Next Generation Waveform Design for Communication Systems

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Digital Communication system

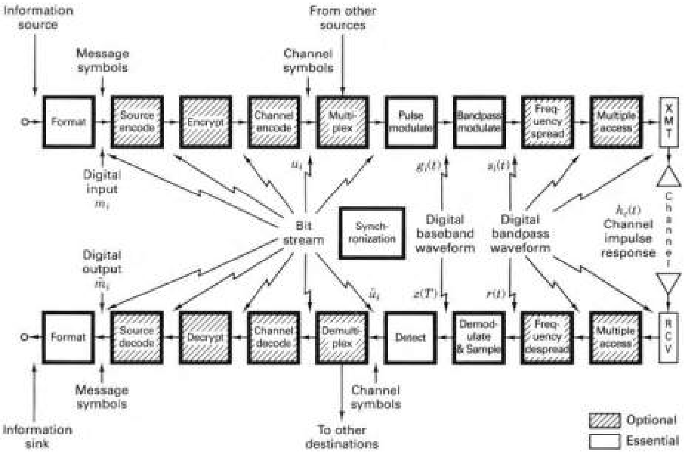

Figure: Block diagram of typical digital communication system [1]

Digital Communication systems (with Essentials)

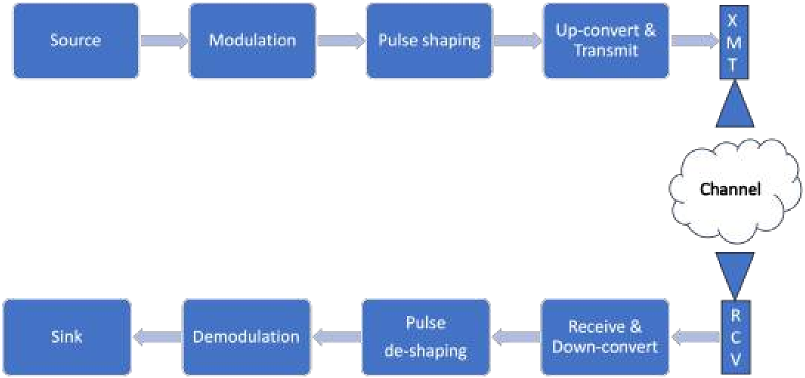

Figure: Block diagram of digital communication system

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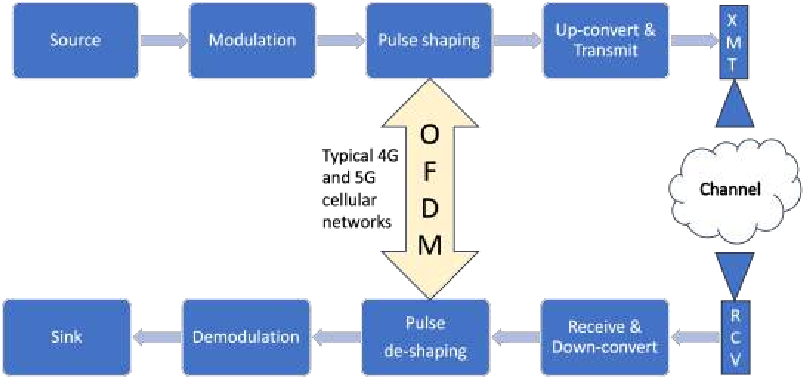

