# Strategies for Radar-Communication Spectrum Sharing


Ammar Ahmed

Advanced Signal Processing Laboratory
Department of Electrical and Computer Engineering
Temple University

# Outline

- Spectrum Sharing and Its Importance
- Joint Radar-Communication Spectrum Sharing
- Proposed Approaches
- Miscellaneous Work

# Importance of Spectral Resources

- Spectrum of this world is like Real Estate
- The radio frequency (RF) spectrum is a finite but exceedingly valuable natural resource

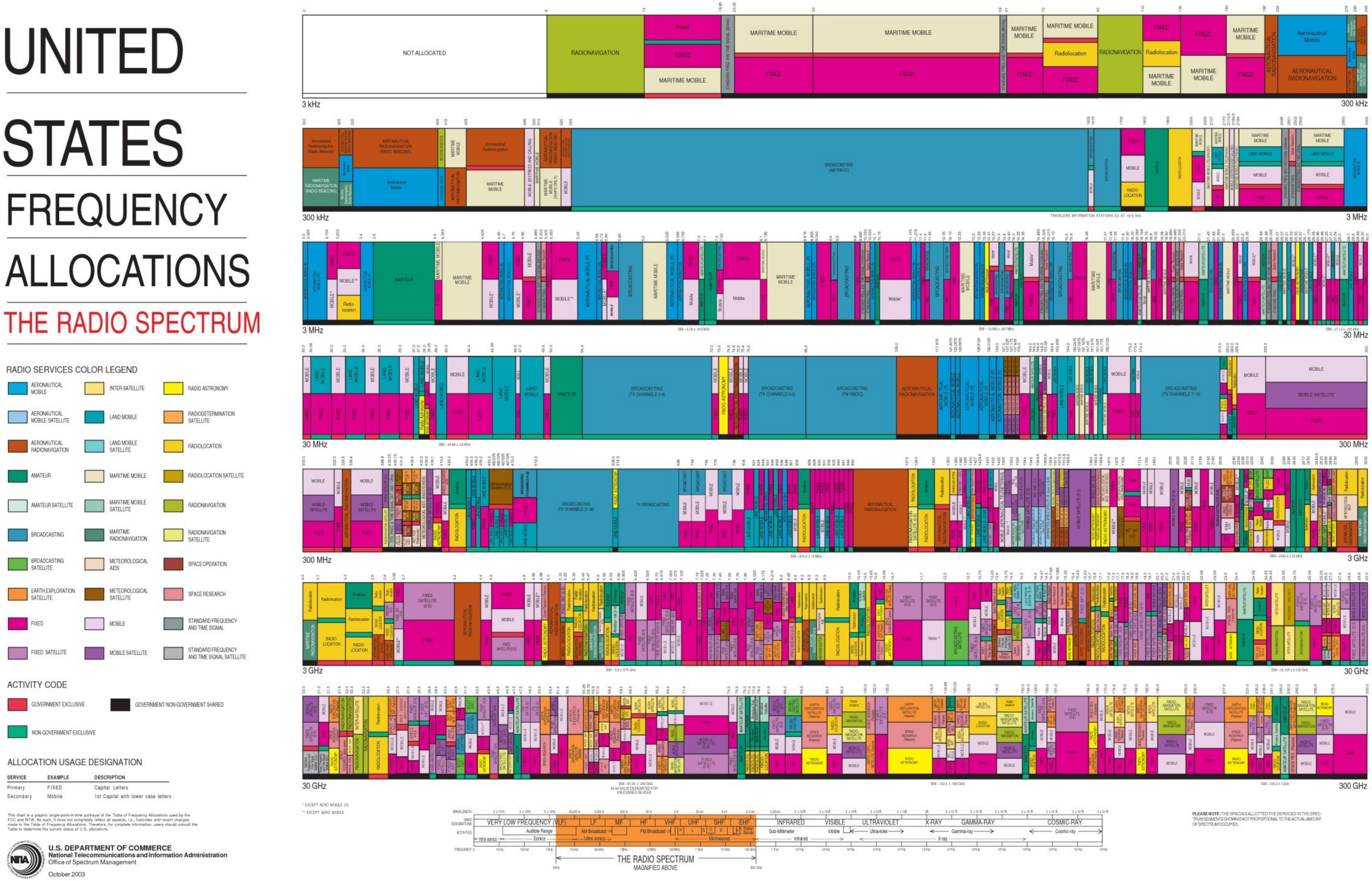
REUTERS U.S. wireless spectrum auction raises record $44.9 billion

**U.S. wireless spectrum auction raises record $44.9 billion**


A man looks at the Federal Communications Commission (FCC) headquarters. Photograph by Andrew Harrer— Bloomberg/Getty Images

FCC SPECTRUM AUCTION

**FCC's TV-for-Mobile Spectrum Auction Ends With $19.6 Billion Bid**


UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
AERONAUTICAL MOBILE
AERONAUTICAL MOBILE SATELLITE
AERONAUTICAL RADIONAVIGATION
AMATEUR
AMATEUR SATELLITE
BROADCASTING
BROADCASTING SATELLITE
EARTH EXPLORATION SATELLITE
FIXED
FIXED SATELLITE
INTER-SATELLITE
LAND MOBILE
LAND MOBILE SATELLITE
MARITIME MOBILE
MARITIME MOBILE SATELLITE
MARITIME RADIONAVIGATION
METEOROLOGICAL AIDS
METEOROLOGICAL SATELLITE
MOBILE
MOBILE SATELLITE
RADIO ASTRONOMY
RADIODETERMINATION SATELLITE
RADIOLOCATION
RADIOLOCATION SATELLITE
RADIONAVIGATION
RADIONAVIGATION SATELLITE
SPACE OPERATION
SPACE RESEARCH
STANDARD FREQUENCY AND TIME SIGNAL
STANDARD FREQUENCY AND TIME SIGNAL SATELLITE
ACTIVITY CODE
GOVERNMENT EXCLUSIVE
GOVERNMENT/ NON-GOVERNMENT SHARED
NON-GOVERNMENT EXCLUSIVE
ALLOCATION USAGE DESIGNATION
SERVICE
EXAMPLE
DESCRIPTION
Primary
FIXED
Capital Letters
Secondary
Mobile
1st Capital with lower case letters
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
300 kHz
3 MHz
3 MHz
30 MHz
30 MHz
300 MHz
300 MHz
3 GHz
3 GHz
30 GHz
30 GHz
300 GHz
NOT ALLOCATED
RADIONAVIGATION
MARITIME MOBILE
BROADCASTING (AM RADIO)
BROADCASTING (TV CHANNELS 2-4)
BROADCASTING (FM RADIO)
BROADCASTING (TV CHANNELS 7-13)
BROADCASTING (TV CHANNELS 21-36)
TV BROADCASTING
VERY LOW FREQUENCY (VLF)
LF
MF
HF
VHF
UHF
SHF
EHF
INFRARED
VISIBLE
ULTRAVIOLET
X-RAY
GAMMA-RAY
COSMIC-RAY
THE RADIO SPECTRUM
MAGNIFIED ABOVE

# Why Spectrum Sharing?

- 5G and 6G will be providing tremendous throughput gain
  - 5G is significantly efficient than 4G
  - Requires more spectrum

- New applications (IoT)

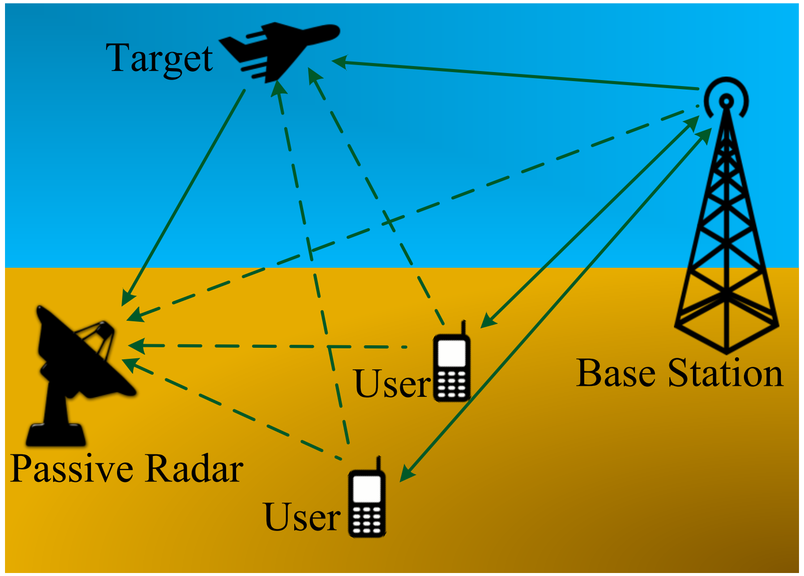
- Regulatory bodies are forcing applications to leave/share the spectrum
  - DARPA initiated Shared Spectrum Access for Radar and Communications

https://www.darpa.mil/program/shared-spectrum-access-for-radar-and-communications

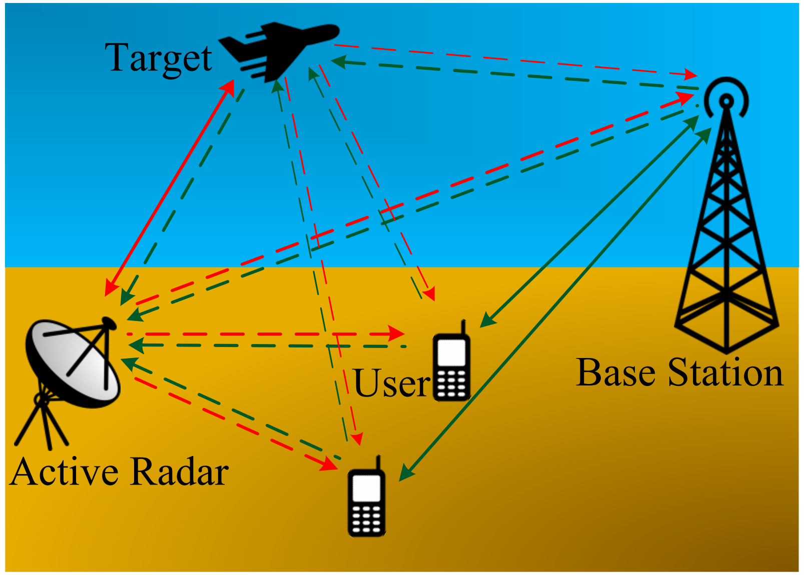
# Radar-Communication Spectrum Sharing

- Spectrum efficiency is important
  - Cognitive Radio
  - Spectrum Sharing
- Three types of radar-communication spectrum sharing scenario

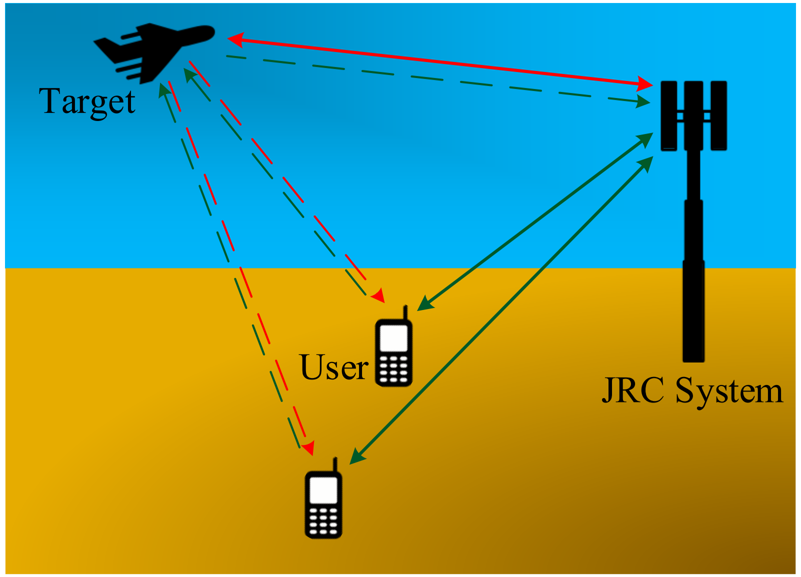
**Passive Radar**




**Co-existence**

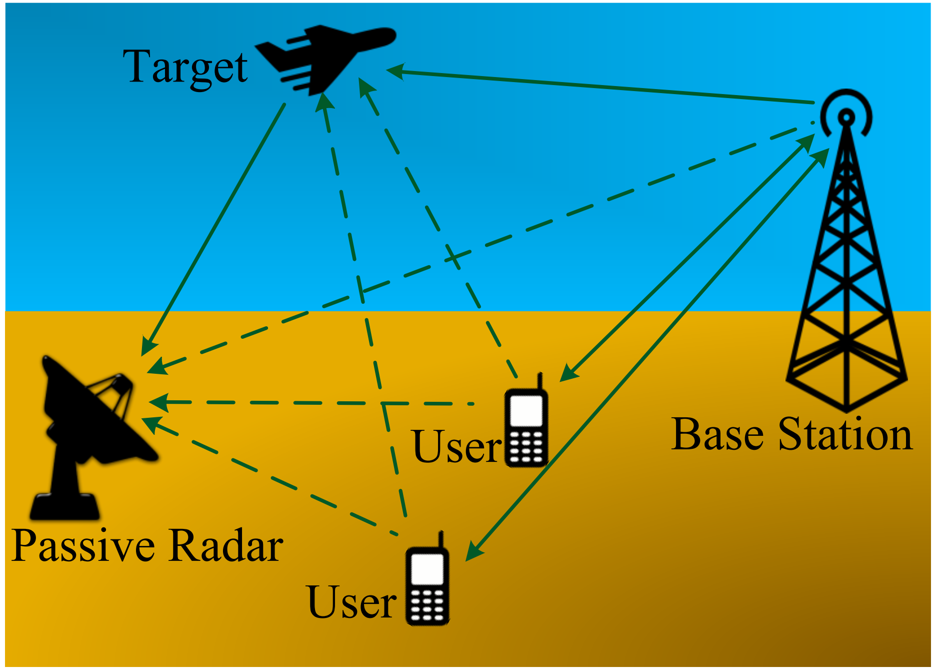



**Joint Radar-Communication**



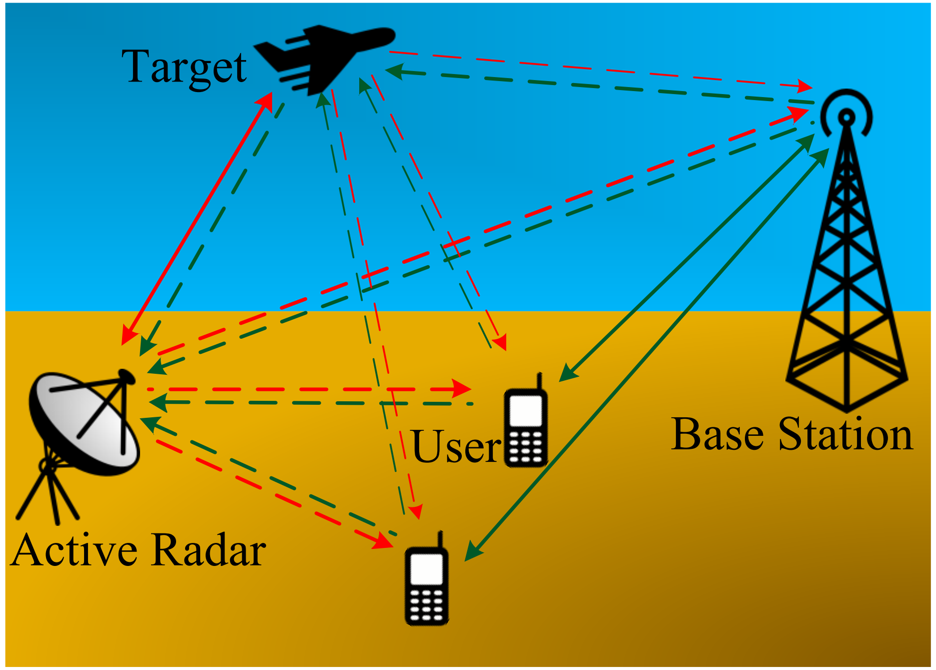
# Passive Radar

- Radar uses non-cooperative sources
  - FM radio signals
  - Cellular base stations
- Advantages on radar side
  - Low cost (no radar transmitters)
  - Covert
  - No need of frequency allocations
  - Resistance to jamming
- Disadvantages
  - No control on transmitters
  - Complex receivers



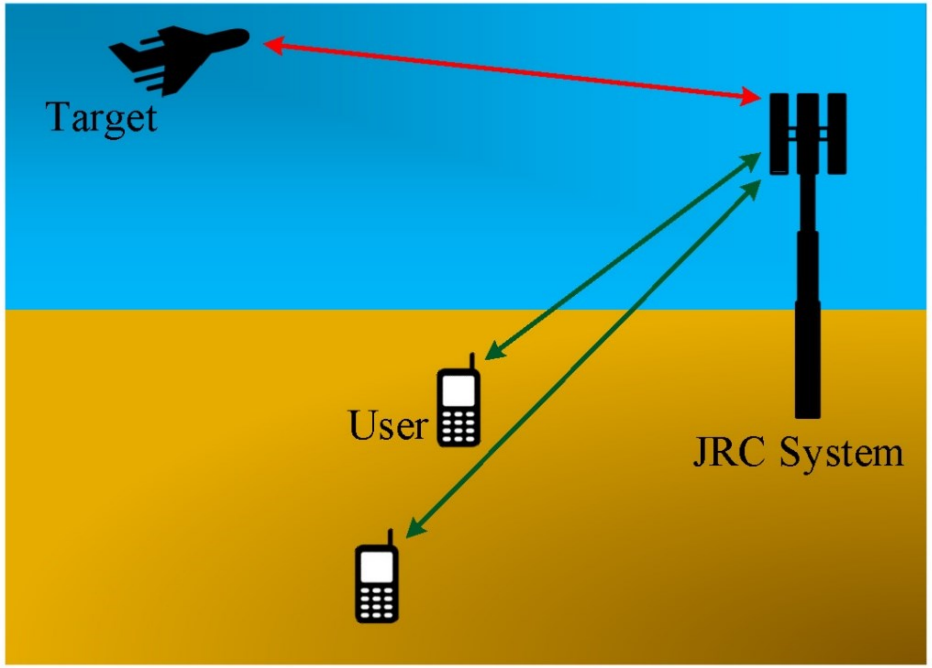
# Co-existence

- Sharing of frequency spectrum by
  - Radar
  - Communications
- Advantage
  - Same frequency spectrum is used
- Disadvantage
  - Interference between radar and communication systems
  - Huge difference between transmit powers
    - Base station ~ 100W
    - Radar ~ KW-MW



