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Corso di Laurea Specialistica in Scienze di Internet
Corso di Laurea Specialistica in Informatica (mutuato)

IEEE 802.15.4, ZigBee & Open Source

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This presentation includes some figures and slides available from the following Web sources: ZigBee Alliance (www.zigbee.org), IEEE 802.15.4 (www.ieee802.org/15), Motorola (www.motorola.com)
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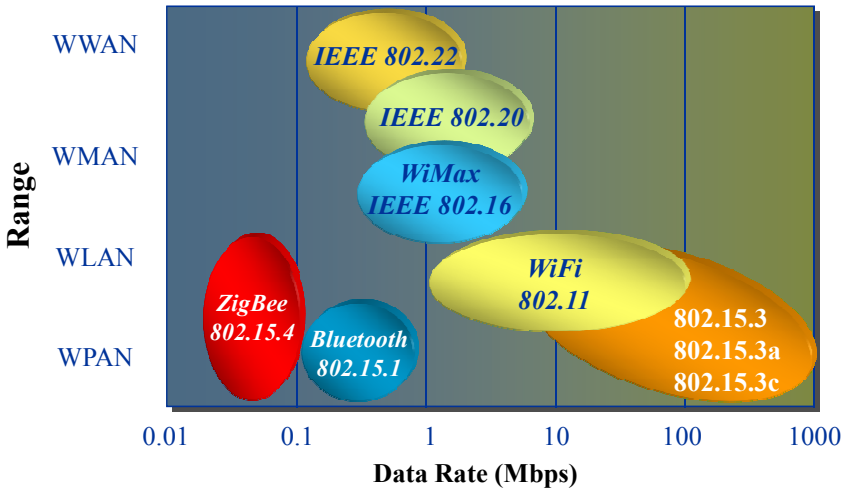
Outline

- Introduction
  - IEEE 802.15.4 technology and characteristics
  - ZigBee Alliance e ZigBee certification
  - Motivations and target scenarios/applications
- ZigBee MAC
- ZigBee Network
  - Devices, Nodes, Roles and Topologies
- ZigBee Application
- Open Source Protocol Stack Initiatives
- Conclusions

IEEE 802.15.4
Technology and characteristics

The 802 Wireless Space



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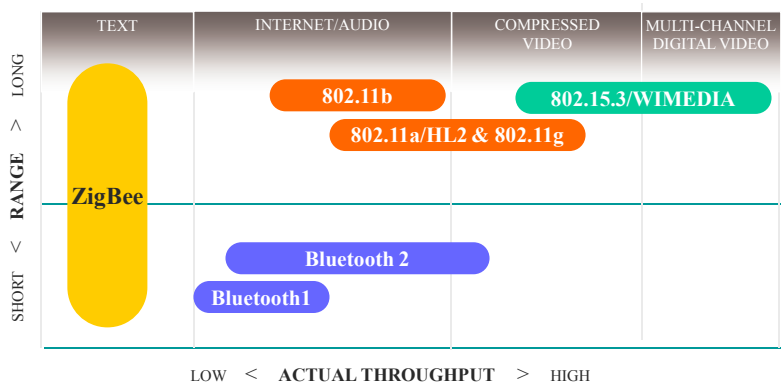
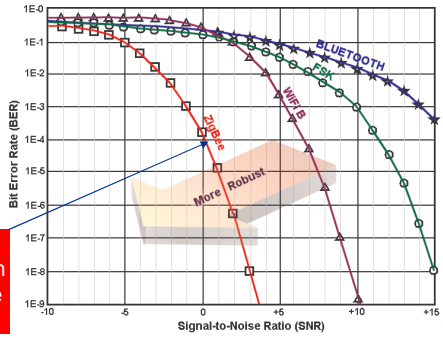
The Wireless Market



Basic Radio Characteristics

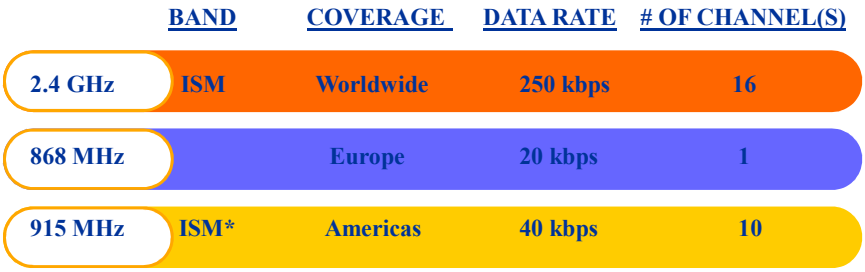


ZigBee technology relies upon IEEE 802.15.4, which has excellent performance in low SNR environments

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

Slide credits: ZigBee Alliance

IEEE 802.15.4 Frequencies and Data Rates



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Comparison of complementary protocols

Feature(s)	IEEE 802.11b/g/a	Bluetooth	ZigBee
Application focus	Web, e-mail, Mmedia	Cable replacement	Monitoring & control
Stack size	>1000kB	>250kB	< 64kB
Power Profile	Hours	Days	Years
Complexity	Very Complex	Complex	Simple
Nodes/Master	many (IP)	7	65536 (local).. Up to 2^64
Latency	Enumeration upto 3 seconds	Enumeration upto 10 seconds	Enumeration 30ms
Range	100 m	10m	70m-300m
Extendability	Roaming possible	No	YES
Data Rate	11-54 Mbps (up to 108)	1Mbps	up to 250Kbps
Target cost	50 EUR	10 EUR	2 EUR
Security	Authentication Service Set ID (SSID)	64 bit, 128 bit	128 bit AES and Application Layer user defined

How is ZigBee related to IEEE 802.15.4?

- ZigBee takes full advantage of a powerful physical radio specified by IEEE 802.15.4
- ZigBee adds logical network, security and application software
- ZigBee continues to work closely with the IEEE to ensure an integrated and complete solution for the market

IEEE 802.15.4 Protocol Mission

- 15.4 Protocol was developed for very different reasons than Bluetooth
  - 802.15.4
    - *Very low duty cycle, very long* primary *battery life applications as well as mains-powered*
    - *Static and dynamic mesh, cluster tree and star network structures with potentially a very large number (>65534) of client units, low latency available as required*
    - *Ability to remain quiescent for long periods of time without communicating to the network*
  - Bluetooth
    - *Moderate duty cycle, secondary battery operation where battery lasts about the same as master unit*
    - *Wire replacement for consumer devices that need moderate data rates with very high QoS and very low, guaranteed latency*
    - *Quasi-static star network structure with up to 7 clients (and ability to participate in more than one network simultaneously)*
    - *Generally used in applications where either power is cycled (headsets, cellphones) or mains-powered (printers, car kits)*
- Protocol differences can lead to tremendous optimizations in power consumption

Why ZigBee?

- Reliable and self healing
- Supports large number of nodes
- Easy to deploy
- Very long battery life
- Secure
- Low cost
- Can be used globally
- Designer concentrates on end application
  - Silicon vendors and ZigBee Alliance take care of transceiver, RF channel and protocol stack (*)
- More Information
  - ZigBee: www.zigbee.org

ZigBee Alliance e ZigBee certification

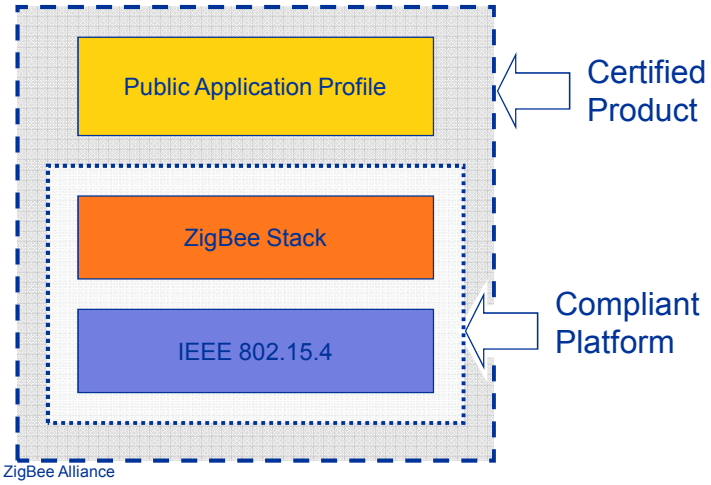
What is the ZigBee Alliance?

