Faster-than-Nyquist transmission for wireless and optical fibre communication

Lutz Lampe
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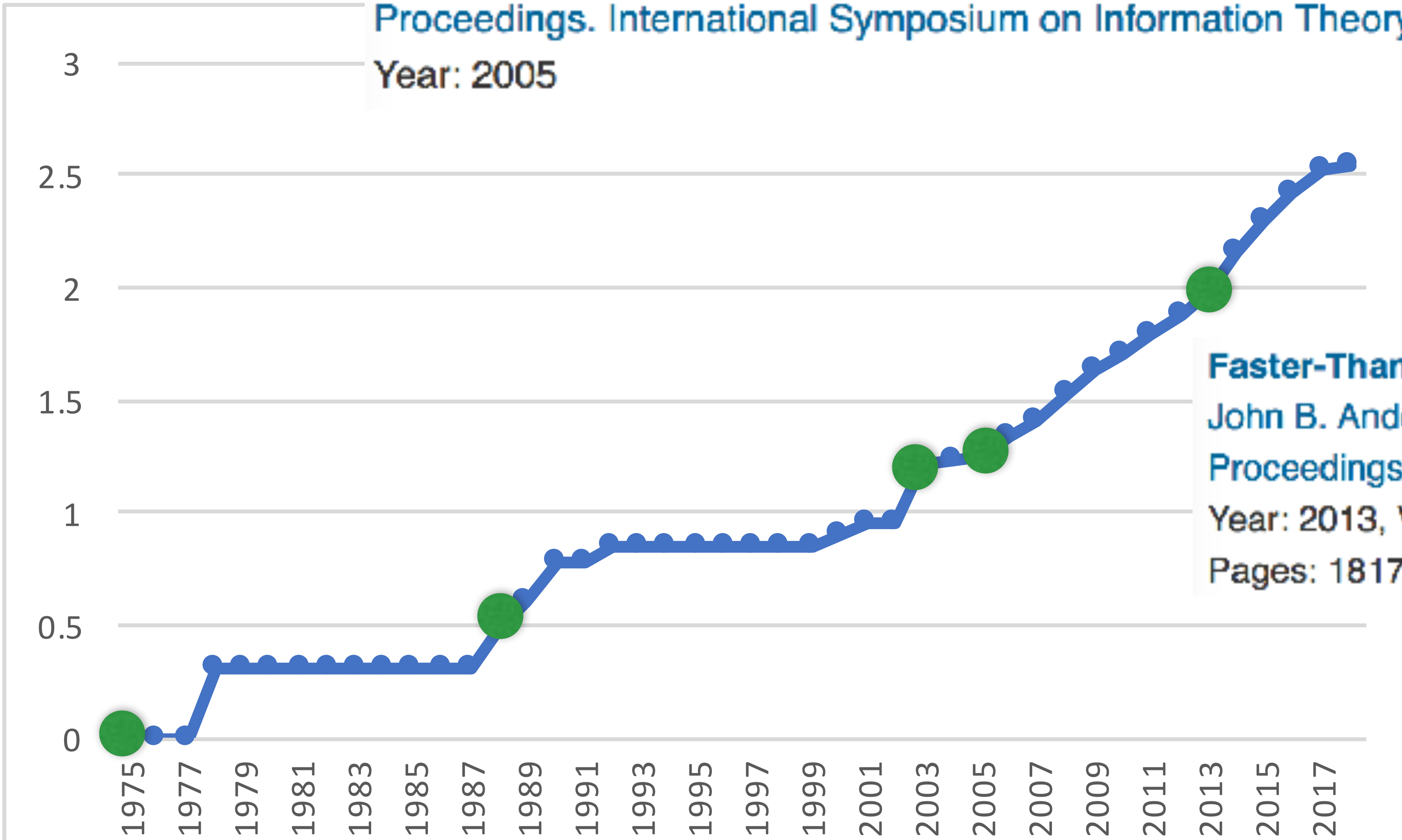
(FTN) OR (Faster than Nyquist) OR (time-frequency packing) OR (super Nyquist)

The two dimensional Mazo limit
F. Rusek; J. B. Anderson
Proceedings. International Symposium on Information Theory, 2005. ISIT 2005.
Year: 2005



Faster-Than-Nyquist Signaling
John B. Anderson; Fredrik Rusek; Viktor Öwall
Proceedings of the IEEE
Year: 2013, Volume: 101, Issue: 8
Pages: 1817 - 1830

Faster-than-nyquist signaling
J. E. Mazo
The Bell System Technical Journal
Year: 1975, Volume: 54, Issue: 8
Pages: 1451 - 1462

On the minimun
J. E. Mazo; H. J.
IEEE Transactior
Year: 1988, Volur
Pages: 1420 - 14

Exploiting faster-than-Nyquist signaling
A. D. Liveris; C. N. Georghiades
IEEE Transactions on Communications
Year: 2003, Volume: 51, Issue: 9
Pages: 1502 - 1511

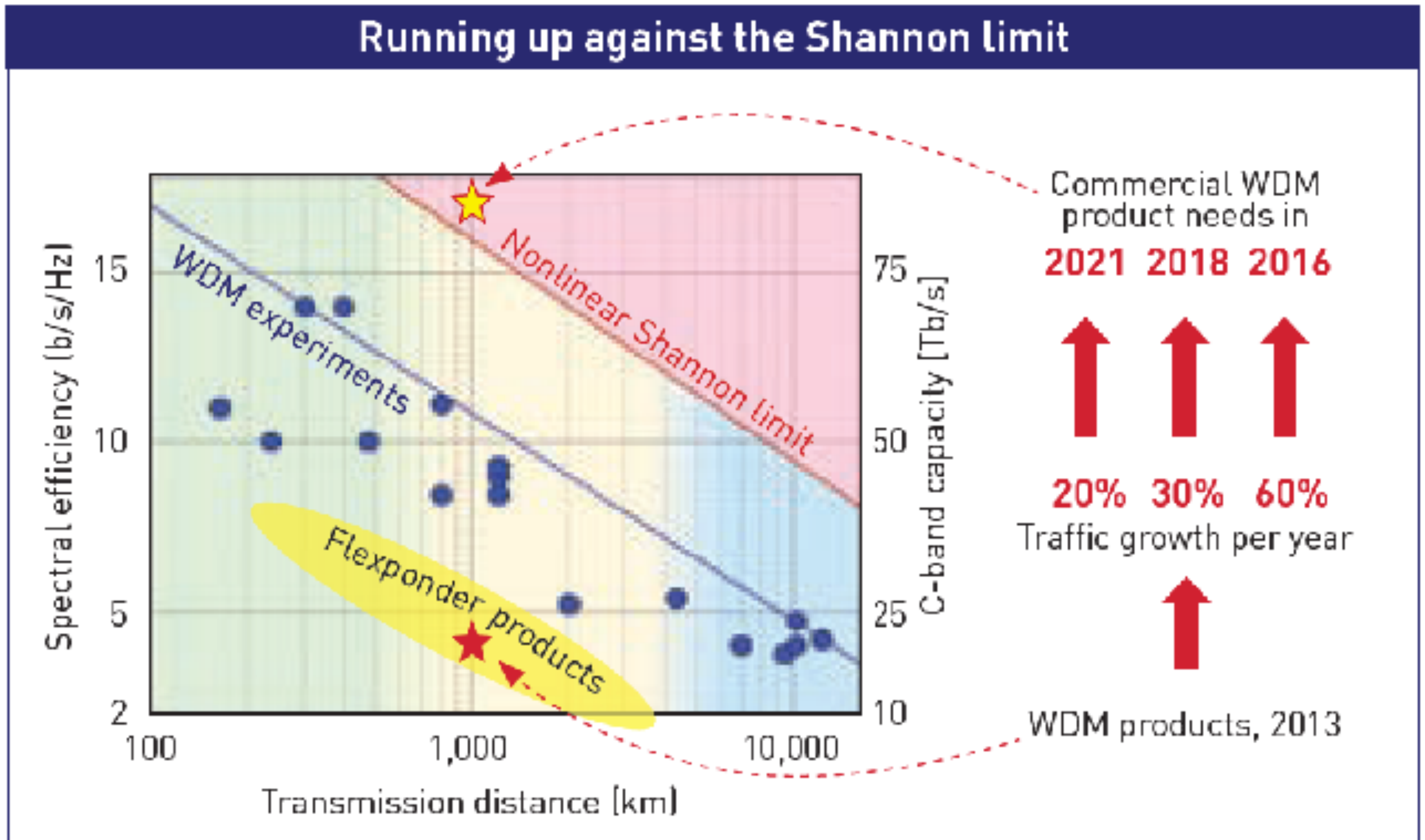
ıaling

What is faster than Nyquist?

More bits per second per Hertz, i.e., higher spectral efficiency

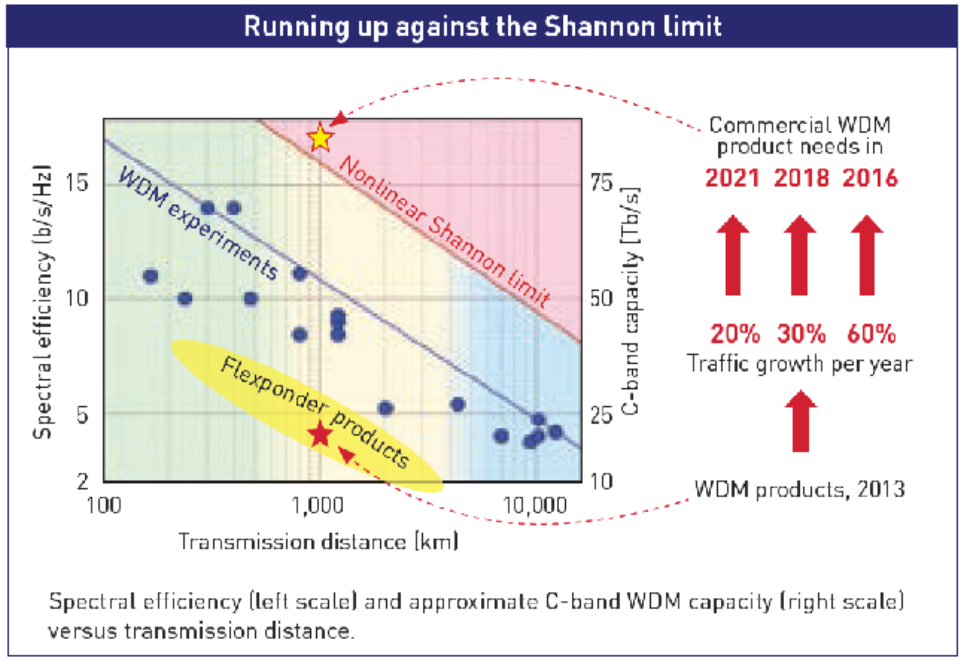
Why fast (-er than Nyquist)?

© Scaling Optical Fiber Networks: Challenges and Solutions
Peter J. Winzer,
Optics and Photonics News Vol. 26, Issue 3, pp. 28-35 (2015)
https://doi.org/10.1364/OPN.26.3.000028

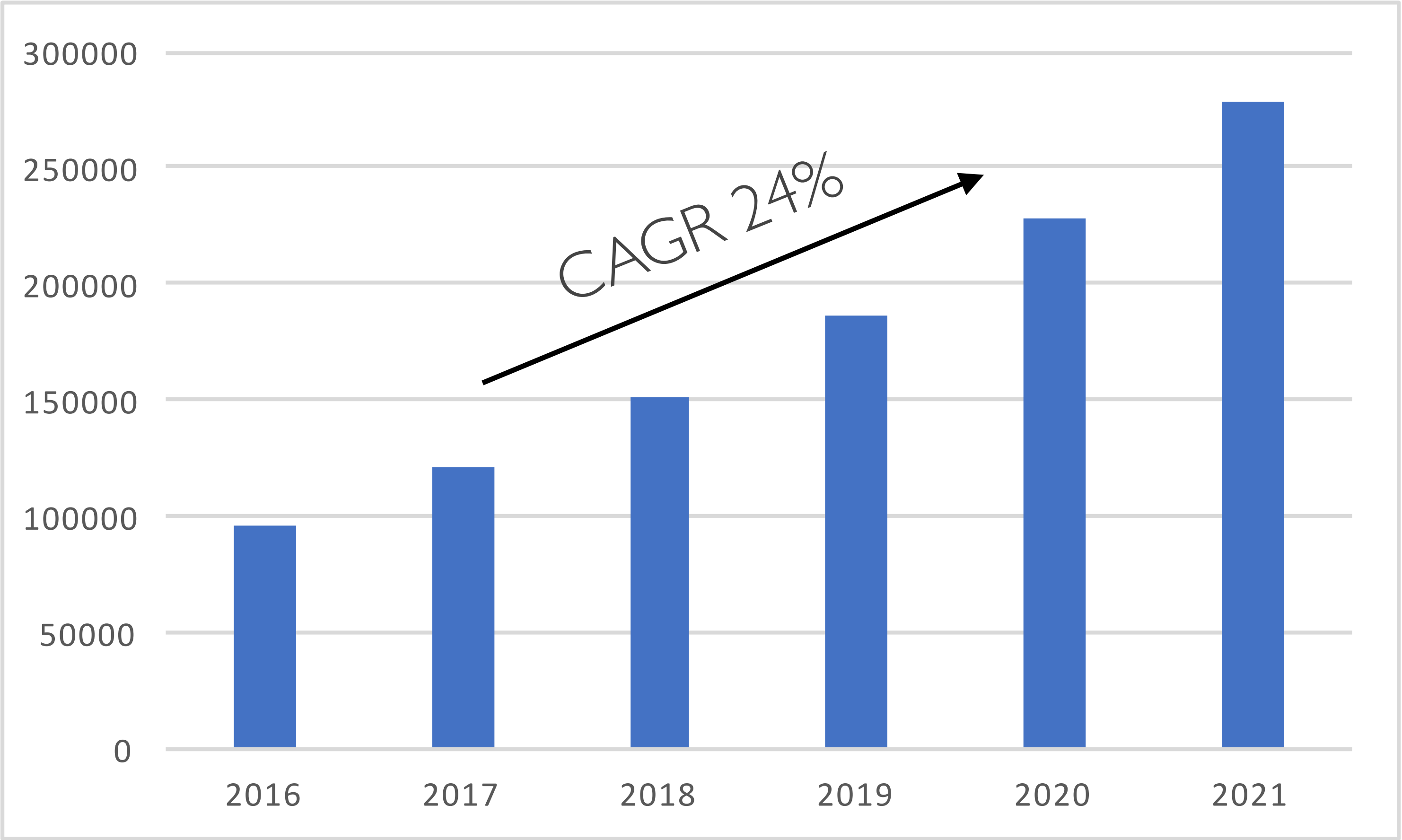


Spectral efficiency (left scale) and approximate C-band WDM capacity (right scale) versus transmission distance.

