Joint MIMO-Radar-MIMO-Communications in the 5G Era

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Webinar
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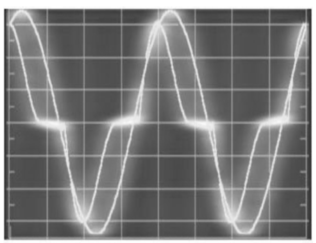
Cover Photograph Courtesy: Iowa Flood Center

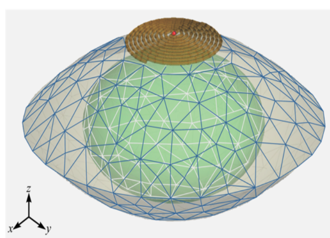
About the Speaker

- Kumar Vijay Mishra
  - National Academies Diamond Fellow, U. S. Army Research Laboratory
  - Research Fellow, SnT, University of Luxembourg
  - Technical Advisor, Hertzwell, Singapore

- Research interests:


Radar


Signal Processing



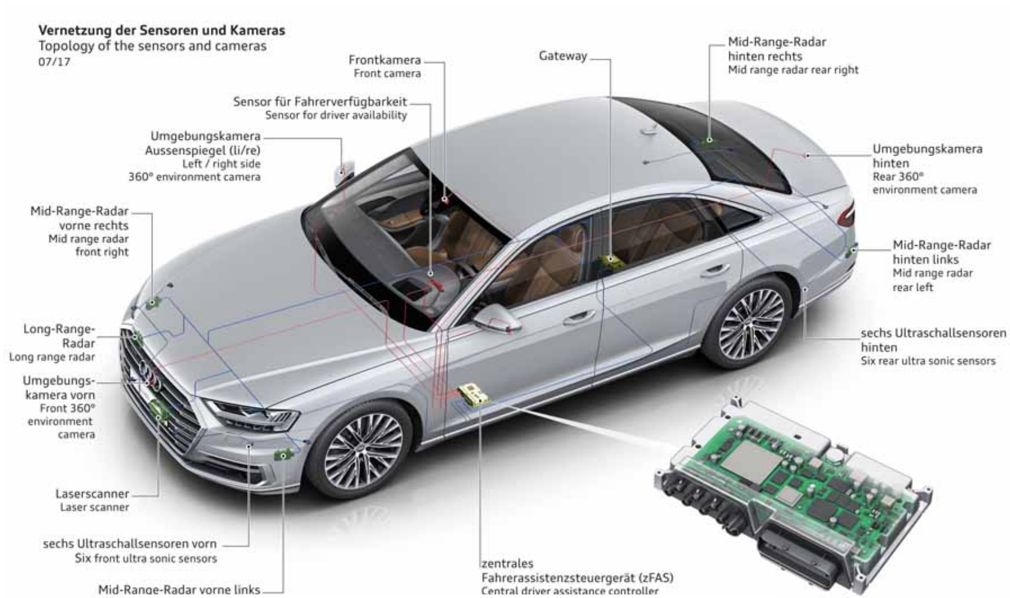
Electromagnetics

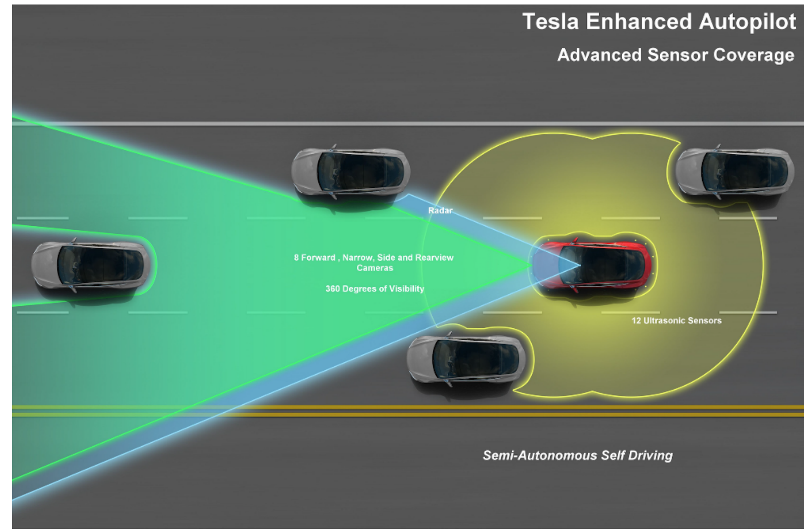

Communications

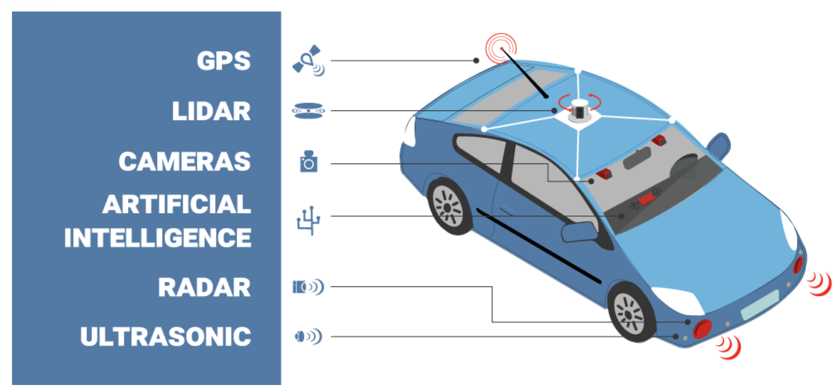

Remote Sensing

- Acknowledgements: Dr. M. R. Bhavani Shankar (SnT), Prof. M. Kobayashi (TUM), Prof. B. Ottersten (SnT), Prof. M. Saquib (UT Dallas), Prof. S. S. Ram (IIIT-D), Jiawei Liu (UT Dallas), S. H. Dokhanchi (SnT), and many collaborators

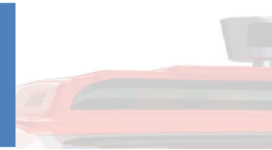
Motivation: Sensor-Driven Autonomous Vehicles





