Flexible waveforms for 6G

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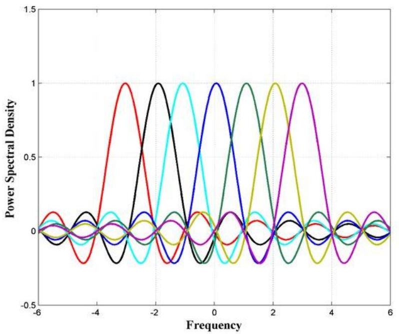

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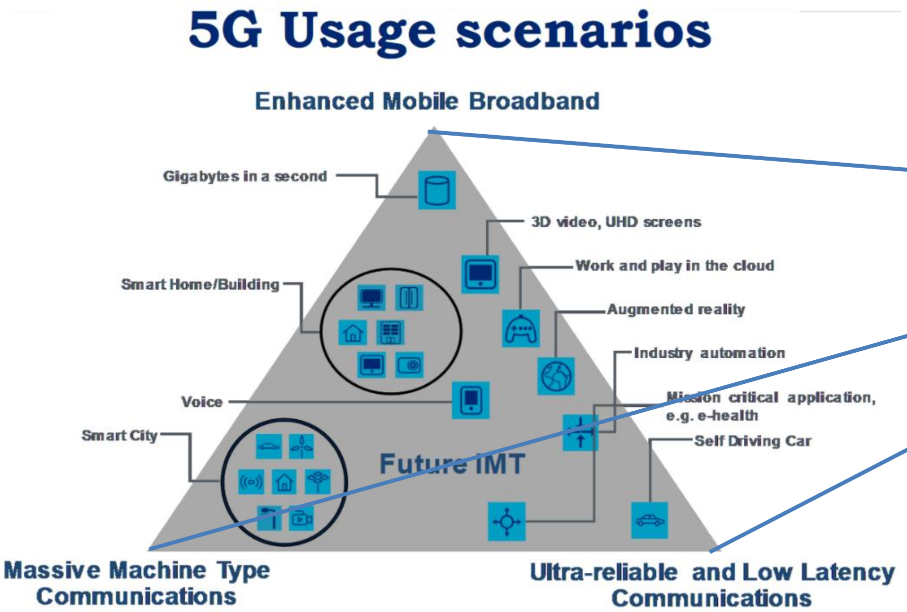
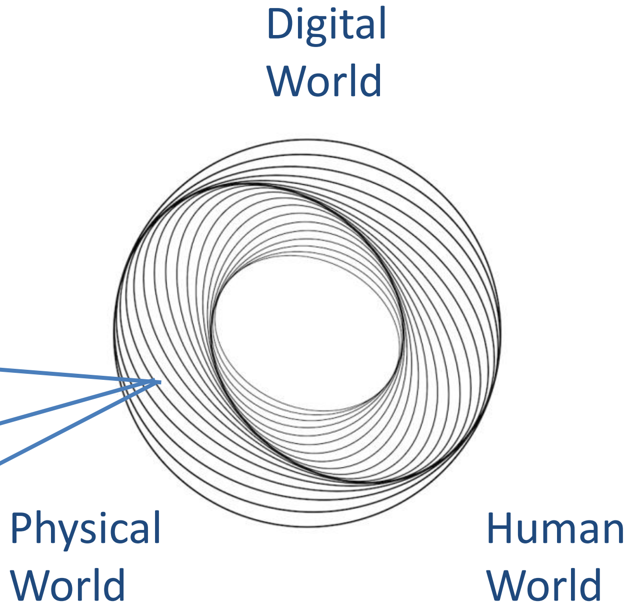
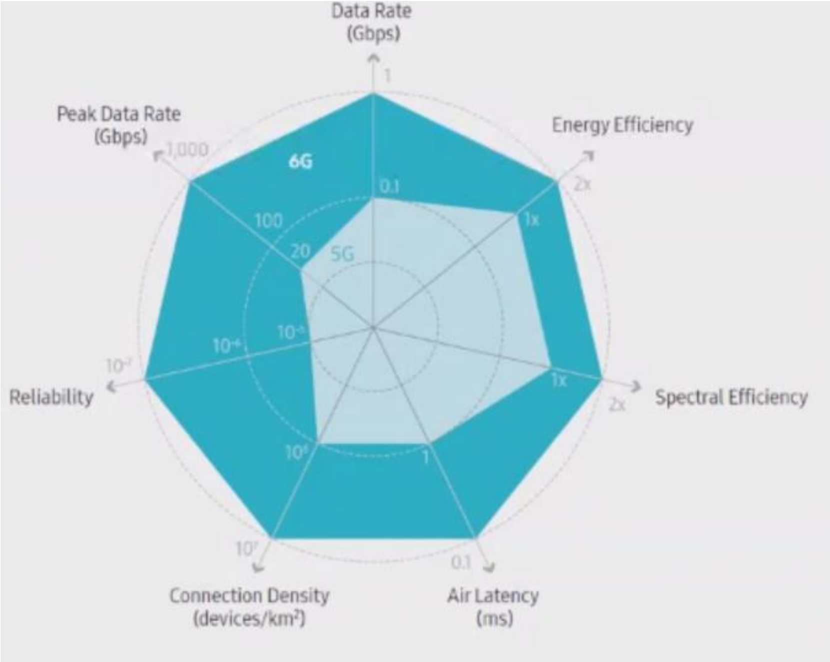
Towards 6G





- **Sustainability**
- **Global coverage**

6G KPIs (ITU vision beyond 2030)



- Throughput/data rate up to 1 Tbit/s (x50 5G)
- User-experienced data rate of 1 Gbit/s (x10 5G),
- End-to-end latency less than 1 ms
- Vehicle speeds of up to 1,000 km/h
- Localization precision equal to 1 cm in three dimensions
- Etc ...