Why fast (-er than Nyquist)?



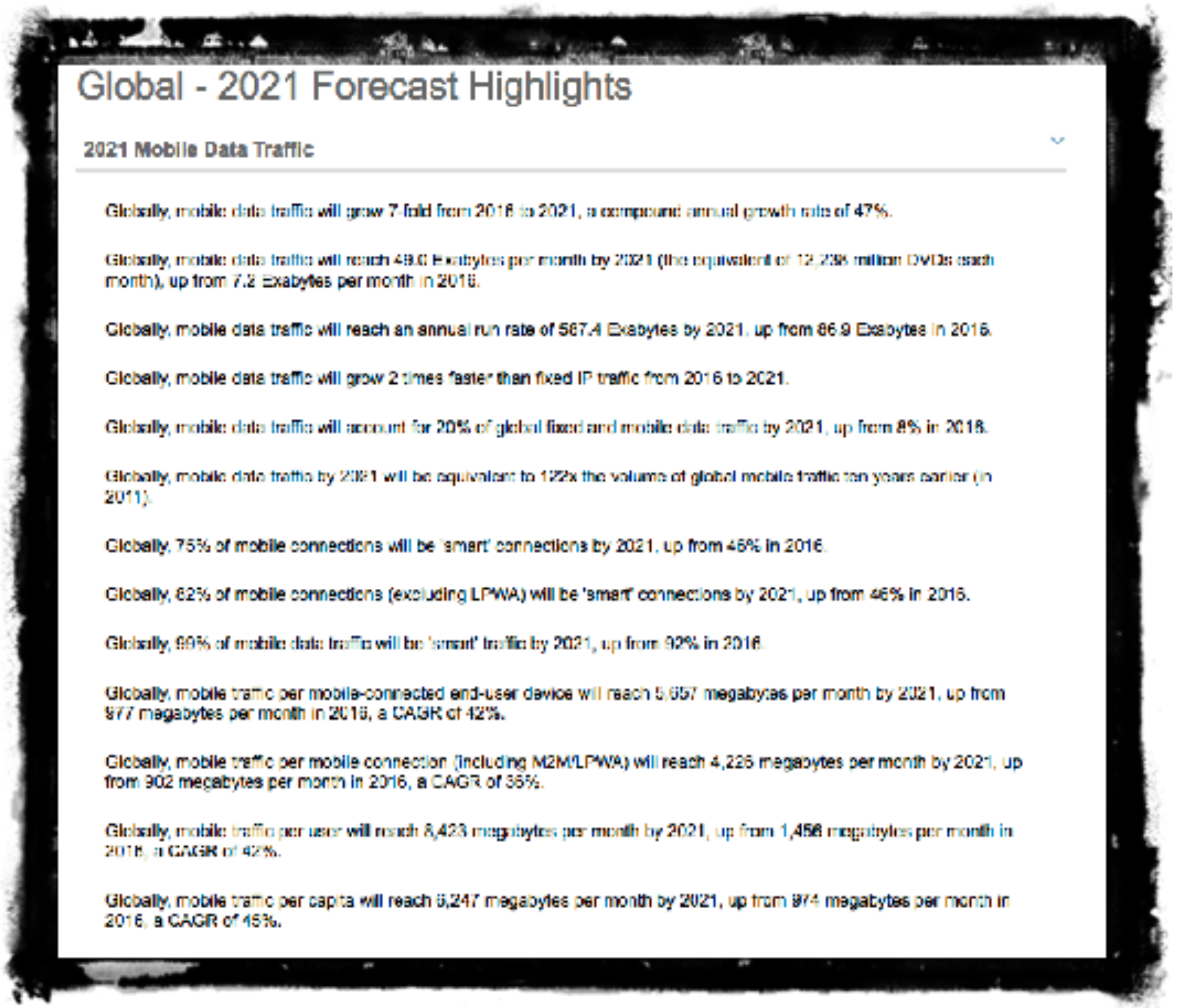
Global IP traffic in PB per month



© Scaling Optical Fiber Networks: Challenges and Solutions
Peter J. Winzer,
Optics and Photonics News Vol. 26, Issue 3, pp. 28-35 (2015)
https://doi.org/10.1364/OPN.26.3.000028

Cisco Visual Networking Index:
Forecast and Methodology, 2016–2021

Why fast (-er than Nyquist)?



Global - 2021 Forecast Highlights

2021 Mobile Data Traffic

Globally, mobile data traffic will grow 7-fold from 2016 to 2021, a compound annual growth rate of 47%.

Globally, mobile data traffic will reach 49.0 Exabytes per month by 2021 (the equivalent of 12,238 million DVDs each month), up from 7.2 Exabytes per month in 2016.

Globally, mobile data traffic will reach an annual run rate of 587.4 Exabytes by 2021, up from 86.9 Exabytes in 2016.

Globally, mobile data traffic will grow 2 times faster than fixed IP traffic from 2016 to 2021.

Globally, mobile data traffic will account for 20% of global fixed and mobile data traffic by 2021, up from 8% in 2016.

Globally, mobile data traffic by 2021 will be equivalent to 122x the volume of global mobile traffic ten years earlier (in 2011).

Globally, 75% of mobile connections will be 'smart' connections by 2021, up from 46% in 2016.

Globally, 82% of mobile connections (excluding LPWA) will be 'smart' connections by 2021, up from 46% in 2016.

Globally, 99% of mobile data traffic will be 'smart' traffic by 2021, up from 92% in 2016.

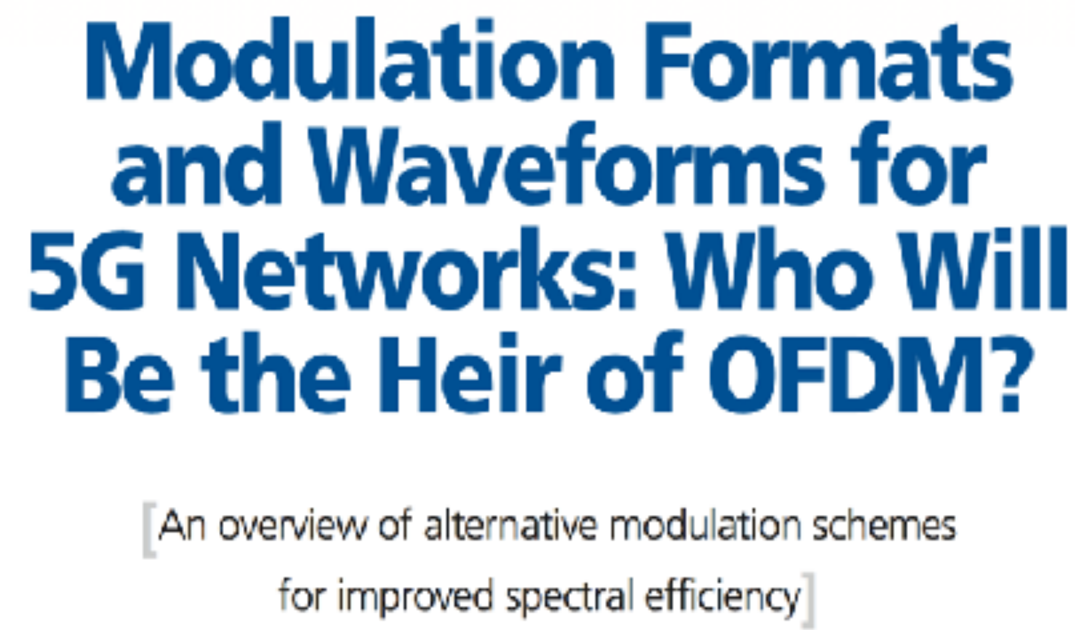
Globally, mobile traffic per mobile-connected end-user device will reach 5,657 megabytes per month by 2021, up from 877 megabytes per month in 2016, a CAGR of 42%.

Globally, mobile traffic per mobile connection (including M2M/LPWA) will reach 4,226 megabytes per month by 2021, up from 902 megabytes per month in 2016, a CAGR of 36%.

Globally, mobile traffic per user will reach 8,423 megabytes per month by 2021, up from 1,456 megabytes per month in 2016, a CAGR of 42%.

Globally, mobile traffic per capita will reach 6,247 megabytes per month by 2021, up from 974 megabytes per month in 2016, a CAGR of 45%.

VNI Mobile Forecast Highlights, 2016-2021



Modulation Formats and Waveforms for 5G Networks: Who Will Be the Heir of OFDM?

[An overview of alternative modulation schemes for improved spectral efficiency]

IEEE Signal Processing Magazine, 2014

Why fast (-er than Nyquist)?

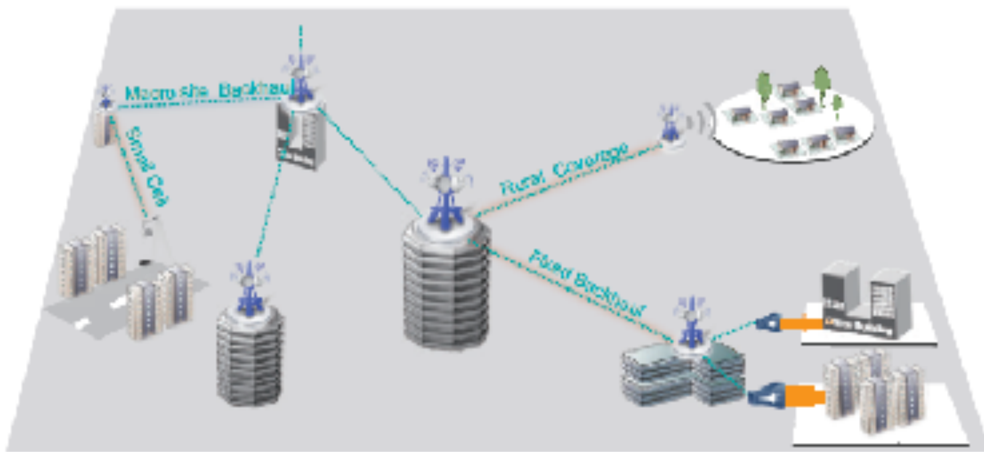
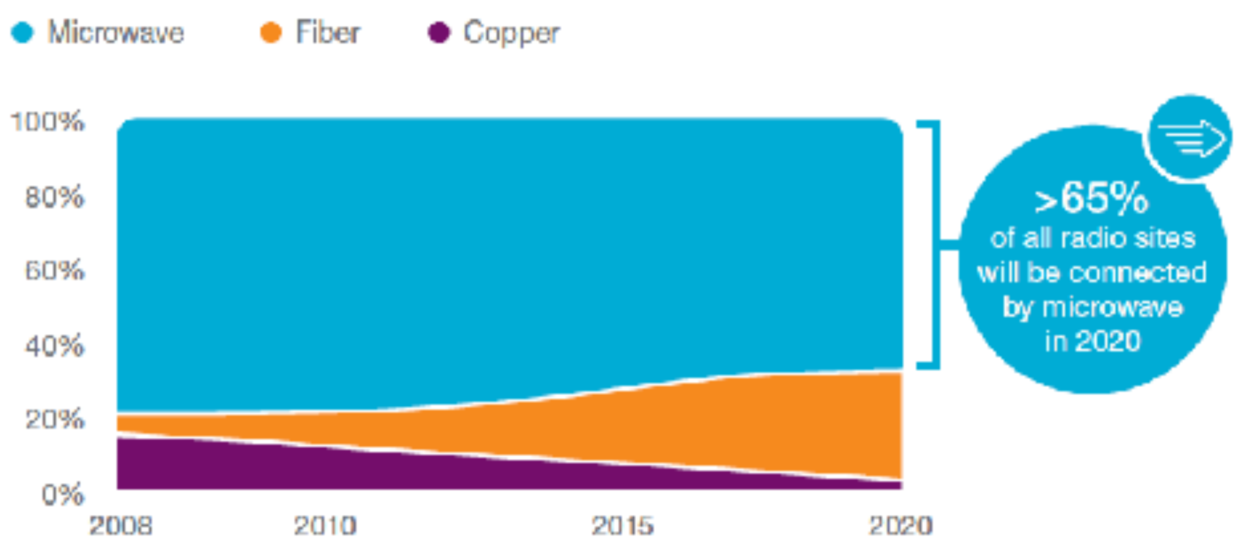


Figure 1 Microwave Application Scenario

Figure 3: Backhaul media distribution (excluding China, Japan, Korea and Taiwan)



Source: Ericsson (2015)

Figure 2: Backhaul capacity requirements per base station for operators at two different stages of mobile broadband evolution

Mobile broadband introduction	2015	2020
80% of sites	8 Mbps	25 Mbps
20% of sites	25 Mbps	90 Mbps
Few % of sites	90 Mbps	180 Mbps

Advanced mobile broadband	2015	2020
80% of sites	90 Mbps	270 Mbps
20% of sites	360 Mbps	1 Gbps
Few % of sites	1 Gbps	5/10 Gbps

Source: Ericsson (2015)

