Integrating Sensing and Communication

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Abstract: We describe how to integrate sensing and communication within a single Zak-OTFS subframe by combining a spread pulsone used for channel sensing with point pulsones used for data transmission.

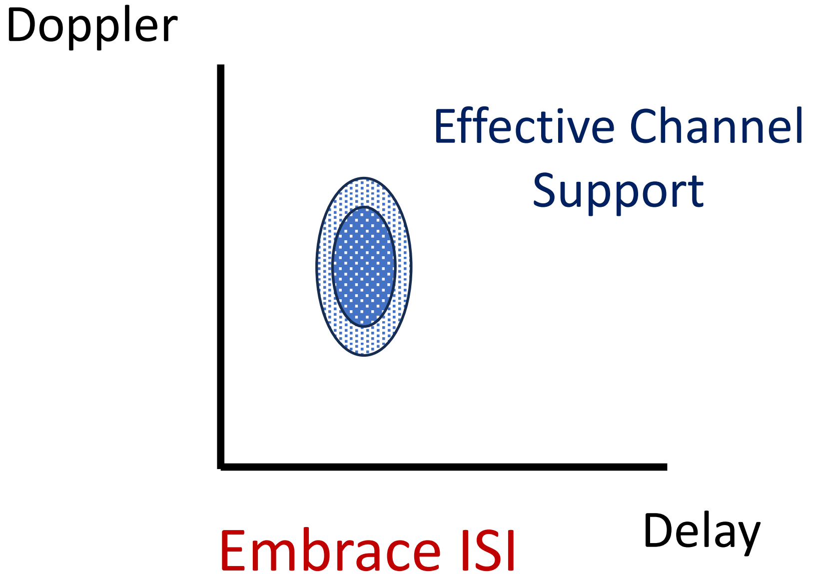
Background - Zak-OTFS and Integration of Sensing and Communication– in collaboration with Muhammad Ubadah, Saif Khan Mohammed, Ronny Hadani, Shachar Kons, and Ananthanarayanan Chockalingam

Disclosure: Advisor to Cohere Technologies

George Orwell: *Every generation imagines itself to be more intelligent than the one that went before it, and wiser than the one that comes after it.*

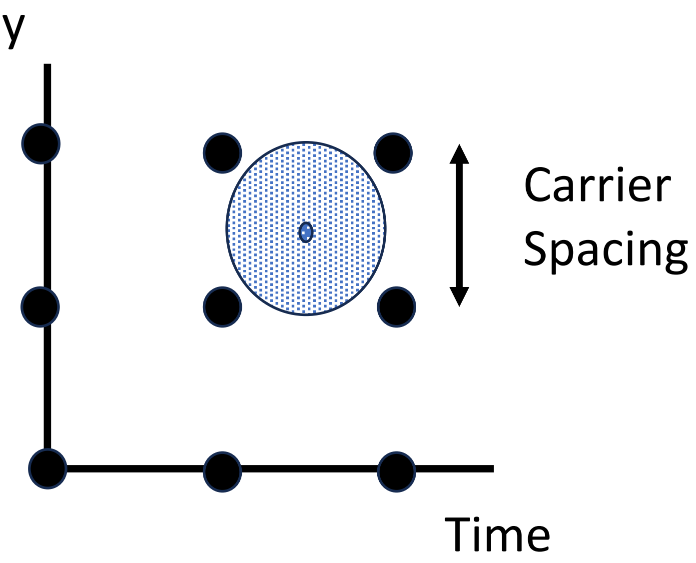
	TDMA vs CDMA	CDMA	OFDMA	Scalable OFDM mmWave
Voice	Voice / SMS	Data / Voice	Mobile Broadband (MBB)	Beyond MBB
Analog	GSM (pre 3GPP) IS 95 (pre 3GPP2)	WCDMA (3GPP) cdma2000 (3GPP2)	LTE (3GPP) UMB (3GPP2) WiMax (IEEE)	NR (3GPP)
1G (1980s)	**2G (1990s)**	**3G (2000s)**	**4G (2010s)**	**5G (2020s)**

