Increasing Automotive Safety with 77/79 GHz Radar Solutions for ADAS Applications

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A P R . 2 0 1 4
Agenda

• Market Overview
• The Fundamentals of Radar Systems
• Freescale Automotive 77/79 GHz Radar Roadmap
  – Bare Die Radar Chipset
  – MR2001 Scalable Packaged Radar Chipset
  – MR3000 Single Package Radar Transceiver
• Summary and Conclusions
Market Overview
Why is Radar Exciting?

Market is taking off
- Assistance, safety
- Autonomous driving trend
- Units are small, BOM ~$50-100
- TAM ~$100M in 2016, CAGR 40%

Chips are highly differentiated
- Valuable
- Difficult to replicate
- Currently few qualified suppliers

Freescale investing in total solution
- Radar transceiver (Analog)
- Radar processor (Auto MCU)
Fundamentals of Radar Systems
The basic radar system (1 Transmit & 1 Receive channel)

RADAR (Radio Angle Detection And Ranging)

Microprocessor
- Control
- Signal Processing
- Object Detection
- Object Classification

Signal Generation
Transmitter Chain

Receiver Chain
Down Conversion

Radar Equation:

\[ P_r = \frac{P_t G_t A_r \sigma}{R^4} \times \left[ \frac{F^4}{(4\pi)^2} \right] \]

Symbols
- \( P_r \) = Received power
- \( P_t \) = Transmitted power
- \( G_t \) = Gain of the transmitting antenna
- \( \sigma \) = Scattering cross section of object
- \( A_r \) = Area of the receiving antenna
- \( R \) = Range to the object
Radar Equation Calculation

GTx = 23 dBi
GRx = 23 dBi
PTx = 10 dBm
F=76.5 GHz

RCS = 10 ➔ Car
RCS = -20 ➔ Pedestrian
What is required for the transmit and receive chain?

**Signal Generation Transmitter Chain**

- **VCO**
- **PLL**
- **PA**
- **State Machine SPI**
- **Timing**
- **LO**
- **SPI**
- **Tx**

**Tx Performance Metrics**
- Output power
- Phase noise
- FMCW linearity
- Temp performance

**Receiver Chain Down Conversion**

- **LNA**
- **Mixer**
- **BB VGA**
- **State Machine SPI**
- **SPI**
- **Rx**
- **IF**

**Rx Performance Metrics**
- Noise figure
- Conversion gain
- Input linearity
- Temp performance
The basic radar system (1 Transmit & 1 Receive channel)

Signal Generation
- Transmitter Chain
- Receiver Chain
- Down Conversion

Microprocessor
- Control
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- Object Classification

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Electronically Scanned Automotive Radar

FUJITSU TEN Develops "Automotive Compact 77GHz 3D Electronic Scan Millimeter Wave Radar"  
Distance, Azimuth and Elevation range Detection  
- Reference Exhibit at "19th ITS World Congress Vienna, Austria" -

Older Style Mechanically Scanned Radar

Source: F-TEN, FCC website

Source: Continental, Gruson, 2012 Workshop on Antenna

Delphi Electronically Scanning Radar

Delphi has applied more than 20 years of radar experience to develop its award-winning electronically scanning radar (ESR). Leveraging expertise gained from radar production that began in 1990, Delphi brought ESR to market at a price that is helping make radar-based safety and convenience systems more affordable in the automotive market.

Delphi's multimode ESR combines a wide field of view at mid-range with long-range coverage to provide two measurement modes simultaneously. While earlier forward looking radar systems used multiple beam radars with mechanical scanning or several fixed, overlapping beams to attain the view required for systems like adaptive cruise control, Delphi's multimode ESR provides wide coverage at mid-range and high-resolution long-range coverage using a single radar. Wide, mid-range coverage not only allows vehicles cutting in from adjacent lanes to be detected but also identifies vehicles and pedestrians across the width of the equipped vehicle. Long-range coverage provides accurate range and speed data with powerful object discrimination that can identify up to 94 targets in the vehicle's path.
The Electronic Scanning Radar ESR
(n Transmit & m Receive channel)

- Different Tx channels can be used to drive different antennas (near and long range scans for instance)
- Multiple Tx channels can be used simultaneously to provide beam steering capability
- Multiple Rx channels can be used to obtain angular information about the objects due to phase change of the arriving signal at different receive antenna
Electronic Beam Forming: Rx

- Targets are illuminated with a wide TX pulse.
- From the phase difference between the 2 RX signals, the angle can be determined.