Faster-than-Nyquist transmission for wireless and optical fibre communication

I. Concept of FTN

II. Pragmatic approaches

III. Two case studies: some numerical results

Nyquist Signalling

$$s(t) = \sum_n a[n]h(t - nT)$$

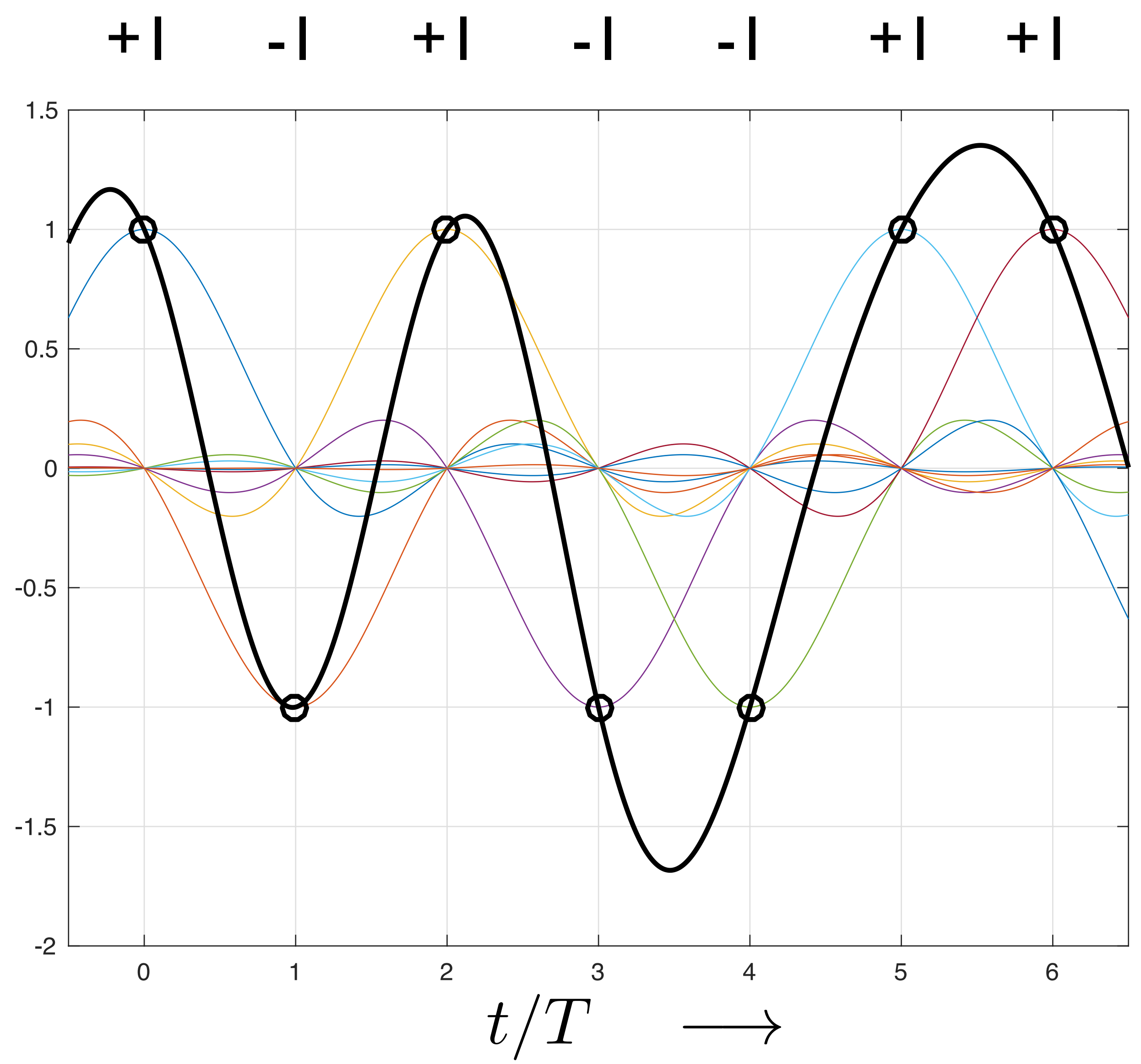
AWGN, matched filter

$$r(t) = \sum_n a[n]g(t - nT) + w(t)$$

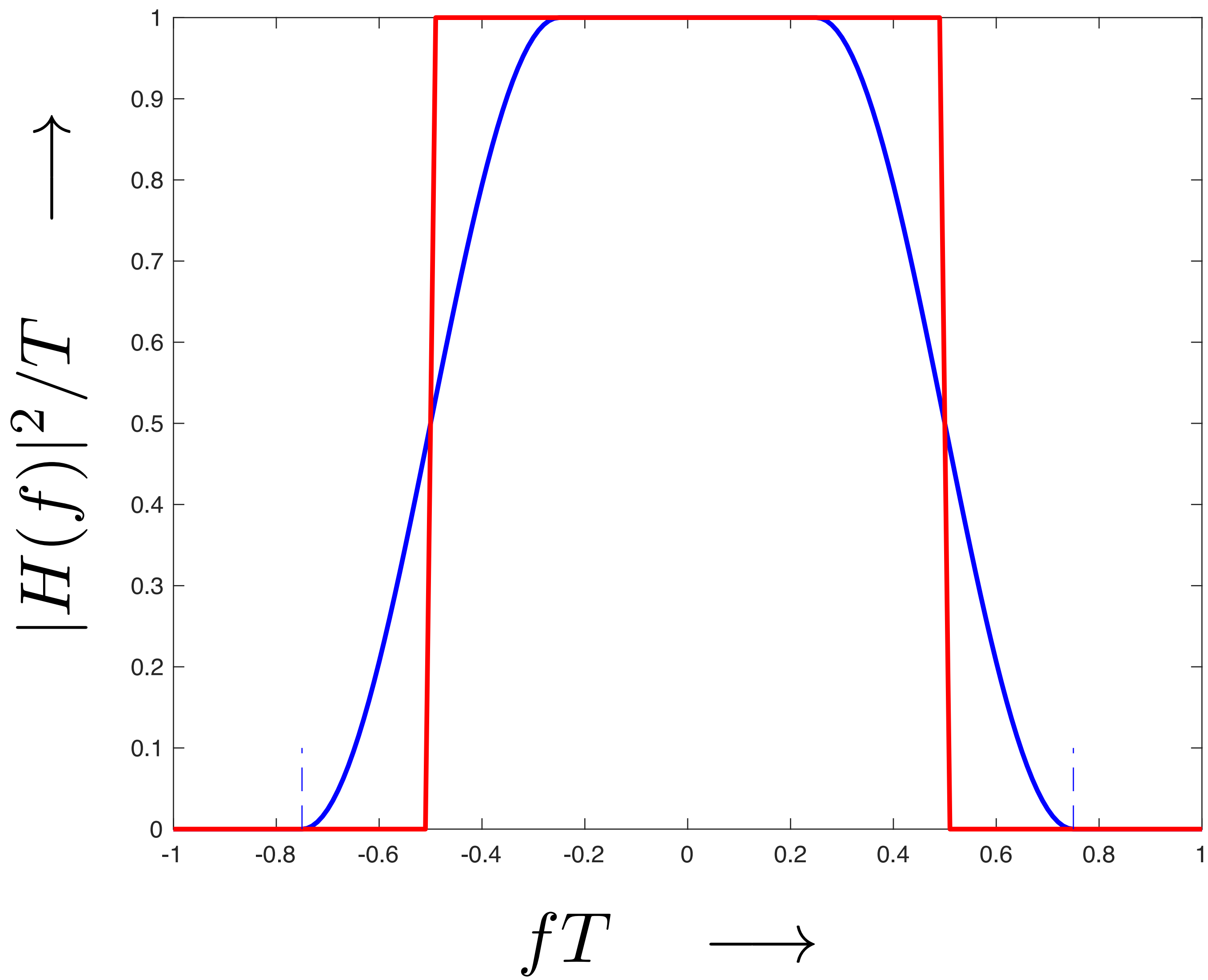
Nyquist pulse

Sampling

$$r[n] = a[n] + w[n]$$



Nyquist Signalling



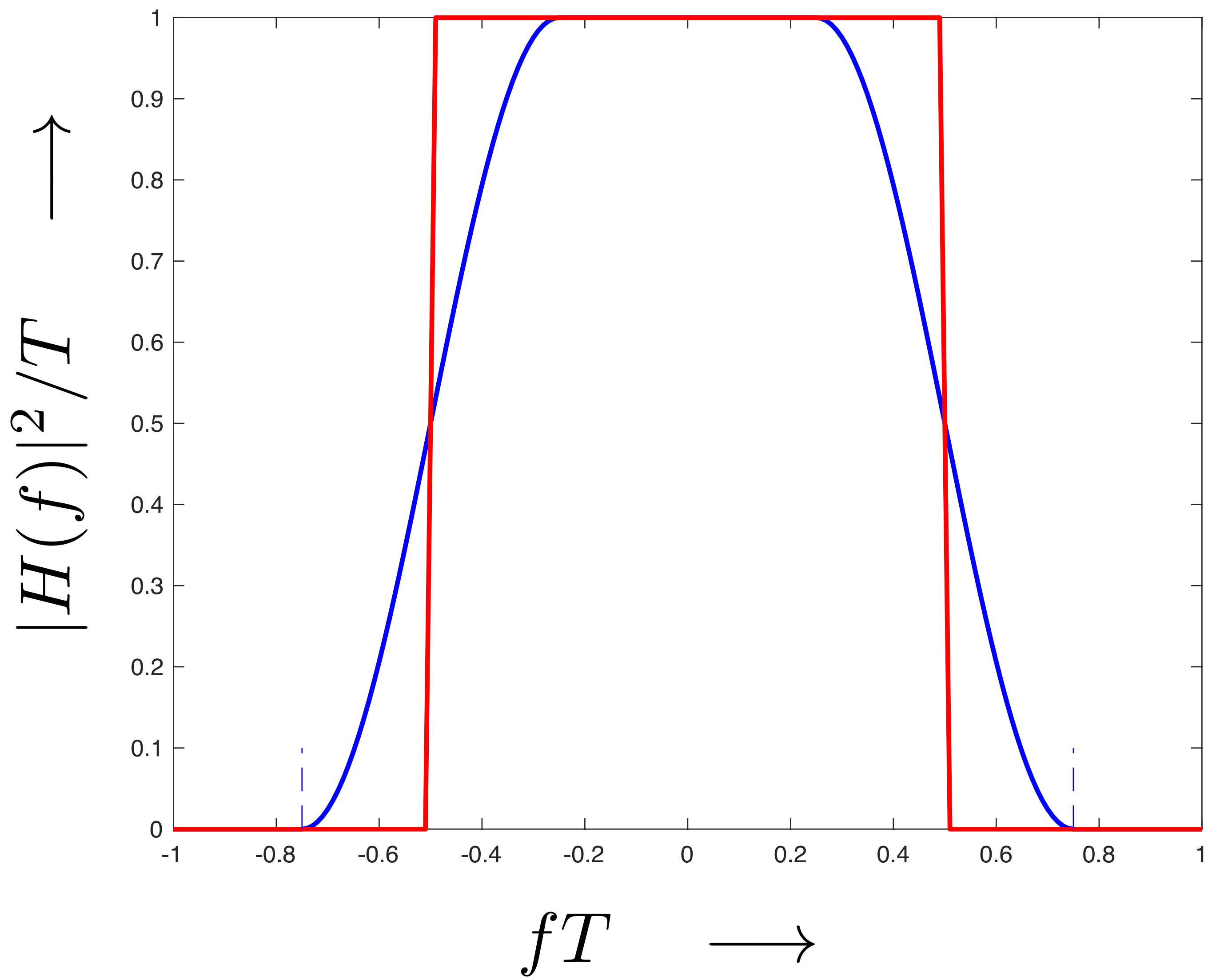
Achievable rate*:

$$C_{\mathrm{N}} = \frac{1}{T}\log_2\left(1 + \frac{P}{N_0/T}\right)$$

Observation: rate is independent of pulse shape

*complex baseband signal

Not Nyquist Signalling



Achievable rate*:

$$C = \int_{-\infty}^{\infty} \log_2\left(1 + \frac{P}{N_0}|H(f)|^2\right) df$$

$$= \int_{-W/2}^{W/2} \log_2\left(1 + \frac{P}{N_0}|H(f)|^2\right) df$$

$$\overset{W \geq \frac{1}{T}}{>} \frac{1}{T}\log_2\left(1 + \frac{P}{N_0/T}\right) = C_{\mathrm{N}}$$