OFDM vs Zak-OTFS



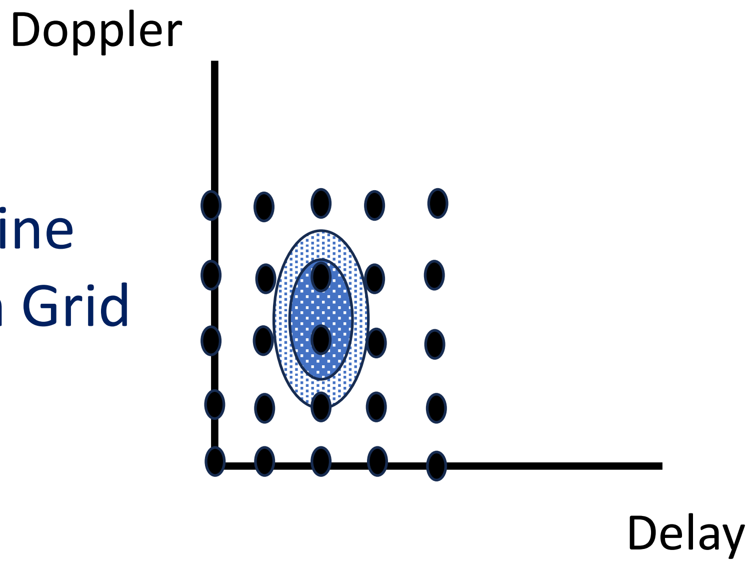
Effective Channel Support

Prevent ISI



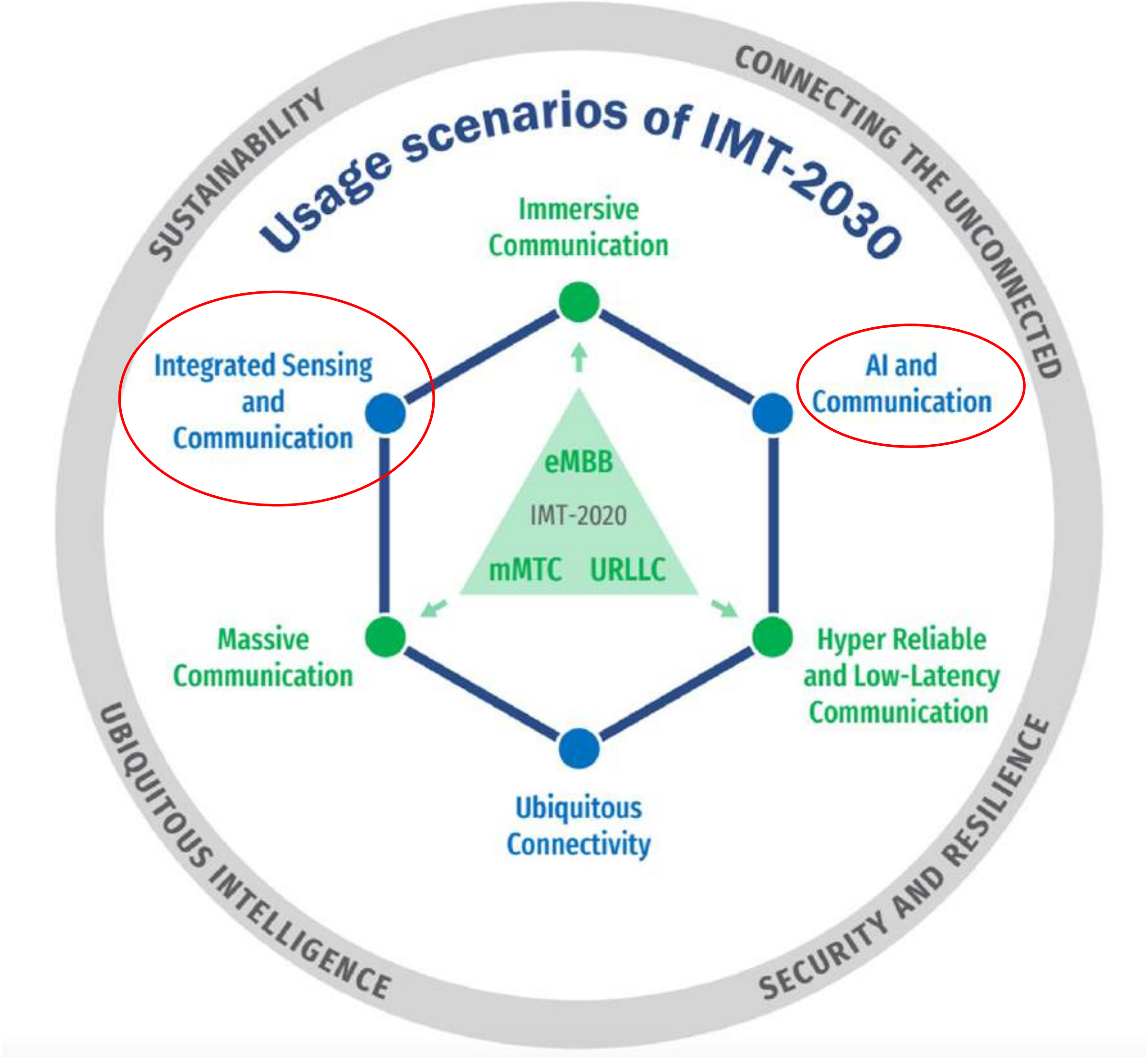
OFDM: Coarse Information Grid

Embrace ISI



Zak-OTFS: Fine Information Grid

How to Choose?



Research Challenges for 6G

AI & Communication: Machine learning algorithms have revolutionized image and natural language processing, but if they are to revolutionize wireless then they need to learn at the speed of wireless.

Integrating Sensing and Communication: Coexistence in the same subframe increases effective throughput but it requires minimizing interference between sensing and data transmission.

Overview

Separating Sensing and Communication

Integrating Sensing and Communication with Point Pulsones

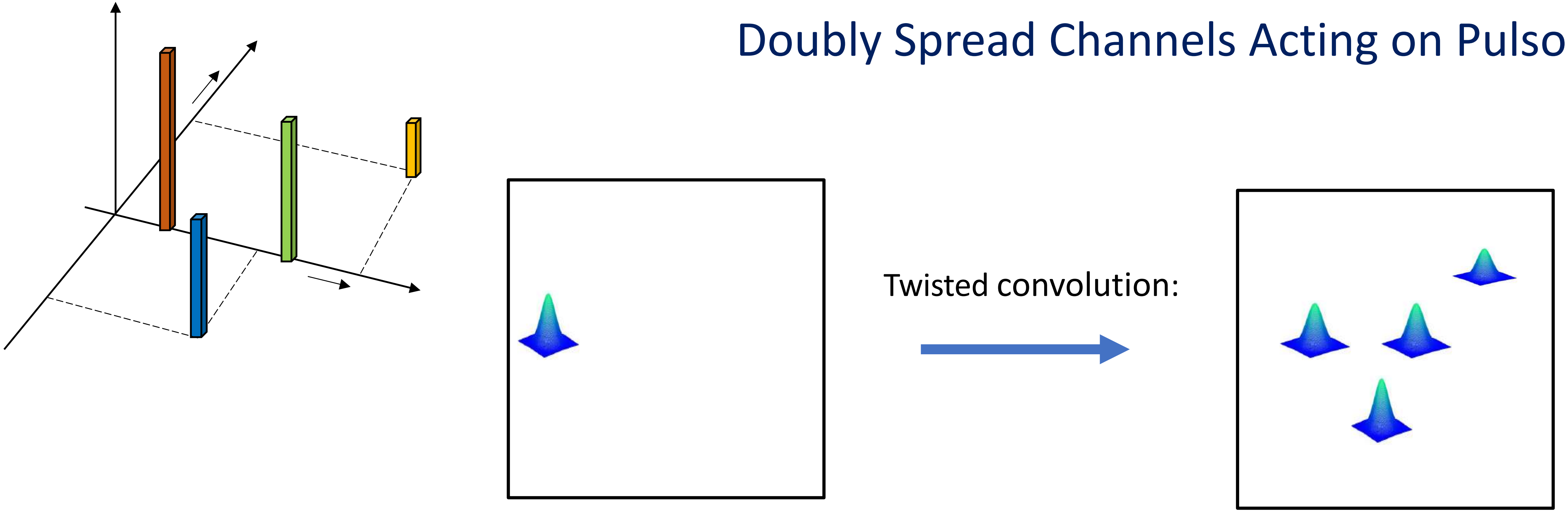
Filters in the Discrete Delay-Doppler Domain

Integrating Sensing and Communication with Spread Pulsones

Conclusions

Background - IEEE BITS Magazine: *A Mathematical Foundation for Communications and Sensing in the Delay-Doppler Domain, Parts I and II* – in collaboration with Saif Khan Mohammed, Ronny Hadani, and Ananthanarayanan Chockalingam

Doubly Spread Channels Acting on Pulsones

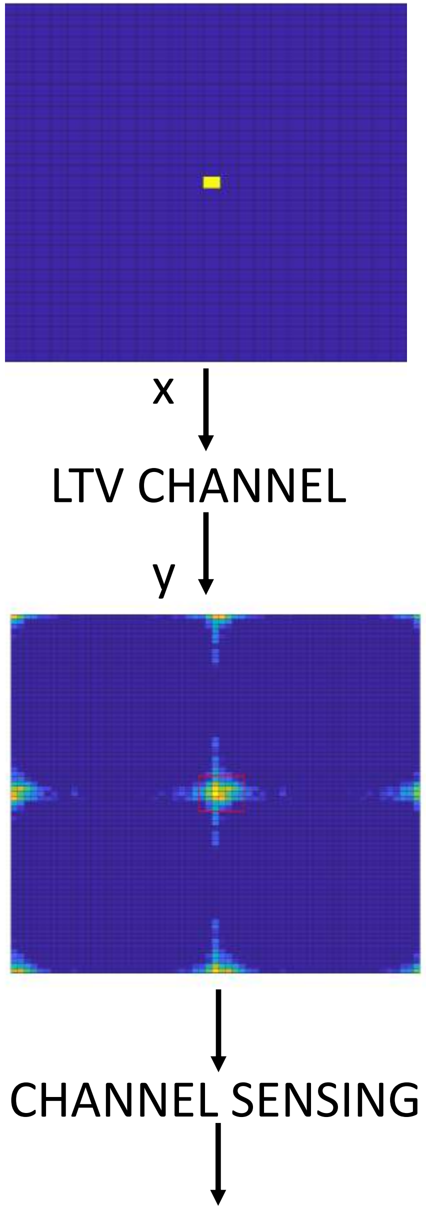

Twisted convolution:

Crystalline Regime: The delay domain period τ_p is greater than the channel path delay spread, and the Doppler domain period ν_p is greater than the path Doppler spread:

$$\tau_p > \text{delay spread} \quad \text{and} \quad \nu_p > \text{Doppler spread}$$

The interaction of a doubly spread channel with a TD pulsone is predictable and geometric