- An Organization with a mission to define reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on an open global standard
- Alliance provides
  - upper layer stack and application profiles
  - compliance and certification testing
  - branding
- Result is a set of interoperable solutions recognizable in the market

Who is supporting the ZigBee Alliance?

- Eight promoter companies
  - Ember, Freescale, Honeywell, Invensys, Mitsubishi, Motorola, Philips and Samsung
- A rapidly growing list (Over 120 participants) of industry leaders worldwide committed to providing ZigBee-compliant products and solutions

The ZigBee Platform and certification



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ZigBee Motivations

need for ZigBee technology?

- No standard approach today that addresses the unique needs of most remote monitoring and control applications
  - Enables the broad-based deployment of reliable wireless networks with low complexity, low cost solutions
  - Provides the ability to run for years on inexpensive primary batteries for a typical monitoring application
  - Capable of inexpensively supporting robust mesh networking technologies

Advantages of ZigBee vs. proprietary solutions?

- Product interoperability
- Vendor independence
- Increased product innovation as a result of industry standardization
- A common platform is more cost effective than creating a new proprietary solution from scratch every time
- Companies can focus their energies on finding and serving customers

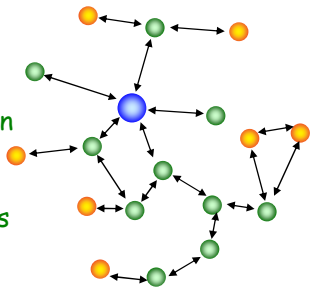
- How is Open Source intended in this vision?

Slide credits: ZigBee Alliance

ZigBee:
Examples of target scenarios/applications

802.15.4 Application Space

- Sensors & Controls:
  - Home Automation
  - Industrial Automation
  - Remote Metering
  - Automotive Networks
  - Interactive Toys
  - Active RFID/ asset tracking
  - Medical
  - ...and more

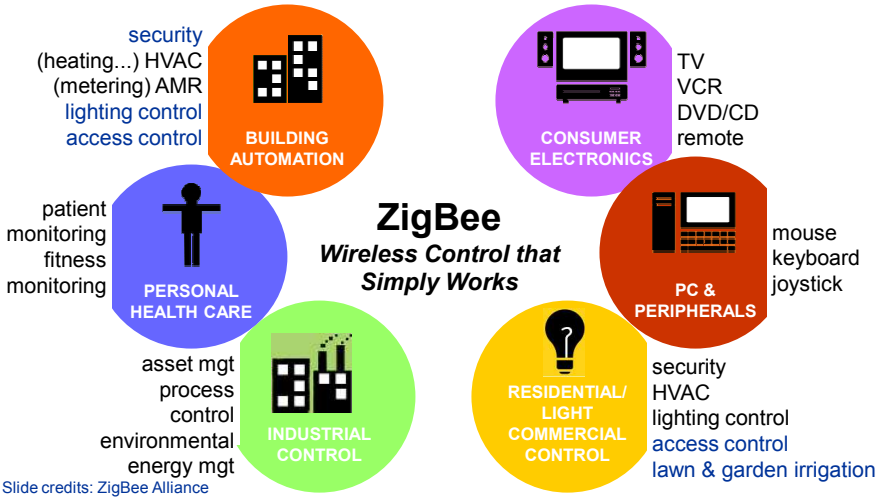


Slide credits: ZigBee Alliance

Sensor/Control Network Requirements

- Large networks (large number of devices and large coverage area)
  - can form autonomously
  - operate very reliably for years without any operator intervention
- Very long battery life (years off of a AA cell)
- very low infrastructure cost (low device & setup costs) and very low complexity and small size
- Device data rate and QoS needs are low (*)
- Standardized protocols are necessary to allow multiple vendors to interoperate

Applications field



Slide credits: ZigBee Alliance

ZigBee Application classes and traffic types

- ZigBee networks can support different traffic:
  - Periodic data
    - *E.g. wireless sensors and metering applications*
    - *beaconing principle: scheduled wakeup time + send + sleep*
  - Intermittent data
    - *E.g. wireless light switch*
    - *Beaconless system: device attach to network only upon need, and sleep o.w.*
  - Repetitive (low latency) data
    - *E.g. security systems*
    - *Guaranteed Time Slot (GTS) capability: a MAC superframe structure managed by network coordinator for QoS-based scheduling of reserved slots within fixed latency limits (no contention)*

Application examples: Lighting Control

- Advance Transformer
  - Wireless lighting control
    - *Light switches anywhere*
    - *Customizable lighting schemes*
    - *Energy savings on bright days*
  - Extendable networks
    - *Additional sensors*
    - *Other networks*

Slide credits: ZigBee Alliance

HVAC Energy Management

- Hotel energy management
  - Major operating expense for hotel
    - *Centralized HVAC management allow hotel operator to make sure empty rooms are not cooled*
  - Retrofit capabilities
  - Battery operated t-stats can be placed for convenience
  - Personalized room settings at check-in

Slide credits: ZigBee Alliance

Asset Management

- Within each container, sensors form a mesh network.
- Multiple containers in a ship form a mesh to report sensor data
- Increased security through on-truck and on-ship tamper detection
- Faster container processing. Manifest data and sensor data are known before ship docks at port.

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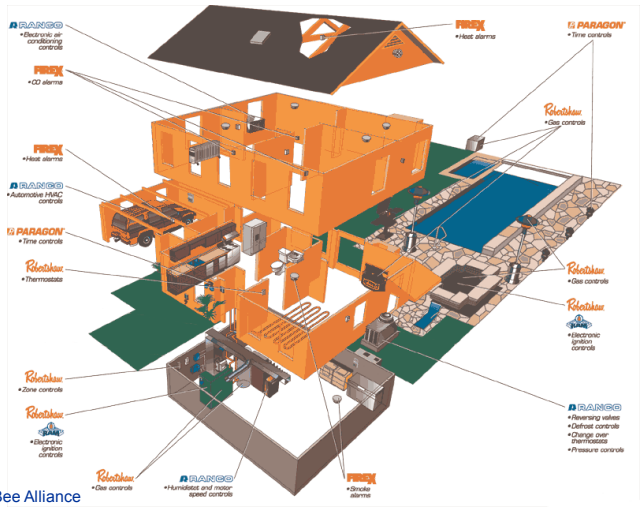
Residential Control



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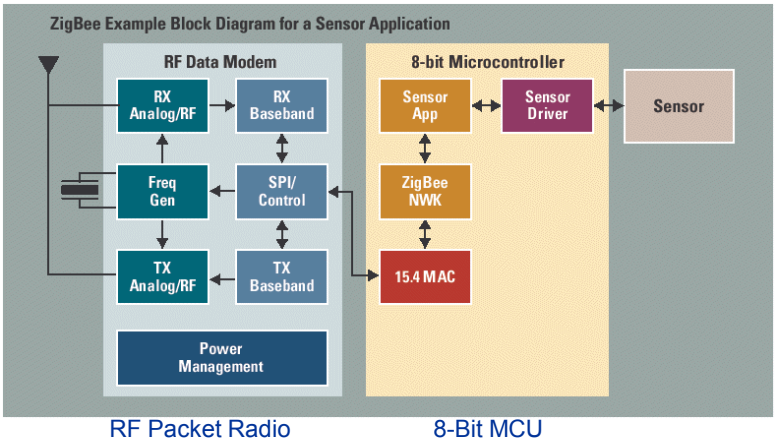
System Simplicity and Flexibility (example)



