A 60GHz 16QAM/8PSK/QPSK/BPSK Direct-Conversion Transceiver for IEEE 802.15.3c

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Motivation

• 60GHz CMOS direct-conversion transceiver for multi-Gbps wireless communication

- 57.24GHz - 65.88GHzが利用可能
- QPSK $\rightarrow$ 14Gbps/ch
- 16QAM $\rightarrow$ 28Gbps/ch
- 64QAM $\rightarrow$ 42Gbps/ch
IEEE 802.15.3c Specifications

- 57.24GHz - 65.88GHz
- 2.16GHz/ch x 4 channels
- QPSK ➔ 3.5Gbps/ch
- 16QAM ➔ 7Gbps/ch

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Low Freq. (GHz)</th>
<th>Center Freq. (GHz)</th>
<th>High Freq. (GHz)</th>
<th>Nyquist BW (GHz)</th>
<th>Roll-Off Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>57.24</td>
<td>58.32</td>
<td>59.40</td>
<td>1.76</td>
<td>0.25</td>
</tr>
<tr>
<td>A2</td>
<td>59.40</td>
<td>60.48</td>
<td>61.56</td>
<td>1.76</td>
<td>0.25</td>
</tr>
<tr>
<td>A3</td>
<td>61.56</td>
<td>62.64</td>
<td>63.72</td>
<td>1.76</td>
<td>0.25</td>
</tr>
<tr>
<td>A4</td>
<td>63.72</td>
<td>64.80</td>
<td>65.88</td>
<td>1.76</td>
<td>0.25</td>
</tr>
</tbody>
</table>

from IEEE802.15.3c-2009
性能比較

16QAMダイレクトコンバージョンが重要ターゲット

<table>
<thead>
<tr>
<th></th>
<th>Data rate / Modulation</th>
<th>Distance for BER &lt;10⁻³</th>
<th>Integration</th>
<th>Power consumption</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Gatech</td>
<td>7Gbps/QPSK, 15Gbps/16QAM</td>
<td>–</td>
<td>90nm, Tx, Rx, 49-55GHz PLL, 8-9GHz QPLL</td>
<td>173mW (Tx)</td>
<td>6.5mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>189mW (Rx)</td>
<td></td>
</tr>
<tr>
<td>[2] NEC</td>
<td>2.6Gbps/QPSK</td>
<td>wired</td>
<td>90nm, Tx, Rx w/o LO</td>
<td>133mW (Tx)</td>
<td>4.5mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>206mW (Rx)</td>
<td></td>
</tr>
<tr>
<td>[3] UCB</td>
<td>4Gbps/QPSK</td>
<td>1m with 25dBi external horn antenna</td>
<td>90nm, single-chip TRx inc. 30GHz PLL and BB</td>
<td>170mW (Tx mode)</td>
<td>6.88mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>138mW (Rx mode)</td>
<td></td>
</tr>
<tr>
<td>[4] U. Toronto</td>
<td>4Gbps/BPSK</td>
<td>2m with 25dBi external horn antenna</td>
<td>65nm, single-chip TRx w/o LO</td>
<td>374mW with 1.2V</td>
<td>1mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(233mW with 1.0V)</td>
<td></td>
</tr>
<tr>
<td>[5] NTU</td>
<td>4Gbps/OOK</td>
<td>2cm with 5dBi on-board antenna</td>
<td>90nm, Tx, Rx, VCO, on-board antenna</td>
<td>183mW (Tx)</td>
<td>0.43mm²(Tx)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>103mW (Rx)</td>
<td>0.68mm²(Rx)</td>
</tr>
<tr>
<td>[6] NTU</td>
<td>2Gbps/FSK</td>
<td>120cm (1Gbps), 55cm (2Gbps) with 5dBi on-board antenna</td>
<td>90nm, single-chip TRx inc. PLL with on-board antenna</td>
<td>280mW (Tx)</td>
<td>1.26mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150mW (Rx)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80mW (PLL)</td>
<td></td>
</tr>
</tbody>
</table>

トロント大のBPSK無線機

• 差動LO(not 直交)によるBPSK変調
• QPSK以上は対応不可
• LOは未実装
• 4Gbps/QPSK
UCBのDirect-conversion無線機

- 90° hybridにより直交信号を生成
- 60.48GHz QPSKのみ対応
- LPFなし（帯域制限していない）
- 16QAM対応不可：-72dBc/Hz-1MHz offset (60GHz)
Challenges for 60GHz Transceivers

• **Direct-conversion** full CMOS integration
• **16QAM/8PSK/QPSK/BPSK** support for IEEE802.15.3c, WiGig, Wireless HD, etc.

