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Radar as Signal of Opportunity, A New Paradigm for Wireless Communications

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RF Co-Existence

The RF spectrum is getting increasingly crowded

Motivations

Due to constantly increasing demand on bandwidth, defense applications are losing spectrum to commercial communications.

Ongoing research is developing multi-function methods to share aperture and spectrum between radar, electronic warfare, and military communications.

Moving away from independent systems and dedicated components.

Co-Existence Approaches

- Cohabitation: Address the interference which separately operated systems could cause to one another

- Co-Design: Involves cooperative control within the same system.

Radar/Communications Co-Design

- **A primary goal of radar is to efficiently track and detect targets, whereas that of communications is to maximize information transfer reliably**

CATEGORIES

- **Joint Resources and Platforms**
  - Joint waveform design, power, etc (compatible vs compounded)
- **One Service Mandates and the Other Accepts**
  - Communications **LEAD** and Radar **FOLLOWS**

    Communication Signals are Signals of Opportunities
  - Radar **LEADs** and Communications **FOLLOW**

    Radar Signals are Signals of Opportunities

Dual Function

Signal of opportunity

Signal vs. System of Opportunity

SIGNAL OF OPPORTUNITY

Using someone else's signal for a different function/task/mission

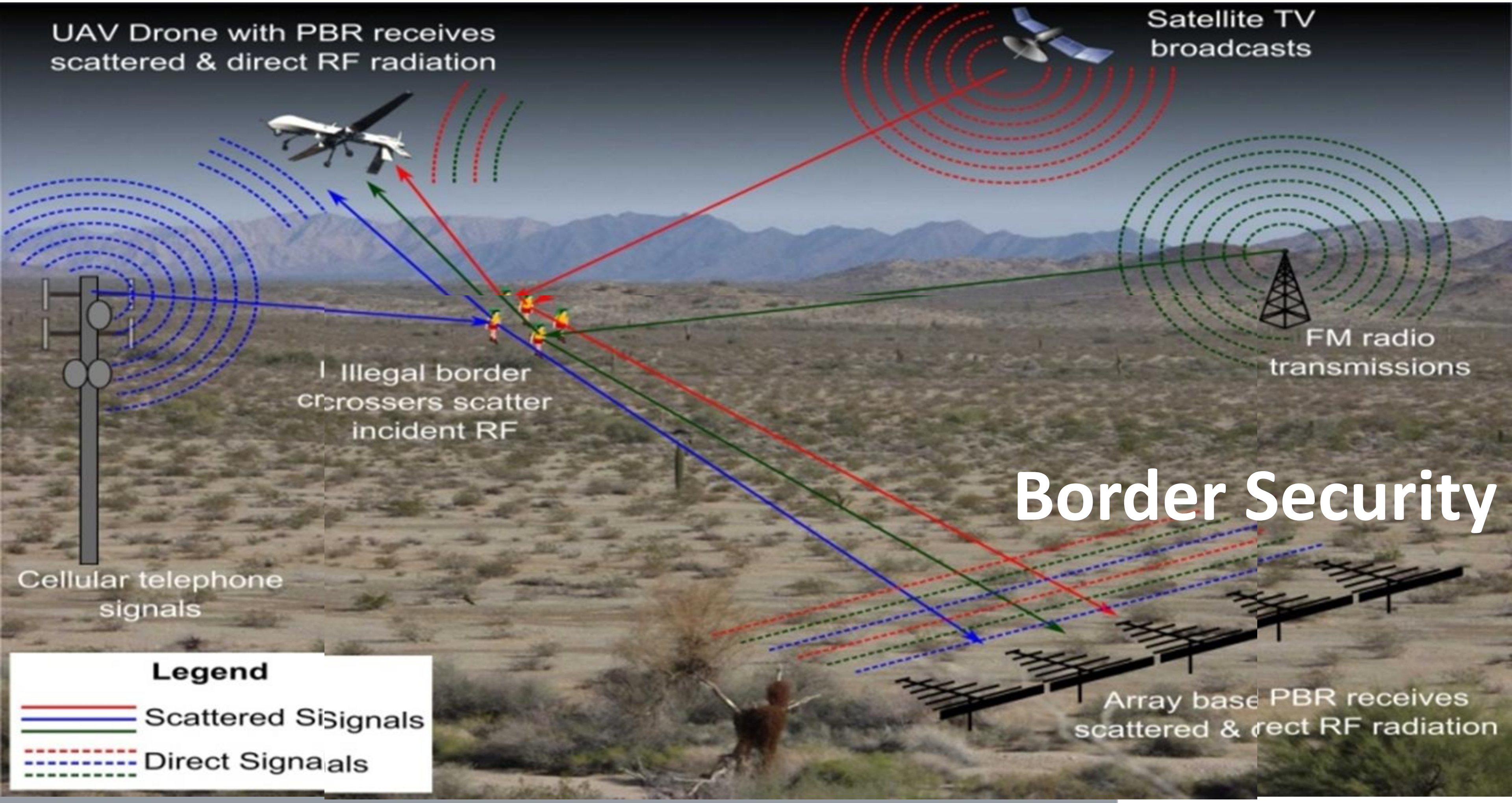
It is not your transmitter, but it is your own receiver

SYSTEM OF OPPORTUNITY

Using someone else's system for a different function/task/mission

You are a "Guest" on the transmitter, but it is your own receiver

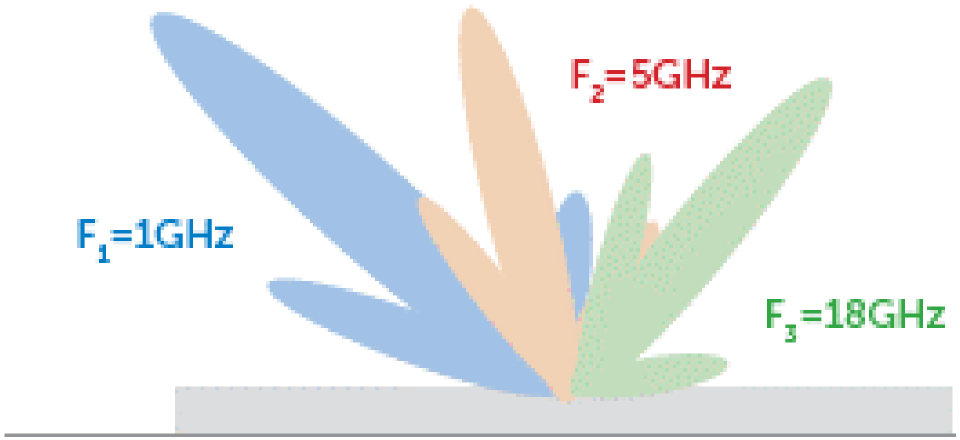
Signal of Opportunity- Passive Radar

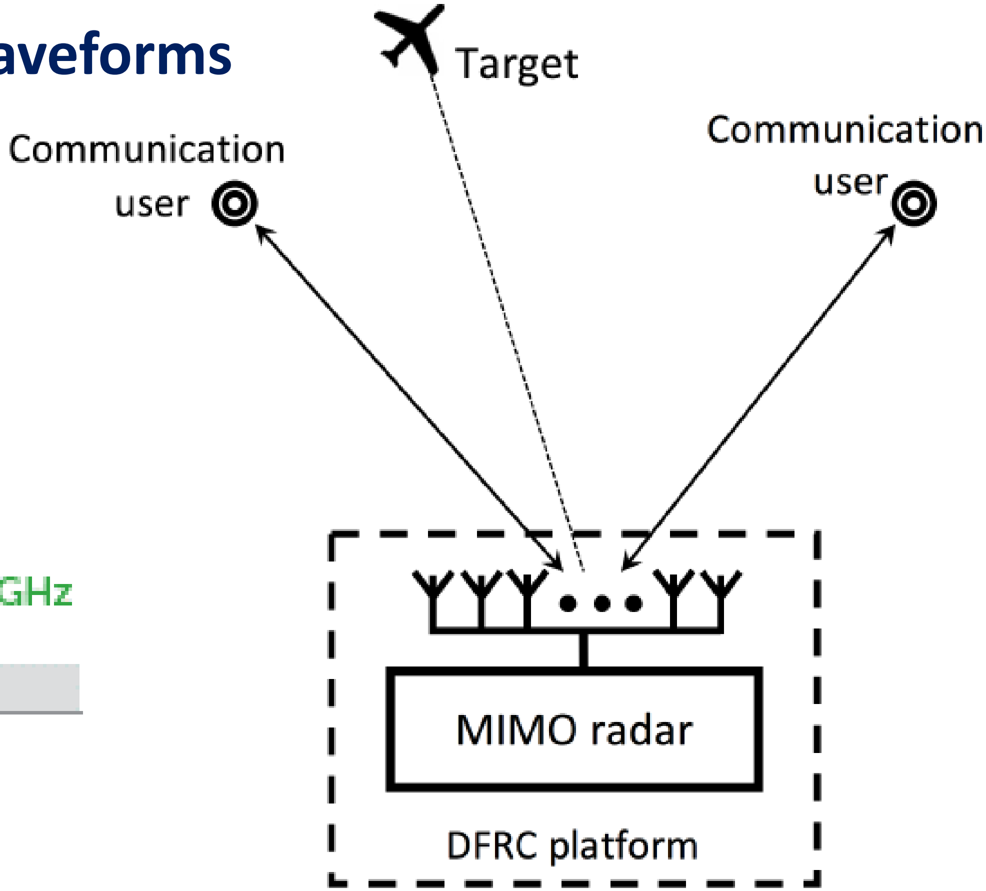


Border Security

System of Opportunity

Modulating or scaling the radar waveforms





DFCR System

Communications dictates

- Array Configuration
- Beamformer
- Carrier frequency
- Frequency bandwidth
- Signal waveform
- Power
- Modulation
- Antennas

Radar Receiver uses Communications as Signals of Opportunities

DFRC System

Radar dictates

- Beamformer,
- Array structure,
- Frequency bandwidth
- Signal waveform
- Power
- Antennas
- Coherent Processing Interval
- MIMO configuration

Communications Receiver uses Radar as System of Opportunity

Dual Function Radar Communications System (DFRC)

Primary: Radar

Secondary: Communications

- Identical signals, same frequency and bandwidth, and a common antenna array are used for both radar and communication operations

- Radar function remains the same over the entire processing interval

- Secondary Communications Function:
  - Embeds *a* sequence of binary data $b_1, \ldots, b_K$ during each radar pulse
  - Should not disturb the primary function of the joint system

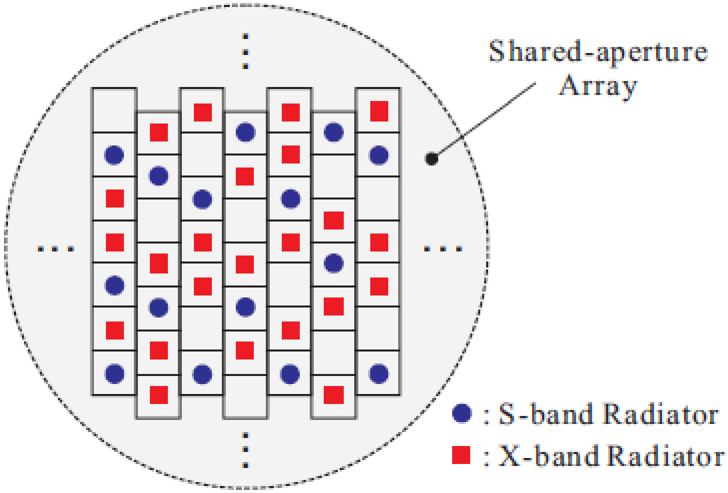
DFRC System General Objectives

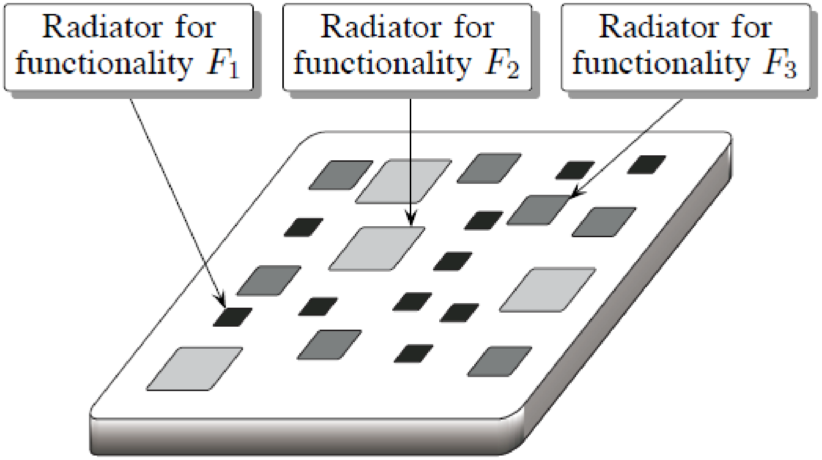
- Establishing dual system functionality, allowing radar to house voice and data transmission and reception.