Separating Sensing and Communications



x

LTV CHANNEL

y

CHANNEL SENSING

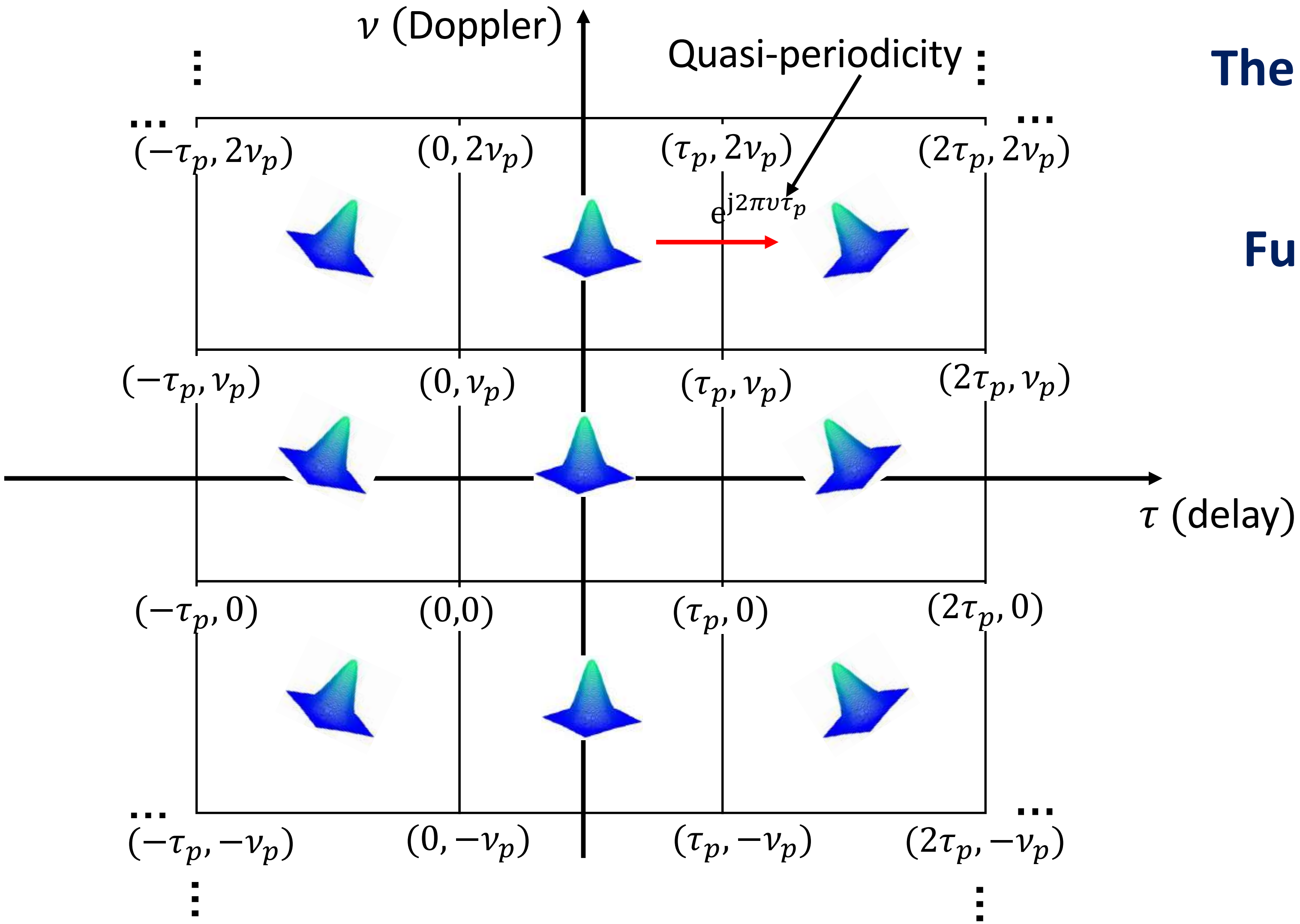
Pilot Signal: point pulsone $x = x_s$

The discrete I/O relation is read off from the response to a single pilot signal

Cross-Ambiguity: $A_{y,x}[k, l]$

The channel estimate is used to recover data in a subsequent Zak-OTFS subframe

A Pulse in the Delay-Doppler Domain



The DD realization of a TD signal is a quasi-periodic function

Fundamental Domain defined by the delay period τ_p and the Doppler period ν_p

Doppler Period

ν_p= 20 KHz

Delay Period

τ_p= 50 μs

TD Pulsone from a Quasi-Periodic DD Domain Pulse

TD Pulsone

Delay Period

ν_p= 20 KHz

