Wireless Networks for 6G and Beyond: Not Just Communications

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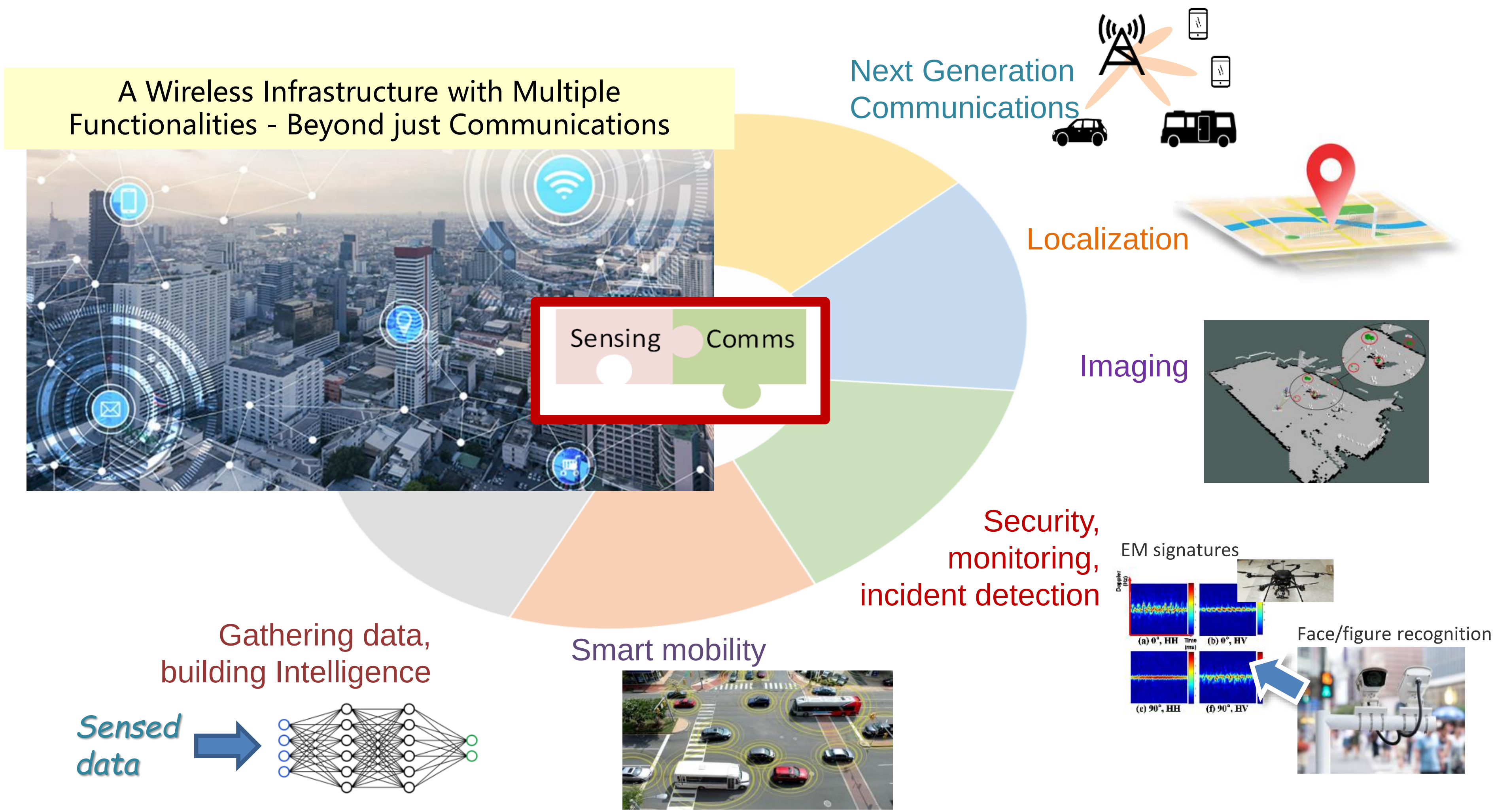
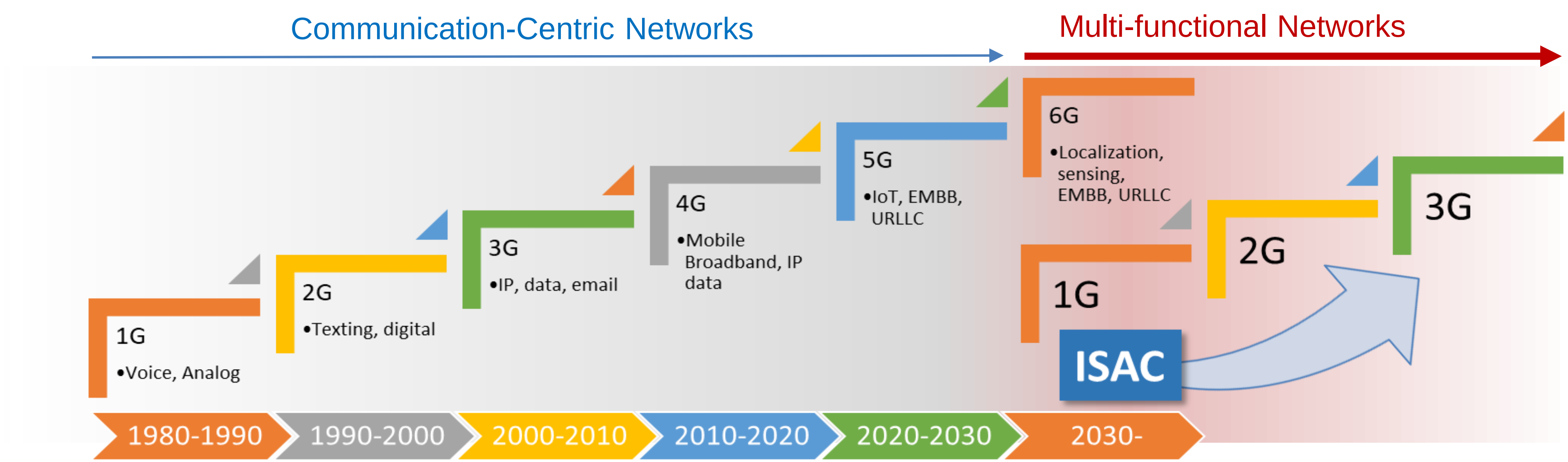
Next Generations of Networks



F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, A. Hassanien, Y. Eldar, S. Buzzi, "Integrated Sensing and Communications: Toward Future Dual-functional Wireless Networks", IEEE Journal on Sel. Areas Comms., vol. 40, no. 6, pp. 1728-1767, June 2022

Mobile Comms Generations' Evolution

6G will be the first generation of multi-functional networks



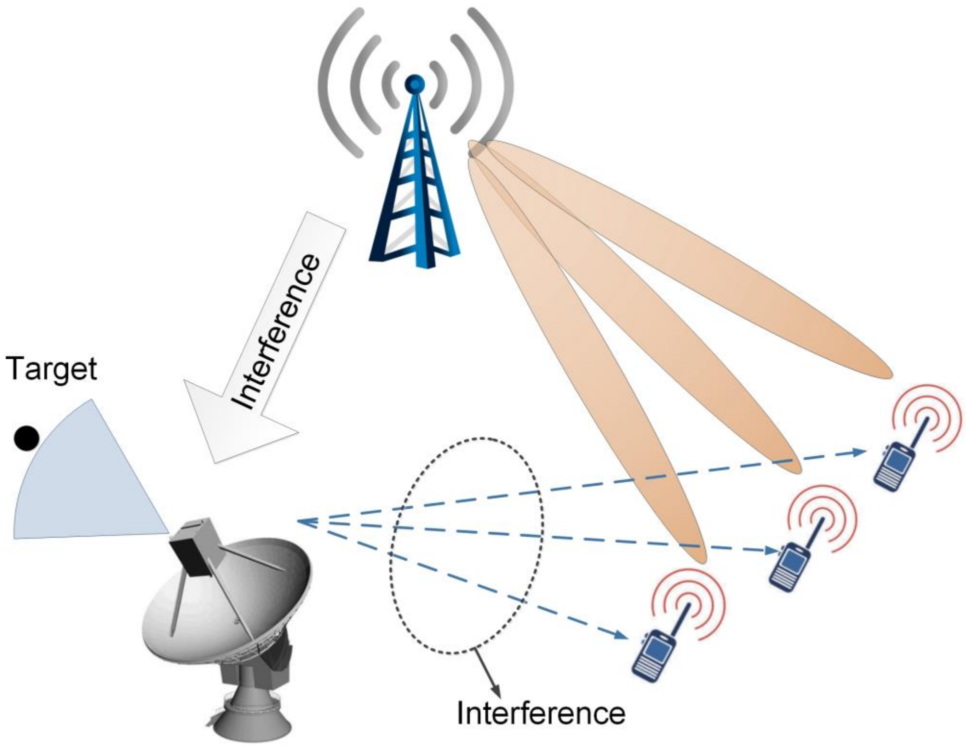
Integrated Sensing and Communications (ISAC)

Radar Spectrum being released for commercial comms services




Frequency Band	Radar Systems	Communication Systems
L-band (1-2GHz)	Long-range surveillance radar, ATC radar	LTE, 5G NR
S-band (2-4GHz)	Moderate-range surveillance radar, ATC radar, airborne early warning radar	IEEE 802.11b/g/n/ax/y WLAN, LTE, 5G NR
C-band (4-8GHz)	Weather radar, ground surveillance radar, vessel traffic service radar	IEEE 802.11a/h/j/n/p/ac/ax WLAN
MmWave band (30-300GHz)	Automotive radar, high-resolution imaging radar	IEEE 802.11ad/ay WLAN, 5G NR

Radar-Communication Coexistence (RCC)



Challenges

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

Risky for radar-critical / comms-critical operations

BBC NEWS

US airlines warn of impending 5G flight disruption

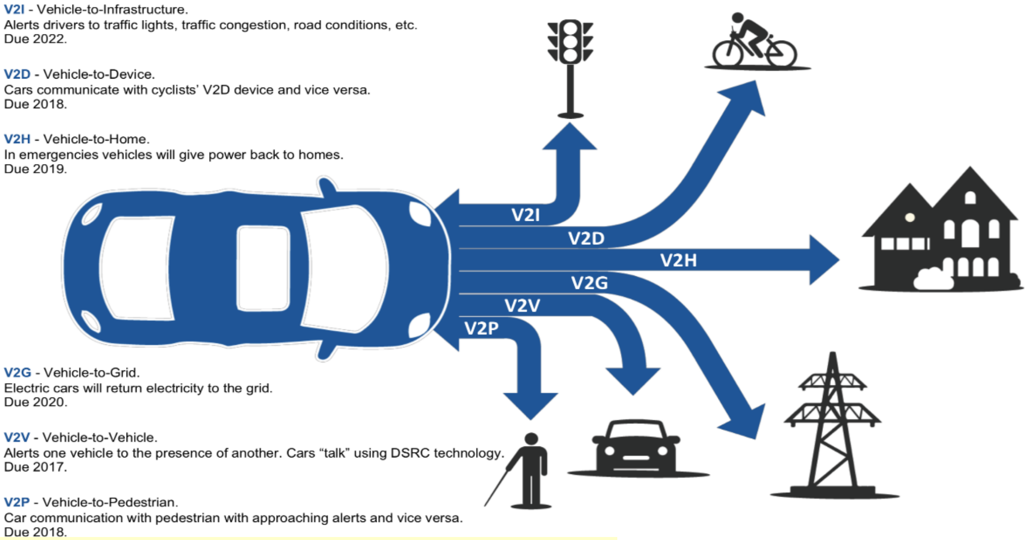
18 January

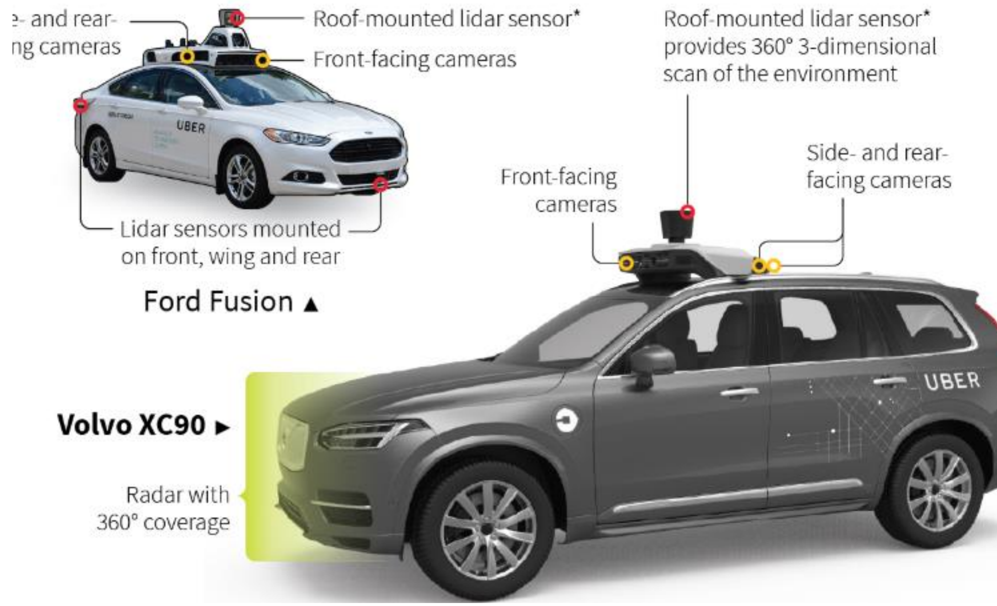
B. Paul, A. R. Chiriyath, and D. W. Bliss, “Survey of RF communications and sensing convergence research,” IEEE Access, vol. 5, pp. 252–270, 2017.

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.