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OFDM

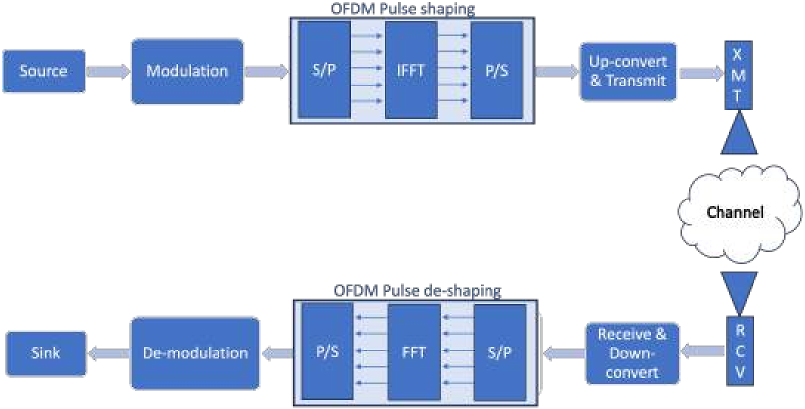

Figure: Block diagram of OFDM

Effects of Doppler spread in OFDM

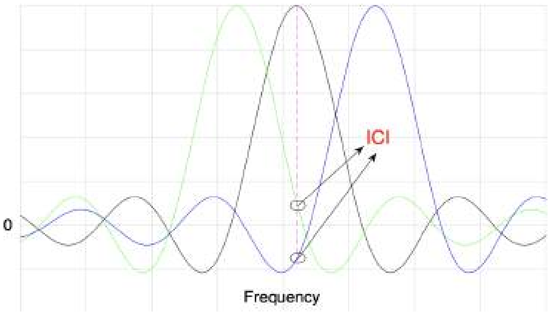

Figure: ICI in OFDM [2]

- High Doppler channels cause ICI because sub-carriers lose orthogonality.

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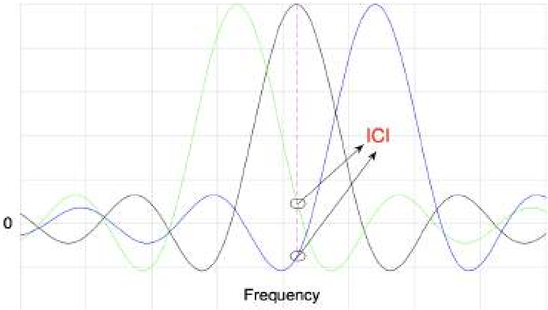

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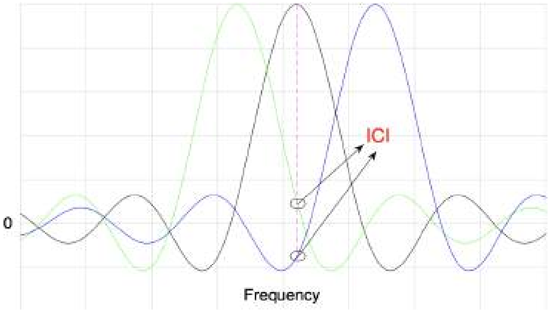

Figure: ICI in OFDM [2]

- High Doppler channels cause ICI because sub-carriers lose orthogonality.
- Causes severe bit error and spectral efficiency performance at high Dopplers.
- Channel estimation and equalization in high Doppler channels is difficult.

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OTFS Communication system

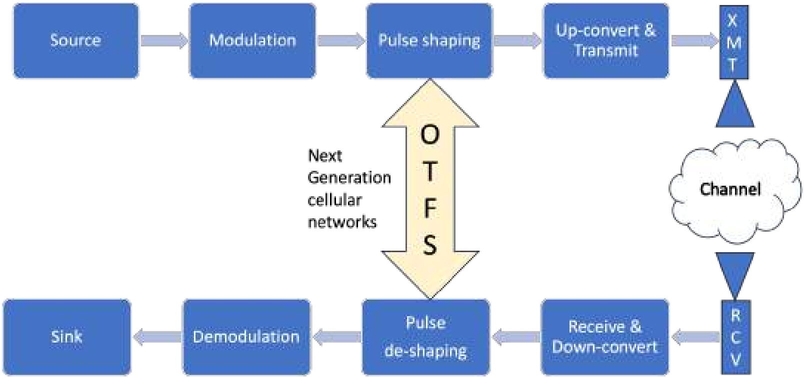
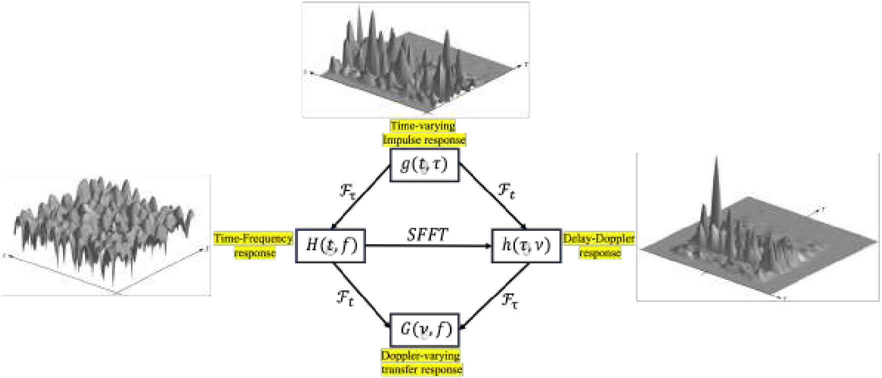


Figure: Block diagram of digital communication system

Channel in DD domain

LTV multipath channels can be represented as a function of

- Time-Frequency, $H(t, f)$,
- Time-Delay, $g(t, \tau)$,
- Delay-Doppler, $h(\tau, \nu)$



Key features of OTFS

- Information symbols are multiplexed in the delay Doppler (DD) domain rather than in the time or frequency domain.

