Dual-Functional Transmission for Radar and Communications (DFRC)

Christos Masouros
Professor of Signal Processing and Wireless Communications
Dept. Electronics & Electrical Engineering | University College London

Work led by Dr Fan Liu, Dr Aryan Kaushik, Ms Nanchi Su

T2.3. Joint Waveform Design for Sensing and Signaling
T2.4. Hardware and Nonlinearity Resilient Waveform Design

EP/S026622/1

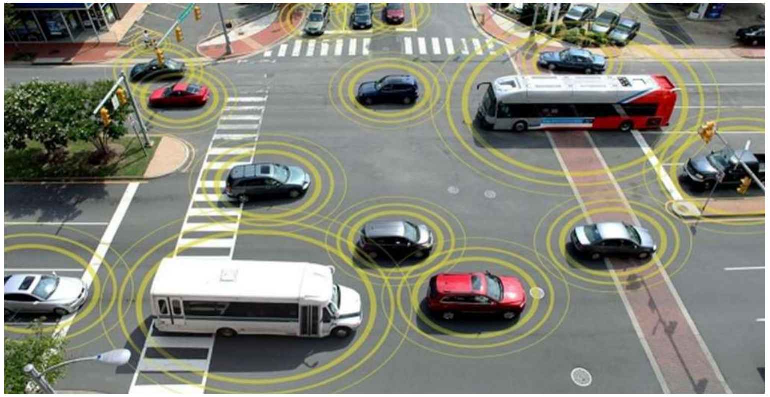
Marie Curie Fellowship, No. 793345

Outline

- Motivation
- DFRC through weighted optimization
- Hardware efficient designs for DFRC
- Security for DFRC

Growing scenarios requiring Sensing and Comms

- Explosive comms traffic growth - need for extra spectrum resources
- Large spectrum resources traditionally allocated to the radar, have seen increasing cohabitation wireless communication systems, e.g.
  - 1-10GHz: ATC, Airborne / Shipborne radars + LTE, WiFi
  - mmWave: automotive / imaging radars + 5G NR



Connected + Autonomous Vehicles

LTE BS

Shipborne Radar

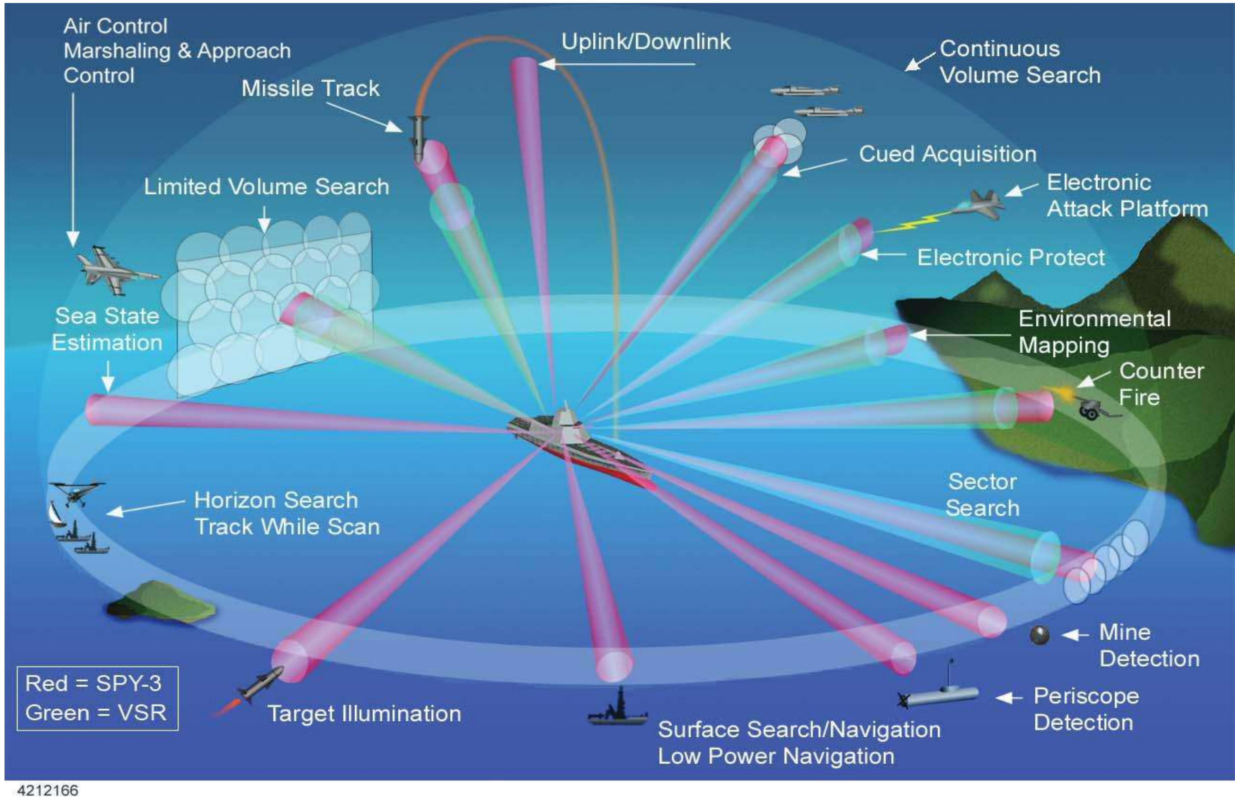
ATC Radar

F. Liu, C. Masouros, H. Griffiths, A. Petropulu, and L. Hanzo, "Joint Radar and Communication Design: Applications, State-of-the-art, and the Road Ahead", IEEE Trans Commun., vol. 68, no. 6, pp. 3834-3862, June 2020

Too many RF systems

The independent growth of radar and comms systems leads to:

- increasing weight and volume of the shipborne or airborne platforms;
- increasing antenna array size and radar cross section;
- electromagnetic compatibility issues.

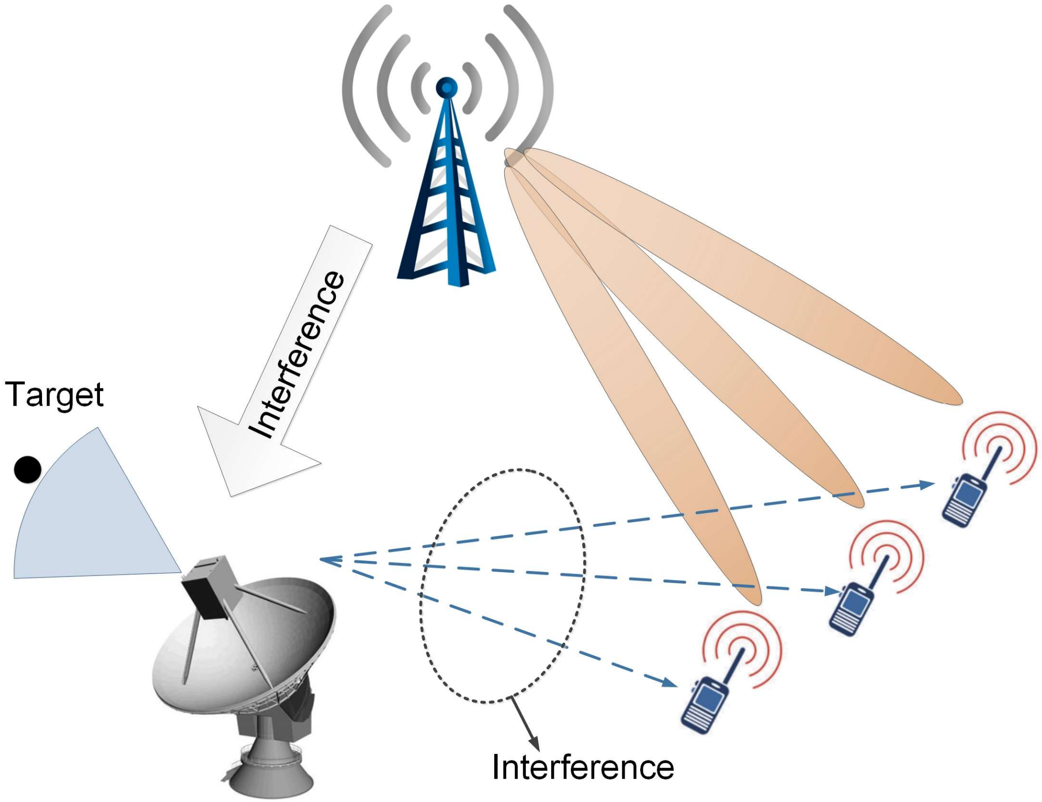


Multifunction RF concept: Combining many RF functionalities in a single platform

Could radar and communication transmission be merged?

G. C. Tavik et al., "The advanced multifunction RF concept," IEEE Trans. Microw. Theory Techn., vol. 53, no. 3, pp. 1009–1020, Mar. 2005.

