A Wireless Revolution: CMOS, Cognitive and mmW

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Outline

Motivation
(Challenges, Opportunities)

Enabling Technology

- Architecture:
  - mW Digital Radio Architecture
  - BIST
  - Collaborative Processing

- Functional Blocks
  - Waveform Generation
  - Mixed-Signal Pre-Processor
  - Digitally assisted analog phased array architectures

Summary
Challenges
Mobile data traffic increase ‘Exponentially’!

The Challenge
- 26-fold increase in mobile user traffic
- Mobile video over 60% of traffic by 2016
80% of cell sites do not have fiber backhaul network access.

Current backhaul wireless solutions have limited bandwidth and prohibitive cost structure for future networks demands

Data centers are facing bandwidth, power consumption (consume 5% of total energy generated in US), and scalability limitations

pressure on CapEx and OpEx to bolster market elasticity ... How to provide an order of magnitude lower cost per bit than current networks?
Opportunities
Original RF-Solutions spun out of Basic Research is a leader in this market due to its success on Intel's Centrino platform for WiFi-based notebook PC's.
The Next Wireless Wave...

wavelength (mm)
The Next Wireless Wave...

The Multimedia Trend

- 100Gbps
- 10Gbps
- 1 Gbps
- 100 Mbps
- 10 Mbps
- 1 Mbps

- USB 2
- UWB
- PCIe-1 [x4]
- PCIe-2 [x4]
- HDMI 1.3
- 8x8 MIMO
- 4x4
- 802.11n
- 802.11g
- 802.11b

- 2000
- 2005
- 2010
- 2015
Solution: Broadband Wireless Link

A large under-used spectrum is available

40.5-43.5 GHz,
59-64 GHz,
71-76/81-86 GHz,
92-95 GHz

> 20 GHz of BW

Broadband Short Link
1-10m
10-40Gbps/link
<100mW
< $10

- Reconfigurable Data Centers
- Wireless Server Area Network (Wireless SAN)
- High-speed data storage and backups
- Real-time full HD content distribution

Broadband Backhaul Link
1-10Km
1-10Gbps/link
<1W
< $500

- Fiber backbone extensions
- Broadband telecom, internet and cable services
- 3G / 4G / WiMAX backhaul
- Metropolitan area fiber alternative access

4G
5G
Intersection of Gaming and Connectivity

100 mW @ 3 Gbps
Untethered
Solution
**Transfer Time and Energy Requirements**

<table>
<thead>
<tr>
<th></th>
<th>DVD (4 GB)</th>
<th>Photos &amp; Songs (100 MB)</th>
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<tbody>
<tr>
<td>InSite</td>
<td>10 sec</td>
<td>250 msec</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>&lt; 3 J</td>
<td>75 mJ</td>
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<tr>
<td>WiFi</td>
<td>&gt; 20 hrs</td>
<td>&gt; 30 min</td>
</tr>
<tr>
<td></td>
<td>1 hr</td>
<td>&gt; 180 J</td>
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<tr>
<td></td>
<td>1000 J</td>
<td>36 J</td>
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<table>
<thead>
<tr>
<th></th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
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<tbody>
<tr>
<td>Activity</td>
<td>Ramp</td>
<td>Volume</td>
<td>Volume</td>
</tr>
<tr>
<td>BOM</td>
<td>&lt;$4</td>
<td>&lt;$3</td>
<td>&lt;$2</td>
</tr>
<tr>
<td>Volume</td>
<td>&gt;5M Units</td>
<td>&gt;20M Units</td>
<td>&gt;100M Units</td>
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<tr>
<td>GM</td>
<td>≥60%</td>
<td>≥60%</td>
<td>≥60%</td>
</tr>
<tr>
<td>ASP</td>
<td>≥$10</td>
<td>≥$7</td>
<td>≥$5</td>
</tr>
<tr>
<td>Revenue</td>
<td>&gt;$50M</td>
<td>&gt;$140M</td>
<td>&gt;$500M</td>
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</table>
- 5Gbps, 5m, 250mW

Package with Built-in Antenna

Solution

- 1 V
  - LDO Regulator

DAC

PLL

PHY

MAC

AV

PAL

USB

HDMI

Digital Enhancement and Control Unit

GND
Vertical Architecture of LFR

Radio (Comm.+Radar+Sensor)

- Software MODEM
- MIMO Processing
- Radar Signal Processing
- Global Positioning System
- Spectrum Sensing

Digital Transceiver

- Analog Signal Processing

ASIC DSP

Software

Data converter

Analog

RF Front-end Antenna

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MMW Communication

MMW Radar / sensing
Millimeter wave CMOS SOC

10 GbE Wireless Backhaul
Millimeter wave CMOS SOC

- 10 Gbps
- Digital Enhancement Unit
- Mixed Signal Modem
- Digital Enhancement Unit
- Mixed Signal Modem
- 10 Gbps CMOS TRX
- 70 GHz CMOS TRX
- 802.3ae
- PAL

