# Networking Layer Protocols for Internet of Things: 6LoWPAN and RPL


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These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-22/

**Student Questions**


- 6LowPAN
  - Adaptation Layer
  - Address Formation
  - Compression
- RPL
  - RPL Concepts
  - RPL Control Messages
  - RPL Data Forwarding

Note: This is part 3 of a series of class lectures on IoT.

## Student Questions

# Recent Protocols for IoT

| Layer | Protocols |
| --- | --- |
| Session | MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC, IEEE 1888, … |
| Network | Encapsulation: **6LowPAN**, 6TiSCH, 6Lo, Thread… |
| | Routing: **RPL**, CORPL, CARP |
| Datalink | Wi-Fi, Bluetooth Low Energy, Z-Wave, ZigBee Smart, DECT/ULE, 3G/LTE, NFC, Weightless, HomePlug GP, 802.11ah, 802.15.4e, G.9959, WirelessHART, DASH7, ANT+, LTE-A, LoRaWAN, ISA100.11a, DigiMesh, WiMAX, … |

**Security**

IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …

**Management**

IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856

Ref: Tara Salman, Raj Jain, "A Survey of Protocols and Standards for Internet of Things," Advanced Computing and Communications, Vol. 1, No. 1, March 2017, http://www.cse.wustl.edu/~jain/papers/iot_accs.htm

## Student Questions

# IEEE 802.15.4

- Wireless Personal Area Network (WPAN)
- Allows mesh networking.
  Full function nodes can forward packets to other nodes.
- A PAN coordinator (like Wi-Fi Access Point) allows nodes to join the network.
- Nodes have 64-bit addresses
- Coordinator assigns 16-bit short address for use during the association
- Maximum frame size is 127 bytes





**Student Questions**

# EUI64 Addresses

- **Ethernet addresses**: 48 bit MAC

| Unicast Multicast | Universal Local | Organizationally Unique ID (OUI) | Manufacturer Assigned |
|---|---|---|---|
| 1b | 1b | 22b | 24b |

- **IEEE 802.15.4 Addresses**: 64 bit Extended Unique Id (EUI)

| Unicast Multicast | Universal Local | Organizationally Unique ID (OUI) | Manufacturer Assigned |
|---|---|---|---|
| 1b | 1b | 22b | 40b |

- **Local bit** was incorrectly assigned. L=1 ⇒ Local
  but all-broadcast address = all 1's is not local
  IETF RFC4291 changed the meaning so that L=0 ⇒ Local
  The 2nd bit is now called Universal bit (U-bit)
  ⇒ U-bit formatted EUI64 addresses

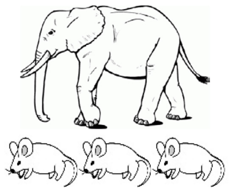
## Student Questions

- Does "U-bit formatted EUI64 addresses" mean global or local address formatting?

*IEEE 802:*
*2nd bit = 1 ⇒ Local*
*IEEE 802.15.4:*
*2nd bit = 1 ⇒ Universal*

# 6LowPAN

- IPv6 over Low Power Wireless Personal Area Networks
- How to transmit IPv6 datagrams (elephants) over low power IoT devices (mice)?



- **Issues**:

1. **IPv6 address formation**: 128-bit IPv6 from 64-bit EUI64
2. **Maximum Transmission Unit** (MTU): IPv6 at least 1280 bytes vs. IEEE 802.15.4 standard packet size is 127 bytes

| 802.15.4 Header | Security Option | Payload |
|---|---|---|
| 25B | 21B | 81B |

3. **Address Resolution**: 128b or 16B IPv6 addresses. 802.15.4 devices use 64 bit (no network prefix) or 16 bit addresses
4. **Optional mesh routing in datalink layer**
   ⇒ Need destination and intermediate addresses.

## Student Questions

- In the review question, what problem does 6LowPan address?

*See 7 issues in this slide and next.*

Ref: G. Montenegro, et al., "Transmission of IPv6 Packets over IEEE 802.15.4 Networks," RFC 4944, Sep 2007, http://tools.ietf.org/pdf/rfc4944

# 6LowPAN Adaptation Layer

5. **MAC-level retransmissions versus end-to-end**:
   - Optional hop-by-hop ack feature of 802.15.4 is used but the max number of retransmissions is kept low (to avoid overlapping L2 and L4 retransmissions)
6. **Extension Headers**: 8b ***or less*** Shannon-coded dispatch ⇒ header type
   - $10_2$: Mesh addressing header (2-bit dispatch)
   - $11x00_2$: Destination Processing Fragment header (5-bit)
   - $01010000_2$: Hop-by-hop LowPAN Broadcast header (8-bit)
7. **IPv6 and UDP header compression**

| Frame Control | Seq. # | Adrs | [Security] | **Disp bits** | Ext Hdr | Disp bits | Ext Hdr | Disp bits | Ext Hdr | IPv6 Payload |
|---|---|---|---|---|---|---|---|---|---|---|
| 2B | 1B | 0-20B | 0-21B | 6LowPAN | | | | | | |

Adrs: Receiver/Transmitter addresses

Disp bits through the last Ext Hdr: 6LowPAN

## Student Questions

- What is the reason behind 6LowPAN Header compression?