# Joint Radar-Communication

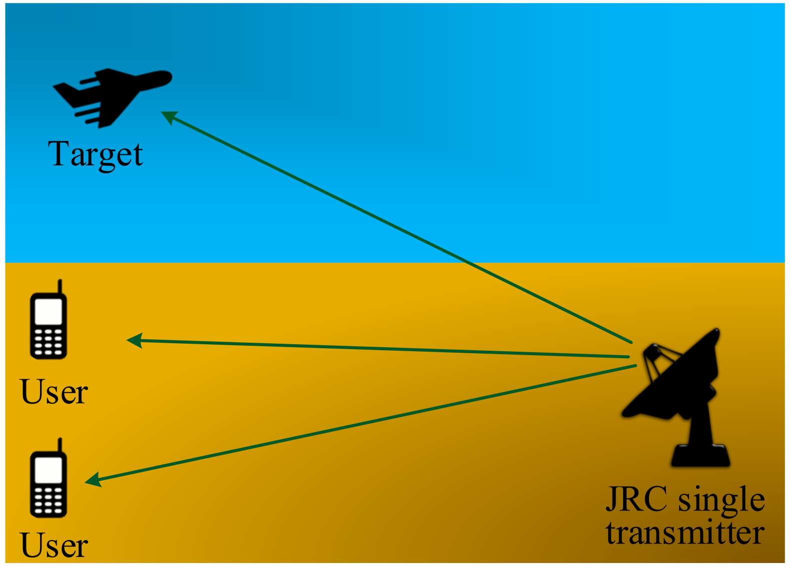
- Joint transmission
  - Transmit system is shared by radar and communication systems
  - Primary operation: radar task
  - Secondary operation: communication task
- Advantages
  - No mutual interference
  - Simple hardware design
- Disadvantages
  - Communication and radar signals are not optimal for each other

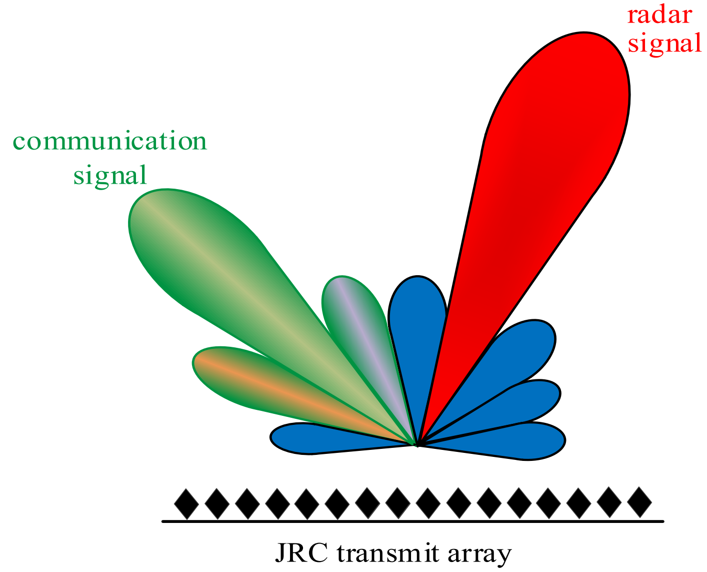


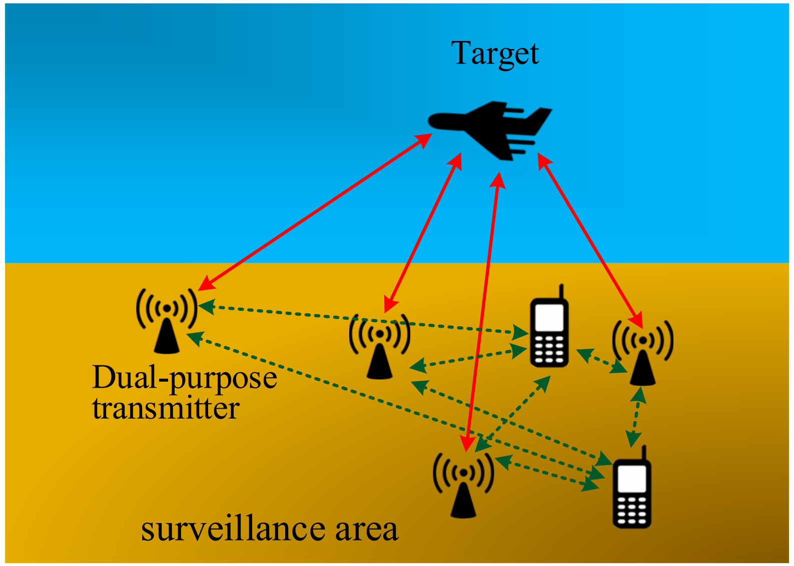
# Joint Radar-Communication (JRC) System[1]

## Three types of JRC systems

| Single JRC transmitter[2] | JRC transmit array[3] | Distributed JRC[4] |
|---|---|---|



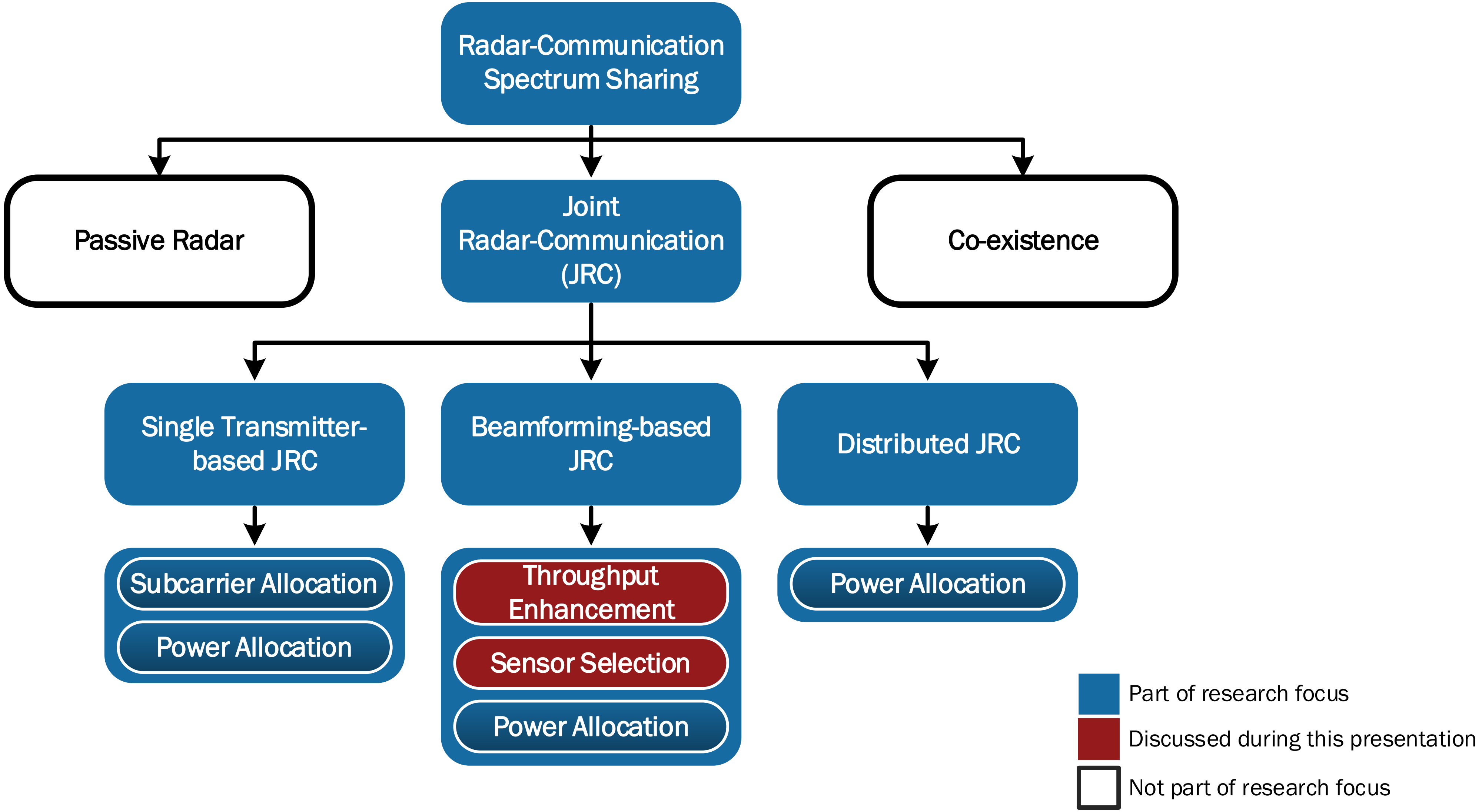





1. **A. Ahmed**, Y. D. Zhang, "Optimized resource allocation for joint radar-communications," in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.
2. **A. Ahmed**, Y. D. Zhang, A. Hassanien, B. Himed, "OFDM-based joint radar-communication system: optimal sub-carrier allocation and power distribution by exploiting mutual information," Asilomar Conference on Signals, Systems, and Computers, Nov. 2019.
3. **A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.
4. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Distributed dual-function radar-communication MIMO system with optimized resource allocation," IEEE Radar Conference, April 2019.

# Research Scope



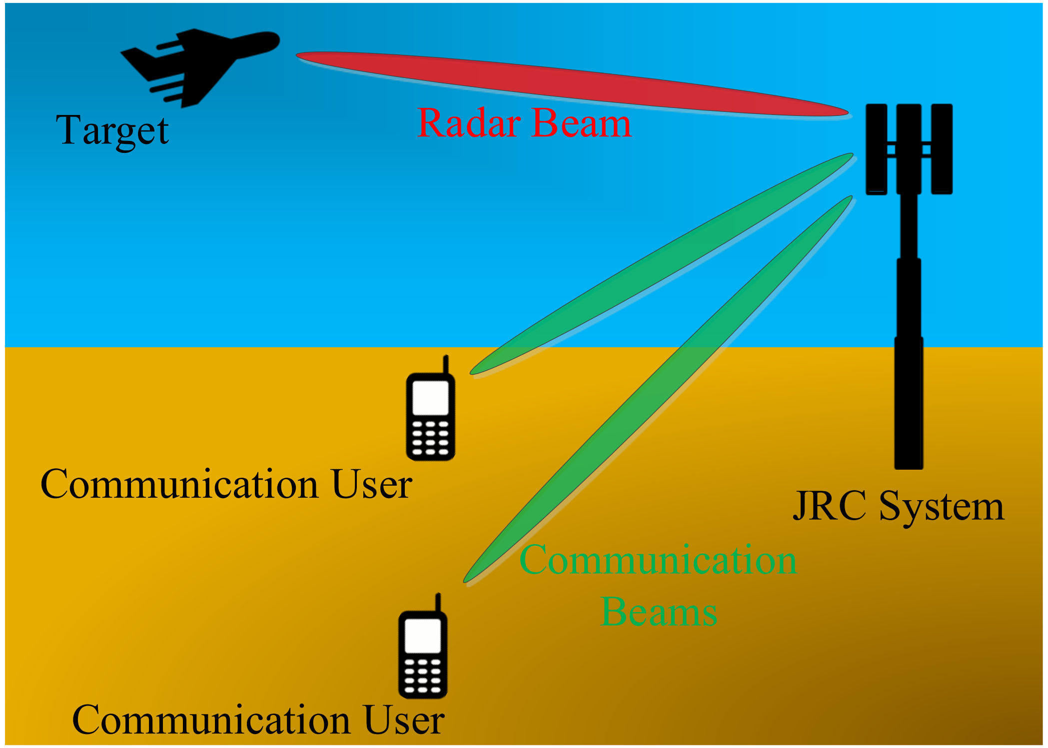
# Beamforming-based JRC

# Beamforming-based JRC

- Beamforming is employed by exploiting a sensor array
  - Radar beam serves radar purpose
  - Communication beams serve communication purpose

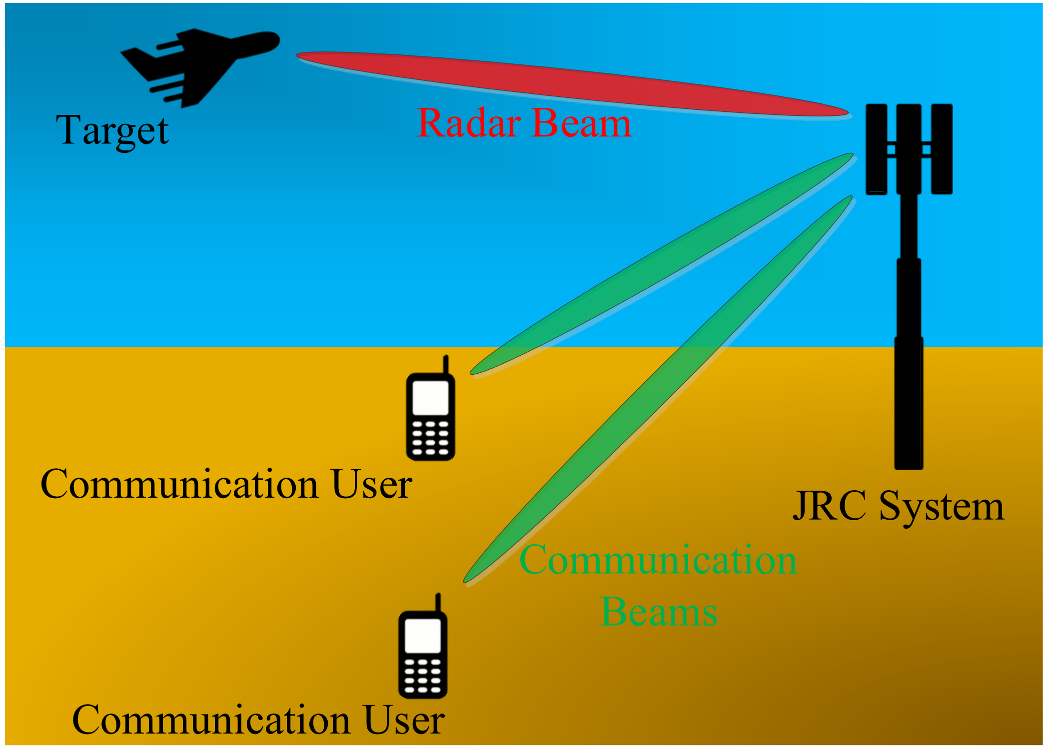
- Spectrum sharing techniques
  - Spatial multiplexing
  - Waveform diversity

  (similar concept as CDMA)



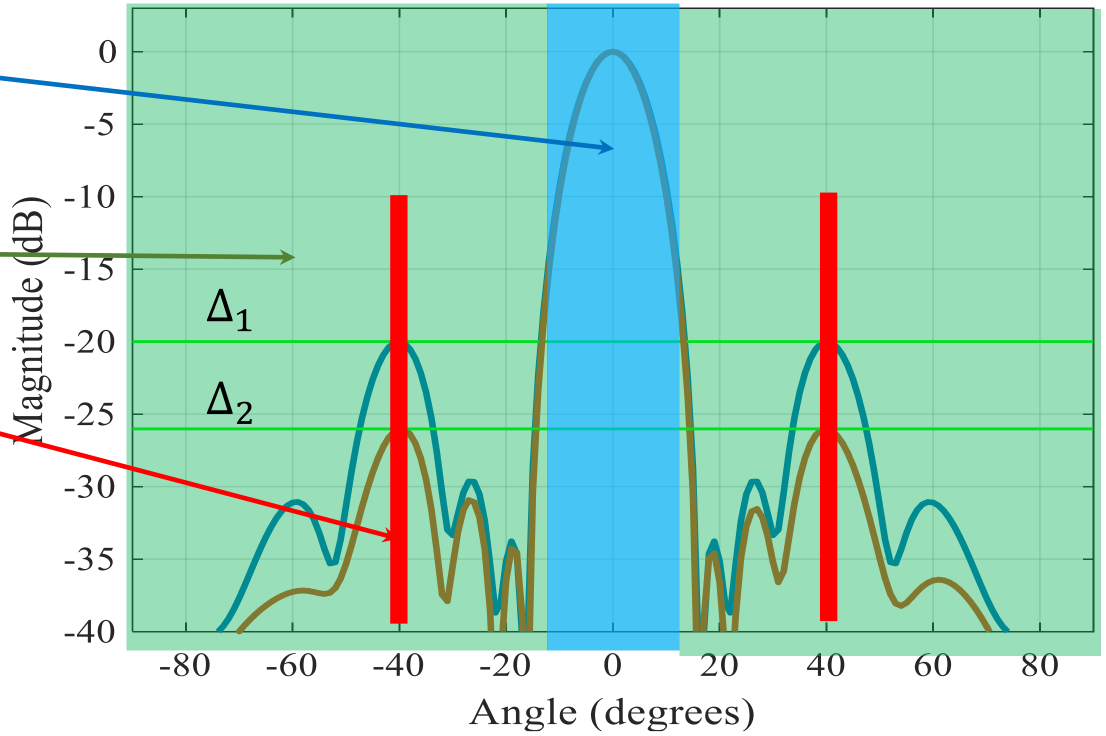
# Existing Approaches

- Sidelobe communication
  - Sidelobe Amplitude Shift Keying (ASK)
  - Sidelobe Phase Shift Keying (PSK)
- Mainlobe communication
  - Phase Shift Keying (PSK)
  - Will not discuss



# Sidelobe Amplitude Shift Keying

- Objective is to design beamforming weight vector
  - $\boldsymbol{\theta}$ contains directions of radar operation
  - $\bar{\boldsymbol{\theta}}$ is the compliment set of $\boldsymbol{\theta}$
  - $\boldsymbol{\theta}_c$ contains directions of communication operation
  - $\Delta_n$ is the amplitude level

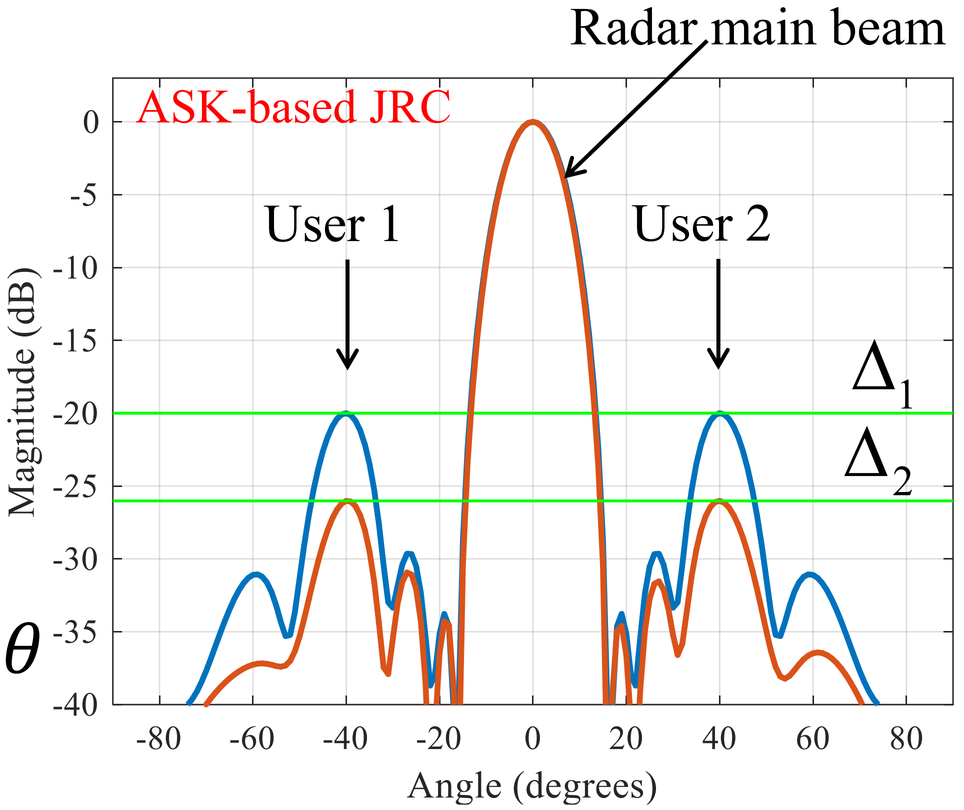


# Sidelobe Amplitude Shift Keying

- Narrow main beam synthesis

$$\begin{aligned} \min_{\mathbf{u}_n} \quad & \left|\mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta)\right| \\ \text{subject to} \quad & \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_r) = 1, \quad \theta_r \in \boldsymbol{\Theta} \\ & \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_c) = \Delta_n, \quad \theta_c \in \boldsymbol{\Theta}_\mathrm{c} \end{aligned}$$

