Millimeter Wave Sensing Technology for Automotive and Consumer Applications

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Corporate Research and Advance Engineering

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Millimeter Wave Sensing Technology
Overview

- Motivation
- Radar for Fully Automated Driving vs. Advanced Driver Assistance
- Current Automotive Radars
- Next Generation Radar Technologies
- Radar Interference
- Radar beyond Automotive & Higher Frequencies
- JCAS and 6G
- Conclusion

Millimeter Wave Sensing Technology
Why Radar ?

Millimeter-wave radars provide robust and high-resolution information about remote objects:

Amplitude, *distance*, *velocity*, *angle* and

Small *movements* (Micro-Doppler)

Since it's introduction in the automotive area, Radar has become a key sensing modality for driver assistance and automated driving

Semiconductor Technology allows constantly higher integration density

Algorithms move radar sensing from simple detection to classification and mapping

Small size, invisible integration, low cost, and privacy are advantages of Radar that make it attractive for markets beyond Automotive

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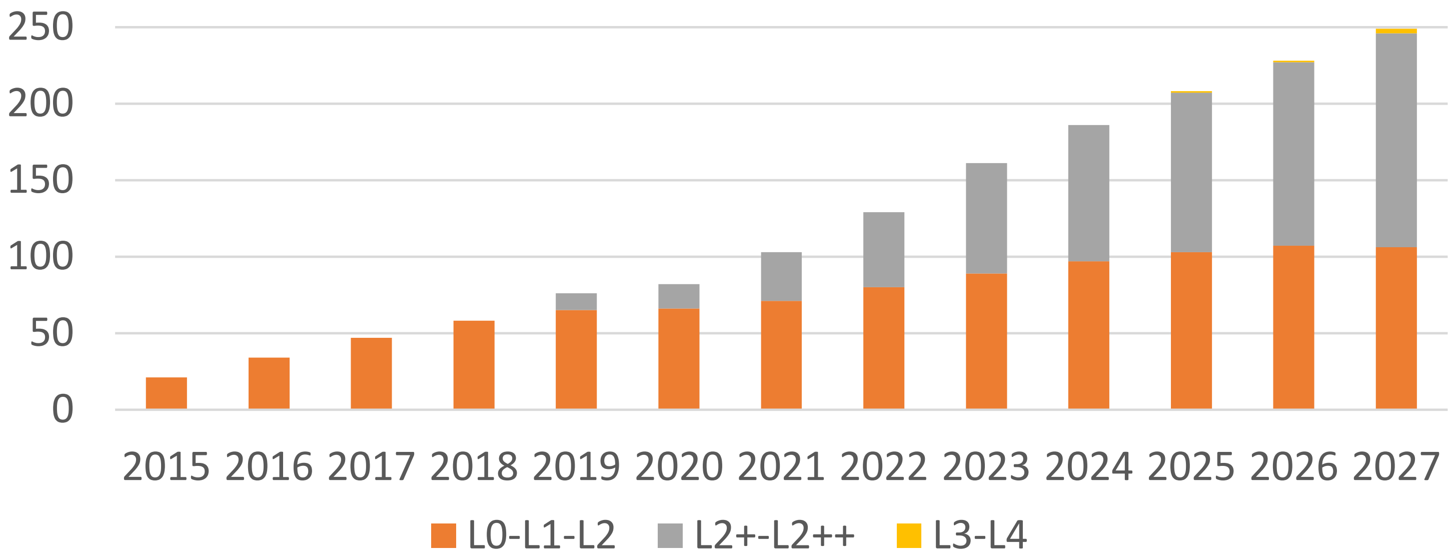
Millimeter Wave Sensing Technology
Automotive Radar Market

- Expected to reach 10B $USD in 2025
- Vast majority of volume is in “traditional” driver assistance systems L0…L2 and enhanced driver assistance L2+…L2++



Source: Yole Developpement

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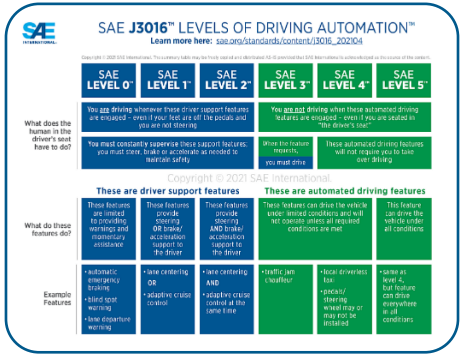
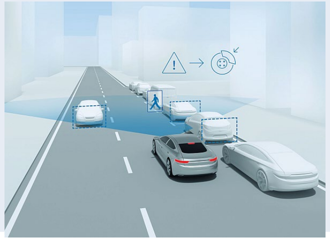
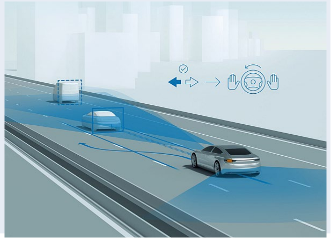
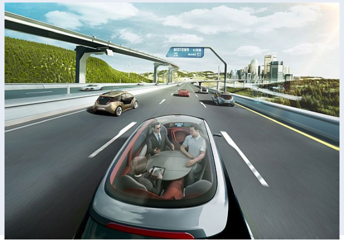
Automation Levels


SAE J3016™ LEVELS OF DRIVING AUTOMATION™
Learn more here: sae.org/standards/content/j3016_202104

	SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
What does the human in the driver's seat have to do?	You are driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You are not driving when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

- SAE J3016 definition is not fitting well anymore
- "Unofficial" additional levels L2+, L2++ added for new driver assistance functions
- A definition using driver involvement seems more practical:

SAE Level	L0-L1-L2	L2+-L2++	L3-L4	L5
Driver Involvement	Eyes-on Hands-on	Eyes-on Hands-off	Eyes-off Hands-off	No-driver „Mind-off"
Definition	Driver assistance	Partial automation	Conditional automation	Automated driving
Radar type	Standard	Hires	Imaging	
Example				

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Automotive Radar Categories

Main technical differentiator between the sensor types are angle resolution and cost

Radar Category	Standard	Hires	Imaging
Range	up to 150…200 m	up to 300 m	300 m and more
Azimuth angle resolution	< 5° @ ± 60°	< 3° @ ± 60°	< 1° @ ± 60°
Elevation angle resolution	< 10° @ ± 20°	<6° @ ± 15°	<2° @ ± 15°
Cost vs. performance	Cost-optimized		Performance-optimized

Based on publications and Yole reports

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Standard Radars

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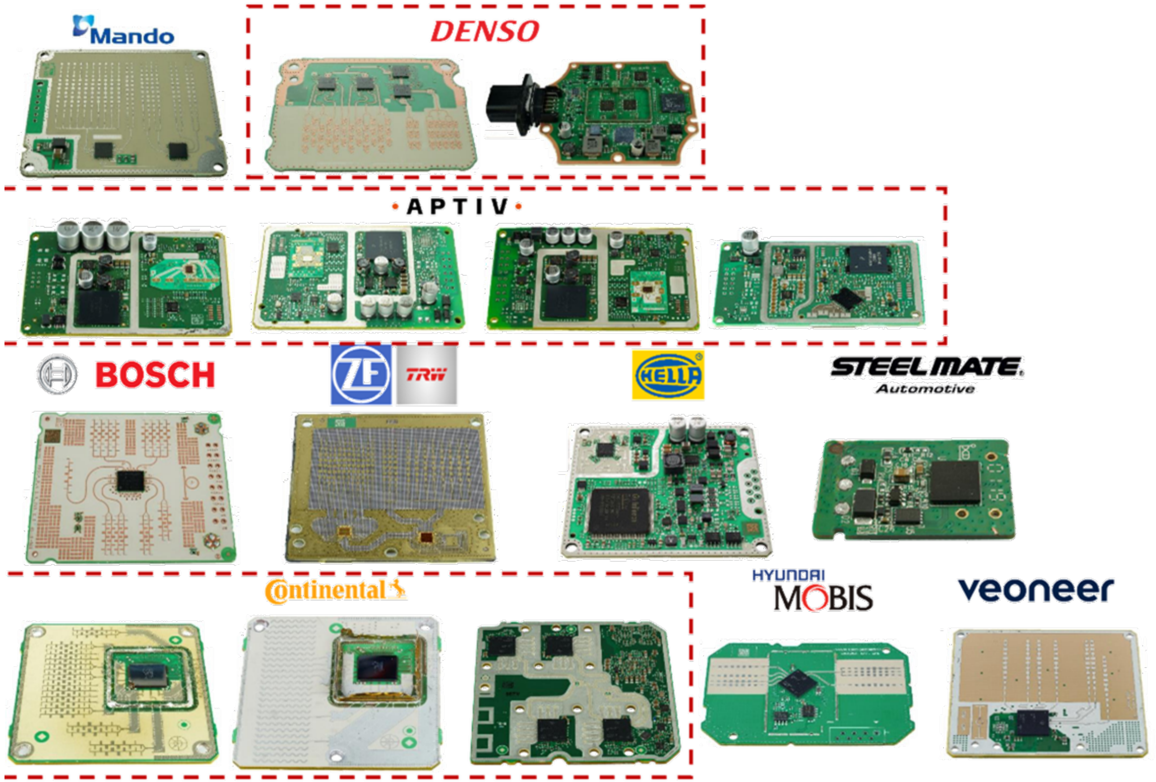
Standard Automotive Radars

- Mass market, high volume
- High cost pressure
- Dominated by established players
- Typical setup
  - Single chip frontend
  - Application processor
  - Single PCB
  - PCB antenna
- Next Generation
  - Even more cost pressure
  - Higher integration density
  - Trend to waveguide antennas



Source: Systemplus

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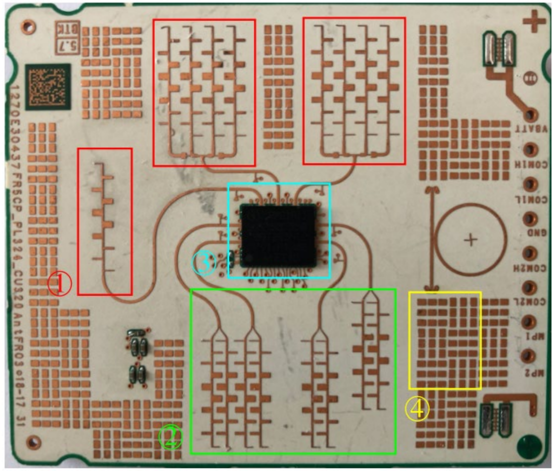
Standard Automotive Radars: Example