Doppler Period

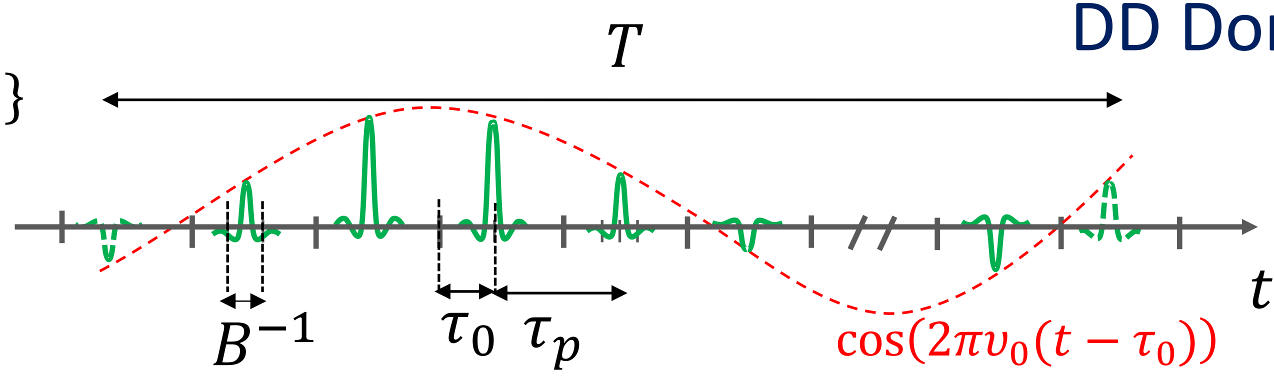
τ_p= 50 μs

$$B = \frac{1}{100ns} = 10Mhz$$

$$T = \frac{1}{1KHz} = 1ms$$

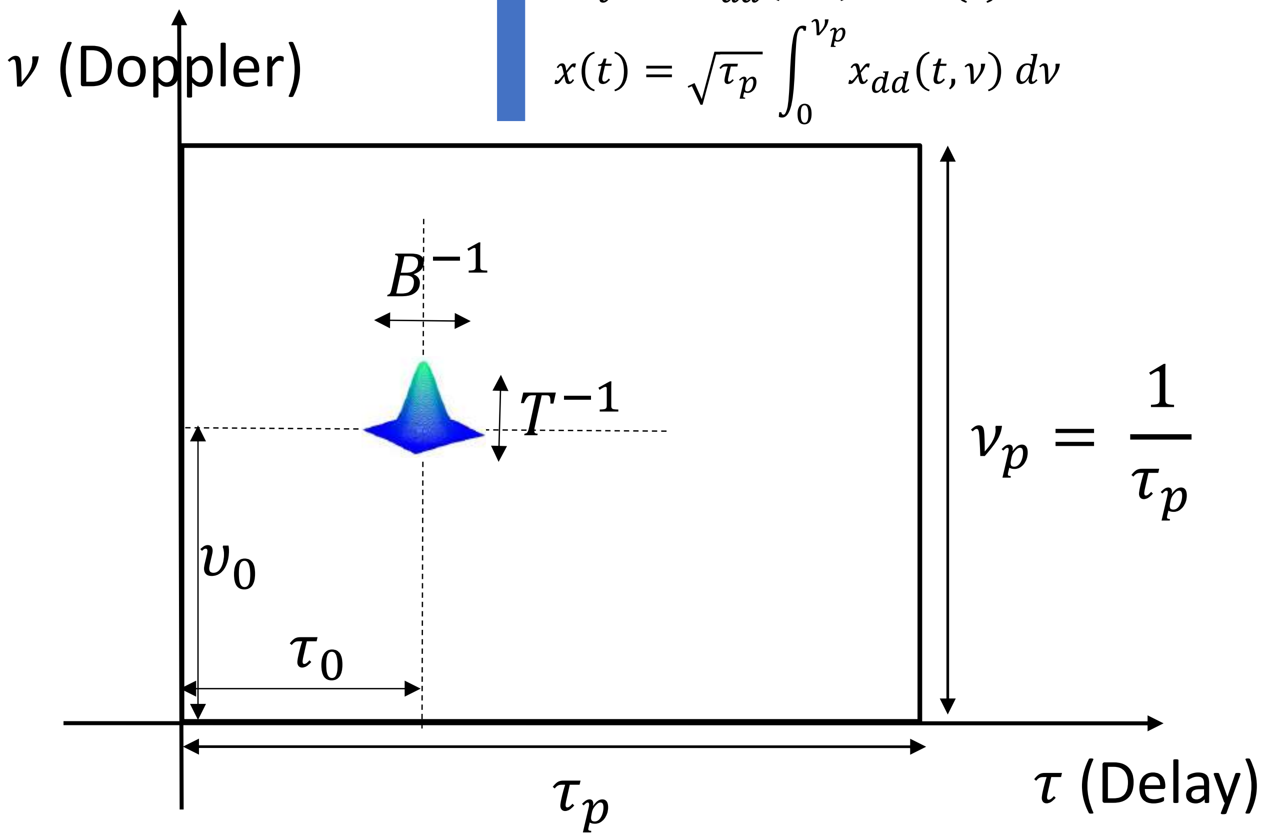
$$N = \frac{50\mu s}{100ns} = 500$$

$$M = \frac{20KHz}{1KHz} = 20$$

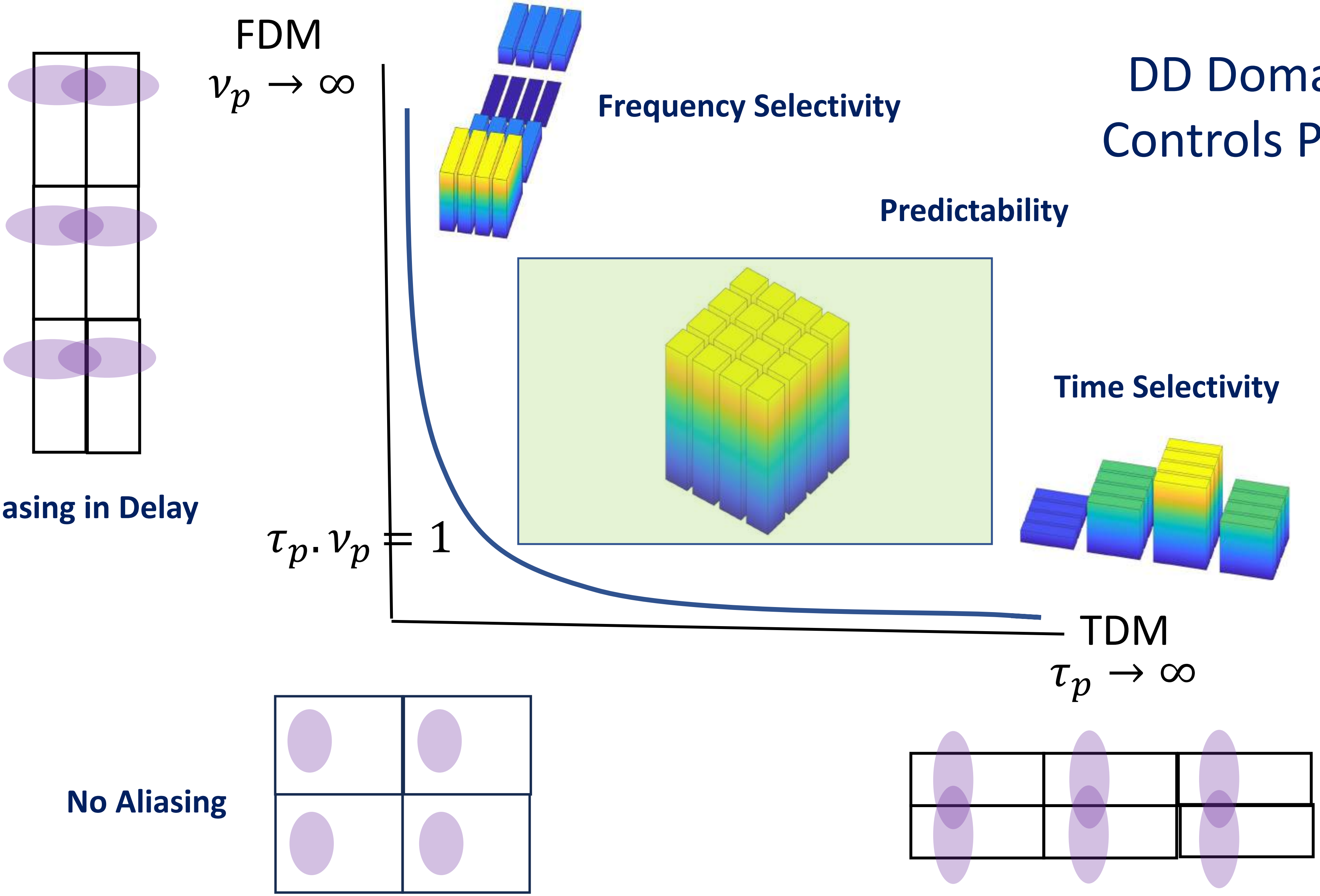


$Z_t^{-1}: \; x_{dd}(\tau,\nu) \rightarrow x(t)$

$$x(t) = \sqrt{\tau_p}\int_0^{\nu_p} x_{dd}(t,\nu)\,d\nu$$



DD Domain Aliasing Controls Predictability



FDM

$\nu_p \to \infty$

Frequency Selectivity

Predictability

Time Selectivity

Aliasing in Delay

$\tau_p . \nu_p = 1$

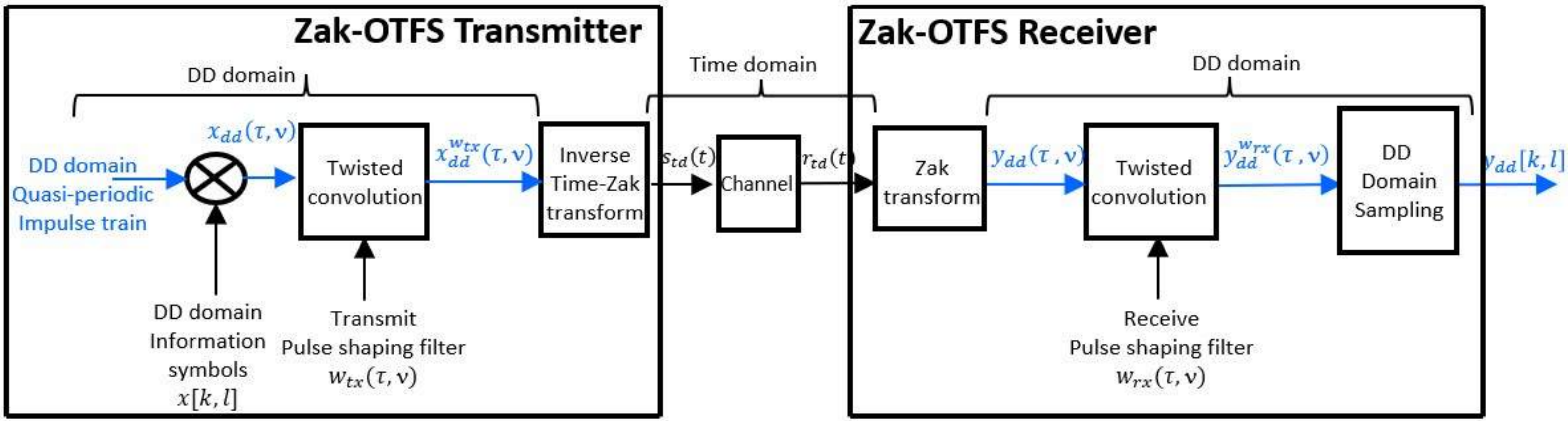
TDM

$\tau_p \to \infty$

No Aliasing

Aliasing in Doppler