6G KPIs (ITU vision beyond 2030)

Spectrum availability -> operating carrier frequency to unprecedently high values -> amplification and RF impairments are more severe

Short symbols vs Long symbols
Channel variability -> pilots, ICI

ISAC: integrated communications and sensing

- Throughput/data rate up to 1 Tbit/s (x50 5G)
- User-experienced data rate of 1 Gbit/s (x10 5G),
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- Localization precision equal to 1 cm in three dimensions
- Etc ...

Can we still use the same waveforms as in 4G / 5G?

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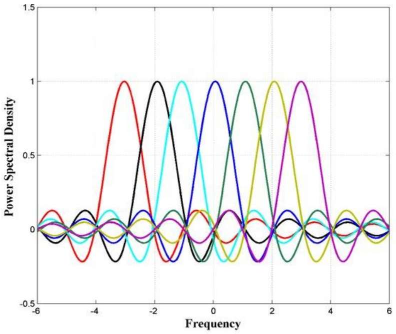
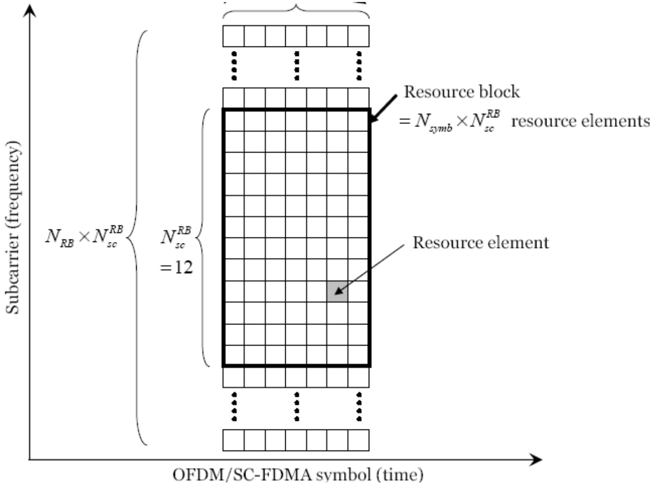
Multicarrier Waveforms



Orthogonal Frequency division multiplexing (OFDM)

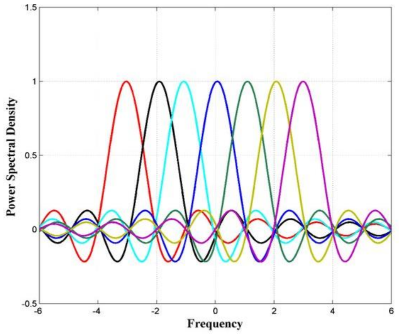
- Robust to multipath propagation
- Easy implementation (FFT)
- Time-frequency grid

- Time-domain + frequency-domain scheduler

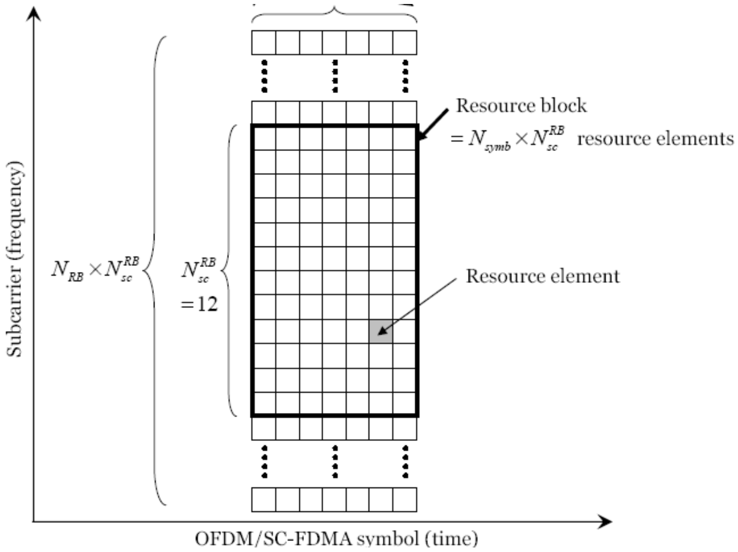


Muti-user DIVERSITY

Multicarrier Waveforms



Orthogonal Frequency division multiplexing (OFDM)



- Phase noise
- Synchronization
- PAPR
- Out of band emissions

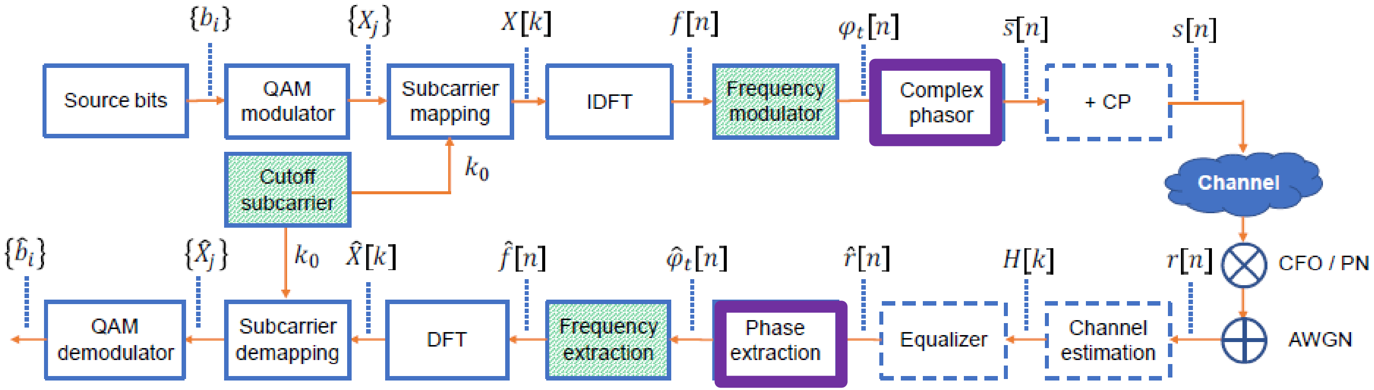
- Not good for rapidly varying channels

Muti-user DIVERSITY

Revisiting PAPR - Constant envelope

Reducing the PAPR (with pre- or post-processing)

