mmWave Radar for Automotive and Industrial Applications

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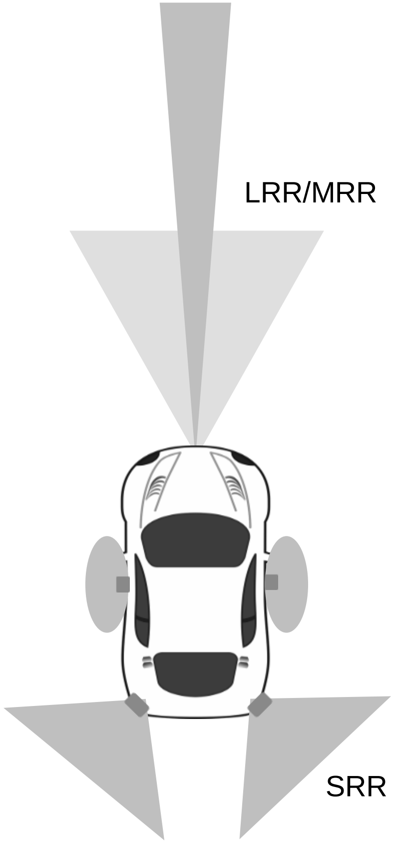
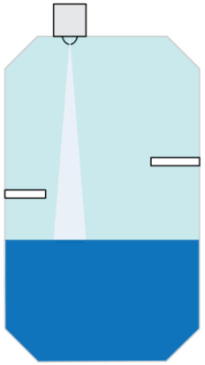
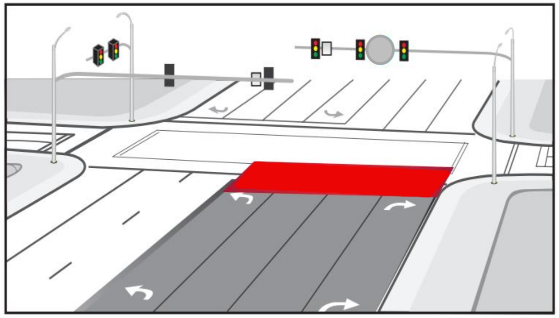
Introduction

- Radar technology has been in existence for several decades
  - Military, Weather, Law enforcement, and so on
- In the past decade, use of radar has exponentially increased
  - Automotive and Industrial applications
- Automotive applications
  - Front-facing radar (LRR/MRR)
    - Adaptive Cruise Control, Autonomous Emergency Braking
  - Corner radar (SRR)
    - Blind Spot Detection, Lane Change Assist, Front/Rear Cross Traffic Alert
  - Newer applications
    - Automated parking, 360 degree surround protection
    - Body/Chassis and In-cabin applications
- Industrial applications
  - Fluid level sensing
  - Solid volume identification
  - Traffic monitoring and Infrastructure systems
  - Robotics, and many others

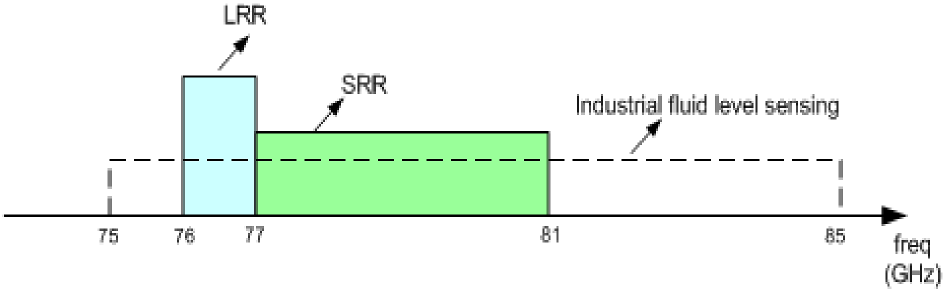






77GHz mmWave Radar

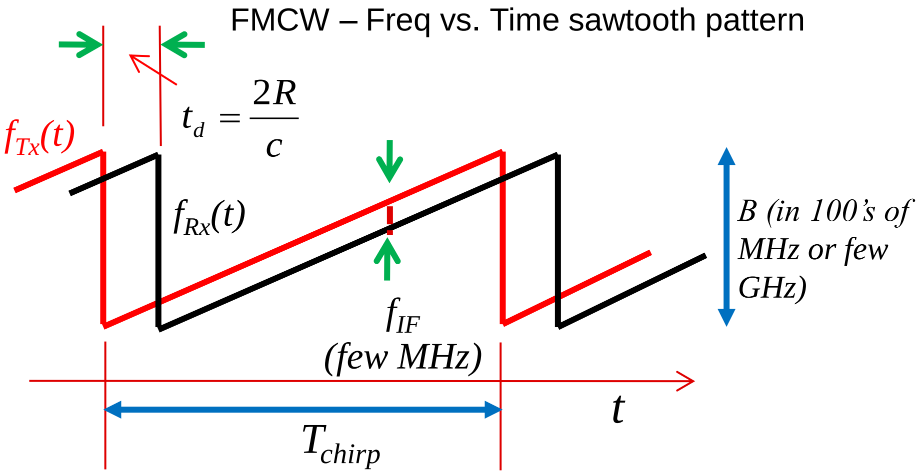
- mmWave: RF frequencies within 30 GHz to 300 GHz
  - Wavelength is in the order of few millimeters
- 77GHz mmWave radar bands
  - 76-77 GHz
    - Allocated for vehicular radar in many countries
    - Also available for infrastructure systems in certain regions
  - 77-81 GHz
    - Recently made available for short range radar
    - Legacy 24 GHz UWB short range radar to be phased out by 2022
  - 75-85 GHz: Available for level probing radar
- mmWave radar sensors can measure
  - Radial distance (range) to the object
  - Relative radial velocity to the object
  - Angle of arrival using multiple TX, RX



- Some benefits of radar
  - Robust to environmental conditions like dust/fog/smoke
  - Operation in dazzling light, or no ambient light
  - Operation behind plastic enclosure

FMCW Radar – Overview

- Multiple types of radar modulation waveforms used
  - Pulsed radar, CW Doppler radar, UWB, FSK, FMCW, PN-modulated radar
- FMCW: Frequency Modulated Continuous Wave
  - FMCW (sometimes called LFMCW or Linear FMCW) is the most commonly used scheme in automotive radar today
  - Linear FMCW: TX signal has frequency changing linearly with time (i.e., chirp)

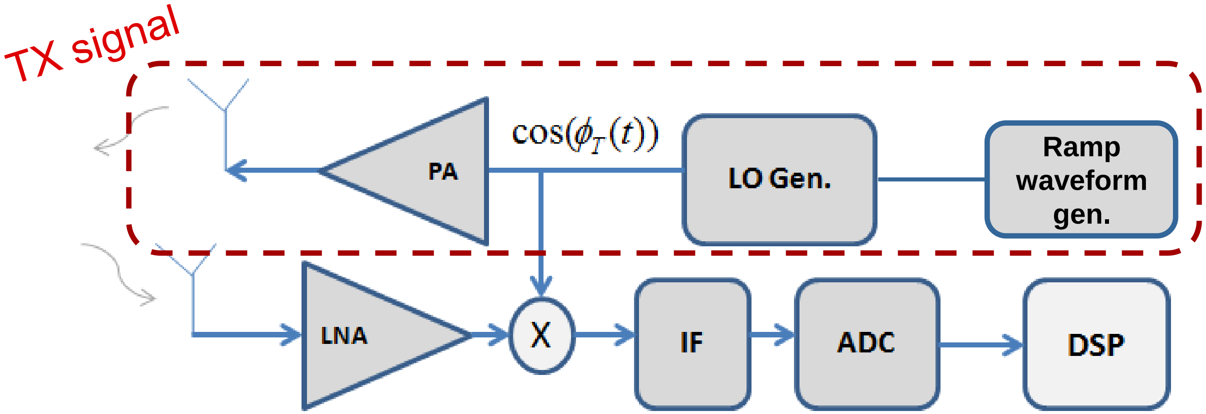

FMCW – Freq vs. Time sawtooth pattern

- Key benefits of FMCW radar
  - Ability to sweep wide RF bandwidth (GHz) while keeping IF bandwidth small (MHz)
    - Better range resolution. RF sweep bandwidth of 2 GHz can achieve 7.5cm range resolution, while IF bandwidth can still be <15MHz
  - Lower peak power requirement, compared to pulsed radar

FMCW Radar – System Model (1/3)