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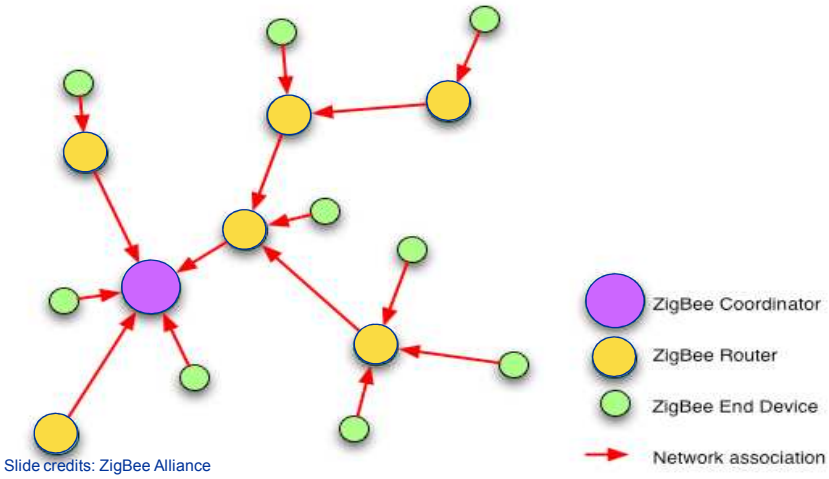
ZigBee (and IEEE 802.15.4) Protocol Stack:

General concepts

ZigBee 1.0: (static) tree network structure



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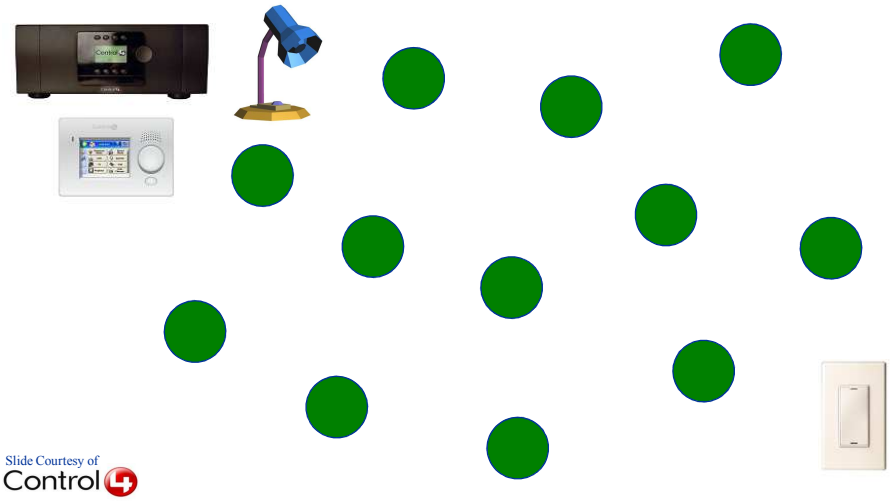
ZigBee Pro: (dynamic) Mesh Networking



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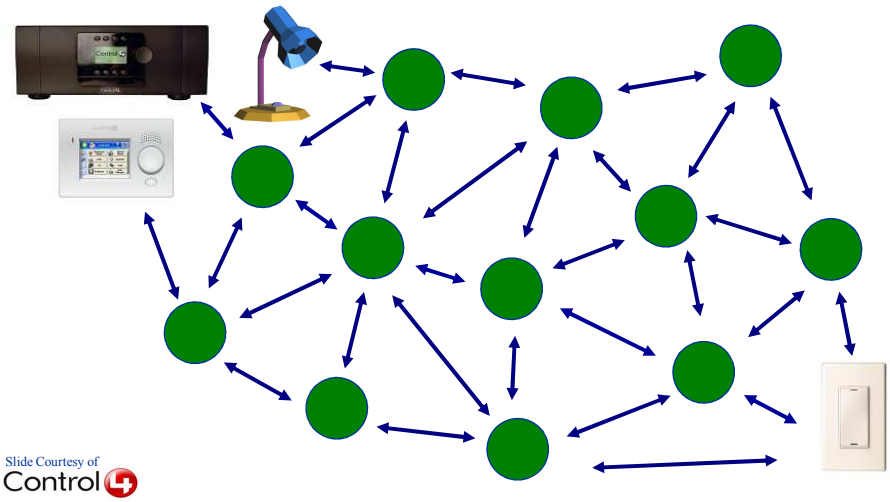
ZigBee Mesh Networking example



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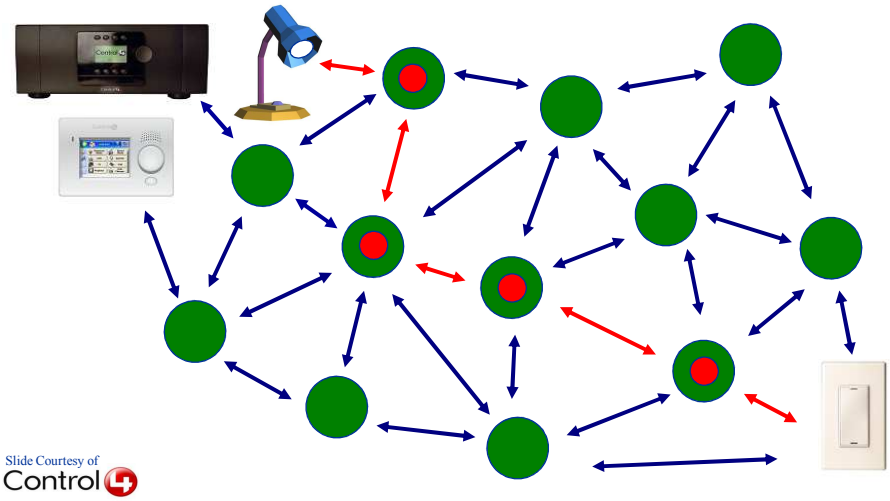
ZigBee Mesh Networking example



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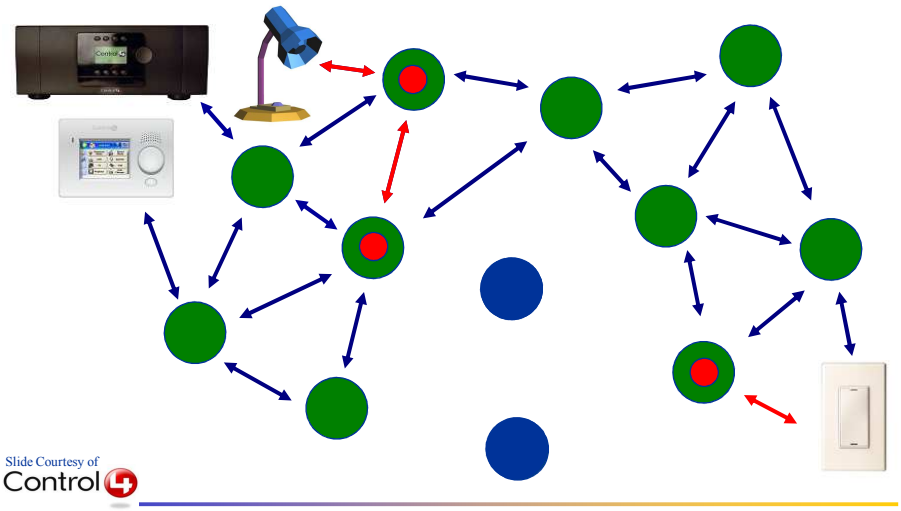
ZigBee Mesh Networking example