- SC-FDMA (DFTs-OFDM)
- CE-OFDM
- FM-OFDM



- **Constant envelope**
- **Time-domain + frequency-domain scheduler**

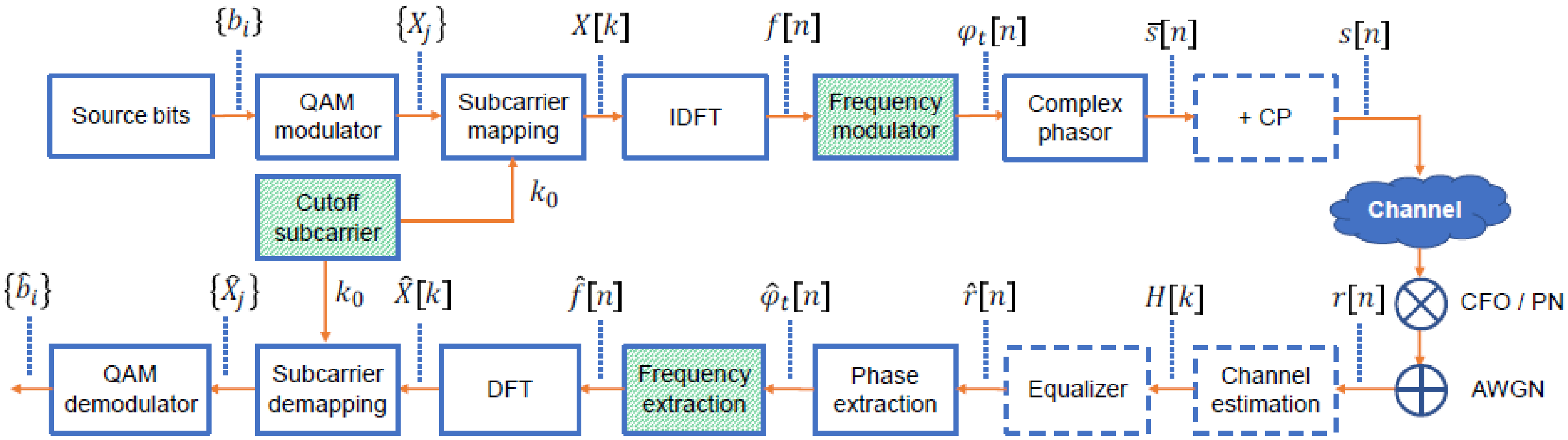
- **½ subcarriers "lost" to ensure hermicity (real signal)**
- **Channel estimation at the Rx before the DFT**

Revisiting High mobility

FM-OFDM

$$\begin{cases} X_{k-(k_0+1)}, & k = k_0+1,\ldots,k_0+N_s \\ X^*_{N-2-(k+k_0)}, & k = N-N_s-(k_0+1),\ldots,N-2-k_0 \\ 0, & \text{elsewhere} \end{cases}$$

$$\varphi_t[n] = \varphi_0 + 2\pi \sum_{n'=0}^{n} f[n'], \qquad \bar{s}[n] = A_c \exp j\varphi_t[n].$$



$$\hat{\varphi}_t[n] = \arg \hat{r}[n] = \arctan \frac{\Im\{\hat{r}[n]\}}{\Re\{\hat{r}[n]\}}, \quad n = 0,\ldots,N-1.$$

$$\hat{f}[n] = \frac{1}{2\pi}\nabla\hat{\varphi}_t[n],$$

To avoid ambiguities, the arctan operation must be followed by a phase unwrapper that adds or subtracts multiples of 2π until the difference between two consecutive phases lies within $[-\pi,\pi)$.

J. Lorca Hernando, A. García Armada, "Frequency-Modulated OFDM: a new Waveform for High-Mobility Wireless Communications," IEEE Trans. on Communications, vol. 71, no.1, pp. 1540 - 552 , Jan. 2023.

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FM-OFDM

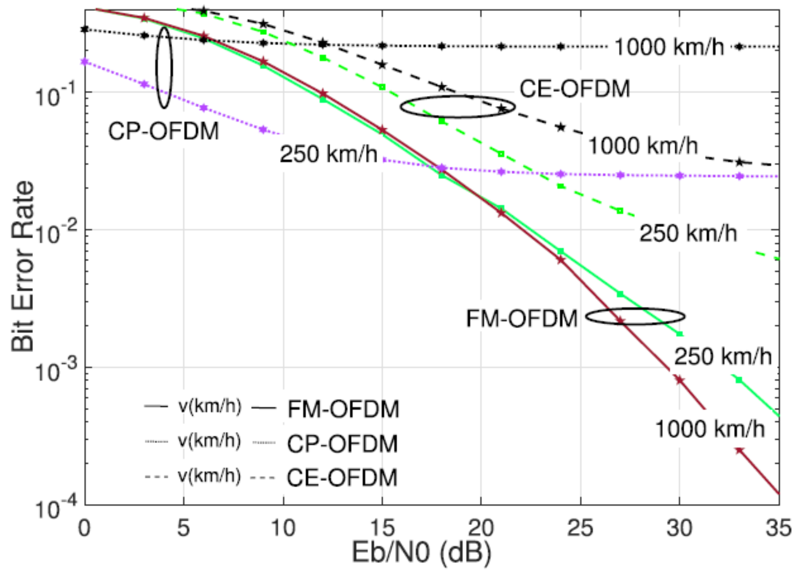
- Doppler and phase noise effects are avoided with a cut-off frequency:

$$k_0 \gtrsim \left\lfloor \frac{\max(f_D, W_{PN})}{SCS} \right\rfloor.$$

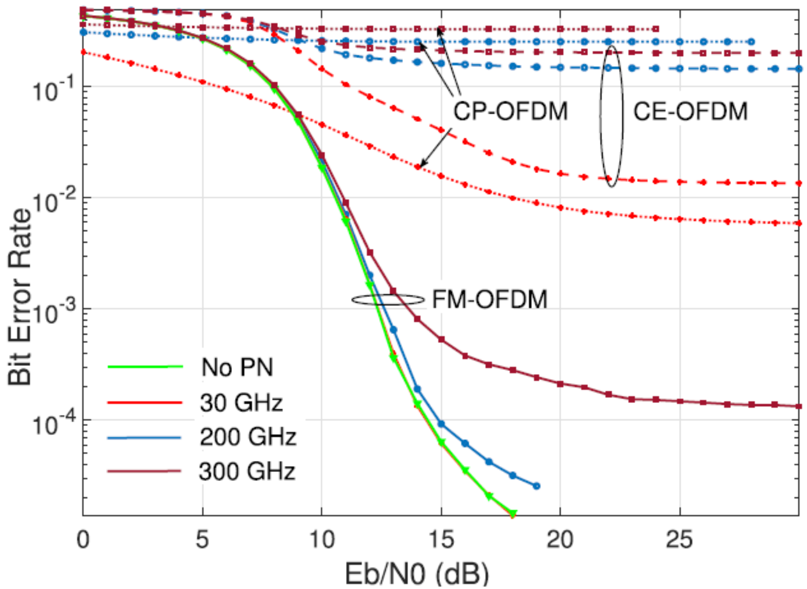
- FM-OFDM can overcome phase and frequency impairments without any channel estimation or equalization in flat-fading channels.
- CSI estimation is needed in frequency-selective channels.

FM-OFDM

- If the channel changes even within an OFDM symbol



Rayleigh flat-fading channel, QPSK modulation at **250 km/h** (fD = 1.38 kHz) and **1,000 km/h** (fD = 5.55 kHz). N = 512, Na = 128, SCS = 15 kHz, m = 0.6/2π, k0 = 0



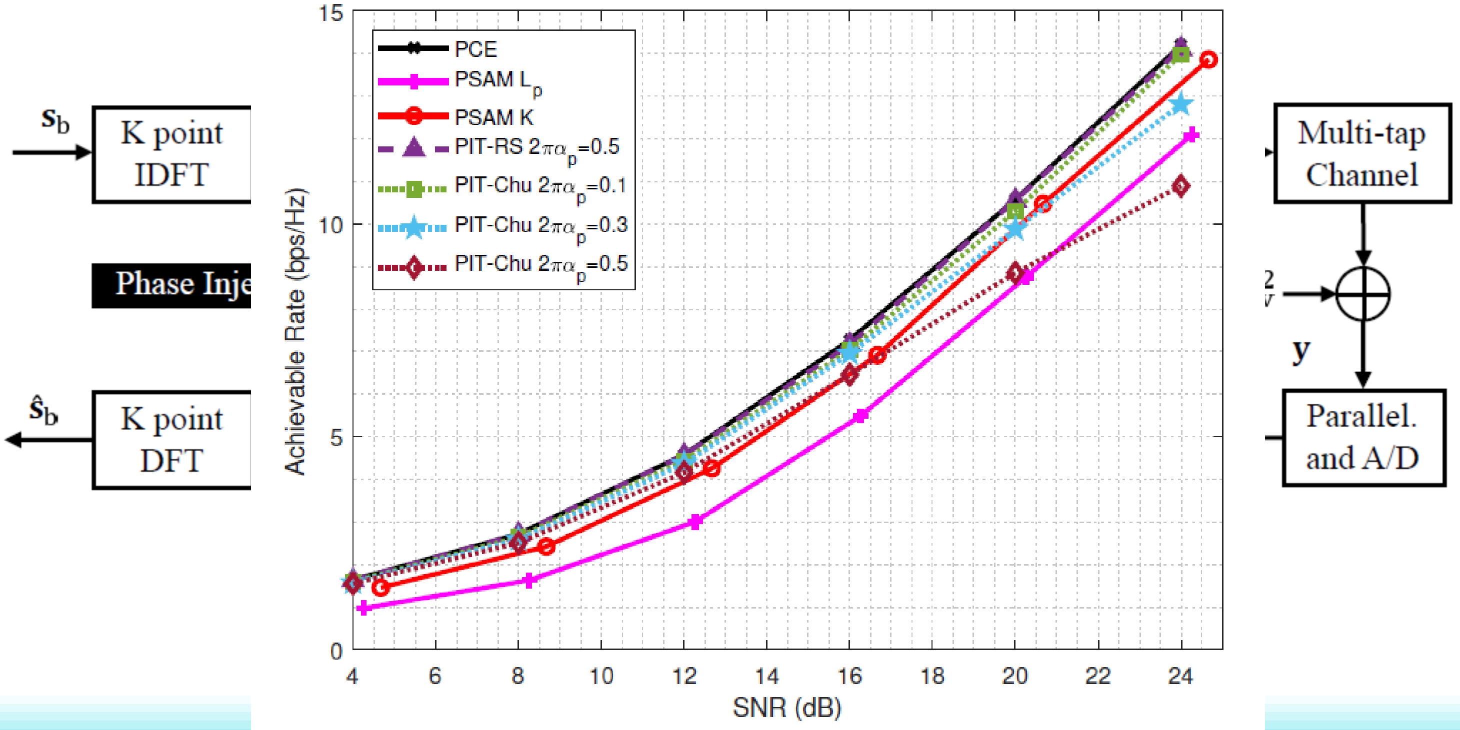
AWGN channel, 64QAM modulation with **phase noise**. *N* = 512, *Na* = 128, SCS = 120 kHz, *m* = 0.6/2*π*, *k*0 = 0.

Revisiting Channel estimation

PSAM vs superimposed training

- PSAM = pilot symbol aided modulation (classical pilots in the time-frequency grid) with channel estimation and compensation in the freq domain
- Channel estimation and compensation in the freq domain does not work for CE-OFDM, FM-OFDM
- Superimposed training works better in the time domain. Averaging is needed to cancel interference
- CE-OFDM and FM-OFDM may suggest different ways of superimposing the pilots (phase domain)

ST for CE-OFDM: phase-domain injected training



K. Chen-Hu, M. J. Fernández-Getino García, A. M. Tonello, A. García Armada, "Phase-domain Injected Training for Channel Estimation in Constant Envelope OFDM," IEEE Trans. on Wireless Communications, vol. 22, no.6, pp. 3869-3883, Jun. 2023.

