ZigBee/IEEE 802.15.4 Overview

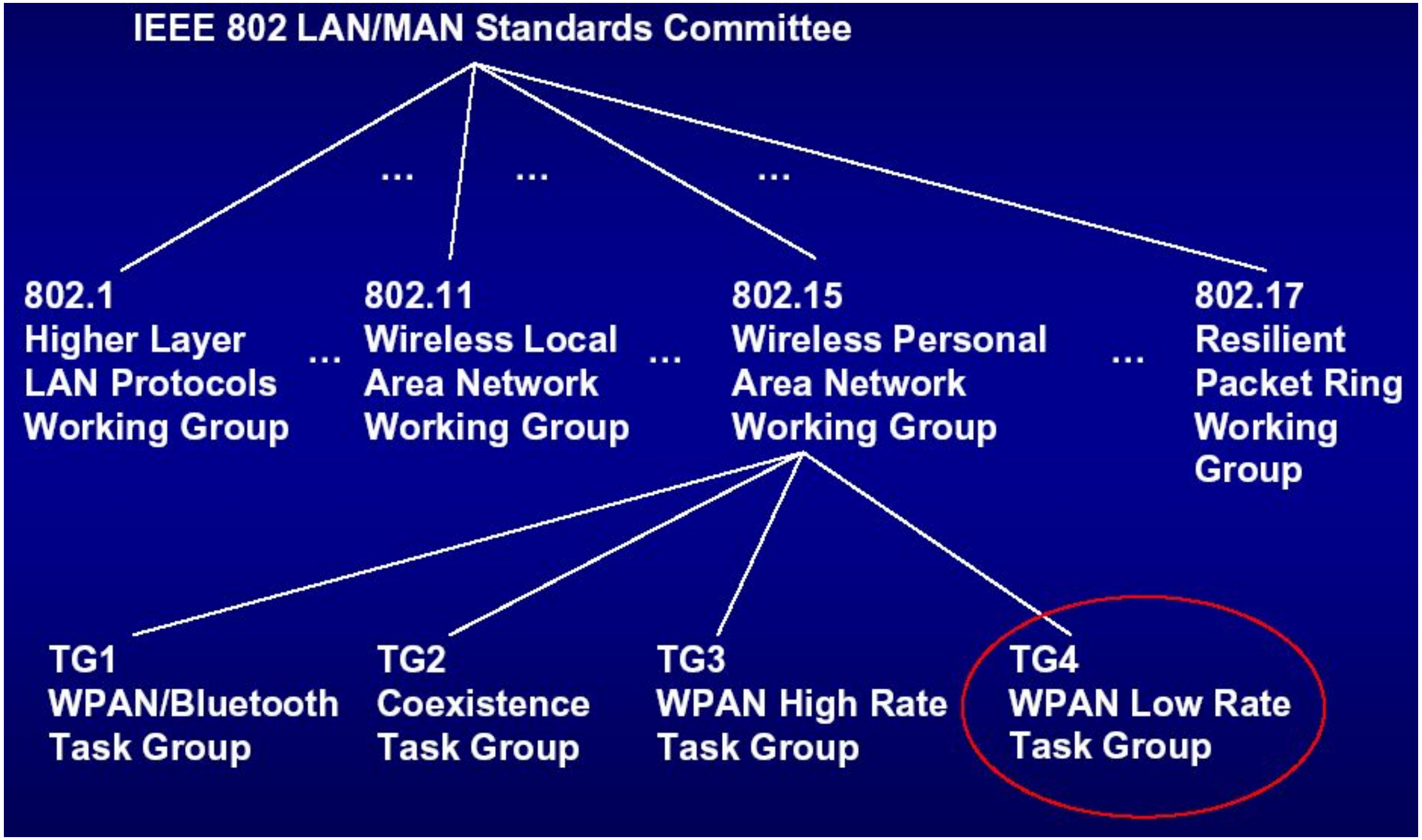
New trend of wireless technology

- Most Wireless industry focuses on increasing high data throughput
- A set of applications require simple wireless connectivity, relaxed throughput, very low power, short distance and inexpensive hardware.
  - Industrial
  - Agricultural
  - Vehicular
  - Residential
  - Medical

What is 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 interoperability, certification testing, and branding