*IPv6 headers are long since they contain 128-bit source and destination addresses.*

Ref: O. Hersent, et al., "The Internet of Things: Key Applications and Protocols," Wiley, 2013, 344 pp., ISBN: 9781119994350 (Safari Book)

# IPv6 Address Formation

- **Link-Local IPv6 address** = FE80::U-bit formatted EUI64
- **Example**:
  - EUI64 Local Address = 40::1 = 0100 0000::0000 0001
  - U-bit formatted EUI64 = 0::1
  - IPv6 Link-local address = FE80::1 = 1111 1110 1000 0000::1
- IEEE 802.15.4 allows nodes to have 16-bit **short addresses** and each PAN has a 16-bit **PAN ID**.
  1$^{st}$ bit of Short address and PAN ID is Unicast/Multicast
  The 2$^{nd}$ bit of Short Address and PAN ID is Local/Universal.
  You can broadcast to all members of a PAN or to all PANs.
- IPv6 Link Local Address = FE80 :: PAN ID : Short Address
  Use 0 if PAN ID is unknown.
  2$^{nd}$ bit of PAN ID should always be zero since it is always local.
  2$^{nd}$ most significant = 6$^{th}$ bit from right)





## Student Questions

- In the IPv6 Link Local Address, it says Use 0 if PAN ID is unknown. Does this mean all 128 bits are 0?

*IPv6 Addresses are two parts: Network part and host part. The network part is zero. Similarly, there are short PAN Ids and Short Node Ids (Addresses)*

- Also can you go over the 2nd most significant bit = 6th bit from the right again?

  *Yes, msb is always written on the left. The storage inside the memory depends upon the CPU architecture.*

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- Can you explain the 0::1 in U-bit formatted EUI64 means and how many 0 in ::?

*0::1 is not EUI; it is an IPv6 address. IPv6 uses 128-bit addresses. You must fill in enough zeros to make it 128-bits or 16 bytes.*

# IPv6 Address Formation

- **Link-Local IPv6 address** = FE80::U-bit formatted EUI64
- **Example**:
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  - U-bit formatted EUI64 = 0::1
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## Student Questions

- Why is FE80 used as the prefix for link-local IPv6 addresses? I understand that it converts to (1111 1110 1000 0000)_2, but what is the significance of this bit string?

*Just a unique reserved prefix. No one can use this bit sequence for any other purpose.*

# Homework 14A

- What is the IPv6 Link-Local address for a IEEE 802.15.4 node whose EUI64 address in hex is 0000::0002. Indicate your final answer in hex without using ::
- EUI64 in Binary =
- U-bit EUI64 Binary =
- U-bit EUI64 Hex =
- IPv6 Link Local Address =

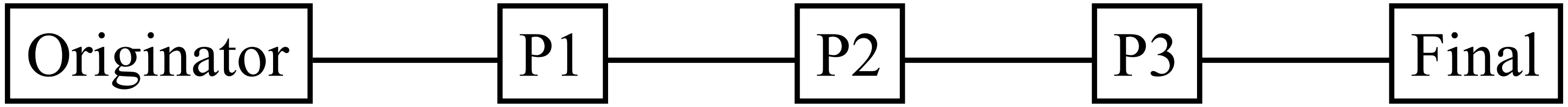
## Student Questions

- Would you please provide solutions to HW14A?

*Sure.*

# Mesh Addressing Header

- Dispatch = $10_2$ (2 bits) ⇒ Mesh Addressing Header
- MAC header contains only originator and final addresses. each FFD node on the path looks up the final address in its routing table ⇒ Mesh routing not path routing. Transmitter and receiver addresses are up front in IEEE802.15 header.
- A 4-bit hops-left field is decremented at each hop




| Dispatch 10 | V | F | Hops Left | Originator Address | Final Address |
|---|---|---|---|---|---|
| 2b | 1b | 1b | 4b | 16b/64b | 16b/64bit |

V=0 ⇒ Originator address is EUI64, V=1 ⇒ 16bit
F=0 ⇒ Final address is EUI64, F=1 ⇒ 16-bit

## Student Questions

- So where are the per hop source and destination addresses stored in the diagram?