*complex baseband signal

Faster-than-Nyquist Signalling

$$s(t) = \sum_n a[n] h(t - n\tau T) \qquad 0 < \tau \leq 1$$

Rate increases by a factor τ

Power is scaled: $P = \frac{\sigma_a^2}{\tau T}$

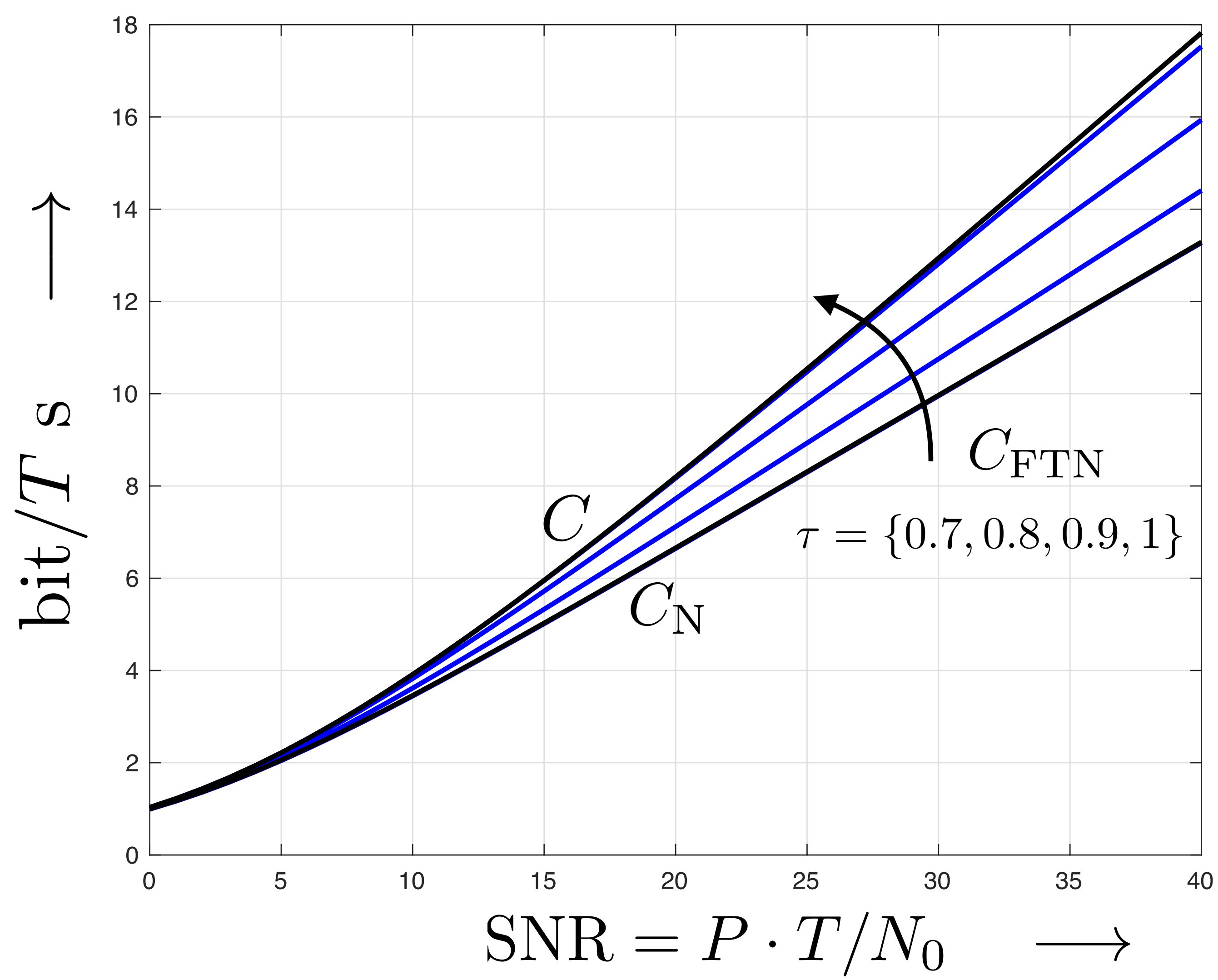
Faster-than-Nyquist Capacity

$$C_{\mathrm{FTN}} = \int_{-1/(2\tau T)}^{1/(2\tau T)} \log_2 \left(1 + \frac{P}{N_0} \sum_{k=-\infty}^{\infty} \left| H\left(f + \frac{k}{\tau T}\right) \right|^2 \right) df$$

$$\overset{\tau = 1/WT}{>} \quad C_{\mathrm{N}}$$

$$\overset{\tau = 1/WT}{=} \quad C$$

Observation: capacity increases with decreasing τ



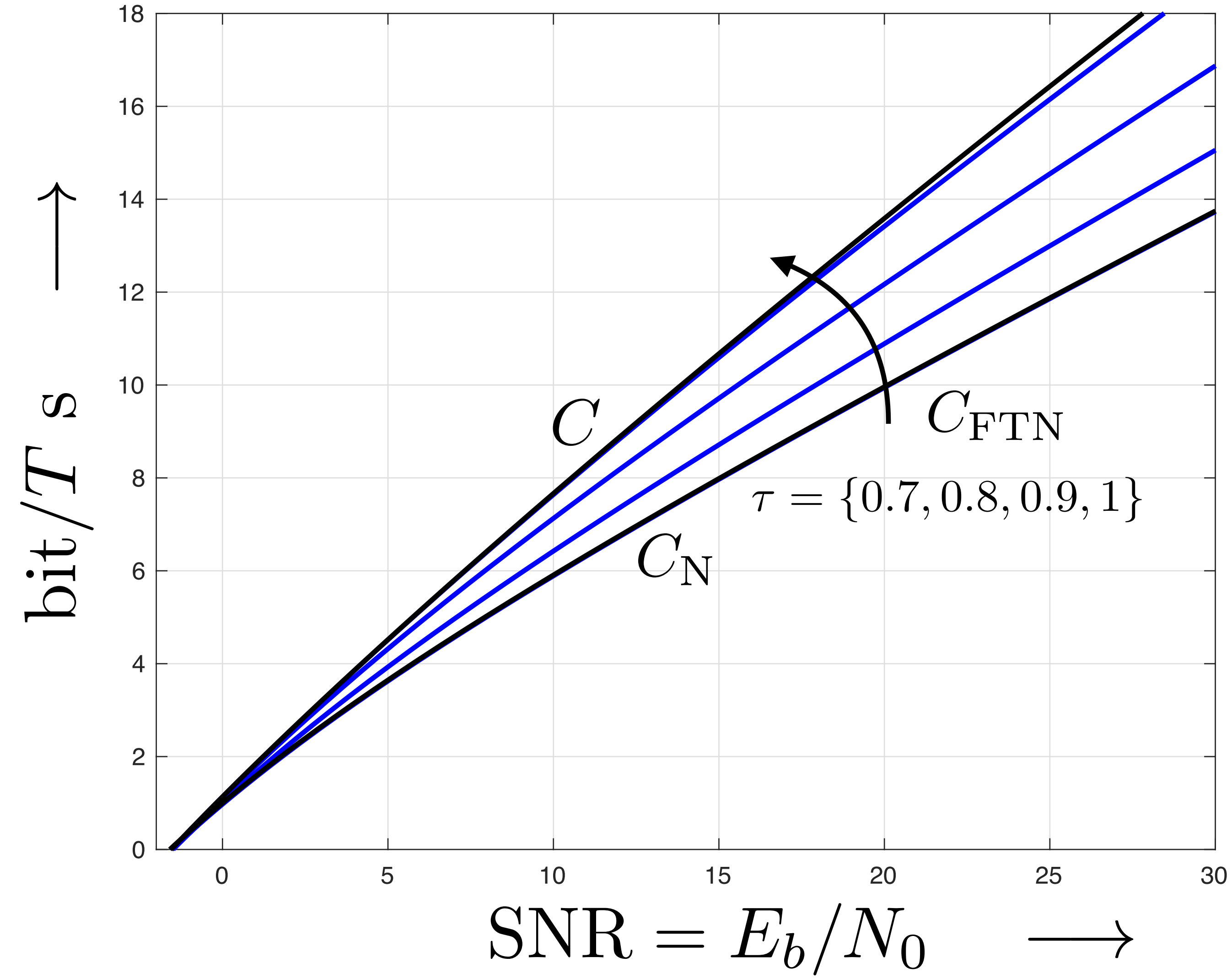
Faster-than-Nyquist Capacity

$$C_{\text{FTN}} = \int_{-1/(2\tau T)}^{1/(2\tau T)} \log_2 \left(1 + \frac{P}{N_0} \sum_{k=-\infty}^{\infty} \left| H\left(f + \frac{k}{\tau T}\right)\right|^2 \right) df$$

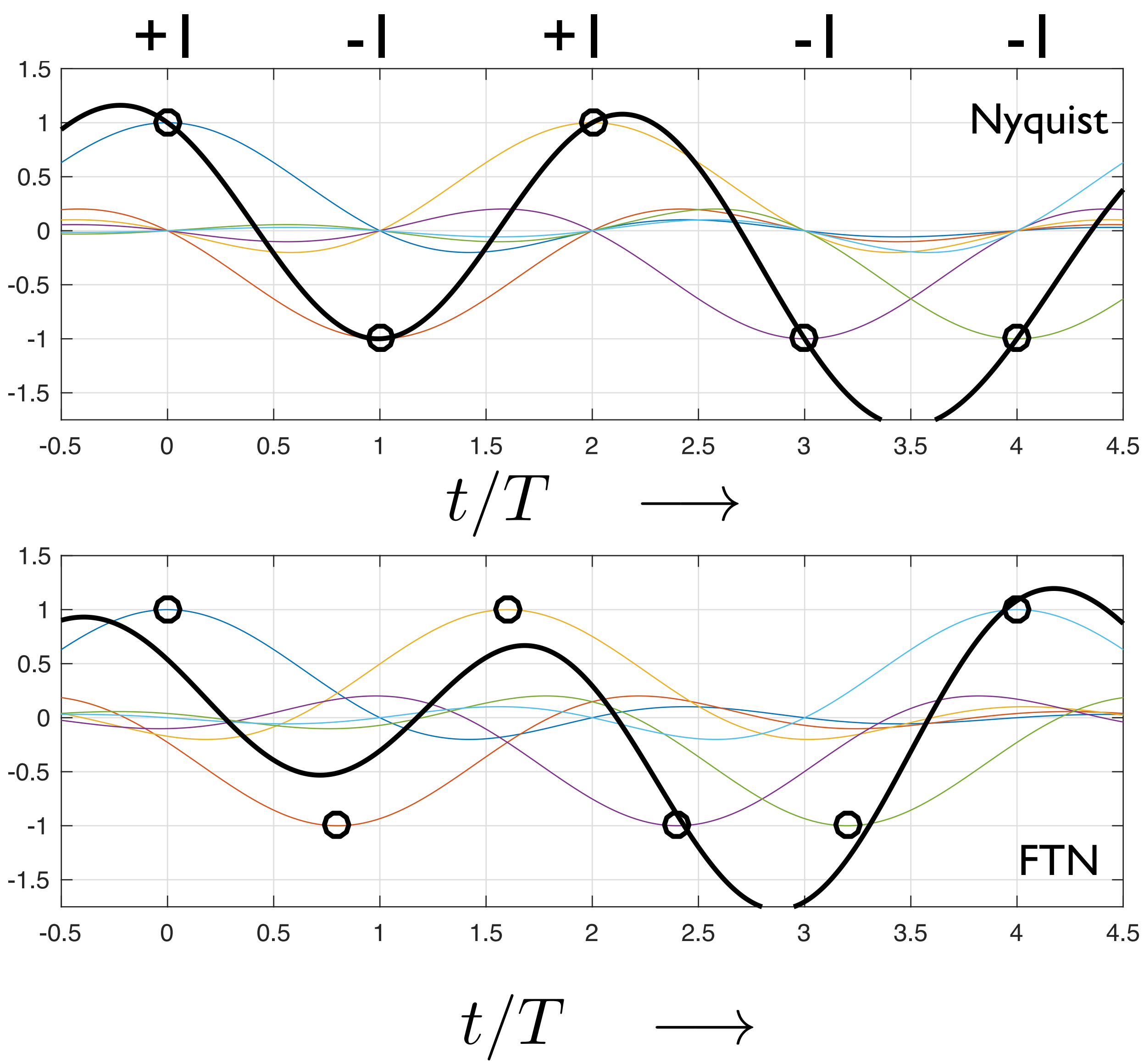
$$\overset{\tau = 1/WT}{>} \quad C_{\text{N}}$$

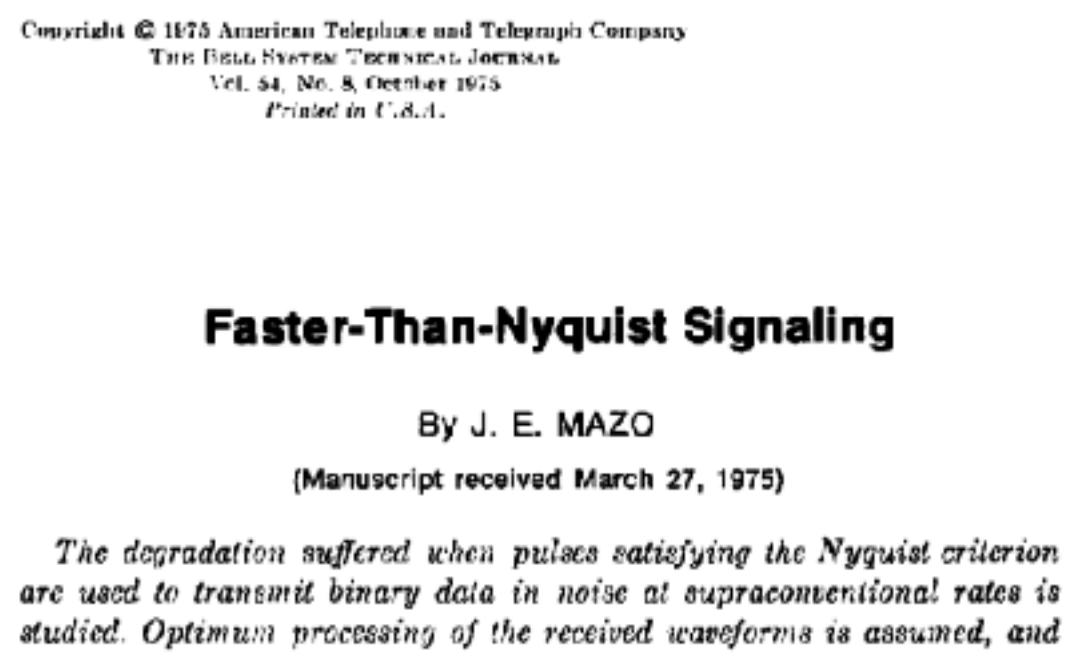
$$\overset{\tau = 1/WT}{=} \quad C$$

Observation:
capacity increases
with decreasing $\boldsymbol{\tau}$



Faster-than-Nyquist Distance





THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 54, No. 8, October 1975
Printed in U.S.A.

