Part 4

Waveform Design beyond Classical Sensing

Outline

- ISAC Motivation and Topologies
- Radar Waveforms for Communications
- Communication Waveforms for Sensing
- Co-existence Design Examples
- HW Prototype

Integrated Sensing and Communications

- Radar and Comm systems need large bandwidths
  - Bandwidth is a scarce resource
  - Share the mmWave Spectrum
  - Operate in a mutually beneficial manner
- Reuse of resources
  - Viable mass market solutions
  - Technological evolution
- Motivational Application : Automotive
  - V2V,V2X
  - Low latency, short messaging

- Spectral Coexistence
  - Radar and communications operate as separate entities
  - Devise strategies to mitigate the interference adaptively
  - Some information exchange
  - Minimal changes in standard, HW
- Spectral Co-design
  - New joint sensing and communications techniques
  - Single unit is employed
  - Opportunistic access of spectrum

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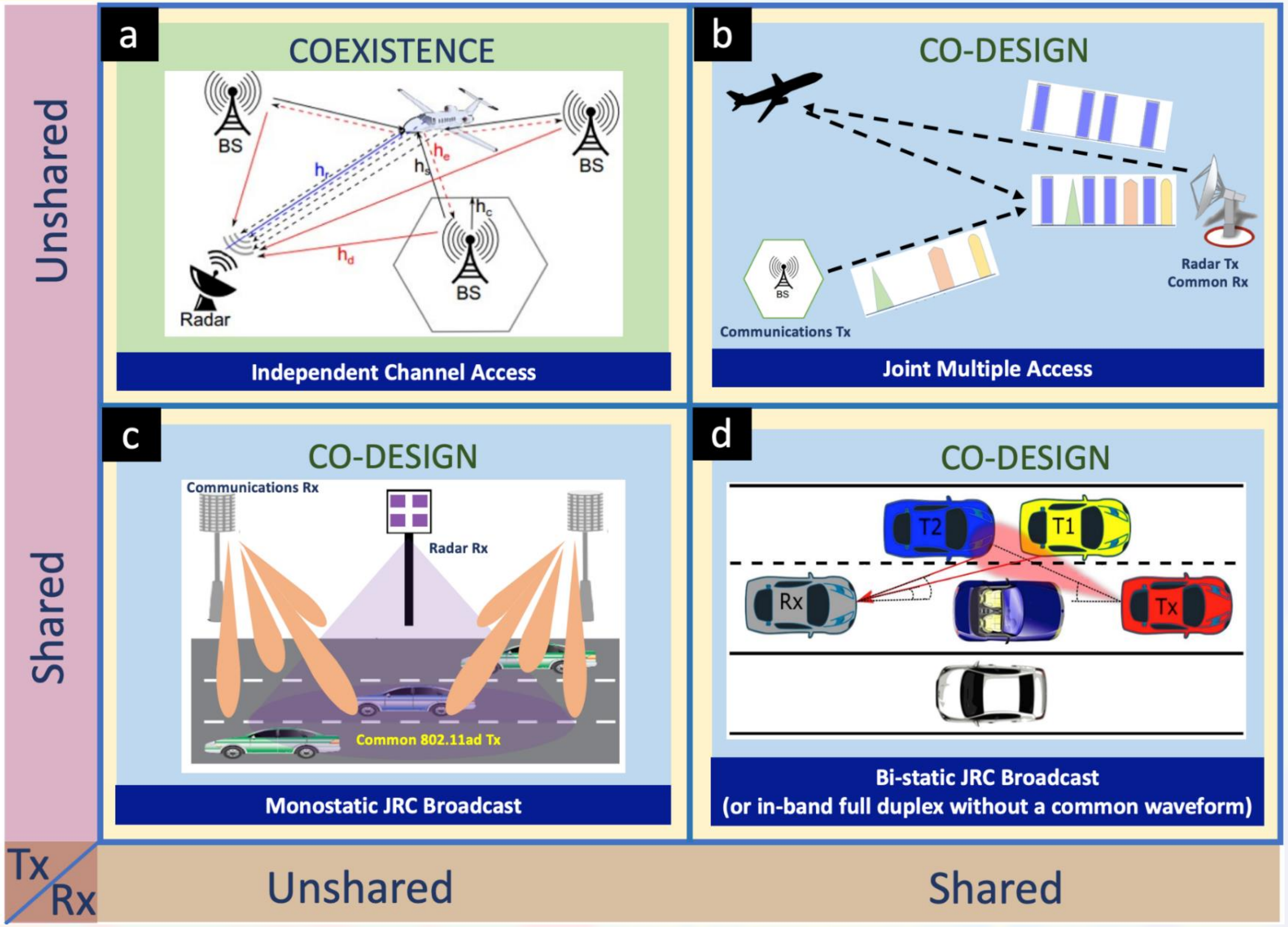
ISAC Topologies



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Radar and Comm Design Considerations

- Two Systems: Which performance metric to use?
  - Communications : Quality of Service, Data Rate, etc
  - Radar : Dependent on Radar Tasks
    - RMSE, RoC ..
  - Unified Criteria?
    - Mutual Information
- Transmitter Degrees of Freedom
  - Co-existence
    - Different antennas, frequency, coding, transmission slots, power, or polarization, possibly Channel State Information
  - Co-design
    - Waveform
- Receiver Degrees of Freedom
  - Multiple antennas, Channel State Information

Signal Processing Approaches

- Adapting waveform parameters
  - Enabling ISAC
  - Precoder/ Beamformer design using SINR maximization for co-existence
- Design of new waveforms
  - Multiple performance metrics/ constraints
  - System oriented constraints
    - Fewer antennas excited, constant modulus
  - Resource allocation
- Receiver
  - Multitude of Beamform designs
  - Successive Interference Cancellation
  - Multiple antenna-based processing
    - Subspace estimation, Eigenspace processing

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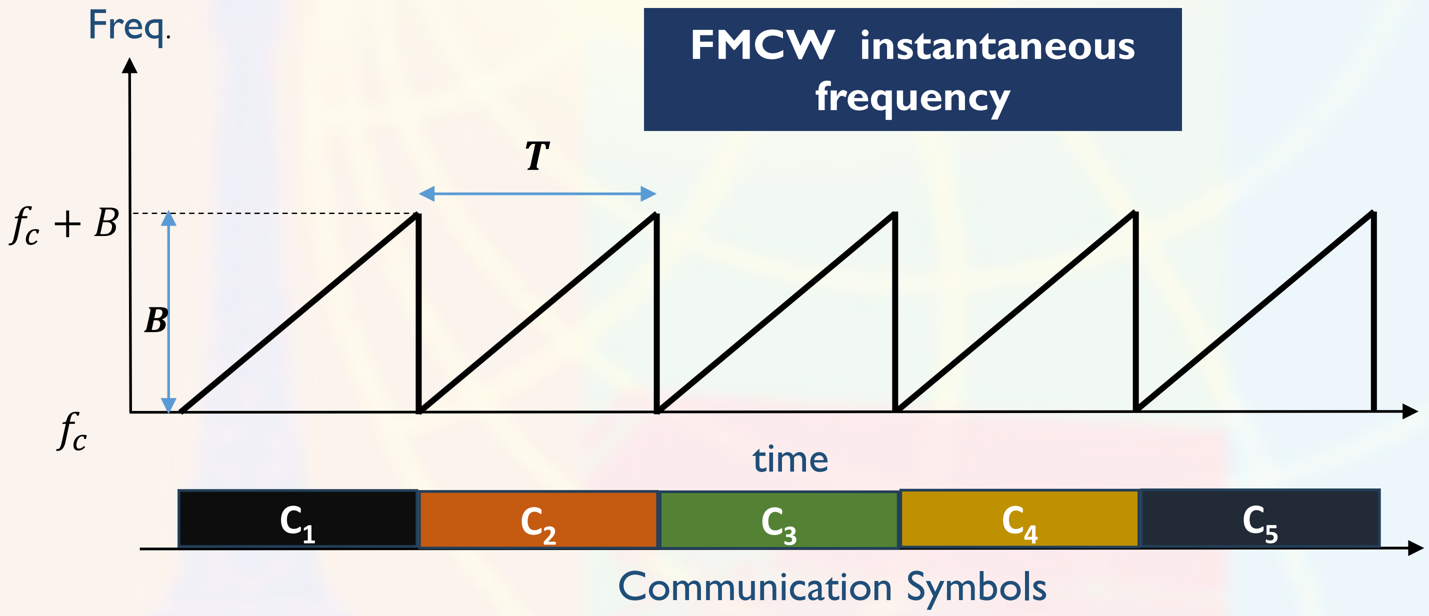
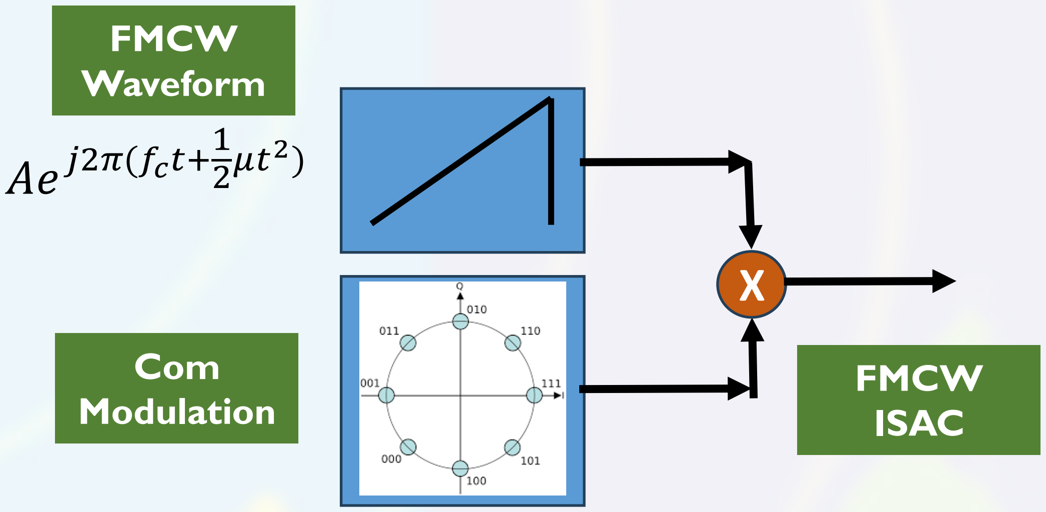
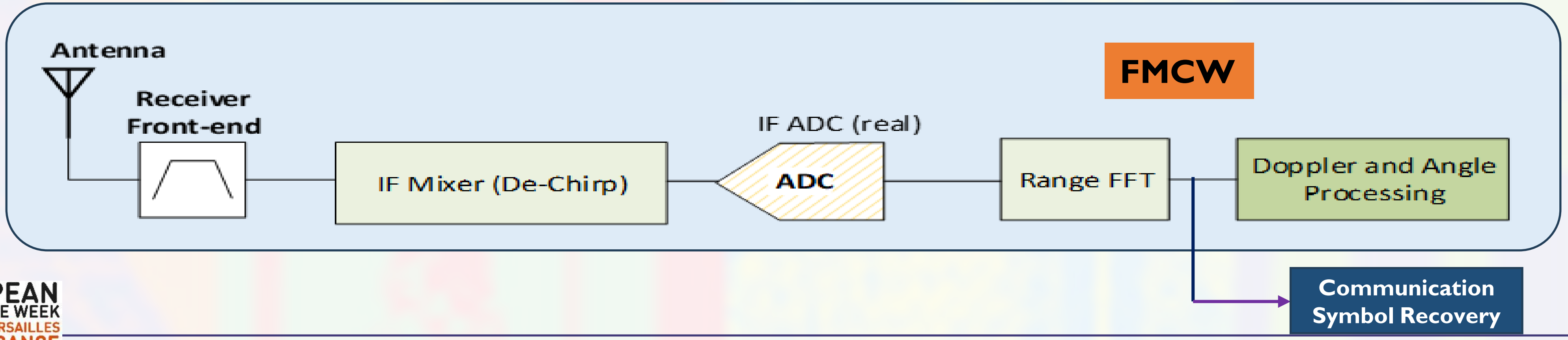
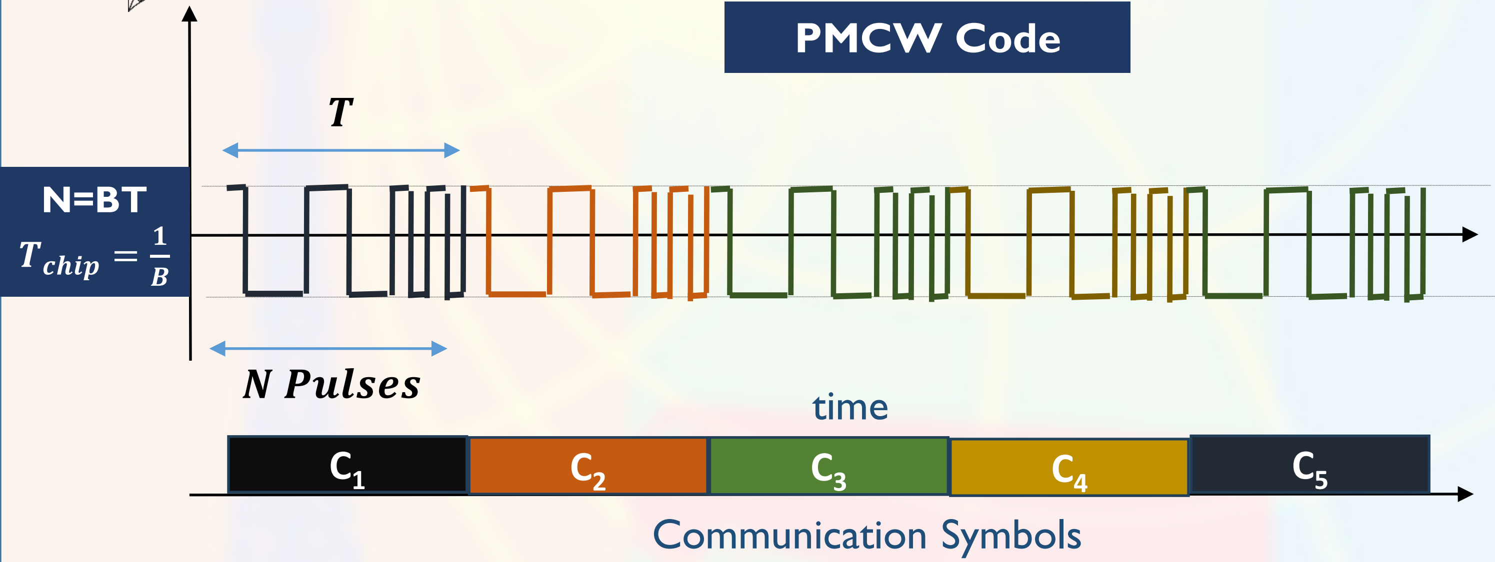
Communication Embedding in FMCW