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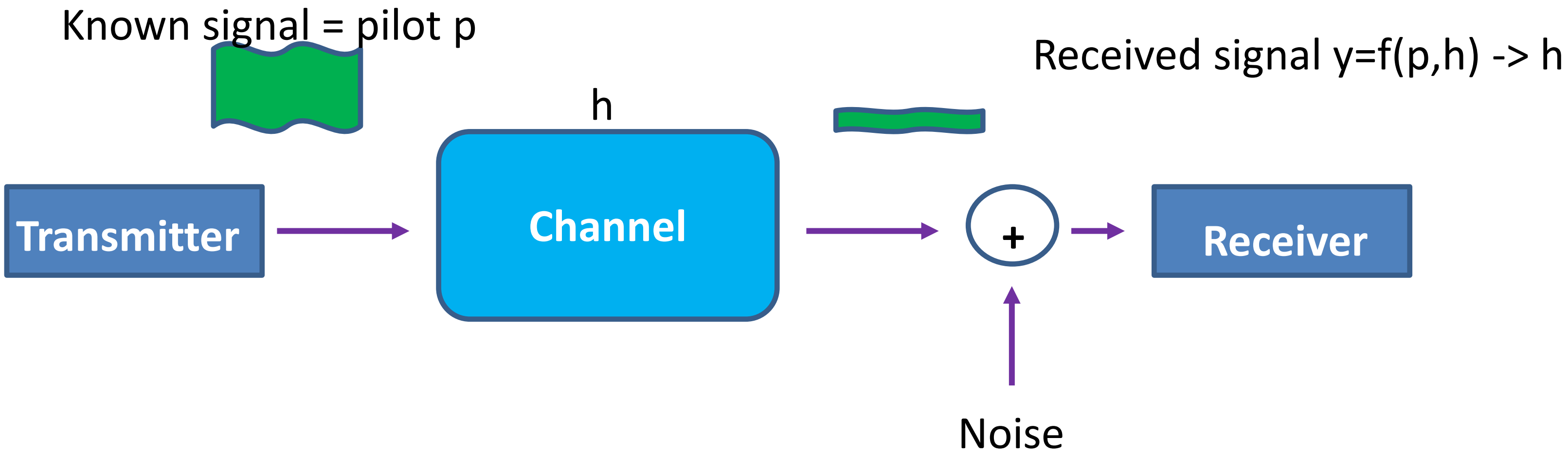
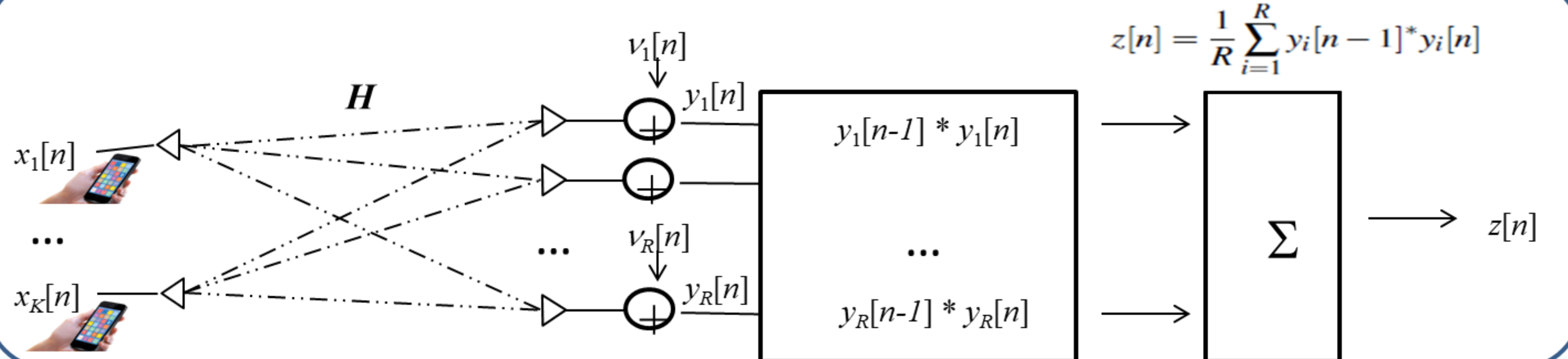
Coherent communications need acquiring CSI



Non-coherent massive MIMO

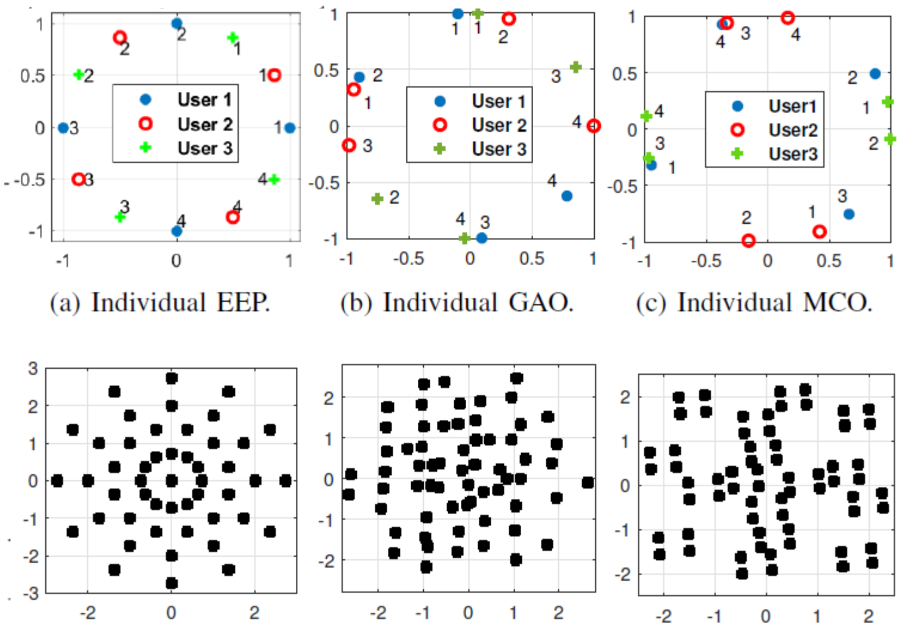
- ASK (amplitude shift keying) energy-detector schemes
  - They achieve rates which are not different from coherent schemes in a scaling law sense
- Differential PSK schemes
  - Single user with improved performance (wrt req. number of antennas)
  - Multi-user through constellation design



M. Chowdhury, A. Manolakos, A.J. Goldsmith, "Design and Performance of Noncoherent Massive SIMO Systems," 48th Annual Conference on Information Sciences and Systems, 2014.

