WSH-3

Architectures for Scalable MIMO Transceivers at RF and mm-wave


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Contents

- Introduction
- Spatial Equalization for RF Massive MIMO Systems
- Single-Wire Interfaces for mm-Wave MIMO Systems
- Future Work
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Massive MIMO at RF

3GPP:
• Rel. 13, FD-MIMO, x16
• Rel. 14, eFD-MIMO, >x32
(courtesy: 3GPP, Samsung)

Pre-commercial development in progress.
Expected to be in market by 2020.
(courtesy: Ericsson)

• Industry attention: Ericsson, Fujitsu, Huaiwei, Intel, KeySight Technologies, MediaTek, Mitsubishi Electric, NEC, Nokia, Panasonic, Qualcomm, Rohde & Schwarz, Samsung etc.
Challenges in RF Massive MIMO Systems

RF/Analog parts of conventional RF MIMO arrays are exposed to spatial blockers.
Challenges In Scalable mm-wave Massive MIMO Systems

Efficient antenna interface/front-ends

LO synchronization for coherence

Simple IF interface for scalability and per element digitization

MIMO arrays require per-element digitization which brings the challenge of supporting high data-rate I/O in a large-scale tiled MIMO mm-wave array.
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A 65nm CMOS 0.1-1.7GHz spatio-spectral-filtering 4-element MIMO receiver array can form a single arbitrary spatial notch to reject interferers.
A 65nm CMOS 0.1-3.1GHz 4-element MIMO receiver array with an arbitrary spatial filter can form an arbitrary number of notches with arbitrary depth.
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From Phased Array to Scalable MIMO Array

- Large-scale phased array systems

384-Element@90GHz [Bell Labs]  144-Element@60GHz [Broadcom]
From Phased Array to Scalable MIMO Array

• Large-scale phased array systems
  384-Element@90GHz [Bell Labs]  144-Element@60GHz [Broadcom]

• Next paradigm: Massive MIMO

MIMO array enables full digital beamforming, simultaneous multi-beam formation, mm-wave spatial multiplexing, and per-PA digital pre-distortion.
Single-Wire Interface

• Prior work: Single-Wire interface in mm-wave phased array

  • IF signal, LO, and digital control are multiplexed over single coax cable

  ✓ Simplify scalability by easing I/O interface through a single-wire interface

  ✗ Signal combining in front-end precludes MIMO operation and throws away spatial information

Beoadcom, JSSC’14

M. Boers et al., “A 16TX/16RX 60GHz 802.11ad chipset with single coaxial interface and polarization diversity,” IEEE JSSC, 2014
Single-wire Interface multiplexes IF modulated signals along with LO for the elements in an IC to enable digital beamforming.
How to Multiplex Data on a Single Wire?

• Code-domain (De)Multiplexing

4-Element MIMO @28GHz [Oregon State Uni.]

A 4-element 28 GHz millimeter-wave MIMO RX with single-wire interface using walsh-function code-domain multiplexing.

How to Multiplex Data on a Single Wire?

• Code-domain (De)Multiplexing of IF Data

4-Element MIMO @28GHz [Oregon State Uni.]

Channel isolation trades off with code length

- Higher-order filtering in code-domain requires active correlators that consume power.

Channel isolation trades off with code length: Problem for high BW IF signals
Proposed method: (De)Mux Data on a Single Wire

- Frequency-domain (De)Multiplexing of IF Data

- Channel Isolation does not trade with SWI BW

- High isolation can be obtained in the frequency domain with small guard bands using higher-order passive filtering

- Need for different LOs (f1, f2, f3, f4)

FDM of data on a single wire is promising for scalable MIMO array providing that we can solve the need for different LOs for (de)multiplexing!
Data (De)Multiplexing Using Harmonic Mixing Concept

- Utilizing harmonic mixing concept, we can translate the stream of each antenna to different harmonics of a single LO.
- On the other end, demultiplexing can be done again using harmonic mixing concepts with the same LO.

Harmonic Mixing can be used for frequency (de)multiplexing using a single LO.
Harmonic Rejection Mixing (HRM) for Freq. domain Multiplexing

By choosing appropriate weights for each of the samples in harmonic mixer, we can emulate desirable harmonics of the LO while rejecting some others.

Harmonic amplitude for a 16-path HRM with ideal coefficients

\[ A_{NK} = \sin\left(\frac{2\pi KN}{16}\right) \]

N: desirable harmonic  K: path number

[T. Forbes, JSSC 2013]

Source of Errors in Harmonic Rejection Mixing

- Phase error in LO
  - Proper layout / design of LO phase generation and routing

- Deviation of actual rational weights from ideal irrational values

- Using Multiple stages of HRM
  [Z. Ru, ISSCC 2009]

Z. Ru et al., “A software-defined radio receiver architecture robust to out-of-band interference,” ISSCC, 2009
Two-Stage Harmonic Rejection Mixing

- Multiple-stage HRM achieves higher harmonic rejection thanks to:
  - More accurate approximation of ideal harmonic recombination irrational weights
  - Randomizing mismatch between different phases paths

Two-stage HRM can achieve harmonic rejection >40dB.
Implementation: HRM Based De-Multiplexing

Both Stages of HR are implemented using resistor banks in base-band (after the mixer) which enables us to realize the concept for a high frequency wideband system with minimum power consumption.
Implementation: Single Wire Interface

Single Wire Interface (4 I & Q Data Channels corresponding to 4 Antennas + 30G LO)