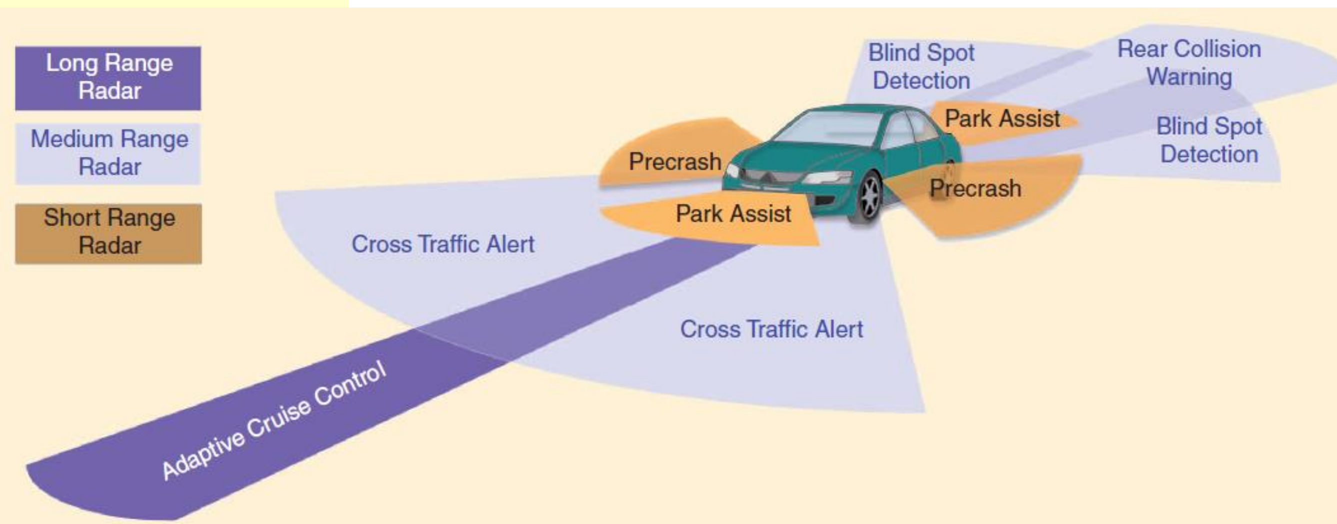
Challenges: Autonomous Vehicles Example

Too many sensors





Vehicular Communications



- **Cameras**
- **LIDAR**
- **Radar**

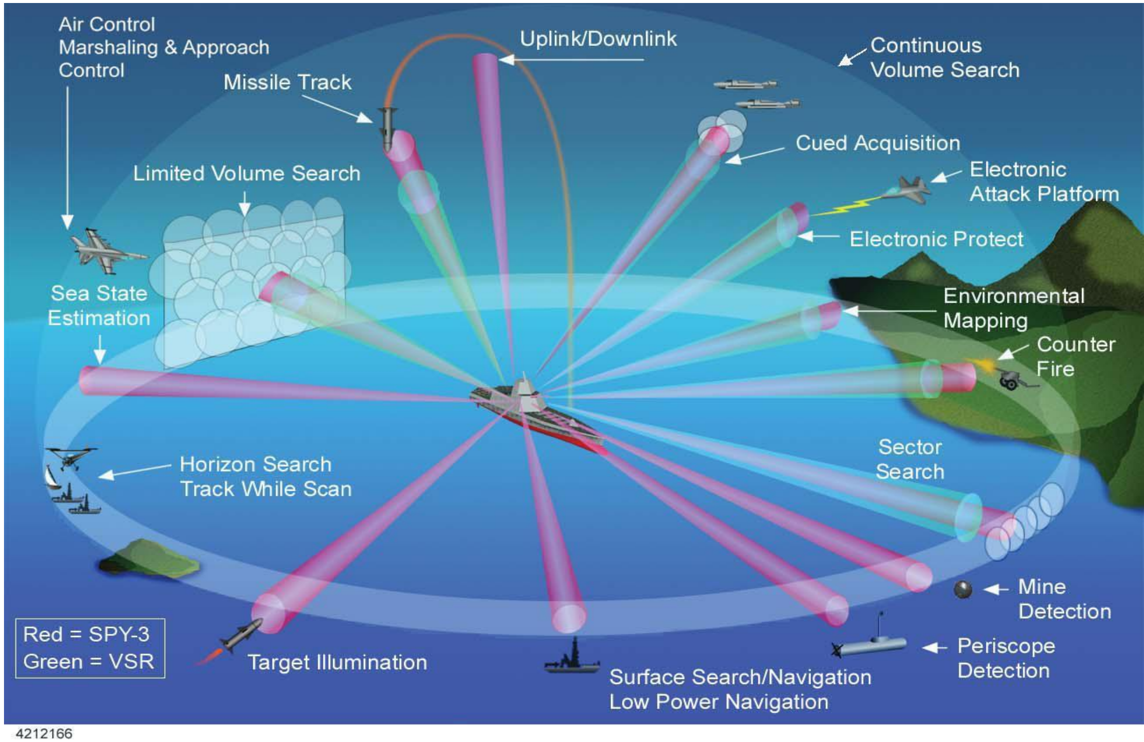
https://medium.com/datadriveninvestor/is-5g-friend-or-foe-for-autonomous-vehicle-72ee70800031
https://semiwiki.com/ip/moortec/8148-meeting-automotive-ic-design-challenges-for-safety-using-on-chip-sensors/

Too many RF systems

Shipborne / airborne platforms to support a number of comms and sensing operations;

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.

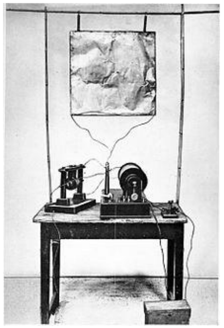


Could radar and communication transmission be merged?

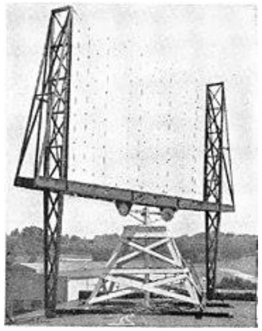
G. C. Tavik et al., "The advanced multifunction RF concept," IEEE Trans. Microw. Theory Techn., vol. 53, no. 3, pp. 1009–1020, Mar. 2005.

Wireless Communications

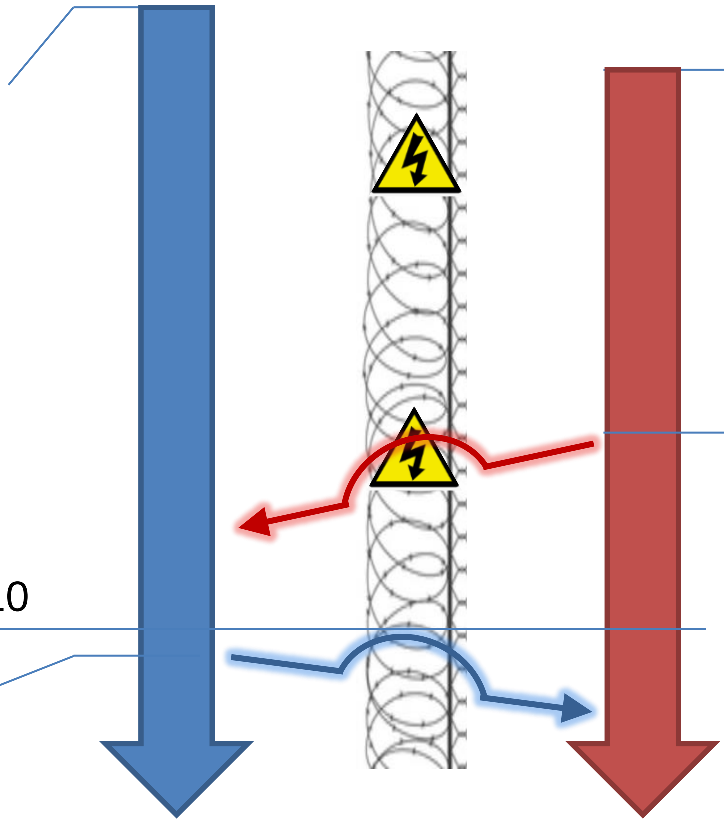
Radar

Guglielmo Marconi 1894

Sir Robert Watson Watt 1915



Pulse Interval modulation, 1967

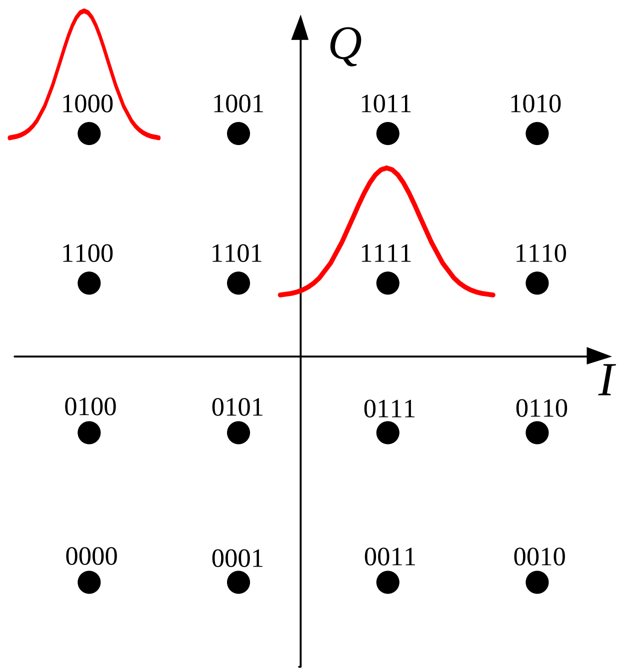
Spectrum Co-Existence, ~2010

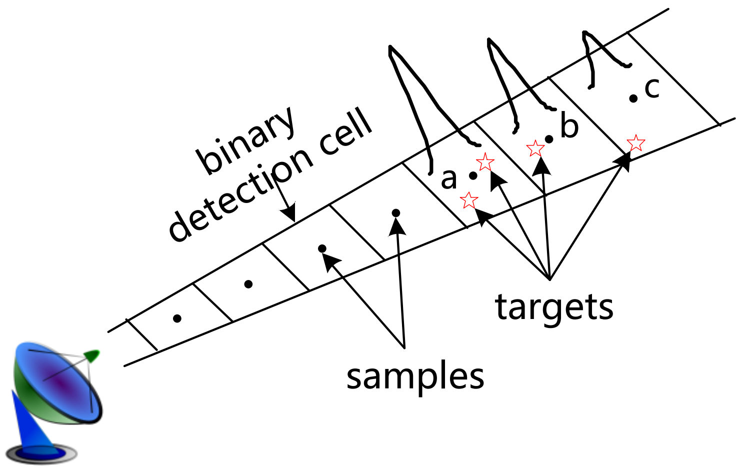
OFDM based sensing, 2013

The relation between radar and communication

Communication Symbol Detection - Multiple Hypotheses Testing Problem (MHT)

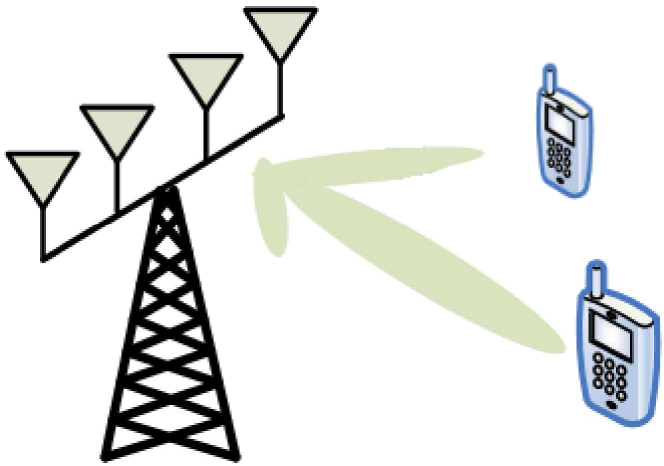
Target Detection - Binary Hypothesis Testing for multiple cells



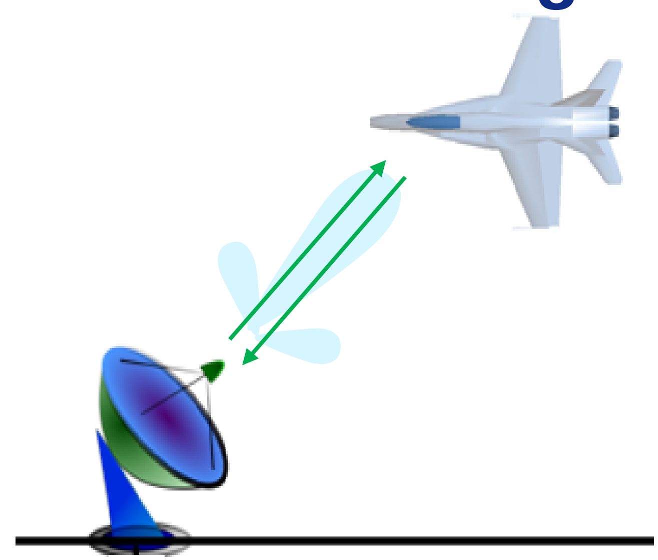


A highly densely arranged MHT problem or a very large constellation

Communication and Radar Beamforming



Base Station



Radar

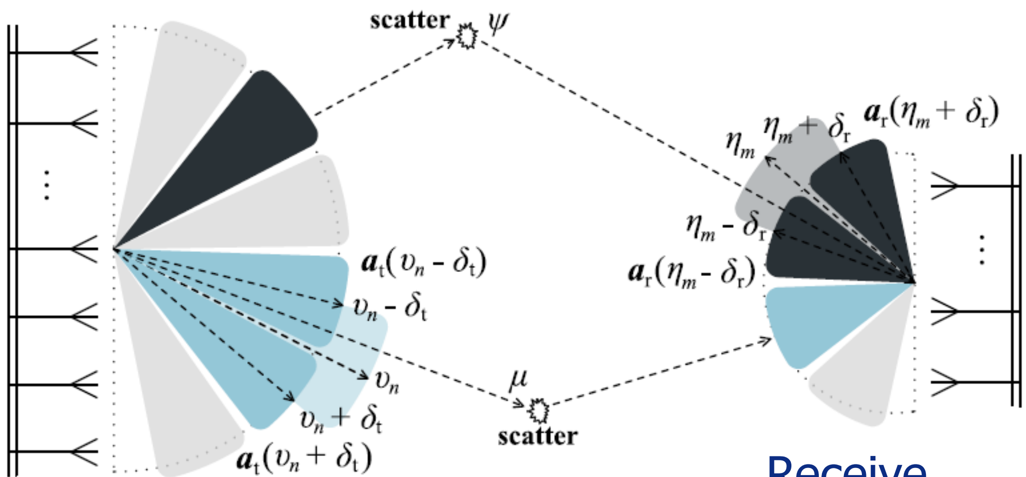
- Comms beamforming tailored to channel – Radar to geometry – but in LoS sparse channels the two converge
- Targets (echoes) ~ virtual uplink users that unwillingly communicate with the radar
- MmWave - beam training/tracking becomes virtually the same for Comms-Radar

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*

A. R. Chiriyath, B. Paul, G. M. Jacyna, and D. W. Bliss, "Inner bounds on performance of radar and communications co-existence," IEEE Trans. Signal Process., vol. 64, no. 2, pp. 464–474, Jan. 2016.

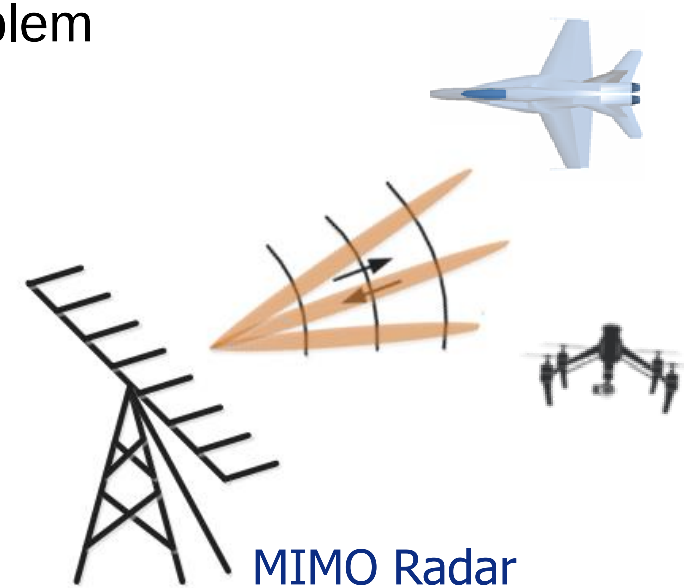
mmWave CSI estimation – vs – radar angle estimation

Parameter Estimation Problem



Transmit antenna array

Receive antenna array



MIMO Radar

$$\mathbf{y} = \sum_{l} \beta_l \boldsymbol{b}(\phi_l)\boldsymbol{a}^T(\theta_l)\,\mathbf{p} + \mathbf{n}$$

Comms Channel

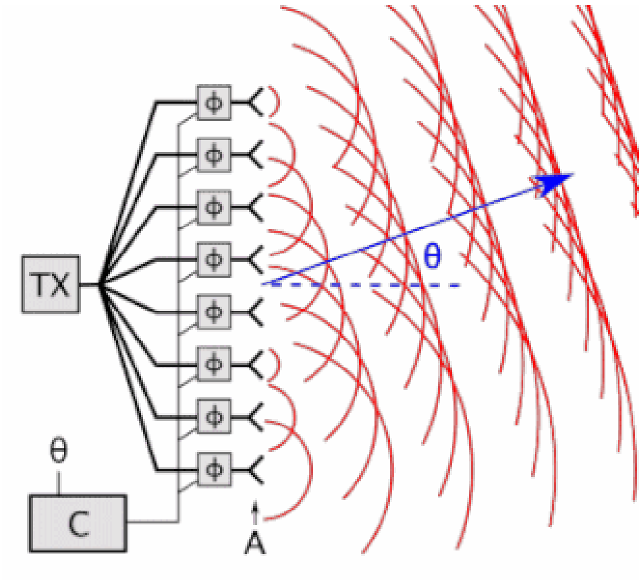
$$\mathbf{Y}_{echo} = \sum_{i} \alpha_i \boldsymbol{b}(\theta_i)\boldsymbol{a}^T(\theta_i)\,\mathbf{s} + \mathbf{n}$$

