A 64-QAM 60GHz CMOS Transceiver with 4-Channel Bonding

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Tokyo Institute of Technology, Japan
Outline

• Motivation
• Transmitter
  • Mixer-first transmitter
• Receiver
  • Open-loop FVF-based amp.
• Measurement and Comparison
• Conclusion
60GHz-Band Capability

- QPSK \(\rightarrow\) 3.52Gbps/ch
- 16QAM \(\rightarrow\) 7.04Gbps/ch
- 64QAM \(\rightarrow\) 10.56Gbps/ch (not reported yet)

- 16QAM
  - 2-ch bonding \(\rightarrow\) 14.08Gbps
  - 3-ch bonding \(\rightarrow\) 21.12Gbps (not reported yet)
  - 4-ch bonding \(\rightarrow\) 28.16Gbps (not reported yet)
Design Considerations

• Wideband gain characteristics
  • RF: 57-66GHz
  • BB: 1.2GHz(1ch), 5GHz(4-ch bonding)

• Wide dynamic range
  • Linearity & Sensitivity
  • RX SNDR >40dB

• Low phase noise (performance limiter)*
  • -96dBc/Hz@1MHz (64QAM)

• I/Q mismatch & LO leakage**
  • Image rejection ratio <-40dBc

*K. Okada, et al., JSSC 2013
**S. Kawai, et al., RFIC 2013
Block Diagram

- Direct-conversion
- TX
  - Mixer-first topology
- RX
  - FVF BB amp.
  - Current-bleeding mixer
- LO
  - Injection-lock
  - 60GHz QILO*
  - +20GHz PLL

*K. Okada, et al., ISSCC 2011*
TX Design Considerations

Previous work*  

This work

4x

<3GHz

-29mW

50Ω input

+15dB

+13mW

+15dB

-29mW

OIP3 -15dB

*K. Okada, et al., ISSCC 2012
Mixer-First Transmitter

Mixer-first receiver*, **

Mixer-first transmitter

This work

BBout \rightarrow RFin \rightarrow LO

10MHz \rightarrow 2GHz \rightarrow (20MHz-BW)

up-converted**

RFout \rightarrow BBin \rightarrow LO

57-66GHz \rightarrow 4.5GHz

(9GHz-BW)

down-converted even for \( Z_{in} \)

* M. Soer, et al., ISSCC 2009
** C. Andrews, et al., ISSCC 2010
Input Impedance and Leakage Cancel

\[ Z_{\text{in}}(\omega_{\text{BB}}) = 200\Omega / \left[ R_{\text{sw}} + \frac{4}{\pi^2} \{ Z_{\text{RF}}(\omega_{\text{BB}} + \omega_{\text{LO}}) + Z_{\text{RF}}(\omega_{\text{BB}} - \omega_{\text{LO}}) \} \right] \]

Wideband \( Z_{\text{RF}} \) is realized by \( R_f \)-feedback.

*C. Andrews, et al., ISSCC 2010*
TX Measurement Result

Lower-side-band gain including RF path
LO=61.56GHz

Lower-side-band gain including RF path
LO=61.56GHz

Gain [dB]

Frequency [GHz]
I/Q mismatch calibration* is applied. RF VGA & QILO phase adjustment

* S. Kawai, et al., RFIC 2013
TX EVM Measurement

EVM [dB]

Average output power [dBm]

ch.3 with 7.04Gb/s

16QAM

0 1 2 3 4 5 6 7 8 9 10

EVM [dB]

Average output power [dBm]
RX Mixer

- Current-bleeding to reduce LO power
- CCC at RF input

- $P_{dc}: 11\,\text{mW}$
- $CG: -7\,\text{dB}$
- $f_{\text{low}}: 0.27\,\text{MHz}$
- $f_{\text{high}}: >4\,\text{GHz}$
RX Baseband Amplifier

• Wide bandwidth (>5GHz)
• High gain and high linearity
• Low power consumption

⇒ Open-loop FVF-based amplifier

\[ A_V \approx -\frac{g_{ds3}}{g_{m3}} \]

Flipped Voltage Follower* (FVF)

*R. Carvajal, et al., TCAS-I 2005
RX Baseband Amplifier (Cont.)

\[ A_V \approx - \frac{1}{g_{m3}R_S} \]
modified FVF

\[ A_V \approx \frac{g_{m7}R_L}{g_{m3}R_S} \]
by 6mW

\[ -g_{m7}R_L - \frac{1}{g_{m3}R_S/(1/j\omega C_S)} \]
RX Measurement Result

Lower-side-band gain including RF path
LO=61.56GHz

![Graph showing RX measurement result with lower-side-band gain including RF path. The graph plots gain in dB against frequency in GHz.]
60GHz LO Considerations

-96dBc/Hz@1MHz for 64QAM

- 60GHz Quadrature Injection Locked Oscillator*

Channel bonding

- 7 carrier frequencies

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4ch-bond

2ch-bond

Ch.1  Ch.2  Ch.3  Ch.4

58.32  59.40  60.48  61.56  62.64  63.72  64.80

* K. Okada, et al., JSSC 2013

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20.3: A 64-QAM 60GHz CMOS Transceiver with 4-Channel Bonding
60GHz Quadrature LO Design

36/40MHz ref.