  - $\mathbf{u}_n$ is the beamforming weight vector
  - $\mathbf{a}(\theta)$ is array manifold in the direction of $\theta$
  - $\Delta_n$ is the level corresponding to $\mathbf{u}_k$

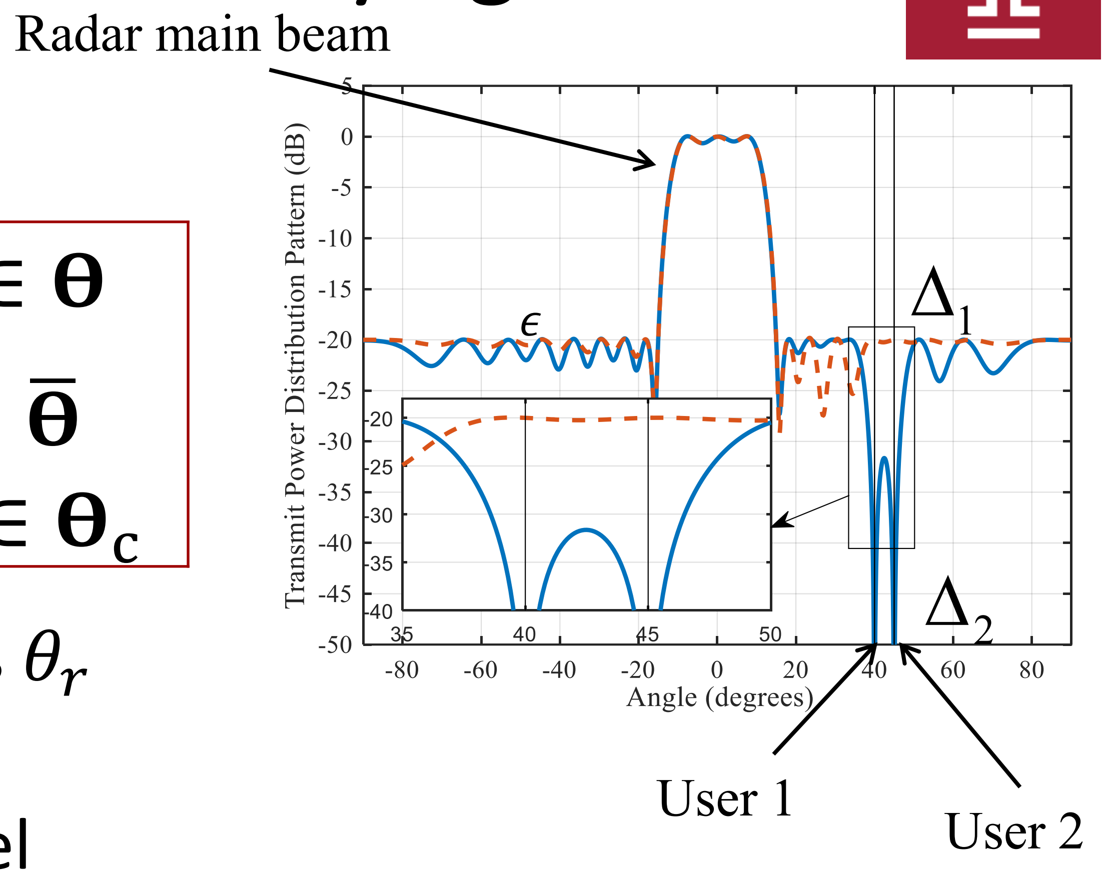



A. Hassanien, M. G. Amin, Y. D. Zhang and F. Ahmad, "Dual-function radar-communications: Information embedding using sidelobe control and waveform diversity," IEEE Transactions on Signal Processing, April 2016.

# Sidelobe Amplitude Shift Keying

- Wide main beam (convex form)

$$
\begin{aligned}
\min_{\mathbf{u}_n}\ \max_{\theta_r}\quad & \left|e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_r)\right|, && \theta_r \in \boldsymbol{\Theta} \\
\text{subject to}\quad & \left|\mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta)\right| \le \epsilon, && \theta \in \bar{\boldsymbol{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_c) = \Delta_n, && \theta_c \in \boldsymbol{\Theta}_c
\end{aligned}
$$




  - $\phi(\theta_r)$ radar phase response towards $\theta_r$
  - $\phi(\theta_r)$ is the free parameter
  - $\epsilon$: worst-case allowable sidelobe level
- This optimization is convex; however, different solutions exist for different $\phi(\theta_r)$

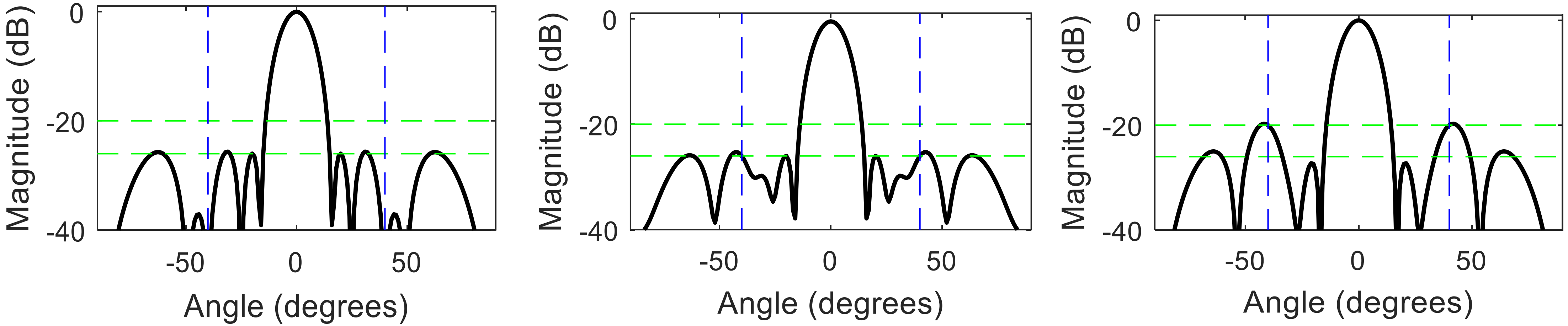
A. Hassanien, M. G. Amin, Y. D. Zhang and F. Ahmad, "Dual-function radar-communications: Information embedding using sidelobe control and waveform diversity," IEEE Transactions on Signal Processing, April 2016.

# Communication Operation

- If one radar waveform $\psi(t)$ is used

$$\mathbf{s}(t,\tau) = \sqrt{P}\mathbf{u}_n(\tau)\psi(t)$$

  - $P$ is the total transmit power
  - $\tau$ is slow time, $t$ is fast time
  - Note that the beamforming vector changes with slow time




Low data rate because only one waveform is utilized

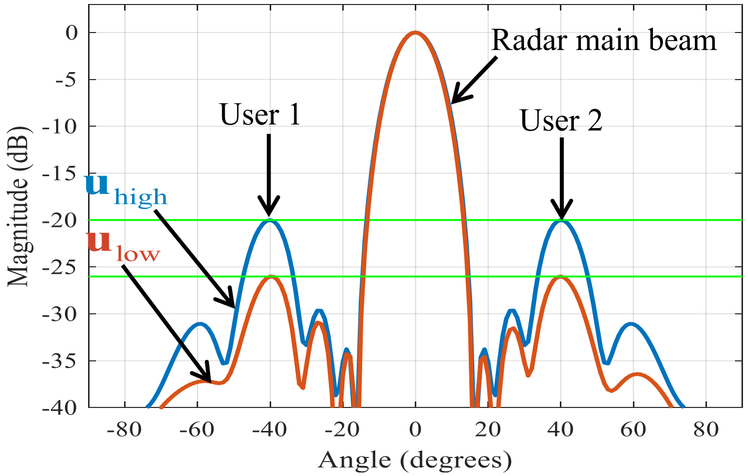
J. Euziere, R. Guinvarc'h, M. Lesturgie, B. Uguen, R. Gillard, "Dual-function radar-communication time-modulated array," International Radar Conference, Oct. 2014.

# Communication Operation

- With waveform diversity, $K$ orthogonal waveforms are used

$$\mathbf{s}(t,\tau) = \sqrt{\frac{P}{K}} \sum_{k=1}^{K} \left(b_k(\tau)\mathbf{u}_{\text{low}}^* + \left(1 - b_k(\tau)\right)\mathbf{u}_{\text{high}}^*\right)\psi_k(t)$$

- At communication receivers
  - $\mathbf{u}_{\text{high}}$ corresponds to low sidelobe level
  - $\mathbf{u}_{\text{low}}$ corresponds to low sidelobe level
  - $b_k$ is selection coefficient
    - (changes with slow-time)




This has low data rate because same information is broadcast to all users (multiplexing will be required for multiple access)

A. Hassanien, M. G. Amin, Y. D. Zhang and F. Ahmad, "A dual function radar-communications system using sidelobe control and waveform diversity," IEEE Radar Conference, May 2015.

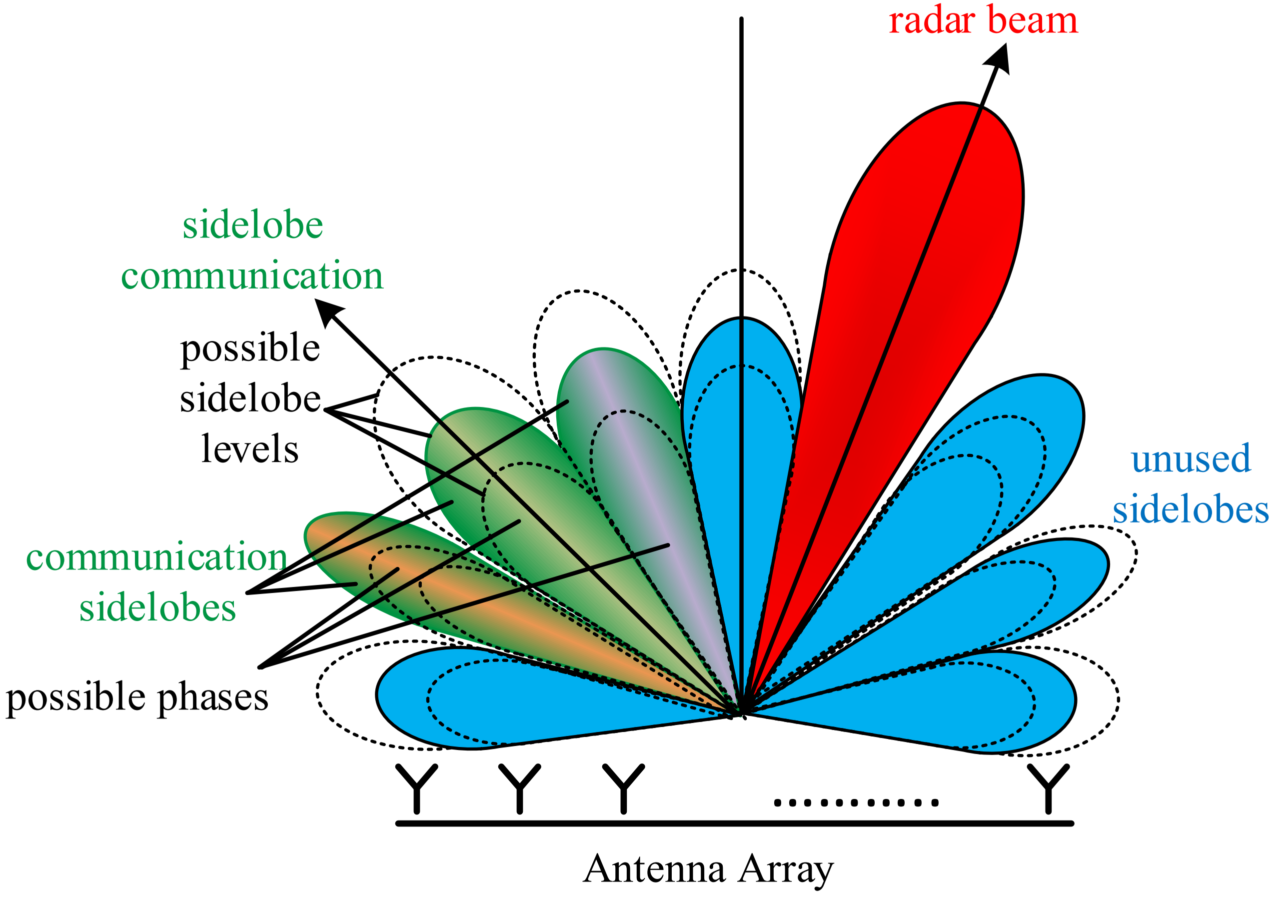
# Proposed Beamforming-based JRC Approaches

- Throughput enhancement
  - Multiple access-based ASK scheme[1]
  - Multiple access-based QAM scheme[2]
- Power allocation for beamforming based JRC system[3]
- Sensor selection for beamforming based JRC system[4,5]


1. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Multi-user dual-function radar-communications exploiting sidelobe control and waveform diversity," IEEE Radar Conference, April 2018.
2. **A. Ahmed**, Y. Gu, D. Silage, and Y. D. Zhang, "Power-efficient multi-user dual-function radar-communications," IEEE International Workshop on Signal Processing Advances in Wireless Communications, June 2018.
3. **A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.
4. **A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.
5. **A. Ahmed**, Y. D. Zhang, "" Optimized resource allocation for joint radar-communications," in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.

# Proposed Multiple Access-based QAM Scheme

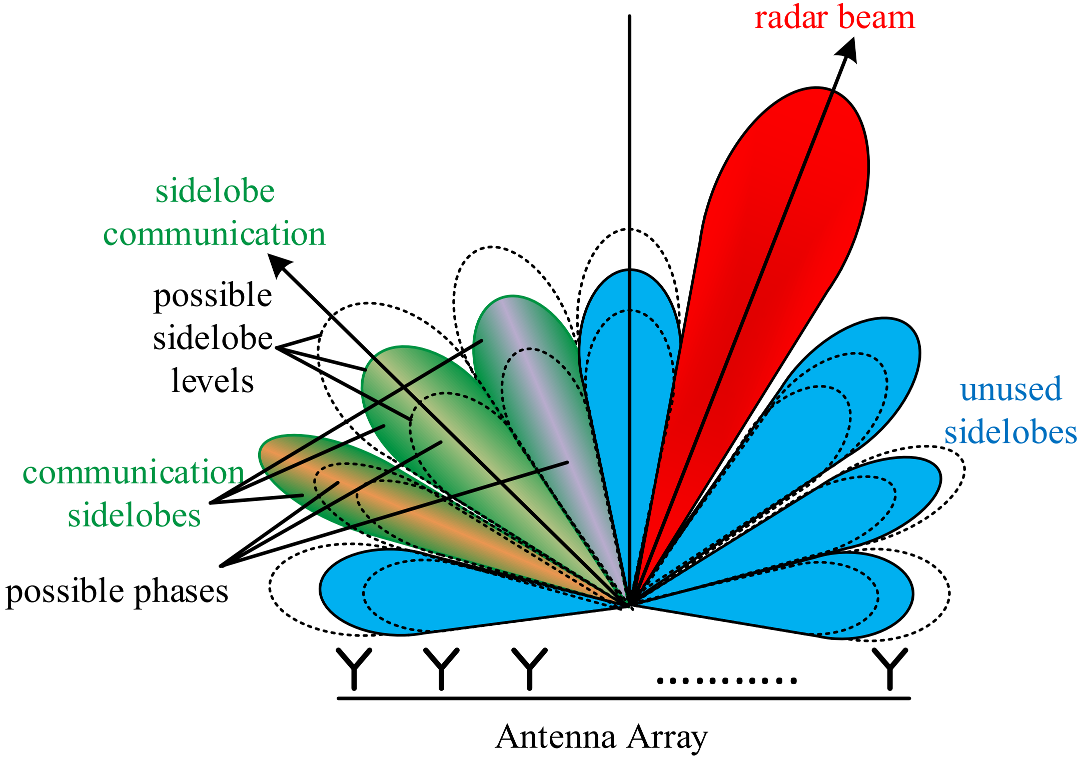
- Design the beamforming vectors such that multiple access is possible
- Communication users get distinct amplitude levels and phases
- The projected amplitudes and phases towards different users can be different and controllable
- This is contrary to the existing schemes which send the same information to all users




A. **Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

# Proposed Multiple Access-based QAM Scheme

- Transmit array-based beamforming for radar and communication tasks
- $C$: communication users
  - $c$th communication user located towards $\theta_c$ $(c = 1, \cdots, C)$
  - Sidelobe communication is considered
- At each communication user, we can have
  - $L$: number of possible amplitude levels
  - $Q$: number of possible phases
  - All the waveforms used at the transmitter are known by the communication users




