

WSI-1

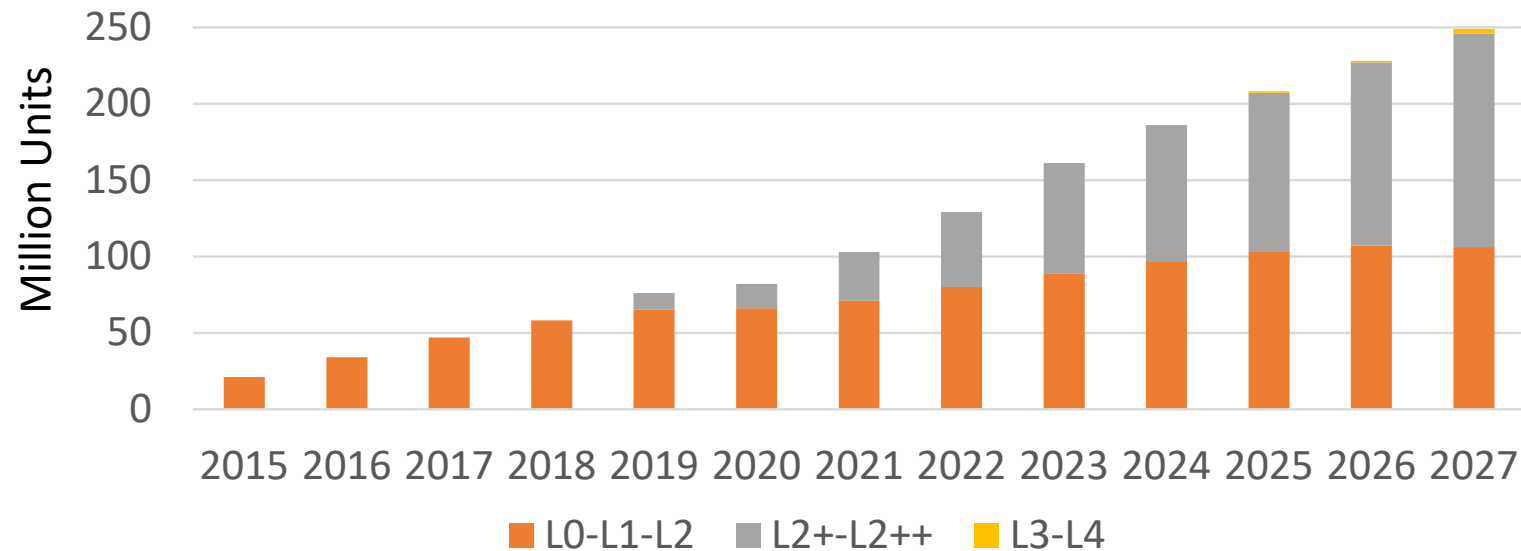
Automotive Radar Applications and Technology Trends

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- Automotive Radar
- Radar Categories
- Antennas
- Digital Radar
- Radar Interference
- Higher Frequencies
- Conclusion

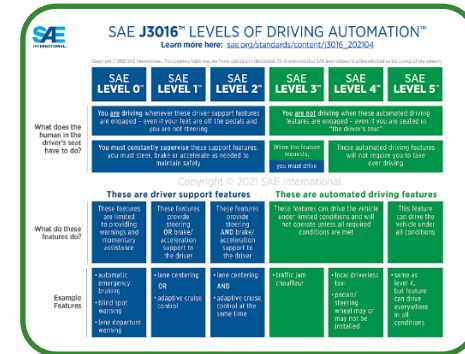
- Expected to reach 10B \$USD in 2025
- Vast majority of volume is in “traditional” driver assistance systems L0...L2 and enhanced driver assistance L2+...L2++

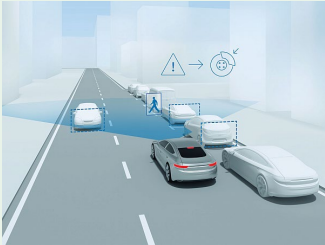
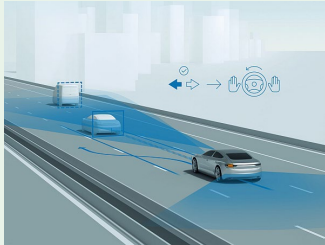


Source: Yole Development

Automation Levels

- SAE J3016 definition is not fitting well anymore
- “Unofficial” additional levels L2+, L2++
- Definition of driver involvement is 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				

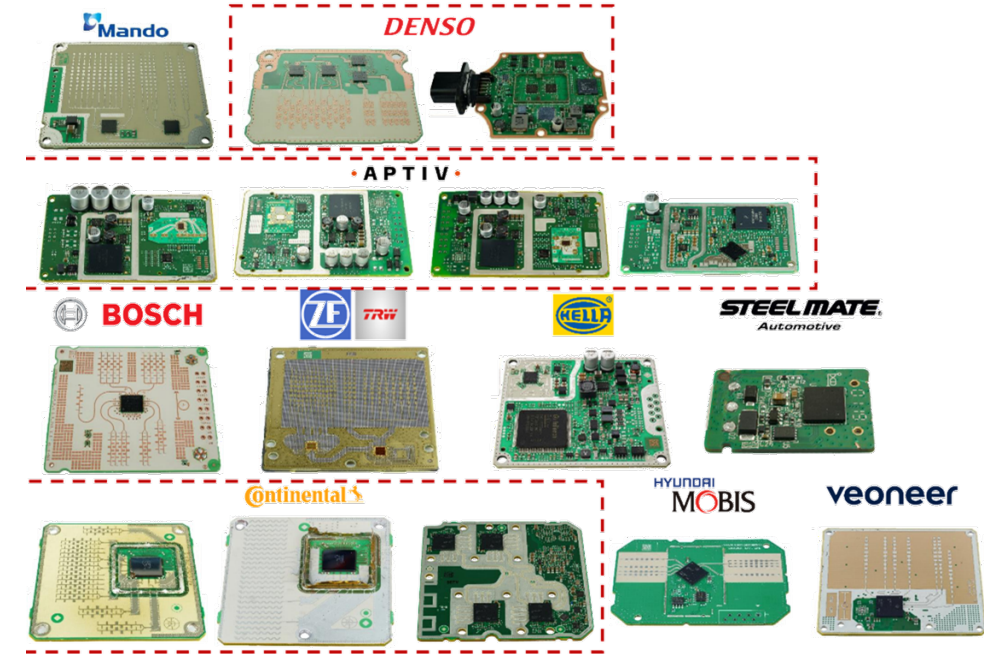
Main technical differentiator is angle resolution

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

Based on publications and Yole reports

Standard Radars

- Mass market, high volume
- High cost pressure
- Dominated by established players
- Typical setup
 - Single chip frontend
 - Application processor
 - Single PCB
 - PCB antenna