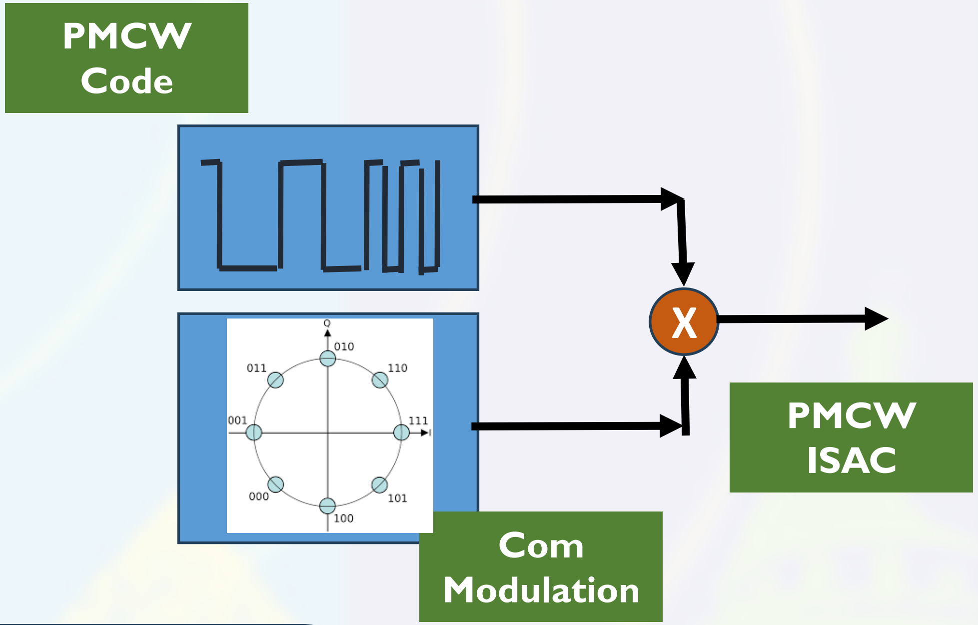


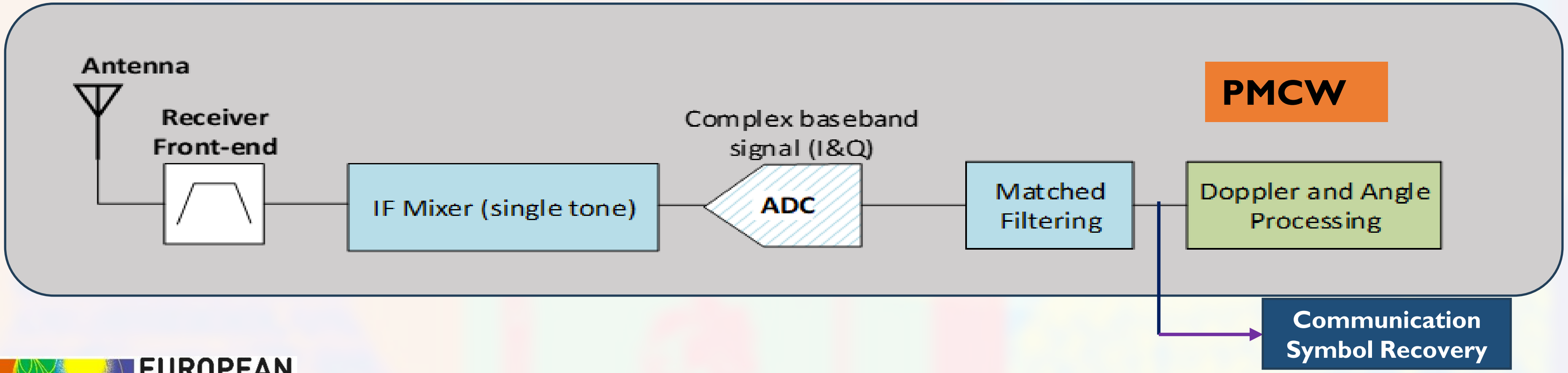




Communication Embedding in PMCW





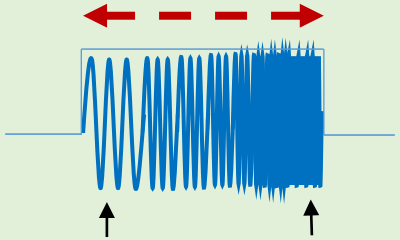


Summary

- ❑ Radar Signals → High Time Bandwidth Product
- ❑ Communication Figure of Merit
  - ❑ Spectral Efficiency = Bits/ second/ Hertz
  - ❑ Inversely proportional to TBP
- ❑ Communication embedding directly into radar signals is not spectrally efficient
- ❑ Other mechanisms can be used
  - ❑ E,g, : Communications in the sidelobe of radar → needs array and works in static situations

FMCW

Pulse Width, T



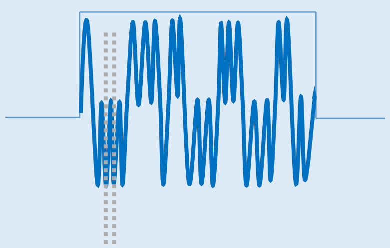
Frequency F_1 Frequency F_2

Bandwidth = $\Delta F = F_2 - F_1$

Time × Bandwidth = $T \times \Delta F$

PMCW

Pulse Width, T



T_{chip}

Bandwidth = $\frac{1}{T_{chip}}$

Time × Bandwidth = $\frac{T}{T_{chip}}$

Source: CTIA, from https://www.telecompetitor.com/ctia-5g-will-provide-big-spectral-efficiency-gains/

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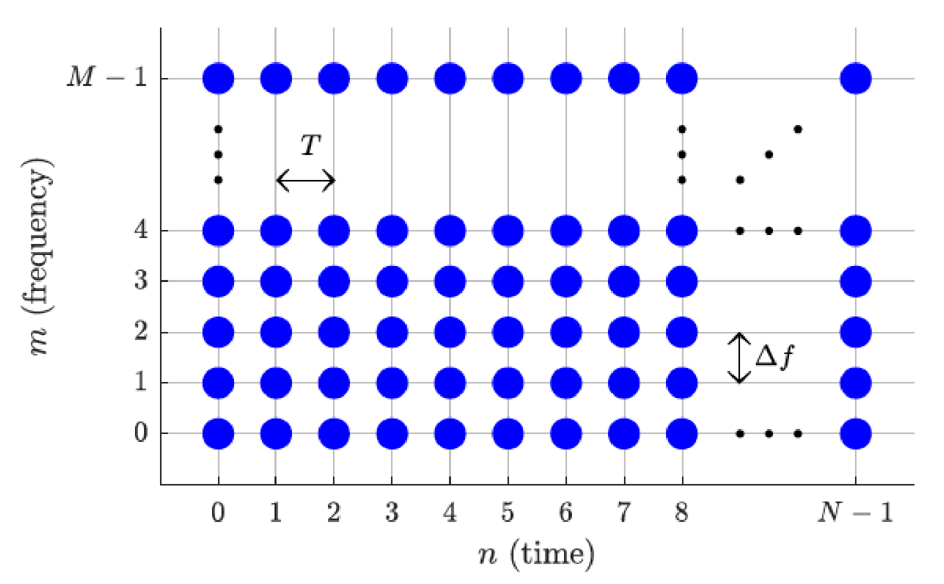
OFDM and OFDMA