Target Steering vectors

Duplication in hardware

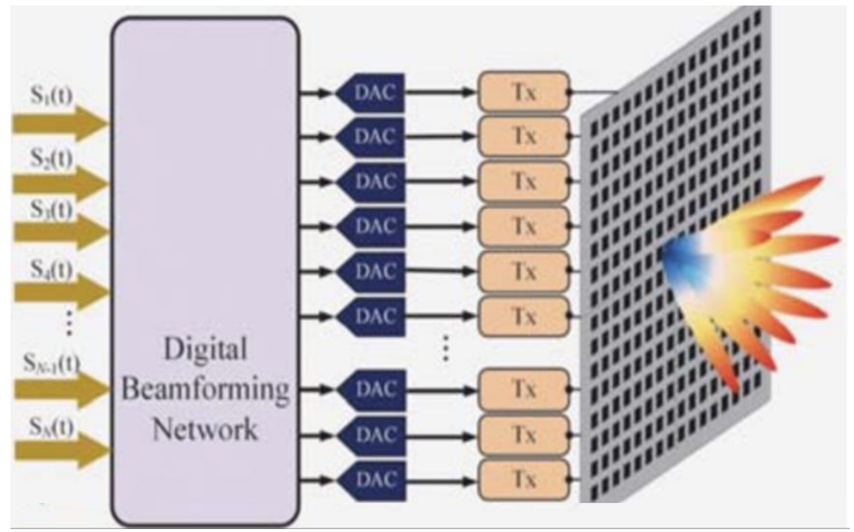
Communication Phased Arrays

Radar Phased Arrays



MIMO / massive MIMO communications

MIMO Radar



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A. Zhang, F. Liu, C. Masouros, R. Heath, Z. Feng, L. Zheng, A. Petropulu, "An Overview of Signal Processing Techniques for Joint Communication and Radar Sensing", IEEE Journal Selected Topics in Signal Processing., vol. 15, no. 6, pp. 1295-1315, Nov. 2021

Performance Metrics

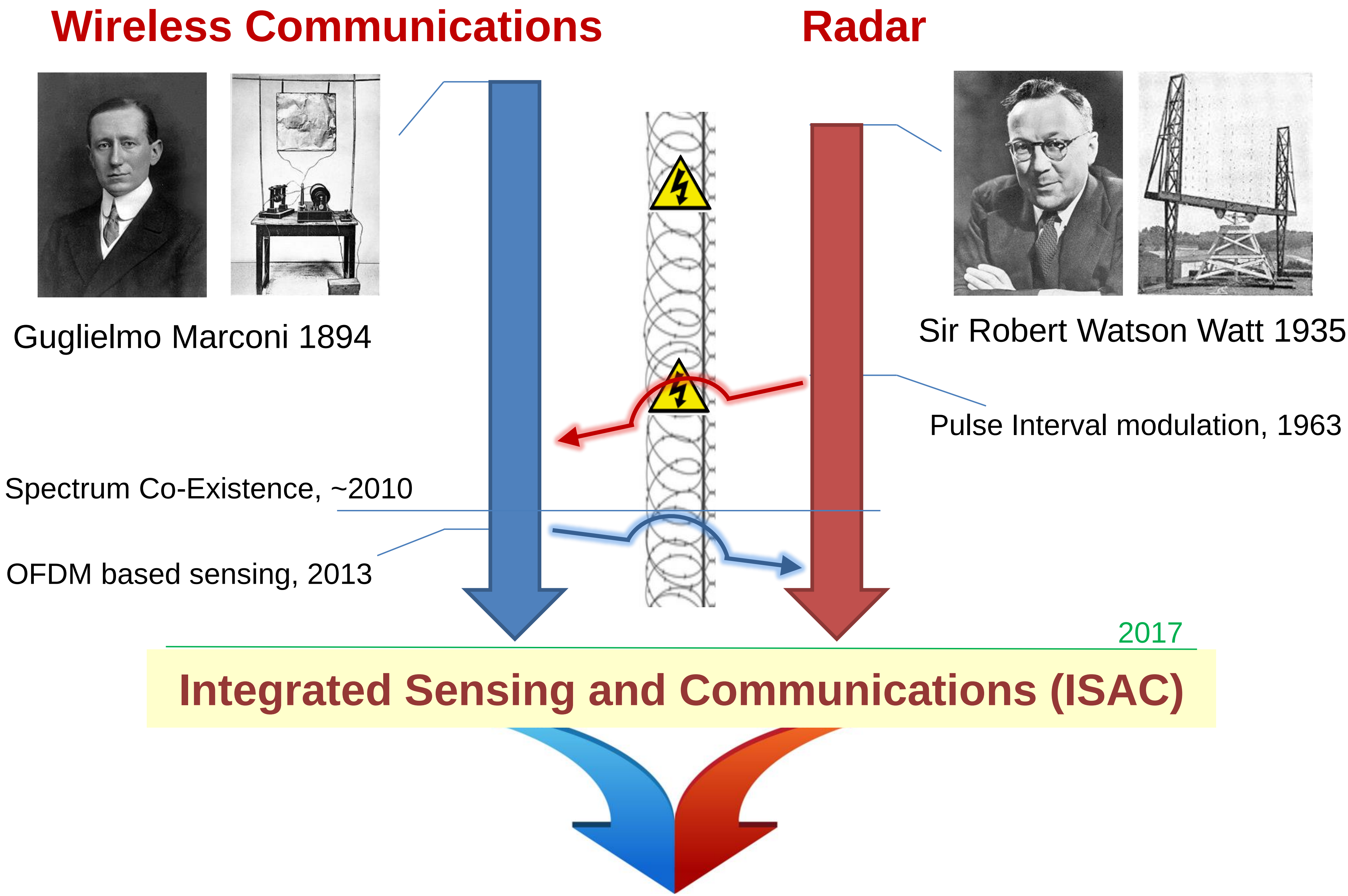
Communication Metric

- SINR;
- Bit Error Probability;
- CSI MSE
- Channel Capacity – Mutual Information;
- Achievable sum rates

Radar Metric

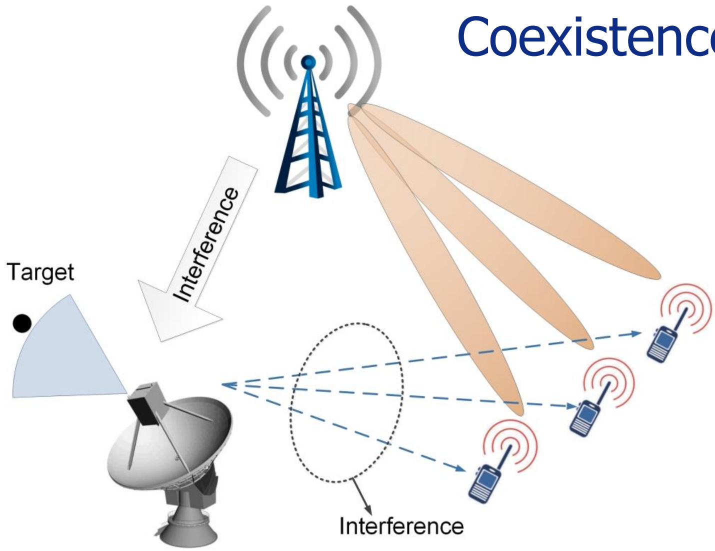
- SCNR;
- Detection/FA Probability;
- AoA /Parameter MSE
- Cramer-Rao Bound;
- Estimation Capacity - Mutual Information.

A. R. Chiriyath, B. Paul, G. M. Jacyna, and D. W. Bliss, "Inner bounds on performance of radar and communications co-existence," IEEE Trans. Signal Process., vol. 64, no. 2, pp. 464–474, Jan. 2016

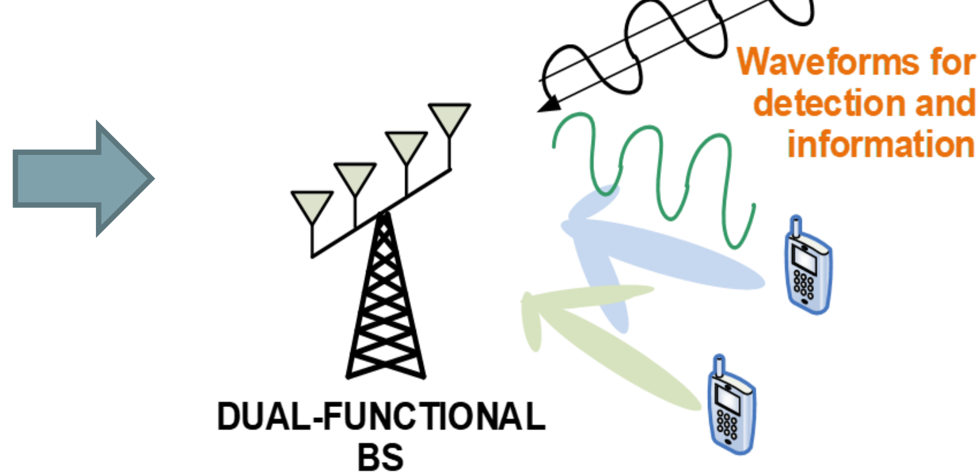

Wireless Communications
Radar
Guglielmo Marconi 1894
Sir Robert Watson Watt 1935
Pulse Interval modulation, 1963
Spectrum Co-Existence, ~2010
OFDM based sensing, 2013
2017
Integrated Sensing and Communications (ISAC)

The step change from RCC to DFRC

Radar-Comms Coexistence (RCC)

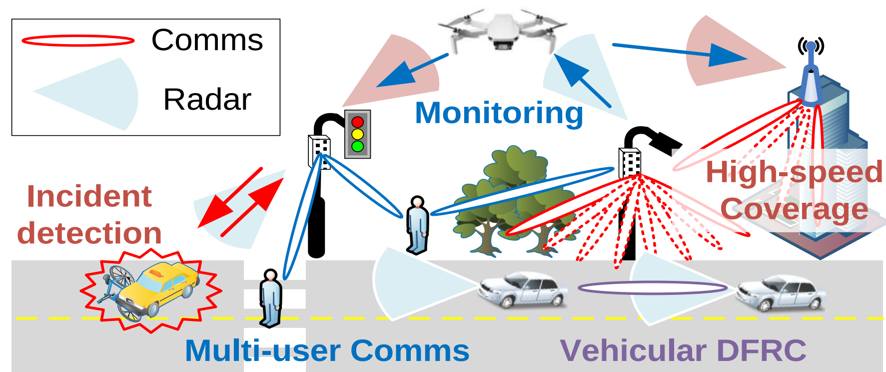


Dual-Functional Radar-Comms



Comms and Radar systems cooperate instead of competing for resources.

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



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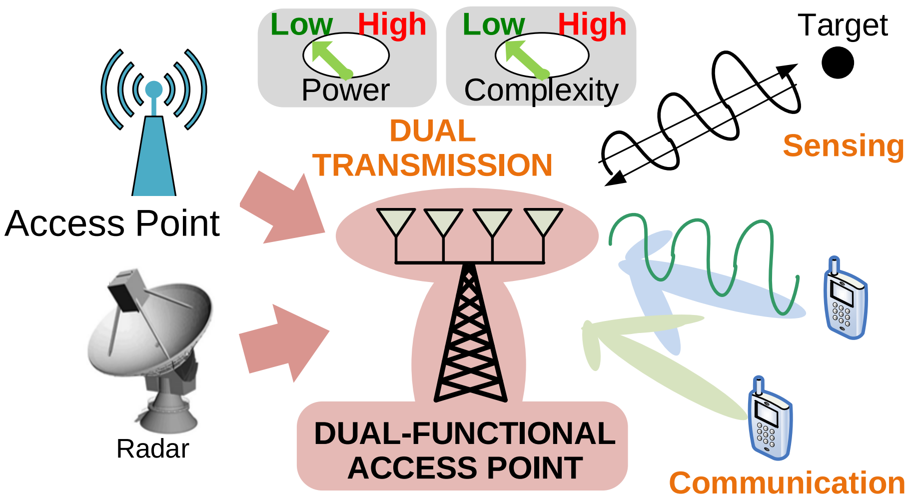
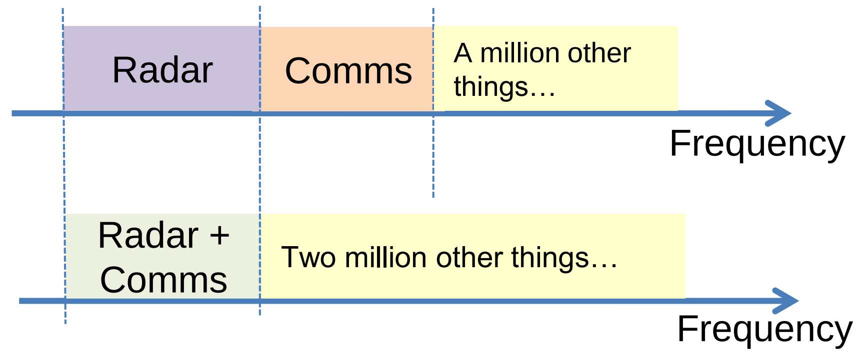
The DFRC gains

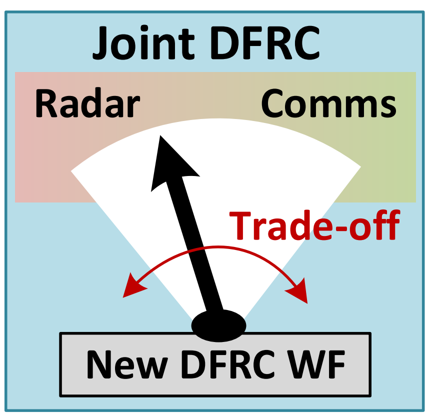
Hardware Gain



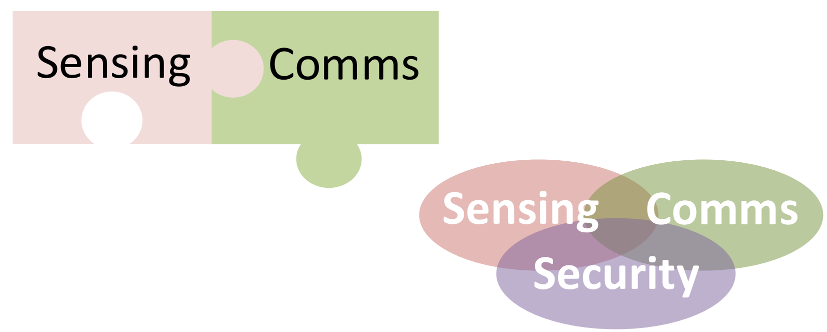
Spectrum Gain



Scalable Trade-offs

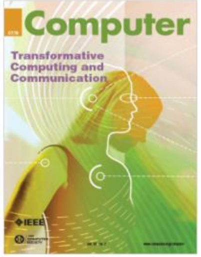


Synergies – Mutual Benefits



Industry buy-in

Nokia Bell Labs propose a unified mmWave system for joint communication and sensing



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Computer

Future Millimeter-Wave Indoor Systems: A Blueprint for Joint Communication and Sensing

July 2019, pp. 16-24, vol. 52
DOI Bookmark: 10.1109/MC.2019.2914018

Authors

Mohammed Alloulah, Nokia Bell Labs, Cambridge, United Kingdom
Howard Huang, Nokia Bell Labs, Cambridge, United Kingdom

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Keywords

Indoor Radio, Millimetre Wave Communication, Mobile Radio, Next Generation Networks, Telecommunication Network Planning, Wir Networks, Future Millimeter Wave Indoor Systems, Joint Communication, Next Generation High Rate Communications, Mm Wave Sy Sensing, Robot Sensing Systems, OFDM, Antenna Arrays, Bandwidth, Radar Imaging, Millimeter Wave Communication

Abstract

Millimeter-wave (mm-wave) technology is emerging as a de facto enabler for next-generation high-rate communications. We propose mm-wave system for combined communication and robust sensing will turbocharge the capabilities of application domains from in-hc to new possibilities for building analytics.

Ericsson 6G White Paper

Extreme performance and coverage

The future wireless access solution must provide truly extreme performance in a multitude of dimensions and in all relevant scenarios in order to enable future in-demand services at acceptable costs. This includes, for example, extreme data rates and latency performance when so required, extreme system capacity to be able to deliver the services to a massive number of users, and truly global coverage of the wireless access. The key to enabling dense deployments with extreme system capacity in a cost-effective way is to introduce packet fronthaul and new wireless transport technologies, such as relay and mesh networking, free-space optics, and further integrated access and backhaul.

Enablers for sensing/positioning

Cellular networks are widely deployed to support wireless connectivity, where the propagation of the radio waves depends on many factors in the environment. Using data analytics on the radio signals received, it is possible to sense and estimate quantities impacting the radio propagation. (For example, the received signal quality in microwave links is affected by the presence of rainfall — information that is valuable for weather forecasting.) Active sensing, where radio signals are transmitted solely for the purpose of sensing, is also possible, allowing a base station to act as a radar system in addition to serving the communication needs of an area. This can be used to build and continuously update a map of surrounding areas to, for example, detect changes in road traffic or set off alarms if a person enters a restricted area in a factory hall. Reusing cellular systems for sensing can provide more cost-efficient sensing compared to the dedicated systems specifically deployed for sensing only.