Source: Systemplus

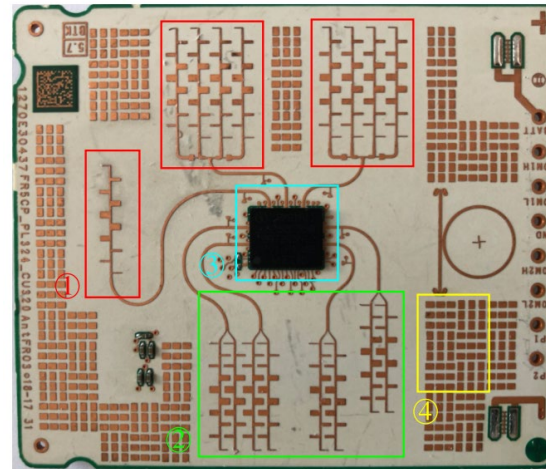
Standard Radars: Example

- Bosch Gen5 Front Radar
- 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



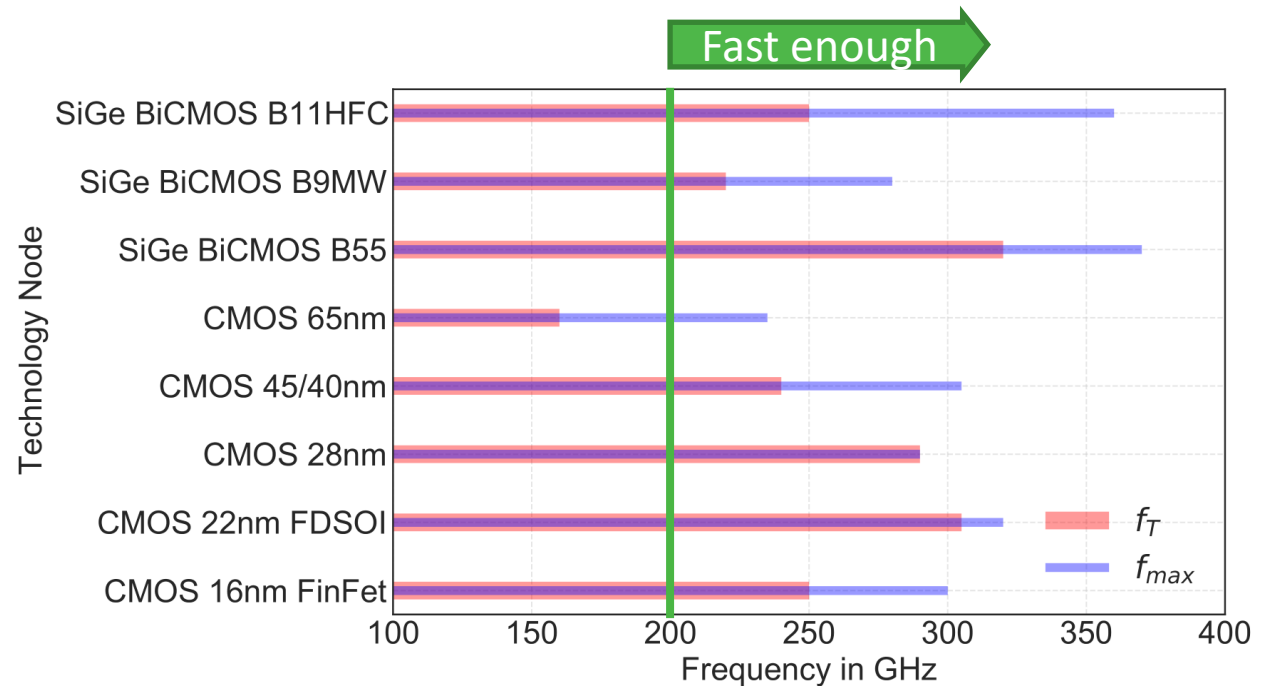
Frontside



Backside

For reference see [1]

- Small is cheap:
Save money by reducing # of components and size
- Exploit technological progress: Higher integration density
- Modern CMOS technology nodes and higher volumes allow realization as System on Chip (SoC).

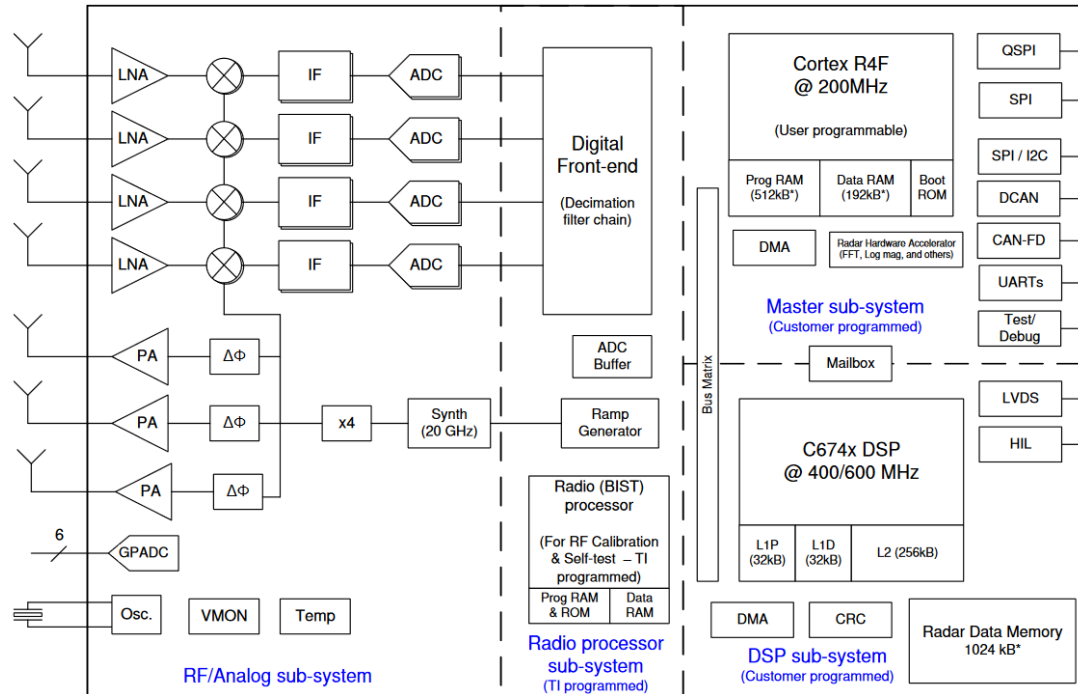


Radar SoCs: Example

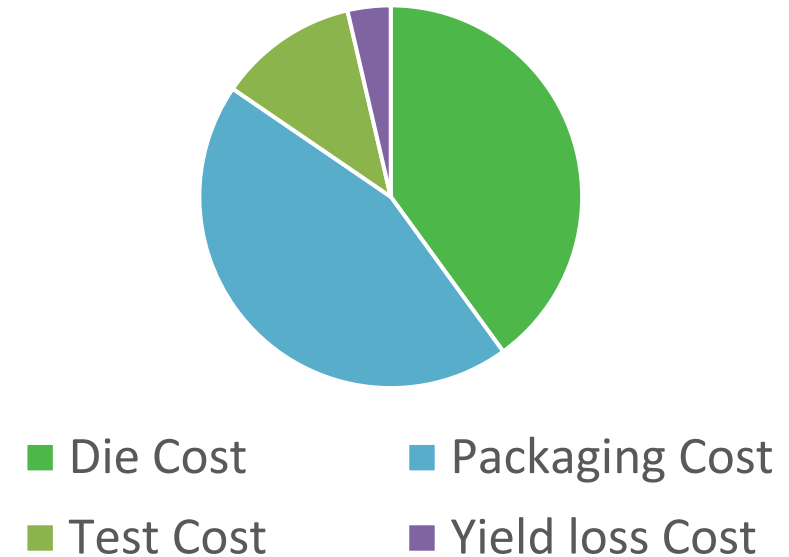
- Example: Texas Instruments
- 45nm CMOS Technology System-on-Chip
- Estimated chip cost $\approx$ 5 US\$ (not sales price!)



Size: 15x15mm



Chip Cost

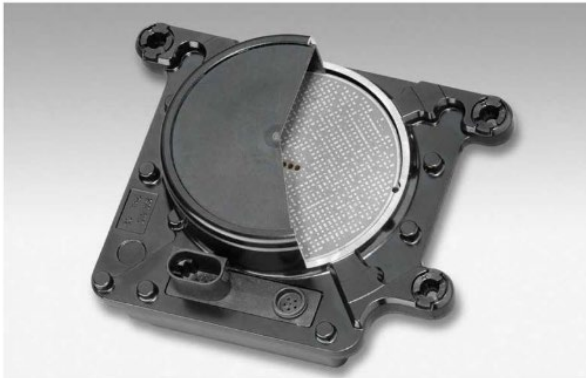
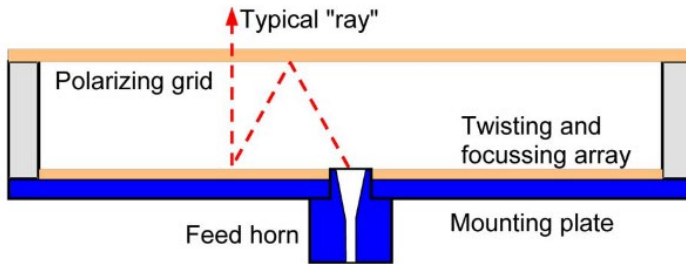


Sources: Texas Instruments, SystemPlus, IC Knowledge

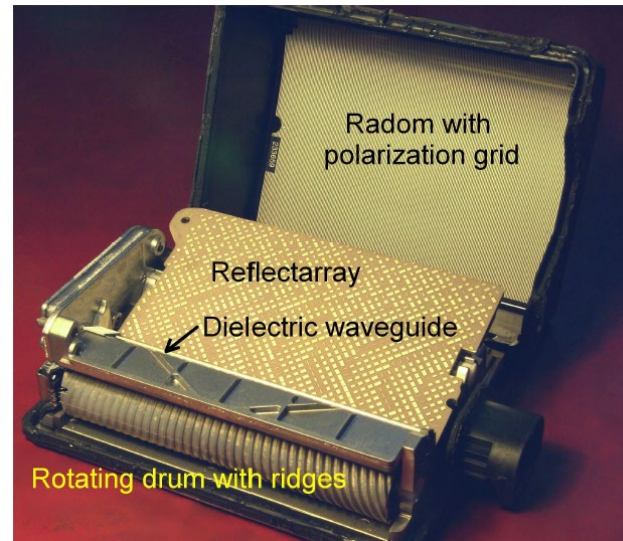
Antenna Technology

- The antenna system is a key component of any radar
- Let's look at three generations of antenna systems:
 - Quasi-optical antennas
 - Microstrip antennas
 - Waveguide antennas

