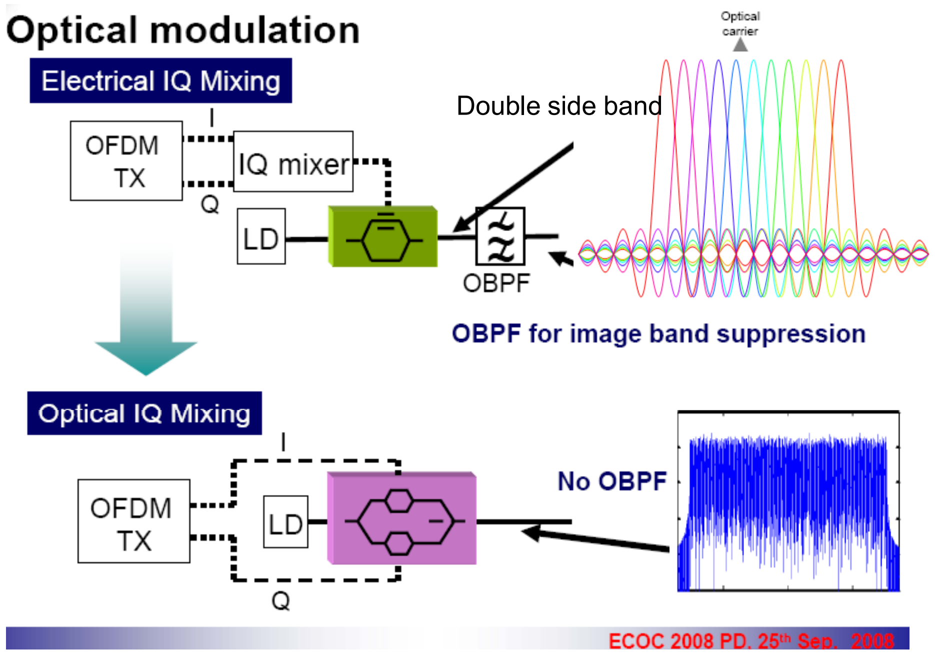
M.Seimetz et.al.,, ECOC 2007 Tu1E1

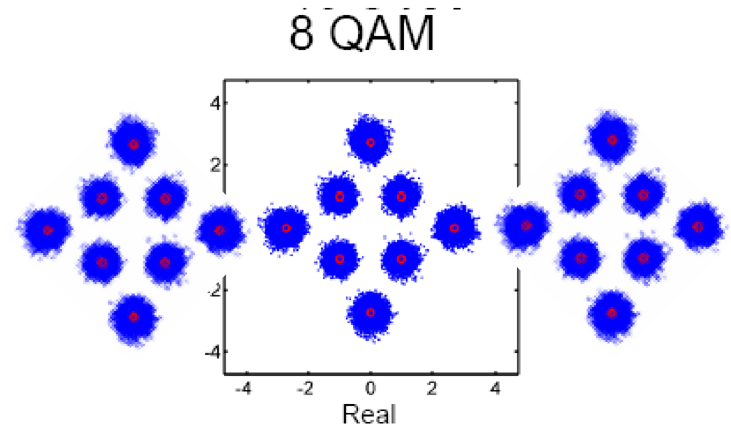
Coherent Detection 2: OFDM

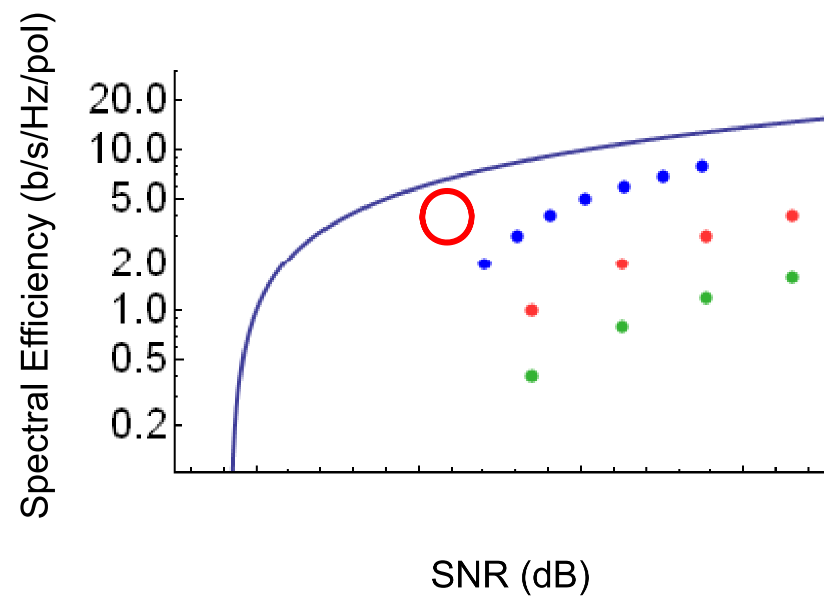
4,160km 5.6 b/s/Hz

Orthogonal Frequency Domain Multiplexing

- Data spread amongst many *orthogonal* carriers
- Orthogonal carriers give SSB performance (less overhead)
- Modulate each subcarrier with QAM constellation
- Increase constellation size electronically
- FEC