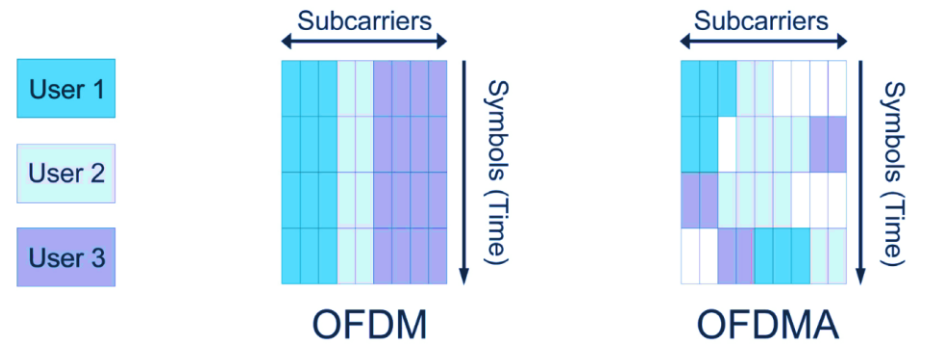
Orthogonal Frequency Division Multiplexing (OFDM)

- Transmission using M subcarriers and N time slots
- Favorable ambiguity function to provide high tolerance against Doppler shift
- No range-Doppler coupling → Independent, unambiguous range and Doppler processing
- Transmit signal is a continuous sequence of OFDM symbols → OFDM radar interpreted as CW



Orthogonal Frequency-Division Multiple Access (OFDMA)

- Differentiates users in both time and frequency
- Stable performance in multipath fading and relative simple synchronization
- High dynamic range and efficient receiver processing based on FFT



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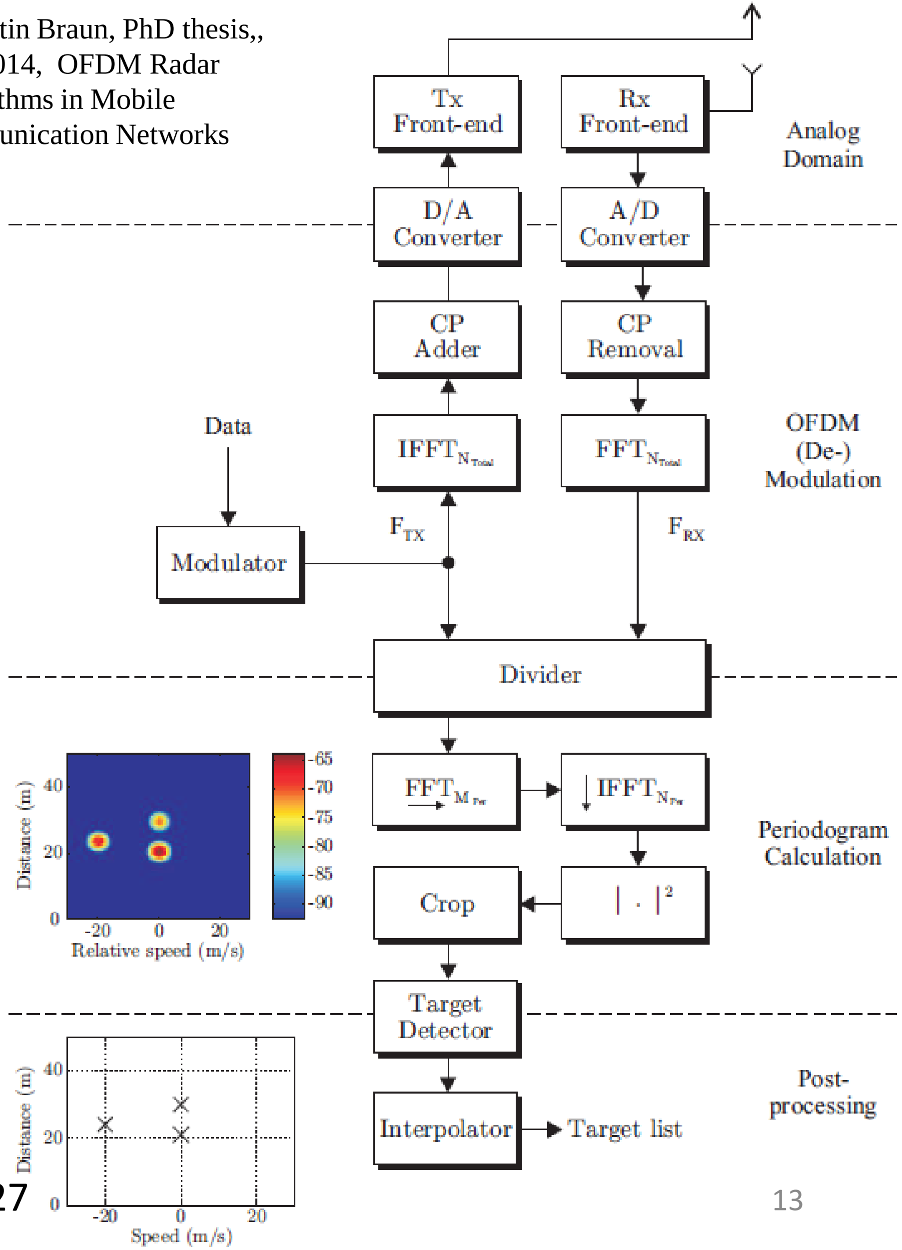
OFDM

EuMA
European Microwave Association

- N subcarriers in a bandwidth B with spacing $\Delta f = \frac{B}{N}$
- M OFDM symbols in a CPI
- Duration of each symbol T (without guard)
- Orthogonality of sub-carriers $\Delta f = \frac{k}{T} = \frac{B}{N}, k \in Z^{+}$
- Classical operations regarding CP, IFFT, FFT,
- Waveform : 2D, $N \times M$

$$\boldsymbol{F_{tx}} = \begin{pmatrix} \boldsymbol{a_{0,0}} & \boldsymbol{a_{1,0}} & \cdots & \boldsymbol{a_{M-1,0}} \\ \boldsymbol{a_{1,0}} & & \ddots & \vdots \\ \vdots & & & \\ \boldsymbol{a_{N-1,0}} & \boldsymbol{a_{N-1,1}} & \cdots & \boldsymbol{a_{N-1,M-1}} \end{pmatrix}$$

- Columns correspond to fast time (Range), Rows correspond to slot time (Doppler)



OFDM

- Received Signal on n^{th} subcarrier and m^{th} OFDM subcarrier

$$(\mathbf{F}_{rx})_{m,n} = b(\mathbf{F}_{tx})_{m,n}\, e^{j2\pi f_D T_0 m}\, e^{-j2\pi(n\Delta f)\tau}\, e^{-j2\pi f_c \tau} e^{j\tilde{\varphi}}$$

- $b, \tilde{\varphi}$: Equivalent gain and phase, f_D:Doppler, τ : Delay,
- $T_0 = T + T_G$: total OFDM symbol duration, T_G: Guard time
- Received signal after Tx constellation compensation

$$(\boldsymbol{F})_{m,n} = \frac{(\mathbf{F}_{rx})_{m,n}}{(\mathbf{F}_{tx})_{m,n}} = b e^{j2\pi f_D T_0 m}\, e^{-j2\pi(n\Delta f)\tau}\, e^{-j2\pi f_c \tau} e^{j\tilde{\varphi}}$$

- Doppler and Range on different dimensions
- 2D Processing (FFT/ Periodogram) to obtain

© Johannes Fink, Freidrich Jondral, "Comparison of OFDM Radar and Chirp Sequence Radar", https://www.cel.kit.edu/download/irs_2015_final_b.pdf

OFDM

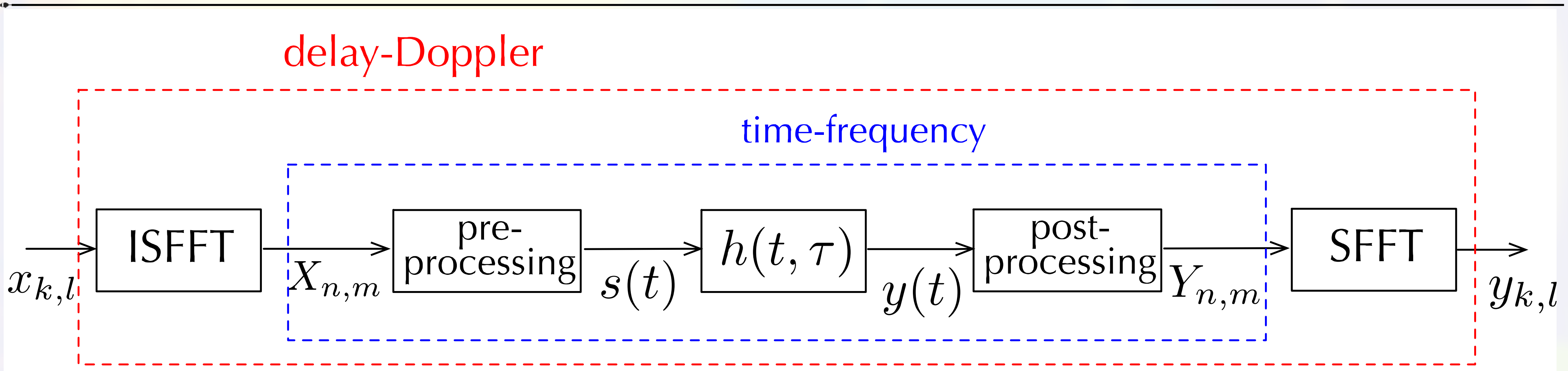
	Requirement
Range Resolution	ΔR
Doppler Resolution	Δv

	Requirement
Unambiguous Range	R_{max}
Unambiguous Doppler	v_{max}

Quantity	Constraint	Remark
Bandwidth	$B = N\Delta f > \frac{c}{2\Delta R}$	Range resolution is inversely proportional to total bandwidth
Subcarriers	$N \geq \frac{R_{max}}{\Delta R}, \quad N \ll \frac{cB}{2v_{max}f_c}$	Due to periodicity of the exponentials Avoid intercarrier interference/ loss of orthogonality
Guard Interval	$T_G \geq \frac{2R_{max}}{c}$	Avoids inter-symbol interference
OFDM Symbol Duration	$T_0 \leq \frac{c}{2v_{max}\, f_c}$	Using $\lvert f_D T_0 \rvert < \frac{1}{2}$
Number of OFDM Symbols	$M \geq \frac{c}{2M\Delta v\, f_c}$ $M < \frac{\Delta R}{2T_0 v_{max}}$	Velocity resolution is inversely proportional to the total CPI Range Migration