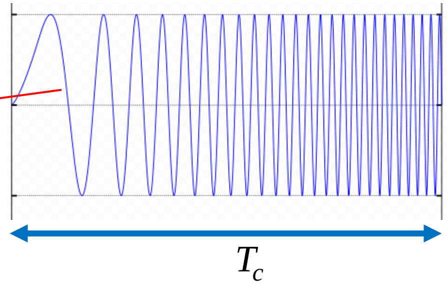
1. TX signal

- High-level block diagram



- The transmitted FMCW waveform (chirp) is

$$x_T(t) = \cos\underbrace{\left(2\pi f_c t + \pi \frac{B}{T_c} t^2\right)}_{\phi_T(t)}$$

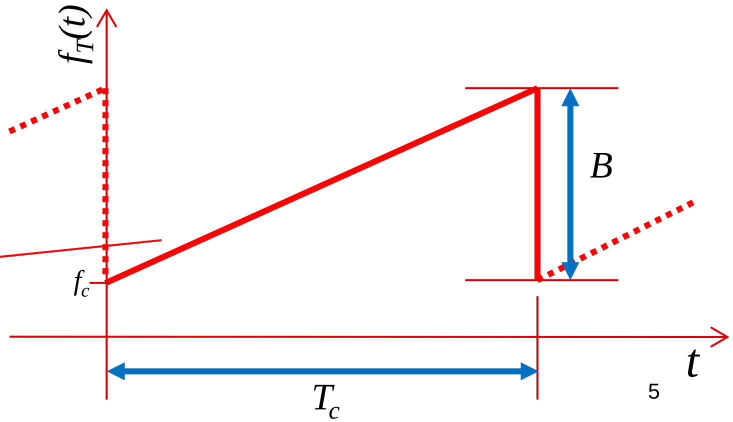


$B =$ Sweep bandwidth of transmitted chirp (Hz)

$T_c =$ Chirp duration (s)

- The instantaneous frequency of FMCW waveform is

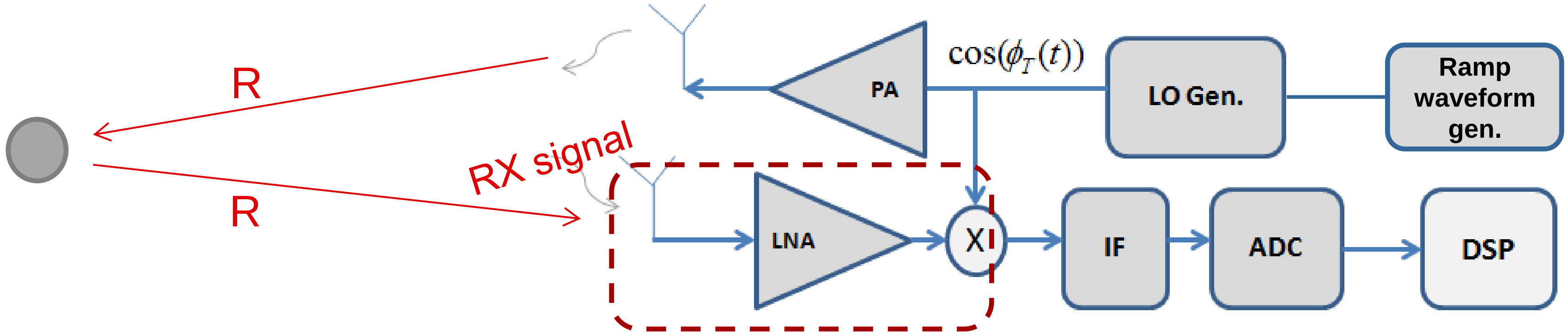
$$f_T(t) = \frac{1}{2\pi}\frac{d\phi_T(t)}{dt}$$
$$= f_c + \frac{B}{T_c} t$$



FMCW Radar – System Model (2/3)

2. RX signal

- High-level block diagram



- Received signal is a scaled and delayed version of transmitted signal

$$x_R(t) = \alpha\, x_T(t-t_d) = \alpha \cos\left(2\pi f_c (t-t_d) + \pi \frac{B}{T_c}(t-t_d)^2\right)$$

$\alpha =$ Path loss attenuation

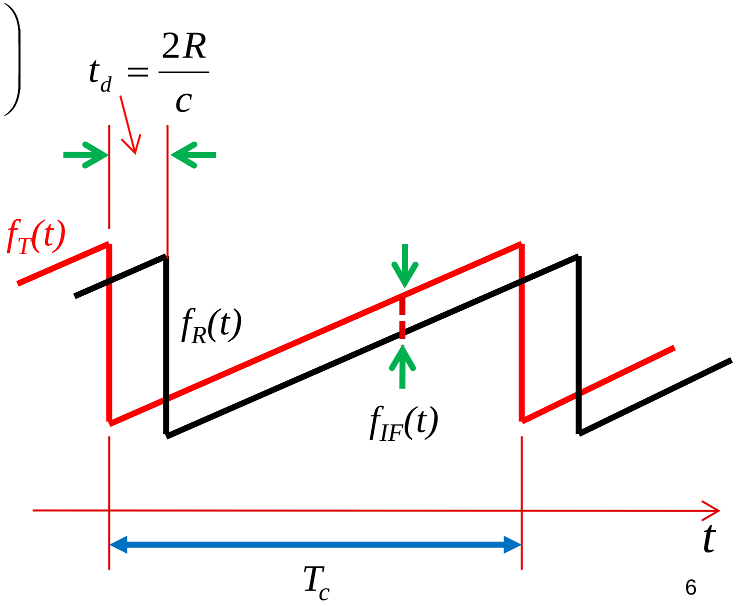
$t_d =$ Time delay of reflection (from object)

- Round-trip delay of reflection t_d is

$$t_d = \frac{2R}{c}$$

$R =$ Range (Distance) of the object

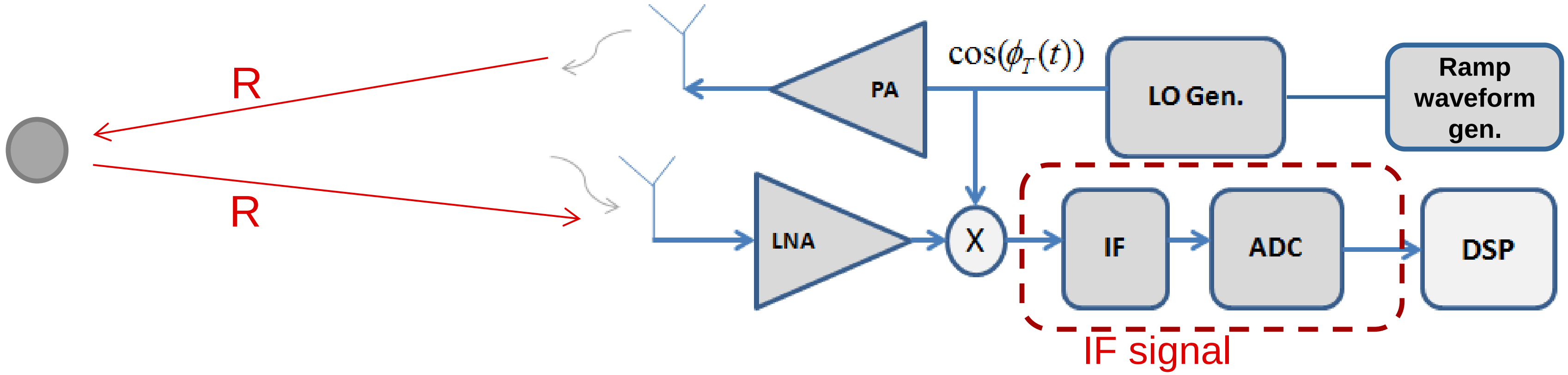
$c =$ Speed of light



FMCW Radar – System Model (3/3)