*See the text update on this slide. Also, see Slide 14-7 bottom for the receiver/transmitter address for this hop.*

- 4-bit hop limits the number of possible hops to 16 stations per system. Wouldn't this be too small?

*7 hops in IP are sufficient to travel the entire world. Large number of hops are undesirable as the chances of not-making it go increase with hops.*

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- Can you please explain the first point?

*Dispatch indicates the message type. It is a variable length field. 10 indicates mesh addressing header.*

- Could you please explain where each of the header bits go again?

*The bottom figure shows the location of the header bits.*

# 6LowPAN Broadcast Header

- For Mesh broadcast/multicast
- A new sequence number is put in every broadcast message by the originator

| Dispatch $01010000_2$ | Sequence Number |
|---|---|
| 8b | 8b |

**Student Questions**

# 6LowPAN Fragment Header

- Dispatch = 11*x*00 (5 bits) ⇒ Fragment Header
- Full packet size in the first fragment's fragment header
- Datagram tag = sequence number
  ⇒ Fragments of the same packet
- Fragment Offset in multiples of 8 bytes

1st Fragment:

| 11000 | IP Pkt Size | Datagram tag | Payload |
|---|---|---|---|
| 5b | 11b | 16b | |

Other Fragments:

| 11100 | IP Pkt Size | Datagram tag | Datagram Offset | Payload |
|---|---|---|---|---|
| 5b | 11b | 16b | 8b | |

## Student Questions

- "What is the *x* in the Dispatch code (11*x*00)?

*Shown in red in the figure. It can be 0 or 1.*

- Does the fact that the offset is in 8 bytes mean the fragment payload size must be in a multiple of 8 bytes?

*Yes.*

- If the offset is in multiples of 8 bytes, then how can the offset be 15 bytes in the 120-byte packet example you gave in the video?

*Offset=15 words of 8 bytes each*
*Þ Fragment size=15×8=120*

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- If there is a datagram tag present already in the header, can the fragments not be put into the correct order based on the sequence number alone? Will it just increase the computational overhead a lot?

*Datagram tag does not indicate where in the datagram the fragment fits.*

# IP+UDP Header Compression: Stateless

- Called **HC1-HC2 compression** (not recommended)
- IP version field is omitted
- Flow label field if zero is omitted and C=1
- Only 4b UDP ports are sent if between 61616-61631 (F0B*x*)
- UDP length field is omitted. IP addresses are compressed.

← HC1 Header → | ← HC2 Header →

| Dispatch 01000010 | SA Encoding | DA Encoding | C | NH | 0 | S | D | L | Uncompressed Fields |
|---|---|---|---|---|---|---|---|---|---|

- L: UDP Length omitted
- D: UDP Dest Port 61616-61631
- S: UDP Src Port 61616-61631

SA/DA Encoding:

| | **Prefix** | **IID** |
|---|---|---|
| 00 | Uncompressed | Uncompressed |
| 01 | Uncompressed | Derived from L2 |
| 10 | FE80::/80 omitted | Uncompressed |
| 11 | FE80::/64 omitted | Derived from L2 |

NH:

| | |
|---|---|
| 00 | Next Hdr inline |
| 01 | Next Hdr= 17 (UDP) |
| 10 | Next Hdr = 1 (ICMP) |
| 11 | Next Hdr = 6 (TCP) |

## Student Questions

- What does it mean that the header compression is stateless?

*Stateless = Nodes do not need to remember what they did on the previous packet*

- Why HC2 Header starts with zero?

*To align the fields*

- Can you point out the flow label field in the figure?

*If it is present, it will be in the uncompressed fields. Most often it is zero. This is indicated by C=1.*

- Does the length of each part of the header change when there is/is not compressing, or it remains the same expect for the the uncompressed part in the end?

