50 Billion devices connected to the Internet, $19 Trillion market, 1 Trillion sensors by 2020 – Cisco
New Operating System for the Internet of Things

What is the Internet of Things? (IoT)
Why now? What are the enablers?
IoT Node design challenges
New IoT Operating System approach
Benefits of Paqet OS in IoT applications
The Internet of Things: A Broad Set of Applications

- Predictive maintenance
- Enable New Knowledge
- Agriculture
- Smart Grid
- Energy Saving (I2E)
- Transportation and Connected Vehicles
- Intelligent Buildings
- Defense
- Industrial Automation
- Enhance Safety & Security
- Healthcare
- Smart City
- Smart Home

Source: Cisco, Flavio Bonomi
Cisco: Internet of Everything

The “Horizontal” IoE Platform Architecture: Is It Like This?

**Data Center Cloud**
Application Hosting, Management

**Core**
IP/MPLS, QoS, Multicast, Security, Network Services, Mobile Packet Core

**Multi-Service Edge**
3G/4G/LTE/WiFi/ Ethernet/PLC

**Embedded Systems and Sensors**
smart and less smart things, vehicles, machines
Wired or Wireless

**Smart Things Network**

**IP/MPLS Core**

**Field Area Network**

**Dumb Network Fabric**

**End-Point Intelligence**

Source: Cisco, Flavio Bonomi
IoT Node

Must Have:
- Sensors: Acc, Gyr, Mag, Temp, Pres, Hum, SiP
- Operating System
- MCU - RAM/Flash
- RF Communications

May Have:
- External power
- Battery
- Energy Harvesting
- Wired IP or Serial

SOFTWARE Applications

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IoT Projections

Figure 1. Total of Connected Devices, Billions of Units (Installed Base)

Source: Gartner (November 2013)
Big Companies Already Get It
Value of autonomous sensors

Benefit from Sensors:

- Monitor temperature, humidity, air flow, air quality, current
- Allows reduction or elimination of air conditioning
- Mega data center can deploy 4,000 to 20,000 sensors

Benefit from Wireless:

- Wireless sensors cost 1/10th that of wired sensors due to labor & wiring costs

Heat map of a data center

Source: Microsoft, MegaWatt Consulting
New IoT operating system

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### Motion Sensor: A Disruptive Solution

<table>
<thead>
<tr>
<th>From 2003 to 2013</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>&gt;100x</td>
</tr>
<tr>
<td>Cost</td>
<td>&gt;10x</td>
</tr>
<tr>
<td>Performance</td>
<td>&gt;10x</td>
</tr>
<tr>
<td>Power</td>
<td>&gt;20x</td>
</tr>
<tr>
<td>Production Volume</td>
<td>&gt;100x</td>
</tr>
<tr>
<td>Turn key solution</td>
<td></td>
</tr>
</tbody>
</table>

| ~12x5x2mm Single Axis | 3x3x0.9mm 6-axis |

Source: Steve Nasiri Ventures
MEMS manufacturers shipping billions

<table>
<thead>
<tr>
<th>Company</th>
<th>Quantity</th>
<th>Product</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avago</td>
<td>&gt;2B</td>
<td>Cell phone filters</td>
<td>As of Q2 2010</td>
</tr>
<tr>
<td>Robert Bosch</td>
<td>&gt;1B</td>
<td>Automotive sensors</td>
<td>As of Nov 2008</td>
</tr>
<tr>
<td>Knowles</td>
<td>&gt;1B</td>
<td>Microphones</td>
<td>As of Sept 2009</td>
</tr>
<tr>
<td>Texas Instruments</td>
<td>&gt;10^{14}</td>
<td>Light modulators</td>
<td>As of Dec 2009</td>
</tr>
<tr>
<td>GE NovaSensor</td>
<td>&gt;750M</td>
<td>Pressure sensors</td>
<td>As of Aug 2011</td>
</tr>
<tr>
<td>ST Micro</td>
<td>&gt;1B</td>
<td>Accels and Gyros</td>
<td>As of Dec 2010</td>
</tr>
<tr>
<td>HP</td>
<td></td>
<td>“Billions and Billions of ink jet nozzles”</td>
<td></td>
</tr>
<tr>
<td>Cepheid</td>
<td>~$1B</td>
<td>Microfluidic systems</td>
<td>As of Q4 2010</td>
</tr>
<tr>
<td>SiTime</td>
<td>&gt;100M</td>
<td>MEMS Oscillators</td>
<td>As of Q2 2012</td>
</tr>
</tbody>
</table>