- 20GHz PLL: 64mW
- 60GHz QILO: 18mW(TX) & 15mW(RX)
- QILO frequency range: 58-66GHz
- Phase noise improvement by injection locking*
- -96.5dBc/Hz @ 1MHz at 61.56GHz

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20.3: A 64-QAM 60GHz CMOS Transceiver with 4-Channel Bonding

*K. Okada, et al., ISSCC 2011
Detailed Block Diagram

- TX Output
- PA
  - $P_{sat} = 10.3 \text{ dBm}$
- LNA
  - $NF = 4.2 \text{ dB}$
- RX Input

- RF amp.
- I Mixer
- Q Mixer

- LO buf.
- 60GHz QILO
- 20GHz PLL
- 60GHz QILO
- BB amp.
  - (FVF-FVF-SF)

- Control Logic
Die Photo

65nm CMOS

<table>
<thead>
<tr>
<th>Block</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX</td>
<td>1.03mm²</td>
</tr>
<tr>
<td>RX</td>
<td>1.25mm²</td>
</tr>
<tr>
<td>PLL</td>
<td>0.90mm²</td>
</tr>
<tr>
<td>Logic</td>
<td>0.67mm²</td>
</tr>
</tbody>
</table>

TX: 186mW
RX: 155mW
PLL: 64mW
Measurement Setup

- 25-GS/s AWG
- 100-GS/s oscilloscope (33GHz BW)
- 14-dBi horn antennas
Setup for TX-to-RX Measurement

- Symbol rate: 1.76GS/s (1ch), 7.04GS/s (4ch bonding)
- Roll-off factor: 25% for WiGig spectrum mask
- A maximum distance is defined within a SNR of 9.8dB(QPSK), 16.5dB(16QAM), and 22.5dB(64QAM) for a theoretical BER of $10^{-3}$. 
10.56Gb/s 64QAM

64QAM with 10.56Gb/s is achieved for the full 4 channels.

<table>
<thead>
<tr>
<th>Channel/Carrier freq.</th>
<th>ch.1 58.32GHz</th>
<th>ch.2 60.48GHz</th>
<th>ch.3 62.64GHz</th>
<th>ch.4 64.80GHz</th>
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</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>64QAM</td>
<td></td>
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<td></td>
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<tr>
<td>Data rate</td>
<td>10.56Gb/s</td>
<td>10.56Gb/s</td>
<td>10.56Gb/s</td>
<td>10.56Gb/s</td>
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<tr>
<td>Constellation</td>
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<td></td>
</tr>
<tr>
<td>Spectrum</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>TX EVM</td>
<td>-27.1dB</td>
<td>-27.5dB</td>
<td>-28.0dB</td>
<td>-28.8dB</td>
</tr>
<tr>
<td>TX-to-RX EVM</td>
<td>-24.6dB</td>
<td>-23.9dB</td>
<td>-24.4dB</td>
<td>-26.3dB</td>
</tr>
<tr>
<td>Distance</td>
<td>0.08m</td>
<td>0.08m</td>
<td>0.13m</td>
<td>0.06m</td>
</tr>
</tbody>
</table>
7.04Gb/s 16QAM (max 28.16Gb/s)

28.16Gb/s is achieved by using 4-bonded channel.

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<thead>
<tr>
<th>Channel/Carrier freq.</th>
<th>ch.1 58.32GHz</th>
<th>ch.2 60.48GHz</th>
<th>ch.3 62.64GHz</th>
<th>ch.4 64.80GHz</th>
<th>ch.1-ch.4 Channel bond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulation</strong></td>
<td>16QAM</td>
<td></td>
<td></td>
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<tr>
<td><strong>Data rate</strong></td>
<td>7.04Gb/s</td>
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<td>28.16Gb/s</td>
</tr>
<tr>
<td><strong>Constellation</strong></td>
<td><img src="image1" alt="Constellation of ch.1" /></td>
<td><img src="image2" alt="Constellation of ch.2" /></td>
<td><img src="image3" alt="Constellation of ch.3" /></td>
<td><img src="image4" alt="Constellation of ch.4" /></td>
<td><img src="image5" alt="Constellation of ch.1-ch.4" /></td>
</tr>
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</tr>
<tr>
<td><strong>TX EVM</strong></td>
<td>-27.8dB</td>
<td>-27.6dB</td>
<td>-28.4dB</td>
<td>-28.8dB</td>
<td>-20.0dB</td>
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<tr>
<td><strong>TX-to-RX EVM</strong></td>
<td>-24.6dB</td>
<td>-24.1dB</td>
<td>-24.6dB</td>
<td>-27.0dB</td>
<td>-17.2dB</td>
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<tr>
<td><strong>Distance</strong></td>
<td>0.7m</td>
<td>0.6m</td>
<td>0.8m</td>
<td>0.4m</td>
<td>0.07m</td>
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</table>
3.52Gb/s QPSK (max 14.08Gb/s)

14.08Gb/s is achieved by using 4-bonded channel.