# IP+UDP Header Compression: Stateless

- Called **HC1-HC2 compression** (not recommended)
- IP version field is omitted
- Flow label field if zero is omitted and C=1
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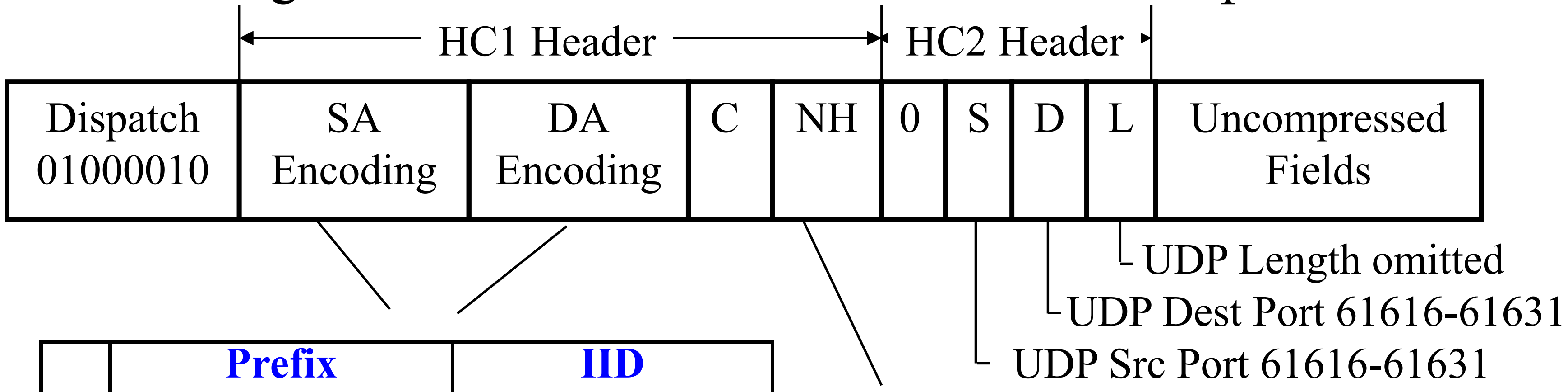
- UDP length field is omitted. IP addresses are compressed.




| | **Prefix** | **IID** |
|---|---|---|
| 00 | Uncompressed | Uncompressed |
| 01 | Uncompressed | Derived from L2 |
| 10 | FE80::/80 omitted | Uncompressed |
| 11 | FE80::/64 omitted | Derived from L2 |

| | |
|---|---|
| 00 | Next Hdr inline |
| 01 | Next Hdr= 17 (UDP) |
| 10 | Next Hdr = 1 (ICMP) |
| 11 | Next Hdr = 6 (TCP) |

## Student Questions

- Does the length of each part of the header change when there is/is not compressing, or it remains the same except for the uncompressed part in the end?

*It remains the same except for the uncompressed part in the end.*

# Context Based Compression

- HC1 works only with **link-local** addresses
- Need globally routable IPv6 addresses for outside nodes
- IPHC uses a 3b dispatch code and a 13-bit base header

| Disp 011 | TF | NH | Hop Limit | CID | SAC | SAM | M | DAC | DAM | SCI | DCI | Uncompressed IPv6 fields |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3b | 2b | 1b | 2b | 1b | 1b | 2b | 1b | 1b | 2b | 4b | 4b | |

Source Adr Mode
Source/Dest Context IDs if CID=1
Source Adr Compression
Multicast Destination

Traffic Class, Flow Label

Next Header uses LowPAN_NHC

Predefined hop limit = uncompressed (00), 1, 64, 255

| | |
|---|---|
| 00 | ECN+DSCP+4b pad+ 20b Flow label (4 Bytes) |
| 01 | ECN +2b pad + 12b Flow label (2 Bytes), DSCP omitted |
| 10 | ECN+DSCP (1B), Flow label omitted |
| 11 | ECN+DSCP+Flow label omitted |

| SAC DAC | SAM DAM | Address |
|---|---|---|
| 0 | 00 | No compression |
| 0 | 01 | First 64-bits omitted |
| 0 | 10 | First 112 bits omitted |
| 0 | 11 | 128 bits omitted. Get from L2 |
| 1 | 00 | Unspecified Address :: |
| 1 | 01 | First 64 bits from context |
| 1 | 10 | First 112 bits from context |
| 1 | 11 | 128 bits from context and L2 |

Ref: O. Hersent, et al., "The Internet of Things: Key Applications and Protocols," Wiley, 2013, 344 pp., ISBN: 9781119994350 (Safari Book)





## Student Questions

- What is the CID?

*Context ID*

# Context Based Compression (Cont)

- If the next header uses LowPAN_NHC
  - For IPv6 base extension headers:

| 1110 | IPv6 Ext Hdr ID (EID) | NH | Uncompressed Fields | Next Hdr |
|---|---|---|---|---|
| 4b | 3b | 1b | | |

NH: 0 = Uncompressed; 1 = LowPAN_NHC encoded

| EID | Header |
|---|---|
| 0 | IPv6 Hop-by-Hop Options |
| 1 | IPv6 Routing |
| 2 | IPv6 Fragment |
| 3 | IPv6 Destination Options |
| 4 | IPv6 Mobility Header |
| 5 | Reserved |
| 6 | Reserved |
| 7 | IPv6 Header |

LowPAN_NHC UDP Header:

| 11110 | C | P |
|---|---|---|
| 5b | 1b | 2b |

C: Checksum omitted

| P | |
|---|---|
| 00 | All 16-bits in line |
| 01 | 1st 8-bits of dest port omitted |
| 10 | 1st 8-bits of src port omitted |
| 11 | 1st 12-bits of src & dest omitted |

Ref: J. Hui and P. Thubert, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks," IETF RFC 6282, Sep 2011, http://tools.ietf.org/pdf/rfc6282



## Student Questions

- So how are those different headers and compressions used? Do they replace each other?

