What waveform would we like for 6G?

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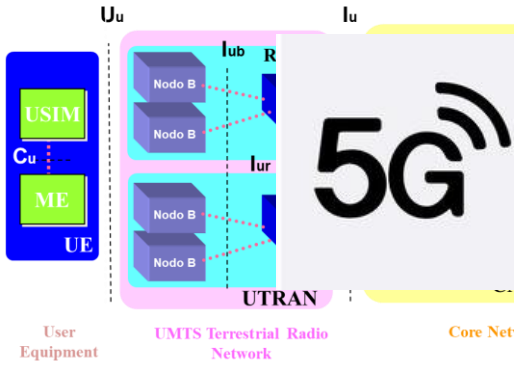
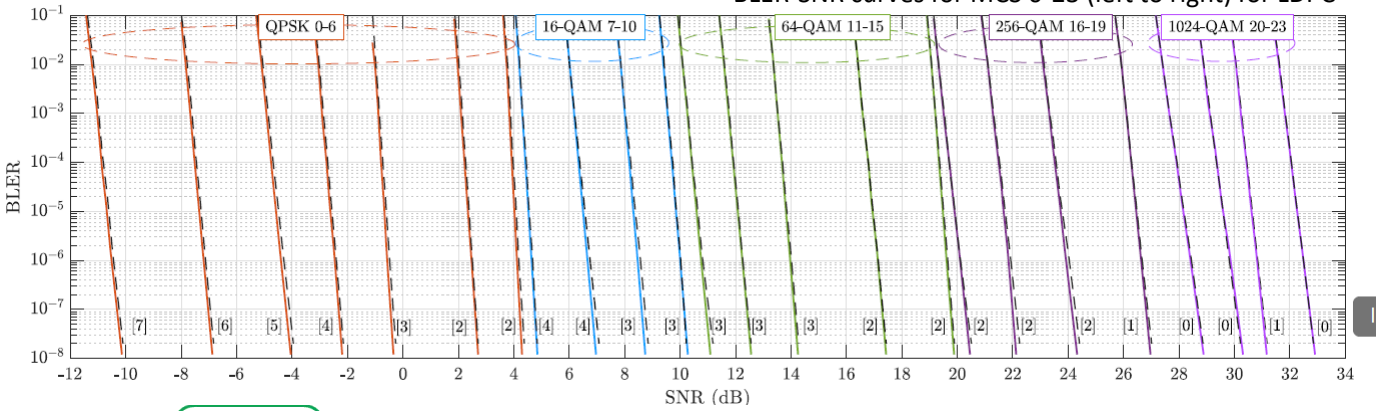
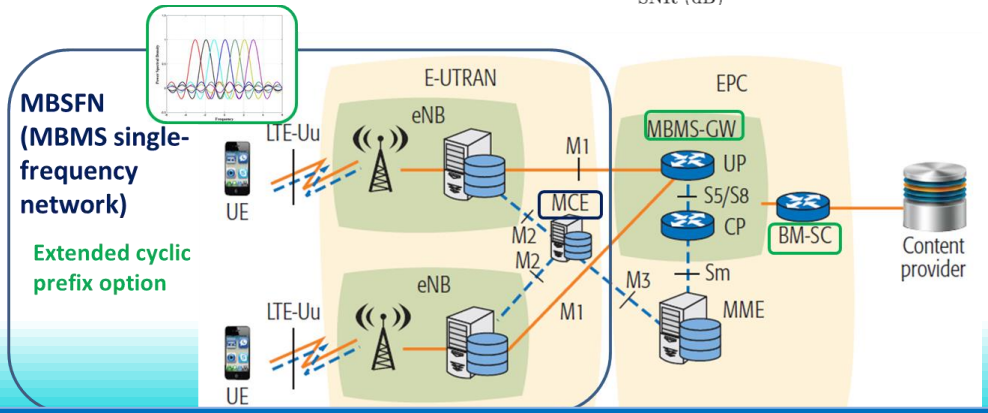
The choice of a waveform



BLER-SNR curves for MCS 0-23 (left to right) for LDPC

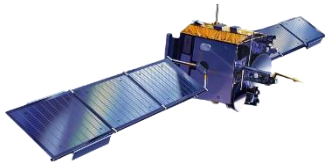




What 6G would we like?

- Profitable
  - Verticals, industry, automotive
- Inclusive, for all
  - Coverage, low complexity options
- Sustainable
  - Energy efficiency
- For people
  - People's communications needs

- Velocity, latency, reliability
- Sensing
- NTN
- Efficient amplification
- Immersive



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- Efficient amplification
- Immersive

6G challenges

(From MiFuture MSCA DN https://mifuture.tsc.uc3m.es/)

