Interference Suppression Techniques for Millimeter-Wave Integrated Receiver Front Ends

Chuang Lu

Introduction

• The demand of higher data rate pushes wireless to mm-wave (>30GHz)
  – Larger bandwidth;
  – Smaller antennas, etc.

• Many attractive potential applications.

Unlicensed 60 GHz band for indoor communication
Introduction

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  – Smaller antennas, etc.
• Many attractive potential applications.

Automotive radar in the 79 GHz band
Introduction

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Introduction

• The demand of higher data rate pushes wireless to mm-wave (>30GHz)
  – Larger bandwidth;
  – Smaller antennas, etc.

• Many attractive potential applications.

And many others, e.g. 5G cellular communication, imaging...
Introduction

- We can envision that mm-wave systems will become popular and common in the future.
- As the number of mm-wave devices, systems or standards will grow dramatically in the future, interference issues will become important for the co-existence of different devices.
Interference Suppression Techniques for Millimeter-Wave Integrated Receiver Front Ends

Outline

• Introduction

• **Spatial-interference issue**
  • Robust null forming phased array
  • High resolution phase shifter design

• **Self-interference issue**
  • A filtering LNA for VSAT scenario
  • A duplexer for same-band TX/RX scenario

• Conclusions
Spatial-interference

- Phased Arrays are commonly used in mm-wave applications.

- However, spatial re-use is not fully explored at mm-wave and nulls are not used, because:
  - RF/Analog arrays
  - Limited accuracy
  - Difficult to estimate precise direction, and create accurate null

- A mm-wave null forming array is desired to be: Robust and Efficient
Proposed Robust Null Forming Array

- Discrete phase shifters and VGAs:
  - MSB: Direct mainlobe to the desired signal
  - LSB: Adjust nulls
- Manipulate the LSBs to minimize the total output power.
- Direction of interference is not needed.
- Not sensitive to the weight errors, but fine steps on the phase shifts is desired for convergence.
Proposed Robust Null Forming Array

- Genetic Algorithm (GA) is used for the optimization
  - Efficient to find the global optimum.
Simulation Results

- Array Pattern Optimization for certain interference scenarios

Assumptions:
- Uniform linear array (ULA): $N_{tot} = 16, d = \lambda/2$
- 6-bit Phase Shifter: 4MSB, 2LSB
- 2-bit VGA: 1MSB, 1LSB
- Desired signal power at RX: $-64\text{dBm at } \theta_s = 0^\circ$
- Co-channel interferences.
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• Conclusions
High resolution phase shifter design

- From the null-forming array, high resolution phase shifters are required: Fine steps rather than accuracy.
- To have enough LSB’s for optimization.
- 6-bit phase shifter is required.
- Two phase shifters are designed and implemented for the null-forming array:
  - LO-path phase shifter
  - Base-band phase shifter
LO-path phase shifter

- Phase shifting implemented by Tunable Tline + Divider-by-4.
- Reduced tuning range requirement on the tline.
- In LO path, de-coupled from the signal path.
LO-path phase shifter Measurement Result

- Average phase step: 3.5°
- Maximum phase step: 5.4°

In 40nm CMOS technology
• Make use of the quadrature signals from the I/Q mixing.
• Combine the I and Q signals with certain amplitudes, to generate output signals with certain phase shifts/amplitudes
Base-band phase shifter
Measurement Result

- 225 points
- Both amplitude and phase tuning.
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• Conclusions
Self-interference issue

- Between colocated TX and RX.

- High power TX can desensitize and saturate RX.

- Two scenarios:
  1. When TX and RX are at relatively separate frequencies
  2. When TX and RX are in the same band
Self-interference issue

1. When TX and RX are at relatively separate frequencies:

Ka-band Very-Small-Aperture terminals (VSAT) is a typical application.

Downlink 17.5 – 22 GHz

Uplink 27.5 - 31 GHz
Duplex in VSAT scenario

Challenge:

High attenuation @ 30GHz and Low NF @20GHz
Filtering LNA for VSAT Duplex

- Distribute filtering at different stages in LNA
- Compression mainly happens after amplifying
- Filtering at later stages contributes less to the total NF
Without filtering:

(Reference case)

With filtering:

0.25 μm SiGe:C BiCMOS technology
### Measurement: Gain

![Graph showing gain measurements with and without filtering at different frequencies.](image)

**Table: Gain Measurements with and without Filtering**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>With Filter</th>
<th>No Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21 (dB) @20GHz</td>
<td>24.3</td>
<td>27</td>
</tr>
<tr>
<td>S21 (dB) @17.5GHz</td>
<td>-12.9</td>
<td>17.5</td>
</tr>
<tr>
<td>S21 (dB) @31GHz</td>
<td>-20</td>
<td>15.2</td>
</tr>
</tbody>
</table>

*More than 30 dB total filtering*
Measurement: NF

0.1 to 0.4 dB NF degradation by the filtering LNA
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• Conclusions
Self-interference issue
Same-band TX/RX scenario

- When the self-interfering TX is in the same band as the RX, lumped filtering is not practical for on-chip solutions.
- Duplexer is typically used to isolate the TX and RX and typically off-chip.
- On-chip duplexers are challenging to be high isolation and low loss at mm-wave.
# Possible Duplexer Solutions