Faster-Than-Nyquist Signaling

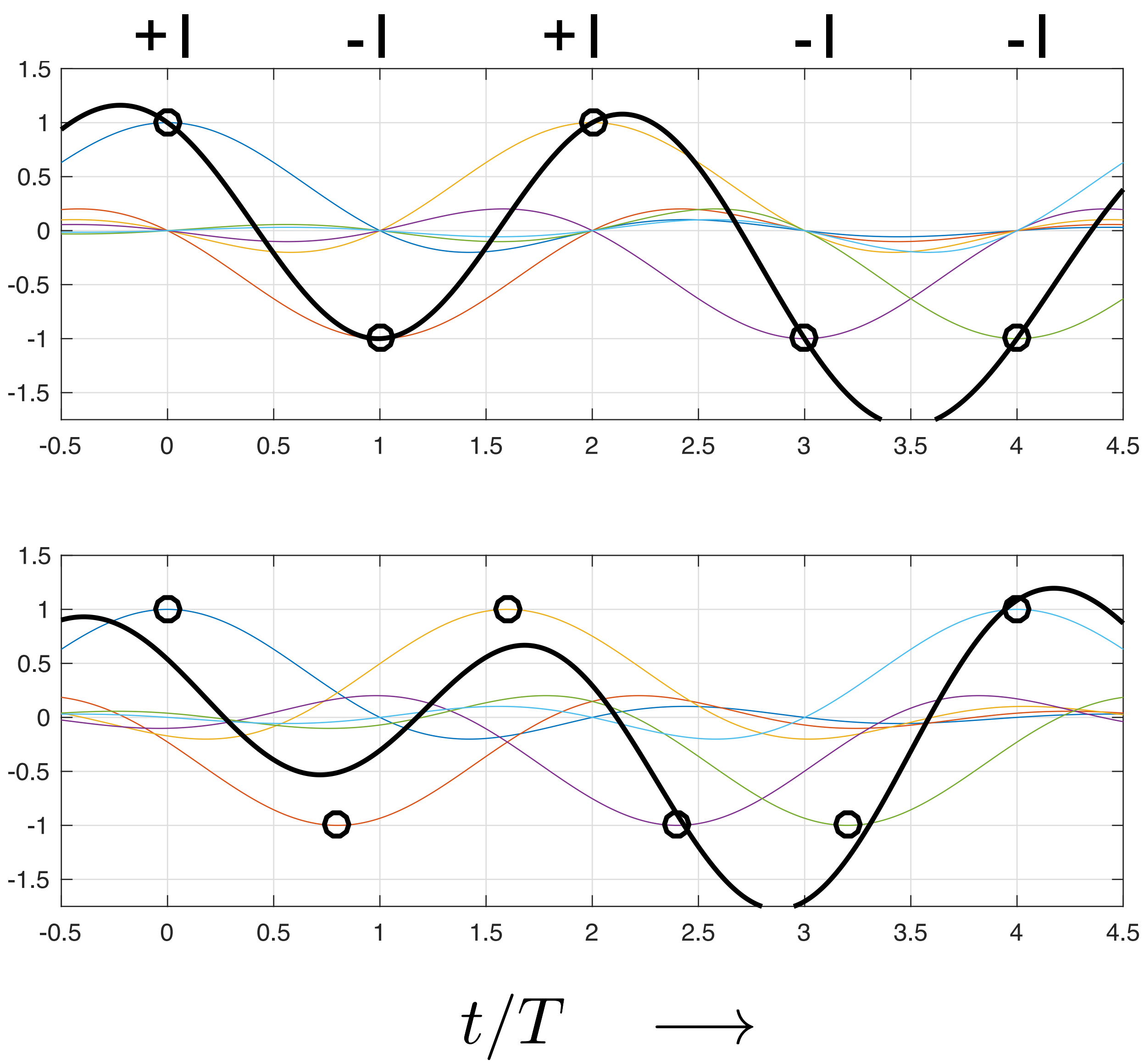
By J. E. MAZO

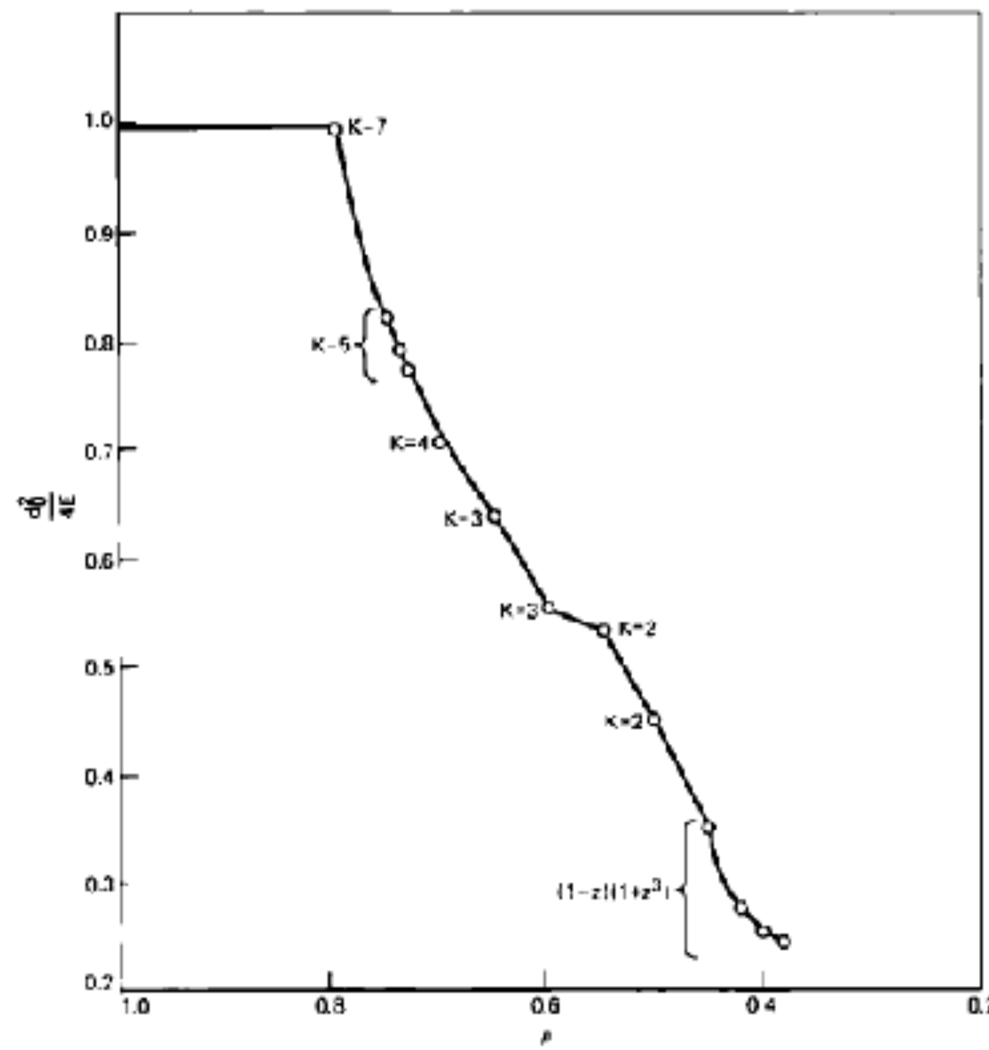
(Manuscript received March 27, 1975)

The degradation suffered when pulses satisfying the Nyquist criterion are used to transmit binary data in noise at supraconventional rates is studied. Optimum processing of the received waveforms is assumed, and

Observation: loss in eye opening …

Faster-than-Nyquist Distance





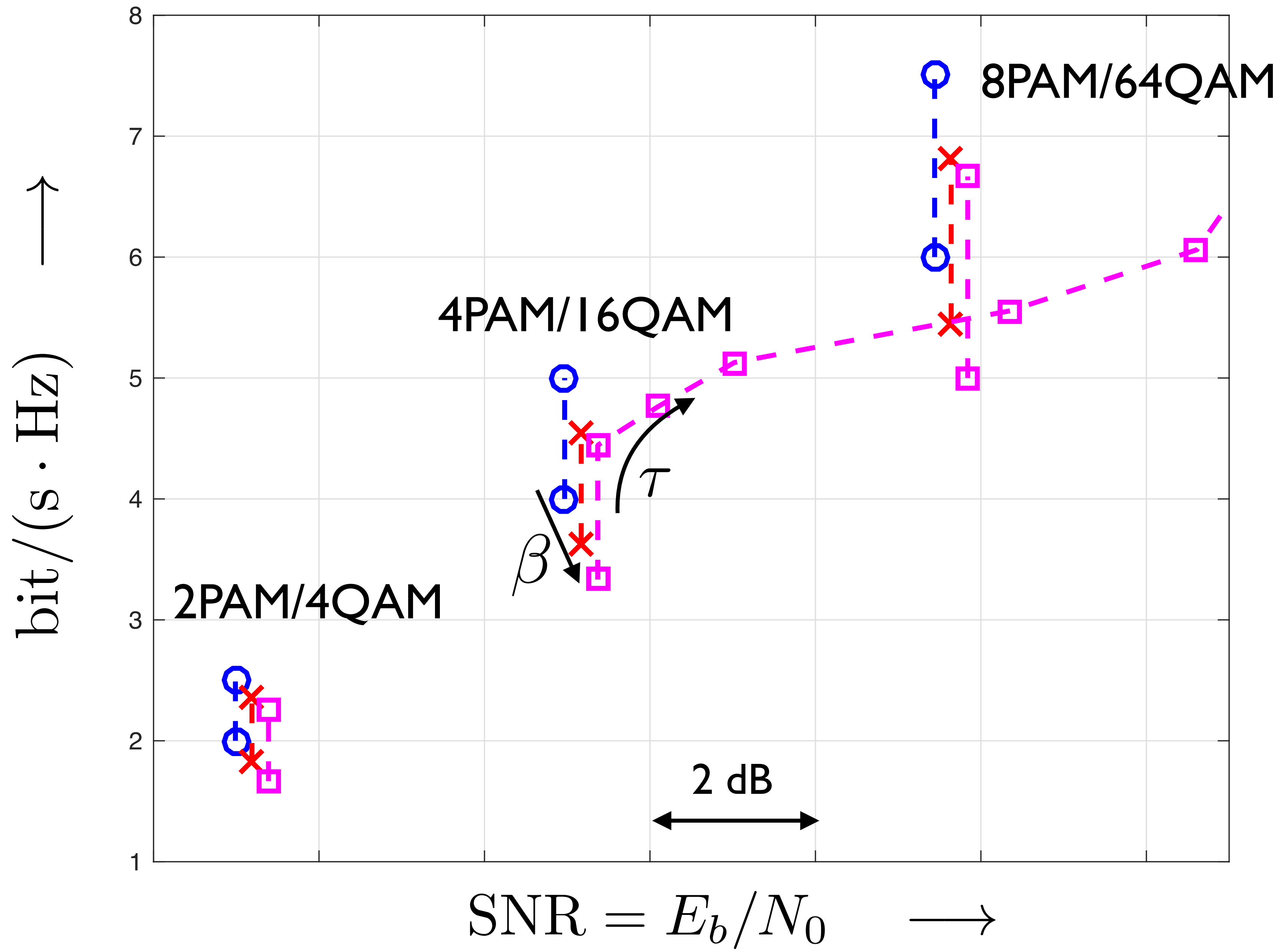
The Bell System Technical Journal
Vol. 54, No. 8, October 1975
Printed in U.S.A.

… but minimum distance retained

Faster-than-Nyquist Mazo Limit

Since d_{min} does not change, spectral efficiency increases for fixed E_b/N_0 *

beyond *Mazo limit*, trade-off between spectral and power efficiency



*absolute numbers need to be verified

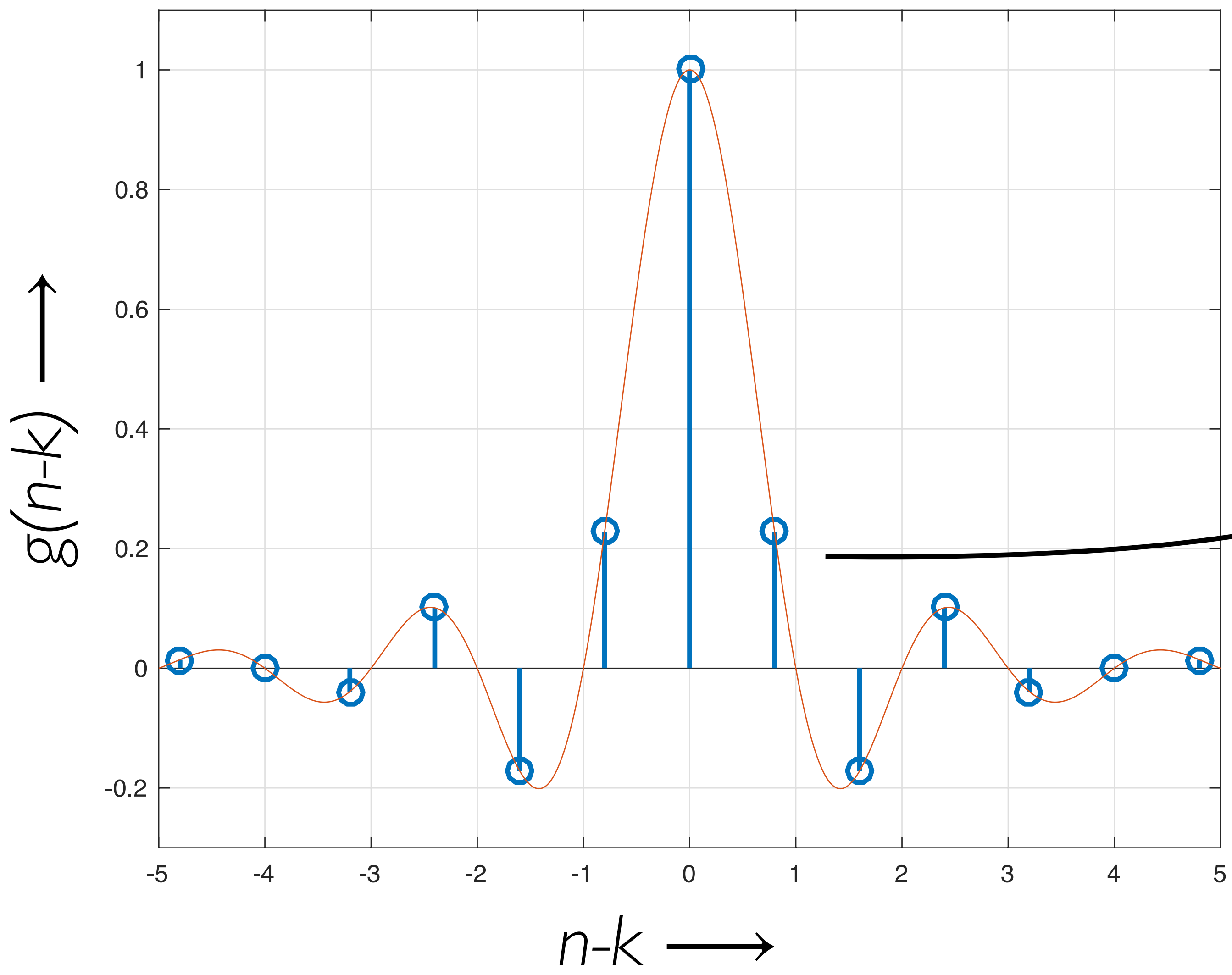
Faster-than-Nyquist transmission for wireless and optical fibre communication