The waveform has an impact in almost all of these

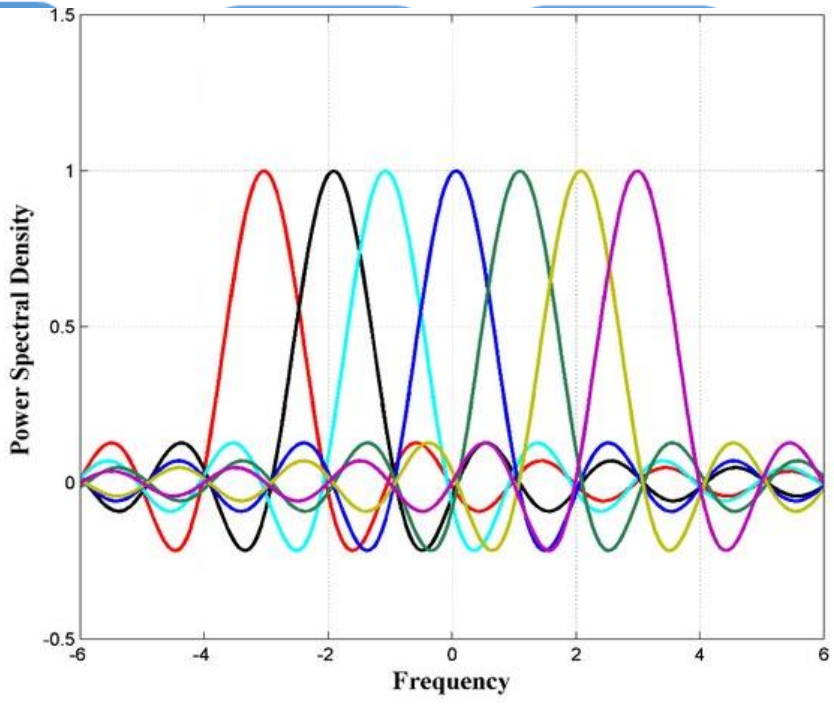
ORAN

Ubiqu
cover

Cell-free

Nati

Architectural chal



Energy efficiency

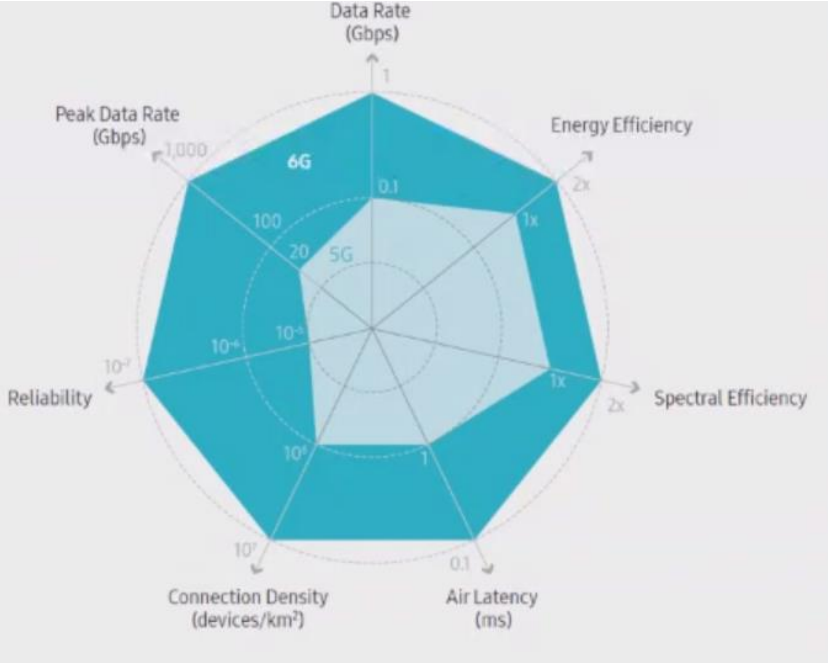
TeraBit data rate

Spectrum utilisation

Reliability

Social challenges

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

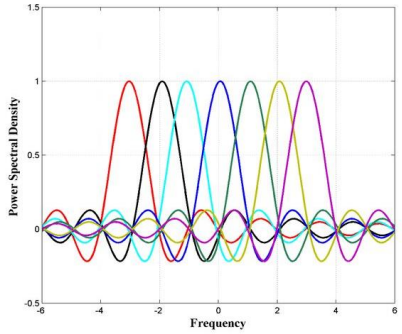
Short symbols vs Long symbols
Channel variability -> pilots, ICI

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),
- 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 …

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

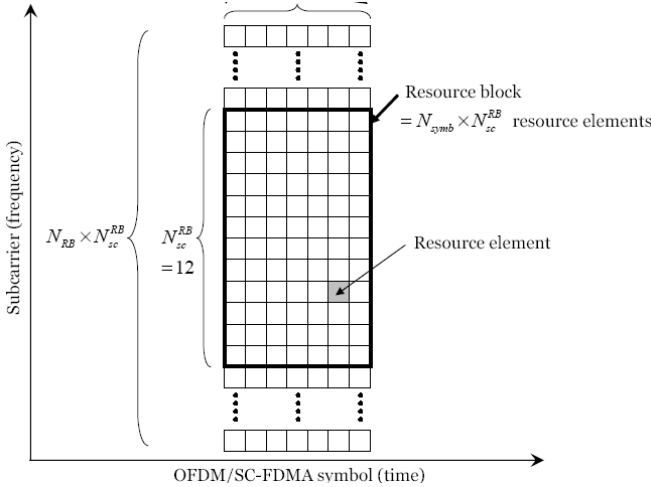
Multicarrier Waveforms



Orthogonal Frequency division multiplexing (OFDM)

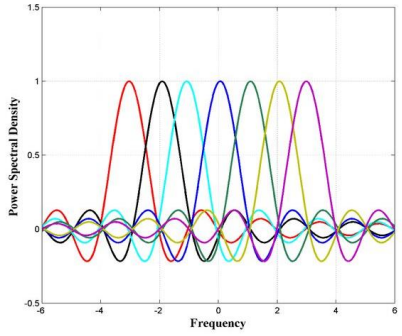
- Robust to multipath propagation
- Easy implementation (FFT)
- Time-frequency grid

- Time-domain + frequency-domain scheduler

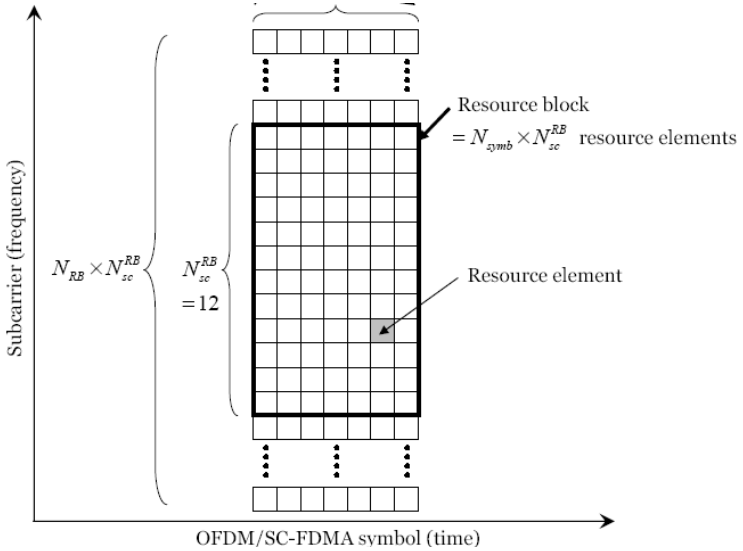


Muti-user DIVERSITY

Multicarrier Waveforms



Orthogonal Frequency division multiplexing (OFDM)