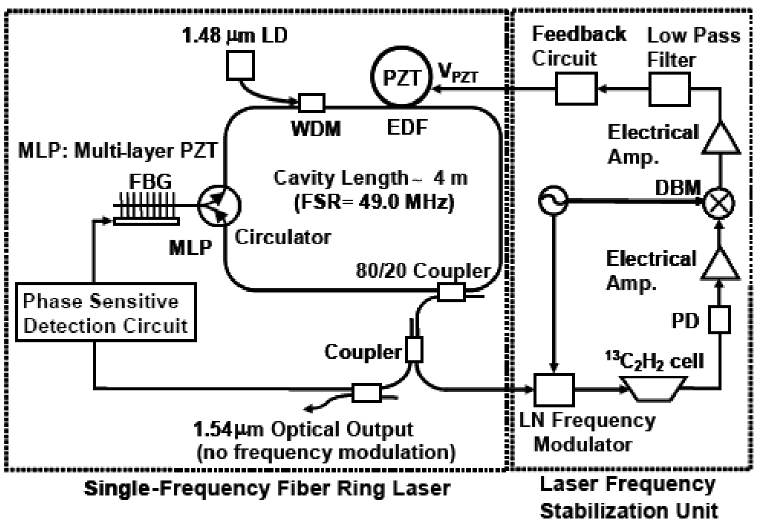


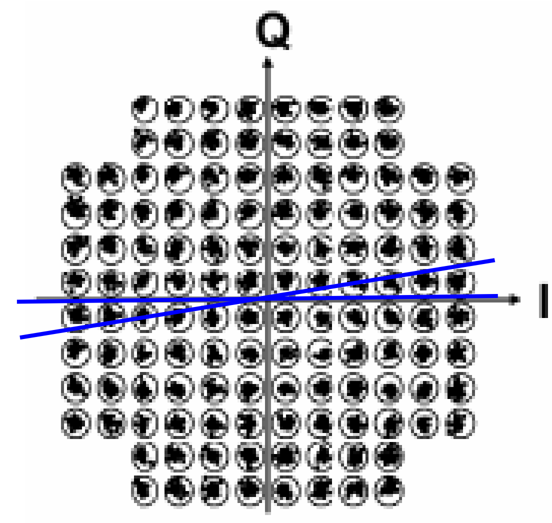


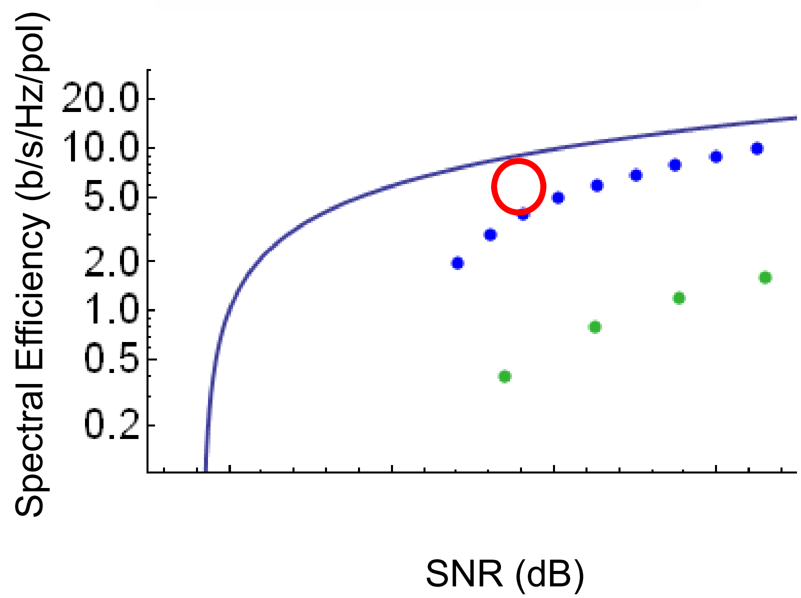
H. Takhashi et.al., , ECOC 2008 PDP Th3E4

Coherent Detection 3: QAM
150km 10b/s/Hz

- Ultra high Spectral Density
  - Maximum QAM Constellation
    - With Niquist filters
  - Ultra narrow line-width laser
  - FEC