Radar and Communications "competing" for the same resources



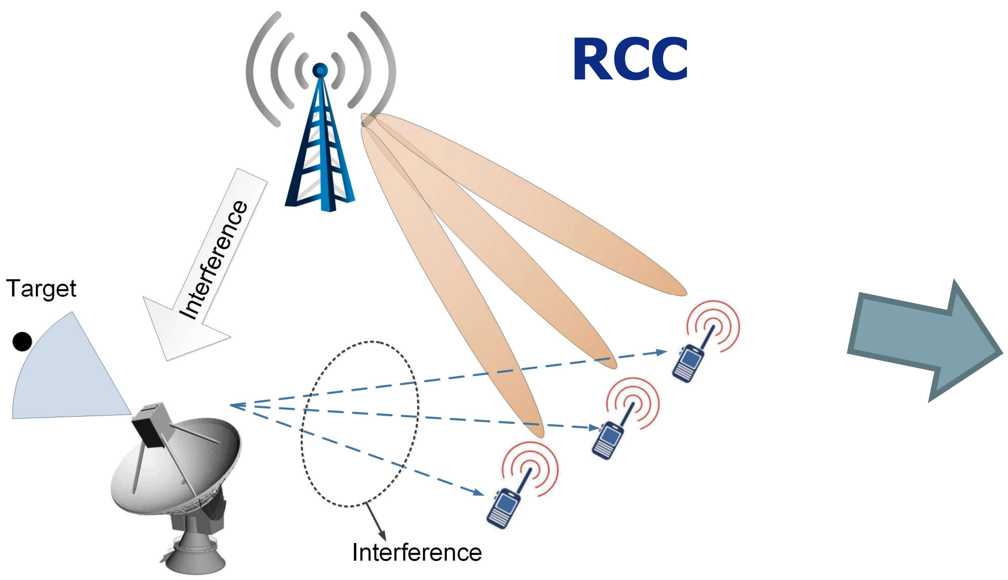
Limitations

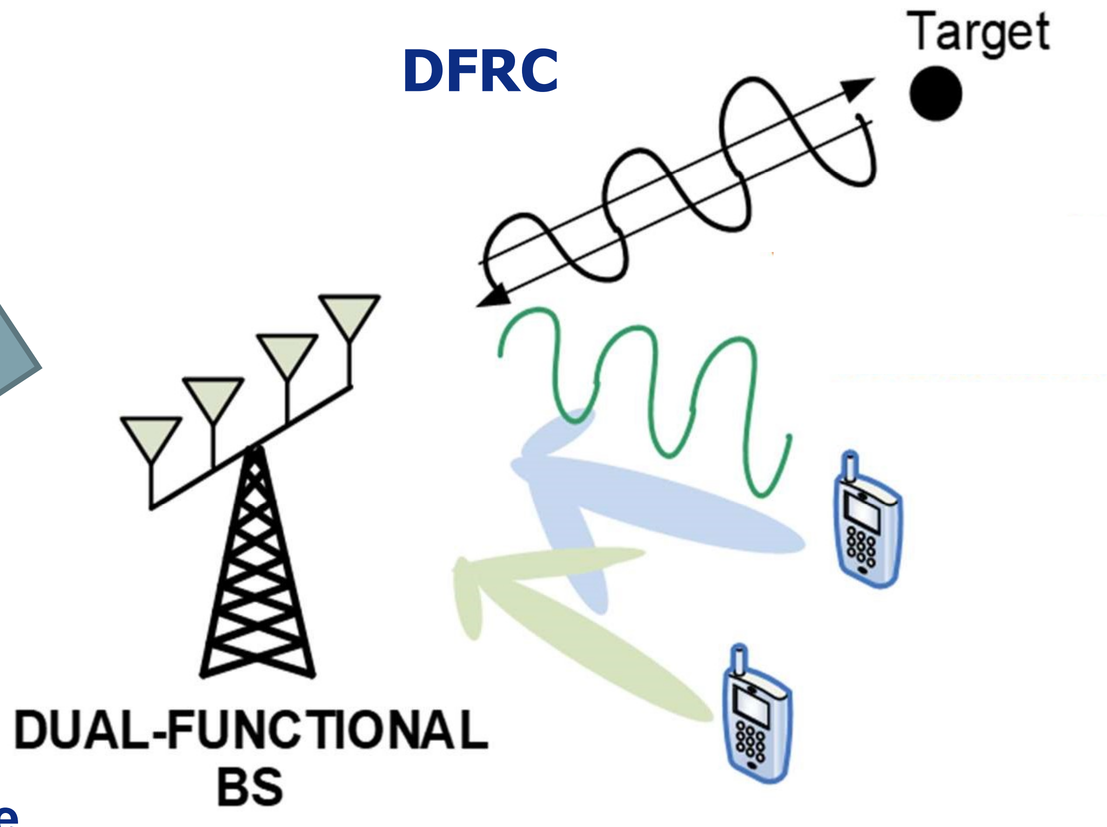
- Need for two different systems to coordinate
- Interference
- Synchronisation
- Side information: channel info exchange, coordination signals
- Compatibility

B. Paul, A. R. Chiriyath, D. W. Bliss, "Survey of RF communications and sensing convergence research," IEEE Access, vol. 5, 2017.

F. Liu, C. Masouros, H. Griffiths, A. Petropulu, L. Hanzo "Joint Radar and Communication Design: Applications, State-of-the-art, and the Road Ahead", IEEE Trans Commun., vol. 68, no. 6, pp. 3834-3862, June 2020. - *EiC Invited Paper*

The step change to DFRC





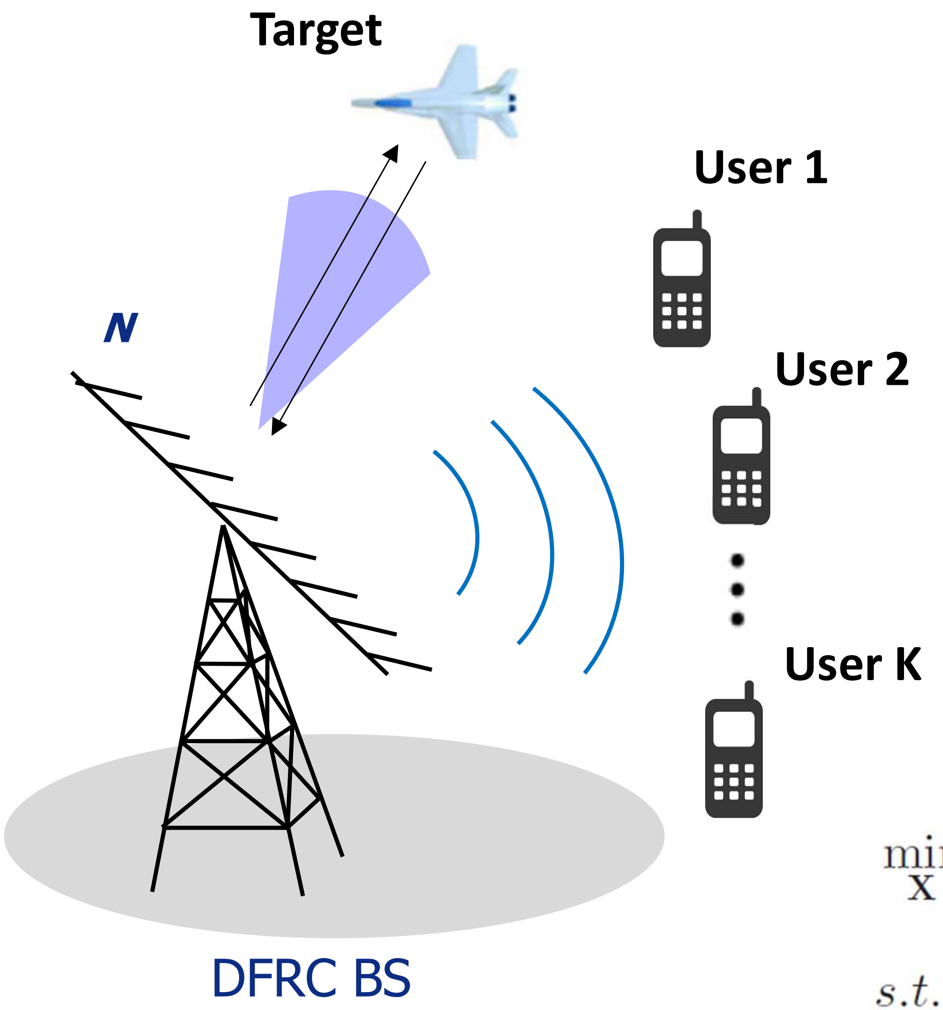
- **Comms and Radar systems cooperate** instead of competing for frequency.
- Single transceiver:
  - Hardware-efficient
  - Cost – efficient
  - Area/space - efficient

- Make radar applications, which are on the rise with emerging IoT applications such as autonomous cars, pervasive.
- Mutually benefit the real-time performance for both radar and communication systems

B. Paul, A. R. Chiriyath, D. W. Bliss, "Survey of RF communications and sensing convergence research," IEEE Access, vol. 5, 2017.

