# Mutual Interference Mitigation in PMCW Automotive Radar


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# Automotive Radars

**Typical Applications:**

- Advanced Driver Assistive Systems
- Autonomous Driving
- Other applications: Drone detection, foliage detection

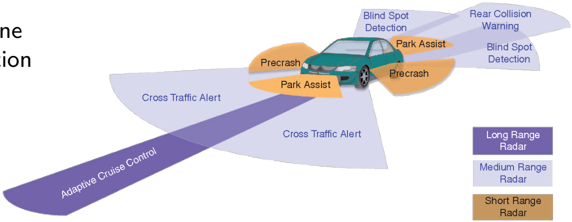


Figure: An ADAS consists of different range radars

Image source: "Automotive radars: A review of signal processing techniques," S. M. Patole, M. Torlak, D. Wang and M. Ali, 2017.

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- Range
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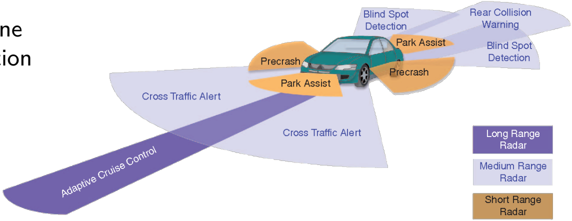
- Direction of Arrival

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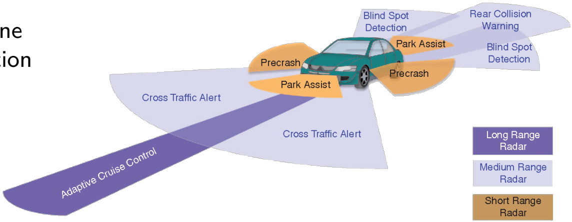
**Radar Type:**

- Frequency Modulation CW
- Phase Modulation CW

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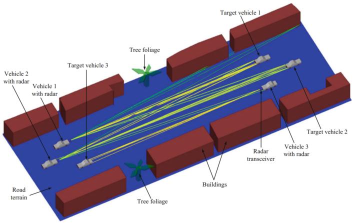


Figure: A typical mutual interference scenario with multiple aggressor radars

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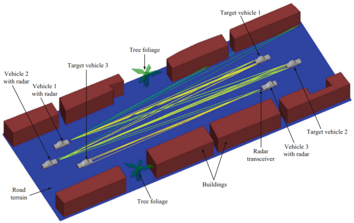


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- Missed detection
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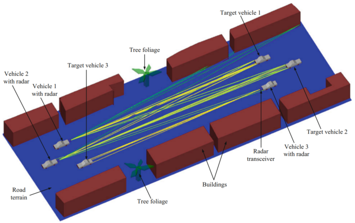


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Degrades radar performance in many ways:

- Missed detection
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There is no silver bullet. Particular situation demands specialized solution.

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# Our Solution

## The Objective

- Target radar domain: identical and synchronized PMCW technology
- Design *mutually cooperative* linear-phase transmit signals to mitigate mutual interference between similar radar systems
- Evaluation of the proposed signals using numerical simulations

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## Comparison with FMCW radars

- In PMCW, orthogonality of transmission does not require TDM, rather CDM
- Different from FMCW, PMCW does not need a linear frequency ramp to determine the time of flight that is instead measured by parallel correlations
- In PMCW radar, interference can be comparatively easily mitigated by designing codes

# PMCW Radar Overview

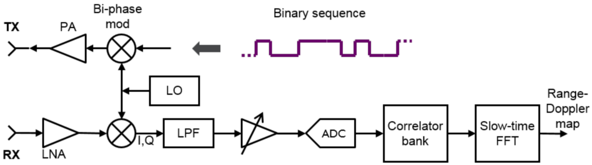


Figure: PMCW Radar Block Diagram[1]

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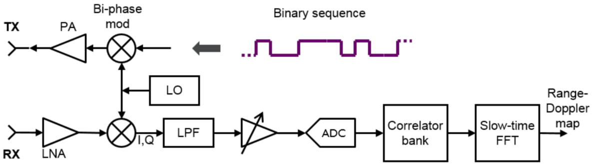


Figure: PMCW Radar Block Diagram[1]

- More suitable for high-resolution but short and medium-range applications
- Bi-phase modulation
- Binary symbols: Barker, Gold, Kasami set, Legendre, Hadamard sequences etc.
- A couple of Bi-Phase SoC chips out there in the market:
  - s80 RoC by Uhnder (77GHz 12Tx/16Rx)
  - RoC by imec (77-79 GHz, 2Tx/2Rx 2x cascade-able)

[1] Image source: "PMCW waveform and MIMO technique for a 79 GHz CMOS automotive radar," A. Bourdoux, U. Ahmad, D. Guermandi, S. Brebels, A. Dewilde and W. Van Thillo, 2016.