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- Performs good in doubly dispersive channels
- The channel response in the DD domain is invariant for a larger observation time
- Each symbol experiences nearly constant channel gain
- Channel interaction with transmit symbols is 2-D convolution rather than multiplication

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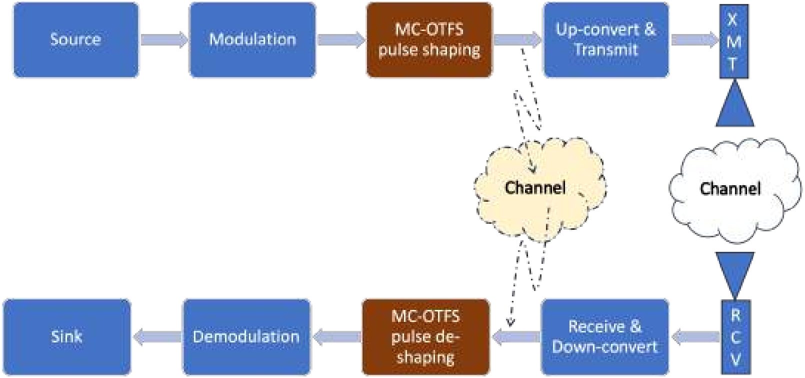
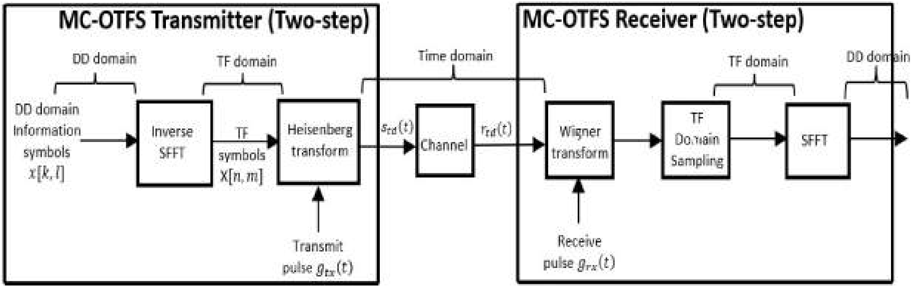
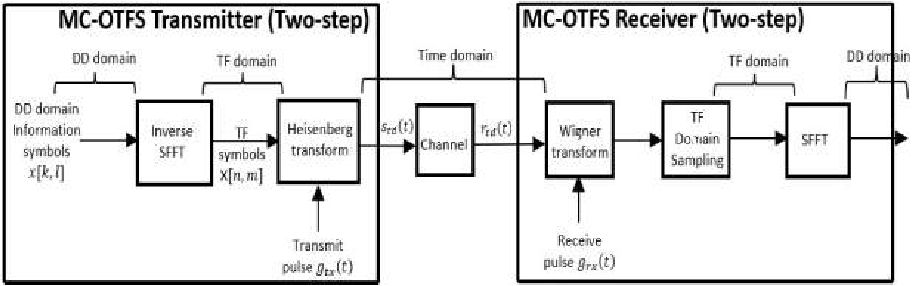
MC-OTFS Communication system



MC-OTFS Transceiver



Issues with MC-OTFS



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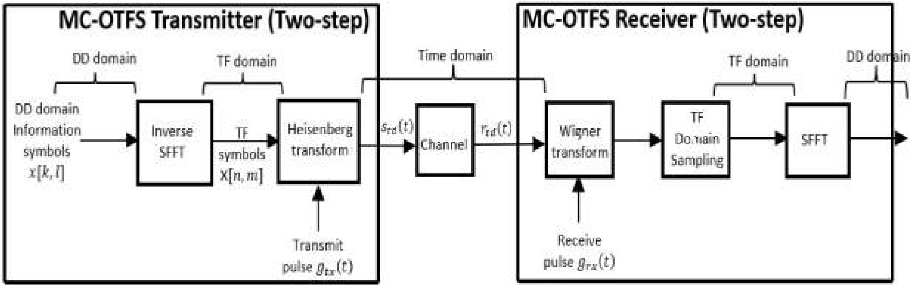

$$y^{w_{rx}}(\tau,\nu) = w_{rx}(\tau,\nu)\star[G^{*}_{\rm dd}(\tau,\nu)\cdot(h_{\rm phy}(\tau,\nu)*_{\sigma}\{G_{\rm dd}(\tau,\nu)\cdot[w_{tx}(\tau,\nu)\star x(\tau,\nu)]\})]$$

where $'\star'$-Convolution, $'\cdot'$-Multiplication, and $'*_{\sigma}'$- Twisted Convolution.