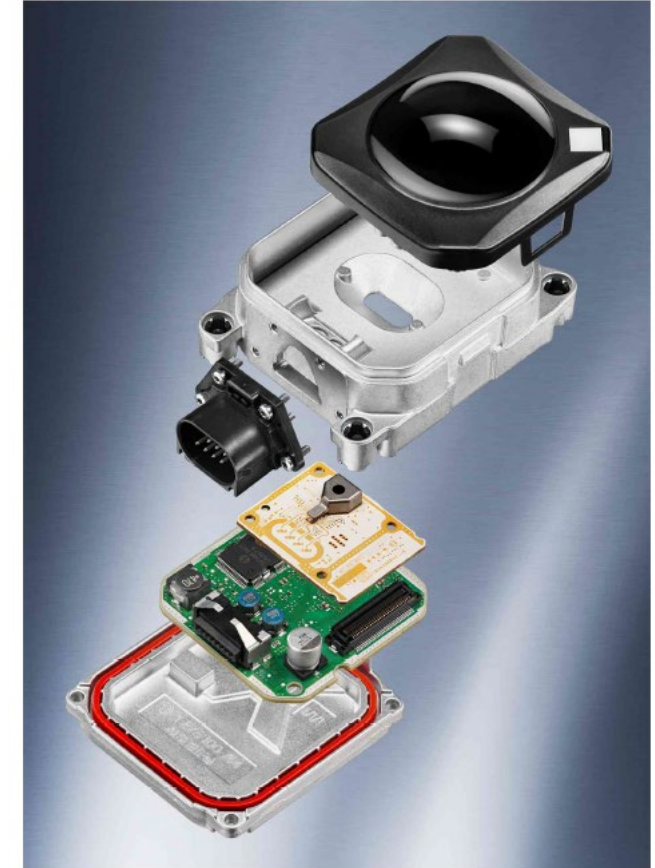
- Used in early radar generations
- Provide high gain at narrow FoV or require mechanical steering



Folded reflector antenna [2]

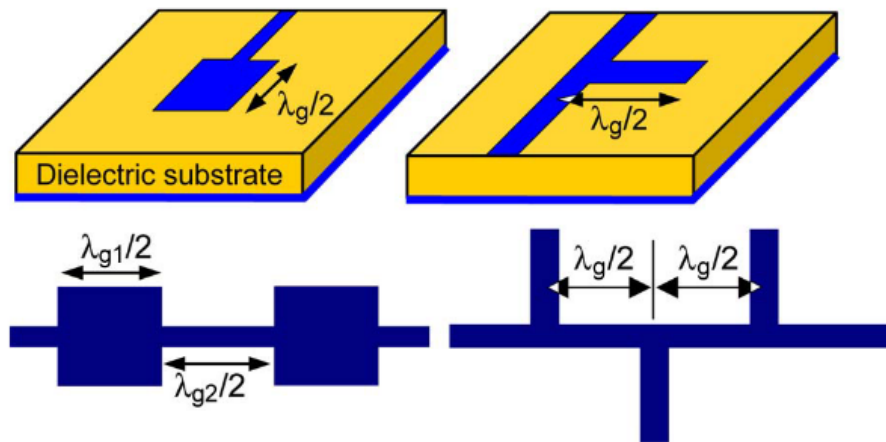


Rotating drum reflector antenna [1]

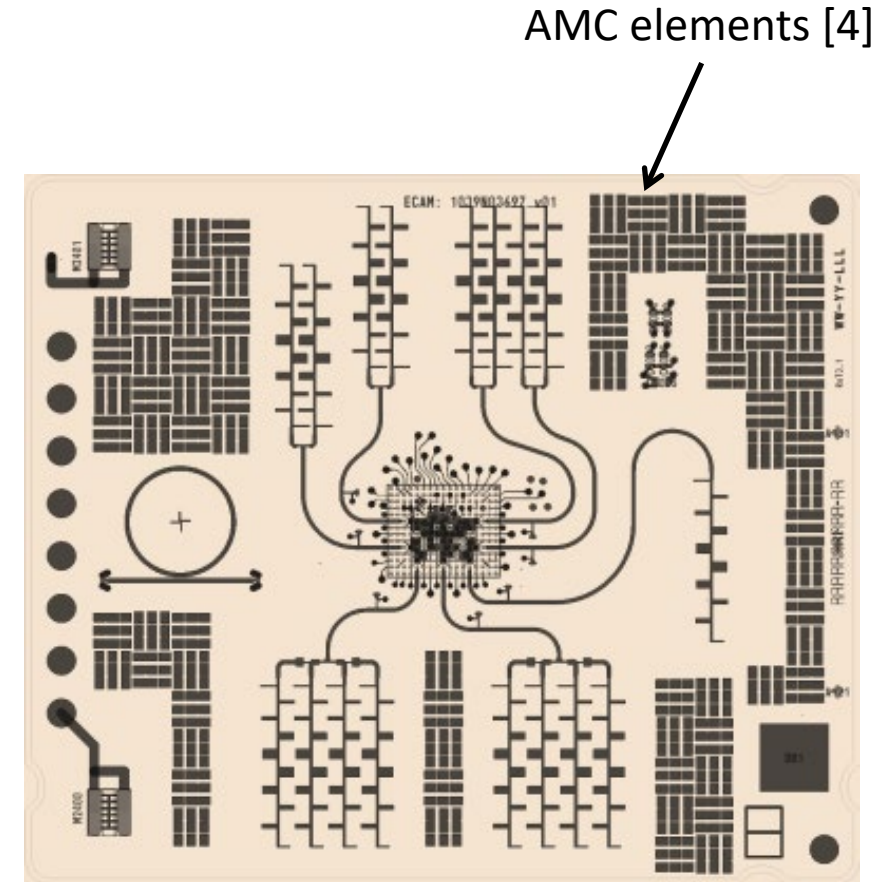


Dielectric lens antenna [1]

- Move to standard PCB technology:
Enabler of volume scaling to
- Flexibility in gain, Field-of-View
- Higher losses compared to
quasi-optical antennas

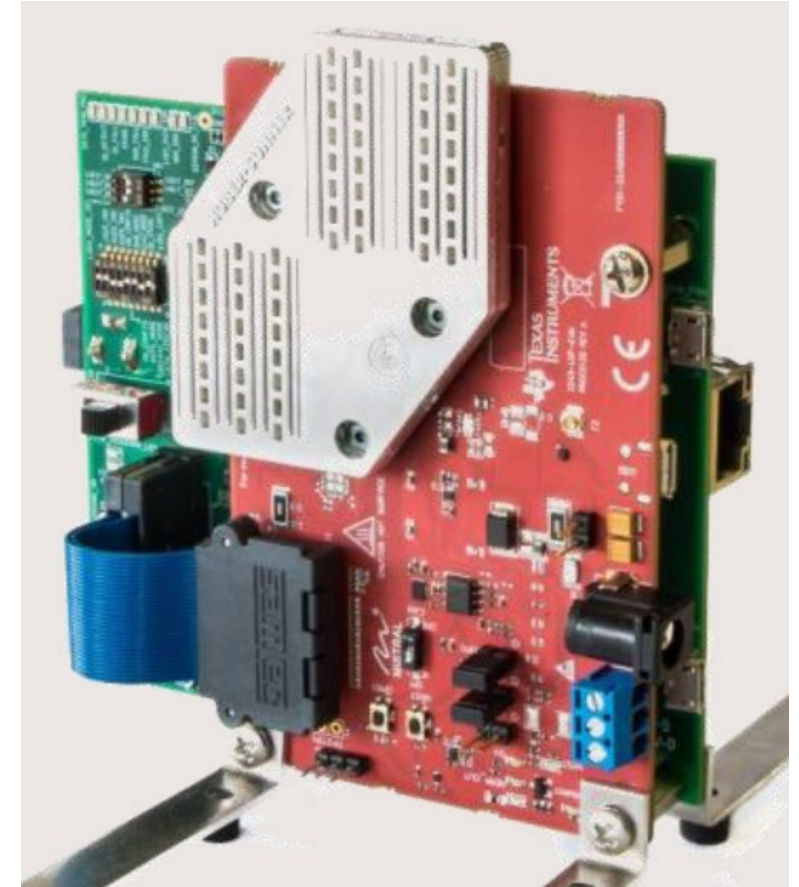


Microstrip antenna elements [2]



