IEEE Std. 802.15.4
Enabling Pervasive Wireless Sensor Networks

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Technology Manager
Embedded Systems & Communications Group
Content

• Introduction: The Wireless Vision
• Existing Applications
• Technology Comparison
• A Brief Description of IEEE 802.15.4
• Current Challenges
• What’s Beyond (and Above) IEEE 802.15.4?
Introduction
Overview

Premier Globally Diversified Industrial Manufacturer of Highly Engineered Products and Systems

- **Automotive**
  - Engine Air Management Systems
  - Power Train & Specialty Controls

- **Eaton Electrical**
  - Electrical Distribution Products
  - Power Control Systems
  - Global Support Systems

- **Fluid Power**
  - Aerospace
  - Hydraulics
  - Fluid Connectors

- **Truck**
  - Heavy Duty Transmissions
  - Light & Medium Duty Transmissions
  - Specialty Systems
  - Clutches

- **Other**
  - Airflex
  - Golf Grip
Vision

• Add value to current and future product offerings using wireless technologies to enable:
  ▪ Increase Productivity
  ▪ Improve Safety
  ▪ Convenience
  ▪ Enhance Reliability
  ▪ Lower System Cost
Vision

Thousands of sensors in a small space → Wireless

But wireless implies Low Power

And low power implies Limited Range
Vision

Furthermore, it has to be **Self-Organizing**

Of course all of this is viable if a **Low Cost** technology can be used
Wireless provides:

• No connectors
• Safe/flexible connectivity
• Improves resources sharing
• Ease of installation
• Mobility

Limit Switch Component

Limit Switch Installed
Low Power

• Fully untethered transponders do not have access to external power

  → Batteries or scavenging of surplus power!

• But if batteries are used, they should last a long time:
  ▪ Automotive applications: 3 to 5 years (in USA)
  ▪ Industrial applications: 5 to 10 years or more!
Limited Range

Since a node has limited transmit range, the transmission of a message beyond this range, requires that the node calls upon one or more of its neighbors in order to relay the message to its final destination.

This technique is commonly called *multi-hop* communication.
Self-Organization (Ad-Hoc)

• Fully automatic routing
  ▪ Each node connects with its immediate neighbors

• Automatic topology adaptation
  ▪ The network automatically adapts as its topology changes, i.e., as nodes arrive at or depart from the network environment
Entry-Level Challenges

- Frequency of operation
- Coexistence and jamming
- Interoperability
- Cost and availability
- Antenna design
Coexistence and Jamming

- ISM bands can be used and are used by standard and non-standard technologies
- Microwaves ovens operate at 2.4GHz
- 802.11b and Bluetooth networks have major issues when collocated
- Spread Spectrum technologies help mitigate coexistence issues

*How can I guarantee that my network will operate in every environment?*
Coexistence and Jamming

\[ f_{offset} = 12 \text{ MHz} \]

\[ f_{offset} = 2 \text{ MHz} \]
Interoperability

- Standard technologies are designed to interoperate....
  … but *different implementations may have slight differences*

- Non-standard technologies may behave as standards

- There are different levels of standardizations
Cost and Availability

- Remember the $5 Bluetooth module?
- What cost are we talking?
  - Transceiver
  - Chipset
  - Module
  - What about the external components needed?
    - and the antenna?
  - Is the stack included?

*The technology will be available on Q4 200x*
Antenna

• The higher the frequency the smaller the antenna …
  ... and the propagation range is worst!

• Antenna connectors are expensive
• Antenna design is considered “black magic”
• Antennas needs to be designed with the entire sensor package in mind
  ▪ Is the antenna integrated to the sensor?
  ▪ PCB antennas acts as attenuators

• Metal, metal, metal….
Which Technology is Good for our Needs?