# Problem Formulation

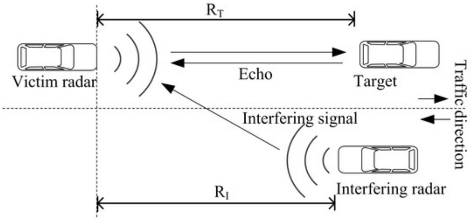


Figure: A simplified radar interference model with two lanes in opposite directions[1]

Two PMCW systems continuously transmit PMCW waves with duration $T$

$$s_{Tx,l}(t) = \phi_l(t)\text{exp}\left(\text{j}\left(2\pi f_c t + \psi\right)\right), \qquad 0 \leq t \leq T, \qquad l \in \{1, 2\}$$

The baseband signal:

$$\phi(t) = \sum_{k=0}^{K-1} x_k \text{rect}\left(\frac{t - kT_c}{T_c}\right), \qquad x_k = e^{\text{j}\varphi(k)}, \qquad \varphi(k) \in (0, \pi]$$

[1] Image source: "Interference Mitigation in Automotive Radars Using Pseudo-Random Cyclic Orthogonal Sequences, " S. Skaria, A. Al-Hourani, R. J. Evans, K. Sithamparanathan, U. Parampalli, 2019.

# Problem Formulation (contd.)

## Transmit Signal

For one CPI with N bursts

$$S_{Tx,l}(t) = \frac{1}{N}\sum_{n=0}^{N-1} s(t-nT)$$
$$= \frac{1}{N}\sum_{n=0}^{N-1}\sum_{k=0}^{K-1} x_k e^{\mathrm{j}2\pi f_c t}\mathrm{rect}\left(\frac{t-kT_c-nT}{T_c}\right)$$

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## Received Signal

For a signal point scatterer, the returned signal without the presence of an interferer:

$$S_{Rx}(t) = \alpha_T S_{Tx}(t-\tau_T(t))$$

$$\approx \frac{\alpha_T}{N} e^{\mathrm{j}2\pi f_c t} e^{-\mathrm{j}2\pi f_c \gamma_T} e^{\mathrm{j}2\pi f_c \frac{2v}{c} t} \times \sum_{n=0}^{N-1}\sum_{k=0}^{K-1} x_k \mathrm{rect}\left(\frac{t-\gamma_T-kT_c-nT}{T_c}\right)$$

$$\hat{S}_{Rx}(t) = \frac{\alpha_T}{N} e^{\mathrm{j}2\pi f_{d,T} t}\sum_{n=0}^{N-1}\sum_{k=0}^{K-1} x_k \mathrm{rect}\left(\frac{t-\gamma_T-kT_c-nT}{T_c}\right)$$

# Mutual Interference Model

Final downconverted discretized received signal from $V_T$ targets and $V_I$ interferes after coherent processing:

$$r[m,n] = \underbrace{r_T[m,n]}_{\text{target}} + \underbrace{r_I[m,n]}_{\text{interference}} + w[m,n]$$

$$= \sum_{v=0}^{V_T-1} \sum_{k=0}^{K-1} \alpha_{v,T} x_k^* x_{k-\hat{n}_T+m} e^{j2\pi f_{v,d,T}((m+k)T_c+nT)}$$

$$+ \sum_{v=0}^{V_I-1} \sum_{k=0}^{K-1} \alpha_{v,I} x_k^* y_{k-\hat{n}_I+m} e^{j2\pi f_{v,d,I}((m+k)T_c+nT)} + w[m,n]$$

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After range-Doppler processing (2D FFT):

$$\mathrm{RD}[m,p] = \sum_{v=0}^{V_T-1} \alpha_{v,T} D_N\left(\tilde{f}_{v,d,T} - p/N\right) \sum_{k=0}^{K-1} x_k^* x_{k-\hat{n}_T+m} e^{j2\pi f_{v,d,T}(m+k)T_c}$$

$$+ \sum_{v=0}^{V_I-1} \alpha_{v,I} D_N\left(\tilde{f}_{v,d,I} - p/N\right) \sum_{k=0}^{K-1} x_k^* y_{k-\hat{n}_I+m} e^{j2\pi f_{v,d,I}(m+k)T_c} + W[m,p]$$

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The cross-correlation between the two codes: $r_{xy}^l(f) = \sum_{k=0}^{K-1} x_k^* y_{(k+l) \bmod K} e^{j2\pi k f}$