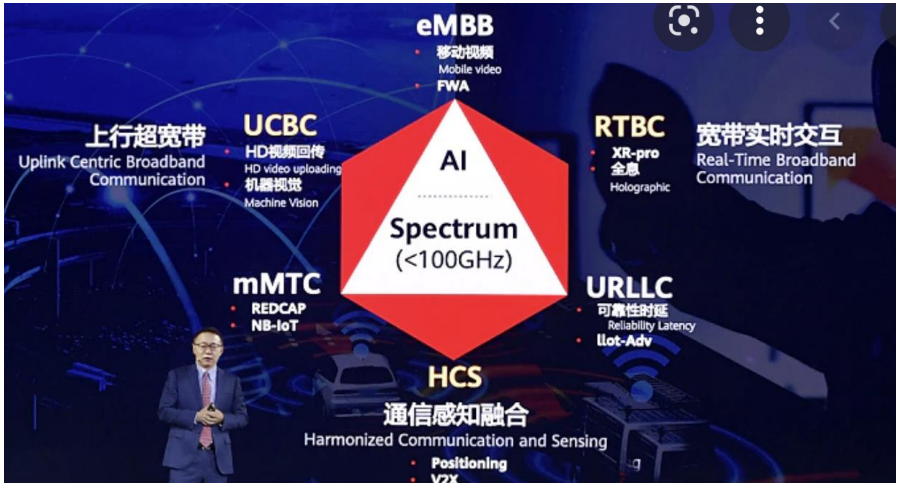
NTT DOCOMO 6G White Paper

3.6. Extreme-massive connectivity & sensing

Wearable user devices and an extremely large number of IoT devices that collect images and sensing information of the real world are expected to spread further in the 6G era, and an extremely large number of connections that are approximately 10 fold (= 10 million devices per square km) more than the 5G requirements are expected. In addition to the approach of connecting a large number of IoT devices to a network, the wireless communication network itself is expected to evolve to have functions for sensing the real world such as positioning and object detection using radio waves. In particular, the study of positioning has already advanced for 5G evolution, and it is expected that ultra-high-precise positioning with the error of several centimeters or less can be achieved in some environments.

Figure 3-7. Extreme-massive connectivity & sensing

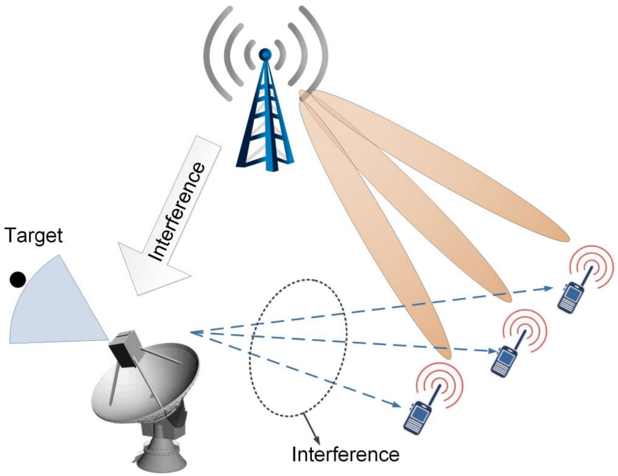
Huawei identifies ISAC as one of the 3 major scenarios in their vision of 5.5G



Standardization Activities

Organization	Associated Works on ISAC	Details
ITU	ITU-T recommendation 1. ITU-TY.IOT-SQAF(under study) 2. ITU-T Y.4809 (10/2021)(In force) 3. ITU-T X.1080.2 (10/2021) (In force)	The recommendation titled “Assessment framework of IoT sensing quality” to provide a unified framework for both developers and users to evaluate sensing quality.
IEEE	New IEEE Standard for Sensing 1. IEEE 802.11bf WLAN Sensing 2. IEEE 802.15.22.3-2020 3. IEEE 802.11-2020	The standard of Spectrum Characterization and Occupancy Sensing defines the formats for system configuration and spectrum measurement parameters, which provides means for conveying value-added sensing information to various spectrum database services.
Next G Alliance (US)	Next G alliance working groups on National 6G Roadmap’s technology layer.	The Technology Working Group will address the key technologies including new air interfaces, network architectures, spectrum access, x-haul, 6G Mobile-Network-Cloud fabric and sensing technologies, et al.
3GPP	New Proposals for ISAC 1. S1-214036; 2. S1-214056; 3. S1-214100; 4. S1-214101; 5. R1-2110894; 6. R1-2104724; 7. R2-210049;	1. New SID on Integrated Sensing and Communication; 2. Cooperative Communication and Sensing; 3. New SID on 5GS-based enhanced Sensing; 4. 3GPP based Wireless Sensing Services; 5. Discussion on relation between sensing beam and transmission beam; 6. Considerations on partial sensing in NR V2X; 7. Discussion on sensing and DRX;
Hexa-X (EU)	1. A 6G vision was jointly defined by the 25 participants of Hexa-X. 2. Hexa-X project: Radio performance towards 6G.	One of the objectives in Hexa-X project is to deliver extreme performance by developing and assessing key radio technology components for the next generation, through higher bands and localization/sensing.
IMT-2030 (China)	White paper Integrated sensing and communication technology report	The basic concept of ISAC, layered design concept, potential application scenarios, and enabling technologies related to air interface and network are deeply discussed.

ISAC Vision and Evolution Path



Spectral Coexistence

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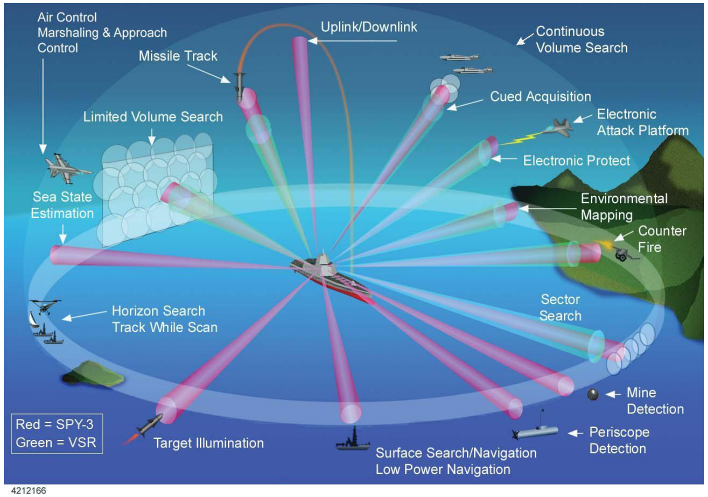
ISAC Vision and Evolution Path



Co-located Hardware

Spectral Coexistence

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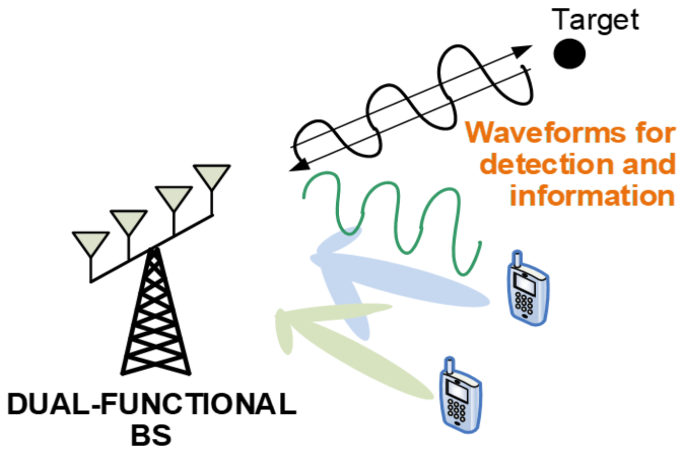

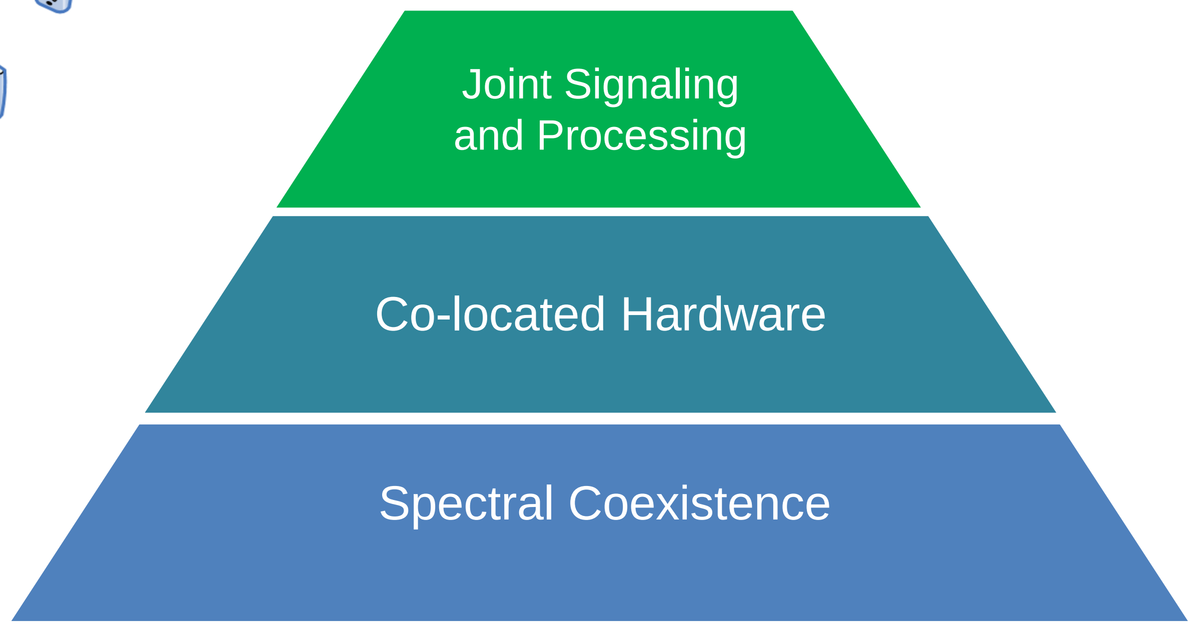

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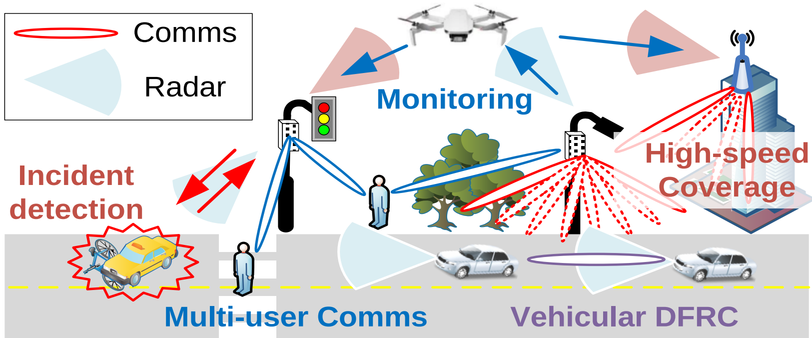

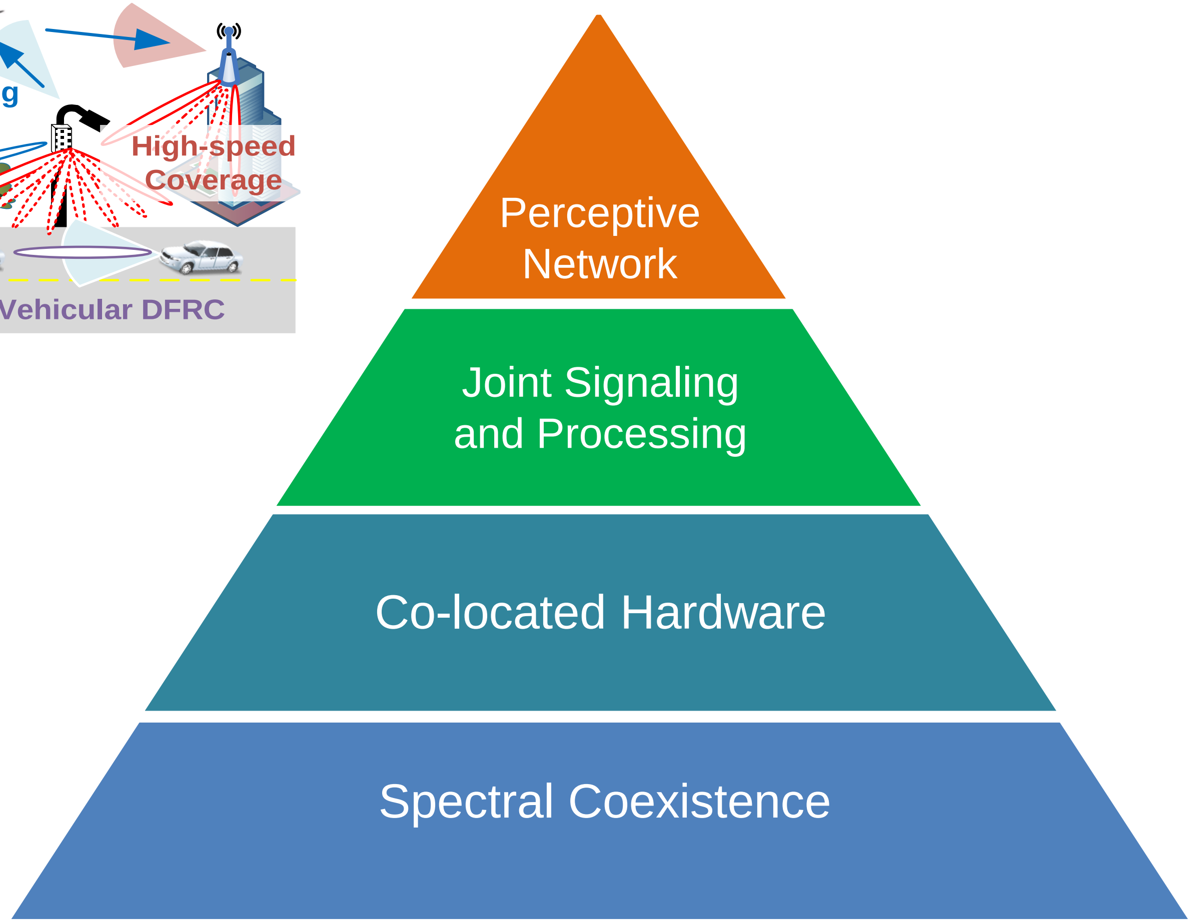

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Unified Framework for Integrated Radar-Communications

Wireless Communications

- Theory ✓
- Signal Processing ✓
- RF Design ✓

Radar

- Theory ✓
- Signal Processing ✓
- RF Design ✓

Integrated Radar and Communications

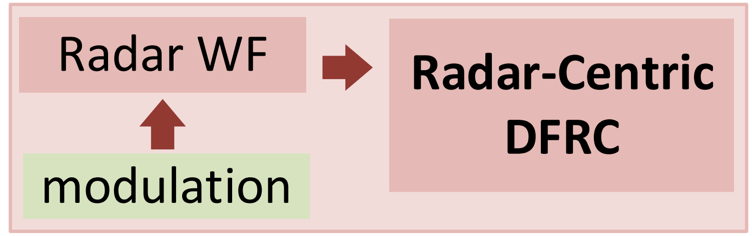
- Theory ✗
- Signal Processing ✗
- RF Design ✗

Outline

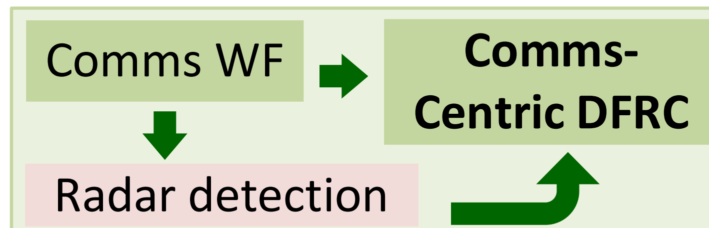
- Motivation
- Technical Overviews
  - Waveforms and Signals for DFRC
  - Sensing-Assisted Vehicular Communications
  - Security for DFRC