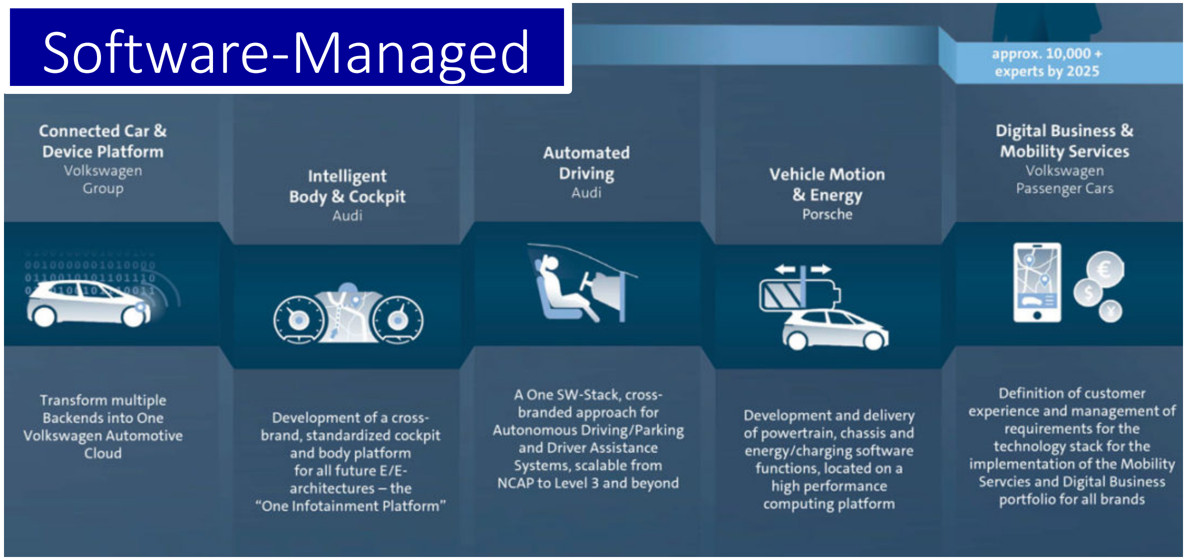


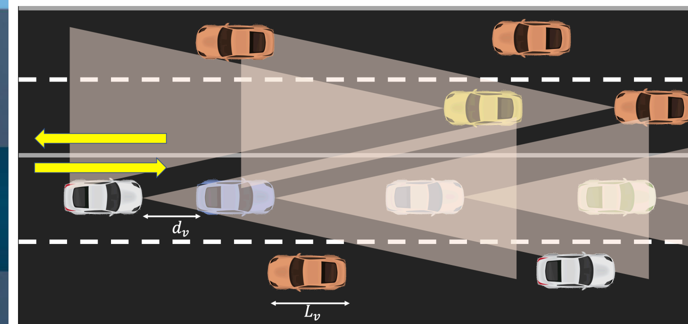
Autonomous Cars : Sensors

Parameter	RADAR 	LIDAR 	Camera 
Nature	Active	Active	Passive
Range	Long Upto 250m	Mid-range Upto 100m	Near range Upto 15-20m
Accuracy	• Descent • 0.1 m, • ±0.1 m/s • H/V-FOV 30/50	• Good • 0.02 m • 0.1deg • 360deg H-FOV	• Good • Recognition at 15m
Observations	• Robust to harsh conditions • Detecting Doppler • Low cost • Lack of semantic information	• High Accuracy • 3D Mapping • High cost	• Semantic information • Poor performance in adverse weather, night • No Doppler information

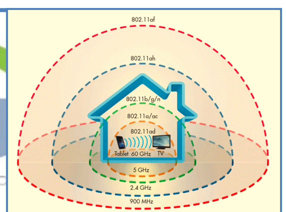
Modern Cars are …

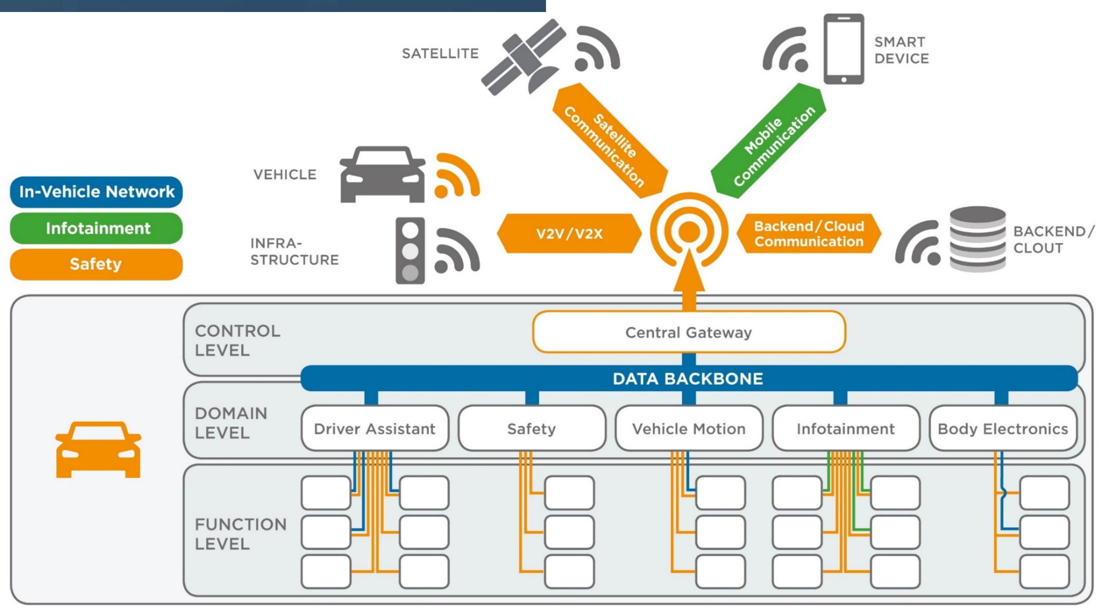
Software-Managed





and Connected!





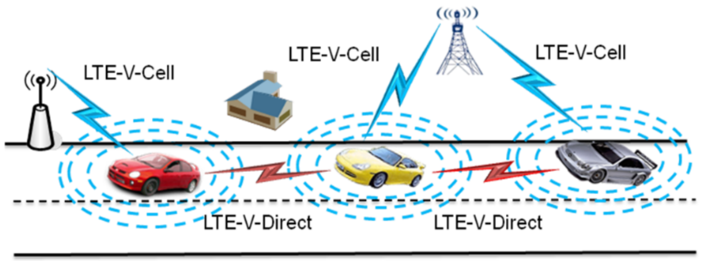
Hence, Cars Generate Huge Data!

Performance	Example Application
24Gbps	Uncompressed ADAS Sensor Data (Level 3-4 Autonomy)
12Gbps	Advanced Infotainment/Uncompressed ADAS Sensor Data (e.g. 4K video, Camera Connectivity)
3Gbps	Infotainment (e.g. full HD video)
1Gbps	Legacy Entertainment Systems/ Dashboard/ Touch Screens
150Mbps	In-vehicle Networks (e.g. Apps, Traffic, Vehicle Health Report)

Safety Infotainment In-vehicle networks

Wireless technologies

- DSRC
- C-V2x



	Data volume (GB)	Cost per GB (€) - low end (Jio, India)	Cost per GB (€)- high end (Proximus, Belgium)
2018 cost*		0.2	17.7
2019 data volume per vehicle	0.053	0.0106	0.9381
2023 forecast cost**		0.009	0.83
2023 data volume per vehicle	8.33	0.07497	6.9139

* - https://www.statista.com/statistics/262747/worldwide-automobile-production-since-2000/

** - using Deloitte 3% depreciation

https://blogs.cisco.com/sp/connected-car-all-that-data-cost-and-impact-on-the-network,
https://spectrum.ieee.org/transportation/advanced-cars/6-key-connectivity-requirements-of-autonomous-driving
https://vtsociety.org/2018/02/vehicles-february-2018/

Spectral Crowding

Question

Cars need both high rate communications and accurate sensing

Why is it difficult to have both?