Leading Wireless Technologies Comparison
Standards Technology Map 2005

- Power Consumption
- Cost/Complexity

- Data Rate:
  - 1 Mb/s
  - 10 Mb/s
  - 100 Mb/s

- LR-WPAN
- W-LAN
- WMAN
- W-WAN
- Satellite
- 802.16
- 802.15.3
- 802.15.4
- 802.11a
- 802.11b
- 802.11g
- HiperLAN
- 2G
- 2.5G
- 3G
- 1G
- Bluetooth
- WiFi
- WiMedia
- ZigBee
- UWB
- WiMax

- EATON

INNOVATION CENTER
## Technology Applications

<table>
<thead>
<tr>
<th></th>
<th>WLAN 802.11</th>
<th>Bluetooth/ WPAN 802.15.1</th>
<th>LR-WPAN 802.15.4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Centralized Wireless Networking (WLAN) in the office environment</td>
<td>Cable replacement for consumer devices in the personal operating space</td>
<td>Low-cost wireless link for industrial/commercial sensor and actuator devices</td>
</tr>
<tr>
<td><em>Embedded Sensors</em></td>
<td><em>(Not applicable)</em></td>
<td><em>(Not applicable)</em></td>
<td><em>(Not applicable)</em></td>
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<tr>
<td><em>Voice/Video Real-Time</em></td>
<td><em>(Not applicable)</em></td>
<td><em>(Not applicable)</em></td>
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<tr>
<td>Cost</td>
<td>$$$</td>
<td>$$</td>
<td>$</td>
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</table>

*EATON INNOVATION CENTER*
### Standard Technology Options

<table>
<thead>
<tr>
<th></th>
<th>LR-WPAN</th>
<th>Bluetooth™</th>
<th>WLAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>10–30 m</td>
<td>~10–100 m</td>
<td>~100 m</td>
</tr>
<tr>
<td>Data Throughput</td>
<td>&lt;0.25 MBPS</td>
<td>1 MBPS</td>
<td>~2–11 MBPS</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>&lt;BT/10</td>
<td>BT</td>
<td>&gt;BT</td>
</tr>
<tr>
<td>Size</td>
<td>Smallest</td>
<td>Smaller</td>
<td>Larger</td>
</tr>
<tr>
<td>Nodes/Net</td>
<td>&lt;&lt;BT</td>
<td>BT</td>
<td>&gt;BT</td>
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<tr>
<td>Cost</td>
<td>~$1</td>
<td>~$10–$15</td>
<td>~$40</td>
</tr>
</tbody>
</table>

Most industrial applications require lower cost and device power than mainstream wireless technology can achieve.
Measuring Standards Complexity

<table>
<thead>
<tr>
<th>Standard</th>
<th>Number of Primitives</th>
<th>Code Size (Kb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.15.4</td>
<td>140</td>
<td>2000</td>
</tr>
<tr>
<td>802.15.1</td>
<td>120</td>
<td>1800</td>
</tr>
<tr>
<td>802.15.3</td>
<td>100</td>
<td>1600</td>
</tr>
<tr>
<td>802.11x</td>
<td>80</td>
<td>1400</td>
</tr>
<tr>
<td>802.11x</td>
<td>60</td>
<td>1200</td>
</tr>
<tr>
<td>802.11x</td>
<td>40</td>
<td>1000</td>
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<td>20</td>
<td>800</td>
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<tr>
<td>802.11x</td>
<td>0</td>
<td>600</td>
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</table>

A.K.A. Bluetooth™

Original 1032 Pages
WSN Architecture

\[
\Sigma \left( \text{Sensor Application} + \text{Application Support Layer} + \text{Network Layer} + \text{Data Link Layer} + \text{Physical Layer} \right) = \text{Wireless Sensor Networks (WSN)}
\]
802.15.4 Main Characteristics

- Data rates of 250 kb/s, 40 kb/s and 20 kb/s
- Star or peer-to-peer operation
- Support for low latency devices
- CSMA-CA channel access
- Dynamic device addressing
802.15.4 Main Characteristics

- Fully handshake protocol for transfer reliability
- Low power consumption
- Frequency bands of operation
  - 16 channels in the 2.4GHz ISM band
  - 10 channels in the 915MHz ISM band
  - 1 channel in the European 868MHz band
802.15.4 Protocol Architecture

Upper Layers

IEEE 802.2 LLC

Other LLC

IEEE 802.15.4 MAC

IEEE 802.15.4
868/915 MHz
PHY

IEEE 802.15.4
2400 MHz
PHY
802.15.4 Physical Layer

Operating Frequency Bands

868MHz/915MHz PHY

- 868.3 MHz (Channel 0)
- 902 MHz to 928 MHz (Channels 1-10)