IEEE 802.15 working group



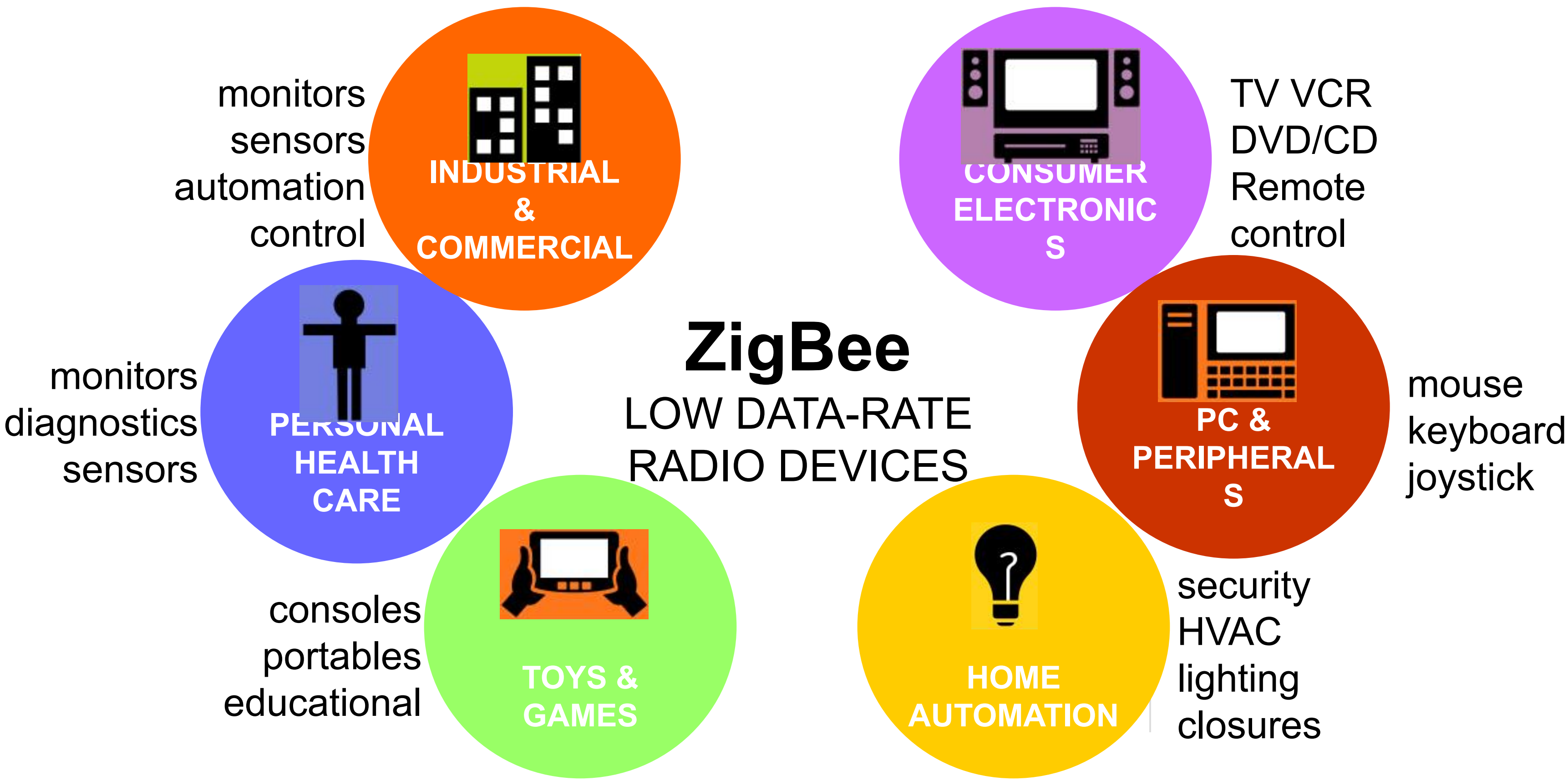
Comparison between WPAN

Project	Data Rate	Range	Configuration	Other Features
802.15.1 (Bluetooth)	1 Mbps	10M (class 3) 100M (class 1)	8 active device Piconet/ Scatternet	Authentication, Encryption, Voice
802.15.3 High Rate	22, 33, 44, 55 Mbps	10M	256 active device Piconet/ Scatternet	FCC part 15.249 QoS, Fast Join Multi-Media
802.15.4 Low Rate	up to 250Kbps	10M nominal 1M-100M based on settings	Master/Slave (256 Devices or more) Peer to Peer	Battery Life: multi-month to infinite
802.15.2 Coexistence	Develop a Coexistence Model and Mechanisms Document as a Recommended Practice			

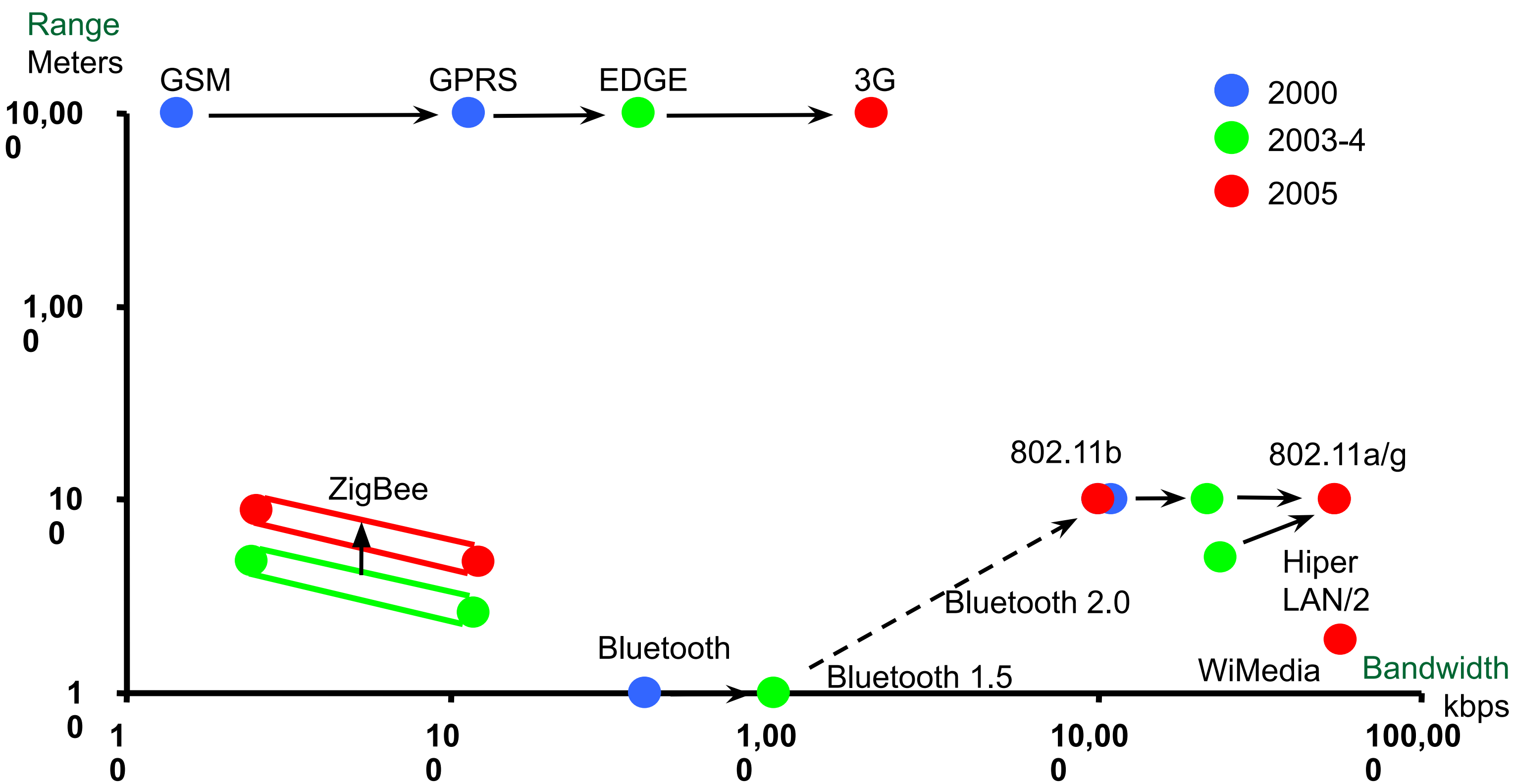
ZigBee/IEEE 802.15.4 market feature

- Low power consumption
- Low cost
- Low offered message throughput
- Supports large network orders (<= 65k nodes)
- Low to no QoS guarantees
- Flexible protocol design suitable for many applications