- Bosch Gen5 Front Radar [1]
- RF Frontend in SiGe BiCMOS technology

Parameter		Value
Frequency	band	76–77 GHz
Distance	max.	210 m
	accuracy	0.1 m
	resolution	0.2 m
Velocity	accuracy	0.05 m/s
	resolution	0.1 m/s
Hor. angle	accuracy	0.1 deg
	resolution	3.0 deg
Vert. angle	accuracy	0.2 deg
	resolution	6.0 deg

Sensor Performance



Frontside

Backside

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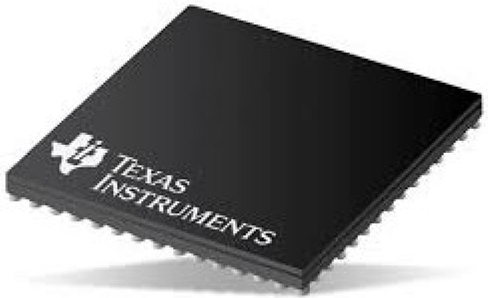
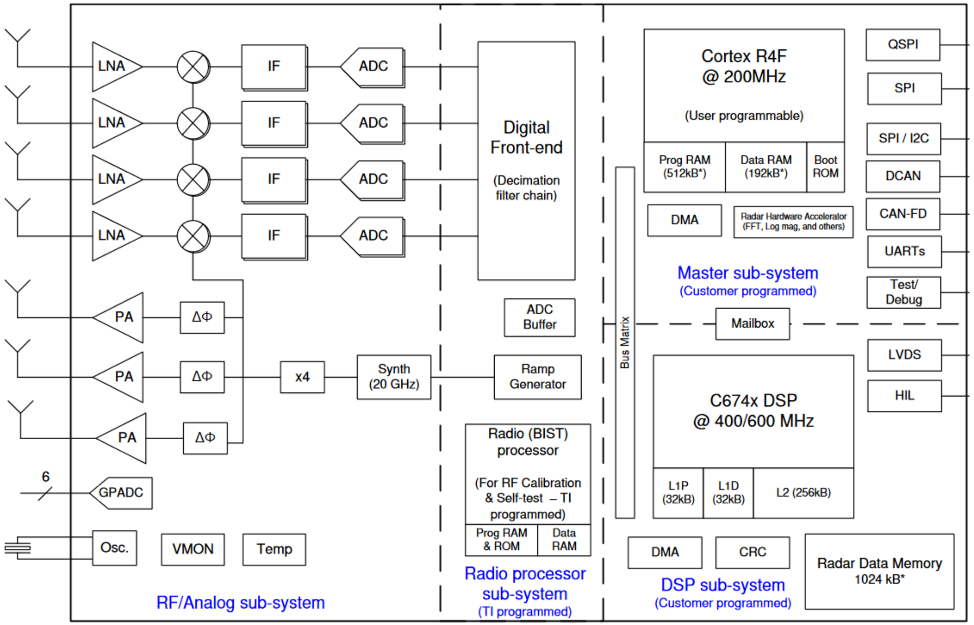
Standard Automotive Radars: SoC

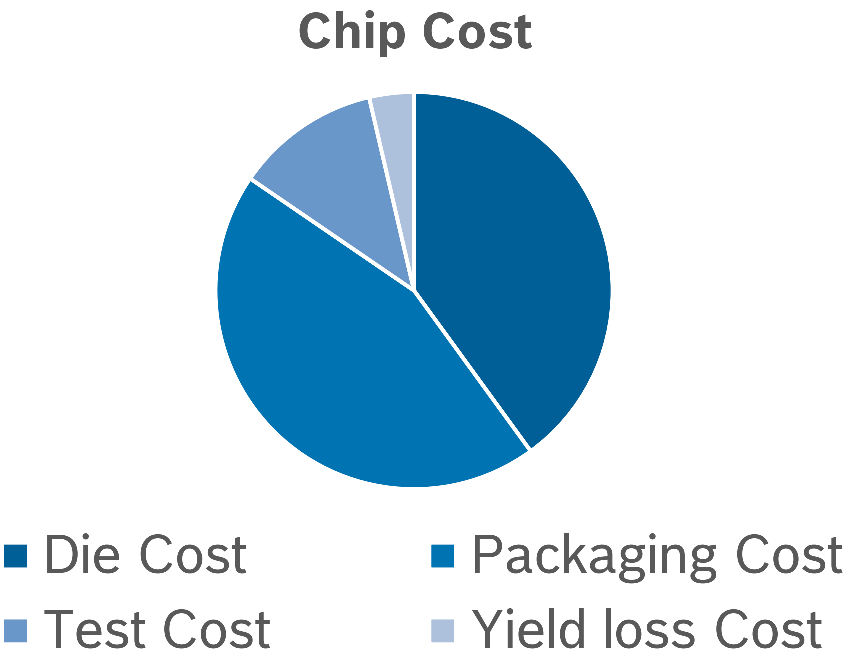
- Example: Texas Instruments
- 45nm CMOS Technology System-on-Chip with AoP
- Estimated chip cost ≈ 5 US$ (not sales price!)



Size: 15x15mm



Sources: Texas Instruments, SystemPlus, IC Knowledge



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Highres & Imaging Radars

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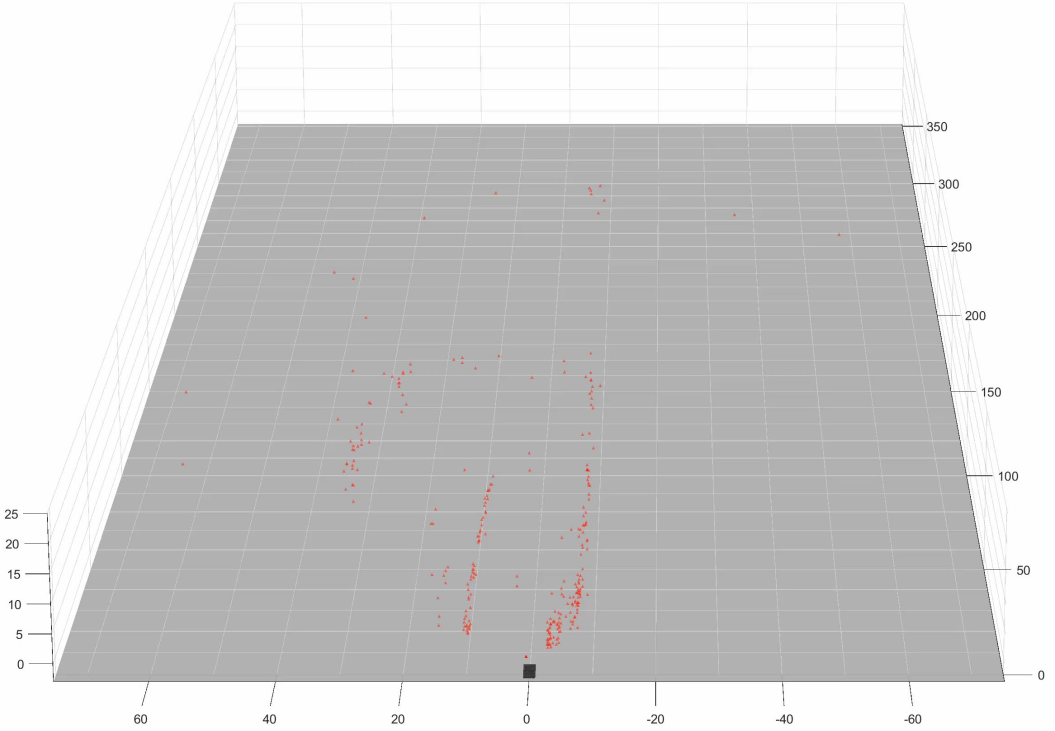
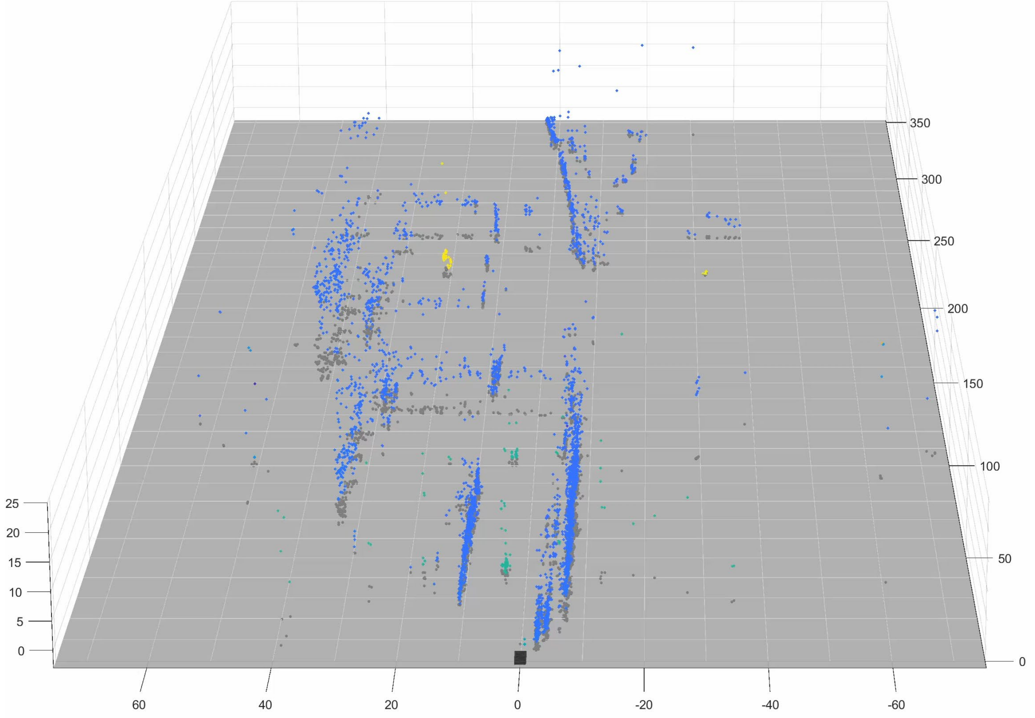
Increasing the Number of Channels

Significant performance improvement from improved angle information:



Highres Sensor (8 TX, 16 RX)



Imaging Sensor (30 TX, 40RX)

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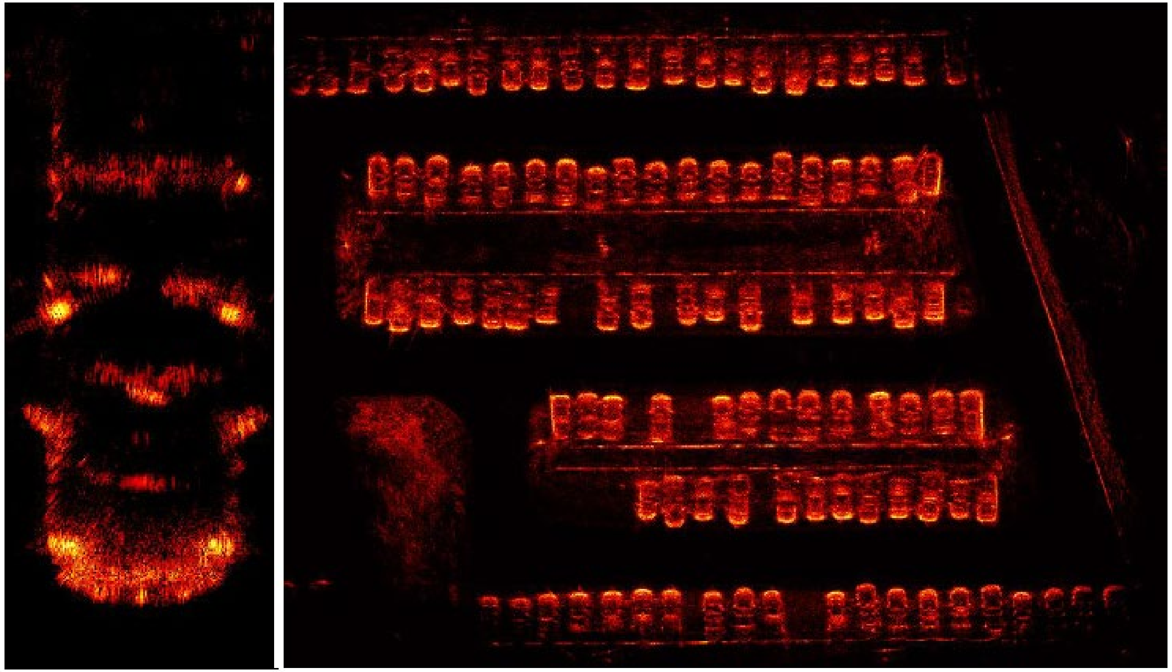
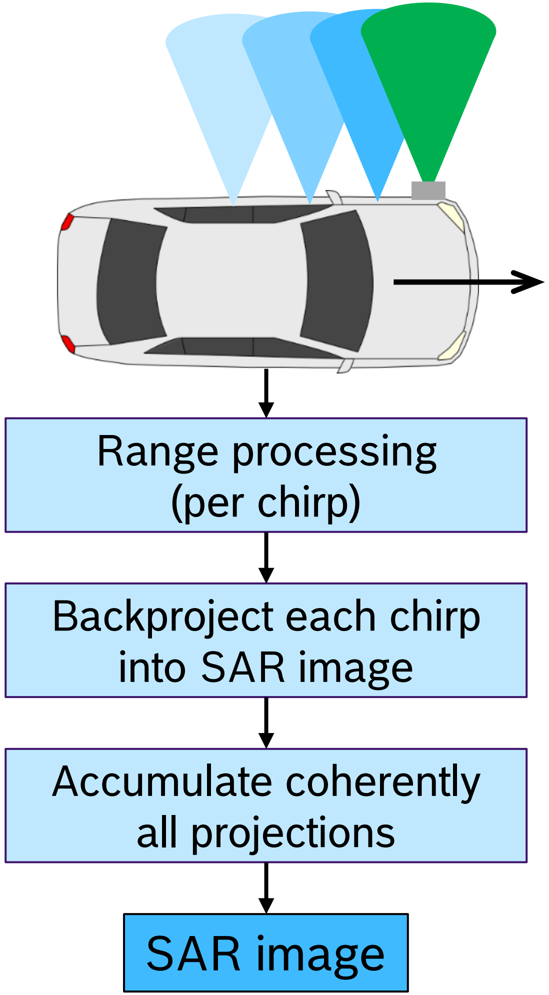
Synthetic Aperture Radar

Integrating over several measurements to create a large virtual aperture allows “image”-like maps:



University of Ulm:Grid Mapping and Synthetic Aperture Radar based on Millimeter Wave MIMO Radar for Automotive Applications, Automotive Forum 2022



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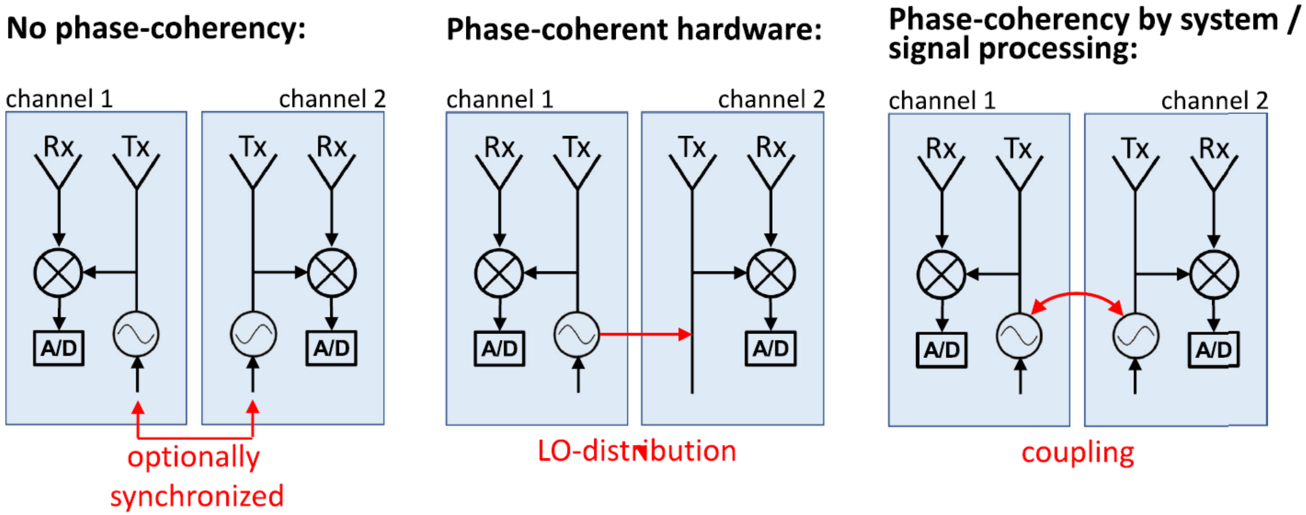
Distributed Radar Networks

- Distribute Radar Sensors across a large aperture:
  - Multiple monostatic detections
  - Multistatic detection
  - High angular resolution
- Coupling mechanisms:



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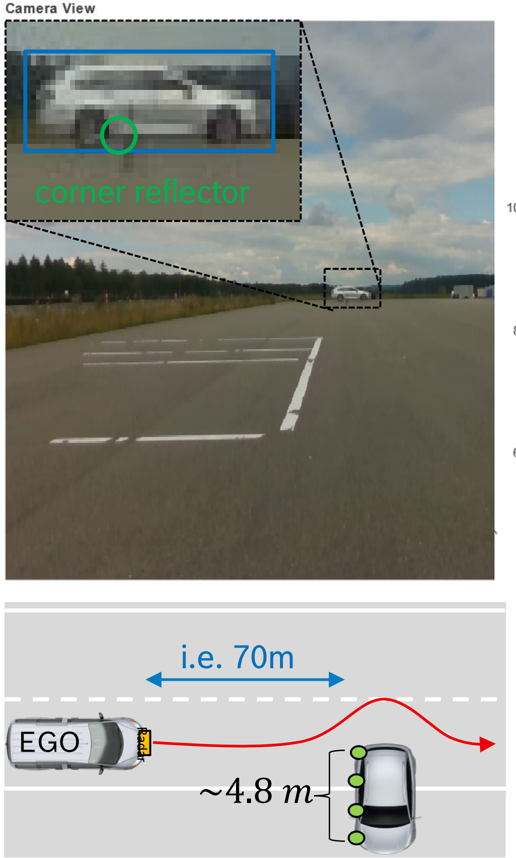
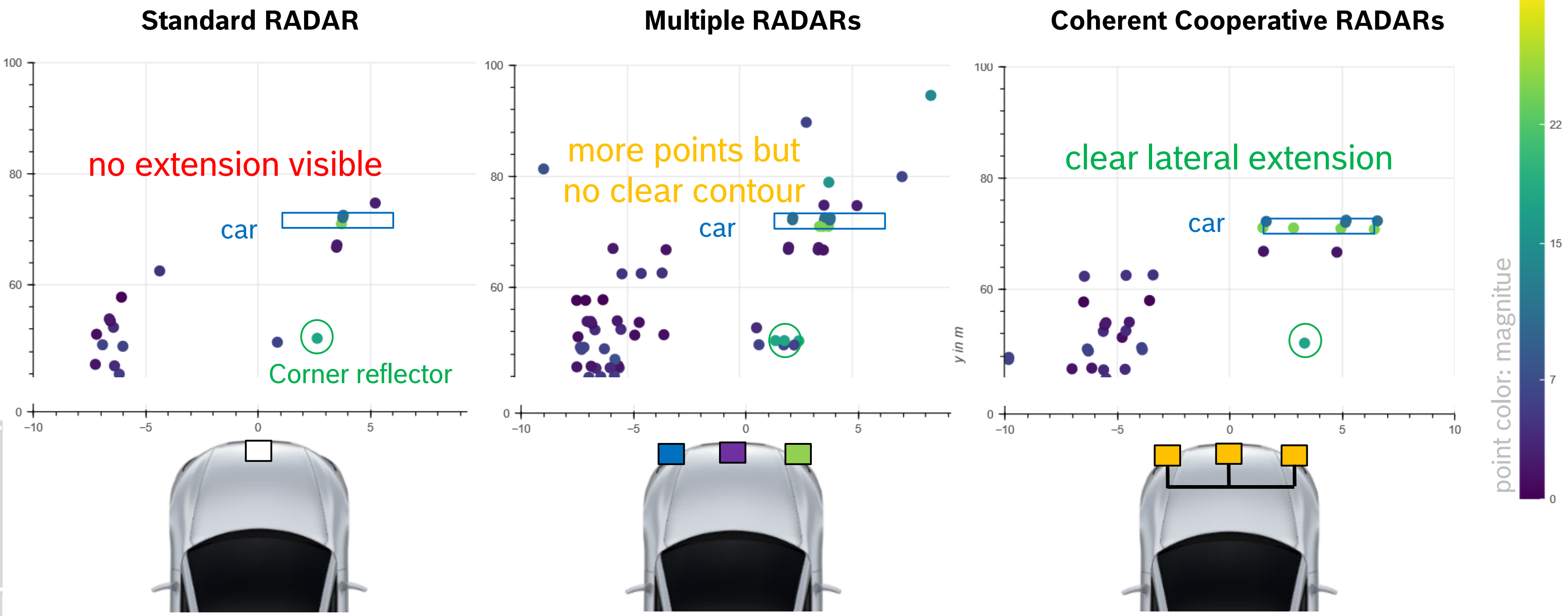
Distributed Radar Network Example