Phase difference

2 RX antennas

Wide TX pulse in azimuth

Mix1

Mix2

from VCO

elevation

azimuth
Transmit Signal Modulation Types

**Pulse Modulation**

\[ f \]

\[ t_f \]

\[ t \]

**FMCW Modulation (Slow Modulation)**

\[ f \]

\[ BW \]

\[ T_{chirp} = 5mS \]

**Pulse Chirp FMCW (Fast Modulation)**

\[ f \]

\[ BW \]

\[ T_{chirp} = 30\mu S \]

**Time of Flight vs Object Distance**

<table>
<thead>
<tr>
<th>Distance</th>
<th>1000 meters</th>
<th>100 meters</th>
<th>10 meters</th>
<th>1 meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_f )</td>
<td>6.6( \mu s )</td>
<td>667ns</td>
<td>67ns</td>
<td>6.7ns</td>
</tr>
</tbody>
</table>

- Very short pulse generation is difficult in general
- Difficult to contain the frequency spectrum to regulations
- Object velocity obtained from Doppler shift
- At short distances Tx and Rx signal overlap

**Beat Frequency**

\[ f_b = \frac{2RBW}{c_0 t_{chirp}} \]

**Doppler Frequency**

\[ f_{doppler} = \frac{2v_r f_{tx}}{c_0} \]

**IF Frequencies**

\[ f_{IF} = [f_{beat}, f_{doppler}] \]

**Range Resolution**

\[ \Delta R = \frac{0.5c_0}{BW} \]
Example calculation of the radar equations

<table>
<thead>
<tr>
<th>Radar Equations</th>
<th>Slow</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Vrel (km/h)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Ftx (GHz)</td>
<td>76.5</td>
<td>76.5</td>
</tr>
<tr>
<td>BW (MHz)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Tchirp (uS)</td>
<td>5000</td>
<td>30</td>
</tr>
<tr>
<td>Fbeat (kHz)</td>
<td>6.7</td>
<td>1111.9</td>
</tr>
<tr>
<td>Fdoppler (kHz)</td>
<td>7.088</td>
<td>7.088</td>
</tr>
<tr>
<td>ΔR (m)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Beat and doppler frequency for fast and slow modulation

**Fast Modulation IF Band**

**Slow Modulation IF Band**

- \( V_r = 10 \text{ km/h} \)
- \( V_r = 50 \text{ km/h} \)
- \( V_r = 200 \text{ km/h} \)
# Tradeoffs Between Slow And Fast Modulation Systems

## Near Range Scan

<table>
<thead>
<tr>
<th>Velocity - 0km/h</th>
<th>Slow</th>
<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
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<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>50</td>
<td>75</td>
<td>75</td>
<td>100</td>
<td>100</td>
<td>175</td>
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<td>250</td>
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<td>Vrel (km/h)</td>
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<td>0</td>
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<tr>
<td>BW (MHz)</td>
<td>500</td>
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<td>250</td>
</tr>
<tr>
<td>Tchirp (us)</td>
<td>5000</td>
<td>30</td>
<td>5000</td>
<td>30</td>
<td>5000</td>
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</tr>
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<td>Fbeat (kHz)</td>
<td>6.7</td>
<td>1111.9</td>
<td>33.4</td>
<td>5559.4</td>
<td>50.0</td>
<td>8339.1</td>
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<td>83.4</td>
<td>6949.3</td>
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<tr>
<td>Fdoppler (kHz)</td>
<td>0.000</td>
<td>0.000</td>
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<td>ΔR (m)</td>
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<td>0.3</td>
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<td>0.3</td>
<td>0.3</td>
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</table>