ZigBee network applications

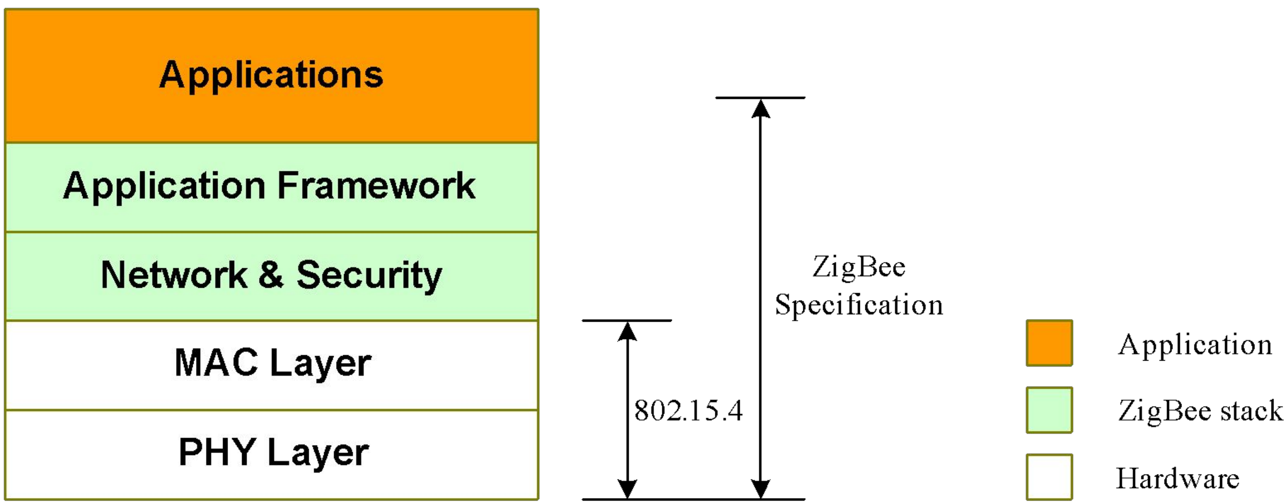


Wireless technologies



ZigBee/802.15.4 architecture

- ZigBee Alliance
  - 45+ companies: semiconductor mfrs, IP providers, OEMs, etc.
  - Defining upper layers of protocol stack: from network to application, including application profiles
  - First profiles published mid 2003
- IEEE 802.15.4 Working Group
  - Defining lower layers of protocol stack: MAC and PHY



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 overview

General characteristics

- Data rates of 250 kbps , 20 kbps and 40kpbs.
- Star or Peer-to-Peer operation.
- Support for low latency devices.
- CSMA-CA channel access.
- Dynamic device addressing.
- Fully handshaked protocol for transfer reliability.
- Low power consumption.
- Channels:
  - 16 channels in the 2.4GHz ISM band,
  - 10 channels in the 915MHz ISM band
  - 1 channel in the European 868MHz band.
- Extremely low duty-cycle (<0.1%)

IEEE 802.15.4 basics

- 802.15.4 is a simple packet data protocol for lightweight wireless networks
  - Channel Access is via Carrier Sense Multiple Access with collision avoidance and optional time slotting
  - Message acknowledgement
  - Optional beacon structure
  - Target applications
    - Long battery life, selectable latency for controllers, sensors, remote monitoring and portable electronics
  - Configured for maximum battery life, has the potential to last as long as the shelf life of most batteries

IEEE 802.15.4 Device Types

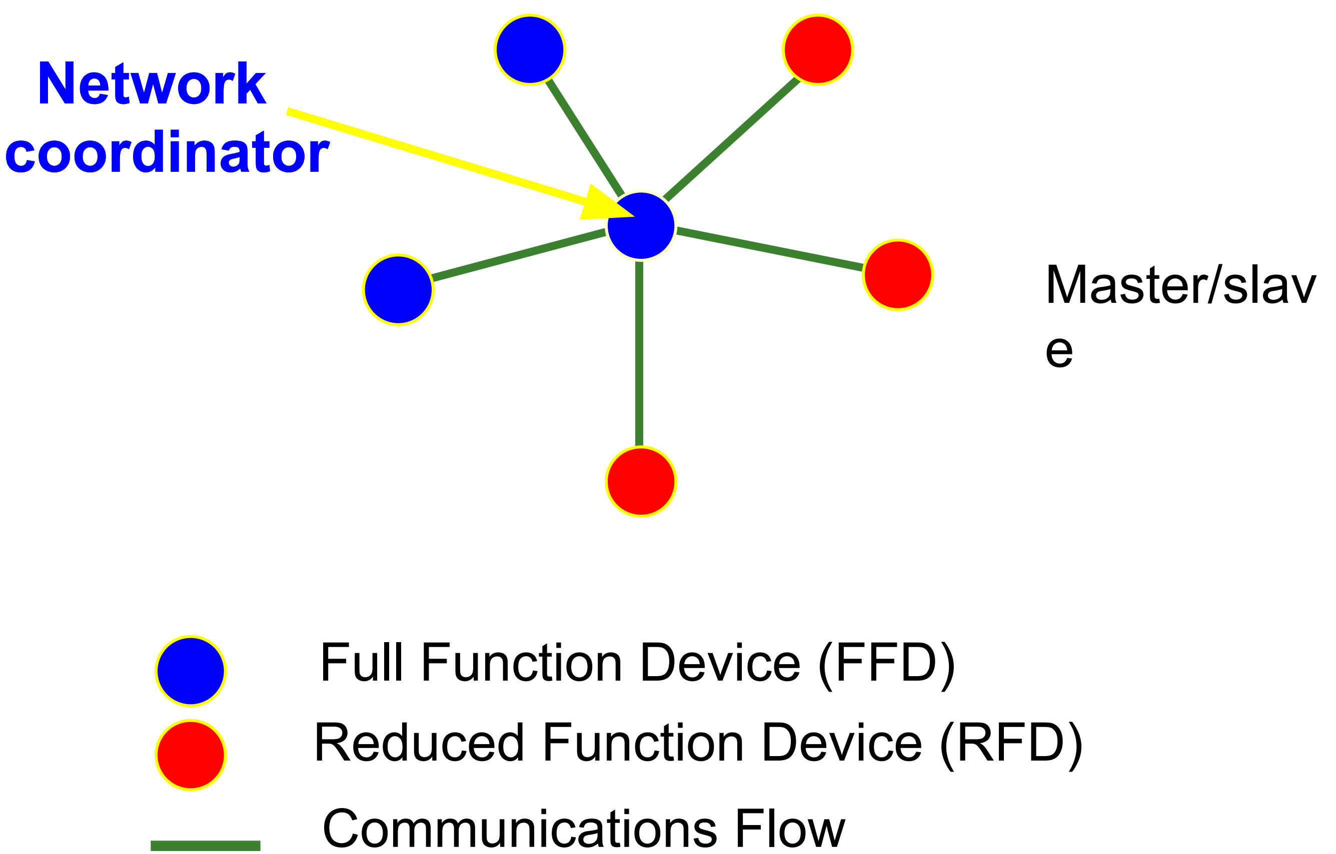
- There are two different device types :
  - A full function device (FFD)
  - A reduced function device (RFD)
- The FFD can operate in three modes by serving as
  - Device
  - Coordinator
  - PAN coordinator
- The RFD can only serve as:
  - Device