Bird's eye view of measured RADAR reflections:



➔ **Coherent distributed RADARs can significantly increase angular resolution**

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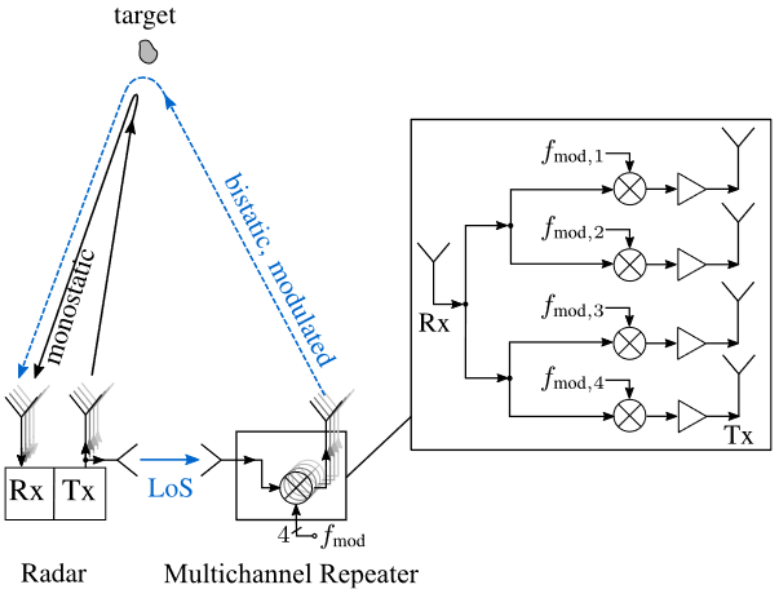
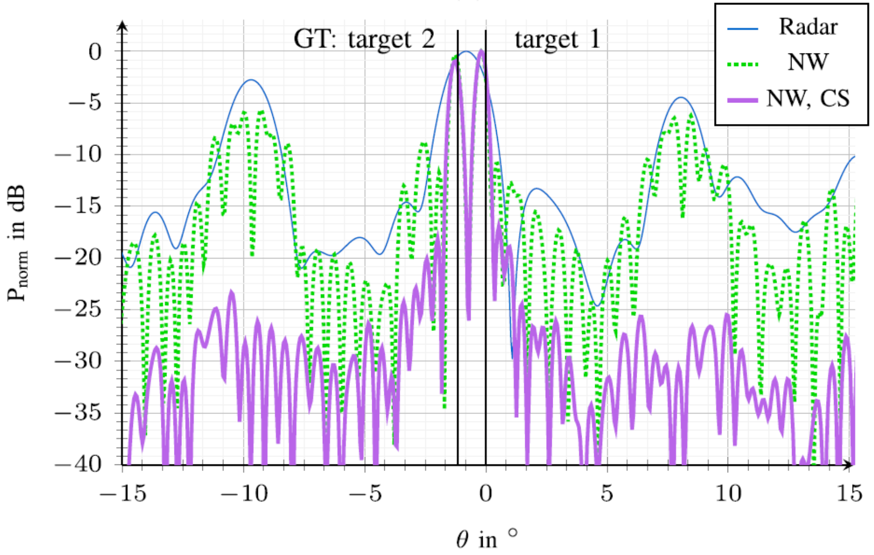
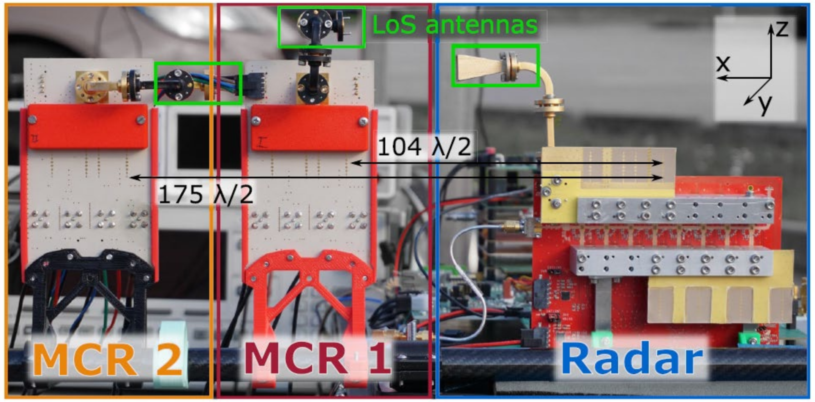
Technologies: Active Tag Network

- Virtual mirroring of Radar sensors using distributed tags [13]:







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Next Generation Radars

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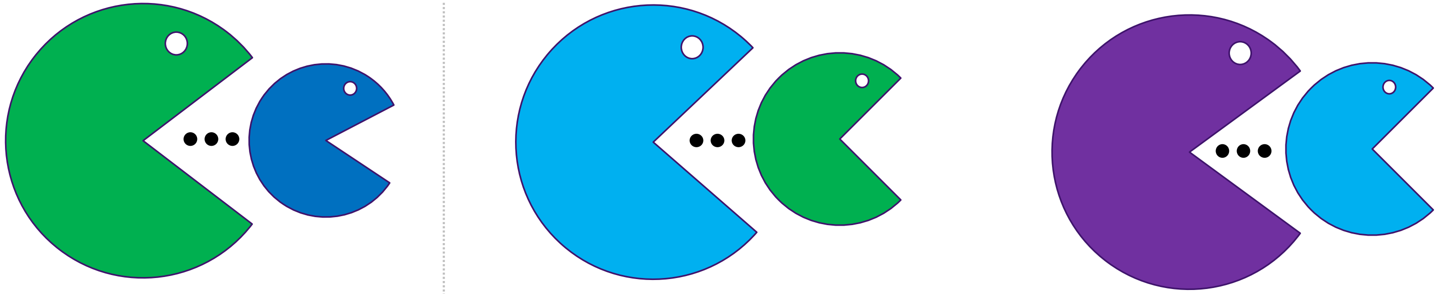
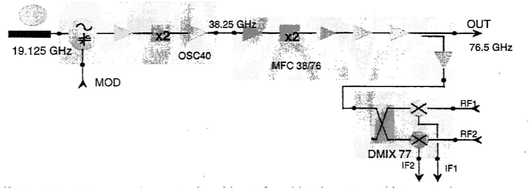
Technologies: Digital Radar

Silicon ate III/V semiconductors | CMOS ate SiGe silicon | Digital eats analog design

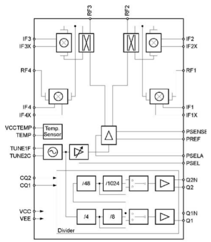


Silicon | III/V | CMOS | SiGe | Digital | Analog

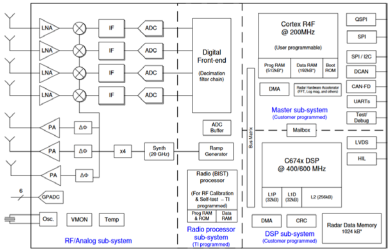
Comm.	2000...	2010...	2020...
Radar	2010...	2020...	2030...

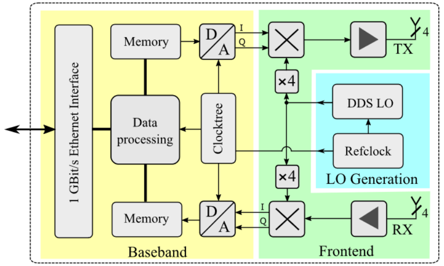


[13]



[14]





[15]

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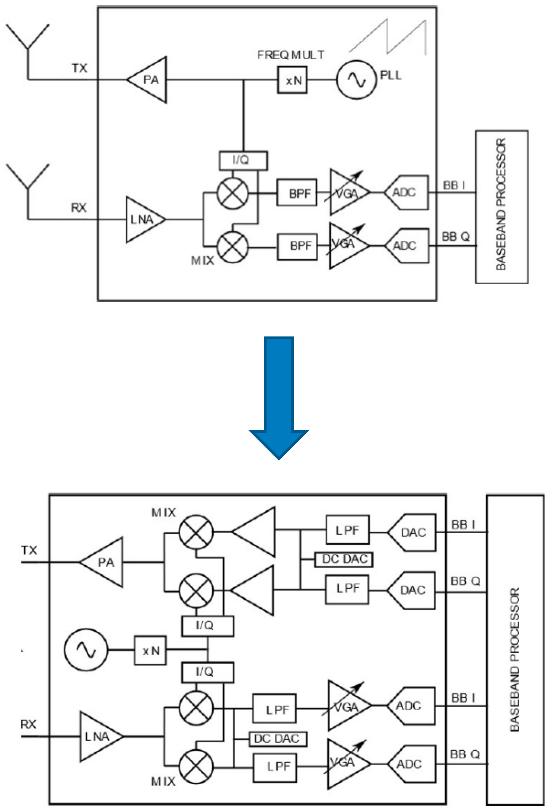
Millimeter Wave Sensing Technology
Why do we need a Digital Radar ?