3. Beat signal (IF)

- High-level block diagram



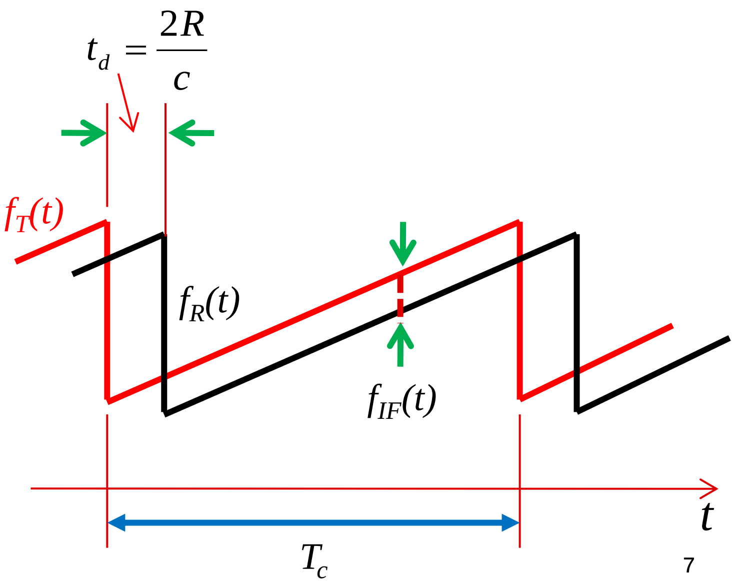
- Beat frequency or IF signal after receive mixer is as follows

$$y(t)=x_R(t)\times x_T(t)=\alpha\cos\big(\phi_T(t-t_d)\big)\times\cos\big(\phi_T(t)\big)$$

$$y(t)=\frac{\alpha}{2}\Big[\underbrace{\cos\big(\phi_T(t-t_d)-\phi_T(t)\big)}_{\text{Can be calculated as}}+\underbrace{\cos\big(\phi_T(t-t_d)+\phi_T(t)\big)}_{\text{Filtered out in the receiver}}\Big]$$

$$\phi_0-2\pi\underbrace{\left(\frac{B}{T_c}t_d\right)}t$$

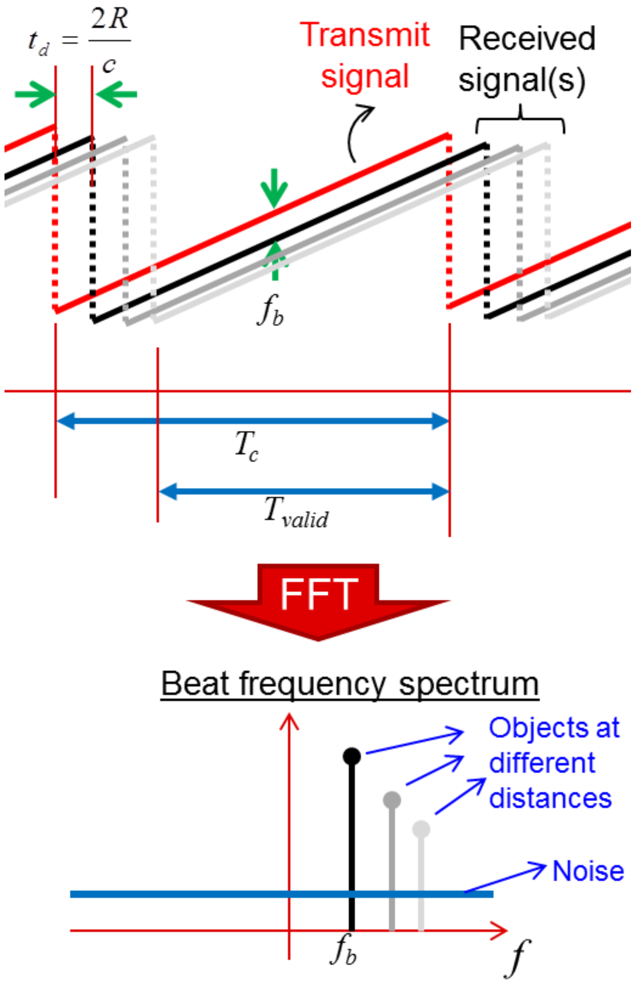
Beat frequency corresponding to the target



FMCW Radar – How it works (1/2)

Static objects

- For static objects, the beat frequency is simply proportional to the distance (round-trip delay)
  - Beat frequency is the product of FMCW frequency slope (B/T_c) and round-trip delay (t_d)
  - For multiple objects, the beat signal is a sum of tones, where each tone’s frequency is proportional to the distance of the object
  - The frequencies of these tones gives the distances to the different objects
- Detection of objects and Distance (Range) estimation is done typically by taking FFT of received IF signal



Beat freq = Round-trip delay * Slope

$$f_b = \left(\frac{2R}{c}\right)\left(\frac{B}{T_c}\right)$$

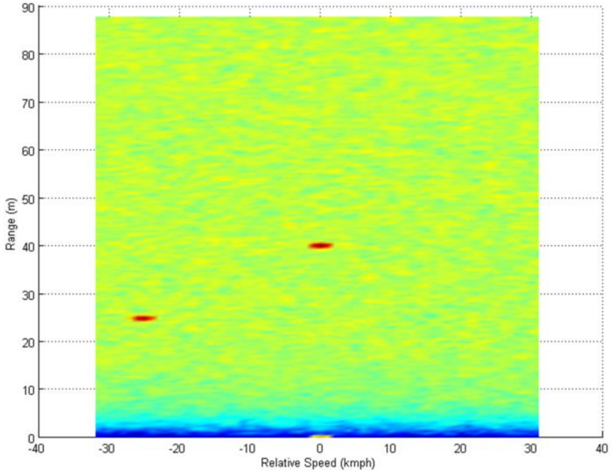
FMCW Radar – How it works (2/2)

Moving objects

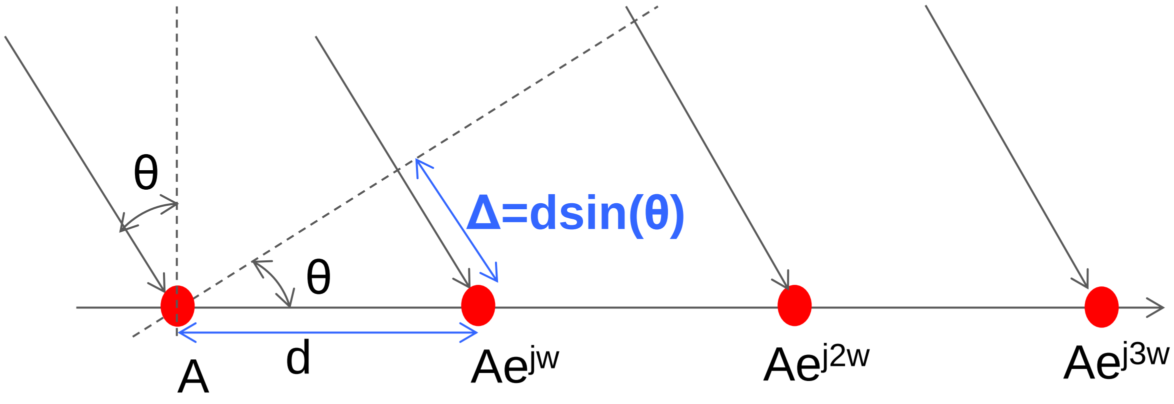
- For moving objects, velocity (v) is determined using phase change across multiple chirps
- Phase and frequency of the received beat signal for the nth chirp can be calculated as

$$\phi_0 \underbrace{-2\pi\frac{2v}{c}f_c\,nT_c}_{\text{Phase change from chirp-to-chirp that depends only on the velocity (not on range)}} - 2\pi\left[\overbrace{\frac{2v}{c}(f_c + nB)}^{\text{New terms in beat frequency}} + \frac{B}{T_c}t_d\right]t$$

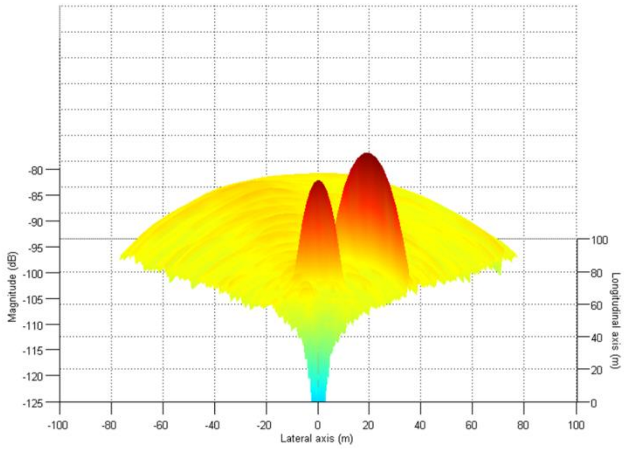
- Second dimensional FFT is performed across chirps to determine the phase change and thus the velocity
- The two-dimensional FFT process gives a 2D range-velocity image (FFT heatmap)
- Typically, detection of objects is done on this image
  - After detection, the range and relative speed of the objects are easily calculated



Angle Estimation - Beamforming



Uniform linear array



- Consider received signal for multiple RX antennas (say, four) as shown in figure
- Additional distance (Δ) travelled at successive antennas depends on the angle of arrival θ

$$\Delta = d\sin(\theta)$$

- This additional distance results in a phase change (w) across consecutive antennas