**A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

# Proposed Multiple Access-based QAM Scheme

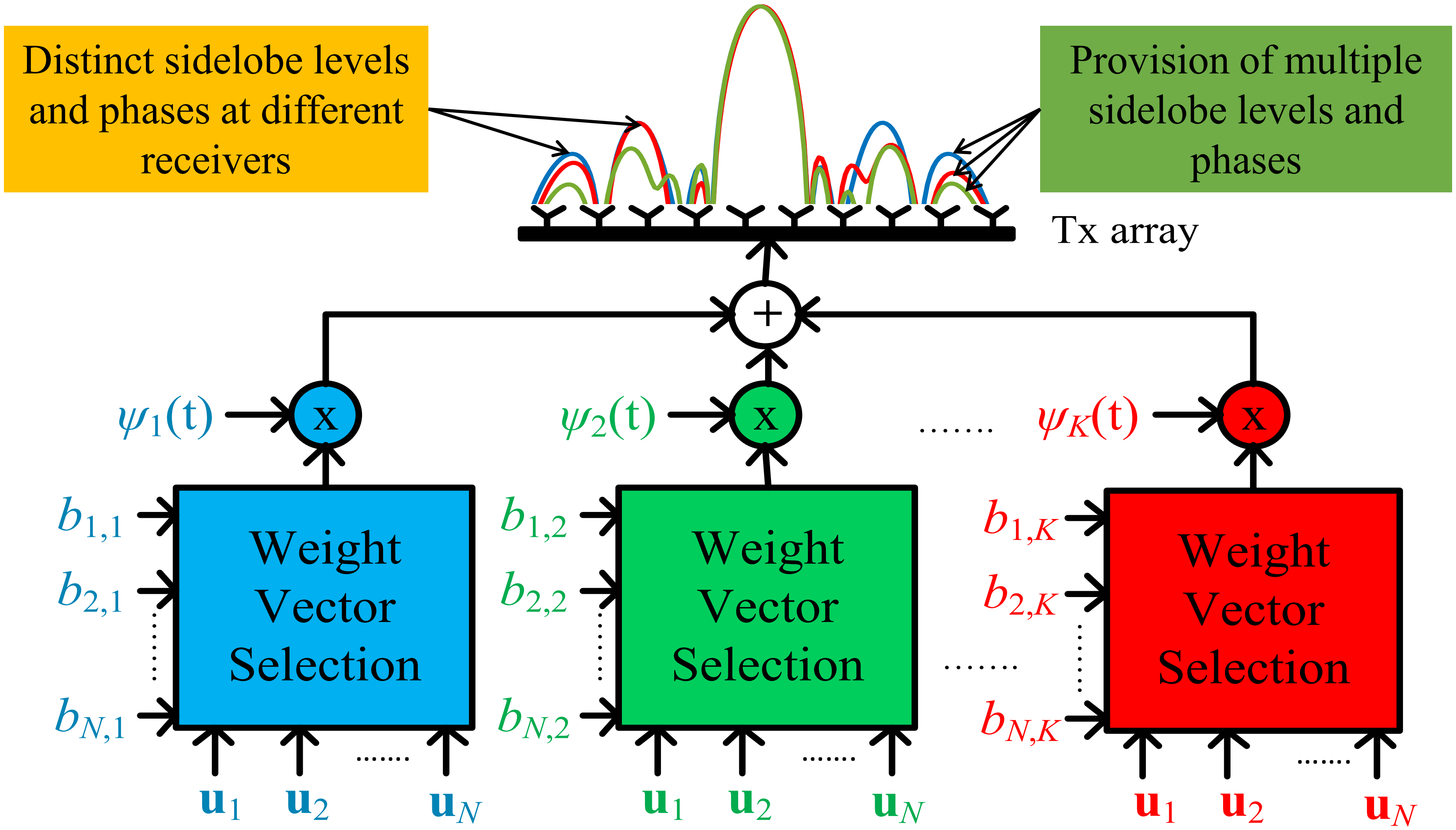
- Wide main beam (convex form)

$$
\begin{aligned}
\min_{\mathbf{u}_n} \max_{\theta_r} \quad & \left| e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r) \right|, && \theta_r \in \boldsymbol{\Theta} \\
\text{subject to} \quad & |\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta)| \le \epsilon, && \theta \in \overline{\boldsymbol{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c) e^{j\varphi_n(\theta_c)}, && \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}}
\end{aligned}
$$

- $\Delta_n(\theta_c)$ is the amplitude projected by $n$th beamforming vector towards $c$th user
- $e^{j\varphi_n(\theta_c)}$ is the phase projected by $n$th beamforming vector towards $c$th user
- $N = (LQ)^C$ beamforming weight vectors will be required

**A. Ahmed**, Y. D. Zhang, and Y. Gu, “Dual-function radar-communications using QAM-based sidelobe modulation,” Digital Signal Processing, Nov. 2018.

# Proposed Multiple Access-based QAM Scheme




**A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

# Communication Operation

- With waveform diversity, $K$ orthogonal waveforms are used

$$\mathbf{s}(t,\tau) = \sqrt{\frac{P}{K}} \sum_{k=1}^{K} \mathbf{U}\mathbf{b}_k(\tau)\psi_k(t)$$

- $\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_N]$ is dictionary of beamforming vectors
- $\mathbf{b}_k$ is $(N \times 1)$ binary selection vector whose element-wise sum is unity

**A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

# Sum Data Rate Analysis

- At each receiver
  - $L$ allowable sidelobe levels
  - $Q$ allowable phases
  - Each waveform transmits $\log_2(LQ)$ bits/pulse to each user
  - $K$ waveforms transmit $K\log_2(LQ)$ bits/pulse to each user
- $C$ users, each user can get different data simultaneously

Overall data rate: $CK\log_2(LQ)$

**A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

# Proposed Multiple Access-based QAM Scheme

- ASK-based simplification

$$\begin{aligned} \min_{\mathbf{u}_n} \max_{\theta_r} \quad & \left| e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r) \right|, && \theta_r \in \boldsymbol{\Theta} \\ \text{subject to} \quad & \left| \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta) \right| \le \epsilon, && \theta \in \overline{\boldsymbol{\Theta}} \\ & \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c), && \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}} \end{aligned}$$

- For ASK-based scheme, allowable phases $Q = 1$
- Overall data rates
  - Proposed ASK[1]: $CK\log_2(L)$
  - Proposed QAM[2]: $CK\log_2(LQ)$
  - Existing approaches: $K\log_2(L)$

1. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Multi-user dual-function radar-communications exploiting sidelobe control and waveform diversity," IEEE Radar Conference, April 2018.
2. **A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

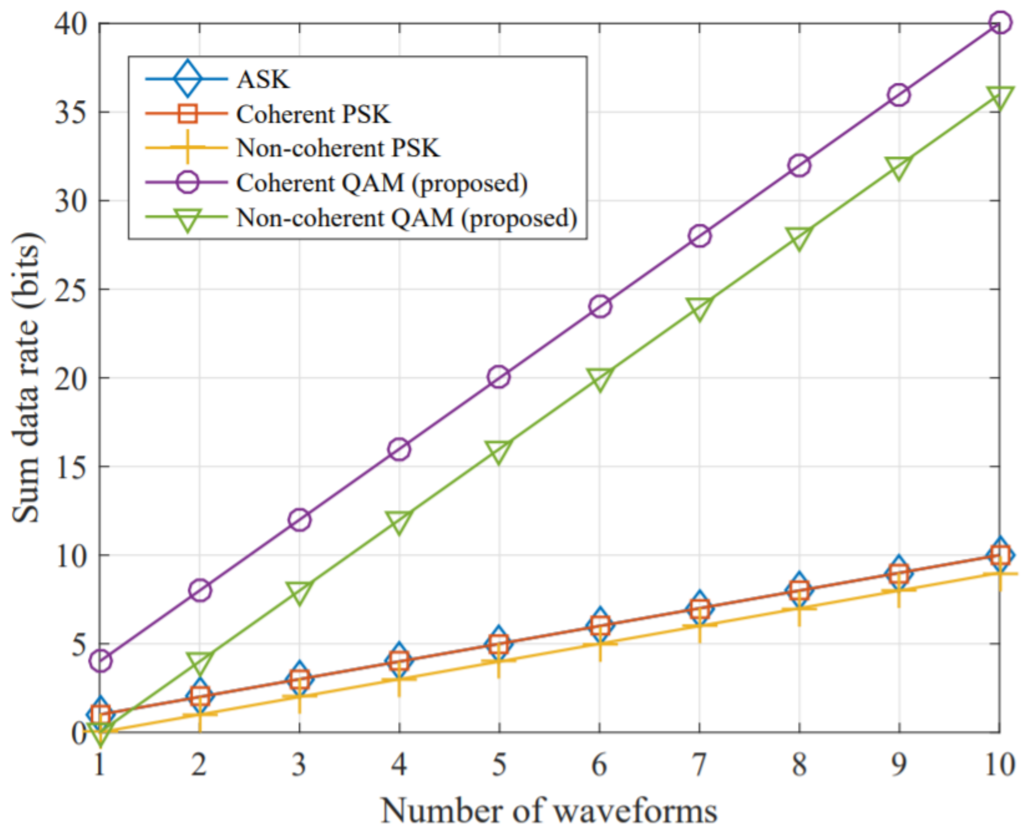
# Coherent vs Non-coherent Detection

- Coherent detection
  - The start time of pulses are known at the communication receivers
- Non-coherent detection
  - Communication receivers are blind about the pulse start time
  - One waveform can be used as reference that can be exploited to estimate the start time of the pulse (matched filtering)
- Non-coherent communication sum data rates
  - Proposed ASK[1]: $C(K-1)\log_2(L)$
  - Proposed QAM[2]: $C(K-1)\log_2(LQ)$
  - Existing approaches: $(K-1)\log_2(L)$

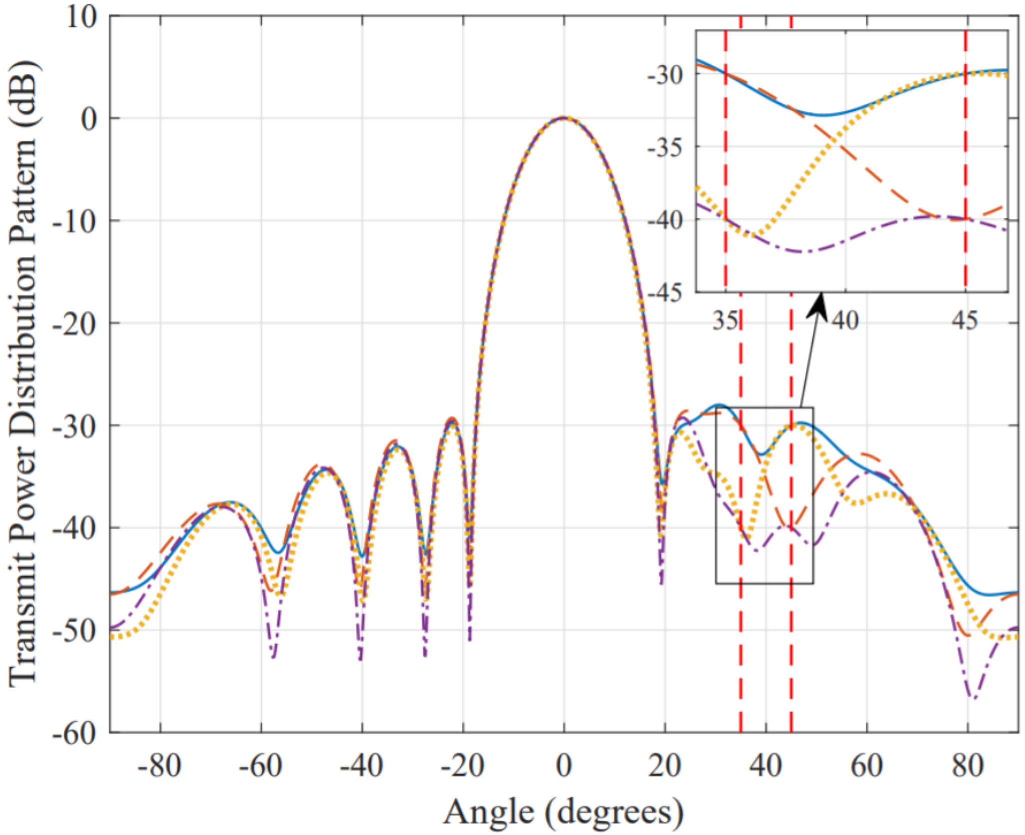

1. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Multi-user dual-function radar-communications exploiting sidelobe control and waveform diversity," IEEE Radar Conference, April 2018.
2. **A. Ahmed**, Y. D. Zhang, and Y. Gu, "Dual-function radar-communications using QAM-based sidelobe modulation," Digital Signal Processing, Nov. 2018.

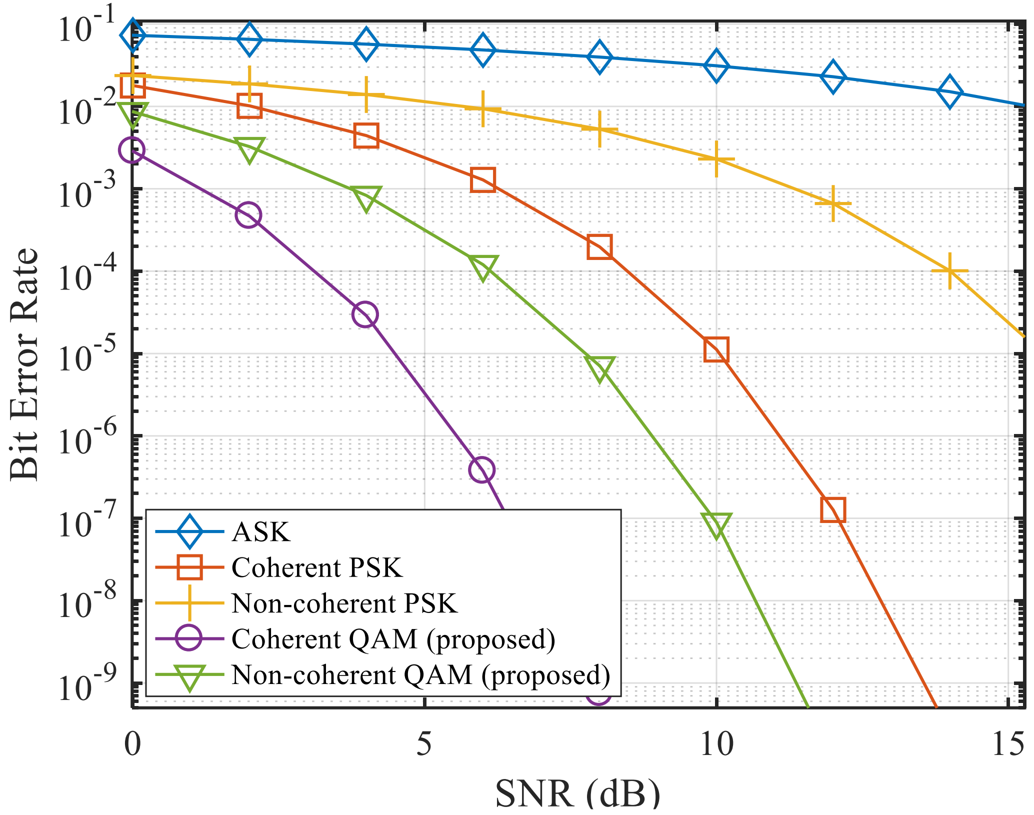
# Simulation Results

- Communication users located at 35º and 45º
- Radar main beam directed towards 0º
- Possible communication sidelobe levels are two
- Possible communication sidelobe phases are two
- Uniform linear array consisting of 20 sensors is used



# Simulation Results

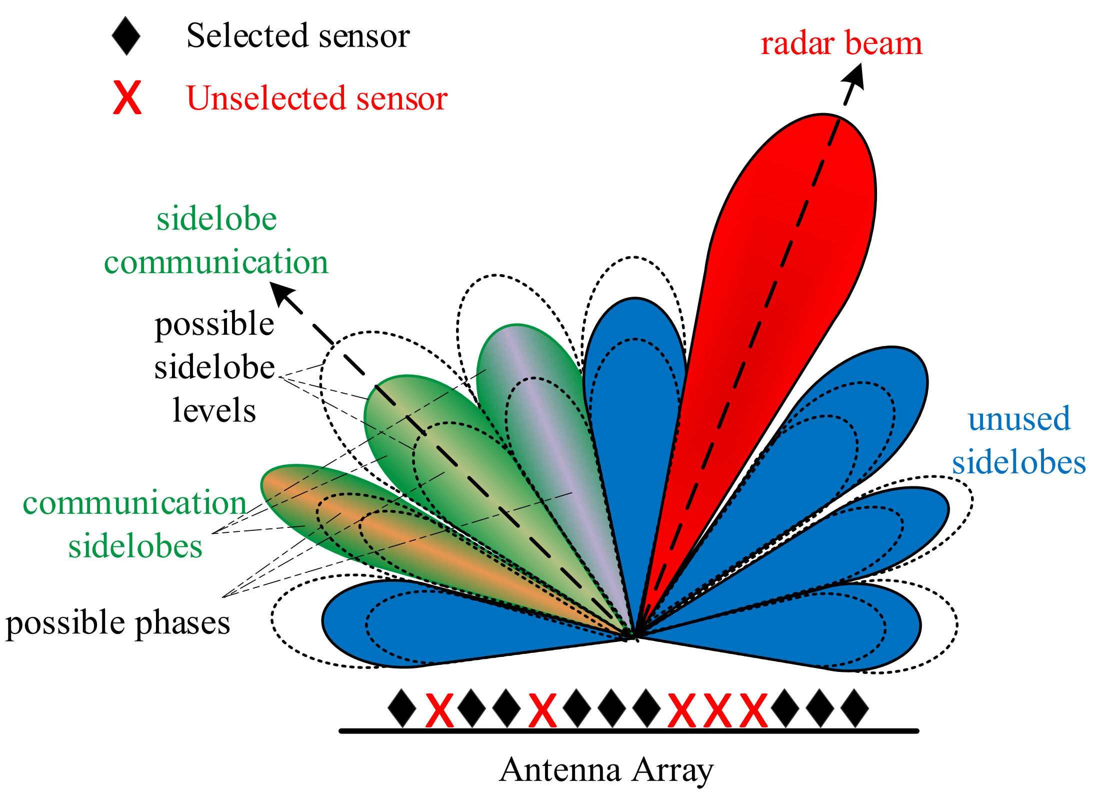



*BER are plotted for the same overall data rate with two waveforms, i.e, the number for levels for ASK and number of phases for PSK have been increased to match the QAM data rate

# Proposed Sensor Selection-based Beamforming Strategy

- Sensor deployment is cheaper than the radio frequency (RF) chains
- Total number of sensors exceeds the available RF chains
- Optimized sensor selection is anticipated as attractive means to achieve superior performance

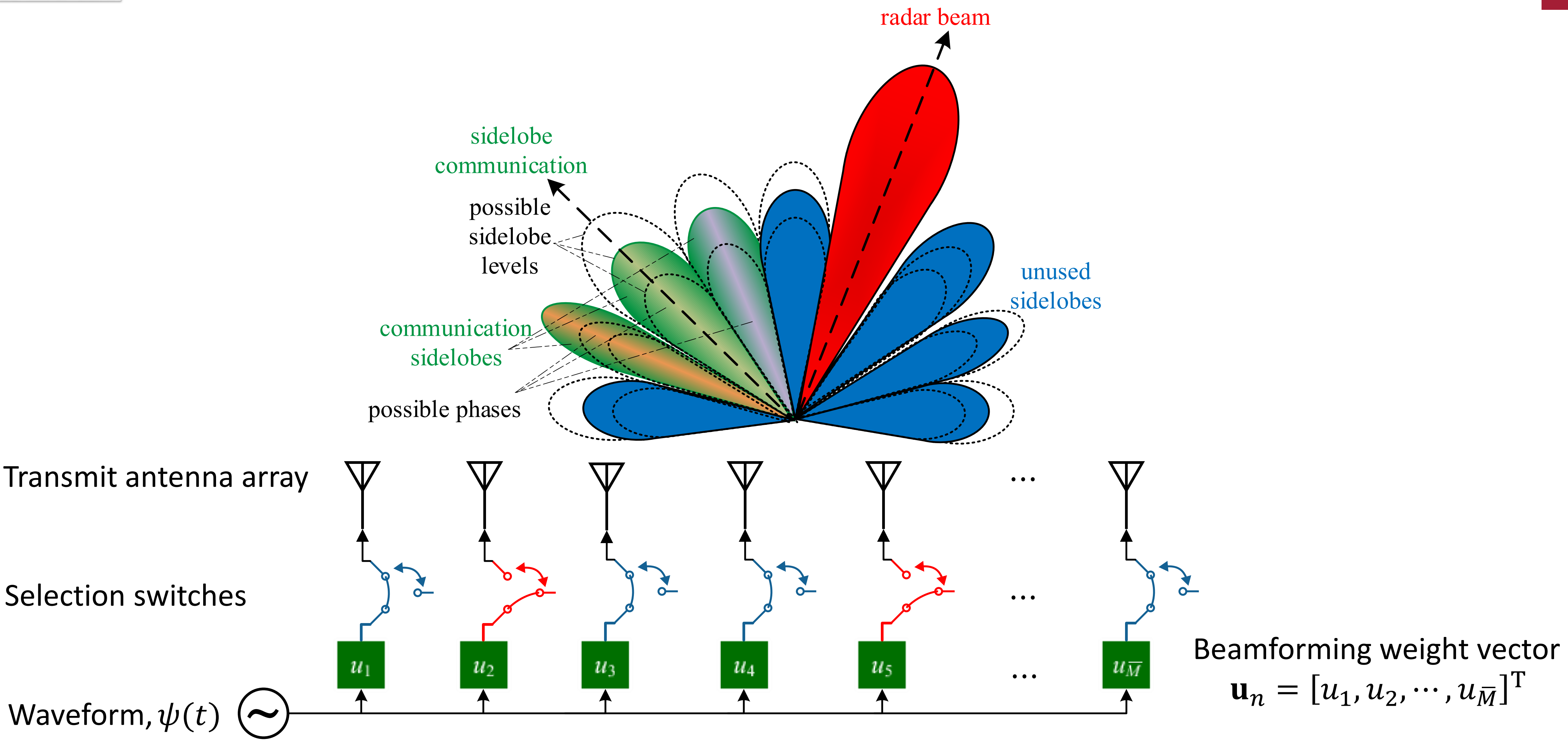



**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

**A. Ahmed**, Y. D. Zhang, "Optimized resource allocation for joint radar-communications," in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.