# The Optimization Problem

$$\mathcal{P} : \underset{\mathbf{x},\mathbf{y}}{\text{minimize}} \sum_{l=-(L)}^{L} \sum_{p=-P}^{P} \left|r_{xy}^{l}(f_p)\right|^2$$
$$\text{subject to} \quad |x_k| = 1 \,, |y_k| = 1 \,, \forall\, k \in \{0, \cdots, K-1\}.$$

where,

$$r_{xy}^{l}(f_p) = \mathbf{x}^{\mathrm{H}} \mathrm{Diag}(\mathbf{f}_p) \mathbf{C}_l \mathbf{y}$$
$$\mathbf{x} = [x_0, \ldots, x_{K-1}]^{\top}$$
$$\mathbf{y} = [y_0, \ldots, y_{K-1}]^{\top}$$
$$\mathbf{f}_p = [1, e^{\mathrm{j}2\pi f_p}, \ldots, e^{\mathrm{j}2\pi(K-1) f_p}]^{\top}$$
$$\mathbf{C}_l = \mathbf{C}_{-l}^{H} = \begin{bmatrix} \mathbf{0} & \mathbf{I}_{K-l} \\ \mathbf{I}_l & \mathbf{0} \end{bmatrix}$$

# Cyclic Algorithm

- Optimization *w.r.t.* $\mathbf{x}$

$$\mathcal{P}_{\mathbf{x}} : \underset{\mathbf{x}}{\text{maximize}} \quad \mathbf{x}^{\mathrm{H}} \widetilde{\mathbf{B}}_y \mathbf{x}$$

$$\text{subject to} \quad |x_k| = 1 \,, \forall\, k,$$

$$\widetilde{\mathbf{B}}_y = \lambda_{m,y} \mathbf{I} - \mathbf{B}_y$$

$$\mathbf{B}_y = \sum_{l=-(L)}^{L} \sum_{p=-P}^{P} \mathrm{Diag}(\mathbf{f}_p) \mathbf{C}_l \mathbf{y}\mathbf{y}^{\mathrm{H}} \mathbf{C}_l \mathrm{Diag}(\mathbf{f}_p)^{\mathrm{H}}$$

$\Rightarrow$

$$\mathbf{x}^{(s+1)} = e^{\mathrm{j} \arg \widetilde{\mathbf{B}}_y \mathbf{x}^{(s)}}$$

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$$\Rightarrow \quad \boxed{\mathbf{y}^{(s+1)} = e^{\text{j} \arg \widetilde{\mathbf{B}}_x \mathbf{y}^{(s)}}}$$

# The Algorithm

**Algorithm** PMCW waveform design for mutual interference mitigation

**Initialize:** $\mathbf{x}^0$, $\mathbf{y}^{(0)}$, $s = 0$.
**Output:** $\mathbf{x}^*$, $\mathbf{y}^*$.

**while** $|(J^{(s+1)} - J^{(s)})/J^{(s)}| \geq \epsilon$ **do**
  Update $\widetilde{\mathbf{B}}_y^{(s)}$, $t \leftarrow 0$
  **repeat** $t \leftarrow t + 1$
    $\mathbf{x}^{(s,t)} = e^{\mathrm{j} \arg \widetilde{\mathbf{B}}_y^{(s)} \mathbf{x}^{(s,t-1)}}$
  **until** convergence
  $\mathbf{x}^{(s)} \leftarrow \mathbf{x}^{(s,t)}$
  Update $\widetilde{\mathbf{B}}_x^{(s)}$, $t \leftarrow 0$
  **repeat** $t \leftarrow t + 1$
    $\mathbf{y}^{(s,t)} = e^{\mathrm{j} \arg \widetilde{\mathbf{B}}_x^{(s)} \mathbf{y}^{(s,t-1)}}$
  **until** convergence
  $\mathbf{y}^{(s)} \leftarrow \mathbf{y}^{(s,t)}$
  $s \leftarrow s + 1$
**end while**
**return** $\mathbf{x}^* = \mathbf{x}^{(s)}$ and $\mathbf{y}^* = \mathbf{y}^{(s)}$.