*Headers are extension headers. They are optional. Extension headers are added at the source and remain in the frame.*
*Only one compression method is sufficient. Newer compression methods are better. However, some older nodes may not support newer compression method.*

# 6LowPAN: Summary

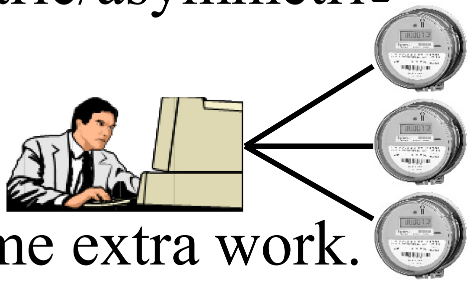
- **3 New Headers**:
  - Mesh addressing: Intermediate addresses
  - Hop-by-Hop: Mesh broadcasts
  - Destination processing: Fragmentation
- **Address Formation**: 128-bit addresses by prefixing FE80::
- **Header compression**:
  - HC1+HC2 header for link-local IPv6 addresses
  - IPHC compression for all IPv6 addresses




**Student Questions**

# Routing Protocol for Low-Power and Lossy Networks (RPL)

- Developed by IETF Routing over Low-Power and Lossy Networks (ROLL) working group
- Low-Power and Lossy Networks (LLN) Routers have constraints on processing, memory, and energy.
  ⇒ Can't use OSPF, OLSR, RIP, AODV, DSR, etc.
- LLN links have high loss rate, low data rates, and instability
  ⇒ expensive bits, dynamically formed topology
- Covers both wireless and wired networks
  Requires **bidirectional** links. May be symmetric/asymmetric data rate.
- Ideal for n-to-1 (**data sink**) communications, e.g., meter reading
  1-to-n (multicast) and 1-to-1 possible with some extra work.



- Multiple LLN instances on the same physical networks

Ref: T. Winder, Ed., et al., "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar 2012, https://datatracker.ietf.org/doc/rfc6550/



## Student Questions

- What does symmetric/asymmetric mean in 4th bullet?

*Symmetric/Asymmetric data rate*

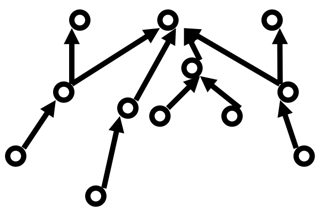
- What would be some uses for the 1 to n capability of RPL?

*1-n is multicast or broadcast*

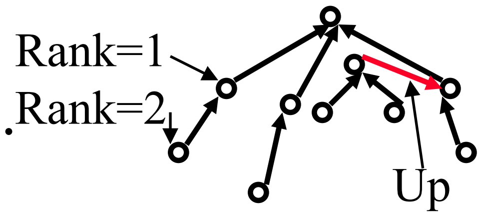
# RPL Concepts

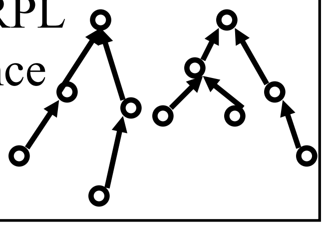
- **Directed Acyclic Graph (DAG)**: No cycles
- **Root**: No outgoing edge
- **Destination-Oriented DAG (DODAG)**: Single root
- **Up**: Towards root
- **Down**: Away from root
- **Objective Function**: Minimize energy, latency, …
- **Rank**: Distance from root using specified objective
- **RPL Instance**: One or more DODAGs. A node may belong to multiple RPL instances.
- **DODAG ID**: IPv6 Adr of the root
- **DODAG Version**: Current version of the DODAG. Every time a new DODAG is computed with the same root, its version incremented.

**DAG**



**DODAG**






## Student Questions

- Are up/down only applicable in DODAG?

*Yes, if there is no root, there is no up or down.*

---

- If a node belongs to multiple RPL instances, how does it decide on its root?

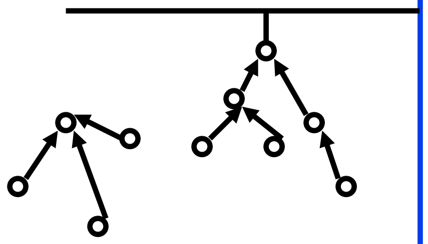
*Instance = Objective Function, e.g., temperature control, humidity control, etc. All DODAGs in one RPL instance share the objective function. A node can belong to at most one DODAG in any RPL instance. All packets contain the instance ID.*

- The distance means latency? num of hops?