DFRC Technologies

- Radar-centric design
  - Pulse Interval Modulation (PIM)
  - Radar beampattern sidelobe signalling
  - Index Modulation (IM) using radar waveforms
  - …



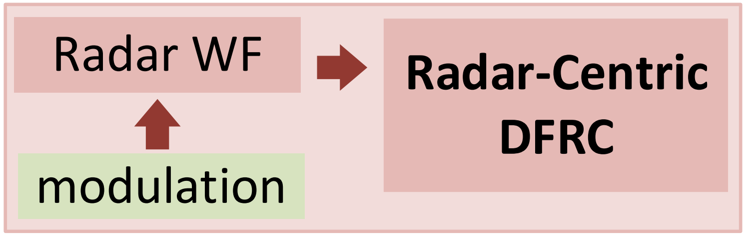
- Comms-centric design
  - OFDM based DFRC
  - IEEE 802.11ad based DFRC

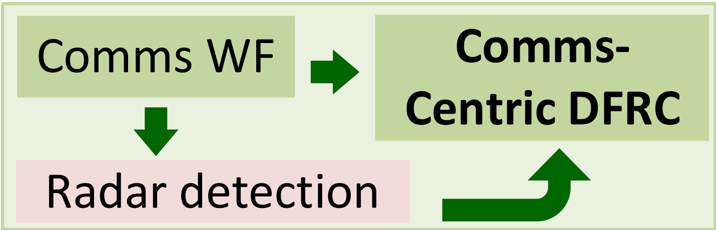


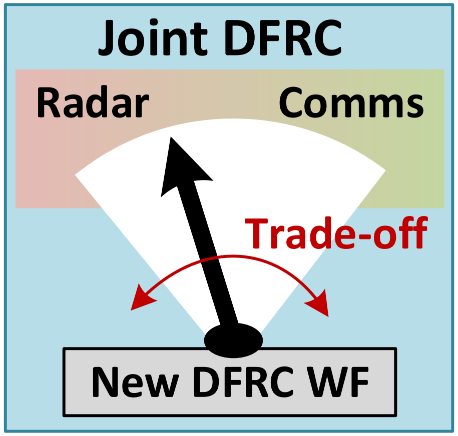
- Radar-Centric DFRC:
  - Radar-compatible, minimal changes to radar waveforms
  - Limited data rates
- Comms-Centric DFRC:
  - Comms-Compatible, close to standards
  - Limited estimation accuracy – difficult to tune

DFRC Technologies

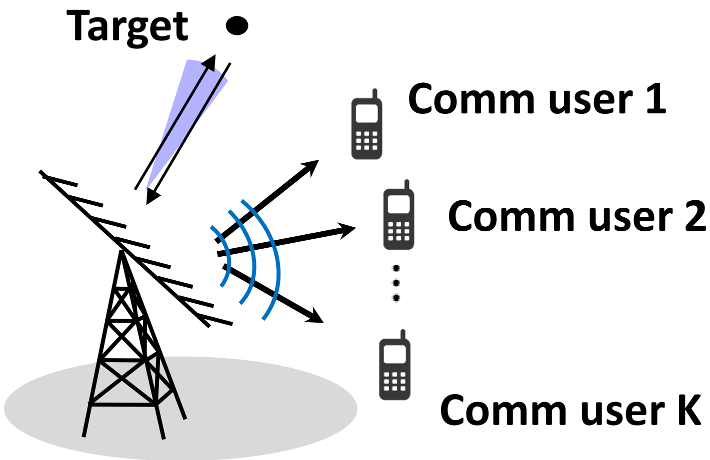
- Radar-centric design
  - Pulse Interval Modulation (PIM)
  - Radar beampattern sidelobe signalling
  - Index Modulation (IM) using radar waveforms
  - …
- Comms-centric design
  - OFDM based DFRC
  - IEEE 802.11ad based DFRC
  - …
- Jointly optimized design
  - Radar-centric joint design
  - Weighted Comms-Radar optimization
  - …







DFRC- Joint Design



Weighted Comms-Radar optimization

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

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

Ideal radar waveform

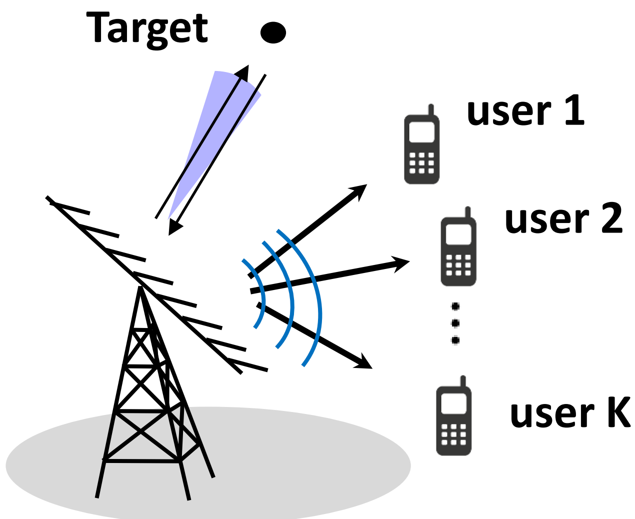
- ρ - Comms priority
- ρ - Radar priority

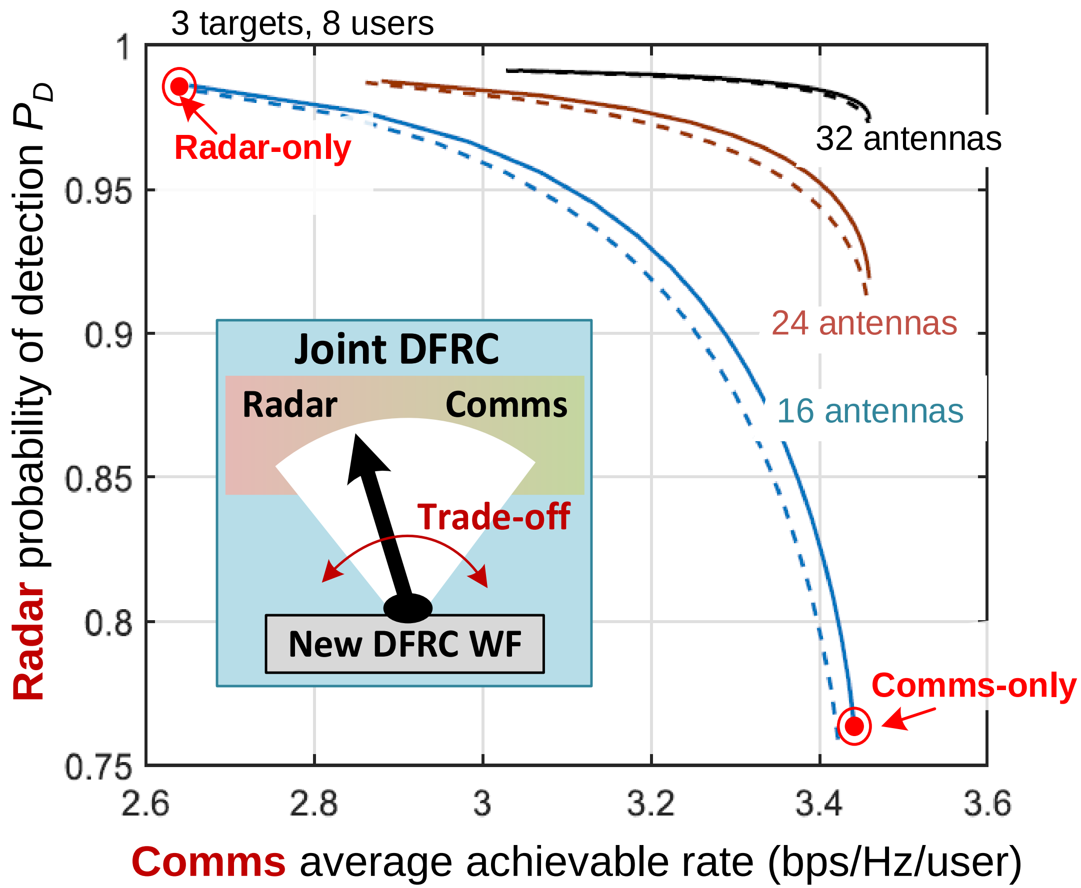
- Co-design of Comms and Radar functionalities
- Flexible use of time / frequency / spatial resources
- Scalable Comms vs Radar performance tradeoffs

- 100% Radar ↔ 100% Comms performance tradeoff
- High data rates
- Radar Reliability
- Hardware friendly design

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.

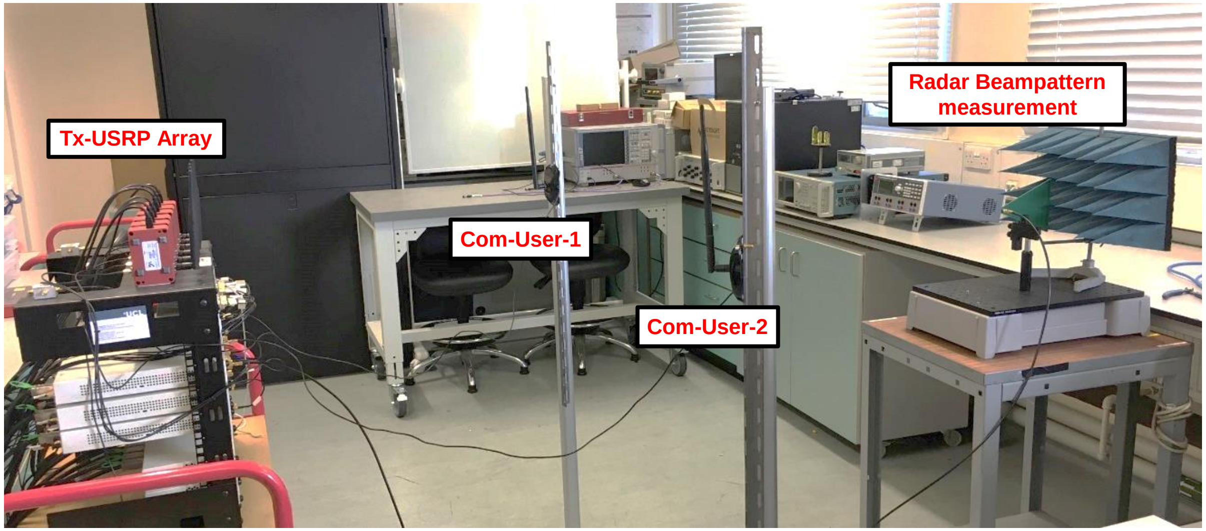
Tuneable Trade-offs



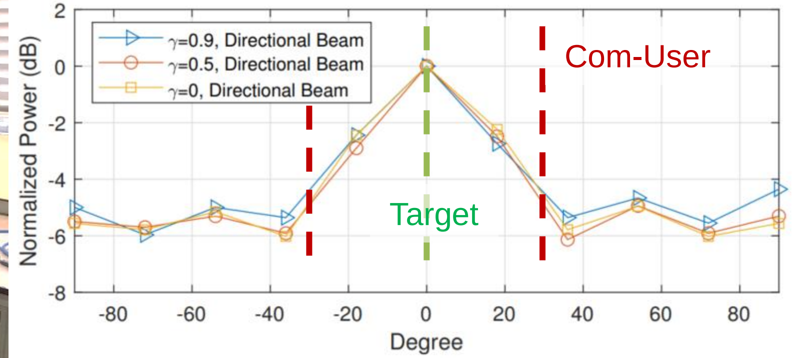


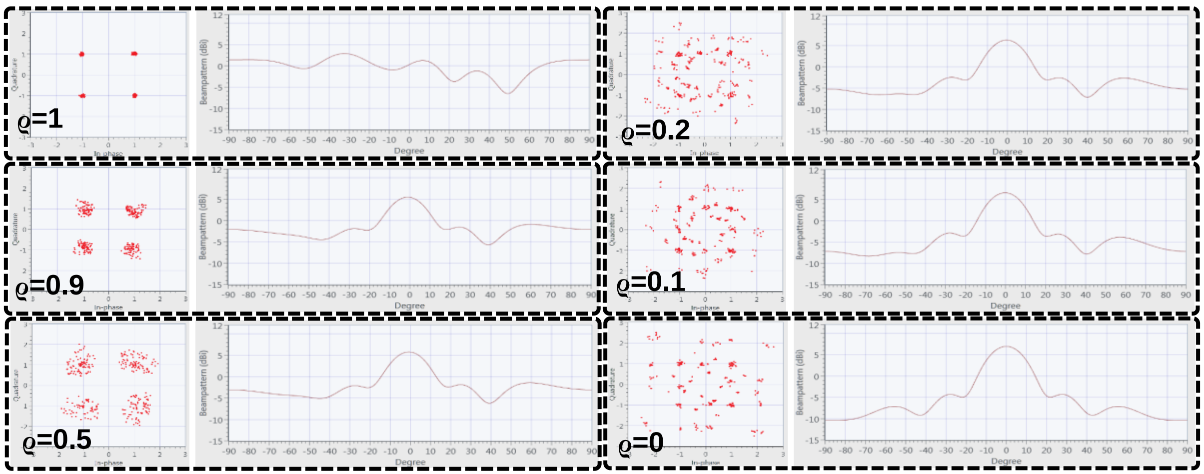
F. Liu, L. Zhou, C. Masouros, A. Li, W. Luo, and A. Petropulu, "Toward dual-functional radar-communication systems: Optimal waveform design," IEEE Trans. Signal Process., vol. 66, no. 16, pp. 4264–4279, Aug 2018.