FFD vs RFD

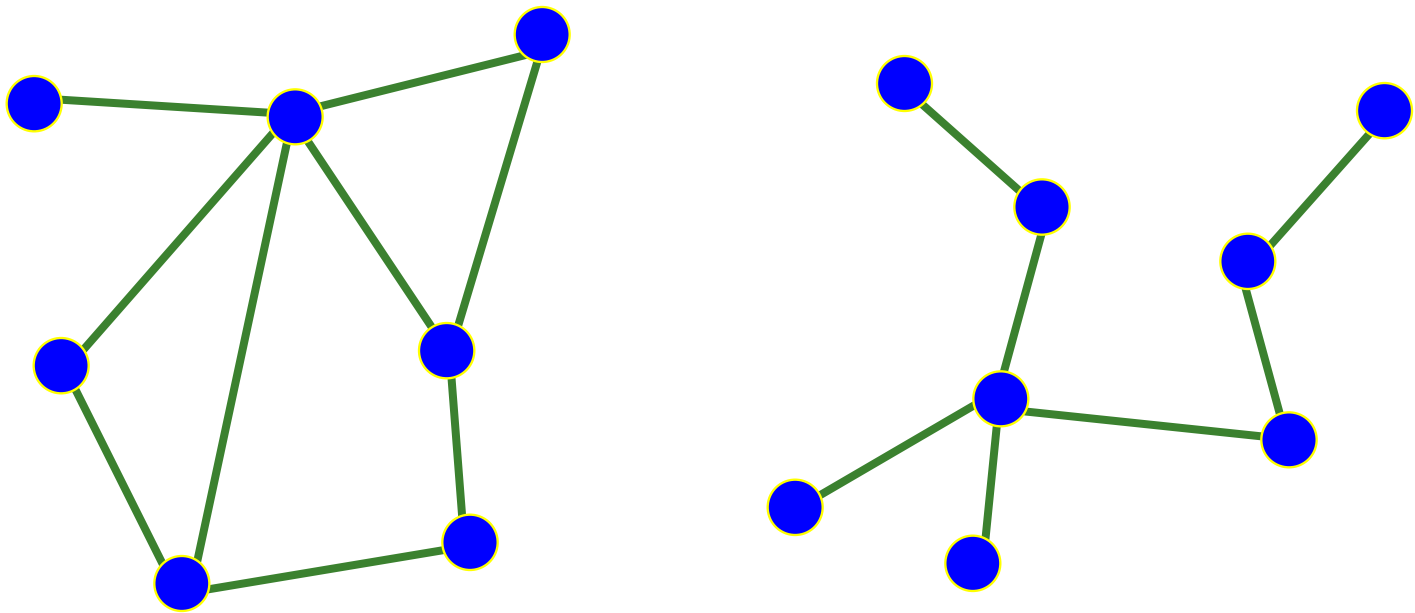
- Full function device (FFD)
  - Any topology
  - Network coordinator capable
  - Talks to any other device

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

Star topology



Peer to peer topology



Point to point **Tree**

Full Function Device (FFD)

Communications Flow

Device addressing

- Two or more devices communicating on the same physical channel constitute a WPAN.
  - A WPAN includes <u>at least one FFD (PAN coordinator)</u>
  - Each independent PAN will select a unique PAN identifier
- Each device operating on a network has a unique 64-bit extended address. This address can be used for direct communication in the PAN
- A device also has a 16-bit short address, which is allocated by the PAN coordinator when the device associates with its coordinator.

IEEE 802.15.4 physical layer

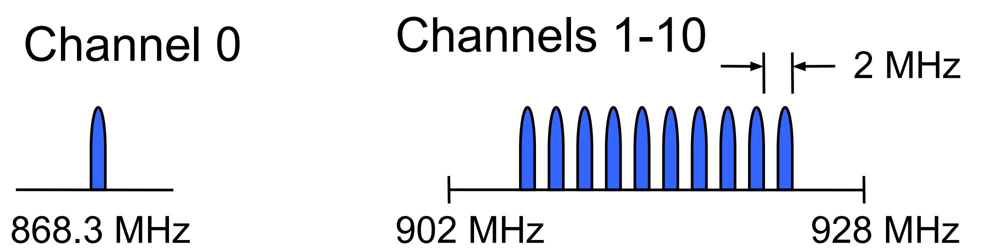
IEEE 802.15.4 PHY overview

- PHY functionalities:
  - Activation and deactivation of the radio transceiver
  - Energy detection within the current channel
  - Link quality indication for received packets
  - Clear channel assessment for CSMA-CA
  - Channel frequency selection
  - Data transmission and reception

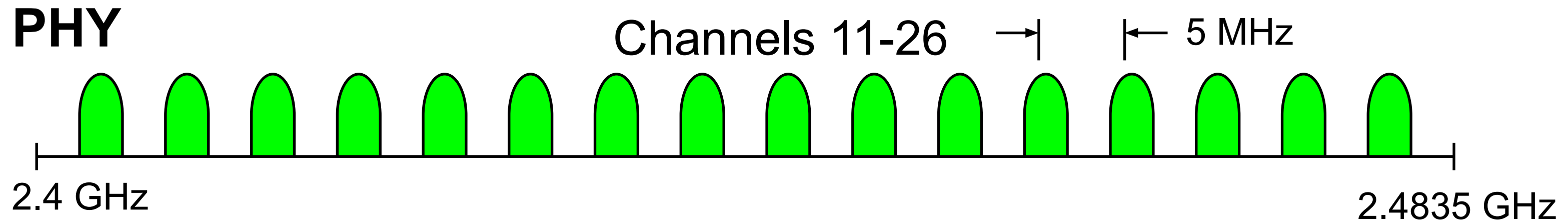
IEEE 802.15.4 PHY Overview

- Operating frequency bands

868MHz/ 915MHz PHY



2.4 GHz PHY



Frequency Bands and Data Rates

- The standard specifies two PHYs :
  - 868 MHz/915 MHz direct sequence spread spectrum (DSSS) PHY (11 channels)
    - 1 channel (20Kb/s) in European 868MHz band
    - 10 channels (40Kb/s) in 915 (902-928)MHz ISM band
  - 2450 MHz direct sequence spread spectrum (DSSS) PHY (16 channels)
    - 16 channels (250Kb/s) in 2.4GHz band

PHY Frame Structure

- PHY packet fields
  - Preamble (32 bits) – synchronization
  - Start of packet delimiter (8 bits) – shall be formatted as “11100101”
  - PHY header (8 bits) –PSDU length
  - PSDU (0 to 127 bytes) – data field

Sync Header		PHY Header		PHY Payload
Preamble	Start of Packet Delimiter	Frame Length (7 bit)	Reserve (1 bit)	PHY Service Data Unit (PSDU)
4 Octets	1 Octets	1 Octets		0-127 Bytes