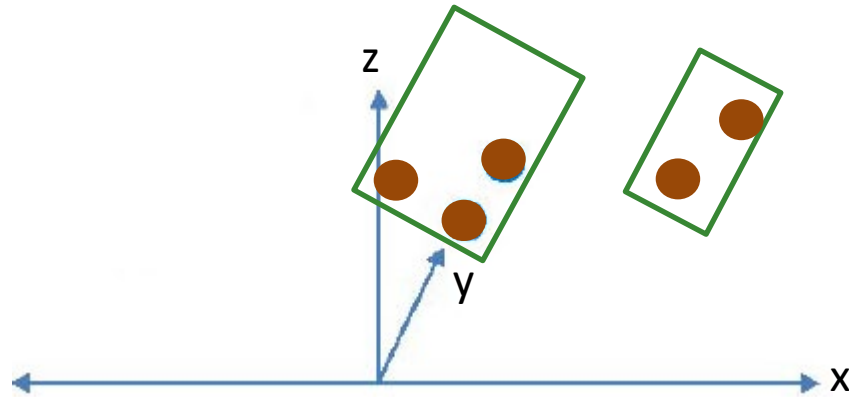
Example: Bosch Gen5 Radar

- Improved performance requirements needed new antennas
- Improved radiation pattern
- Significantly lower losses
- Downsides:
 - Higher complexity
 - Transition from IC package or PCB to waveguide
 - $\lambda/2$ spacing difficult



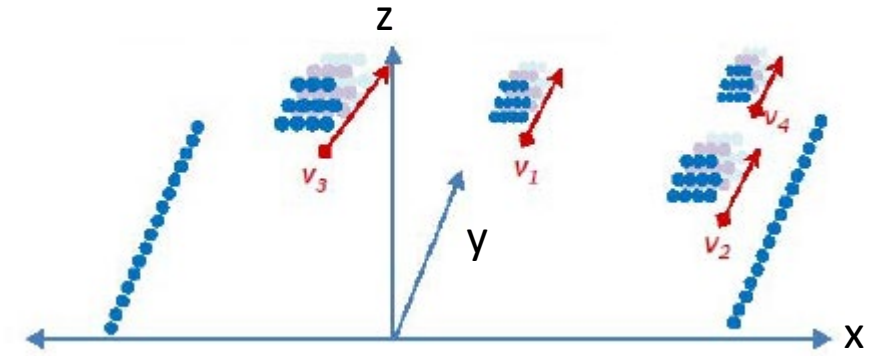
Example: Huber&Suhner, Automotive Forum 2022

Standard Radar



- Only tens to a few hundred reflexes
- Optimized for a certain use-case
- Only basic classification

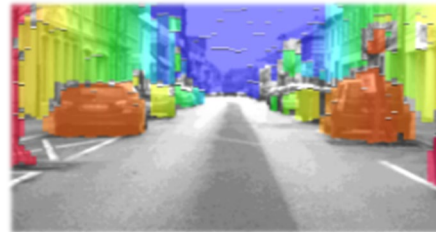
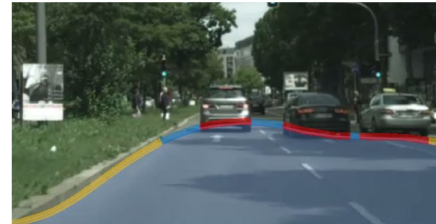
Imaging Radar



- Thousands of reflexes creating high-resolution Radar “images”
- Enables dependable object classification
- Video-like update rates

Video sensor capabilities

- Street lane detection
- Free space estimation
- Reconstruction and Segmentation
- Traffic light detection, road signs
- Object Detection and Classification
(e.g. vehicles, persons)

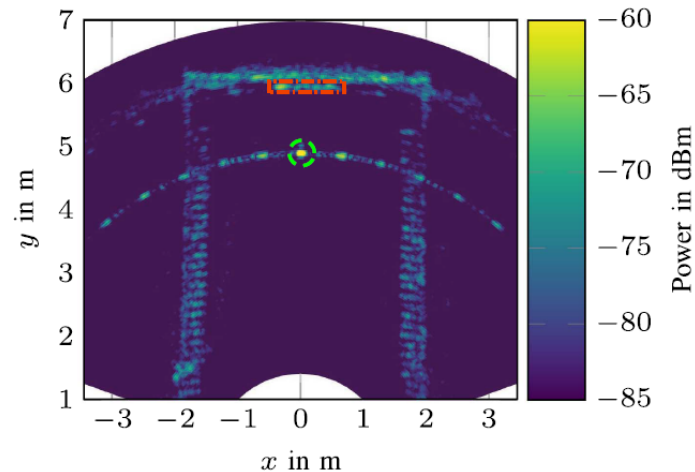
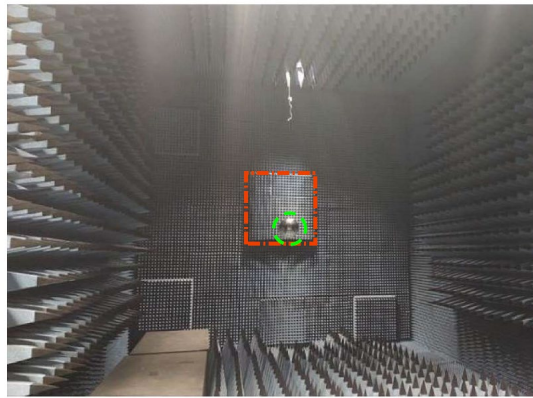


Feasible using Imaging Radar ?



University of Ulm [5]

- 36 transmitters
- 48 receivers
- $0.78^\circ \times 3.6^\circ$ in azimuth and elevation



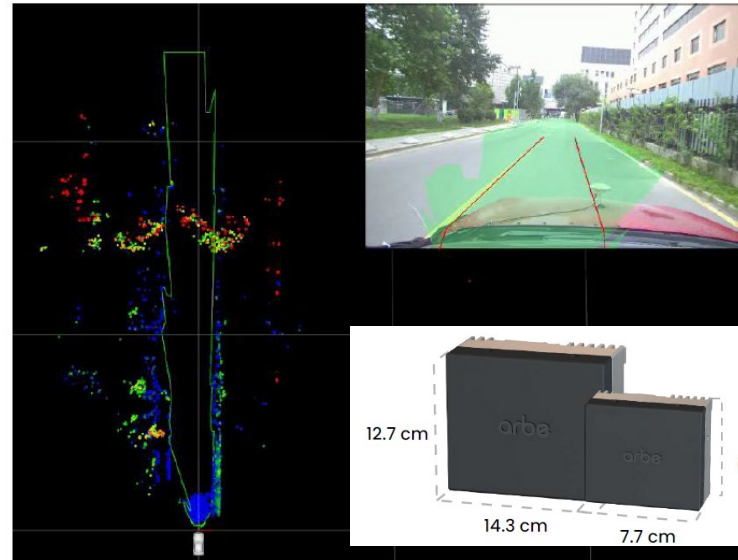
Arbe

Phoenix Perception Radar
48 x 48 RF Channels

1° Azimuth Resolution*
1.7° Elevation Resolution*
350m Long Range
100° Wide Field of View
2,304 Virtual channels

Lynx Imaging Radar
24 x 12 RF Channels

2.5° Azimuth Resolution*
6.4° Elevation Resolution*
300m Long Range
140° Wide Field of View
288 Virtual Channels