Joint DFRC – Over-the-air Proof of concept

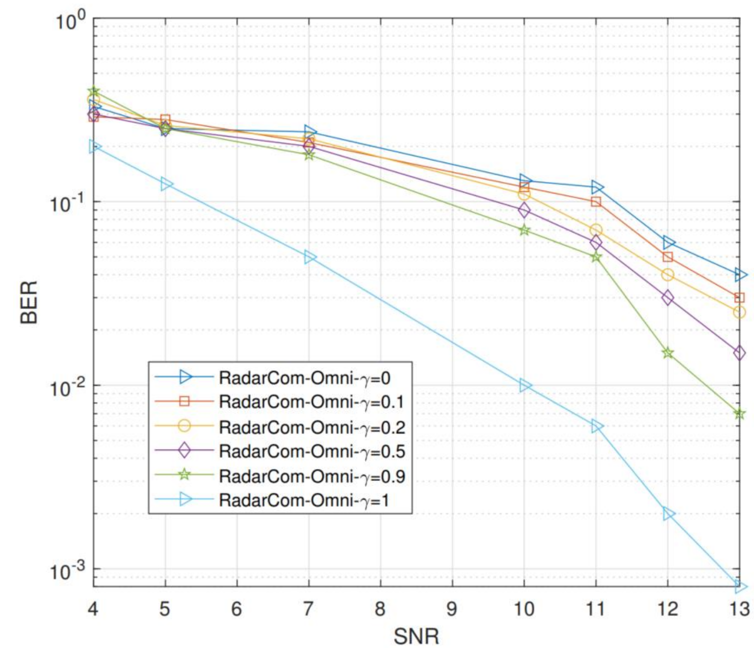


Measured Radar beampattern





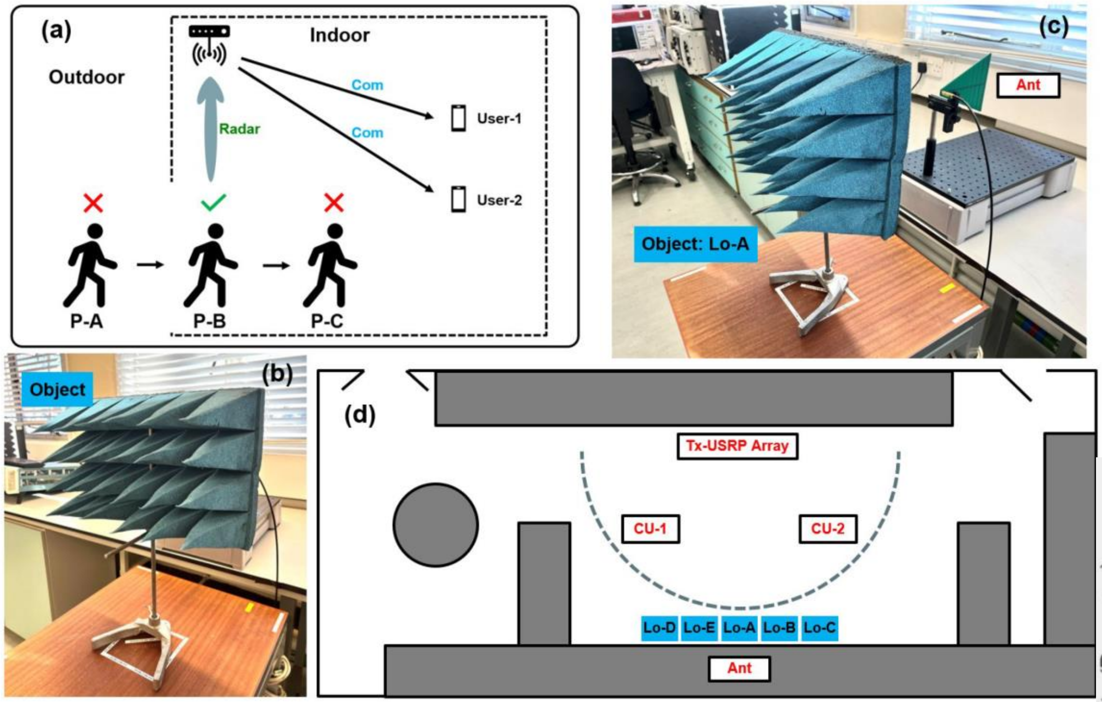
Comms BER

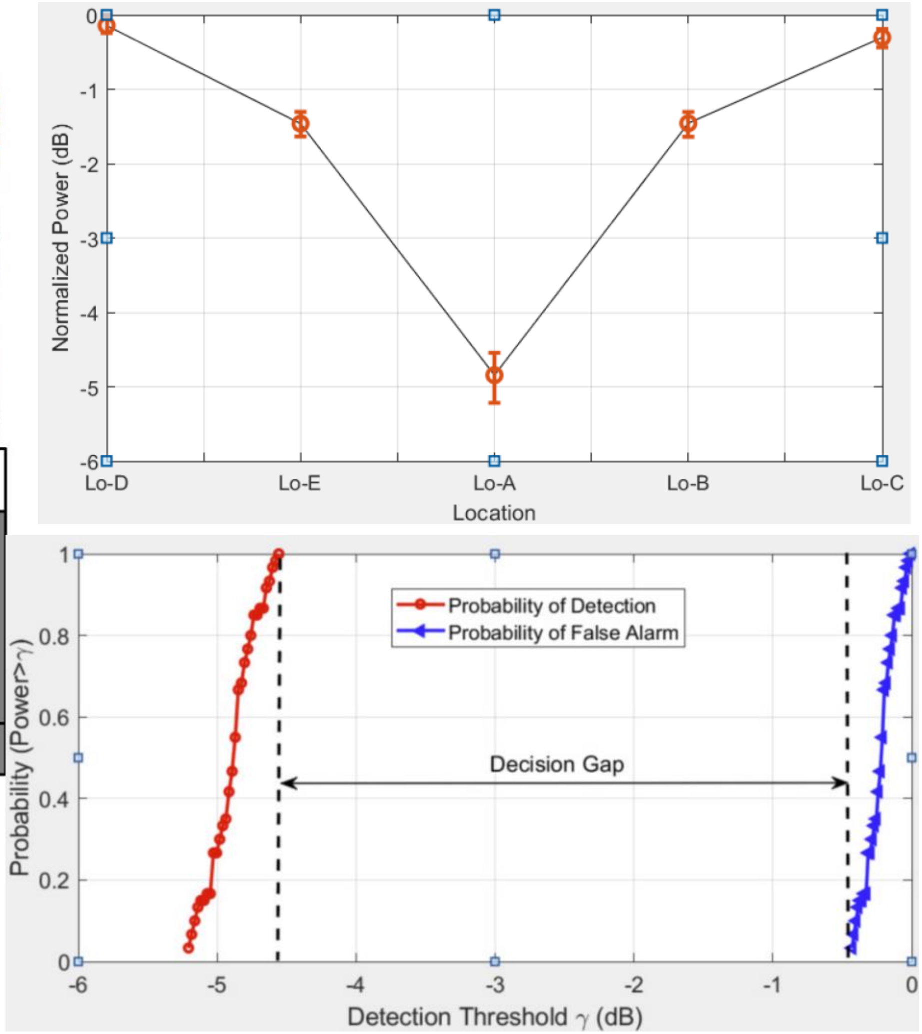


T. Xu, F. Liu, C. Masouros, I. Darwazeh, "An Experimental Proof of Concept for Integrated sensing and Communications Waveform Design", IEEE Open Journal of ComSoc, vol. 3, pp. 1643-1655, 2022

Joint DFRC – Over-the-air Proof of concept

Elementary activity detection





$$P_D = Pr(Power < \gamma \mid obstacle\ present)$$
$$P_{FA} = Pr(Power < \gamma \mid obstacle\ not\ present)$$

T. Xu, F. Liu, C. Masouros, I. Darwazeh, "An Experimental Proof of Concept for Integrated sensing and Communications Waveform Design", IEEE Open Journal of ComSoc, vol. 3, pp. 1643-1655, 2022

Over-The-Air Lab Setup

Radar node is situated behind the 'bin' target next to the dual radar Tx and Rx dishes.

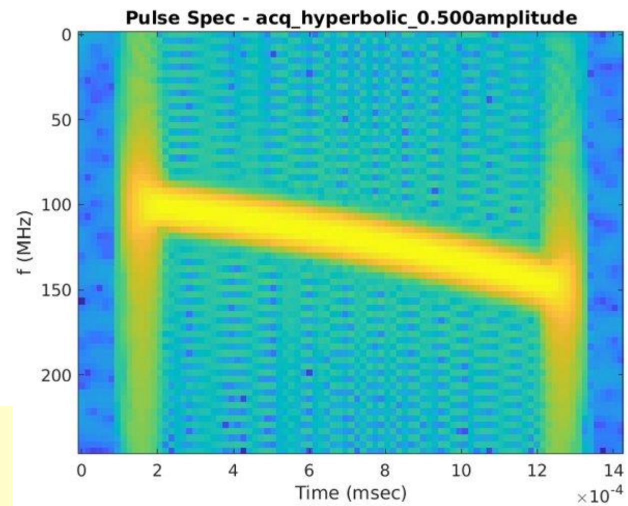
The comms Rx ARESTOR node is seen on the bench behind its receiving dish to the right of the image.

Three indices are considered

- centre frequency
- bandwidth
- polarization

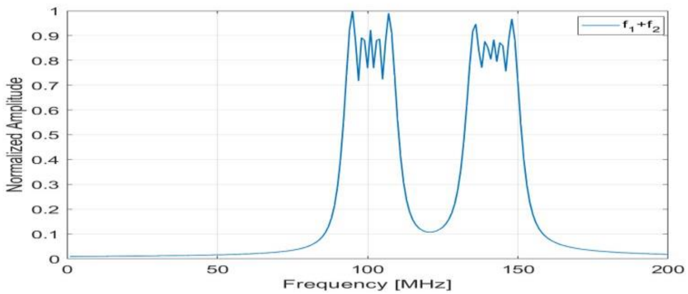
Radar RFSoC platform

LFM waveform



M. Temiz, N. Peters, C. Horne, M. Ritchie, C. Masouros, "An Experimental Study of Radar-Centric Transmission for Integrated Sensing and Communications", IEEE Transactions on Microwave Theory and Techniques, in press

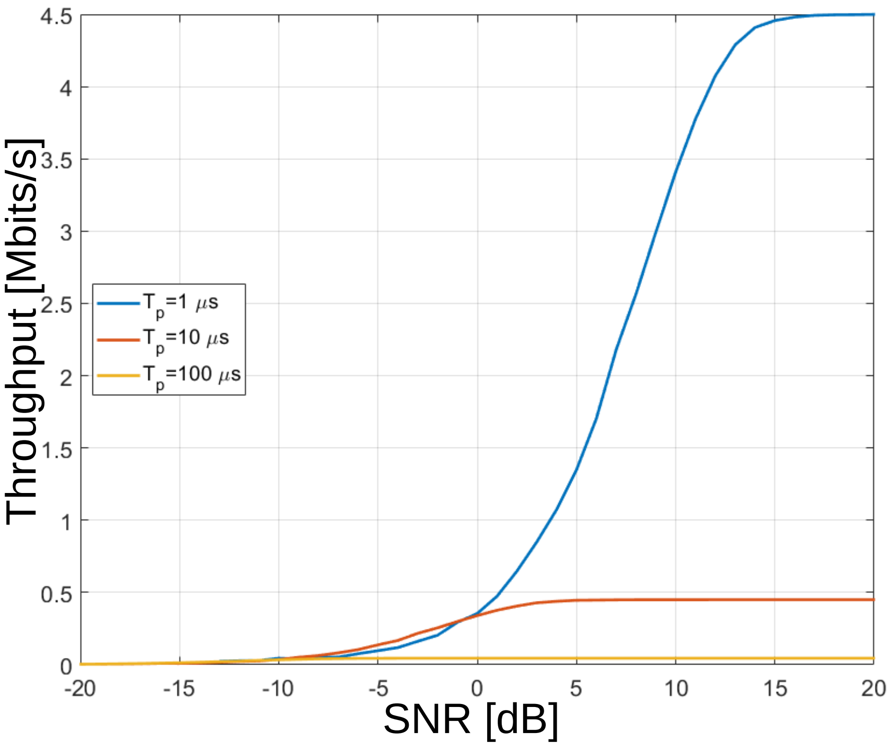
Radar vs Communication Trade-off

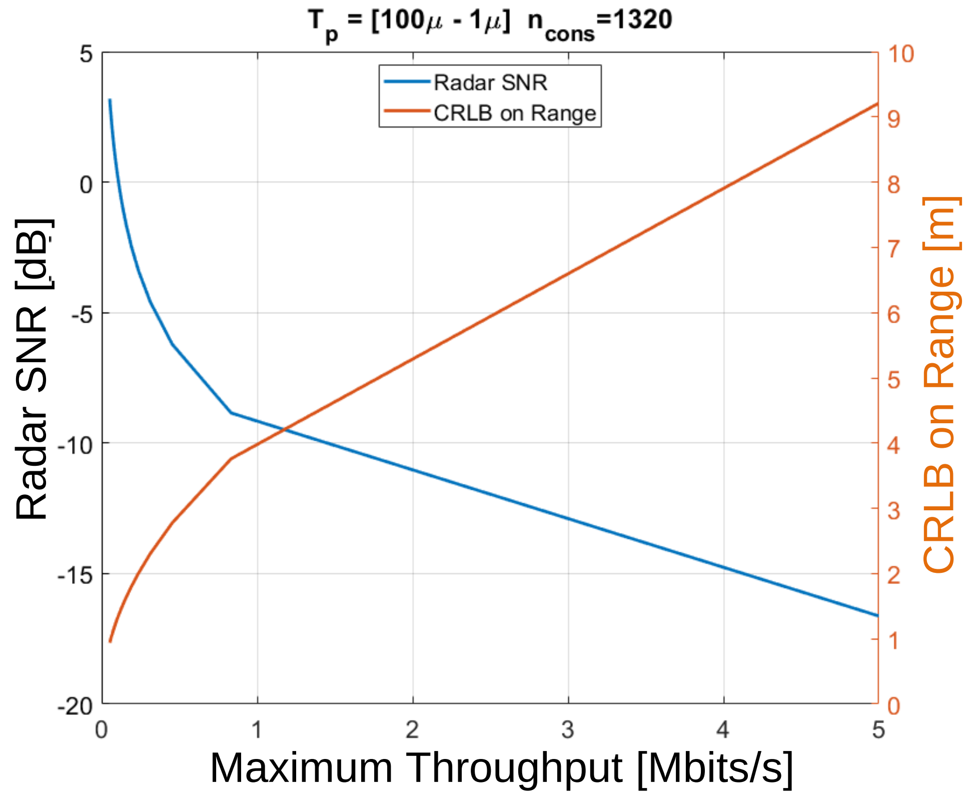


Three indexes are considered – 10 bits per symbols

- 11 bandwidths (1 MHz BW spacing)
- 40 frequencies (1 MHz central frequency spacing)
- 3 polarization options (V, H, H-V)

Tuning pulse duration is between 1-100 µs.