- Modern radar systems operate in an increasingly crowded radio-frequency (RF) spectrum

Radar Band	VHF/UHF	L	S	C	X	Ku, K, Ka, V and W
Radar examples	FOPEN	ARSR	ASR, NEXRAD	TDWR	CASA	Automotive radars, cloud radars
Interference Source	TV/broadcast, 802.11ah/f	WiMAX, JTIDS	LTE	802.11 a/ac	LTE	802.11ad, mmwave comm

Shared Spectrum Access for Radar and Communications (SSPARC)

Outline

1 • Motivation

2 • mm-Wave Channel

3 • MIMO Communications

4 • MIMO Radar

5 • MRMC Topologies

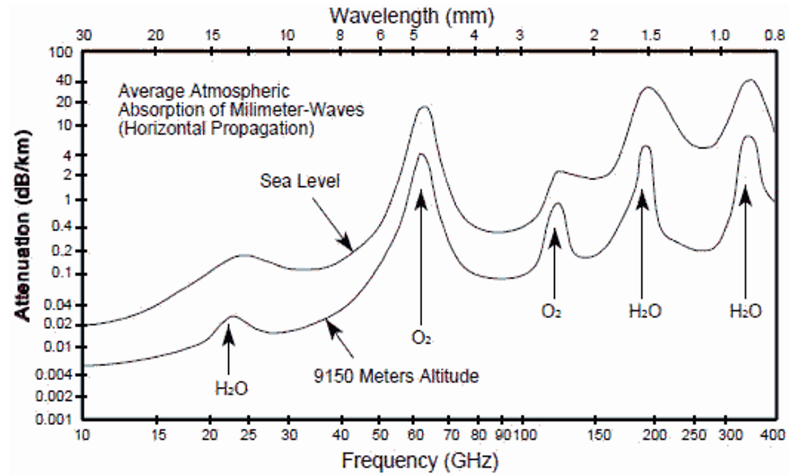
6 • Colocated MRMC

7 • Statistical MRMC

Photograph Courtesy: Hertzwell

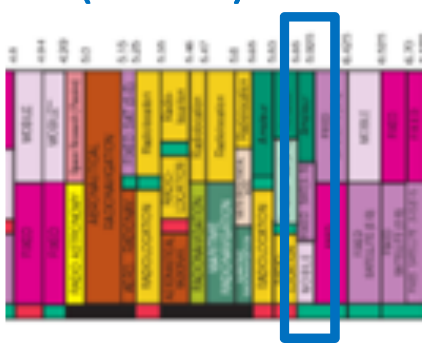
mm-Wave Bands as a Possible Solution

- Higher bands → Higher bandwidth
- Are all bands possible?
  - Propagation
  - Technology
- mm-Wave Band: 30 to 300 GHz
- Contiguous bandwidth of the order of GHz.



DSRC at 5.9GHz (75 MHz) **60GHz (7GHz)** **80GHz (5GHz for Autom. Radar)**

Spectrum Availability



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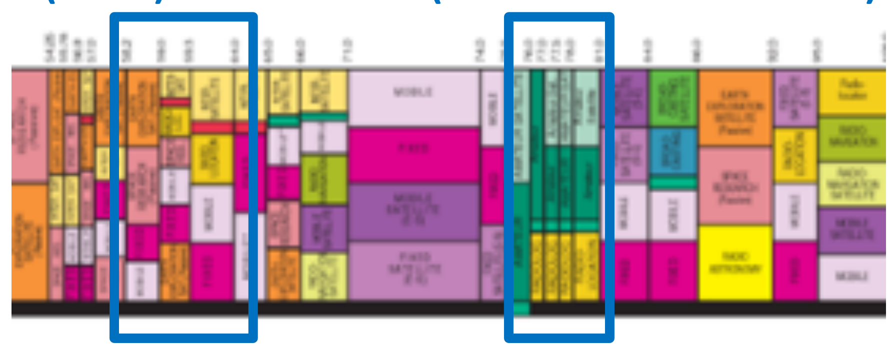

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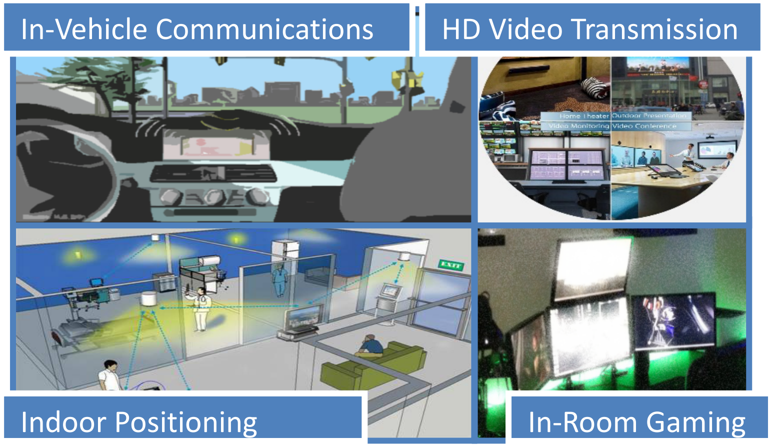
- R. W. Heath Jr., “Vehicular Millimeter Wave Communications: Opportunities and Challenges,” Wireless Networking and Communications Group, The University of Texas, Austin, 2015
- Y. Niu, Y. Li, D. Jin, L. Su, A. V. Vasilakos, “A Survey of Millimeter Wave (mmWave) Communications for 5G: Opportunities and Challenges”, arXiv:1502.07228, submitted in February 2015
- A. Cardama, Ll. Jofre, J. M. Rius, J. Romeu, S. Blanch and M. Fernando, “Antennas,” Edicions UPC, 2002

Millimeter-Wave Band

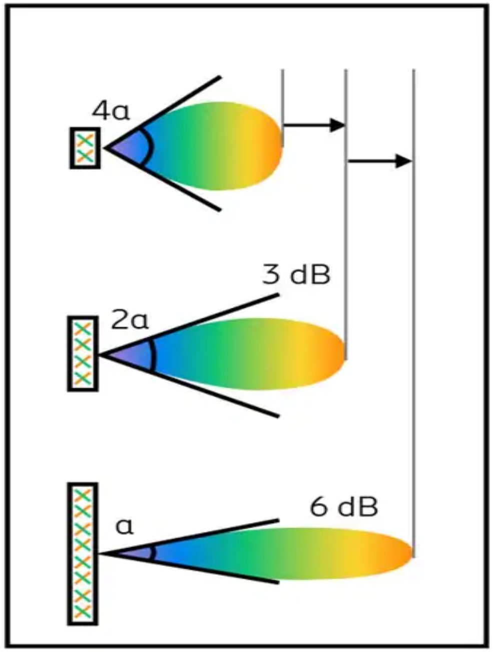
- Wide Bandwidth
  - Comms: High data rates, more users
  - Radar: Better Range Resolution
- Compact form factors
- High path loss, severe attenuation, short coherence times



- Prior works on spectrum sharing
  - Manage radar and comms units separately
  - Largely focused on cm-wave
  - Improve only one system
  - Monostatic automotive radar, infeasible hardware implementations, analysis restricted to single/point targets, micro-Doppler not included, etc.

mmWave Band : Impact on Design

Parameter	Observation
• Poor received power	• Large scale arrays → Massive MIMO
• Higher noise	• 64 Tx, 64 Rx array gives power gain of 120 dB
• Compact antenna placement	• Small Form factors
• High sampling rates	• 64 Tx, 64 Rx Sprint deployment is 700×400 mm • Sparse channel, clustered model