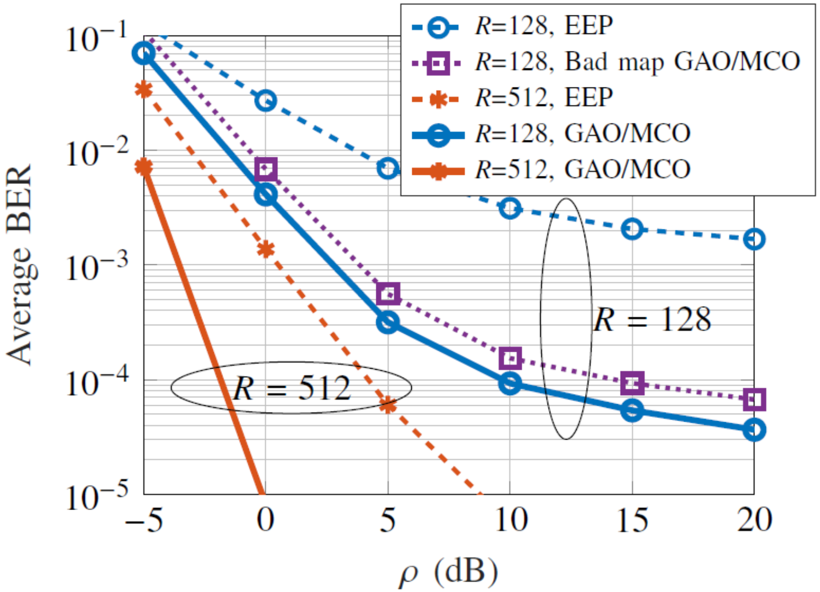
A. G. Armada, L. Hanzo, "A Non-Coherent Multi-User Large Scale SIMO System Relying on M-ary DPSK," IEEE ICC, Jun. 2015.

Multi-user constellations for NC massive MIMO



(a) Individual EEP. (b) Individual GAO. (c) Individual MCO.

(d) Joint EEP. (e) Joint GAO. (f) Joint MCO.



Performance example with 2 users and DQPSK

M. J Lopez Morales, K. Chen-Hu, A. García Armada, O. Dobre, "Constellation Design for Multi-User Non-Coherent Massive SIMO based on DMPSK Modulation," IEEE Trans. on Communications, vol. 70, no. 12, pp. 8181-8195, Dec. 2022.

Combination of coherent and non coherent schemes

	n=1	n=2	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10	n=11	n=12	n=13	n=14
k=1			P			P			P			P		
k=2														
k=3														
k=4														
k=5														
k=6														
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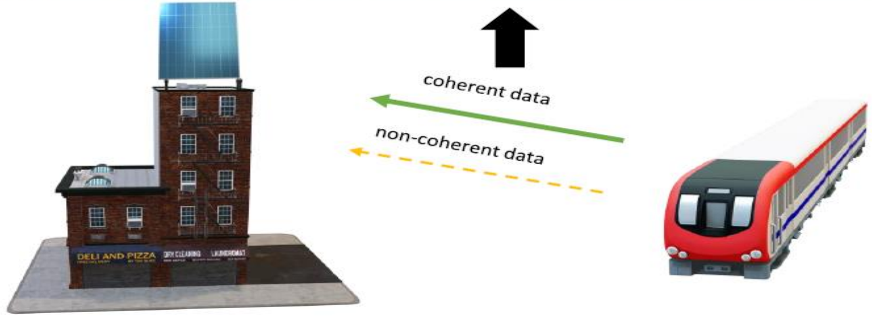
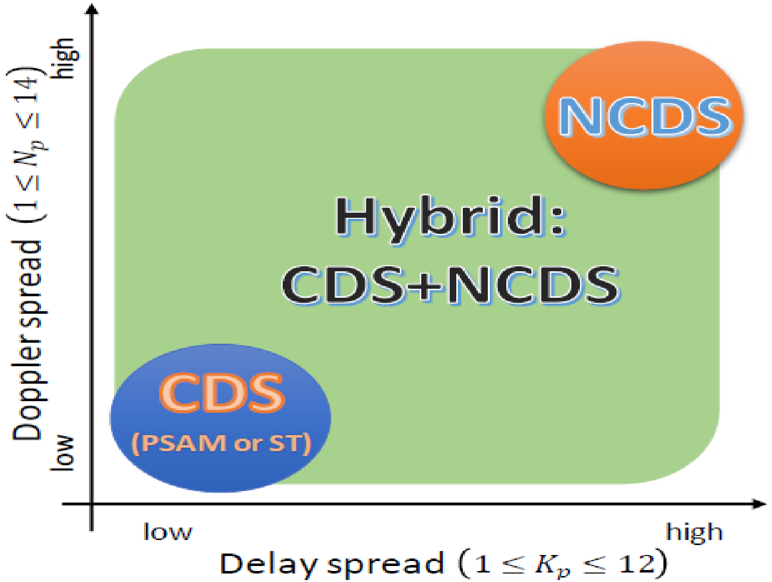
k=12														