Johannes Fink, Freidrich Jondral, “Comparison of OFDM Radar and Chirp Sequence Radar”, https://www.cel.kit.edu/download/irs_2015_final_b.pdf
Martin Braun, PhD thesis,, KIT 2014, OFDM Radar Algorithms in Mobile Communication Networks

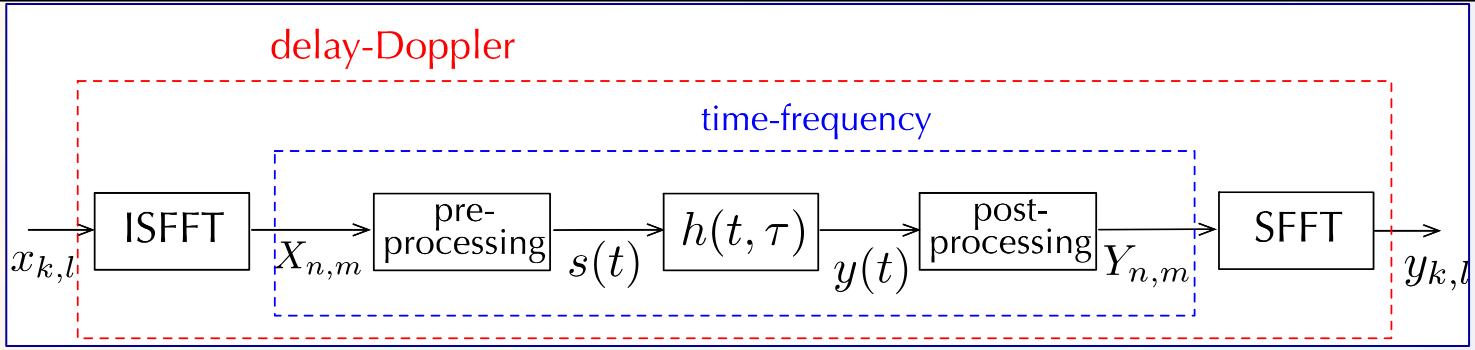
OFDM and OTFS



- Orthogonal time-frequency space (OFTS) modulation is patented by Cohere
- Employs the inverse symplectic fast Fourier transform (SFFT) and its inverse (ISFFT) to switch between Zak and time-frequency domain
- delay-Doppler to time-frequency domain : $$X[n,m] = \frac{1}{\sqrt{NM}} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} x_{k,l} e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)}$$
- Cyclic prefix OFDM uses Inverse DFT/DFT in TF domain

- R. Hadani et al., "Orthogonal time frequency space modulation," *IEEE Wireless Communications and Networking Conference* (WCNC), 2017
- H. Bolcskei and F. Hlawatsch, "Discrete zak transforms, polyphase transforms, and applications," *IEEE Transactions on Signal Processing*, vol. 45, no. 4, 1997
- Yi Hong, E Viterbo, P Raviteja, OTFS and its Applications, Tutorial in SPCOM2020, IISc, Bangalore. July 2020 → Source of the picture

OTFS Processing



- Pre-processing:

$$s(t) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} X[n,m]\, g_{\text{tx}}(t-nT)\, e^{j2\pi m\Delta f(t-nT)}$$

- Post-processing: matched filter and sampling at t = nT, f = mΔf.

$$Y(t,f) = C_{r,g_{\text{rx}}}(t,f) = \int y(t')\, g^{*}_{\text{rx}}(t'-t)\, e^{-j2\pi f t'} dt'$$

- After SFFT, the output of dimension NM in delay-Doppler domain (for every Tx-Rx pair)

$$\mathbf{y} = \sum_{p=0}^{P-1} h'_p \boldsymbol{\Psi}^p(\tau_p,\nu_p)\mathbf{x} + \boldsymbol{w}$$

- ML Estimation → Complicated Receiver

- R. Hadani et al., "Orthogonal time frequency space modulation," *IEEE Wireless Communications and Networking Conference* (WCNC), 2017
- H. Bolcskei and F. Hlawatsch, "Discrete zak transforms, polyphase transforms, and applications," *IEEE Transactions on Signal Processing*, vol. 45, no. 4, 1997
- Yi Hong, E Viterbo, P Raviteja, OTFS and its Applications, Tutorial in SPCOM2020, IISc, Bangalore. July 2020 → Source of the picture

Ambiguity Functions

Ambiguity function contains information on:

- range resolution
- range sidelobe level
- range ambiguity spacing
- Doppler resolution
- Doppler sidelobe level
- Doppler ambiguity spacing

Ideal ambiguity function : thumbtack –

- i.e. an infinitely-narrow spike at the origin
- infinitely-high resolution in range and Doppler
- no sidelobes, and no ambiguities.

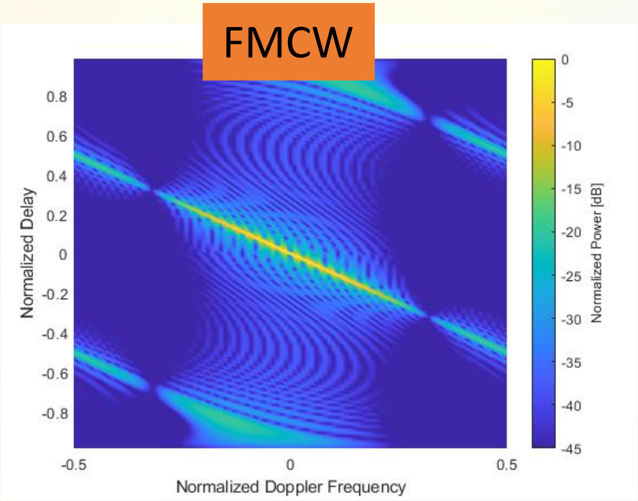
- $s(t)$: **Transmitted Waveform**
- $r(t)$: **Received Waveform**
  - $r(t) = s(t)e^{j2\pi f_D t}$
- **Receiver filter :** $h(t) = s^*(-t)$
- **Output of the receiver filter at time**

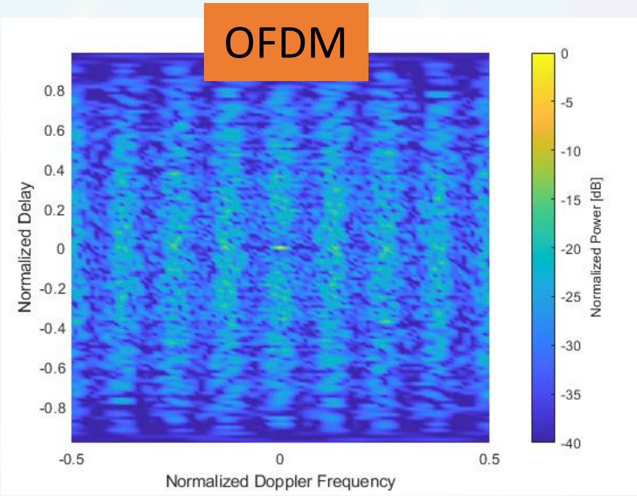
  $$\chi(\tau, f_D) = \int r(t)h^*(\tau - t)\, dt$$

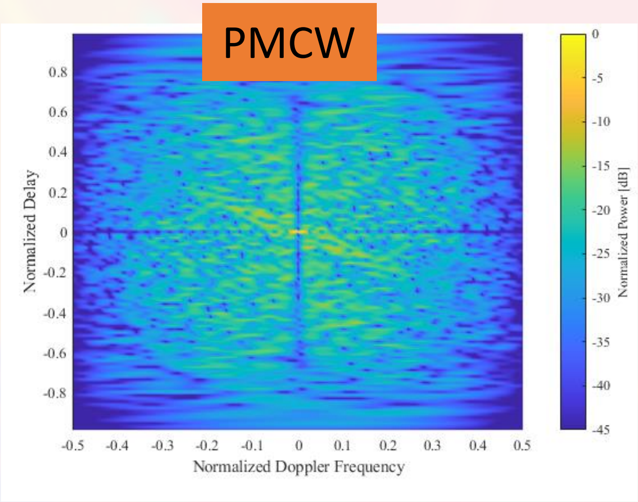
- $\chi(\tau, f_D) = \int s(t)s^*(t-\tau)e^{j2\pi f_D t} dt$

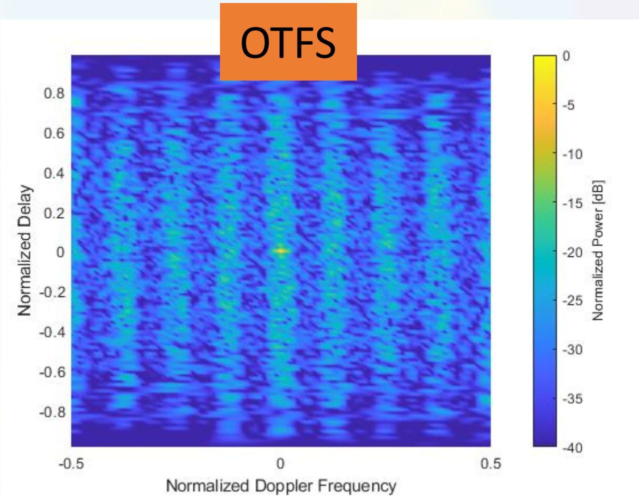
  Ambiguity Function

Which Waveform?



