Frequency-Modulated Continuous-Wave (FMCW) Radar

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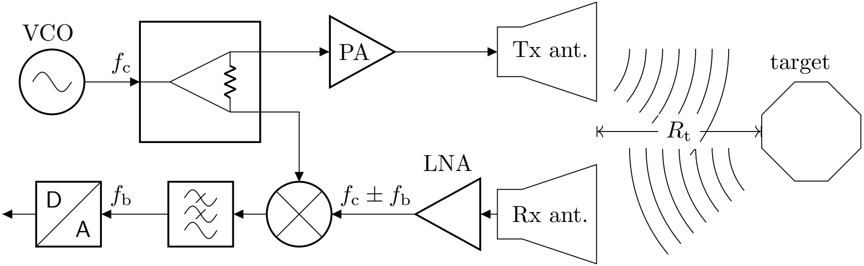
Outline

1. CW Radars
2. FMCW Radars
3. Signal Processing
4. Real Radar Parameters
5. Azimuth Estimation
6. Commercial Radars

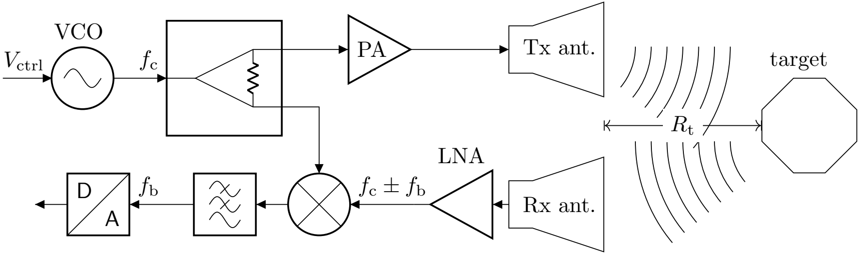
CW Radars

- Transmists a continuous-wave signal.
- Widely utilized in a traffic surveillance.
- Detects target's radial speed v_r via a harmonic beat signal with Doppler frequncy:
$$f_\mathrm{D} = \frac{2v_\mathrm{r}}{\lambda} = \frac{2v_\mathrm{r} f_\mathrm{c}}{c_0},$$
- λ is wevelength in a vacuum, f_c is transmitted signal frequency and c_0 is speed of light.



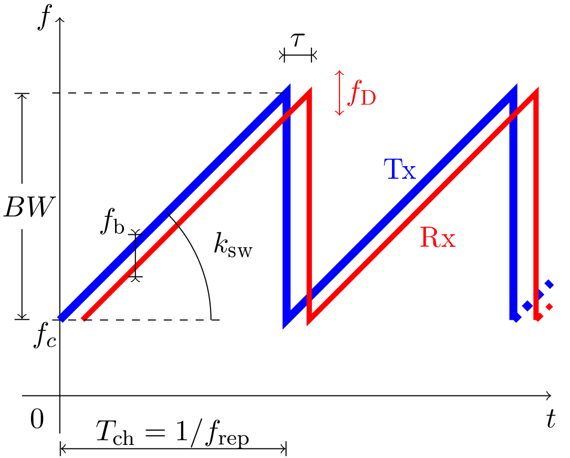
FMCW Radars - Block Scheme

- On contrary of CW radars, simple evaluation of range of a target is possible.
- Frequency-modulated continuous-wave (FMCW) radars.
- Widely utilized in automotive industry and robotics.
- Detects round-trip delay (range of a target) via frequency of a beat signal.
- Received power is determined through a radar equation.
- Transmit sequence of individual chirps, so-called frame.



Transmitted Signal

- τ - time delay between transmitted and received signals.
- f_c - carier frequency (typically 24, 60, 76, 77 GHz).
- BW - bandwidth (from ≈100 MHz to ≈6 GHz).
- k_sw - chirp slope (up to ≈100 MHz/μs).
- T_ch - chirp length/period (from tens to hundreds of μs).
- f_D - Doppler frequency of moving target.

