

IEEE 802.15.4 and Zigbee

CS 687
University of Kentucky
Fall 2015

Acknowledgment: Some slides are adapted from presentations by Bob Heile from ZigBee Alliance, Joe Dvorak from Motorola, Geir E. Oien from NTNU, and Marco Naevve from Eaton Corporation.

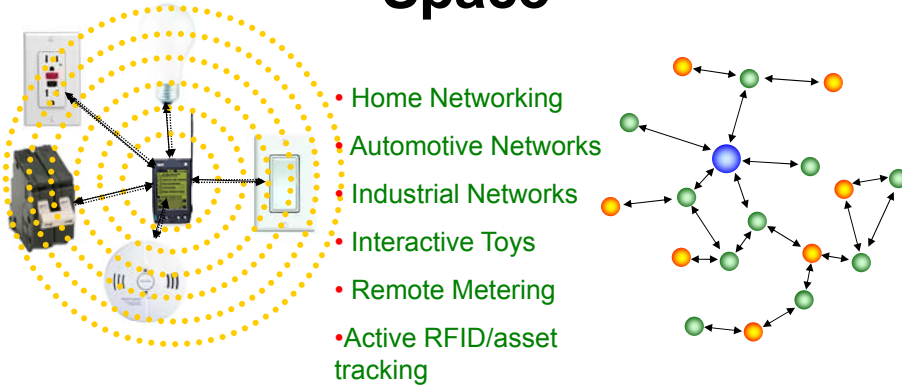
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Outline

- Introduction
- PHY Layer
- MAC Layer
- Network Layer
- Applications

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IEEE 802.15.4 Application Space



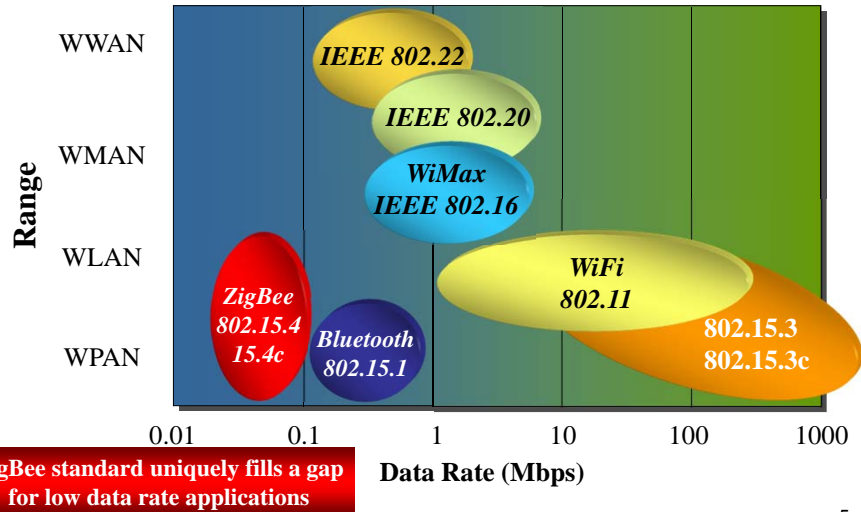
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Sensor/Control Network Requirements

- Networks form by themselves, scale to large sizes and operate for years without manual intervention
- Extremely long battery life (years on AA cell),
 - low infrastructure cost (low device & setup costs)
 - low complexity and small size
- Low device data rate and QoS
- Standardized protocols allow multiple vendors to interoperate

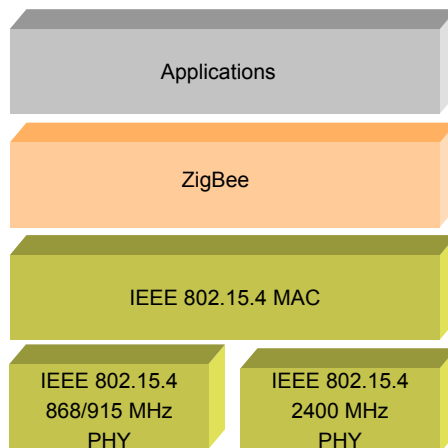
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The IEEE 802 Wireless Space



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802.15.4 / ZigBee Architecture



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802.15.4 General 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.

Fully handshaked 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.

* ISM: Industrial, Scientific, Medical

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Wireless Technology Comparison Chart

Standard	Bandwidth	Power Consumption	Protocol Stack Size	Stronghold	Applications
Wi-Fi	Up to 54Mbps	400+mA TX, standby 20mA	100+KB	High data rate	Internet browsing, PC networking, file transfers
Bluetooth	1Mbps	40mA TX, standby 0.2mA	~100+KB	Interoperability, cable replacement	Wireless USB, handset, headset
ZigBee	250kbps	30mA TX, standby 356 μ A	34KB /14KB	Long battery life, low cost	Remote control, battery-operated products, sensors

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ZigBee Alliance

- Organized as an independent, neutral, nonprofit corporation in 2002
- Open and global
 - Anyone can join and participate
 - Membership is global
- Activity includes
 - Specification creation
 - Certification and compliance programs
 - Branding, market development, and user education

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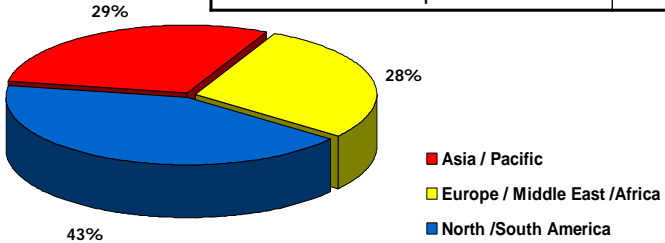
The ZigBee Promoters