Source: Kurt Petersen, MEMS Engineer Forum 2013
Potential Sensor Platforms

- **Motion Tracking Platform:**
  - Gyro, Accel, Compass, Altimeter, Microphone, Bolometer...

- **Clock and Filters Platform:**
  - Clocks, Resonators, Filters, Tuners,...

- **Ambient Sensor Platform:**
  - Oxygen, Chemical, Light, Proximity,...

- **Health Monitoring Platform:**
  - Heart, Temperature, Sugar,...

- **Physical Platform:**
  - Auto Focus, Stabilization, Touch, Joystick,...

Source: Steve Nasiri
Three ENORMOUS IoE Initiatives

Qualcomm Tricorder X PRIZE

Trillion Sensor Roadmap !! initiated by Janusz Bryzek

Introducing the Qualcomm Tricorder X PRIZE
A $10 million competition to bring healthcare to the palm of your hand

Source: Kurt Petersen IEEE talk, TSensor Roadmap, HP
ARM dominates IoT

**ARM in the Internet of Things**

- **>3 billion**
  ARM-based embedded computing chips shipped in 2013

- **160**
  Companies enabled with Cortex-M processor technology

**ARM-based microcontrollers** are being combined with radios, sensors and controllers to create new markets

- **Sensor**
  - ARM Share: 22%

- **MCU**
  - >75%

- **Radio**

**Multiple Opportunities per smart device**

- **Main processor**
  - Cortex-A or Cortex-M

- **Connectivity**
  - 1-2 Cortex-M based chips

**Wearables showing momentum with 10’s millions shipping in 2013**

- Connected Life
- Health Wellness
- Info-tainment

- >70 ARM-based wearable designs in flight

>200m unit market in 2018*

* Source: IMS Research, Juniper Research

Source: ARM 2014
## Plunging IoT costs

<table>
<thead>
<tr>
<th>Component</th>
<th>2012</th>
<th>2016</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM Cortex M0+</td>
<td>$0.49</td>
<td>$0.30</td>
<td>$0.30</td>
</tr>
<tr>
<td>Software</td>
<td>$0.20</td>
<td>$0.15</td>
<td>$0.10</td>
</tr>
<tr>
<td>Bluetooth LE</td>
<td>$0.75</td>
<td>$0.35</td>
<td>$-</td>
</tr>
<tr>
<td>MEMS Sensor</td>
<td>$1.30</td>
<td>$0.65</td>
<td>$0.40</td>
</tr>
<tr>
<td>Battery</td>
<td>$0.40</td>
<td>$0.30</td>
<td>$0.20</td>
</tr>
<tr>
<td>PV</td>
<td>$0.30</td>
<td>$0.20</td>
<td>$0.20</td>
</tr>
<tr>
<td>Electronics &amp; Packaging</td>
<td>$1.00</td>
<td>$0.70</td>
<td>$0.50</td>
</tr>
<tr>
<td>COGS in volume</td>
<td>$4.44</td>
<td>$2.65</td>
<td>$1.70</td>
</tr>
</tbody>
</table>

Estimated IoT node costs could drop dramatically
## Summary: IoT Enablers / Pain Points