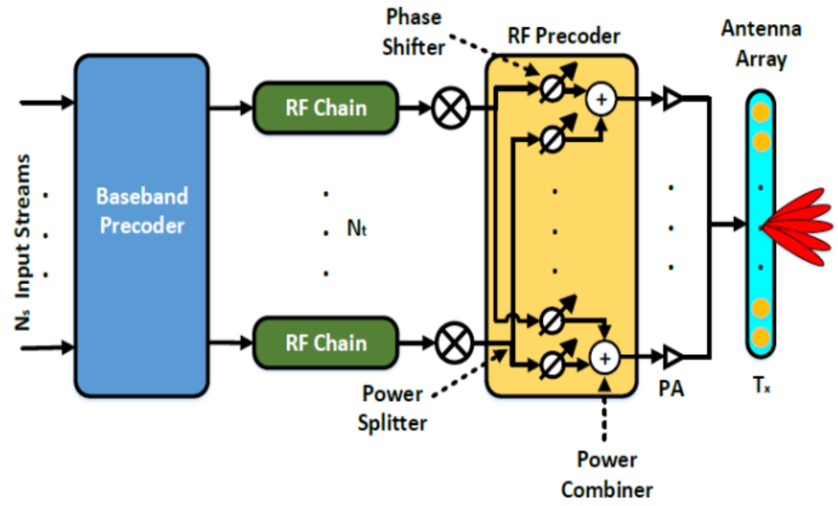


Sub-array gain

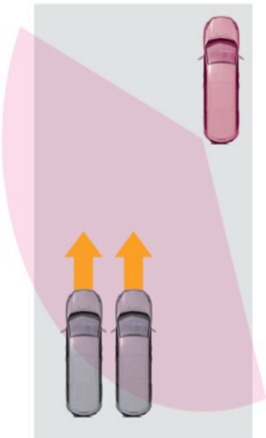
Source:: https://ustrademedia.com/global-massive-mimo-market/, Ericsson https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks

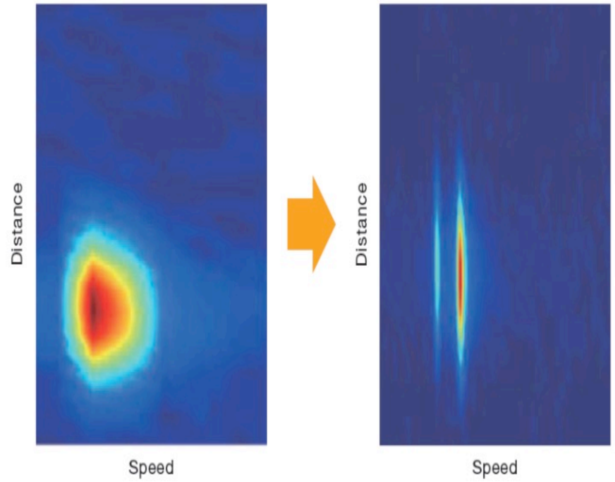
mmWave: Architecture Implications

- Large Arrays
  - Dedicated digital chain per antenna not feasible due to cost and power
  - Mixed analog-digital components
  - 1-bit sampling ADCs
- Wideband processing
  - High rate digital processing HW
  - High power consumption of analog and digital components
  - High cost
- Shorter Coherence times
  - Rapidly varying channel
  - Limits reliability of operation in highly mobile environments



MIMO Radar and MIMO Comms

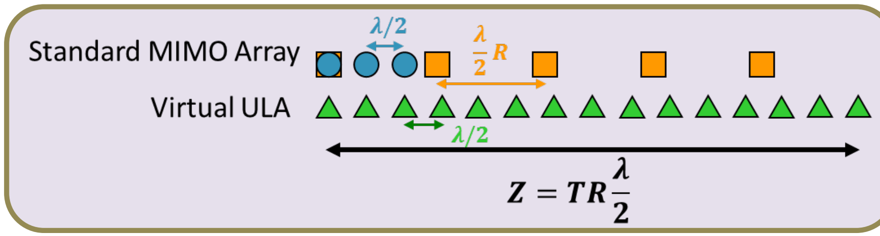




Low BW High BW

MIMO Radar

- High bandwidth allows resolving closely-spaced targets
- Aperture and spatial resolution

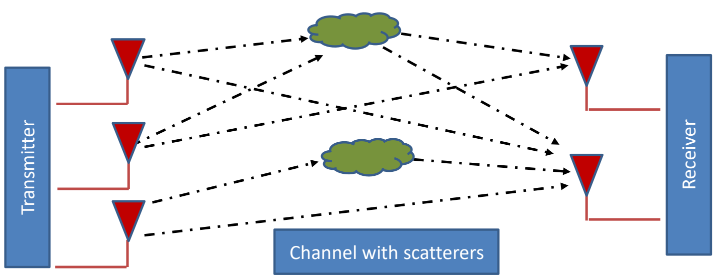


Measure for Throughput : Shannon formula as a guide

$$C = n\,W \log(1 + \mathrm{SINR})$$

MIMO Communications

- Multiple paths between transmitter and receiver
  - Different scatterers → Independent fading → Diversity in transmission
  - Multiple antennas → more streams
- Intelligent spread of information across transmitters
- Diversity and multiplexing



MIMO Systems Are Ubiquitous!

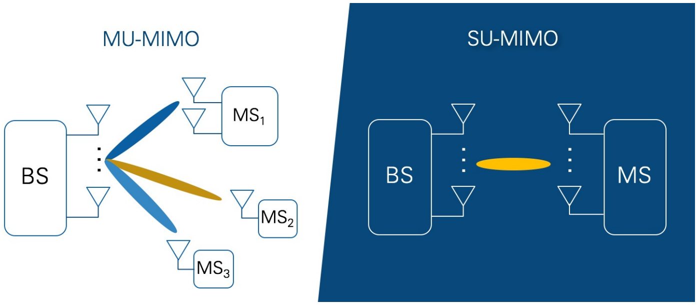
- IEEE 802.11n (Wi-Fi),
- IEEE 802.11ac (Wi-Fi),
- HSPA+ (3G),
- WiMAX (4G),
- Long Term Evolution (4G LTE).

Now : Massive MIMO for 5G!