- Developing novel signaling schemes for embedding information into the radar pulsed emissions, which, in most cases, is blind to the primary radar operation.

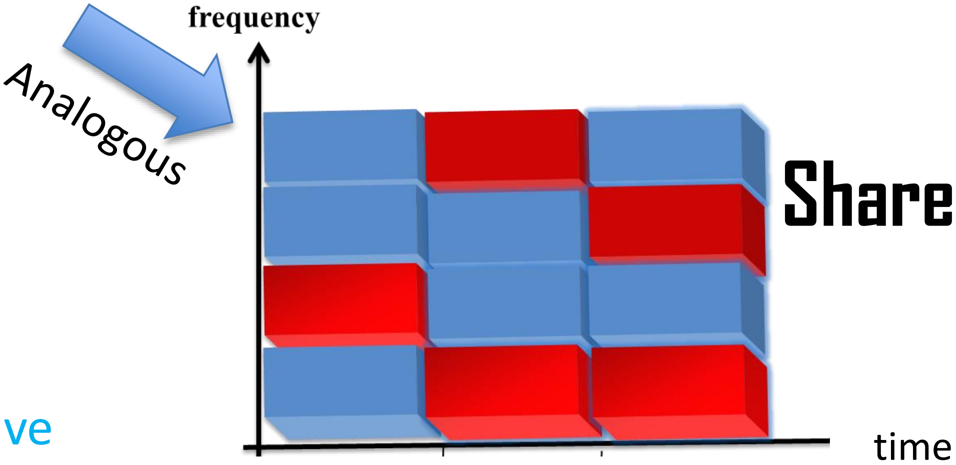
- Considering different transmit and receive antenna configurations, including MIMO radars, achieving high data rate communications by combining amplitude and phase-shift keying modulations with waveform-diversity, while satisfying an overall power constraint

Aperture Co-design





Shared Aperture

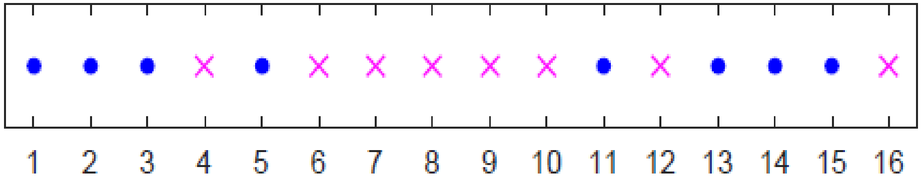


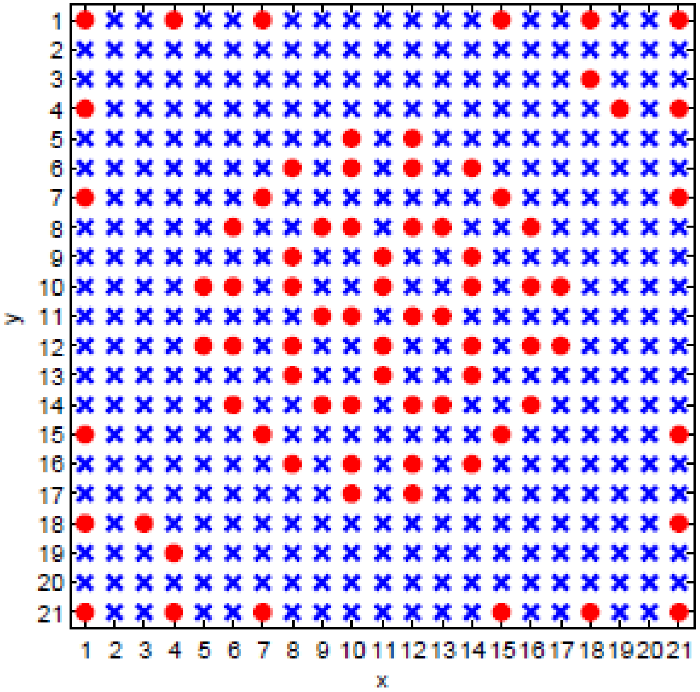
Shared Spectrum

Different Frequencies
Different Bandwidths
Different Polarizations
Different Transmit/Receive

Sparse Arrays

- They change

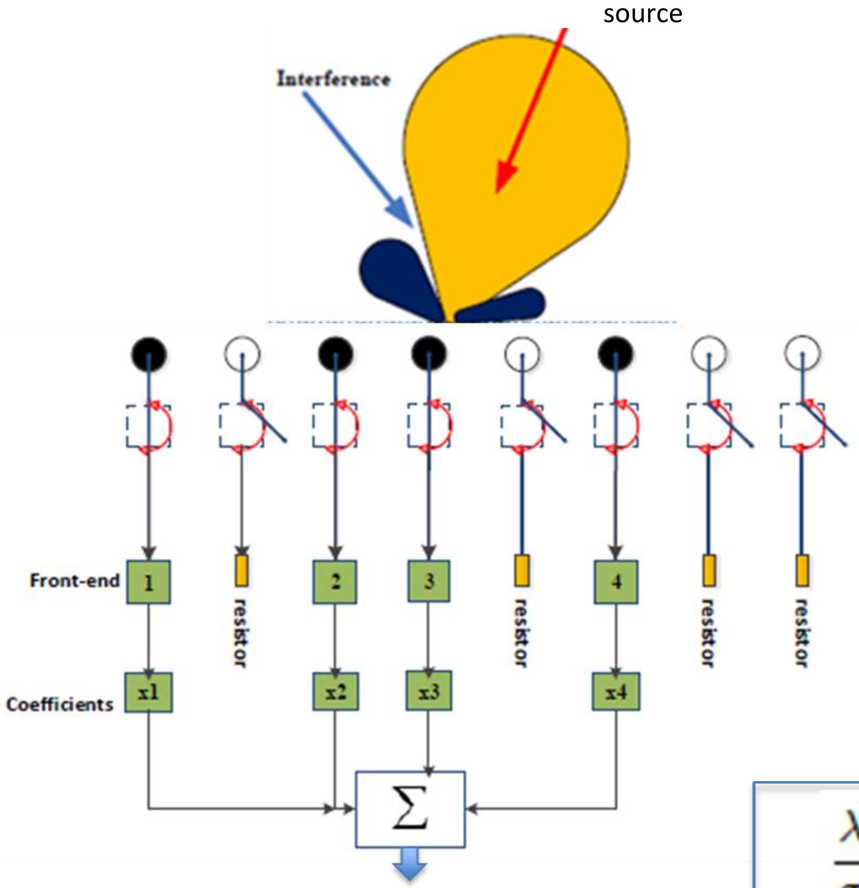




Criteria

SNR, SINR, DOA

MaxSINR Beamformers



Single Beamformer

Array Thinning

Antenna Selections

Array Reconfiguration

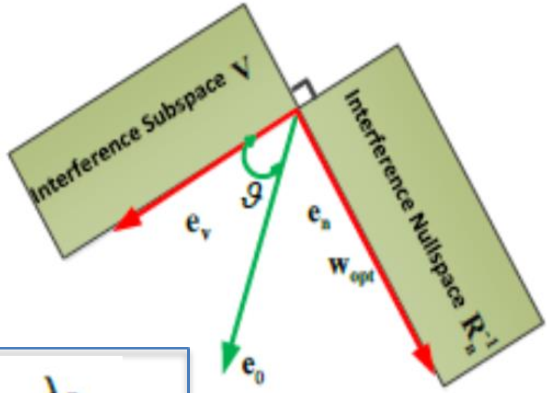
Changes Covariance Matrix

Changes Eigenvalues/Vectors

$$\max_{\mathbf{z}} \quad \mathrm{SINR}_{oi}$$

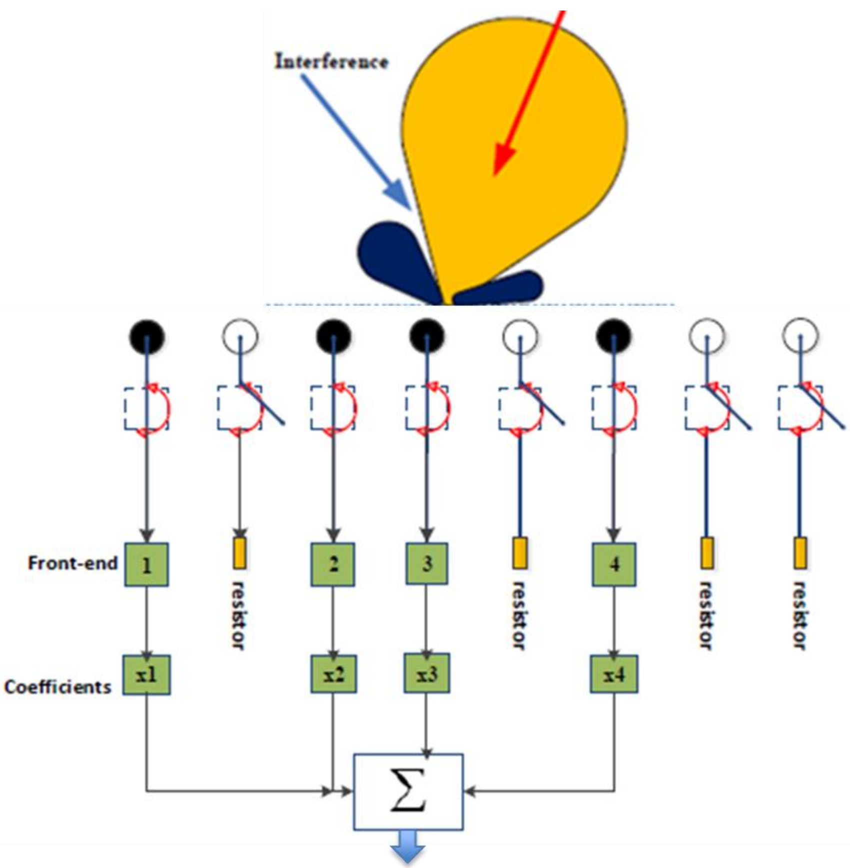
$$s.t. \quad \mathbf{1}_N^T \mathbf{z} = K$$

$$0 \le \mathbf{z} \le 1$$

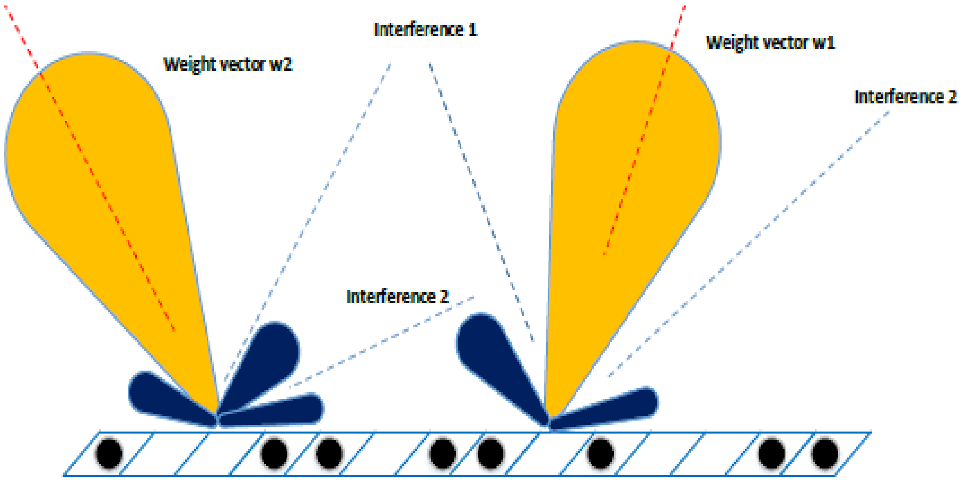


$$\boxed{\frac{\lambda_0}{\sigma_n^2}(1-|\alpha|^2) \le \mathrm{SINR}_{\mathrm{opt}} \le \frac{\lambda_0}{\sigma_n^2},}$$