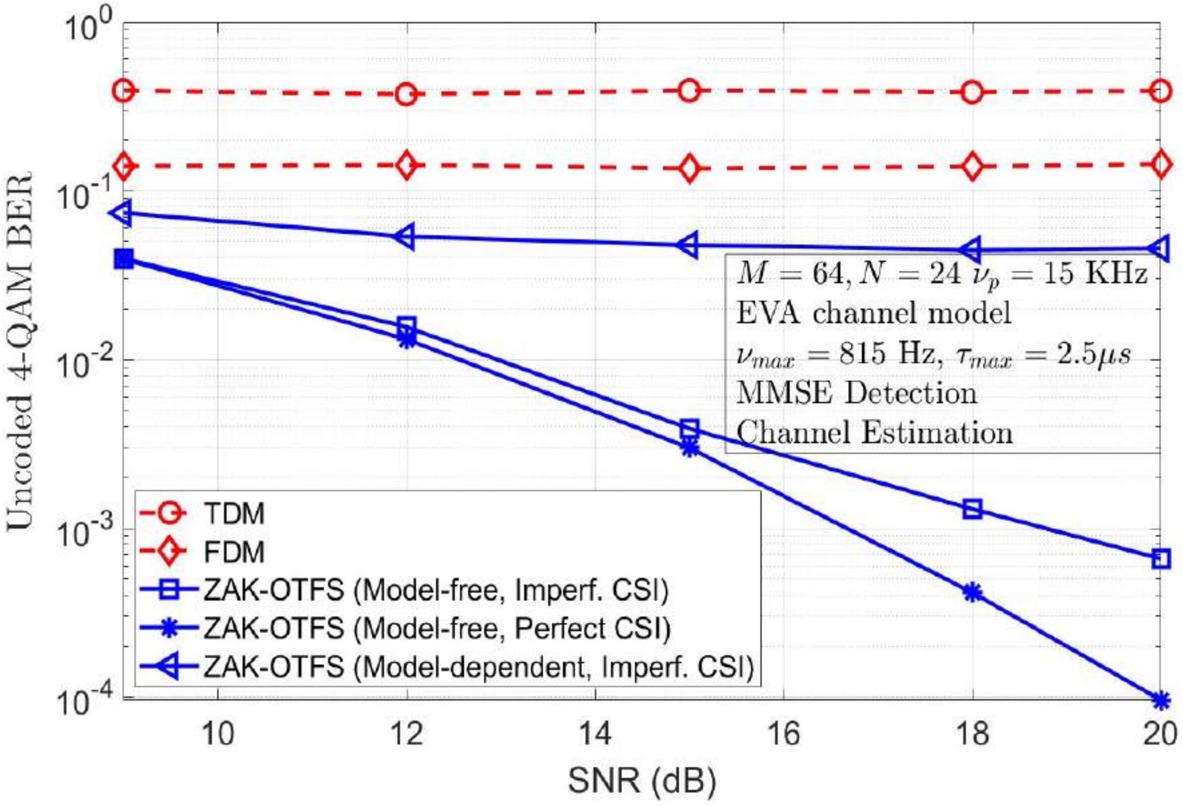
Signal Processing in Zak-OTFS



Zak-OTFS I/O Relation

$$y_{dd}^{w_{rx}}(\tau,\nu) = w_{rx}(\tau,\nu) \ *_\sigma \ h(\tau,\nu) \ *_\sigma \ w_{tx}(\tau,\nu) *_\sigma \ x_{dd}(\tau,\nu) \ = h_{dd}(\tau,\nu) *_\sigma \ x_{dd}(\tau,\nu)$$

Model-Free vs Model-Dependent



When it is not possible to learn the channel:

Pulsones support model-free operation in the crystalline regime

Not shown: Improvements in filtering – root raised cosine vs. sinc – extend the region of reliable operation

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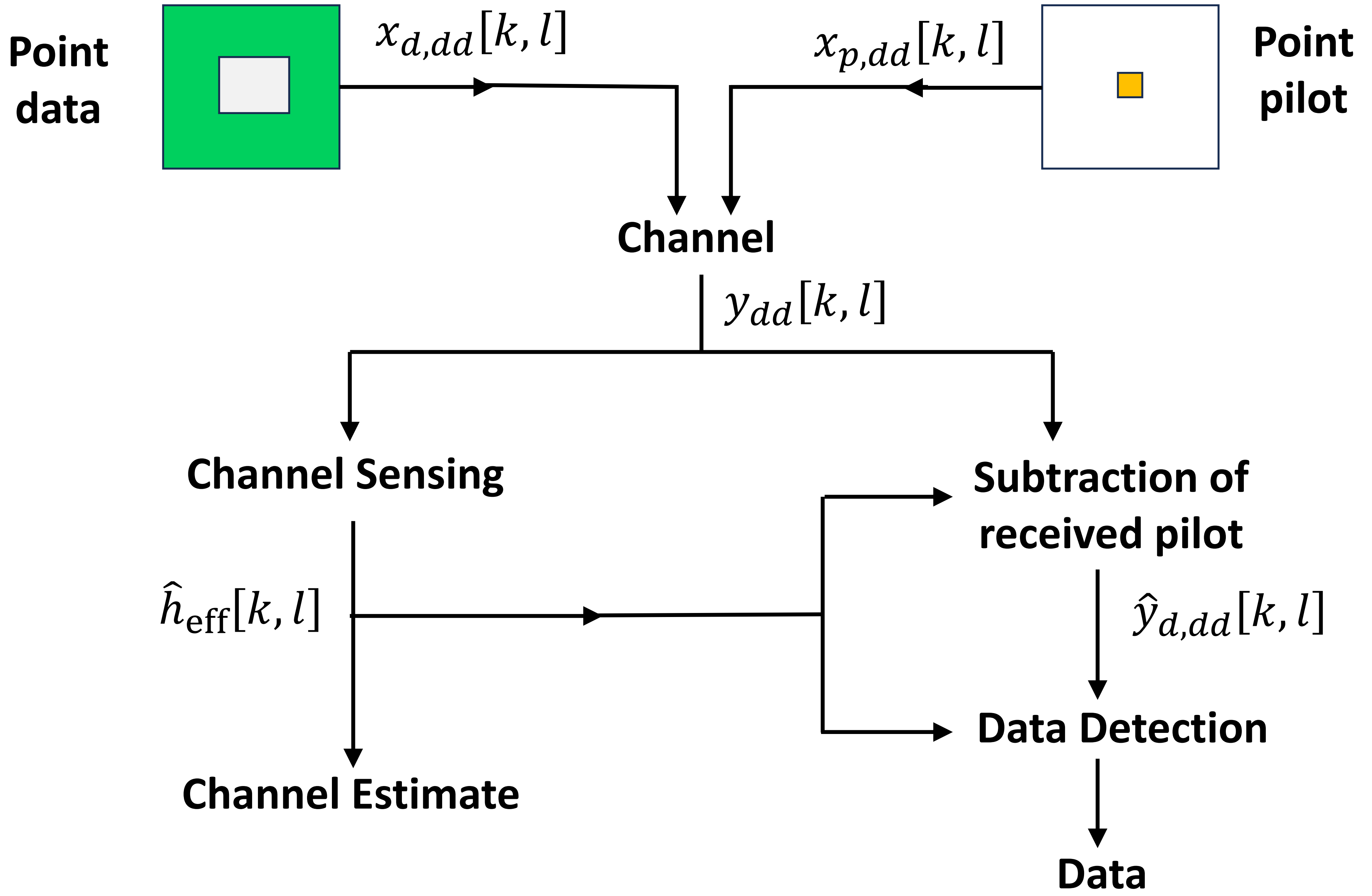
Integrating Sensing and Communication with Point Pulsones