I. Concept of FTN

II. Pragmatic approaches

III. Two case studies: some numerical results

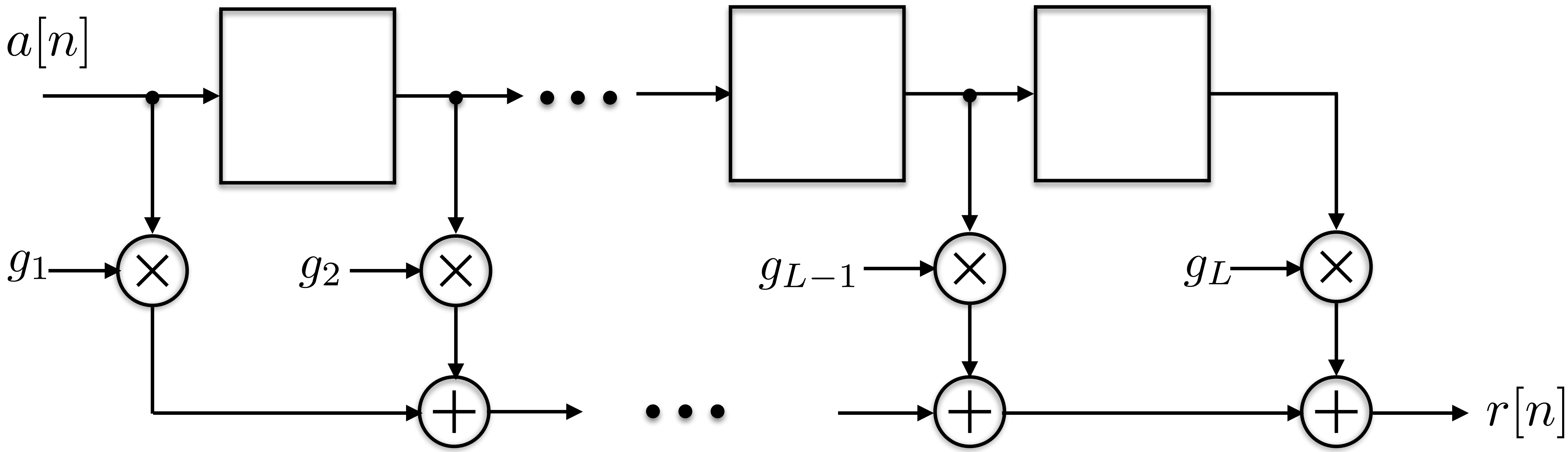
Faster-than-Nyquist ISI



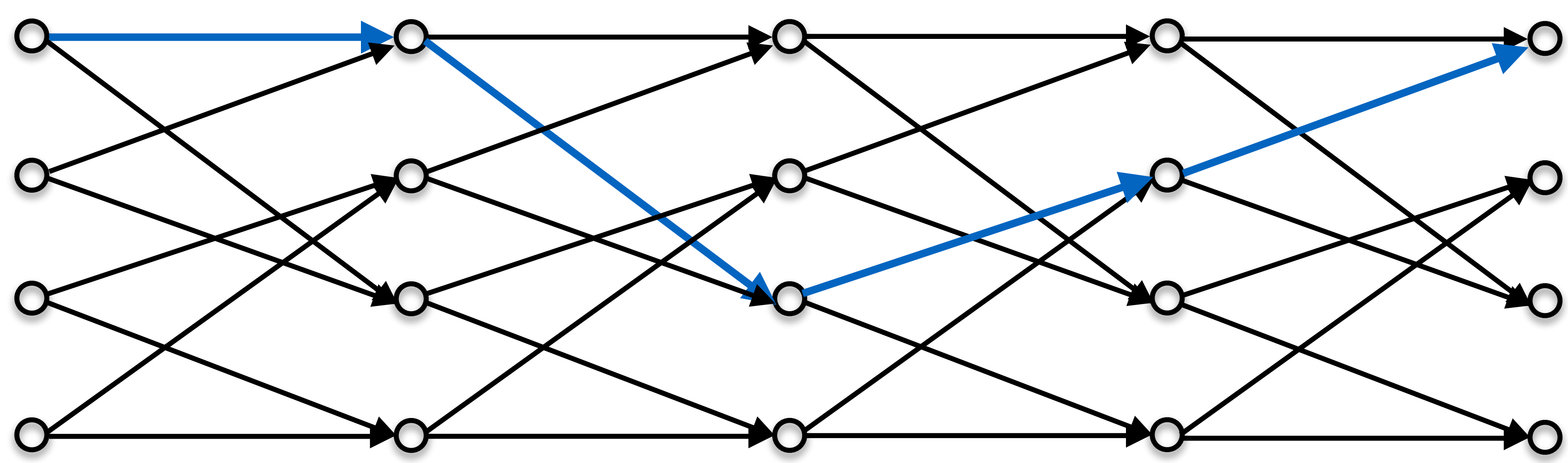
$$r[n] = \sum_k a[k]g(n-k) + w[n]$$

Intersymbol-interference (ISI) channel

Faster-than-Nyquist Equalization



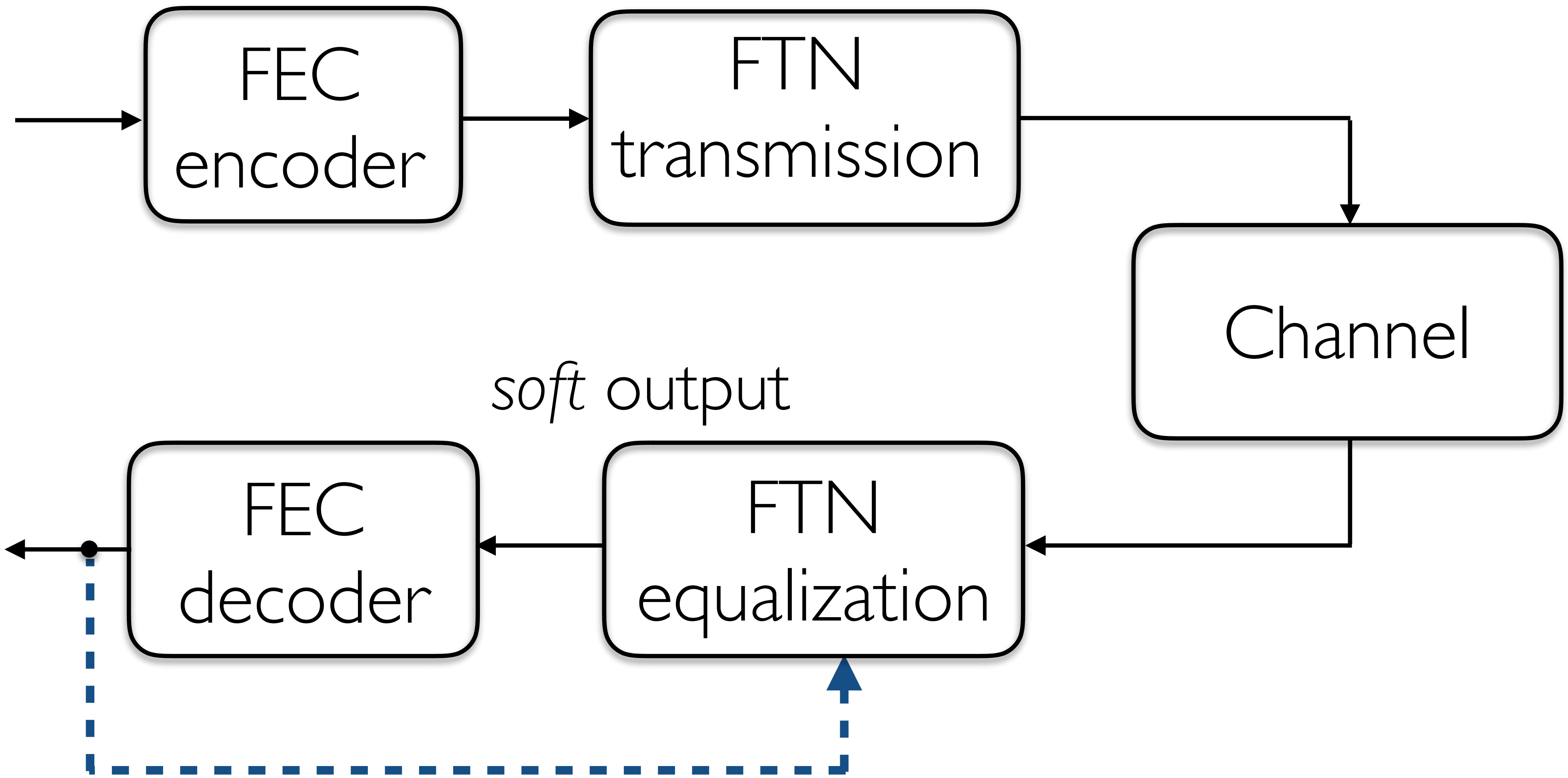
E.g. binary transmission, *L*=3



Faster-than-Nyquist Equalization

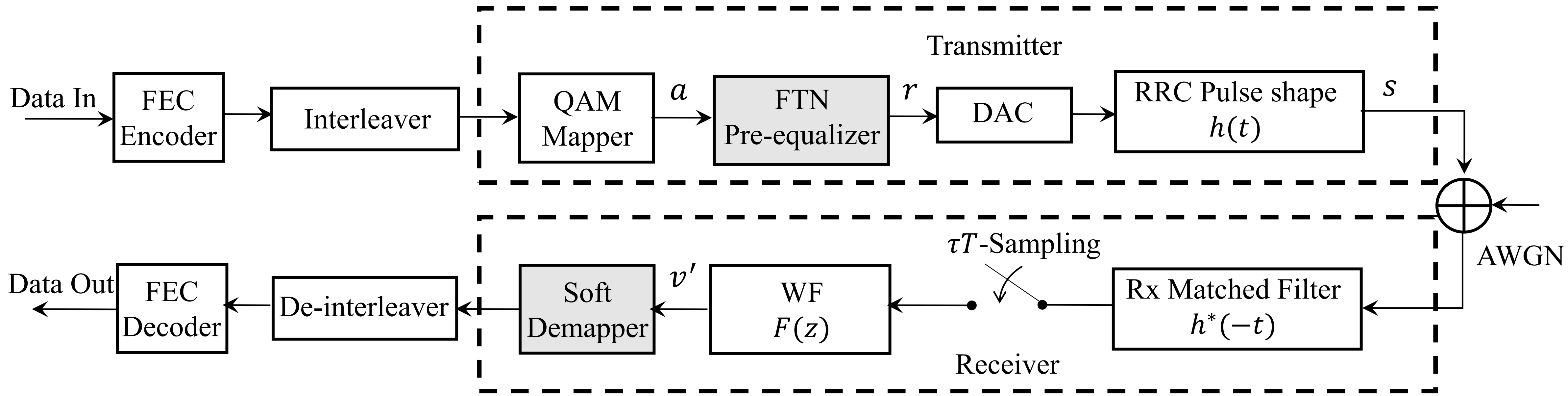
Method	Pro	Con
MLSE	performance optimal	complexity polynomial in constellation size and exponential in *L*
RSSE **M-algorithm**	close to optimal performance with reduced complexity	relatively high complexity
DFE **Linear**	complexity independent of constellation size and about linear in *L*	performance loss
FDE	reduce complexity further through filtering via FFT	possibly use of cyclic prefix
Relaxed combinatorial optimization	complexity independent of constellation size and polynomial in *L*	block based and complexity polynomial in block size, requires random trials

Faster-than-Nyquist Coding



Turbo equalization

Faster-than-Nyquist Prequalization



Tomlison-Harashima Precoding

Linear Precoding

© M. Jana, A. Mehdra, L. Lampe, J. Mitra "Pre-equalized Faster-than-Nyquist Transmission," IEEE Transactions on Communications, vol. 65, no. 10, pp. 4406-4418, October 2017.