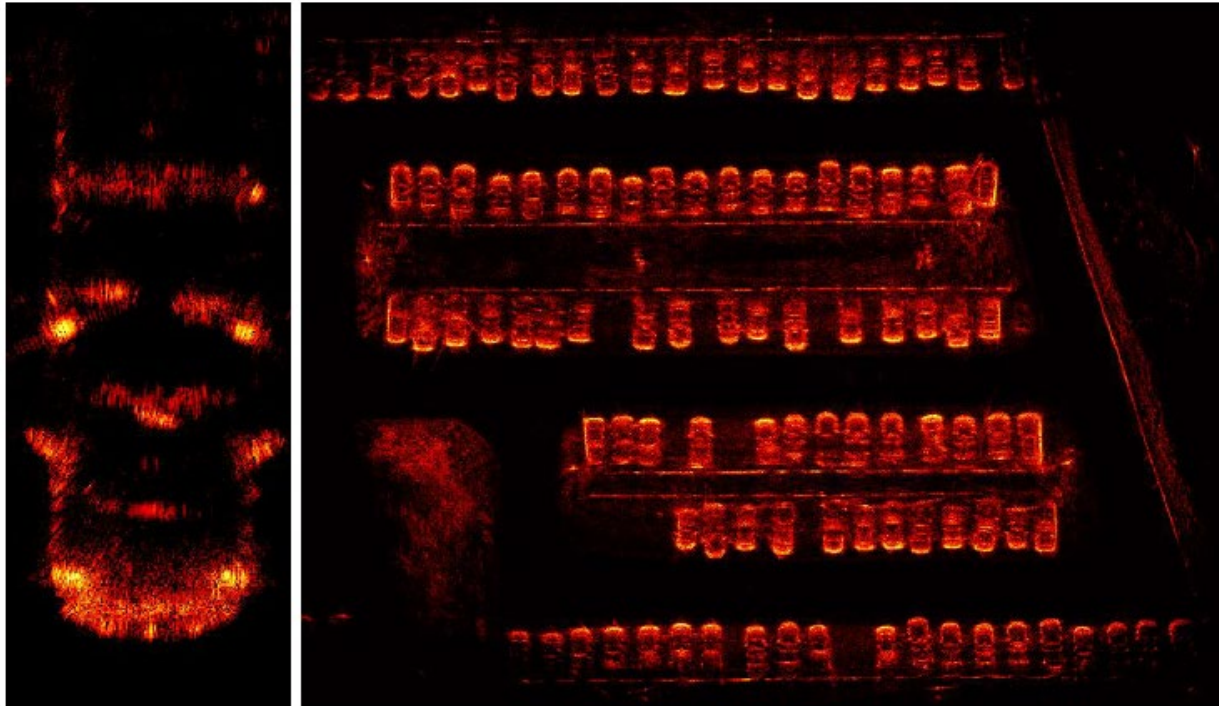
Uhnder

- 12 transmitters
- 16 receivers
- 2 GHz modulation bandwidth

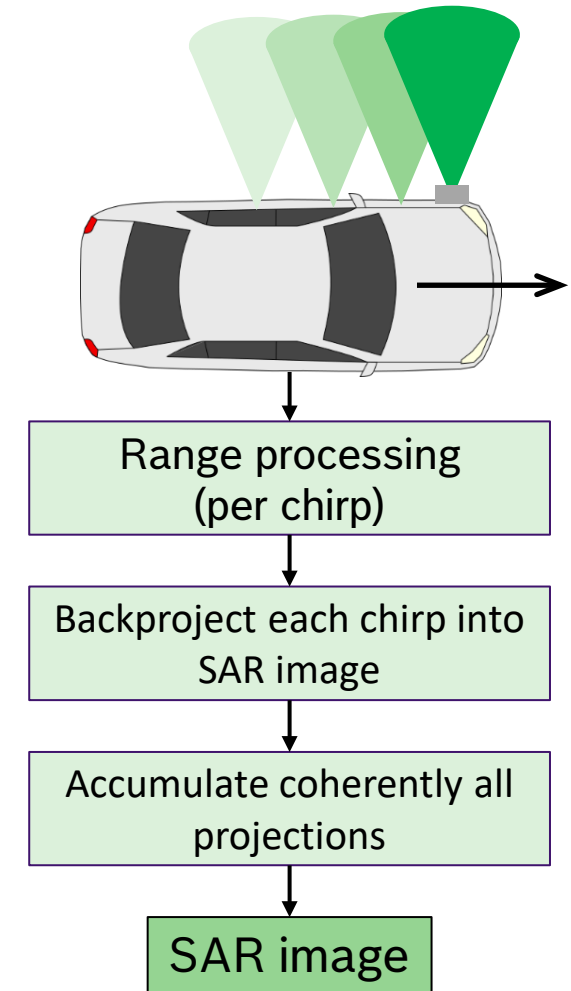


Synthetic Aperture Radar

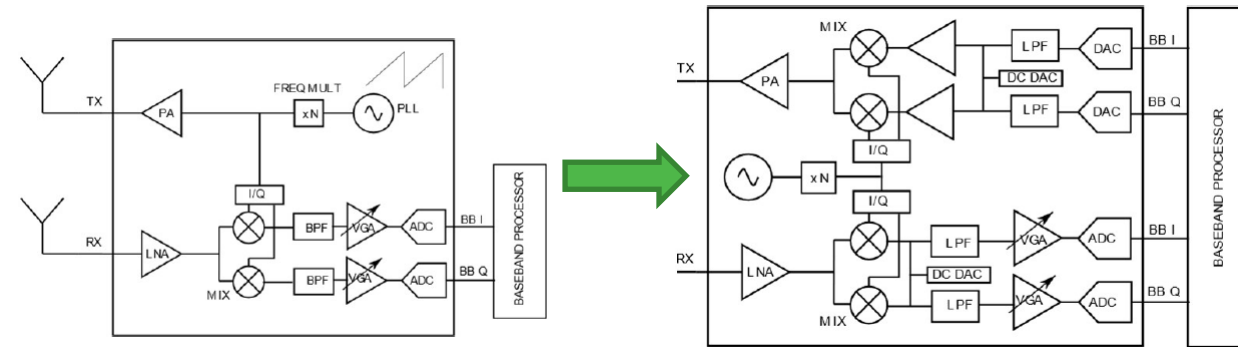
- Integrating over several measurements to create a large virtual aperture



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



- + 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



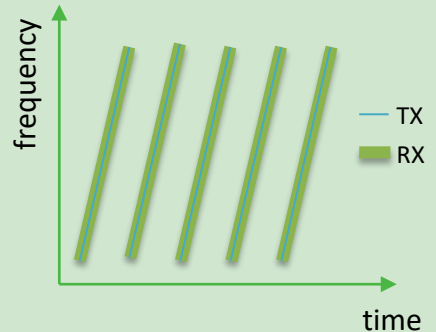
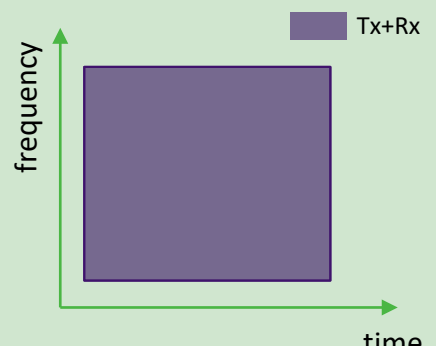
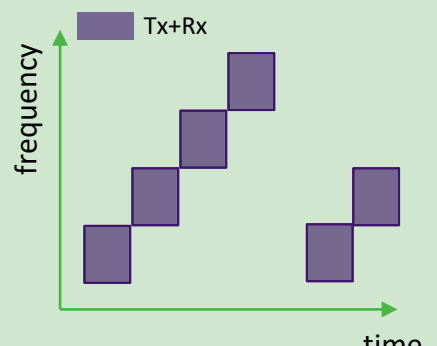
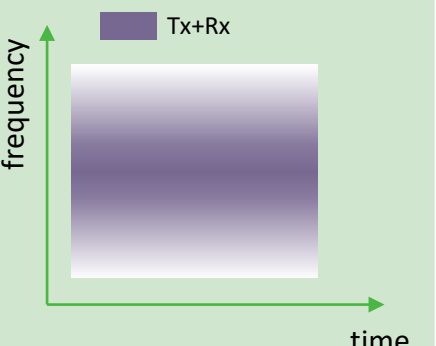
From Analog to Digital Radar [10]

- KPI improvements
- higher implementation costs
- more stringent requirements on analog frontend (linearity, efficiency)
- faster ADCs and DACs required

wisdom of mankind

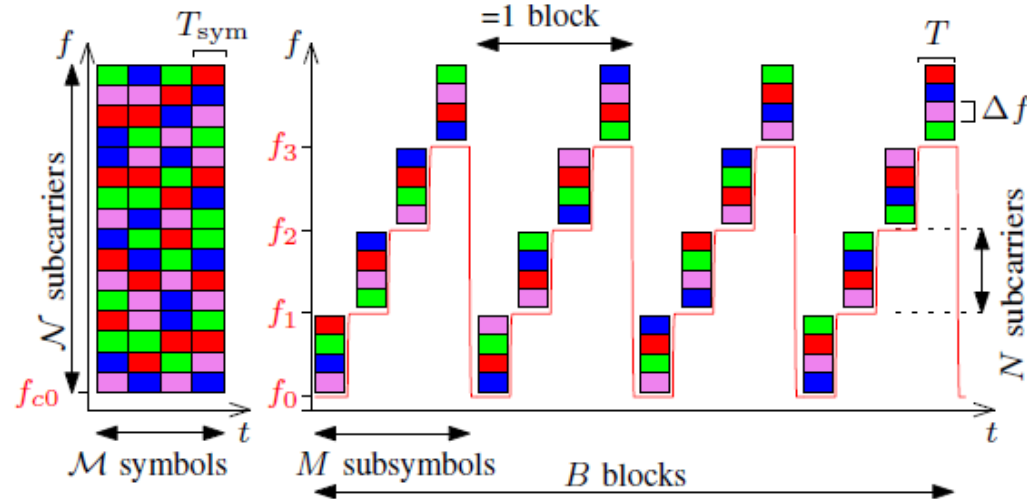
the known knowns the available knowledge for our daily work	the known unknowns the knowledge that could boost our daily work
the unknown knowns our white spots where we have organizational blindness	the unknown unknowns further improvement potential we don't see at all