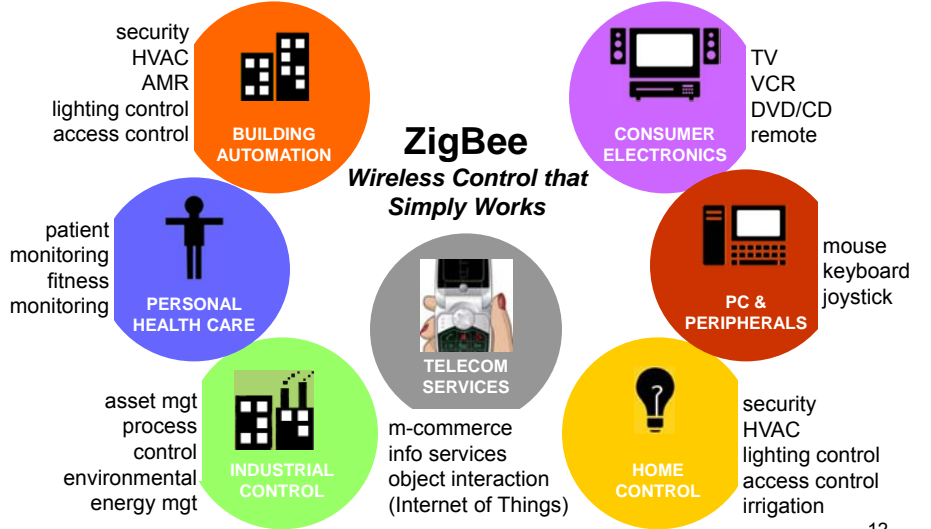
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ZigBee Member Geographic Distribution

Region	November 2006
Asia / Pacific	60 (29%)
Europe / Middle East/Africa	58 (28%)
North/South America	86 (43%)
Total Member Companies	204



ZigBee Applications

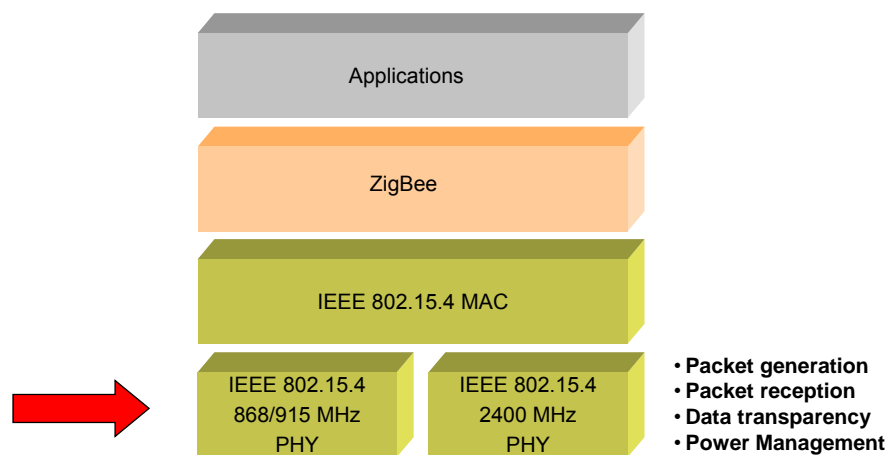


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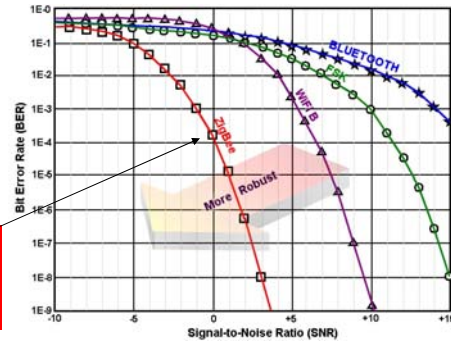
802.15.4 / ZigBee Architecture



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Basic Radio Characteristics

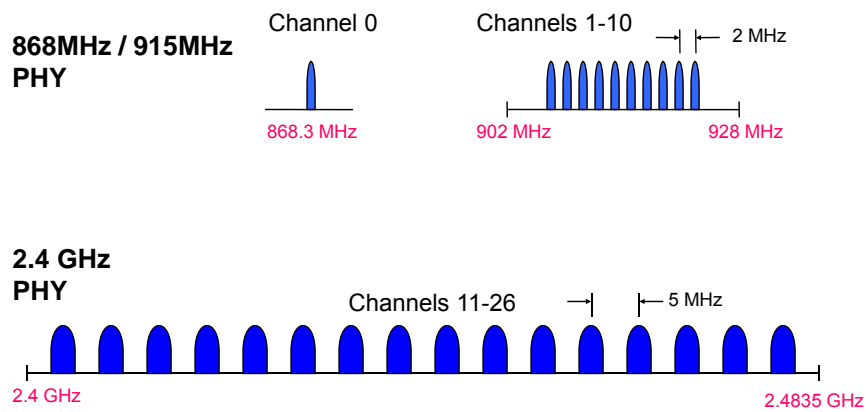
ZigBee technology relies upon IEEE 802.15.4, which has excellent performance in low SNR environments



Frequency Band	License Required?	Geographic Region	Data Rate	Channel Number(s)
868.3 MHz	No	Europe	20kbps	0
902-928 MHz	No	Americas	40kbps	1-10
2405-2480 MHz	No	Worldwide	250kbps	11-26

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Operating Frequency Bands



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IEEE 802.15.4 PHY layer tasks

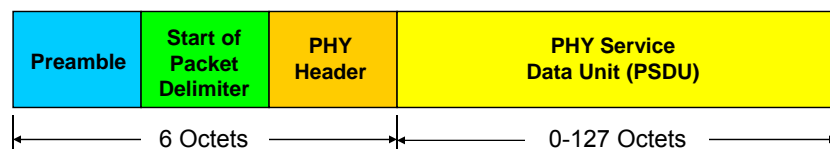
- activate/deactivate transceivers (low duty cycle saves energy)
- estimate signal strengths (energy detection) as part of CSMA mechanism
- compute link quality indicators (LQI, or SINR)
- listen to channels and declare availability or not (clear channel assessment -CCA)
- tuning of transceivers to supported channels
- transmit and receive data (16-symbol "quasi-orthogonal" modulation using O-QPSK and DSSS)
- conform to out-of-band power level regulations