**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Optimized sensor selection for joint radar-communication systems," IEEE International Conference on Acoustics, Speech, and Signal Processing, May 2020.

# Sensor Selection-based Beamforming Strategy



# Proposed JRC Scheme Based on Sensor Selection

- Suppose
  - JRC system is equipped with $\bar{M}$ transmit antennas
  - $M < \bar{M}$ RF up-conversion chains are available

$$
\begin{aligned}
\min_{\mathbf{u}_k} \max_{\theta_r} \quad & \left| e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r) \right|, && \theta_r \in \boldsymbol{\Theta} \\
\text{subject to} \quad & |\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta)| \leq \epsilon, && \theta \in \bar{\boldsymbol{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c) e^{j\varphi_n(\theta_c)}, && \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}} \\
& |\mathbf{u}_n|_0 \leq M.
\end{aligned}
$$

- Above formulation is non-convex due to $\ell_0$-norm

A. Ahmed, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

# Proposed JRC Scheme Based on Sensor Selection

- Previous formulation can be written as follows to optimize the sensors and transmit power simultaneously

$$
\begin{aligned}
\min_{\mathbf{u}_n} \quad & |\mathbf{u}_n|_2 + \gamma |\mathbf{u}_n|_0 \\
\text{subject to} \quad & \left|\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta)\right| \leq \epsilon, & \theta \in \overline{\boldsymbol{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c) e^{j\varphi_n(\theta_c)}, & \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}} \\
& \left| e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r) \right| \leq \gamma_{\mathrm{tol}}, & \theta_r \in \boldsymbol{\Theta}
\end{aligned}
$$

- $\gamma_{\mathrm{tol}}$ is the tolerance parameter of radar main lobe
- $\gamma$ is the tradeoff between power and sensor utilization
- Above formulation is non-convex due to $\ell_0$-norm
- We can relax $\ell_0$-norm by using $\ell_1$-norm

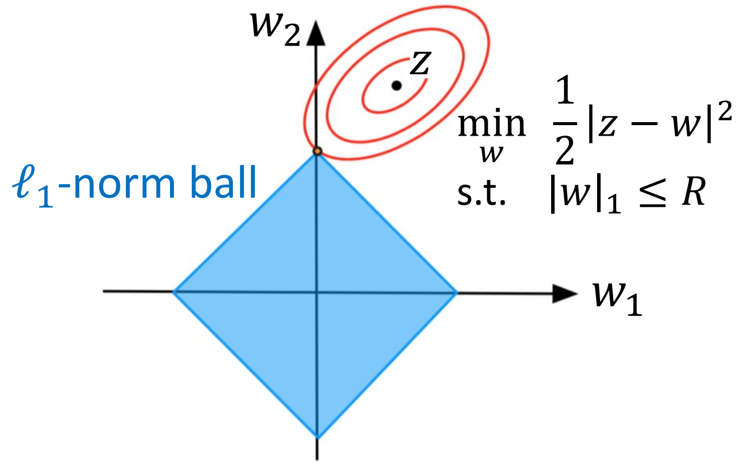
**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

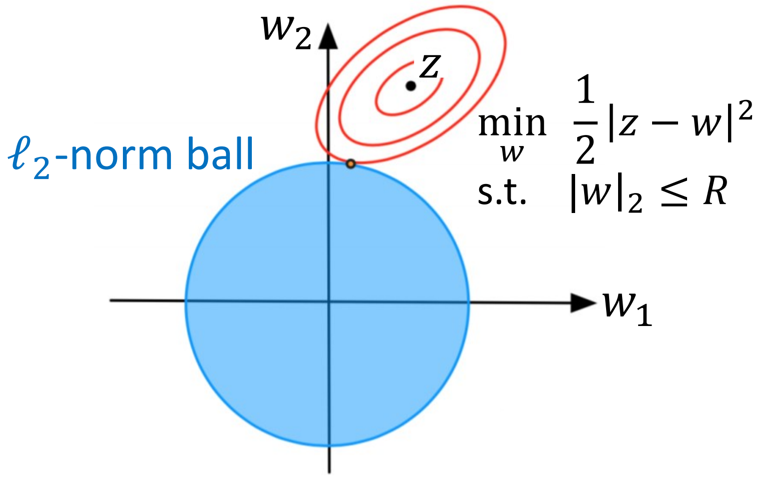
# Proposed JRC Scheme Based on Sensor Selection

- Previous formulation can be relaxed as

$$
\begin{aligned}
\min_{\mathbf{u}_n} \quad & |\mathbf{u}_n|_2 + \eta |\mathbf{u}_n|_1 \\
\text{subject to} \quad & \left|\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta)\right| \leq \epsilon, & \theta \in \bar{\mathbf{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c) e^{j\varphi_n(\theta_c)}, & \theta_c \in \mathbf{\Theta}_{\mathrm{c}} \\
& \left| e^{j\emptyset(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r) \right| \leq \gamma_{\mathrm{tol}}, & \theta_r \in \mathbf{\Theta}
\end{aligned}
$$

  - $\ell_1$-norm is the loose measure of sparsity
    - Higher amplitudes in $\mathbf{u}_n$ are penalized more than the smaller ones
  - Above optimization does not provide highly sparse solutions for antenna selection

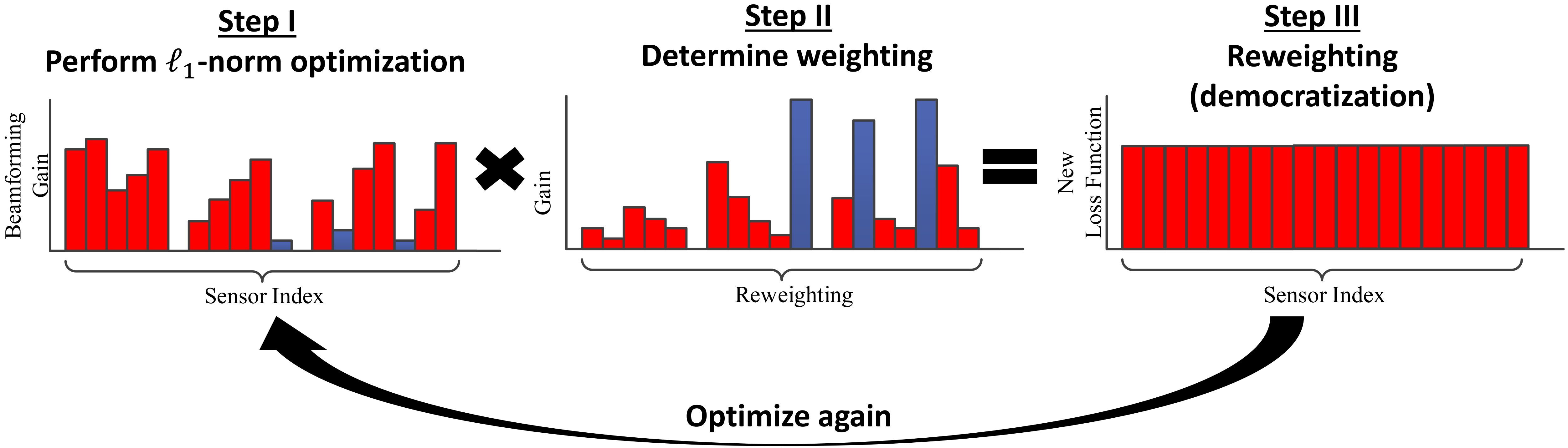



**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

# Sparsity Enhancement by Reweighting

- We can democratize the selection process by employing reweighting in an iterative manner
  - Small amplitudes are amplified by weighting




E. J. Candès, M. B. Wakin, and S. P. Boyd, "Enhancing sparsity by reweighted $\ell_1$ minimization," Journal of Fourier Analysis and Applications, Oct. 2008

# Optimal Sensor Selection

- Employ weighting to punish small beamforming weights

$$\begin{array}{lll} \min\limits_{\mathbf{u}_n} & |\mathbf{u}_n|_2 + \eta|\mathbf{w} \odot \mathbf{u}_n|_1 & \\ \text{subject to} & \left|\mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta)\right| \leq \epsilon, & \theta \in \bar{\boldsymbol{\theta}} \\ & \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_c) = \Delta_n(\theta_c)e^{j\varphi_n(\theta_c)}, & \theta_c \in \boldsymbol{\theta}_{\mathrm{c}} \\ & \left|e^{j\phi(\theta_r)} - \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_r)\right| \leq \gamma_{\mathrm{tol}}, & \theta_r \in \boldsymbol{\theta} \end{array}$$

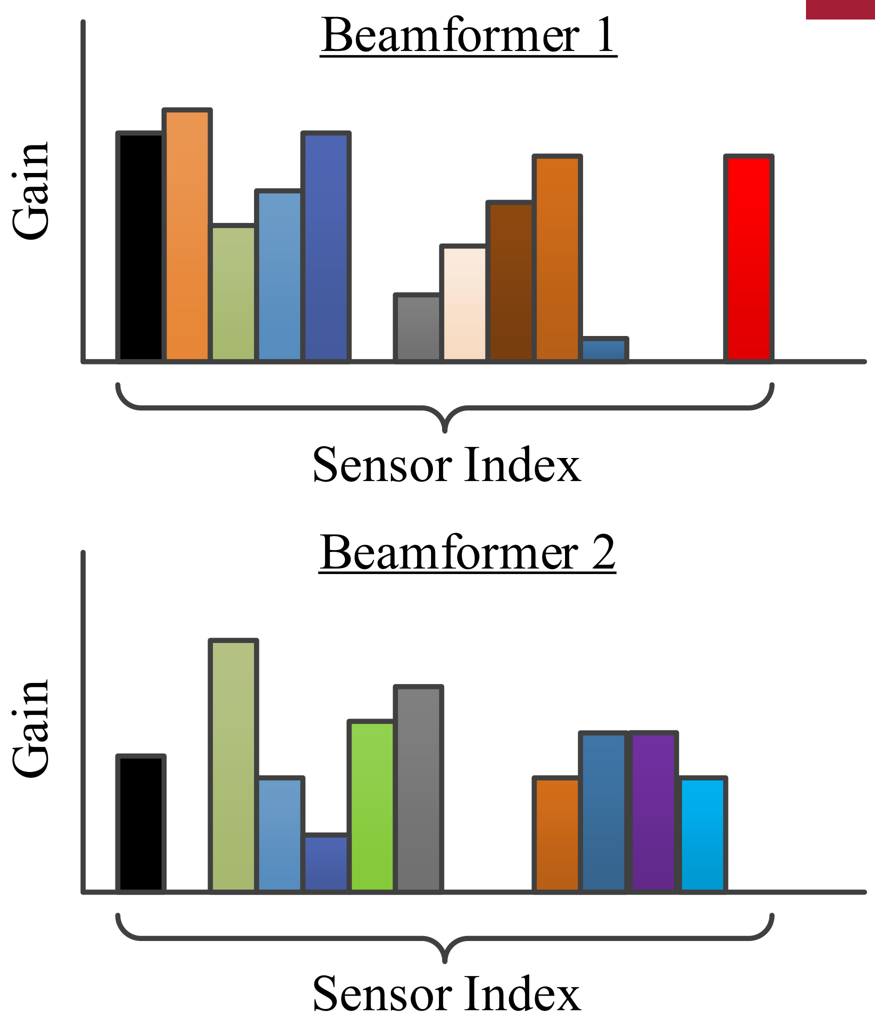
where $m$th element of $\mathbf{w}$ is given by $w_m = \begin{cases} \frac{1}{|u_{n,m}|}, & \text{if } |u_{n,m}| > 0 \\ \kappa & \text{if } |u_{n,m}| = 0 \end{cases}$, $\kappa$ is very large number

- Above optimization is performed iteratively.

E. J. Candès, M. B. Wakin, and S. P. Boyd, "Enhancing sparsity by reweighted $\ell_1$ minimization," Journal of Fourier Analysis and Applications, Oct. 2008

# Optimal Sensor Selection

- Different beamformers might select different sensors
  - Frequent sensor switching
  - Cumbersome hardware design
- Group Sparsity
  - We employ strong group sparsity to select the same sensors for all beamformers

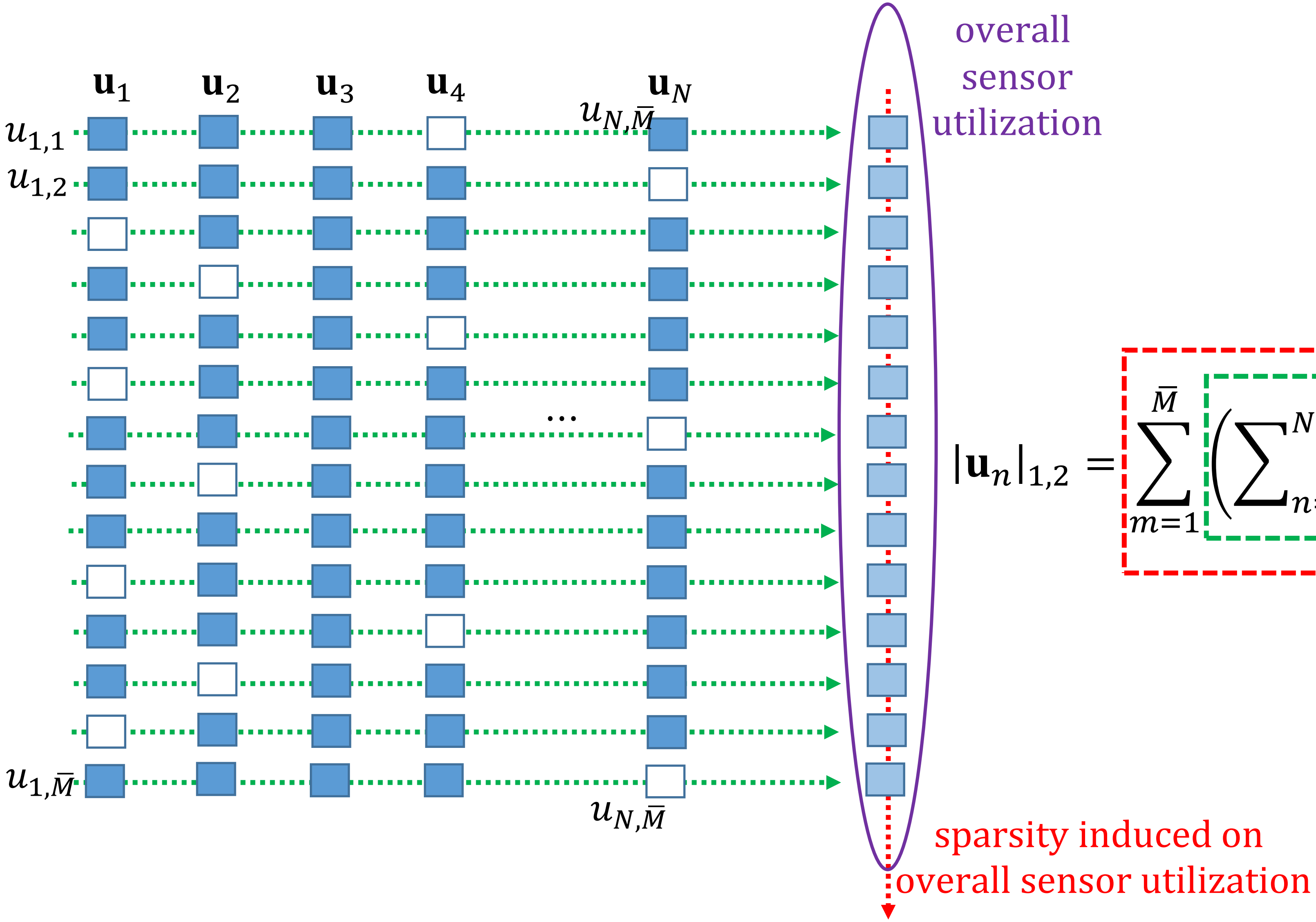



M. Yuan and Y. Lin, "Model selection and estimation in regression with grouped variables," Journal of the Royal Statistical Society: Series B, Feb. 2006.