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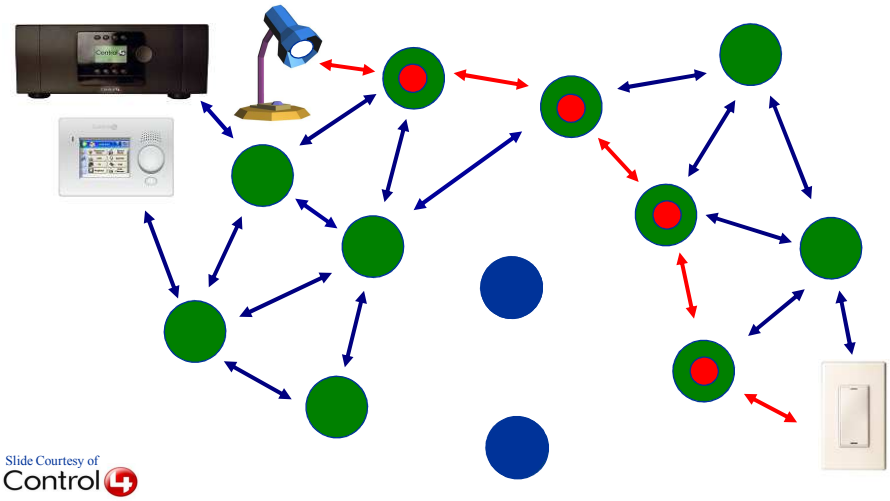
ZigBee Mesh Networking example



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ZigBee Device Types

- ZigBee Network Coordinator (ZNC)
  - One and only one required for each ZB network.
  - Initiates network formation.
  - Acts as 802.15.4 2003 PAN coordinator (FFD).
  - May act as router once network is formed.
- ZigBee Network Router (ZNR)
  - Optional network component.
  - May associate with ZNC or with previously associated ZNR.
  - Acts as 802.15.4 2003 coordinator (FFD).
  - Participates in multihop routing of messages.
- ZigBee End Device (ZED)
  - Optional network component.
  - Shall not allow association.
  - Shall not participate in routing.

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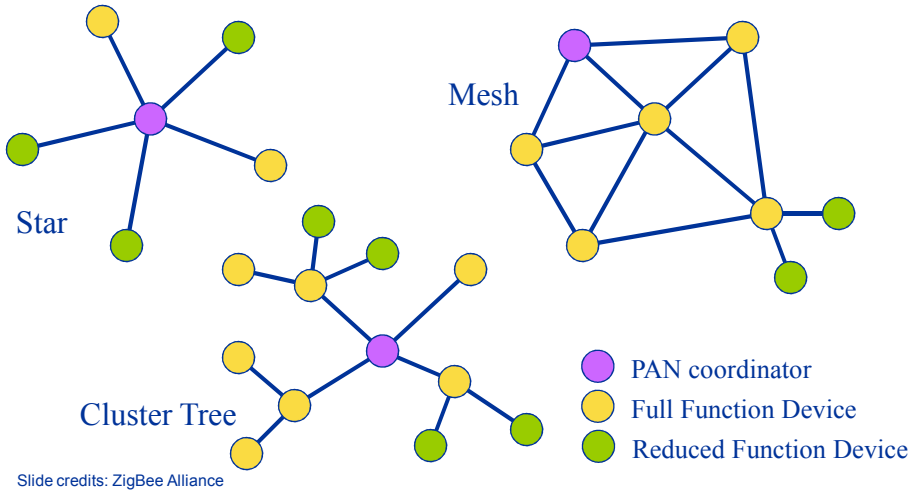
ZigBee Network Topologies



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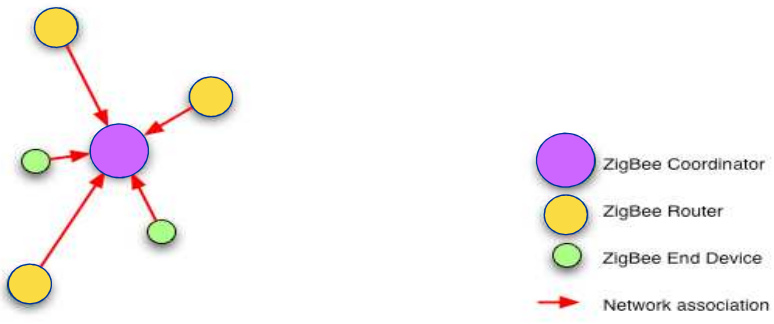
Network Structure (association)



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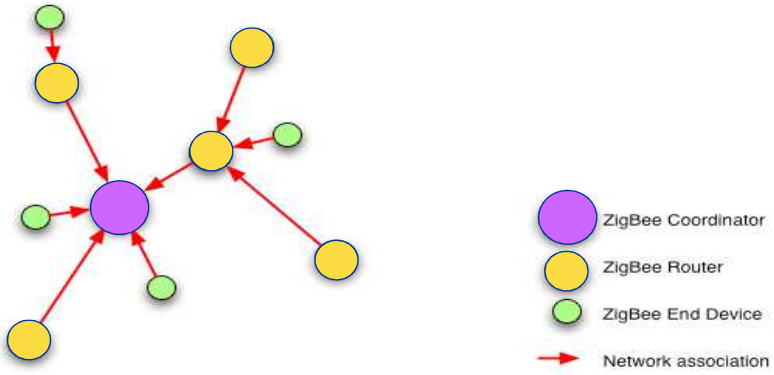
Network Structure



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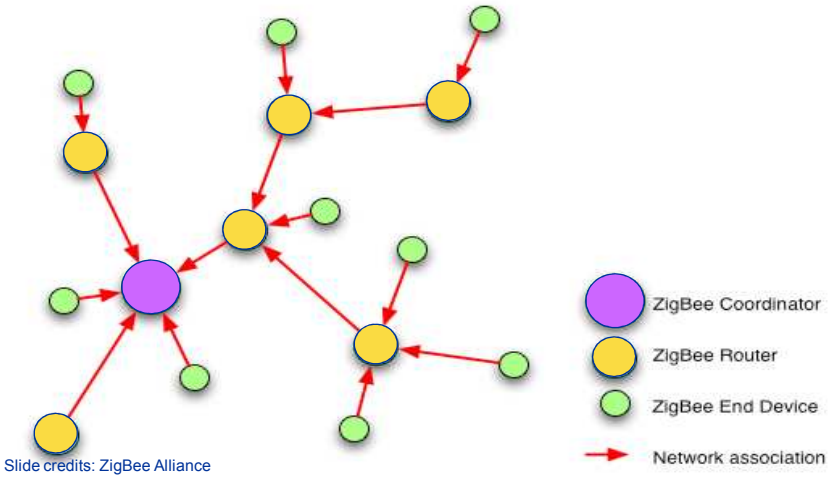
Network Structure



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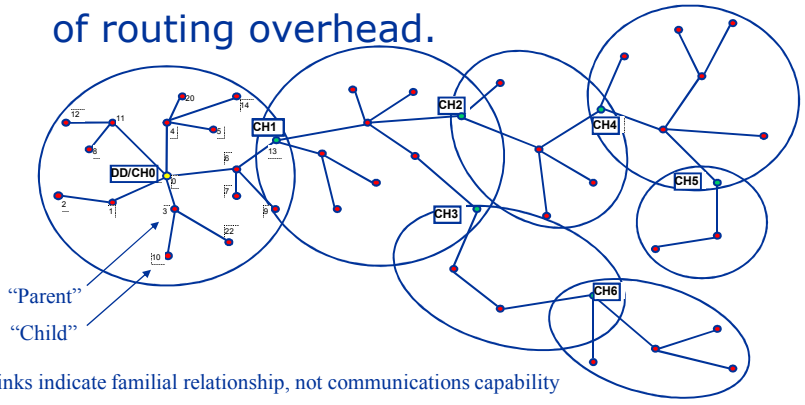
Cluster Tree Networks

- Cluster tree networks enable a peer-peer network to be formed with a minimum of routing overhead.