• **60GHz quadrature LO**
  – Low phase noise for 16QAM
  – Wide frequency tuning (58-to-65GHz)
  – I/Q phase balance

• **60GHz LNA**
  – Low NF & High linearity
  – Wide bandwidth (gain flatness)

• **60GHz PA**
  – 10dBm output
  – High PAE (>10%)
Phase Noise Requirement

For 16QAM direct-conversion, -90dBc/Hz@60GHz is required.
60GHz Quadrature LO Scenario

- 60GHz quadrature PLL
  - Phase noise degradation
    e.g. -75dBc/Hz@1MHz-offset at 60GHz [1]

- 60GHz PLL with 90° hybrid [2]
  - I/Q mismatch

- 60GHz quadrature ILO with 20GHz PLL [3,4]
  - ILO: Injection-locked oscillator
  - Very wide tuning (58GHz-64GHz [4])
  - Excellent phase noise (-96dBc/Hz@1MHz-offset [4])

Direct-Conversion Architecture

Two 60GHz QILOs with 20GHz PLL

36MHz REFCLK

20GHz PLL

I Mixer

Q Mixer

60GHz QILO

Rx input

LNA

I+

I-

Q+

Q-

Tx output

PA

60GHz QILO
60GHz Quadrature LO

- Wide frequency tuning range
- Phase noise improvement by injection locking

In the diagram:
- 36MHz ref.
- 20GHz PLL
- 60GHz QILO
- PFD
- CP
- LPF
- (27,28,29,30)
- 4 CML

Frequencies:
- 19.44GHz
- 20.16GHz
- 20.88GHz
- 21.60GHz
- 58.32GHz
- 60.48GHz
- 62.64GHz
- 64.80GHz
Injection-Locked Oscillator

Previous work [3]

20GHz

PPF

Δθ

60GHz

I/Q mismatch

This work

20GHz

Single-side injection
- Small I/Q mismatch
- The same locking range

PPF: polyphase filter

Quadrature Injection-Locked Oscillator

- Phase noise is not important.
- Frequency coverage
- I/Q phase balance
Phase Noise

- Operation range: 54-61GHz
- Phase noise: -95dBc/Hz @1MHz (60.48GHz)
- Ref. spur: < -58dBc @20.16GHz
- 15mW (60GHz QILO), 66mW (20GHz PLL)
ILO Lock Test

20 chips with ±5% Vdd variation at room temp.

- Required injection power [dBm]
- P_{out} of PLL
  -2dBm
Performance Comparison of 60GHz LO

<table>
<thead>
<tr>
<th></th>
<th>This work</th>
<th>[1]</th>
<th>[5]</th>
<th>[6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{ref}}$ [MHz]</td>
<td>36.0</td>
<td>100.0</td>
<td>251.3</td>
<td>234.1</td>
</tr>
<tr>
<td>Freq. range [GHz]</td>
<td>54~61</td>
<td>57~66</td>
<td>64~66</td>
<td>58~60</td>
</tr>
<tr>
<td>Phase noise @1MHz [dBc/Hz]</td>
<td>-95</td>
<td>-75</td>
<td>-84</td>
<td>-85</td>
</tr>
<tr>
<td>$P_{dc}$ [mW]</td>
<td>81</td>
<td>78</td>
<td>72</td>
<td>80</td>
</tr>
<tr>
<td>Output type</td>
<td>Quadrature</td>
<td>Quadrature</td>
<td>Differential</td>
<td>Differential</td>
</tr>
</tbody>
</table>

4-Stage PA

- TL-based design for simulation accuracy
- Low-loss TL & MIM TL

Z₀ = 3Ω
50Ω, 0.8dB/mm

1st, 2nd stage
W = 2µm x 20

3rd, 4th stage
W = 2µm x 40

MIM TL for decoupling
Low-Loss Transmission Line

- 0.8 dB/mm
- Manually-placed dummy metal

![Diagram of transmission line with signal and ground layers, as well as a gap and dummy metal.]

Graphs showing frequency versus attenuation and impedance for manual and auto modes.