<table>
<thead>
<tr>
<th>Sub system</th>
<th>Current state of art</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS sensors: Low Cost &amp; Power</td>
<td>MEMS motion sensors sub $1 2011</td>
<td>Atmospheric &amp; optical sensors in MEMS</td>
</tr>
<tr>
<td>Microcontrollers: Low cost &amp; power 32 bit</td>
<td>ARM Cortex M series 3rd generation - 2012 &gt;6 big suppliers</td>
<td>Sub threshold MCU 4th gen ARM 32 bits/32 cents</td>
</tr>
<tr>
<td>Radios: low power, mesh</td>
<td>Multiple low power PAN radios &amp; standards</td>
<td>Integrated radio Low power mesh</td>
</tr>
<tr>
<td>Power source</td>
<td>Alkaline, Lithium Li-Ion</td>
<td>Harvesting: PV, Vibe, Temp</td>
</tr>
<tr>
<td>Operating System</td>
<td>Embedded RTOS from 80s &amp; 90s + Hand Chiseling</td>
<td>Purpose built IoT: Ultra low power Ultra small footprint</td>
</tr>
<tr>
<td>Application/ analytics</td>
<td>Hardware specific code, eg MCU, RF, Sensor dependencies</td>
<td>Virtualizable hardware using IoT O/S</td>
</tr>
</tbody>
</table>
New IoT operating system

What is the Internet of Things? (IoT)
Why now? What are the enablers?
**IoT Node design challenges**
New IoT Operating System approach
Benefits of Paqet OS in IoT applications
Embedded microcontroller has limited resources: ARM M series
   Memory Flash ROM ranges from 2 kB to 256 kB
   RAM ranges from 2 kB to 32 kB
   Typically serial I/O: SPI, I2C, UART

But I wanted that $0.50 ARM! Typically M0+
   Memory Flash ROM ranges from 2 kB to 16 kB
   RAM ranges from 2 kB to 4 kB

Dozens of radios:
   High Power: WiFi
   Low power standards: ZigBee, Z-wave, ANT+, Bluetooth Smart
   Low power proprietary: sub GHz, Dust, GreenNet

Thousands of Sensors – different interface/registers/calibration:
   Motion/force: Accelerometer, Magnetometer, Gyro, Strain
   Atmospheric: Temp, humidity
   Light: Gas sensors, spectrometers
## IoT ARMs: Cheaper and less filling

<table>
<thead>
<tr>
<th>CPU</th>
<th>Flash</th>
<th>SRAM</th>
<th>Active/ deep shutdown</th>
<th>MSRP @10ku</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortex M0⁺</td>
<td>4kB</td>
<td>1kB</td>
<td></td>
<td>$0.49</td>
</tr>
<tr>
<td>Cortex M0⁺</td>
<td>8kB</td>
<td>2kB</td>
<td></td>
<td>$0.58</td>
</tr>
<tr>
<td>Cortex M0⁺</td>
<td>16kB</td>
<td>4kB</td>
<td>2.8 ma/ 0.22 µa</td>
<td>$0.68</td>
</tr>
<tr>
<td>Cortex M3</td>
<td>8kB</td>
<td>2kB</td>
<td></td>
<td>$1.00</td>
</tr>
<tr>
<td>Cortex M3</td>
<td>16kB</td>
<td>4kB</td>
<td>14 ma/ 0.63 µa</td>
<td>$1.72</td>
</tr>
<tr>
<td>Cortex M3</td>
<td>32kB</td>
<td>4kB</td>
<td></td>
<td>$1.60</td>
</tr>
</tbody>
</table>

Within M0⁺ reducing memory saves $0.20 in system cost
Drop from M3 to M0⁺ saves $0.50 to ~$1.00 and 80% active power!
A. Real Time (RTOS) for embedded

20 years embedded development/ most are open source
Focus on fast interrupt response, deterministic response time
Typical OS desires > 64 kB flash (plus application)
Conventional embedded applications running on beefy power:
Automotive, industrial control, appliances

Features:
Fast Interrupt processing
Deterministic behavior
Multitasking, multithread
Protected, user modes
Open Source