MaxSINR Beamformers



Single Beamformer

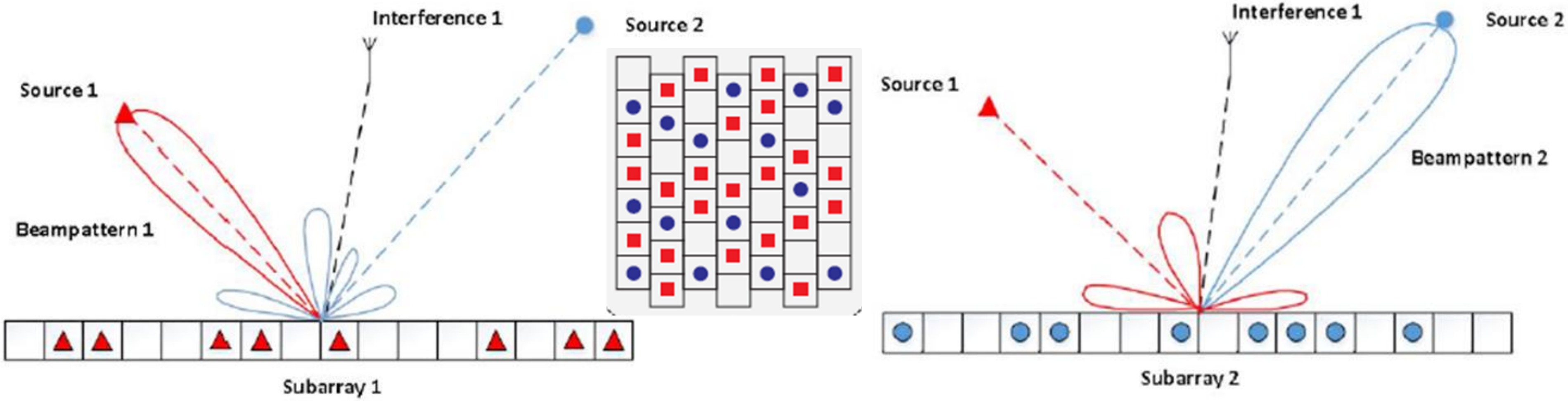


Multiple Beamformers

Different sets of weights,
but the same optimum sparse array
Use Capon beamformer for each

Analogous to multiple frequencies

Shared Aperture



$$\max_{\substack{\mathbf{z}_1,\dots,\mathbf{z}_P\\ K_1,\dots,K_P}} \sum_{i=L+1}^{P} \mathrm{SINR}_i$$

$$s.t.\quad \mathrm{SINR}_l \geq \gamma_l^*,\ l = 1, \dots, L$$

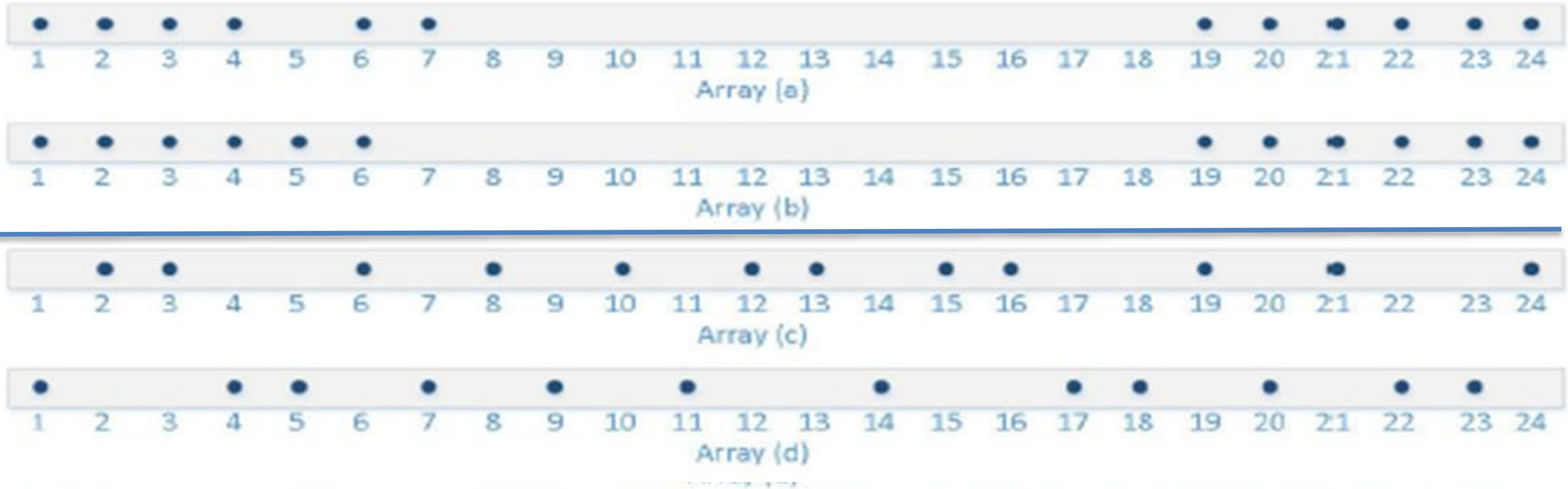
$$\mathbf{1}_N^T \mathbf{z_i} = K_i,\ \forall i$$

$$\mathbf{z}_i \in \{0,1\}^N,\ \forall i$$

Multi-Mission
Multi-Task
Multi-Function

Example

- 2 Sources at SNR=0 dB, INR=20 dB

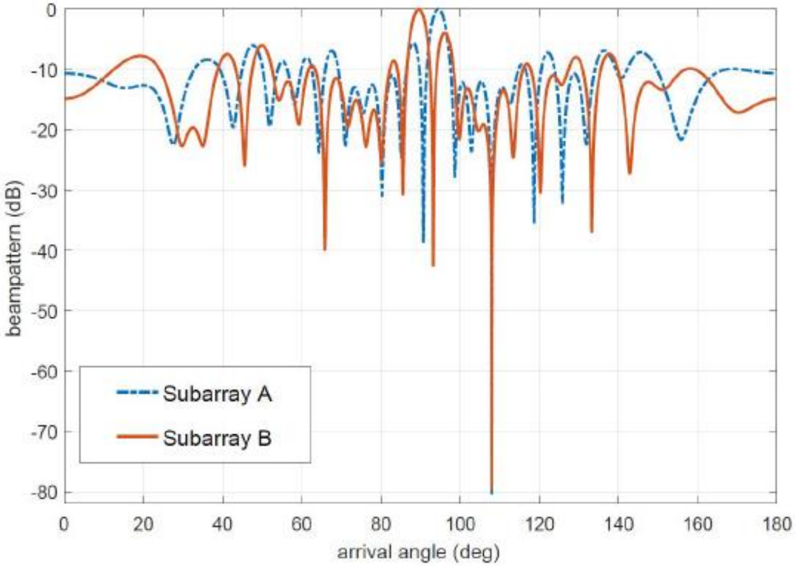


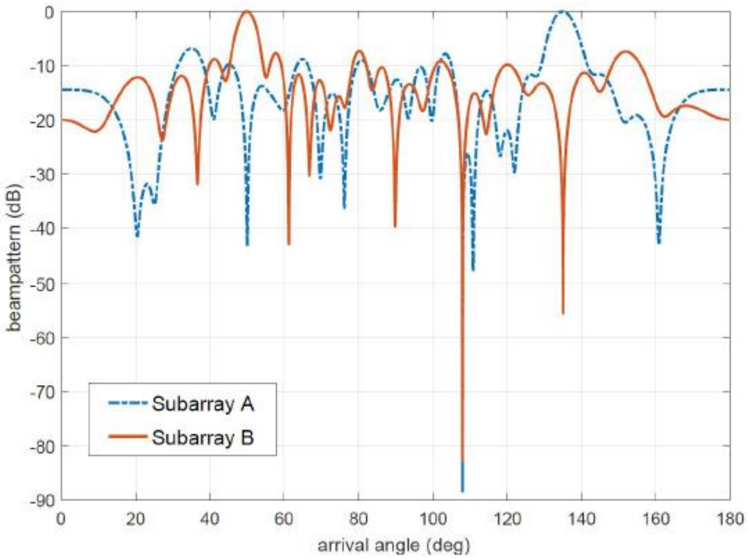
Strongly correlated Sources

Weakly correlated Sources

SINR Comparison

	Joint opt.(Eq.(14))	Separate opt.(Eq.(17))
$SINR_{oA}, \phi_A = 93^o$	7.5068	9.2781
$SINR_{oB}, \phi_B = 91^o$	7.9369	9.3065
$SINR_{oA}, \phi_B = 135^o$	10.7526	10.7743
$SINR_{oB}, \phi_B = 50^o$	10.7426	10.7730





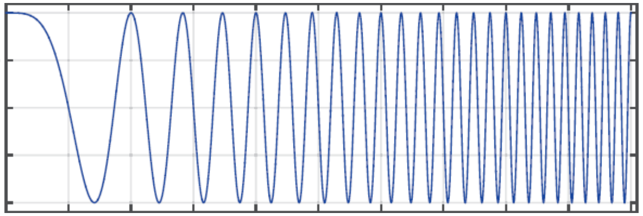
Co-Design -Same Antennas Shared Bandwidth

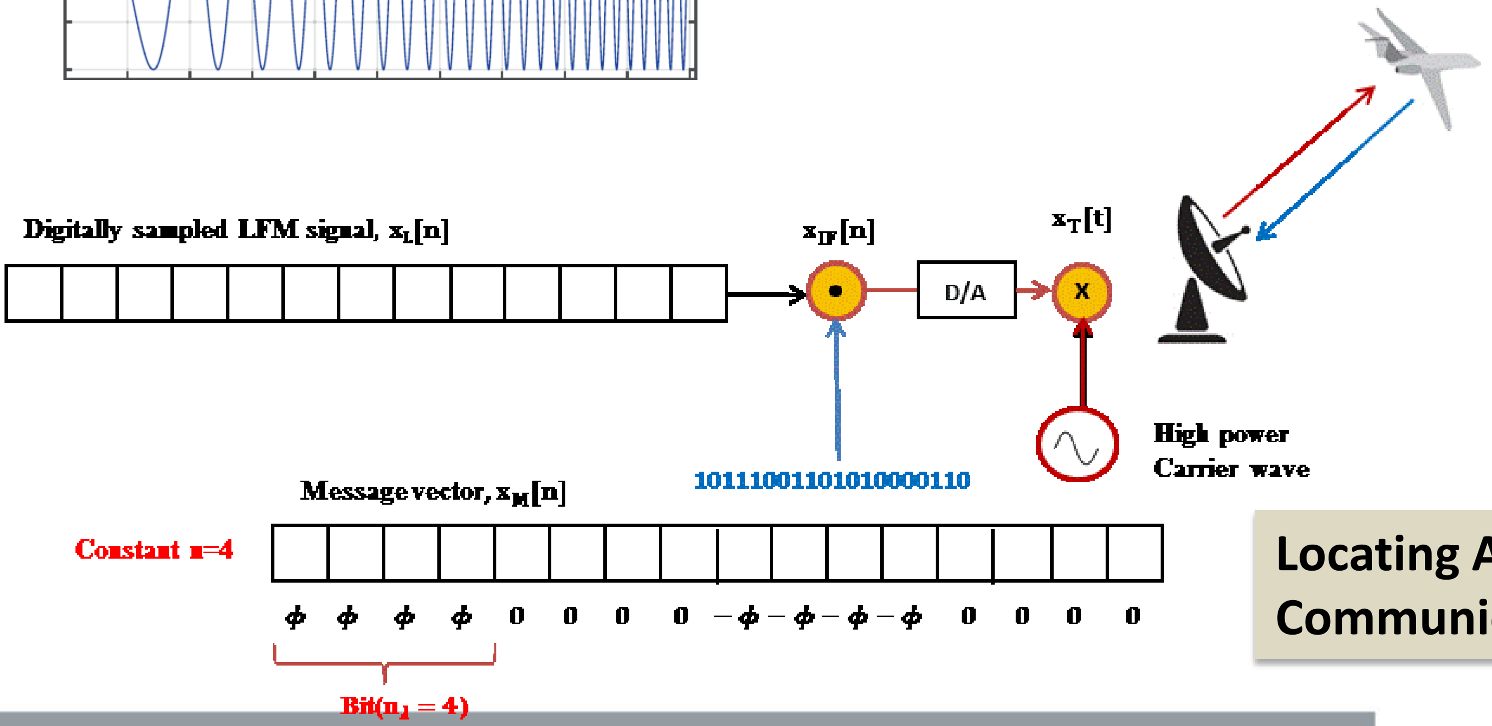
Embedding through modulation over fast time