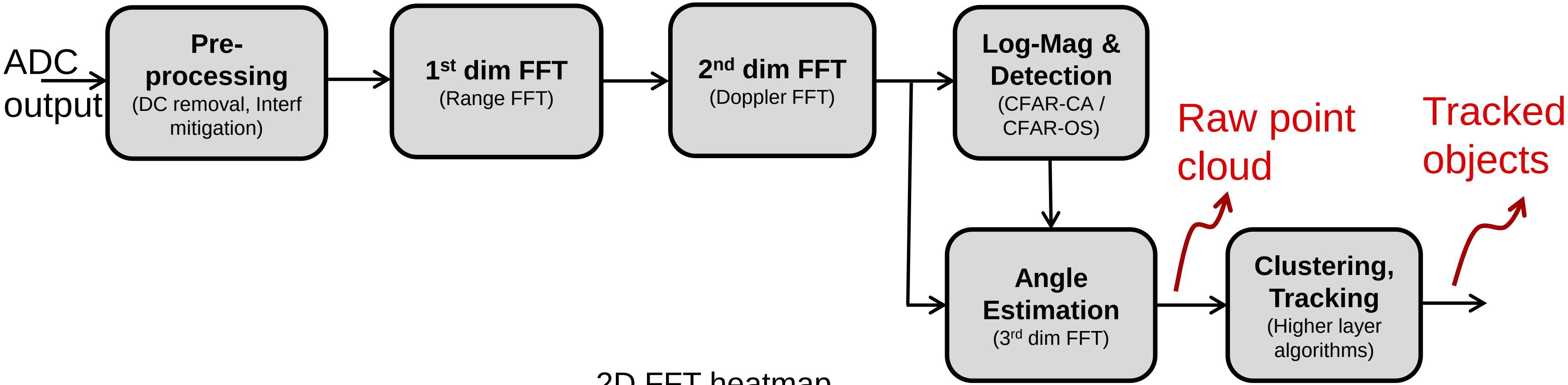
$$w = \frac{2\pi}{\lambda} d\sin(\theta)$$

- This phase change can be estimated (w_{est}) using an FFT (3rd dimension FFT)
- Once w is estimated, the angle of arrival (θ) can be derived easily

$$\theta_{est} = \sin^{-1}\left(\frac{w_{est}\lambda}{2\pi d}\right)$$

Sample FMCW Radar processing flow (1/2)

- Typical processing flow used in FMCW (sawtooth) Radar signal processing



ADC output

Pre-processing
(DC removal, Interf mitigation)

1st dim FFT
(Range FFT)

2nd dim FFT
(Doppler FFT)

Log-Mag & Detection
(CFAR-CA / CFAR-OS)

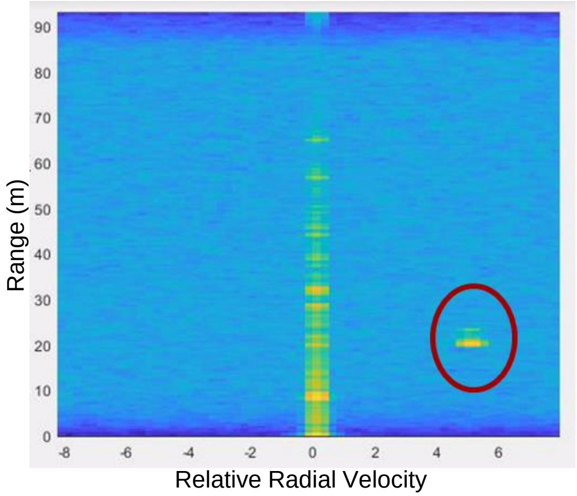
Angle Estimation
(3rd dim FFT)

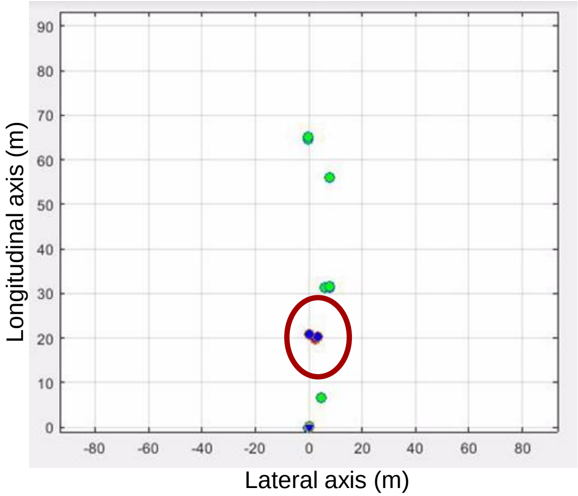
Clustering, Tracking
(Higher layer algorithms)

Raw point cloud

Tracked objects

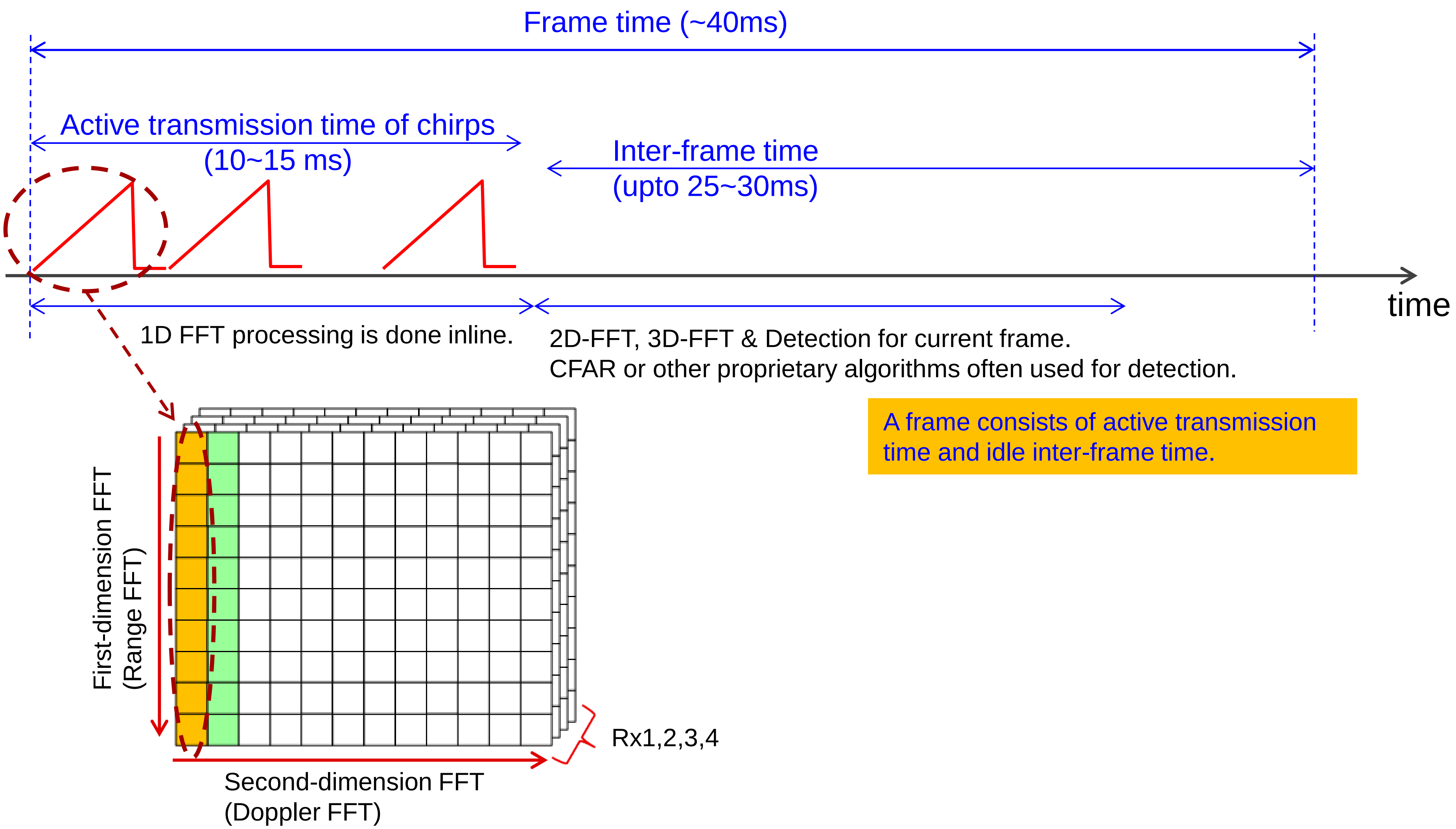
2D FFT heatmap





Sample FMCW Radar processing flow (2/2)

- Typical (simple) FMCW chirp configuration consists of a sequence of chirps followed by idle time



Frame time (~40ms)

Active transmission time of chirps (10~15 ms)

Inter-frame time (upto 25~30ms)

time

1D FFT processing is done inline.