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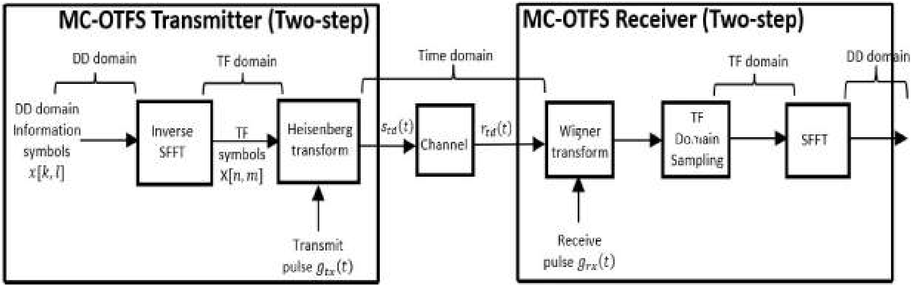

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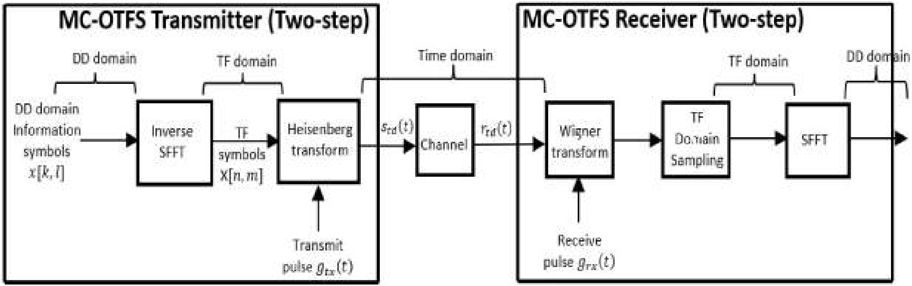

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where $'\star'$-Convolution, $'\cdot'$-Multiplication, and $'*_{\sigma}'$- Twisted Convolution.

- Cannot be expressed as a simple action with some effective filter
- Inefficient acquisition of I/O relation as simple prediction seems impossible

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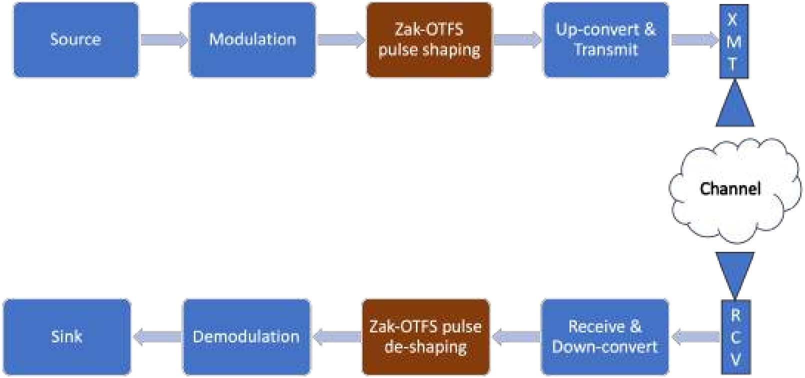
Zak-OTFS Communication system