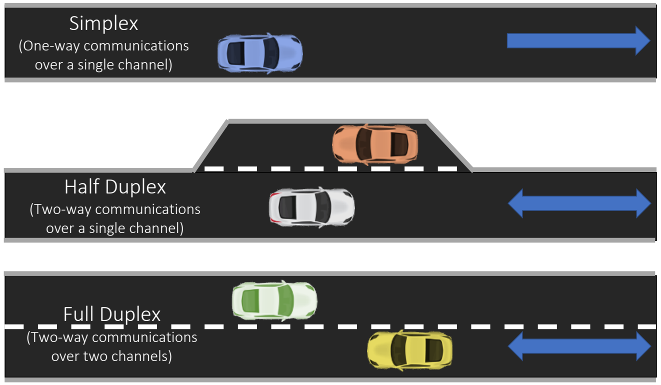
MIMO is part of communication standards
Millions of chipsets supporting MIMO

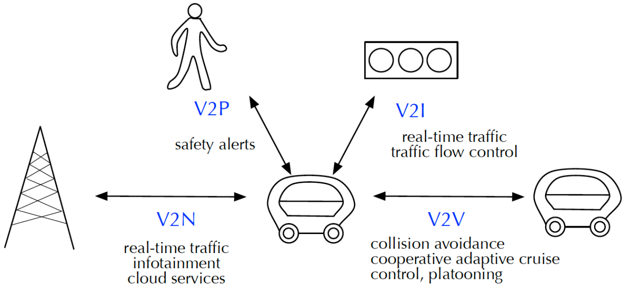
Joint Radar Communications : Topologies

- Spectral Coexistence
  - Radar and communications operate as separate entities
  - Devise strategies to mitigate the interference adaptively for either
  - Some information exchange
  - Minimal changes in standard, HW
- Spectral Co-design
  - New joint radio-frequency sensing and comms techniques
  - Single unit is employed
  - Opportunistic access of spectrum
  - Joint MIMO-Radar-MIMO-Communications (MRMC)
- Focus Applications: V2V, V2X, V2N



© NI, 5G Massive MIMO Testbed: Mar 5, 2019

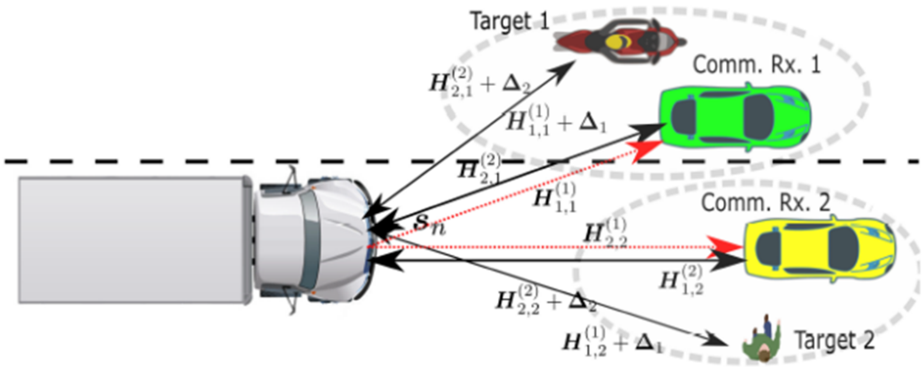




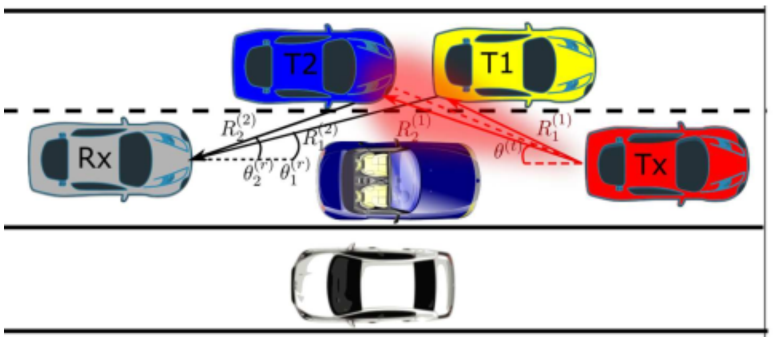
Monostatic and Bi-Static Systems

(Dokhanchi, Shankar, Mishra and Ottersten, IEEE TAES, 2019)