- Using the radar signal, comprised of a radar pulse, as the carrier and the communications message as the modulating signal
- Communications receiver removes radar signal before demodulation
- Radar receiver may or may not remove communications signal before target detection

Co-Design -Same Antennas Shared Bandwidth

- Sample LFM and embed BFSK with reduced phase angle





Digitally sampled LFM signal, $x_L[n]$

$x_{IF}[n]$

D/A

$x_T[t]$

10111001101010000110

High power Carrier wave

Message vector, $x_M[n]$

Constant n=4

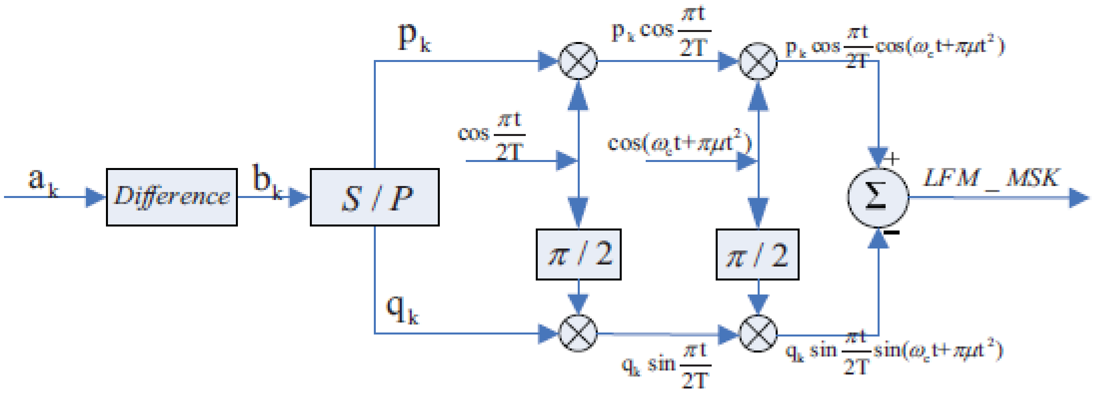
$\phi \quad \phi \quad \phi \quad \phi \quad 0 \quad 0 \quad 0 \quad 0 \quad -\phi \quad -\phi \quad -\phi \quad -\phi \quad 0 \quad 0 \quad 0 \quad 0$

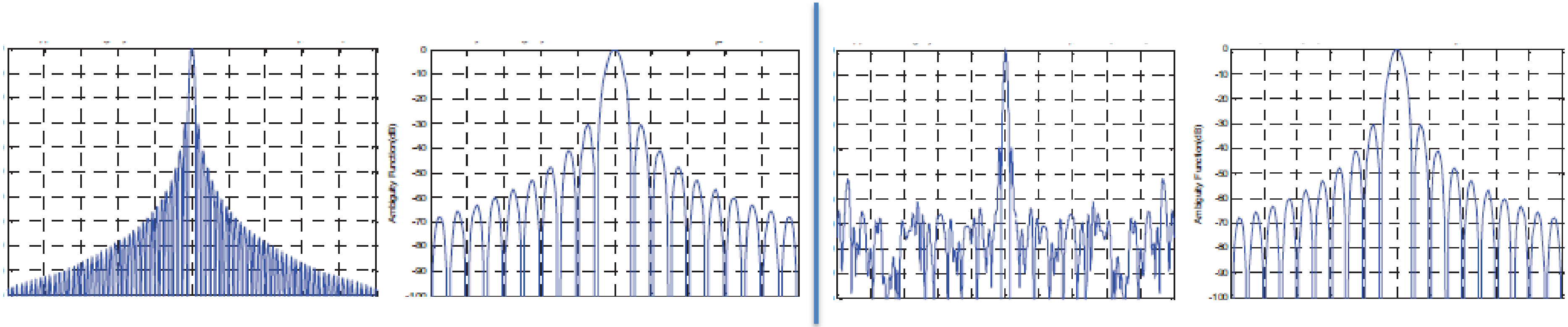
$\text{Bit}(n_1 = 4)$

Locating Aircraft and Communication with pilot

Co-Design -Same Antennas Shared Bandwidth

- Embedding MSK through modulation



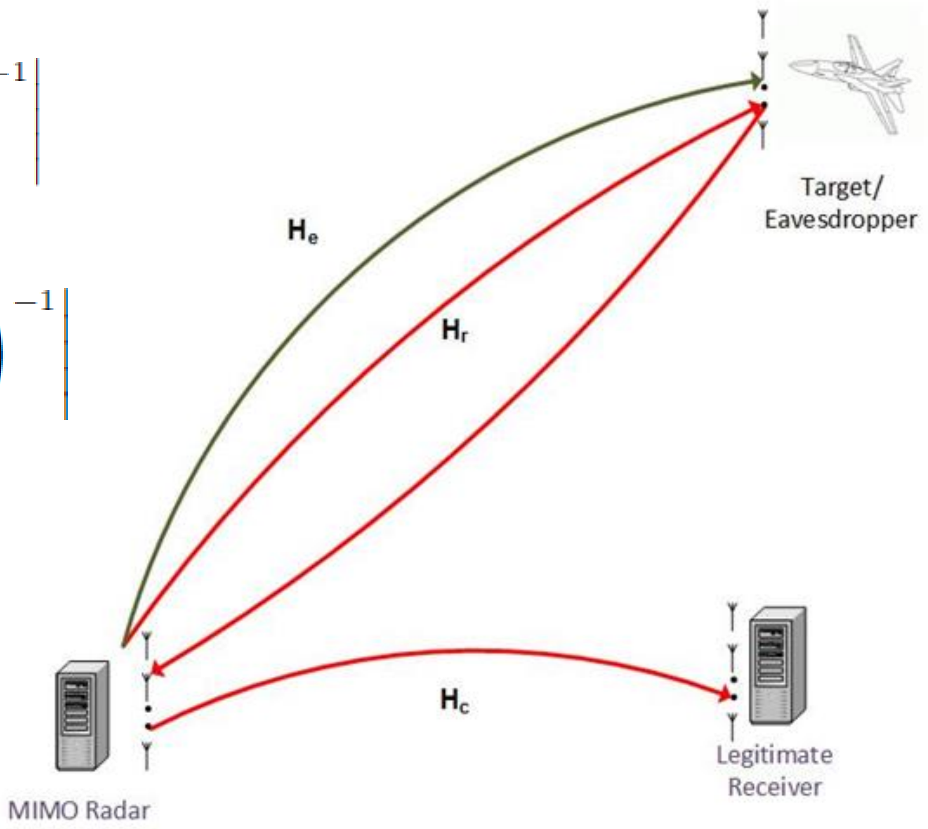


Secrecy Rate Optimizations for DFRC

$$R_c = \log \left| \mathbf{I} + (\mathbf{H}_c \mathbf{W}_1 \mathbf{H}_c^H) \left(\frac{\mathbf{H}_c \mathbf{W}_2 \mathbf{H}_c^H}{L_m} + \sigma_c^2 \right)^{-1} \right|$$

$$R_e = \log \left| \mathbf{I} + (\mathbf{H}_e \mathbf{W}_1 \mathbf{H}_e^H \left(\frac{\mathbf{H}_e \mathbf{W}_2 \mathbf{H}_e^H}{L_m} + \sigma_e^2 \right)^{-1} \right|$$

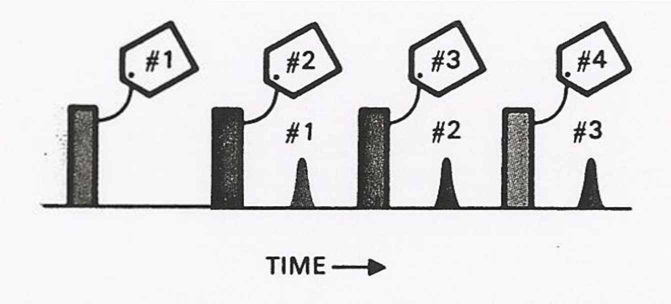
$$SR = [R_c - R_e]^+$$



Embedding-Modulation Over Slow-Time

- A dictionary of 2^K orthogonal waveforms employed

$$\{b_1, \ldots, b_K\} \Leftrightarrow \mathrm{D}_{\mathrm{WD}} = \{s_1(t), \ldots, s_{2^K}\}$$



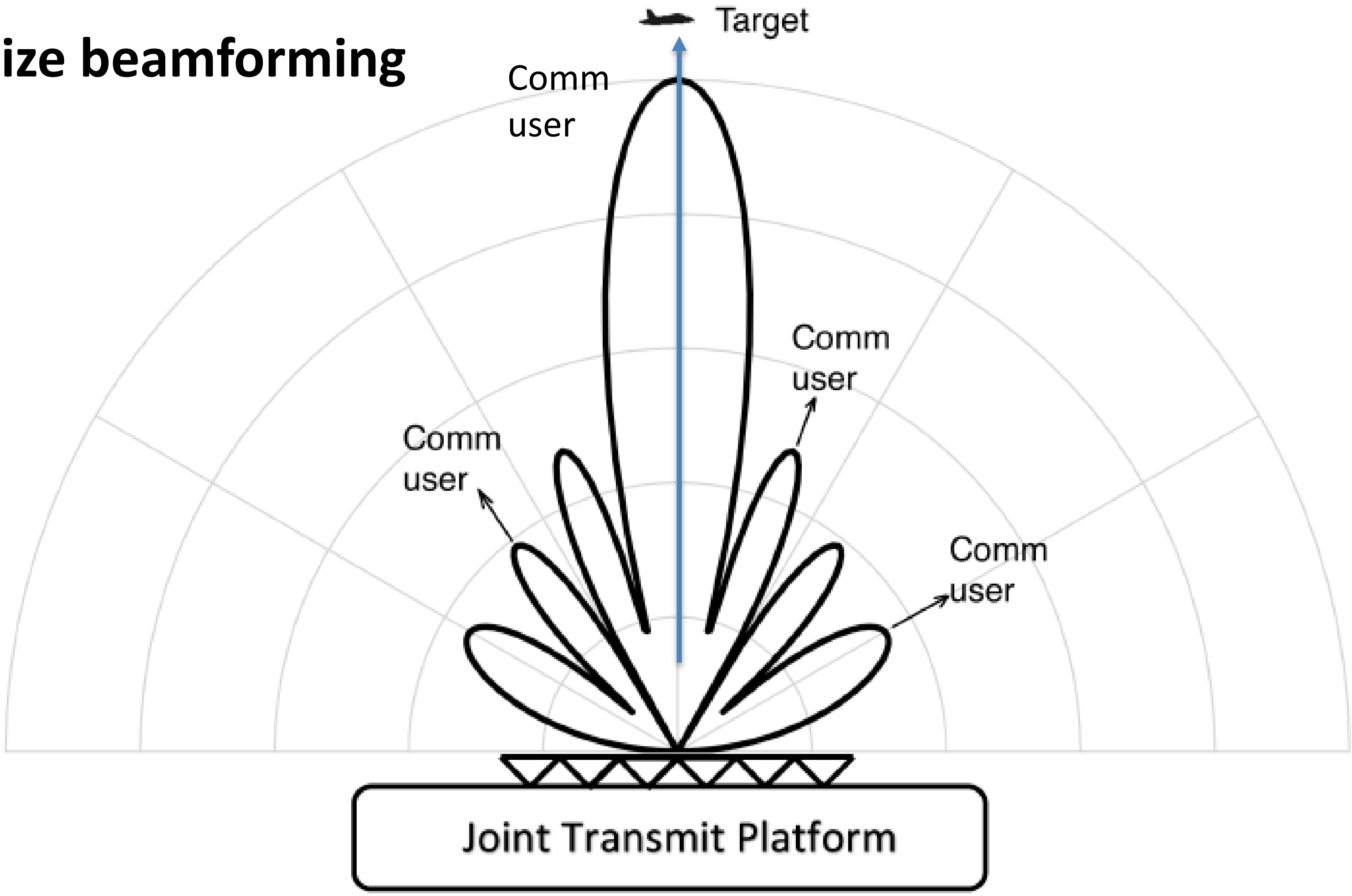
- During each radar pulse, one of the waveforms is transmitted
- Communication receiver detects the received waveform and decodes the corresponding binary information
- Limitations:

Low bit rate - Symbol rate=Pulse rate

S. D. Blunt *et*. al., "Embedding information into radar emissions via waveform implementation," *Int. Waveform Diversity* and *Design Conf.*, 2010.