Point data

$x_{d,dd}[k,l]$

$x_{p,dd}[k,l]$

Point pilot

Channel

$y_{dd}[k,l]$

Channel Sensing

Subtraction of received pilot

$\hat{h}_{\text{eff}}[k,l]$

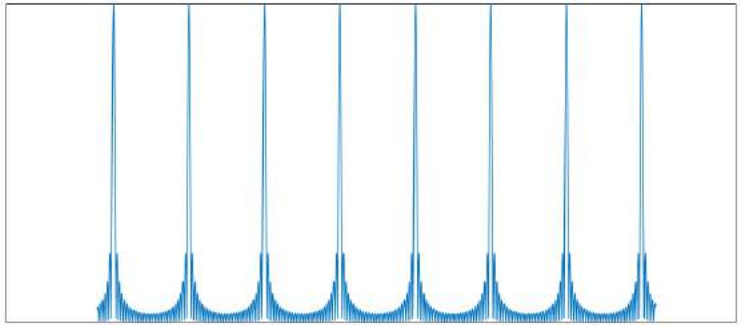
$\hat{y}_{d,dd}[k,l]$

Data Detection

Channel Estimate

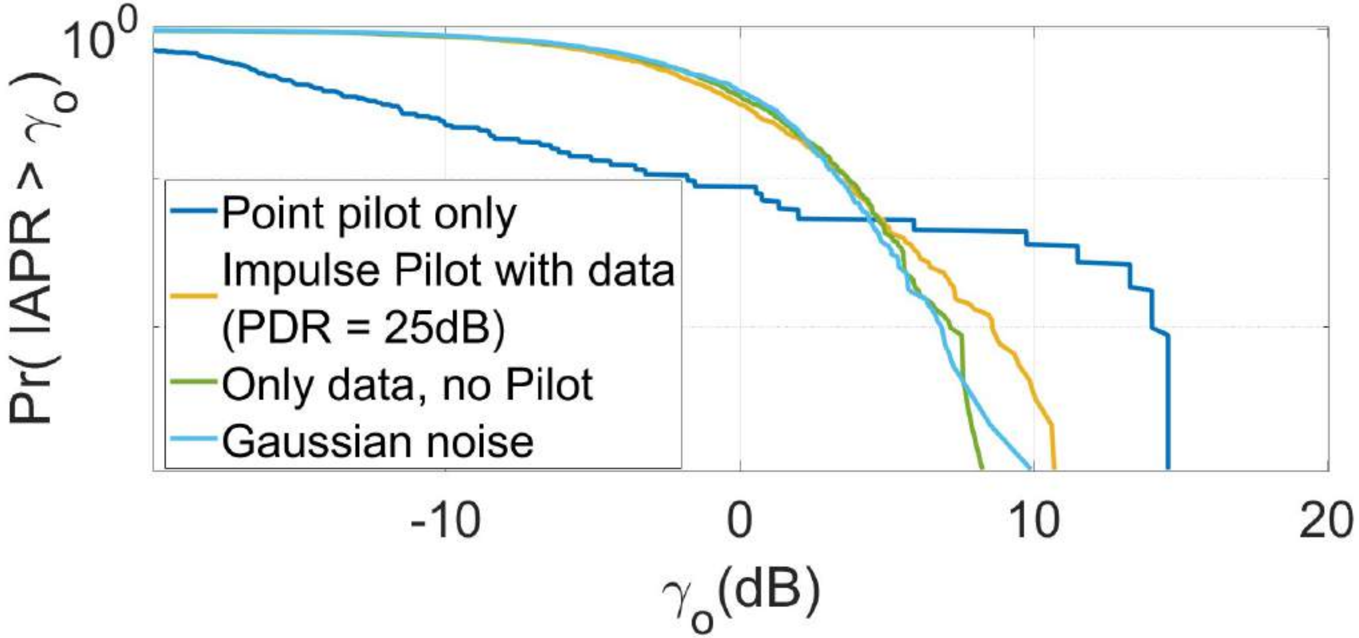
Data

Peak to Average Power Ratio (PAPR)



TD realization of a point pulsone:
Doppler period 30 KHz, $M = 31, N = 37$.
RRC pulse shaping ($\beta_\tau = \beta_\nu = 0.6$).

High PAPR: Requires highly linear power amplifiers which are typically power-inefficient



Complementary CDF (CCDF) of Instantaneous to Average Power Ratio (IAPR): RRC pulse shaping

($\beta_\tau = \beta_\nu = 0.6$)

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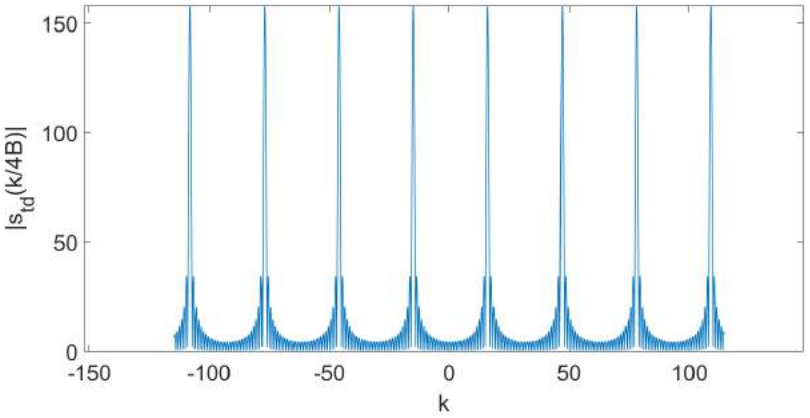
Spreading in TD and DD domain

