CMOS mm-wave imaging radars: State-of-the-art and a peek into the future!

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1TU Braunschweig, 2 Texas Instruments
D-Band FMCW Radars: System and Circuits

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FMCW Radars : Range Auto-correlation

- IF beat proportional to ToF (and range)
- Observation time ≈ Chirp duration
High Frequency Radars: Fine resolution

- Broad bandwidth: Finer range resolution
- A high $f_c$: Higher displacement responsivity
- Larger arrays (fixed form factor): Finer angular resolution

\[ \phi_{\text{res}} = \frac{\lambda_0}{A_{\text{array}}} \]
\[ \frac{c \, \omega_f}{2 \Delta f_{RF}} \]
\[ \phi = \frac{d \, \lambda_0}{4 \pi} \]
Target applications at 145 GHz: Heartbeat detection and Gesture recognition

- Broad bandwidth: 10GHz at <10% $\Delta f/f_0$
  - Minimum Range resolution: 1.5 cm
  - Displacement responsivity: $2\pi$-rad/mm
  - Angular resolution: 0.5 rad
  - Velocity resolution: 1-km/hr
  - IF Bandwidth: 15 MHz

- Integrated antennas → compact, reliable
- MIMO Radar: 16-element virtual array
- Complete system performance and link summary: JSSC 2021-[1]

<table>
<thead>
<tr>
<th></th>
<th>Gestures</th>
<th>Heartbeat</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS (dBsm)</td>
<td>-40</td>
<td>-40</td>
</tr>
<tr>
<td>Range (m)</td>
<td>0.1 – 1</td>
<td>0.5 – 7</td>
</tr>
</tbody>
</table>
The SNR bottleneck at High Frequencies

- Pathloss increases for a SISO link due to smaller antennas
- RCS reduces with object size: -40dBsm (people: 0-5 dBsm, cars 10-13 dBsm)
- Fast chirps help circumvent flicker noise at IF

Reflected power $P_{RX}$ and Captured fraction

$$P_{RX} = \frac{P_{TX}}{4\pi \cdot d^2} G_{TX} \cdot \sigma \times \frac{1}{4\pi \cdot d^2 \cdot A_w}$$

where

$$A_w = \frac{G_{RX} \cdot \lambda_0^2}{4\pi}$$

Floor noise $N_{floor}$

$$N_{floor} = -174 + 10 \cdot \log \Delta f_{IF} + NF$$

$$\Delta f_{IF} = \left[ \left( \frac{2R_{min} \cdot \Delta f_{RF}}{c \cdot T_c} \right), \left( \frac{2R_{max} \cdot \Delta f_{RF}}{c \cdot T_c} \right) \right]$$
# Negative SNR at IF and Processing Gain

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gesture</th>
<th>H.Beat</th>
<th>Units</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar range – ([R_{min}, R_{max}])</td>
<td>[0.1,1]</td>
<td>[0.5,7]</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Output RF power per TX – (P_{TX})</td>
<td>0.1 (-10)</td>
<td>10 (10)</td>
<td>mW (dBm)</td>
<td></td>
</tr>
<tr>
<td>Received SISO power – (P_{RX})</td>
<td>-132.7</td>
<td>-146.5</td>
<td>dBm</td>
<td>(10 \cdot \log \left( \frac{P_{TX}G_{TX}G_{RX}\lambda_0^2}{(4\pi)^3 \cdot d^4} \right) + 30)</td>
</tr>
<tr>
<td>RX Noise figure – (NF)</td>
<td>8</td>
<td>8</td>
<td>dB</td>
<td></td>
</tr>
<tr>
<td>Noise Floor – (N_{floor})</td>
<td>-94.2</td>
<td>-94.2</td>
<td>dBm</td>
<td>(-174 + 10 \cdot \log \Delta f_{IF} + NF)</td>
</tr>
<tr>
<td>SNR at IF – (SNR_{IF})</td>
<td>-38.4</td>
<td>-52.2</td>
<td>dB</td>
<td>(P_{RX} - N_{floor})</td>
</tr>
</tbody>
</table>