2D-FFT, 3D-FFT & Detection for current frame.
CFAR or other proprietary algorithms often used for detection.

A frame consists of active transmission time and idle inter-frame time.

First-dimension FFT (Range FFT)

Rx1,2,3,4

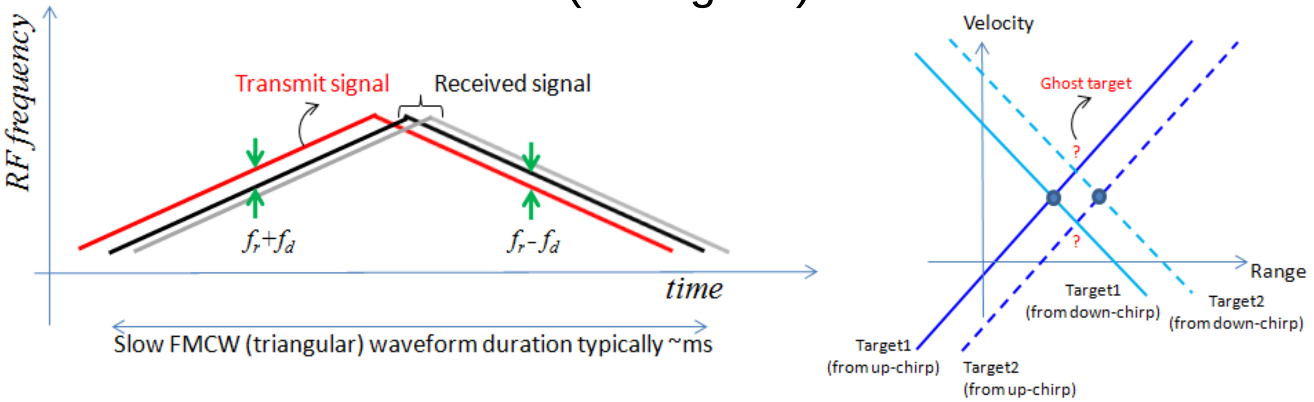
Second-dimension FFT (Doppler FFT)

Radar data cube memory

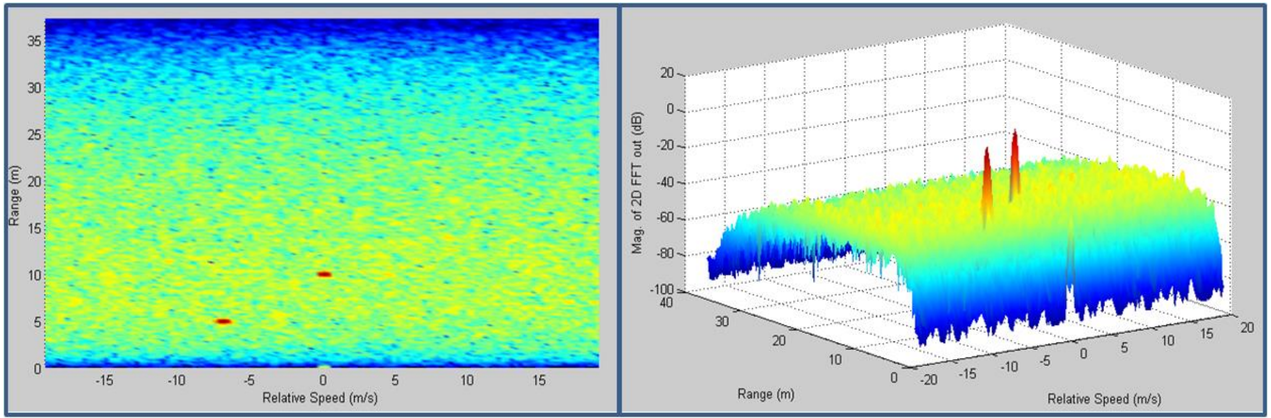
Advantages of Fast FMCW modulation

- Slow FMCW (Triangular) waveform used in many legacy systems
  - Chirp duration in ms, instead of us
- Slow FMCW has advantage of low DSP MIPS requirement
  - No two-dimensional FFT processing
- However, it suffers from ambiguity issues
  - No elegant way of getting range-doppler image
- Fast FMCW (Sawtooth) waveform is preferred in newer systems
- Fast FMCW has ability to provide range-doppler two dimensional image of objects

Slow (Triangular) FMCW

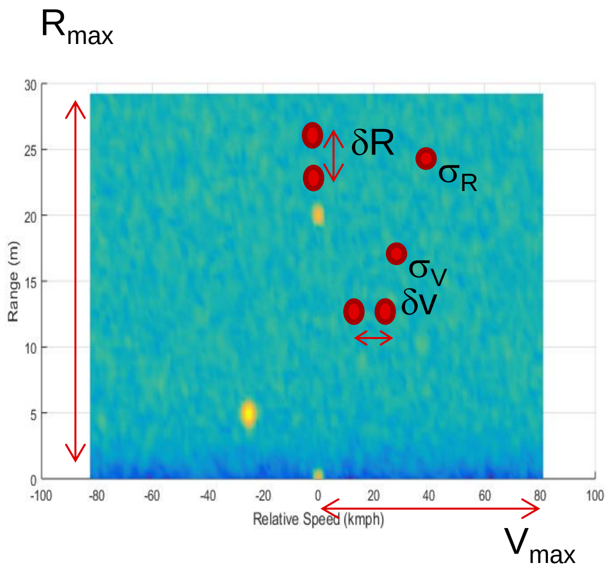


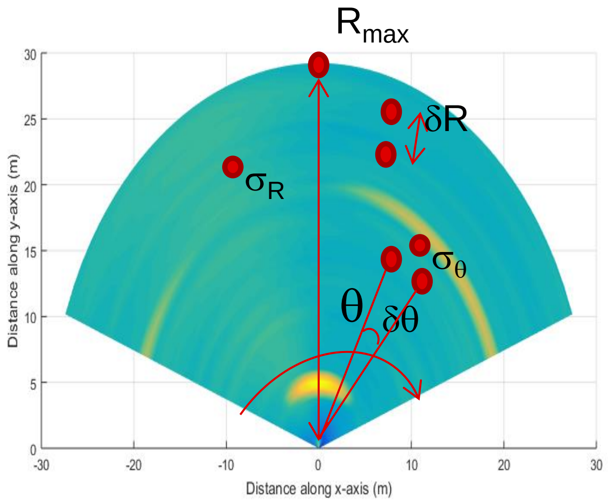
Fast (sawtooth) FMCW



Radar system performance parameters

- Key parameters
  - Max range
  - Range resolution
  - Range accuracy
  - Max velocity
  - Velocity resolution
  - Velocity accuracy
  - Field of view
  - Angular resolution
  - Angular accuracy
  - Cycle time



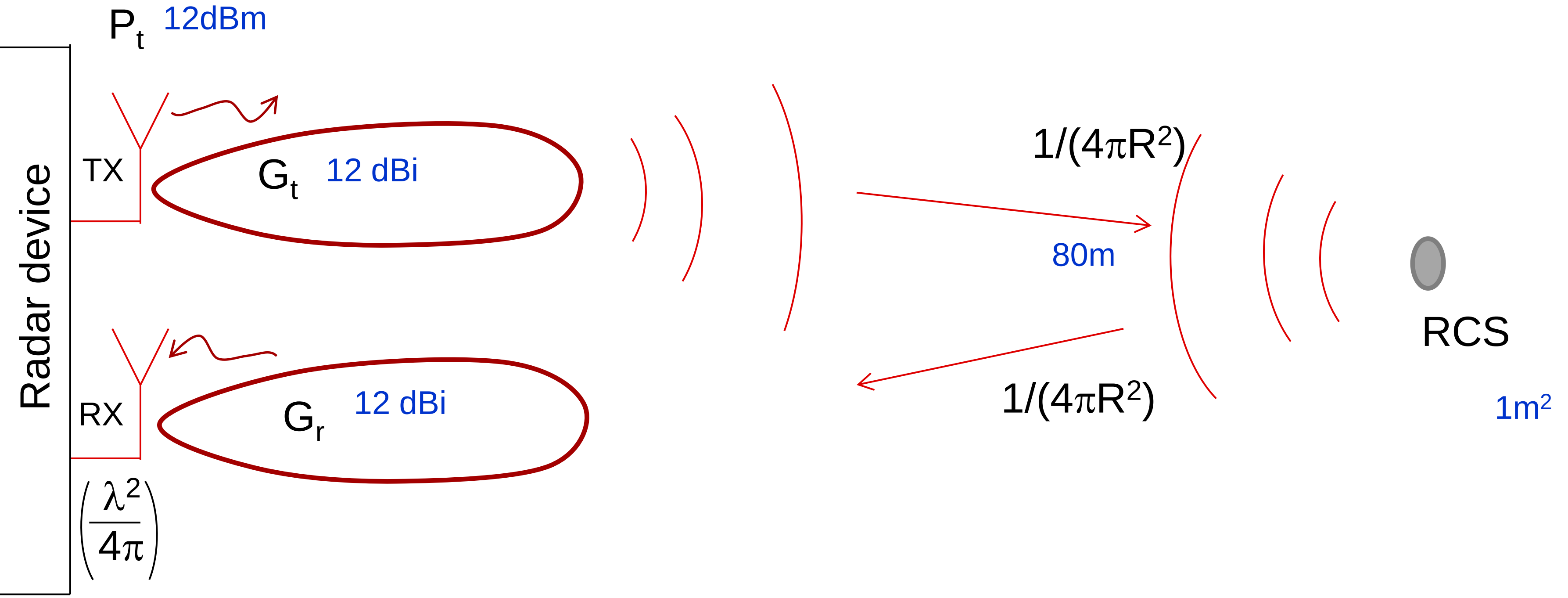


Max range (1/2)