+ Higher flexibility in system design
  (tradeoff in range, velocity, angle)
+ More transmit multiplexing options for MIMO
+ Cooperative operation of multiple sensors
+ Joint communication and sensing
+ Better interference measures
+ Stable and robust digital processing
+ Better spectrum efficiency
+ Dynamic spectrum sharing

- KPI improvements
- Higher implementation costs
- More stringent requirements on analog frontend (linearity, efficiency)
- Faster ADCs and DACs required



From Analog to Digital Radar [10]

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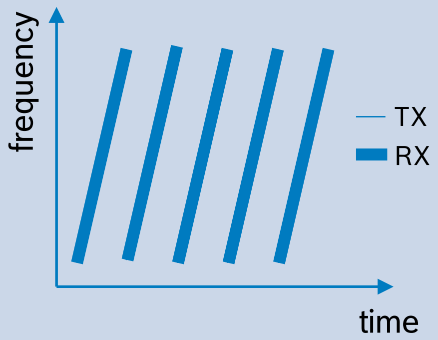
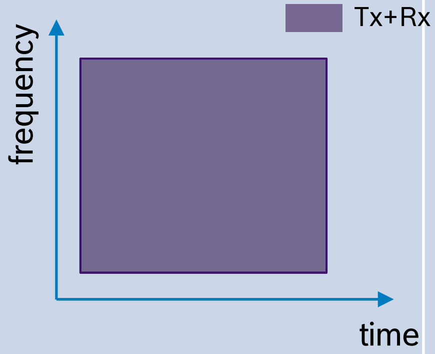
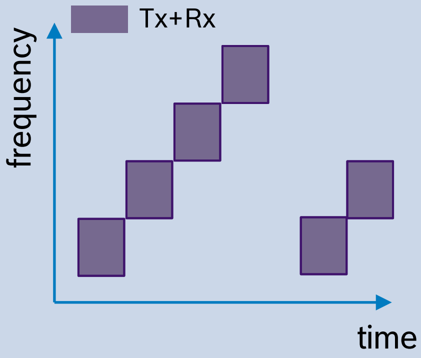
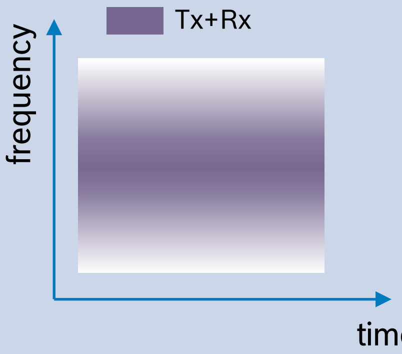
Millimeter Wave Sensing Technology
Radar Modulation Schemes

Spectrum occupied by different modulations

Modulation	Chirp Sequence	OFDM	Stepped OFDM	PMCW
Bandwidth	B_{BB} = 500kHz ··· 10MHz ··· 100MHz	B_{BB} = 50MHz ··· 500MHz ··· 1GHz	B_{BB} = 25MHz ··· 125MHz ··· 250MHz	B_{BB} = 50MHz ··· 500MHz ··· >1GHz
Spectrum use	Signal power concentrated in TFP	Widely distributed in TFP	Fairly distributed in TFP	Widely distributed TFP
Envelope	Chirp pulse	Sum of subcarriers results in noise like pulse.	Sum of subcarriers results in noise like pulse.	Subsequent GMSK pulses
Coding	Ramp slope or phase between ramps	Symbol coding	Symbol Coding	Direct Sequence Spread Spectrum
Time-frequency map				

OFDM: Orthogonal Frequency Division Multiplex, PMCW: phase modulated continuous wave, Tx: Transmitter, Rx: receiver, TFP: time frequency plane
Sinc: sin(πBt)/(πBt), GMSK: Gaussian Minimum Shift Keying, DSSS: direct sequence spread spectrum

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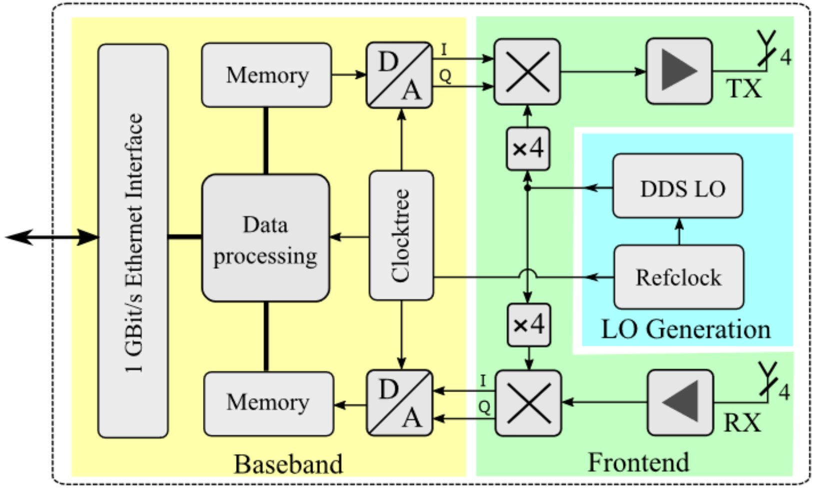
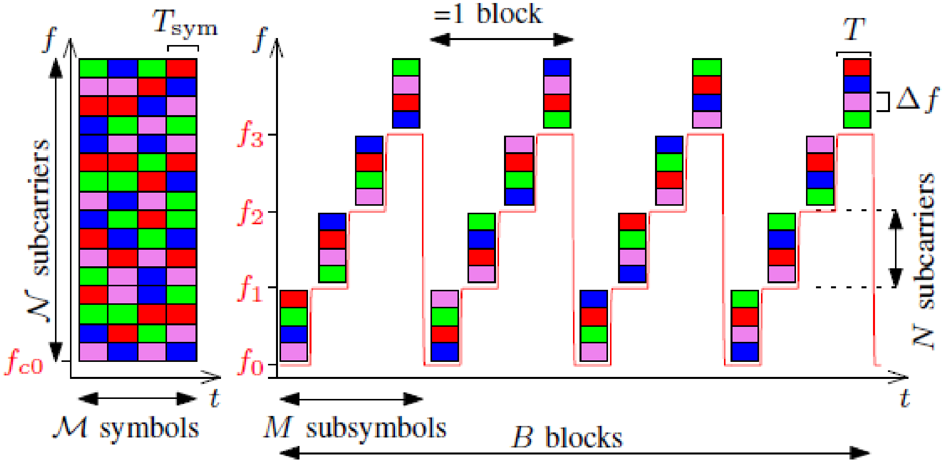
All Digital Radar Realization

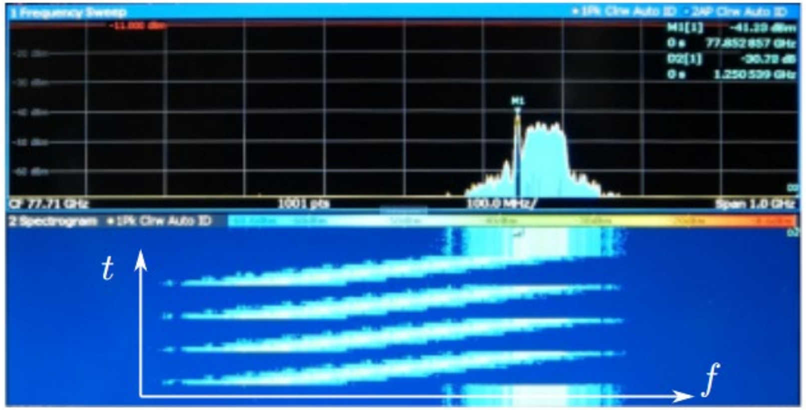
Demonstrator using stepped-OFDM modulation to verify performance and test new capabilities [15]



Block Diagram



Stepped frequency OFDM scheme



Fast LO frequency stepping

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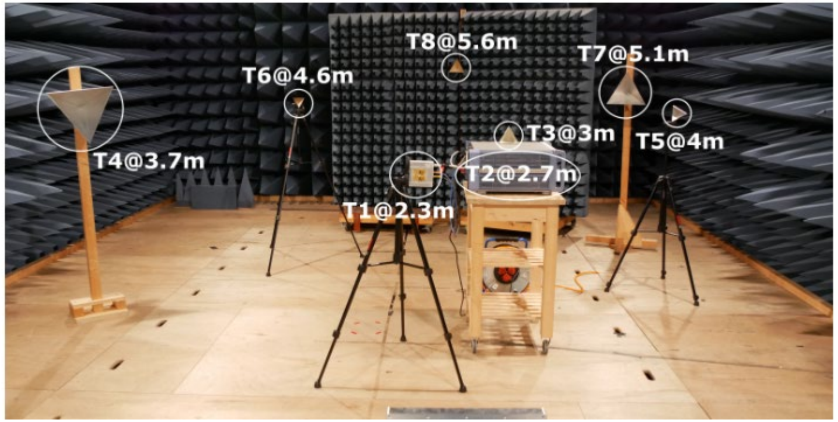
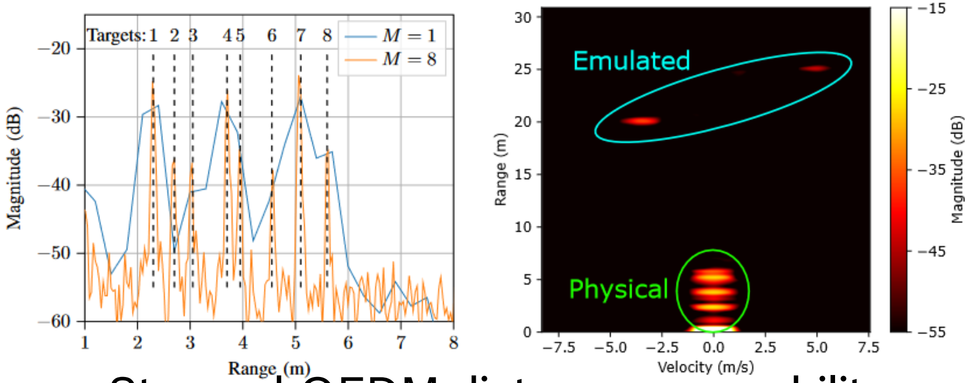
Millimeter Wave Sensing Technology
All Digital Radar Realization