Faster-than-Nyquist Equalization

Method	Pro	Con
MLSE	performance optimal	complexity polynomial in constellation size and exponential in *L*
RSSE M-algorithm	close to optimal performance with reduced complexity	relatively high complexity
DFE **Linear**	complexity independent of constellation size and about linear in *L*	performance loss
FDE	reduce complexity further through filtering via FFT	possibly use of cyclic prefix
Relaxed combinatorial optimization	complexity independent of constellation size and polynomial in *L*	block based and complexity polynomial in block size, requires random trials
Precoding	low complexity, high performance	application to limited FTN acceleration range

Faster-than-Nyquist Complications

Synchronization	No excess bandwidth for timing synchronization Varying signal amplitude complicates carrier-phase estimation
Channel estimation	Effective constellation changes due to FTN signalling is a challenge for pilot-based and blind channel estimation
Peak-to-average power ratio	Generally increases

Faster-than-Nyquist transmission for wireless and optical fibre communication

I. Concept of FTN

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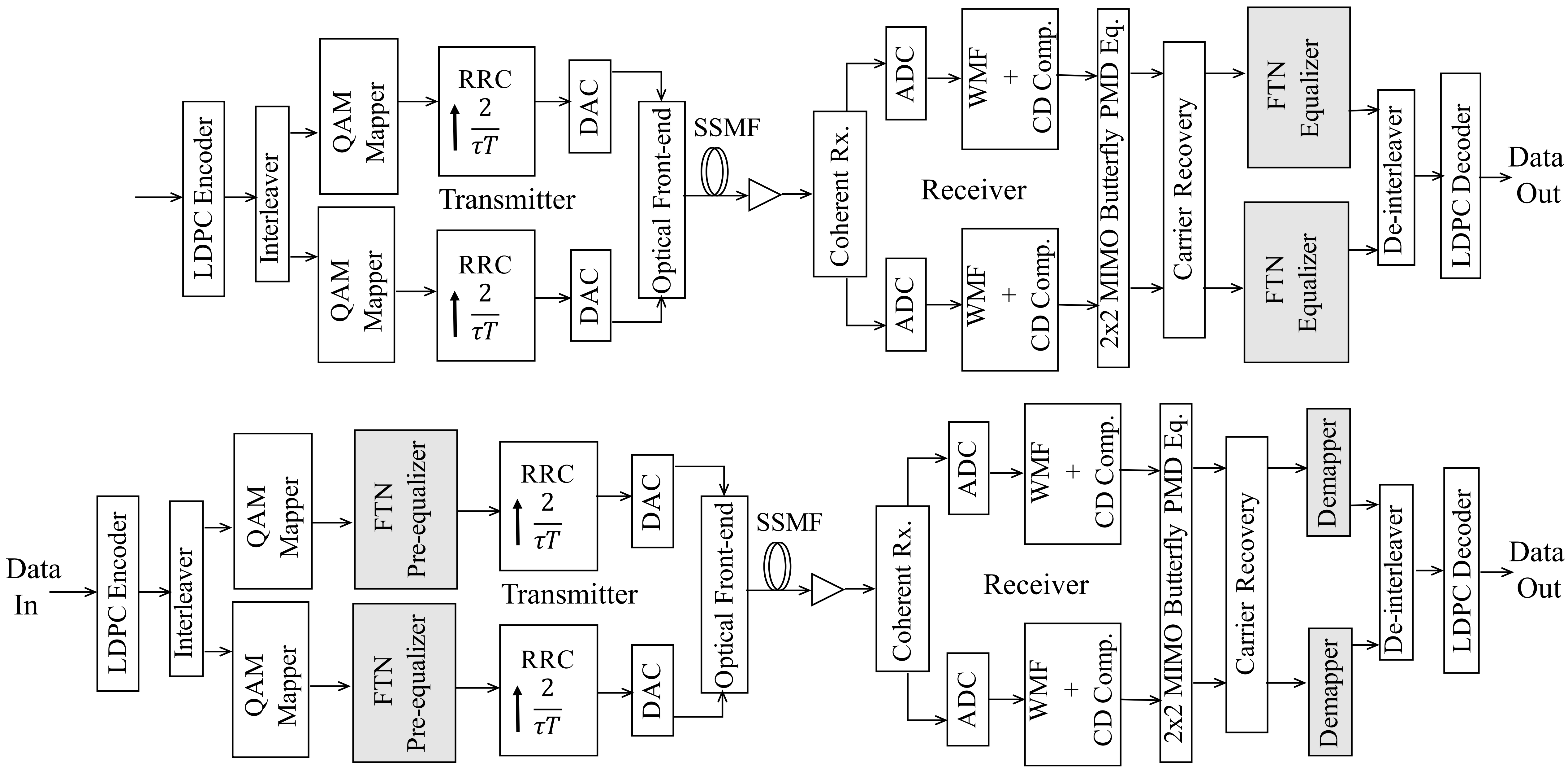
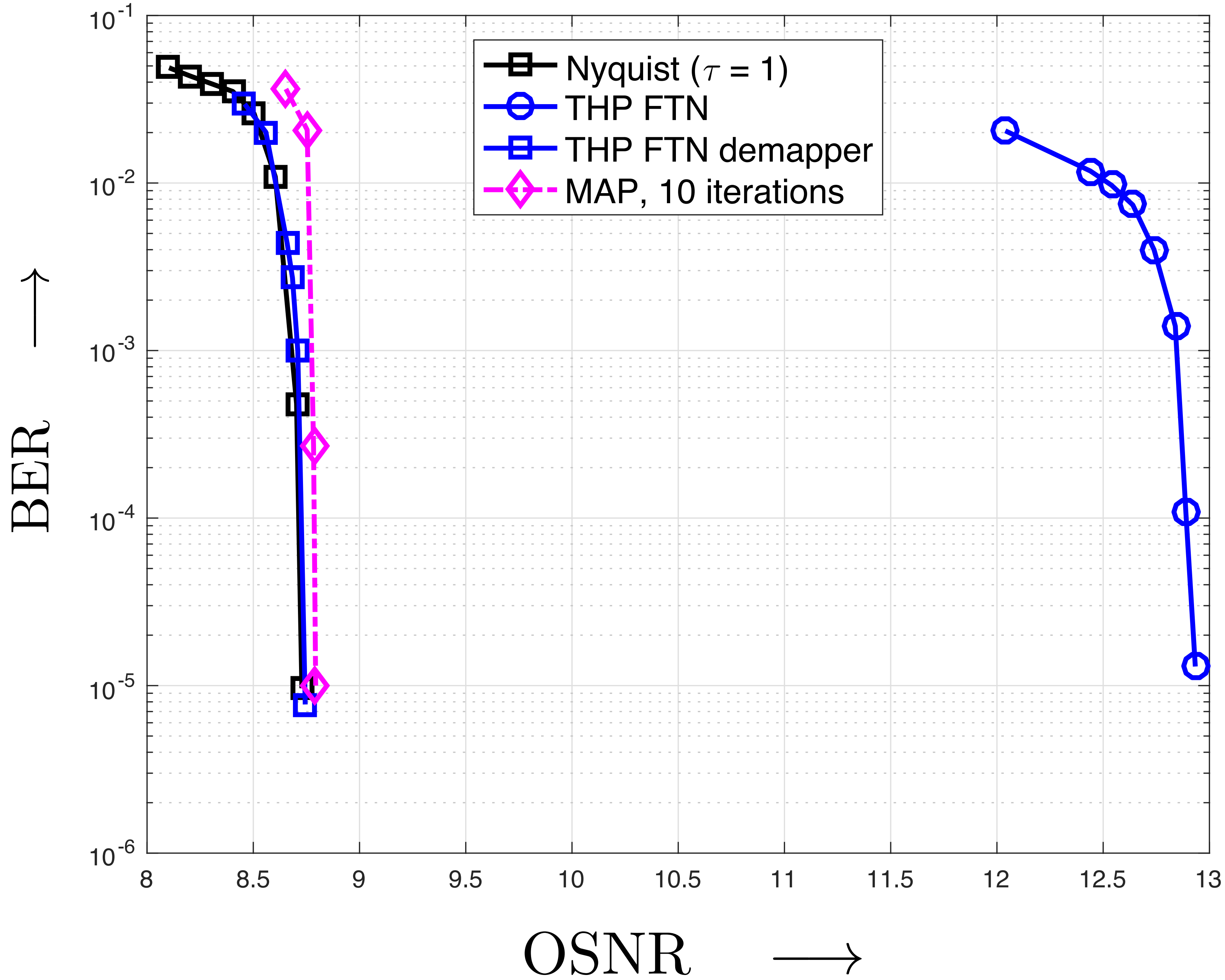
III. Two case studies: some numerical results

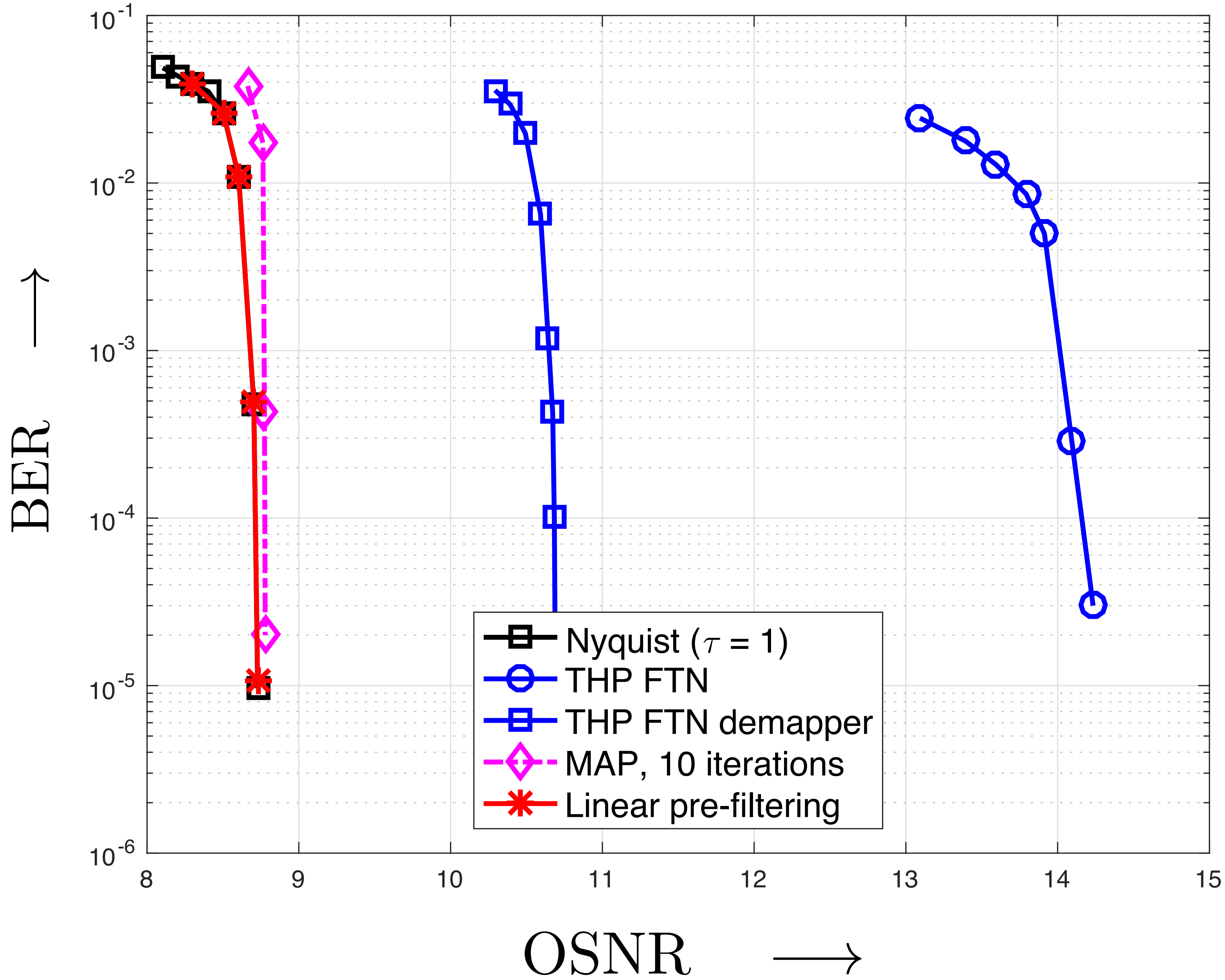
Optical Fibre Communication



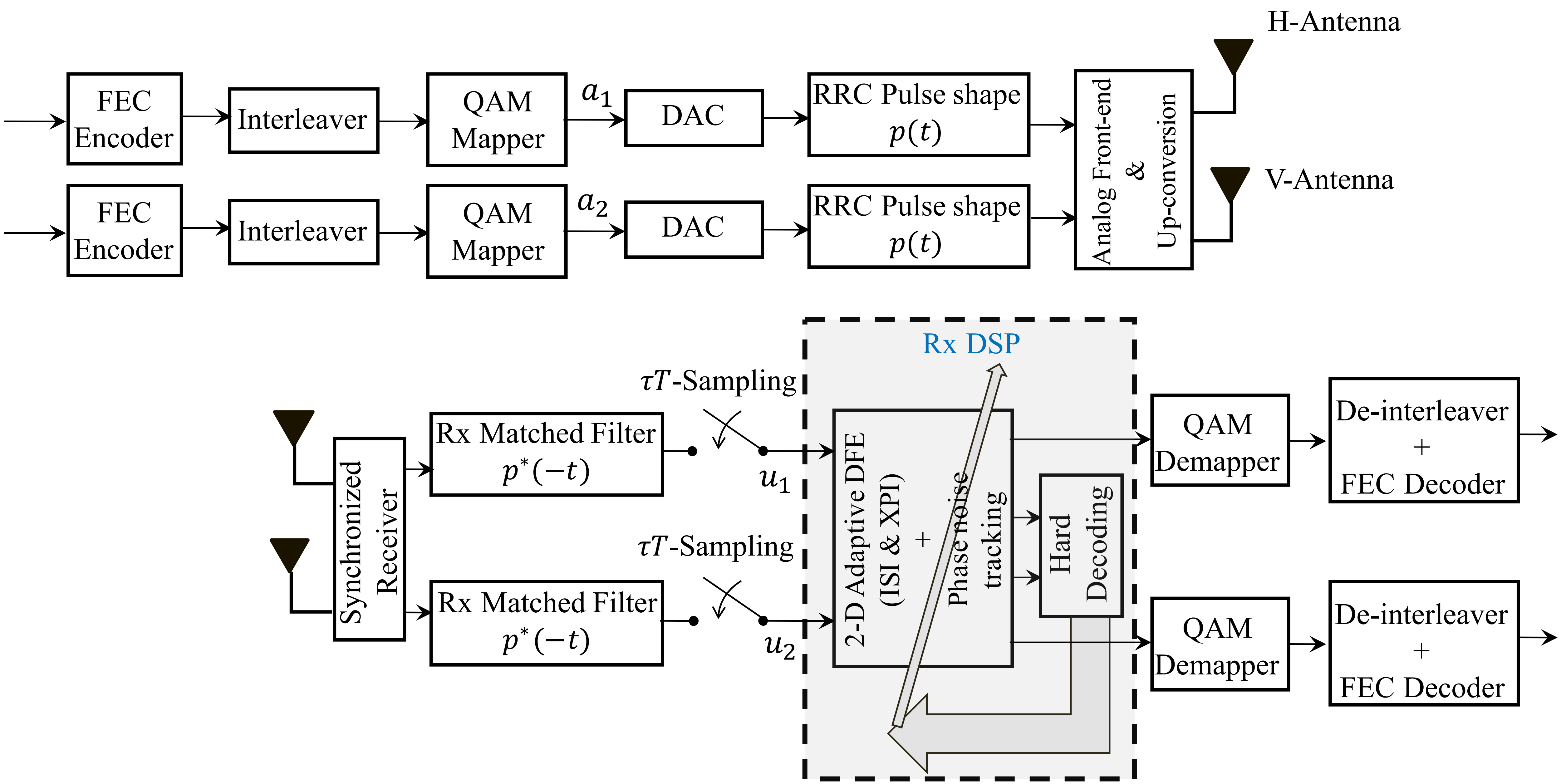
QPSK, roll-off 0.3, optical comms setting, fixed baud rate
τ=0.85