- Based on Friis transmission equation

$$\mathrm{SNR} = \overbrace{\frac{P_t\, G_t\, (\mathrm{RCS})\, G_r}{(4\pi R^2)\,(4\pi R^2)}\left(\frac{\lambda^2}{4\pi}\right)}^{\text{Rx signal level}}\underbrace{\frac{T_f}{(kT)(NF)}}_{\text{Noise level}}$$

(linear scale)



RX signal level:
= -121 dBm

Noise level: -174 dBm/Hz + 16 dB + 10*log10(100 Hz) = -138dBm

Thermal noise floor (kT)

Noise figure (NF)

10ms active frame (T_f) (integration time)

SNR = 17dB

Max range (2/2)

$$R_{max} = \sqrt[4]{\frac{P_t\, G_t\, (RCS)\, G_r \lambda^2\, T_f}{(4\pi)^3 (SNR)\, (kT)(NF)}}$$

- Max range depends on the below factors

	Typical range	
TX Output power	10 dBm – 13 dBm	
TX Antenna gain	9 dBi – 23 dBi (USRR – LRR)	Depends on Azimuth and Elevation field of view
RCS of target	$0.1m^2 – 50m^2$ (-10 dBsm to 17 dBsm)	Pedestrian vs. Truck
RX Antenna gain	9 dBi – 23 dBi	Depends on Azimuth and Elevation field of view
Noise figure	11 dB – 18 dB	Implementation dependent
Active frame time	2 ms – 20 ms	
Detection SNR	10 dB – 18 dB	

	Azim FOV (deg)	Elev FOV (deg)	Antenna gain (dB)
SRR	120	30	9.21
MRR	90	12	14.44
LRR	24	8	21.94

Target	RCS
Pedestrian	0.1 ~ 1 sq.m
Motorbike	5 sq.m
Car	10 sq.m
Truck	50 sq.m

Thumb rule:
3 dB loss = 15% loss of range
12 dB loss = 50% loss of range

RX array beamforming gain can be additionally included.

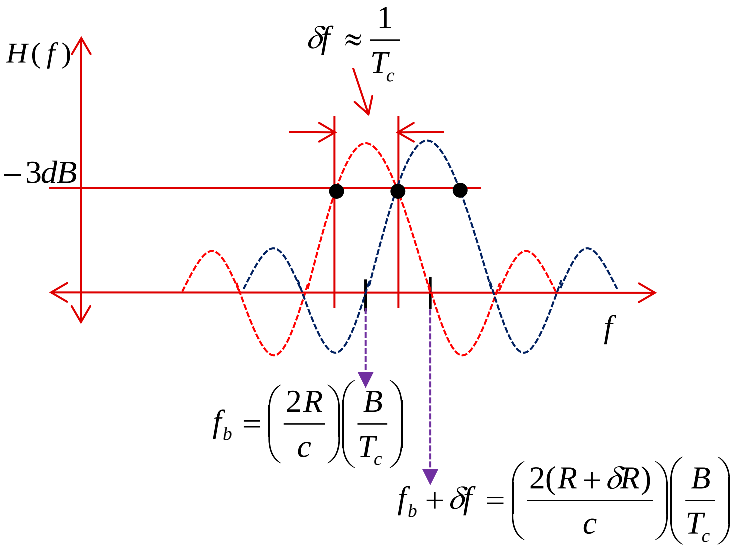
Range resolution and Range accuracy

- Range resolution
  - Ability to separate two closely spaced objects in range
  - Range resolution is a function of RF bandwidth used

$$f_b = \left(\frac{2R}{c}\right)\left(\frac{B}{T_c}\right)$$

$$\Rightarrow \delta f = \left(\frac{2\delta R}{c}\right)\left(\frac{B}{T_c}\right)$$

$$\text{But } \delta f \approx \frac{1}{T_c}\text{, therefore, } \boxed{\delta R = \frac{c}{2B}}$$



Sweep BW (MHz)	Range resolution (cm)
200	75
600	25
1000	15
2000	7.5
4000	3.75

- Range accuracy
  - Accuracy of range measurement of one object
  - Depends on SNR
  - Typically range accuracy is a small fraction of range resolution

$$\boxed{\sigma_R = \frac{c}{3.6B\sqrt{2SNR}}}$$

Max velocity

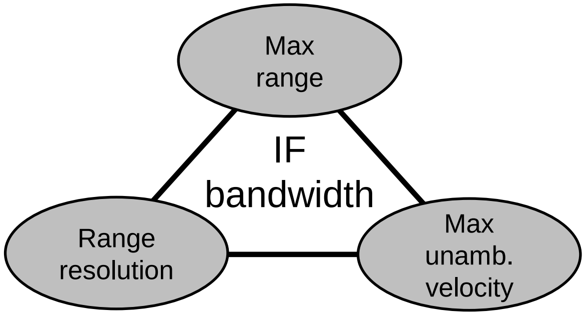
- Max unambiguous velocity in Fast FMCW modulation depends on chirp repetition period
  - Higher velocity needs faster ramps

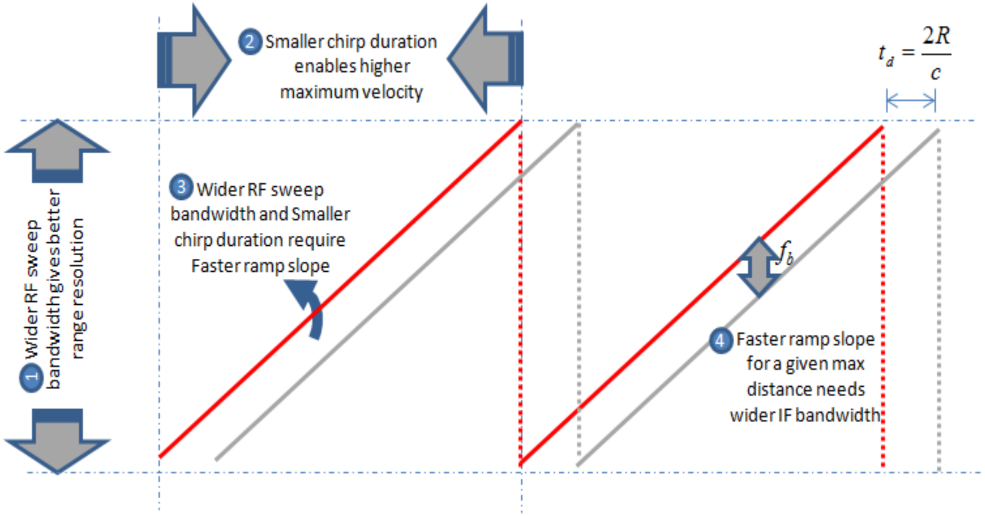
$$\boxed{v_{\max} = \frac{\lambda}{4T_c}}$$

λ = wavelength
T_c = Total chirp duration (incl. inter-chirp time)

Total Chirp duration (us)	Max unamb velocity (+/-kmph)
50	70
38	92
25	140

- For a given max range and range resolution, higher max velocity needs higher IF bandwidth





- Advanced techniques are often used to increase the max velocity
  - Ambiguity resolution techniques can be used to resolve aliased velocity into true velocity

Velocity resolution and Velocity accuracy

- Velocity resolution
  - Ability to separate two objects in velocity
  - Depends on the active duration of the frame

$$\boxed{\delta v = \frac{\lambda}{2NT_c}}$$

λ = wavelength
N = number of chirps in the frame
T_c = Total chirp duration (incl. inter-chirp time)

Active Frame duration (ms)	Velocity resolution (+/-kmph)
5	1.40
10	0.70
15	0.47
20	0.35