*Distance = Cost = Bandwidth/Latency*

# RPL Concepts (Cont)

- **Goal**: Reachability goal, e.g., connected to database
- **Grounded**: Root can satisfy the goal
- **Floating**: Not grounded. Only in-DODAG communication.
- **Parent**: Immediate successor towards the root
- **Sub-DODAG**: Sub tree rooted at this node
- **Storing**: Nodes keep routing tables for sub-DODAG
- **Non-Storing**: Nodes know only parent. Do not keep a routing table.

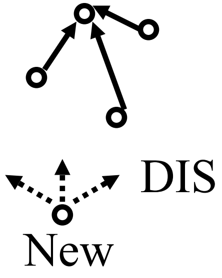


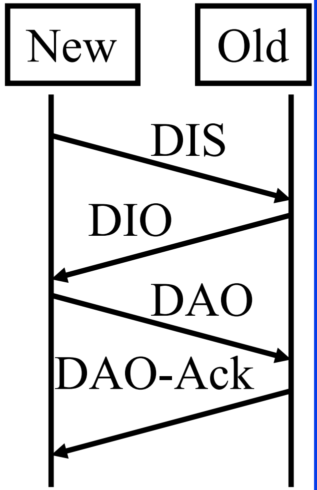
Ref: M. Richardson and I. Robles, "RPL-Routing over Low Power and Lossy Networks," IETF 94 presentation, https://www.ietf.org/proceedings/94/slides/slides-94-rtgarea-2.pdf

## Student Questions

# RPL Control Messages

1. **DODAG Information Object (DIO)**:
   - Downward RPL instance multicasts
   - Allows other nodes to discover an RPL instance and join it
2. **DODAG Information Solicitation (DIS)**:
   - Link-Local multicast request for DIO (neighbor discovery).
     Do you know of any DODAGs?
3. **Destination Advertisement Object (DAO)**:
   - From child to parents or root.
   - Can I join you as a child on DODAG #x?
4. **DAO Ack**: Yes, you can! Or Sorry, you cant!
5. **Consistency Check**: Challenge/response messages for security




Ref: S. Kuryla, "RPL:IPv6 Routing Protocol for Low Power and Lossy Networks,"
http://cnds.eecs.jacobs-university.de/courses/nds-2010/kuryla-rpl.pdf