**SNR improvement:**
- Array gain from MIMO operation
- Signal processing (Range-Doppler FFTs and digital filtering)
- Virtual array of $N_{TX} \times N_{RX} \rightarrow$ TX: $\lambda_0/2$ and RX: $N_{TX_A} \times \lambda_0/2$
- One-way pattern containing TX and RX : Array gain = $10\log(N_{TX} \times N_{RX})$
- Orthogonality (cross-corr. of all TX signals ~0) – Code domain MIMO
- Reduction in max. unambiguous velocity by a factor $1/N_{TX}$
Range processing gain: Fast-time FFT

- Spectrum from \(-f_s/2\) to \(f_s/2\) in steps of \(f_s/N\)
- Gain = \(10\times\log[(1/2)\times(N_R/\text{OSF})]\)
- Freq. res. at IF = \(f_s/N_R = 1/T_c\) → Range res. = \(c/2\Delta f_{RF}\)
- Windowing: Range res. = \([c\times w_f/2\Delta f_{RF}]\) and Gain = \(10\times\log(N_R/(2\times\text{OSF})) - W_{PL}\) ([1]-[3])
**Doppler processing gain:** Slow-time FFT

**Range-Doppler Map**

- Doppler FFT → $f_{s_dop} = 1/(T_C + T_r)$: $-f_{s_dop}/2$ to $f_{s_dop}/2$ in steps of $f_{s_dop}/N_{dop}$
- Gain = $10 \times \log(N_{dop})$
- $N_{dop} = (f_{s_dop} \lambda_0 / 2v_{res})$

**Digital filtering:** Heart beat

- Range FFT: complex values in range bins
- Rel. phase change monitored via digital filtering in target range bin
- Gain = $10 \times \log10(f_{s_dop}/\Delta f_{filter})$
Signal processing gain enables detection

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<th>H.Beat</th>
<th>Units</th>
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<td>-38.4</td>
<td>-52.2</td>
<td>dB</td>
<td>$P_{RX} - N_{floor}$</td>
</tr>
<tr>
<td>Range Processing gain - $G_{PR}$</td>
<td>12.2</td>
<td>20.7</td>
<td>dB</td>
<td>$10 \cdot log \left( \frac{1}{2 OSF} \right) - W_{PL}; W_{PL, Blackman, Harris} \sim 3dB$</td>
</tr>
<tr>
<td>Doppler Processing gain – $G_{PDop}$</td>
<td>27.2</td>
<td>-</td>
<td>dB</td>
<td>$10 \cdot log(N_{Dop})$</td>
</tr>
<tr>
<td>Digital filtering gain – $G_{DF}$</td>
<td>-</td>
<td>32.5</td>
<td>dB</td>
<td>$10 \cdot log \left( \frac{f_{s, Dop}}{\Delta f_{Digital, filt}} \right)$</td>
</tr>
<tr>
<td>Array Gain – $G_{A}$</td>
<td>6</td>
<td>6</td>
<td>dB</td>
<td>$10 \cdot log(N_{TX} \cdot N_{RX}); N_{TX} = N_{RX} = 2$</td>
</tr>
<tr>
<td>Code-domain MIMO gain– $G_{CM}$</td>
<td>3</td>
<td>3</td>
<td>dB</td>
<td>$10 \cdot log(N_{TX})$</td>
</tr>
<tr>
<td>Signal Processing Gain – $G_{DSP}$</td>
<td>48.4</td>
<td>62.2</td>
<td>dB</td>
<td>$G_{PR} + G_{A} + G_{DF} + G_{CM}$</td>
</tr>
<tr>
<td>Target SNR – $SNR_{eff}$</td>
<td>10</td>
<td>10</td>
<td>dB</td>
<td>$SNR_{IF} + G_{DSP}$</td>
</tr>
</tbody>
</table>
Overview of the Radar System

- On-chip antennas → Leakage suppression
- Duty-cycled FM transmission (low power mode)
- Fast chirps (5-50us, 103kHz $e_{rms}$) : ↑Doppler resolution + avoid 1/f noise