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

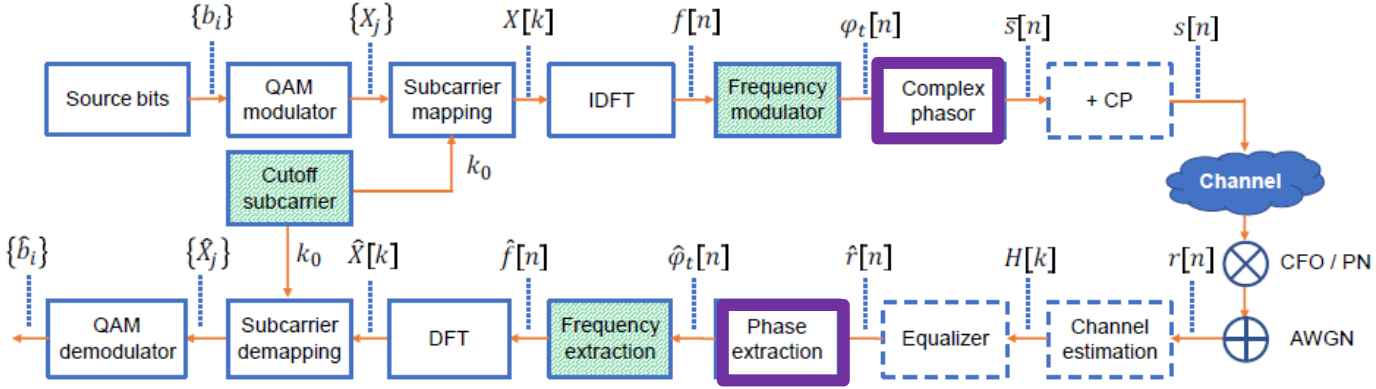
- Not good for rapidly varying channels

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**

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

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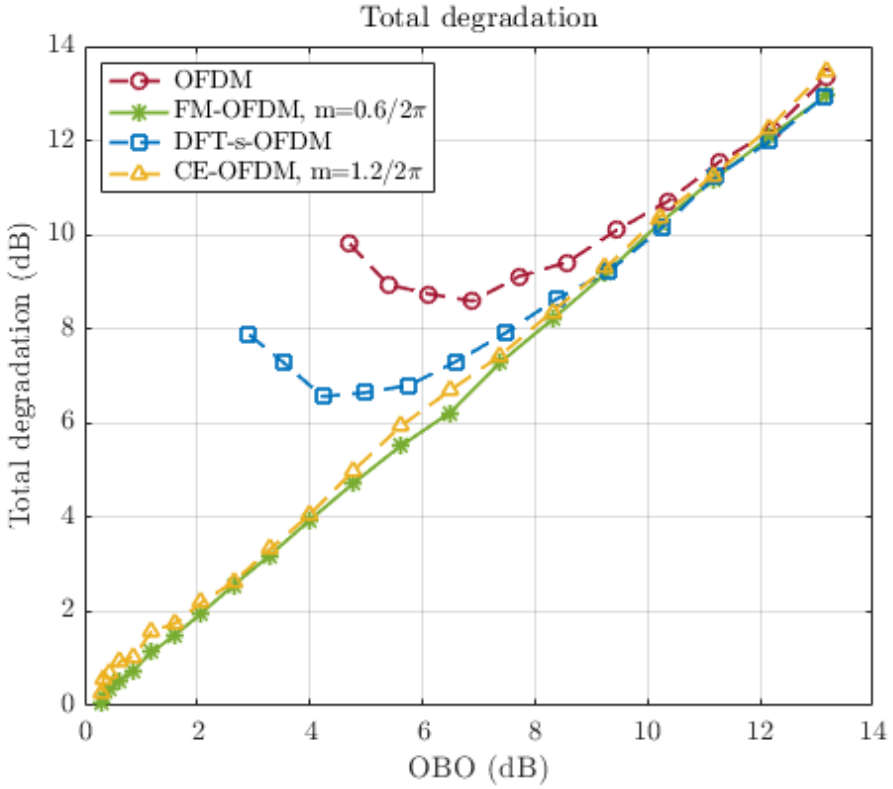
- FM-OFDM



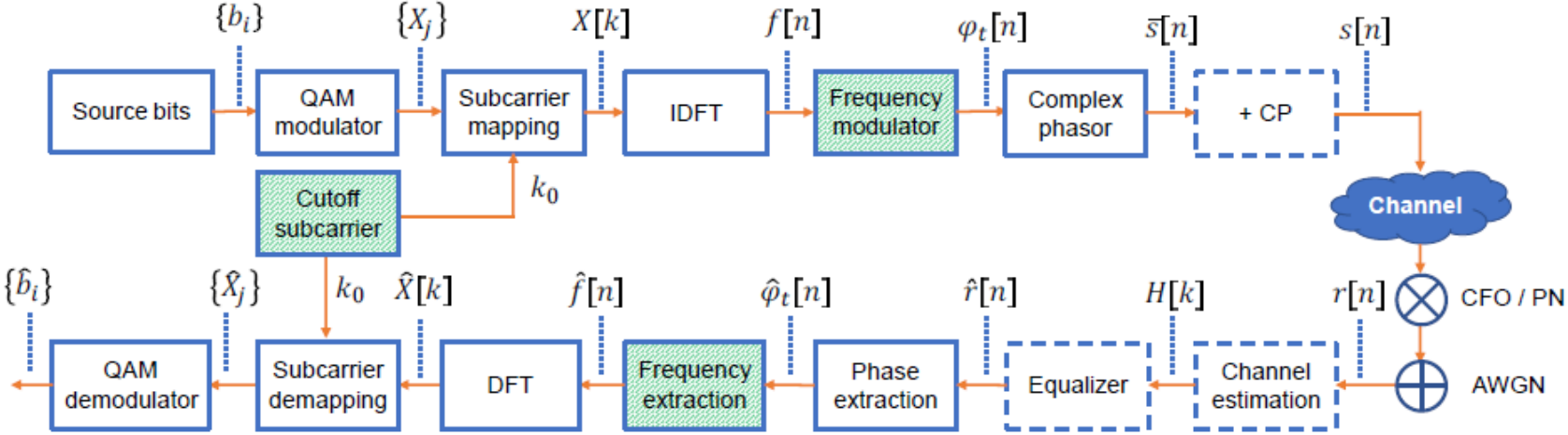
- **Constant envelope**
- **Time-domain + frequency-domain scheduler**

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 $[-\pi, \pi)$.

FM-OFDM

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

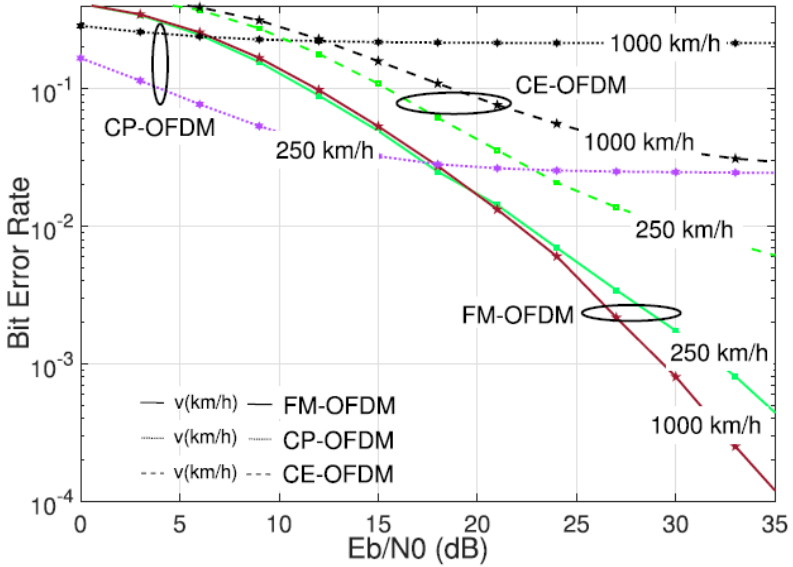
$$k_0 \gtrsim \left\lfloor \frac{\max(f_D, W_{PN})}{SCS} \right\rfloor.$$