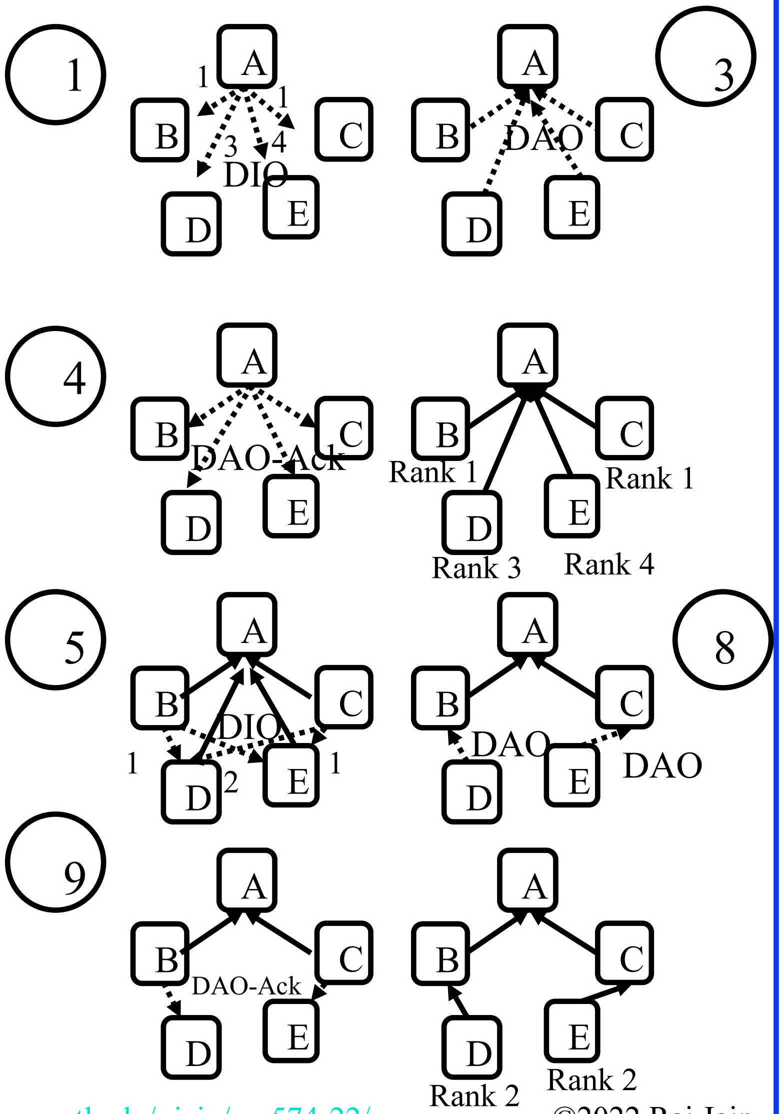
 



## Student Questions

# DODAG Formation Example

1. A multicasts DIOs that it's member of DODAG ID itself with Rank 0.
2. B, C, D, E hear and determine that their rank (distance) is 1, 1, 3, 4, respectively from A
3. B, C, D, E send DAOs to A.
4. A accepts all
5. B and C multicast DIOs
6. D hears those and determines that its distance from B and C is 1, 2
7. E hears both B, C and determines that its distance from B and C is 2, 1
8. D sends a DAO to B
   E sends a DAO to C
9. B sends a DAO-Ack to D
   C sends a DAO-Ack to E




## Student Questions

- ❑ Can we go over the DODAG formation step by step again?

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❑How does a node determine what other node to connect to?

*They listen to multicasts and connect to nodes with the shortest path to the root.*

❑How do they determine which is a parent and which is a child?

*Lower Rank = Parent*

❑How do B, C, D, and E determine their rank or distance?

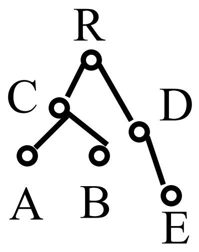
*Rank=Distance from the root.*

❑How could RPL support mobility?

*Original RPL was designed for a non-mobile static environment. There are mobile extensions, e.g., mRPL, MT-RPL, etc.*

# RPL Data Forwarding

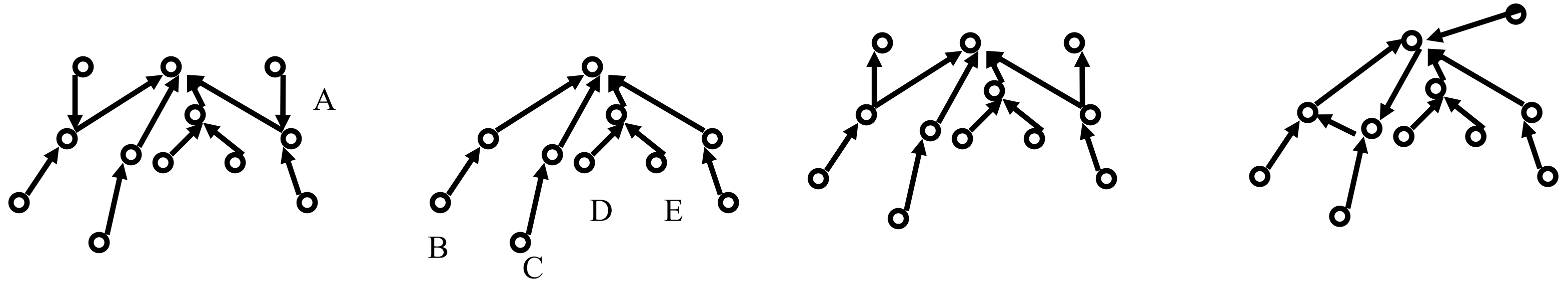
- Case 1: To the root (n-to-1)
  - Address to root and give to parent
- Case 2: A to B
  - 2A: Storing (Everyone keeps a routing table)
    - Forward up from A to common parent
    - Forward down from common parent to B
  - 2B: Non-storing (No routing tables except at root)
    - Forward up from A to root
    - Root puts a source route and forwards down
- Case 2: Broadcast from the root (1-to-n)
  - 2A: Storing (everyone knows their children)
    - Broadcast to children
  - 2B: Non-Storing (Know only parents but not children)
    - Root puts a source route for each leaf and forwards




**Student Questions**

# Homework 14B

- A. Which of the following is not a DODAG and why?
- B. What is the direction of Link A? (Up or Down):
- C. Assuming each link has a distance of 1, what is the rank of node B?
- D. Show the paths from B to C if the DODAG is non-storing.
- E. Show the paths from D to E if the DODAG is storing.



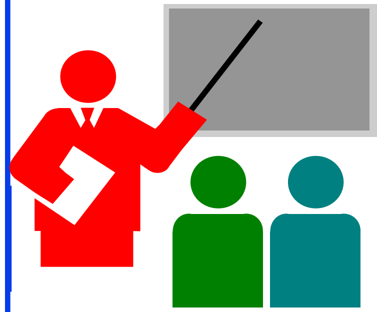





## Student Questions

- How would DODAG formation prevent loops like the one on the far right?