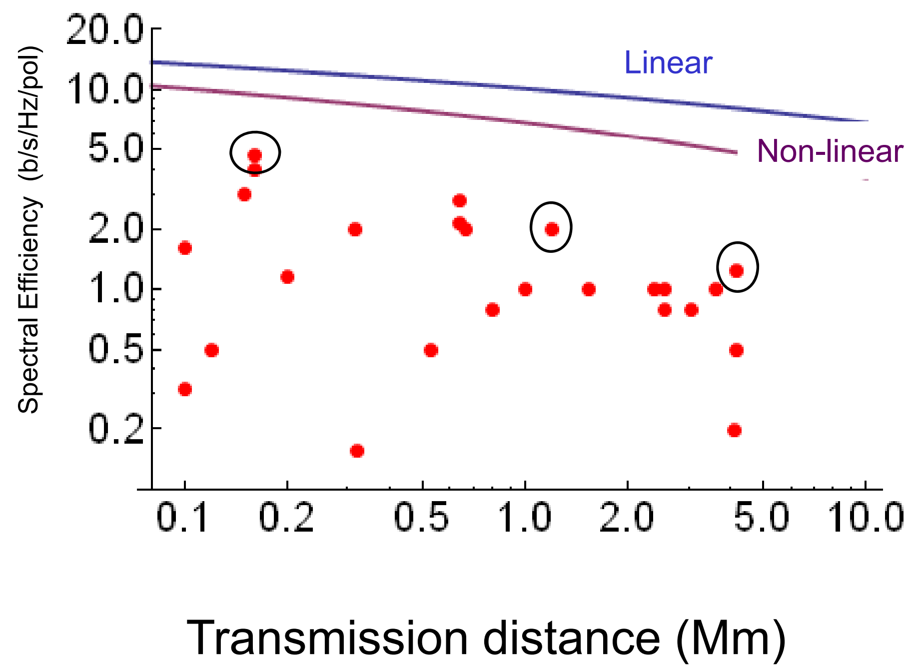




21 January 2008 / Vol. 16, No. 2 / OPTICS EXPRESS 829
M. Yoshida, Optics Express, **16** 2 pp829 (2008)

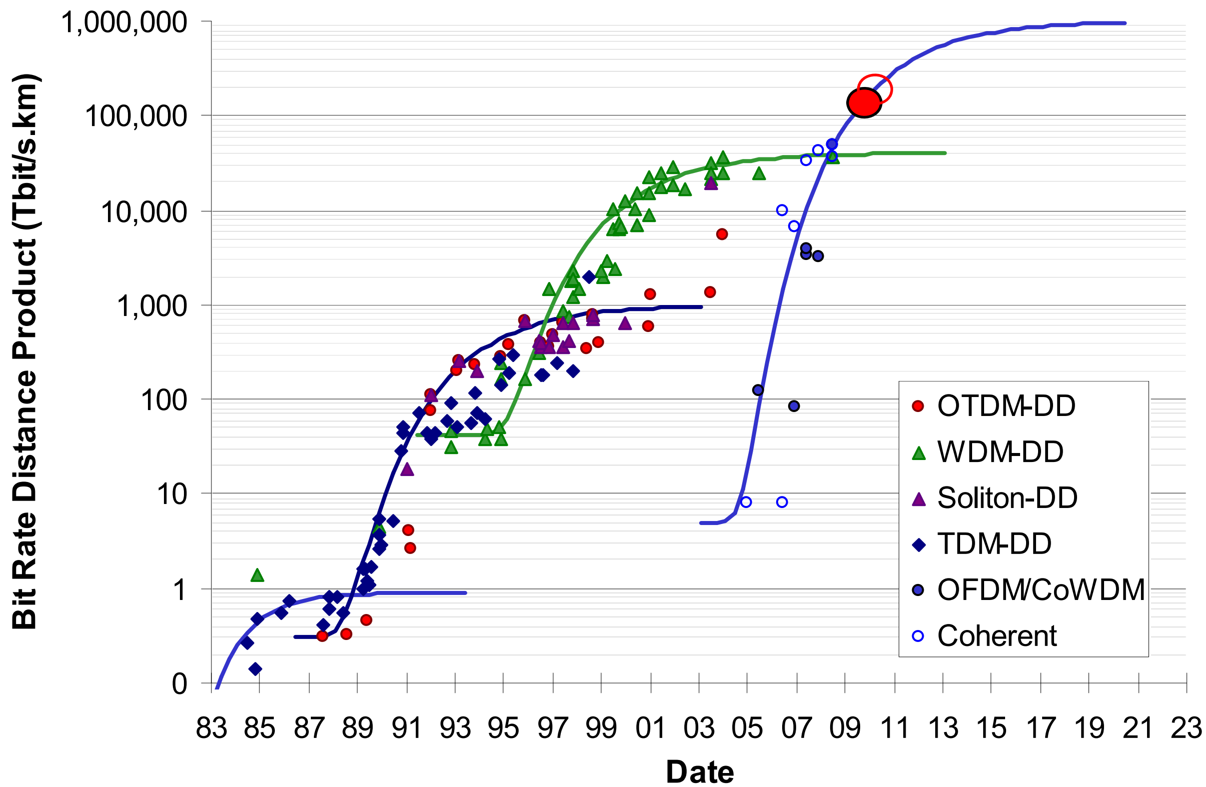
Coherent Detection Modulation Formats

- Performance
  - > x2 performance gap
  - Relative performance degrades with reach
- **Key Features**
  - All polarisation multiplexed
    - Often comes for "free"
  - Multi-level modulation essential
  - PSK performs well
    - Is performance limited by nonlinear effects?
  - Orthogonal modulation and/or spectrum control used
- **Optimum Solution**
  - Still to be established
  - Perhaps
    - 256 QAM over OFDM over CoWDM



Latest Capacity Distance Results

- Coherent detection already outstripping direct detection
- Record result is coherently detected OFDM
- Post Deadline Papers?
  - > 0.1 Pbit/s.Mm