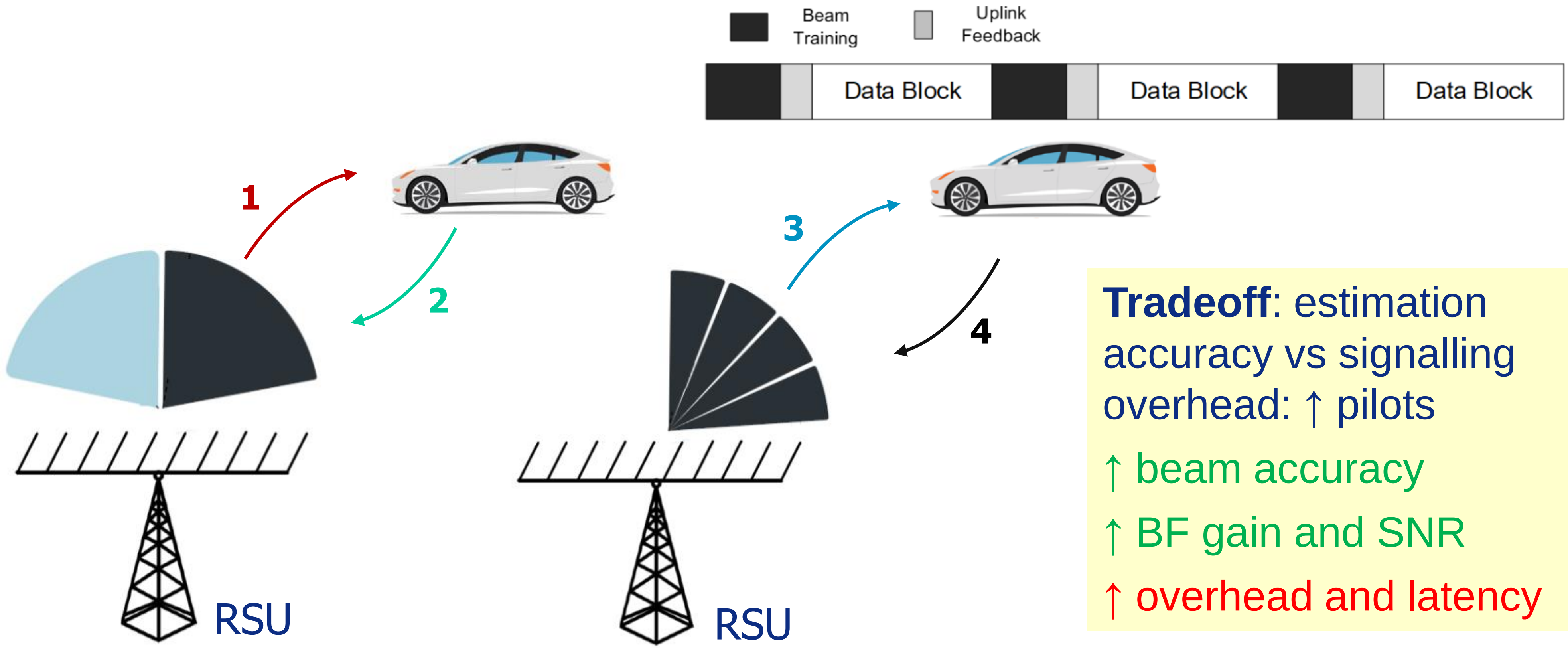


- ↓ Radar pulse duration → ↑ Comms throughput, ↓ Radar integration gain

Radar-assisted Vehicular Network

Communication Served by Sensing

Comms-based Beam Training



Tradeoff: estimation accuracy vs signalling overhead: ↑ pilots

↑ beam accuracy

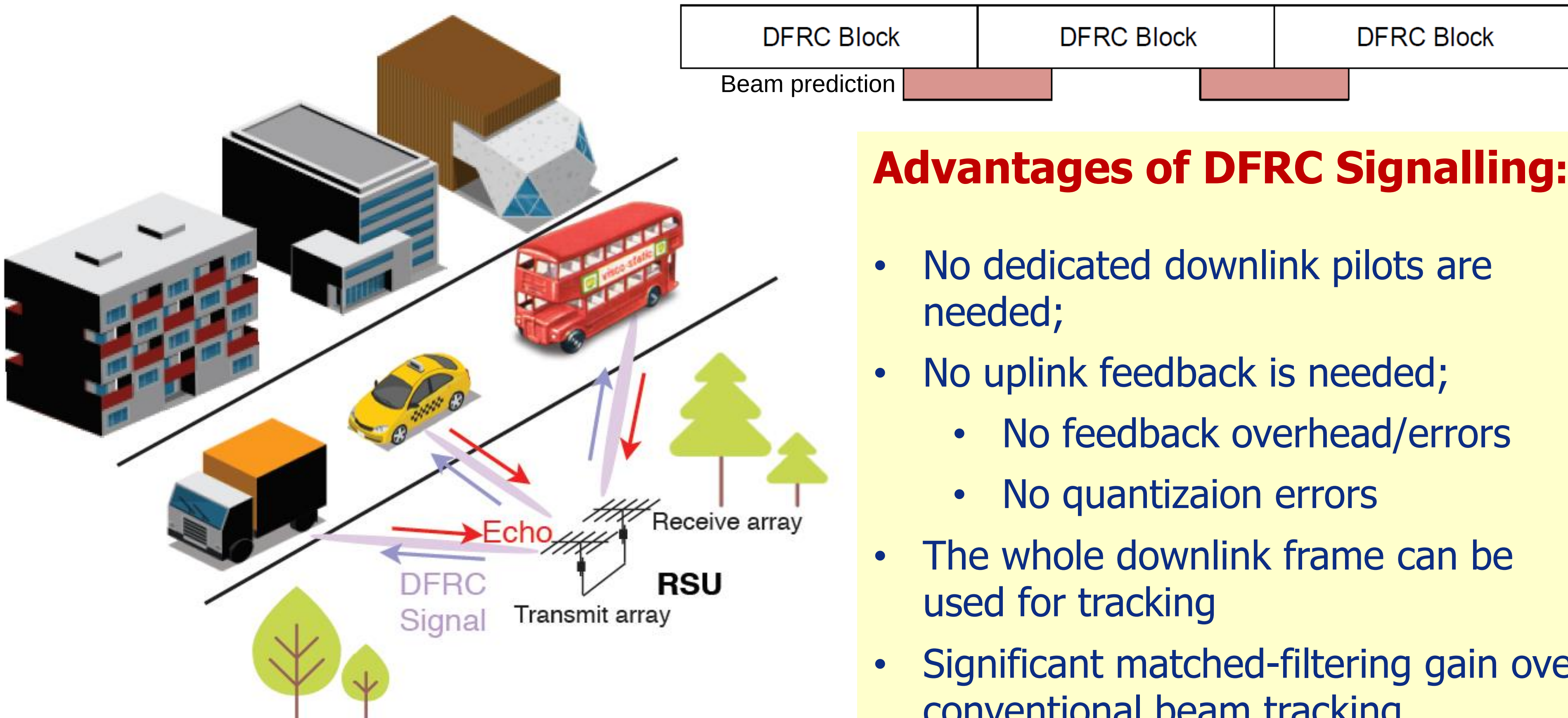
↑ BF gain and SNR

↑ overhead and latency

1. RSU transmits with different AoA, to scan the angular interval of interest
2. User 1) measures signal strength and 2) feeds back the SNR / beam index
3. RSU identifies a narrower angular interval and scans with narrow beams
4. User 1) measures signal strength and 2) feeds back the SNR / beam index

A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 831–846, 2014

Comms served by Sensing: Radar tracking for Comms beam-steering

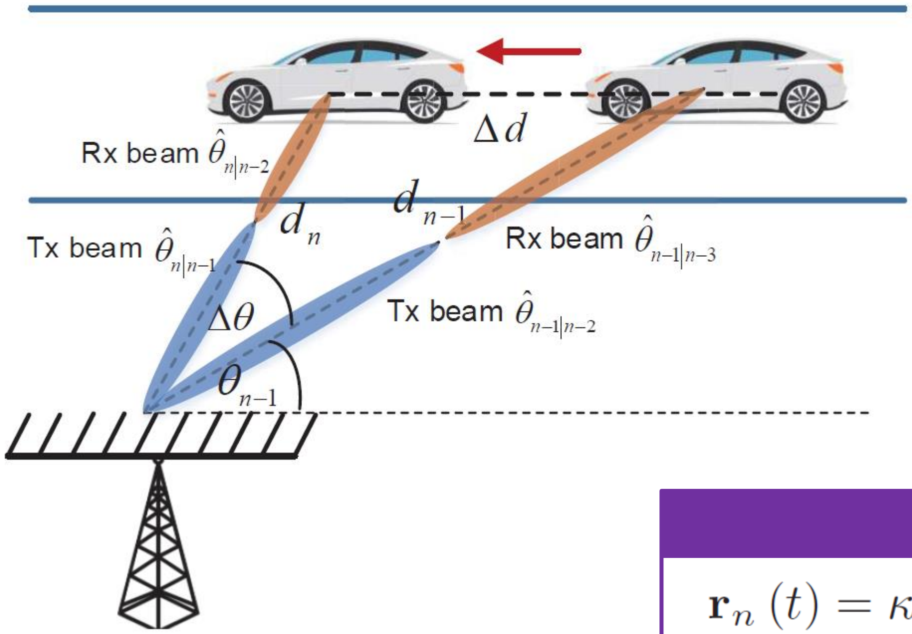


Advantages of DFRC Signalling:

- No dedicated downlink pilots are needed;
- No uplink feedback is needed;
  - No feedback overhead/errors
  - No quantizaion errors
- The whole downlink frame can be used for tracking
- Significant matched-filtering gain over conventional beam tracking

- **Assumptions**: LoS channel, straight road, parallel mMIMO antenna arrays **- AoA equals to AoD**
- Separate Rx array, inc RF isolator

System Model - Signal Model



State transition model

$$\mathbf{x}_n = \mathbf{g}(\mathbf{x}_{n-1}) + \boldsymbol{\omega}_n$$

$$= \begin{cases} \theta_n = \theta_{n-1} + d_{n-1}^{-1} v_{n-1} \Delta T \sin\theta_{n-1} + \omega_{\theta,n}, \\ d_n = d_{n-1} - v_{n-1}\Delta T \cos\theta_{n-1} + \omega_{d.n}, \\ v_n = v_{n-1} + \omega_{v,n}, \\ \beta_n = \beta_{n-1}\left(1 + d_{n-1}^{-1} v_{n-1}\Delta T \cos\theta_{n-1}\right) + \omega_{\beta,n}, \end{cases}$$

Radar measurement model

$$\mathbf{r}_n(t) = \kappa\sqrt{p_n}\beta_n e^{j2\pi\mu_n t}\mathbf{b}(\theta_n)\mathbf{a}^H(\theta_n)\mathbf{f}_n s_n(t-\tau_n) + \mathbf{z}_n(t)$$

matched filtering

$$\mathbf{y}_n = \mathbf{h}(\mathbf{x}_n) + \tilde{\mathbf{z}}_n$$

$$= \begin{cases} \tilde{\mathbf{r}}_n = \beta_n\sqrt{Gp}\kappa\mathbf{b}(\theta_n)\mathbf{a}^H(\theta_n)\mathbf{f}_n + \mathbf{z}_{\theta,n} \\ \hat{\tau}_n = \dfrac{2d_n}{c} + z_{\tau,n} & \text{Round-trip delay} \\ \hat{f}_{D,n} = \dfrac{2v_n\cos\theta_n f_c}{c} + z_{f,n} & \text{Doppler offset} \end{cases}$$

Communication model

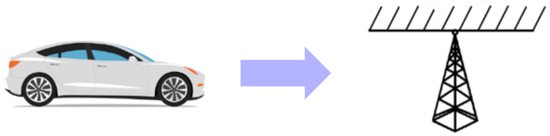
$$c_n(t) = \tilde{\kappa}\sqrt{p_n}\alpha_n\mathbf{w}_n^H\mathbf{u}(\theta_n)\mathbf{a}^H(\theta_n)\mathbf{f}_n s_n(t) + z_c(t),$$

Predictive Beamformers

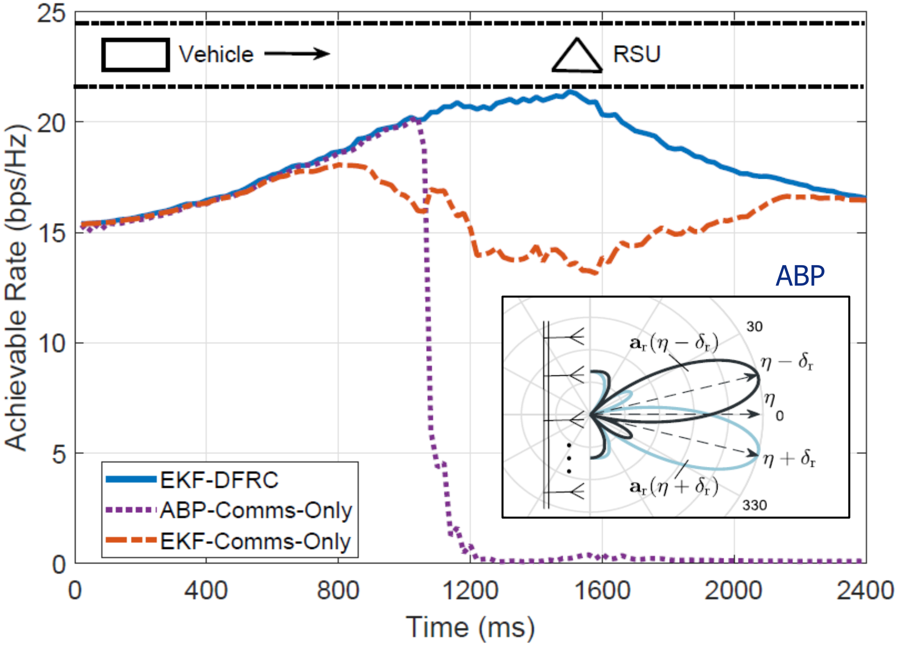
Tx: $\mathbf{f}_n = \mathbf{a}\left(\hat{\theta}_{n|n-1}\right)$ Rx: $\mathbf{w}_n = \mathbf{u}\left(\hat{\theta}_{n|n-2}\right)$

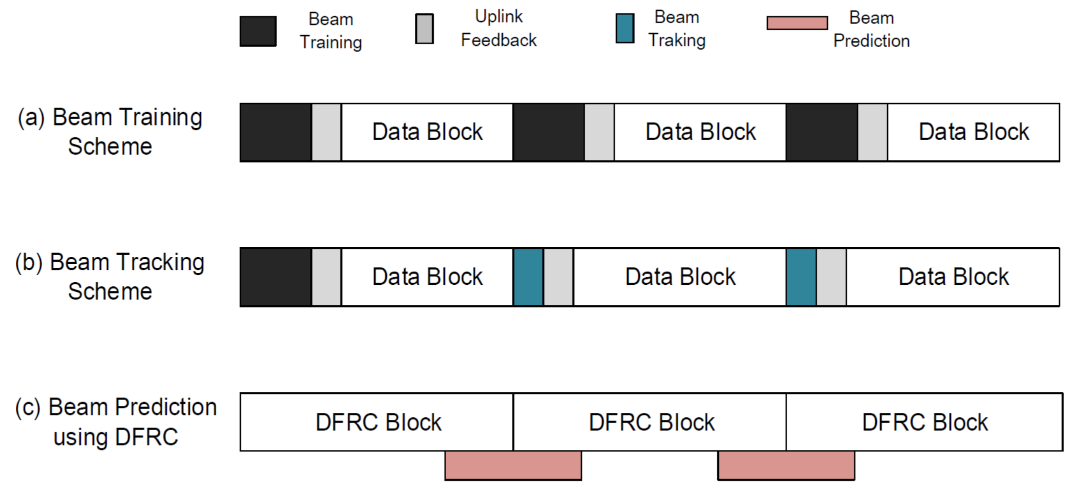
F. Liu, W. Yuan, C. Masouros and J. Yuan, "Radar-Assisted Predictive Beamforming for Vehicular Links: Communication Served by Sensing", IEEE Trans. Wireless Commun., *vol. 19, no 11, pp. 7704-7719, Nov. 2020*

Numerical Results - DFRC vs Comms only



$N = 64$, $v_0 = 18$m/s





- EKF-Comms-only: poor angle estimation at RSU crossing point – suffering data rate
- Auxiliary Beam Pair (ABP) tracking: at RSU crossing point the correct beam will unlikely fall into angle search interval – beam goes beyond the search space and is not recovered
- EKF-DFRC: Minimal disruption in the rate

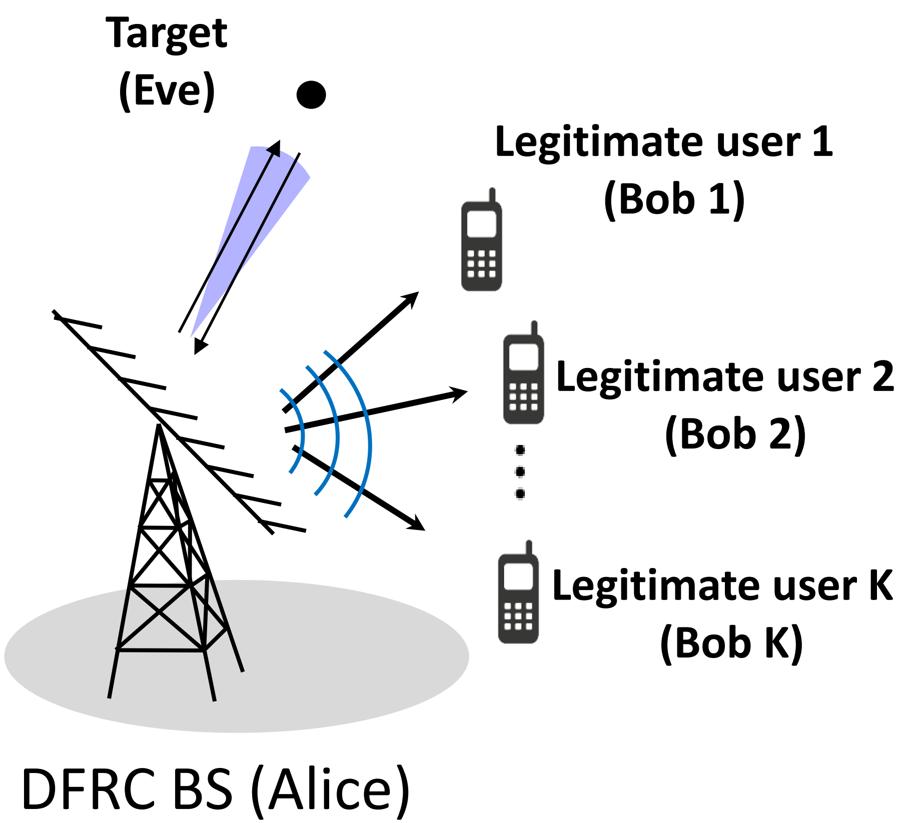
F. Liu, W. Yuan, C. Masouros and J. Yuan, "Radar-Assisted Predictive Beamforming for Vehicular Links: Communication Served by Sensing", IEEE Trans. Wireless Commun., *vol. 19, no 11, pp. 7704-7719, Nov. 2020*

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., *vol. 25, no. 2, pp. 327-331, Feb. 2021- EiC Invited Paper*

Dual-functional Radar-Communication

Subject to Security threats?