World first V-band CMOS fully integrated digital multi-gigabit radio with embedded mixed signal Modem

- up to 100 Gbps aggregate bandwidth
- Fully integrated single chip Millimeter wave CMOS SOC benefiting from Moore’s law
- Breakthrough Ultra low power cross-layer architecture
- Collaborative Mixed-signal processing for Pico-joule/bit operation
Analog or Collaborative Signal Processing

“Partitioning Methodology”

Generic analog operations that can be reconfigured by Controller to perform specific DSP operation

DSP can be used more effectively, by moving part of time/power consuming operation to ISSP.

Radar Control Unit /MODEM
A Solution: mmW Digital Radio Architecture
Enabled Digital Control, feedback/calibration loops and real-time monitoring
Address-based serial interface 1024 bits (write) for programming and 128 bits (read) for monitoring
Each SPI slave block features an embedded decoder to support a 32-bit “broadcast” mode for fast switching (<1us latency) between operation modes.
Once initialized, can also be controlled by only TX/RX optional control pins (<1us latency) for TDD operations
Closed Loop Control and Temperature Sensor: mmW PA

Digitally controlled + BIST
Integrated Signal Processor

Temperature Sensor - Measured Result

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>ADC Ref Read</th>
<th>Voltage</th>
<th>ADC Output Logic</th>
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<tr>
<td>-10</td>
<td>845.3</td>
<td>1</td>
<td>1 1 1 1</td>
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<tr>
<td>0</td>
<td>839.6</td>
<td>1</td>
<td>1 1 1 0</td>
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<tr>
<td>10</td>
<td>824.6</td>
<td>1</td>
<td>1 0 1 0</td>
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<tr>
<td>20</td>
<td>809.8</td>
<td>1</td>
<td>1 0 0 1</td>
</tr>
<tr>
<td>30</td>
<td>795.0</td>
<td>1</td>
<td>1 0 0 0</td>
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<tr>
<td>40</td>
<td>780.2</td>
<td>1</td>
<td>1 0 0 0</td>
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<td>45</td>
<td>771.6</td>
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<td>50</td>
<td>763.1</td>
<td>1</td>
<td>1 0 0 0</td>
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<td>55</td>
<td>754.6</td>
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<td>1 1 1 1</td>
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<td>60</td>
<td>746.0</td>
<td>0</td>
<td>1 1 1 0</td>
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<td>65</td>
<td>737.5</td>
<td>0</td>
<td>1 1 0 0</td>
</tr>
<tr>
<td>70</td>
<td>728.9</td>
<td>0</td>
<td>1 0 0 0</td>
</tr>
<tr>
<td>75</td>
<td>720.4</td>
<td>0</td>
<td>1 0 0 0</td>
</tr>
<tr>
<td>80</td>
<td>711.9</td>
<td>0</td>
<td>0 0 1 0</td>
</tr>
<tr>
<td>85</td>
<td>703.3</td>
<td>0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>90</td>
<td>694.7</td>
<td>0</td>
<td>0 0 0 0</td>
</tr>
</tbody>
</table>
Embedded Performance Control
Pulse Shaping in Transmitter Modem

- 13-tap raised-cosine FIR digital filter
- Pre-calculated coefficients stored in look-up table
- Time interleaving enables very high speed of operation (4.4GS/s)
- Integrated 6Bit DAC
- Ultra low-power (2mW from < 1V supply)

65nm
Pulse Shaping in Transmitter Modem

- Standard spectral mask requirement have been met
- Deterministic jitter has been introduced by pulse shaping...
Move power hungry DSP algorithms into digitally enhanced sub-threshold Continuous-Time Signal Processing.

Functions include Pulse-Shaping Filtering, Equalization, Auto-correlation, Bit Synchronization, Demodulation, Phase Rotation...

Ultra low power ADC technology

Demodulated QPSK

mW operation

Multi-gigabit ultra-low power back-end DSP
IQ Demodulator with Digital Modem integrated in CMOS

2mW DSP demodulator + 3mW ADC perform multi-gigabit BPSK demodulation

Collaborative Processing provides 2bit ENOB improvement to 5 Bits: QPSK and QAM16

Requires neither external processing nor synchronization control

4Gbps, BER 10E-11
Digital Radio/Radar Enabling Elements

Enabling Technologies

Arbitrary Waveform Generation

Mixed-Signal Pre-Processing

Combiner / Splitter technology
Arbitrary Waveform Generation

- Fully integrated Arbitrary Waveform Generator is key Functional Block

- Low Power
- Small Size / Lightweight
- Flexibility for multifunction
- Integration with DSP

- Spectrum Sensing
- Adaptive Filtering
- ECM/ECCM
- Pulse Compressor

Fully integrated Arbitrary Waveform
mmW CMOS Phased Array

48 Elements Phased Array

48 elements
Gain > 20dBi
Beam-width ~ 5Deg.
Scanning ~120 Deg.