![Graph 1: Attenuation (dB/mm) vs. Frequency (GHz) for manual and auto modes.]

![Graph 2: Impedance (ohm) vs. Frequency (GHz) for manual and auto modes.]
MIM Transmission Line

- De-coupling use
- Modeling accuracy
- Avoiding self-resonance of parallel-plate capacitors

Up-Conversion Mixer

- Double-balanced Gilbert mixer
- Only one side is used
Tx Measurement

$P_{\text{sat}}$: 10.9 dBm
$P_{1\text{dB}}$: 9.5 dBm
PAE: 8.8% (only PA)

CG: 18.3 dB
LO freq.: 60.48 GHz (ch2)

$P_{\text{DC}}$: 186 mW
4-Stage CS-CS LNA

- $W_f = 1\mu m$ (1\textsuperscript{st} & 2\textsuperscript{nd} stages) for noise opt.
- $W_f = 2\mu m$ (3\textsuperscript{rd} & 4\textsuperscript{th} stages) for gain opt.
- Small resistors to prevent oscillations
- Variable gain by adjusting bias voltages
Down-Conversion Mixer

- Parallel-line transformer
- High common-mode rejection in matching blocks
Parallel-Line Transformer

- Split patterned ground shield (PGS)
- Center-tap with C

---

**Graph 1:**
- **MAG [dB]**
  - -0.8dB@60GHz

**Graph 2:**
- **Phase diff. [deg.]**
  - 5deg@60GHz
Rx Measurement

- NF: <6.8dB
- CG: 17.3dB (high-gain mode)
- CG: 4.7dB (low-gain mode)
- LO freq.: 60.48GHz (ch2)
- Lower cut-off freq: 5MHz
- P_{DC}: 106mW
Die Photo

65nm CMOS
Rx: 3.8mm$^2$
Tx: 3.5mm$^2$
PLL: 1.2mm$^2$

20GHz PLL
Face-up mount with a $270 \mu$m wire on a BGA package

## Performance Summary

<table>
<thead>
<tr>
<th>Tx</th>
<th></th>
<th>Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>18.3dB</td>
<td>CG</td>
</tr>
<tr>
<td>$P_{1dB}$</td>
<td>9.5dBm</td>
<td>17.3dB (high-gain mode)</td>
</tr>
<tr>
<td>$P_{sat}$</td>
<td>10.9dBm</td>
<td>4.7dB (low-gain mode)</td>
</tr>
<tr>
<td>PAE</td>
<td>8.8% (only for PA)</td>
<td>NF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;6.8dB (high-gain mode)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IIP3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-5dBm (only for LNA)</td>
</tr>
</tbody>
</table>

### LO

<table>
<thead>
<tr>
<th>Injection PLL</th>
<th>18-21GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. spur</td>
<td>&lt;-58dBc @20.16GHz</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>-2dBm @20.16GHz</td>
</tr>
<tr>
<td>Phase noise at 1MHz-offset</td>
<td>-108dBc/Hz @20.16GHz</td>
</tr>
<tr>
<td>Quadrature ILO</td>
<td>54-61GHz</td>
</tr>
<tr>
<td>Phase noise at 1MHz-offset</td>
<td>-95dBc/Hz @60.48GHz</td>
</tr>
</tbody>
</table>
Measured Spectrum

- 1.760Gs/s QPSK with 25% roll-off, 3dB back-off

IEEE802.15.3c spectrum mask
## Modulation Characteristics

<table>
<thead>
<tr>
<th>Constellation</th>
<th>BPSK</th>
<th>QPSK</th>
<th>8PSK</th>
<th>16QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1585 points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3170 points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4755 points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6340 points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td><strong>BPSK</strong></td>
<td><strong>QPSK</strong></td>
<td><strong>8PSK</strong></td>
<td><strong>16QAM</strong></td>
</tr>
<tr>
<td><strong>Data rate 2.16GHz-BW</strong></td>
<td>1.76Gb/s</td>
<td>3.52Gb/s</td>
<td>5.28Gb/s</td>
<td>7.04Gb/s</td>
</tr>
<tr>
<td><strong>EVM</strong></td>
<td>-18dB (-24dB with DFE)</td>
<td>-18dB (-28dB with DFE)</td>
<td>-17dB</td>
<td>-17dB</td>
</tr>
<tr>
<td><strong>Distance (BER &lt; 10^{-3})</strong></td>
<td>0.5–274cm</td>
<td>0.5–270cm</td>
<td>0.5–20cm</td>
<td>0.5–17cm</td>
</tr>
</tbody>
</table>