IEEE 802.15.4 MAC

Superframe

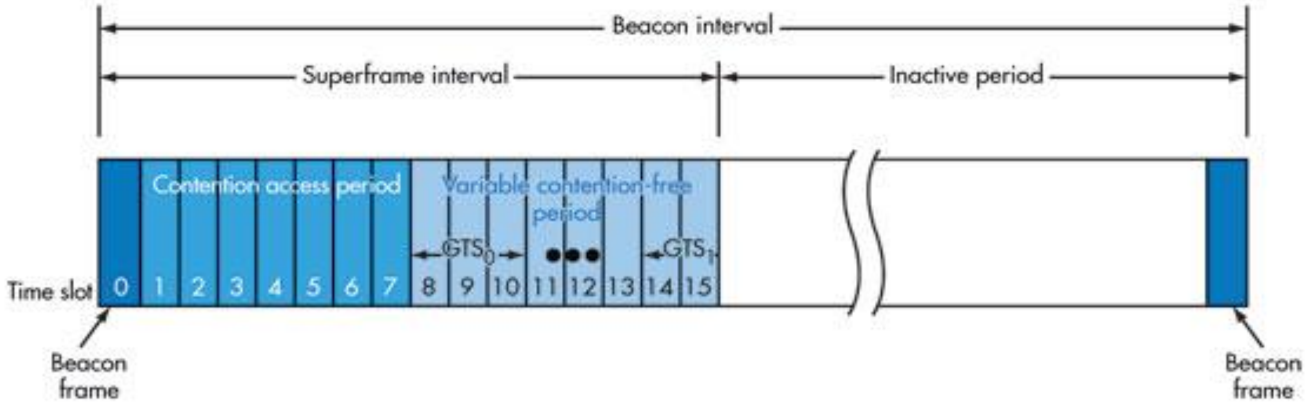


Fig 3. Nodes in a beacon-enabled frame structure are synchronized to the superframe boundaries by beacon frames broadcast at a regular interval from a network controller.

- A superframe is divided into two parts
  - Inactive: all station sleep
  - Active:
    - Active period will be divided into 16 slots
    - 16 slots can further divided into two parts
      - Contention access period
      - Contention free period

Superframe

- Beacons are used for
  - starting superframes
  - synchronizing with other devices
  - announcing the existence of a PAN
  - informing pending data in coordinators
- In a “beacon-enabled” network,
  - Devices use the slotted CAMA/CA mechanism to contend for the usage of channels
  - FFDs which require fixed rates of transmissions can ask for *guarantee time slots (GTS)* from the coordinator

Superframe

- The structure of superframes is controlled by two parameters:
  - *beacon order (BO)* : decides the length of a superframe
  - *superframe order (SO)* : decides the length of the active potion in a superframe
- For a beacon-enabled network, the setting of BO and SO should satisfy the relationship $0 \leqq SO \leqq BO \leqq 14$

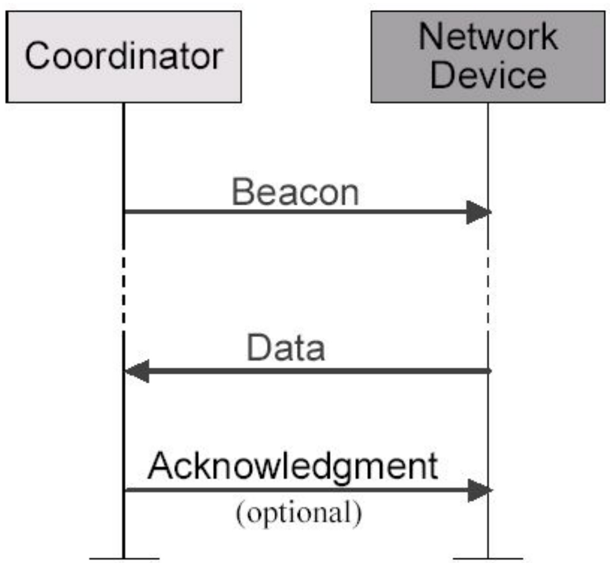
Superframe

- Each device will be active for $2^{-(BO-SO)}$ portion of the time, and sleep for $1-2^{-(BO-SO)}$ portion of the time
- Duty Cycle:

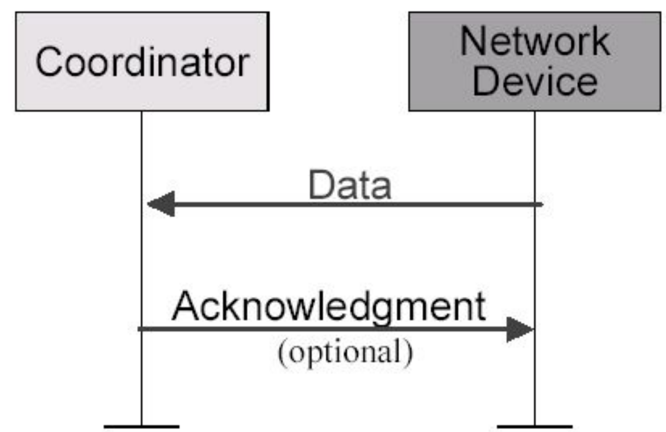
BO-SO	0	1	2	3	4	5	6	7	8	9	≧10
Duty cycle (%)	100	50	25	12	6.25	3.125	1.56	0.78	0.39	0.195	< 0.1

Data Transfer Model (I)

- Data transferred from device to coordinator
  - In a beacon-enable network, a device finds the beacon to synchronize to the superframe structure. Then it uses slotted CSMA/CA to transmit its data.
  - In a non-beacon-enable network, device simply transmits its data using unslotted CSMA/CA



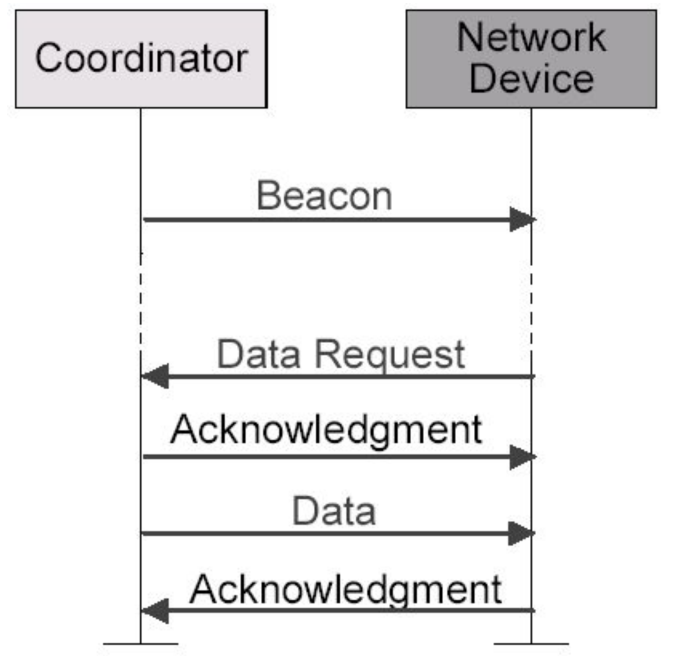
Communication to a coordinator
In a beacon-enabled network



Communication to a coordinator
In a non beacon-enabled network

Data Transfer Model (II)

- Data transferred from coordinator to device in a beacon-enabled network:
  - The coordinator indicates in the beacon that some data is pending.
  - A device periodically listens to the beacon and transmits a Data Requst command using slotted CSMA/CA.
  - Then ACK, Data, and ACK follow …



Communication from a coordinator
In a beacon-enabled network

Channel Access Mechanism

- Two type channel access mechanism:
  - beacon-enabled networks slotted CSMA/CA channel access mechanism
  - non-beacon-enabled networks unslotted CSMA/CA channel access mechanism

Slotted CSMA/CA algorithm

- In slotted CSMA/CA
  - The backoff period boundaries of every device in the PAN shall be aligned with the superframe slot boundaries of the PAN coordinator
    - i.e. the start of first backoff period of each device is aligned with the start of the beacon transmission
  - The MAC sublayer shall ensure that the PHY layer commences all of its transmissions on the boundary of a backoff period

Slotted CSMA/CA algorithm (cont.)