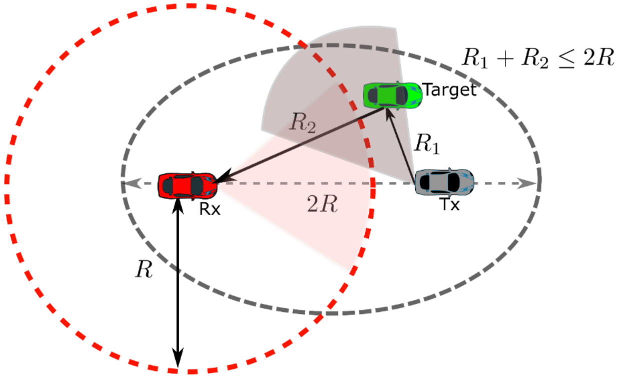
Monostatic



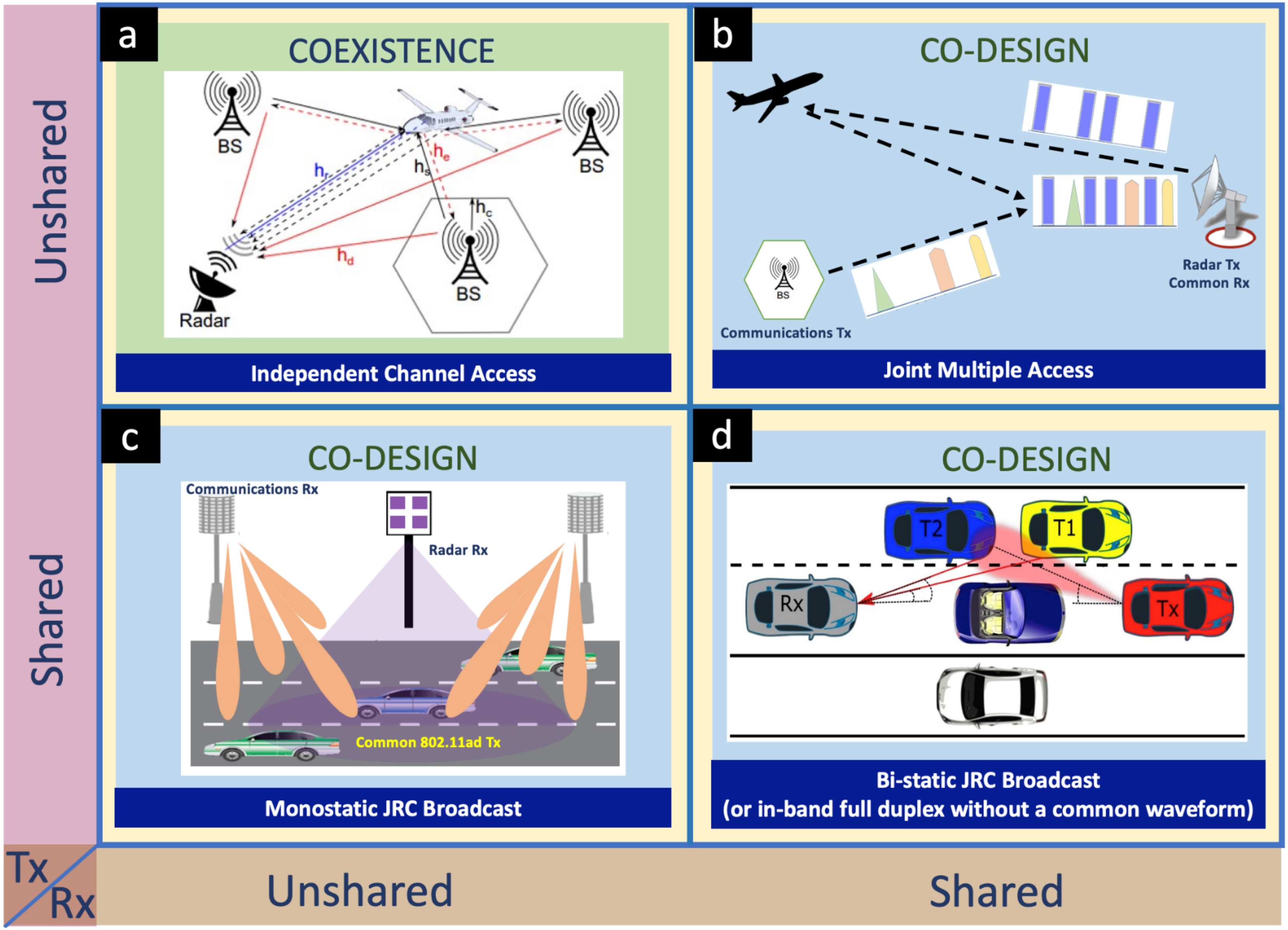
Bi-static



- Bi-static radar exploits bounced-off Tx signals from other vehicles
- Extends sensing area to NLOS w.r.t. Rx
- Communications is more susceptible to interference from surroundings than the direct path
- Bi-static system is more general



Spectrum Sharing Topologies



Radar and Comm Design Considerations

- Two Systems: Which performance metric to use?
  - Communications : Quality of Service, Data Rate, …
  - Radar : Dependent on Radar Tasks
    - RMSE, RoC, …
  - Unified Criteria?
    - Mutual Information

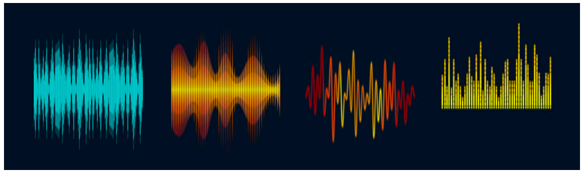
Mutual Information for Comm : $I(\boldsymbol{X};\boldsymbol{Y}|\boldsymbol{H})$

Mutual Information for Radar : $I(\boldsymbol{Y};\boldsymbol{H}|\boldsymbol{X})$

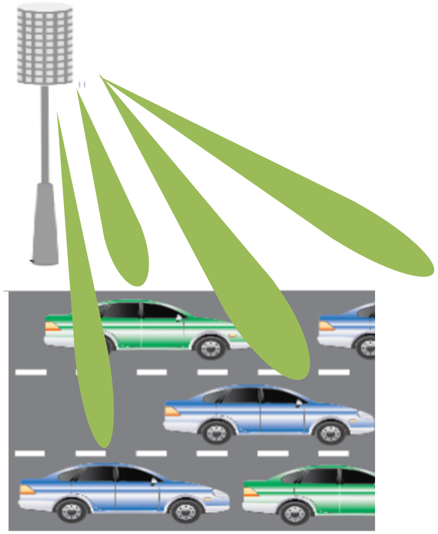
- Transmitter Degrees of Freedom
  - Co-existence
    - Different antennas, frequency, coding, transmission slots, power, or polarization, possibly Channel State Information
  - Co-design
    - Waveform
- Receiver Degrees of Freedom
  - Multiple antennas, Channel State Information

Signal Processing Approaches

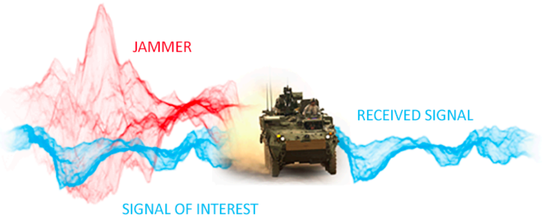
- Design of new waveforms
  - Multiple performance metrics/ constraints
  - System oriented constraints
    - Fewer antennas excited, constant modulus
  - Resource allocation



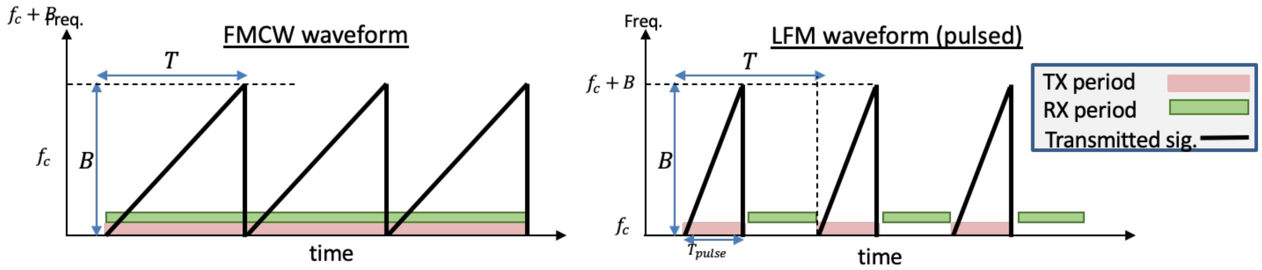
- Adapting waveform parameters to mitigate interference
  - Precoder/Beamformer design using SINR maximization



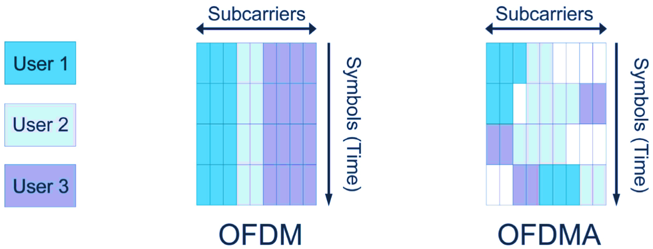
- Receiver
  - Multitude of beamformer designs
  - Successive Interference Cancellation
  - Multiple antenna-based processing
    - Subspace estimation, Eigenspace processing



Two waveforms for mm-Wave MRMC



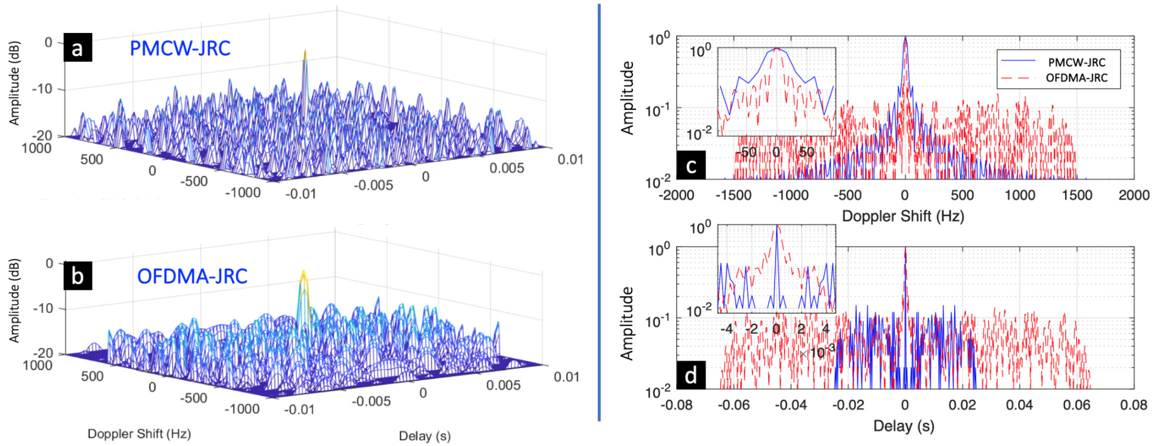
- PMCW
  - Viable alternative to FMCW for high-res radars
  - No linear frequency ramp (and simpler on-chip implementations) for range estimation
  - Sharp, thumbtack ambiguity function; MIMO radar in code domain; embedded comms
- OFDMA
  - Differentiates users in both time and frequency (unlike OFDM in time-only)
  - Stable performance in multipath fading and relative simple synchronization
  - High dynamic range and efficient receiver processing based on FFT



- Question: How do these properties compare in JRC mode?