Links indicate familial relationship, not communications capability

Slide credits: ZigBee Alliance

Cluster Tree Networks

- Employ multi-hop routing (table driven)
  - AODV considered for dynamic routing in Meshes
- Can be very large: 255 clusters of 254 nodes each = 64,770 nodes
- May span physically large areas
- Suitable for latency-tolerant applications

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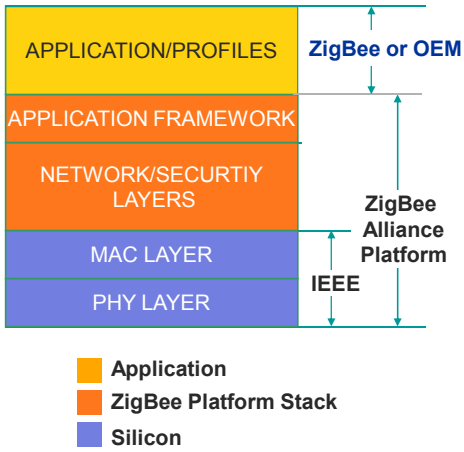
Protocol Stack Features

- 8-bit microcontroller (e.g. 80c51)
- Compact protocol stack
- Supports even simpler slave-only stack



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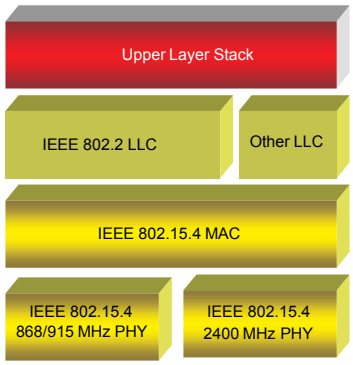
IEEE 802.15.4 Protocol Stack:

Phy and MAC layers

What IEEE 802.15.4 Addresses

- IEEE 802.15.4
  - MAC and PHY only



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ZigBee Channel Access Options

Two channel access mechanisms:

- Non-beacon network
  - A simple, traditional multiple access system used in simple peer and near-peer networks
  - Standard ALOHA CSMA-CA communications
  - Positive acknowledgement for successfully received packets
- Beacon-enabled network
  - Superframe structure- network coordinator transmits beacons at predetermined intervals
  - Dedicated bandwidth and low latency
  - Low Power Consumption mode for Coordinator

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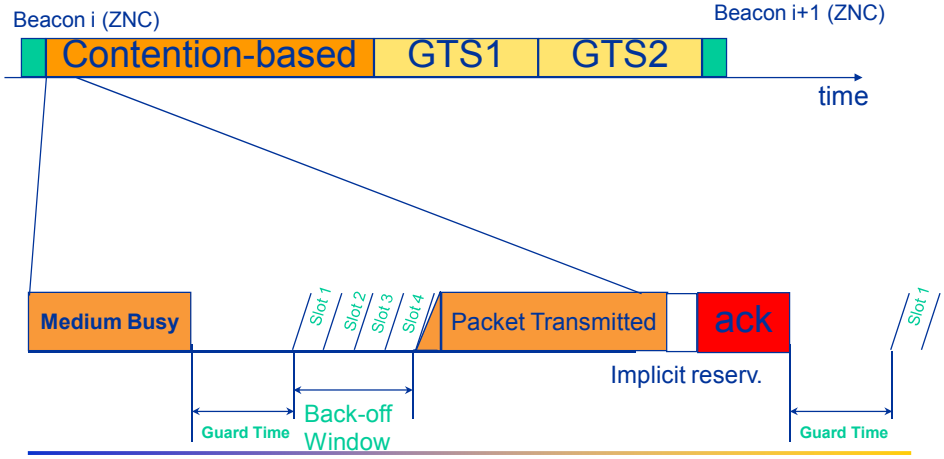
IEEE 802.15.4 MAC channel access in one slide

- Example of superframe structure (optional) and basic contention-based MAC access scheme



Other Benefits of Beacon Mode

- Beacon Mode
  - A very powerful mechanism 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 has a coordinator that manages the channel and arranges the calls
  - Significant value will be in system power consumption for networks which are primarily battery powered

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ZigBee – Highly Reliable

- Mesh and tree networking protocol provides redundant paths
- Automatic retries and acknowledgements
- Broadcast delivery scheme ensures reliable broadcasts across the network
- Parents keep track of messages for sleeping children
- High intrinsic interference tolerance
  - Multiple channels
  - Frequency agility
  - Robust modulation

Slide credits: ZigBee Alliance

ZigBee – Highly Secure

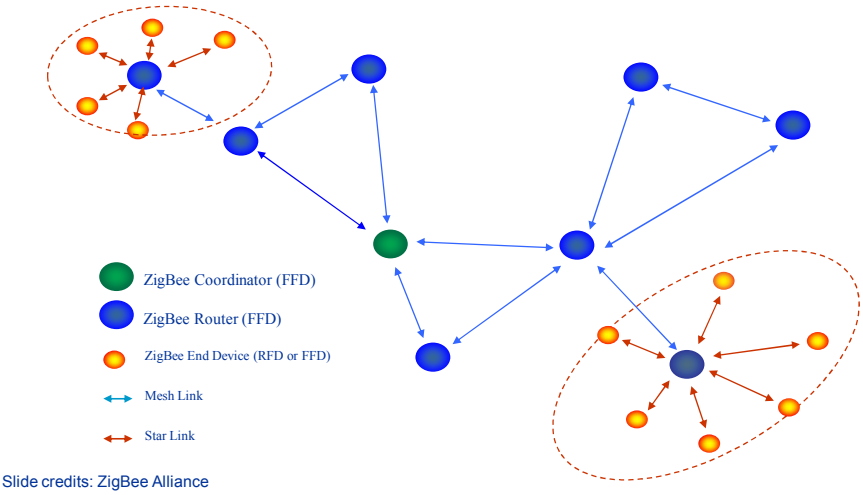
- Utilizes AES 128-bit encryption
- Concept of a "trust center"
- Link and network keys
- Authentication and encryption
- Security can be customized for the application
- Keys can be "hard-wired" into application

Slide credits: ZigBee Alliance

IEEE 802.15.4 MAC summarized

- Employs 64-bit IEEE & 16-bit short addresses
  - Up to 2^{64} nodes (more than we'll probably need…)
  - local addressing, simple networks (65,000 nodes = 2^16)
- Two (physical) devices specified
  - Full Function Device (FFD)
  - Reduced Function Device (RFD)
- Three (logical) device roles specified:
  - ZigBee Network Coordinator (ZNC)
  - ZigBee Network Router (ZNR)
  - ZigBee End Node (ZED)
- Simple frame structure
- Reliable delivery of data (ACK)
- Association/disassociation
- AES-128 security
- Distributed CSMA-CA channel access (basic access mode)
- Optional superframe structure with beacons: GTS mechanism

ZigBee Pro is Mesh Networking



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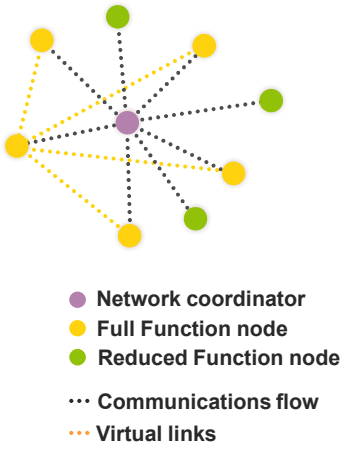
Basic Network Characteristics

- 65,536 network (client) nodes
- Optimized for timing-critical applications
  - **Network join time**: 30 ms (typ)
  - Sleeping slave changing to active: 15 ms (typ)
  - Active slave channel access time: 15 ms (typ)