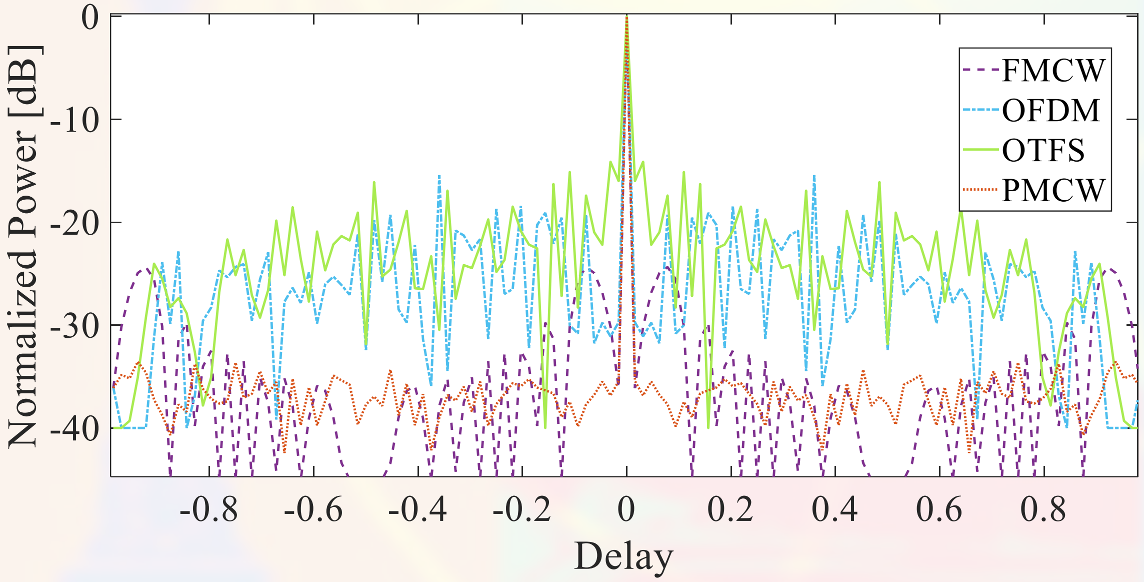




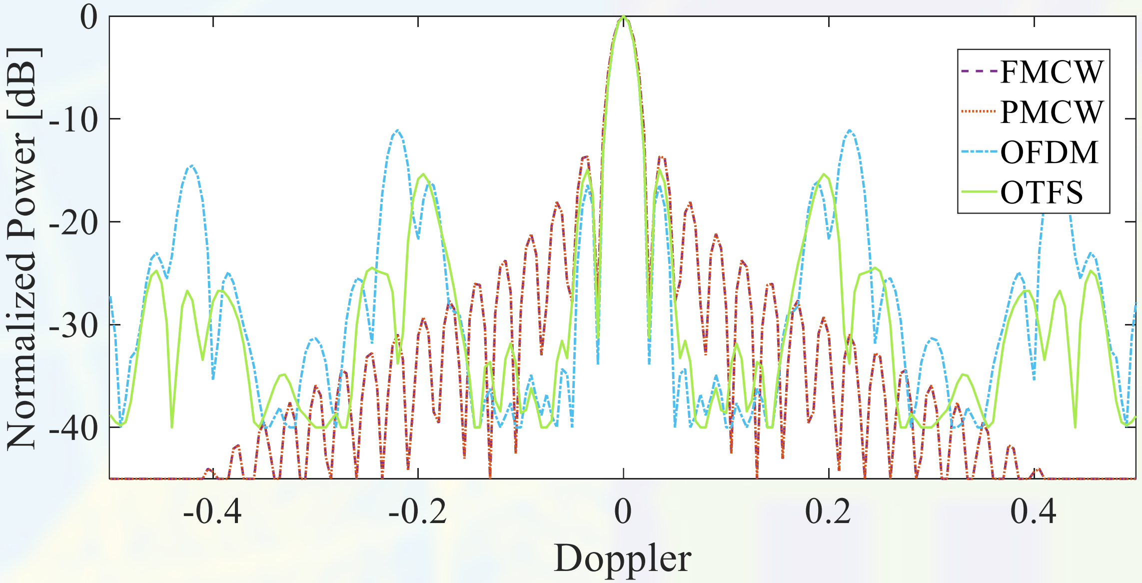


From: OTFS for Automotive Radars: Waveform Optimization and Ambiguity Function Analysis Nazila Karimian-Sichani, Mohammad Alaee-Kerahroodi, Maria S. Greco, Fulvio Gini, Bhavani Shankar M. R.

Which Waveform?



Zero Doppler Cut of Ambiguity Functions

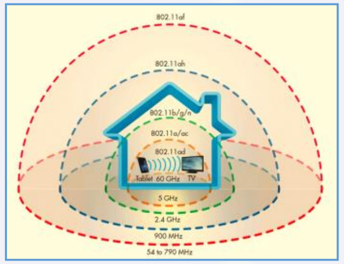


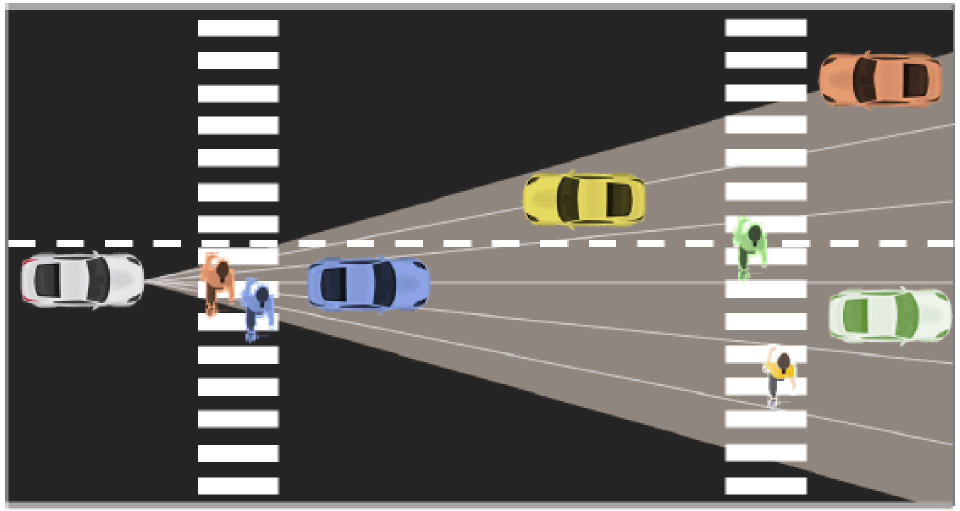
Zero-Delay Cut of Ambiguity Functions

From: OTFS for Automotive Radars: Waveform Optimization and Ambiguity Function Analysis
Nazila Karimian-Sichani, Mohammad Alaee-Kerahroodi, Maria S. Greco, Fulvio Gini, Bhavani Shankar M. R.

802-11ad-Based Joint Radar-Comms

- IEEE 802.11ad Wi-Fi standard enables high-throughput (7 Gbps) at 60 GHz
  - Very high rate (~GHz) ADCs → More power, space and cost
  - Can be exploited for a concurrent radar application
- Applications: parking assistance, lane change assistance, object detection





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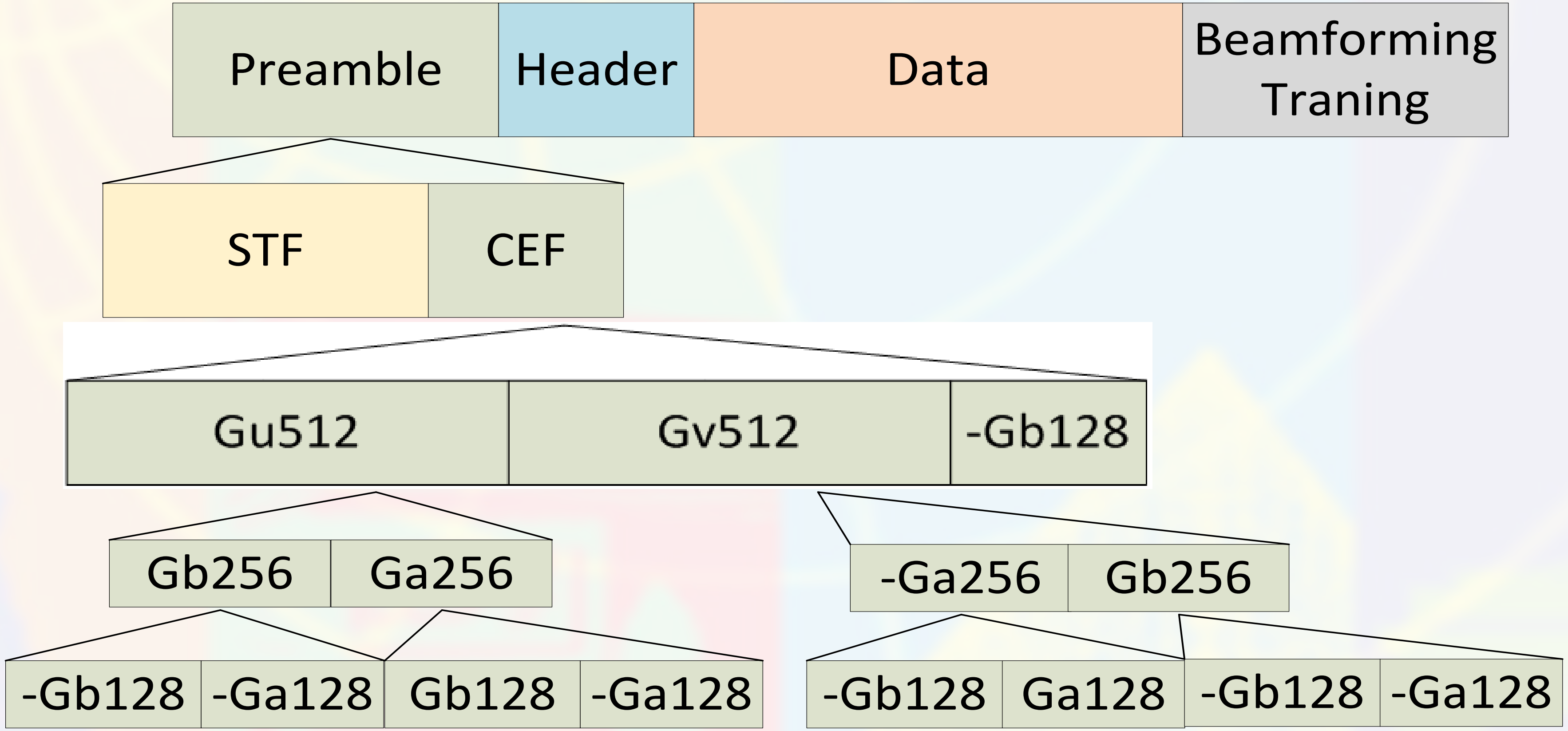
Parameters	Current literature	Proposed radar
Range	Long range (200m)	Short range (40m)
Target model	Simple point targets	Extended targets
Type of target	Static targets	Dynamic targets
Golay sequence	Standard	Modified / Doppler resilient

IEEE 802.11ad Frame Structure

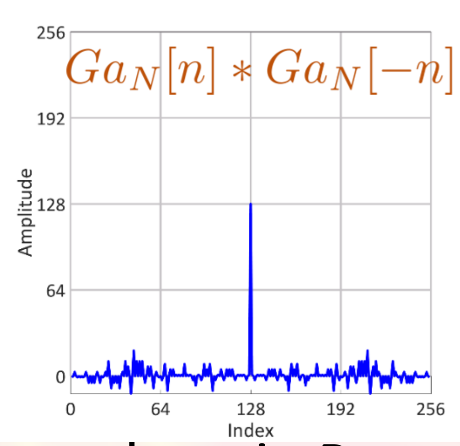
- **S**ingle **C**arrier **PHY**sical layer (SCPHY) encapsulates Golay sequences



- 802.11ad Golay sequences: Two 256-length or four 128-length pairs

Golay Complementary Sequences (Golay Pairs)