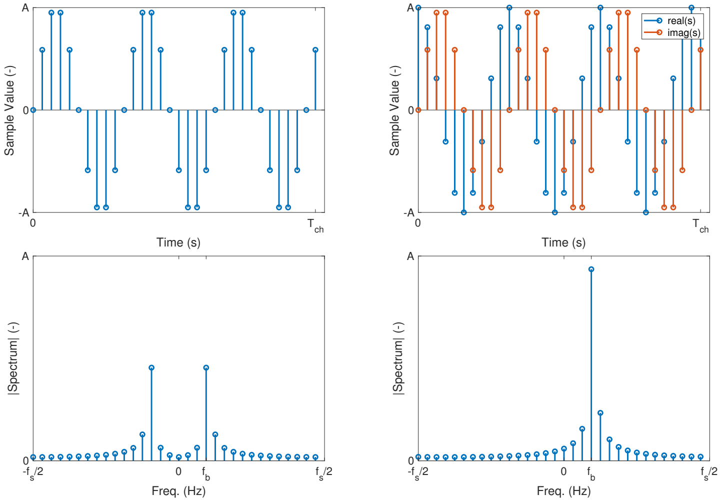


Basic Equations

- Filtered harmonic beat signal in radar's receiver: $f_\mathrm{b} = \frac{2R_\mathrm{t}}{c_0}\frac{BW}{T_\mathrm{ch}} = \tau k_\mathrm{sw}$.
- Range of the target: $R_\mathrm{t} = \frac{f_\mathrm{b} c_0}{2k_\mathrm{sw}}$.
- Sampling of the beat signal by sampling frequency f_s obtaining $N_\mathrm{s} = f_\mathrm{s} T_\mathrm{ch}$ samples (ideally).
- Maximal beat signal frequency: $f_\mathrm{bmax} = f_\mathrm{s}/2$.
- Maximal target's range: $R_\mathrm{tmax} = \frac{f_\mathrm{s} c_0}{4k_\mathrm{sw}}$.
- Fourier transform of the beat signal returns N_s-sample complex frequency spectrum with a range $\pm f_\mathrm{s}/2$ and with resolution $\Delta f_\mathrm{b} = f_\mathrm{s}/N_\mathrm{s}$.
- Range resolution: $\Delta R_\mathrm{t} = \frac{\Delta f_\mathrm{b} c_0}{2k_\mathrm{sw}} = \frac{f_\mathrm{s} c_0 T_\mathrm{ch}}{2N_\mathrm{s} BW} = \left(T_\mathrm{ch} = \frac{N_\mathrm{s}}{f_\mathrm{s}}\right) = \frac{c_0}{2BW}$.

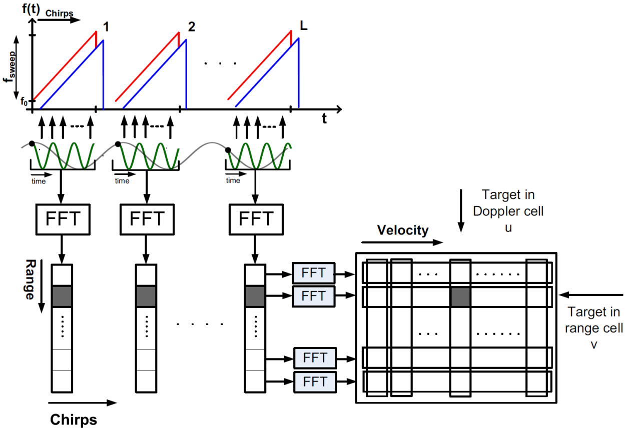
Beat Signal Spectrum

- Real or IQ sampling.
- Negative frequencies → negative range.
  - Estimation of noise parameters.
- Superposition of several beat signals.
- Oversampling does not increase the resolution.
- Window function choice.



Speed Evaluation

- Doppler frequency shift changes received f_b beat frequency.
- It is not possible to determine the target's speed from a single chirp.
- Usually $\frac{2R_\mathrm{t}k_\mathrm{sw}}{c_0} \gg \frac{2v_\mathrm{r}f_\mathrm{c}}{c_0}$.
- Doppler shift does not change a bin of f_b, but just its phase.
- Measure of Doppler shift from every chirp.
- Complex samples available even from real-sampled beat signal.
  - $\rightarrow$ double-sided spectrum.