PMCW-JRC vs OFDMA-JRC

(Dokhanchi, Shankar, Mishra and Ottersten, IEEE TAES 2019)

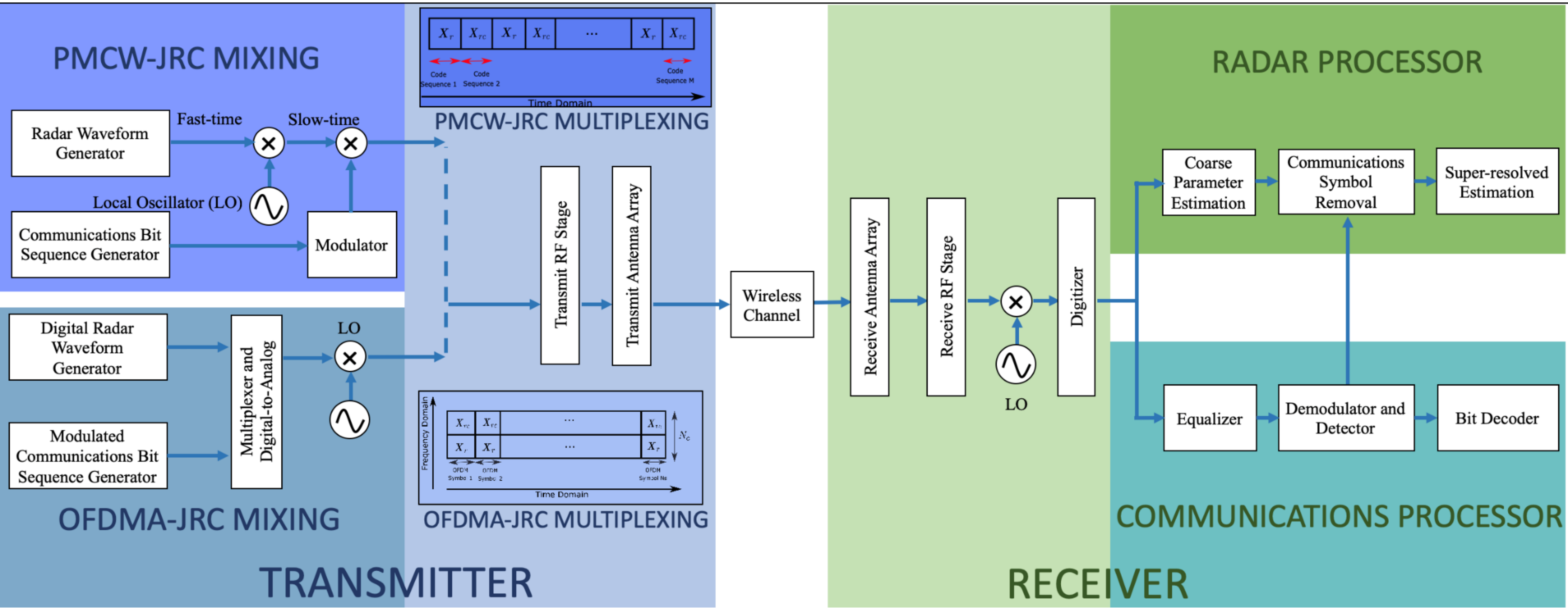


Waveform type	Resolution	Max. throughput per CPI	Max. unambiguous range	Characteristics
PMCW-JRC	$\Delta f_D = \frac{1}{t_{\text{CPI}}}$ $\Delta R = \frac{c}{2B}$ $\Delta\theta = \frac{\pi}{\mathrm{N_r}}$	$\frac{T_{\text{CPI}}(1\text{-}\mu)}{t_b}$	ct_{b}	• Higher range resolution in comparison with OFDMA-JRC • Larger maximum unambiguous range in comparison with state-of-the-art mono-static JRC
OFDMA-JRC	$\Delta f_D = \frac{1}{t_{\text{CPI}}}$ $\Delta R = \frac{c}{2B_u}$ $\Delta\theta = \frac{\pi}{\mathrm{N_r}}$	$\frac{T_{\text{CPI}}(1-\mu)N_c}{T_{\text{sym}}}$	$\frac{c}{\Delta f}$	• Higher throughput in comparison with PMCW-JRC • Larger maximum unambiguous range in comparison with state-of-the-art mono-static JRC

c: speed of light, B: total available bandwidth, B_u: user bandwidth, Δf: sub-carrier intervals.

mm-Wave JRC Tx-Rx Design

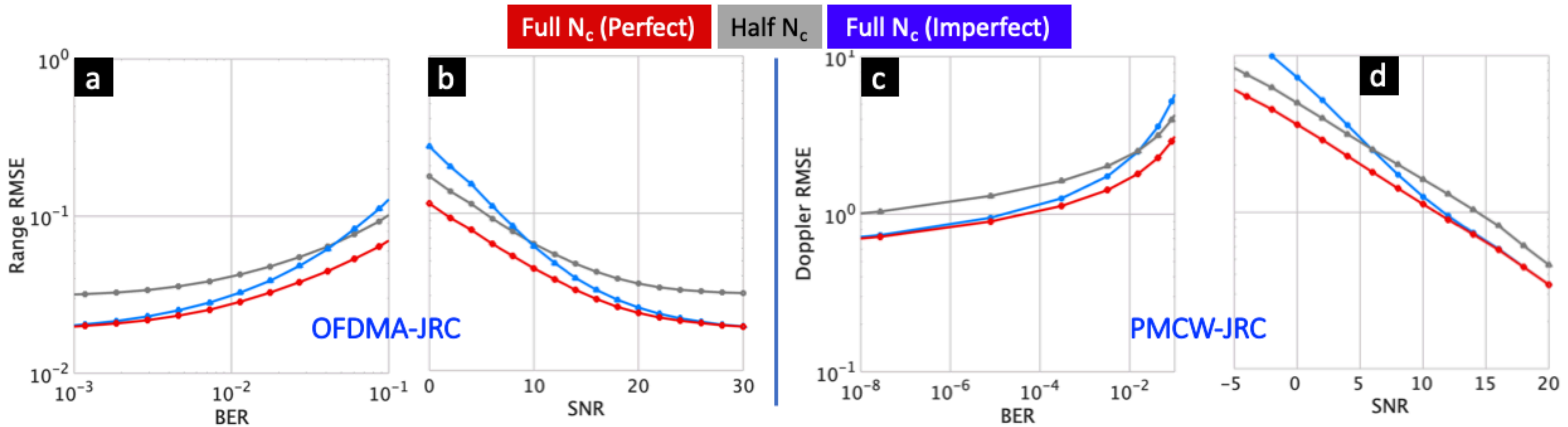
(Mishra, Shankar, Koivunen, Ottersten and Vorobyov, IEEE SP Magazine, 2019)