- Each device maintains 3 variables for each transmission attempt
  - NB: number of times that backoff has been taken in this attempt
    BE: the backoff exponent which is determined by NB
  - CW: contention window length, the number of clear slots that must be seen after each backoff
- Battery Life Extension:
  - designed for very low-power operation, where a node only contends in the first 6 slots

GTS Concepts (I)

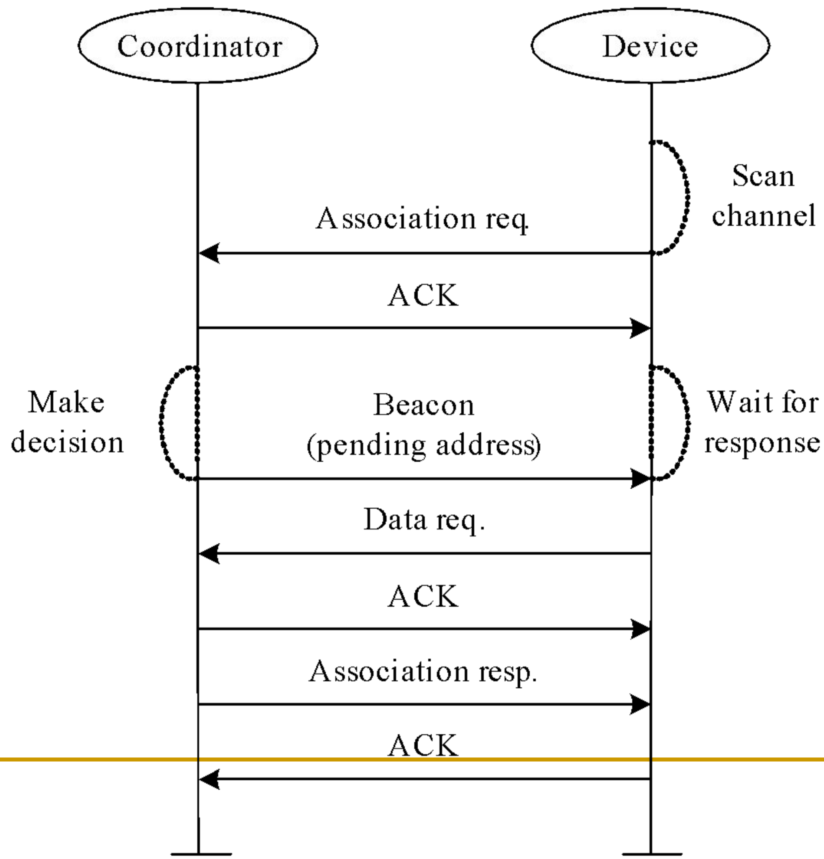
- A guaranteed time slot (GTS) allows a device to operate on the channel within a portion of the superframe
- A GTS shall only be allocated by the PAN coordinator
- The PAN coordinator can allocated up to 7 GTSs at the same time
- The PAN coordinator decides whether to allocate GTS based on:
  - Requirements of the GTS request
  - The current available capacity in the superframe

GTS Concepts (II)

- A GTS can be deallocated
  - At any time at the discretion of the PAN coordinator or
  - By the device that originally requested the GTS
- A device that has been allocated a GTS may also operate in the CAP
- A data frame transmitted in an allocated GTS shall use only short addressing

Association Procedures (1/2)

- A device becomes a member of a PAN by associating with its coordinator
- Procedures



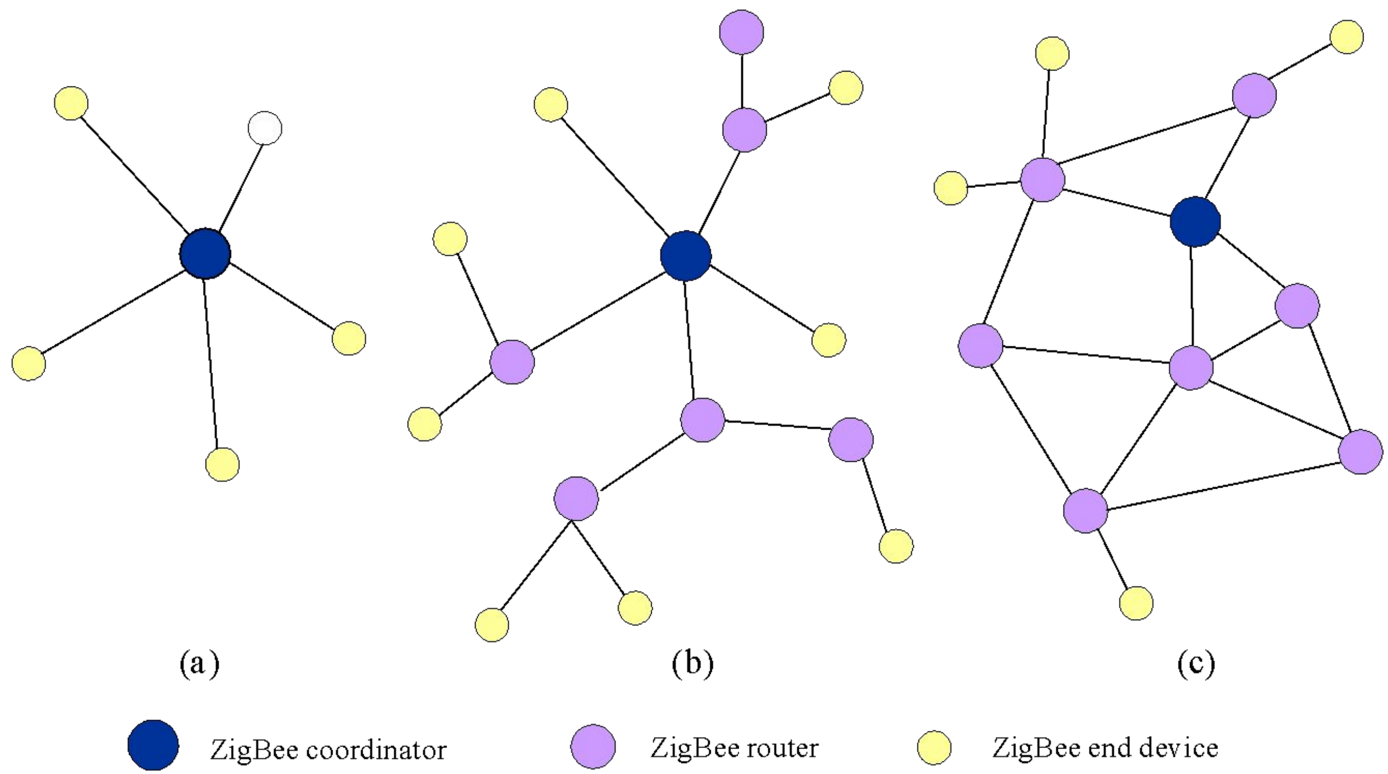
Association Procedures (2/2)