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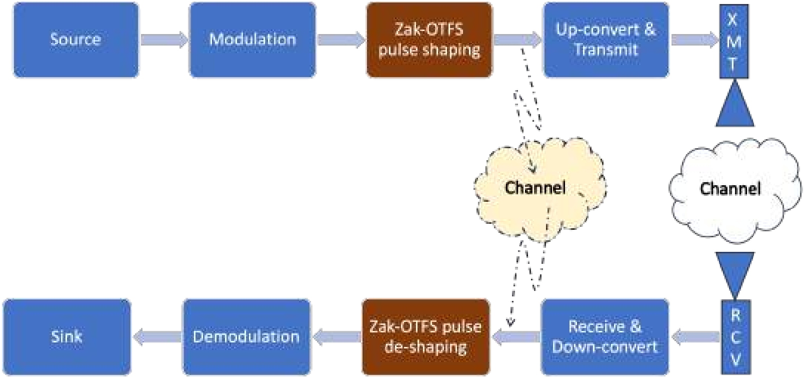
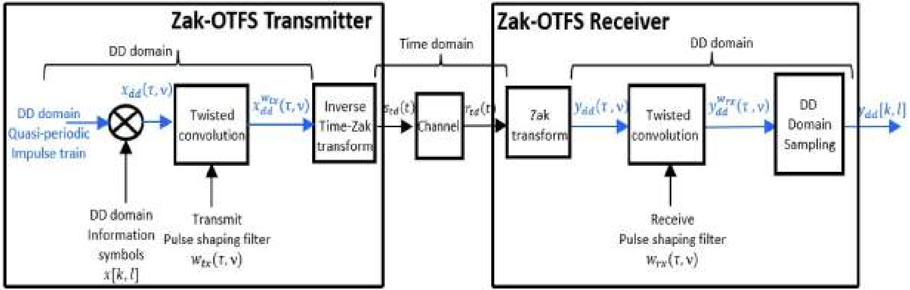


Zak-OTFS Transceiver



Features of Zak-OTFS/OTFS 2.0

- One-step conversion from DD to time and time to DD domains

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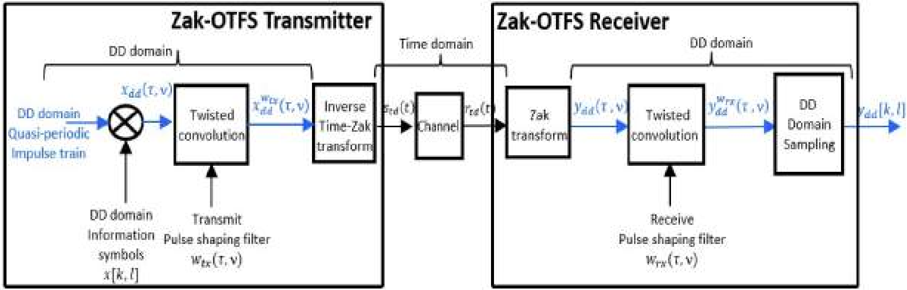
- One-step conversion from DD to time and time to DD domains
- More robust to large channel spreads compared to OTFS 1.0
- When operating in a crystalline regime, the predictability of the I/O relation is simple.

Zak-OTFS Transceiver



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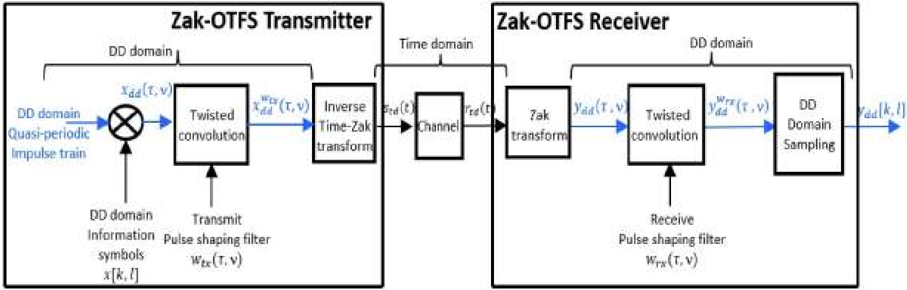

- I/O relation is a simple twisted convolution with effective channel filter.

  Zak-OTFS I/O :-

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

  MC-OTFS I/O :-

$$y^{w_{rx}}(\tau,\nu) = w_{rx}(\tau,\nu) \star [G_{\text{dd}}^*(\tau,\nu) \cdot (h_{\text{phy}}(\tau,\nu) *_\sigma \{G_{\text{dd}}(\tau,\nu) \cdot [w_{tx}(\tau,\nu) \star x(\tau,\nu)]\})]$$