**JSSC 2021**, [1]

TX: 127-154GHz; EIRP = 11dBm
RX: 138-151GHz; NF = 8dB; Gain 24-84dB
The Transmit path (0.9V supply)

- Spatial power combining via on-chip dipoles
- $\phi$-inversion for outer-code MIMO
- x3 frequency multiplication ($15\% \Delta f/f_0$):
  - Harmonic self-mixing tripler
  - $2f_0$ trap at transformer center-tap
145-GHz Front-End Components: PA and LNA

- Custom Imec device models (up to 67GHz)
- \( C_n : \) MOM capacitors
- Fan-out + round-table layout
- Stand-alone PA: \( P_{\text{sat}} = 7 \text{dBm} (7\%) \) – [5]
- LNA: Stagger tuned for flat response
- On-chip Antenna customized for RX NF (~8dB)

PA: \( W_{\text{stages}_1-4} = 16,20,40,80\mu\text{m} \)
LNA: \( W_{\text{stages}_1-4} = 12,20,20,20\mu\text{m} \)
Simulated Performance of the Transmitter

- \( P_{sat} \) of 9 dBm with a DC-RF efficiency of \(~5.8\%\)
- Bandwidth expansion when the PA is saturated: 25 GHz
Sub-arrayed Dipole Antenna

- Constructive interfere (pattern-fill AMC)
- Thin silicon substrate ~100µm (attenuate higher order modes)
- \( d = \lambda_{\text{half-guide}} \) TM\(_0\) : partially cancel substrate waves (\(\uparrow \eta_{\text{rad_sim}}\) by ~15%)
- RF absorber on PCB mitigates effect of edge radiation
Sub-arrayed Dipole Antenna: E-field distribution

- Substrate waves are partially cancelled
- Reduction of edge radiation
- $\eta_{rad\_sim}$ by ~15%
Receive path (0.9V RF and 1.8V IF)

- Replica of TX buffering and up-conversion
- 6\textsuperscript{th} order filter for noise and alias at $f_s/2$ (DSP clock rate 80MHz)
- $G_m$ interface: preserves NF + HPF + shift supply domain + DC-offset block
- TX-leakage suppression : delay control + offset cancellation
Delay controlled leakage neutralization

\[ \tau_{\text{comp}} = \Sigma \tau \] : removes DC component, PN skirt; residual PA noise stays

\[ \tau_{\text{comp}} < \Sigma \tau : f_{\text{beat}} > f_{\text{ramp}} \] : leakage appears as \( f_{\text{beat}} \) at IF

\[ \tau_{\text{comp}} < \Sigma \tau : f_{\text{beat}} < f_{\text{ramp}} \] : DC + sidebands at \( n f_{\text{ramp}} \) (decay as \( \tau_{\text{comp}} \rightarrow \Sigma \tau \))

Fixed delay compensates the array: range resolution is 2.7 cm ~ 15 \( \times \) \( \lambda \)
ICs: SISO TRX and Single-RX Dual-TX Chipset

- SISO TRX: dual PA drive to sub-array elements
- Dual-TX chipset: Single PA drive to sub-array elements
- RX is the same in the SISO and stand-alone version
MIMO radar implementations: 1x4 and 4x4

2x2 MIMO assembly

\[
\begin{array}{c}
\text{TX} & \xrightarrow{\lambda/2} & \text{TX} & \xrightarrow{\lambda} & \text{RX} & \xrightarrow{\lambda/2} & \text{RX} \\
\xrightarrow{\text{3-dB Splitter}} & & & & & & \\
\xrightarrow{\text{PLL}} & & & & & & \\
\xrightarrow{\text{pcb}} & & & & & & \\
\end{array}
\]

4x4 MIMO assembly

\[
\begin{array}{c}
\text{TX} & \xrightarrow{\lambda/2} & \text{TX} & \xrightarrow{\lambda} & \text{RX} & \xrightarrow{\lambda/2} & \text{RX} \\
\xrightarrow{\text{PLL}} & & & & & & \\
\xrightarrow{\text{pcb}} & & & & & & \\
\end{array}
\]
MIMO Radar Module