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<th>ch.4 64.80GHz</th>
<th>ch.1-ch.4 Channel bond</th>
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<td>Data rate</td>
<td>3.52Gb/s</td>
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<td>3.52Gb/s</td>
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<td>14.08Gb/s</td>
</tr>
<tr>
<td>Constellation</td>
<td><img src="image1" alt="Constellation" /></td>
<td><img src="image2" alt="Constellation" /></td>
<td><img src="image3" alt="Constellation" /></td>
<td><img src="image4" alt="Constellation" /></td>
<td><img src="image5" alt="Constellation" /></td>
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<td>Spectrum</td>
<td><img src="image6" alt="Spectrum" /></td>
<td><img src="image7" alt="Spectrum" /></td>
<td><img src="image8" alt="Spectrum" /></td>
<td><img src="image9" alt="Spectrum" /></td>
<td><img src="image10" alt="Spectrum" /></td>
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<tr>
<td>TX EVM</td>
<td>-28.1dB</td>
<td>-27.7dB</td>
<td>-29.0dB</td>
<td>-29.7dB</td>
<td>-20.1dB</td>
</tr>
<tr>
<td>TX-to-RX EVM</td>
<td>-25.3dB</td>
<td>-24.5 dB</td>
<td>-24.5dB</td>
<td>-26.6dB</td>
<td>-17.9dB</td>
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<tr>
<td>Distance</td>
<td>2.4m</td>
<td>2.0m</td>
<td>2.6m</td>
<td>0.9m</td>
<td>0.3m</td>
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</table>
## Performance Comparison of 60GHz TRX

<table>
<thead>
<tr>
<th></th>
<th>Data rate / Modulation</th>
<th>TX-to-RX EVM</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiBeam [3]</td>
<td>7.14Gb/s (16QAM)</td>
<td>-19dB</td>
<td>TX: 1,820mW, RX: 1,250mW</td>
</tr>
<tr>
<td>Tokyo Tech [4, 5]</td>
<td>16Gb/s (16QAM)</td>
<td>-21dB</td>
<td>TX: 319mW, RX: 223mW</td>
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<tr>
<td></td>
<td>20Gb/s (16QAM) [5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMEC [6]</td>
<td>7Gb/s (16QAM)</td>
<td>-18dB</td>
<td>TX: 167mW, RX: 112mW</td>
</tr>
<tr>
<td>Panasonic [9]</td>
<td>2.5Gb/s (QPSK)</td>
<td>-22dB</td>
<td>TX: 347mW, RX: 274mW</td>
</tr>
<tr>
<td>This work</td>
<td>10.56Gb/s (64QAM)</td>
<td>-26dB</td>
<td>TX: 251mW, RX: 220mW</td>
</tr>
<tr>
<td></td>
<td>28.16Gb/s (16QAM)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Measurement for IEEE802.11ad/WiGig

<table>
<thead>
<tr>
<th>MCS</th>
<th>Modulation</th>
<th>Data rate [Mb/s]</th>
<th>TX EVM [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>QPSK</td>
<td>2502.5</td>
<td>-15</td>
</tr>
<tr>
<td>12</td>
<td>16QAM</td>
<td>4620</td>
<td>-21</td>
</tr>
<tr>
<td>24</td>
<td>64QAM</td>
<td>6756.75</td>
<td>-26</td>
</tr>
</tbody>
</table>

Measured by Agilent AWG + Osc. + VSA + 81199A in ch.3
60GHz CMOS Transceiver

First 64QAM
16QAM(4ch bonding)

Year

Data rate [Gb/s]

2007 2008 2009 2010 2011 2012 2013 2014

UCB
Univ. of Toronto
NEC
SiBeam, CEA-LETI
IMEC
Panasonic
Broadcom
Toshiba
Tokyo Tech
Conclusion

• A 60GHz direct-conversion transceiver in 65nm CMOS

• The first 64QAM transceiver (10.56Gbps/ch)
  – IEEE802.11ad/WiGig conformance: MCS1-MCS24(64QAM/OFDM)

• The first transceiver capable of 4-channel bonding (28.16Gbps by 16QAM) realized by
  – Mixer-first transmitter
  – Open-loop FVF-based baseband amplifier
  – Quadrature injection-locked oscillator
Acknowledgement

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References


References


Backup slides
Setup for TX Measurement

Symbol rate: 1.76GS/s (1ch), 7.04GS/s (4ch bonding)
Roll-off factor: 25% for WiGig spectrum mask
Measurement Results

Conversion gain of Tx

Conversion gain of Rx

Output power of Tx

Output power of Rx

SNDR [dB]

SNDR [dB]

P_{in} [dBm], CG [dB]

P_{out} [dBm], IM3, Noise Floor [dBm]

Frequency [GHz]

Frequency [GHz]