# $\ell_{1,2}$-norm-based Group Sparsity

- unused sensor
- utilized sensor
- $\ell_2$-norm
- $\ell_1$-norm

Each beamforming weight vector performs the same radar task but has different communication profile

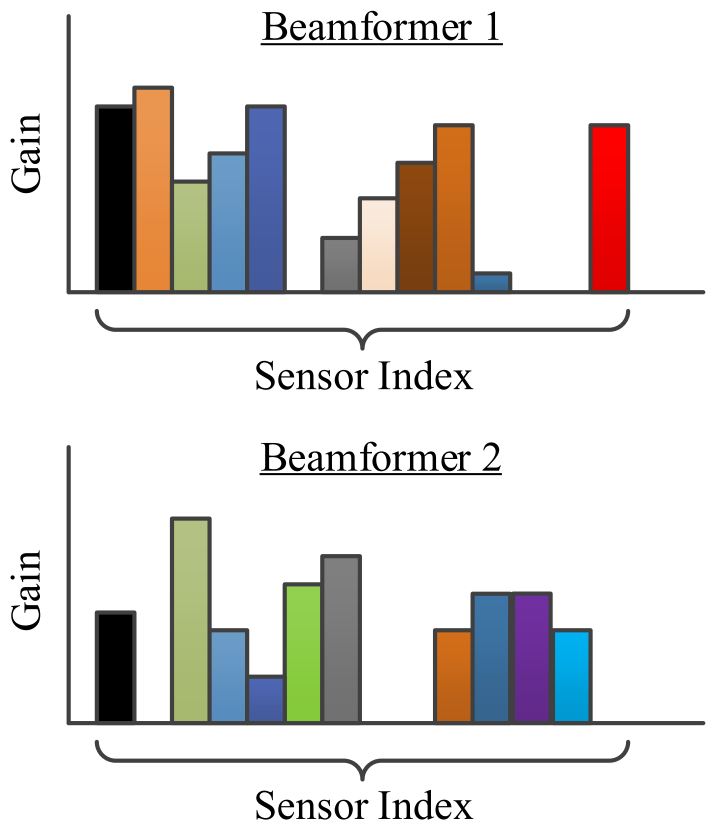



$$\|\mathbf{u}_n\|_{1,2} = \sum_{m=1}^{\bar{M}} \left( \sum_{n=1}^{N} |u_{n,m}|^2 \right)^{1/2}$$

# Optimal Sensor Selection

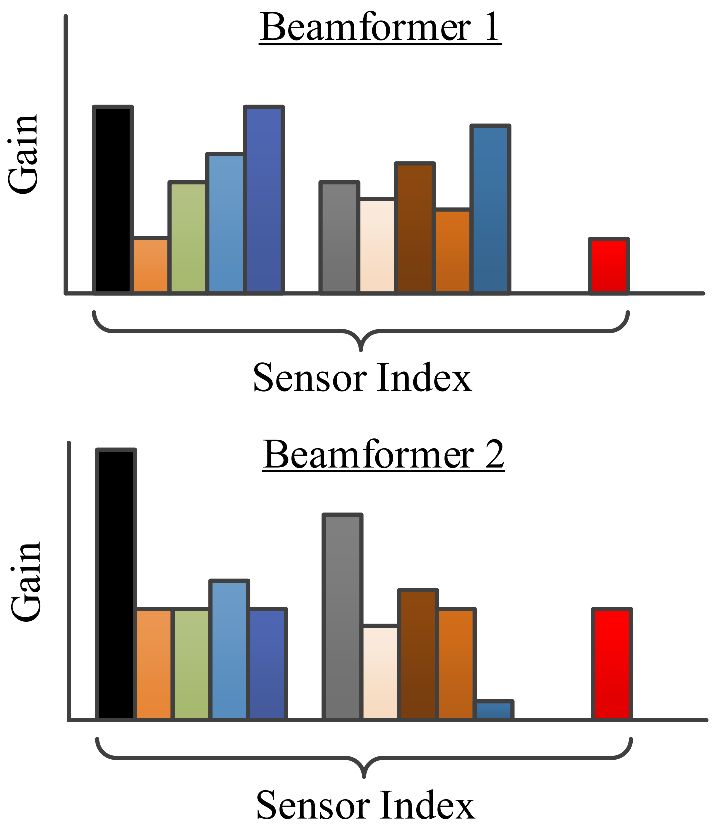
## Without Group Sparsity

- Different sensors are selected




## With Group Sparsity

- Same sensors are selected



# Optimal Sensor Selection using Group Sparsity

- Employ group sparsity

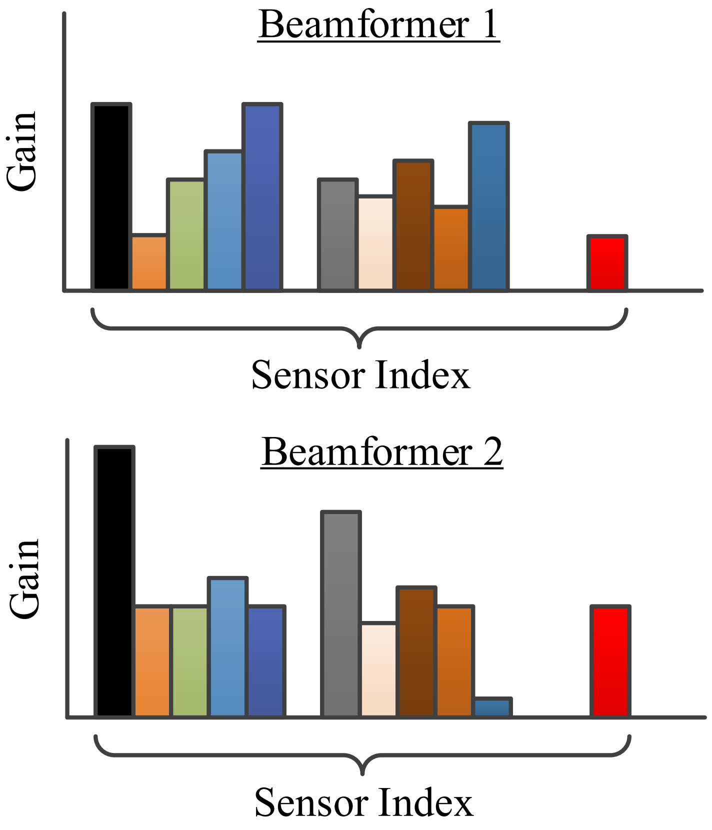
$$\min_{\mathbf{u}_{n,\forall n}} \quad \left(\sum_{n=1}^{N} |\mathbf{u}_n|_2\right) + \eta |\mathbf{u}_n|_{1,2}$$

$$\text{subject to} \quad \left|\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta)\right| \leq \epsilon, \qquad \theta \in \bar{\boldsymbol{\Theta}}$$

$$\mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_c) = \Delta_n(\theta_c) e^{j\varphi_n(\theta_c)}, \qquad \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}}$$

$$\left| e^{j\emptyset(\theta_r)} - \mathbf{u}_n^{\mathrm{H}} \mathbf{a}(\theta_r)\right| \leq \gamma_{\mathrm{tol}}, \qquad \theta_r \in \boldsymbol{\Theta}$$

where $$|\mathbf{u}_n|_{1,2} = \sum_{m=1}^{\bar{M}} \left(\sum_{n=1}^{N} |u_{n,m}|^2\right)^{1/2}$$




**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

# Optimal Sensor Selection using Group Sparsity

- Reweighed group sparsity

$$
\begin{aligned}
\min_{\mathbf{u}_n} \quad & \sum_{n=1}^{N}\left(|\mathbf{u}_n|_2 + \eta|\mathbf{v} \odot \mathbf{u}_n|_{1,2}\right) \\
\text{subject to} \quad & \left|\mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta)\right| \le \epsilon, \qquad \theta \in \bar{\boldsymbol{\Theta}} \\
& \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_c) = \Delta_n(\theta_c)e^{j\varphi_n(\theta_c)}, \qquad \theta_c \in \boldsymbol{\Theta}_{\mathrm{c}} \\
& \left|e^{j\emptyset(\theta_r)} - \mathbf{u}_n^{\mathrm{H}}\mathbf{a}(\theta_r)\right| \le \gamma_{\mathrm{tol}}, \qquad \theta_r \in \boldsymbol{\Theta}
\end{aligned}
$$

$$
v_m = \begin{cases} \left(\sum_{n=1}^{N}\left|u_{n,m}\right|^2\right)^{-1/2}, & \text{if} \sum_{n=1}^{N}\left|u_{n,m}\right|^2 > 0 \\ \kappa, & \text{if} \sum_{n=1}^{N}\left|u_{n,m}\right|^2 = 0 \end{cases}
$$

, $\kappa$ is very large number

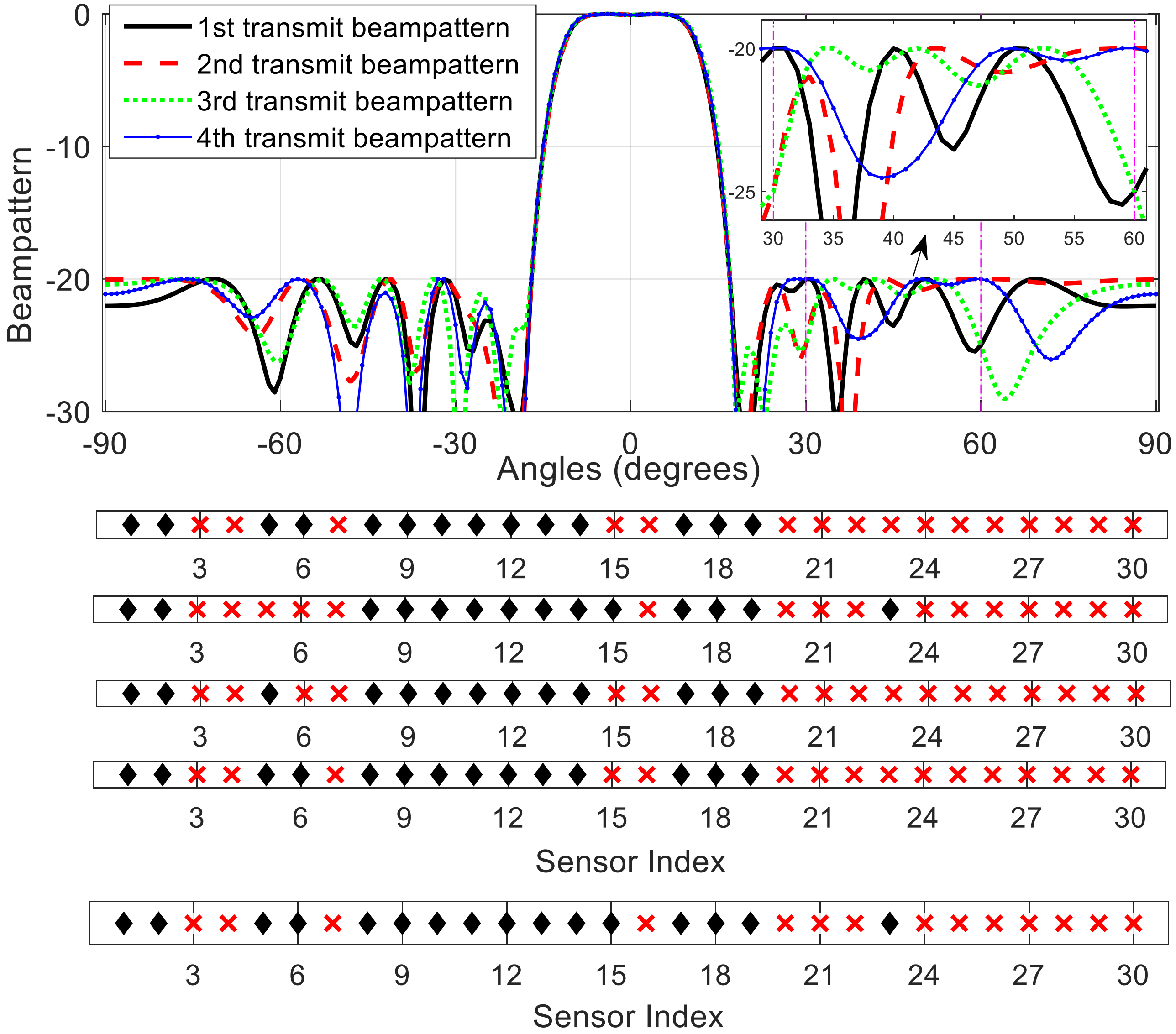
$$
|\mathbf{v} \odot \mathbf{u}_n|_{1,2} = \sum_{m=1}^{\bar{M}}\left(\sum_{n=1}^{N}\left|v_m u_{n,m}\right|^2\right)^{1/2} = \sum_{m=1}^{\bar{M}} v_m\left(\sum_{n=1}^{N}\left|u_{n,m}\right|^2\right)^{1/2}
$$

**A. Ahmed**, S. Zhang, and Y. D. Zhang, “Antenna selection strategy for transmit beamforming-based joint radar-communication system,” Digital Signal Processing, Oct. 2020.

# Simulation Results

- 30 transmit antennas
  - Minimize the number of selected antennas
- Radar objective
  - 0 dB gain between $-7^{o}$ and $7^{o}$
- Communication objective
  - Two users at $30^{o}$ and $60^{o}$
  - Employ amplitude shift keying ($-20$dB, $-25$ dB)

# Simulation Results (without group sparsity)




14 sensors selected

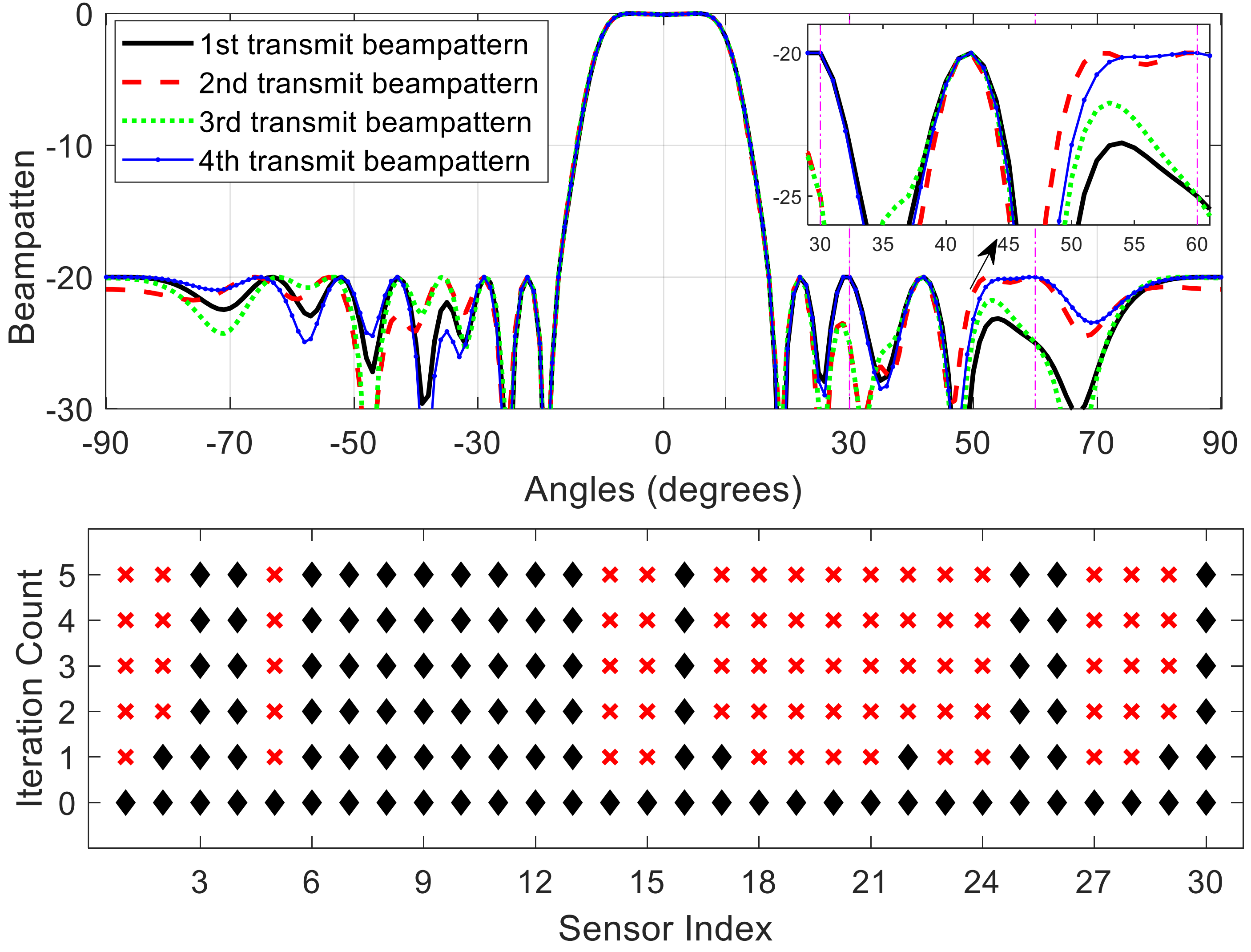
14 sensors selected

13 sensors selected

14 sensors selected

**16 sensors selected (overall)**

# Simulation Results (with group sparsity)

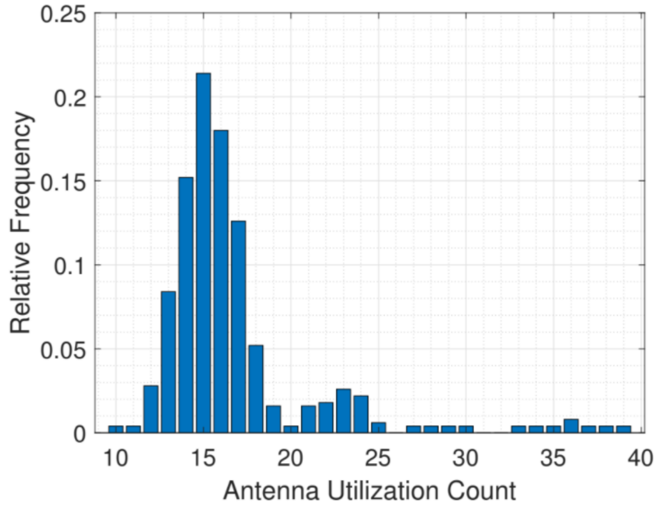



**Algorithm converges in 2 iterations**

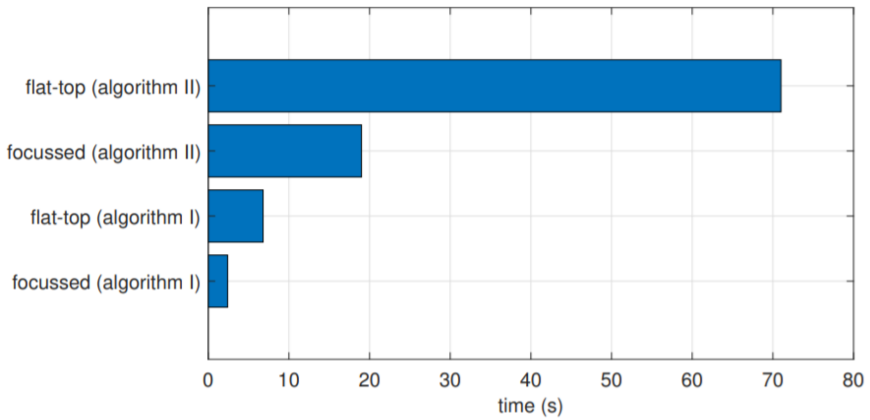
**14 sensors selected**

# Performance

- We simulated 1000 scenarios with randomly located communication users and 40 antennas
  - Antenna utilization percentage was observed to be less than 63% for most of the cases




- Group sparsity-based antenna selection strategy was seen to be computationally expensive




**A. Ahmed**, S. Zhang, and Y. D. Zhang, "Antenna selection strategy for transmit beamforming-based joint radar-communication system," Digital Signal Processing, Oct. 2020.