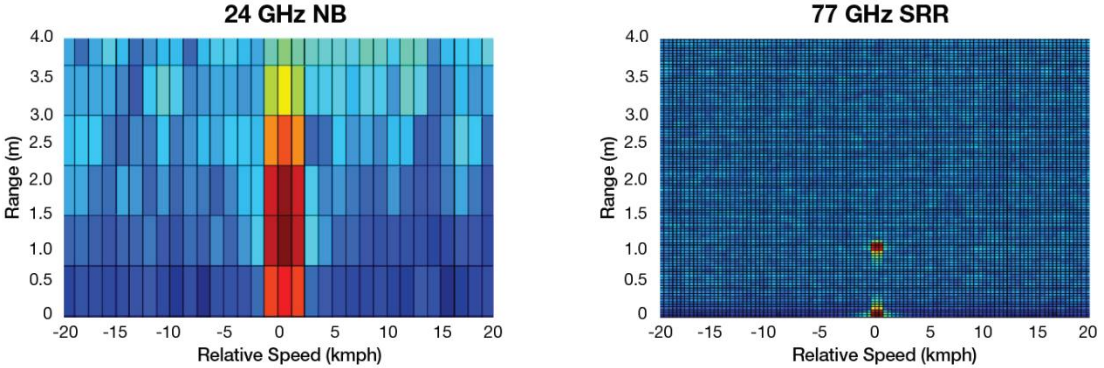
- Velocity accuracy
  - Accuracy of velocity measurement of one object
  - Depends on SNR
  - Typically a fraction of velocity resolution

$$\boxed{\sigma_v = \frac{\lambda}{3.6NT_c\sqrt{SNR}}}$$

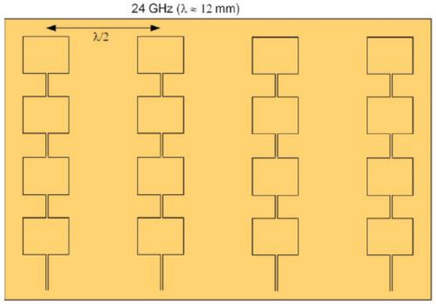
Benefits of 77GHz mmWave

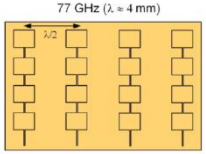
- Wide RF bandwidth (4 GHz) provides good range resolution and range accuracy
  - 20X better than legacy 24GHz narrowband sensors (which use ~200MHz bandwidth)
- High RF frequency (small wavelength) provides good velocity resolution and accuracy
  - 3X better than 24GHz sensors

Better resolution performance with 77GHz

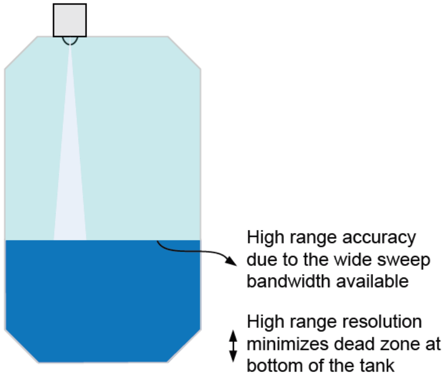


- Smaller form-factor for the sensor





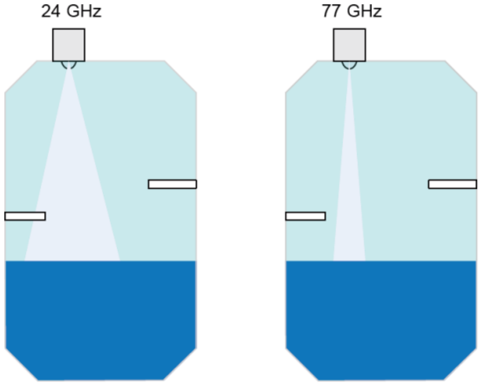
Improved performance



High range accuracy due to the wide sweep bandwidth available

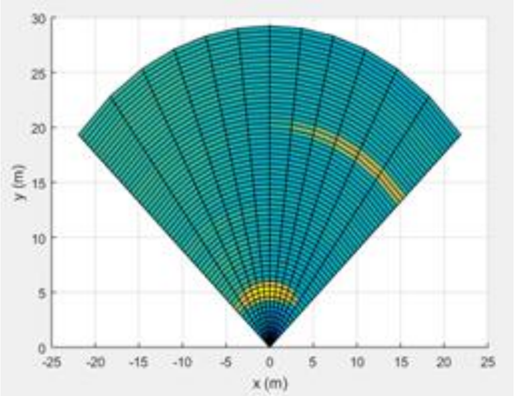
High range resolution minimizes dead zone at bottom of the tank

More focused beam with 77GHz



Angular resolution

- Angular resolution
  - Ability to separate objects in angle (for same range and velocity)
  - Radar sensors have poorer angular resolution typically (compared to LIDAR for example)
  - However, in many real life situations, objects get resolved in range or velocity, due to good resolution in those dimensions
  - Angular resolution (in radians) for K-length array is given by:



Array length	Ang. Resolution (deg)
8	14.32
12	9.55
24	4.77
40	2.86

$$\boxed{\underset{\text{(in radians)}}{\delta\theta} = \frac{\lambda}{Kd\cos(\theta)}}$$

← Note the dependency of the resolution on θ.

