Technical Groups

Emerging Waveform Technology for 6G Optical and Wireless Access

Featuring Xing Ouyang from Tyndall National Institute

15 February 2023

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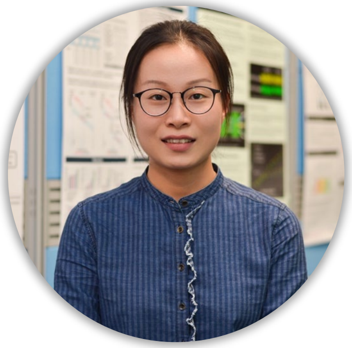

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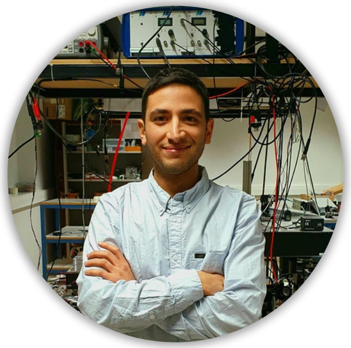

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About Our Technical Group

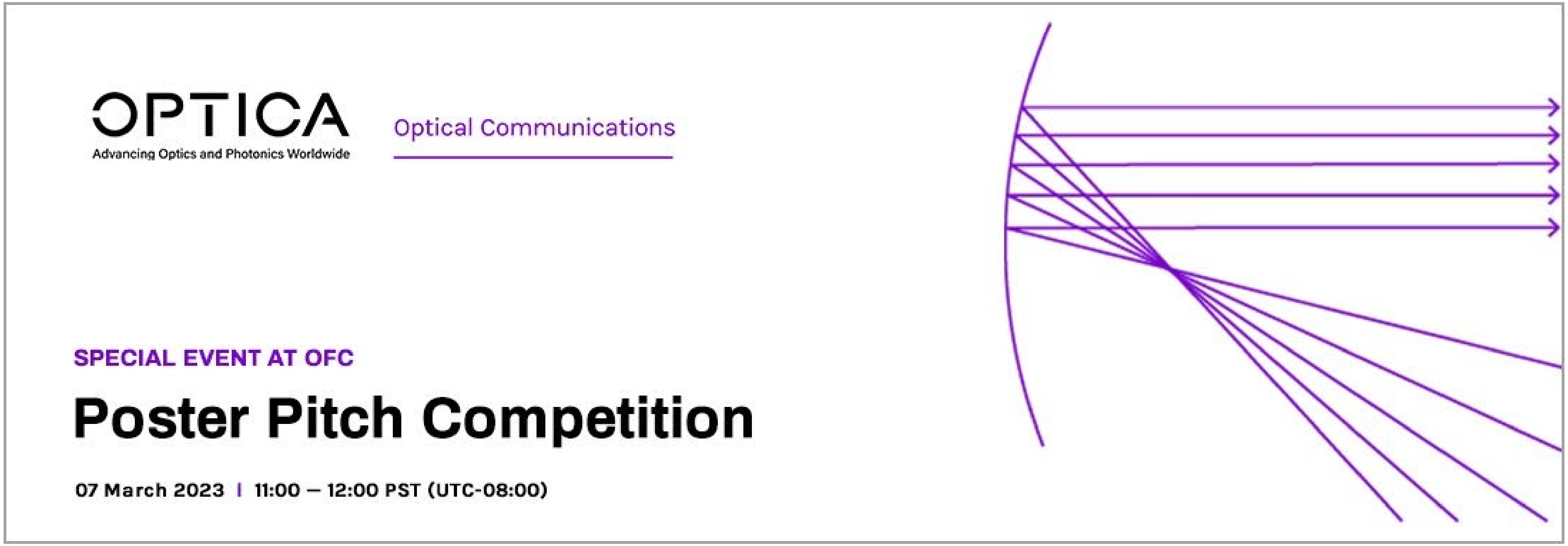
Our technical group deals with aspects of optical transmission ranging from chip-to-chip to ultra-short haul to long haul links. It deals with aspects of optical networking, coding and decoding of information onto photons, optical signal processing and other transmission-related aspects.

Our mission is to connect the 3800+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Research Lab Stories: Special Event at OFC 2022, featuring Dr Mable Fok, Prof Darko Zibar, Prof Liam Barry, Prof Deepa Venkitesh
- Copackaged Silicon Photonics based Optical Transceivers for high-speed data-center interconnects by Dr Jahnavi Sharma

Upcoming Events



Q2 Tutorial : Coherent Optical Communication

Q2 Webinar : Quantum Communication

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/PC
- Our LinkedIn group www.linkedin.com/groups/12607066/
- Our Facebook group www.facebook.com/groups/OpticaOpticalCommunications
- Email us at TGactivities@optica.org

Today’s Speaker

Dr. Xing Ouyang

Tyndall National Institute, Ireland

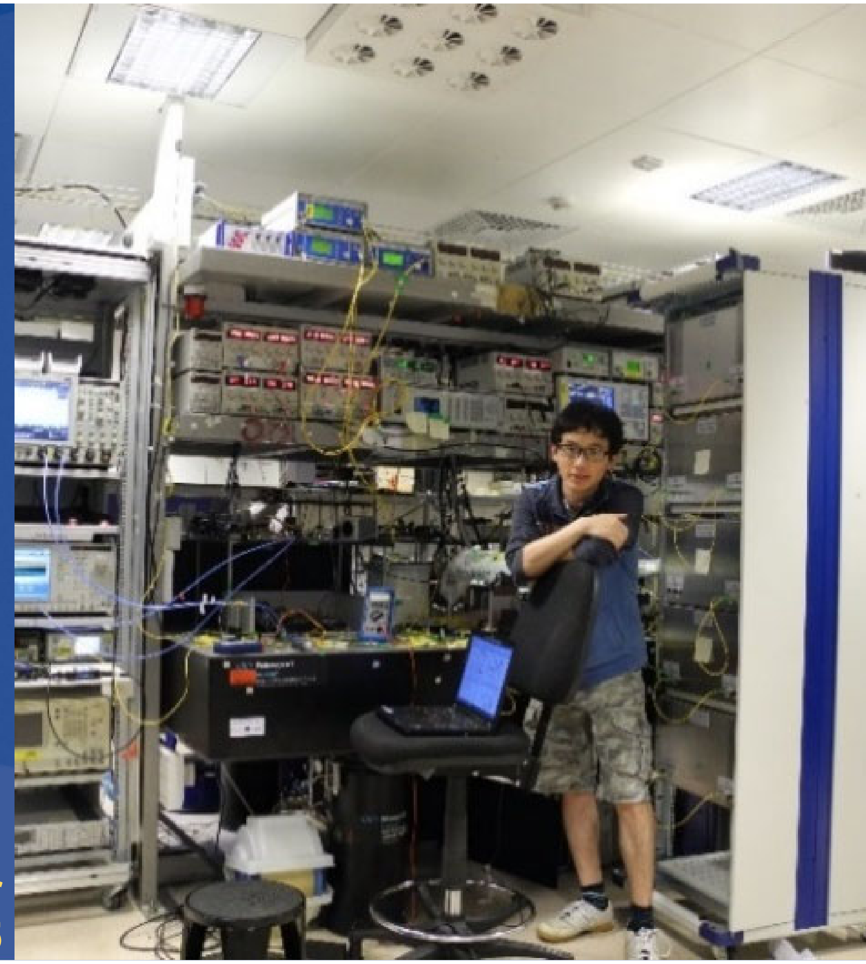
Xing Ouyang is a Research Fellow at the Tyndall National Institute and University College Cork, Ireland. Xing completed his Ph.D. thesis in 2017 from the Photonic Systems Group of the SFI Irish Photonics Integration Centre led by Prof. Paul Townsend in Ireland.

His current research interest includes information theory, advanced modulation formats such as OCDM and OFDM and DSP techniques for communication and radar, high speed wireless and optical systems. His work on the orthogonal chirp division multiplexing waveform has helped him to secure a start-up grant for the “ChirpComm” initiative. Xing has recently secured a prestigious Starting and Consolidator Laureate Award from the Irish Research Council to further advance his ChirpComm technology.

Emerging Waveform Technology for 6G Optical and Wireless Access

Xing Ouyang
Tyndall National Institute, University College Cork
Email: xing.ouyang@tyndall.ie

Optical Communications Technical Group Webinar
2023.02.15



Outline

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  - ➢ A Brief History
  - ➢ Waveform Modulation Technologies
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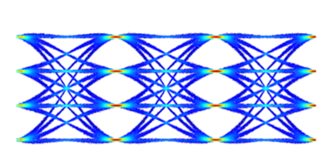
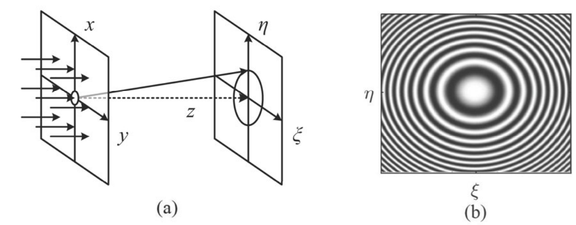
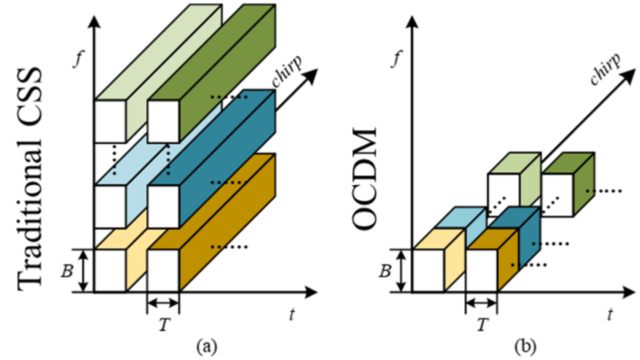
  - ➢ Chirps are Everywhere
  - ➢ From Fresnel Diffraction to (Discrete) Fresnel Transform
  - ➢ OCDM
- ❑ **Applications and Current Progress**
  - ➢ Wireless Access Systems
  - ➢ Fiber-Optic and Radio-over-Fiber Systems
  - ➢ What’s More
- ❑ **Conclusion and Outlook**







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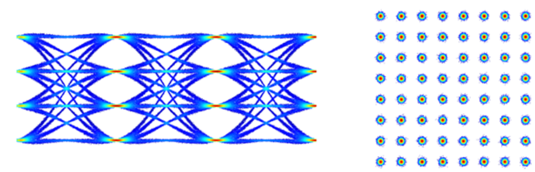
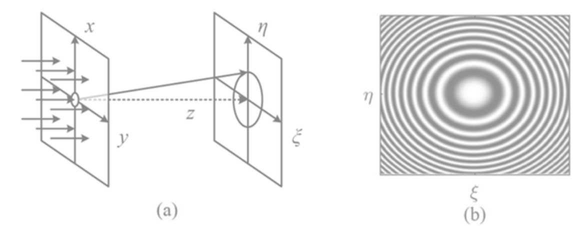
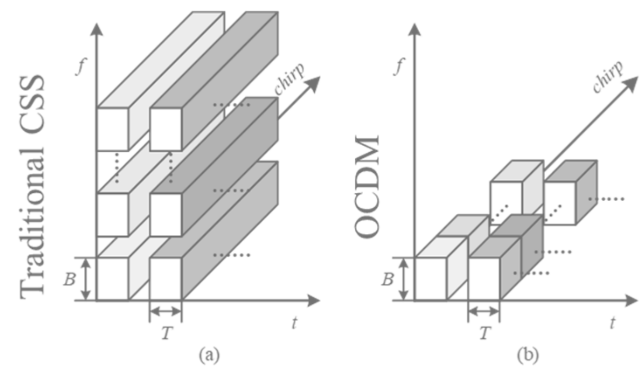
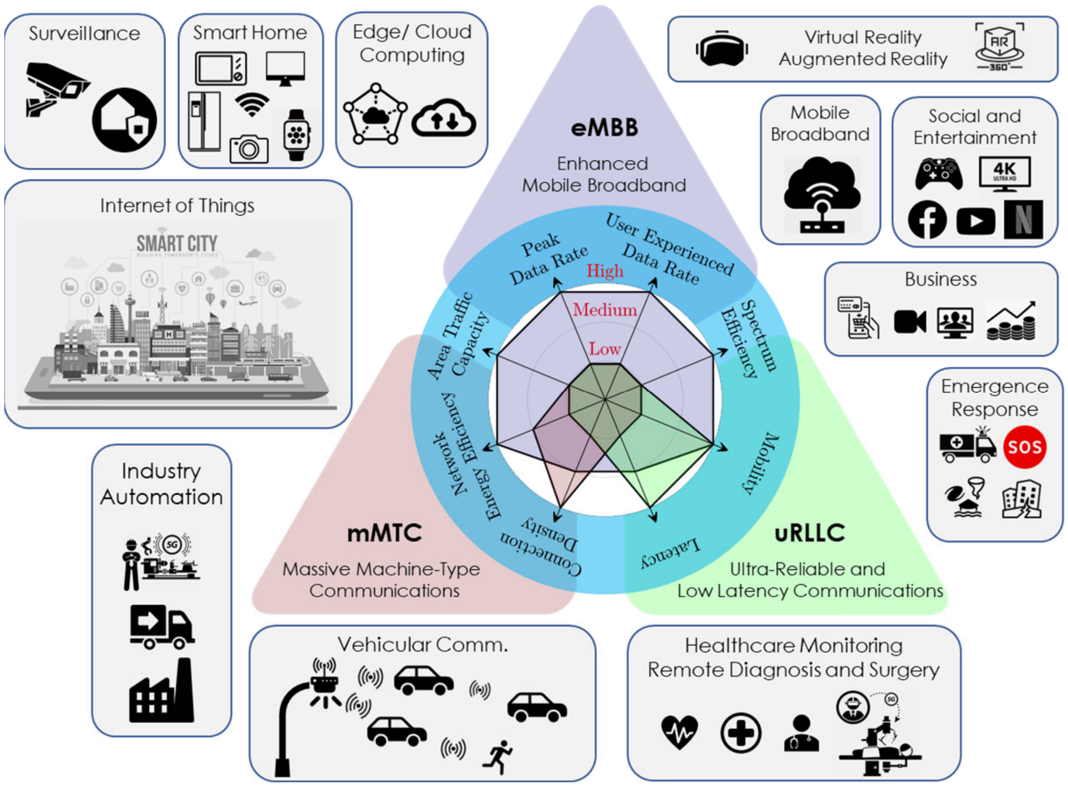
- ❑ **Conclusion and Outlook**







A Brief Outlook for Future Connected World

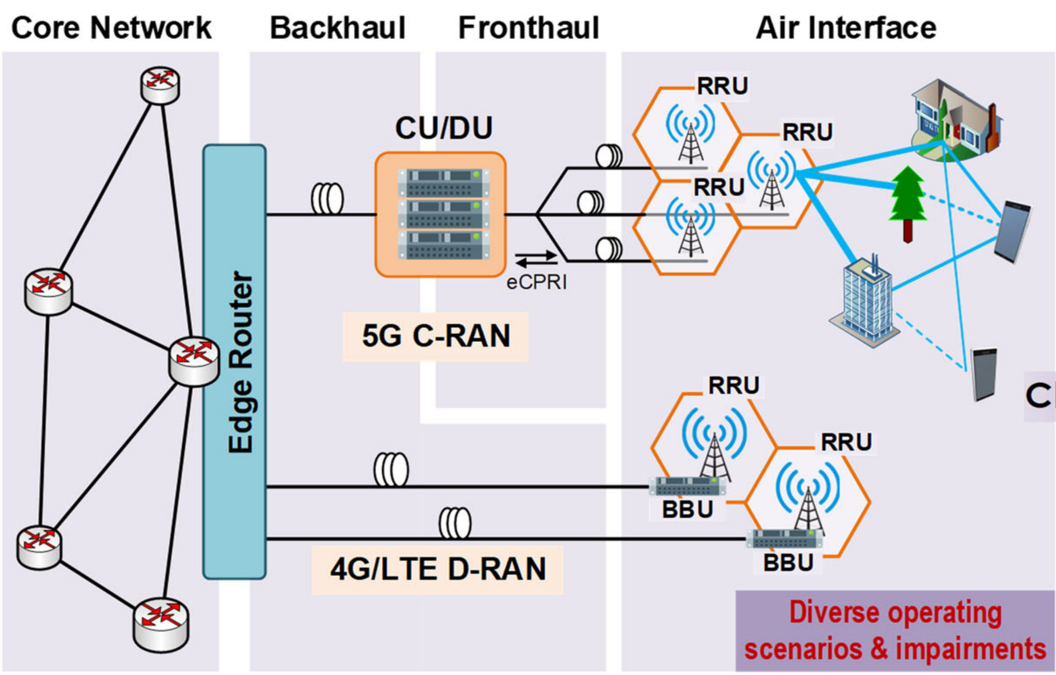


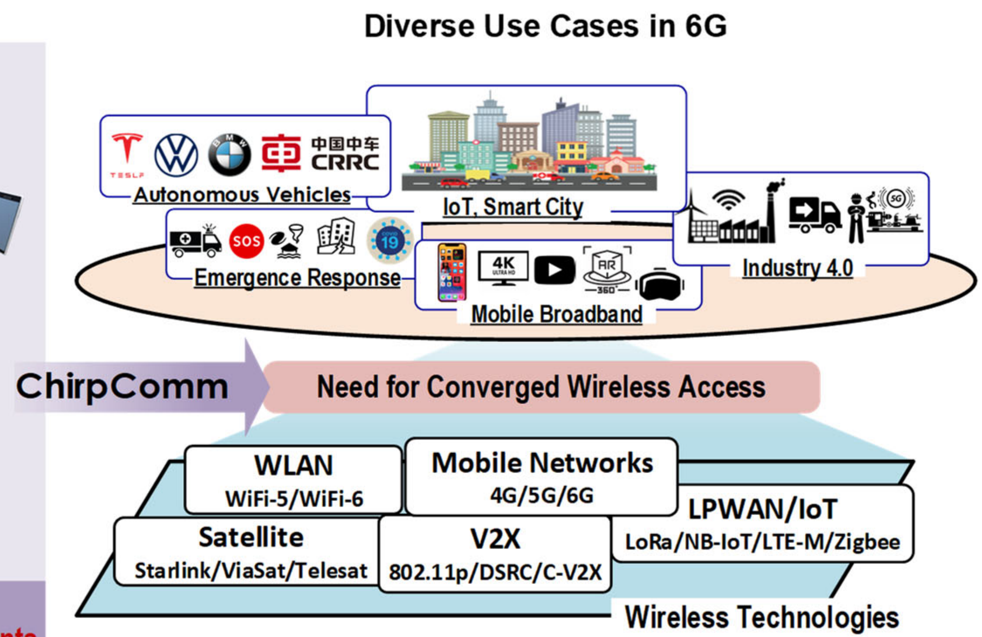
Human to Human

Human to Machine

Machine to Machine

Future Optical and Wireless Access Networks



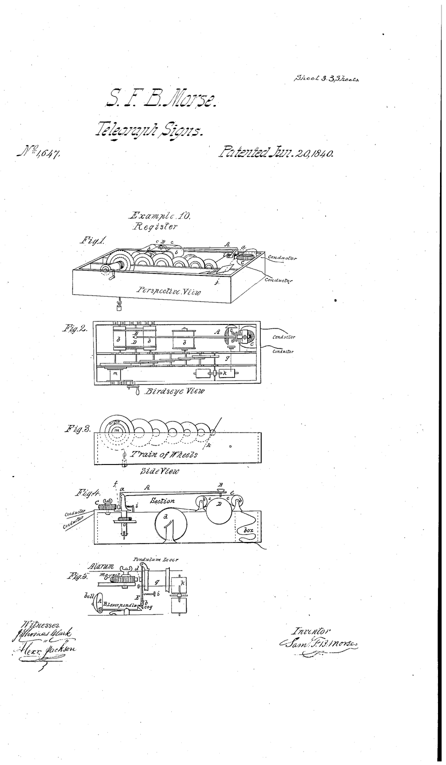


Looking for A Flexible and Versatile **Signal Modulation Technology as the Unified Air Interface** enabling the so-called **Ubiquitous Connectivity** for Everyone, Everything, Anytime, and Anywhere

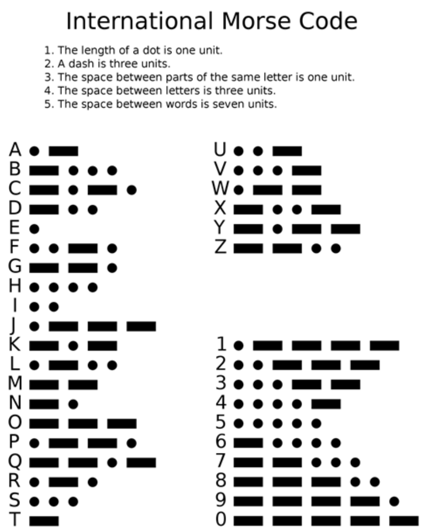
B. Farhang-Boroujeny, *et al.*, "OFDM Inspired Waveforms for 5G," *IEEE Commun. Surveys & Tutorials*, **18**(4): 2474-2492, 2016.
X. Zhang, et al., "On the Waveform for 5G," *IEEE Commun. Mag.*, **54**(11): 74-80, 2016.
Dang, *et al.* "What should 6G be?" *Nat Electron* **3**, 20–29 (2020).
M. A. Uusitalo et al., "Hexa-X The European 6G flagship project," *2021 EuCNC/6G Summit*, Porto, Portugal, 2021, pp. 580-585.