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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



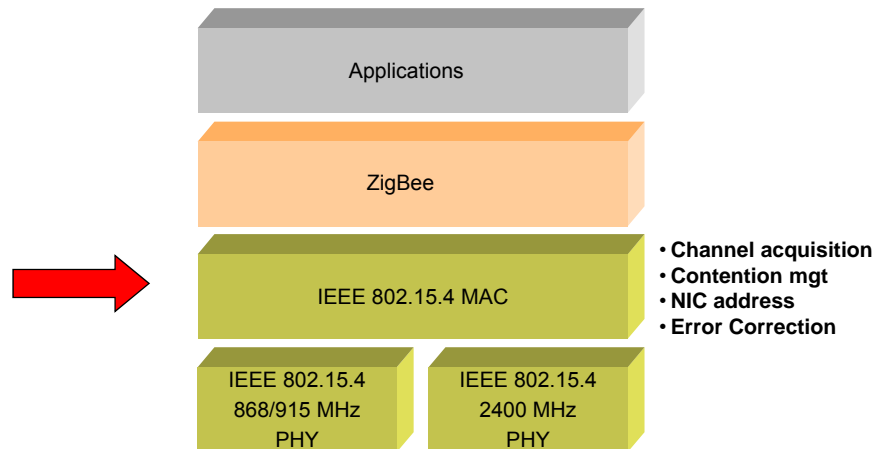
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- **MAC Layer**
- Network Layer
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802.15.4 Architecture



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Design Drivers

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

Simple but flexible protocol

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IEEE 802.15.4 Device Classes

- Full function device (FFD)
 - Any topology
 - PAN coordinator capable
 - Talks to any other device
 - Implements complete protocol set
- Reduced function device (RFD)
 - Limited to star topology or end-device in a peer-to-peer network.
 - Cannot become a PAN coordinator
 - Very simple implementation
 - Reduced protocol set

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IEEE 802.15.4 Definitions

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

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IEEE 802.15.4 MAC layer tasks

- for PAN coordinators: generate *beacons* (if operating in beacon-enabled mode)
 - A beacon is a special frame sent out by the PAN coordinator for the purpose of synchronization with other units. Beacon-enabled mode offers power savings since units can "sleep" between being "woken up" by beacons.
- for all nodes: synchronize against received beacons
- maintain and break up PAN connections
- give channel access to nodes according to CSMA-CA (based on PHY layer info)
- maintain *guaranteed time slot* mechanism in beacon-enabled mode
- frame acknowledgement, ARQ, CRC

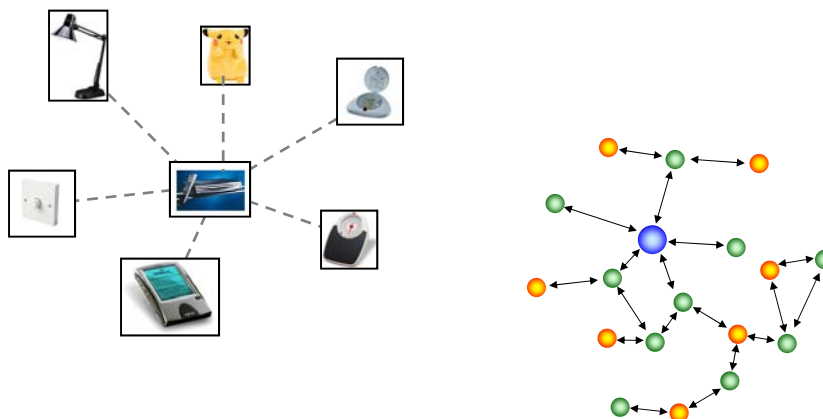
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802.15.4 Channel Access Options

- Non-beacon network
 - A simple, traditional multiple access system used in simple peer and near-peer networks–
 - Standard CSMA-CA communications
 - Positive acknowledgement for successfully received packets
- Beacon-enabled network:
 - Network coordinator transmits beacons (start and end of time-slotted superframe) at predetermined intervals
 - Superframe may be split between *contention access period*, *contention free period* (containing *guaranteed time slots*), and *inactive period*
 - Beacon Mode powerful for controlling power consumption in extended networks like cluster tree or mesh
 - Allows all clients in a local piece of the network the ability to know when to communicate with each other
 - PAN coordinator manages the channel and arranges the calls

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Typical Network Topologies



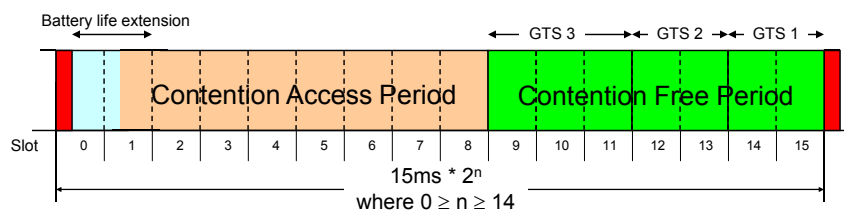
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Low-Power Operation

- Duty-cycle control using superframe structure
 - Beacon order and superframe order
 - Coordinator battery life extension
- Indirect data transmission
- Devices may sleep for extended period over multiple beacons
- Allows control of receiver state by higher layers

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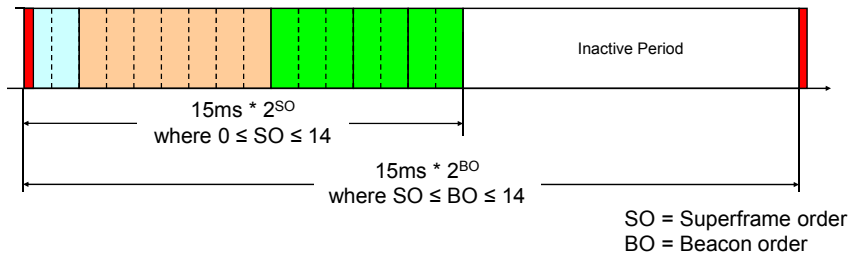
Optional Frame Structure