Spectrum occupied by different modulations

Modulation	Chirp Sequence	OFDM	Stepped OFDM	PMCW
Bandwidth	$B_{BB} = 500\text{kHz} \cdots \underline{10\text{MHz}} \cdots 100\text{MHz}$	$B_{BB} = 50\text{MHz} \cdots \underline{500\text{MHz}} \cdots 1\text{GHz}$	$B_{BB} = 25\text{MHz} \cdots \underline{125\text{MHz}} \cdots 250\text{MHz}$	$B_{BB} = 50\text{MHz} \cdots \underline{500\text{MHz}} \cdots >1\text{GHz}$
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: $\sin(\pi Bt)/(\pi Bt)$, GMSK: Gaussian Minimum Shift Keying, DSSS: direct sequence spread spectrum

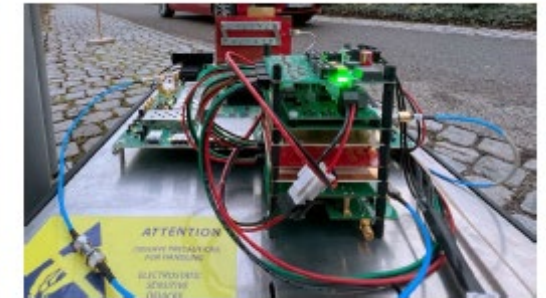
RFSoc-based all digital Radar prototype*



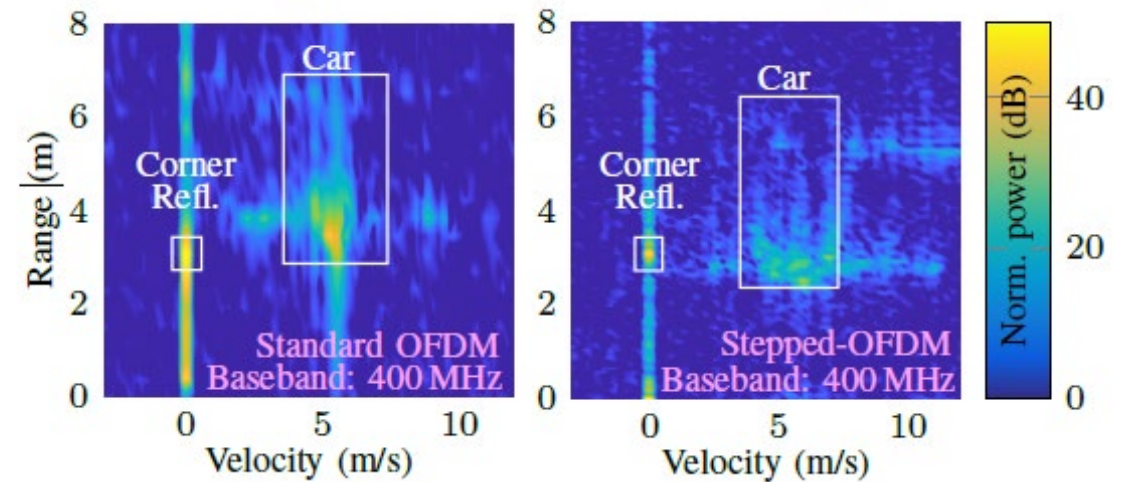
Parameter		Conf. C1	Conf. C2	Conf. C3	Conf. C4
Subsymbols / Steps	M	1	4	1	4
Subcarriers	N	512	500	2000	2000
Subcarrier spacing	Δf	200 kHz	200 kHz	200 kHz	200 kHz
Baseband bandwidth	W	102 MHz	100 MHz	400 MHz	400 MHz
RF bandwidth	$\mathcal{W}$	102 MHz	400 MHz	400 MHz	1600 MHz
Range resolution	ΔR	1.46 m	0.37 m	0.37 m	0.09 m
Velocity resolution	Δv	± 0.16 m/s	± 0.16 m/s	± 0.16 m/s	± 0.16 m/s
Velocity resolution	Δv	± 0.16 m/s	± 0.16 m/s	± 0.16 m/s	± 0.16 m/s
Unambiguous vel.	v_{ua}	± 162.1 m/s	± 40.5 m/s	± 162.1 m/s	± 40.5 m/s



(a)



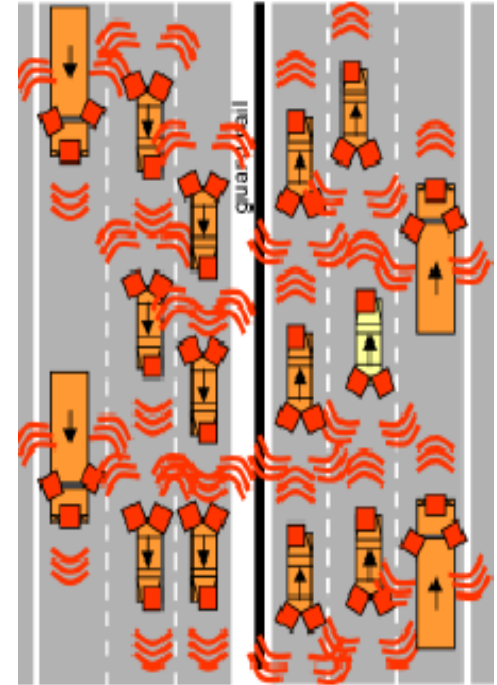
(b)



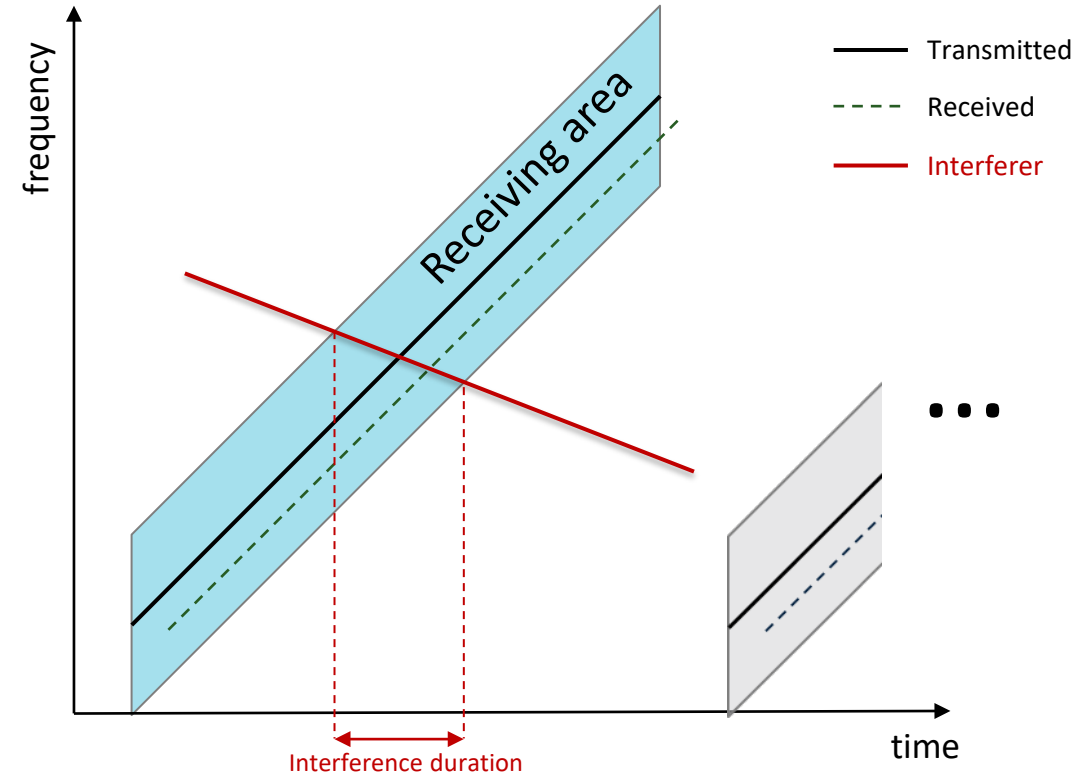
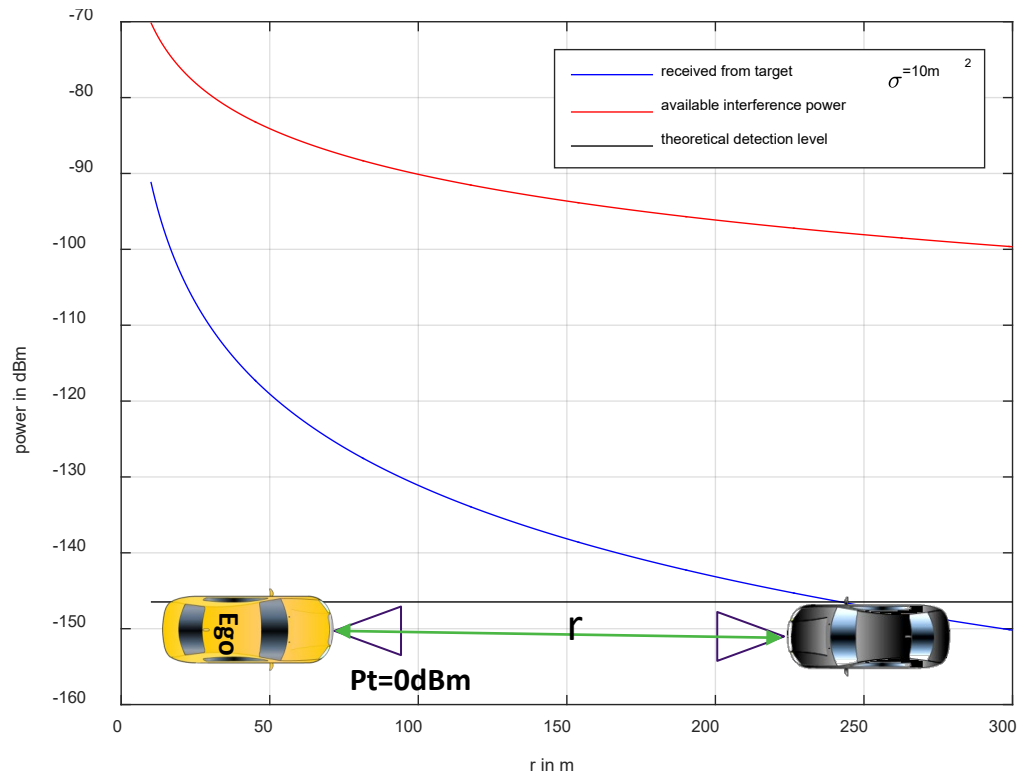
*University of Ulm [9]