Radar + Information: Subject to Security Threats



Target can be:

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

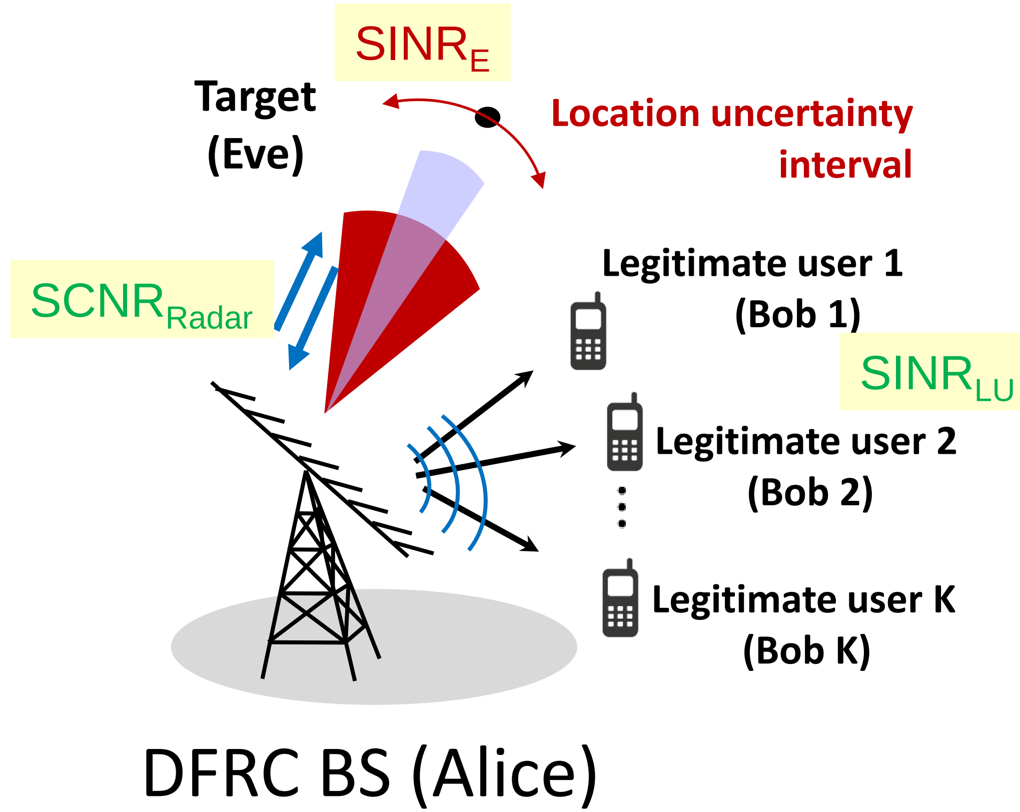
Malicious target can:

- 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

Unique Sensing Performance vs Security Trade-offs

- ↑ Power towards the direction of target
- ↓ Useful signal power ($SINR_E$) towards the target
- ↑ $SINR_{LU}$ towards the users



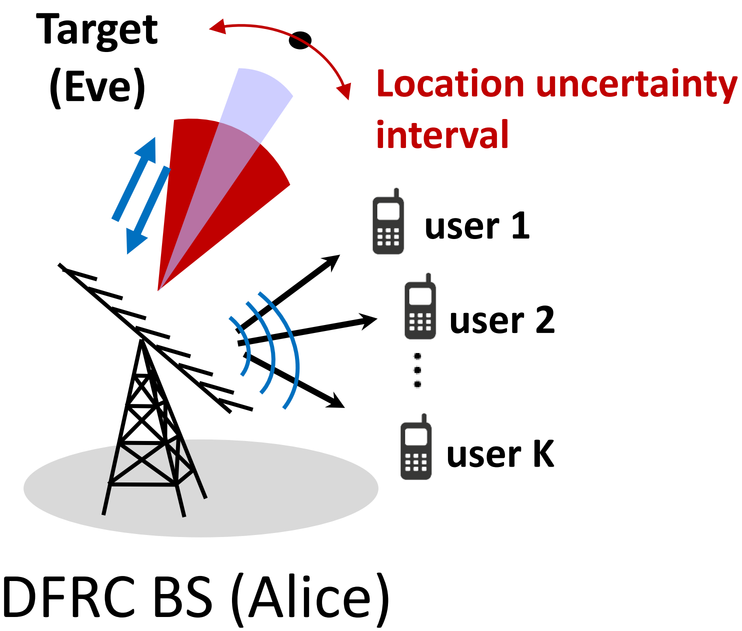
Apply PHY Sec approaches

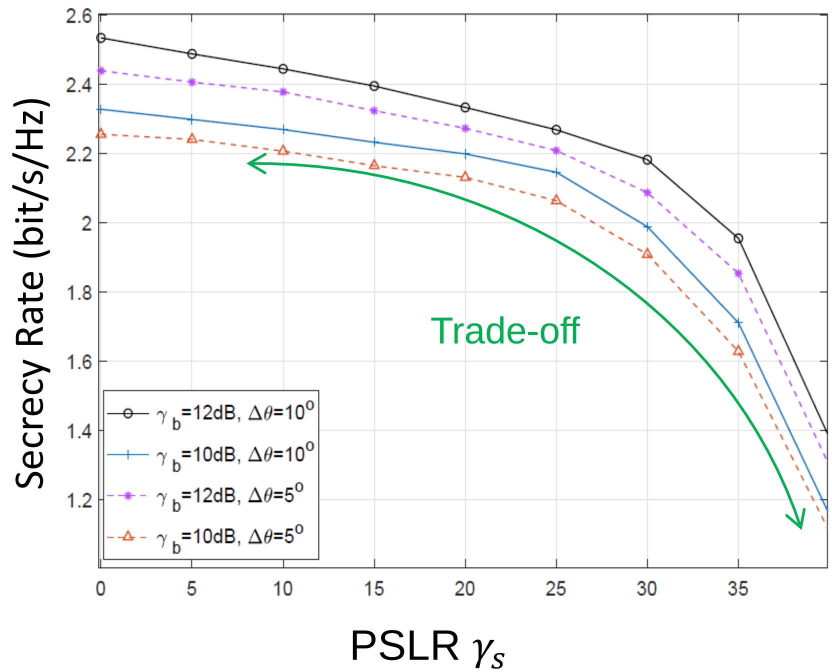
- Secure BF
- AN, Jamming
- Cooperative Security
- …

Z. Wei, F. Liu, C. Masouros, N. Su, A. Petropulu, "Towards Multi-Functional 6G Wireless Networks: Integrating Sensing, Communication and Security" IEEE Comms Mag., *vol. 60, no. 4, pp. 65-71, April 2022*

Secure DFRC Transmission – An Artificial Noise Design

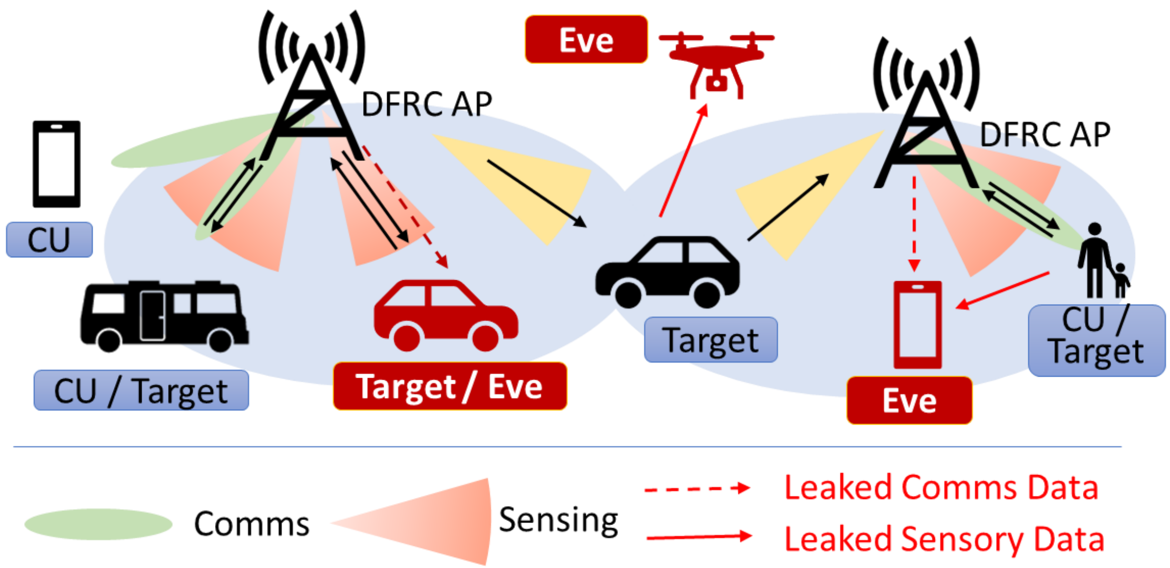
N = 18 antennas, *K* = 4 legitimate users, one target – LU SNR $\gamma_b = 10\text{dB}$.





N. Su, F. Liu, C. Masouros, "Secure Radar-Communication Systems with Malicious Targets: Integrating Radar, Communications and Jamming Functionalities", IEEE Trans. Wireless Comms., vol. 20, no. 1, pp. 83-95, Jan. 2021

DFRC Infrastructure: Opportunity for Malicious Sensing



- Need to secure both Communications and Sensing Functionalities
    - Secure DFRC Communication
    - Secure DFRC Sensing

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
- New Signaling opportunities
  - Radar-centric / Communications-centric / Joint
  - Hardware-informed
- Sensing – Assisted Communications
  - Sensing to assist high mobility (beam alignment, cell handover)
- Unique Security Challenges – Opportunities
  - Secure Comms vs Sensing trade-off
  - Sensing Security

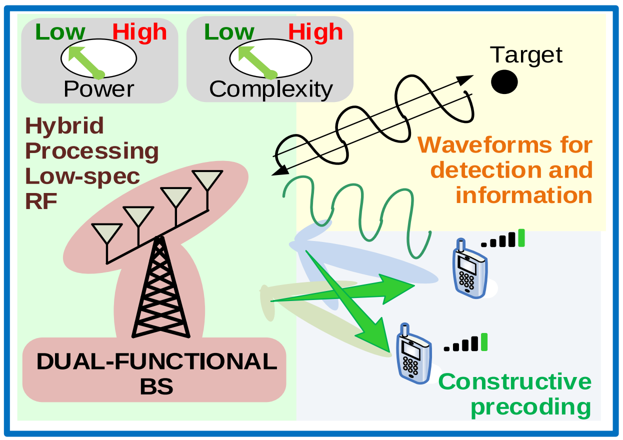
Future outlook - Cellular as a Sensor for 6G and Beyond

Integrated Sensing and Communications (ISAC)

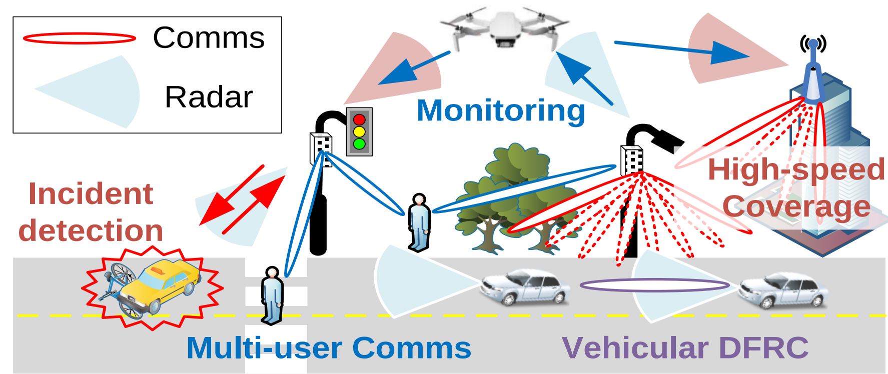
c.masouros@ucl.ac.uk

UCL

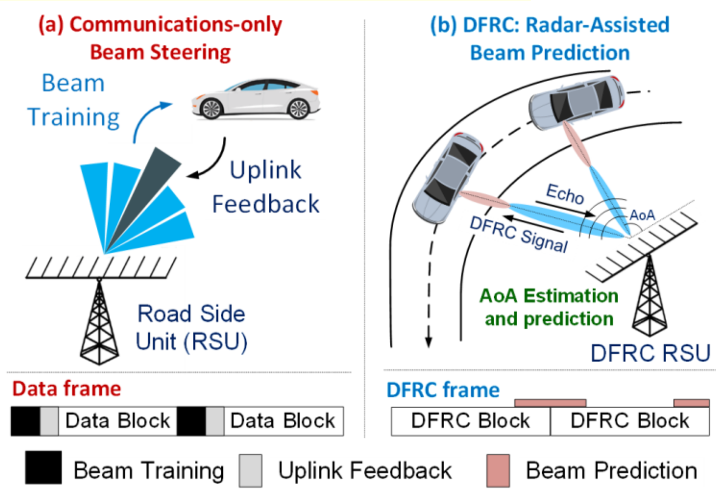
Hardware-Efficient DFRC



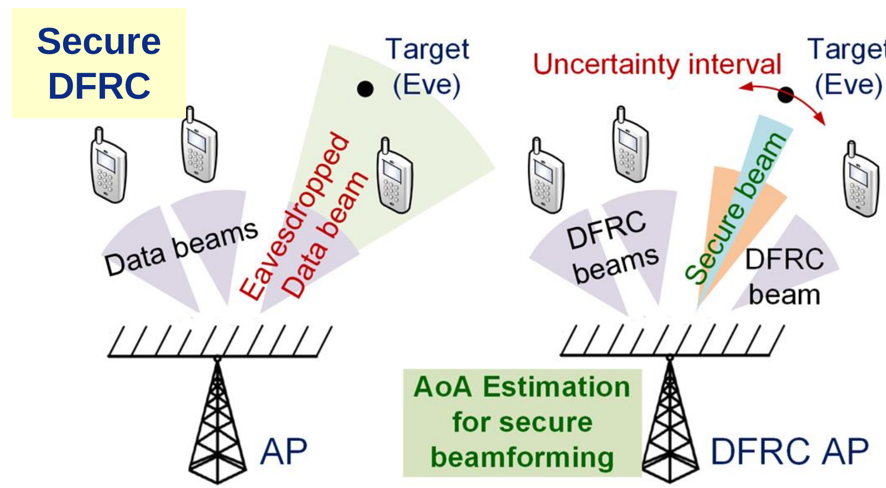
Pervasive sensing through dense cellular infrastructure



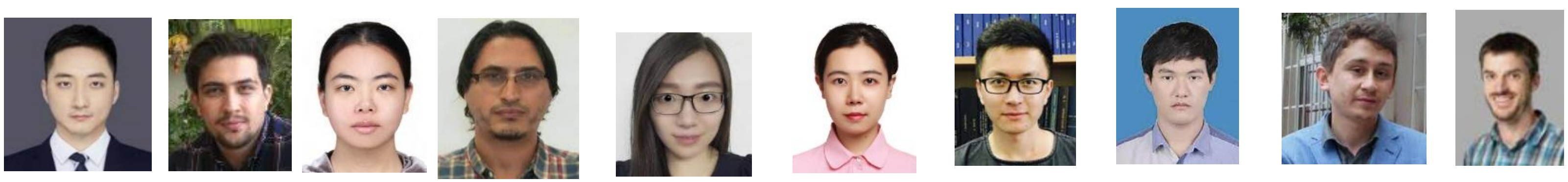
Sensing-Assisted Comms



Multicell / multi-static DFRC



Thank you



Fan Liu | Iman Vailulahi | Xiaoye Jing | Abdel Salem | Xiaoyan Hu | Nanchi Su | Tongyang Xu | Ang Li | Murat Temiz | Nial Peters

UDRC Project
Mar 2019 – Dec 2021 (£1m)

Marie Curie Fellowship
Nov 2018 – Oct 2020 (£160k)

Defence and Security Accelerator

MoD DASA Project
Jul 2021 – Mar 2022 (£100k)

CI-PHY Project
Apr 2018 – Jul 2021 (£1.1m)

LeanCom Project
Oct 2019 – Nov 2023 (£860k)

PAINLESS Project
Oct 2018 – Sep 2022 (€4.2m)

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Radar-Comms Coexistence

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 Comm., vol. 18, no. 9, pp. 4238-4253, Sept. 2019
8. 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. Sig Proc, vol. 66, no. 14, pp. 3681-3695, July 2018,
9. F. Liu, C. Masouros, A. Li, and T. Ratnarajah, "Robust MIMO Beamforming for Cellular and Radar Coexistence," IEEE Wireless Commun. Lett., vol. 6, no. 3, pp. 374-377, June 2017.
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17. L. Chen, F. Liu, W. Wang, and C. Masouros, "Joint Radar-Communication Transmission: A Generalized Pareto Optimization Framework", IEEE Trans. Signal Process., vol. 69, pp. 2752-2765, 2021.
18. F. Liu, C. Masouros, T. Ratnarajah, and A. Petropulu, “On Range Sidelobe Reduction for Dual-functional Radar-Communication Waveforms”, IEEE Wireless Commun. Lett., 2020.
19. F. Liu, C. Masouros, A. Li, H. Sun, and L. Hanzo, “MU-MIMO Communications and MIMO Radar: From Co-existence to Joint Transmission”, IEEE Trans. Wireless Commun., vol. 17, no. 4, pp. 2755-2770, April 2018
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Hardware-efficient DFRC Transmission

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Secure DFRC Transmission

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