2.4 GHz PHY

- 2.4 GHz to 2.4835 GHz (Channels 11-26)
# 802.15.4 Channel Assignment

<table>
<thead>
<tr>
<th>Channel</th>
<th>Center Frequency (MHz)</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>868 MHz Band</strong></td>
<td>0</td>
<td>868.3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>906</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>908</td>
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<td>3</td>
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<td>922</td>
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<td></td>
<td>10</td>
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<td><strong>915 MHz Band</strong></td>
<td>11</td>
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<td></td>
<td>26</td>
<td>2480</td>
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<tr>
<td><strong>2.4 GHz Band</strong></td>
<td>27</td>
<td>2485</td>
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<td>2575</td>
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<tr>
<td></td>
<td>46</td>
<td>2580</td>
</tr>
</tbody>
</table>

**Notes:**
- The availability of channels varies by region:
  - Europe
  - Americas
  - Worldwide

**Sources:**
- IEEE 802.15.4 standard
- Wireless communication regulations of various countries
802.15.4 Packet Structure

PHY Packet Fields
- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Start of Packet Delimiter</th>
<th>PHY Header</th>
<th>PHY Service Data Unit (PSDU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

6 Octets 0–127 Octets
2.4 GHz PHY
- 250 kb/s (4 bits/symbol, 62.5 kBaud)
- Data modulation is 16-ary orthogonal modulation
- 16 symbols are ~orthogonal set of 32-chip PN codes
- Chip modulation is MSK at 2.0 Mchips/s

868MHz/915MHz PHY
- Symbol rate
  - 868 MHz Band: 20 kb/s (1 bit/symbol, 20 kBaud)
  - 915 MHz Band: 40 kb/s (1 bit/symbol, 40 kBaud)
- Data modulation is BPSK with differential encoding
- Spreading code is a 15-chip m-sequence
- Chip modulation is BPSK at
  - 868 MHz Band: 300 kchips/s
  - 915 MHz Band: 600 kchips/s
802.15.4 Common Parameters

**Transmit Power**
- Capable of at least 1 mW

**Transmit Center Frequency Tolerance**
- ± 40 ppm

**Receiver Sensitivity** (packet error rate <1%)
- –85 dBm @ 2.4 GHz band
- –92 dBm @ 868/915 MHz band

**RSSI Measurements**
- Packet strength indication
- Clear channel assessment
802.15.4 MAC Design Drivers

- Extremely low cost
- Ease of implementation
- Reliable data transfer
- Short range operation
- Very low power consumption

*Simple but flexible protocol!*
802.15.4 Network Topologies

**Star**

- A simple topology where each node is connected to a central node.

**Mesh**

- A more complex topology where nodes are interconnected forming a network with multiple paths between nodes.

Diagram illustrating the differences between Star and Mesh topologies.
802.15.4 Device Classes

- **Full function device (FFD)**
  - Any topology
  - PAN coordinator capable
  - Talks to any other device

- **Reduced function device (RFD)**
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation
802.15.4 Definitions

**Coordinator**
- An FFD with network device functionality that provides coordination and other services to the network.

**PAN Coordinator**
- A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.

**Network Device**
- An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium.
802.15.4 Low-Power Operation

- Duty-cycle control using superframe structure
- Indirect data transmission
- Devices may sleep for extended period over multiple beacons
- Allows control of receiver state by higher layers
802.15.4 MAC Star Topology

Master/Slave

PAN Coordinator

Full function device
Reduced function device
Communications flow
802.15.4 MAC Peer-to-Peer

Point To Point

Cluster Tree

Full function device

Communications flow
Clustered Stars—for example, cluster nodes exist between rooms of a hotel and each room has a star network for control.

- **Full function device**
- **Reduced function device**
- **Communications flow**
4 Types of MAC Frames:
- Data frame
- Beacon frame
- Acknowledgment frame
- MAC command frame
802.15.4 MAC Superframe Structure

- **Network Beacon**—Transmitted by network coordinator. Contains network information, frame structure and notification of pending node messages.
- **Beacon Extension Period**—Space reserved for beacon growth due to pending node messages
- **Contention Period**—Access by any node using CSMA-CA
- **Guaranteed Time Slot**—Reserved for nodes requiring guaranteed bandwidth \([n = 0]\)

\[15 ms \times 2^n\]

where \(0 \geq n \geq 14\)
802.15.4 MAC Traffic Types

• Periodic data
  ▪ Application defined rate (e.g., sensors)

• Intermittent data
  ▪ Application/external stimulus defined rate (e.g., light switch)

• Repetitive low latency data
  ▪ Allocation of time slots (e.g., mouse)
802.15.4 MAC Data Service

Originator MAC

MCPS-DATA.request

Channel Access

Data frame

Acknowledgement (if requested)

MCPS-DATA.confirm

Recipient MAC

MCPS-DATA.indication
802.15.4 MAC Management Service

- Access to the PAN Information Base
- Association / disassociation
- Guaranteed Time Slot allocation
- Message pending
- Node notification
- Network scanning/start
- Network synchronization/search
Eaton Applications!