F. Liu, C. Masouros, H. Griffiths, A. Petropulu, L. Hanzo "Joint Radar and Communication Design: Applications, State-of-the-art, and the Road Ahead", IEEE Trans Commun., vol. 68, no. 6, pp. 3834-3862, June 2020. - *EiC Invited Paper*

System Model and Formulation



- MIMO Communication Model

$$\mathbf{Y} = \mathbf{HX} + \mathbf{Z} = \mathbf{S} + \underbrace{(\mathbf{HX} - \mathbf{S})}_{\text{MUI}} + \mathbf{Z}$$

$$P_{\text{MUI}} = \|\mathbf{HX} - \mathbf{S}\|_F^2$$

- MIMO Radar Orthogonal Waveform

$$\mathbf{R}_X = \frac{1}{L}\mathbf{XX}^H = \frac{P_T}{N}\mathbf{I}_N \quad \textbf{(}\boldsymbol{L}\textbf{ timeslots)}$$

Benchmark: strict Radar waveform
Closed-form Design

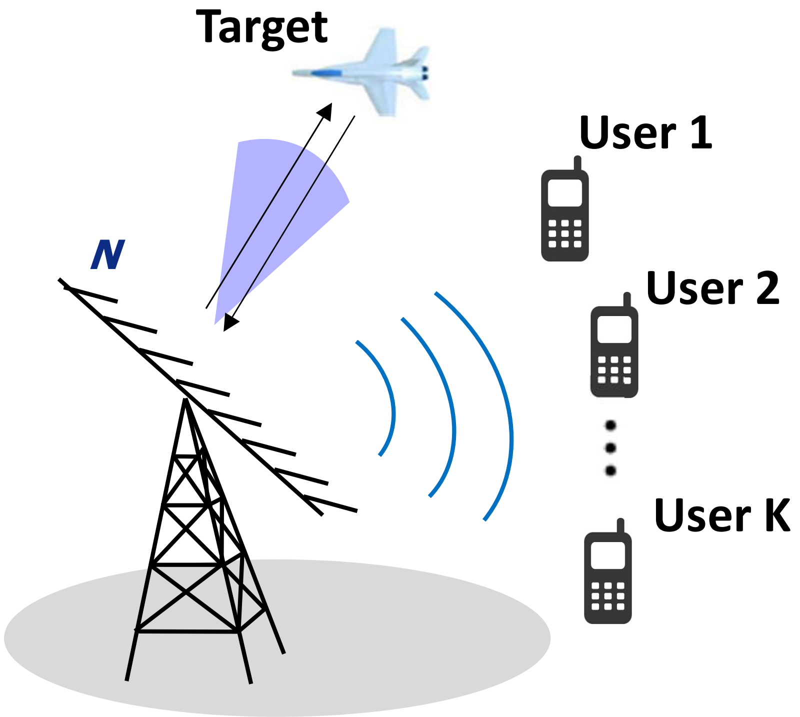
$$\min_{\mathbf{X}} \|\mathbf{HX} - \mathbf{S}\|_F^2$$
$$s.t.\ \frac{1}{L}\mathbf{XX}^H = \frac{P_T}{N}\mathbf{I}_N,$$

$$\Rightarrow \boxed{\mathbf{X} = \sqrt{LP_T/N}\,\tilde{\mathbf{U}}\mathbf{I}_{N\times L}\tilde{\mathbf{V}}}$$

$$\tilde{\mathbf{U}}\boldsymbol{\Sigma}\tilde{\mathbf{V}} = \mathbf{H}^H\mathbf{S}$$

F. Liu, L. Zhou, C. Masouros, A. Li, W. Luo, and A. Petropulu, "Toward dual-functional radar-communication systems: Optimal waveform design," IEEE Trans. Signal Process., vol. 66, no. 16, pp. 4264–4279, Aug 2018.

Weighted optimization



Tradeoff design - Total power constrained

$$\min_{\mathbf{X}} \rho \left\|\mathbf{H}\mathbf{X}-\mathbf{S}\right\|_F^2 + (1-\rho)\left\|\mathbf{X}-\mathbf{X}_0\right\|_F^2$$

$$s.t. \ \frac{1}{L}\left\|\mathbf{X}\right\|_F^2 = P_T,$$

Ideal radar waveform ($\mathbf{X}_0$)

Tradeoff design - Per-antenna power constrained

$$\min_{\mathbf{X}} \rho \left\|\mathbf{H}\mathbf{X}-\mathbf{S}\right\|_F^2 + (1-\rho)\left\|\mathbf{X}-\mathbf{X}_0\right\|_F^2$$

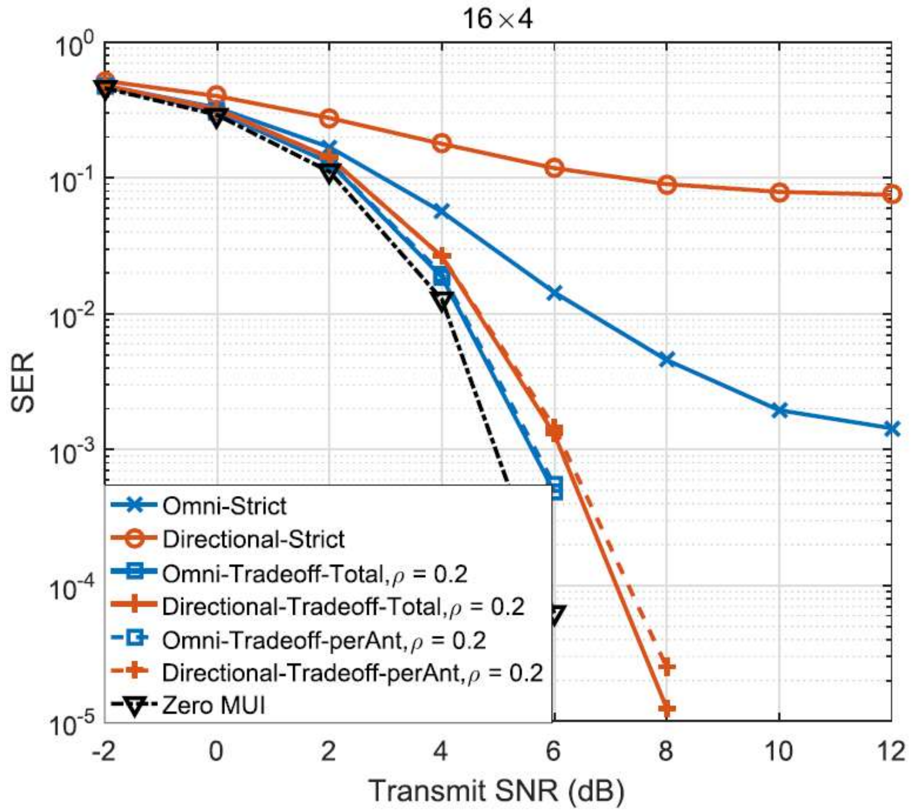
$$s.t. \ \frac{1}{L}\operatorname{diag}\left(\mathbf{X}\mathbf{X}^H\right) = \frac{P_T}{N}\mathbf{1},$$

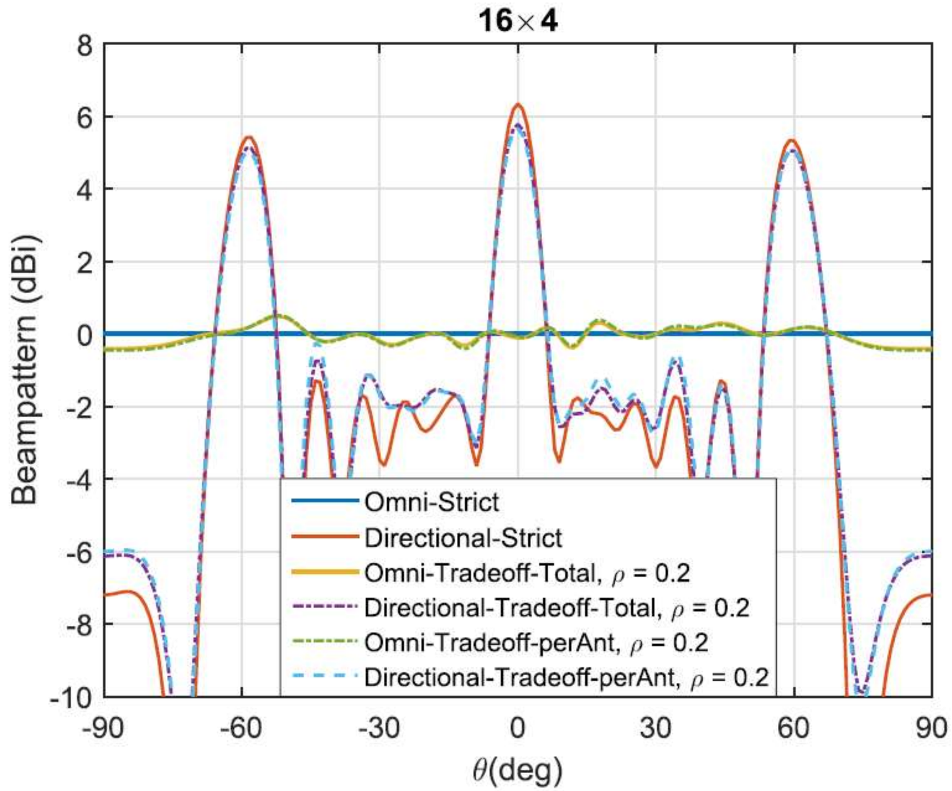
- ⇧ ρ - Comms priority
- ⇩ ρ - Radar priority

F. Liu, L. Zhou, C. Masouros, A. Li, W. Luo, and A. Petropulu, "Toward dual-functional radar-communication systems: Optimal waveform design," IEEE Trans. Signal Process., vol. 66, no. 16, pp. 4264–4279, Aug 2018.