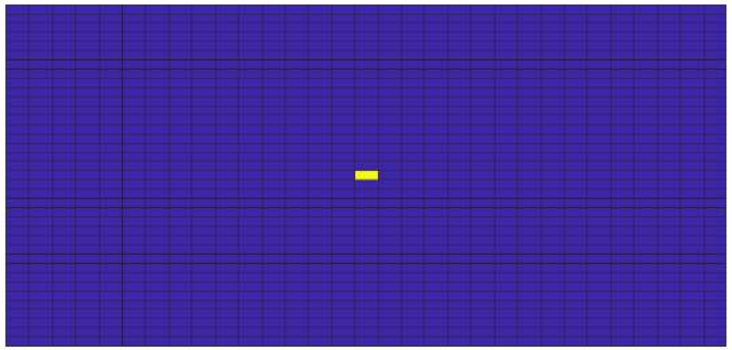
TD

DD domain

x_p



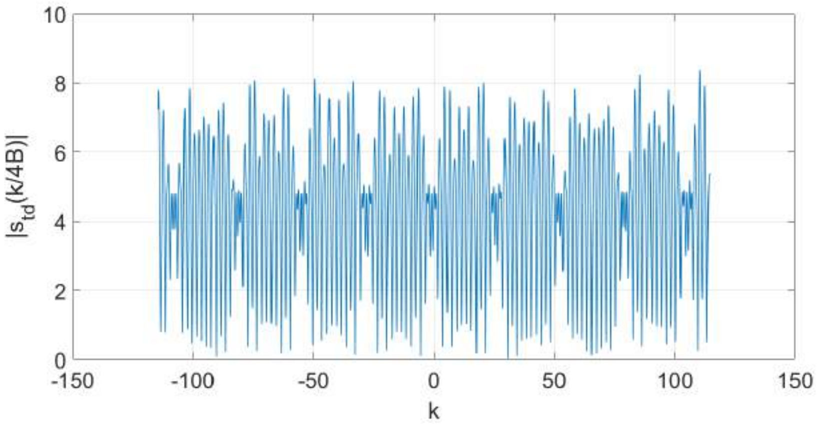
peaky waveform



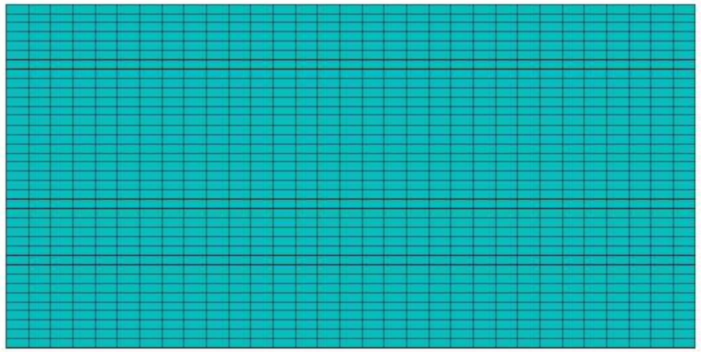
energy focussed at pilot location

Chirp filter with slope $q = 3$

x_s

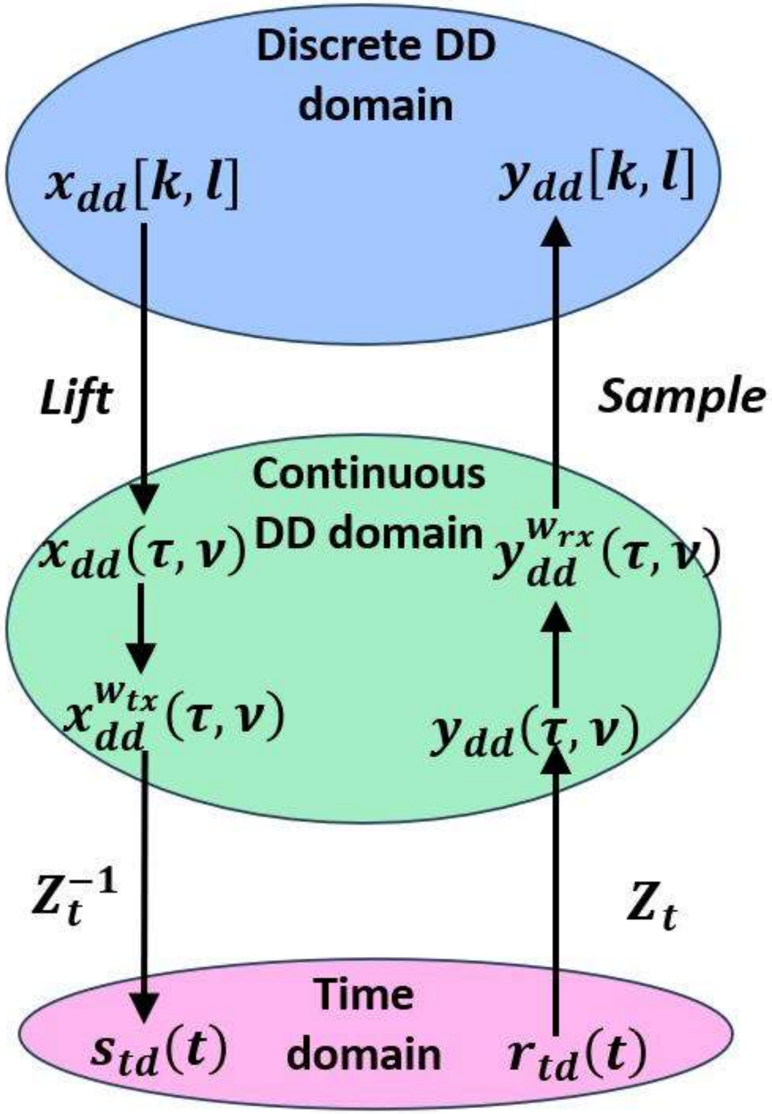


noise-like waveform



Energy $\left|x_{s,dd}[k,l]\right|^2 \approx \frac{1}{MN}$

Filters in the Discrete DD Domain



Discrete DD domain

$x_{dd}[k,l]$

$y_{dd}[k,l]$

Lift

Sample

Continuous DD domain

$x_{dd}(\tau,\nu)$

$y_{dd}^{w_{rx}}(\tau,\nu)$

$x_{dd}^{w_{tx}}(\tau,\nu)$

$y_{dd}(\tau,\nu)$

Z_t^{-1}

Z_t

Time domain

$s_{td}(t)$

$r_{td}(t)$

Summary

Possible to construct spread waveforms with desirable characteristics by applying a chirp filter in the discrete DD domain to a point pulsone

Low PAPR: about 5 dB versus 15 dB for the point Pulsone

Possible to read off the I/O relation provided a second crystallization condition is satisfied w.r.t. Λ_q

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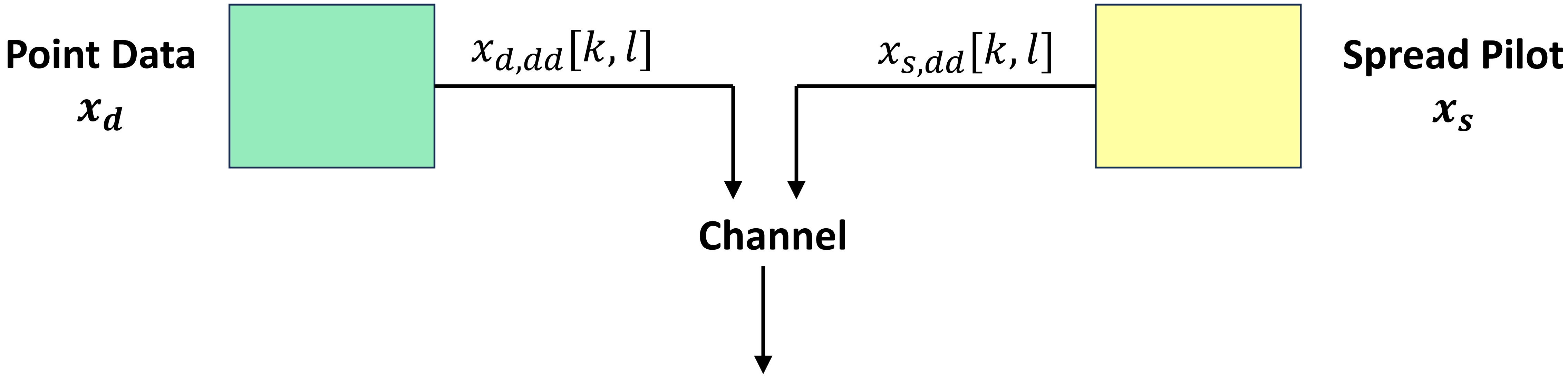
Data Interferes with Spread Pilot



Point Data
$\boldsymbol{x_d}$

$x_{d,dd}[k,l]$

$x_{s,dd}[k,l]$

Spread Pilot
$\boldsymbol{x_s}$

Channel

$$\boldsymbol{y_{dd}[k,l] = y_{d,dd}[k,l] + y_{s,dd}[k,l] + n_{dd}[k,l]}$$

In the absence of noise

$$y_{dd}[k,l] = \sqrt{E_d}\left(h_{\text{eff}}[k,l] \quad *_\sigma \; x_{d,dd}[k,l]\right) + \sqrt{E_p}\left(h_{\text{eff}}[k,l] \quad *_\sigma \; x_{s,dd}[k,l]\right)$$

Cross-Ambiguity $A_{y,x_s}[k,l]$ between $y_{dd}[k,l]$ and $x_{s,dd}[k,l]$

$$A_{y,x_s}[k,l] = \sqrt{E_p}\left(h_{\text{eff}}[k,l] \quad *_\sigma \; A_{x_s,x_s}[k,l]\right) + \sqrt{E_d}\left(h_{\text{eff}}[k,l] \quad *_\sigma \; A_{x_d,x_s}[k,l]\right)$$

Data Interference is Noise-Like

Crystallization Condition: Translates of the channel support $S_{(0,0)}$ by lattice points in Λ_q are disjoint

$$\mathbb{E}\left[\left|\sqrt{E_d}\ \ h_{\text{eff}}[k,l]\quad *_{\sigma}\ A_{x_d,x_s}[k,l]\right|^2\right] = \frac{E_d}{MN}\ \ \sum_{(k,l)\in S_{(0,0)}} |h_{\text{eff}}[k,l]|^2$$