- Multiplexing strategy required to enhance waveform identifiability
- The receive processing consists of coarse and super-resolution steps
- JRC super-resolution algorithm has lower complexity than 2D-FFT and 2D-MUSIC

mm-Wave JRC Performance

(Mishra, Shankar, Koivunen, Ottersten and Vorobyov, IEEE SP Magazine, 2019)

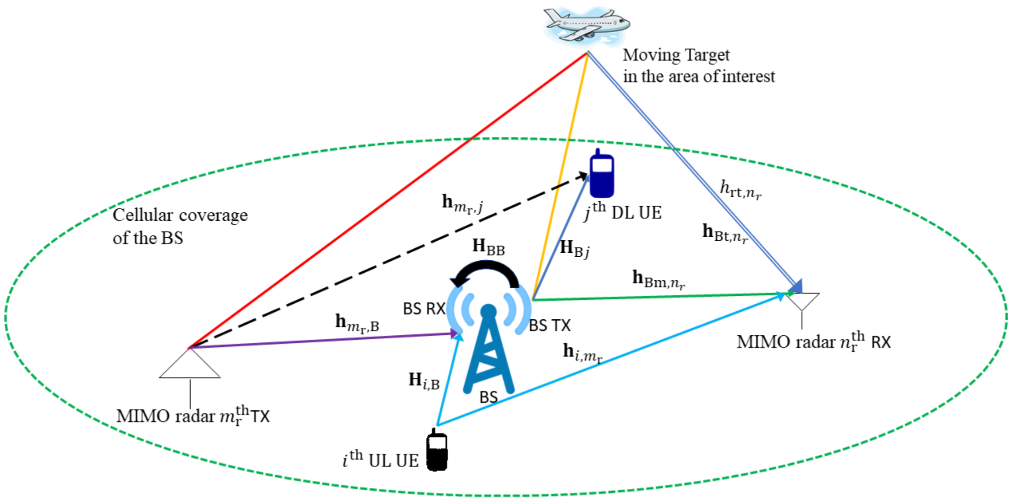


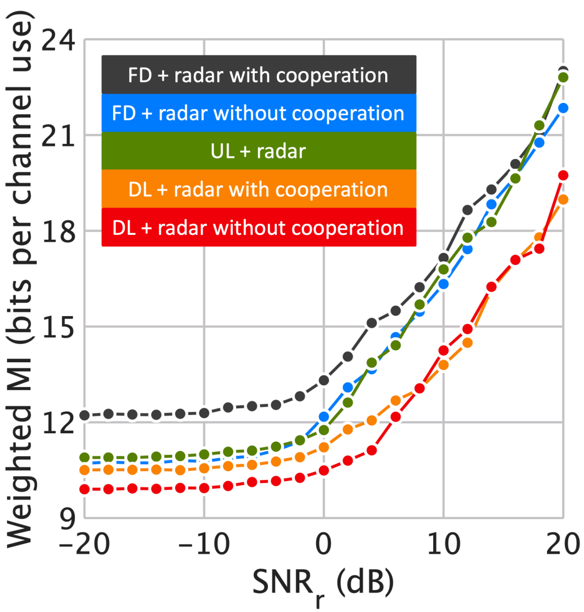
- A comparison of estimation errors in the coupled parameter - range for OFDMA-JRC and Doppler for PMCW-JRC
- When SNR is above a threshold, re-estimating coupled parameter using all subcarriers after comm removal enhances the recovery
- At low SNR, radar-only frames/carriers are a more optimal choice

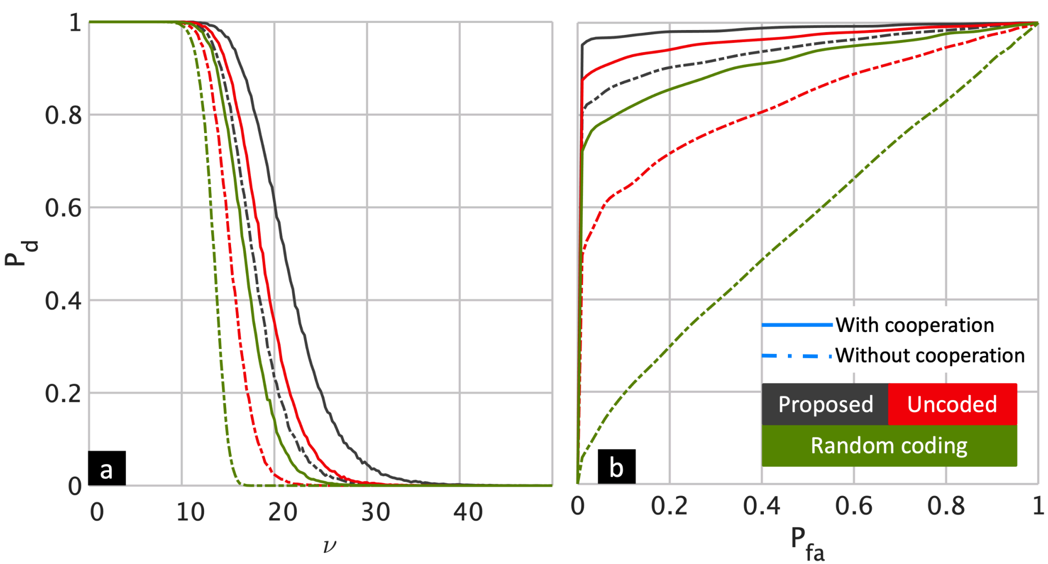
Statistical/Distributed MRMC

(Liu, Mishra, Saquib, 2020: *Co-Designing Statistical MIMO Radar and In-band Full-Duplex Multi-User MIMO Communications*)

- Statistical/Distributed MIMO: Target radar cross-section is not identical for all Tx-Rx pairs
- Radars could work in cooperation with the downlink-reflected signal
- Proper design of waveform, receive filters, comm precoders is critical
- Mutual information could be a design metric







Summary

- MIMO technology is essential to enable spectrum sharing at mm-Wave band

- Joint MRMC
  - Waveform design is a challenge
  - Both radar- and comms-centric solutions possible
  - Advanced receiver processing to estimate parameters

- Coexistence and co-design topologies

- Colocated and Statistical MRMC

- Adapt existing waveforms or design new waveforms with customized constraints

More:

Overview Article: K. V. Mishra, Bhavani Shankar M. R., B. Ottersten, V. Koivunen, and S. Vorobyov., "**Toward millimeter wave joint radar-communications: A signal processing perspective**," *IEEE Signal Processing Magazine*, vol. 36(5), pp. 100-114, 2019

Tutorial: K. V. Mishra, M. R. Bhavani Shankar, and M. Kobayashi, "**Information Extraction in Joint Millimeter-Wave State Sensing and Communications: Fundamentals to Applications**," ICASSP 2020, RadarConf 2020, RADAR 2020

MS/PhD internships and career opportunities: grow@hertzwell.com

THANK YOU!