- | | | |
|-------------------------|--|--|
| Network beacon | | Transmitted by PAN 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 [$n = 0$]. |

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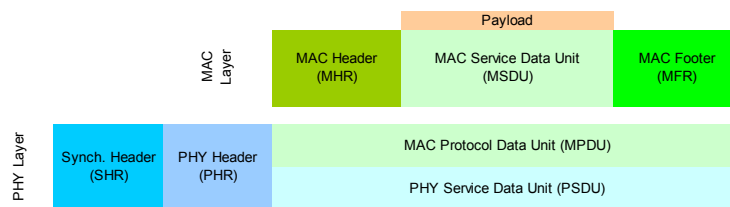
Optional Frame Structure



- Superframe may have inactive period

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General Frame Structure



4 Types of MAC Frames:

- Data Frame
- Beacon Frame
- Acknowledgment Frame
- MAC Command Frame

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General MAC Frame Format

Octets:2	1	0/2	0/2/8	0/2	0/2/8	variable	2	
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	Frame check sequence	
		Addressing fields						
MAC header						MAC payload	MAC footer	
Bits: 0-2	3	4	5	6	7-9	10-11	12-13	14-15
Frame type	Security enabled	Frame pending	Ack. Req.	Intra PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Frame control field

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Beacon Frame Format

Octets:2	1	4 or 10	2	variable	variable	variable	2
Frame control	Beacon sequence number	Source address information	Superframe specification	GTS fields	Pending address fields	Beacon payload	Frame check sequence
			MAC header				
Bits: 0-3	4-7	8-11	12	13	14	15	
Beacon order	Superframe order	Final CAP slot	Battery life extension	Reserved	PAN coordinator	Association permit	

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MAC Command Frame

Octets:2	1	4 to 20	1	variable	2
Frame control	Data sequence number	Address information	Command type	Command payload	Frame check sequence
MAC header			MAC payload		MAC footer

- Command Frame Types

- Association request
- Association response
- Disassociation notification
- Data request
- PAN ID conflict notification
- Orphan Notification
- Beacon request
- Coordinator realignment
- GTS request

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Data Frame Format

Octets:2	1	4 to 20	variable	2
Frame control	Data sequence number	Address information	Data payload	Frame check sequence
MAC header			MAC Payload	MAC footer

Acknowledgement Frame Format

Octets:2	1	2
Frame control	Data sequence number	Frame check sequence
MAC header		MAC footer

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Data Service

- Data transfer to neighboring devices
 - Acknowledged or unacknowledged
 - Direct or indirect
 - Using GTS service
- Maximum data length (MSDU)
aMaxMACFrameSize (102 bytes)

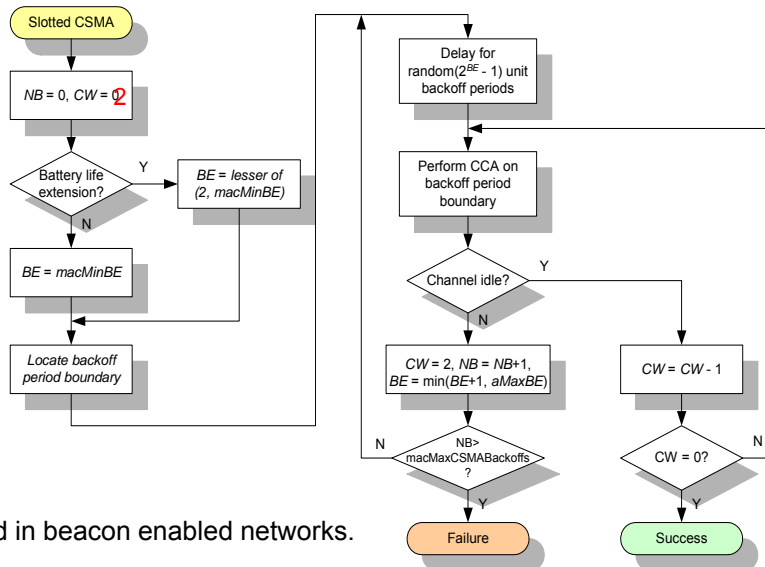
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Traffic Types

- 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**)

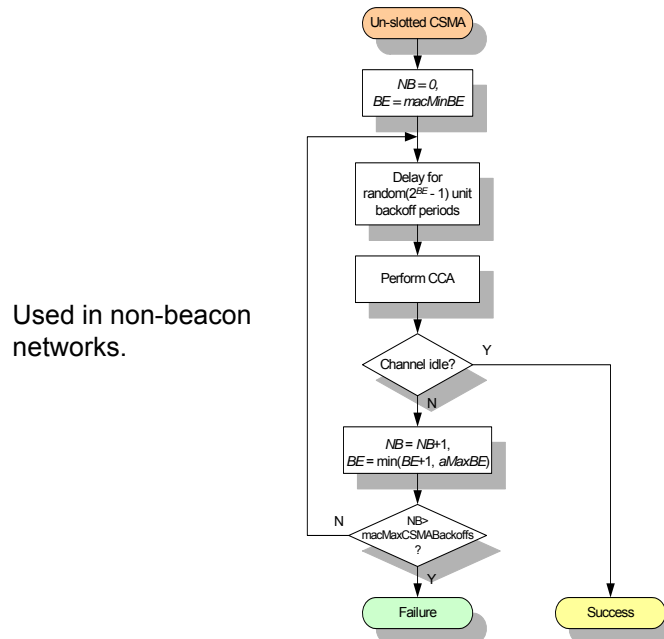
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Slotted CSMA Procedure