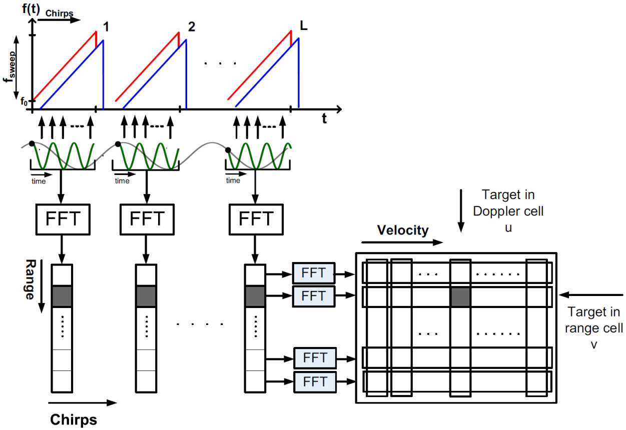


[1]

[1] M. Kronauge, C. Schroeder, and H. Rohling, "Radar target detection and Doppler ambiguity resolution", in *11-th International Radar Symposium*, 2010, pp. 1–4

Unambiguous Radial Speed Limit

- Determination of f_D frequency from a phase → FFT.
- Radial speed of the target:
$$v_\mathrm{r} = \frac{f_\mathrm{D} c_0}{2 f_\mathrm{c}}.$$
- Sampling of f_D with $f_\mathrm{rep} = 1/T_\mathrm{ch}$, *i.e.*, $f_\mathrm{Dmax} = \pm f_\mathrm{rep}/2$.
- Speed resolution:
$$\Delta v_\mathrm{t} = \frac{c_0}{4 T_\mathrm{ch} N_\mathrm{ch} f_\mathrm{c}}.$$
- Unambiguous speed limit:
$$v_\mathrm{rmax} = \pm \frac{f_\mathrm{rep} c_0}{4 f_\mathrm{c}}.$$



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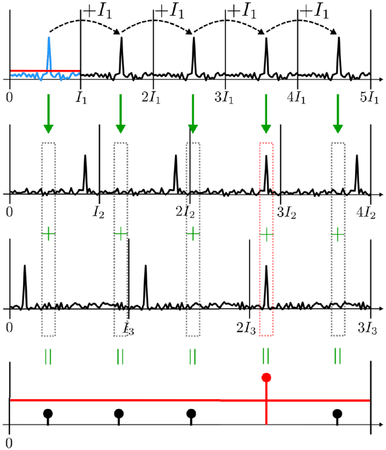
[1] M. Kronauge, C. Schroeder, and H. Rohling, "Radar target detection and Doppler ambiguity resolution", in *11-th International Radar Symposium*, 2010, pp. 1–4

Extension of the Speed Limit

- Transmitting at least two sets of chirps with different slopes $k_{\mathrm{sw}i}$.
- Every set of chirps preserves total time of frames $N_{\mathrm{ch}i} T_{\mathrm{ch}i} = const$.
- Numbers of chirps in every frame are coprime integers, *e.g.*, $N_{\mathrm{ch}} = \{15, 16, 17\}$.
- Utilize Chinese Remainder Theorem.
- Set of equations solved for integers n_i:

$$
\begin{gathered}
f_{\mathrm{D}} = f_{\mathrm{D}1} + n_1 I_1 \\
f_{\mathrm{D}} = f_{\mathrm{D}2} + n_2 I_2 \\
\vdots \\
f_{\mathrm{D}} = f_{\mathrm{D}N\mathrm{ch}} + n_{N\mathrm{ch}} I_{N\mathrm{ch}}.
\end{gathered}
$$