High Data Rate Non-Fast-Time Modulations

Utilize beamforming



Sidelobe AM Based Signaling

- To embed K bits, a constellation of size 2^K is employed

$$\{b_1, \ldots, b_K\} \Leftrightarrow \mathrm{D}_{\mathrm{AM}} = \{\Delta_1, \ldots, \Delta_{2^K}\}$$

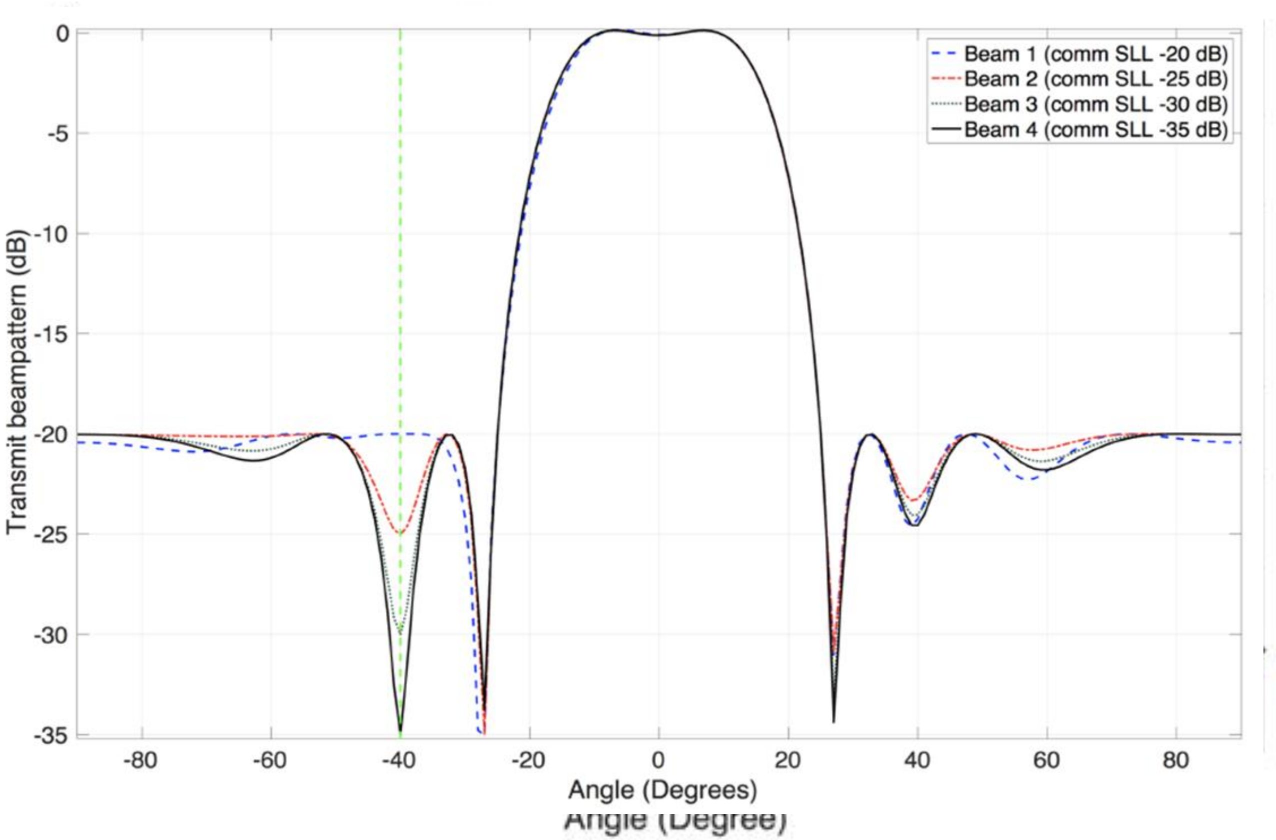
- Each symbol $\Delta_k, k = 1, \ldots, 2^K$ is represented by a specific SLL

- Communication receiver detects the SLL and deciphers the associated symbol

J. Euziere *et.* al., " Dual function radar communication time-modulated array," *Int. Radar Conf.*, 2014.

ASK Signaling

M=10, four sidelobe levels −20 dB, −25 dB, −30 dB, and −35 dB,



Switching beams is as fast as pulse repetition frequency

Amplitude Shift-Keying Based DFRC

Basic Idea:

- Stationary main radar beam; variable SLLs

$$\min_{\mathbf{u}_k} \max_{\theta_i} \left| e^{j\varphi(\theta_i)} - \mathbf{u}_k^H \mathbf{a}(\theta_i) \right|, \ \theta_i \in \mathbf{\Theta}, \ i = 1, \ldots, I$$

$$\text{subject to} \ \left| \mathbf{u}_k^H \mathbf{a}(\theta_p) \right| \le \varepsilon, \quad \theta_p \in \bar{\mathbf{\Theta}}, \ p = 1, \ldots, P,$$

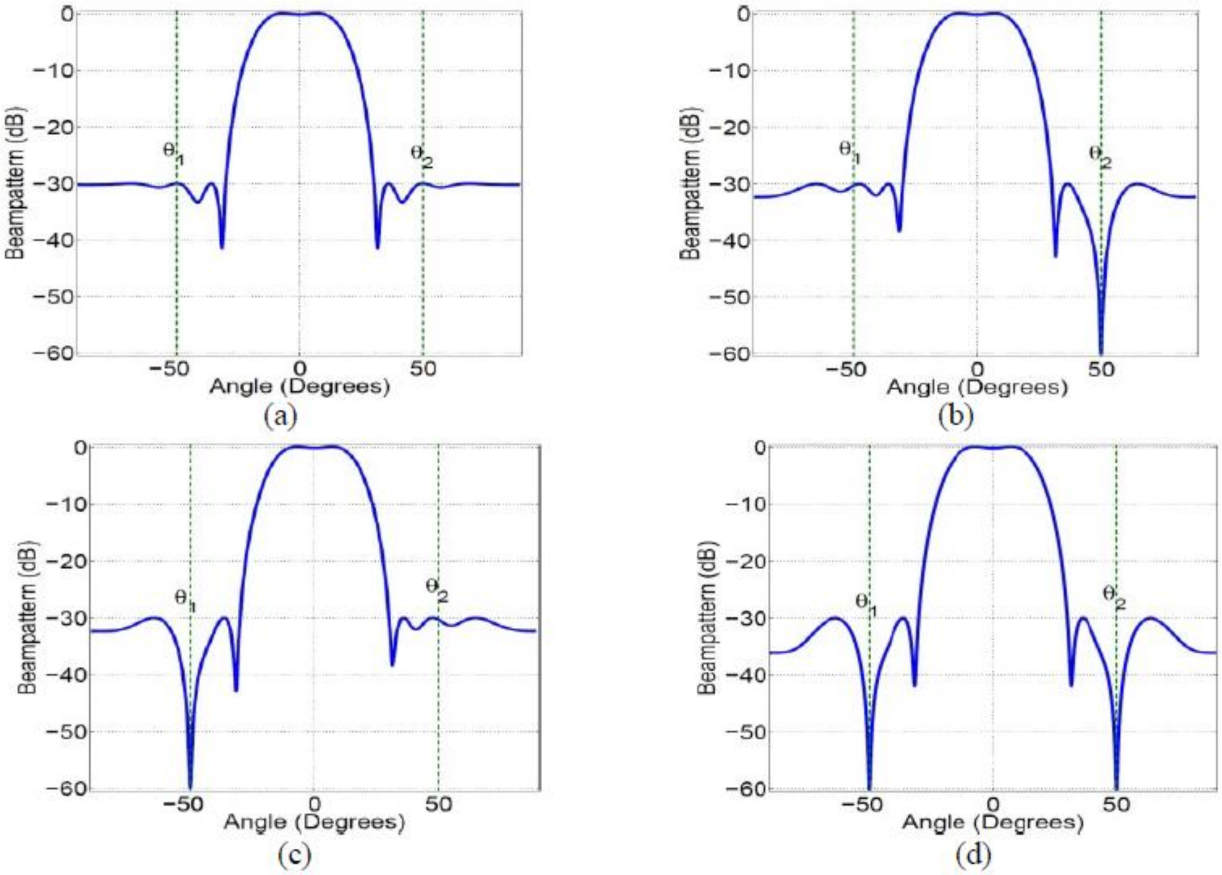
$$\mathbf{u}_k^H \mathbf{a}(\theta_c) = \Delta_k,$$

$$\min_{\mathbf{u}_k} \ \max_{\theta} \ \left| \mathbf{w}_0^H \mathbf{a}(\theta) - \mathbf{u}_k^H \mathbf{a}(\theta) \right|, \quad \forall \theta \in [-\pi, \ \pi]$$

$$\mathbf{u}_k^H \mathbf{a}(\theta_c) = \Delta_k.$$

A. Hassanien, M. Amin, Y. Zhang, F. Ahmad "Dual-function radar-communications: Information embedding using sidelobe control and waveform diversity," *IEEE TSP*, Apr. 2016.

Multiple Access Information Delivery



Number of beams increases with number of users

Sidelobe Signaling

AM constellation of size $K = 2^Q$, denoted as $\mathbb{D}_{\mathrm{AM}} = \{\Delta_1, \ldots, \Delta_K\}$.

$$\Delta_1 > \Delta_2 > \ldots > \Delta_K$$

Transmitted signal $\mathbf{s}(t;\tau) = \mathbf{u}_k^* \phi(t)$

At communication receiver
$$\begin{aligned} y_{\mathrm{com}}(t;\tau) &= \alpha_{\mathrm{ch}}(\tau)\Big(\mathbf{u}_k^H \mathbf{a}(\theta_c)\Big)\phi(t) + n(t;\tau), \\ &= \alpha_{\mathrm{ch}}(\tau)\Delta_k \phi(t) + n(t;\tau), \end{aligned}$$

$$y_{\mathrm{com}}(\tau) = \int_{T_p} y_{\mathrm{com}}(t;\tau)\phi^*(t)dt = \alpha_{\mathrm{ch}}(\tau)\Delta_k + n(\tau).$$

$$\hat{\Delta}(\tau) = \begin{cases} \Delta_1, & \eta_{\mathrm{AM}}(\tau) \geq T_1, \\ \Delta_2, & T_2 \leq \eta_{\mathrm{AM}}(\tau) < T_1, \\ & \vdots \\ \Delta_K, & \eta_{\mathrm{AM}}(\tau) < T_{K-1}. \end{cases}$$

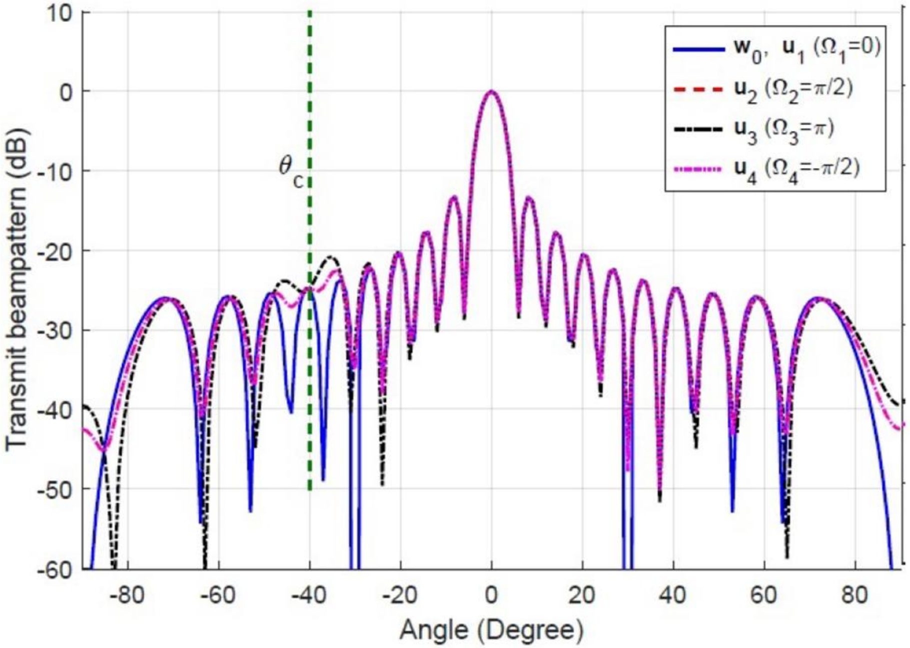
Communication receiver cannot be in the main beam