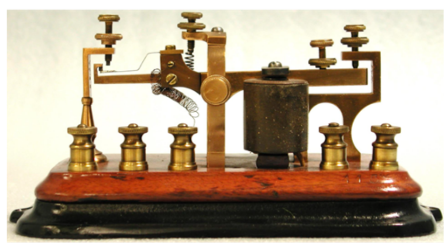
How to Modulate Information onto Waveform (1/3)

- ❑ **Historically …**

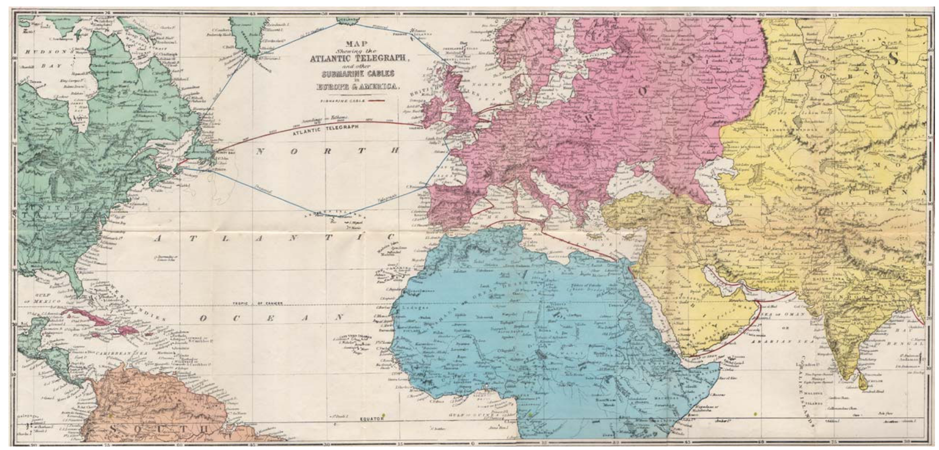


Samuel Morse, US Patent: US1647A, 1840.





Courtesy of National Museum of American History from Western Union Corporation



How to Modulate Information onto Waveform (2/3)

❑ Beginning of Modern Communications …

Certain Topics in Telegraph Transmission Theory

BY H. NYQUIST[1]
Member, A. I. E. E.

Synopsis.—The most obvious method for determining the distortion of telegraph signals is to calculate the transients of the telegraph system. This method has been treated by various writers, and solutions are available for telegraph lines with simple terminal conditions. It is well known that the extension of the same methods to more complicated terminal conditions, which represent the usual terminal apparatus, leads to great difficulties.

The present paper attacks the same problem from the alternative standpoint of the steady-state characteristics of the system. This method has the advantage over the method of transients that the complication of the circuit which results from the use of terminal apparatus does not complicate the calculations materially. This method of treatment necessitates expressing the criteria of distortionless transmission in terms of the steady-state characteristics. Accordingly, a considerable portion of the paper describes and illustrates a method for making this translation.

A discussion is given of the minimum frequency range required for transmission at a given speed of signaling. In the case of carrier telegraphy, this discussion includes a comparison of single-sideband and double-sideband transmission. A number of incidental topics is also discussed.

* * * * *

Harry Nyquist, Trans. of the AIEE **47**(2): 617-644, 1928.

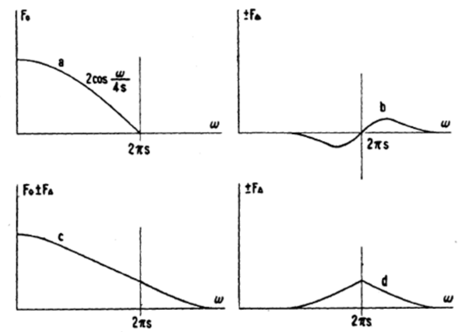


FIG. 3—IDEAL SHAPE FACTORS

In this figure, the criterion of distortionless transmission is that the width or duration of each signal element at the mean-value point should be udistorted

a and *c* represent real shape factors which produce a non-distorting wave,—*b* and *d* shape factors which may be added without producing distortion, the former representing an imaginary and the latter a real value

$$C = W \log \frac{P+N}{N}.$$

The Bell System Technical Journal

Vol. XXVII *July, 1948* *No. 3*

A Mathematical Theory of Communication

By C. E. SHANNON

Claude E. Shannon, *Bell System Technical Journal* **27**(4): 623-656, 1948.

Theorem 13: Let $f(t)$ contain no frequencies over W. Then

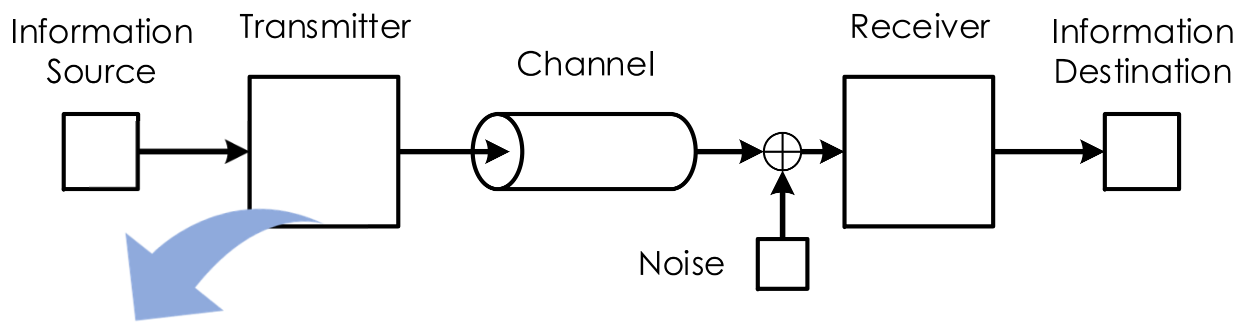
$$f(t) = \sum_{-\infty}^{\infty} X_n \frac{\sin \pi(2Wt-n)}{\pi(2Wt-n)}$$

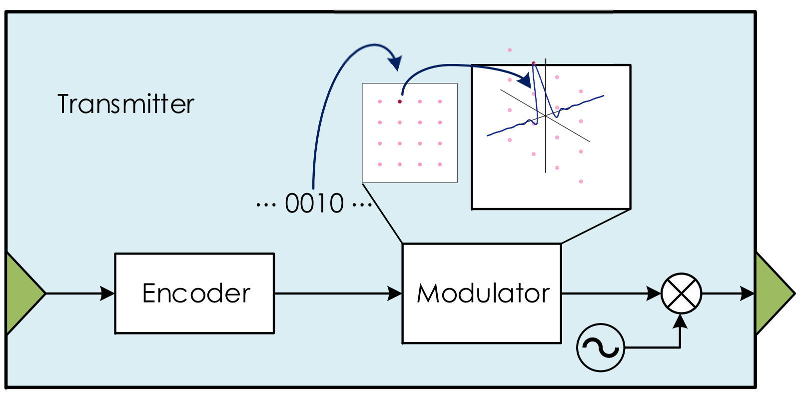
where

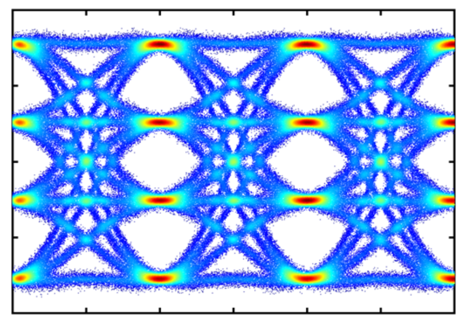
$$X_n = f\left(\frac{n}{2W}\right).$$

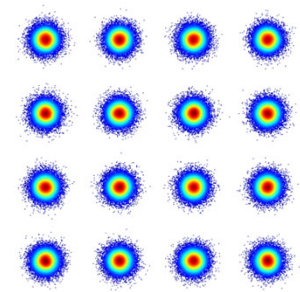
How to Modulate Information onto Waveform (3/3)

- ❑ **Block Diagram of a Communication System**



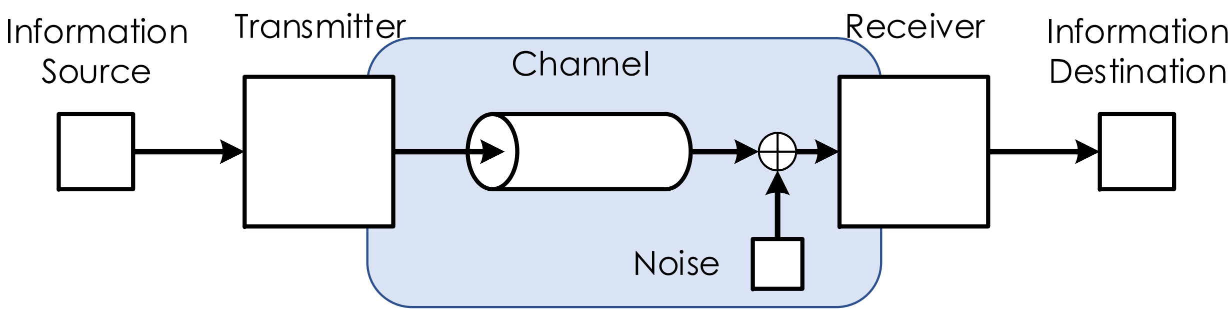




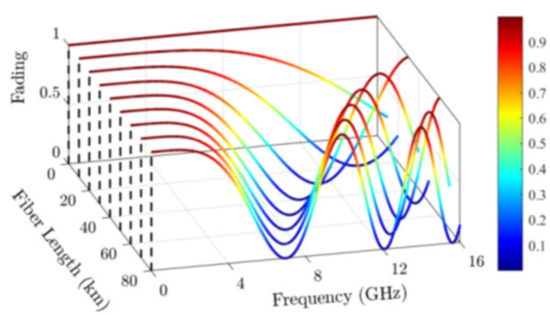


Understanding the Channel

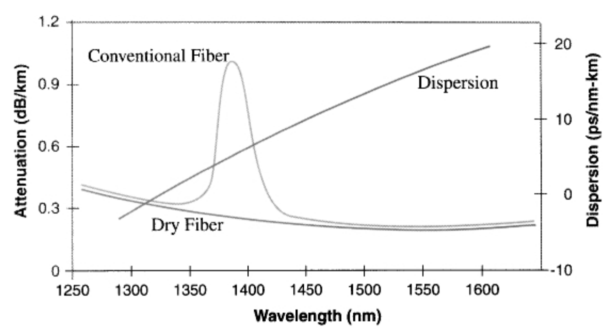
❑ Channel Model



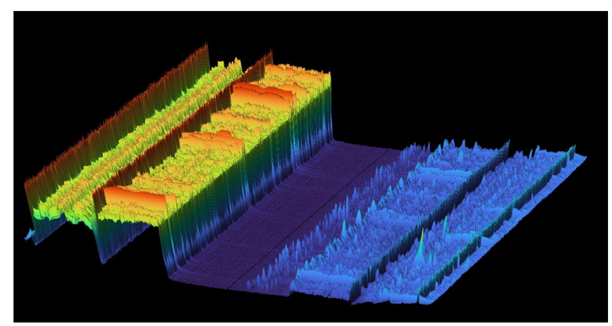
IM/DD Systems



Coherent Optical Systems

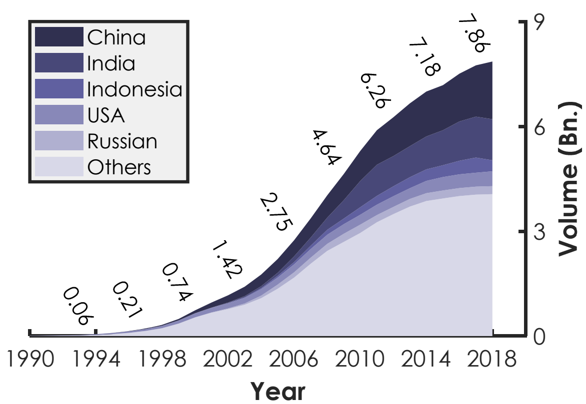


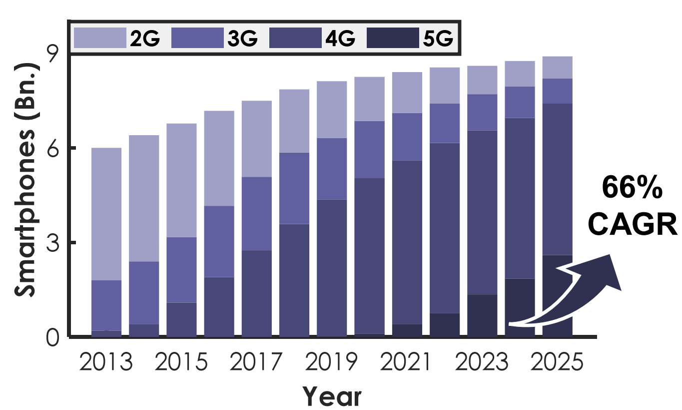
Wireless Systems

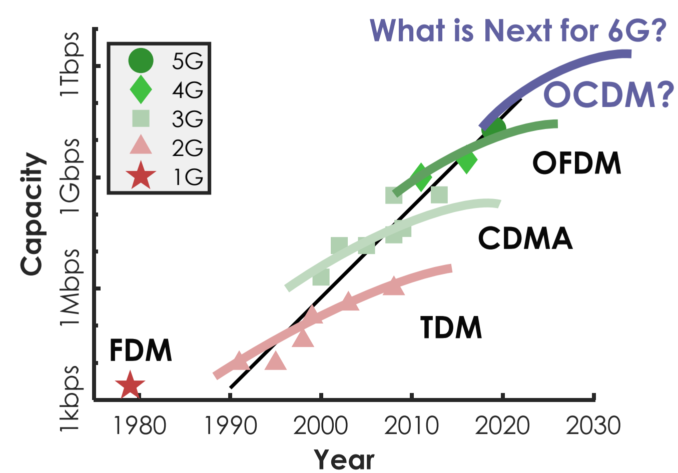


Evolution of Wireless Systems

	1980s	1990s	2000s	2010s	2020s	NEXT
	1G	2G	3G	4G	5G	6G
	Analog Voice	Digital Voice	Mobile Data	Mobile Broadband	Gigabit Broadband	Future Ubiquitous Connectivity
Standard:	TACS, AMPS, NMT, DataTAC	GSM, D-AMPS, IS-95	UMTS (WCDMA, etc.), HSPA+, LTE	LTE-Advance, LTE-Pro	5G-NR, 5G+	What will be the core techniques in 6G?
Air Interface: Antenna Tech.:	FDMA	TDMA, CDMA	CDMA, OFDM (B3G)	OFDM, MIMO	OFDM, OCDM (5G+)? Massive MIMO	OFDM/OCDM? Massive MIMO

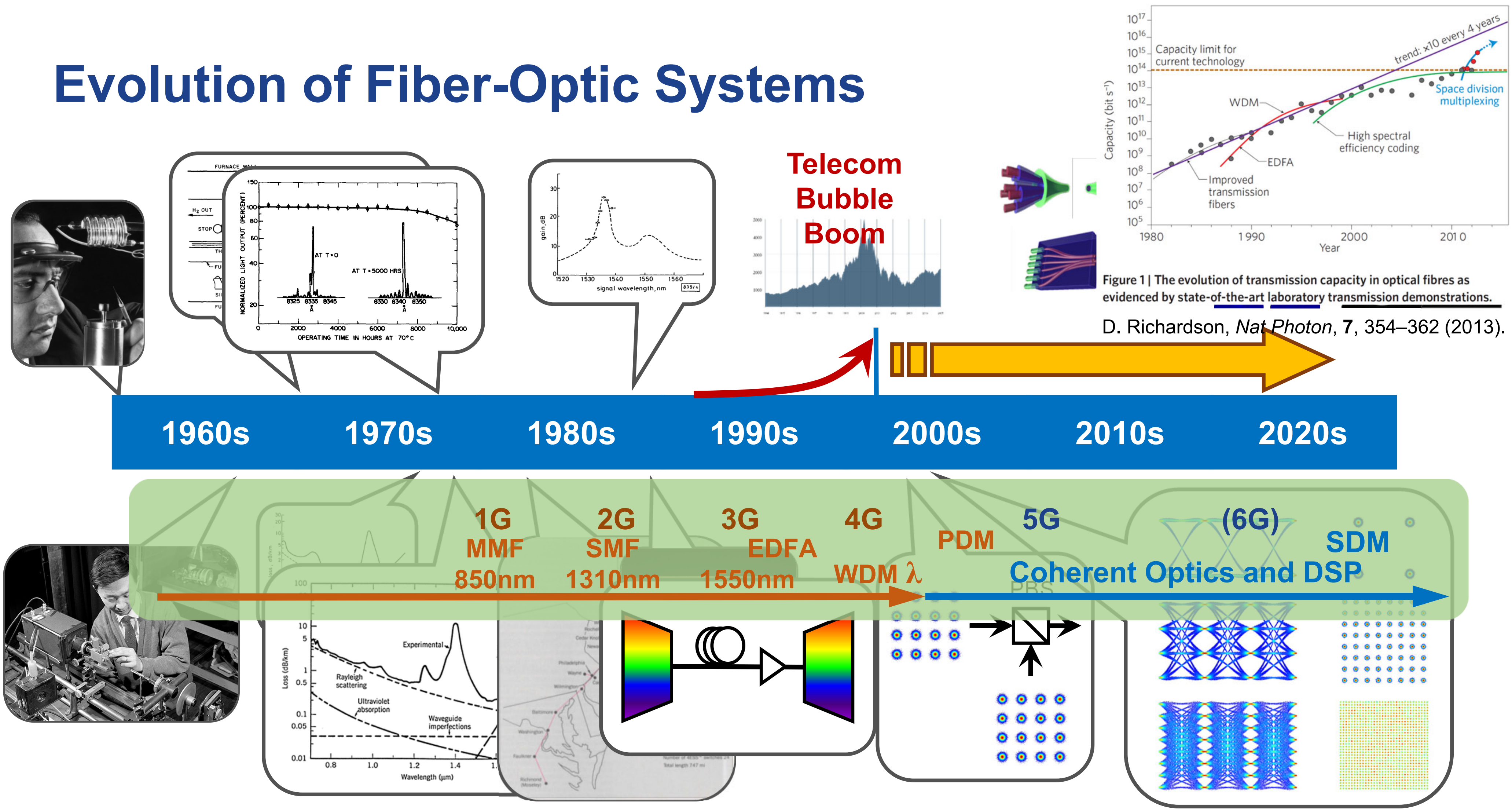






The World Bank https://data.worldbank.org/indicator/IT.CEL.SETS.P2
Ericsson Mobility Report 2022: https://www.ericsson.com/en/reports-and-papers/mobility-report

Evolution of Fiber-Optic Systems



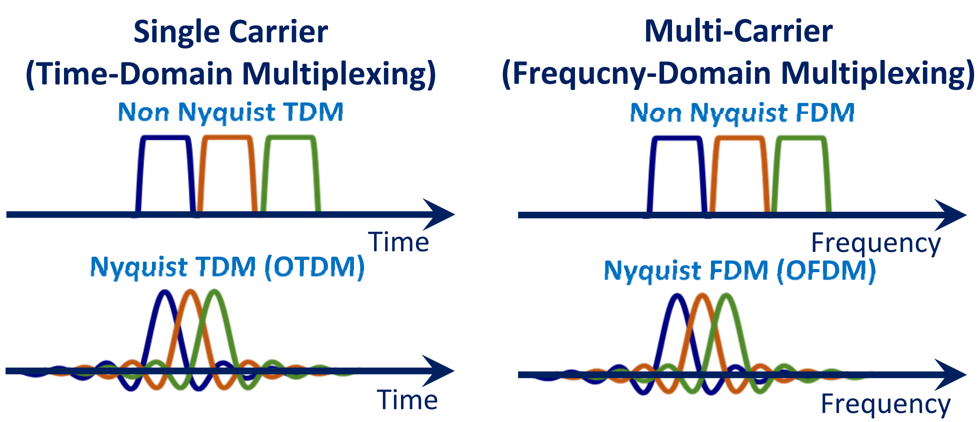
Jeff Hecht, “City of Light: The Story of Fiber Optics”, Oxford University Press, 1999
David Richardson, “Space-division multiplexing in optical fibres,” *Nat Photon*, **7**, 354–362 (2013).