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Un-slotted CSMA Procedure



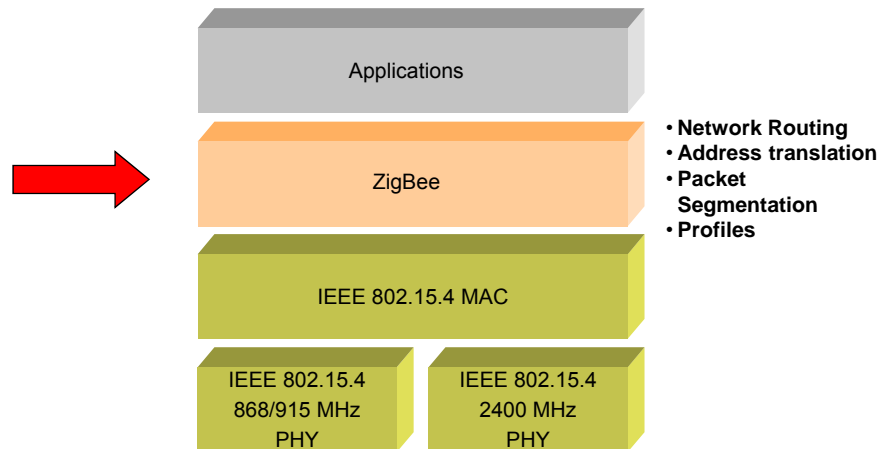
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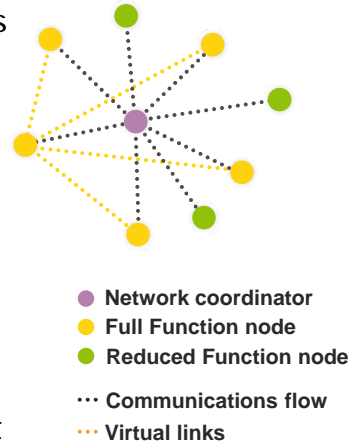
802.15.4 Architecture



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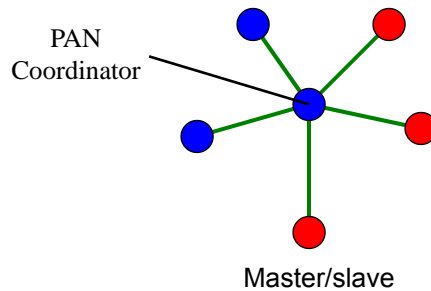
Basic Network Characteristics

- 65,536 network (client) nodes
- 27 channels over 2 bands
- 250Kbps data rate
- Optimized for timing-critical applications and power management
- Full Mesh Networking Support



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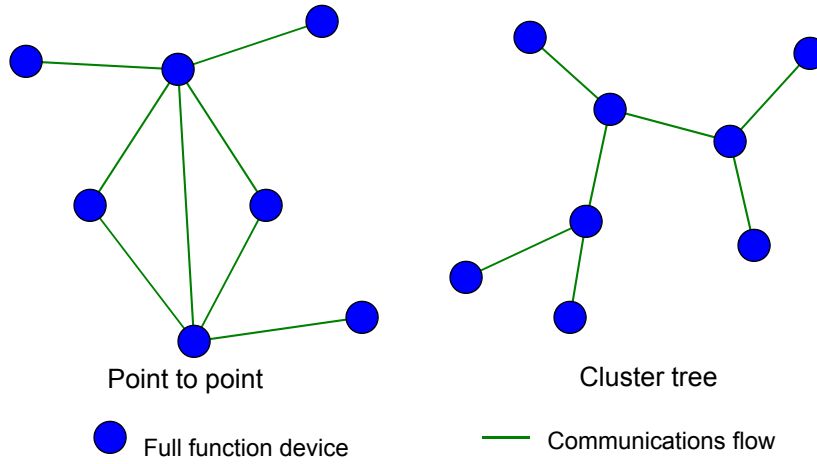
Star Topology



- Full function device
- Reduced function device
- Communications flow

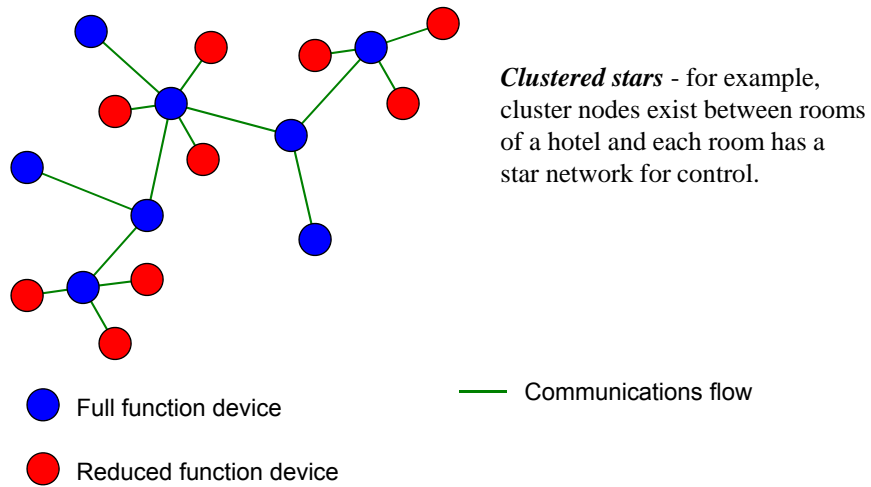
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Peer-Peer Topology



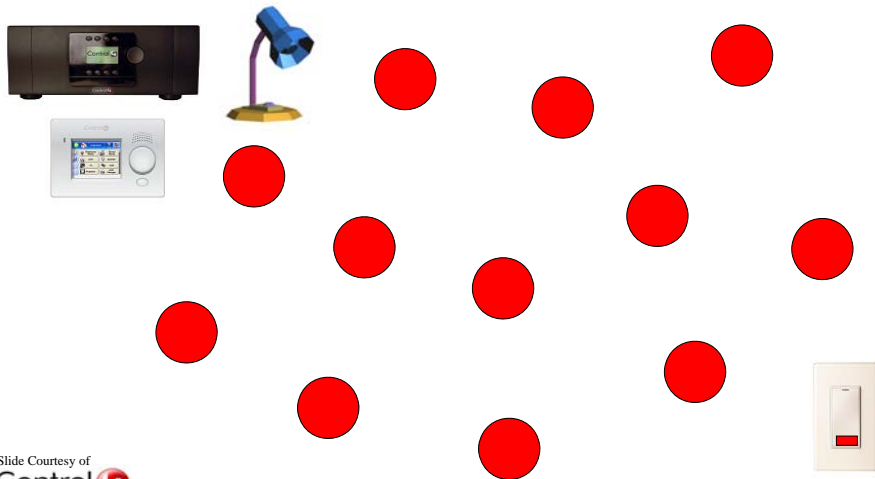
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Combined Topology