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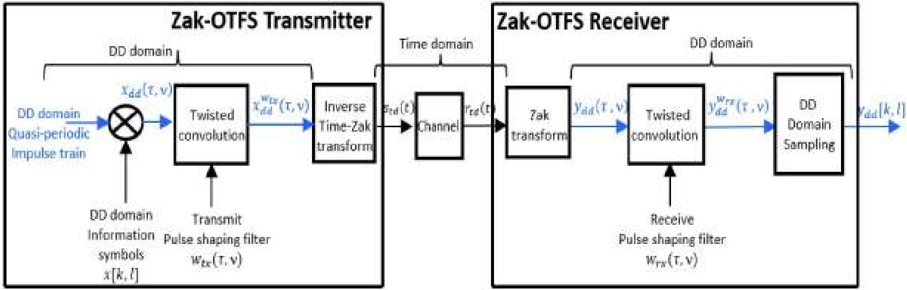
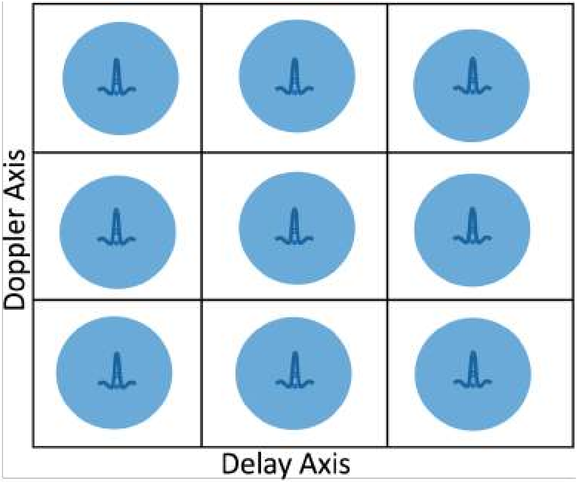


- I/O relation is a simple twisted convolution with effective channel filter.
- Efficient acquisition of I/O relation is a simple prediction in crystalline regime.

Crystalline condition



$$\tau_p > \left(\max_i \tau_i - \min_i \tau_i \right) \text{ and } \nu_p > \left(\max_i \nu_i - \min_i \nu_i \right)$$

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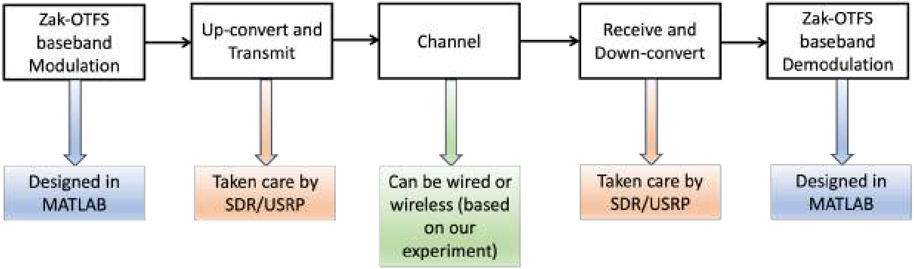
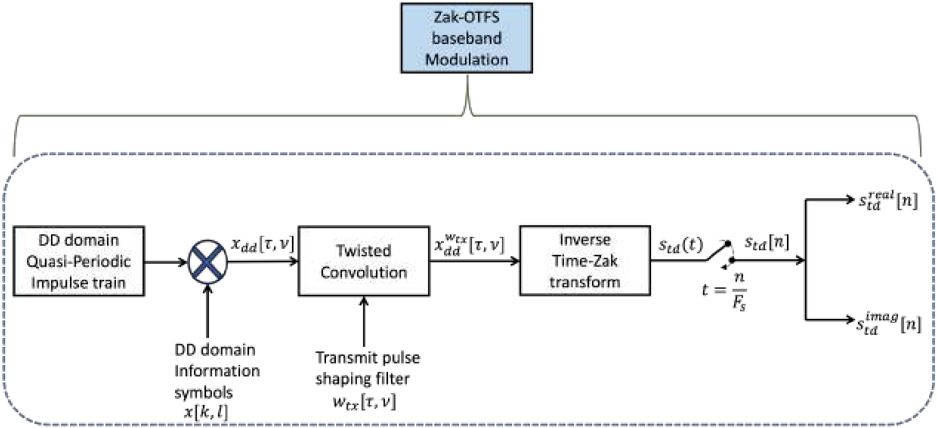
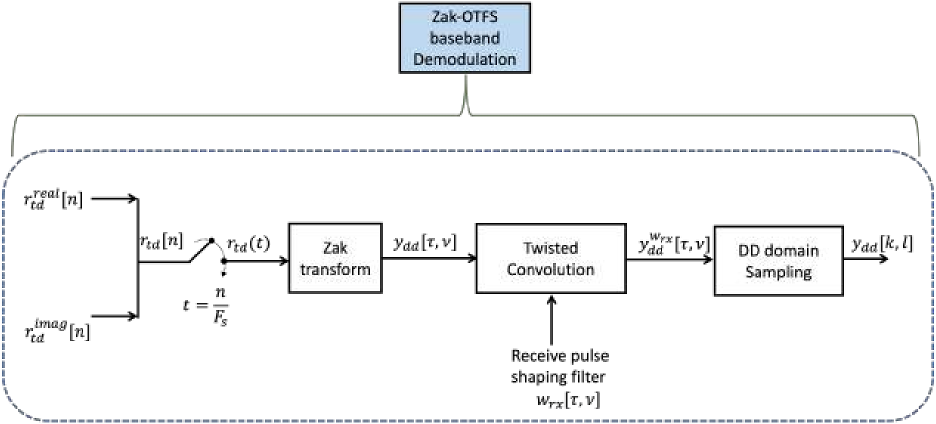
Over the air Design Flow