# Conclusion

- Sensor selection for JRC system was presented
- Re-weighted $l_1$-norm optimization was exploited to select the optimal number of sensors
- Group sparsity was incorporated to avoid sensor switching and reduce overall sensor utilization
- Simulation results support the proposed strategy

# Review of other work

# Overview of the work

## Sparse Array Design and Direction-of-Arrival Estimation

- Second order statistics-based DOA estimation
  - Zero redundancy sparse array design
  - Multi-frequency sparse array design
  - Coprime array with reduced lag redundancy
- Fourth order statistics-based DOA estimation
  - Multi-frequency sparse array design
  - Sparse array with continuous co-array lags

## Over-the-Horizon Radar

- Target altitude estimation in OTHR
  - In the presence of ionosphere layer perturbations/uncertainties
  - In the presence of target acceleration/perturbation
- Target altitude estimation in OTHR for O- and X-mode propagation
  - Group sparsity-based signal separation

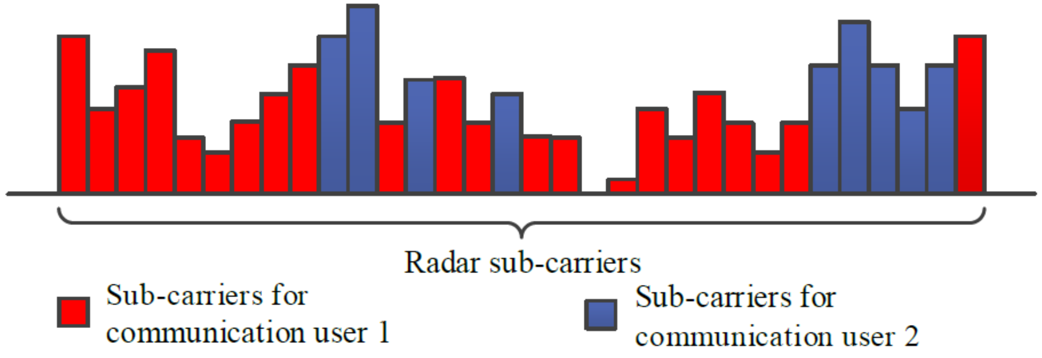
## Spectrum Sharing

- Resource allocation for JRC systems
  - Single transmitter-based JRC
  - Sensor array-based JRC
  - Distributed JRC
- Throughput enhancement for sensor array-based JRC systems
- JRC system design in the presence of channel uncertainties

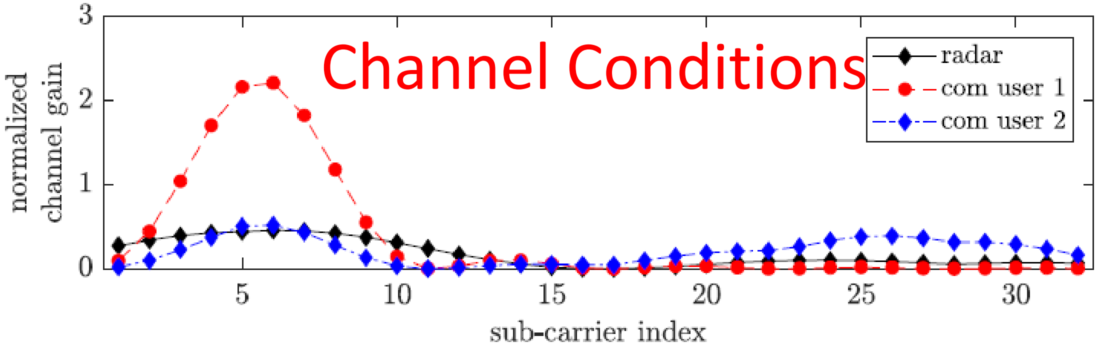
# Single Transmitter JRC: Subcarrier Selection

- We use mutual information as the optimization criteria

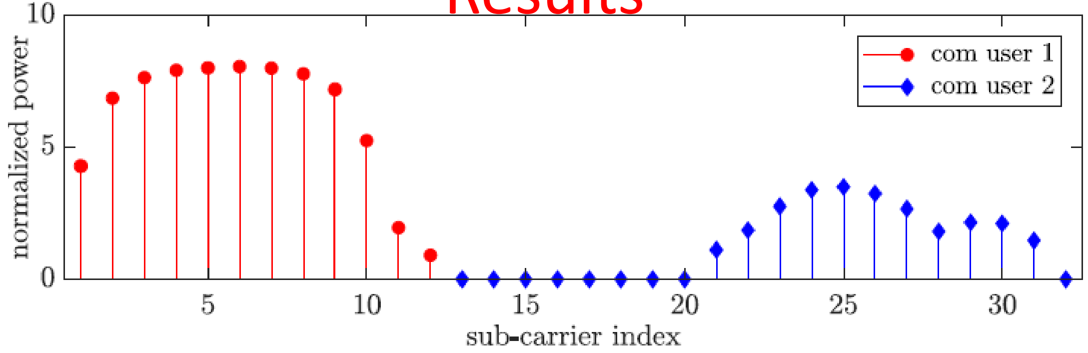
## Basic Principle



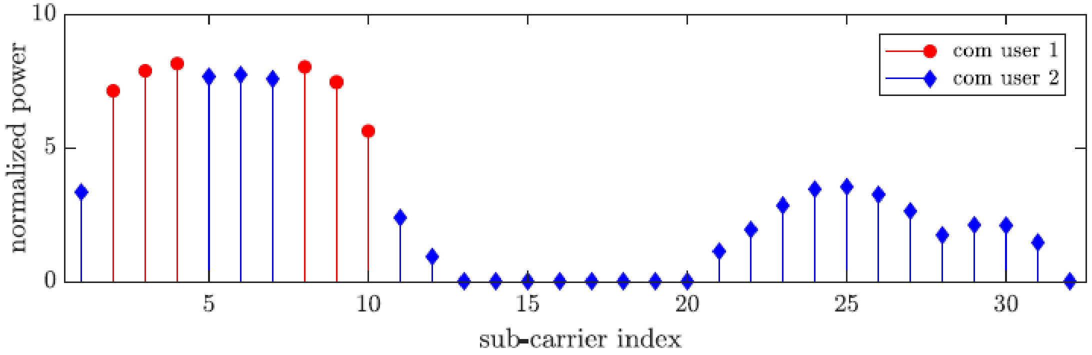

## Channel Conditions




## Results




(a) Maximum communication capacity optimization




(b) Worst-case communication capacity optimization


**A. Ahmed**, Y. D. Zhang, "Optimized resource allocation for joint radar-communications," in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.

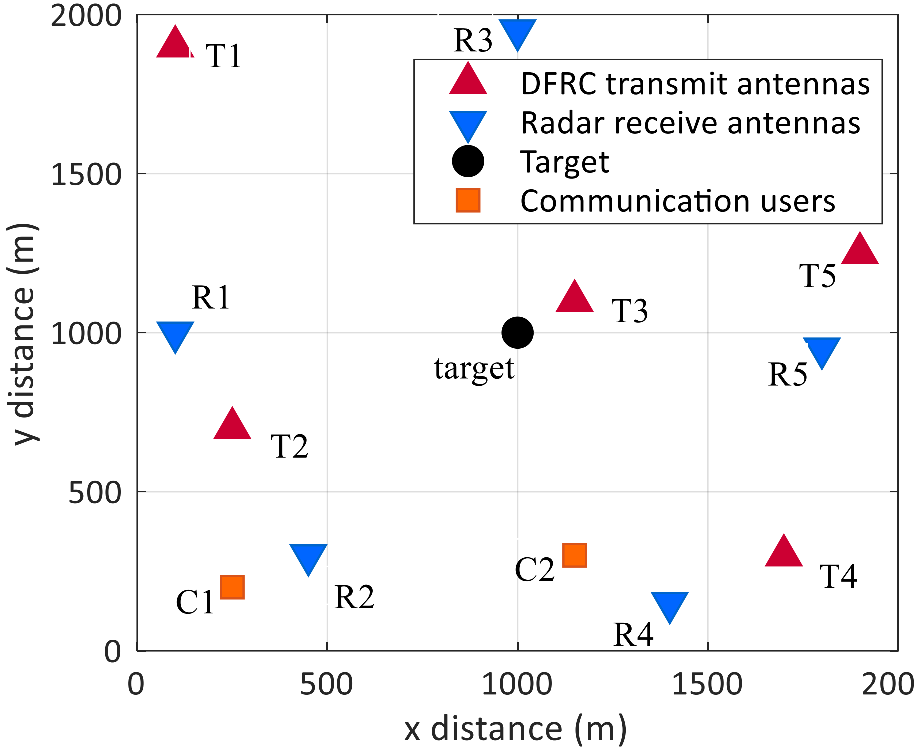
**A. Ahmed**, Y. D. Zhang, A. Hassanien, B. Himed, "OFDM-based joint radar-communication system: optimal sub-carrier allocation and power distribution by exploiting mutual information," Asilomar Conference on Signals, Systems, and Computers, Nov. 2019.

# Distributed JRC: Resource Allocation Results

**Scenario:**

We considered distributed MIMO joint radar-communication system.
Radar had best performance for third transmitter (high channel gain).
Communication users had worse performance for the third transmitter (deep fade).
Localization error and mutual information can be used as performance criteria.

| | Radar-only | Communication-only | JRC |
|---|---|---|---|
| Power, $\mathbf{p}_{tx}$ (W) | $\begin{bmatrix}1.0\\1.0\\90.46\\1.0\\1.0\end{bmatrix}$ | $\begin{bmatrix}99.45\\99.95\\1.02\\99.86\\99.72\end{bmatrix}$ | $\begin{bmatrix}89.39\\81.27\\72.22\\79.43\\77.69\end{bmatrix}$ |
| Total Power, $P_{\text{total}}$ (W) | 400 | 400 | 400 |
| Localization Error, $\eta$ (m$^2$) | 5.97 | 30.59 | 8.21 |
| Shannon Capacity, $\mathfrak{R}$ (bits/s/pulse) | 8.87 | 51.16 | 50.44 |



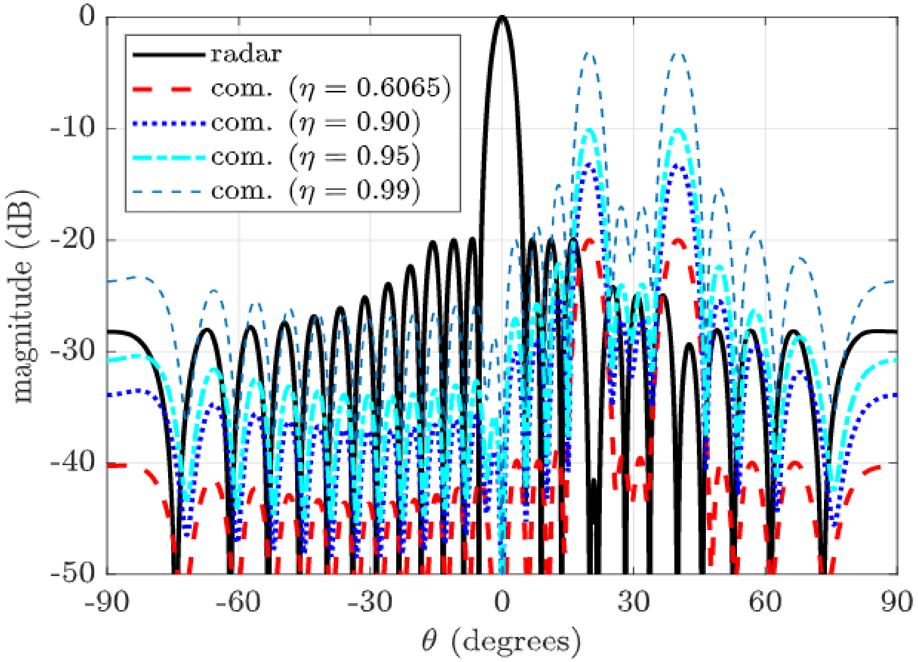


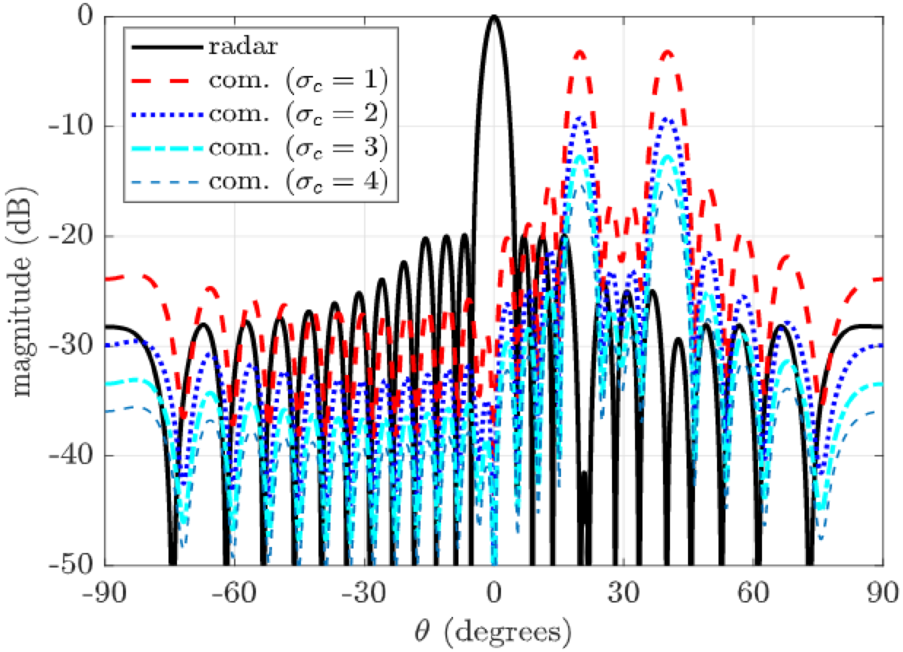
1. **A. Ahmed**, Y. D. Zhang, “” Optimized resource allocation for joint radar-communications,” in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.
2. **A. Ahmed**, Y. D. Zhang, and B. Himed, “System and method for distributed dual-function radar-communication,” U.S. Non-Provisional Application No. 16/854,251; filed: April 21, 2020.
3. **A. Ahmed**, Y. D. Zhang, and B. Himed, “Distributed dual-function radar-communication MIMO system with optimized resource allocation,” IEEE Radar Conference, April 2019.

# Chance Constrained Beamforming for JRC Systems

- We employed chance constrained beamforming
  - This reduces the outage probability of the communication by considering channel uncertainties

Beamforming profiles for different quality-of-service $\eta$ considering a Rayleigh channel with $\sigma = 1$



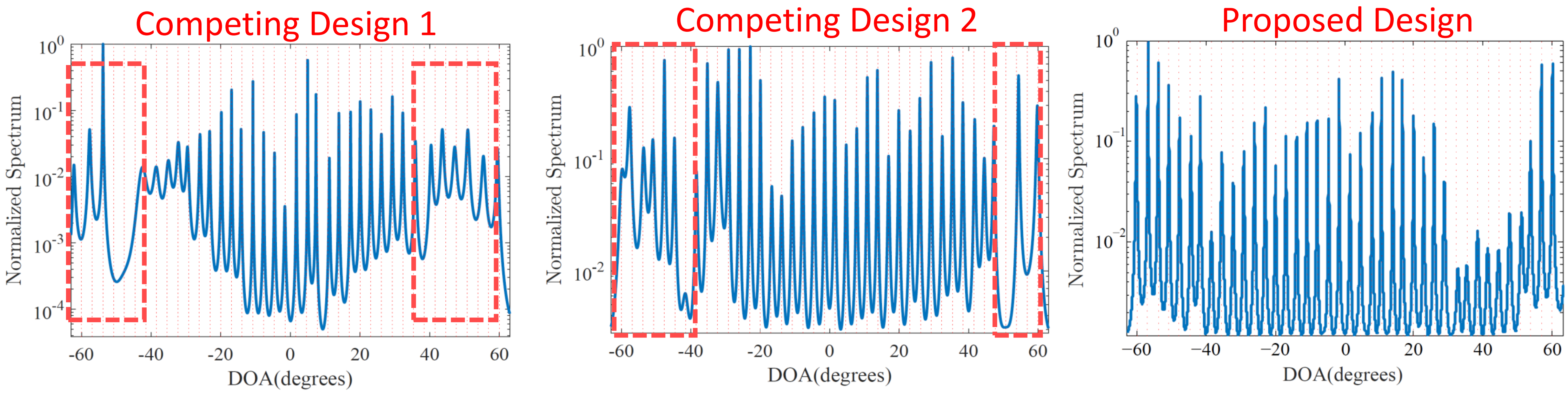




Beamforming profiles for Rayleigh channels with different $\sigma$ considering the quality-of-service $\eta = 0.9$

**A. Ahmed**, D. Silage, and Y. D. Zhang, "High-resolution target sensing using multi-frequency sparse array," IEEE Sensor Array and Multichannel Signal Processing Workshop, June 2020.