## Velocity - 50km/h

<table>
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<tr>
<th>Velocity - 50km/h</th>
<th>Slow</th>
<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
<th>Slow</th>
<th>Fast</th>
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<td>100</td>
<td>100</td>
<td>175</td>
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## Velocity - 200km/h

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</tr>
</tbody>
</table>
• Range FFTs
  - real to complex transform, provide SNR gain
Signal Analysis – Doppler

- Doppler FFTs
  - Complex to complex
  - Provide SNR gain
  - Determine the relative speed (Doppler gates)
## Why Fast Modulation?

<table>
<thead>
<tr>
<th>Application and System Requirements</th>
<th>Fast Modulation Benefits</th>
<th>Fast Modulation Tradeoffs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR, MRR, &amp; LRR radar</td>
<td>Fully supports all modes of operation in one sensor</td>
<td>Larger data cube requires high performance process engine and memory for 3D-FFT</td>
</tr>
<tr>
<td>Multiple target tracking, SNR</td>
<td>Direct separation of speed and distance since they are not in the same IF band</td>
<td>Larger data cube requires high performance process engine 3D-FFT</td>
</tr>
<tr>
<td>Target separation, PN</td>
<td>IF frequency band (500 K to 10 MHz) in lower region of PN</td>
<td>Complex design for fast chirp VCOPLL and Tx switching</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>High in MHz range, but out of the 1/f noise range</td>
<td>Requires higher performance A/D</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Fast chirps allow reduced operational duty cycle</td>
<td>None</td>
</tr>
</tbody>
</table>
MR1500 Chipset
**Differentiating Points**

- Highly integrated 77 GHz automotive radar chipset supports up to 4 Tx and 16 Rx channel configurations for 2D, 3D, DBF, and SAR automotive radar applications
- Supports slow and fast modulation to 10 MHz / 100 ns
- Fully integrated PLL and chirp generator programmed via SPI along with Tx power level, channel activation, and state machine control
- Designed for integration with a multitude of microprocessors including Freescale’s MPC567xK MCU

**Samples**: Available  
**PPAP**: Q1 2013
MR2001 Chipset
MR2001 Packaged 77 GHz Radar Chipset

The MR2001 chipset is a scalable radar solution for high end and low end ADAS applications, industrial safety, security, and robotics

**Differentiating Points**

- Scalable to 4 TX channels and 12 RX channels
- Activate simultaneous Tx channels for electronic beam steering
- Supports fast modulation at 100 MHz / 100 ns
- Integrated baseband filter and VGA saves system bill-of-materials cost
- Local oscillator at 38 GHz to lower the distribution loss and reduce system interference

**Key Characteristics**

- Low power consumption 2.5 W typical for the complete transceiver chipset
- Differential Tx outputs delivering minimum 10 dBm with 5-bit digital power control
- Advanced packaging technology with BGA format
- Integrated bi-phase modulator for advanced correlation coding
- Built-in receive chain test mode when using Qorivva MPC577xK microprocessor
- Best phase noise performance < -85 dBc/Hz at 100 kHz offset, and -95 dBc/Hz at 1 MHz offset
- Temperature detector on each MR2001 chip

**Typical Application Diagram**

- **Samples:** Now
- **PPAP:** Q3 2014

Preliminary—Subject to Change Without Notice
MR2001 77 GHz Chipset and Qorivva MPC577xK MCU

Previous Generation

MR2001 77 GHz Chipset
- Replaces:
  - Bare Die RF solutions with a RF Chipset based on RCP package technology
  - Discrete Filter Components and Amplifiers
- Enables:
  - Significantly lower assembly cost
  - Lower PCB cost