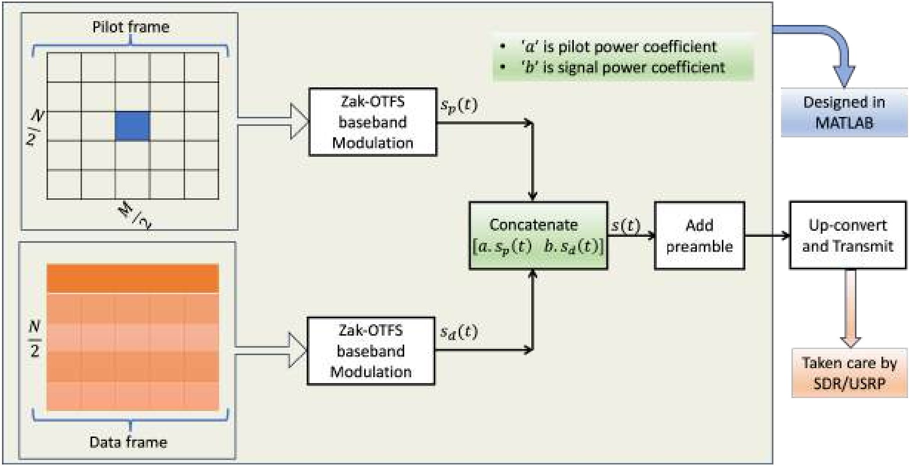
Zak-OTFS baseband modulation/Zak-OTFS Transmitter



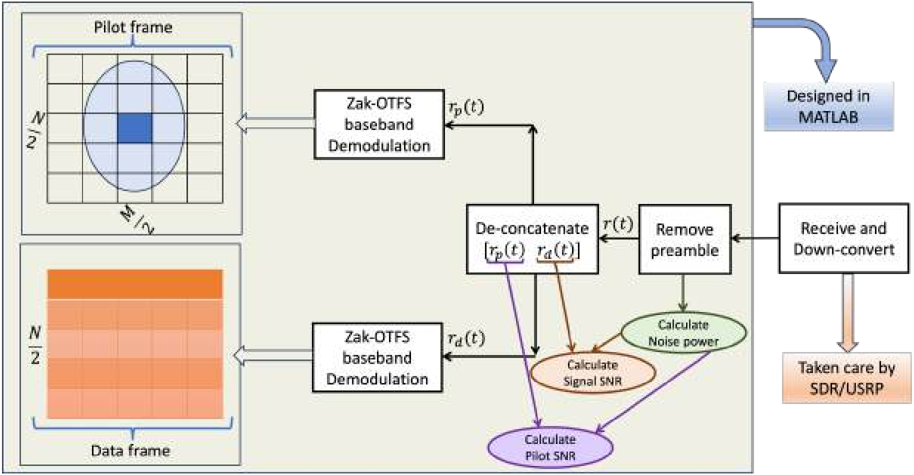
Zak-OTFS baseband de-modulation



Zak-OTFS modulation for channel Estimation



Zak-OTFS demodulation with channel Estimation



Channel Estimation and Equalization

- The received pilot symbols in vector form,

$$\boldsymbol{y}_p = \boldsymbol{H}\boldsymbol{x}_p + \boldsymbol{n}$$

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- With the estimated channel $\widehat{\boldsymbol{H}}$ and using the calculated received SNR, we can perform MMSE on the received data to detect the transmit symbols, i.e.,

$$\widehat{\boldsymbol{x}}_d = \left(\widehat{\boldsymbol{H}}^* \widehat{\boldsymbol{H}} + \frac{1}{SNR}\boldsymbol{I}_{MN}\right)^{-1} \widehat{\boldsymbol{H}}^* \boldsymbol{y}_d$$