Challenges:
Too Big > 64kB
Poor OOBE
Not extreme power optimized
Everyone has the source
? Security
## Typical IoT hardware properties

- **Microcontroller**
  - Memory
    - Flash ROM on the order of 64-512 kilobytes
    - RAM on the order of 8-32 kilobytes
  - I/O to connect sensors and actuators
    - Serial ports, ADCs, SPI, etc
- **Radio**
  - External transceivers
  - Systems-on-a-Chip
    - Radio integrated with microcontroller

## Radio hardware

- **Microcontroller + transceiver**
  - CC1120 – sub-GHz
  - CC2520 – IEEE 802.15.4
  - nRF8001 – Bluetooth Smart
  - CC3300 – WiFi
- **Connected via SPI**
- **System-on-a-Chip**
  - CC2538 – IEEE 802.15.4 + ARM Cortex M3
  - Broadcom Wiced – WiFi + ARM Cortex M3
FreeRTOS memory

Claim:
23K

Actual out of the box:
42K+
29K
High cost of free operating systems

- **Old architectures**
  - Poor power management
  - Too big out of the “box”: 44k to 96k
  - Need High end of ARM M series

- **High Total Cost of Ownership**
  - Build an OS porting team to:
    - Strip out unused features to reduce size
    - Customize for ARM MCU features
    - Add IPv6 & power management
  - Complexity increases as IoT deployments grow

- **Not secure**
  - Source code widely available => think Open SSL
  - Nodes may not be updateable for security flaws
New IoT Operating System

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New IoT Operating System approach
Benefits of Paqet OS in IoT applications
A new approach

B. State Machine => How Internet works

Most internet stacks are state machines, Event Driven
Good for simple functions, small data streams, small code size
Harder for programmers to build a state machine in an RTOS
Solution: Build State Machine into the OS ground up

Programming concept:
Event driven / state machine

- Reactive - events control program flow
  - Timers, hardware interrupts, radio, etc
- More kind on resources
- However, callbacks and state variables makes programming harder
State used in low power radios

<table>
<thead>
<tr>
<th></th>
<th>Voice</th>
<th>Data</th>
<th>Audio</th>
<th>Video</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth ACL / HS</td>
<td>x</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Bluetooth SCO/eSCO</td>
<td>Y</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Bluetooth low energy</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>(VoIP)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
</tr>
<tr>
<td>Wi-Fi Direct</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>ZigBee</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
<tr>
<td>ANT</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
</tbody>
</table>

State = low bandwidth, low latency data

Source: Joe Decuir, CSR, Presentation to IEEE CES
IoT OS: Memory vs. Support

**Memory**
- 4k ROM/2k RAM
- 32k ROM/16k RAM
- Minimum Memory
- 1024k ROM/512k RAM

**Support Level**
- Unsupported
- Marginal
- Highly Supported
  - Support level, e.g. C++, Sensor Drivers, APIs, OOBE

- **TinyOS**
- **DIY**
- **Contiki**
- **FreeRTOS**
- **OpenRTOS**
- **Thingsquare**
- **Intel VxWorks**
- **Linux**
- **Paqet OS**

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IoT OS by Type

OS Structure:

- State Machine
- Event Driven
- Ultra Low Power

Real Time

DIY

Open Source

Supported

- FreeRTOS
- OpenRTOS
- Contiki
- TinyOS
- RIOT
- Thingsquare
- Intel VxWorks
- Micrium

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New IoT operating system

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Drivers of power in IoT nodes

**Duty Cycle:** how often active
- Radio: Standards, protocol efficiency
- CPU: OS # cycles, Fast CPU wakeup, "Reflex” support

**Active power consumption:**
- Radio: Tx Power, Rx Power, PA efficiency, simple protocols
- CPU: State OS, Simple CPU, XIP, slow clock, latest S/C node

**Duration of active state:**
- Radio: High data rate, least energy/bit, simple protocol
- CPU: State OS, Simple OS, native IPv6 support, number of cycles to complete