Based on IEEE 802.15.4 Technology
Current Applications

• Residential applications
• Industrial and commercial applications
• Awarded DOE contract to increase energy efficiency of the Industries of the Future using Wireless Sensor technology
• Awarded DOE contract to secure US national energy infrastructure
Home Heartbeat™ System

The World’s First Home Awareness System

Base Station:
Logic and memory

Sensors
• Temperature
• Water
• Power
• Door/window open
• Other

User interface
Commissioning tool
Home Heartbeat™

The World’s First Home Awareness System
Home Heartbeat™

Home HeartBeat Application Challenges

- Sensing Points/node
- Multi-PHY Nodes/Total Nodes
- Bridge Nodes/Total Nodes
- % Mobile Nodes
- Max Number Nodes/Address Space
- Mobility/Link Connectivity
- Wireless/Wired Cost Ratio
- %Disposable Batteries
- Minimum MOP
- Lifetime/10yrs.
- 2+Hop links/ Total links
- Unplanned Deployment
- FFD/RFD Ratio
- Uncontrolled Mobility

EATON INNOVATION CENTER
Wireless Lighting Control

- Wireless Lighting Control in Commercial buildings provides:
  - Simple installation process
  - Lower total installed cost for labor and materials
  - No need to pull/install new control wires or disturb ceilings in older buildings where asbestos exists
  - Wiring devices installed at desired locations
Wireless Lighting Control

- Integrates with existing Pow-R-Command Panelboards
- Small RF module attaches to wiring device
- Battery powered when required

---

Logical Link

- Wireless Dimming Module
- Wireless Switch
- Wireless Occupancy Sensor
Wireless Lighting Control
Wireless Lighting Control

WFM Application Challenges

- Sensing Points/node
- Multi-PHY Nodes/Total Nodes
- Bridge Nodes/Total Nodes
- % Mobile Nodes
- Max Number Nodes/Address Space
- Mobility/Link Connectivity
- Wireless/Wired Cost Ratio
- FFD/RFD Ratio
- % Disposable Batteries
- Minimum MOP
- Lifetime/10 yrs.
- 2+Hop links/Total links
- Unplanned Deployment
- Uncontrolled Mobility
Energy Savings for Industrial

Motor efficiency improvements 4.5%
System efficiency improvements 9.6%

Energy usage data to drive energy savings via capital improvements
Energy and condition sensing data to drive process uptime through diagnostics & prognostics
Energy and condition sensing data to drive local process efficiency improvement
Energy usage data and spot energy pricing to improve enterprise efficiency / costs.

Eaton’s WSN enables continuous energy savings!
Energy Sensing

Architectural Concept

Motor Control Center

- Voltage
- Current

Motor

- Temperature
- RPM
- Vibration

3 Phase AC Power (no control/signal wires)

Driven Load
Wireless communication also enables a wide range of cost effective conditions based maintenance features and capabilities.
Wireless Energy Sentinel
LRWPAN Field Test Site

200 ft.

110 ft.

30 Type A Nodes
10 Type B Nodes
NC
Closing the Loop on Energy Savings
Closing the Loop on Energy Savings

Energy Management Application Challenges

- Sensing Points/node
- Multi-PHY Nodes/Total Nodes
- Bridge Nodes/Total Nodes
- % Mobile Nodes
- Max Number Nodes/Address Space
- Mobility/Link Connectivity
- Wireless/Wired Cost Ratio
- Uncontrolled Mobility
- % Disposable Batteries
- FFD/RFD Ratio
- Unplanned Deployment
- 2+Hop links/Total links
- Lifetime/10yrs.
- Minimum MOP

Innovation Center

EATON
Since the recent terrorist attacks, there have been increased concerns in the protection of the Nation’s critical infrastructure from willful or vandalous attacks. Without protection, these vulnerable resources could become a target.