Numerical Results

Omni / Directional radar waveform X_0



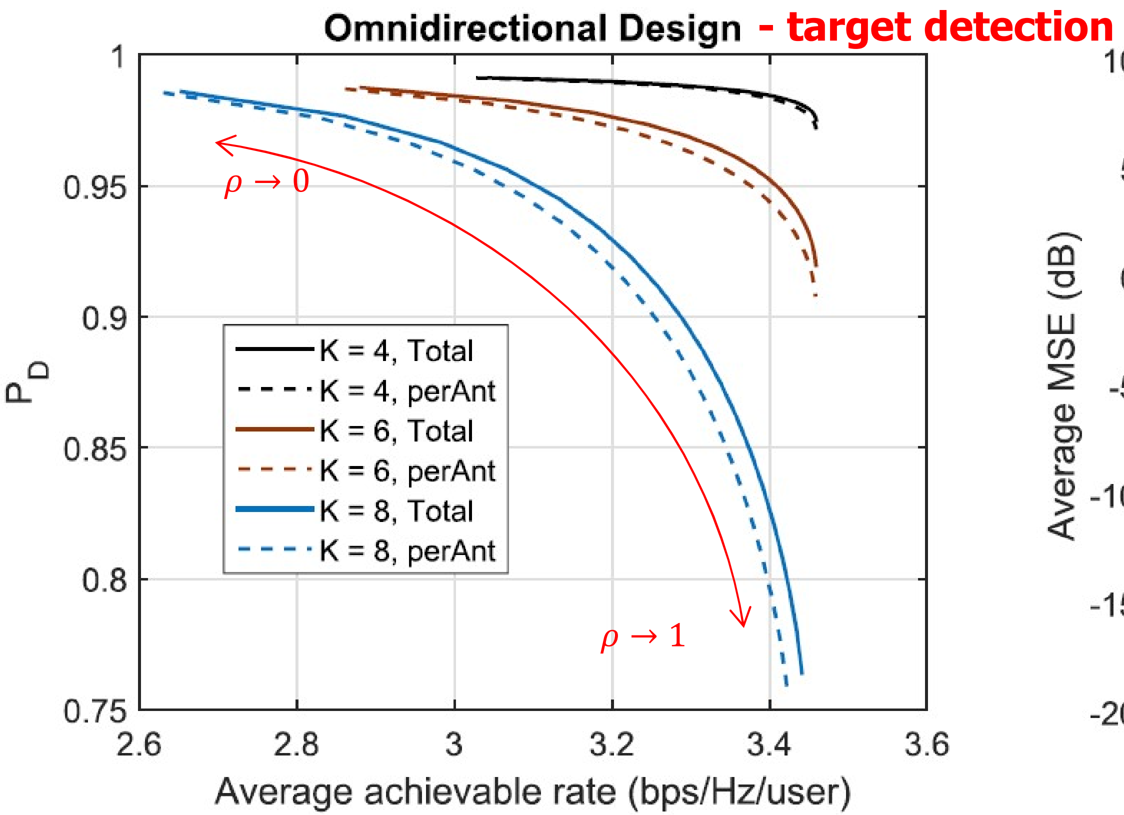


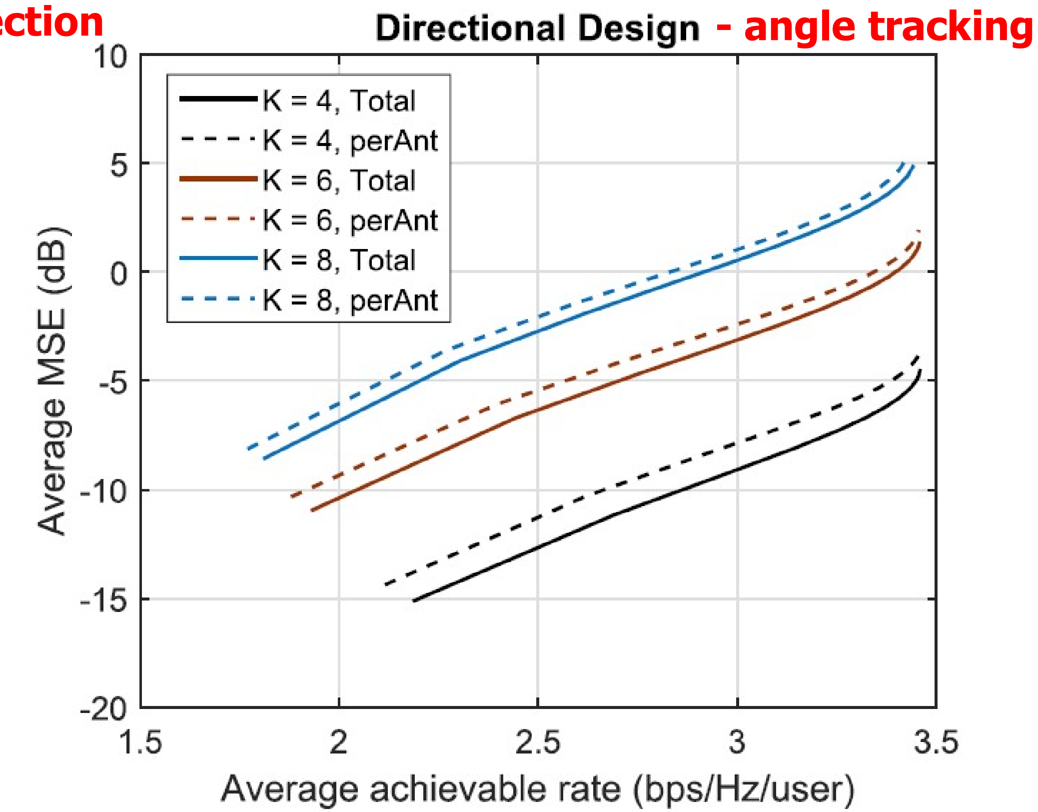
- SER: Both Omni/Directional with Radar priority $(\rho = 0.2)$ close to Zero-MUI SER
- Beampattern: with Radar priority, beampattern closely approaches ideal $\mathbf{X}_0$

F. Liu, L. Zhou, C. Masouros, A. Li, W. Luo, and A. Petropulu, "Toward dual-functional radar-communication systems: Optimal waveform design," IEEE Trans. Signal Process., vol. 66, no. 16, pp. 4264–4279, Aug 2018.

Numerical Results - Performance tradeoff

N = 16 BS antennas

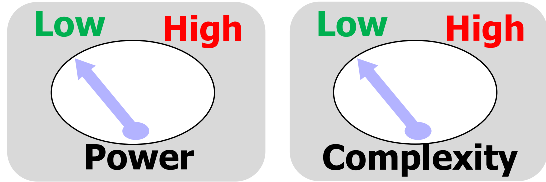




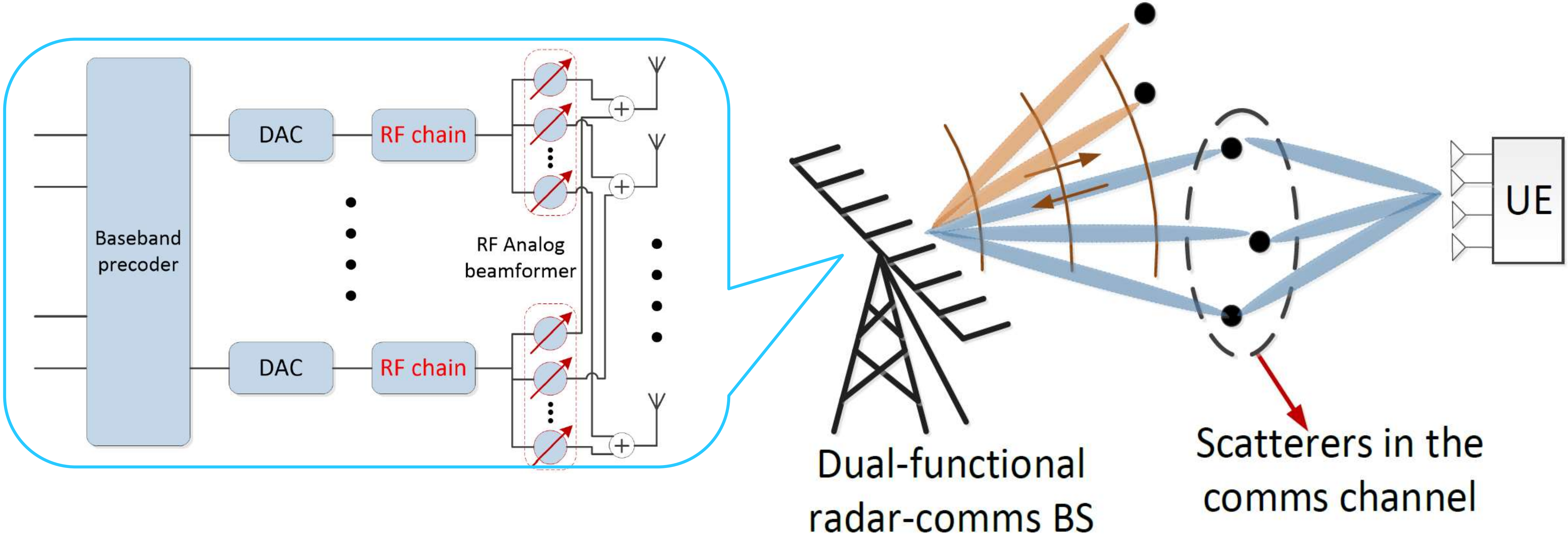
- ⬇ #users: close to ideal Radar P_D with considerable per-user rate
- ⬆ #users: a more noticeable trade-off between P_D vs. per-user rate
- Non-zero rate even with optimal Radar P_D ($\rho \to 0$)

F. Liu, L. Zhou, C. Masouros, A. Li, W. Luo, and A. Petropulu, "Toward dual-functional radar-communication systems: Optimal waveform design," IEEE Trans. Signal Process., vol. 66, no. 16, pp. 4264–4279, Aug 2018.