Beampattern Synthesis with Phase Control

$$\mathbf{v}_k,\ k = 1, \ldots, K \qquad \Omega_k = \angle(\mathbf{v}_k^H \mathbf{a}(\theta_c)), \qquad \mathbb{D}_{\mathrm{PM}} = \{\Omega_1, \ldots, \Omega_K\}$$

$$\min_{\mathbf{v}_k} \left\| \mathbf{w}_0 - \mathbf{v}_k \right\| \quad \text{subject to} \ \ \mathbf{v}_k^H \mathbf{a}(\theta_c) = G_0 e^{-j\Omega_k}, \quad k = 1, \ldots, K,$$

$$G_0 = |\mathbf{w}_0^H \mathbf{a}(\theta_c)|$$



Transmit Radiation Pattern Invariance

Start with a principal transmit beamforming weight vector

- Consider the polynomial *f(z)* of order *2M-2*

$$f(z) \triangleq \overbrace{\left(w_1 + w_2 z + w_3 z^2 + \cdots + w_M z^{M-1}\right)}^{\text{First term}}$$
$$\times \overbrace{\left(w_1^* + w_2^* z^{-1} + w_3^* z^{-2} + \cdots + w_M^* z^{-M+1}\right)}^{\text{Second term}}$$

- The transmit radiation pattern can be represented as

$$\left|\mathbf{w}^H \mathbf{a}(\theta)\right|^2 = f\left(e^{-j\pi \sin(\theta)}\right)$$

- If r is a root of the first term, then ${}^{1}/_{r^*}$ is a root of the second term**!**

Transmit Radiation Pattern Invariance

- *f(z)* can be decomposed as

$$f(z) = \prod_{i=1}^{M-1}(z - r_i)\prod_{i=1}^{M-1}(z^{-1} - r_i^*)$$

- 2^{M-1} different combinations can be constructed!

$$\mathbf{W}_{\text{pop}} = \{\mathbf{w}, \mathbf{w}_1, \ldots, \mathbf{w}_{2^{M-1}-1}\}$$

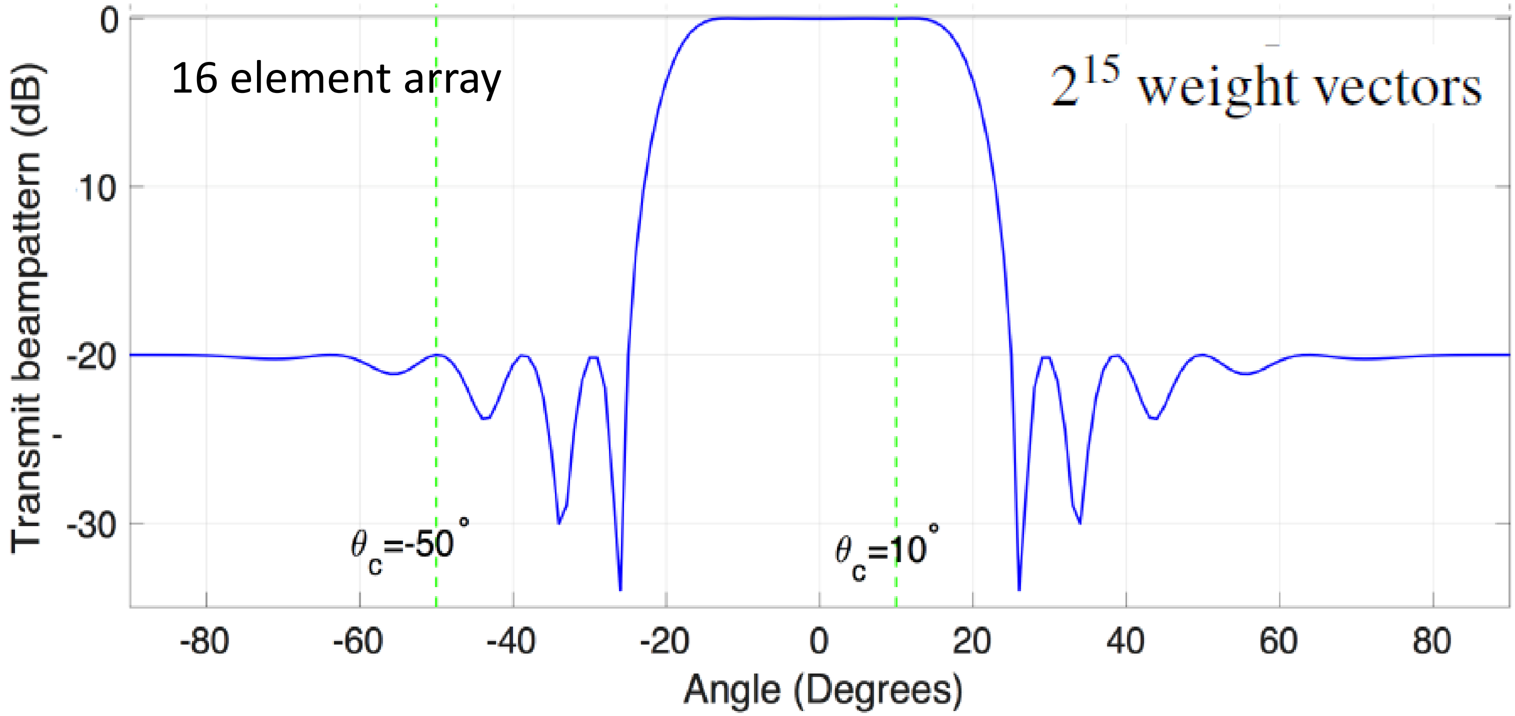
- All generated weight vectors have same transmit radiation pattern

$$\min_{\mathbf{v}_k \in \mathbf{W}} \left| \angle(\mathbf{v}_k^H \mathbf{a}(\theta_c) - \Omega_k \right|, \qquad k = 1, \ldots, K.$$

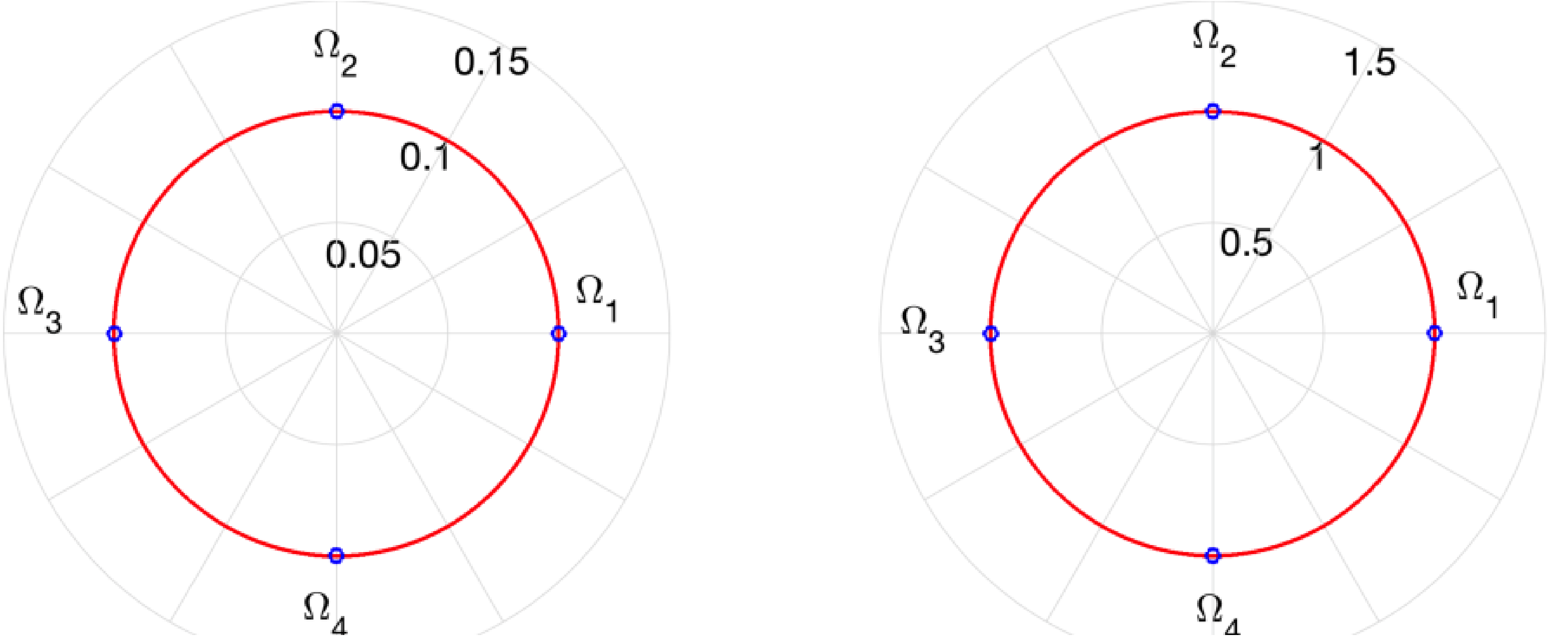
Example- 16 Element Array

$$\min_{\mathbf{w}_0} \max_{\theta_i} \left|1-\mathbf{w}_0^H \mathbf{a}(\theta)\right|, \ \theta \in [-10^\circ, 10^\circ]$$

$$\text{subject to} \ \left|\mathbf{w}_0^H \mathbf{a}(\theta)\right| \le 0.1, \quad \theta \in [-90^\circ, -25^\circ] \cup [25^\circ, 90^\circ].$$



