Automotive Radar

Maria S. Greco
Automotive RADAR – Why?

Automotive RADARs as core sensor (range, speed) of driver assistance systems: long range (LRR) for Adaptive Cruise Control, medium range (MRR) for cross traffic alert and lane change assist, short-range (SRR) for parking aid, obstacle/pedestrian detection.
Automotive RADAR – Why?

- W.r.t. to other sensing technology, RADAR is robust in harsh environments (bad light, bad weather, extreme temperatures)
- Multiple RADAR channels required for additional angular information
- Data fusion in the digital domain with other on-board sensors
Automotive RADAR – a bit of Story

- First tentative for mm-wave automotive RADAR since 70’s (but integrated-unfriendly technologies lead to large size, high cost)
- Since 1998-1999 first generation of radar sensors (Daimler, Toyota)
- Last generation based on 180/130 nm SiGe chipset and advanced packaging with integrated antenna commercially available (e.g. Bosch)
- High RADAR frequency (small $\lambda$) allows small size and weight, highly integration with SiGe and future CMOS tech. will reduce assembly and testing costs and hence final user cost much below US$1000
- Market expanding at 40%/year and is expected increasing with all premium/middle cars having a RADAR in next years (7% of all vehicles sold world-wide, mainly in Europe, Japan and US, will have RADARs)
### Automotive RADAR – Technical spec

<table>
<thead>
<tr>
<th>Type</th>
<th>LRR</th>
<th>MRR</th>
<th>SRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum transmit power (EIRP)</td>
<td>55 dBm</td>
<td>-9 dBm/MHz</td>
<td>-9 dBm/MHz</td>
</tr>
<tr>
<td>Frequency band</td>
<td>76-77 GHz</td>
<td>77-81 GHz</td>
<td>77-81 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>600 MHz</td>
<td>600 MHz</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Distance range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{\min...R_{max}}$</td>
<td>10-250 m</td>
<td>1-100 m</td>
<td>0.15-30 m</td>
</tr>
<tr>
<td>Distance resolution $\Delta R$</td>
<td>0.5 m</td>
<td>0.5 m</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Distance accuracy $\delta R$</td>
<td>0.1 m</td>
<td>0.1 m</td>
<td>0.02 m</td>
</tr>
<tr>
<td>Velocity resolution $\Delta v$</td>
<td>0.6 m/s</td>
<td>0.6 m/s</td>
<td>0.6 m/s</td>
</tr>
<tr>
<td>Velocity accuracy $\delta v$</td>
<td>0.1 m/s</td>
<td>0.1 m/s</td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>Angular accuracy $\delta \varphi$</td>
<td>0.1°</td>
<td>0.5°</td>
<td>1°</td>
</tr>
<tr>
<td>3 dB beamwidth in azimuth $\pm \varphi_{max}$</td>
<td>±15°</td>
<td>±40°</td>
<td>±80°</td>
</tr>
<tr>
<td>3 dB beamwidth in elevation $\pm \theta_{max}$</td>
<td>±5°</td>
<td>±5°</td>
<td>±10°</td>
</tr>
</tbody>
</table>
Automotive RADAR with SiGe mm-Wave T/R

- Commercially available from Bosch based on SiGe Infineon Chipset
- 2 PCB boards
- FCMW modulation
- LRR 7dBm Pout, 4 channels (2 TX/RX, 2 RX only), dielectric lens antenna provides high gain for Rmax 250m
- Alternative versions with PCB or on-chip Integrated antennas

Example on-chip integrated antenna for 77 GHz automotive RADAR

- On-chip antenna elements based on shorted \(\lambda/4\) microstrip lines, formed by the top and bottom metal layers of the chip backend
- Quartz glass resonators are positioned above the on-chip patch antenna elements to improve efficiency and bandwidth. The antennas are spaced at a distance to allow direction of arrival (DOA) estimation of a target or provide separate beams illuminating a dielectric lens

(J. Hasch et al., IEEE Tran. Micr Theory Tech, 2012)
Main signal processing functions in automotive RADARs:

<table>
<thead>
<tr>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range estimation</td>
</tr>
<tr>
<td>Doppler frequency estimation</td>
</tr>
<tr>
<td>CFAR techniques</td>
</tr>
<tr>
<td>Direction of arrival (DOA) estimation</td>
</tr>
<tr>
<td>Tracking</td>
</tr>
</tbody>
</table>
Long Range Radar (LRR)

Observation area

Requirements for LRR RADAR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity resolution</td>
<td>$\Delta v_r = 2.25 \text{ km/h}$</td>
</tr>
<tr>
<td>Range resolution</td>
<td>$\Delta R = 1 \text{ m}$</td>
</tr>
<tr>
<td>Unambiguous radial velocity</td>
<td>$v_{\text{max}} = 250 \text{ km/h}$</td>
</tr>
<tr>
<td>Maximum range</td>
<td>$R_{\text{max}} = 200 \text{ m}$</td>
</tr>
<tr>
<td>Short measurement time</td>
<td>$T_{\text{CPI}} = 10 \text{ ms}$</td>
</tr>
</tbody>
</table>

Functionalities: Autonomous Cruise Control (ACC)  
Collision warning
LRR for vehicular applications

Transmitted signals

Some special waveforms must be used to fulfill the requirements of simultaneous range and radial velocity measurement:

- Pulse Doppler
- FMCW with (at least) up- and down-chirp signals
- Frequency Shift Keying (FSK) CW
- MFSK CW

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LRR for vehicular applications

Single channel scheme

\[ s_T(t) = \cos \left[ 2\pi \left( f_T t \pm \frac{B_{sw}}{T_{CPI}} \frac{t^2}{2} \right) \right] \]

\[ s_R(t) = s_T \left[ t - \tau(t) \right] \]

Parameters for an LRR radars
24 GHz or 77 GHz

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>( f_T = 24 \text{ GHz} )</td>
</tr>
<tr>
<td>Time on target</td>
<td>( T_{CPI} = 10 \text{ ms} )</td>
</tr>
<tr>
<td>Sweep bandwidth</td>
<td>( B_{sw} = 150 \text{ MHz} )</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>( \Delta V_t = 2.25 \text{ km/h} )</td>
</tr>
<tr>
<td>Range resolution</td>
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<td>Unambiguous radial velocity</td>
<td>( V_{max} = 250 \text{ km/h} )</td>
</tr>
<tr>
<td>Unambiguous range</td>
<td>( R_{max} = 200 \text{ m} )</td>
</tr>
<tr>
<td>Base band bandwidth</td>
<td>( f_{B,max} = 31.2 \text{ kHz} )</td>
</tr>
</tbody>
</table>

H. Rohling, Automotive Radar tutorial, 2008
LRR for vehicular applications

FFT: applied on each segment (up and down chirp)

frequency and range estimation accuracy depends on the number of FFT points. Typical values: 128-4096 points

H. Rohling, Automotive Radar tutorial, 2008

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With only one up and down chirp, two targets are ambiguous. With four chirps two targets can be easily resolved.
LRR for vehicular applications

CFAR techniques for detection
Most common: 1D-CA-CFAR applied on FFT output (frequency domain)

DOA estimation
Most common: Monopulse with two antennas

Tracking techniques after detection
Most common: linear KF
Incoherent CFAR detectors

Depending on the adaptive threshold $Z$ we have different CFAR techniques:

- **CA-CFAR**: $Z = \text{mean}(X_1, X_2, \ldots, X_N)$

- **GO-CFAR**: $Z_1 = \text{mean}(X_1, X_2, \ldots, X_{N/2})$
  $Z_2 = \text{mean}(X_{N/2+1}, X_{N/2+2}, \ldots, X_N)$
  $Z = \max(Z_1, Z_2)$

- **SO-CFAR**: $Z_1 = \text{mean}(X_1, X_2, \ldots, X_{N/2})$
  $Z_2 = \text{mean}(X_{N/2+1}, X_{N/2+2}, \ldots, X_N)$
  $Z = \min(Z_1, Z_2)$