Next Generation

Qorivva MPC577xK MCU
- Replaces:
  - 8 ADC
  - 1 DAC
  - 1 FPGA
  - External SRAM
  - General purpose MCU
- Enables:
  - Significant PCB area saving
  - Reduced assembly cost
MR2001 Packaged 38 GHz 4-Channel VCO

- 38 to 38.5 GHz Output
- Supply Voltage 3.3 V, 4.5 V +/- 5%
- Supply Current typ. 180 mA, 50 mA
- Power Dissipation 0.8 W
- Tuning Voltage 0.2 to 4.2 V
- \( KVCO = 2.5 \text{ GHz/V}^* \)
- Pushing typ. 250 MHz/V^*
- Static Pulling < 10 MHz^*
- Phase Noise typ. -95 dBc/Hz@1 MHz^*
- LO Power min. 3 dBm
- Power Control (4 steps)

^*values are transferred to 77 GHz
Targeted Parameters

<table>
<thead>
<tr>
<th>Index</th>
<th>Parameter Name</th>
<th>Max Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCO28</td>
<td>PN_10kHz</td>
<td>-40 dBc/Hz</td>
</tr>
<tr>
<td>VCO29</td>
<td>PN_100kHz</td>
<td>-70 dBc/Hz</td>
</tr>
<tr>
<td>VCO30</td>
<td>PN_1MHz</td>
<td>-92 dBc/Hz</td>
</tr>
<tr>
<td>VCO31</td>
<td>PN_10MHz</td>
<td>-112 dBc/Hz</td>
</tr>
</tbody>
</table>

Measured Max Values

<table>
<thead>
<tr>
<th>Offset-freq</th>
<th>dBc/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN@10kHz</td>
<td>-45</td>
</tr>
<tr>
<td>PN@100kHz</td>
<td>-71</td>
</tr>
<tr>
<td>PN@1MHz</td>
<td>-94</td>
</tr>
<tr>
<td>PN@10MHz</td>
<td>-117</td>
</tr>
</tbody>
</table>

Phase noise vs. Offset Frequency

- VCC+/−5%, T=25°C Cell=RCP363
- VCC+/−5%, T=−40°C Cell=RCP363
- VCC+/−5%, T=125°C Cell=RCP363

Related to FC=2* oscillation frequency
MR2001 Packaged 77 GHz 2-Channel Tx

- 76 to 81 GHz Tx Output
- 38 to 40.5 GHz LO Input
- Supply Voltage 3.3 V +/- 5%
- Supply Current typ. 280 mA
- Power Dissipation 0.9 W
- Power Control (6-bit)
- Tx Power typ. 2 x 10 dBm
- Bi-Phase Modulation
- SPI (slow) and dedicated control (fast)
MR2001 Tx Output Power vs Temperature

FSL-ES3-PA/TX: Board2 - TX1 - Power @ Balls vs PA-Code; 3,3V; 76,5GHz

PA-Code [decimal]

P_{@Balls} [dBm]

-30 -28 -26 -24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20

-25°C / 3,3V / 76,5GHz
-105°C / 3,3V / 76,5GHz
-125°C / 3,3V / 76,5GHz
-45°C / 3,3V / 76,5GHz
MR2001 Packaged 77GHz 3-Channel Rx

- 76 to 77 GHz RX input
- 38 to 38.5 GHz LO input
- Supply Voltage 3.3 V +/- 5%
- Supply Current typ. 240 mA
- Power Dissipation typ. 0.8 W
- Baseband suitable for Qorivva MPC577xK MCU (5 MHz)
- On Chip RF and baseband test concept
- Linearity > -5 dBm
- Conversion Gain 23-60 dB @ 4 MHz
- SSB Noise Figure typ. 14 dB
- Saturation Detectors
- Tri-State IF Outputs
# Channel to Channel Isolation Performance