Reducing hardware footprint

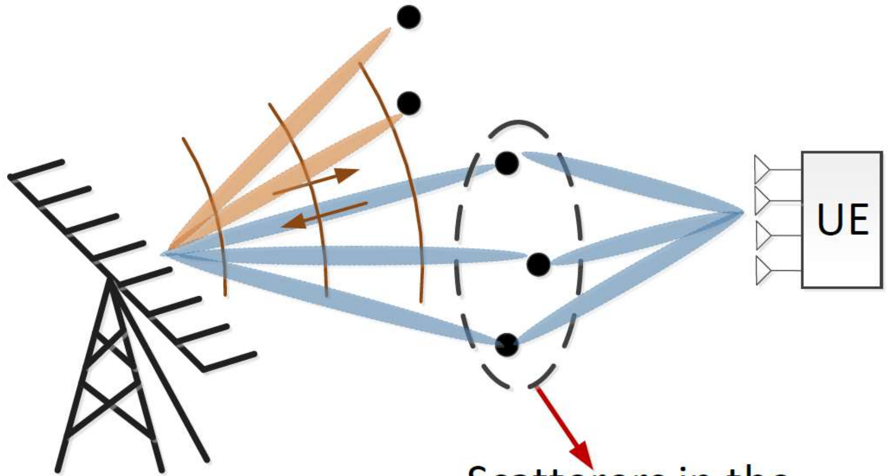


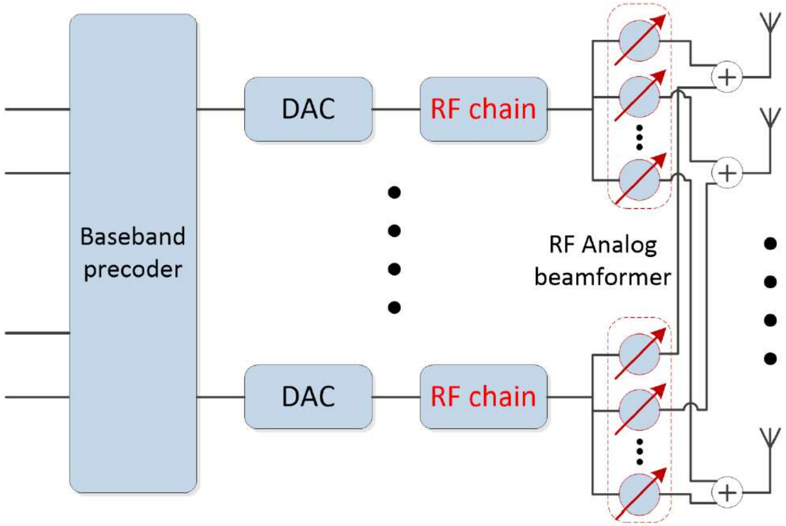
- ↑ DoF in the transmission to accommodate ↑ users + ↑ angle resolution
- ↑ #antennas → Massive MIMO BS
- Need to maintain hardware complexity → Hybrid Analog-Digital Structure



A. Kaushik, C. Masouros, F. Liu, "Hardware Efficient Joint Radar-Communications with Hybrid Precoding and RF Chain Optimization", IEEE ICC 2021

Problem formulation





Weighted Comms-Radar optimization

$$
\begin{aligned}
\min_{\mathbf{F}_{RF},\mathbf{F}_{BB},\mathbf{U}} \quad & \eta \left\|\mathbf{F}_{RF}\mathbf{F}_{BB} - \mathbf{F}_{com}\right\|_F^2 \\
& + (1-\eta)\left\|\mathbf{F}_{RF}\mathbf{F}_{BB} - \mathbf{F}_{rad}\mathbf{U}\right\|_F^2 \\
s.t. \quad & \mathbf{F}_{RF} \in \mathcal{A}_p, \ \left\|\mathbf{F}_{RF}\mathbf{F}_{BB}\right\|_F^2 = P_T, \\
& \mathbf{U}\mathbf{U}^H = \mathbf{I}_{N_{tar}}
\end{aligned}
$$

Solved by Alternating Minimization

- $\mathcal{A}_p$ - the set of feasible RF beamformers
- $\mathbf{F}_{com}$ - optimal communication beamformer
- $\mathbf{F}_{rad}$ - optimal radar beamformer
- η - weighting factor
- $\mathbf{U}$ - auxiliary unitary matrix
- P_T - transmit power budget

A. Kaushik, C. Masouros, F. Liu, "Hardware Efficient Joint Radar-Communications with Hybrid Precoding and RF Chain Optimization", IEEE ICC 2021

Numerical results: comms rate / EE vs. radar beampattern

N=128 antennas
N_{RF}=6 RF chains
K=6 users, L=3 targets

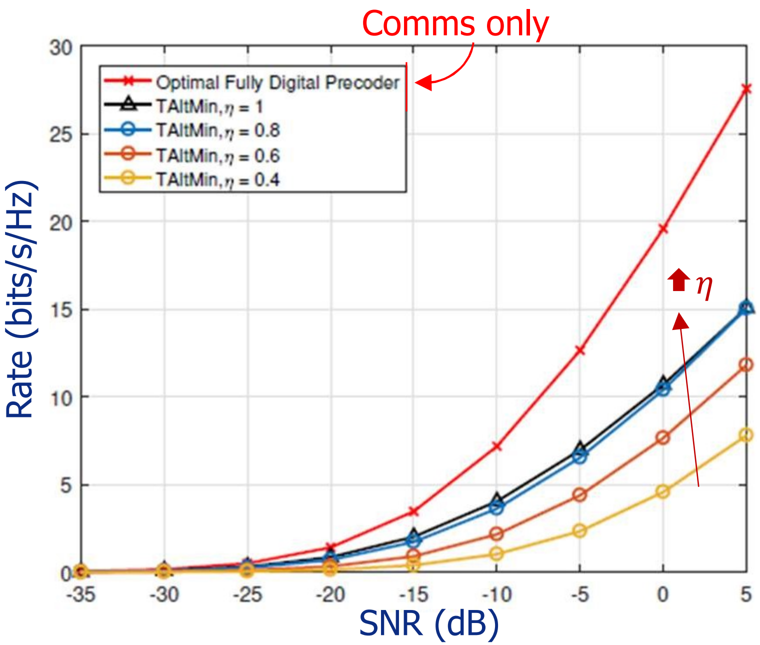


Figure: Rate vs SNR.

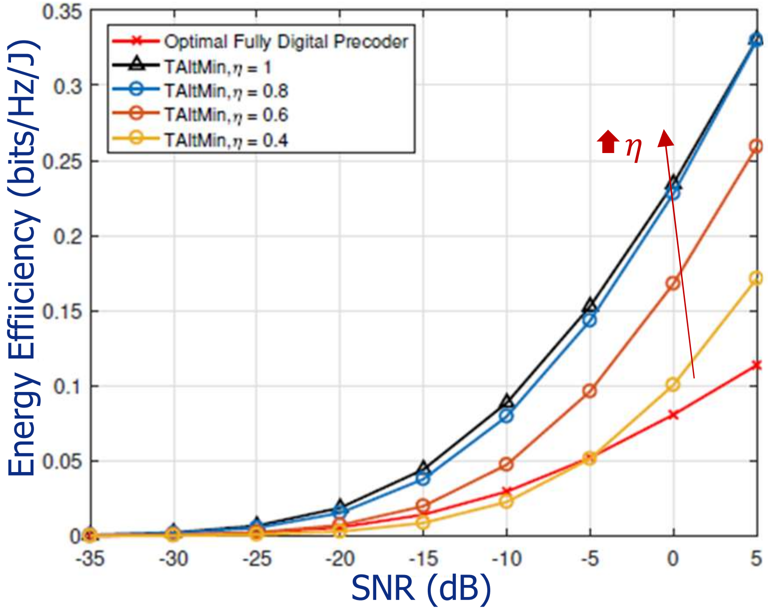


Figure: EE vs SNR.

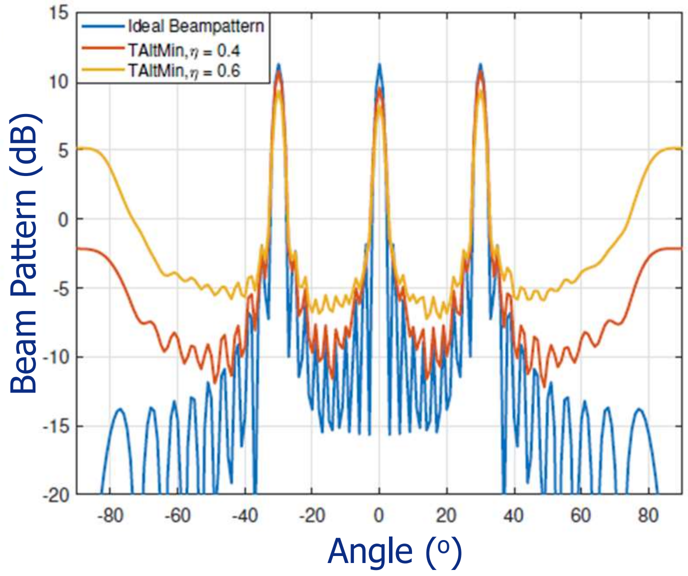


Figure: Radar Beampatterns Comparison.

