Energy Efficient Communications with Wi-Fi
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Sr. VP, Advanced Technologies

Class ID: 8C04I
N.Venkatesh

- Senior Vice President, Advanced Technologies
  Redpine Signals, Inc.
  - Responsible for wireless systems development
  - 26 years of Engineering and Management experience in
    - Wireless Systems Development
    - Semiconductor Design
    - Avionics

- Previous Experience
  - General Manager at Paxonet Communications
    - Semiconductor products for telecom and optical networking
  - Deputy Manager at Hindustan Aeronautics, Ltd.
    - Development of airborne communication systems
Redpine Signals

Company profile:
- Founded: 2001; Headquarters: San Jose, CA; Employees: 150

Accomplishments:
- World’s 1st Wi-Fi® certified ultra low power 802.11n 1x1 chipset in 2008
- World’s 1st reconfigurable simultaneous dual-band 802.11n 3x3 chipset in 2011
- World’s 1st low power 11ac technology for smartphones Dec/2011

Technology expertise
- OFDM/MIMO / Low Power / Multi-threaded processors -ThreadArch® / CMOS RF / CMOS PA
- 45 patents awarded and over 100 in the pipeline
- 10 Years and 1000 person years of R&D

Leading technology provider for the ‘Internet of Things’ market

Tier-1 manufacturing partners:
# Redpine Wi-Fi Product Portfolio

<table>
<thead>
<tr>
<th>Part</th>
<th>Product</th>
<th>Applications</th>
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</thead>
<tbody>
<tr>
<td>Lite-Fi</td>
<td>RS9110</td>
<td>Mobile Phone, Vo-Wi-Fi Phone, Tablet PCs, Camera, Multimedia Players, Gaming Adapters, etc.</td>
</tr>
<tr>
<td>Maxx-Fi</td>
<td>RS9330</td>
<td>High End Workstations, Wireless NAS, Wireless Displays, AP, Router, Gateway, STB, Media Server, Gaming Consoles, Projectors, etc.</td>
</tr>
<tr>
<td>n-Link</td>
<td>RS9110-N-11-02/03</td>
<td>Vo-Wi-Fi Phone, Tablet PCs, Industrial control, Medical applications, Cameras, Multimedia Players, Gaming Adapters, Headphones, Printer, etc.</td>
</tr>
<tr>
<td>Connection</td>
<td>RS9110-N-11-22</td>
<td>PC Input devices, WSN, Industrial Control, Data Acquisition, Medical Applications, Home Automation, Thermostats, Smart Meters, POS terminals, etc.</td>
</tr>
<tr>
<td>WiSeMote</td>
<td></td>
<td>“Real Time Asset Tracking &amp; Management” for Enterprises like Healthcare, Hospitality, Manufacturing, Logistics &amp; Transportation, etc.</td>
</tr>
</tbody>
</table>
WiSeConnect™

Industry’s first Wi-Fi® Module with Wi-Fi Direct™, Enterprise Security and Access Point in a Single Package

- Wi-Fi direct
- Enterprise Security
- USB 2.0, SPI and UART Interfaces
- Access Point Mode Supported
- HTTP Server
- Wireless Firmware Upgrade for Field Updates
- Full Software Integration with TCP/IP, WLAN Stacks
- Integrated Antenna - Requires no External BOM
Agenda

- Wi-Fi in the Smart Society
- Fundamentals on operational range of wireless links
- Power consumption in 802.11 WLAN systems
- Energy saving techniques in WLAN
- Optimal integration into embedded systems
Wi-Fi in the Smart Society

- Natively compatible protocol – IP
- Wi-Fi infrastructure is everywhere
- Wide range of applications
  - High bandwidth video, data transfer
  - Long battery life sensors
- Already present in smartphones, other handheld devices
- Easy to integrated into embedded devices – with the right Wi-Fi products
Fudamentals – Sending data across

Why is there a limit on operational range?

- A certain minimum signal-to-noise ratio (SNR) is required to decode data
- Received signal power reduces with range
- Noise power is independent of range
  - Largely dependent on operational temperature
  - Also dependent on RF circuits.

<table>
<thead>
<tr>
<th>Transmitted Power</th>
<th>Cable Losses</th>
<th>Antenna Gain</th>
<th>Radio Path Losses</th>
<th>Antenna Gain</th>
<th>Cable Losses</th>
<th>Receiver Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
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Diagram:

- Transmitter
- Receiver
- Transmitted Power
- Cable Losses
- Antenna Gain
- Radio Path Losses
- Antenna Gain
- Cable Losses
- Receiver Sensitivity
Various Data Modulation Schemes

- More bits/symbol = higher data rate, but requires higher SNR
- Therefore, in practice:
  - Smaller ranges = higher SNR = higher data rate
  - Longer ranges = lower SNR = lower data rate
  - Results in the ‘Rate Vs Range’ characteristic of a communication link
The Power Amplifier (PA) drains energy!