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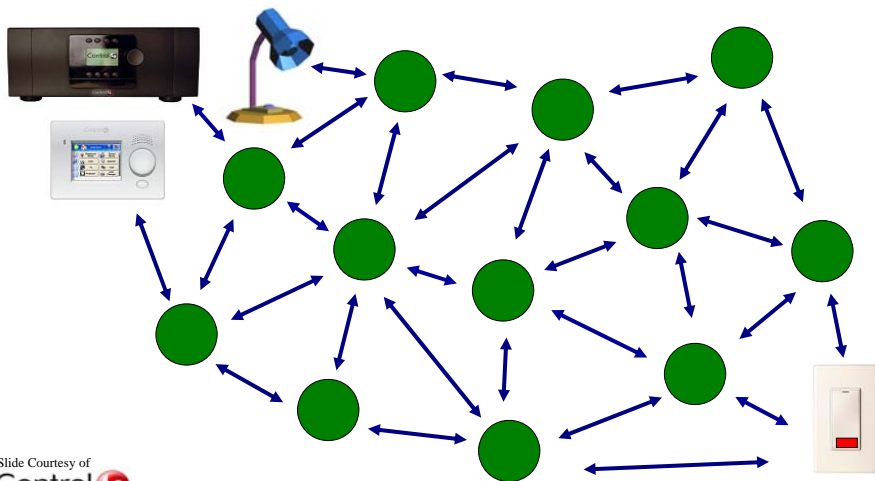
ZigBee Mesh Networking



Slide Courtesy of
Control 

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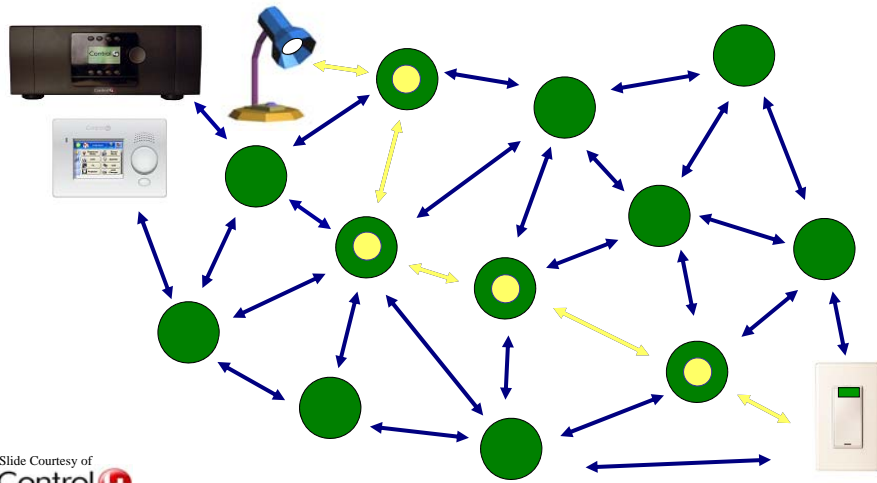
ZigBee Mesh Networking



Slide Courtesy of
Control 

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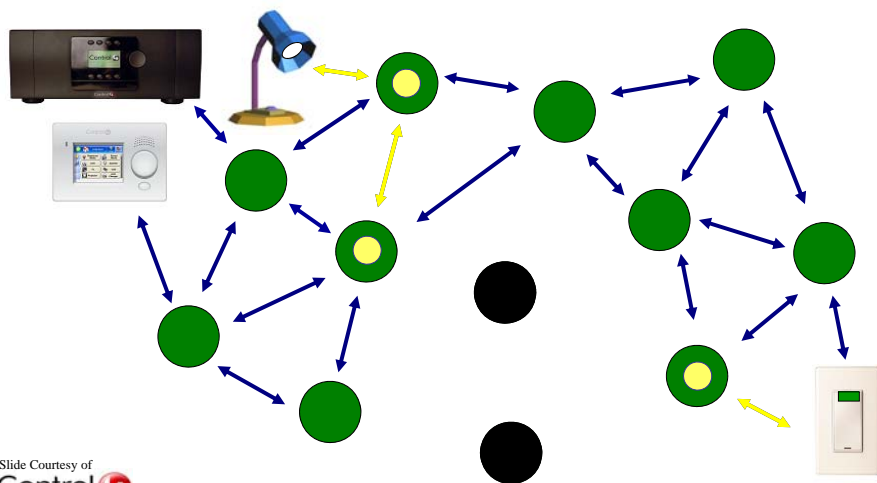
ZigBee Mesh Networking



Slide Courtesy of
Control 

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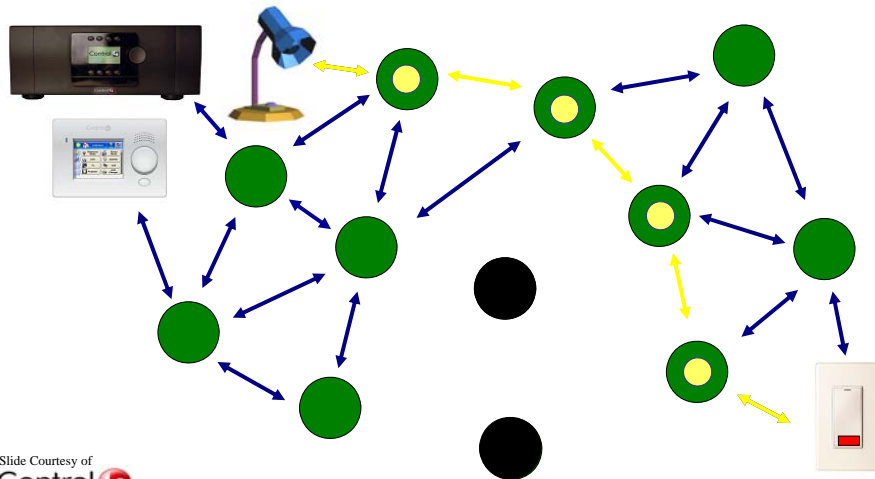
ZigBee Mesh Networking