- **OS-CFAR**: $Y = \text{sort}(X_1, X_2, \ldots, X_N)$
  $Z = Y_K$
Incoherent CFAR detectors

Square Law Detector

Processing on $K/2$ samples

Calculation of $Z$

Estimated clutter power

Detector scale factor $T$

Comparator

$H_1 / H_0$
Incoherent CFAR detectors

Plot of the absolute value of the FFT for up- and down-chirp
DOA estimation - Monopulse

- It needs two beams for each angular coordinate
- Sum and difference patterns are used
- It can use single or multiple pulses

H. Rohling, Automotive Radar tutorial, 2008
DOA estimation - Monopulse

Example, with Gaussian antenna pattern and 
-3dB beamwidth = 3°

Ideally, without noise

\[ \alpha = \frac{\Delta}{\Sigma} \]
DOA estimation – Sequential lobing
Tracking - Linear Kalman filter

Object parameters → Sensor → Measurement → Linear Kalman Filter → Track estimate

Object parameters:

\[ y_k = \begin{pmatrix} t_{xk} \\ t_{yk} \\ v_{xk} \\ v_{yk} \end{pmatrix} \]

Measurement:

\[ \tilde{y}_k = \begin{pmatrix} \tilde{t}_{xk} \\ \tilde{t}_{yk} \\ \tilde{v}_{xk} \\ \tilde{v}_{yk} \end{pmatrix} \]

Linear model:

\[ \begin{pmatrix} t_{xk} \\ t_{yk} \\ v_{xk} \\ v_{yk} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \Delta T & 0 \\ 0 & 1 & 0 & \Delta T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t_{xk-1} \\ t_{yk-1} \\ v_{xk-1} \\ v_{yk-1} \end{pmatrix} \]

Prediction:

\[ \hat{y}_k = \begin{pmatrix} \hat{t}_{xk} \\ \hat{t}_{yk} \\ \hat{v}_{xk} \\ \hat{v}_{yk} \end{pmatrix} \]

Kalman filter:

\[ K_k = P_k^* \left( P_k^* + R \right)^{-1} \]

Final track estimate:

\[ \hat{y}_k = \begin{pmatrix} \hat{t}_{xk} \\ \hat{t}_{yk} \\ \hat{v}_{xk} \\ \hat{v}_{yk} \end{pmatrix} \]

H. Rohling, Automotive Radar tutorial, 2008

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Linear Kalman filter

Prediction step:
- Prediction estimation based on Process matrix $A$:
  \[
  \hat{\gamma}_k = A \hat{\gamma}_{k-1}
  \]
- Track estimation:
  \[
  P_k = AP_{k-1}A^T + Q
  \]

Track estimation step
- Prediction accuracy estimation based on tracking accuracy and process noise:
  \[
  \hat{\gamma}_k = \hat{\gamma}_k^* + K_k \left( \tilde{y}_k + \hat{\gamma}_k^* \right)
  \]
- Tracking accuracy estimation:
  \[
  P_k = \left( I + K_k \right) P_k^* \\
  K_k = P_k^* \left( P_k^* + R \right)^{-1}
  \]
Linear Kalman filter
UWB radars

Characteristics:
- Low power consumption
- Low cost circuitry
- Low probability of detection
- Different materials and environments distort pulses differently

Applications:
- Vehicular radar (Short range)
- Ground Penetrating Radar (GPR)
- Through-the-wall imaging
- Medical radars
UWB RADAR definition

The amount of spectrum occupied by a signal transmitted by a UWB-radar (i.e. the bandwidth of the UWB signal) is at least 25% of the center frequency. Thus, a UWB signal centered at 2 GHz would have a minimum bandwidth of 500 MHz and the minimum bandwidth of a UWB signal centered at 4 GHz would be 1 GHz. Often the absolute bandwidth is bigger than 1 GHz.
UWB RADAR

Waveform of UWB SRR, Gaussian pulse and Gaussian doublet