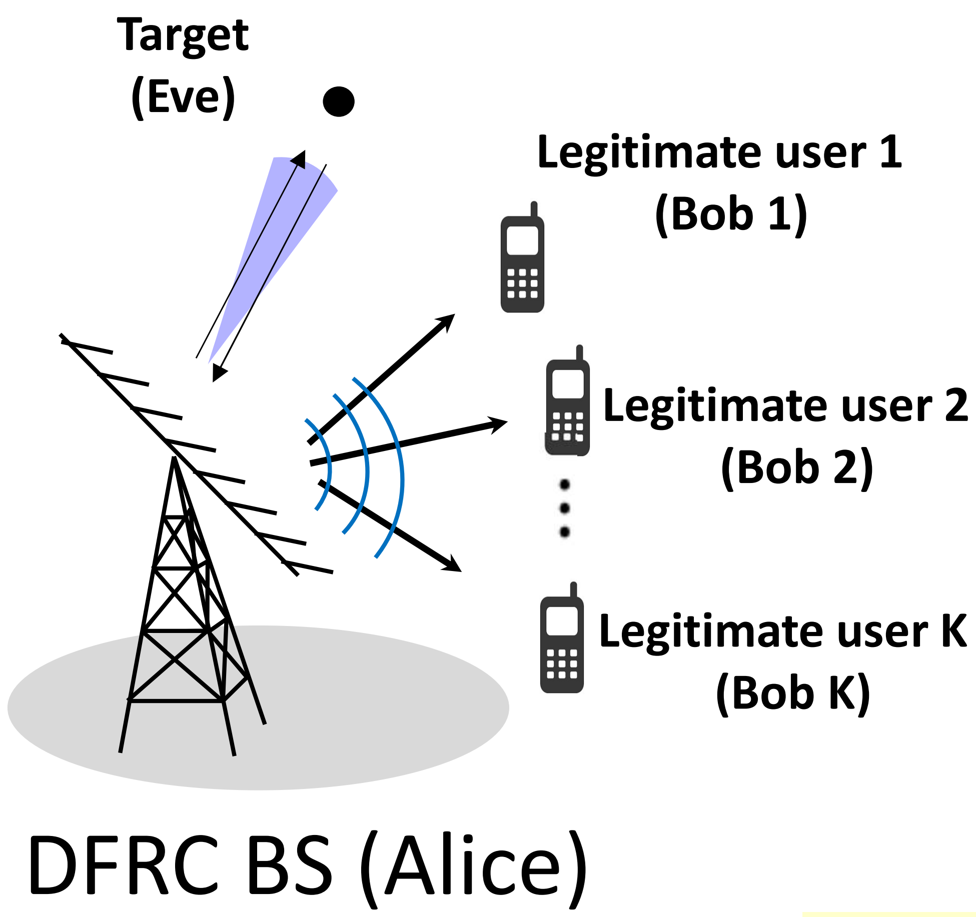
$$EE = \frac{Rate\ (F_{BB}, F_{FR}, \#RF\ chains)}{Power\ Consumption\ (F_{BB}, F_{FR}, \#RF\ chains)}$$

- ⬆ η – Comms priority: Comms achieves increasing rate – Radar BP deteriorates
- Hybrid precoding achieves higher EE compared to digital precoding
- $\eta = 1$ - communication-only performance with partially-connected hybrid beamformer, where the radar performance is not addressed

Dual-functional Radar-Communication

Subject to Security threats?

Radar + Information: Subject to Security Threats



Target can be:

- Enemy aircraft
- Malicious UAV
- Non-cooperative car
- …

Malicious target can:

- Detect Data intended for LUs – unique to DFRC
- Infer critical radar info (location, ID, …, …)

- Need for PHY security guarantees over the Radar beamwidth
- Secure Beamforming / Artificial Noise

Secure DFRC Transmission

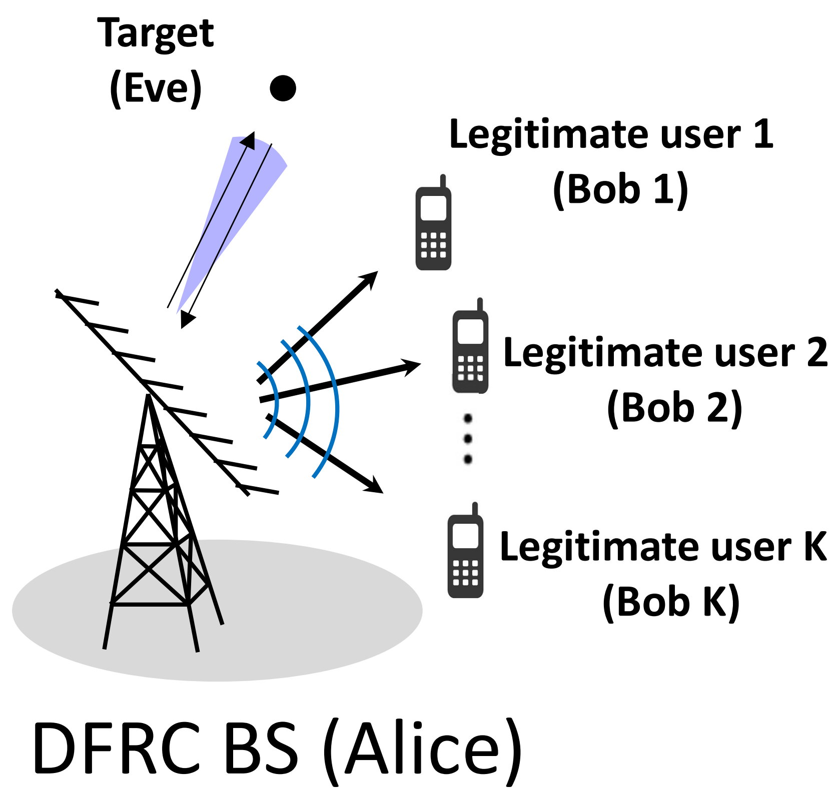
Introduce Artificial Noise

Tx signal

$$\mathbf{x} = \mathbf{W}\mathbf{s} + \mathbf{n} \qquad \mathbf{R}_X = \mathrm{E}\left[\mathbf{x}\mathbf{x}^H\right] = \sum_{i=1}^{K} \mathbf{W}_i + \mathbf{R}_N$$

SINR of i-th user

$$\mathrm{SINR}_i = \frac{\mathbb{E}\left[\left|\mathbf{h}_i^T \mathbf{w}_i s\right|^2\right]}{\sum_{k\neq i,k=1}^{K} \mathbb{E}\left[\left|\mathbf{h}_i^T \mathbf{w}_k s\right|^2\right] + \mathbb{E}\left[\left|\mathbf{h}_i^T \mathbf{n}\right|^2\right] + \sigma^2}$$
$$= \frac{\mathbf{h}_i^T \mathbf{W}_i \mathbf{h}_i^*}{\sum_{k\neq i,k=1}^{K} (\mathbf{h}_i^T \mathbf{W}_k \mathbf{h}_i^*) + (\mathbf{h}_i^T \mathbf{R}_N \mathbf{h}_i^*) + \sigma^2},$$



Comms SINR of Target (Eve) $\quad \mathrm{SINR}_E = \dfrac{|\alpha|^2 \mathbf{a}^H(\theta) \sum_{i=1}^{K} \mathbf{W}_i \mathbf{a}(\theta)}{|\alpha|^2 \mathbf{a}^H(\theta) \mathbf{R}_N \mathbf{a}(\theta) + \sigma^2}$

Worst Case Secrecy Rate $\quad \mathrm{SR} = \min_i \left[R_{C_i} - R_E\right]^+$

$$R_{C_i} = \log_2(1 + \mathrm{SINR}_i)$$
$$R_E = \log_2(1 + \mathrm{SINR}_E)$$

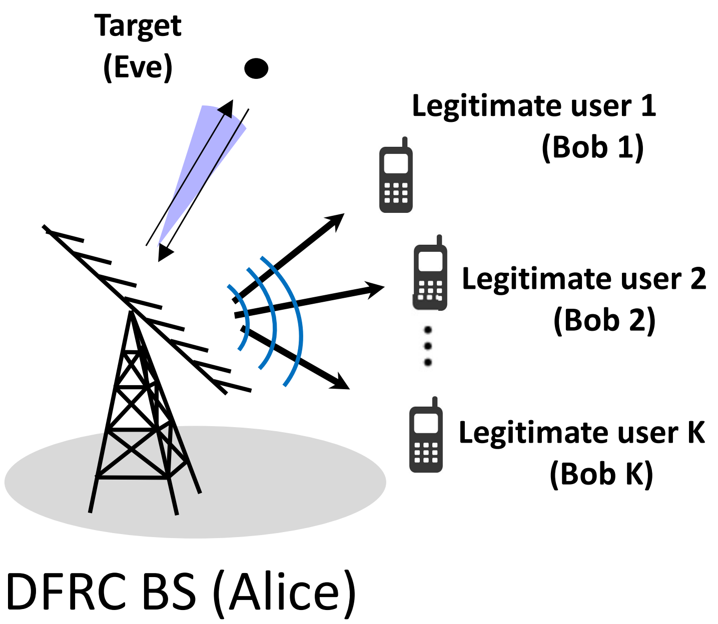
N. Su, F. Liu, C. Masouros, "Secure Radar-Communication Systems with Malicious Targets: Integrating Radar, Communications and Jamming Functionalities", IEEE Trans. Wireless Comms., *in press*

Secure DFRC Beamforming - Perfect CSI

Optimization problem:

Well-designed Radar Waveform

$$\min_{\eta,\mathbf{R}_d} \sum_{m=1}^{M} \left|\eta P_d(\theta_m) - \mathbf{a}^H(\theta_m)\mathbf{R}_d\mathbf{a}(\theta_m)\right|^2$$
$$s.t.\quad \mathrm{tr}(\mathbf{R}_d) = P_0,$$
$$\mathbf{R}_d \succeq 0, \mathbf{R}_d = \mathbf{R}_d^H,$$
$$\eta \geq 0,$$