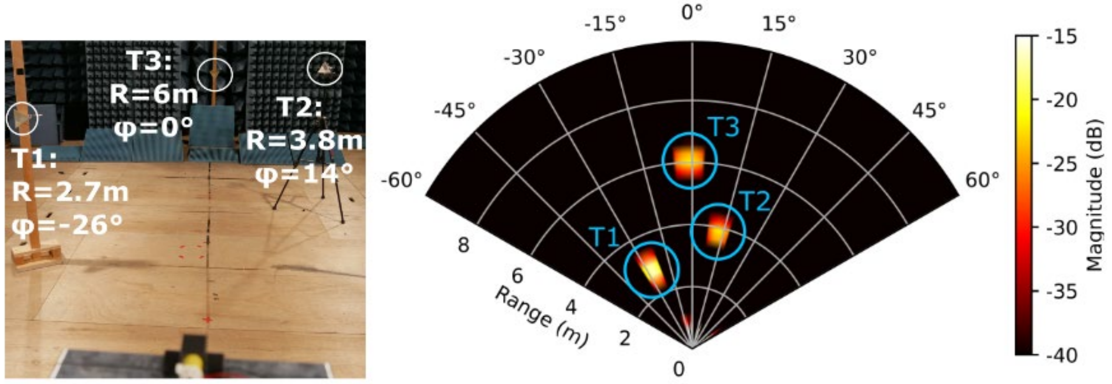
Parameter	Symbol	Config. 1	Config. 2
Initial carrier frequency	f_0	76.5 GHz	
Bandwidth per subsymbol	B_M	500 MHz	
Sampling rate	F_s	2 GS/s	
Number of subcarriers (total)	$\mathcal{N}$	1024	
Subcarrier spacing	Δf	488.28 kHz	
Block size	M	1	8
Number of blocks	B	256	32
Total RF bandwidth per block	B_T	500 MHz	4 GHz
Range resolution	ΔR	30 cm	3.75 cm
Unambiguous Range	R_ua	307 m	
Velocity resolution	Δv	±0.38 m/s	
Unambiguous velocity	v_ua	±98 m/s	±12.25 m/s

Modulation parameters





Stepped OFDM distance separability



4x4 MIMO angle estimation

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Interference

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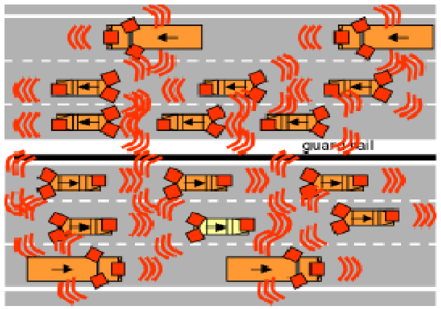
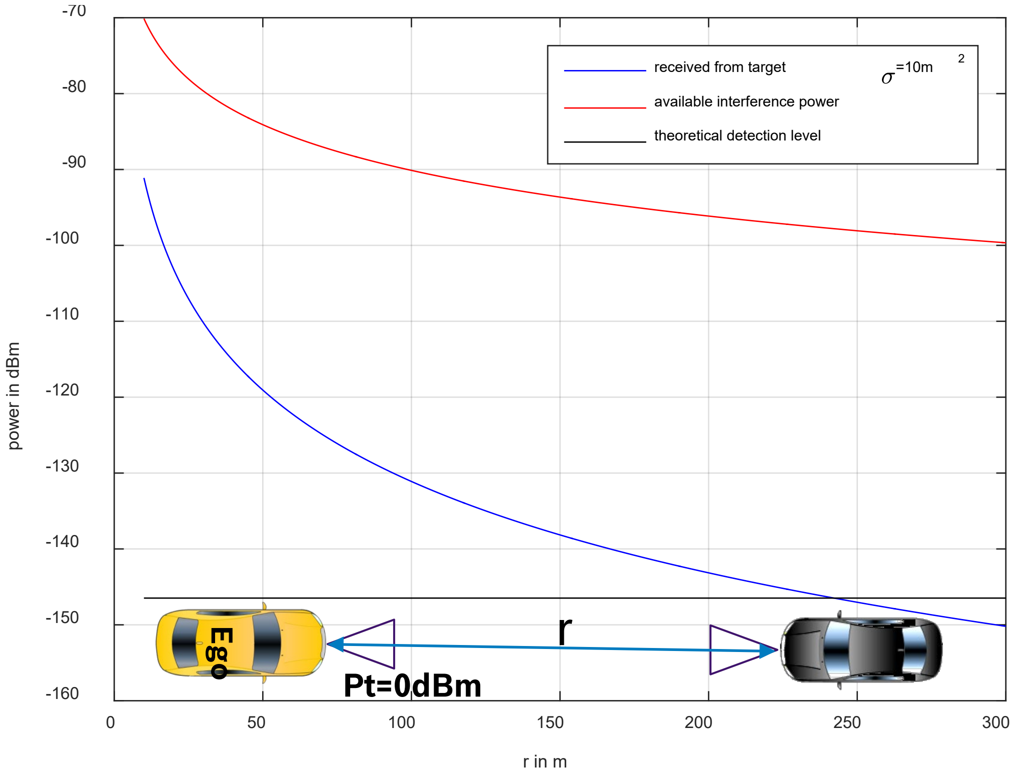
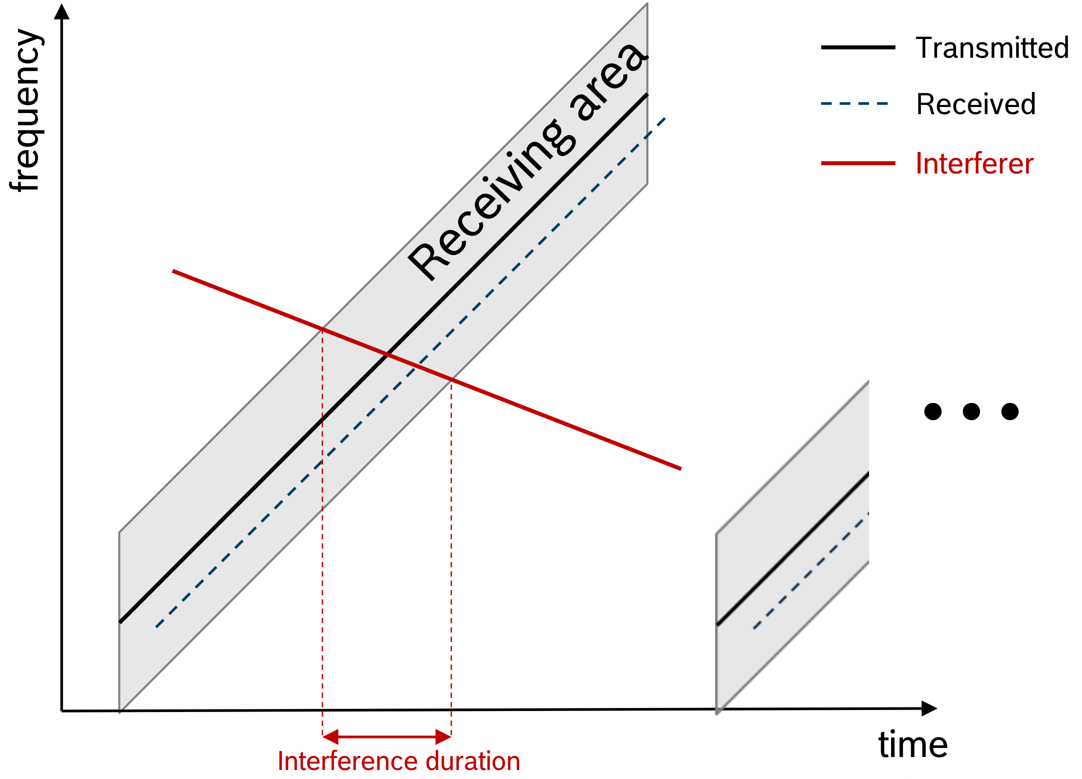
Interference



- Received interference signal can be much larger than reflected signal
- Interference susceptance is **proportional to radar performance** (bandwidth, sensitivity, measurement duration)





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Modified from Tom Schipper, Modellbasierte Analyse des Interferenzverhaltens von Kfz-Radaren, Dissertation, KIT, 2017.

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Interference Mitigation Approaches

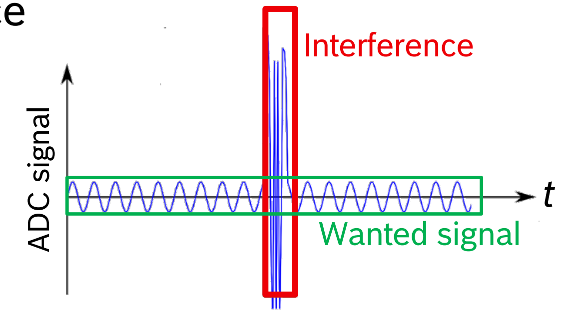
Numerous approaches have been investigated in [9]:

Increasing cooperation

	Cooperation	Method	Implementation Effort (0=low ... 5=high)	Benefit (I/N-Improvement) (0 low ... 5 high)
State of the Art	none	Manufacturer individual random method	0.2	0.2
	none	Detect and Repair*)	2.2	3.0 for the case of less interferer
IMIKO-Mitigation Methods	weak	Manufacturer common random method	1.8	1.4
	weak	Compass Method	2.7	3.2
	weak	Analyze before Measure	3.7	2.7
	weak	Random Timing	1.7	1.7
	weak	immediate Chirp Interruption	3.7	1.3
	medium strong	Heuristic Avoidance Method based on CPM	3.7	2.7
	medium strong	Cognitive Radar with Communication Capability	4.7	3.0
	medium strong	Radar Network with Central Server	4.5	3.2
	strong	Modified Radar Mac / Central Control	4.5	3.5