- High peak-to-average power ratio (PAPR) in complex OFDM waveforms.
  - Orthogonal Frequency Division Multiplexing (OFDM) is used in 802.11a/g/n signals
- PA operated at large back-off – high quiescent current.
The Baseband Processor is large, complex, and power hungry.
The analog to digital converter (ADC) also drains power.
Signal Degradation

Causes of signal degradation

- **Distance**
  - Signal power reduces with distance
  - Noise power depends only on temperature
    - (and quality of front-end circuits)
- **Multipath**
  - Causes fading, intersymbol interference
- **Receiver variation**
  - Frequency and timing offsets
- **RF impairments**
  - DC Offset, I-Q Imbalance.

What turns this into this? Or this?
Rate Vs Range

<table>
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<tr>
<th>Data Rate</th>
<th>SNR Required for &lt;10% PER, AWGN</th>
</tr>
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<tbody>
<tr>
<td>54 Mbps</td>
<td>21.0 dB</td>
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<tr>
<td>36 Mbps</td>
<td>15.0 dB</td>
</tr>
<tr>
<td>24 Mbps</td>
<td>11.0 dB</td>
</tr>
<tr>
<td>6 Mbps</td>
<td>5.0 dB</td>
</tr>
<tr>
<td>1 Mbps</td>
<td>0.0 dB</td>
</tr>
</tbody>
</table>

![Graph showing Rate Vs Range with data points and a line plot]
Sending Packets of Data

- Packets are acknowledged by the recipient.
- Lack of an ack means that either:
  - The transmitted packet was not decoded correctly
    - Perhaps the SNR was not sufficient
    - Perhaps there was interference
    - Perhaps there was a collision
  - Or there was an ack but it was not received correctly
- The transmitter ‘retries’ the packet.
- The transmitter ‘downshifts’ to a lower data rate.
WLAN Operational Profile

- Several distinct power phases during a data transfer operation
- Each phase has its own hardware characteristic
- Transmit
  - Receive blocks are powered down, or set in low power states
  - Power consumption dominated by the power amplifier
- Receive
  - Transmit blocks are turned off
  - Receive blocks can be turned on in a sequence
Battery Life Example in WLAN

- Typical power consumption numbers
  - Transmit mode: 1000 mW
  - Receive mode: 400 mW
  - Listen mode: 300 mW
  - Power numbers are largely independent of data rate

- Task: receive a 10 MB file over the WLAN connection
  - Involves a series of packet transfers
  - Typical packet size: 1.5 kB
    - Over 600 packets to be sent
  - Overhead (non Productive time)
    - WLAN ACKs
    - TCP ACKs
    - Packet retries
    - Inter-frame spacing
  - How much energy is spent receiving this 10 MB file?
Battery Life Example in WLAN – Saving Power

- Energy = Power x Time
- Power saving techniques (chip level and system level)
  - Reducing device gatecount
  - Limiting clock rate
  - Clock gating
  - Dynamic frequency scaling
  - Dynamic voltage scaling
  - Use of low-leakage cells
  - Low granularity power gating
  - Use of CMOS RF
  - Improved PA efficiency
  - Dynamic performance scaling
  - Use of dc-dc convertors
  - Low-power crystal oscillators

Next slides – saving time
Battery Life in WLAN – Saving Time

- Packet duration of a 1.5 kB packet
  - @54 Mbps: 244 us
  - @36 Mbps: 356 us
  - @24 Mbps: 520 us
  - @1 Mbps: > 12 ms!

- Duration of overhead
  - Relatively independent of data rate

- Use of larger packets (802.11n packet aggregation)
  - 4 kB packet @65 Mbps: 532 us
Battery Life in WLAN – Energy Computation

- Energy spent per packet exchange sequence
  - Sum of individual power x time for each state in the sequence

- Total energy spent in receiving a 10 MB file
  - Energy spent per packet exchange sequence
    x
    Total number of sequences per file

- With normal packet sizes (1.5kB), about 6,700 sequences would be required

- With the computation carried out offline,
  - Energy spent = 740 mW-s

Now that we have a method of finding energy spent, let’s look at how we can reduce it!
Improving Receiver Performance

- ‘Rate fallback’ in the transmitter is triggered by packets having to be retried
- Packets fail in the receiver. Why?
  - Due to signal degradation
- Receivers that can handle adversely affected signals enable the transmitter to use higher data rates
- How is receiver performance improved?
  - More complex algorithms
  - Higher levels of precision
  - More processing
  - Resulting in
    - Better multipath handling
    - Better noise figure
    - Better error correction performance
Cost of increasing Rx performance

- Higher area or gatecount
- Higher clock speed
- Increased memory accesses
- Higher power consumption
- The standard chip design approach at optimizing power causes
  - Reduced receiver performance
  - Lower data rates used
  - Longer time spent in data transfer
  - Higher energy drain!
Performance Enhancement – a WLAN Perspective