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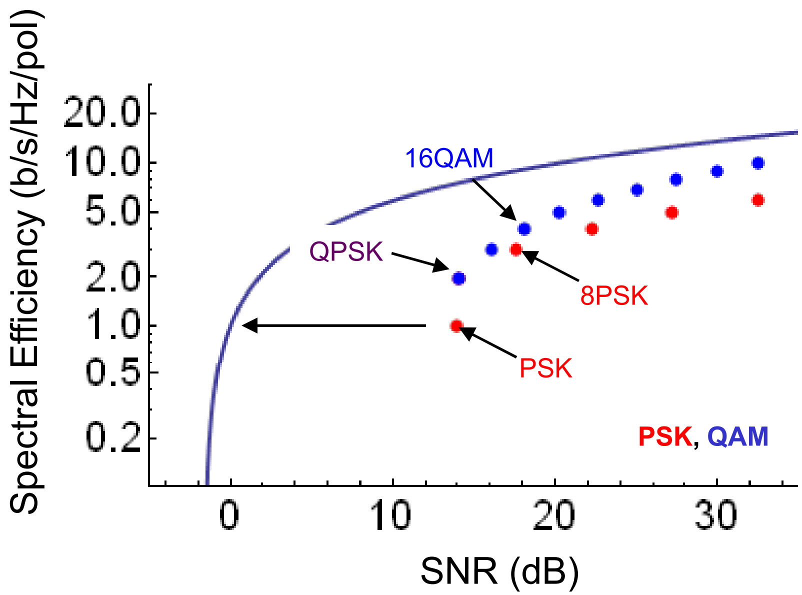
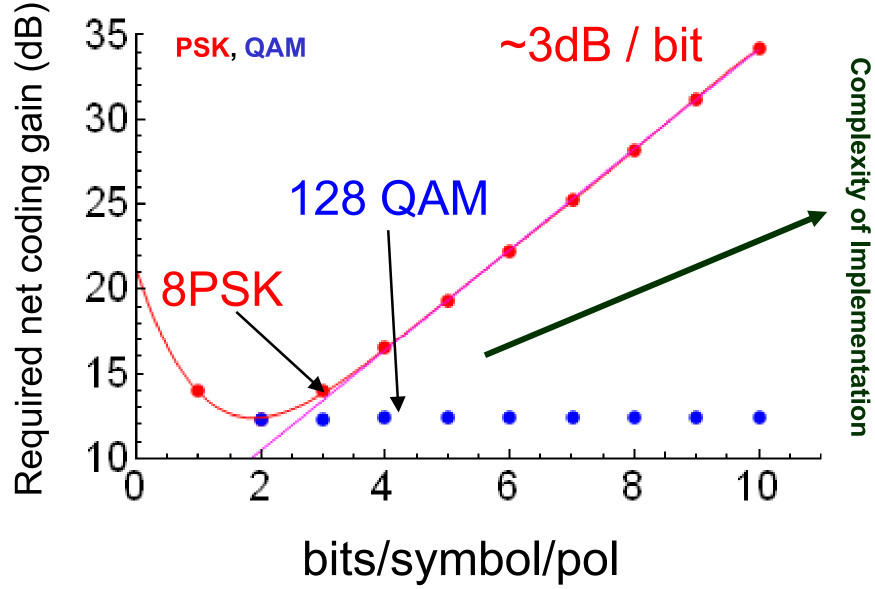
  - Multi-level modulation formats
  - Breaking the current limit

How to increase the capacity further: Optimisation of current technology

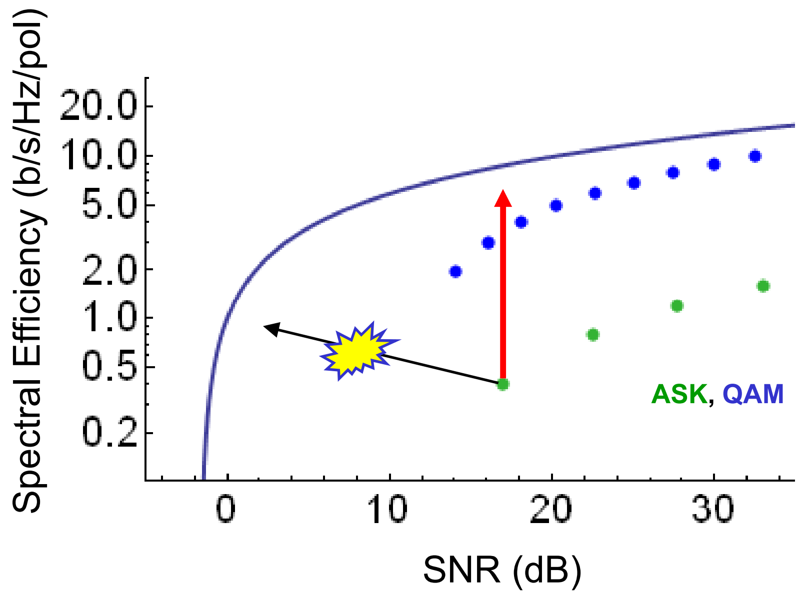


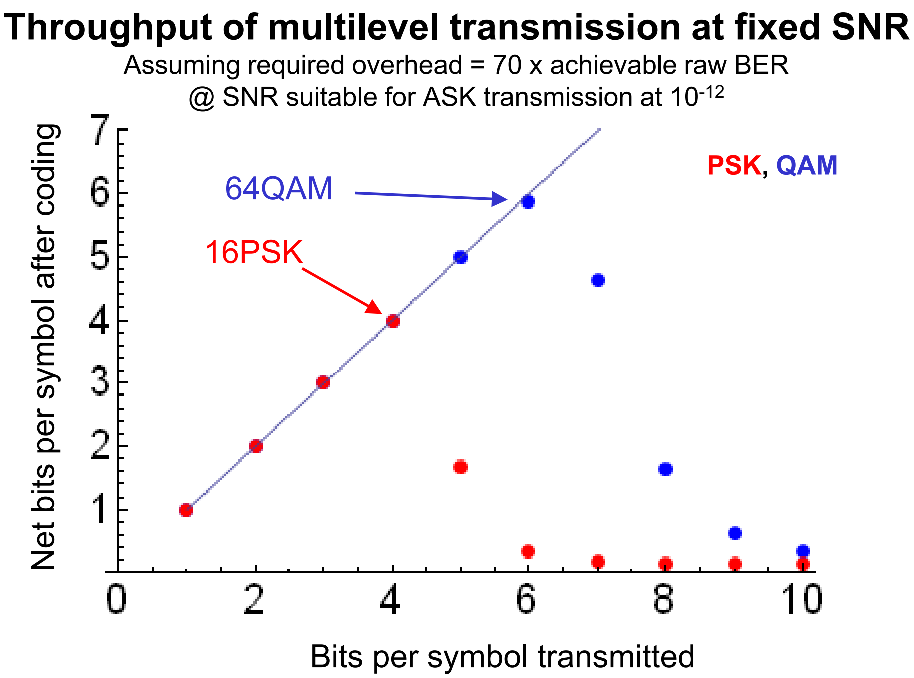


- Multi-level modulation formats with coherent detection
- Required FEC strength increases significantly with signal bits
  - Maximise number of orthogonal channels first
    - Polarisation
    - Quadrature
    - Subcarrier
  - Expect significant (≥100%) overhead for 128 QAM and above

