Integrating Sensing and Communication

Robert Calderbank
Duke University

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.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Technology</th>
<th>Voice Services</th>
<th>Data Services</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G (1980s)</td>
<td>Analog</td>
<td>Voice / SMS</td>
<td></td>
<td>GSM (pre 3GPP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IS 95 (pre 3GPP2)</td>
</tr>
<tr>
<td>2G (1990s)</td>
<td>CDMA</td>
<td>Data / Voice</td>
<td></td>
<td>WCDMA (3GPP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cdma2000 (3GPP2)</td>
</tr>
<tr>
<td>3G (2000s)</td>
<td>TDMA vs CDMA</td>
<td>Voice / SMS</td>
<td></td>
<td>LTE (3GPP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UMB (3GPP2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WiMax (IEEE)</td>
</tr>
<tr>
<td>4G (2010s)</td>
<td>OFDMA</td>
<td>Voice / SMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5G (2020s)</td>
<td>Scalable OFDM</td>
<td>Voice / SMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mmWave</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beyond MBB</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
OFDM vs Zak-OTFS

**Prevent ISI**

- **OFDM**: Coarse Information Grid
- **Zak-OTFS**: Fine Information Grid

**How to Choose?**

**Effective Channel Support**

- Embrace ISI
- Prevent ISI

**Frequency**

- Carrier Spacing
- Time

**Carrier Spacing**

- Delay
- Doppler
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
Crystalline Regime: The delay domain period $\tau_p$ is greater than the channel path delay spread, and the Doppler domain period $\nu_p$ 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

**Pilot Signal:** point pulse $x = x_s$

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 $\tau_p$ and the Doppler period $\nu_p$

**Doppler Period**

$\nu_p = 20$ KHz

**Delay Period**

$\tau_p = 50$ $\mu$s
TD Pulsone from a Quasi-Periodic DD Domain Pulse

**TD Pulsone**

- **Delay Period**
  - \( \nu_p = 20 \text{ KHz} \)

- **Doppler Period**
  - \( \tau_p = 50 \mu s \)

**Parameters**

- \( B = \frac{1}{100ns} = 10 \text{ MHz} \)
- \( T = \frac{1}{1 \text{ KHz}} = 1 \text{ ms} \)
- \( N = \frac{50 \mu s}{100ns} = 500 \)
- \( M = \frac{20 \text{ KHz}}{1 \text{ KHz}} = 20 \)

Mathematical Formulas:

\[
x(t) = \sqrt{\tau_p} \int_{0}^{\nu_p} x_{dd}(t, \nu) d\nu
\]

**Diagram**

- \( R\{x(t)\} \)
- \( T \)
- \( t \)
- \( B^{-1} \)
- \( \tau_0 \)
- \( \tau_p \)
- \( \cos(2\pi \nu_0 (t - \tau_0)) \)
- \( Z_t^{-1} : x_{dd}(\tau, \nu) \rightarrow x(t) \)
- \( \nu_p = \frac{1}{\tau_p} \)
\[ \tau_p \cdot \nu_p = 1 \]

**Frequency Selectivity**

**Time Selectivity**

**Predictability**

**DD Domain Aliasing Controls Predictability**

**Aliasing in Delay**

**Aliasing in Doppler**

**No Aliasing**

**FDM**

\[ \nu_p \rightarrow \infty \]

**TDM**

\[ \tau_p \rightarrow \infty \]
Signal Processing in Zak-OTFS

Zak-OTFS I/O Relation

\[ y_{dd}^{wrx}(\tau, \nu) = w_{rx}(\tau, \nu) \ast_\sigma h(\tau, \nu) \ast_\sigma w_{tx}(\tau, \nu) \ast_\sigma x_{dd}(\tau, \nu) = h_{dd}(\tau, \nu) \ast_\sigma x_{dd}(\tau, \nu) \]
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
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** - Zak-OTFS and Integration of Sensing and Communication— in collaboration with Muhammad Ubadah, Saif Khan Mohammed, Ronny Hadani, and Ananthanarayanan Chockalingam
Integrating Sensing and Communication with Point Pulsones

Channel Estimate

Point data

\( x_{d,dd}[k, l] \)

\( x_{p,dd}[k, l] \)

Channel Sensing

\( \hat{h}_{eff}[k, l] \)

Subtraction of received pilot

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

Data Detection

Data
Peak to Average Power Ratio (PAPR)

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

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

Complementary CDF (CCDF) of Instantaneous to Average Power Ratio (IAPR): RRC pulse shaping ($\beta_\tau = \beta_\nu = 0.6$).
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** - Zak-OTFS and Integration of Sensing and Communication— in collaboration with Muhammad Ubadah, Saif Khan Mohammed, Ronny Hadani, and Ananthanarayanan Chockalingam
Spreading in TD and DD domain

\[ x_p \]

peaky waveform

Chirp filter with slope \( q = 3 \)

\[ x_s \]

noise-like waveform

Energy \( |x_{s,dd}[k,l]|^2 \approx \frac{1}{MN} \)
Filters in the Discrete DD Domain

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. $\Lambda_q$. 
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** - Zak-OTFS and Integration of Sensing and Communication— in collaboration with Muhammad Ubadah, Saif Khan Mohammed, Ronny Hadani, and Ananthanarayanan Chockalingam
Data Interferes with Spread Pilot

In the absence of noise

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

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

$$A_{y,x_s}[k, l] = \sqrt{E_p} \left( h_{\text{eff}}[k, l] \ast \sigma A_{x_s,x_s}[k, l] \right) + \sqrt{E_d} \left( h_{\text{eff}}[k, l] \ast \sigma A_{x_d,x_s}[k, l] \right)$$
Data Interference is Noise-Like

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

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

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

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

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

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

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

Recover the data from $\hat{y}_{d,dd}[k, l]$
Two turbo iterations suffice to match the performance of separate sensing and communication across a wide range of Doppler shifts.

**Turbo-aided Communication and Sensing**

**Standard Veh-A Channel**

Data SNR $\rho_d = 25$ dB

PDR = 10 dB
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 - Zak-OTFS and Integration of Sensing and Communication– in collaboration with Muhammad Ubadah, Saif Khan Mohammed, Ronny Hadani, and Ananthanarayanan Chockalingam
Conclusions

• Integrated sensing and communications reduces to geometric properties of a lattice $\Lambda_p$ used for data transmission and a lattice $\Lambda_q$ 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 $\Lambda_q$ 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 $\Lambda_p$, 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.
• 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 pulse we simplify acquisition of the radar scene – we can simply read it off from the received pilot signal