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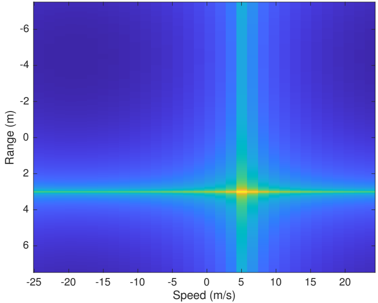
Range-Doppler (2D-FFT) Processing

```
R = 3; % range of target
vr = 5; % speed of target
fc = 77e9; % carrier frequency
BW = 4e9; % bandrwidth
ksw = 100e12; % slope of chirp
fs = 10e6; % sampling frequency
Nch = 32; % number of chirps in frame

c0 = 299792458; % speed of light
tau = 2*R/c0; % round-trip delay
Tch = BW/ksw; % length of single chirp
fb = tau*ksw; % beat frequency
fD = 2*vr*fc/c0; % Dopple shift
Ns = ceil(Tch*fs) + 1; % number of samples per chirp
RMax = fs*c0/(4*ksw); % maximal range
dR = c0/(2*BW); % range resolutuon
RAxis = linspace(-RMax, RMax-dR, Ns); % range axis
dv = c0/(4*Tch*Nch*fc); % speed resolution
vrmax = c0/(4*fc*Tch); % maximal speed
vAxis = linspace(-vrmax, vrmax-dv, Nch); % speed axis
t = linspace(0, (Ns - 1)/fs, Ns).'; % time vector
sRx = exp(1j*(2*pi*fb*t + 2*pi*fD*(1:Nch)*Tch)); % Rx signal
% SRx = fftshift(fft(fft(sRx, [], 1), [], 2));
% SRx = fftshift(fft(fft(sRx).').');
SRx = fftshift(fft2(sRx));
figure
imagesc(vAxis, RAxis, log10(abs(SRx)))
ylabel('Range (m)')
xlabel('Speed (m/s)')
```

- Matlab function `fft2`.
  - No window applicable.
  - Spectrum leakage.
- Usually computationally expensive.
  - Lack of a memory on processors.
  - 1D-FFT and CFAR.



Achievable Radar Parameters

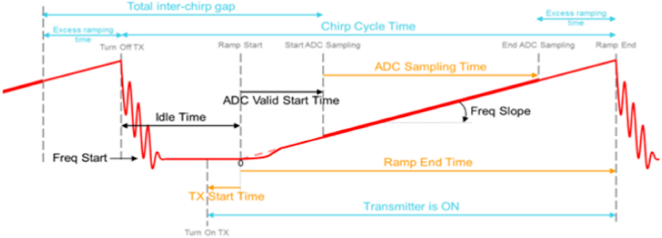
- Usual radar parameters ($f_s = 10\,\text{MHz}$, $N_{ch} = 64$):

Radar	f_c (GHz)	BW (MHz)	T_{ch} (μs)	f_{rep} (kHz)	k_{sw} (MHz/μs)	R_{tmax} (m)	ΔR_t (m)	v_{rmax} (m/s)	Δv_r (m/s)
24 GHz	24.0	250	1500	0.6	0.17	4500	0.60	2.1	0.03
76 GHz	76.0	400	85	11.0	4.7	160	0.38	11.6	0.18
77 GHz	77.0	4000	40	25.0	1004	7.5	0.038	24.3	0.38

- 24 GHz - Old automotive front long-range radars for autonomous emergency braking (AEB) and adaptive cruise control (ACC).
  - Industrial, Scientific and Medical (ISM) band, forbidden in new cars.
- 76 GHz - Front mid-range radars for AEB, ACC.
- 77 GHz - Short-range radar for blind-spot detection, scross-trafic alert, lane-change assist, autonomous parking.
- Data acquisition: 4 receivers, $f_s = 10\,\text{MHz}$, 16 bits, IQ.
  - Bit-rate: $4 \times 10\text{e}6 \times 16 \times 2/8/1024^3 \approx 150\,\text{MB/s}$.

Real Chirp Timing

- Idle Time is always present.
  - Minimal length depends on BW.
- Sampling only during a stabilized part of a chirp.
  - Loosing range resolution.

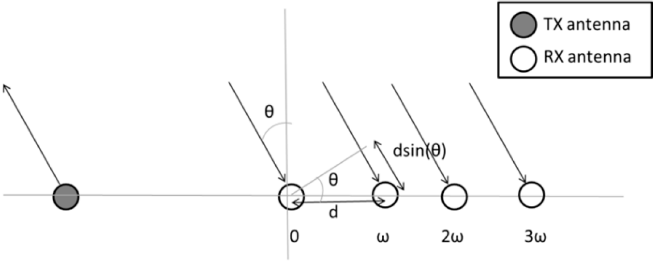


[2]

[2] V. Dham, *Programming Chirp Parameters in TI Radar Devices*, Texas Instruments, 2017

Target Azimuth Estimation I.