Digital Modulation Technologies

- **Fundamental Dimensions available for encoding information**
  - Time
  - Frequency
  - Space
  - Polarization
  - Code

Time ⬄ Frequency

Digital Signal Modulation



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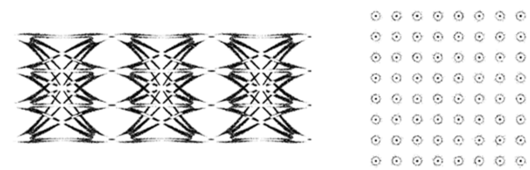
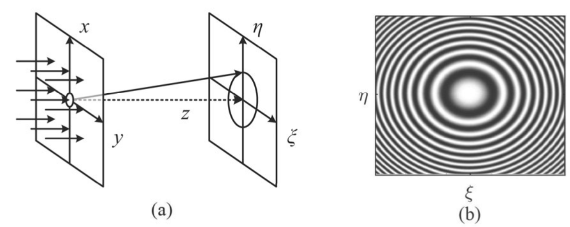
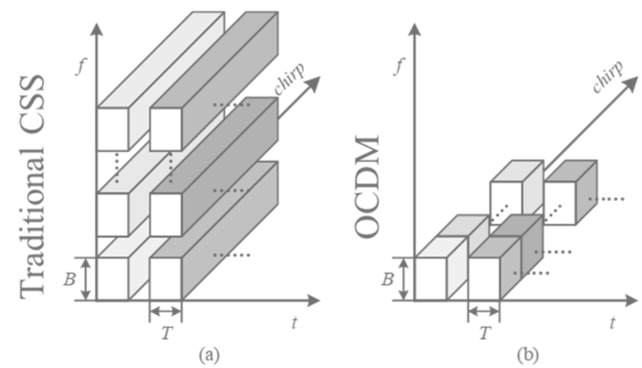
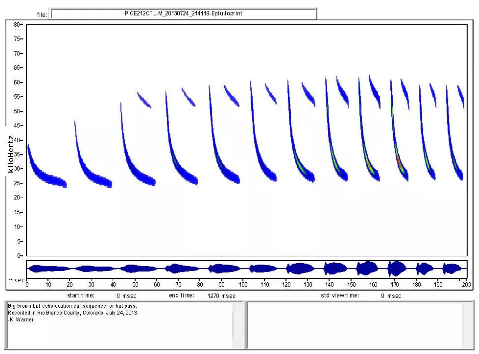




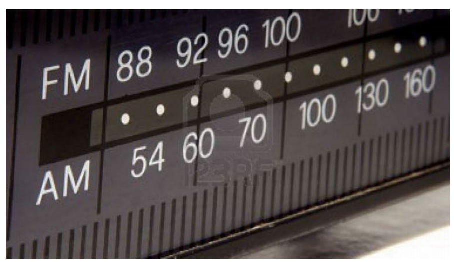


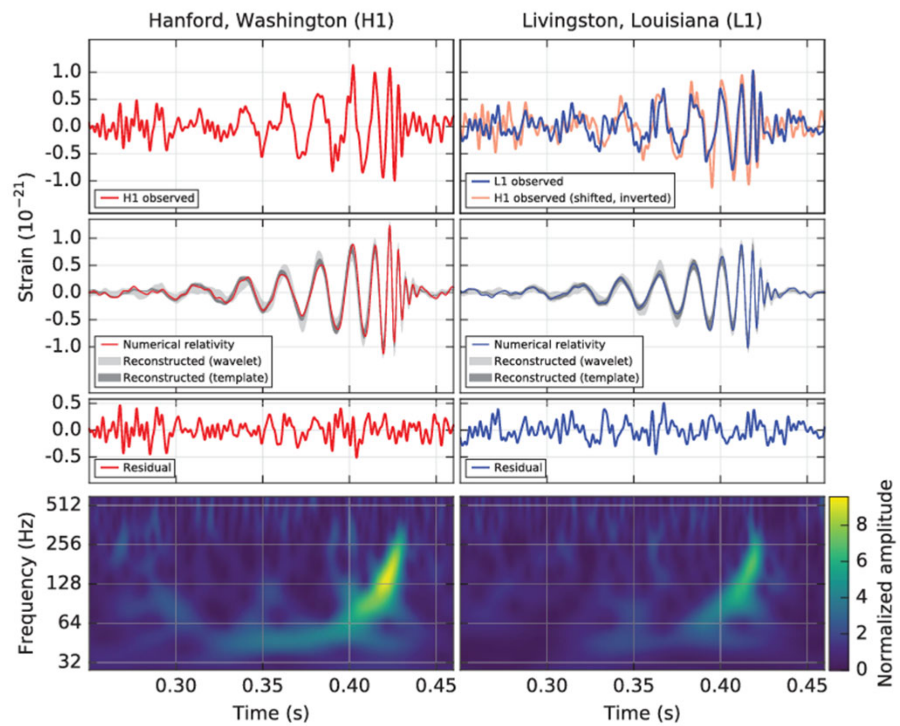
Chirps are Everywhere



Echolocation, Studying Bats, National Park Service

Periodicity in Perspective





LIGO/Phys. Rev. Lett. 116 061102

Chirps for Radar and Communications

THE BELL SYSTEM
TECHNICAL JOURNAL

VOLUME XXXIX | JULY 1960 | NUMBER 4

The Theory and Design of Chirp Radars

By J. R. KLAUDER, A. C. PRICE,
S. DARLINGTON and W. J. ALBERSHEIM

(Manuscript received April 5, 1960)

R. Klauder, J. R., et al. “The theory and design of chirp radars.” *Bell System Technical Journal,* **39**(4): 745-808, 1960.

THE BELL SYSTEM
TECHNICAL JOURNAL

VOLUME XLIII | JANUARY 1964 | NUMBER 1, PART 2

Demodulation of Wideband, Low-Power FM Signals*

By SIDNEY DARLINGTON

(Manuscript received October 3, 1963)

Sidney Darlington, “Demodulation of wideband low-power FM signals,” *Bell System Technical Journal*, **43**(1p2): 339-374, (1964).

FM DEMODULATION

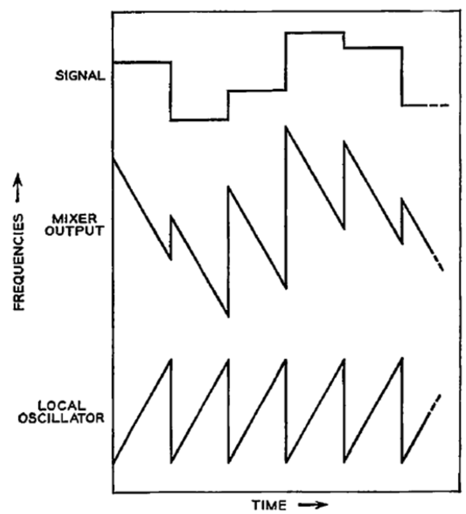
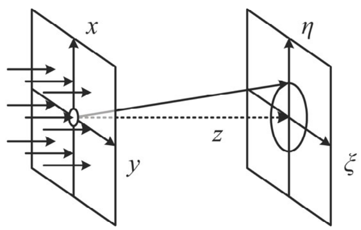


Fig. 5 — Frequency conversion.

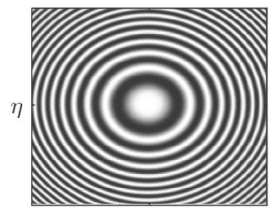
- **Applications**
  - Communications
  - Localization
  - Telemetry
  - Military

Towards Orthogonality …? (1/3)

❑ Fresnel Diffraction



(a)



(b)

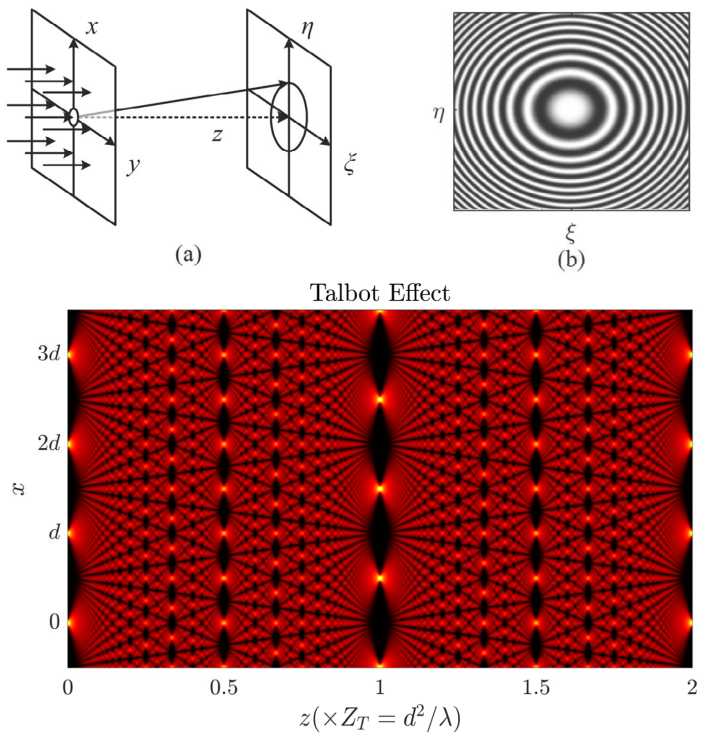
$$
\begin{aligned}
r &= \sqrt{(\eta - x)^2 + (\xi - y)^2 + z^2} \\
&= \sqrt{\rho^2 + z^2} \\
&= z\left(1 + \frac{\rho^2}{z}\right)^{\frac{1}{2}} \\
&= z + \frac{\rho^2}{2z} - \frac{\rho^4}{8z^3} + \cdots
\end{aligned}
$$

$$E(\eta, \xi, z) = \frac{1}{i\lambda} \iint_{-\infty}^{+\infty} E(x, y, 0)\, e^{i\frac{2\pi}{\lambda}r}\, \frac{z}{r^2}\, dx\, dy$$

$$E(\eta, \xi, z) \approx \frac{e^{i\frac{2\pi}{\lambda}z}}{i\lambda z} \iint_{-\infty}^{+\infty} E(x, y, 0)\, e^{i\frac{\pi}{\lambda z}\rho^2}\, dx\, dy$$

Towards Orthogonality …? (2/3)

❑ Fresnel Diffraction to Talbot Effect



$$E(\eta, z) = \frac{e^{i\frac{2\pi}{\lambda}z}}{i\lambda z}\int_{-\infty}^{+\infty} E(x,0)e^{i\frac{\pi}{\lambda z}(\eta-x)^2}\,dx$$

$$E_{\mathrm{T}}(\eta, z) = \frac{e^{i\frac{2\pi}{\lambda}z}}{i\lambda z}\sum_{m}\int_{-\frac{d}{2}}^{+\frac{d}{2}} E(x,0)e^{i\frac{\pi}{\lambda z}(\eta-x-md)^2}\,dx$$

Rayleigh's definition of Talbot distance:

$$Z_T = \frac{2d^2}{\lambda}, \qquad \lambda \ll d$$

H. F. Talbot, "Facts relating to optical science. No. IV," *Philosophical Magazine Series 3*, **9**(56): 401-407, (1836)
Lord Rayleigh, "On copying diffraction-gratings, and on some phenomena connected therewith," *Philosophical Magazine Series 5* **11**(67): 196-205, (1881).
John T. Winthrop and C. R. Worthington, "Theory of Fresnel Images. I. Plane Periodic Objects in Monochromatic Light," *J. Opt. Soc. Am.* **55**, 373-381 (1965)

Towards Orthogonality …? (3/3)

Tyndall National Institute
Institiúid Náisiúnta

❑ What we want from Fresnel transform

CHAPTER TEN

Why is the Fresnel Transform So Little Known?

F. Gori

10.1. INTRODUCTION

Fresnel diffraction integrals are customarily evaluated by nearly everyone working in optics. Nevertheless, they are seldom classified under the heading of the Fresnel transform. In other words, the Fresnel transform, thought of as a mathematical tool, is not very well known. Let us make a comparison with the use of the Fourier transform, whose theory is generally well known. As repeatedly experienced by anyone dealing with Fourier analysis, a handful of theorems can often save considerable labour and give a clear insight into a problem. A certain knowledge of the Fresnel transform theory could afford similar advantages. Yet, while most optics textbooks furnish some material on the Fourier transform, they hardly do the same for the Fresnel transform. Generally speaking, they do not even mention it.

There are of course reasons for this state of affairs. From a mathematical standpoint, it could be said: "The Fresnel transform is nothing else than the result of a suitable filtering operation on the Fourier spectrum. Hence, there is no need to give it a special status". Although the premise is correct, the conclusion is questionable. Indeed, by the same token, we could dispose of the Fourier transform itself because it is a particular case of the (bilateral) Laplace transform. Obviously enough, the knowledge of theorems that directly apply to the Fresnel transform is more practical and useful than an indirect deduction of results via Fourier theory. In addition, only in certain papers is the connection with the Fourier transform actually exploited. Another objection that could be raised against the study of the Fresnel transform theory is: "Much of the usefulness of Fourier analysis stems from the existence of extensive tables where the Fourier transforms of very many functions can be found. This makes it easy to apply Fourier theory and generally gives rise to closed form results. The situation is much worse with the Fresnel transform whose closed form expression is known for a few functions only". Such an objection probably explains the real origin of the lack of interest for the Fresnel transform. Indeed even a simple function such as rect(x) requires the use of special functions (the

139

10.3. THEOREMS AND EXAMPLES

Several theorems on the Fresnel transform can be mentioned (Table 10.1). A few words about notations are in order. The symbol $*$ between two functions stands for convolution defined in the usual manner, i.e.,

Table 10.1 Theorems

(1) Convolution	$\mathcal{F}_\alpha\{f * g\}(x) = (\hat{f}_\alpha * g)(x) = (f * \hat{g}_\alpha)(x)$
(2) Correlation	$\mathcal{F}_\alpha\{f \otimes g\}(x) = (\hat{f}_\alpha \otimes g)(x) = (f(\xi) * \hat{g}^*_{-\alpha}(-\xi))(x)$
(3) Derivative	$\mathcal{F}_\alpha\left\{\frac{\mathrm{d}f}{\mathrm{d}\xi}\right\}(x) = \frac{\mathrm{d}\hat{f}_\alpha}{\mathrm{d}x}$
(4) Integral	$\mathcal{F}_\alpha\left\{\int f(\xi)\mathrm{d}\xi\right\}(x) = \int \hat{f}_\alpha(x)\,\mathrm{d}x$
(5) Shift	$\mathcal{F}_\alpha\{f(\xi)\mathrm{e}^{iK\xi}\}(x) = \exp\left(iKx - i\frac{K^2}{4\pi\alpha}\right)\hat{f}_\alpha\left(x - \frac{K}{2\pi\alpha}\right)$
(6) Scaling	$\mathcal{F}_\alpha\left\{f\left(\frac{\xi}{D}\right)\right\}(x) = \mathcal{F}_{\alpha D^2}\{f\}\left(\frac{x}{D}\right)$
(7) Cylinder	$\mathcal{F}_\alpha\{f(\xi)\mathrm{e}^{\pi i\beta\xi^2}\}(x) = \sqrt{\frac{\alpha}{\alpha+\beta}}\exp\left(\pi i\frac{\alpha\beta}{\alpha+\beta}x^2\right)\hat{f}_{\alpha+\beta}\left(\frac{\alpha x}{\alpha+\beta}\right)$
(8) x-product	$\mathcal{F}_\alpha\{\xi f(\xi)\}(x) = x\hat{f}_\alpha(x) + \frac{i}{2\pi\alpha}\frac{\mathrm{d}\hat{f}_\alpha}{\mathrm{d}x}$
(9) Correlation invariance	$(f \otimes g)(x) = (\hat{f}_\alpha \otimes \hat{g}_\alpha)(x)$
(10) Parseval	$\int_{-\infty}^{\infty}\lvert f(x)\rvert^2\mathrm{d}x = \int_{-\infty}^{\infty}\lvert\hat{f}_\alpha(x)\rvert^2\mathrm{d}x$
(11) Sampling	If $f(x)=0$ for $\lvert x\rvert > x_0$ then

$$\hat{f}_\alpha(x) = \mathrm{e}^{\pi i\alpha x^2}\sum_{n=-\infty}^{\infty}\hat{f}_\alpha\left(\frac{n}{2x_0\lvert\alpha\rvert}\right)\exp\left[-\pi i\alpha\left(\frac{n}{2x_0\alpha}\right)^2\right]\mathrm{sinc}(2x_0\lvert\alpha\rvert x - n)$$

- C. H. Zhou and L. R. Liu, "Simple equations for the calculation of a multilevel phase grating for Talbot array illumination," *Opt. Commun.*, vol. 115, pp. 40-44, Mar 1 1995.
- J. M. Wen, *et al.*, "The Talbot effect: Recent advances in classical optics, nonlinear optics, and quantum optics," *Adv. Opt. Photonics*, **5**: 83-130, (2013).
- D. P. Kelly, "Numerical calculation of the Fresnel transform," (in English), *J. Opt. Soc. Am. A-Opt. Image Sci. Vis.*, **31**(4): 755-64, (2014)
- C. J. Cheng, *et al.*, "Efficient FPGA-based Fresnel transform architecture for digital holography," *J. Display Technol.*, **10**: 272-281, (2014).
- I. Aizenberg and J. T. Astola, "Discrete generalized Fresnel functions and transforms in an arbitrary discrete basis," *IEEE Trans. Signal Process.*, vol. 54, pp. 4261-4270, Nov 2006.
- Etc.

❑ Desired Properties

- ➢ Orthogonality
- ➢ Convolution
- ➢ Duality
- ➢ Discrete Transformation
- ➢ Etc.