Slide Courtesy of
Control 

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ZigBee Mesh Networking



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ZigBee Routing

- Ad hoc On Demand Distance Vector (AODV)
 - Path discovery on demand
 - Path maintenance (inform upstream nodes of broken links for active source nodes)
- Cluster-Tree Algorithm
 - Single cluster network
 - Cluster head selection
 - Multi-cluster network
 - Designated device for assigning a unique cluster ID to each cluster head

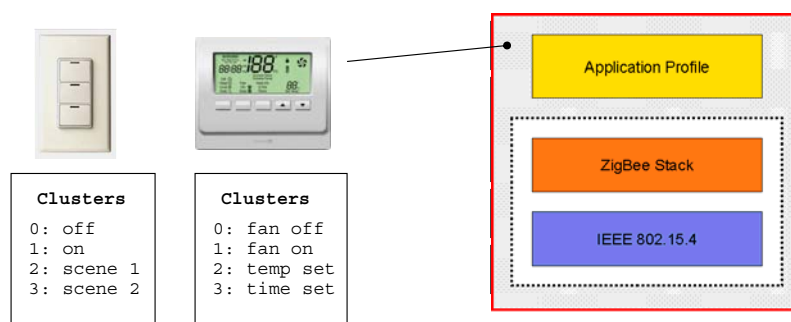
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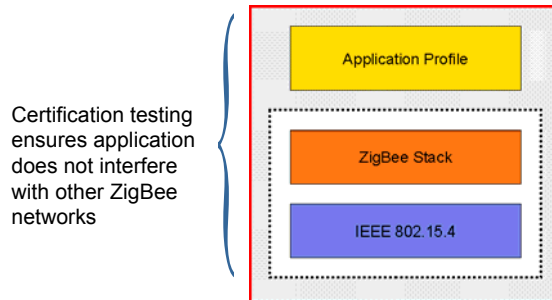
Application Profiles



- Application profiles define what messages are sent over the air for a given application
- Devices with the same application profiles interoperate end to end
- ZigBee publishes a set of public profiles, but vendors may create manufacturer specific ones as well

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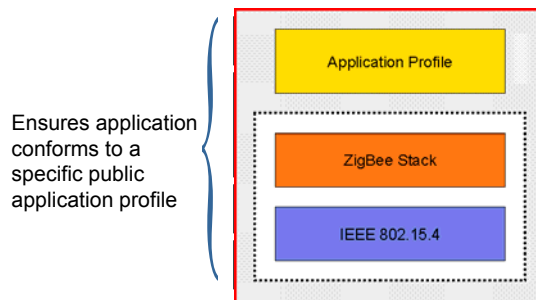
Manufacturer Specific Profiles



Certification testing ensures application does not interfere with other ZigBee networks

- Allows a vendor to build specialized products with a ZigBee Compliant Platform
- Certification testing ensures their product does not harm other ZigBee networks
- Manufacturer specific applications are not intended to interoperate at the application layer
- Allows product vendor to use ZigBee language and logos on their product

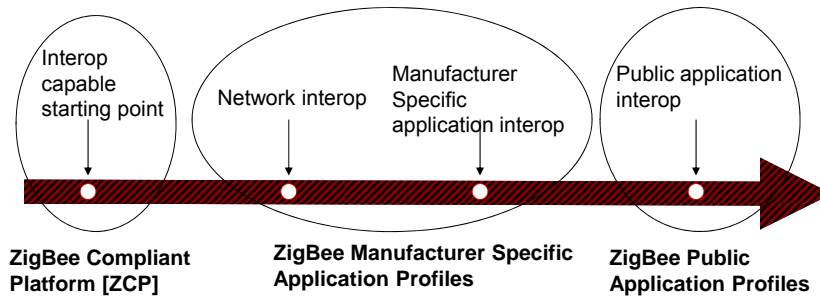
ZigBee Public Profiles



Ensures application conforms to a specific public application profile

- Guarantees interoperability between products all running the same public application profile
- Product vendors may add additional features to the public profiles
- Allows product vendor to use ZigBee language and logos on their product

Interoperability Summary



- Devices built on ZigBee interoperate on different levels
- Wide spectrum of interoperability choices
- It's a designer choice on level of vendor interoperability to support

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Some Application Profiles



- Home Automation [HA]
 - Defines set of devices used in home automation
 - Light switches
 - Thermostats
 - Window shade
 - Heating unit
 - etc.



- Industrial Plant Monitoring
 - Consists of device definitions for sensors used in industrial control
 - Temperature
 - Pressure sensors
 - Infrared
 - etc.