Enabling Technologies

Injection locked VCO

mmW phase shifters technology

Combiner / Splitter
Planar Phased Array Technology

48 Elements Phased Array

- 48 elements
- Gain > 20dBi
- Beam-width ~ 5Deg.
- Scanning ~120 Deg.

Determination of DoA Algorithm
Multi resolution code-book

H2 matrix (2 bits resolution)
H3 matrix (3 bits resolution)
H4 matrix (4 bits resolution, etc.)
Planar Phased Array Technology

- EIRP (dBm)
- Radiated Pattern
- Variation of output phase (0°-360°)
- Phase shift: 0°, 315°
- Measured vs. Simulated
- Frequency (GHz)
- 4 by 4 antenna array
- 1 by 4 single chip CMOS phased array
- Bias Core
- Digital Control Unit
- Mixed Signal Processor
- ADC
- PLL
- QOUT
- IOUT
- REF SWH
- SPI
- RFOUT 1
- RFOUT 2
- RFOUT 3
- RFOUT 4
Scaleable Element Beam Former
Mixed Signal Pre-Processor

- Reduce power consumption by off-loading power hungry DSP needed for digital beam-forming
  - Multi-beam & Smart phase shifting and combining

- Increase performance and functionality compared to traditional RF beam-forming approach
  - Multi-beam & Smart phase shifting and combining
  - Bandwidth, linearity, calibration...

- Frequency agnostic, Front-end technology agnostic
  - Scalable Solution for RF, MMW, THz...
  - III-V or CMOS front-end
  - Back compatible with legacy front-end
Multi-beam Beam-forming/nulling
Mixed Signal Pre-Processor

Multi-beam Phase shifting
Smart combining

Mixed-Signal baseband Phase shifting technology

<table>
<thead>
<tr>
<th>Vector rotator</th>
<th>Mixed-signal approach</th>
<th>Conventional digital approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>Continuous, analog</td>
<td>14bits</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt; 1000MHz</td>
<td>&lt;100 MHz</td>
</tr>
<tr>
<td>Latency</td>
<td>&lt; 10 ns</td>
<td>&gt; 1us</td>
</tr>
<tr>
<td># of transistor/gates</td>
<td>&lt; 50 transistors</td>
<td>&gt; 50000 gates</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;1mW</td>
<td>&gt;100mW</td>
</tr>
</tbody>
</table>
Multi-beam Beam-forming/nulling Mixed Signal Pre-Processor

Mixed-Signal baseband Phase shifting technology

<table>
<thead>
<tr>
<th>Performances</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Shift Range</td>
<td>360°</td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt;1 deg.</td>
</tr>
<tr>
<td>Operating Bandwidth</td>
<td>DC–5GHz</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>&lt; 1mW</td>
</tr>
<tr>
<td>RMS Gain Error (dB)</td>
<td>&lt; 1dB</td>
</tr>
<tr>
<td>RMS Phase Error (°)</td>
<td>&lt; 1°</td>
</tr>
<tr>
<td>Active area</td>
<td>100um x 150um</td>
</tr>
</tbody>
</table>
Multi-beam Smart Combiner Technology

- Digitally controlled Smart Combiner
- Sub-threshold design, <1mW / branches
- Wideband (GHz) and wide dynamic range (>60dB)
- Programmable (linear, logarithmic compression/expansion, thresholding...)

- Advanced features
  - Nulling Smart combiner
  - Jamming Smart combiner

Nulling
Future Implementation: Chip Level MIMO Radar

- MIMO radar: multiple different waveforms transmitted
- Phased-array radar: single waveform scaled and transmitted.

10 GbE Wireless Backhaul
Millimeter wave CMOS SOC

- 10 Gbps Wireless Backhaul
- Millimeter wave CMOS SOC
- 10 Gbps aggregate bandwidth
- Fully integrated single chip Millimeter wave CMOS SOC benefiting from Moore’s law
- Breakthrough Ultra low power cross-layer architecture
- Collaborative Mixed-signal processing for Pico-joule/bit operation
E/F/G Band
Communication / Sensing
node

70/80GHz

120/220/320GHz

X-band to W-Band
Super resolution
Phased Array
Radar

CMOS MMW System-On-Chip portfolio
**Summary**

- mmW Digital Radio Architecture with BIST and Calibration
- Scaleable “Digital” Radio Architectures for Comm, Radar and Sensing
- Expect Drastically Reduced SWAP in Future
Thank You For Your Attention