The Ultimate Quest

Maximum capacity for fixed installed plant



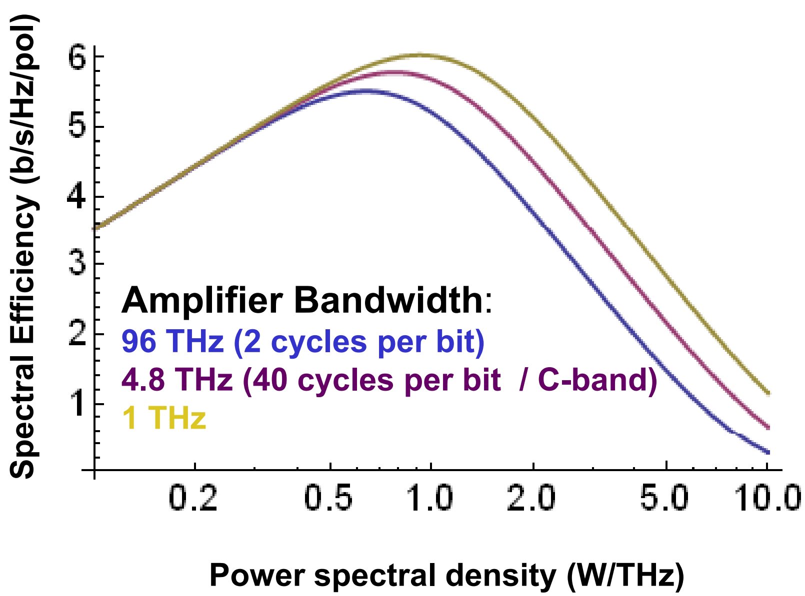


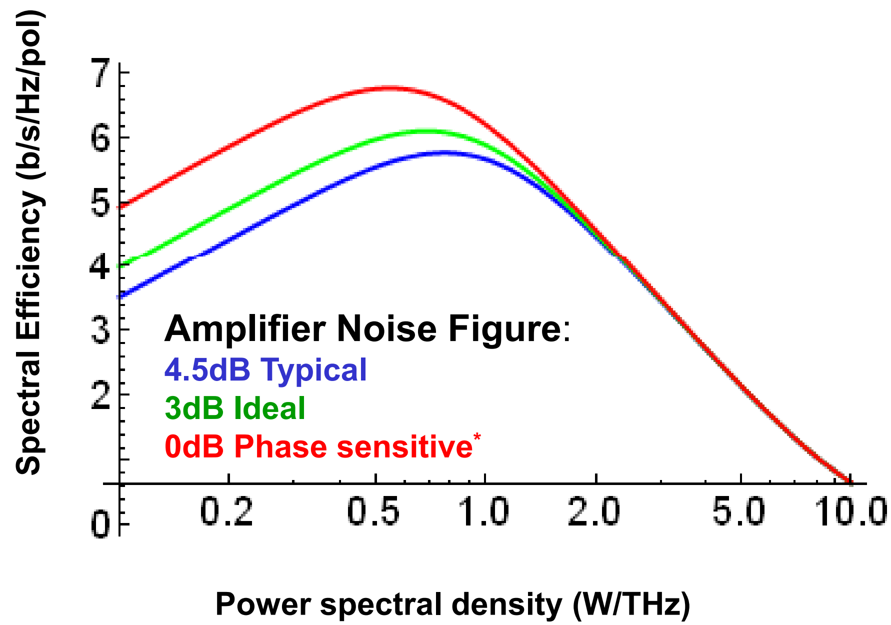
- Fixed Plant – Terminal Changes Only
  - Fixed SNR
  - Modulation format changes
  - Coding (FEC) changes

How to increase the capacity further: Amplifier optimisation

- Amplifier bandwidth
  - Capacity scales ~linearly with bandwidth
- Amplifier Noise figure
  - Modest capacity increase ~ Log_2 noise reduction

$$C = B.\log_2\left(1+\frac{P}{N_o B}\right)$$





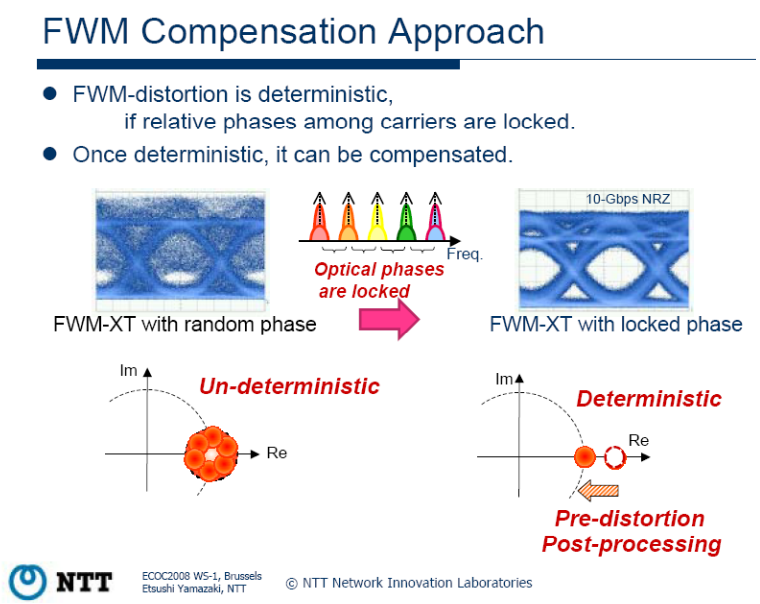
2000km, 80km spacing, (4.5dB noise figure), 50 GHz channels at 50 Gbaud, (5THz amplifier bandwidth), 0.2dB/km loss