- Xilinx Zedboard IF outputs
- MIMO radar
- ADC board
- Add-on board
- PLL
- ADC board
- IC assembly
  - ADCs 14-bit TI™
  - MIMO Radar, 16-GHz PLL
- SPI control
- Voltage regulators, 32b µ-controller
- 80-MHz clock
- Sync pulse
- Network (Gbps Ethernet)
- USB
- HOST PC MATLAB™

- Xilinx™ Zedboard Memory, FFTs, Digital filtering
- Development platform

- Development platform

- Add-on board

- Add-on board
TX characterization: Agilent PNAx & VDI Extender

- Power at 145GHz vs. distance: expected $1/r^2$ far-field gradient
- 3dB bandwidth: 127-154GHz (SISO TX) and 131-153 GHz (dual-TX IC)
- EIRP 11.6 dBm (SISO TX) and 8.4 dBm (dual-TX IC)
- 138-151GHz RF bandwidth
- Peak CG= 84dB with 57dB prog.
- IF bandwidth 400kHz to 17MHz
Radar Measurements: Delay control

- Noise autocorrelation test: shows improvement in NF with delay control
- During radar operation, delay control plays a significant role in mitigating leakage
Radar Measurements: Range resolution

- Measurements compare well with theory taking into account chirp non-linearity
Heart beat and respiration Measurements

(a) Heartbeat Emulator
(b) MIMO Board

(c) Speaker diaphragm

(d) Phase (degrees)

Respiration

Nexus-10 resp. rate: 16.9 breaths/min.

Radar resp. rate: 16.7 breaths/min. (filtered)

(a) Heartbeat probes
Our Radar
NexXus-10 MK-II
Sync pulse, and readout
Respiration waist belt

(b) ECG Nexus-10 heartrate: 78.7 bpm
(c) Radar Heartrate: 79.1 bpm (filtered)
(d) Nexus-10 resp. rate: 16.9 breaths/min.
Gesture detection and recognition

- Hand illuminated at several 100 frames/sec
- R-D maps in each beam direction (+30, 0, -30 degrees)
- Gesture is captured in data cubelets (range bins x Doppler bin x Angle bins)
- Sent to a machine learning classifier for recognition
## Comparison with State of the Art designs