F. Gori, "Why is the Fresnel transform so little known?," in *Current Trends in Optics, Academic Press, 1994, pp. 139-148.*

Discrete Fresnel Transform

❑ From Continuous to Discrete

- ➢ Periodicity ⇔ Discretization
- ➢ Time ⇔ Frequency

$$\alpha = \lambda z = \left.\frac{d^2}{N}\right|_{z=\frac{Z_T}{N}=\frac{d^2}{N\lambda}}$$

$$Ш_d(t) = \sum_{n=-\infty}^{+\infty} \delta(t-nd) = \frac{1}{d}\sum_{n=-\infty}^{+\infty} e^{i2\pi n\frac{t}{d}}$$

$$Ш_d\left(t-\frac{1}{2}d\right) = \frac{1}{d}\sum_{n=-\infty}^{+\infty} e^{i2\pi n\frac{t-\frac{1}{2}d}{d}} = \frac{1}{d}\sum_{n=-\infty}^{+\infty} e^{i\pi n} e^{-i2\pi n\frac{t}{d}}$$

$$\sum_{n=-\infty}^{+\infty} e^{-i\frac{2\pi}{d/N}n(\eta-t)} e^{i\pi N n^2} = \begin{cases} Ш_{\frac{d}{N}}(t) & N \equiv 0 (\mathrm{mod}\ 2) \\ Ш_{\frac{d}{N}}\left(t-\frac{1}{2}\frac{d}{N}\right) & N \equiv 1 (\mathrm{mod}\ 2) \end{cases}$$

Fresnel Integral: $s(\eta,z) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{\alpha}}\int_{-\infty}^{+\infty} s(t,0) e^{i\frac{\pi}{\alpha}(\eta-t)^2}\,dt$

$$\hat{s}_T(\eta) = s(\eta) * Ш_d(t)$$

$$(1) = \sum_{n=-\infty}^{+\infty} s(\eta) * \delta(\eta - nd)$$

$$(2) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{\alpha}} \sum_{n=-\infty}^{+\infty} \int_{-d/2}^{+d/2} s(t) e^{i\frac{\pi}{\alpha}(\eta-t-nd)^2}\,dt$$

$$(3) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{\alpha}} \int_{-d/2}^{+d/2} s(t) e^{i\frac{\pi}{\alpha}(\eta-t)^2} \sum_{n=-\infty}^{+\infty} e^{-i\frac{2\pi}{\alpha}nd(\eta-t)} e^{i\frac{\pi}{\alpha}(nd)^2}\,dt$$

$$(4) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{d^2/N}} \int_{-d/2}^{+d/2} s(t) e^{i\frac{\pi}{d^2/N}(\eta-t)^2} \sum_{n=-\infty}^{+\infty} e^{-i\frac{2\pi}{d/N}m(\eta-t)} e^{i\pi N m^2}\,dt$$

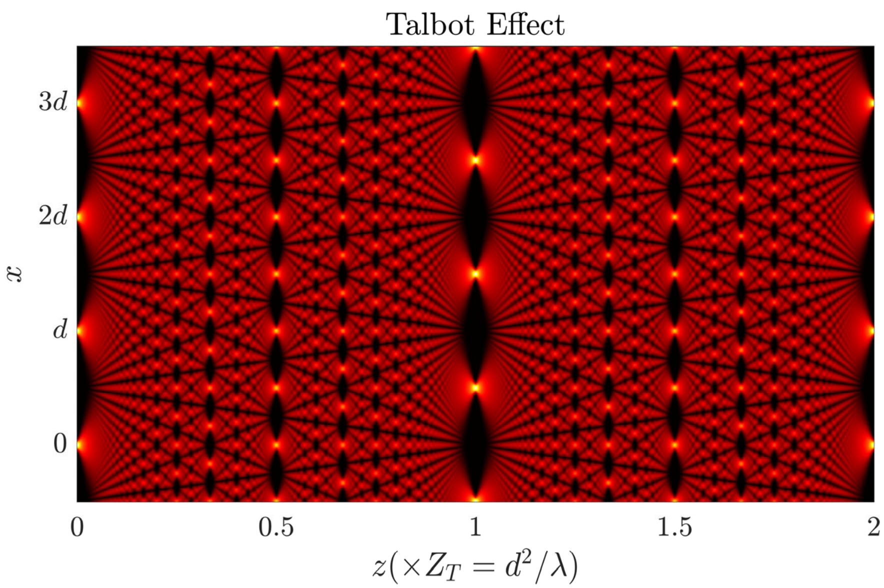
$$(5) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{N}} \sum_{n=0}^{N} \begin{cases} s\left(n\frac{d}{N}\right) e^{i\frac{\pi}{d^2/N}\left(\eta - n\frac{d}{N}\right)^2} & N \equiv 0 (\mathrm{mod}\ 2) \\ s\left(\left(n+\frac{1}{2}\right)\frac{d}{N}\right) e^{i\frac{\pi}{d^2/N}\left(\eta-\left(n-\frac{1}{2}\right)\frac{d}{N}\right)^2} & N \equiv 1 (\mathrm{mod}\ 2) \end{cases}$$

Xing Ouyang, et al., "Discrete Fresnel Transform and Its Circular Convolution," arXiv:1510.00574v1, 2015.

Discrete Fresnel Transform – Cont'd

❑ From Continuous to Discrete

- ➢ Periodicity ⇔ Discretization
- ➢ Time ⇔ Frequency



$$\hat{s}_T(\eta) = s(\eta) * \text{Ш}_d(t)$$

$$(5) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{N}} \sum_{n=0}^{N} \begin{cases} s\left(n\frac{d}{N}\right) e^{i\frac{\pi}{d^2/N}\left(\eta - n\frac{d}{N}\right)^2} & N \equiv 0(\text{mod } 2) \\ s\left(\left(n+\frac{1}{2}\right)\frac{d}{N}\right) e^{i\frac{\pi}{d^2/N}\left(\eta-\left(n-\frac{1}{2}\right)\frac{d}{N}\right)^2} & N \equiv 1(\text{mod } 2) \end{cases}$$

Set $\eta = k\frac{d}{N}$

Then we get the Discrete Fresnel Transform:

$$\hat{s}_T(k) = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{N}} \sum_{n=0}^{N} s\left(n\frac{d}{N}\right) \times \begin{cases} e^{i\frac{\pi}{N}(k-n)^2} & N \equiv 0(\text{mod } 2) \\ e^{i\frac{\pi}{N}\left(k-n+\frac{1}{2}\right)^2} & N \equiv 1(\text{mod } 2) \end{cases}$$

Xing Ouyang, et al., "Discrete Fresnel Transform and Its Circular Convolution," arXiv:1510.00574v1, 2015.

Discrete Fresnel Transform – Cont'd

❑ Discrete Fresnel Transform (DFnT)

$$\boldsymbol{\Psi} = \frac{e^{-i\frac{\pi}{4}}}{\sqrt{N}} \begin{cases} e^{i\frac{\pi}{N}(k-n)^2} & N \equiv 0(\mathrm{mod}\ 2) \\ e^{i\frac{\pi}{N}\left(k-n+\frac{1}{2}\right)^2} & N \equiv 1(\mathrm{mod}\ 2) \end{cases}$$

❑ Properties

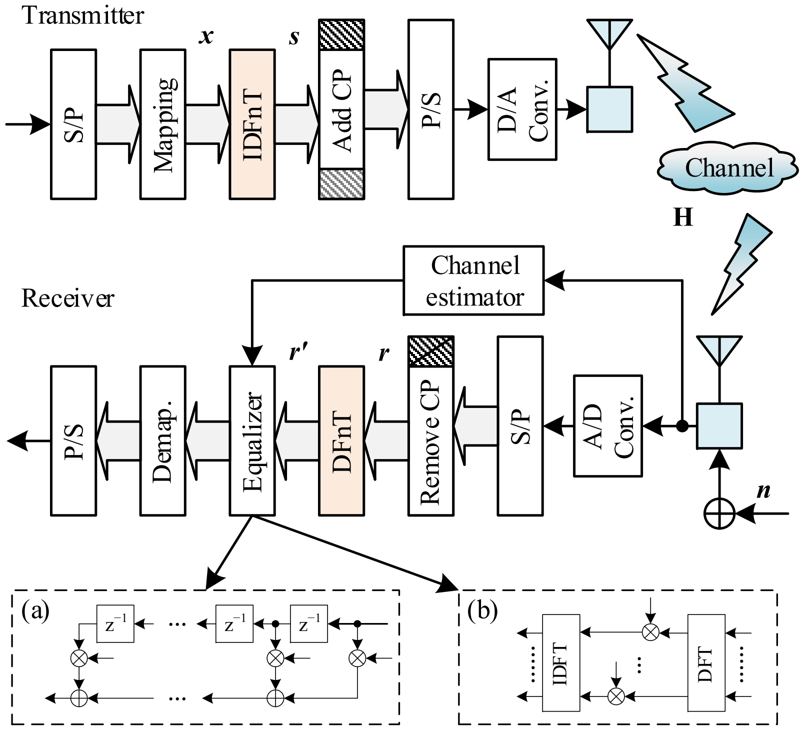
- Unitary
- Circulant
- Eigenvalues and Eigenvectors
- Determinant
- Similarity Transformation
- Convolution Theorem:

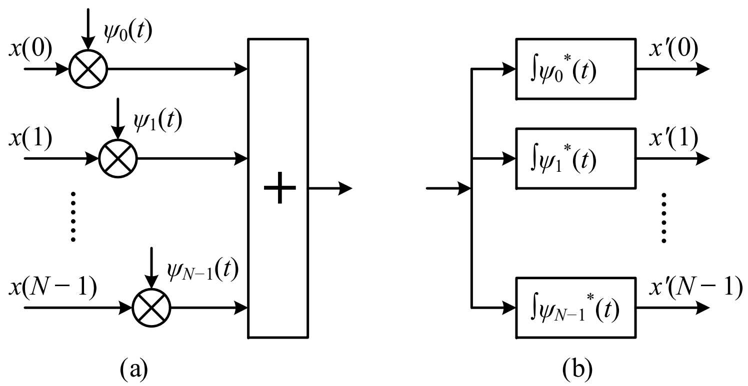
The DFnT of a convolution is the convolution of one with the DFnT of the other

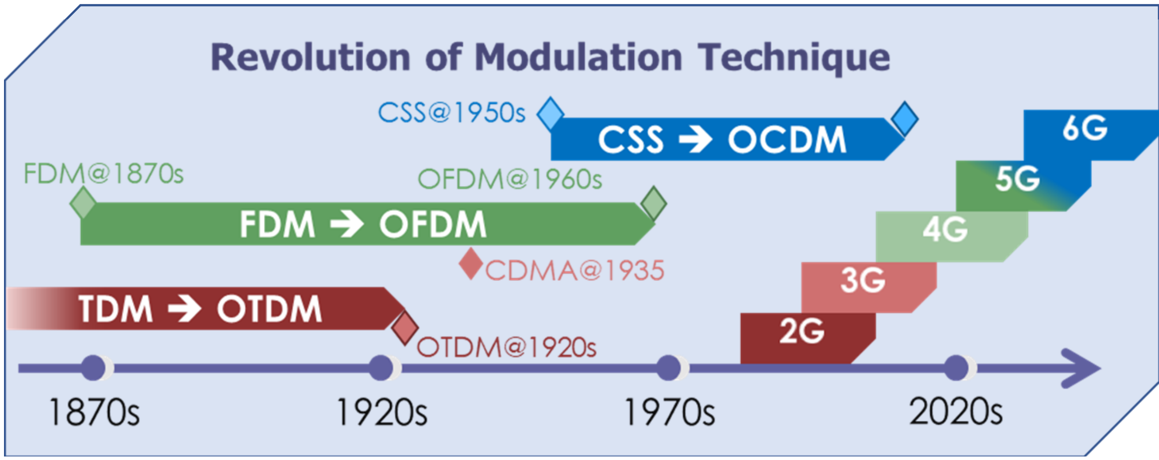
Xing Ouyang, et al., "Discrete Fresnel Transform and Its Circular Convolution," arXiv:1510.00574v1, 2015.

Finally … Orthogonal Chirp-Division Multiplexing

❑ A Typical OCDM System



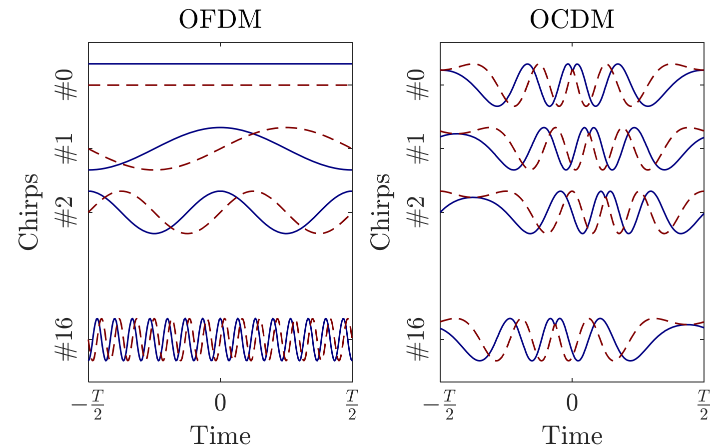




OFDM versus OCDM

❑ Similarities and Differences (Compatibility and Improvement)

OFDM		OCDM
➢ Waveforms		
Narrowband Subcarriers	–	Wideband Chirps
$\omega(t) = e^{j2\pi k\Delta f \times t}, \left(\Delta f = \frac{1}{T}\right)$		$\psi(t) = e^{j\frac{2\pi}{\alpha}(t-k\Delta c)^2}, \left(\alpha = \frac{N}{T^2}, \Delta c = \frac{1}{T}\right)$
➢ Orthogonality		
Fourier Transform	–	Fresnel Transform
➢ Linear System Transmission		
Block Transmission (CP)	–	Block Transmission (CP)



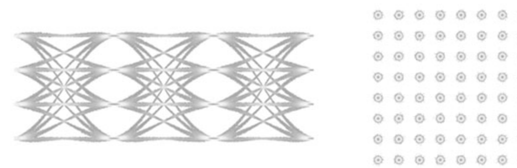
❑ Applications

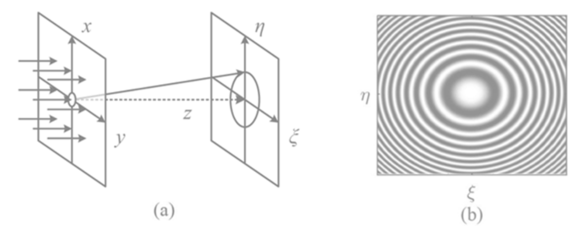
Bandwidth-Limited Systems

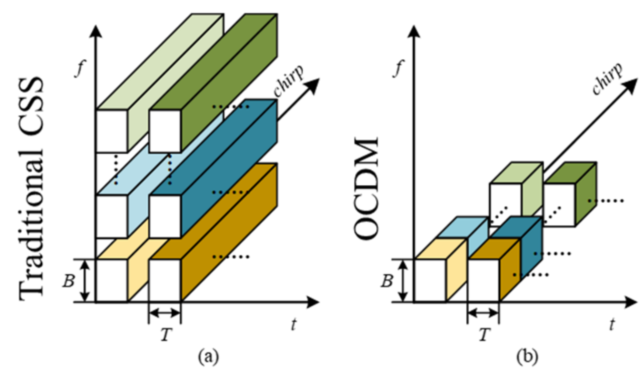
Power-Limited Systems

Outline

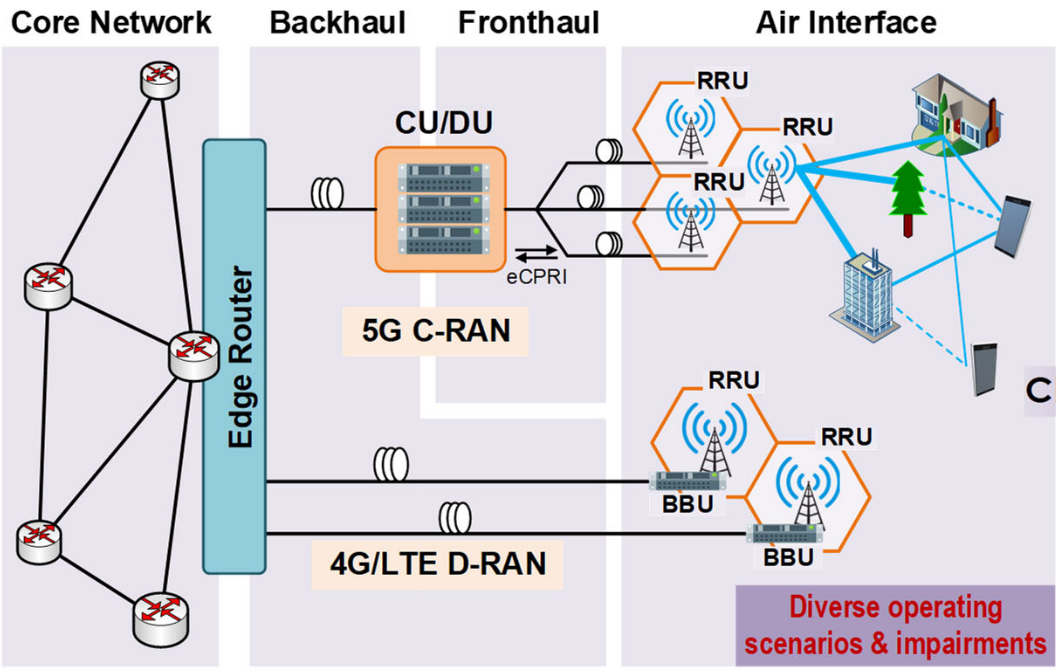
- ❑ **Waveforms for Optical and Wireless Access**
  - ➢ Why, What & How
  - ➢ A Brief History
  - ➢ Waveform Modulation Technologies
- ❑ **Orthogonal Chirp-Division Multiplexing (OCDM)**
  - ➢ Chirps are Everywhere
  - ➢ From Fresnel Diffraction to (Discrete) Fresnel Transform
  - ➢ OCDM
- ❑ **Applications and Current Progress**
  - ➢ Wireless Access Systems
  - ➢ Fiber-Optic and Radio-over-Fiber Systems
  - ➢ What's More
- ❑ **Conclusion and Outlook**

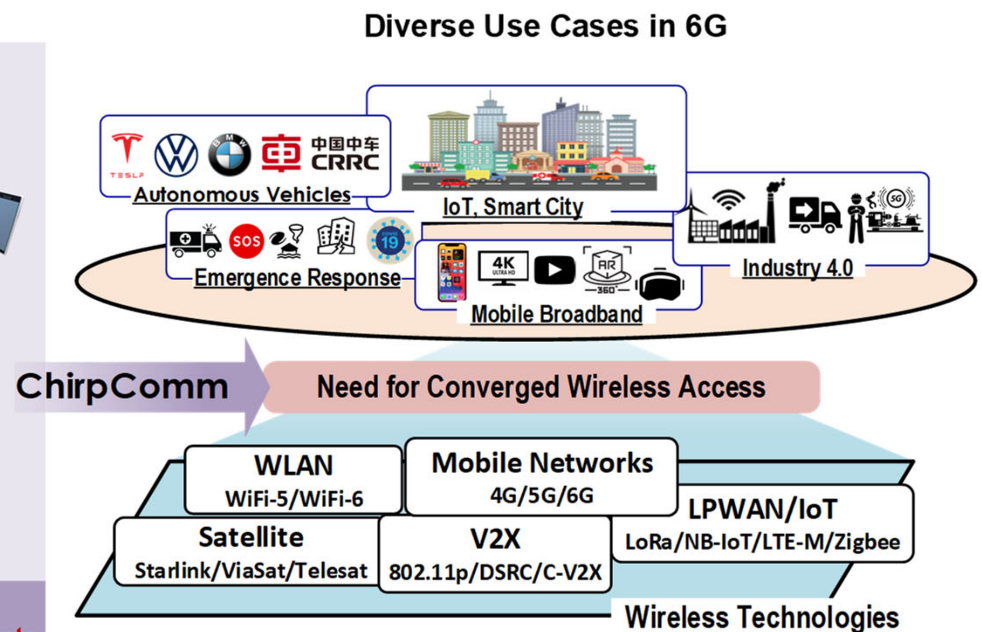






Future Optical and Wireless Access Networks





Looking for A Flexible and Versatile **Signal Modulation Technology as the Unified Air Interface** enabling the so-called **Ubiquitous Connectivity** for Everyone, Everything, Anytime, and Anywhere

Can OCDM be the Solution as the Converged Air Interface?