<table>
<thead>
<tr>
<th>Ferrite based circulators</th>
<th>On-chip active quasi circulator</th>
<th>Hybrid-Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Ferrite based circulators" /></td>
<td><img src="image" alt="On-chip active quasi circulator" /></td>
<td><img src="image" alt="Hybrid-Transformer" /></td>
</tr>
<tr>
<td>Isol $&gt;20$dB, Loss $&lt;0.9$dB @30GHz</td>
<td>On-chip, low-cost</td>
<td>+ Compact</td>
</tr>
<tr>
<td>But:</td>
<td>But:</td>
<td>+ Tunable</td>
</tr>
<tr>
<td>— External component, increased area and cost</td>
<td>— High loss and NF</td>
<td>+ Passive</td>
</tr>
<tr>
<td>— Limited isolation at mm-wave</td>
<td>— Linearity issue</td>
<td>+ High Isolation</td>
</tr>
</tbody>
</table>

But:
- Inherent loss at $Z_{bal}$ (3dB)
Possible Duplexer Solutions

- Isolation achieved by electrical balance
- Tunable $Z_{\text{bal}}$ to balance the impedance for high isolation
- Wideband duplexer with high isolation
- More than 6 dB total loss in link budget
Dual Antenna Hybrid-Transformer Duplexer

Replace $Z_{\text{bal}}$ by an identical antenna?

- Dual antenna duplexed by TX and RX at the same time.
- Avoid the inherent loss
- Wideband impedance balance $\rightarrow$ Wideband isolation

However, TX and RX signals at Ant1 and Ant2 are differential and common-mode signals respectively
Dual Antenna Hybrid-Transformer Duplexer

- With Orthogonally Linear-polarized (LP) Antennas

- Vertically and horizontally polarized antenna’s
- With a $1/4\lambda$ delay line (90°) on one side
Dual Antenna Hybrid-Transformer Duplexer

For TX: RHCP

For RX: LHCP
Dual Antenna Hybrid-Transformer Duplexer

- TX and RX duplexes dual-antenna with orthogonal CP towards and from the same direction
- “Circular polarization duplexer”
- Can be very useful for radar/imaging application
Tunable Hybrid-Transformer

**Why tunable?**
- Impedance transform by the $1/4\lambda$ T-line
- Mismatch between $Z_{\text{Ant1}}$ and $Z_{\text{Ant2}}$ can degrade the isolation significantly

**Impedance imbalance in:**
- Imaginary part
- Real part

**Compensated respectively by:**
- Shunt varactor
- Auxiliary coil with series varactor
Dual Antenna Hybrid-Transformer Duplexer

- Chip Implementation in 0.25 μm SiGe:C BiCMOS technology
Dual Antenna Hybrid-Transformer Duplexer

- Chip Measurement, TX and RX modes.

RX: $\text{Gain} = 18 \text{ dB}$, $\text{NF} \approx 4.1 \text{ dB}$

TX: $\text{Loss} = 3.1 \text{ dB}$ (including the balun)

$\text{BW}_{3\text{dB}}$ from 27.5 GHz to 34.5 GHz
Dual Antenna Hybrid-Transformer Duplexer

- **Chip Measurement, Isolation.**
  - S34 includes gain of LNA (about 20 dB)
- Without tuning:
  - S34 = -3dB
  - Only 23dB isolation by the duplexer
  - Degraded by the layout non-idealities
- With tuning:
  - Notches tuned for different frequencies
  - S34<-20dB for about 2GHz BW, S34<-30dB for about 1GHz
  - Corresponding to duplexer isolation of 40dB and 50dB.
Dual Antenna Hybrid-Transformer Duplexer

- **Prototype Implementation**

- On-board antennas are made and integrated with the duplexing chip.
- Sequentially rotated linearly-polarized patch antennas.
Dual Antenna Hybrid-Transformer Duplexer

- **Prototype Measurement**

- Antenna patterns.
- RX and TX patterns are orthogonal.
- Dashed lines are after tuning for high isolation.
- Minor impact on the co-pol of TX and RX.
Dual Antenna Hybrid-Transformer Duplexer

- **Prototype Measurement**

  - The plotted isolations include the 20 dB gain from the LNA on-chip.
  - High isolation achieved after tuning.
Conclusions

Interference Suppression Techniques for Millimeter-Wave Integrated Receiver Front Ends

Spatial Interference

Robust Null-forming Antenna array

Phase shifter

Desired signal

Interference

Self Interference

Different bands (VSAT scenario)

Co-located transmitter 30 GHz
coupling

Receiver - 20 GHz

Filtering LNA

Same band

Duplexer

Leakage
You are warmly welcomed to attend the defense at:

16:00 on 24th November 2015,
in Collegezaal 4, Auditorium in TU/e
and the reception afterwards.
Thank you for your attention!
Appendix

- Limited accuracy

- Difficult to estimate precise direction, and create accurate null
Table 2.3: The convergence of the algorithm and optimized SINR range by different number of LSBs. The interferences are assumed with power of -60 dBm and with AoAs of -10° and 26° for the 8-path ULA and -21° and 38° for the 8-path ULA.

<table>
<thead>
<tr>
<th>Set #</th>
<th>Phase Shifter</th>
<th>VGA</th>
<th>8-path ULA</th>
<th>16-path ULA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSB</td>
<td>LSB</td>
<td>MSB</td>
<td>LSB</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
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</tr>
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<td>8</td>
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<td>2</td>
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