Most of the pilots can be replaced by NC data

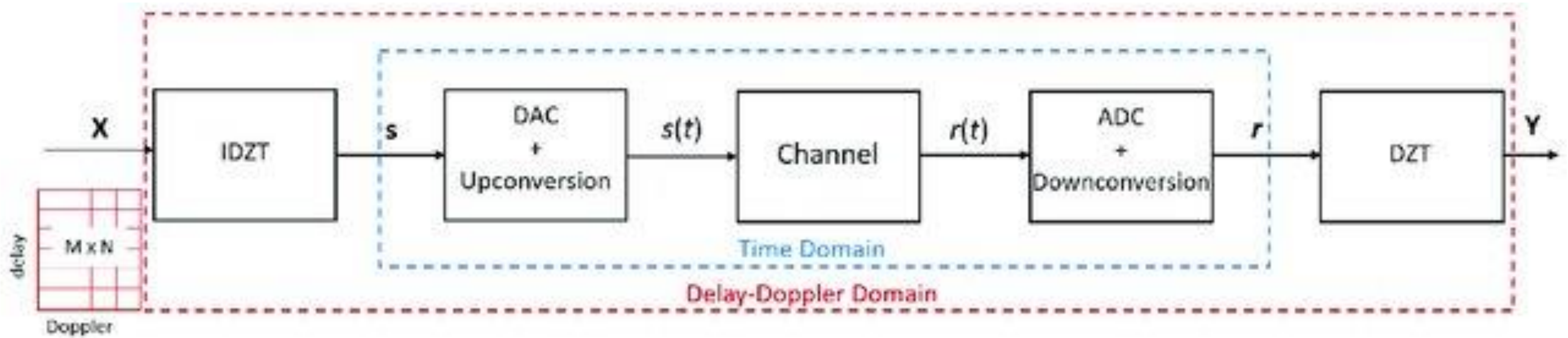
M.López Morales, K. Chen-Hu, A. G. Armada, "Differential Data-aided Channel Estimation for Up-link Massive SIMO-OFDM", IEEE Open Journal of the Communications Society, Vol. 1, pp. 976-989, Jul 2020.

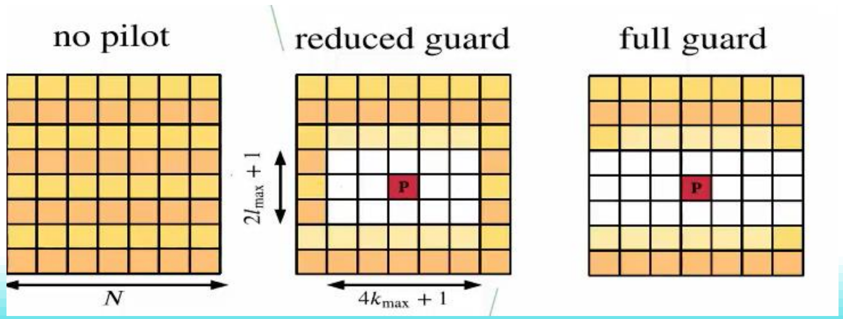
Revisiting the time – frequency grid: A new grid for ISAC?

Transmitting in the Delay – Doppler grid

- OTFS: *Orthogonal Time Frequency Space* is a 2D modulation technique that carries the information in the Delay-Doppler coordinate system
- There are other multicarrier variants with similar approach, e.g. ODDM
- DFTs-OTFS as well!

OTFS with discrete Zak transform

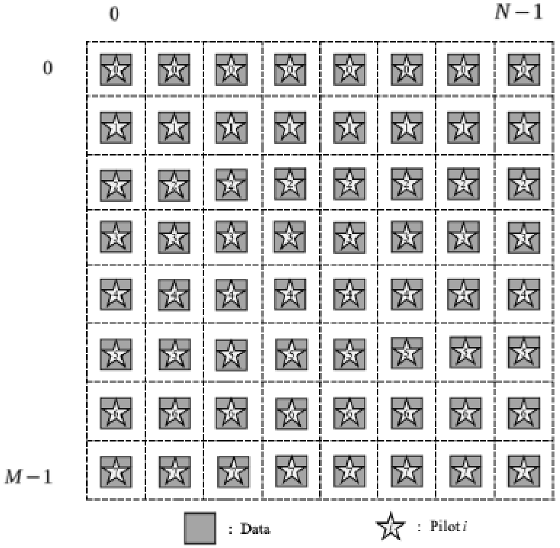




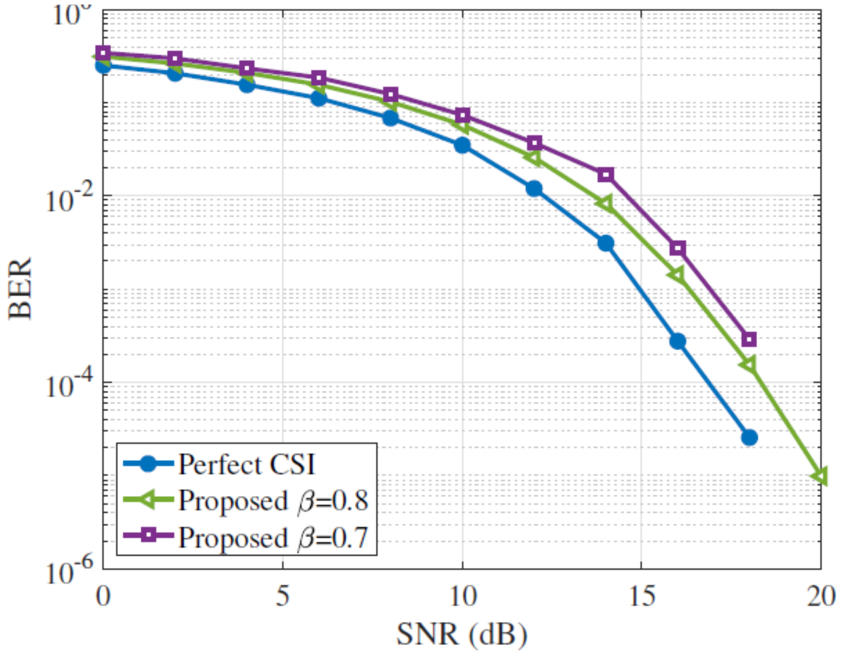
CSI for OTFS with superimposed training

Our pilot design makes it possible to perform an averaging method in the DD domain - interference and the noise can be reduced