OCDM in High-Speed Wireless Systems (1/3)

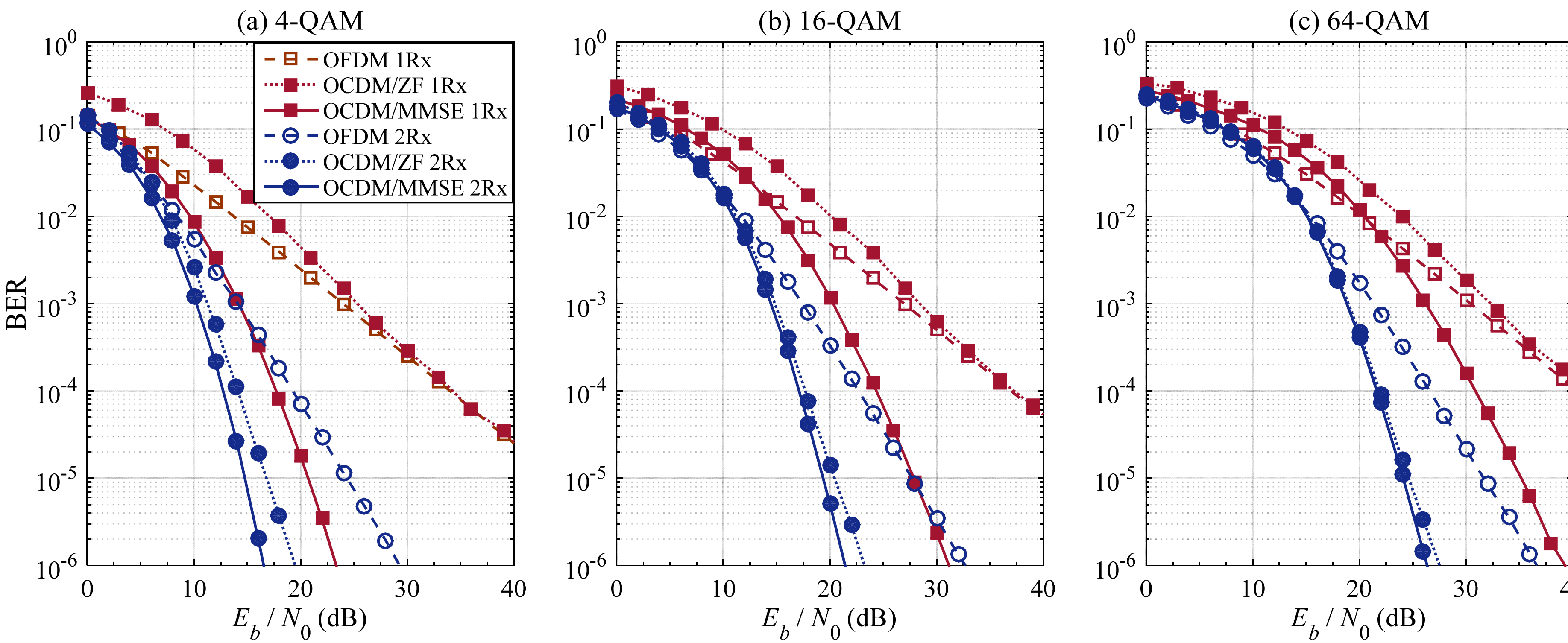


Figure:. BER performance of the OCDM systems with both ZF and MMSE equalizers and the OFDM system under the LTE extended vehicle A channel model with receiver diversity; (a) 4-QAM, (b) 16-QAM, and (c) 64-QAM.

X. Ouyang and J. Zhao, "Orthogonal chirp division multiplexing," *IEEE T Commun*, **64**(9): 3946–3957 (2016)

OCDM in High-Speed Wireless Systems (2/3)

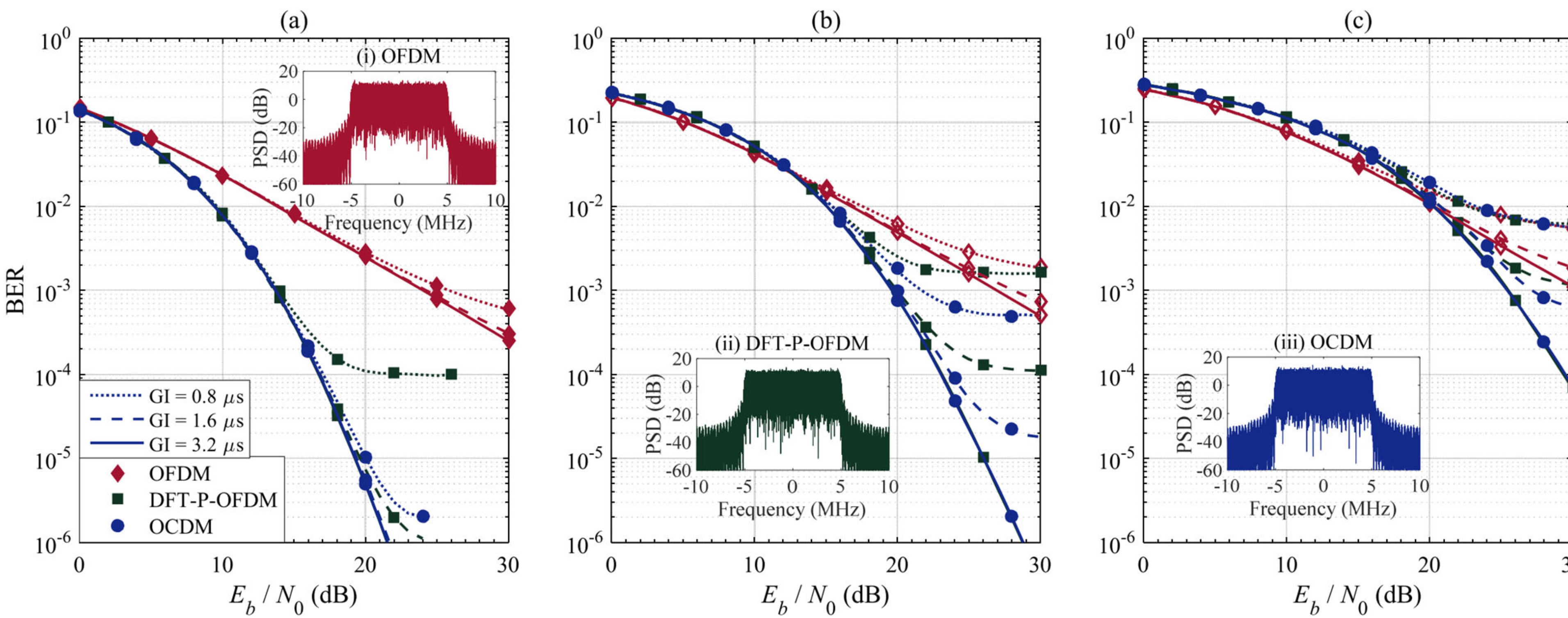


Figure:. BER performance of the OFDM, DFT-precoded OFDM, and OCDM systems under the LTE extended vehicle A channel model with various guard interval length. (a) 4-QAM, (b) 16-QAM, and (c) 64-QAM.

X. Ouyang and J. Zhao, "Orthogonal chirp division multiplexing," *IEEE T Commun*, **64**(9): 3946–3957 (2016)

OCDM in High-Speed Wireless Systems (3/3)

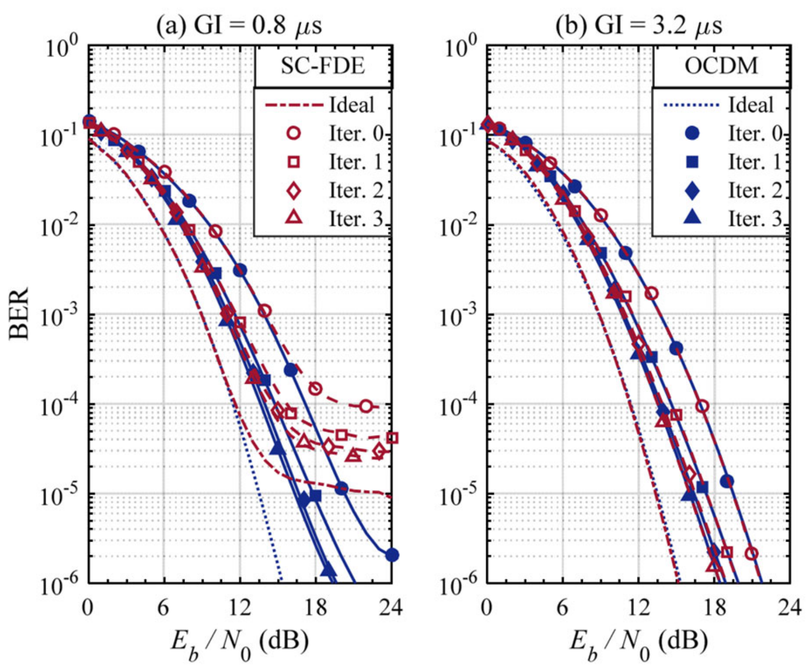


Fig. 14. The BER performance of SC-FDE and OCDM systems with iterative block decision feedback equalization with (a) 0.8-μs and (b) 3.2-μs GI.

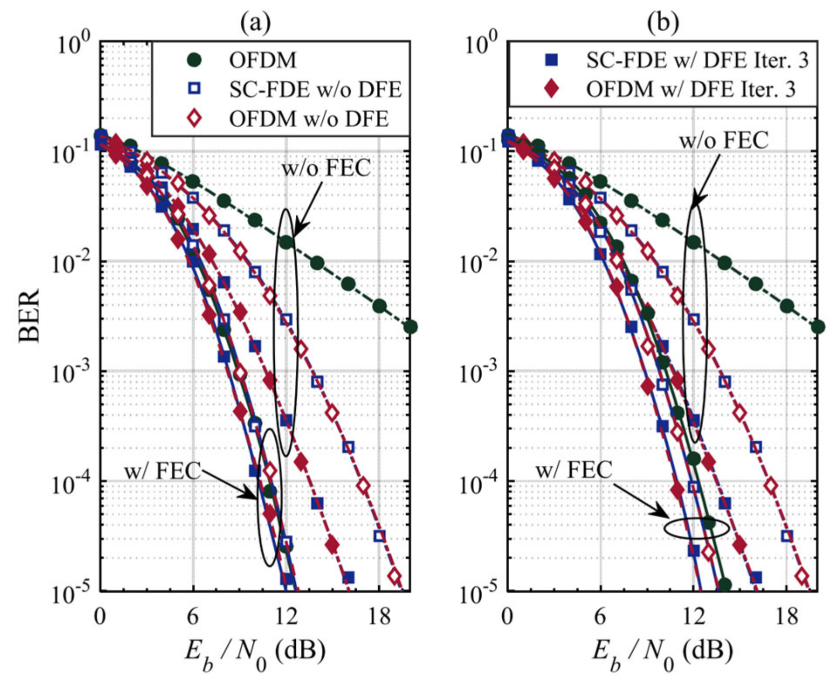


Fig. 15. The BER performance of the OFDM, SC-FDE and OCDM using forward error coding with 3.2-μs GI and code rates of (a) 2/3 and (b) 3/4.

X. Ouyang and J. Zhao, "Orthogonal chirp division multiplexing," *IEEE T Commun*, **64**(9): 3946–3957 (2016)

OCDM in Low-Power/Long-Range Wireless Systems

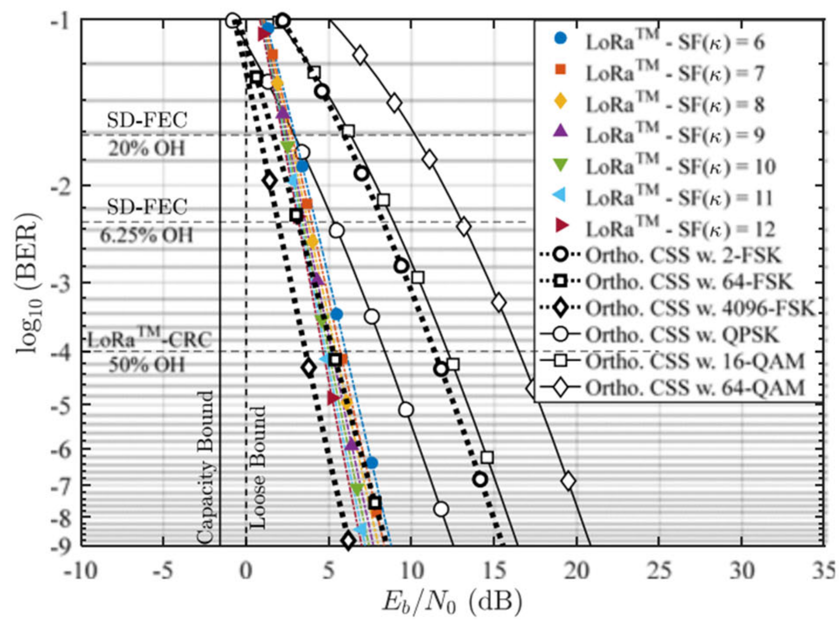


Fig. 6. Normalized modulation rate of the orthogonal chirps as a function of processing gain N for different number of chirps M.

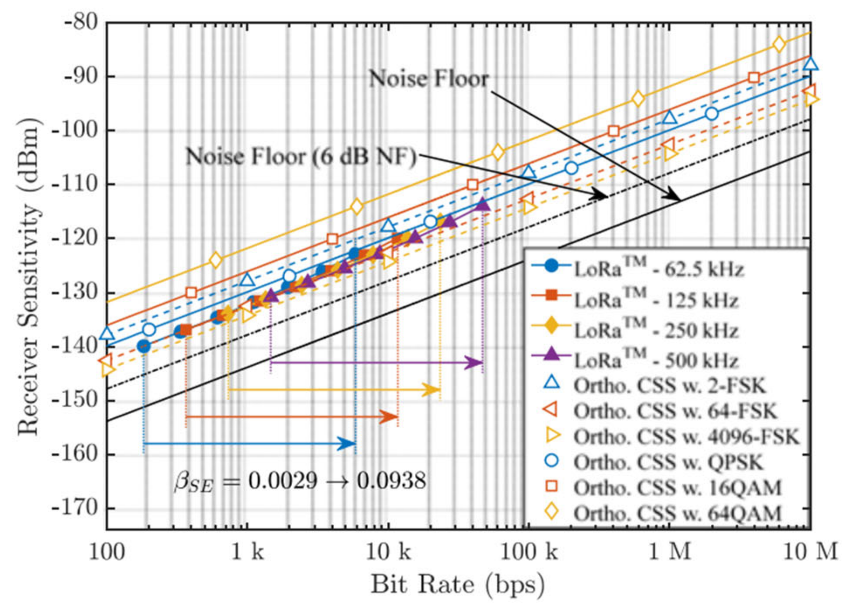
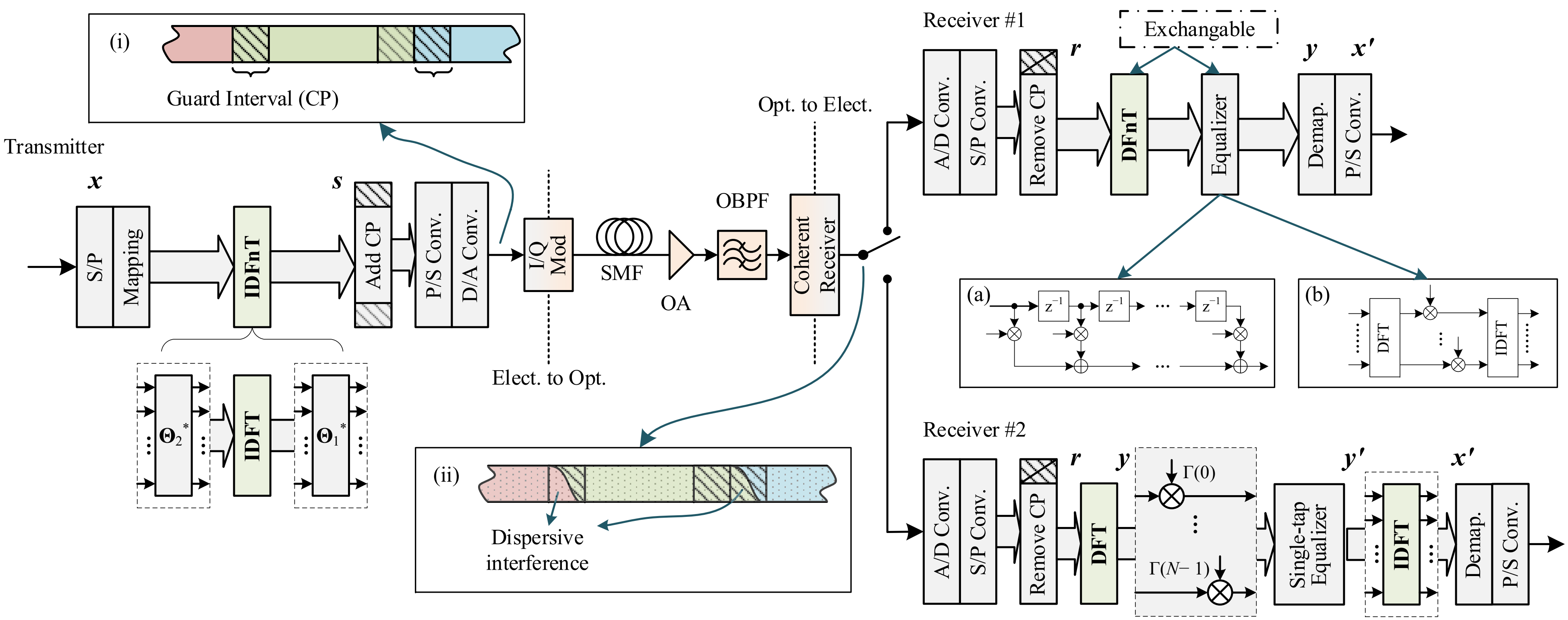


Fig. 7. Receiver sensitivities of LoRa-CSS and the proposed orthogonal CSS with FSK and QAM modulations vs. bit rate.

X. Ouyang, et al., "Chirp spread spectrum toward the Nyquist signaling rate — Orthogonality condition and applications," IEEE Signal Proc Let, **24**(10): 1488–1492, (2017)

OCDM in Fiber-Optic Systems (Coherent Optics)

❑ Coherent Optical OCDM (CO-OCDM)



X. Ouyang, et al., "Orthogonal Chirp Division Multiplexing for Coherent Optical Fiber Communications," *J. Lightwave Technol.* **34**, 4376-4386 (2016)

Experiment Results @ 36 Gbit/s

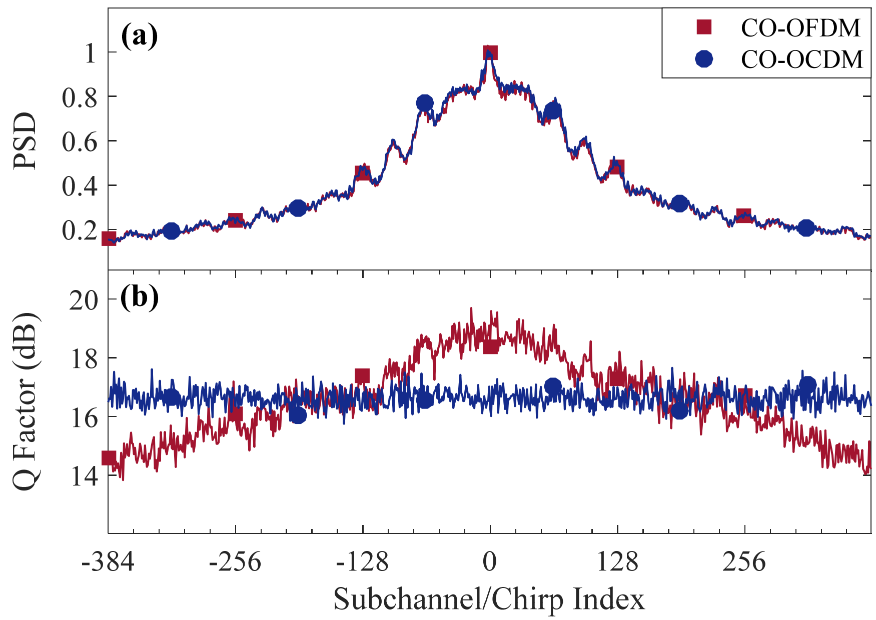


Figure.: The measured (a) power spectral densities (PSDs) and (b) Q-factors of each subchannel/chirp in the CO-OFDM and CO-OCDM systems.