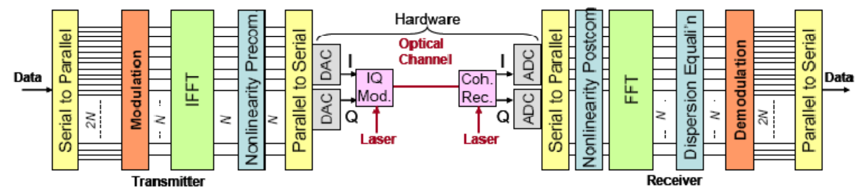
* Phase sensitive amplifier: 0dB noise figure, but quantum noise for attenuation ~ ½ of 3dB noise figure case[1]

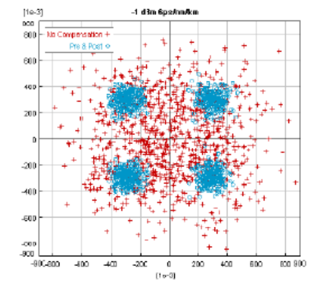
1: L.Thylen et.al., Channel capacity of optical fibres, Private communication (2002)

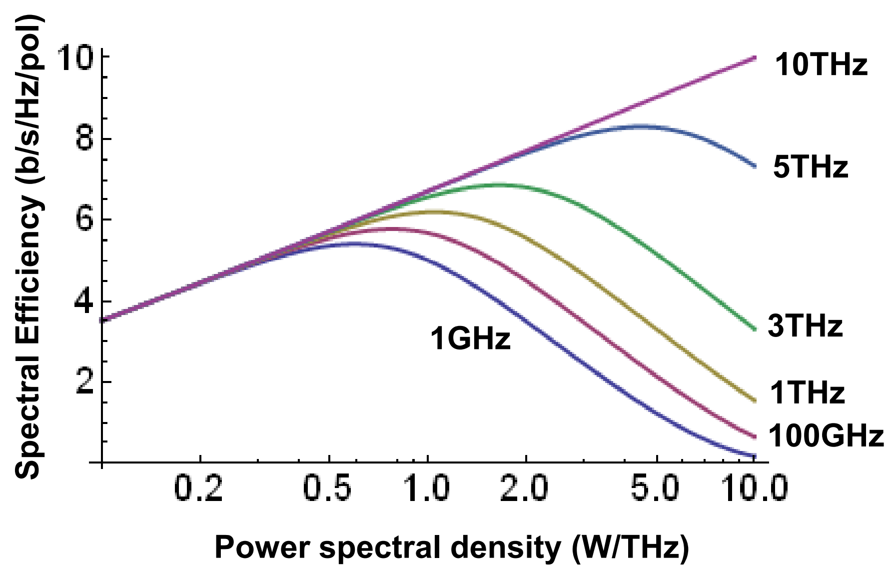
How to increase the capacity further: Multi-tone transmission

- Non-linear index effects may be compensated at the terminals.
  - Backwards propagation
  - For OFDM[1]
  - Multiple coherent channels[2]
- Increase bandwidth of channel







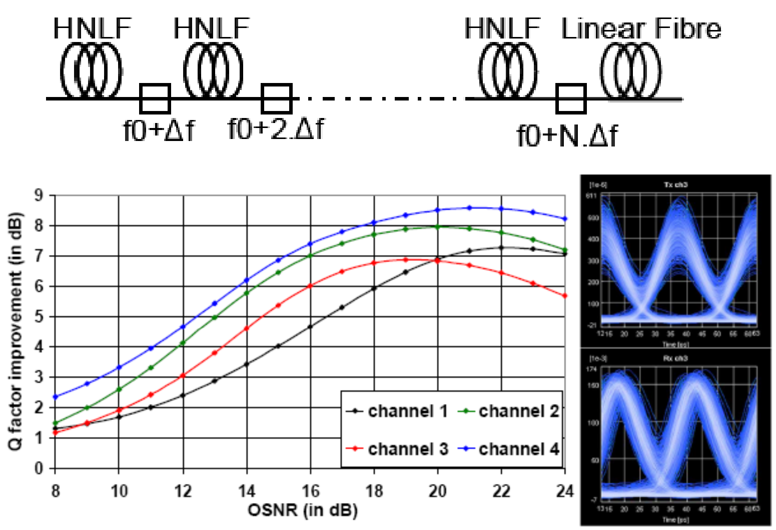


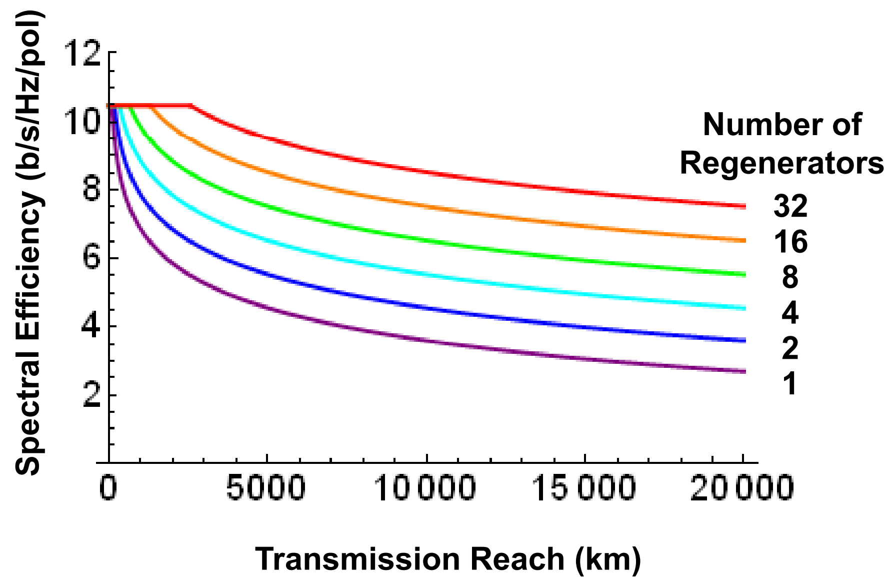
2000km, 80km spacing, 4.5dB noise figure, 10THz amplifier