<table>
<thead>
<tr>
<th>Reference</th>
<th>This work SISO TRX</th>
<th>This work TRX chipset</th>
<th>[54]</th>
<th>[55]</th>
<th>[56]</th>
<th>[57]$^c$</th>
<th>[58]</th>
<th>[7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>28nm CMOS</td>
<td>28nm CMOS</td>
<td>0.13μm SiGe</td>
<td>65nm CMOS</td>
<td>45nm CMOS</td>
<td>0.35μm SiGe</td>
<td>55nm SiGe</td>
<td>35nm mHEMT</td>
</tr>
<tr>
<td>Radar type</td>
<td>FMCW</td>
<td>FMCW</td>
<td>FMCW</td>
<td>Pulsed</td>
<td>FMCW</td>
<td>FMCW</td>
<td>FMCW</td>
<td>FMCW</td>
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<tr>
<td>RF frequency [GHz]</td>
<td>145</td>
<td>145</td>
<td>240</td>
<td>160</td>
<td>79</td>
<td>60</td>
<td>221</td>
<td>240</td>
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<tr>
<td>TRX Bandwidth [GHz]</td>
<td>13</td>
<td>13</td>
<td>60</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>62.4</td>
<td>40</td>
</tr>
<tr>
<td>Range resolution [mm]</td>
<td>30$^a$</td>
<td>30$^a$</td>
<td>3</td>
<td>21</td>
<td>38</td>
<td>21</td>
<td>2.4</td>
<td>3.7</td>
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<tr>
<td>Channels</td>
<td>1TX-1RX</td>
<td>2TX Chip</td>
<td>1RX Chip</td>
<td>1TX-1RX</td>
<td>4TX-4RX</td>
<td>3TX-4RX</td>
<td>2TX - 4RX</td>
<td>1TX-1RX</td>
</tr>
<tr>
<td>TX Power/EIRP [dBm]$^a$</td>
<td>11.6 (EIRP)</td>
<td>8.5 (EIRP)</td>
<td>5</td>
<td>4</td>
<td>10.8</td>
<td>4</td>
<td>14$^b$ (EIRP)</td>
<td>6</td>
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<tr>
<td>RX Gain [dB]</td>
<td>87</td>
<td>94</td>
<td>10</td>
<td>42.5</td>
<td>NA</td>
<td>19</td>
<td>NA</td>
<td>10</td>
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<td>Noise Figure [dB]$^b$</td>
<td>8</td>
<td>8</td>
<td>21</td>
<td>22.5</td>
<td>18</td>
<td>9.5</td>
<td>28</td>
<td>7</td>
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<tr>
<td>EIRP/NF variation [dB]</td>
<td>1.5/2.5</td>
<td>1.5/2.5</td>
<td>18/25</td>
<td>3/-</td>
<td>-</td>
<td>3/1</td>
<td>7.7/7</td>
<td>3/3</td>
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<tr>
<td>IF Bandwidth [MHz]</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>100</td>
<td>15</td>
<td>1</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Chip size [mm$^2$]</td>
<td>6.5</td>
<td>3.8 (2TX)</td>
<td>3.3 (RX)</td>
<td>3.2</td>
<td>20</td>
<td>22</td>
<td>20.2</td>
<td>0.5</td>
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<tr>
<td>TRX Power diss. for all channels [mW]</td>
<td>500</td>
<td>610</td>
<td>1800</td>
<td>2200$^c,e$</td>
<td>3500$^d$</td>
<td>990$^e$</td>
<td>87</td>
<td>315</td>
</tr>
<tr>
<td>PLL power diss. [mW]</td>
<td>Off-chip</td>
<td>Off-chip</td>
<td>Off-chip</td>
<td>Off-chip</td>
<td>On chip</td>
<td>On-chip</td>
<td>Off-chip</td>
<td>Off-chip</td>
</tr>
</tbody>
</table>

$^a$ For a Single TX; $^b$ At the center frequency; $^c$ On-chip PLL and ADC; $^d$ On-chip PLL, ADC and DSP; $^e$ Pulsed operation; $^f$ RF front-end and VCO; $^g$ with an off-chip lens; $^h$ Windowed radar resolution demonstrated; $^i$ Infineon radar-BGT60TR13C
Summary

- System level overview of D-band MIMO radars: challenges and benefits
- Described SISO TRX and Dual-TX Single-RX chipset for arrayed radars
- Presented delay controlled leakage suppression
  It enables operation at high gain and eliminates leakage and associated PN
- Extensive TRX characterization:
  TX: 11dBm EIRP per on-chip antenna element
  RX: $Z_{antenna}$ customized for RX NF (8dB)
- MIMO radars (1x4 and 4x4) demonstrate heartbeat and gesture detection
The Team

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References


[3]


BACKUP SLIDES
Amplifier Design Details

![Graphs and diagrams related to amplifier design parameters.](image)

- MSG: 145 GHz
- W = 20 μm
- Capacitance, $C_R$ vs. MAG
- Frequency vs. MAG, $K > 1$
- Ref. MSG: $C_R = C_T$
- 11.2 dB
- 5.3 dB
- 145 GHz
- Roller's stability factor, $K$
- $f_a = 137\,\text{GHz}$
- $f_b = 155\,\text{GHz}$
- VSWR = 1.92

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International Microwave Symposium
6 - 11 June 2021, Atlanta, GA
MIMO Radar setup and Gesture pipeline

TX-1
TX-2
PLL
RX-1
ADC
RX-2
ADC

Range, Doppler & Angle Processing

30°

0°

-30°

Cubelets
Hand detection
Conv-1
Conv-2
FC-3
FC-4
LSTM-5
Softmax

Gesture classes