Example

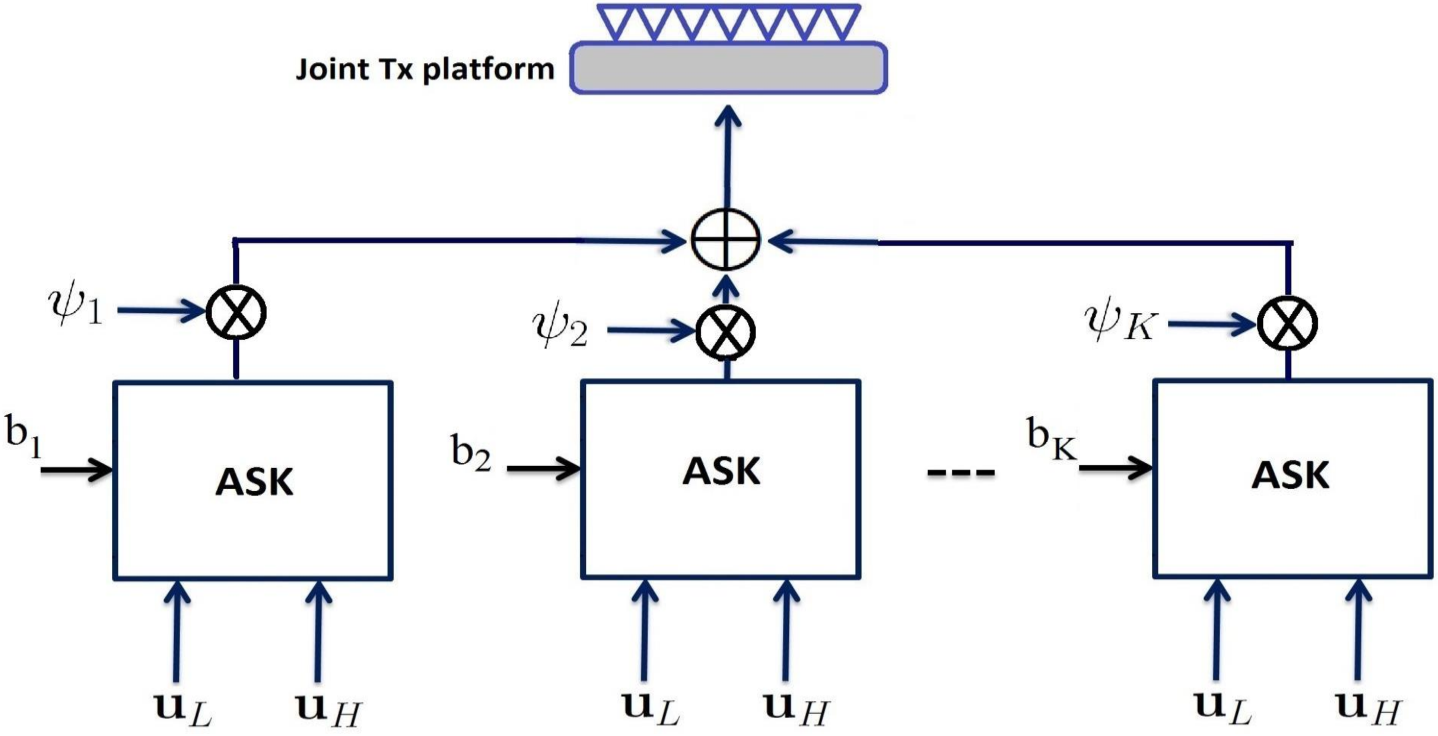


(a) Magnitude versus phase for 2^{15} *weight vectors (red colored dots) and* $K = 4$ *chosen vectors (blue colored circles) towards the communication direction* $\theta_c = -40°$; *(b) Magnitude versus phase for* 2^{15} *weight vectors (red colored dots) and* $K = 4$ *chosen vectors (blue colored circles) towards the communication direction* $\theta_c = 10°$.

Multi Waveform ASK Signaling

Decompose the radar signal into

$\psi_1, \ldots, \psi_K$: K orthogonal waveforms (subbands)



Multi Waveform ASK Signaling

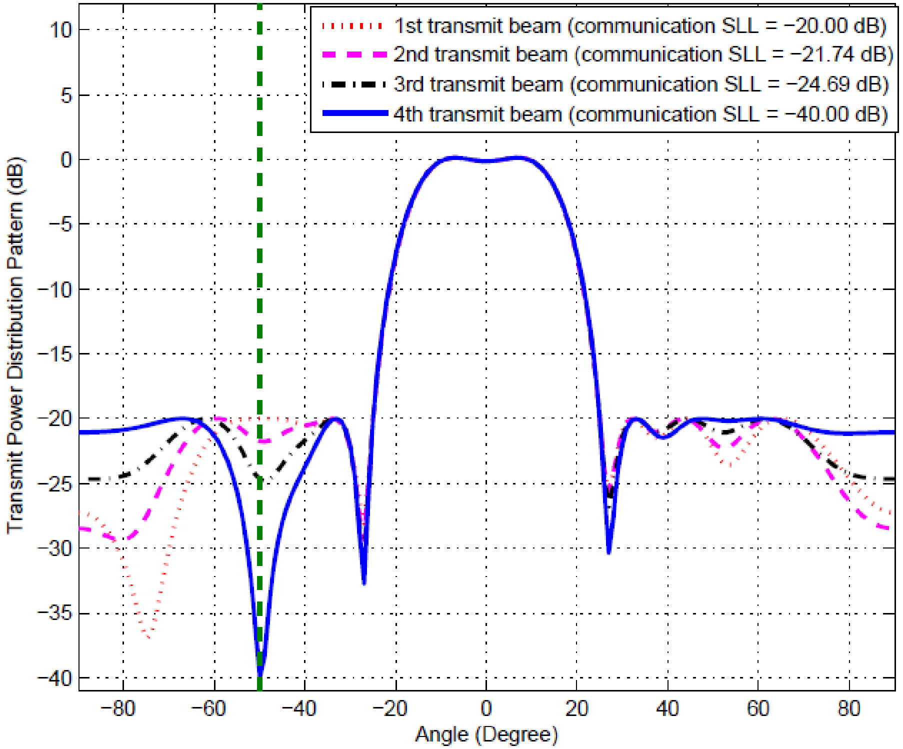
Leaving the transmitter $\mathbf{s}_{\text{ASK}}(t;\tau) = \frac{1}{\sqrt{K_w}} \sum_{k=1}^{K_w} \Big(b_k(\tau)\mathbf{u}_{\text{L}}^{*} + \bar{b}_k(\tau)\mathbf{u}_{\text{H}}^{*} \Big) \psi_k(t),$

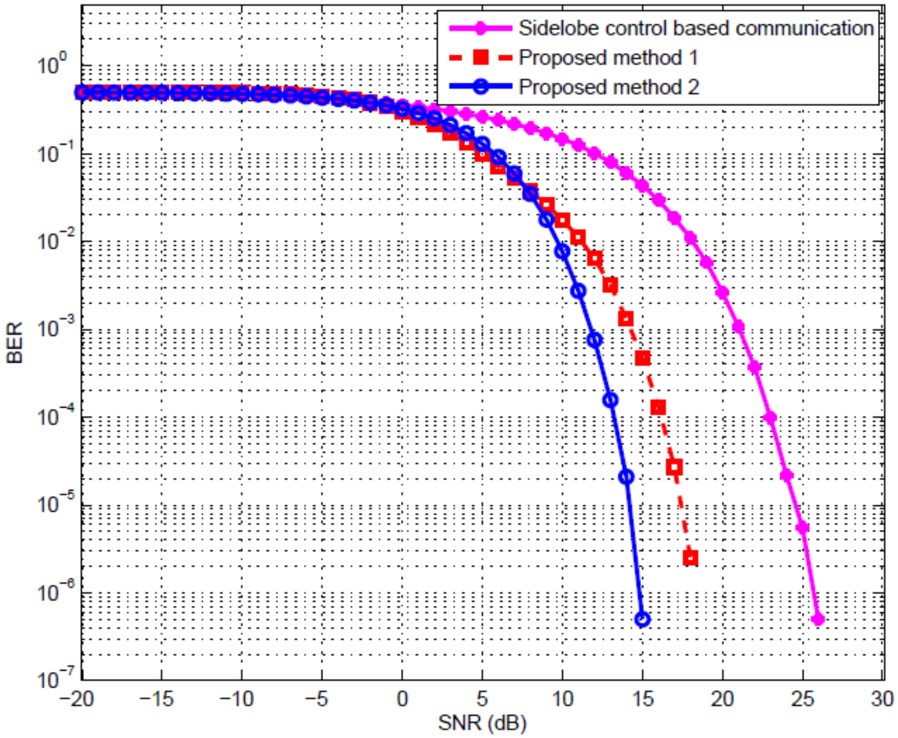
At the communications receiver

$$\begin{aligned} y_{\text{ASK}}(t;\tau) &= \frac{\alpha_{\text{ch}}}{\sqrt{K_w}} \sum_{k=1}^{K_w} \Big(b_k(\tau)\mathbf{u}_{\text{L}}^{H}\mathbf{a}(\theta_c) + \bar{b}_k(\tau)\mathbf{u}_{\text{H}}^{H}\mathbf{a}(\theta_c) \Big) \psi_k(t) + n(t;\tau) \\ &= \frac{\alpha_{\text{ch}}}{\sqrt{K_w}} \sum_{k=1}^{K_w} \Big(b_k(\tau)\Delta_{\text{L}} + \bar{b}_k(\tau)\Delta_{\text{H}} \Big) \psi_k(t) + n(t;\tau). \end{aligned}$$

$$y_k(\tau) = \int_{T_p} y_{\text{ASK}}(t;\tau)\psi_k^{*}(t)dt = \begin{cases} \frac{\alpha_{\text{ch}}}{\sqrt{K_w}}\Delta_{\text{H}} + n_k, & b_k(\tau) = 0, \\ \frac{\alpha_{\text{ch}}}{\sqrt{K_w}}\Delta_{\text{L}} + n_k, & b_k(\tau) = 1, \end{cases} \qquad \hat{b}_k(\tau) = \begin{cases} 0, & \\ & T_0 \\ 1, & \end{cases}$$

Example


1st transmit beam (communication SLL = −20.00 dB)
2nd transmit beam (communication SLL = −21.74 dB)
3rd transmit beam (communication SLL = −24.69 dB)
4th transmit beam (communication SLL = −40.00 dB)
Transmit Power Distribution Pattern (dB)
10
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−80
−60
−40
−20
0
20
40
60
80
Angle (Degree)


Sidelobe control based communication
Proposed method 1
Proposed method 2
BER
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−20
−15
−10
−5
0
5
10
15
20
25
30
SNR (dB)

A Dual-Function MIMO Radar-Communications System

- A new method for information embedding into the emission of MIMO radar
- Each waveform carries an independent phase symbol leading to high data rate
- Fully Transparent to the radar
- Uniform communications performance across the spatial dimension

MIMO Radar Signal Model

- Consider a dual-function system with M colocated transmit antennas
- Let $\phi_m(t), m = 1, \dots, M$ be M orthogonal waveforms
- Assume that Q targets are located in the far-field, the received signal is

$$\mathbf{x}(t,\tau) = \sum_{q=1}^{Q} \alpha_q(\tau) \left[\mathbf{a}^T(\theta_q)\, \boldsymbol{\Phi}(t)\right] \mathbf{b}(\theta_q) + \mathbf{n}(t,\tau)$$

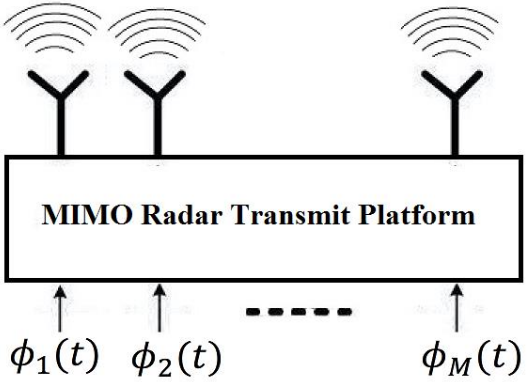
τ: Pulse number

θ_q, α_q: Direction and reflection coefficient of the q-th target

$a(\theta), b(\theta)$: Steering vectors of transmit and receive arrays

$\boldsymbol{\Phi}(t) = [\phi_1(t), \dots, \phi_M(t)]^T$: Vector of orthogonal waveforms

$n(t,\tau)$: Vector of AWGN



MIMO radar

MIMO Radar Signal Model (Cont'd)

Output Signal after Matched-Filtering:

- Matched-filtering the received signals to the orthogonal waveforms yields the MNx1 extended virtual data

$$\begin{aligned}\mathbf{y}(\tau) &= \operatorname{vec}\left(\int_{T_0} \mathbf{x}(t,\tau)\,\mathbf{\Phi}^H(t)\,dt\right)\\ &= \sum_{q=1}^{Q} \alpha_q(\tau)\left[\mathbf{a}(\theta_q)\otimes\mathbf{b}(\theta_q)\right] + \tilde{\mathbf{n}}(\tau)\end{aligned}$$

- The noise term simplifies to

$$\tilde{\mathbf{n}}(\tau) = \operatorname{vec}\left(\int_{T_0} \mathbf{n}(t,\tau)\mathbf{\Phi}^H(t)dt\right)$$