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

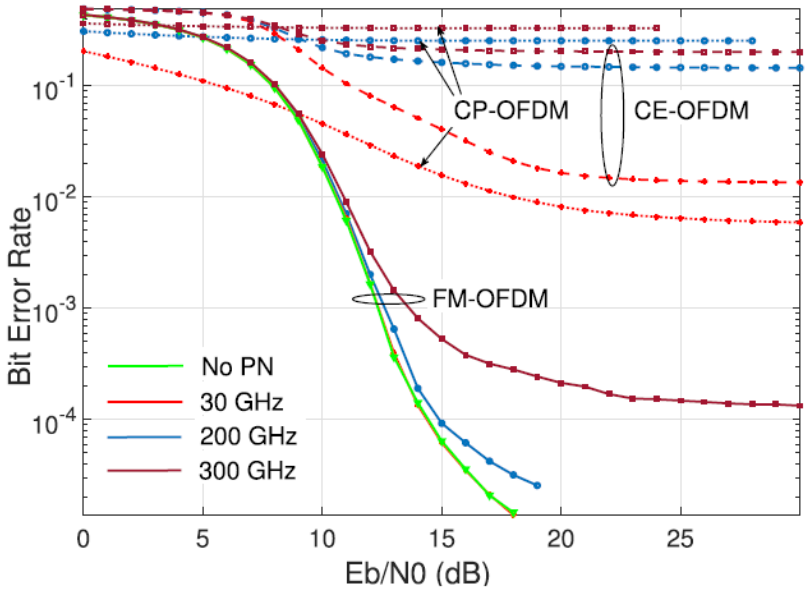
FM-OFDM

MMSE equalization in CE-OFDM and CP-OFDM with ideal channel estimation, whereas no equalization in FM-OFDM

- If the channel changes even within an OFDM symbol



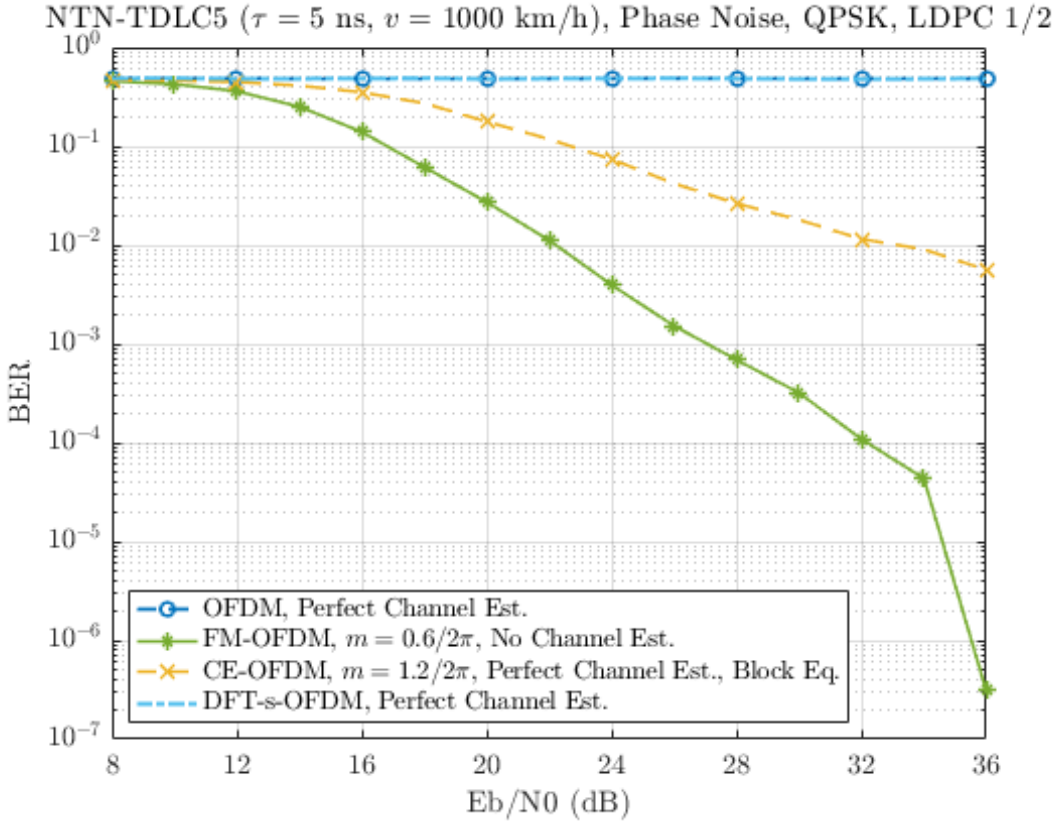
Rayleigh flat-fading channel, QPSK modulation at **250 km/h** (fD = 1.38 kHz) and **1,000 km/h** (fD = 5.55 kHz). N = 512, Na = 128, SCS = 15 kHz, m = 0.6/2π, k0 = 0



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

FM-OFDM in NTN

- Channel 3GPP NTN-TDLC5, 1000 km/h, with PN and TWTA



MMSE equalization in CE-OFDM and CP-OFDM with ideal channel estimation, whereas no equalization in FM-OFDM

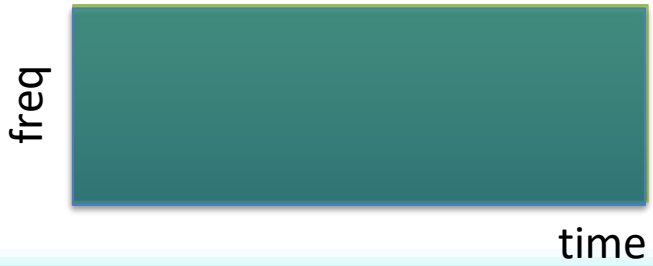
Revisiting Channel estimation

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

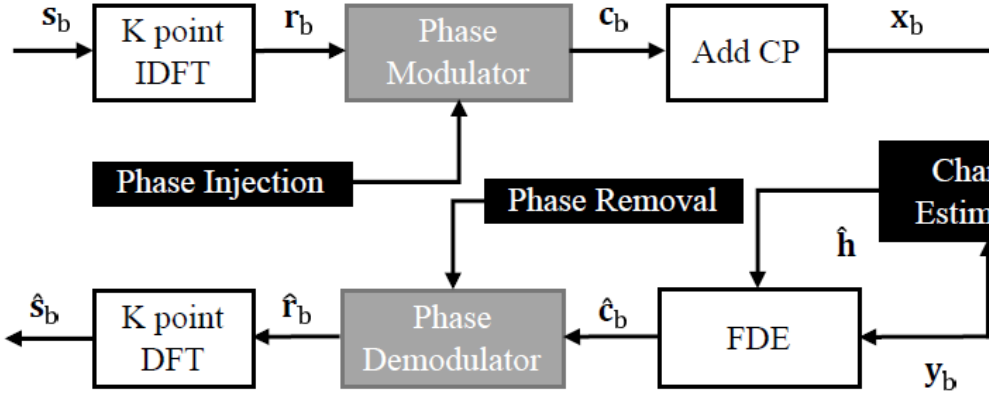
- Channel estimation and compensation in the freq domain does not work for CE-OFDM, FM-OFDM