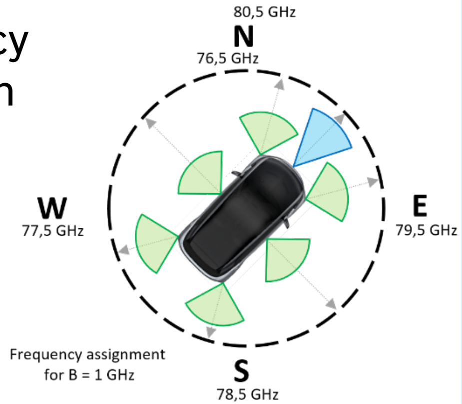
Detect and Repair

- **Detect** interference
- **Repair** distortion in raw data



Weak Cooperation: Compass Method

- **Change** center frequency dependent on orientation
- **Reduce** impact



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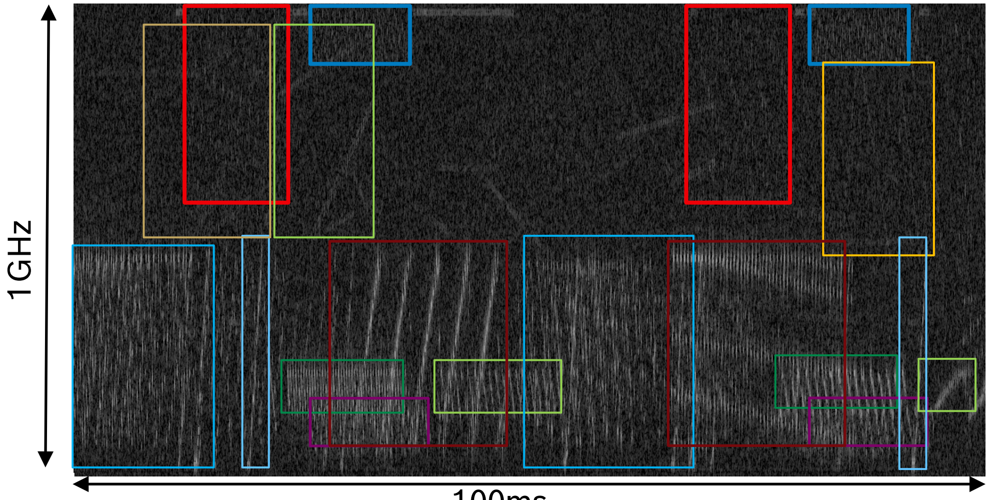
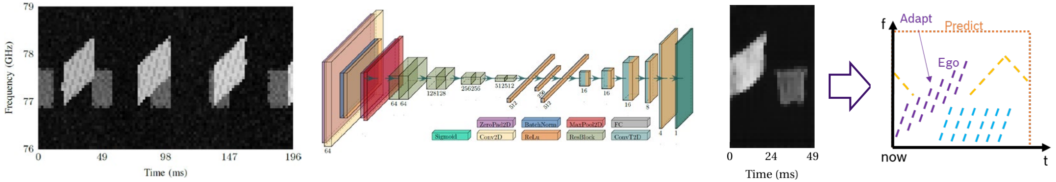
Interference Mitigation using Cognitive Radar

1. Detect and classify Radar signals
2. Predict spectrum occupation
3. Adapt modulation



RF Spectrum



Efficiently measure spectrum

Trained the CNN network

Online predicted spectrum

Adaption of Modulation

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Beyond Automotive
&
Higher Frequencies

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Millimeter Wave Sensing Technology
Additional Applications for the 77 GHz Band ?

Possible new applications [17]:

- Drones
  - Avoid obstacles during flight
  - Autonomous landing systems
  - Inspection flights (power lines, railway tracks)
- Fixed Radar
  - Airport security, port and harbor
  - Foreign object debris on airport runways
  - Incursion monitoring
- Wildlife detection, wide area monitoring

However:

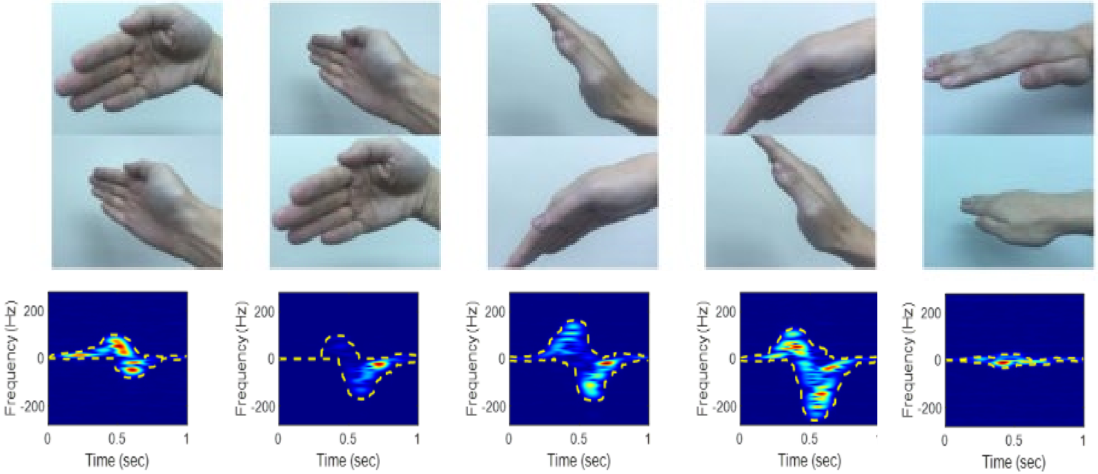
- Regulation is still being discussed
- Sharing issues (interference)!

Millimeter Wave Sensing Technology
Consumer Applications

Millimeter-sensing enables small privacy-preserving devices with excellent movement detection. Typical applications discussed are:

- Gesture Sensing and presence detection for games and smart home
- Health monitoring like respiratory and heart rate or fall detection

60 GHz band is a good candidate, however unclear status in China!



Gesture detection [19]

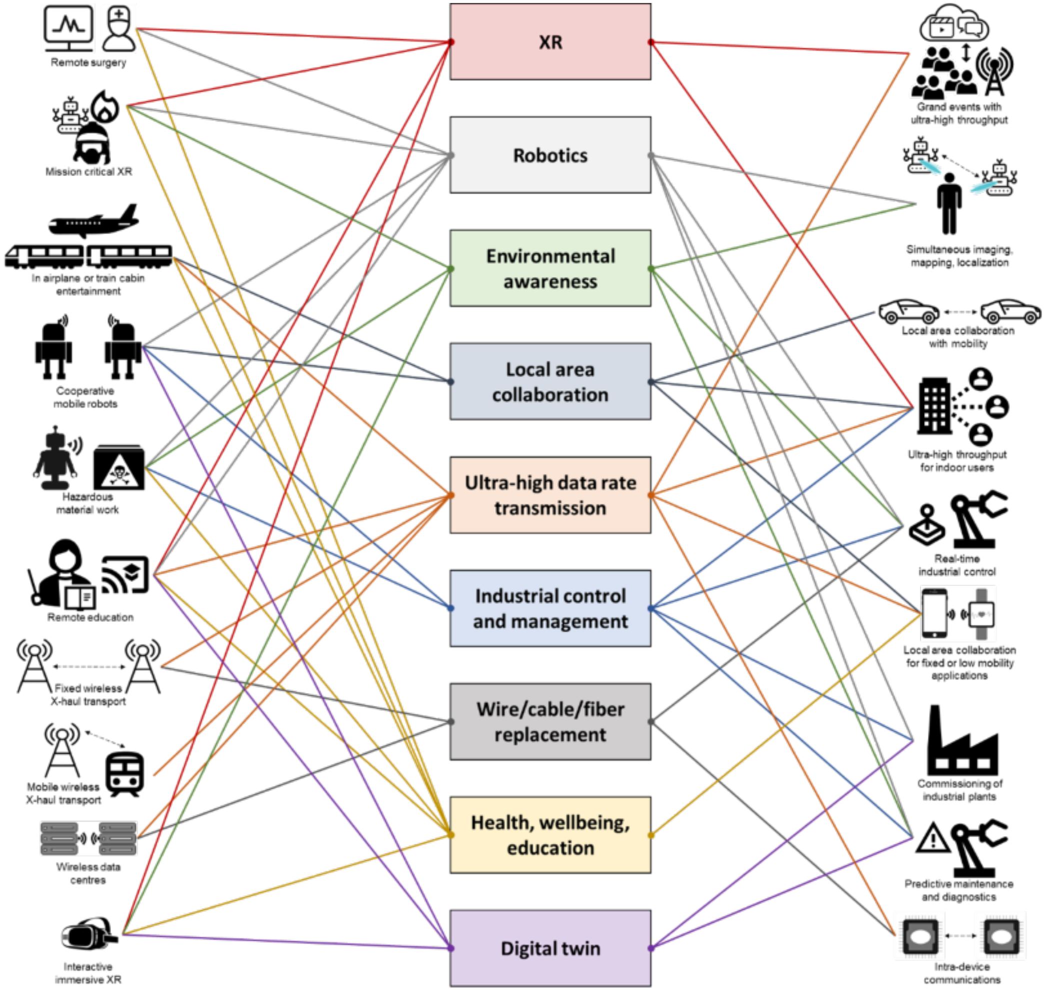
China (2006-2019.12)	59-64 GHz	Unlicensed
China 2019.12-	Suspended	Suspended
EU	57-~~71~~64 GHz	Unlicensed
US	57-71 GHz	Unlicensed
South Korea	57-66 GHz	Unlicensed
Japan	57-66 GHz	Unlicensed
Australia	57-71 GHz	Unlicensed

60 GHz band frequency regulation status

Millimeter Wave Sensing Technology
Applications beyond 100 GHz

- Large amount of bandwidth available in THz bands for high data rates
- Unlock new features such as accurate sensing and imaging capabilities.
- New functionalities not supported by previous communication systems
  (accurate sensing, mapping, and localization)

(ETSI THz Group [16]: Establishing the technical foundation for the development and standardization of THz communications)



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Millimeter Wave Sensing Technology
Performance above 100 GHz

- Motivation
  - „Untainted“ frequency spectrum
  - Better range, angle velocity and angle information
- Range separability