- Improving the link margin through
  - Use of antenna diversity
    - STBC, MRC
- Improving data transfer efficiency through
  - Increased PHY capacity
  - Larger packets at the MAC with packet aggregation
- Improved coding techniques
  - LDPC
- Dynamic increase in antenna gain
  - Advanced beam-forming methods
- Higher on-air throughputs with MIMO

All these techniques result in Energy Savings!
Protocol Supported Energy Saving

- Sleep modes
  - Legacy power-save
  - WMM-PS
Module Architecture

Power Switch

3.3V

MAC Processor

BBP, AFE

RF, PA

WLAN Module

Internal Power Manager

Frequency Reference

Host Interface

Power Control
Power Modes - Transmit

- Transmit
  - 200 to 300 mA (current drawn on 3.3V)

*Green indicates active block
Power Modes - Receive

- Receive
  - 75 to 150 mA
Power Modes - Listen

- **Listen**
  - 50 to 125 mA
Power Modes – Standby

- Standby
  - 100 to 2000 uA
Power Modes – Shutdown

- Shutdown
  - 2 to 10 uA
Power Modes – Boot-up

- Boot up
  - 20 to 75 mA
Mode Transition Times

Control

Operational Mode

Transmit  Rx/Listen  Standby  Rx/Listen  Shutdown  Rx/Listen

3 ms  100 ms

3 ms
Typical Operational Profiles – Examples

- **Standby-Associated**
  - Power Save mode with no traffic

  ![Diagram](image)

- **Voice (VoIP) with uAPSD**

  ![Diagram](image)
Why Wi-Fi in Embedded Systems?

- Universal IP based connectivity

```
Data handler
TCP/IP
MAC
PHY
WLAN

Raw Data
Encapsulated Raw Data
802.11 Frame (IP Packet)
Access Point
LAN

TCP/IP Stack
Control Unit
Raw Data

Microcontroller-based Device

Wireless Link

TCP/IP Stack

Raw Data

TCP/IP
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TCP/IP Stack
Why Wi-Fi in Embedded Systems? (Contd.)

- Use of available infrastructure and network planning
  - Wi-Fi is largely present in most enterprise, industrial, and home environments
  - Access Point location and frequency planning already taken care of
  - Easy addition of devices

- Enterprise class security
  - AES based WPA2
  - Optional 802.1x based authentication

- Throughput and Range
  - 1 Mbps to 600 Mbps data rate (will go up to 7 Gbps!)
  - Up to 500 meters range

- Power consumption
  - Focus on ‘low energy’ as opposed to ‘low power’
Why 11n?

- 802.11n is lower energy than 802.11b or 802.11b/g
  - Minimal MAC overhead
  - Higher throughput

- Higher throughput and range
  - Aggregation
  - STBC

- Increases network capacity
  - Mixed mode protection mechanisms waste bandwidth for all

Energy Consumption for 10 MB of Received Data

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Why 5 GHz?

- The illustration shows traffic pattern in a crowded channel – increases energy consumption!
- Moving to a relatively clearer 5 GHz channel keeps transmissions closer to planned profile.

![Graph showing current drawn over time for planned and actual scenarios.](Image)
Integration of Wi-Fi into an Embedded System

- The benefits of a self-contained module
  - Integrated RF and Antenna
    - Layout considerations taken care of
    - Stable frequency reference included for predictable performance
  - Single power-supply with built-in power management
  - Modular certification for FCC
  - Pre-tested and pre-calibrated for high yield on main system

![Diagram of a self-contained module with labeled components such as Host Interface, MAC, BBP, AFE, RF Transceiver, PA, Front-end, Frequency Reference, Memory, Peripheral Interfaces, SPI, UART, 3.3V, PMU, Internal Voltages, Frequency Reference, and WLAN System-on-Chip. The module is 22 x 28 mm.]
Renesas + Redpine Standard Wi-Fi Solutions

Low power 802.11a/b/g/n Wi-Fi for RX/R8C/RL78 MCU

- 32-bit CISC Flash MCU
- Up to 165DMIPS @ 100MHz
- FPU, Ethernet, USB, CAN

- 8-bit CISC Flash MCU
- 20MHz
- CAN, ADC, Serial, Timers

- 16-bit CISC
- Analog rich
- True low power

- 802.11bgn or 802.11 a/b/g/n
- Plug & Play Serial-to-Wi-Fi module
- Integrated TCP/IP Stack
- Module variants available with option of TCP-IP on microprocessor
How is Renesas + Redpine Solution Unique?

- Works on MCUs ranging from 20MHz to 200MHz
- As small as 2KB of Program Memory Required
- Support for 802.11 b/g/n & a/b/g/n
- Low Power (Down to 30mW) & High Performance (Up to 35Mbps)
- Modules with & without TCP/IP Stack
- May be used with or without RTOS
Questions?
Please Provide Your Feedback...

- Please utilize the ‘Guidebook’ application to leave feedback

or

- Ask me for the paper feedback form for you to use...