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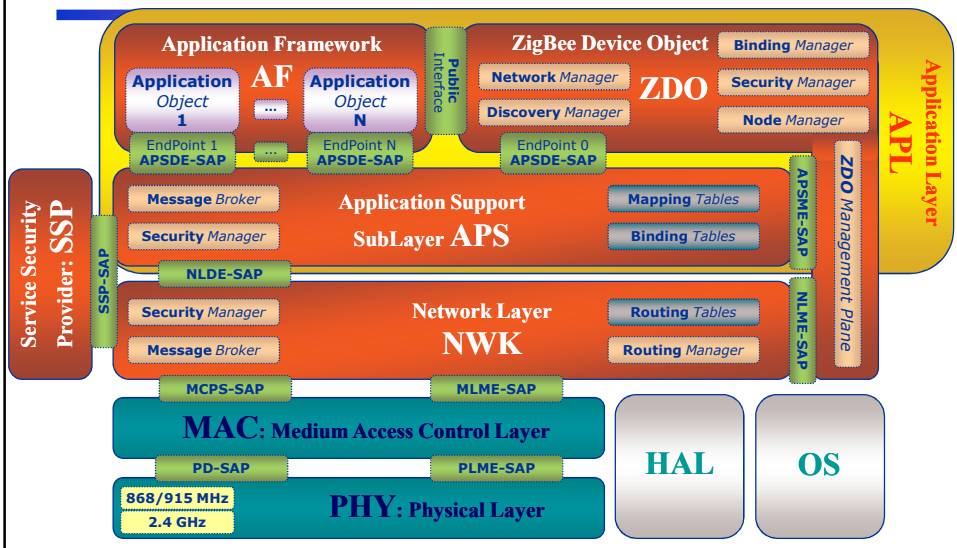
ZigBee Stack components

- Communication Protocol library
  - IEEE 802.15.4
    - Phy & Mac
  - ZigBee
    - Networking Layer
    - Application Framework
    - Security
- Cross-functions
  - HAL: hardware abstraction layer
  - OS-like functionalities

IEEE 802.15.4/ZigBee Architecture



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ZigBee Stack "iper-space" (dimensions)

- **Depending on Topology/features**
  - ZigBee stack: Tree-based (static case),
  - ZigBee Pro stack: Mesh-based (dynamic case)
- **Depending on functionalities**
  - ZigBee Standard
  - Standard + proprietary extension
- **Depending on Nodes' type** (and Responsibilities)
  - *FFD (routing capabilities)*
  - *RFD (simple, end devices)*
  - Resources (Energy)
    - *Sleepy vs Non Sleepy*
    - *Mobile vs quasi-static*

Slide credits: STMicroelectronics

IEEE 802.15.4 PHY/MAC basics

802.15.4 is a simple packet data protocol for lightweight wireless networks

- **3 ISM bands**, 27 channels specified
- **Channel Access**
  - CSMA/CA slotted and unslotted
- Support for Message **Acknowledgement**, optional **Beacon** and **Guaranteed Time Slots**
- Multi-level **security**

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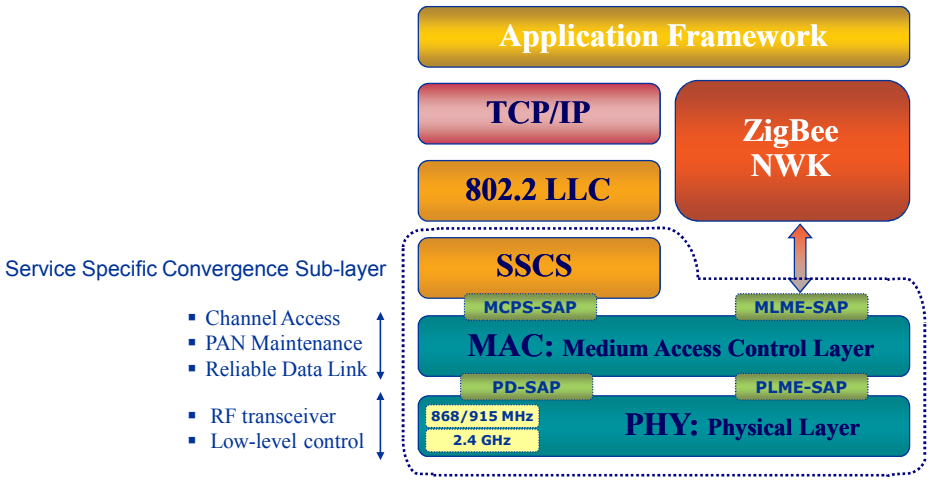
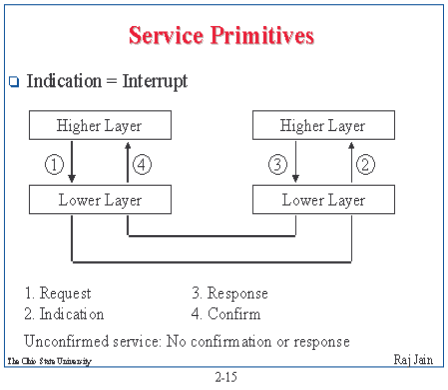
IEEE 802.15.4 Architecture



Slide credits: STMicroelectronics

Services and Primitives

- For confirmed service, 4 primitive's types:
  1) request – higher entity asks for some service
  2) indication - entity is informed about event or remote service request
  3) response - entity to responds to event/requets
  4) confirm - entity is informed about its request status
- For unconfirmed service, only the first 2 types.
- Apply to all Layers.



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IEEE 802.15.4 PHY: Functionalities

- TX/RX packets (PPDU) across physical medium
- Activation/deactivation of the radio transceiver
- Clear channel assessment (CCA)
- Energy detection (ED)
- Link quality indication (LQI)
- Channel selection

Primitives	Description	Req	Conf	Resp	Indic
PD-DATA	Transmitting/ receiving packets	X	X		X
PLME-GET	Getting PHY PAN information base				
PLME-SET	Setting PHY PAN information base				
PLME-SET-TRX-STATE	Activation/deactivation of the radio transceiver	X	X		
PLME-CCA	Clear channel assessment	X	X		
PLME-ED	Energy detection (ED)	X	X		

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MAC responsibilities

- MAC Data services
  - enables MPDU exchange with PHY data service
- MAC Management services
  - Association/Disassociation
  - Orphaning and Sync with parent node
  - Beacon Management
  - Frame validation
  - Frame delivery ACK
  - Hooks up with security mechanisms

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IEEE 802.15.4 Security

- **Security modes**
  - Unsecured mode
  - ACL mode
  - Secured mode
- **Security Services**
  - Access Control
  - Data Encryption
  - Frame Integrity
  - Sequential Freshness

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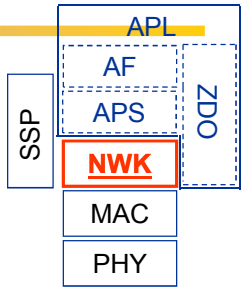
NWK Layer

- **NWK Layer**
  - Structure/Functionalities
  - Responsibilities
- **Reference model**
  - NLDE: Data service
  - NLME: Management services



Slide credits: STMicroelectronics

NWK Layer responsibilities

- Starting a network
  - the ability to successfully establish a new network.
- Joining and leaving a network
  - the ability to gain (join) or relinquish (leave) membership to a node of the network.
- Configuring a new device
  - the ability to sufficiently configure the stack for operation as required.

Slide credits: STMicroelectronics

NWK Layer responsibilities (cont)

- Addressing
  - the ability of a ZBC to assign short addresses (16 bits) to devices joining the network.
- Routing
  - rightful node/route discovery & maintenance operations
  - routing frames to their intended destinations
  - store of pertinent neighbor information
- Security
  - applying security to outgoing frames and removing security to terminating frames

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Routing: device's responsibilities

- **Mandatory** functionalities for both **ZBC** and **ZBR**:
  - Relay DATA frames on behalf of higher layers and/or other ZBRs.
  - Participate in route discovery in order to establish routes for subsequent DATA frames and/or on behalf of end devices.
  - Participate in end-to-end and local route repair.
  - Employ the ZigBee path cost metric as specified in route discovery and route repair.
- **Optional** functionalities for both **ZBC** and **ZBR**:
  - Maintain routing tables in order to remember best available routes.
  - Initiate route discovery on behalf of higher layers and/or of other ZBR.
  - Initiate end-to-end route repair.
  - Initiate local route repair on behalf of other ZigBee routers.