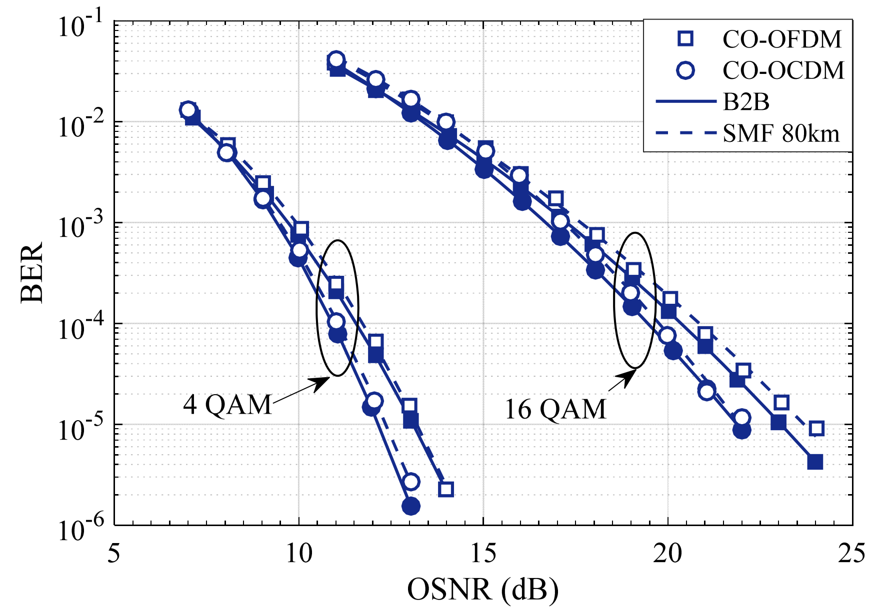
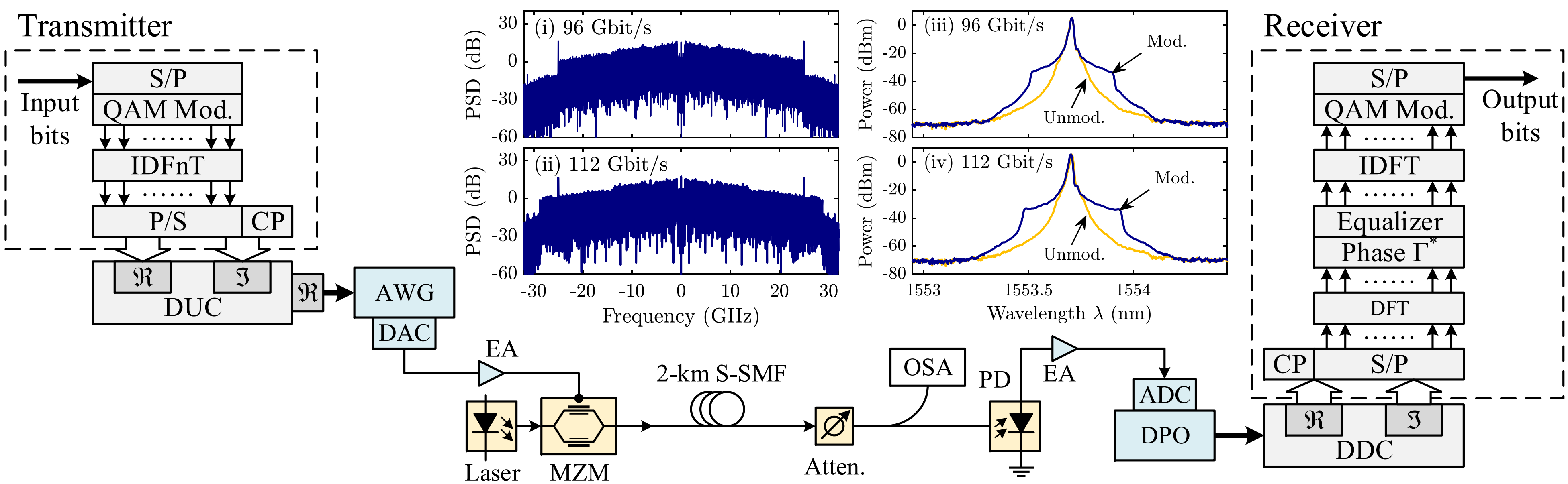


Figure.: Experiments results of the BER versus OSNR of the CO-OFDM and CO-OCDM systems.

X. Ouyang, et al., "Orthogonal Chirp Division Multiplexing for Coherent Optical Fiber Communications," *J. Lightwave Technol.* **34**, 4376-4386 (2016)

OCDM in Fiber-Optic Systems (IM/DD)

❑ Intensity Modulation and Direct Detection



X. Ouyang, et al., "Intensity-modulation direct-detection OCDM system based on digital up-conversion" in CLEO 2018, San Jose, US, 13-18 May, 2018 paper SM2C.2.
X. Ouyang et al., "Experimental demonstration of 112 Gbit/s orthogonal chirp-division multiplexing based on digital up-conversion for IM/DD systems with improved resilience to system impairments," in the 44th ECOC, Rome, Italy, 23-27 Sept., 2018, p. Mo4F.3.
X. Ouyang, et al., "Orthogonal chirp-division multiplexing for IM/DD-based short-reach systems," Optics Express, **27**(16), 2019

Experiment Results @ 96/112 Gbit/s

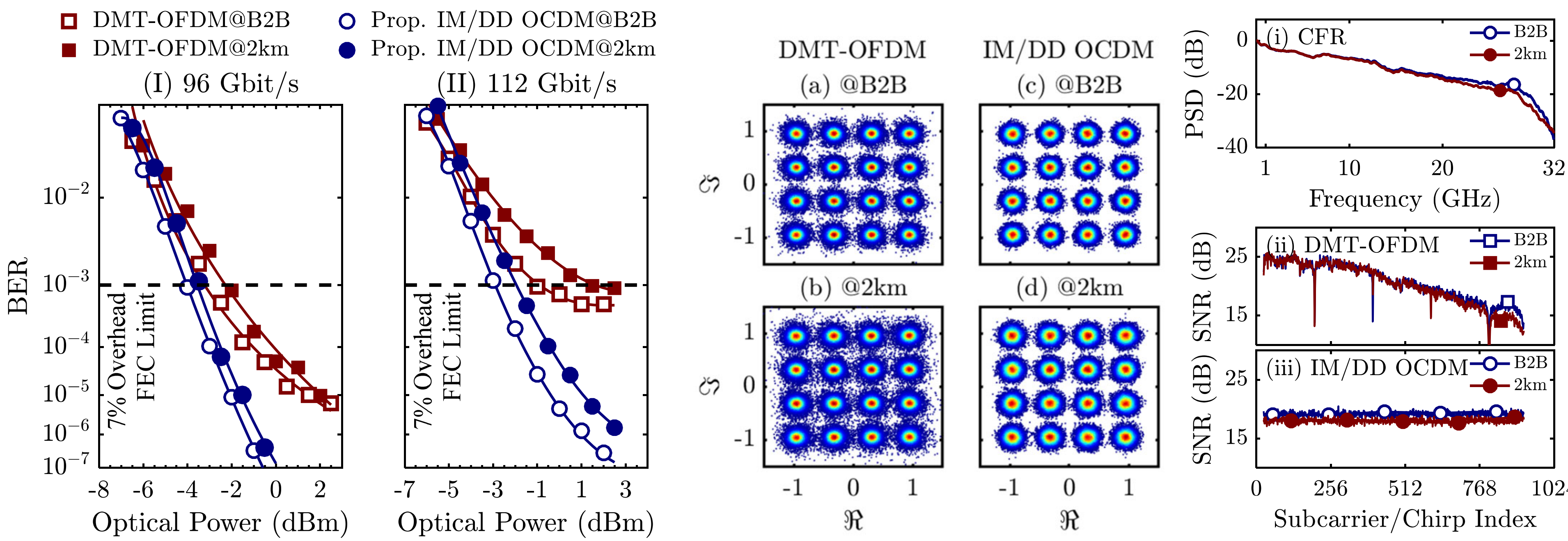
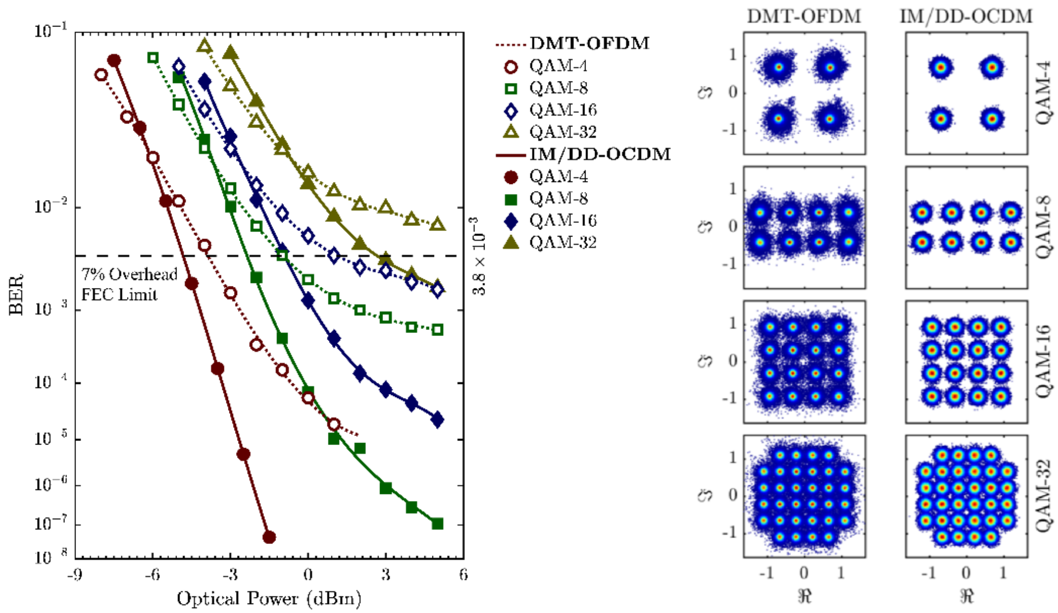


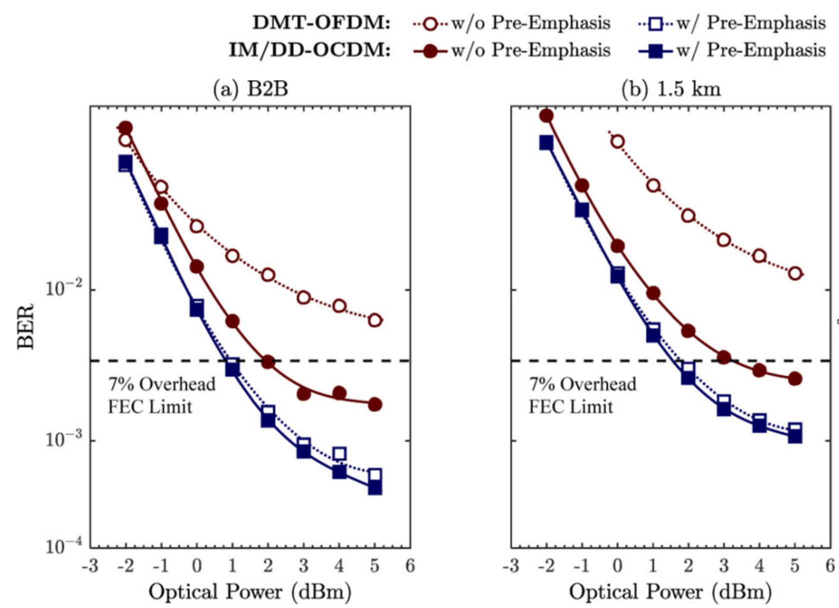
Fig.: Left: The measured BER performance of the conventional DMT-OFDM and the proposed IM/DD OCDM at (I) 96 Gbit/s and (II) 112 Gbit/s. Middle: The received constellation diagrams of the DMT-OFDM signals and that of the proposed IM/DD-OCDM signals with an input power = −1 dBm at 112 Gbit/s. Right: (i) The measured CFR of the systems at 112 Gbit/s, and (ii) the measured SNR of each subcarrier in the DMT-OFDM and (iii) that of each chirp in the proposed IM/DD-OCDM.

X. Ouyang et al., "Experimental demonstration of 112 Gbit/s orthogonal chirp-division multiplexing based on digital up-conversion for IM/DD systems with improved resilience to system impairments," in the 44th ECOC, Rome, Italy, 23-27 Sept., 2018, p. Mo4F.3.

Experiment Results @ 180 Gbit/s



Measured BER performance of OFDM and the proposed OCDM and systems with 36-GHz bandwidth and 32-QAM



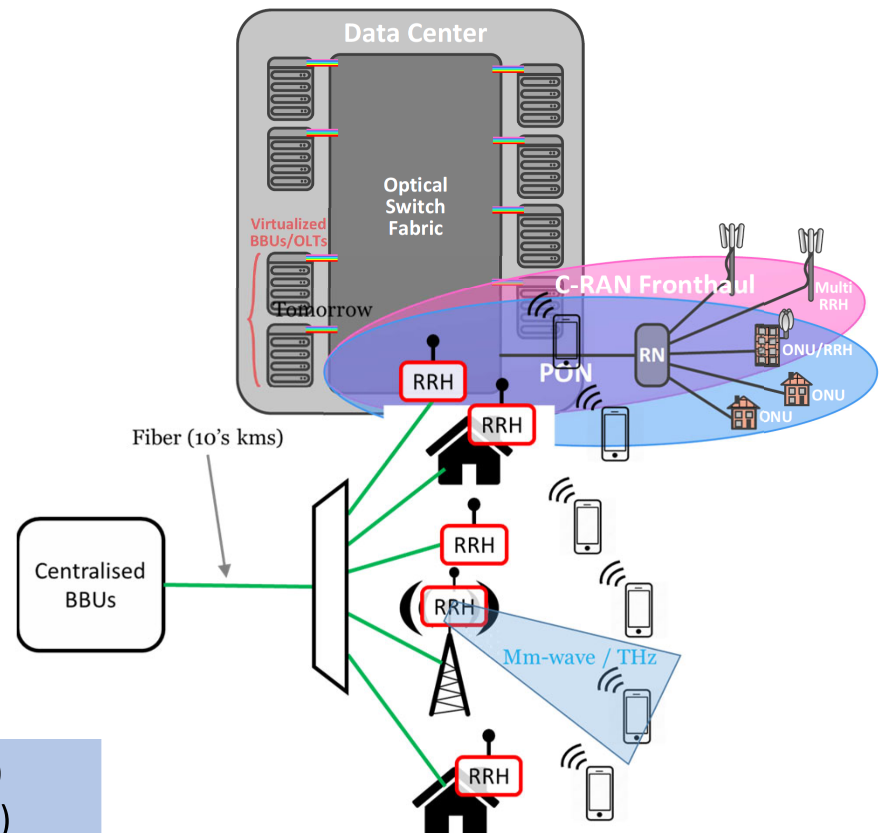
Performance considering Pre-Emphasis

X. Ouyang, et al., "Orthogonal chirp-division multiplexing for IM/DD-based short-reach systems," Optics Express, **27**(16), 2019

Photonics in 5G+/6G and Beyond

- **What do we know about the 5G+/6G**
  - More bandwidth (Frequency Dimension)
  - More antennas (Spatial Dimension)
  - More users (numbers, types, scenarios)
  - Higher Frequencies (> 50Hz)

- **What do photonic technologies offer?**
  - High bandwidth and high speed routing and transport
  - Already deployed multi-user access infrastructure
  - Potential to provide power efficiency
  - Enabling technology for mm-wave and THz systems



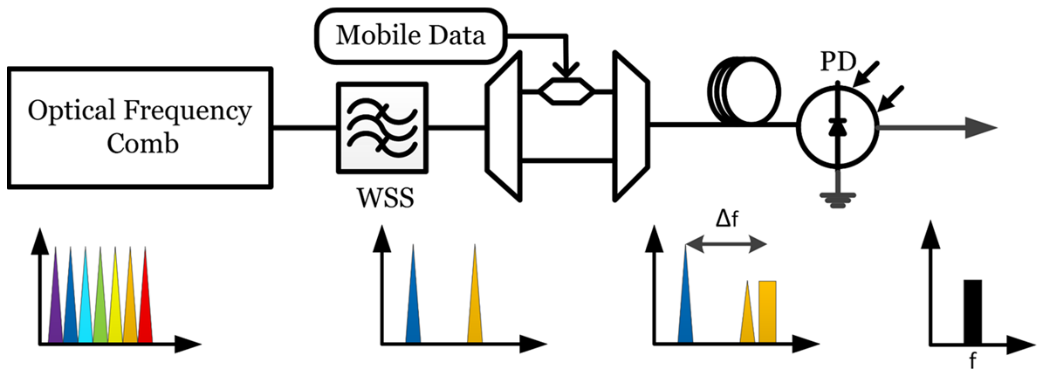
Network (More Fiber Distribution)
Signals (Greater Spectral Efficiency)
Bandwidth (Leverage mm-wave /THz)

Courtesy: Colm Browning, OSA APC, 2021

Colm Browning, "Flexible Converged Photonic and Radio Systems: A Pathway toward Next Generation Wireless Connectivity," OSA APC, 2021

Radio-over-Fiber for Millimeter Fronthaul

❑ Basic Concept

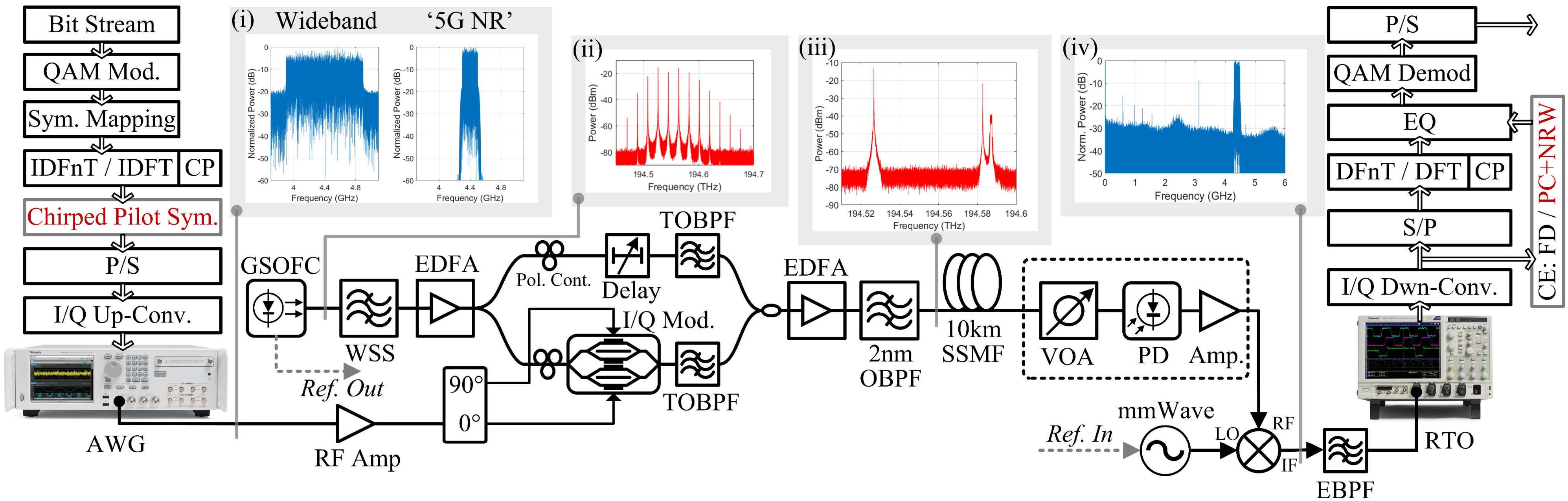


❑ Why considering OCDM

- Chromatic dispersion induced power fading due to heterodyning by direct detection
- Impairments such as phase noise, frequency offset
- Multipath transmission of wireless access