**RCP Packaged on RF Test Board**

## 2chTx, channel to channel isolation

**RCP part#83**

<table>
<thead>
<tr>
<th>Temp</th>
<th>VCC</th>
<th>PTX1 (dBm)</th>
<th>PTX2 (dBm)</th>
<th>Suppression of Tx1 to Tx2</th>
<th>PTX2 (dBm)</th>
<th>PTX1 (dBm)</th>
<th>Suppression of Tx2 to Tx1</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>VCCL</td>
<td>13.3780307</td>
<td>-31.1264364</td>
<td>44.5044671</td>
<td>13.19151078</td>
<td>-29.7696062</td>
<td>42.96111698</td>
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<tr>
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<td>VCCN</td>
<td>13.62436295</td>
<td>-29.1294747</td>
<td>42.75383765</td>
<td>13.36192185</td>
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<td>VCCH</td>
<td>14.0060923</td>
<td>-31.7361246</td>
<td>45.7422169</td>
<td>13.6991058</td>
<td>-33.2508626</td>
<td>46.9499684</td>
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<tr>
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<td>VCCH</td>
<td>14.8796449</td>
<td>-28.1951796</td>
<td>43.0748245</td>
<td>15.2787074</td>
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<td>125°C</td>
<td>VCCL</td>
<td>8.76883911</td>
<td>-39.7677032</td>
<td>48.53654231</td>
<td>7.53366858</td>
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<td>VCCN</td>
<td>9.20925148</td>
<td>-34.2685666</td>
<td>43.47781808</td>
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<td>VCCH</td>
<td>9.81352394</td>
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<td>9.33657767</td>
<td>-33.6667823</td>
<td>43.00335997</td>
</tr>
</tbody>
</table>

| min. suppression | 40.4314196 | min. suppression | 38.81841305 |

## 3chRx, channel to channel isolation @ 1MHz

![Graph showing channel to channel isolation at 1MHz](graph.png)
MR3000 Radar Transceiver
System (MIPI-CSI2): 4 Tx + 4 Rx

- MRD2001Tx
- MRD3000 Master
- SPI

Connections:
- TX3, TX4, TX1, TX2
- RX1, RX2, RX3, RX4
- config & status
- measurements (sense) & control
- calibration & ASIL
- data & clock

Power Supply:
- RF/Analog: 5 V, 3.3 V
- Digital: 3.3 V

FSL packaged solution
General solution

40 MHz
XTAL
System (MIPI-CSI2): 4 Tx + 8 Rx

MRD3000

Slave

MIPI-CSI

TX3
TX4
RX5 RX6 RX7 RX8

SPI

config & status

measurements & control

data & clock

calibration & ASIL

MRD3000

Master

MIPI-CSI

TX1
TX2
RX1 RX2 RX3 RX4

SPI

loop filter

XTAL

config & status

Racerunner

Premium

8 x ΣΔ ADC
2 x SPI
MIPI-CI
SAR ADC
GPIO

40 MHz

XTAL

RF/Analog
5 V
3.3 V
Digital
3.3 V

Power Supply

FSL packaged solution

General solution
Please visit the radar demo A3

77 GHz Radar Using Fast Modulation Technology

- Qoriva MPC577xK MCU, the MRD2001 packaged 77 GHz transmitter, and IP on integrated PLL and ramp generator from future MRD3000 packaged 76-81 GHz transceiver
- Scalable for multichannel operation
- Enables a single radar platform with beam steering and wide field of view
- Applicable across automotive safety and industrial systems
Summary and Conclusions
Summary and Conclusions

• 76/79 GHz automotive radar will play a critical role in Vision Zero and the fully autonomous driving car

• The increasing number of radar modules in the car puts extensive pressure on the following features
  – Size, weight, and power do matter – integration counts
  – Tx and Rx channel count differentiate low and high end systems
  – Packaged products are a must for ease of manufacturing at 77 GHz

• Fast modulation is the trend today for automotive radar
  – The unambiguous direct separation of object range, velocity, and angle is critical in ADAS systems for object rich environments

• Freescale has an extensive portfolio of radar solutions that can address these requirements