8Gb/s(QPSK) and 11Gb/s(16QAM) with wider-BW
## Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Data rate / Modulation</th>
<th>Architecture</th>
<th>Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEC [9]</td>
<td>2.6Gbps/QPSK</td>
<td>Heterodyne w/o LO</td>
<td>Wired</td>
</tr>
<tr>
<td>NTU [10]</td>
<td>4Gbps/OOK</td>
<td>60GHz VCO (Tx) 50GHz VCO (Rx)</td>
<td>On-board</td>
</tr>
<tr>
<td>UCB [2]</td>
<td>4Gbps/QPSK 7Gbps/QPSK (loop-back)</td>
<td>Direct conversion with 30GHz PLL and 90° hybrid</td>
<td>External</td>
</tr>
<tr>
<td>Tokyo Tech</td>
<td>1.76Gbps/BPSK 3.52Gbps/QPSK 5.28Gbps/8PSK 7.04Gbps/16QAM within 2.16GHz-BW &gt;8Gbps/QPSK &gt;11Gbps/16QAM</td>
<td>Direct conversion with 60GHz quadrature oscillators</td>
<td>In-package</td>
</tr>
</tbody>
</table>

伝送レート比較

世界初の60GHz帯16QAMダイレクトコンバージョン無線機を実現

![グラフ]

データレート [Gbps]

- direct-conversion
- other arch.

Tokyo Tech
- 16QAM
- QPSK

UCB(QPSK)
- Toronto Univ.
  (only BPSK)

NEC(QPSK)
- OOK

FSK
- OOK
Summary and Conclusion

• The first 16QAM direct-conversion transceiver
• 60GHz quadrature ILO with 20GHz PLL
  – 20dB improvement in phase noise
• Full-rate 16QAM/8PSK/QPSK/BPSK for IEEE802.15.3c
• Ch1(57.24-59.40GHz) and Ch2(59.40-61.56GHz)
• Standard 65nm CMOS
• Antenna built into a package
  – Post-wall waveguide aperture antenna (PWAA)
• Tx (186mW), Rx (106mW), and PLL (66mW)
• 11Gb/s (16QAM), 8Gb/s (QPSK)
Acknowledgement

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For additional multimedia material: See http://www.isscc.org
60GHz Research Team

Musa (PLL)  
Asada (PA)  
Han (modeling)  
Bunsen (Rx)  
Matsushita (Tx)  
Minami (TRx)  
Yamaguchi (ILO)  
Murakami (ILO)  
Okada  
Bu (LNA)  
Sato (VCO)  

+ W. Chaivipas, N. Li, N. Takayama, S. Ito, Y. Nomiyama

15 Ph.D. & Master students in 4 years
Reference


Backup slides
## Power Consumption

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tx</strong></td>
<td><strong>186mW</strong></td>
<td></td>
</tr>
<tr>
<td>PA</td>
<td>114.6mW</td>
<td></td>
</tr>
<tr>
<td>Mixer</td>
<td>23.0mW x2</td>
<td></td>
</tr>
<tr>
<td>LO buf.</td>
<td>5.0mW x2</td>
<td></td>
</tr>
<tr>
<td>QILO</td>
<td>14.9mW</td>
<td></td>
</tr>
<tr>
<td><strong>Rx</strong></td>
<td><strong>106mW</strong></td>
<td></td>
</tr>
<tr>
<td>LNA</td>
<td>20.7mW</td>
<td></td>
</tr>
<tr>
<td>Mixer inc. IF amp.</td>
<td>30.4mW x2</td>
<td></td>
</tr>
<tr>
<td>LO buf.</td>
<td>5.0mW x2</td>
<td></td>
</tr>
<tr>
<td>QILO</td>
<td>14.9mW</td>
<td></td>
</tr>
<tr>
<td><strong>PLL</strong></td>
<td><strong>66mW</strong></td>
<td></td>
</tr>
</tbody>
</table>
Low-Loss Transmission Line
Low-Loss Transmission Line

- **R [Ohm/mm]**: Resistance as a function of frequency.
- **G [mS/mm]**: Conductance as a function of frequency.
- **L [pH/mm]**: Inductance as a function of frequency.
- **C [fF/mm]**: Capacitance as a function of frequency.