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Tree (1.0) vs Mesh (Pro) Stack

Feature	Tree Stack "ZigBee"	Mesh Stack "ZigBee Pro"
ZigBee Stack Profile	HCL: HW comp. list	ZigBee ZigBee Pro
ZigBee application profiles	HA: home automation	HA, CBA (commercial Buidling), IPM (industrial plant monitoring. WSA...
Messaging model	ZigBee APS messages with fragmentation	APS messages with (Uni-Multi-Broad)-cast
Routing method	Tree or Mesh	Mesh only (table driven)
Addressing method	Distributed Hierarchical (tree based)	Distributed alternative method (stochastic)
Bindings	Centralized: stored on Coordinator or source storage	Source only
Asymmetric Links	No detection	Detected and avoided
ZigBee End Devices	Sleepy ZED supported	Sleepy, Mobile ZEDs supported
Large sensor networks (100+ devices)	Not supported	Single-step route establishment back to data gateway

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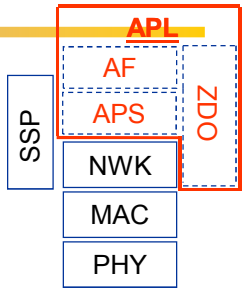
The Application Layer



Components:

- **APS**: Application Support sub-layer
- **ZDO**: ZigBee Device Object
- **AF**: Application Framework
  the manufacturer-defined application objects
- ZigBee **Application Profiles**
  - ZDP: ZigBee Device Profile
  - Per Application segment (HA, CBA, IPM, WSA, …)

Slide credits: STMicroelectronics

ZigBee Profiles

- Generalities:
  - 3 classes: private, public or published
  - Identifier has to be unique (assigned by the Alliance).
- Defined ZigBee profiles
  - ZDP: ZigBee Device Profile (*private*)
  - ZAP: ZigBee Application Profile (*public*)
    - *HCL (obsolete), HA, CBA, IPM, WSA, …*
- ZCL: ZigBee Cluster Library
  - Device and Cluster descriptions are independent from Profile Identifiers
  - Service types (KVP or MSG) → Replaced by ZCL

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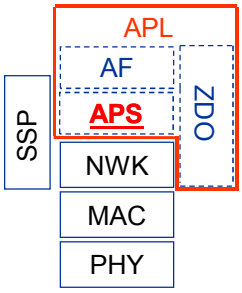
APS Sub-layer

- **APS Sub-Layer**
  - Responsibilities
  - Services
- **Reference model**
  - APSDE: Data service
  - APSME: Management services



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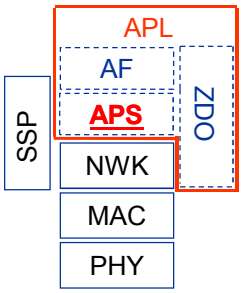
APS Sub-layer

- APS responsibilities
  - maintaining tables for **binding**
    - (the ability to match 2 devices together based on their services and their needs)
  - forwarding messages between bound devices
- Its services are used by
  - the ZDO
  - Manufacturer-defined Application Objects



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APSME: APS Management Entity

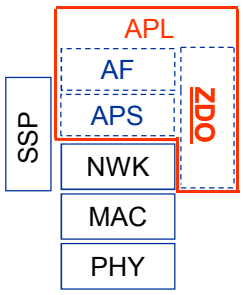
Management services

- Functionalities
  - Binding
    - *The ability to match 2 devices together based on their services and their needs.*
  - Multicast Endpoint groups management
    - *Single address shared by multiple sub-units (application objects).*
  - Information management
    - *To provide to read/write the value of an attribute from the AIB, Mapping/Binding tables, and Multicast Group tables*
  - Security
    - *The ability to set up authentic relationships with other devices through the use of secure keys.*

Slide credits: STMicroelectronics

ZigBee Device Object: ZDO

- **ZDO Layer**
  - Responsibilities
  - Structure
    - *Manager & Configuration Attributes*
- **ZDP: ZigBee Device Profile**
  - Client Services
  - Server Services



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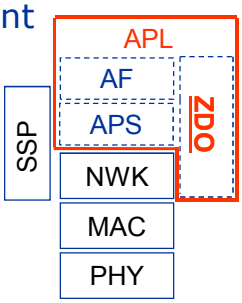
ZigBee Device Object: ZDO

- It's a special application which employs NWK and APS primitives to implement ZBC, ZBR, ZED
- ZDO responsibilities:
  - Defining the role of the device
    - *Coordinator, Router, End Device*
  - Initialize APS, NWK, SSP
  - Devices & Service Discovery
  - Initiating and/or responding to binding requests
  - Establishing a secure relationship between network devices



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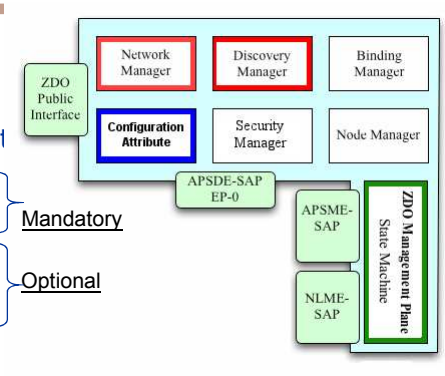
ZDO: structure

- ZDO structure:
  - 1 Configuration Attributes Objec
    (the .ini file for ZigBee devices)
  - 5 Manager Objects:
    - *Device and Service Discovery*
    - *Network Manager*
    - *Binding Manager*
    - *Security Manager*
    - *Node Manager*
  - It presents Public interfaces to the Application objects in the AF layer for control of device and network functions



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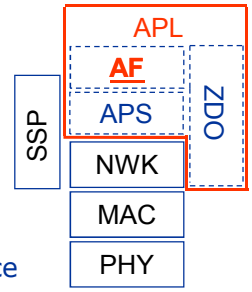
ZDO: Device and Service Discovery

- Device discovery (other ZigBee device by query)
  - *IEEE address requests*
    - Unicast, the NWK address is known
  - *NWK address requests*
    - Broadcast, the IEEE address is known
- Service discovery
  - Discovery of the services available on endpoints
    - *By query for each endpoint on a given device*
    - *By using a match service feature (broadcast or unicast)*
    - *By having devices announce themselves*
  - Utilizes the complex, user, node, or power descriptors

Slide credits: STMicroelectronics

Application Framework: AF

- AF responsibilities
  - Hosting for the application objects
    - *Addressed by an Endpoint number*
  - APS functions used
    - *Data services*
      - By using the new ZCL
      - Superseded KVP & MSG
  - ZDO Functions used via the Public Interface
    - *Control and management of the protocol layers in the ZigBee device*
    - *Initiation of standard network functions*



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Available ZigBee Stack (v.1.0)

Company	Stack name	MAC ver.	Platform used	
Ember	EmberZNet 2.x.0	*integrated*		
TI/Chipcon	F8W Z-Stack 1.0-1.3.0	0.71 -> 1.3	TI 2420 TI 2430-2431	
Freescale	Z-Stack 1.0-1.2.2	v.1.063	MC 13192-13193	Old stack from F8W Probably not supported
Mindteck	BeeStack v.1.0		HCS08/MC13192	for Freescale
Integration UK CompXs	ZigBee Stack v.1.25		Oki ML7065-032	
AirBee	ZNS 0.92	NA		
Institute for Information Ind.-JP	III Zigbee Adv. Protocol	NA v3 / 1.0	CC2420DB JN5121 / UZ2400DBK	for its own test for Jennic / Ubec
Helicomm	Helicomm Stack v.0.9.05	Helicomm v.1.0	iPLink EZDK	Also for Silabs
Silicon Lab				
Korwin	WiniZB v.1.0		Atmel128+ CC2420	
Renesas (RTA)	Renesas ZB v.0.97	NA	M16C+ MC13192 M16C+ CC2420	

Slide credits: STMicroelectronics

Available non-ZCP ZigBee Stack (v.?)