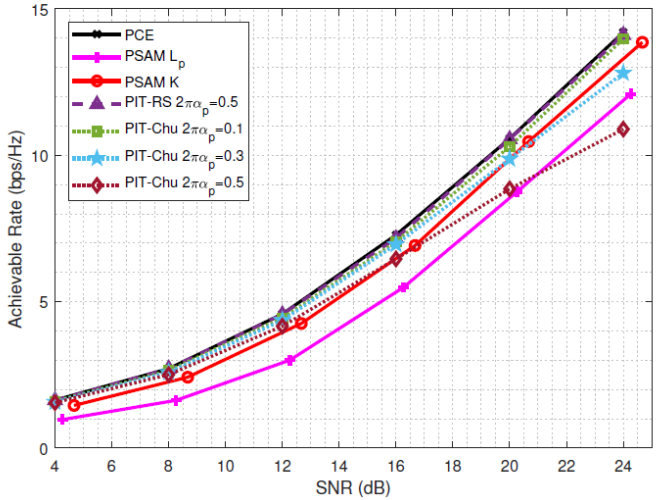
- Superimposed training works better in the time domain. Averaging is needed to cancel interference



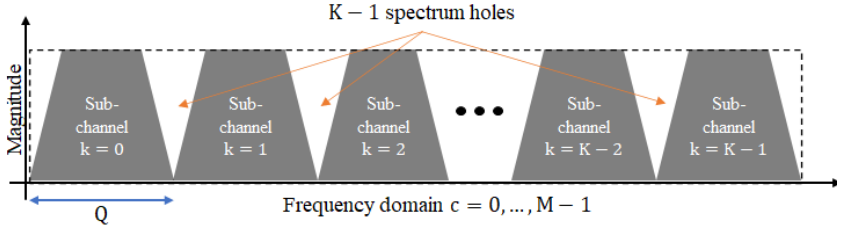
- CE-OFDM and FM-OFDM may suggest different ways of superimposing the pilots (phase domain)