- Time-domain Property: Zero sidelobes



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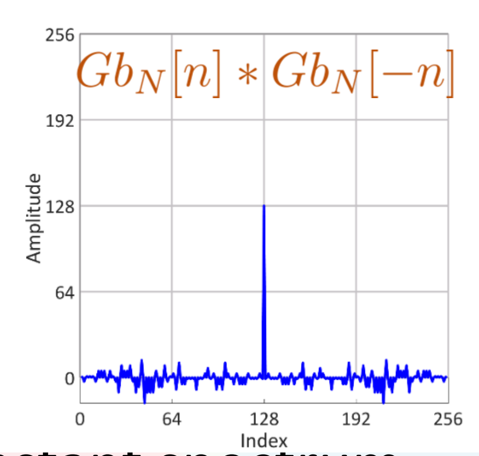

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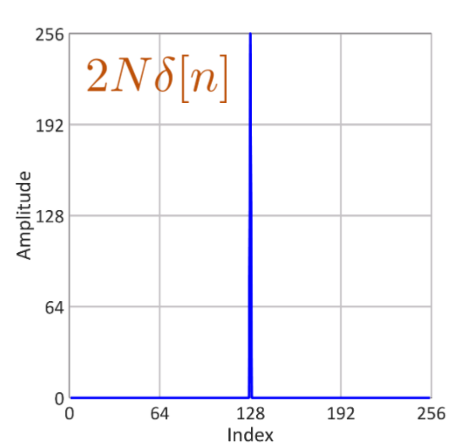
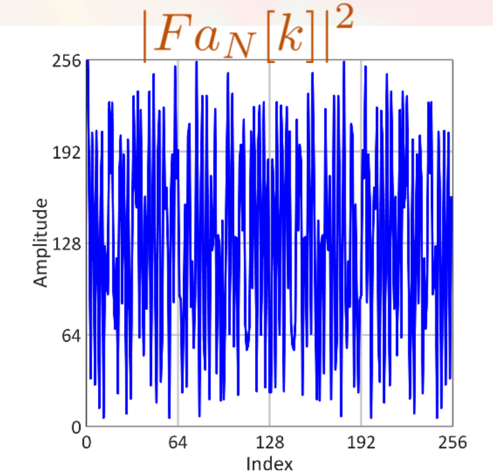


- Frequency-domain Property: Constant spectrum



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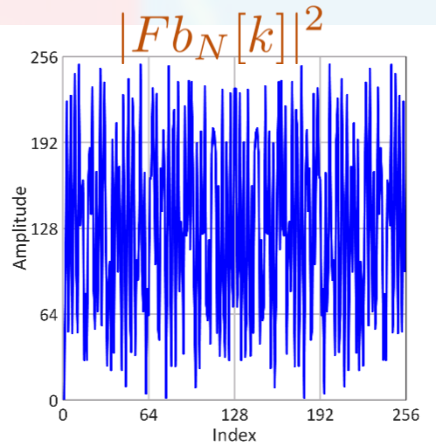

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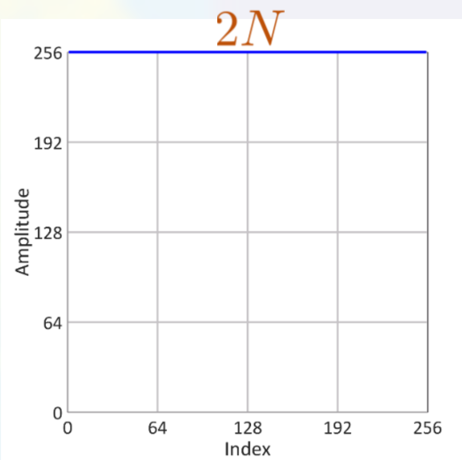


Good Autocorrelation, but Doppler Resilience?

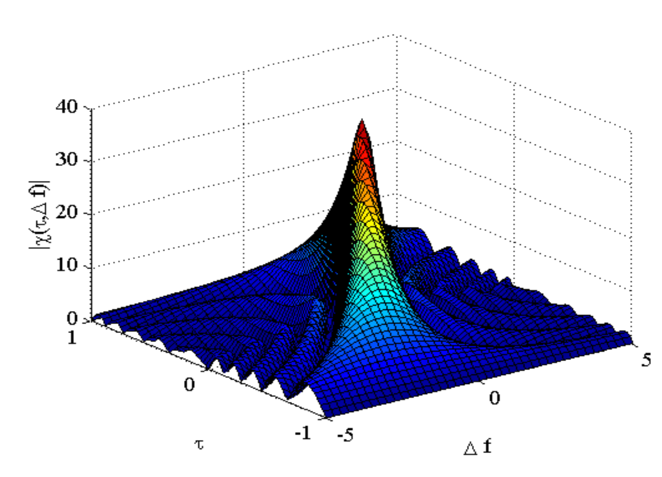
Good Autocorrelation → Low Range Sidelobes → Enhanced Static Target Discrimination → Golay sequences attractive → 802.11ad good for ISAC?

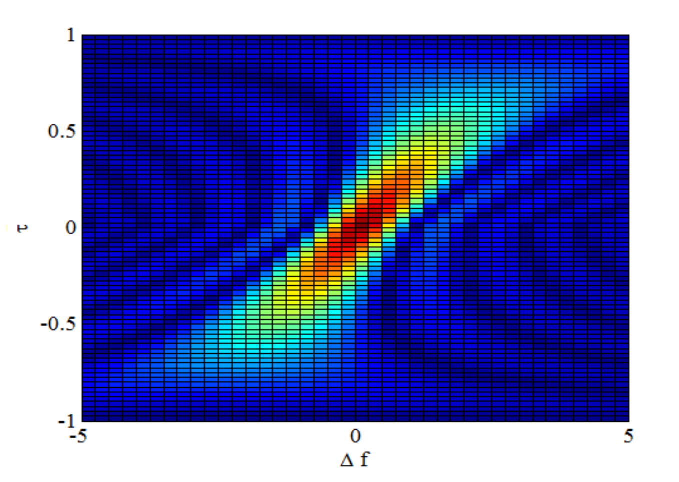
Dynamic Scenarios

Doppler, Delay

Good ACF in both domains

Ambiguity Function : $AF(t,\omega) = \int x(\tau)x^*(\tau - t)e^{j\omega\tau}d\tau$





Doppler-Resilient FMCW Waveform

Is 802.11ad Preamble Doppler-Resilient ?

$$G_{a,N}[n] * G_{a,N}[-n] + G_{b,N}[n] * G_{b,N}[-n] = 2N\delta[n].$$

$$(G_{a,N}[n] * G_{a,N}[-n]) + (G_{b,N}[n] * G_{b,N}[-n])\, e^{-j\theta} \neq 2N\delta[n]$$

Modification to 802.11ad

RQ1 Doppler Resilient Preamble

RQ2 Identical field width

RQ3 Receiver operation unchanged

Prouhet-Thue-Morse (PTM) Sequence

$$q_p = \begin{cases} 0, & \text{if } p = 0 \\ q_{\frac{p}{2}}, & \text{if } (p \text{ modulo } 2) = 0 \\ \overline{q_{\frac{p-1}{2}}}, & \text{if } (p \text{ modulo } 2) = 1, \end{cases}$$

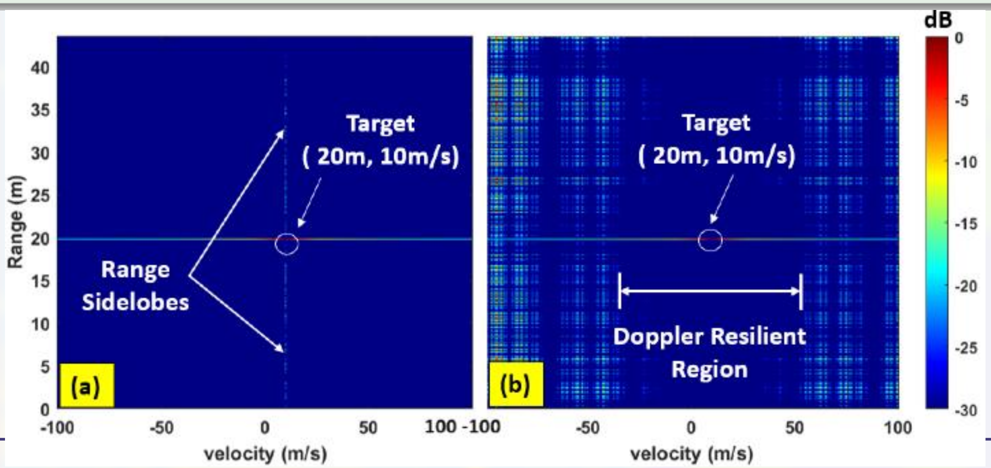
Modified Golay sequence

$$\text{if } q_p = 0, \{G_{a,N}[n], G_{b,N}[n]\}$$
$$\text{if } q_p = 1, \{-G_{b,N}[-n], G_{a,N}[-n]\}$$

Example

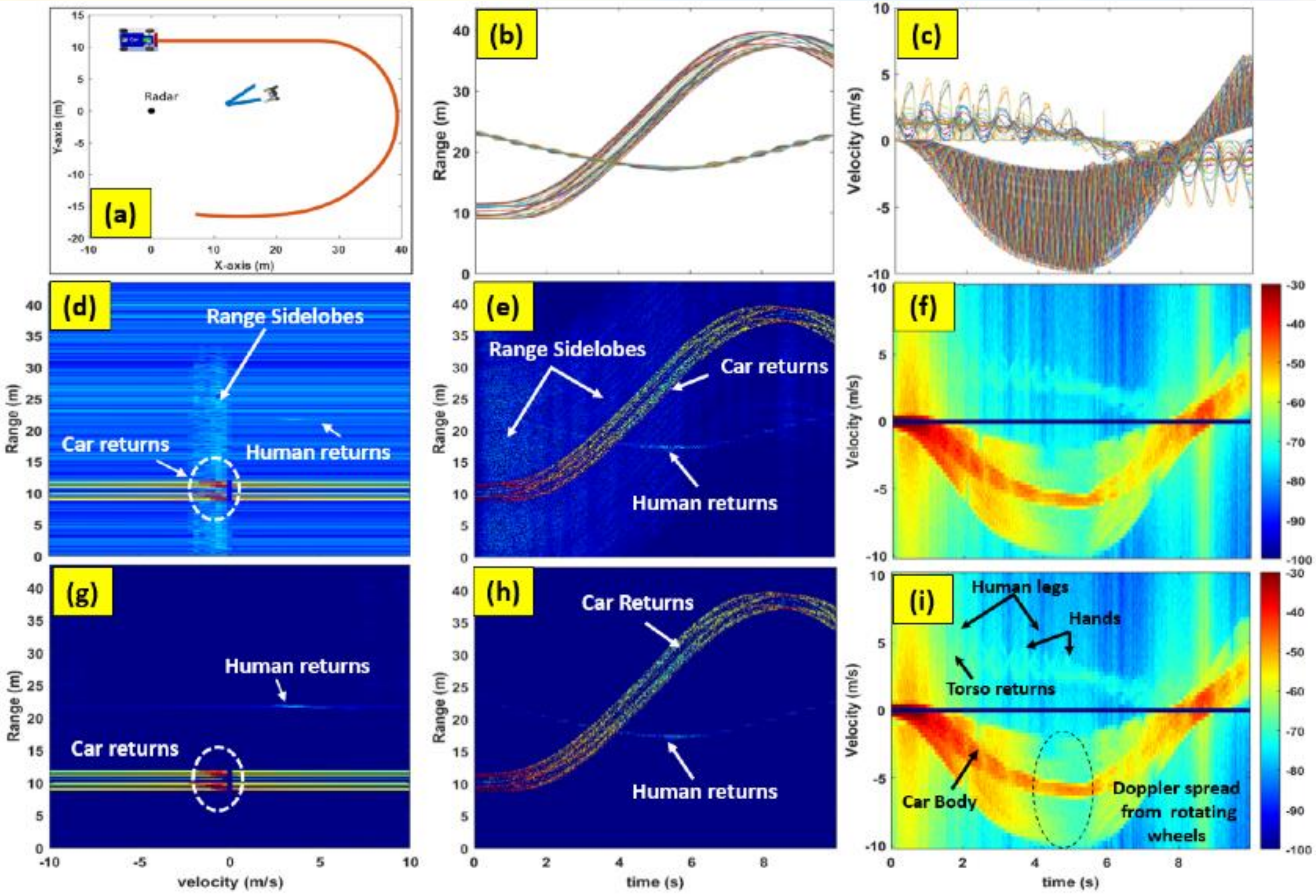
PTM Sequence: [01] : $G_{a,N}[n], G_{b,N}[n], -G_{b,N}[-n], G_{a,N}[-n]$:

$$\sum_{p=0}^{3} e^{-jp\theta}(G_{p,N}[n] * G_{p,N}[-n]) \approx 1((G_{1,N}[n] * G_{1,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$+2((G_{2,N}[n] * G_{2,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$= (2N + 2(2N))\delta[n] = 6N\delta[n].$$



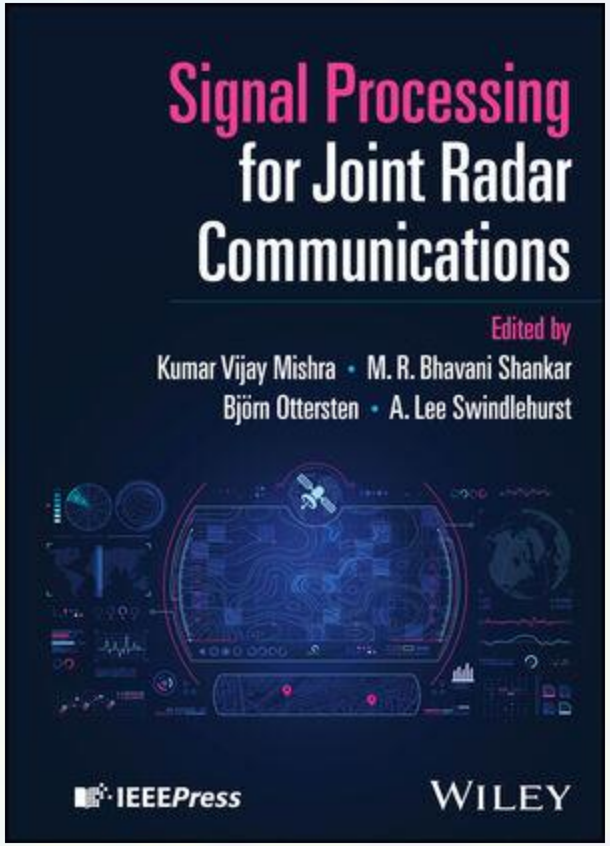
A. Pezeshki, A. R. Calderbank, W. Moran, and S. D. Howard, “Doppler resilient Golay complementary waveforms,” IEEE Transactions on Information Theory, 54(9), 4254-4266, 2008.

Extended Target Modeling Results – Multiple Targets



Summary

- ❑ Communication Waveforms suffer from certain disadvantages
- ❑ Can be useful when the scene is sparse and used in opportunistic way
- ❑ Minor modifications to standards can be considered to help sensing



Signal Processing for Joint Radar Communications
Bjorn Ottersten (Editor), M. R. Bhavani Shankar (Editor), A. Lee Swindlehurst (Editor), Kumar Vijay Mishra (Editor)
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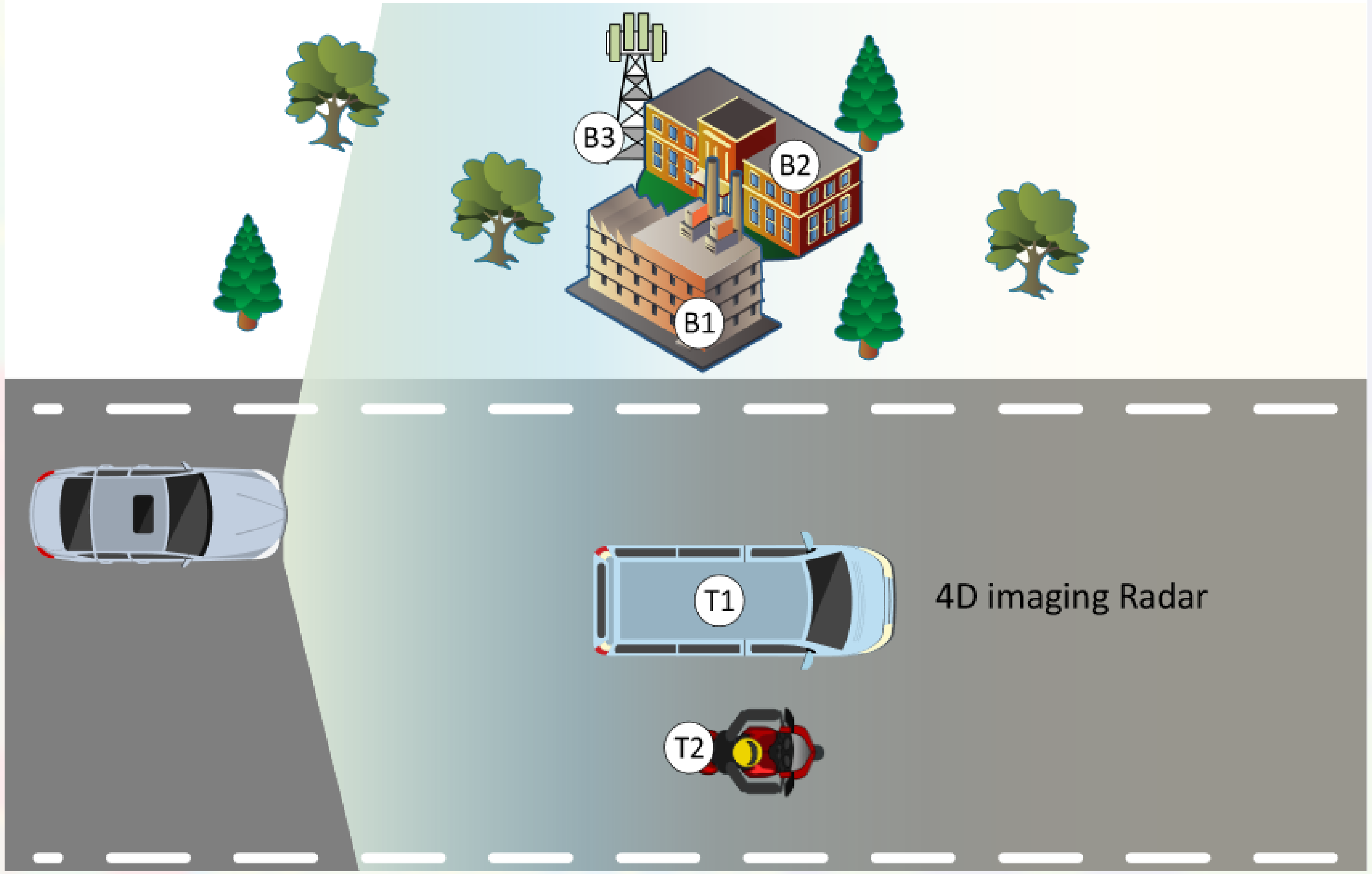
Colocated Systems : Radar waveform

- **Goal**
  - Beampattern nulling and target discrimination simultaneously.
- **Scenario**
  - Two targets with the same velocities and different angles.
  - Three strong clutters with different angles.
  - The targets and clutters have the same range.
  - Can not be separated by range-Doppler processing.



Radar Waveform Design

- **Spatial and Range Integrated Side Lobe Ratio (ISLR)**

$$\bar{f}(\boldsymbol{S}) \triangleq \frac{\frac{1}{M_u}\sum_{r=1}^{M_u} P(\boldsymbol{S},\theta_{u,r})}{\frac{1}{M_d}\sum_{r=1}^{M_d} P(\boldsymbol{S},\theta_{d,r})} = \frac{\sum_{n=1}^{N} \bar{\boldsymbol{s}}_n^H \boldsymbol{A}_u \bar{\boldsymbol{s}}_n}{\sum_{n=1}^{N} \bar{\boldsymbol{s}}_n^H \boldsymbol{A}_d \bar{\boldsymbol{s}}_n}$$

$$\tilde{f}(\boldsymbol{S}) = \frac{\sum_{m,l=1}^{M_t}\sum_{k=-N+1}^{N-1} \|\tilde{\boldsymbol{s}}_m^H \boldsymbol{J}_k \tilde{\boldsymbol{s}}_l\|_2^2 - \sum_{m=1}^{M_t} \|\tilde{\boldsymbol{s}}_m^H \tilde{\boldsymbol{s}}_m\|_2^2}{\sum_{m=1}^{M_t} \|\tilde{\boldsymbol{s}}_m^H \tilde{\boldsymbol{s}}_m\|_2^2}$$

- **Optimization problem**

$$\begin{cases} \min\limits_{\boldsymbol{S}} & \bar{f}(\boldsymbol{S}), \tilde{f}(\boldsymbol{S}) \\ s.t & C \end{cases}$$

$C_1: 0 < \|\boldsymbol{S}\|_F^2 \leqslant M_t N$ ← Power constraint

$C_2: 0 < \|\boldsymbol{S}\|_F^2 \leqslant M_t N, \ \dfrac{\max |s_{m,n}|^2}{\frac{1}{M_t N}\|\boldsymbol{S}\|_F^2} \leqslant \gamma_p$ ← PAR constraint

$C_3: s_{m,n} = e^{j\phi}; \ \phi \in \Phi_\infty$ ← Continuous phase

$C_4: s_{m,n} = e^{j\phi}; \ \phi \in \Phi_L$ ← Discrete phase

  - Usually a feasible solution that minimizes both the objectives simultaneously does not exist