$$\mathbf{x} = \sqrt{\beta}\mathbf{x}_d + \sqrt{1-\beta}\mathbf{x}_p,$$

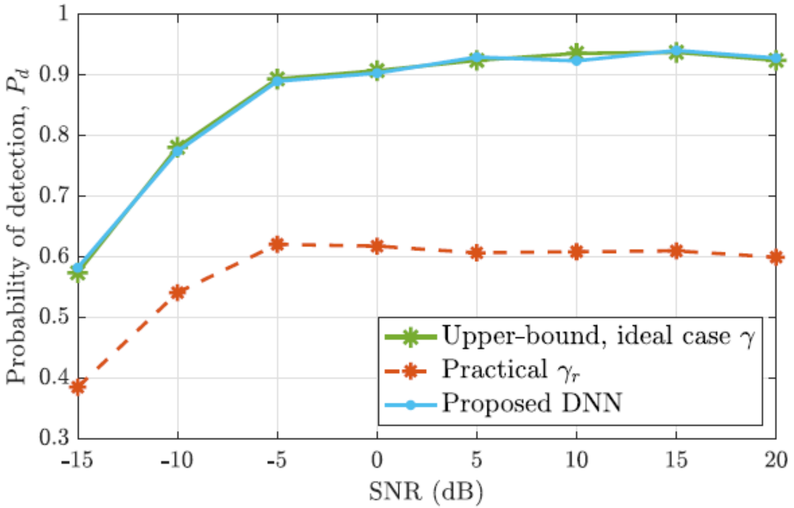


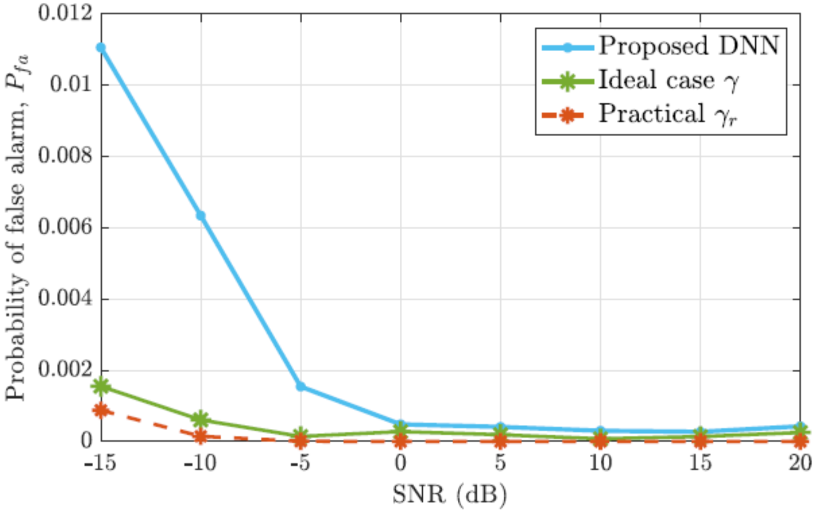
Proposed pilot design in the DD domain for M = 8 and N = 8



Lianet Mendez-Monsanto, Kun Chen Hu, Maria Julia Fernandez-Getino Garcia, Ana Garcia Armada, "Robust Integrated Sensing and Communications in Delay-Doppler Domain using Superimposed Training," IEEE Globecom WS, Dec. 2023.

Extracting positioning information from the CSI with superimposed training





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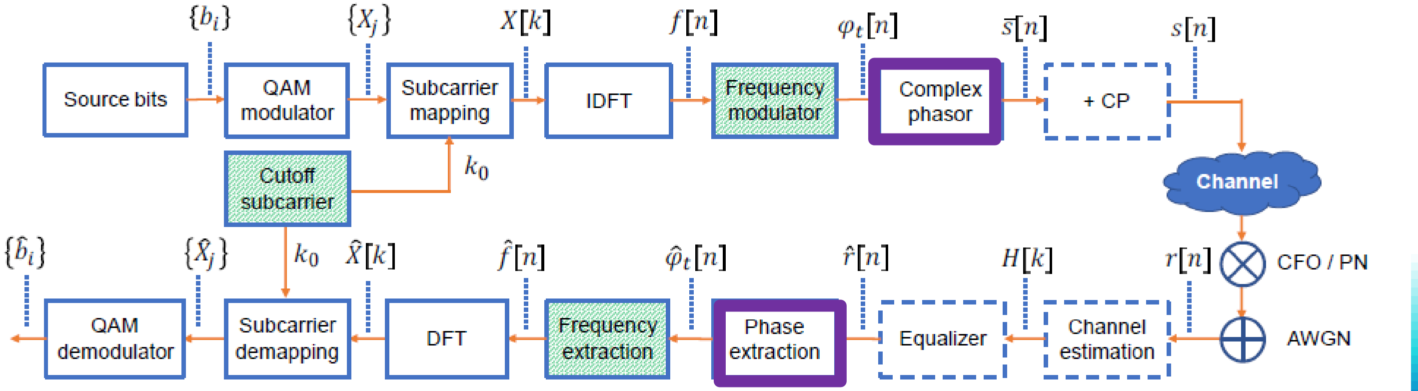
Flexibility beyond 5G Numerology

- There is no one-size-fits-all
- All these waveforms share an IFFT/FFT architecture
- Pilots can be also differently distributed in the time-freq (or another) grid
- Flexible waveforms and pilot structures (incl. without pilots)



What would this enable?

- Ubiquitous: including high speed and low SNR. It means **including everybody**.
- High data rate, large number of simultaneous users: wider spectrum (higher frequencies will all the RF impairments) and suitable multiplexing. It means **advanced services for all**.
- Positioning and sensing accuracy: ISAC. It means **new immersive services**.
- Low energy consumption: calls for low complexity solutions. It means **sustainability**.

Improve people's lives

"6G – forming a better future"


NOKIA

Thank you !

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Some references

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