ST for CE-OFDM: phase-domain injected training

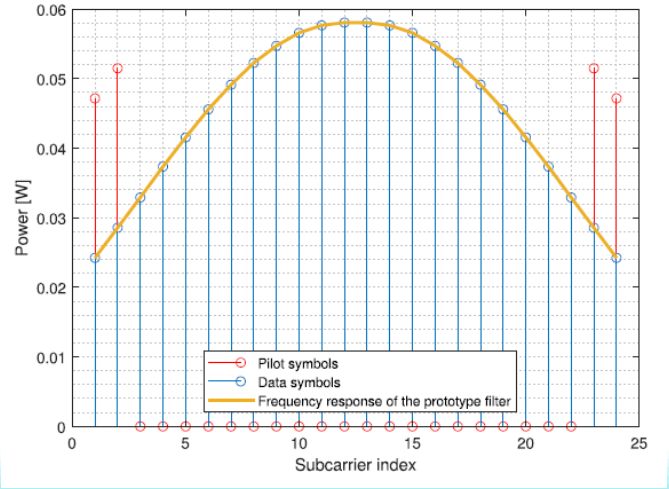


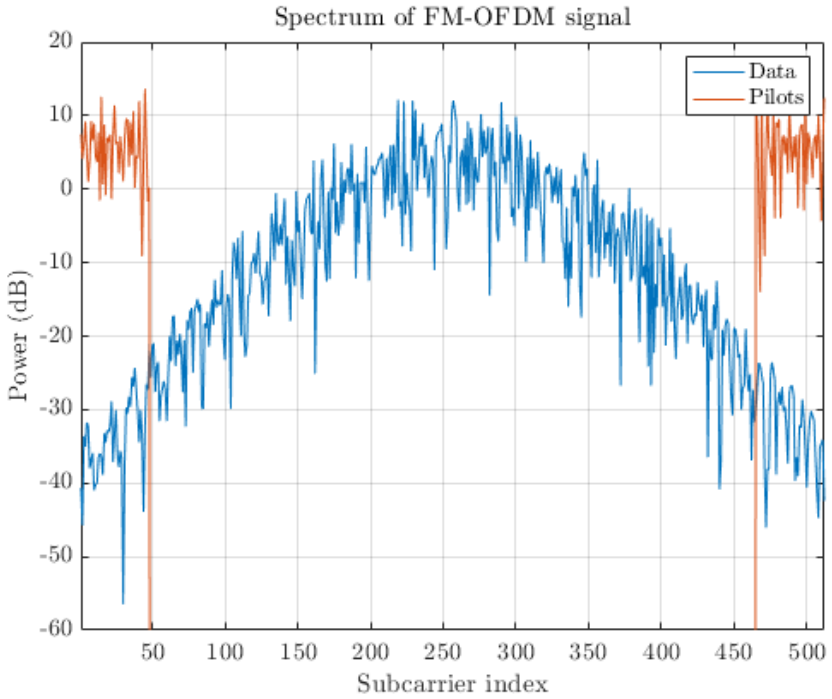


Pilot pouring in CB-FMT and FM-OFDM

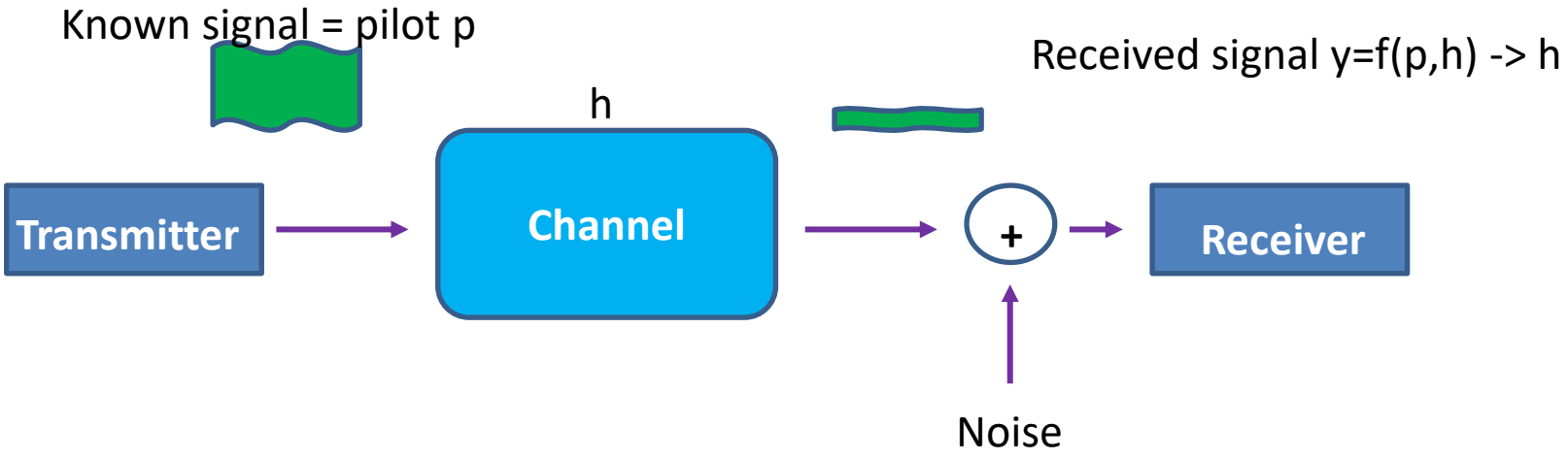


Cyclic block filtered multi-tone (CB-FMT)





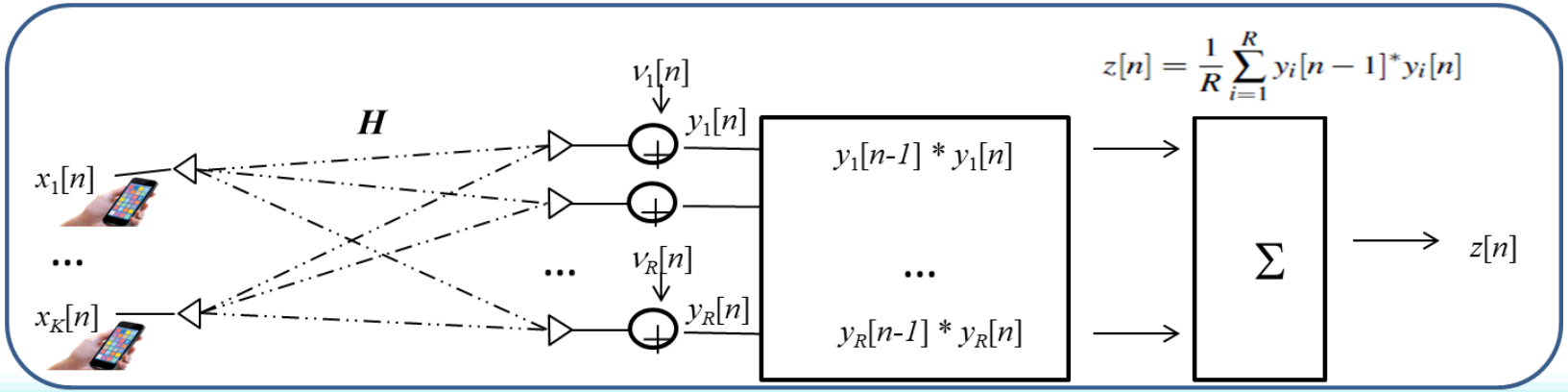
Coherent communications need acquiring CSI



Why Coherent?

Non-coherent massive MIMO

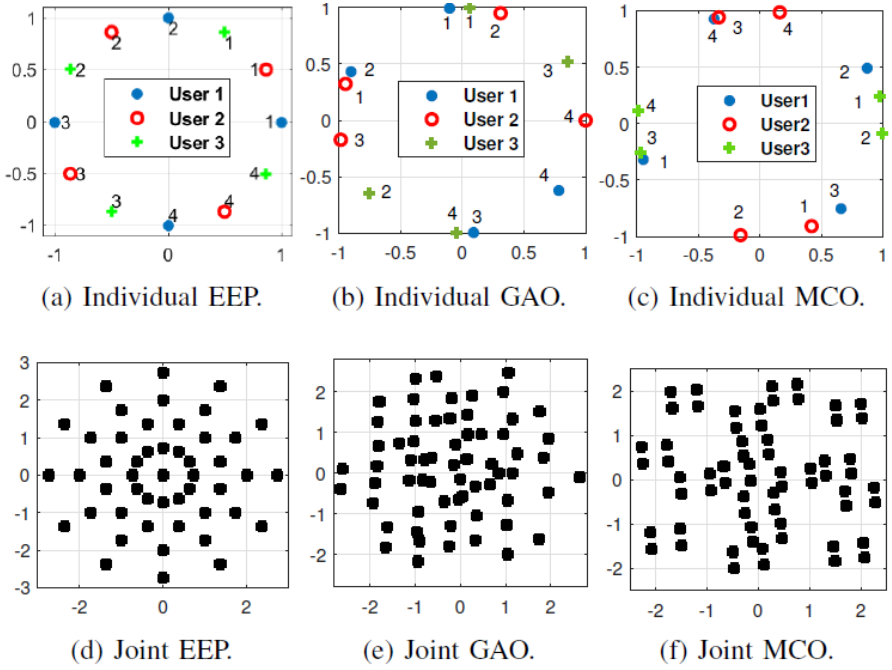
- ASK (amplitude shift keying) energy-detector schemes
  - They achieve rates which are not different from coherent schemes in a scaling law sense
- Differential PSK schemes
  - Single user with improved performance (wrt req. number of antennas)
  - Multi-user through constellation design



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

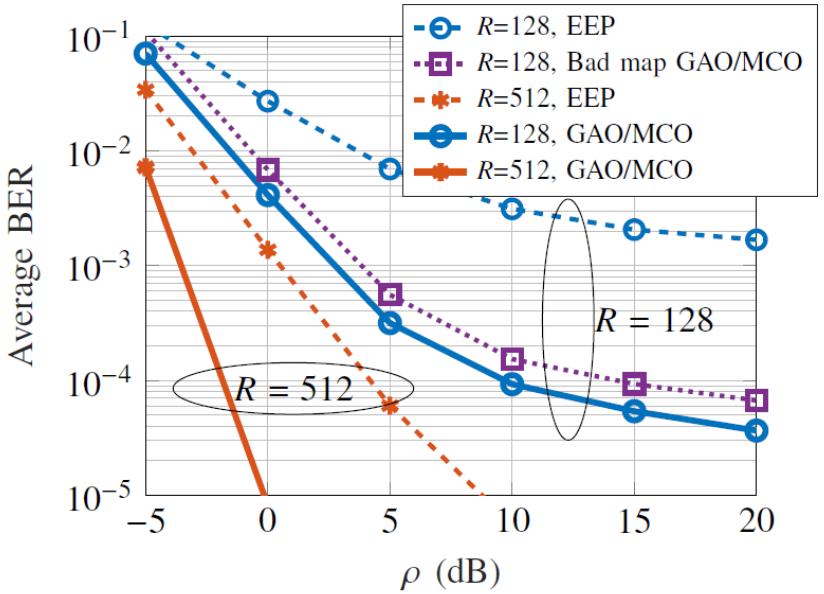
A. G. Armada, L. Hanzo, "A Non-Coherent Multi-User Large Scale SIMO System Relying on M-ary DPSK," IEEE ICC, Jun. 2015.