**Standby power consumption:**
- Radio: Leakage better for older S/C node
- CPU: Deep sleep states, Fast OS wake up, Reflex, Leakage

**Sensor management: Intelligence/hub**
- Use low power sensors most/first, e.g. accelerometer, temperature/ not Gyro

*Event driven:* OS decides whether sensor state demands radio wake up
Wireless Sensor Challenge: Reduce the radio duty cycle

Target power savings, sample configuration

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical</th>
<th>Paqet</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Real IoT servers with minimum resources

- **NXP 810 (4K) ping**

  ```
  C:\>ping -t 83.104.5.56
  Pinging 83.104.5.56 with 32 bytes of data:
  Reply from 83.104.5.56: bytes=32 time=1025ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1063ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1070ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1063ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1071ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1063ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1072ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1075ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1075ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1075ms TTL=44
  Reply from 83.104.5.56: bytes=32 time=1065ms TTL=44
  Ping statistics for 83.104.5.56:
  Packets: Sent = 9, Received = 9, Lost = 0 (0% loss).
  Approximate round trip times in milli-seconds:
  Minimum = 1025ms, Maximum = 1075ms, Average = 1065ms
  ```

- **FRS M0+ with accel, via MQTT (8K)**

  ```
  C:\>ping -t 83.104.5.50
  Pinging 83.104.5.50 with 32 bytes of data:
  Reply from 83.104.5.50: bytes=32 time=236ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=229ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=236ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=228ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=229ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=227ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=227ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=227ms TTL=43
  Reply from 83.104.5.50: bytes=32 time=227ms TTL=43
  Ping statistics for 83.104.5.50:
  Packets: Sent = 7, Received = 7, Lost = 0 (0% loss).
  Approximate round trip times in milli-seconds:
  Minimum = 227ms, Maximum = 236ms, Average = 230ms
  ```

- **TI Cortex M3 with Bosch temp sensor (16K)**

  ```
  C:\>ping -t 83.104.5.55
  Pinging 83.104.5.55 with 32 bytes of data:
  Reply from 83.104.5.55: bytes=32 time=241ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=237ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=239ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=239ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=241ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=237ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=237ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=237ms TTL=44
  Reply from 83.104.5.55: bytes=32 time=237ms TTL=44
  Ping statistics for 83.104.5.55:
  Packets: Sent = 8, Received = 8, Lost = 0 (0% loss).
  Approximate round trip times in milli-seconds:
  Minimum = 237ms, Maximum = 242ms, Average = 239ms
  ```

---

**Temperature inside the Server Barn at Shirl Heath Farm:**

**21.0 °C (69 °F)**

Page ID: 32223; This page should automatically refresh every 1 minute

OS Version 0.75; Platform: Bosch BMA180 on TI Stellaris LM3S6965 (ARM Cortex M3)
Paqet O/S allows Apps to be independent of all the hardware (CPU, Sensors, or Communications) allowing faster initial TTM, faster cost reduction, easy development of 3rd party IoT applications.
Advantage of modern design approach

<table>
<thead>
<tr>
<th>Node hardware</th>
<th>System Software</th>
<th>Integration; application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCU select</td>
<td>O/S hand crafting</td>
<td>Sensor I/F</td>
</tr>
<tr>
<td>Sensor &amp; RF design</td>
<td>O/S customization</td>
<td>RF &amp; Comms I/F</td>
</tr>
<tr>
<td>Power supply</td>
<td>Cloud software</td>
<td>Power mgmt code</td>
</tr>
<tr>
<td>PCB, package</td>
<td></td>
<td>Application code</td>
</tr>
</tbody>
</table>

**RTOS approach**
- ~ 6 months each design
- MCU select
- Sensor & RF design
- Power supply
- PCB, package

**Paqet approach**
- ~ 2 months first design, 1 month revision
- MCU select
- Sensor & RF design
- Power supply
- PCB, package

- O/S load including drivers and cloud
- OTS drivers for sensor, RF, Comms, and Power mgmt
- Application code

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New IoT operating system

Thank You!

Steve Jordan