1: A.J.Lowery, Optics Express **15** 20 pp12965 (2007)
2: E.Yamazaki, WS-1, ECOC 2008

How to increase the capacity further: Multi-wavelength optical regeneration

- Multi-wavelength all optical regeneration ⇒ Breaks up noise accumulation
  - Dispersion managed Mamyshev regenerator[1]
  - Quasi continuously filtered regenerator[2]
  - Bi-directional / dual polarisation[3]
  - Parametric effects[4]



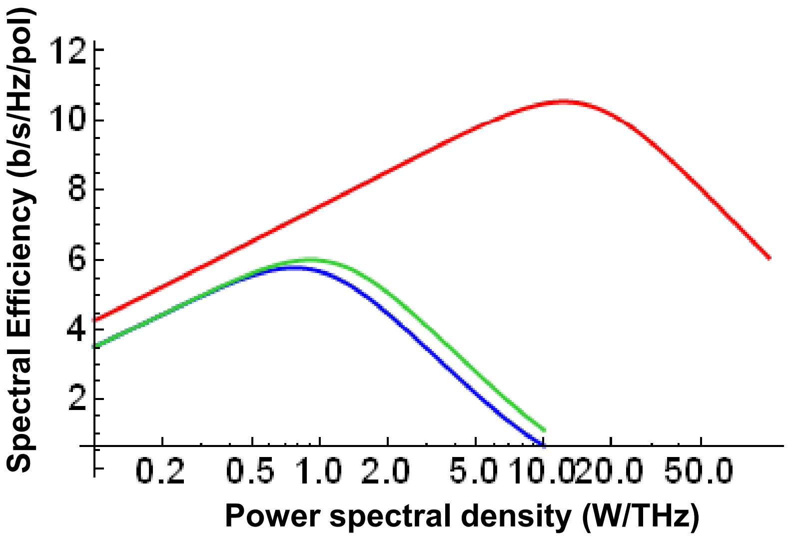


2000km, 80km spacing, 4.5dB noise figure, 5THz amplifier

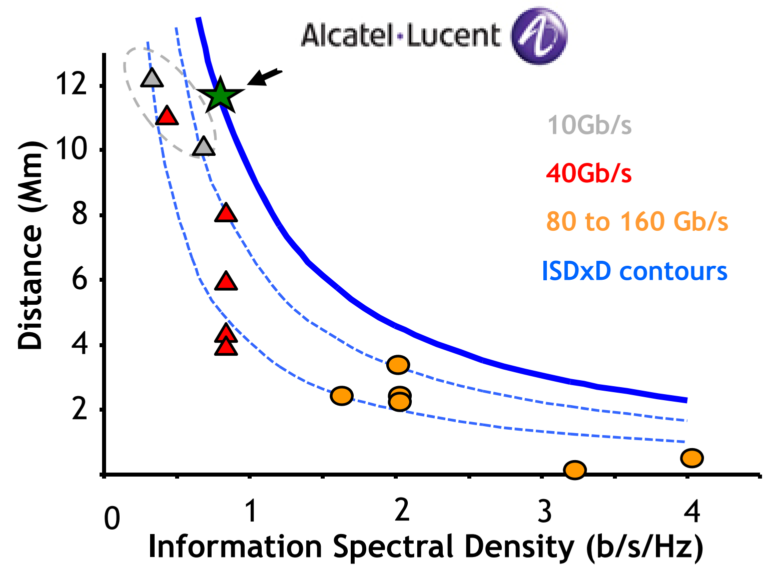
1: M. Vasilyev et.a., OFC 2005, OME62.
2: B.Cuenot et.al., Optics Express **15** 18 pp11492 (2007)
3: L.Provost et.al., ECOC 2007, Tu4.5.1
4: B.Cuenot, OAA 2006, OWA4

How to increase the capacity further: Fibre Design

	SMF-28™	LongLine™ Fiber[1]	Hollow Core PCF[3] (prediction)
Loss (dB/km)	0.2	0.185	.13
Non-linear coefficient ($W^{-1}km^{-1}$)	~ 1	~ .75	~0.01 (99% air propagation)
Waveband (nm)	1550	1550	1900