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

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														
k=7														
k=8														
k=9														
k=10														
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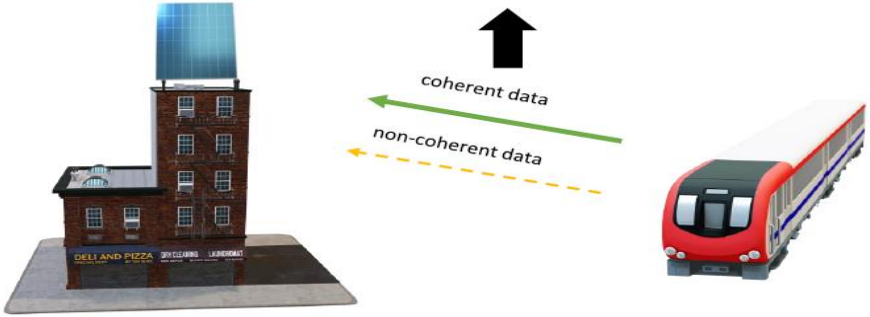
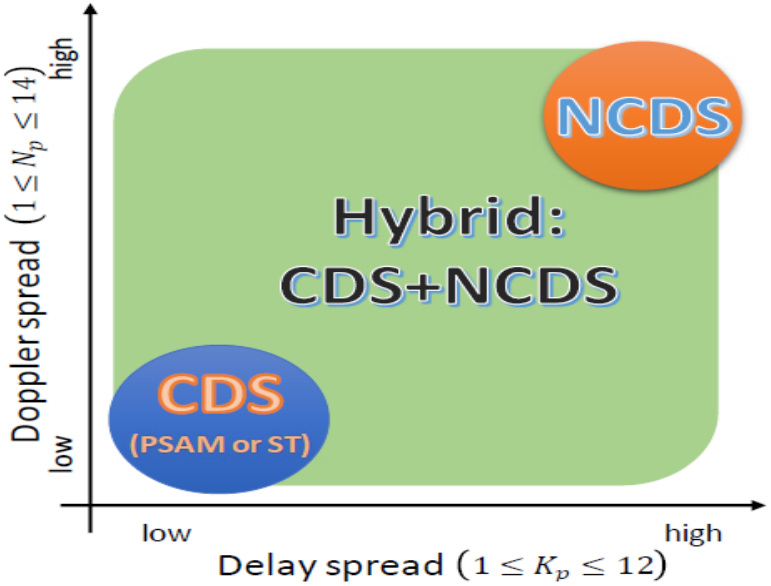
k=12														





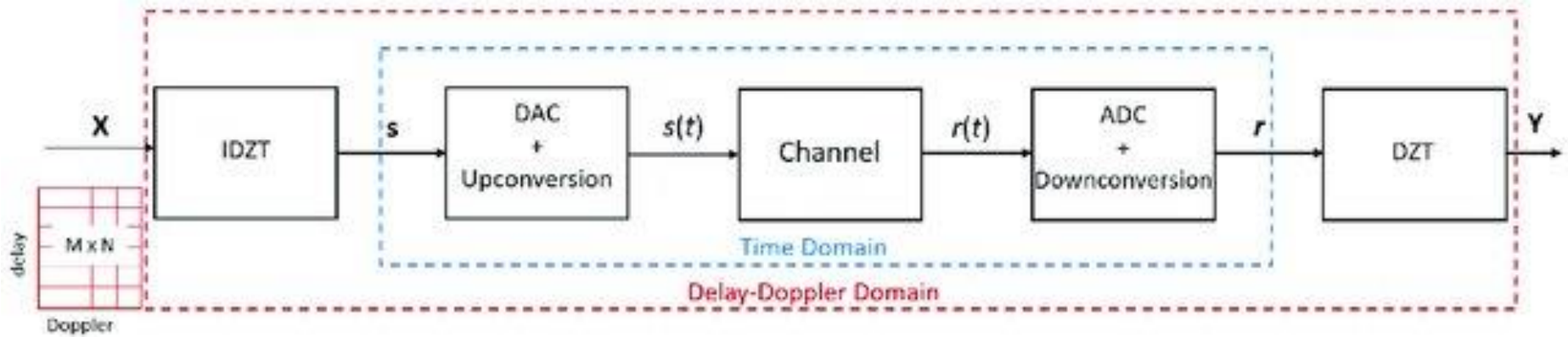
Most of the pilots can be replaced by NC data

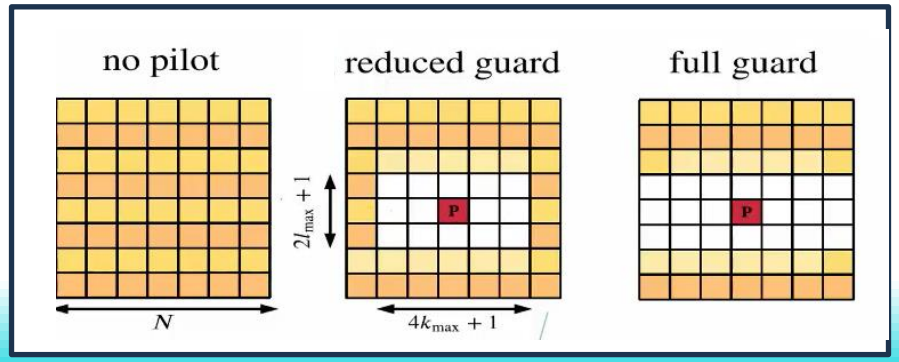
Revisiting the time – frequency grid: A new grid for ISAC?