- Noise statistics remain the same

MIMO Radar with Phase Rotation

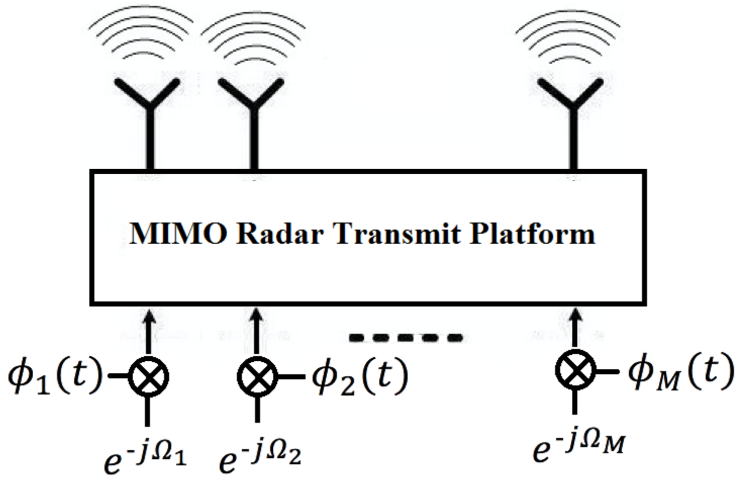
- Let $\boldsymbol{\Omega} = [e^{-j\Omega_1}, \dots, e^{-j\Omega_M}]$ be Mx1 vector of phase rotations
- Consider the vector phase-rotated orthogonal waveforms

$$\boldsymbol{\Psi}(t) = \boldsymbol{\Pi}\boldsymbol{\Phi}(t)$$

$\boldsymbol{\Pi} = diag(\boldsymbol{\Omega})$: Diagonal phase-shift matrix

- Note: The phase rotated waveforms preserve orthogonality

$$\boldsymbol{\Psi}(t)\boldsymbol{\Psi}^H(t) = \boldsymbol{\Pi}\boldsymbol{\Phi}(t)\boldsymbol{\Phi}^H(t)\boldsymbol{\Pi}^H = \boldsymbol{I}_M$$



MIMO radar with phase rotation

Scaling in lieu of Modulations

MIMO Radar with Phase Rotation

- Vector of received signals

$$\tilde{\mathbf{x}}(t,\tau) = \sum_{q=1}^{Q} \alpha_q(\tau)\left[\mathbf{a}^T(\theta_q)\boldsymbol{\Psi}(t)\right]\mathbf{b}(\theta_q) + \mathbf{n}(t,\tau)$$

- Matched-filtering to $\boldsymbol{\Psi}(\mathbf{t})$ yields

$$\begin{aligned}\tilde{\mathbf{y}}(\tau) &= \mathrm{vec}\left(\int_{T_0} \tilde{\mathbf{x}}(t,\tau)\boldsymbol{\Phi}^H(t)\boldsymbol{\Pi}^H dt\right) \\ &= \sum_{q=1}^{Q} \alpha_q(\tau)\left[\mathbf{a}(\theta_q) \otimes \mathbf{b}(\theta_q)\right] + \breve{\mathbf{n}}(\tau),\end{aligned}$$

- The AWGN term becomes

$$\breve{\boldsymbol{n}}(\tau) = [diag(\boldsymbol{\Omega}^*) \otimes \boldsymbol{I}_N]\tilde{\boldsymbol{n}}(\tau)$$

Note: AWGN statistics remain the same

- MIMO radar with Phase rotation yields same signal at matched-filter output

Proposed Information Embedding

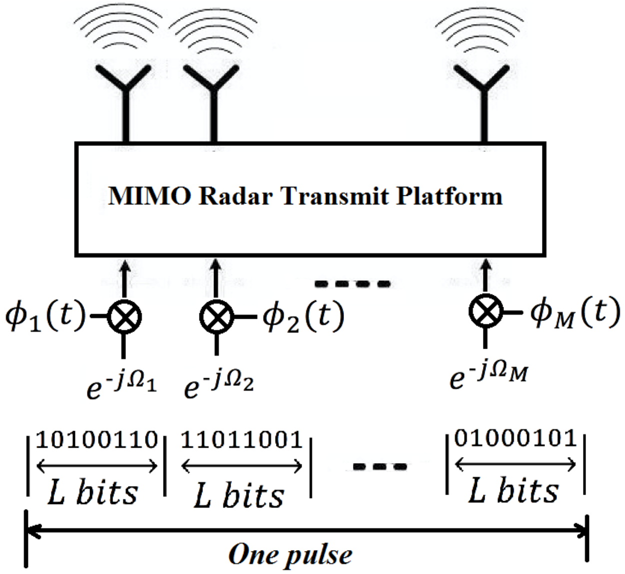
- The phase rotations $\Omega_m, m = 1, \ldots, M$ are used as communications symbols
- Each phase symbol represents '*L*' bits of binary data
- The symbols from a pre-defined constellation of size *K*, e.g.,

$$\mathbb{D}_{\text{PSK}} = \left\{0, \frac{2\pi}{K}, \ldots, \frac{(K-1)2\pi}{K}\right\}$$

- The number of bits per symbol $L = log_2 K$

Bits/pulse= $ML = Mlog_2 K$

Data rate=ML x pulse repetition frequency



Dual-function MIMO radar-communication

Communications Receiver Matched-Filter

- Assume that the waveforms are known at the communications receiver
- Matched-filtering the received signal to $\emptyset_m(t)$ yields

$$\begin{aligned} y_m(\tau) &= \int_{T_0} r(t)\phi_m^*(t)dt \\ &= \alpha_{\mathrm{ch}}\mathbf{a}_{[m]}e^{\Omega_m(\tau)} + w_m(\tau),\ m = 1,\ldots,M \end{aligned}$$

$\boldsymbol{a}_{[m]} = e^{-j2\pi d_m \sin\theta_c}$: m-th entry of transmit array steering vector

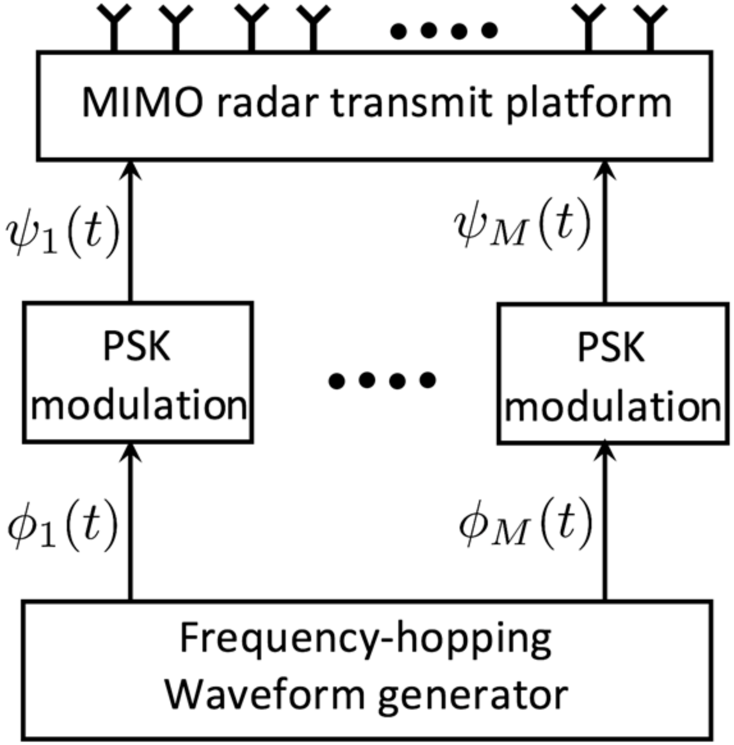
$w_m(\tau) = \int w(t,\tau)\emptyset^*(t)dt$: Additive noise

- The output of the m-th matched filter is a phase-shifted and noisy version of the m-th entry of the steering vector $\boldsymbol{a}(\theta_c)$
- In radar applications with a high PRF, such as in X-band radar, a data rate in the range of Mbps can be easily achieved

Frequency-Hopping Radar

$$\phi_m(t) = \sum_{q=1}^{Q} e^{j2\pi c_{m,q}\Delta f t} u(t-\Delta t),\ m = 1, \ldots, M$$

$$\psi_m(t) = \sum_{q=1}^{Q} e^{j\Omega_{m,q}} e^{j2\pi c_{m,q}\Delta f t} u(t-\Delta t)$$



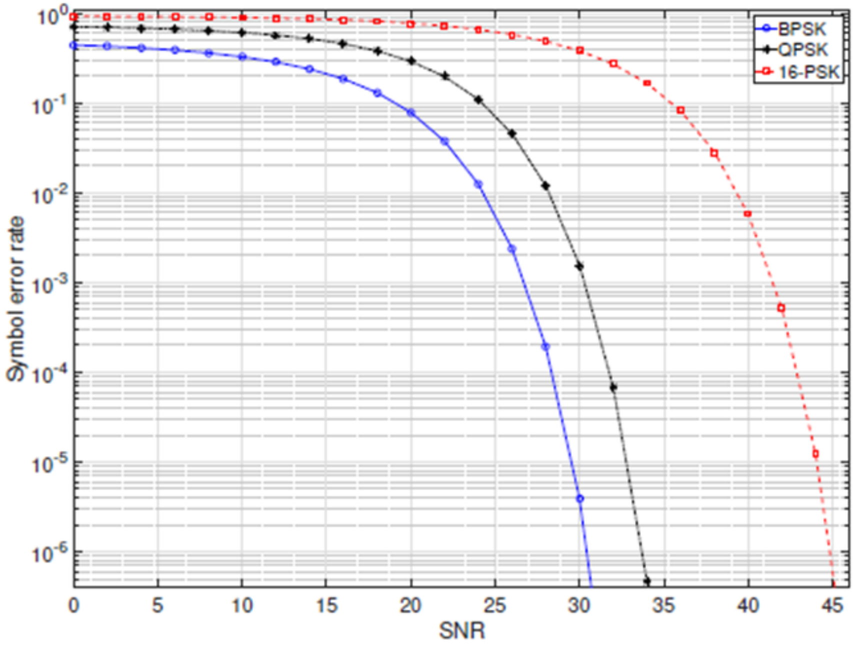
- Higher Data Rate
- Multiply by the length of FH code Q

X-band Radar Example

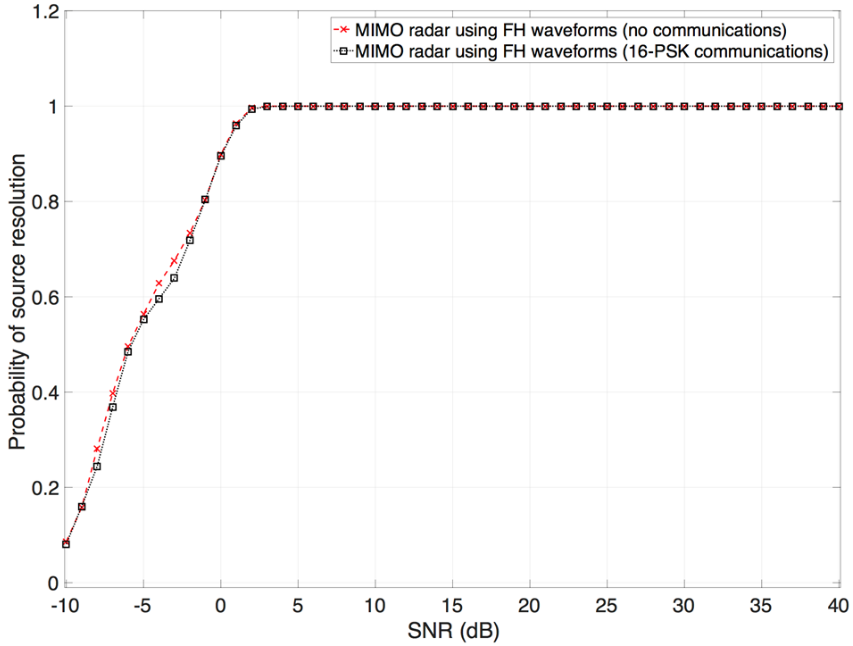
- Carrier Frequency- 8.2 GHz
- Bandwidth-500 MHz
- Sampling frequency- 1 GHz
- Pulse repetition Interval- 10 micro-sec
- Frequency Step- 10 MHz
- Time step- 1 micro-sec
- Number of antennas-16

- R=32, 64, 128 for BFSK, QPSK, and 16-PSK

Radar/Communications



BER
Source at 0 degree



MIMO-ESPRIT
Sources at 2 and 4 degrees

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Conclusions

- *Signal embedding is achieved through slow-time modulation, fast-time modulations, and scaling of radar waveforms.*
- *Proposed method permits information delivering towards arbitrary directions*
- *The communication process is inherently transparent to the primary radar operation of the dual-function system*
- *introduction of an RF system based on a shared frequency bandwidth and antenna aperture allows for integrated command and control systems and integrated sensor management*
- *Co-design and System-of-Opportunity provide the capability of simultaneous transmitting and receiving signals at multiple frequencies, reconfiguring the antenna beam patterns and polarization*