Estimate $h_{\text{eff}}[k,l]$ by reading off $A_{y,x_s}[k,l]$ in $S_{(0,0)}$

$$A_{y,x_s}[k,l] = \sqrt{E_p}\ \ h_{\text{eff}}[k,l]\ \ + \sqrt{E_d}\left(h_{\text{eff}}[k,l]\quad *_{\sigma}\ A_{x_d,x_s}[k,l]\right)$$

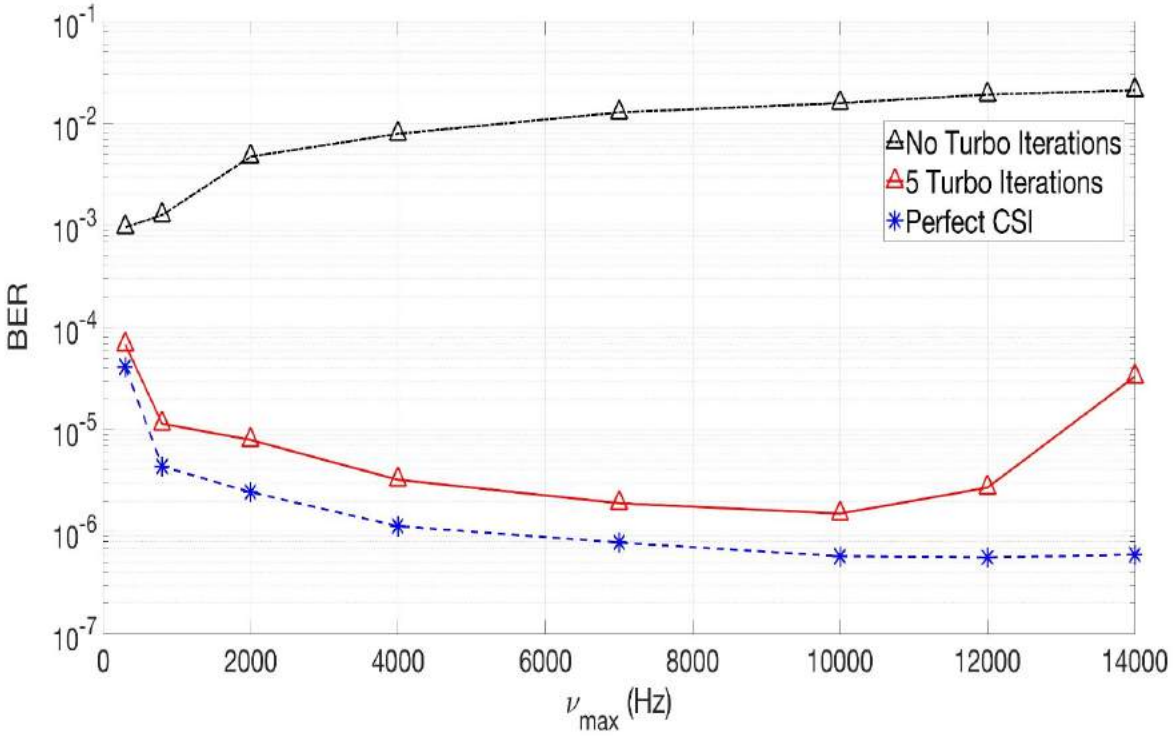
$$\hat{h}_{\text{eff}}[\mathrm{k},\mathrm{l}] = \frac{A_{y,x_s}[k,l]}{\sqrt{E_p}}\quad \text{for } (k,l)\in S_{(0,0)}$$

Estimate $y_{s,dd}[k,l]$

Subtract the estimate from $y_{dd}[k,l]$ to obtain $\hat{\mathrm{y}}_{\mathrm{d,dd}}[\mathrm{k},\mathrm{l}]$

Recover the data from $\hat{\mathrm{y}}_{\mathrm{d,dd}}[\mathrm{k},\mathrm{l}]$

Turbo-aided Communication and Sensing



Standard Veh-A Channel

Data SNR $\rho_d = 25$ dB

PDR $= 10$ dB

Two turbo iterations suffice to match the performance of separate sensing and communication across a wide range of Doppler shifts

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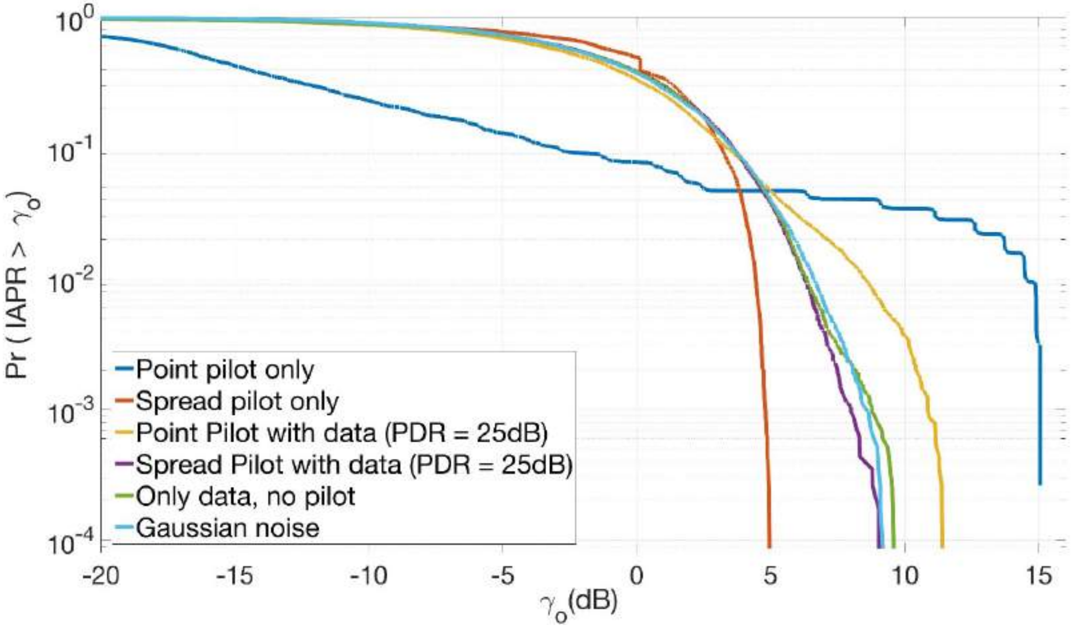
Conclusions

- Integrated sensing and communications reduces to geometric properties of a lattice Λ_p used for data transmission and a lattice Λ_q used for sensing.
- By sharing DD domain resources between sensing and communications it is possible to optimize throughput without compromising BER performance achieved by separating sensing and communication.
- When the channel satisfies the crystallization condition with respect to the lattice Λ_q the effective DD filter taps can be read off from the response to a single spread pilot.
- When the channel satisfies the crystallization condition with respect to the lattice Λ_p, then given the I/O response at one point in a Zak-OTFS subframe it is possible to predict the response at all points in the subframe.



Signal Processing Highlights

- Filters in the discrete DD domain enable integration by minimizing interference between sensing and data transmission – the data pulsones look like noise to the sensing pulsone.

- Filters in the discrete DD domain can be used to design noise-like waveforms with excellent PAPR.

Note on Passive Radar

Passive radar uses existing signals in the environment, often communication signals, as opportunistic illuminating sources.

The advantage of a passive system is invisibility to countermeasures, while the disadvantage is that communication signals are not designed with radar in mind.

The burden falls on the receiver processing to overcome any deficiencies because the transmitted signal cannot be modified.

- When we design the illuminator in a passive radar to be a spread pulsone we simplify acquisition of the radar scene – we can simply read it off from the received pilot signal

J.E. Palmer et al. (2013) – DVB-T Passive Radar Signal Processing