- In IEEE 802.15.4, association results are announced in an indirect fashion.
  - A coordinator responds to association requests by appending devices' long addresses in beacon frames
- Devices need to send a data request to the coordinator to acquire the association result
- After associating to a coordinator, a device will be assigned a 16-bit *short address*.

ZigBee Network Layer Protocols

ZigBee Network Layer Overview

- Three kinds of networks are supported: star, tree, and mesh networks



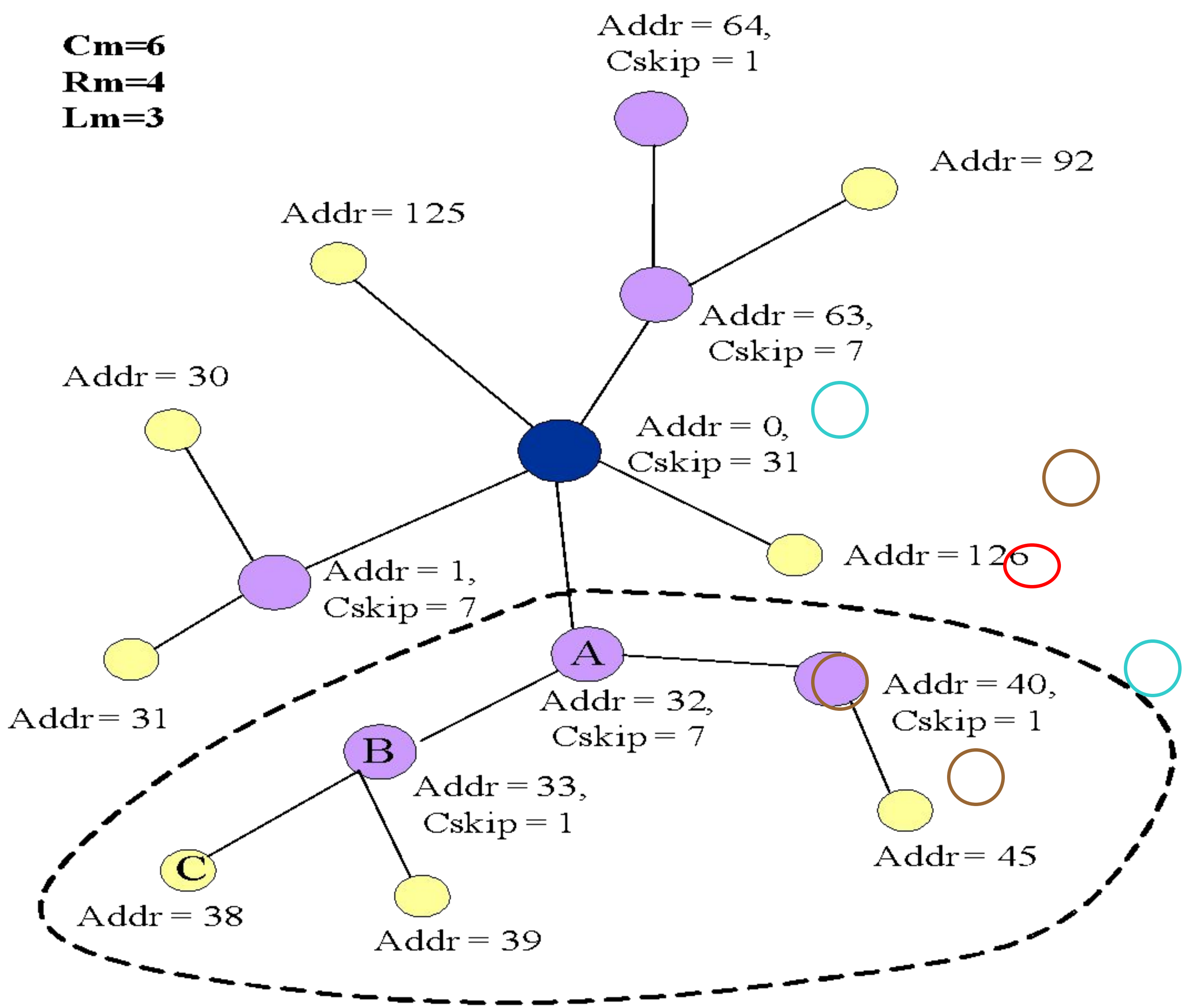
ZigBee Network Layer Overview

- Three kinds of devices in the network layer
  - ZigBee coordinator: responsible for initializing, maintaining, and controlling the network
  - ZigBee router: form the network backbone
  - ZigBee end device: must be connected to router/coordinator

- In a tree network, the coordinator and routers can announce beacons.
- In a mesh network, there is no regular beacon.
  - Devices in a mesh network can only communicate with each other in a peer-to-peer manner

Address Assignment

- In ZigBee, network addresses are assigned to devices by a distributed address assignment scheme
- ZigBee coordinator determines three network parameters
  - the maximum number of children of a ZigBee router
  - the maximum number of child routers of a parent node
  - the depth of the network


Cm=6
Rm=4
Lm=3
Addr = 64,
Cskip = 1
Addr = 92
Addr = 125
Addr = 63,
Cskip = 7
Addr = 30
Addr = 0,
Cskip = 31
Addr = 126
Addr = 1,
Cskip = 7
A
Addr = 40,
Cskip = 1
Addr = 31
Addr = 32,
Cskip = 7
B
Addr = 33,
Cskip = 1
C
Addr = 45
Addr = 38
Addr = 39