QPSK, roll-off 0.3, optical comms setting, fixed baud rate
τ=0.80

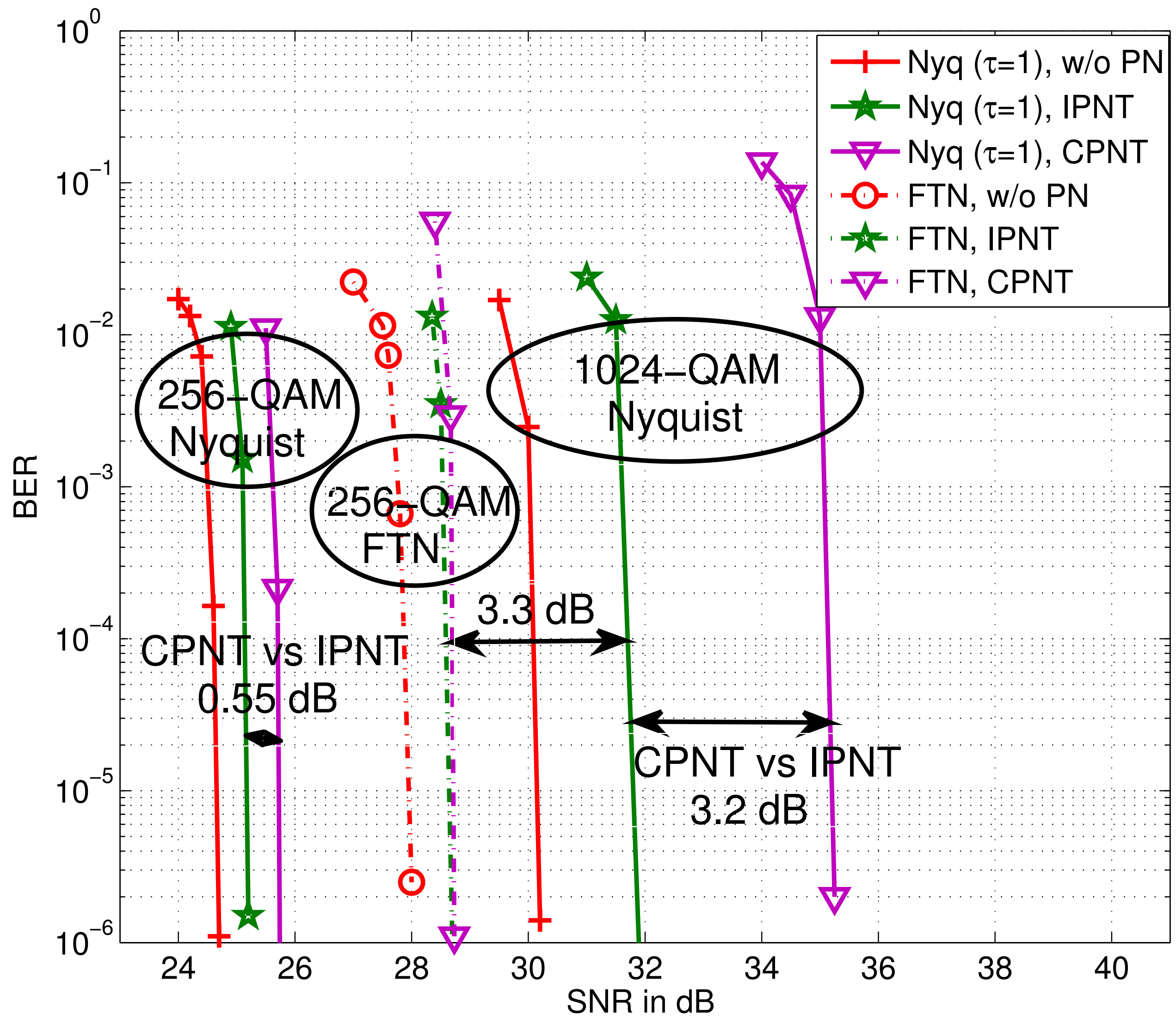


Microwave Communication



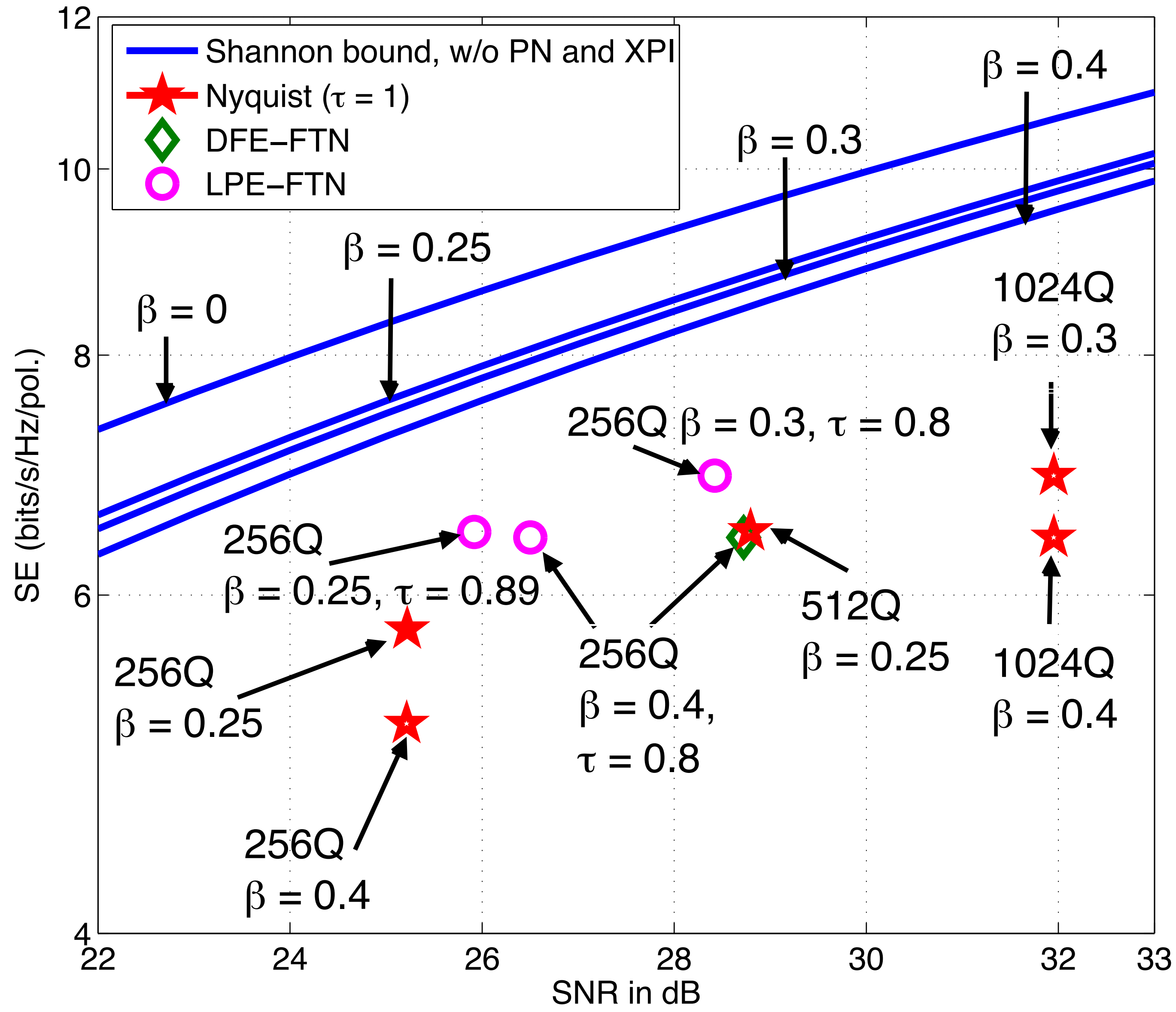
M. Jana, L. Lampe, J. Mitra "Dual-polarized Faster-than-Nyquist Transmission Using Higher-order Modulation Schemes," IEEE SPAWC 2018.

Dual-polarized FTN transmission over microwave channel with phase noise, roll-off 0.4, τ=0.80



M. Jana, L. Lampe, J. Mitra "Dual-polarized Faster-than-Nyquist Transmission Using Higher-order Modulation Schemes," IEEE SPAWC 2018.

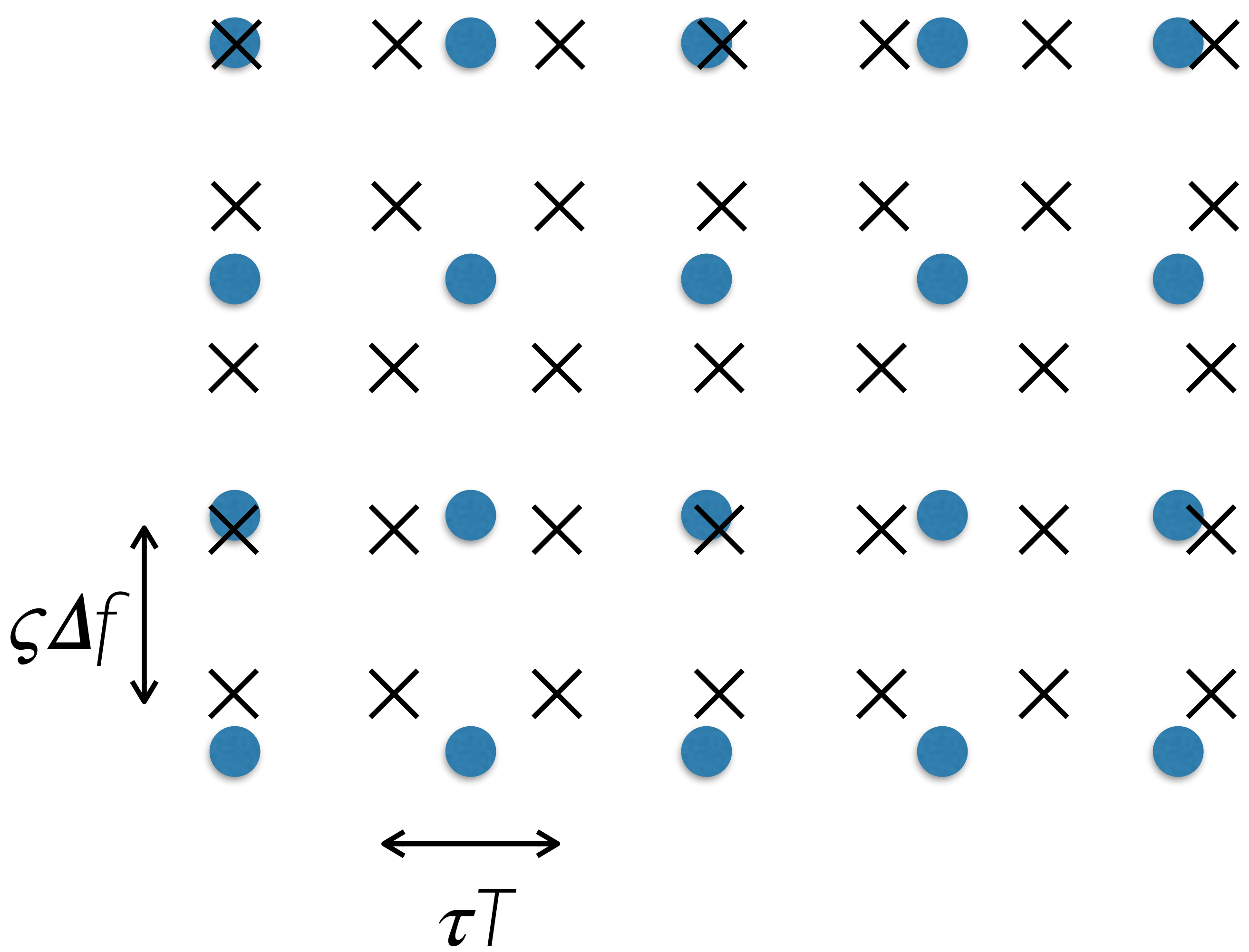
Dual-polarized FTN transmission over microwave channel with phase noise, spectral efficiency (SE)



M. Jana, L. Lampe, J. Mitra "Dual-polarized Faster-than-Nyquist Transmission Using Higher-order Modulation Schemes," IEEE SPAWC 2018.

Faster-than-Nyquist Extension

2D (time-frequency packing)



a good number of works …

Application domain

Faster-Than-Nyquist Signal Design for Multiuser Multicell Indoor Visible Light Communications, IEEE Photonics Journal, 2016

Faster-Than-Nyquist Precoded CAP Modulation Visible Light Communication System Based on Nonlinear Weighted Look-Up Table Predistortion, IEEE Photonics Journal, 2018

Polar coding for faster-than-Nyquist signaling, IEEE/CIC International Conference on Communications in China (ICCC), 2017

Faster-than-Nyquist Transmission

Makes use of excess bandwidth to transmit data

Improves rate in non-(modulation-interference) limited systems

Alternative/complement to larger constellation sizes

Requires equalization, changes to synchronization, channel estimation etc

Pre-filtering is akin to pulse-shaping and partial-response transmission