- Uniform Linear Array (ULA) of N_{Rx} receiving antennas with spacing $d = \lambda_0/2$.
  - ± 90 deg. unambiguous azimuth range.
- Phase shift of received signals by $\omega = 2\pi \frac{d\sin(\theta)}{\lambda_0}$.
- Estimation of ω by FFT from phasors from all receivers.
- Azimuth estimation: $\theta = \sin^{-1}\left(\frac{\omega\lambda_0}{2\pi d}\right)$.
- ω is nonlinear function of $\theta \rightarrow$ best resolution around $\theta = 0$ azimuth.

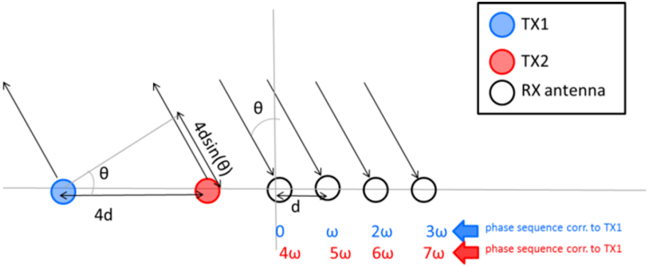


[3]

[3] S. Rao, *MIMO Radar*, Texas Instruments, 2017

Target Azimuth Estimation II.

- In single-chip solutions, usually more transmitters are available.
  - Switching between antenna beams.
- Usually creates virtual array using MIMO principle.
  - $N_{\mathrm{Rx}} \times N_{\mathrm{Tx}}$ virtual antennas.
- Separation of signals from all transmitters $\rightarrow$ orthogonal channels.
  - Time Division Multiplexing (TDM), Binary Phase Modulation (BPM).



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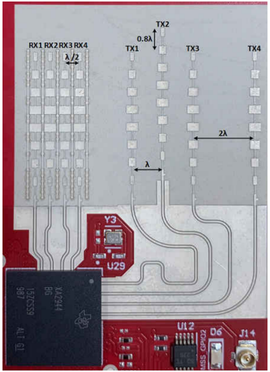
Radar Single Chip Solutions - TI

- Automotive mmWave Radar (AWR) and Industrial mmWave Radar sensors (IWR) from Texas Instruments.
  - AWR - $76 \div 81\,\mathrm{GHz}$, IWR - $60 \div 64\,\mathrm{GHz}$.
- State of the art: AWR2944
  - 4×4 MIMO (azimuth and elevation), $f_{\mathrm{smax}} = 37.5\,\mathrm{MHz}$, 12 bits, 15 MHz IF bandwidth, 12 dBm transmit power, $k_{\mathrm{swmax}} = 250\,\mathrm{MHz}/\mu\mathrm{s}$, 6-bit phase shifter at every Tx, integrated ARM processor, 4 MB internal RAM, BGA package ($12.1 \times 12.1\,\mathrm{mm}$).

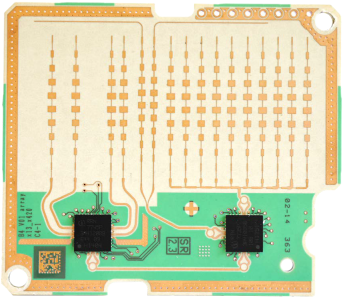


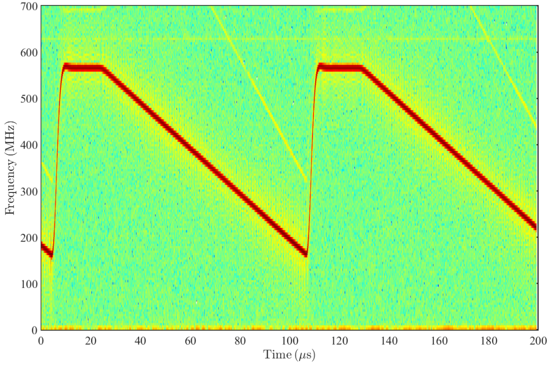
[4]

[4] *AWR2944EVM User's Guide*, Texas Instruments, 2021. [Online]. Available: https://www.ti.com/tool/AWR2944EVM

Bosch Automotive Radar

- Medium range automotive radar.





Thank you for your attention!
Questions?

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