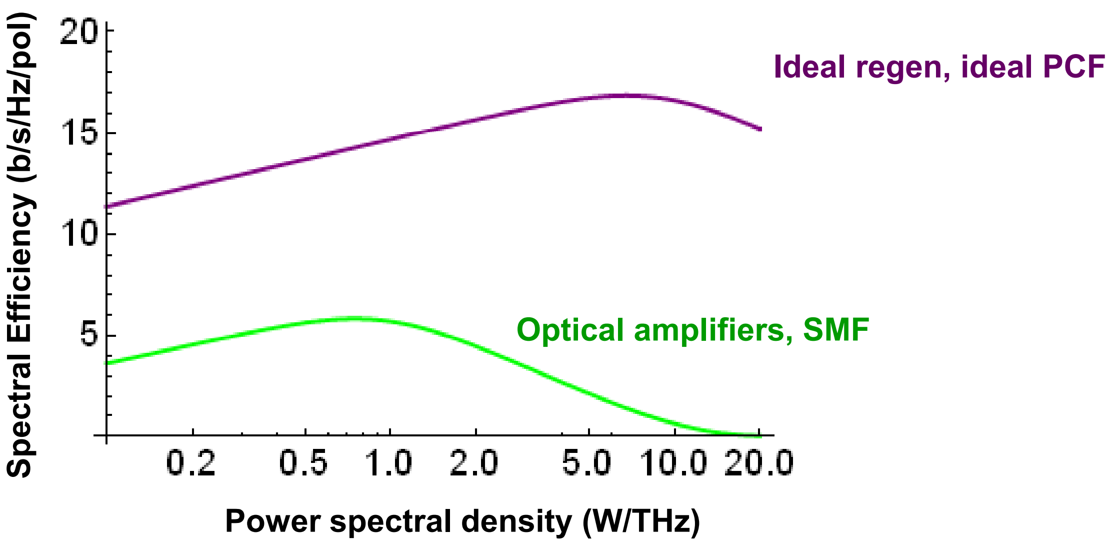
2000km, 80km spacing, 4.5dB noise figure, 50 GHz channels at 50 Gbaud



1: M. Bigot-Astruc, Mo.4.B1, ECOC'08
2 :G.Charlet, Th3Ee, ECOC'08
3: P.J.Roberts et.al., Optics Express **13** 1 pp236 (2005)

The Ultimate Capacity?

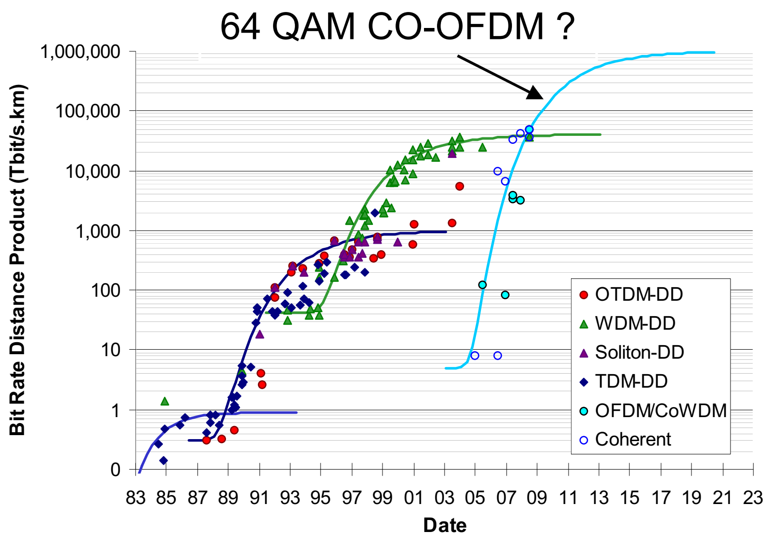
- Transmission link fabricated from hollow core PCF
- Optical amplifiers replaced by ideal WDM regenerators
- Ultimate limit ~ 17 b/s/Hz/pol
  - ~170 Tbit/s in a 40nm bandwidth
  - with a higher bandwidth ~ 1 Pbit/s.Mm



2000km, 80km spacing, 4.5dB noise figure, 50 GHz channels at 50 Gbaud

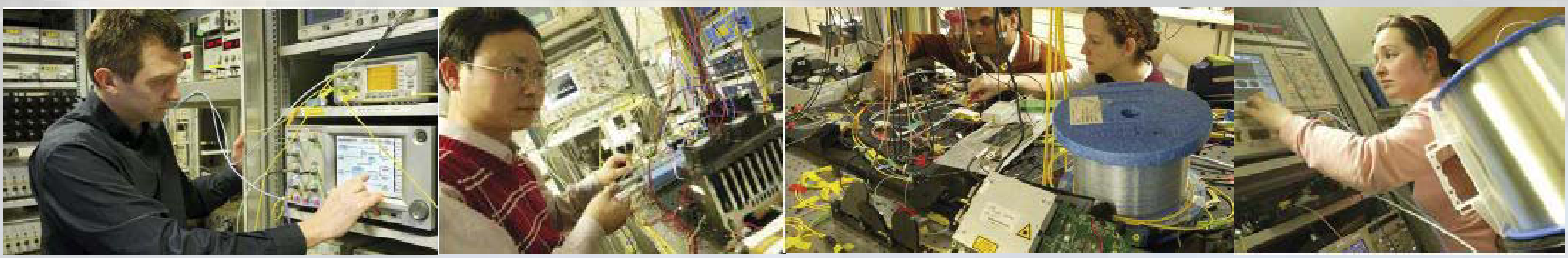
Conclusions:
Reaching the limits of communication capacity

- What do we need to do (system design)?
  - Dispersion management
  - FEC
  - Orthogonal carriers
  - Coherent detection
  - QAM
  - Non-linear compensation
- What do we need to make (components)?
  - Integrated arrays
  - High speed DSP, ASICs
  - Narrow linewidth lasers
  - Linear modulators and drivers
- And to extend the limit…
  - Amplifier for waveband extension
  - Improved transmission medium
  - Undiscovered modulation techniques
  - Multi-wavelength regeneration



- Thank You

- Photonic Systems Group,
  Tyndall National Institute & Department of Physics, University College Cork, Ireland.



physics.ucc.ie/photonics/photonicsJobs.htm