Secure Beamformer

$$\min_{\mathbf{W}_i,\mathbf{R}_N} \frac{|\alpha|^2\mathbf{a}^H(\theta_0)\sum_{i=1}^{K}\mathbf{W}_i\mathbf{a}(\theta_0)}{|\alpha|^2\mathbf{a}^H(\theta_0)\mathbf{R}_N\mathbf{a}(\theta_0)+\sigma^2},$$ ← Eve's SINR
$$s.t.\quad \left\|\mathbf{R}_X - \mathbf{R}_d\right\|^2 \leq \gamma_{bp},$$ ← Match to Radar WF
$$\mathrm{SINR}_i \geq \gamma_b, \forall i,$$ ← LU's SINR
$$\mathrm{tr}(\mathbf{R}_X) = P_0,$$
$$\mathbf{W}_i = \mathbf{W}_i^H, \mathbf{W}_i \succeq 0, \forall i,$$
$$\mathrm{rank}(\mathbf{W}_i) = 1, \forall i,$$
$$\mathbf{R}_N = \mathbf{R}_N^H, \mathbf{R}_N \succeq 0,$$

Fractional Programming + SDR

Secure DFRC BF - Statistical CSI, Target Uncertainty

Secure Beamformer

$$\min_{\mathbf{W}_i,\mathbf{R}_N,\mathbf{Z}_i} \max_{\theta_m\in\Phi} \frac{|\alpha|^2\mathbf{a}^H(\theta_m)\sum_{i=1}^{K}\mathbf{W}_i\mathbf{a}(\theta_m)}{|\alpha|^2\mathbf{a}^H(\theta_m)\mathbf{R}_N\mathbf{a}(\theta_m)+\sigma^2} \quad (27a)$$

$$s.t. \quad -\delta_i\|\mathbf{A}_i+\mathbf{Z}_i\| - \mathrm{tr}(\mathbf{R}_{h_i}(\mathbf{Z}_i+\mathbf{A}_i)) - \gamma_b\mathrm{tr}(\mathbf{R}_{h_i}\mathbf{R}_N) - \gamma_b\sigma^2 \geq 0, \forall i, \quad (27b)$$

$$\mathbf{a}^H(\theta_0)\mathbf{R}_X\mathbf{a}(\theta_0) - \mathbf{a}^H(\theta_m)\mathbf{R}_X\mathbf{a}(\theta_m) \geq \gamma_s, \quad \forall\theta_m\in\Omega \quad (27c)$$

$$\mathbf{a}^H(\theta_k)\mathbf{R}_X\mathbf{a}(\theta_k) \leq (1+\alpha)\mathbf{a}^H(\theta_0)\mathbf{R}_X\mathbf{a}(\theta_0), \quad \forall\theta_k\in\Phi \quad (27d)$$

$$(1-\alpha)\mathbf{a}^H(\theta_0)\mathbf{R}_X\mathbf{a}(\theta_0) \leq \mathbf{a}^H(\theta_k)\mathbf{R}_X\mathbf{a}(\theta_k), \quad \forall\theta_k\in\Phi \quad (27e)$$

$$\mathrm{tr}(\mathbf{R}_X) = P_0, \quad (27f)$$

$$\mathbf{Z}_i = \mathbf{Z}_i^H, \mathbf{Z}_i \succeq 0, \forall i, \quad (27g)$$

$$\mathbf{W}_i = \mathbf{W}_i^H, \mathbf{W}_i \succeq 0, \forall i, \quad (27h)$$

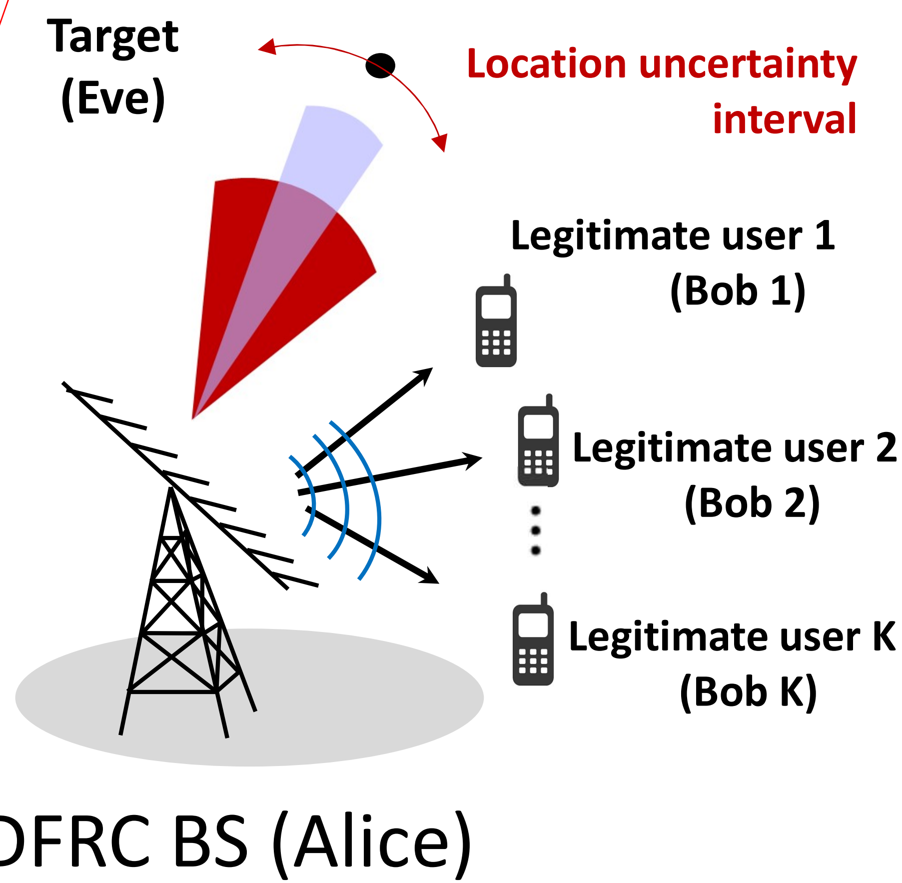
$$\mathrm{rank}(\mathbf{W}_i) = 1, \forall i, \quad (27i)$$

$$\mathbf{R}_N = \mathbf{R}_N^H, \mathbf{R}_N \succeq 0, \quad (27j)$$

Fractional Programming + SDR

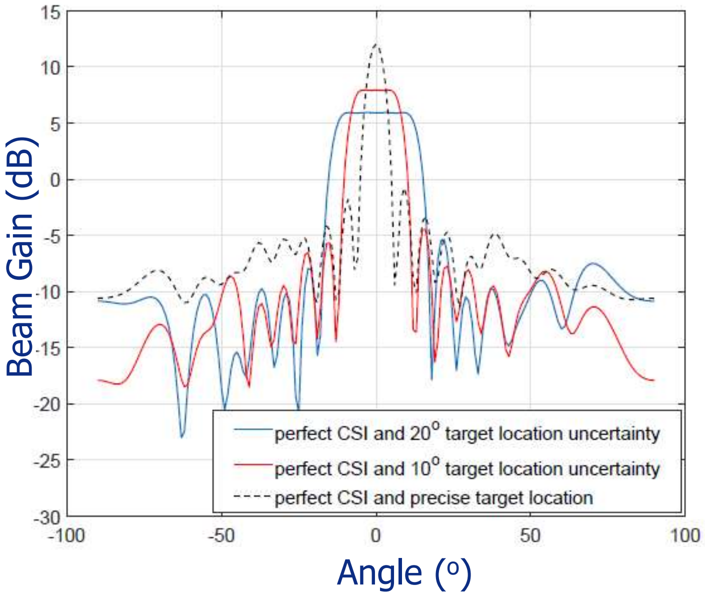
PSRL greater than γ_s

Main beam region within angle spread ϕ, within $\pm\boldsymbol{\alpha}$ of θ_0

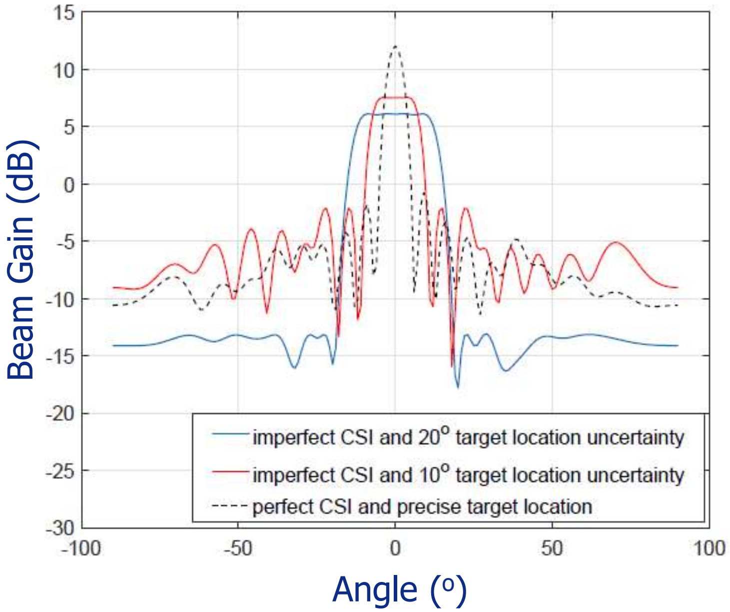


Numerical Results (Beampattern)

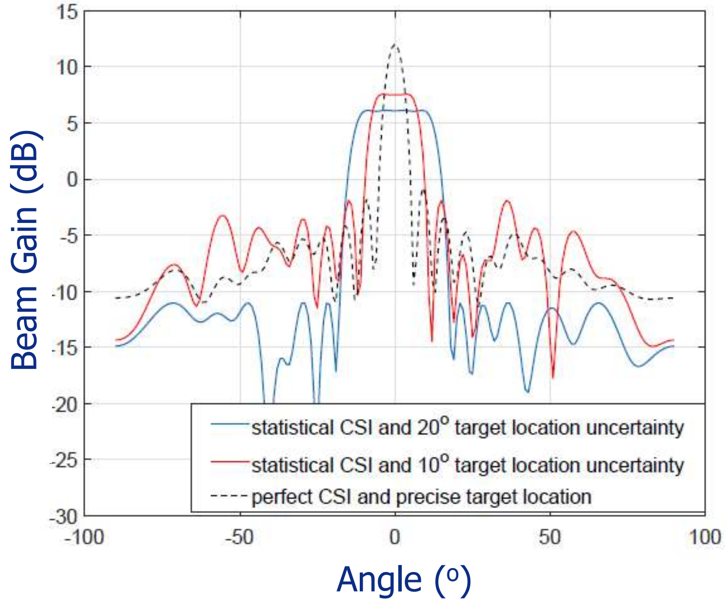
N = 18 antennas, K = 4 legitimate users, one target - $\gamma_b = 10\text{dB}$.