0-10 GHz Data

LPF

HPF

16 Phase Clk @1.25G

÷3

÷8

30G

10G

30 GHz Wilkinson

HRM Clock Phase Gen

Channel 1

Channel 2

Channel 3

Channel 4

60 GHz Routing

LO Buffer

Doubler
Implementation: TX with Single wire interface

45nm RF-SOI 60 GHz MIMO transmitter with frequency-domain-multiplexed single-wire interface with 10GHz IF BW.
Die Photo and Connectorized PCB

Chip Micrograph

Connectorized PCB
Channel 1 has ~ 32dB of gain and > 40 dB of harmonic rejection to other channels for three different samples. (no calibration-no trimming)
Channel 2 has ~ 32dB of gain and > 40 dB of harmonic rejection to other channels for three different samples. (no calibration-no trimming)
Channel 3 has ~ 26dB of gain and > 35 dB of harmonic rejection to other channels for three different samples. (no calibration-no trimming)
Channel 4 has ~ 22dB of gain and > 30 dB of harmonic rejection to other channels for three different samples. (no calibration-no trimming)
Channel 1 has \( \text{OP1dB} \approx 8.87 \text{ dBm} \) and Drain Efficiency \( \approx 3.41\% \) @ OP1dB.
Channel 2 has OP1dB ~ 10.93dBm and Drain Efficiency ~ 5.35% @ OP1dB
Channel 3 has OP1dB ~ 10.93 dBm and Drain Efficiency ~ 5.35% @ OP1dB
Channel 4 has OP1dB ~ 8.8dBm and Drain Efficiency ~ 3.25% @ OP1dB
EVM Measurement Setup

- **M8190A Arbitrary waveform generator**
- **Agilent Signal generator**
- **N9021B MXA Signal Analyzer**

HP 83712B Sig. gen
Anritsu MG3697C Sig. gen
AD5371 PLL Board

RF Lambda Combiner
Anritsu V240C Resistive Power Combiner

30GHz LO
Ch#1, Ch#2, Ch#3, Ch#4
DATA

EVM performance of Channel 1 is measured while signals are provided to all channels.
EVM Measurement Results

EVM\textsubscript{rms} = 3.2\%, Data rate = 200MBaud/s, 64QAM Mod., TX Power \sim 2dBm.

TX transmits 64QAM 200MBaud/sec modulated signal with an EVM\textsubscript{rms} of 3.2\%. Channel-to-channel isolation ensures no EVM degradation.
Beamforming Measurement Results

Four-element array pattern measurement with concurrent dual-beams demonstrates digital beamforming functionality.
## Comparison Table: mm-Wave Systems

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Phased-Array</td>
<td>Phased-Array Rx</td>
<td>2-Way Pol. MIMO</td>
<td>Digital Tx with 2-Way Pol. MIMO</td>
<td>4-element MIMO RX</td>
<td>4-element MIMO TX</td>
</tr>
<tr>
<td>Single-Wire Interface</td>
<td>Yes (IF data, Control, LO ref and DC)</td>
<td>No</td>
<td>No</td>
<td>CDMA based (IF data and LO)</td>
<td>FDMA based (IF data and LO)</td>
</tr>
<tr>
<td>Operation Freq.</td>
<td>60 GHz</td>
<td>60 GHz</td>
<td>60 GHz</td>
<td>28 GHz</td>
<td>60 GHz</td>
</tr>
<tr>
<td># of Elements</td>
<td>16 (Tx), 16 (Rx)</td>
<td>1 (dual polarization)</td>
<td>1 (dual polarization)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MIMO Streams</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>IF Data BW</td>
<td>2 GHz</td>
<td>3.47 GHz</td>
<td>3.52 GHz</td>
<td>400 MHz</td>
<td>8 GHz</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>N/R</td>
<td>N/R</td>
<td>N/R</td>
<td>16 (Rx)</td>
<td>20 – 35</td>
</tr>
<tr>
<td>OP_{1dB} (dBm)</td>
<td>+5.2²</td>
<td>N/R</td>
<td>N/R</td>
<td>N/A</td>
<td>8.8 – 10.9</td>
</tr>
<tr>
<td>OP_{sat} (dBm)</td>
<td>9²</td>
<td>4</td>
<td>11.5³</td>
<td>N/A</td>
<td>9.1 – 12.5</td>
</tr>
<tr>
<td>Channel-to-Channel Isolation</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>20dB</td>
<td>30-40dB</td>
</tr>
<tr>
<td>P_{DC} (mW/element)</td>
<td>74.4</td>
<td>210</td>
<td>182</td>
<td>73 (Rx)</td>
<td>220</td>
</tr>
<tr>
<td>Technology</td>
<td>40nm CMOS</td>
<td>28nm CMOS</td>
<td>28nm CMOS</td>
<td>65nm CMOS</td>
<td>45nm CMOS-SOI</td>
</tr>
<tr>
<td>Active Area (mm²/element)</td>
<td>1</td>
<td>3.9</td>
<td>3.24⁴</td>
<td>1.44</td>
<td>3.92</td>
</tr>
</tbody>
</table>
A 4-element 28 GHz millimeter-wave MIMO RX with single-wire interface using beam-space frequency-domain multiplexing.

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Future Works

- Frequency domain multiplexing can be used to implement IF channel-bonding in high data-rate mm-wave/THz transceivers.

- Harmonic reject mixing, along with image reject mixing can be used to extend the proposed architecture for dual frequency band MIMO systems.

- The proposed architecture can easily be translated to design wideband MIMO transceivers at THz frequencies with efficient wideband IF interfaces.