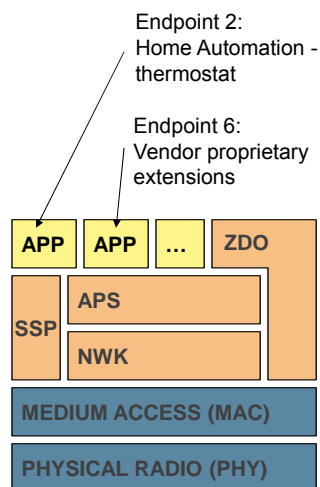
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More Application Profiles

- Multiple profiles at various stages of completion
 - Commercial Building Automation
 - Building control, management, and monitoring
 - Telecom Services/M-commerce
 - Automated Meter Reading
 - Addresses utility meter reading
 - Wireless Sensor Networks
 - Very low power unattended networks
- Vendors may form new profile groups within ZigBee and/or propose private profiles for consideration
- 400+ private profile IDs issued

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Multi-Profile Devices



- Vendor devices may implement multiple profiles
- Additional application profiles live on different endpoints within the device
- Allows creation of vendor specific extensions

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ZigBee – Highly Reliable

- Mesh networking protocol provides redundant paths
- Automatic retries and acknowledgements
- Parents keep track of messages for sleeping children
- High intrinsic interference tolerance
 - Multiple channels
 - Supports Frequency agility
 - Robust modulation



ZigBee – Highly Secure

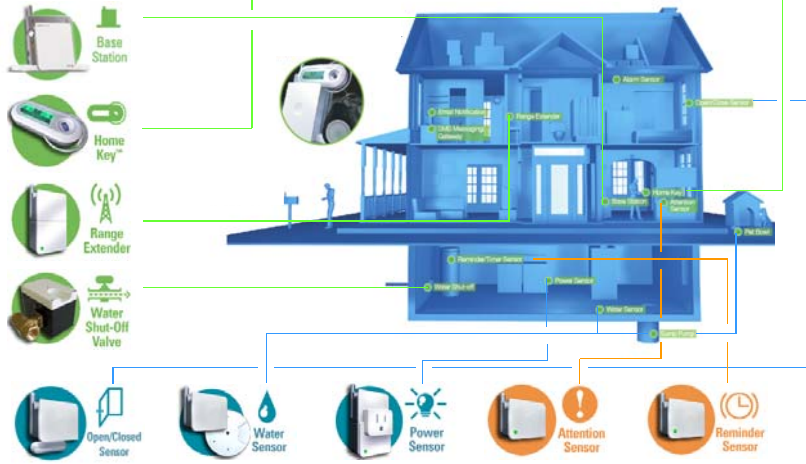
- Utilizes AES 128-bit encryption
- Concept of a “trust center”
- Link and network keys
- Authentication and encryption
- Security can be customized for the application
- Keys can be “hard-wired” into application



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Home Awareness

Home Heartbeat



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Home Entertainment & Control

Control



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In-Home Patient Monitoring

- Patients receive better care at reduced cost with more freedom and comfort---
 - Patients can remain in their own home
 - Monitors vital statistics and sends via internet
 - Doctors can adjust medication levels
 - Allows monitoring of elderly family member
 - Sense movement or usage patterns in a home
 - Turns lights on when they get out of bed
 - Notify via mobile phone when anomalies occur
 - Wireless panic buttons for falls or other problems
 - Can also be used in hospital care
 - Patients are allowed greater movement
 - Reduced staff to patient ratio



Commercial Lighting Control

- Wireless lighting control
 - Dimmable intelligent ballasts
 - Light switches/sensors anywhere
 - Customizable lighting schemes
 - Quantifiable energy savings
 - Opportunities in residential, light commercial and commercial
- Extendable networks
 - Lighting network can be integrated with and/or be used by other building control solutions



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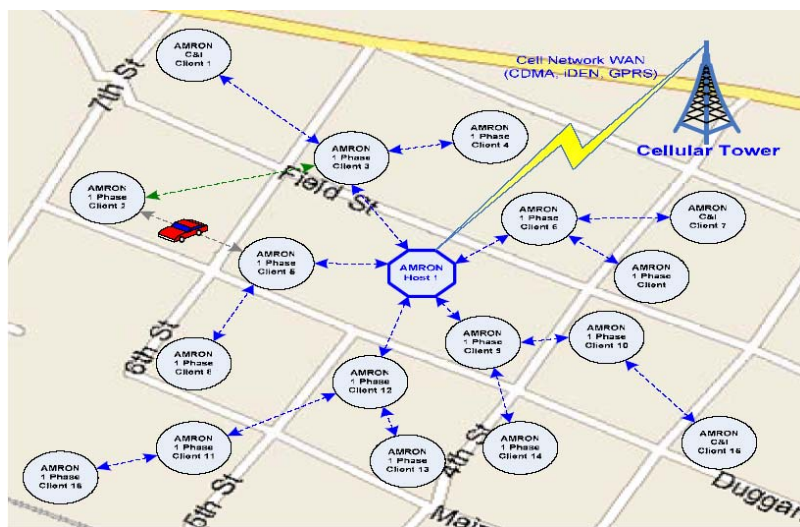
HVAC Energy Management

- Hotel energy management
 - Centralized HVAC management allow hotel operator to ensure empty rooms are not cooled
 - Easy to retrofit
 - Battery operated thermostats, occupancy detectors, humidistats can be placed for convenience
 - Personalized room settings at check-in



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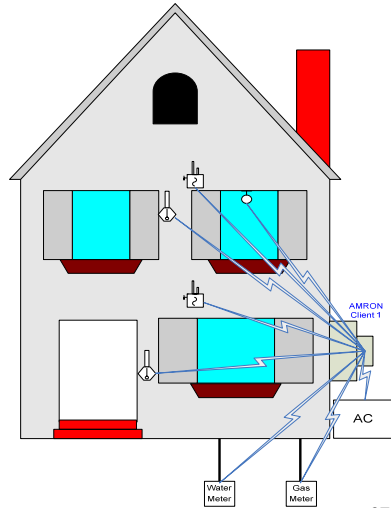
AMR network example



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Advanced Metering Platform with ZigBee

- Rapid method to help manage global electric generation shortage and meet existing and pending legislation for energy control
- Can network with other ZigBee devices in the home for load control – e.g. Heating/AC, Security, Lighting, White Goods
- Worldwide standard ZigBee allows communications between various meter types from different manufacturers.



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Why ZigBee?

- Standards based
- Low cost
- Can be used globally
- Reliable and self healing
- Supports large number of nodes
- Easy to deploy
- Very long battery life
- Secure

- Open Standards Enable Markets

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