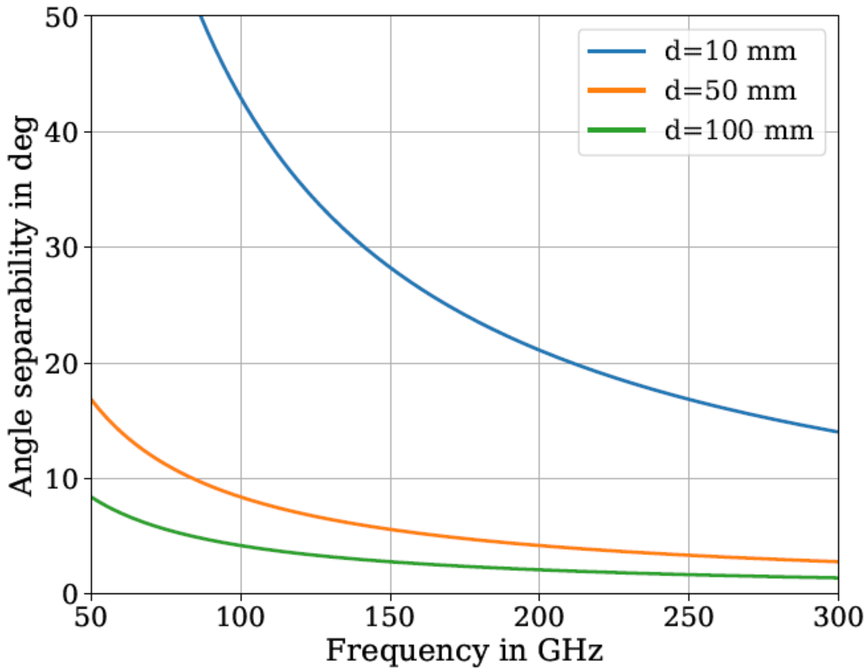
$$\Delta r = \frac{c_0}{2 \cdot BW}$$

- Velocity separability

$$\Delta v = \frac{\lambda}{2 \cdot T_{\mathrm{meas}}}$$

- Angle separability

$$\Theta_{\min} = \arcsin\left(\frac{1.22\lambda}{d}\right)$$



Bandwidth	100 MHz	1 GHz	10 GHz	100 GHz
Separability	1.5 m	15 cm	1.5 cm	1.5 mm
Rel. bandwidth at 150 GHz	0.06%	0.6%	6%	66%

Frequency	50 GHz	77 GHz	100 GHz	200 GHz	300 GHz
Separability	15 m/s	0.1 m/s	0.075 m/s	0.0375 m/s,	0.025 m/s

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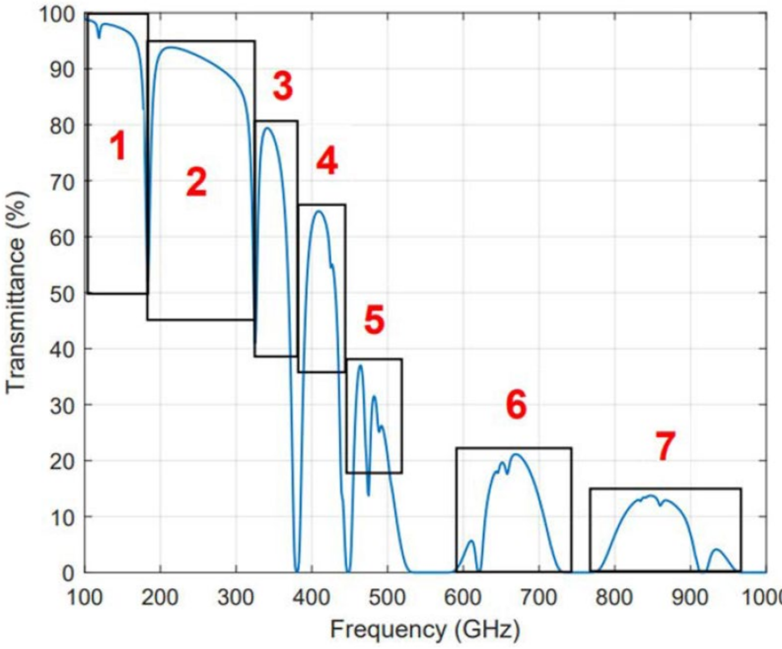
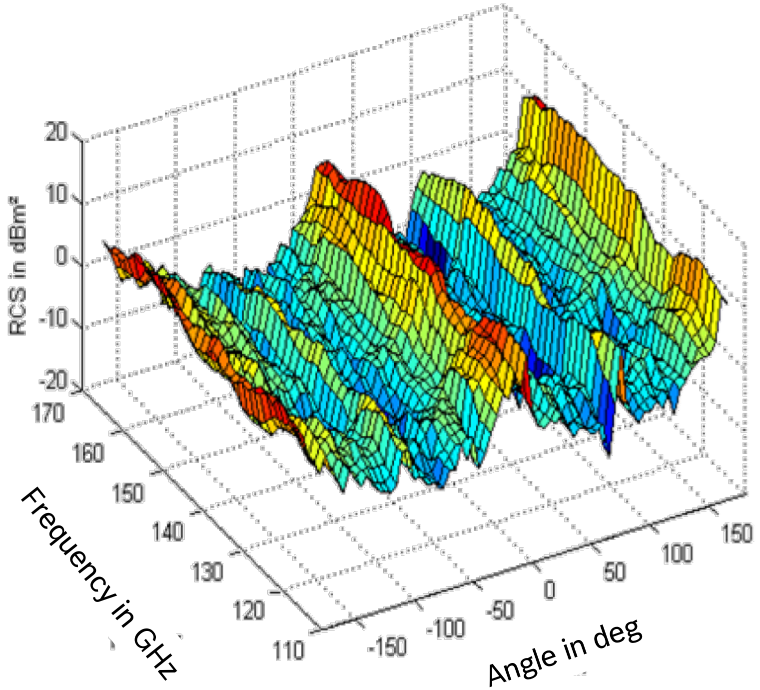
Millimeter Wave Sensing Technology
Wave Propagation above 100 GHz

- Long range sensing >> 100 m more difficult above 170 GHz
- For shorter ranges this is less of an issue
- RCS does not change much for many objects



[16]



Measured RCS of a Motorbike [6]

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Millimeter Wave Sensing Technology
Frequency Regulation

- It‘s a long road to success:
  - No really „free“ spectrum available
  - Different regulations between EU, US, China, Japan…
  - Rising interest in frequencies > 100 GHz for radar, sensing and comm.
- Ongoing activities:
  - ITU: WRC-27(RES 663 WRC-2019 [8]):
    - New allocations for radiolocation service at 231.5-275 GHz
    - New radiolocation service applications at 275-700 GHz
  - ETSI:
    - Studies for automotive radar above 100 GHz ongoing in ERM-TGUWG
    - THz working group https://www.etsi.org/committee/2124-thz

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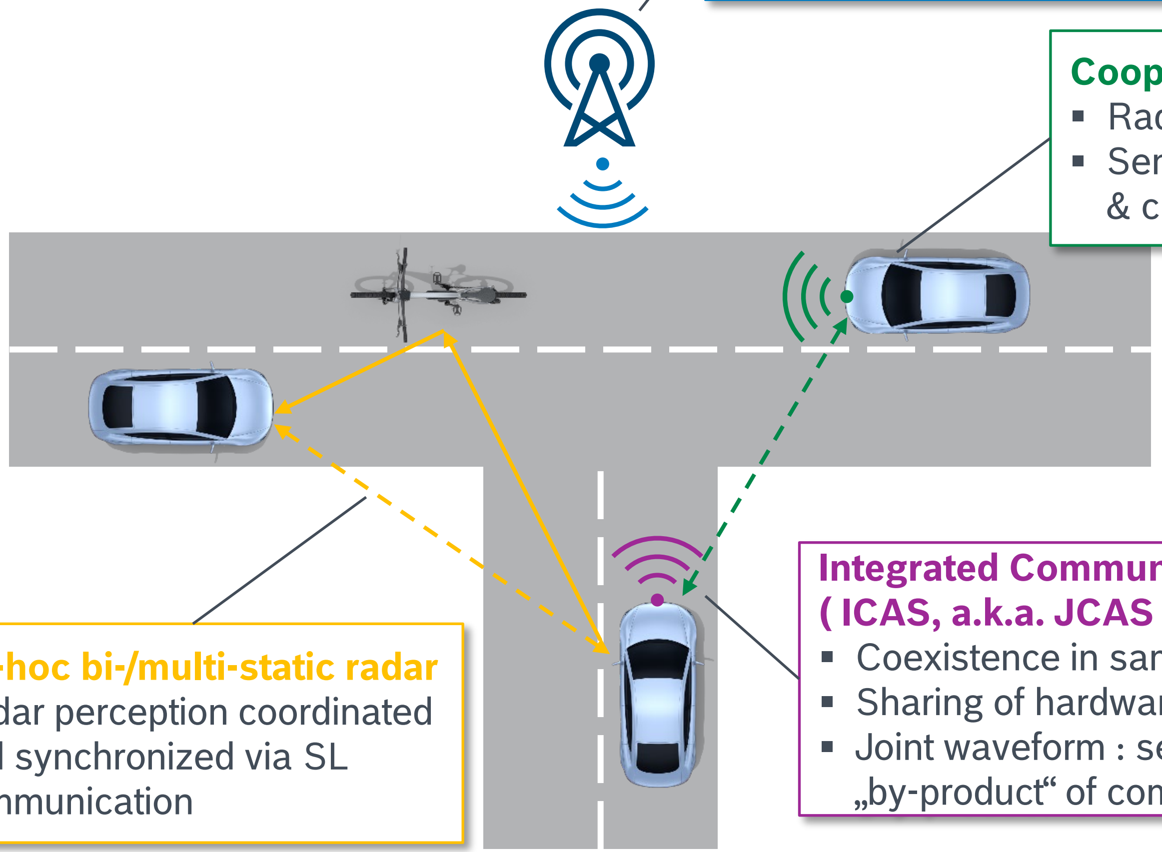
Millimeter Wave Sensing Technology
Joint Communication and Sensing

6G Infrastructure-based sensing (RSU, base station)
Sensing assisted communication (e.g., beam forming)

Today (4G/5G)
- Dedicated radar sensors
- Dedicated radar frequency bands
- Mono-static radar only

With 6G
- Bi-static and cooperative radar
- Radar–assisted communication
- Full convergence



Cooperative radar
- Radar data sharing
- Sensor fusion for object detection & classification

Ad-hoc bi-/multi-static radar
Radar perception coordinated and synchronized via SL communication

Integrated Communication and Sensing (ICAS, a.k.a. JCAS or ISAC)
- Coexistence in same frequency band
- Sharing of hardware resources
- Joint waveform : sensing as a „by-product“ of communication

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Millimeter Wave Sensing Technology
Conclusion

- Automotive Radar market still growing strongly
- Differentiation between “standard” and “imaging” radar for driver assistance and increasing automation
- Many roads lead to higher performance:
  - More Channels
  - Digital Radar
  - Radar Networks
  - Super-Resolution
- Radar interference cannot be ignored, but can be solved
- Push to higher frequencies for radar feasible for shorter ranges, worldwide frequency regulation is slow!
- Consumer applications coming
- 6G will redefine infrastructure-based sensing

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THANK YOU

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