- **Weighted Sum Method:**

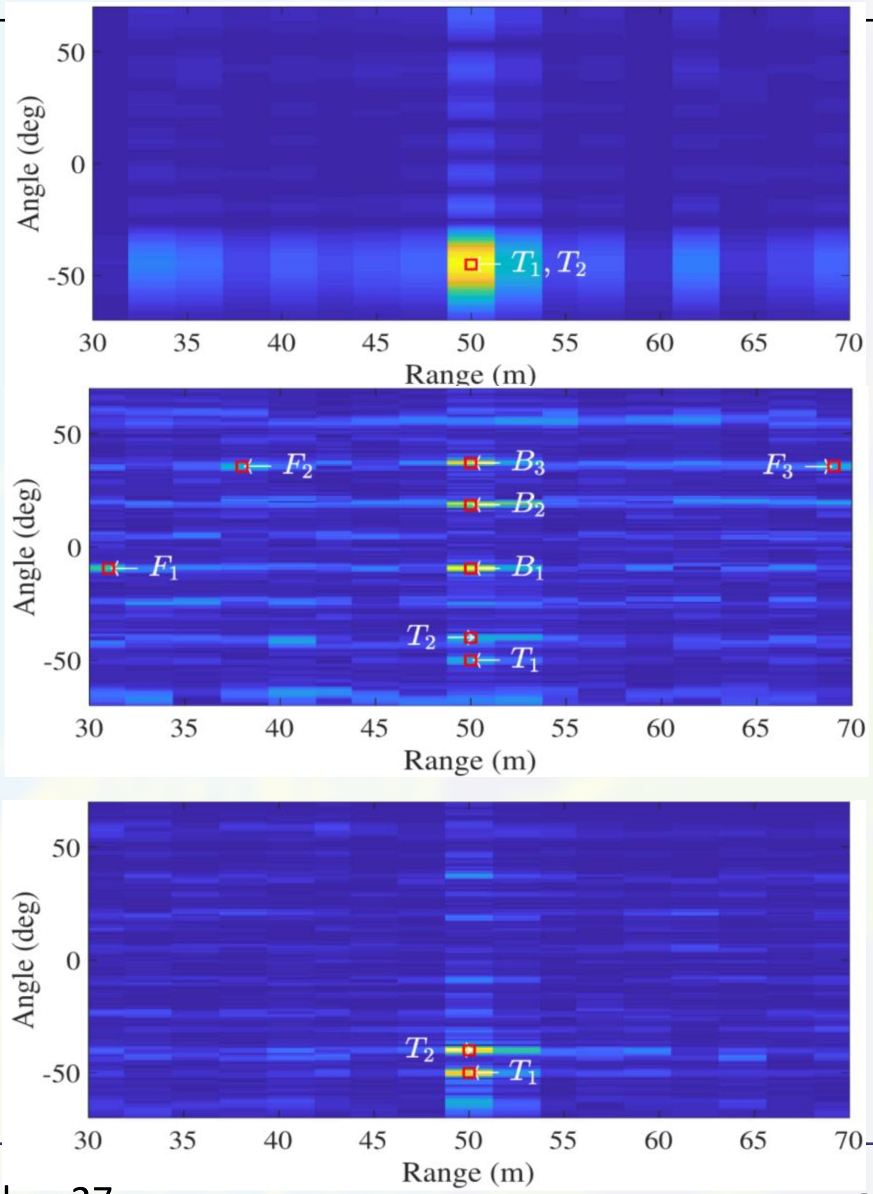
$$\begin{cases} \min\limits_{\boldsymbol{S}} & \bar{f}(\boldsymbol{S}), \tilde{f}(\boldsymbol{S}) \\ s.t & C \end{cases} \longrightarrow \mathcal{P}\begin{cases} \min\limits_{\boldsymbol{S}} & f_o(\boldsymbol{S}) = \eta\bar{f}(\boldsymbol{S}) + (1-\eta)\tilde{f}(\boldsymbol{S}) \\ s.t & C, \end{cases}$$

- **Solved using CD method**

E. Raei, M. Alaee-Kerahroodi and M. R. B. Shankar, "Spatial- and Range- ISLR Trade-Off in MIMO Radar Via Waveform Correlation Optimization," in *IEEE Transactions on Signal Processing*, vol. 69, pp. 3283-3298, 2021

Design Result

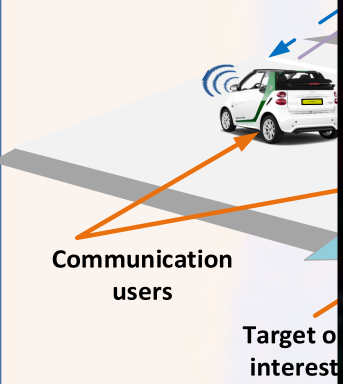
- **Fully correlated waveform ($\eta = 1$):**
  - Phased array processing, The virtual array is not performed.
  - Targets discrimination ✗
  - Clutters mitigation ✓
- **Orthogonal waveform ($\eta = 0$):**
  - MIMO processing, The virtual array is performed.
  - Targets discrimination ✓
  - Clutters mitigation ✗
- **Partially correlated waveform ($\eta = 0.5$):**
  - MIMO processing, The virtual array is performed.
  - Targets discrimination ✓
  - Clutters mitigation ✓

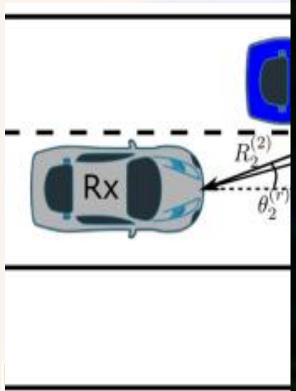


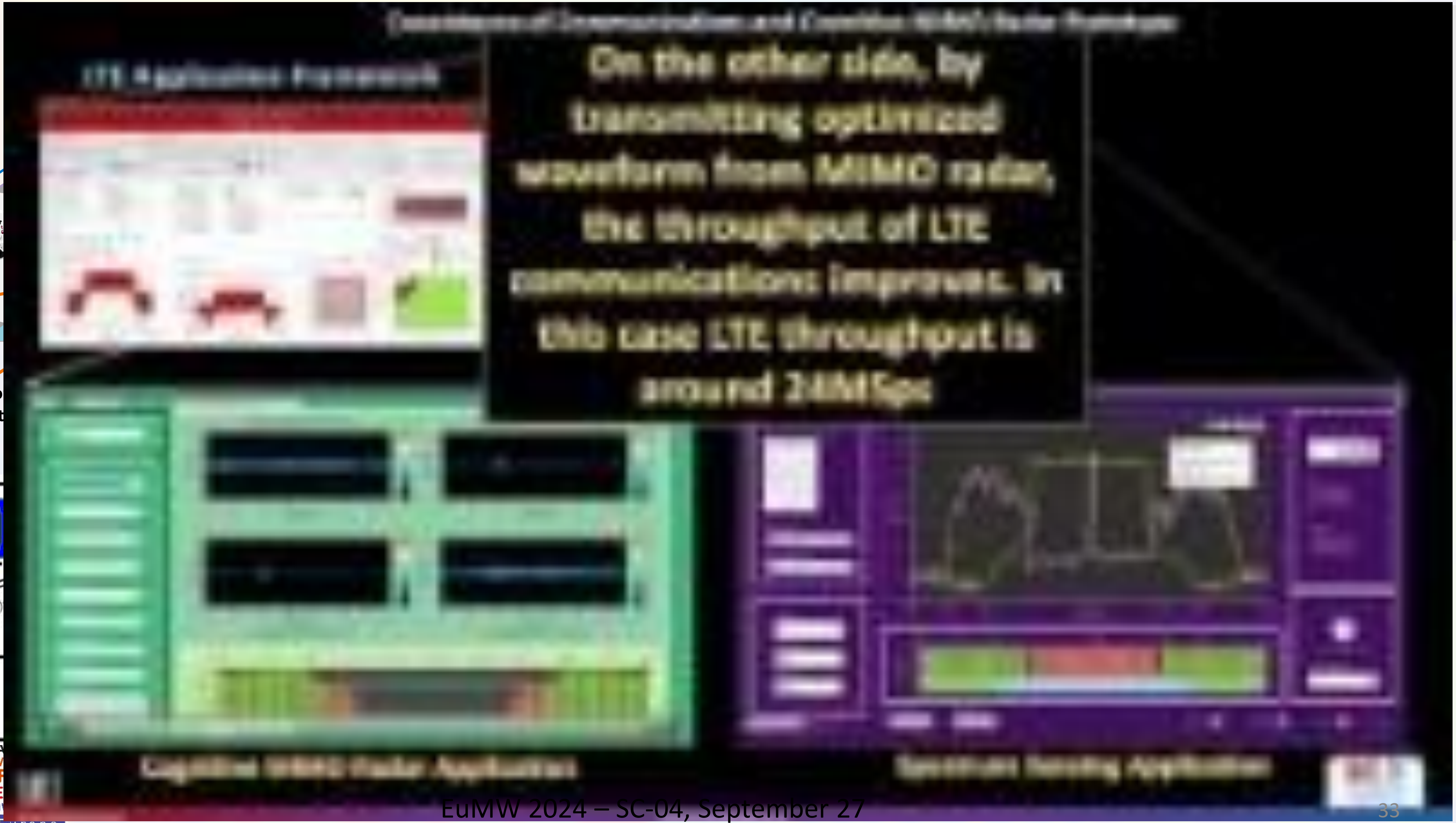
Outline

- ISAC Motivation and Topologies
- Radar Waveforms for Communications
- Communication Waveforms for Sensing
- Co-existence Design Example
- HW Prototype

Hardware Prototype



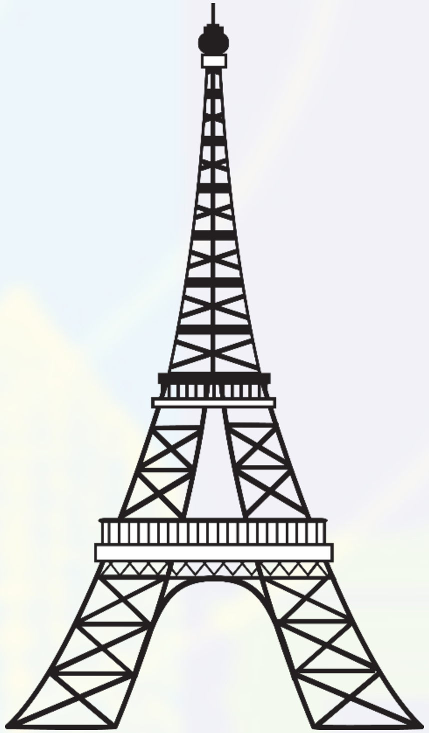




Conclusions

- ISAC offers new avenues for proliferation of sensing without using dedicated radar
- Interesting use cases exist, considered in 6G
- Use case defines ISAC topology and system design (including Waveforms)
- Waveform for ISAC
  - Radar waveforms well suited for radar
  - Comm waveforms well suited for comm
- Way forward
  - Opportunistic sensing with minor modifications
  - Co-existence

Thanks!



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