Over the air implementation

Figure: Massive MIMO mini-rack at Winlabs

Over the air implementation

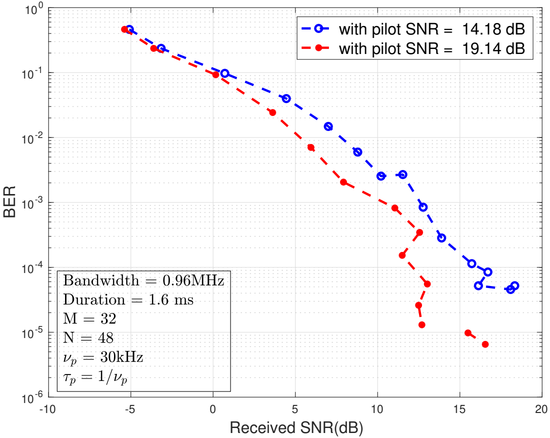

Figure: BER performance using Winlabs setup

Over the air implementation

Figure: Our communication setup in Prof. Tingjun's lab at Duke

Over the air implementation

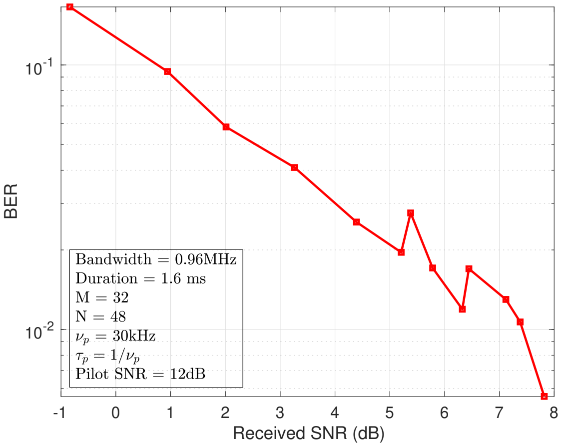

Figure: BER performance using communication setup in Prof. Tingjun's lab at Duke

Duke-Winlabs Project Goal

Stage-1 of Implementation

We use MATLAB to generate Zak-OTFS transmit samples and transmit them using SB1 (ORBIT), where the medium of transmission is a wire. The received samples are processed again in MATLAB.

Stage-2 of Implementation

Signal Processing is same as that of Stage-1, but the medium of transmission is wireless. We use MIMO facility in WINLABS to perform this experiment.

Stage-3 of Implementation

Signal Processing and channel is same as that of Stage-1. But we use SB4 (ORBIT), where the medium of transmission is a wire with a programmable attenuator. Using the results at this stage, we will produce an SNR versus BER curve.

Stage-4 of Implementation

Signal Processing and channel is same as that of Stage-1. But we use Grid (ORBIT) or MIMO facilities, where the medium of transmission is wireless but the transmit and receive antennas are very far apart.

Stage-5 of Implementation

We need to convert MATLAB code to C/C++ or some code that is compatible with GNU Radio, where there is a lot of scope to add additional blocks so as to design Zak-OTFS-based real-time transmission and reception.

Stage-6 of Implementation

We will be transmitting and receiving the signal over mm-wave frequencies.

Note: For these 5 stages of implementation, we will be using sub-6 GHz frequencies (around 2.4 GHz) to transmit and receive signals.

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Goals & Conclusion

- Evaluate the performance of Zak-OTFS over real-time systems.

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- Evaluate the performance of Zak-OTFS over real-time systems.
- Design a more accurate channel estimator and low-complex channel equalizer.

References

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S. K. Mohammed, R. Hadani, A. Chockalingam and R. Calderbank, “OTFS - A Mathematical Foundation for Communication and Radar Sensing in the Delay-Doppler Domain,” in *IEEE BITS the Inf. Theory Mag.*, vol. 2, no. 2, pp. 36–55, 1 Nov. 2022.

S. K. Mohammed, R. Hadani, A. Chockalingam, and R. Calderbank. “OTFS–Predictability in the Delay-Doppler Domain and its Value to Communication

THANK YOU

QUESTIONS &
SUGGESTIONS

Contact Information

Please email us for more details on the Matlab code.

Also, email us if you need Matlab code for "*Over the Air*" Design.

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