Perfect CSI



Imperfect CSI

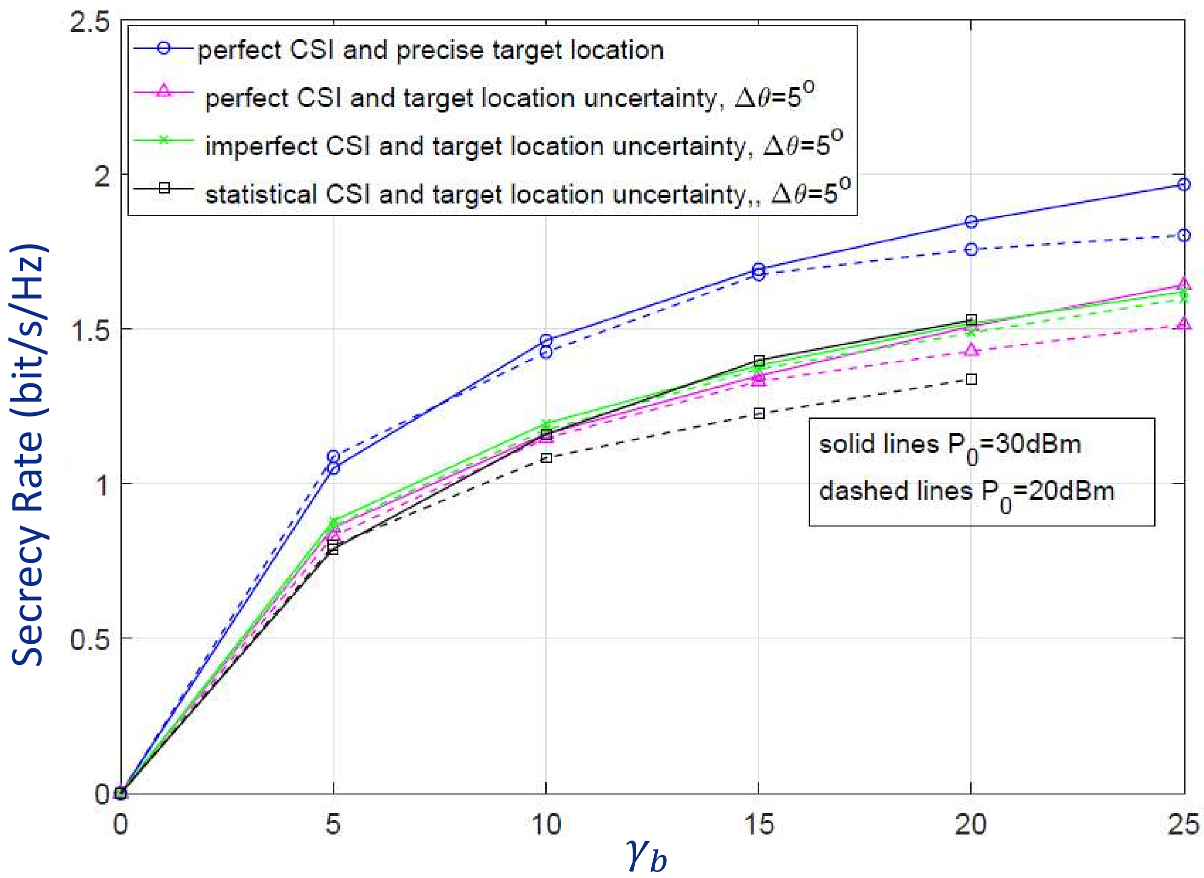


Statistical CSI

- ↑ location uncertainty angular interval → ↓ power gain of mainbeam.
- CSI imperfections deteriorate the radar PSLR

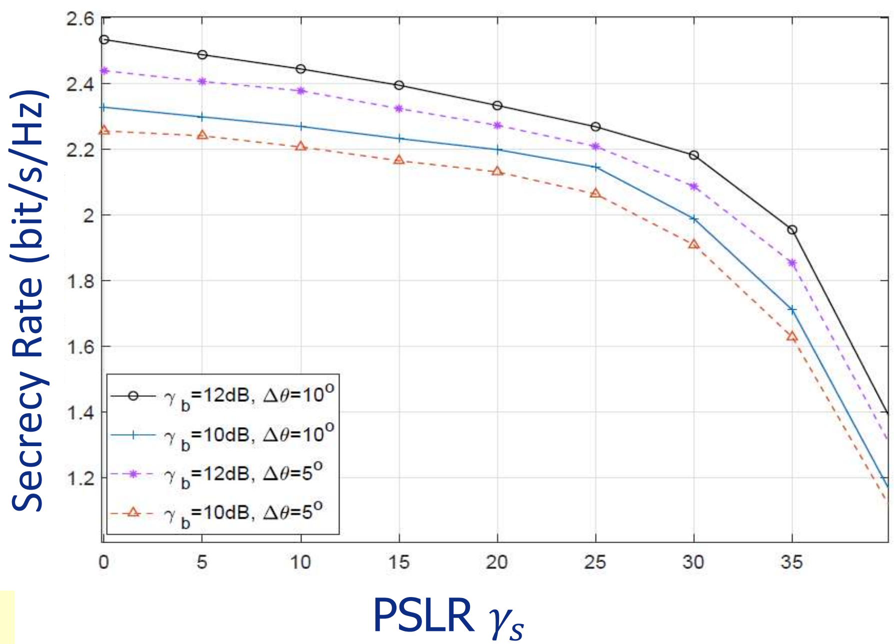
N. Su, F. Liu, C. Masouros, "Secure Radar-Communication Systems with Malicious Targets: Integrating Radar, Communications and Jamming Functionalities", IEEE Trans. Wireless Comms., *in press*

Numerical Results (SR vs Comm SINR)



N = 18 antennas, *K* = 4 legitimate users, one target – PSRL $(\gamma_s) = 40dB$.

$$\mathrm{SR} = \min_i \left[R_{C_i} - R_E \right]^+$$



- ↑ user SINR γ_b → ↑ secrecy rate
- ↑ target location uncertainty and CSI imperfections → ↓ secrecy rate
- ↑ power budget → ↑ secrecy rate
- ↑ PSRL → ↓ Secrecy Rate (more power spent on radar PSRL fulfilment)

N. Su, F. Liu, C. Masouros, "Secure Radar-Communication Systems with Malicious Targets: Integrating Radar, Communications and Jamming Functionalities", IEEE Trans. Wireless Comms., *in press*

Conclusions

- Dual-functional radar-communication system that can serve multiple downlink users while detecting targets – enabler for future applications
  - Spectrally Efficient
  - Energy Efficient
  - Hardware Efficient
- Need to reduce hardware footprint
  - Can borrow techniques from 5G (mmWave, Massive MIMO)
- Security Challenges
  - Cross-domain design between Comms – Radar – PHY Security

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c.masouros@ucl.ac.uk

References

Overviews

1. F. Liu, C. Masouros, H. Griffiths, A. Petropulu, and L. Hanzo, “Joint Radar and Communication Design: Applications, State-of-the-art, and the Road Ahead”, IEEE Trans Commun., vol. 68, no. 6, pp. 3834-3862, June 2020. *– EiC invited paper*
2. F. Liu and C. Masouros, "A Tutorial on Joint Radar and Communication Transmission for Vehicular Networks - Part I: Background and Fundamentals", IEEE Commun. Lett., in press *- EiC Invited Paper*
3. F. Liu and C. Masouros, "A Tutorial on Joint Radar and Communication Transmission for Vehicular Networks - Part II: State of the art and Challenges Ahead", IEEE Commun. Lett., in press *- EiC Invited Paper*
4. F. Liu and C. Masouros, "A Tutorial on Joint Radar and Communication Transmission for Vehicular Networks - Part III: Predictive Beamforming without State Models", IEEE Commun. Lett., in press *– EiC invited paper*

Book Chapter

5. F. Liu, C. Masouros, “Communication and Radar systems: Spectral Co-existence and Beyond”, published by the Wiley Press book “Spectrum Sharing: The Next Frontier in Wireless Networks”, Edited by: Constantinos Papadias, Tharm Ratnarajah, Dirk Slock, 2020 edition Wiley Press *– Invited*

Radar-Comms Coexistence

6. F. Liu, C. Masouros, A. Li, T. Ratnarajah and J. Zhou, “MIMO Radar and Cellular Coexistence: A Power-Efficient Approach Enabled by Interference Exploitation”, IEEE Trans. Sigal Process., vol. 66, no. 14, pp. 3681-3695, July 2018,
7. F. Liu, A. Garcia, C. Masouros, and G. Geraci, “Interfering Channel Estimation in Radar-Cellular Coexistence: How Much Information Do We Need?”, IEEE Trans. Wireless Commun., vol. 18, no. 9, pp. 4238-4253, Sept. 2019

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Dual-functional Radar-Communication

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