# Spatial Spectrum Sensing

- Based on Fourth Order Statistics (3rd best student paper award)
  - Designed a sparse sensor array which provides consecutive correlation lags for efficient utilization of MUSIC algorithm
  - Not an optimal array but simplifies the analysis of degrees-of-freedom

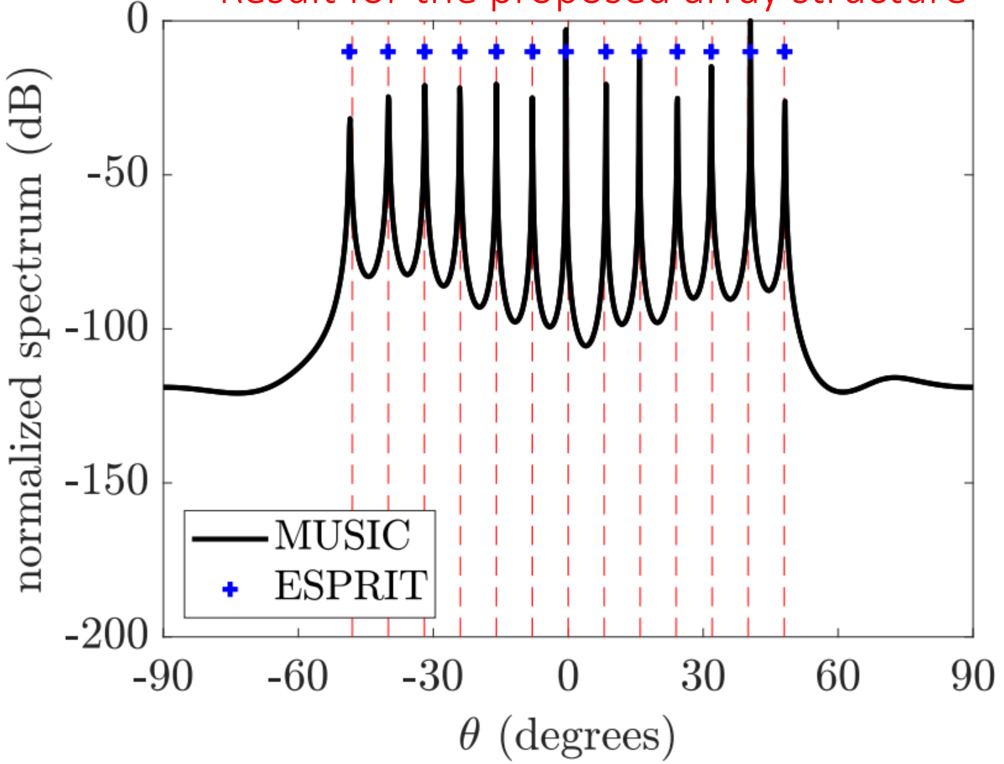



**A. Ahmed**, Y. D. Zhang, and B. Himed, "Effective nested array design for fourth-order cumulant-based DOA estimation," IEEE Radar Conference, May 2017.
**(best student paper award - 3rd position)**

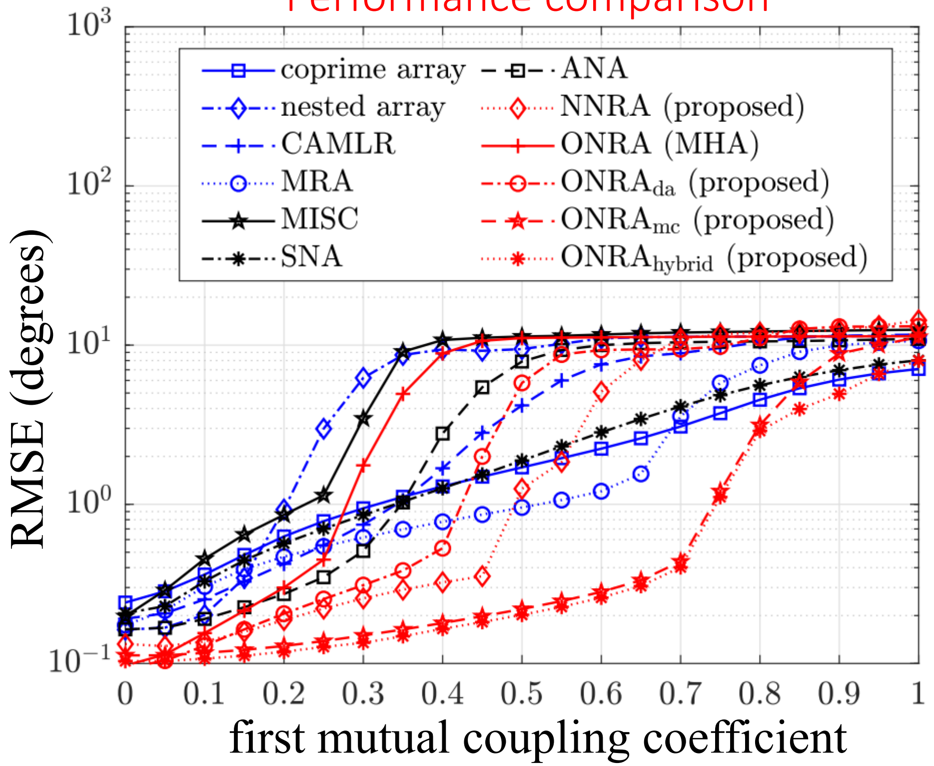
# Non-redundant Sparse Array Design

- Designed sparse arrays with least number of co-array redundancies
- Exploited disjunctive and mixed-integer linear programming tools for sensor location optimization

Result for the proposed array structure



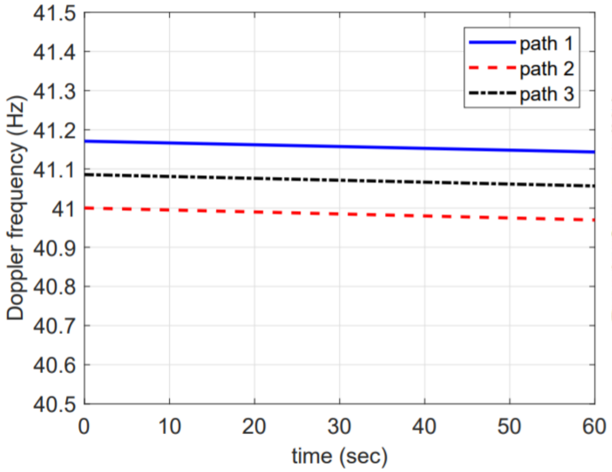

Performance comparison



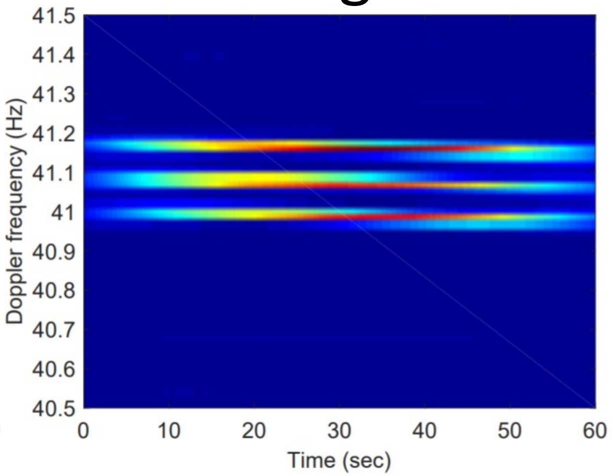

**A. Ahmed**, Y. D. Zhang, "Generalized non-redundant sparse array designs" submitted to IEEE Transactions on Signal Processing.

# Over-The-Horizon Radar (OTHR)

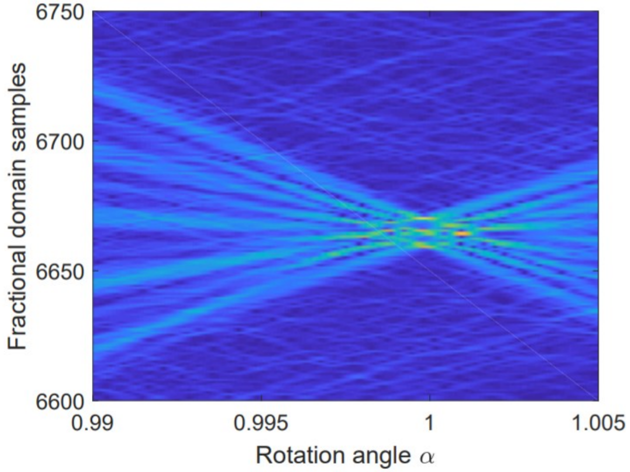
- Target altitude estimation in OTHR
  - We proved that for linear motion of target, the three Doppler signatures take the form of three closely-spaced chirp signals that can be used to estimate target altitude



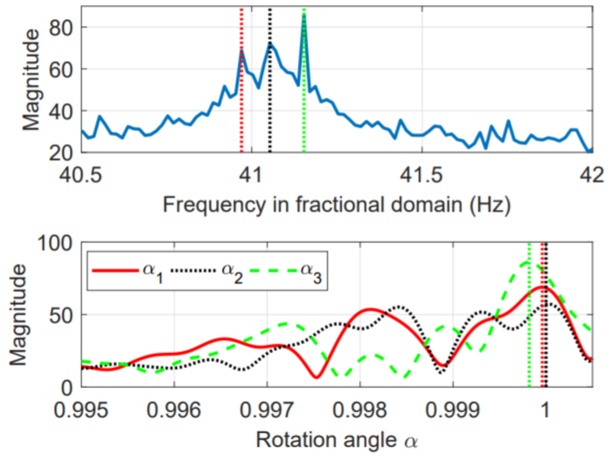
Actual Doppler frequencies



Spectrogram



Fractional Fourier Transform



Frequency Estimation

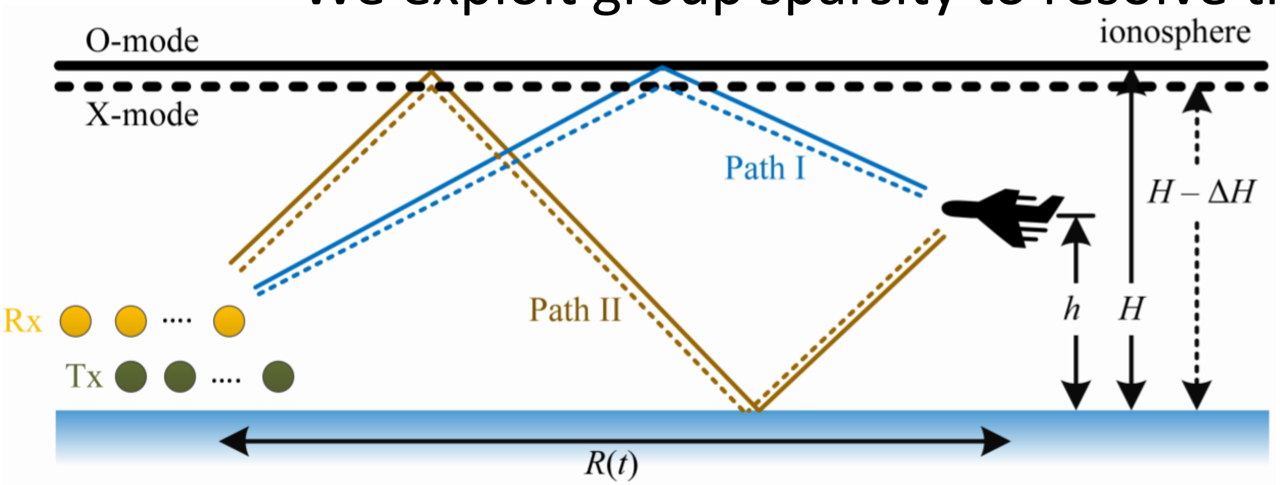
- Once the chirp rate is known, we can also use other methods like MUSIC, LASSO, ESPRIT, etc. after de-chirping the signals

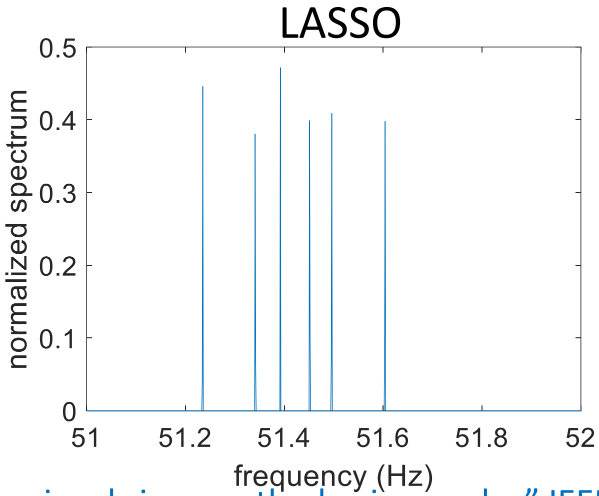

1. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Doppler signature analysis of mixed O/X-mode signals in over-the-horizon radar," IEEE International Radar Conference, April-May 2020.

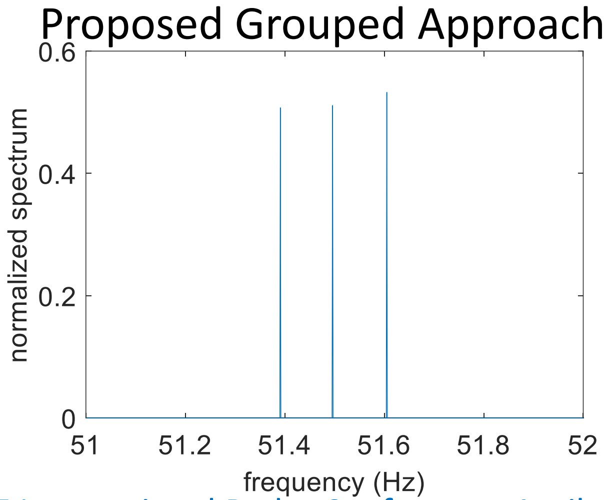
2. **A. Ahmed**, Y. D. Zhang, and B. Himed, "Doppler signature separation of mixed O/X-mode over-the-horizon radar signals," IEEE Radar Conference, Sept. 2020.

# Over-The-Horizon Radar (OTHR)

- Challenge: Signals reflected through two modes (O-mode, X-mode)
- Each mode results in three chirps (total 6 closely-spaced chirps)
  - More challenging to resolve
  - Since height difference of O- and X-mode is known, the three chirps from each mode are inter-related
  - We exploit group sparsity to resolve the frequencies





**1. A. Ahmed**, Y. D. Zhang, and B. Himed, "Doppler signature analysis of mixed O/X-mode signals in over-the-horizon radar," IEEE International Radar Conference, April-May 2020.

**2. A. Ahmed**, Y. D. Zhang, and B. Himed, "Doppler signature separation of mixed O/X-mode over-the-horizon radar signals," IEEE Radar Conference, Sept. 2020.

# Publications as First Author (accepted+submitted)

- **Book Chapter**
  - A. Ahmed, Y. D. Zhang, “” Optimized resource allocation for joint radar-communications,” in K. V. Mishra, B. S. M. R. Rao, B. Ottersten, and L. Swindlehurst (Eds.), Signal Processing for Joint Radar Communications, Wiley, 2021.
- **Journal Publications**
  - A. Ahmed, Y. D. Zhang, and Y. Gu, “Dual-function radar-communications using QAM-based sidelobe modulation,” Digital Signal Processing, Nov. 2018.
  - A. Ahmed, S. Zhang, and Y. D. Zhang, “Antenna selection strategy for transmit beamforming-based joint radar-communication system,” Digital Signal Processing, Oct. 2020.
  - Y. D. Zhang, A. Ahmed, and B. Himed, “Target altitude estimation in over-the-horizon radar,” submitted to Signal Processing.
  - A. Ahmed, Y. D. Zhang, “Generalized non-redundant sparse array designs” submitted to IEEE Transactions on Signal Processing.
  - A. Ahmed, Y. D. Zhang, and B. Himed, “Joint target and ionosphere parameter estimation in over-the-horizon radar” submitted to AFRL for possible submission in IEEE Transactions on Aerospace and Electronic Systems.
- **Invention Disclosure**
  - A. Ahmed, Y. D. Zhang, and B. Himed, “System and method for distributed dual-function radar-communication,” U.S. Non-Provisional Application No. 16/854,251; filed: April 21, 2020.

# Publications as First Author (accepted+submitted)

- **Conference Publications**
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Effective nested array design for fourth-order cumulant-based DOA estimation," IEEE Radar Conference, Seattle, WA, May 2017. **(best student paper award - 3rd position)**
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Cumulant-based direction-of-arrival estimation using multiple co-prime frequencies," Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, Oct. 2017.
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Multi-user dual-function radar-communications exploiting sidelobe control and waveform diversity," IEEE Radar Conference, Oklahoma City, OK, April 2018.
  - A. Ahmed, Y. Gu, D. Silage, and Y. D. Zhang, "Power-efficient multi-user dual-function radar-communications," IEEE International Workshop on Signal Processing Advances in Wireless Communications, Kalamata, Greece, June 2018.
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Distributed dual-function radar-communication MIMO system with optimized resource allocation," IEEE Radar Conference, Boston, MA, April 2019.
  - A. Ahmed, Y. D. Zhang, and J-K. Zhang, "Coprime array design with minimum lag redundancy," IEEE International Conference on Acoustics, Speech, and Signal Processing, Brighton, U.K., May 2019.
  - A. Ahmed, S. Zhang, and Y. D. Zhang, "Multi-target motion parameter estimation exploiting collaborative UAV network," IEEE International Conference on Acoustics, Speech, and Signal Processing, Brighton, U.K., May 2019.

# Publications as First Author (accepted+submitted)

- **Conference Publications (cont.)**
  - A. Ahmed, Y. D. Zhang, A. Hassanien, B. Himed, "OFDM-based joint radar-communication system: optimal sub-carrier allocation and power distribution by exploiting mutual information," Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2019.
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Doppler signature analysis of mixed O/X-mode signals in over-the-horizon radar," IEEE International Radar Conference, Rockville, MD, April-May 2020.
  - A. Ahmed, S. Zhang, and Y. D. Zhang, "Optimized sensor selection for joint radar-communication systems," IEEE International Conference on Acoustics, Speech, and Signal Processing, Barcelona, Spain, May 2020.
  - A. Ahmed, D. Silage, and Y. D. Zhang, "Chance constrained beamforming for joint radar-communication systems," IEEE Sensor Array and Multichannel Signal Processing Workshop, Hangzhou, China, June 2020.
  - A. Ahmed, D. Silage, and Y. D. Zhang, "High-resolution target sensing using multi-frequency sparse array," IEEE Sensor Array and Multichannel Signal Processing Workshop, Hangzhou, China, June 2020.
  - A. Ahmed, Y. D. Zhang, and B. Himed, "Doppler signature separation of mixed O/X-mode over-the-horizon radar signals," IEEE Radar Conference, Florence, Italy, Sept. 2020.
  - A. Ahmed and Y. D. Zhang, "Non-redundant sparse array with flexible aperture," Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2020.

# Publications as First Author (accepted+submitted)

- **Poster Abstracts**
  - A. Ahmed and Y. D. Zhang, “Radar-based dataset development for human activity recognition,” IEEE Signal Processing in Medicine and Biology Symposium, Philadelphia, PA, Dec. 2020.
  - A. Ahmed, S. Zhang, V. S. Amin, Y. D. Zhang, “Spectrum sharing strategy for radio frequency-based medical services,” IEEE Signal Processing in Medicine and Biology Symposium, Philadelphia, PA, Dec. 2019.

# Acknowledgements


- Advisor
  - Dr. Yimin D. Zhang
- Advising Committee Members
  - Dr. Dennis Silage
  - Dr. Joseph Picone
- External Examiner
  - Dr. Yu Wang
- AFRL
  - Dr. Braham Himed
- Coursework at Temple University
- ASP Lab and Department Colleagues
- Family

# Questions and Suggestions

Ammar Ahmed

ammar.ahmed@temple.edu

www.ammar-ahmed.com