Company	Stack name	MAC ver.	Platform used	
Microchip	ZigBee PicDem		PicDemZ	NO ZCP
Atalum	GreenMesh			NO ZCP
Crossbow				
BM				
UbiWave	UbiNet			
Atmel	ZigBeeNet			
Meshnetics (ex LuxoftLabs)				
Mitsubishi (MERL)				Under development with Renesas
Dust Networks				
ArchRock				
One-RF Technology	??	??		Available from Q4-06
OpenBee	OpenBee			Freeware

Slide credits: STMicroelectronics

ZigBee
Open Source protocol stack initiatives

Zigbee Projects on SourceForge

Name	Description	Language	Code	Doc
OpenBee **GPL, 12/2005** **+ Hw dev. kit**	Design of an IEEE 802.15.4 compliant software, target independent	**C**	✓	✗
OpenZig **LGPL, 06/2006**	Open source ZigBee and 802.15.4 stack Open Source (Atmel platform?)	–	✗	✗
ZigBuzz **GPL, 01/2005**	"Implementation of Zigbee Phy, MAC, network, security and Application Stack on the Linux kernel 2.6.x"	–	✗	✗
Linux Wireless Sensor LAN Project **GPL, 01/2005**	"Drivers and utility set for 802.15.4 standard low-rate wireless personal area networking"	–	✓	✗
HomeRun 0.2.1 **10/2006**	Control and automation software for the home environment, multi-channel and multi-protocol (including Zigbee)	**Java**	✓	✓
Open-zb **AFL (academic free), 10/2006**	Implementation of IEEE 802.15.4 in nesC for TinyOS and Crossbow Micaz motes	–	✗	✗

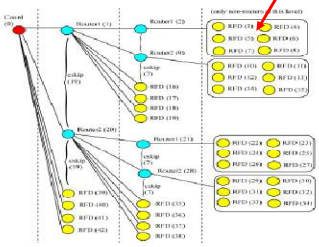
ZigBee and (or vs.) TinyOS

- **TinyOS initiative proposed by Joe Polastre (Moteiv corp.)**
  - **"Zigbee should be the first network protocol released for TinyOS 2.0"**
- **Motivations:**
  - Zigbee is a standard.
  - TinyOS has received lukewarm, at best, recognition in the commercial sector. Embracing a standard protocol suite will bring attention to the project and interest from commercial users.
  - A standard protocol suite is valuable not just for commercial use, but also for academics.
  - A TinyOS-Zigbee implementation opens the door to improvements that the TinyOS community may propose to the Zigbee 2.0 technical working group.
  - Zigbee will help frame the design of TinyOS 2.0's networking architecture.
  - Think of the opportunities! "TinyOS inside" stickers for lightbulbs, thermostats, forklifts, trucks, toasters, microwaves, etc!
  - **Problem:** by downloading ZigBee specifications you agree that any use of the spec for non-Zigbee members is for non-commercial purposes. A company would adopt Zigbee-TinyOS if they can't use it for their commercial purposes?
  - moreover: if open source version of Zigbee exist for TinyOS how can the Open Source community cover themselves against patent infringement cases?

e.g. ZigBee Stack Implementation (1)

- *Mississipi State University*, **Multi-platform Protocol Stack: Implementation of a subset of the Zigbee 1.0 Standard**.
- Source Code: www.ece.msstate.edu/!reese/msstatePAN/
- Zigbee functionalities:
  - Tree Routing topologies
  - Direct Messaging
  - Indirect Messaging

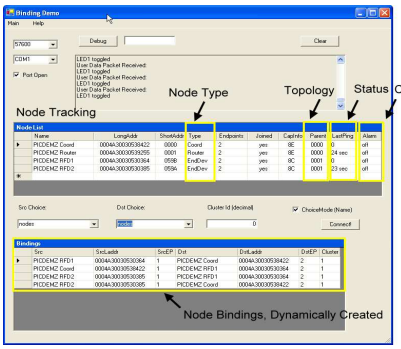
Tree routing with short address assignment



Multiplatorm devices supported

ZigBee Stack Implementation (2)

- **Platform**: PICDEMOZ (PIC18 + CC2420 radio), Compiler: MCC18 or HI-TECH
- **Platform**: CC2430 Evaluation board/SOC_BB (CC2430/31 which has an 8051+802.15.4 Radio integrated in one die), Compiler: IAR51, HI-TECH C51
- **Platform**: WIN32 simulated RF nodes+ Virtual Board interface, Compiler: Microsoft Visual Studio .NET 2005



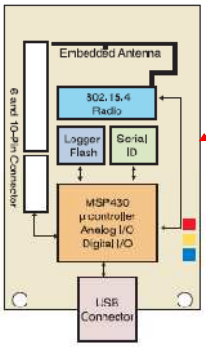
Emulation of virtual hardware sensor devices under Windows/.NET

Virtual device managent, network monitoring, application development

e.g. TelosB Mote Platform (1)

- Crossbow's TelosB mote (TPR2400) is an open source platform designed to enable cutting-edge experimentation for the research community.
- http://www.xbow.com/Products/productsdetails.aspx?sid=126

Hardware with USB interface for device programming



e.g. TelosB Mote Platform (2)

- TelosB platform published by the Berkeley University
- Features:
  - IEEE 802.15.4 compliant
  - Integrated on-board antenna
  - Open-source Operating System (TinyOS)
  - Data Collection and programming via USB interface
- Applications:
  - Platform for low power research development
  - Wireless Sensor Network Experimentation
- Cost: $ 100 / $ 130 (Sw for Wireless sensor experimentation included)

e.g. Chipcon CC2420 Mote Platform (1)

- The CC2420 Chipcon is a low-cost transceiver compliant with the IEEE 802.15.4 standard
- Evaluation of CC2420 performance by using the CC2420DK platform

CC2420DK Evaluation Board:

2 CC2420 chips

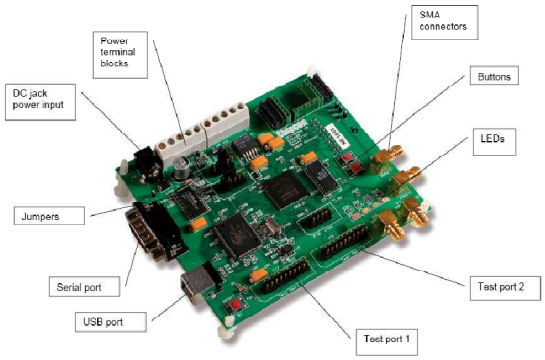
USB PORT

2 LEDS

2 TEST PORTS

1 SERIAL PORT

1 BUTTON



CC2420 Mote Platform (2)

- CC2420 Web Page:
  - www.chipcon.com/index.cfm?kat_id=2&subkat_id=12&dok_id=115
- Resources available:
  - **SMARTRF Studio** sw for device programming
  - CC2420DBK Libraries and Examples
  - CC2420 IEEE 802.15.4 MAC Source Code

Simulation and Commercial Products

- 802.15.4 implementation with ZigBee routing models (Ns2 simulator) free available at:
  - http://ees2cy.engr.ccny.cuny.edu/zheng/pub/
- ZigBee-related projects and products (at National Institute of Standards and Techonlogy (NIST):
  - http://w3.antd.nist.gov/wctg/manet/adhoclinks.html#BLUETOOTH