Radar Interference

- Uncoordinated transmissions from radars may lead to mutual interference
- With the increasing number of radars deployed and improving radar performance, proper operation needs to be ensured



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



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

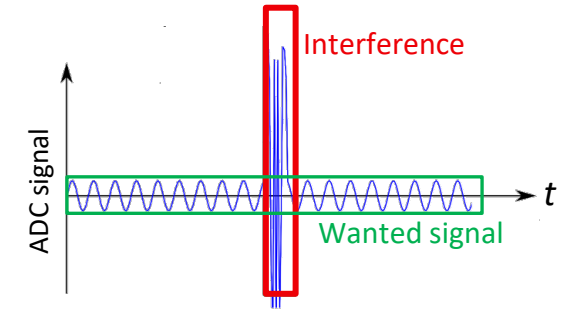
Numerous approaches can be taken [9]:

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

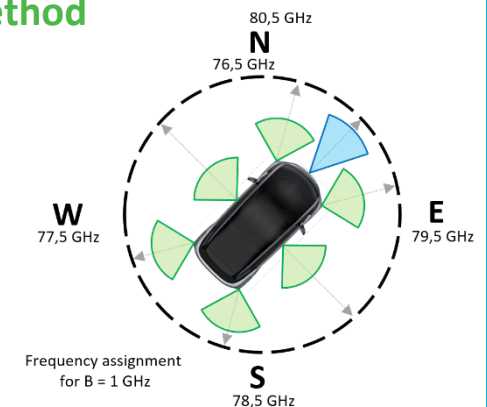
Detect and Repair

- Detect interference
- Repair distortion in raw data



Weak Cooperation: Compass Method

- Change center frequency dependent on orientation
- Reduce impact



^{*)} Detect&Repair represents a respective manufacturer-proprietary signal processing measure

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

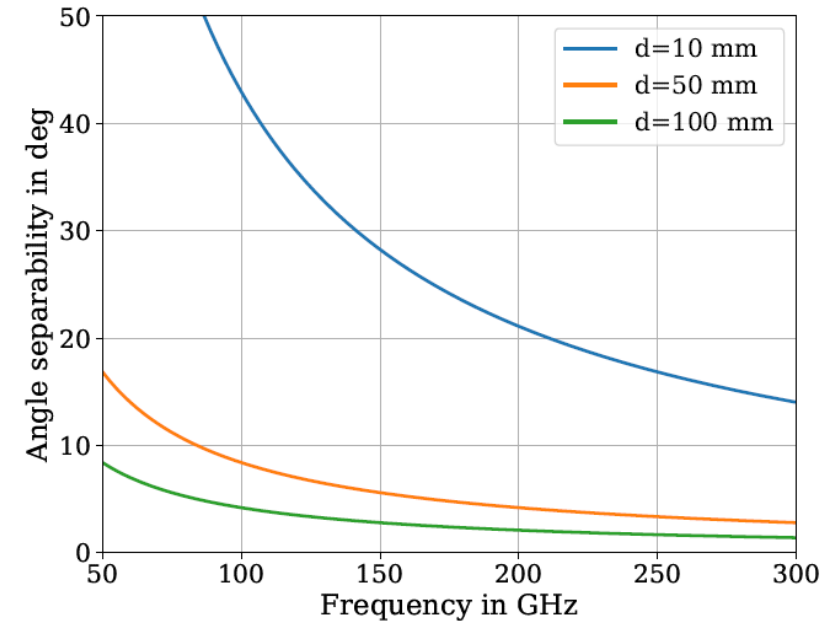
$$\Delta r = \frac{c_0}{2 \cdot BW}$$

- Velocity separability

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

- Angle separability

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

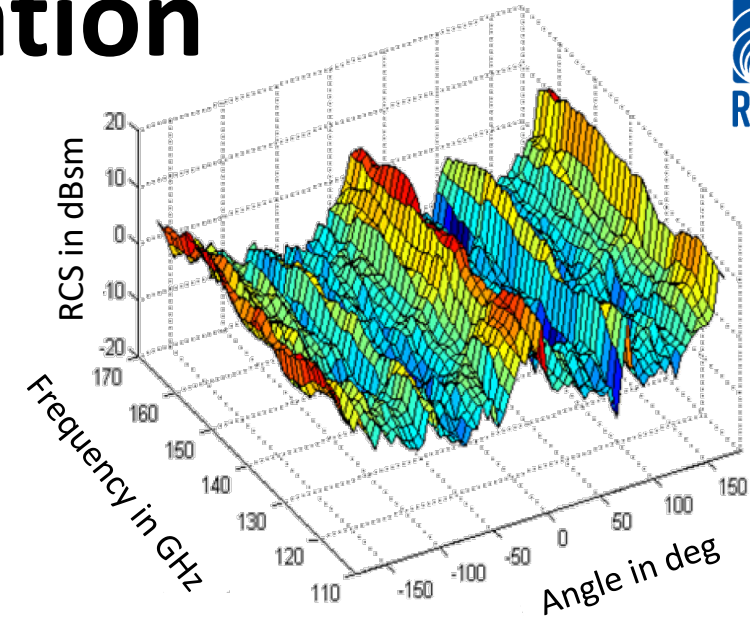


Bandwidth	100 MHz	1 GHz	10 GHz	100 GHz
Separability	1.5 m	15 cm	1.5 cm	1.5 mm
Rel. bandwidth at 150 GHz	0.06%	0.6%	6%	66%