Colm Browning, "Flexible Converged Photonic and Radio Systems: A Pathway toward Next Generation Wireless Connectivity," OSA APC, 2021

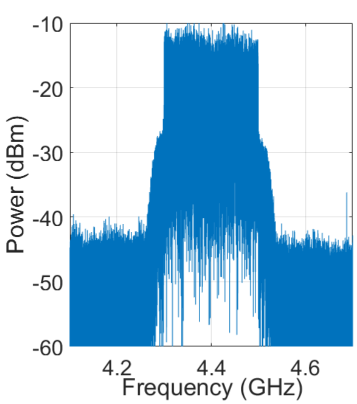
Optical/mm-wave A-RoF System

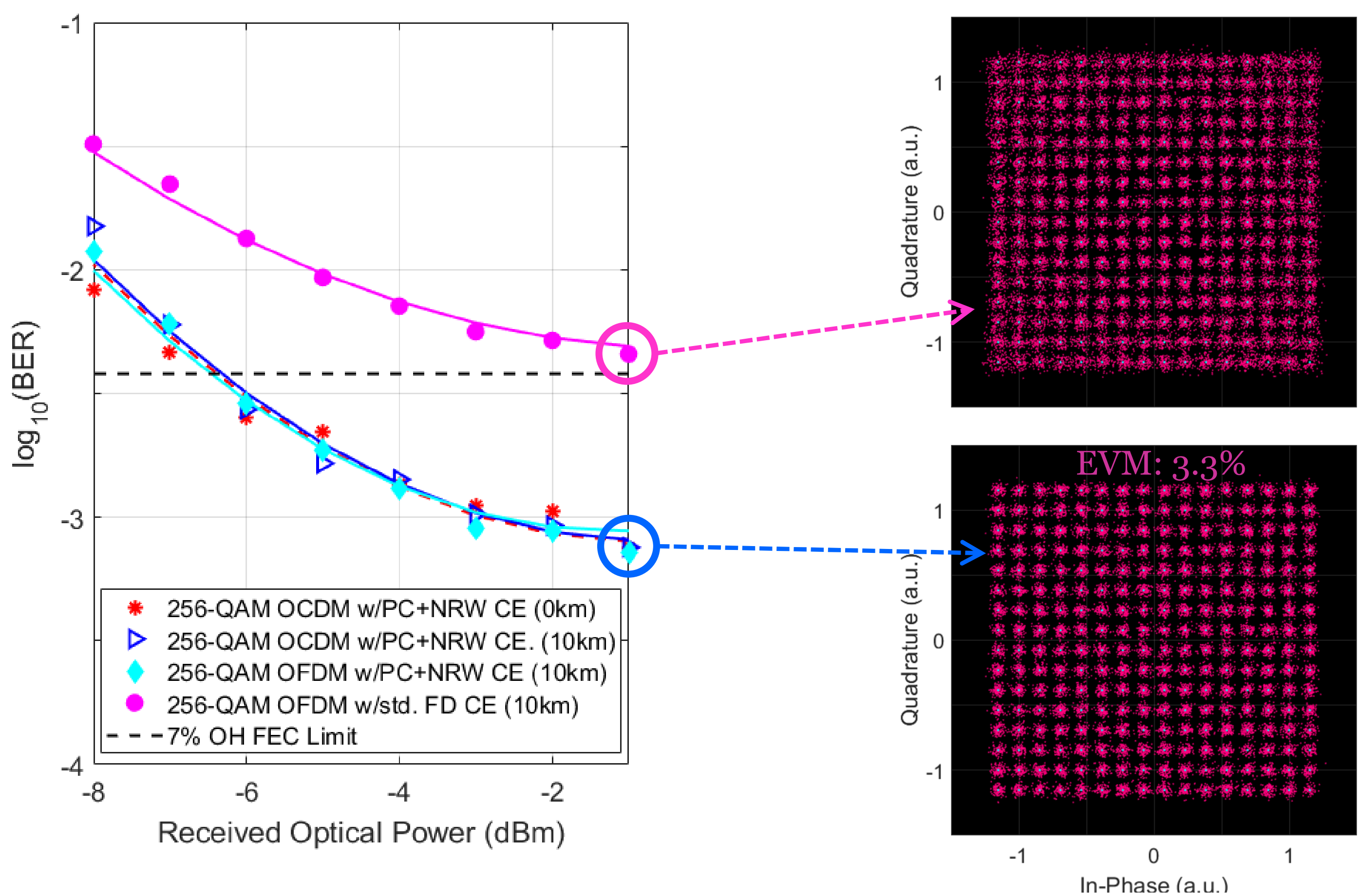


C. Browning et al., "Orthogonal Chirp-Division Multiplexing for Performance Enhanced Optical/Millimeter-Wave 5G/6G Communications", OFC, 2021
X. Ouyang, et al., "Robust Channel Estimation for Coherent Optical Orthogonal Chirp-Division Multiplexing With Pulse Compression and Noise Rejection", Journal of Lightwave Technology, vol. 36, no. 23, pp. 5600–5610, Dec. 2018.

Results – Narrowband (200MHz, 5G NR)

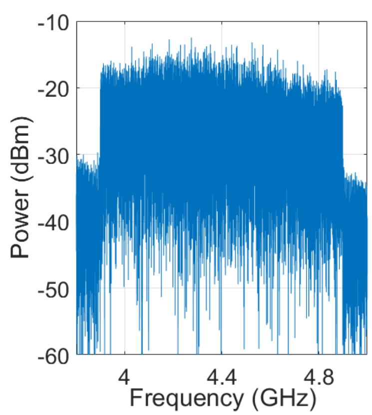
Property	Value
(I)DFT / (I)DFnT	1024
SCs / Chirps	820
QAM-Level	256
Sym. Rate (kHz)	244
BW (MHz)	200
IF (GHz)	4.4
Raw DR (Gb/s)	1.6

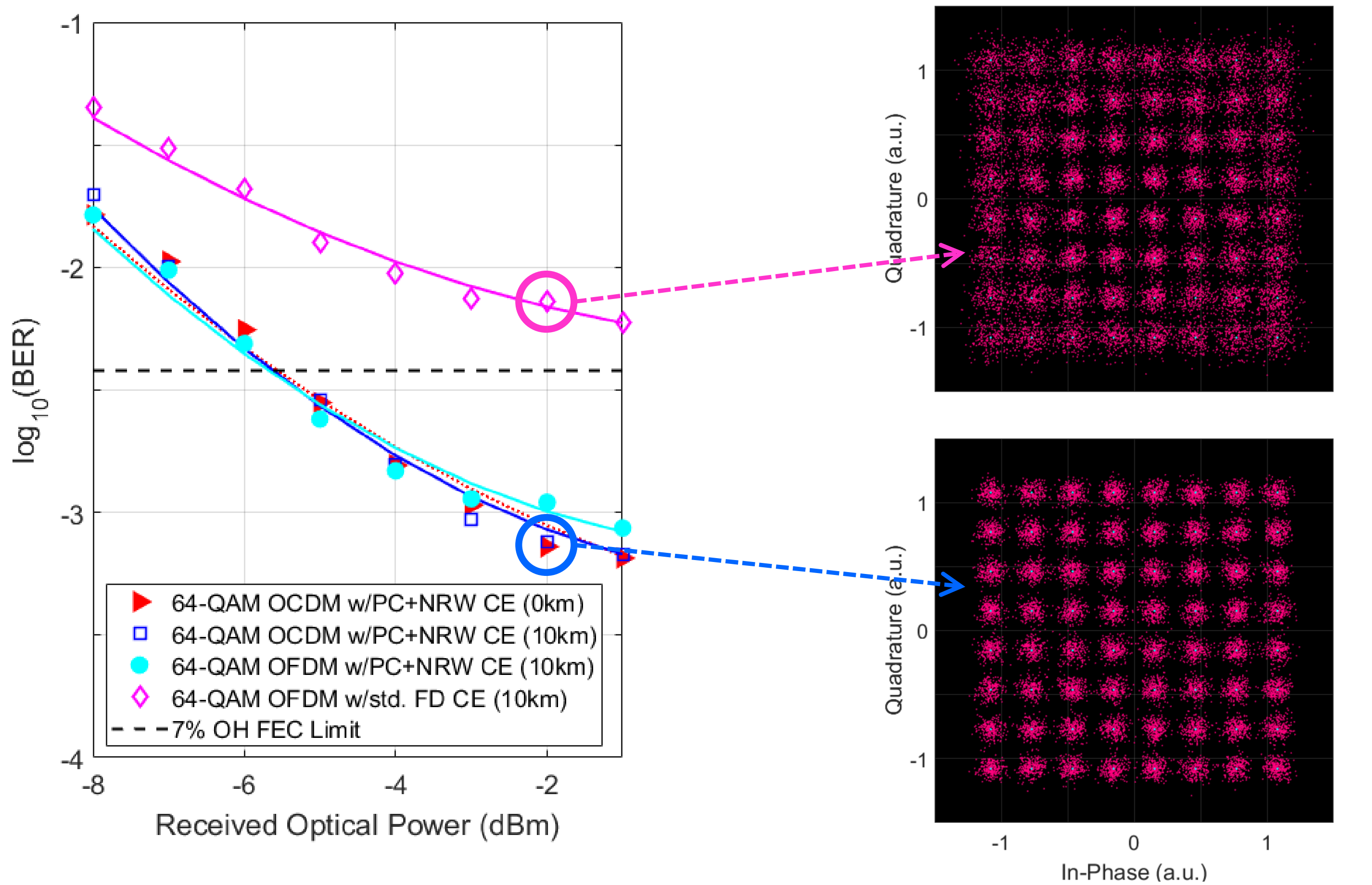




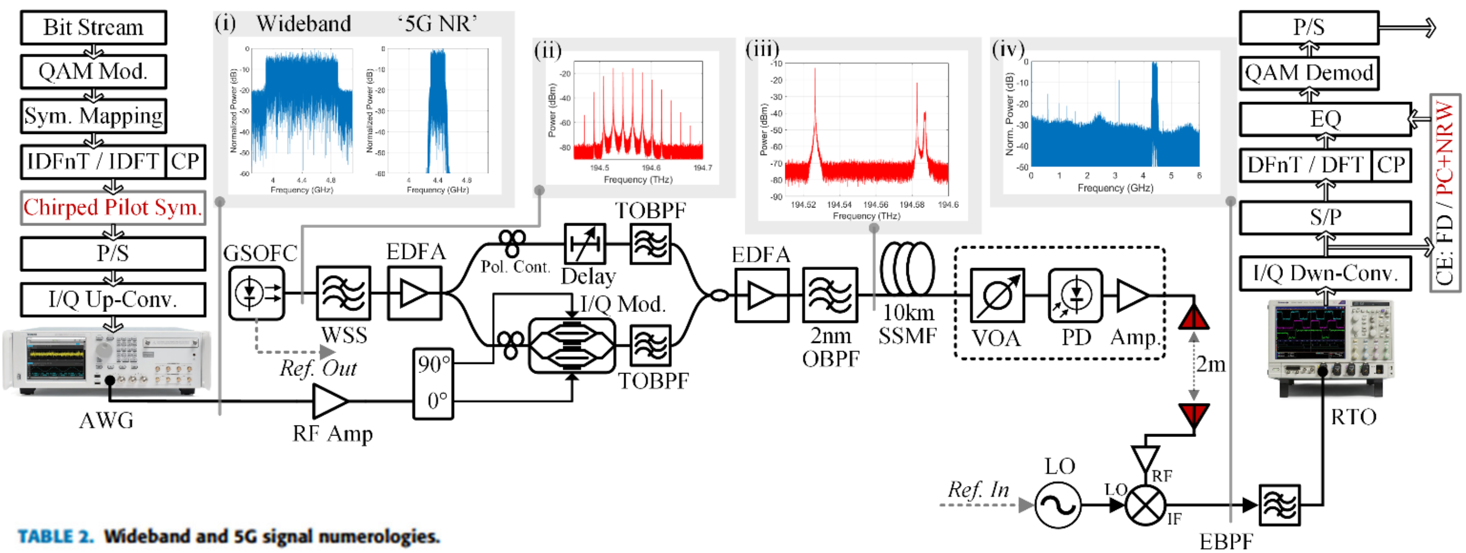
Results – Wideband (1GHz)

Property	Value
(I)DFT / (I)DFnT	1024
SCs / Chirps	512
QAM-Level	64
Sym. Rate (kHz)	1953
BW (MHz)	1000
IF (GHz)	4.4
Raw DR (Gb/s)	6





Optical/mm-wave A-RoF System w. 2m Wireless



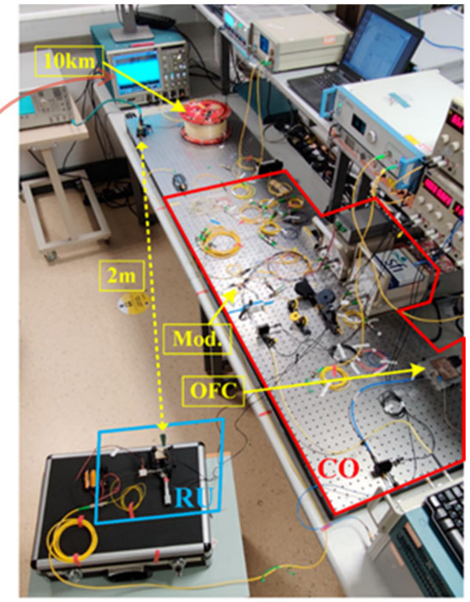
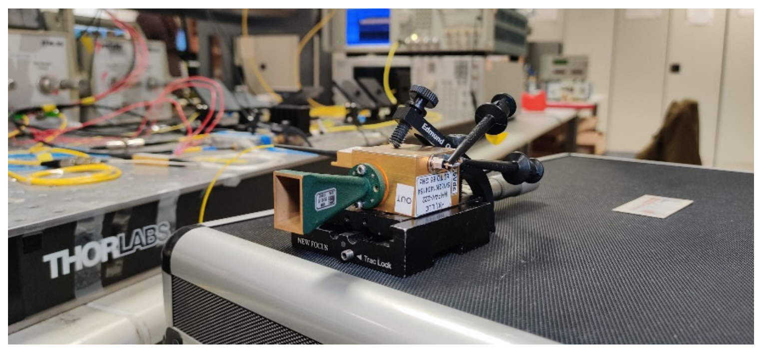
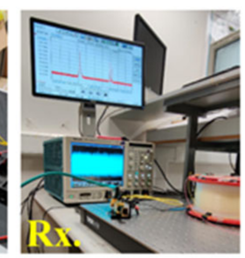


TABLE 2. Wideband and 5G signal numerologies.

Prop.	Wideband	Mobile (5G)	Unit
# Chirps/SCs	128	820	n/a
(I)DF(n)T size	256	1024	n/a
QAM order	16	128 / 256	n/a
Symbol Rate	311.25	0.244	MHz
Bandwidth	4000	200.2	MHz
Cyclic Prefix	6.25	6.25	%
Raw Data Rate	16	1.4 / 1.6	Gb/s

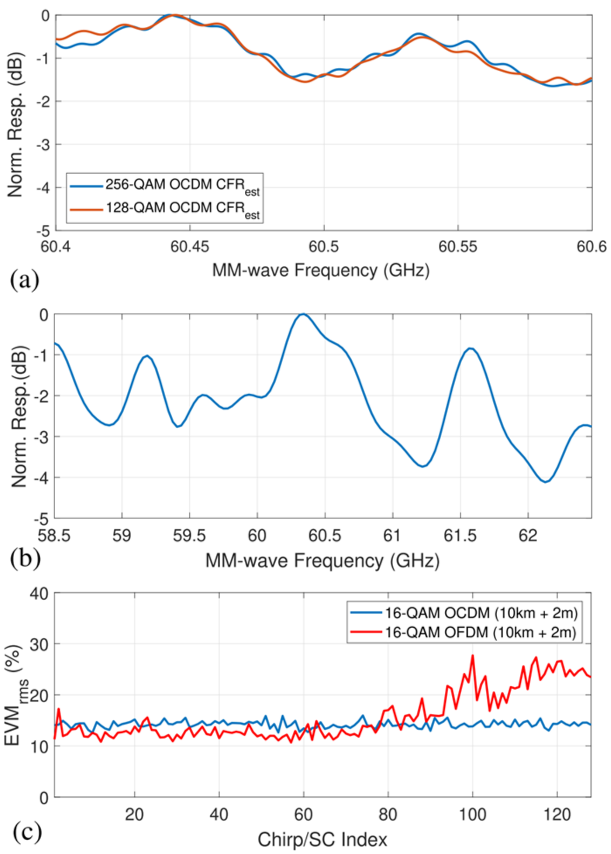
SC: Subcarrier

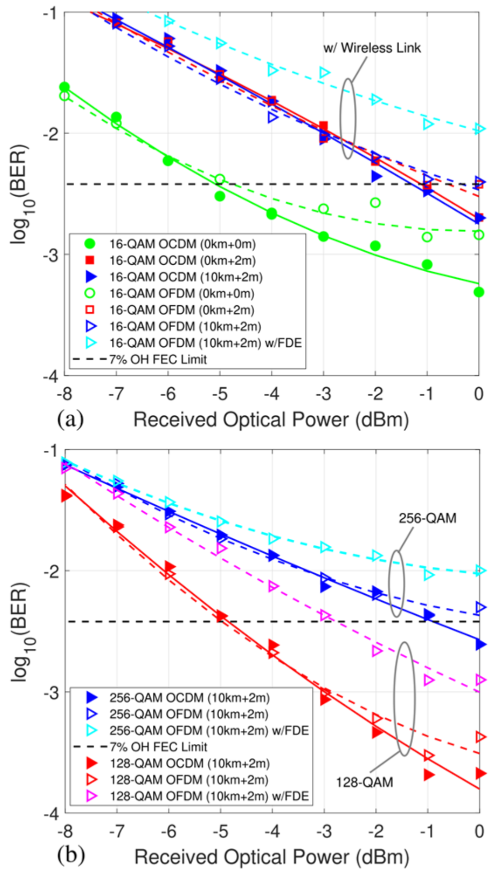


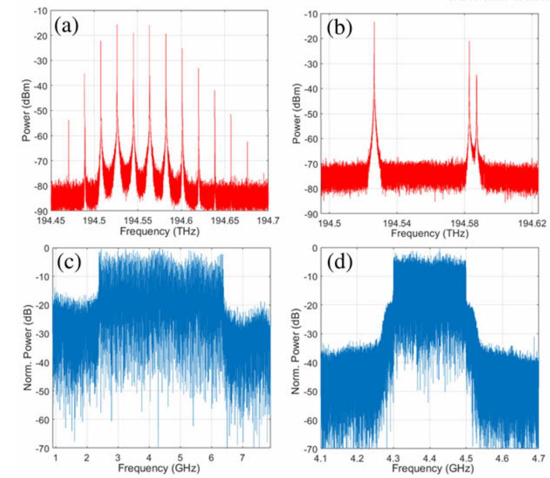


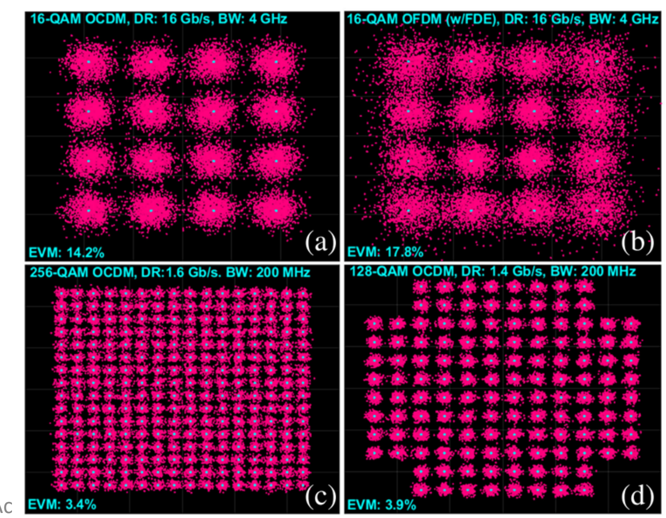
C. Browning, et al., "Orthogonal Chirp-Division Multiplexing for Future Converged Optical/Millimeter-Wave Radio Access Networks," IEEE Access, **10**: 3571-3579 (2022).