The objective of this project is to create a low-cost, robust, Wireless Sensor Network (WSN) to enable pervasive, real-time threat sensing, assessing and evaluation to assure the physical security of the Nation’s energy critical infrastructure.
Anticipatory reasoning is based on a system assessing its own operational capability, its impact on the environment, the environment’s impact on system, and the system’s capability to continue to support mission requirements. In other words, you can have less than 100% operational capability but still maintain required functional capability.
Anticipatory Systems

**Anticipation**

- Resources Used
- Remaining Resources
- Impact on the Whole System Based on the Data From Previous States
- Behavioral Decision
- Prediction of the System Based on Previous States
- Anticipatory Behavior

**Prediction**

- Resources Used
- Remaining Resources
- Prediction Based on System States
Second Level Challenges

For WSNs based on IEEE 802.15.4 Technology
Second-Level Challenges

- Intra-operability
- 3-D Node Models
- Time Synch Services
- Measure of Performance Optimization
- Power Harvesting
- Adaptable Network Layers
- Benchmarking
- Pairing/Binding
- Context Awareness
- Security
What’s after IEEE 802.15.4?
IEEE 802.15.4a

- Defines an alternative PHY (UWB)
  - Precision ranging
  - Extended range
  - Enhanced robustness
  - Mobility
- Amendment to IEEE 802.15.4-2003 standard
IEEE 802.15.4b

- Enhancements and corrections to the existing standard.
  - Support for new frequency allocations for Europe, China, and Japan.
  - Extension of 2.4GHz derivative modulation yielding higher data rates for the lower frequency bands.
  - Mechanism for communicating the revision level.
- Backward compatible with IEEE P802.15.4-2003.
The ZigBee Alliance

- Association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked monitoring and control product based on IEEE 802.15.4

- Consortium of companies defining the protocol layers not defined in IEEE 802.15.4 (aka Upper Layers)

- Marketing arm and certification body for LR-WPAN technology

- More: www.zigbee.org
ZigBee Mission

The ZigBee Alliance is an association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on an open global standard.
Applications

- Remote control
- Consumer Electronics
- Residential and light Commercial
- Lighting control
- Home awareness
- Access control
- HVAC
- Human interface devices
- PC Peripherals
- Building Automation
- Lighting control
- Access control
- HVAC
- Fitness monitoring
- Patient monitoring
- Personal Health Care
- Industrial Control
- Asset management
- Process control
- Energy management
ZigBee Stack Architecture

IEEE 802.15.4 defined
ZigBee™ Alliance defined
End manufacturer defined
Layer function
Layer interface

Application Object
Application Object
ZigBee Device Objects
- Device Mgmt.
- Security Mgmt.
- Binding Mgmt.
- NWK Mgmt.

Endpoint Multiplexing
ASLD-SAP
ASLM-SAP
Application Support Layer (ASL)
- Message Management
- Fragmentation Management
- Discovery Management
- APL Security

Network Layer (NWK)
- Routing Management
- Reflector Management
- NWK Security Management

Endpoint 0
Endpoint 1
Endpoint 31
MLME-SAP
NLDE-SAP
NLME-SAP
MCPS-SAP
PD-SAP
PHY (IEEE 802.15.4)
MCPS-SAP
MLME-SAP
PD-SAP
PLME-SAP
IEEE 802.15.4 defined
ZigBee™ Alliance defined
End manufacturer defined
Layer function
Layer interface

IEEE 802.15.4
IEEE 802.15.4
IEEE 802.15.4
Wireless Industrial Network Alliance

- A coalition of industrial end-user companies, technology suppliers, industry organizations, software developers, system integrators.

- Aims at Improving the understanding of the benefits of using wireless in industrial applications
- Improving the confidence in wireless technology and access to solutions
- Focusing on the end user
WINA Charter

WINA works to accelerate the adoption of wireless technologies in the industrial sector:

- Identify, recommend, and certify appropriate wireless technologies
- Focus on customer requirements
- Promote effective standards, regulations, and practices
- Quantify and communicate the benefits and potential impacts of wireless technologies
Wireless Sensor Network

Internet brought us the *superhighway*; Wireless will take us *off road*!!

LR-WPAN Wireless Sensor Networks

- Fluid Power
- Industrial & Commercial Products
- Automotive
- Truck Components
Thank you!
Industrial Perspective on Wireless Sensor Networks.