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

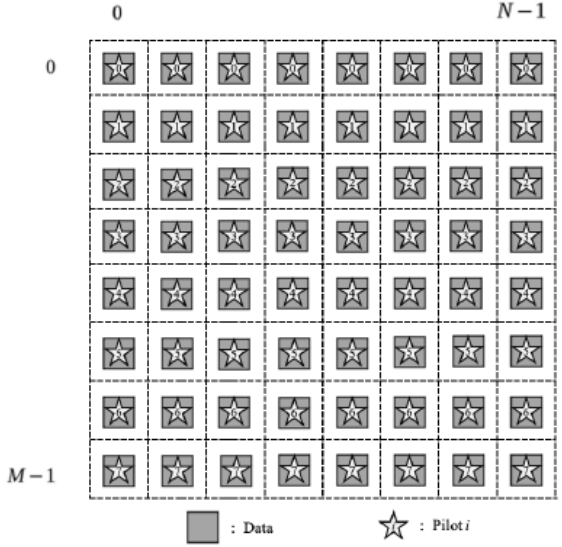




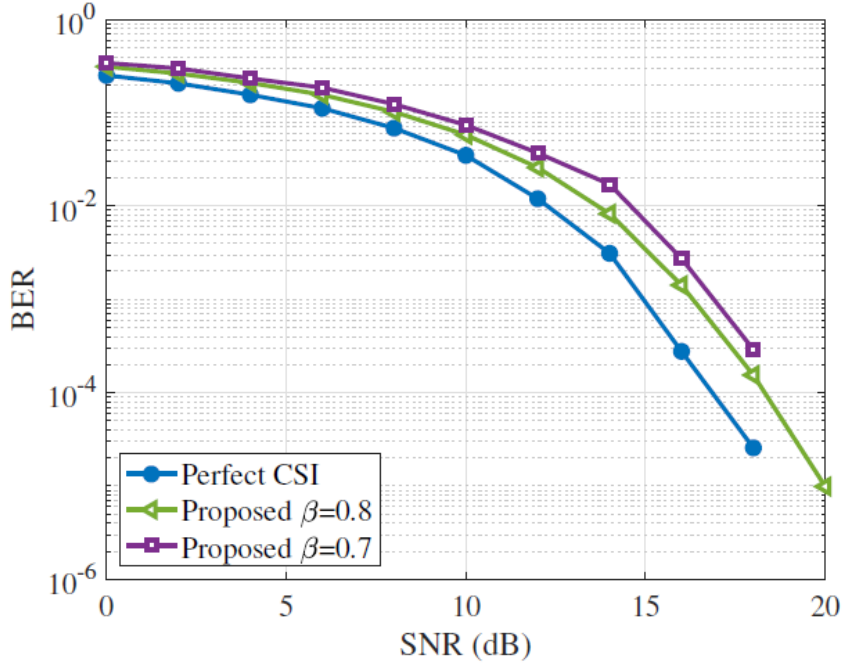
CSI for OTFS with superimposed training

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

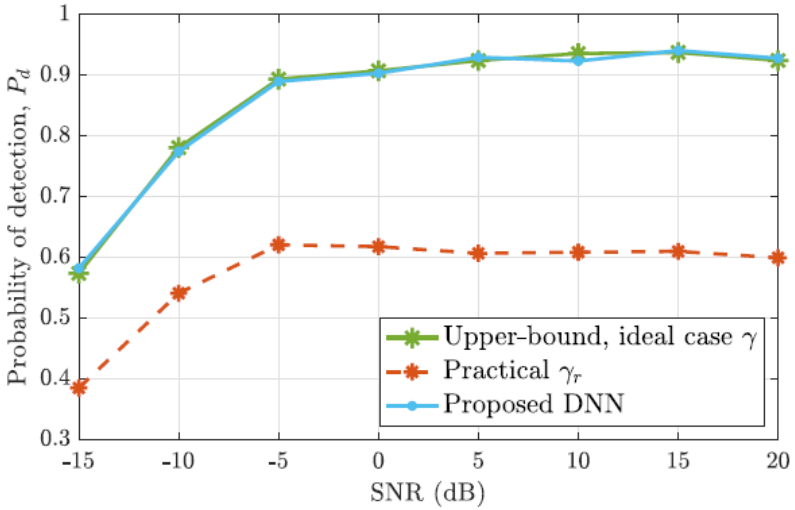
$$\mathbf{x} = \sqrt{\beta}\mathbf{x}_d + \sqrt{1-\beta}\mathbf{x}_p$$

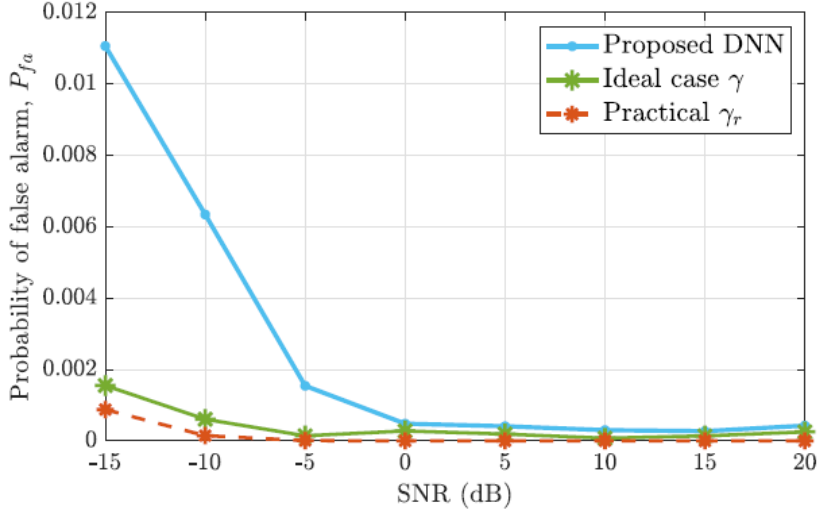


Proposed pilot design in the DD domain for $M = 8$ and $N = 8$



Extracting positioning information from the CSI with superimposed training



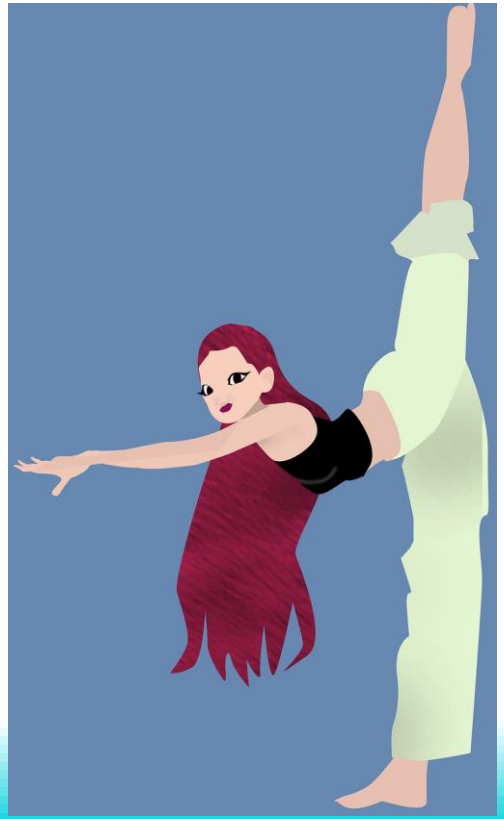


Flexibility

- 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)

Flexibility in standards

- Coding Schemes in GPRS
- MCS in EDGE
- Variable SF in UMTS
- MIMO Modes in LTE
- Cell-centric vs User-centric reference signals in LTE-A
- Numerology in 5G NR



- Can DPSK- based MCS be added?
- Can optional precoding / postcoding be allowed?
- Can reference signals have more diverse formats or even be allowed to be removed?

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