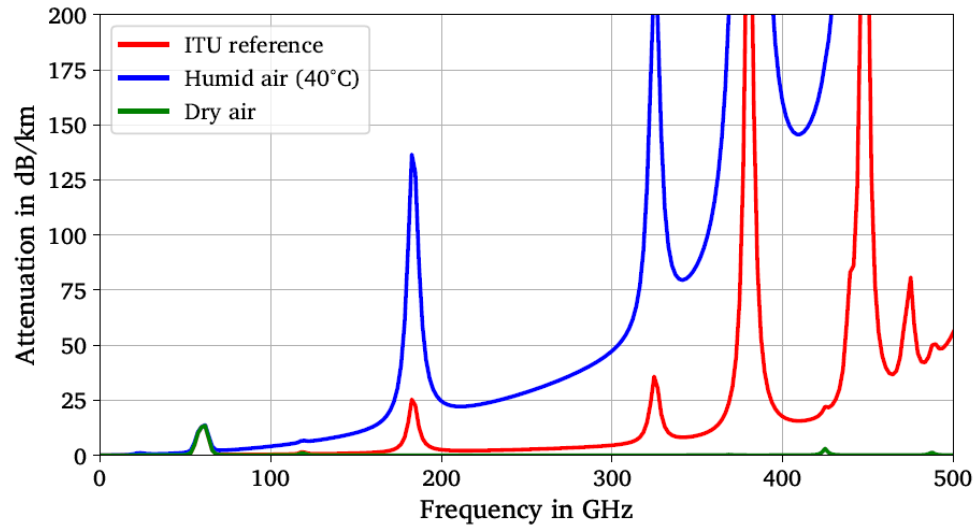
Frequency	50 GHz	77 GHz	100 GHz	200 GHz	300 GHz
Separability	15 m/s	0.1 m/s	0.075 m/s	0.0375 m/s	0.025 m/s

Wave Propagation

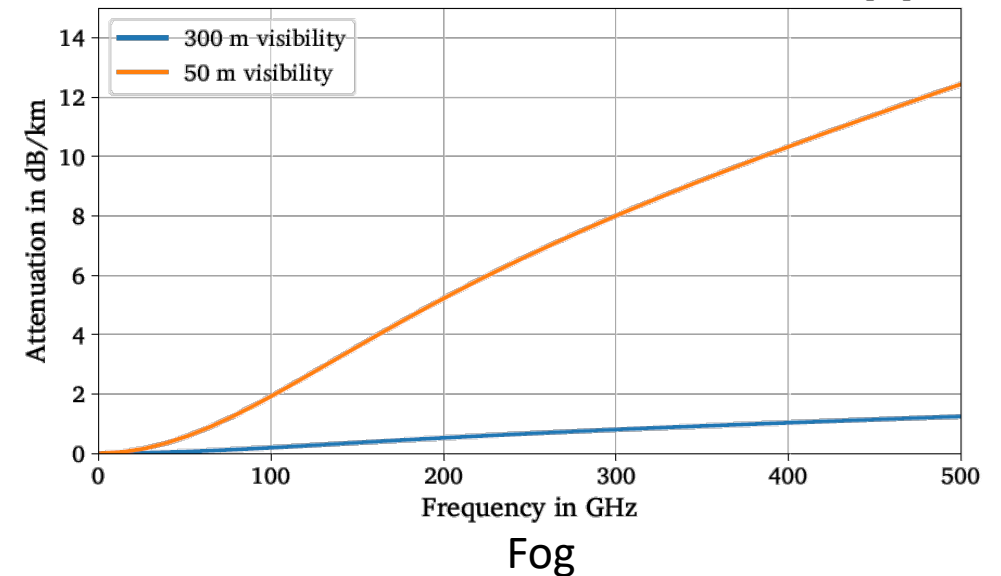
- Long range sensing $\gg 100$ m more difficult above 170 GHz
- For shorter ranges this is less of an issue
- RCS does not change much for many objects



Measured RCS of a Motorbike [6]



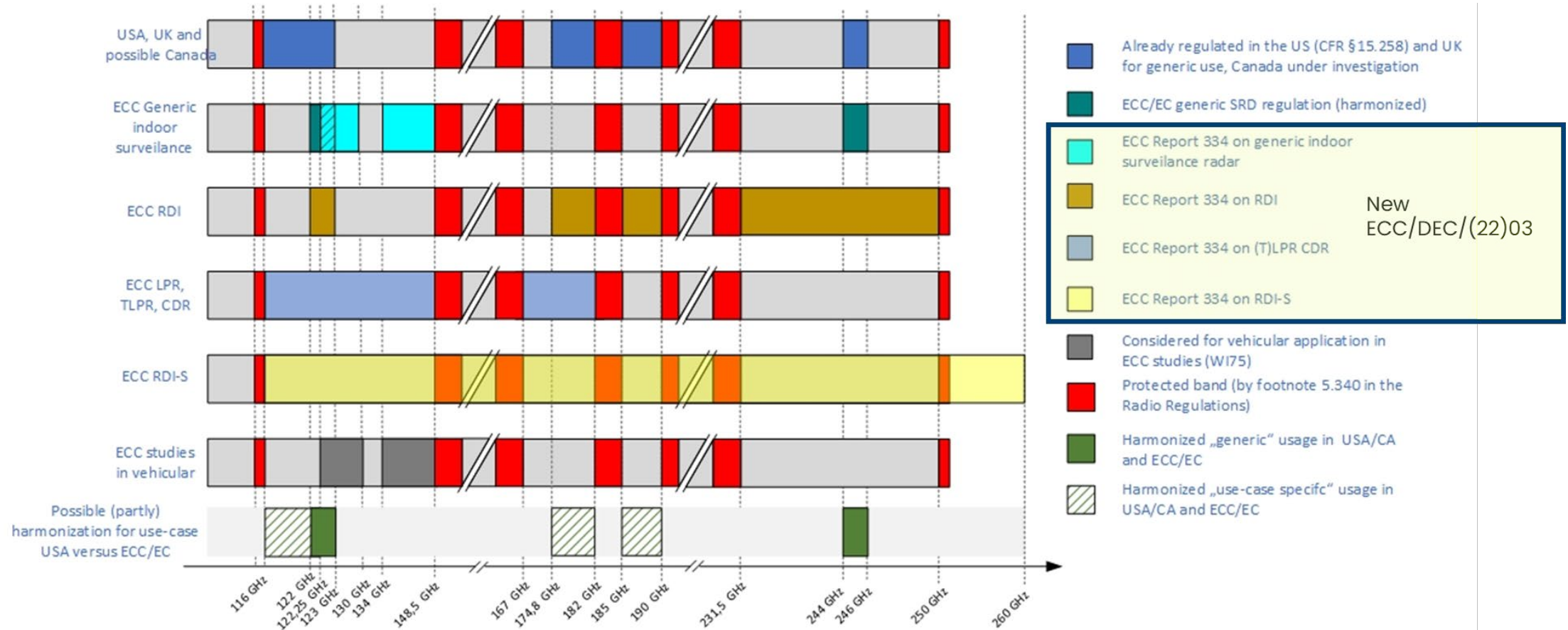
Atmospheric Gases [7]



- 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:
 - CEPT*: 122-148,5 GHz
(122-130GHz, 134-141GHz and 141-148,5GHz)
 - 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

*European Conference of Postal and Telecommunications Administrations

Comparison of the regulatory status USA vs. Europe



Conclusion

- Automotive Radar market is still growing strongly
- Differentiation between radar types for driver assistance and increasing automation levels
- Antenna technology is evolving from only PCB-based antennas
- Radar interference cannot be ignored, but there are ways to solve it
- Push to higher frequencies for radar is feasible for short range, however worldwide frequency regulation is slow!

- [1] Automotive Radar — From First Efforts to Future Systems, <https://doi.org/10.1109/JMW.2020.3033616>
- [2] Antenna Concepts for Millimeter-Wave Automotive Radar Sensors, <https://doi.org/10.1109/JPROC.2012.2184729>
- [3] Clustering and Subsequent Contour and Motion Estimation of Automotive Objects Using a Network of Cooperative Radar Sensors, <https://doi.org/10.1109/TVT.2022.3204965>
- [4] Reducing the radar cross section of microstrip arrays using AMC structures for the vehicle integration of automotive radars
- [5] System Performance of a 79 GHz High-Resolution 4D Imaging MIMO Radar With 1728 Virtual Channels, <https://doi.org/10.1109/JMW.2022.3196454>
- [6] Feasibility of automotive radar at frequencies beyond 100 GHz, <https://doi.org/10.1017/S175907871200075X>
- [7] International Telecommunications Union. Recommendation ITU-R P.676-12: Attenuation by atmospheric gases. ITU, 2019. <https://www.itu.int/rec/recommendation.asp?lang=en&parent=R-REC-P.676-12-201908-I>.
- [8] RESOLUTION 663 (WRC-19), https://www.itu.int/dms_pub/itu-r/oth/0C/0A/R0C0A00000F00142PDFE.pdf
- [9] IMIKO-Radar: AP09 Overall Evaluation
- [10] Gramegna: Architectures for Communication, Sensing and Joined Communication and Sensing, IEEE JC&S Symposium 2023
- [11] An All-Digital Carrier Synthesis for Stepped-OFDM-Radars, IMS 2023