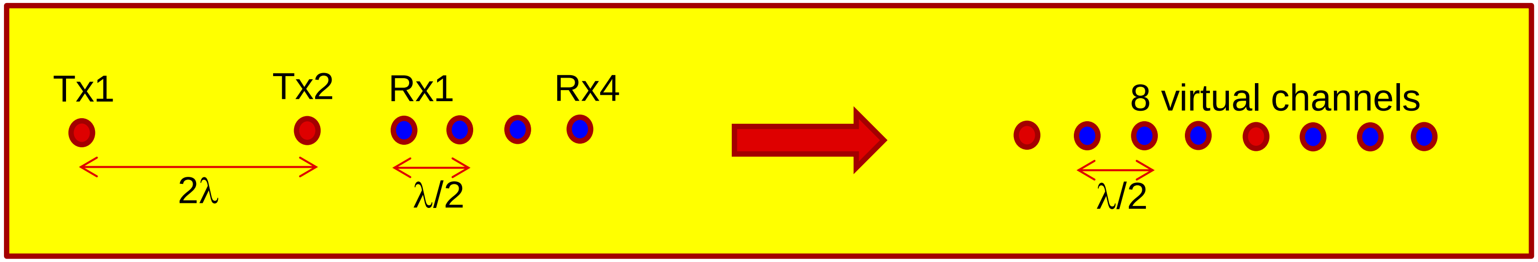
Resolution is best at θ=0

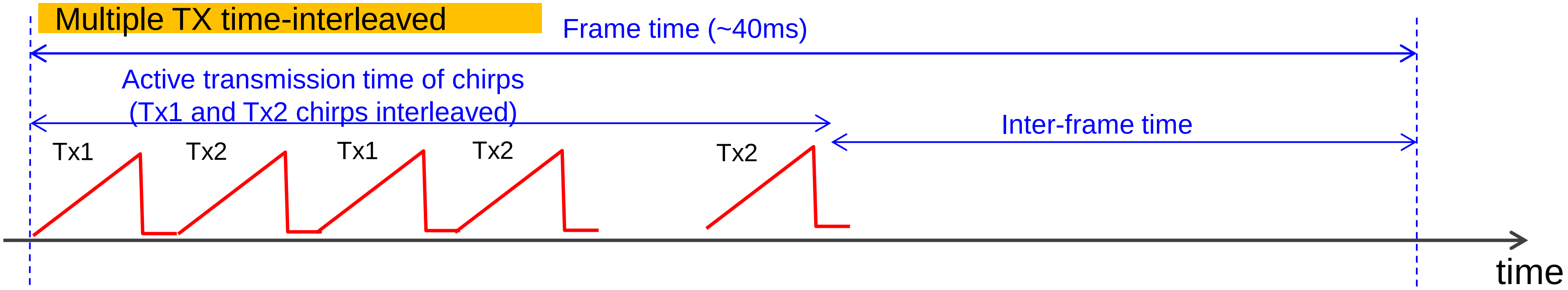
$$\delta\theta = \frac{2}{K}$$

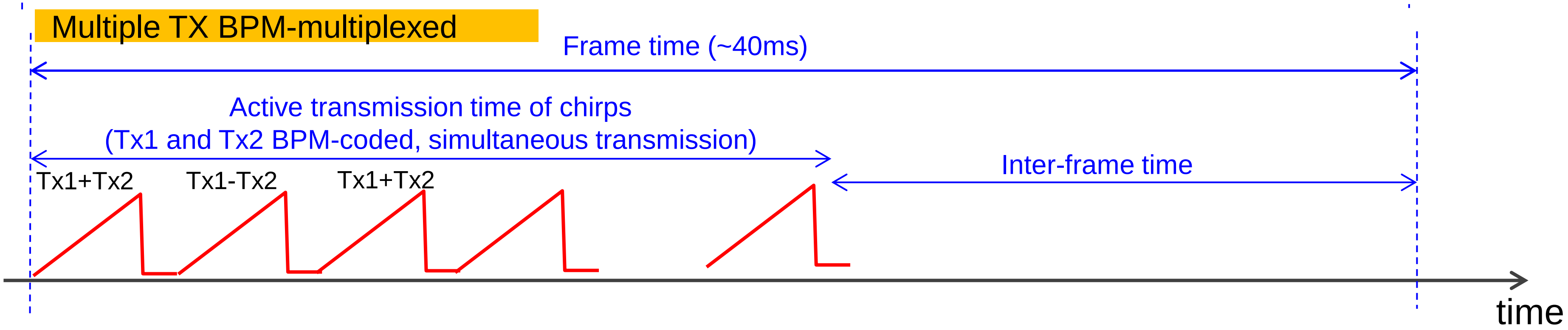
← Resolution is often quoted assuming d=λ/2 and θ=0

Use of Multiple TX – MIMO radar

- Multiple TX along with multiple RX (MIMO radar) to increase angular resolution – eg. 2 TX, 4 RX can give 8 virtual channels

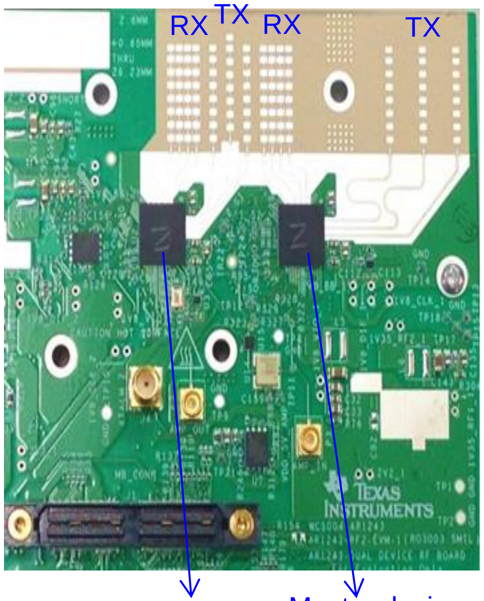






- Multiple TX can also be used for TX beamsteering (simultaneous transmission with linear phase shifter based steering of beam)

Cascaded multi-chip radar



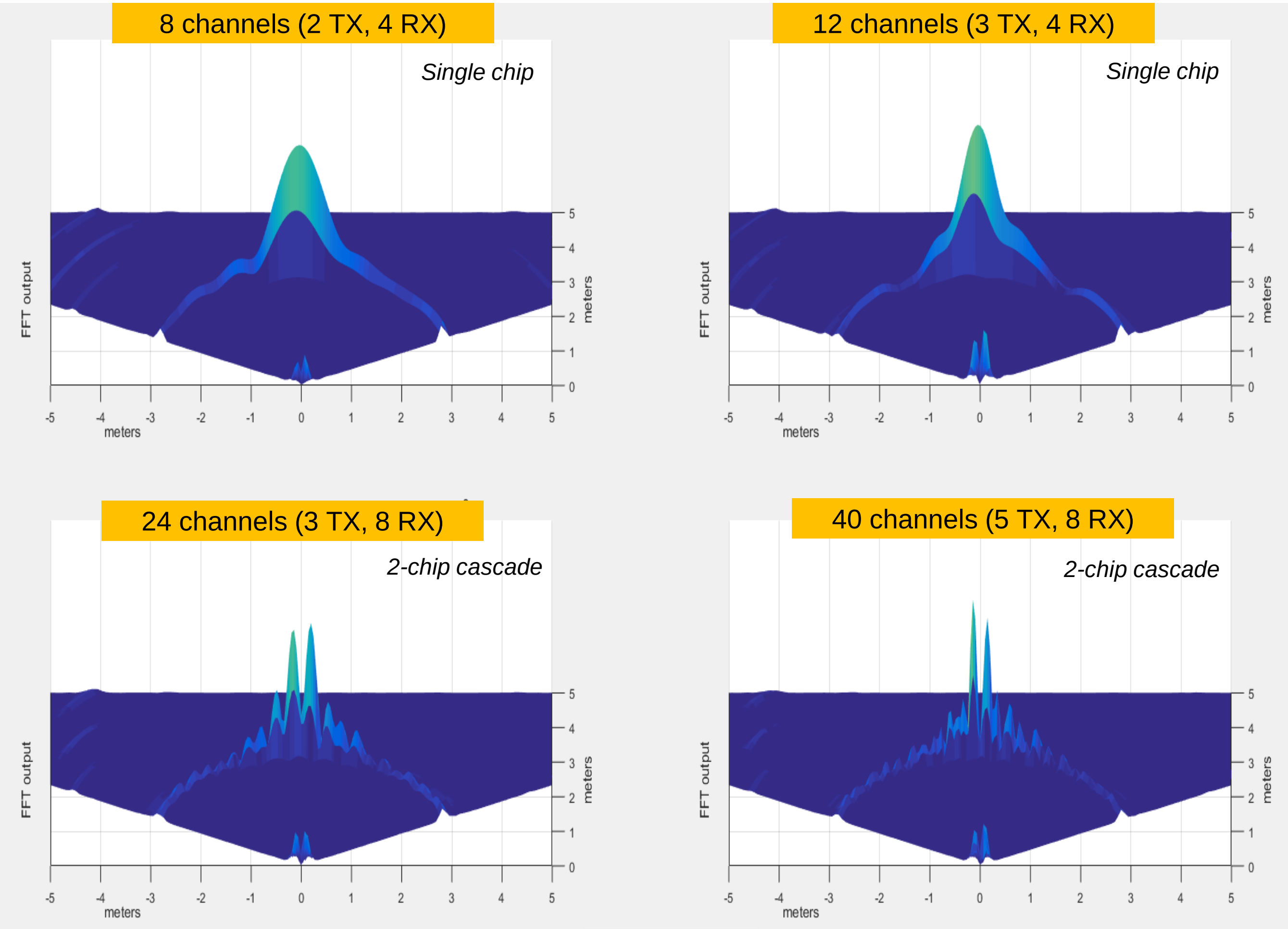
Slave device
(LO sync'ed to master)

Master device

Two corner reflectors

2-chip cascade radar

Measurement results with 2 corner reflectors at ~4deg separation



8 channels (2 TX, 4 RX)

Single chip

12 channels (3 TX, 4 RX)

Single chip

24 channels (3 TX, 8 RX)

2-chip cascade

40 channels (5 TX, 8 RX)

2-chip cascade

2-chip cascade enables better separation of the corner reflectors

TI mmWave radar devices

- TI offers a family of 77GHz radar devices for automotive and industrial applications
  - Highly integrated devices based on RFCMOS
  - High accuracy, Small form-factor, Sensing simplified

Automotive

AWR1243: High performance radar front end

AWR1443: Ultra high resolution single chip radar

AWR1642: Small, low power single chip radar

	AWR1243: High performance radar front end	AWR1443: Ultra high resolution single chip radar	AWR1642: Small, low power single chip radar
Frequency	76-81GHz	76-81GHz	76-81GHz
Number of receivers	4	4	4
Number of transmitters	3	3	2
Max sampling rate	37.5 Msps	12.5 Msps	12.5 Msps
IF bandwidth	15 MHz	5 MHz	5 MHz
Processing		ARM Cortex-R4F 200MHz Radar hardware accelerator - FFT	ARM Cortex R4F 200MHz C674x DSP 600MHz
Memory		576KB	1.5MB
Interfaces	MIPI CSI2 SPI	CAN SPI	CAN-FD CAN SPI
RF bandwidth	4 GHz	4 GHz	4 GHz

Industrial

	IWR1443: Ultra high resolution single chip radar	IWR1642: Small, high performance single chip rada
Frequency	76 - 81GHz	76 - 81GHz
Number of receivers	4	4
Number of transmitters	3	2
Processing	ARM Cortex-R4F 200MHz Radar hardware accelerator-FFT	ARM Cortex R4F 200MHz C674x DSP 600MHz
Memory	576KB	1.5MB
Interfaces	CAN MIPI CSI2 SPI LVDS	CAN SPI LVDS

For more information, visit:
TI.com/mmWave

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