## Generalization to the MIMO case

$$\min_{\{\mathbf{x}_m\},\{\mathbf{y}_k\}} \sum_{m,k} \sum_{l=-(N-1)}^{N-1} \sum_{p=-P}^{P} \Big\{ |\mathbf{x}_m^H \mathrm{Diag}(\mathbf{f}_p)\mathbf{C}_l \mathbf{y}_k|^2 + |\mathbf{x}_m^H \mathrm{Diag}(\mathbf{f}_p)\mathbf{C}_l \mathbf{x}_m|^2 + |\mathbf{y}_k^H \mathrm{Diag}(\mathbf{f}_p)\mathbf{C}_l \mathbf{y}_k|^2 \Big\}$$

s.t. $\mathbf{x}_m$ and $\mathbf{y}_k$ are unimodular for all $m, k$

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$$\text{s.t.} \quad \mathbf{x}_m \text{ and } \mathbf{y}_k \text{ are unimodular for all } m, k$$

- Can be solved using a similar UQP formulation after separating variables
- However some special attention to be paid on the modified formulation
- Can be accelerated using FFT based operations
- Detailed algorithm: "Waveform Design for Mutual Interference Mitigation in Automotive Radar,", A. Bose et al. https://arxiv.org/pdf/2208.04398.pdf

# Simulation Setup

Table: Parameters of all PMCW radars systems

| **Parameters** | | **Value** |
|---|---|---|
| Carrier Frequency | $f_c$ | 79 GHz |
| Chip Duration | $T_c$ | 6.66 $\mu$ s |
| Pulse Repetition Interval | $T$ | 6.32 ms |
| Number of burst | $N$ | 140 |
| Code length | $K$ | $1024$ |
| MIMO | Tx $\times$ Rx | $8 \times 12$ |

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Table: Parameters of the scene objects

| **Parameters** | | **Int1** | **Int2** | **Tgt1** | **Tgt2** | **Tgt3** |
|---|---|---|---|---|---|---|
| Range (m) | $R$ | 140 | 90 | 20 | 60 | 120 |
| Velocity (m/s) | $v$ | 40 | -32 | -40 | 20 | -10 |
| RCS (dBsm) | $P_T$ | 35 | 15 | 35 | 10 | 5 |

# Numerical Results (contd.)

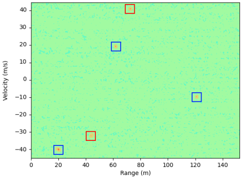



Figure: Range Doppler maps with a random linear-phase PMCW signal

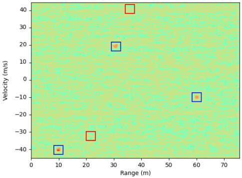



Figure: Range Doppler maps with a bi-phase (Gold code) PMCW signal

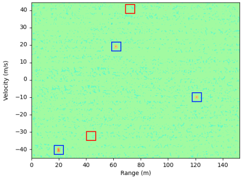
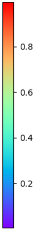



Figure: Range Doppler maps with a multiphase-optimized PMCW signal




☐ Target ☐ Interference

# Numerical Results (contd.)

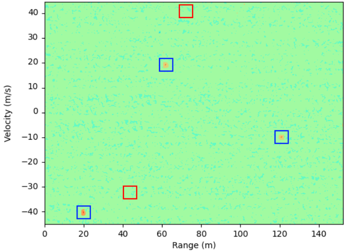



Figure: Range Doppler maps when using two cooperative optimized PMCW signals

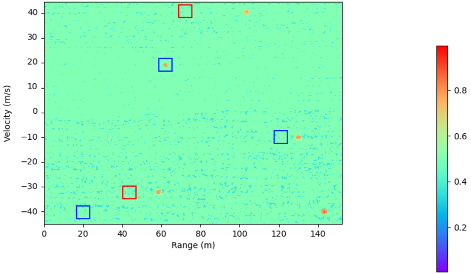



Figure: Range Doppler maps for optimized PMCW signal with a non-cooperative PMCW signal with random linear-phase

□ Target □ Interference

# Numerical Results (contd.)

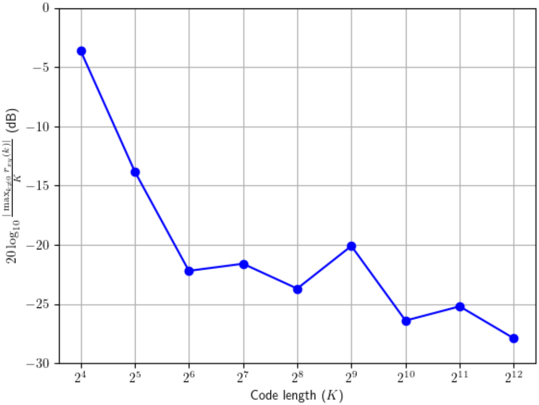



Figure: The normalized cross-correlation peak sidelobe level vs. MIMO code length

# Discussion

## Conclusions

- We discussed the problem of mutual interference in identical or similar PMCW systems
- We proposed mutually cooperative MIMO coding schemes
- These codes performs better when both the victim and aggressor are using them, but not so much when they disagree

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## Future Works

- Experimental evaluation
- Interference study against FMCW radars

Thank you
and
Questions?

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