Results – (200 MHz / 4 GHz)









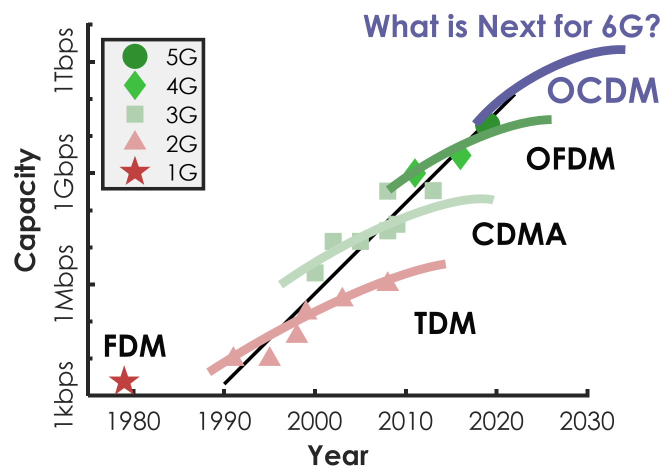
C. Browning, et al., "Orthogonal Chirp-Division Multiplexing for Future Converged Optical/Millimeter-Wave Radio Access Networks," IEEE Ac

What's More …

- ❑ **Wireless and Optical Access**
- ❑ **Submarine Acoustic Communications**
- ❑ **Satellite**
- ❑ **Telemetry**
- ❑ **Integrated Radar/Sensing and Communications**
  - ➢ Radar and Sensing is a type of channel estimation for communications

Conclusion and Outlook

- ❑ **Future Wireless and Optical Access Networks**
  - ➢ Flexible and Unified Air Interface
  - ➢ Wireless and Optical Convergence
  - ➢ Backward and Forward Compatibility



- ❑ **Orthogonal Chirp-Division Multiplexing**
  - ➢ For a variety of wireless systems (Bandwidth/Power Limited)
  - ➢ Suitable for a diversity of scenarios
    - o RF, mmWave, optical systems
    - o Acoustic, Space, etc.
  - ➢ Integrated Radar/Sensing and Communications

- ❑ **Future Work**
  - ➢ Just a waveform modulation technology

Acknowledgement

ENTERPRISE IRELAND

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

Science Foundation Ireland sfi For what's next

KTI
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Thanks and Questions

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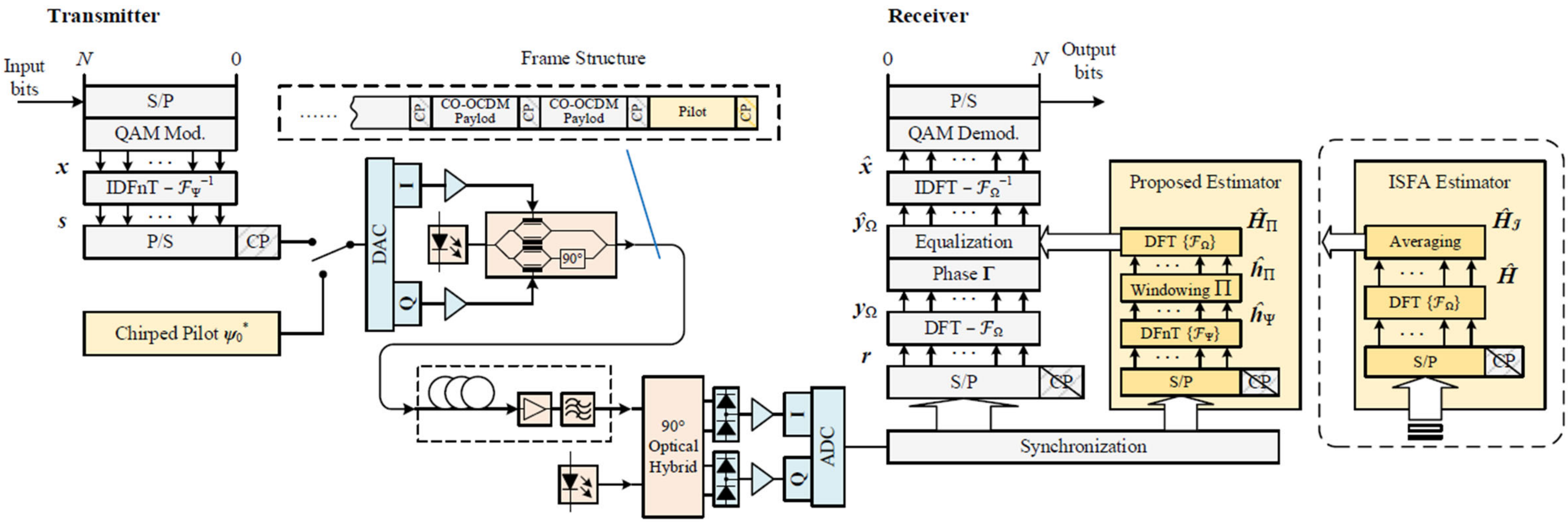
European Union European Structural and Investment Funds

Channel Estimation Based on OCDM Signals (1/5)

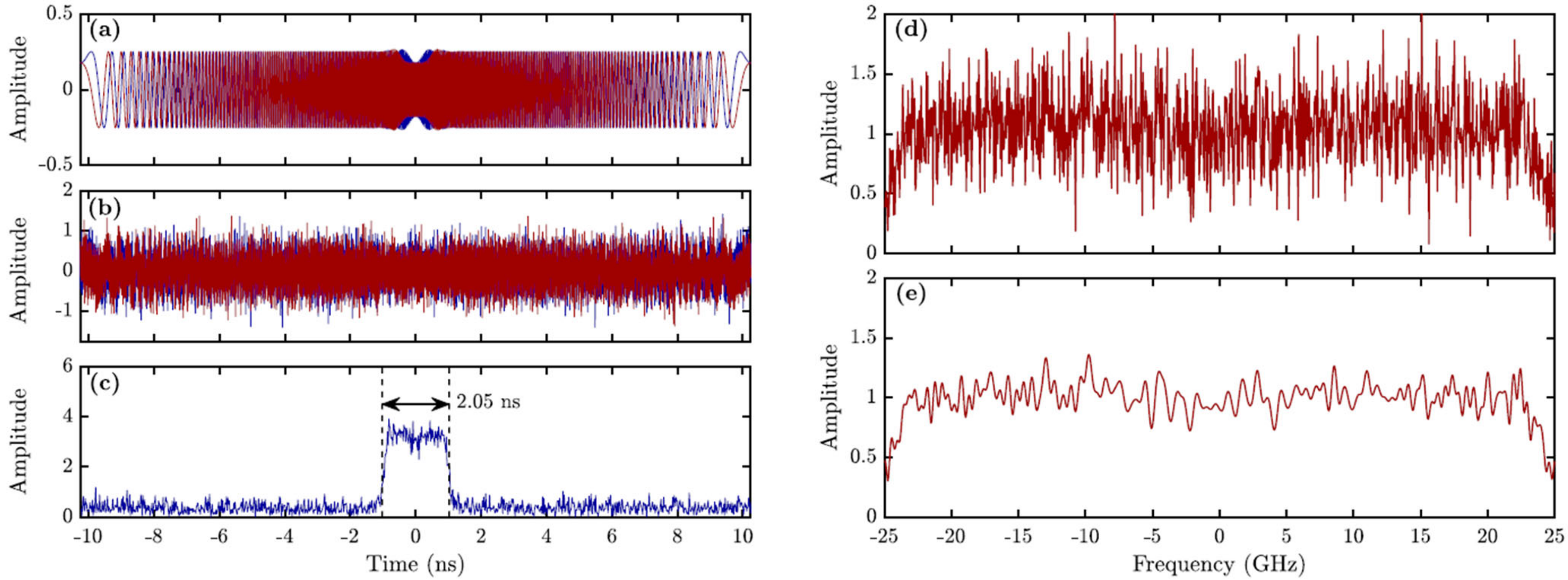
❑ Fibre-Optic Systems (Single-Input Single-Output)



X. Ouyang, et al., "Robust Channel Estimation for Coherent Optical Orthogonal Chirp-Division Multiplexing With Pulse Compression and Noise Rejection", *Journal of Lightwave Technology*, vol. 36, no. 23, pp. 5600–5610, Dec. 2018.

Channel Estimation Based on OCDM Signals (2/5)

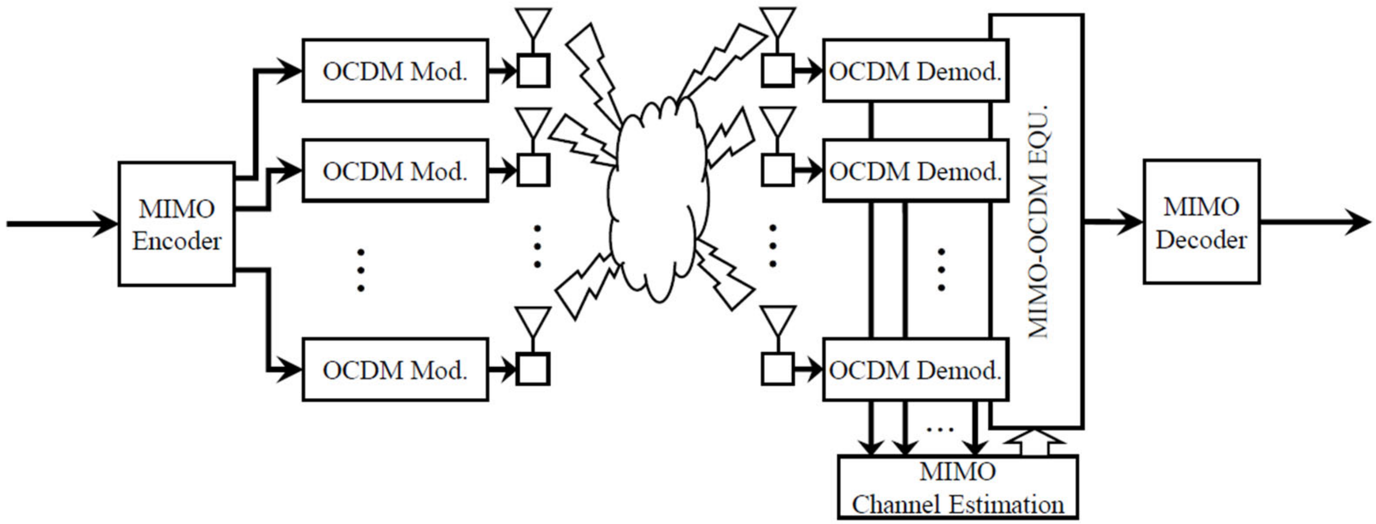
❑ Fibre-Optic Systems (Single-Input Single-Output)



X. Ouyang, et al., "Robust Channel Estimation for Coherent Optical Orthogonal Chirp-Division Multiplexing With Pulse Compression and Noise Rejection", *Journal of Lightwave Technology*, vol. 36, no. 23, pp. 5600–5610, Dec. 2018.

Channel Estimation Based on OCDM Signals (3/5)

❑ MIMO-OCDM Systems



X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems as an Emerging 6G Radio Access Technology," in 2022 IEEE Globecom Workshops (GC Wkshps), Rio de Janeiro, Brazil, 2022, pp. 1573-1578.
X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems," *IEEE Trans. Wireless Comm.*, (Under Review).

Channel Estimation Based on OCDM Signals (4/5)

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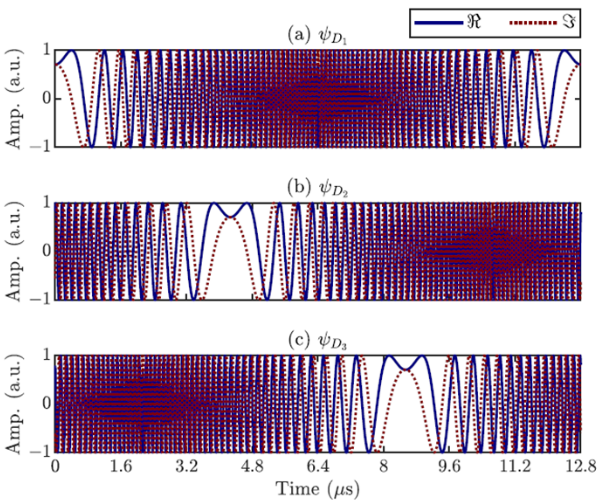
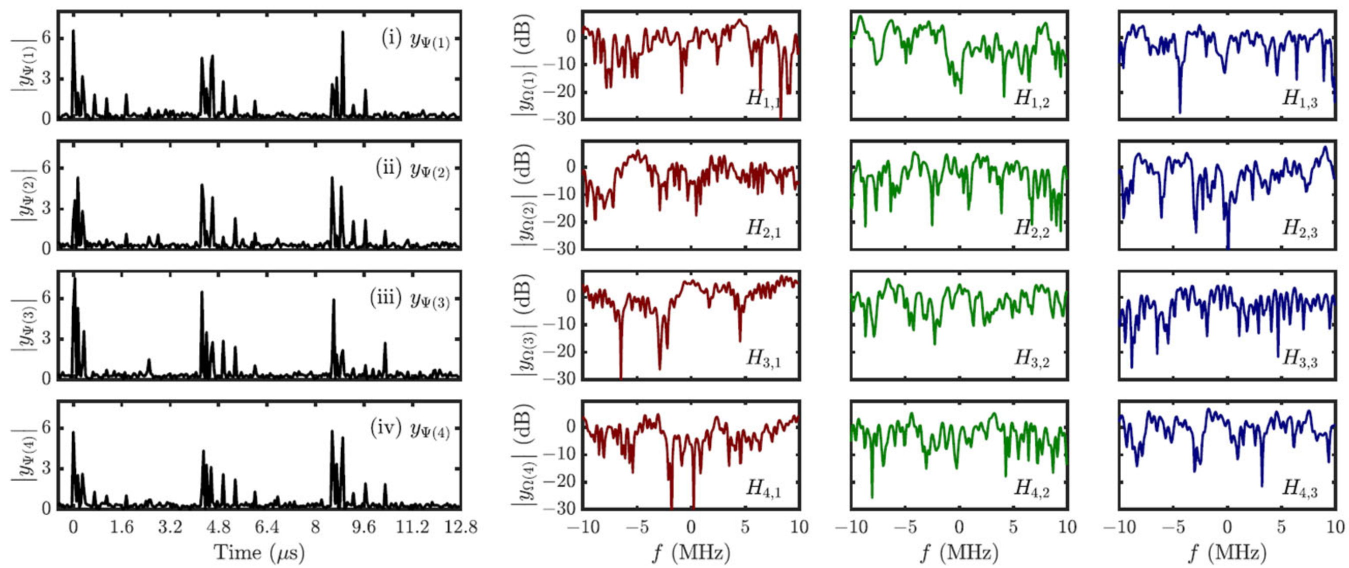
❑ MIMO-OCDM Systems





(a) Received overlapping CIRs after DFnT

(b) Recovered CFRs

X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems as an Emerging 6G Radio Access Technology," in 2022 IEEE Globecom Workshops (GC Wkshps), Rio de Janeiro, Brazil, 2022, pp. 1573-1578.
X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems," *IEEE Trans. Wireless Comm.*, (Under Review).

Channel Estimation Based on OCDM Signals (5/5)

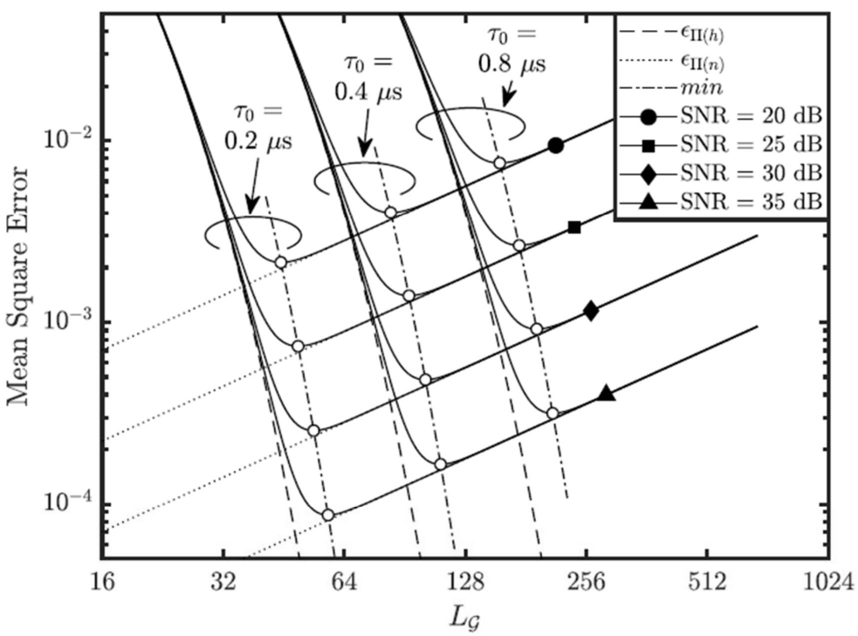


Fig. 6. Performance of the proposed estimator against the window width. The MSE performance (solid lines) are the sum of the noise term (dotted lines) and the distortion due to exceeding the window (dashed lines).

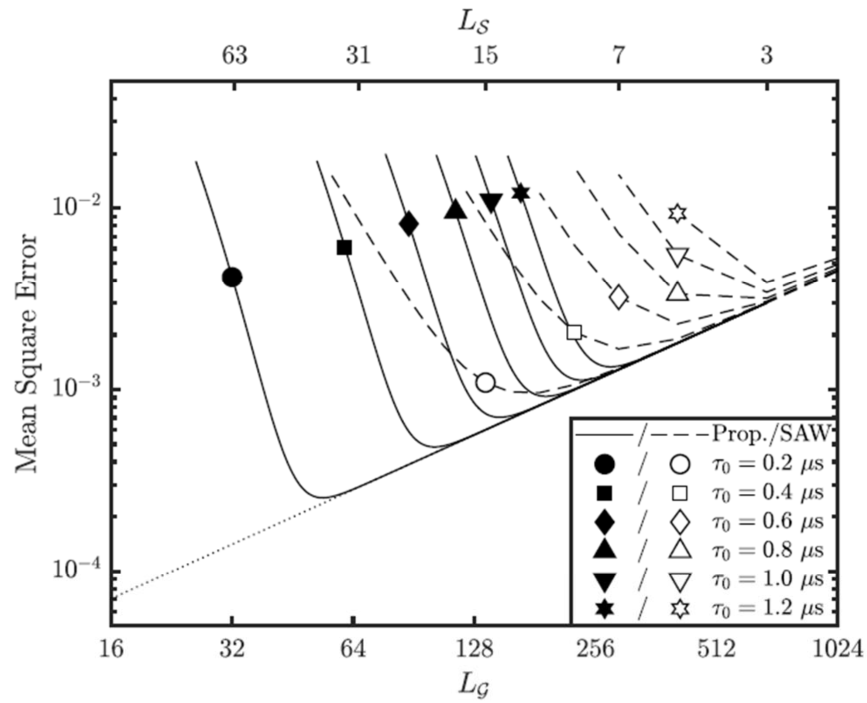


Fig. 7. Performance comparison of the proposed and SAW estimators with a received SNR = 30 dB. Both estimators are normalized to the same noise suppression capability as the noise terms (dotted lines) overlapped.

X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems as an Emerging 6G Radio Access Technology," in 2022 IEEE Globecom Workshops (GC Wkshps), Rio de Janeiro, Brazil, 2022, pp. 1573-1578.

X. Ouyang, et al., "Channel Estimation for MIMO-OCDM Systems," *IEEE Trans. Wireless Comm.*, (Under Review).

OCDM-Baed Integrated Radar/Sensing and Comm