ZigBee Routing Protocols

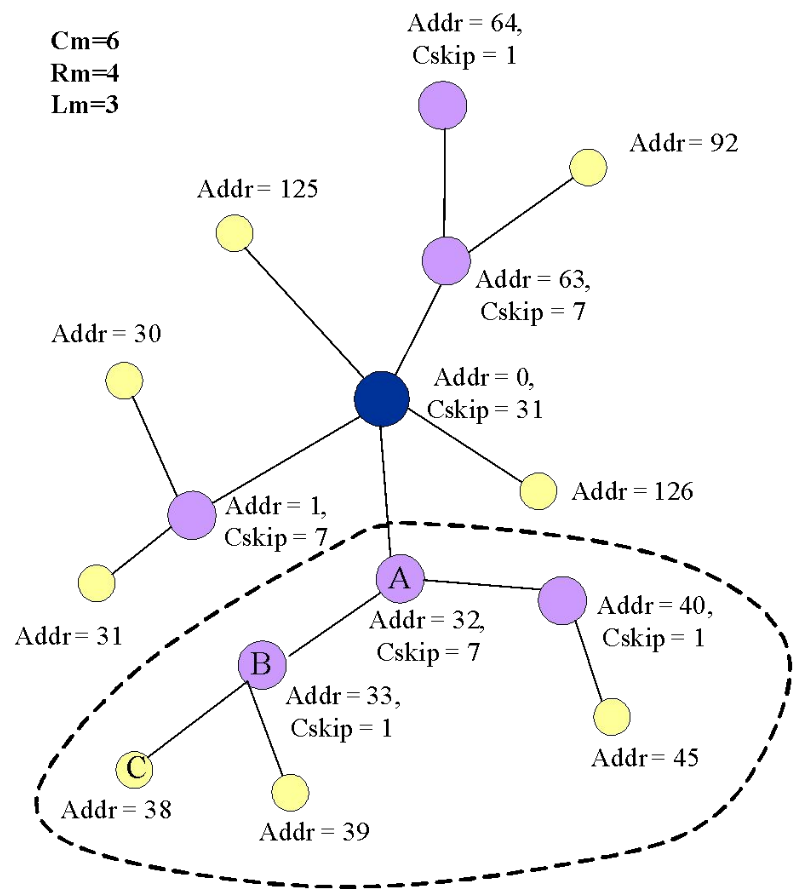
- In a tree network
  - Utilize the address assignment to obtain the routing paths

- In a mesh network:
  - Routing Capability: ZigBee coordinators and routers are said to have *routing capacity* if they have routing table capacities and route discovery table capacities
  - There are 2 options:
    - Reactive routing: if having "routing capacity"
    - Tree routing: if having no routing capacity

ZigBee Tree Routing

- When a device receives a packet, it first checks if it is the destination or one of its child end devices is the destination
  - If so, accept the packet or forward it to a child
  - Otherwise, relay it along the tree

- Example:
  - 38 □ 45
  - 38 □ 92

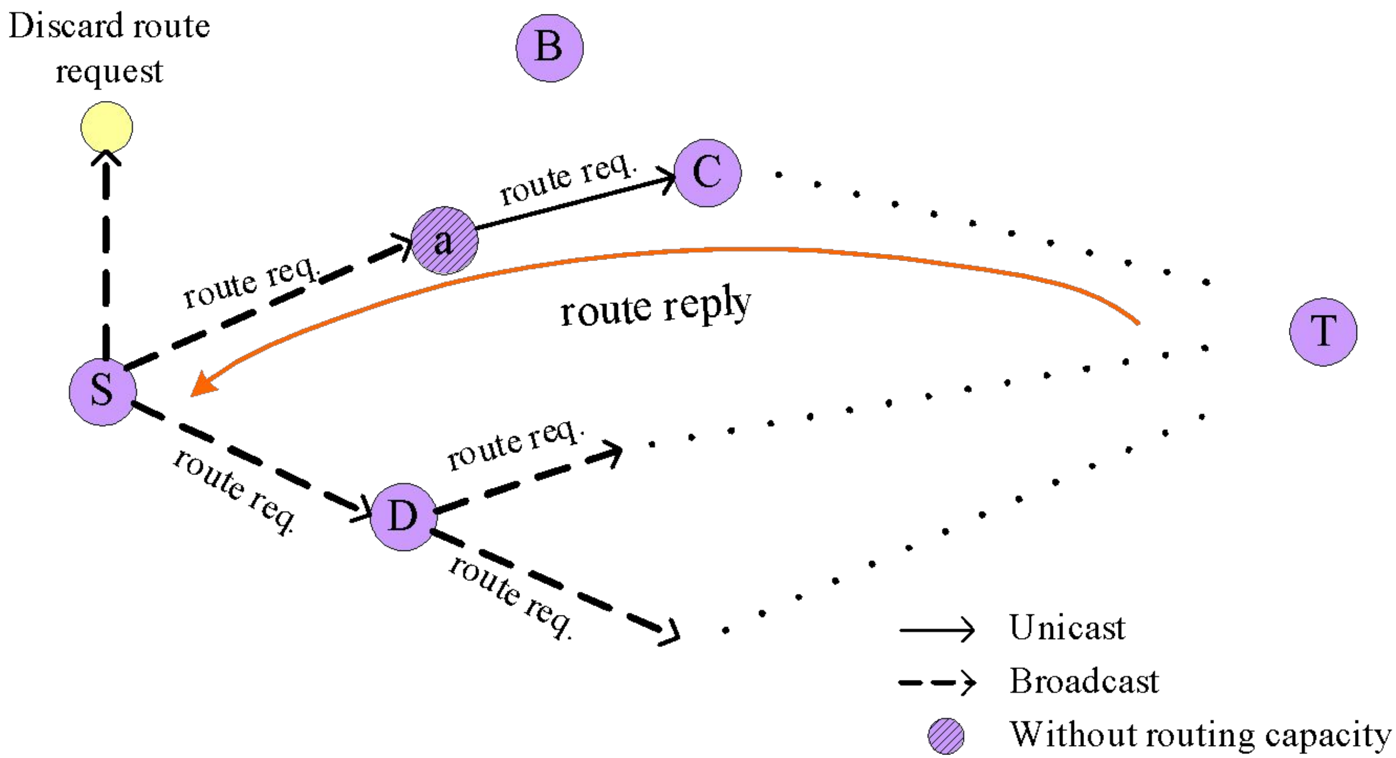


ZigBee Mesh Routing

- Route discovery by AODV-like routing protocol
  - The cost of a link is defined based on the packet delivery probability on that link

- Route discovery procedure
  - The source broadcasts a route request packet
  - Intermediate nodes will rebroadcast route request if
    - They have routing discovery table capacities
    - The cost is lower
  - Otherwise, nodes will relay the request along the tree
  - The destination will choose the routing path with the lowest cost and then send a route reply

Routing in a Mesh network: Example



Summary of ZigBee network layer

	Pros	Cons
Star	1. Easy to synchronize 2. Support low power operation 3. Low latency	1. Small scale
Tree	1. Low routing cost 2. Can form superframes to support sleep mode 3. Allow multihop communication	1. Route reconstruction is costly 2. Latency may be quite long
Mesh	1. Robust multihop communication 2. Network is more flexible 3. Lower latency	1. Cannot form superframes (and thus cannot support sleep mode) 2. Route discovery is costly 3. Needs storage for routing table