*The process shown in Slide 14-21 will prevent this situation. This is not a DODAG because it is not acyclic.*

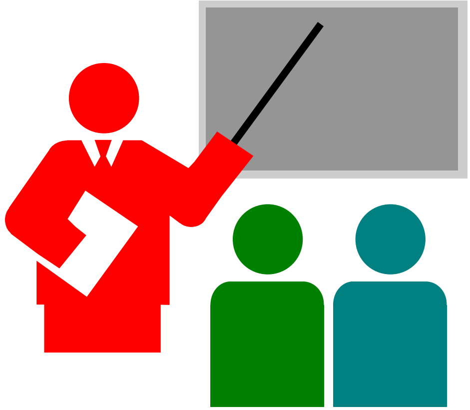


# RPL Summary

1. An RPL instance consists of one or more DODAGs
2. DIO are broadcast downward,
   DAOs are requests to join upward
   DIS are DIO solicitations
   DAO-ack are responses to DAO
3. Non-storing nodes do not keep any routing table and send everything upwards toward the root

**Student Questions**

# Summary



1. 6LowPAN is designed for IPv6 over IEEE 802.15.4
   Frame size and address sizes are primary issues
   Header compression is the key mechanism
2. RPL is designed primarily for data collection
   No assumption about IEEE 802.15.4 or wireless or frame size
   Routing is the primary issue
   Forming a spanning tree like DODAG is the solution





## Student Questions

# Reading List

- O. Hersent, et al., “The Internet of Things: Key Applications and Protocols,” Wiley, 2013, 344 pp., ISBN: 9781119994350 (Safari Book)
- G. Montenegro, et al., “Transmission of IPv6 Packets over IEEE 802.15.4 Networks,” RFC 4944, Sep 2007, http://tools.ietf.org/pdf/rfc4944
- J. Hui and P. Thubert, “Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks,” IETF RFC 6282, Sep 2011, http://tools.ietf.org/pdf/rfc6282
- T. Winder, Ed., et al., "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar 2012, https://datatracker.ietf.org/doc/rfc6550/
- S. Kuryla, “RPL: IPv6 Routing Protocol for Low Power and Lossy Networks,” http://cnds.eecs.jacobs-university.de/courses/nds-2010/kuryla-rpl.pdf

## Student Questions

# Wikipedia Links

- http://en.wikipedia.org/wiki/6LoWPAN
- http://en.wikipedia.org/wiki/IEEE_802.15.4
- http://en.wikipedia.org/wiki/MAC_address
- http://en.wikipedia.org/wiki/IPv6
- http://en.wikipedia.org/wiki/IPv6_address
- http://en.wikipedia.org/wiki/Organizationally_unique_identifier
- http://en.wikipedia.org/wiki/IPv6_packet
- http://en.wikipedia.org/wiki/Link-local_address

**Student Questions**

# References


- N. Kushalnagar, et al., "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals", IETF RFC 4919, Aug 2007, http://www.rfc-editor.org/rfc/pdfrfc/rfc4919.txt.pdf
- G. Montenegro, N. Kushalnagar, J. Hui, D. Culler, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks," IETF RFC 4944, https://tools.ietf.org/pdf/rfc4944
- J. Hui, Ed., P. Thubert, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks," IETF RFC 6282, Sept 2011, https://tools.ietf.org/html/rfc6282
- E. Kim, et al., "Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)," IETF RFC 6568, Apr 2012, http://www.rfc-editor.org/rfc/pdfrfc/rfc6568.txt.pdf
- E. Kim, et al., "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing," IETF RFC 6606, May 2012, http://www.rfc-editor.org/rfc/pdfrfc/rfc6606.txt.pdf
- Z. Shelby, et al., "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs), IETF RFC 6775, Nov. 2012, http://www.rfc-editor.org/rfc/pdfrfc/rfc6775.txt.pdf





**Student Questions**

# References (Cont)


- "Routing Requirements for Urban Low-Power and Lossy Networks," IETF RFC 5548, May 2009, https://datatracker.ietf.org/doc/rfc5548/
- "Industrial Routing Requirements in Low-Power and Lossy Networks," IETF RFC 5673, Oct 2009, https://datatracker.ietf.org/doc/rfc5673/
- "Home Automation Routing Requirements in Low-Power and Lossy Networks," IETF RFC 5826, Apr 2010, https://datatracker.ietf.org/doc/rfc5826/
- "Building Automation Routing Requirements in Low-Power and Lossy Networks," IETF RFC 5867, Jun 2010, https://datatracker.ietf.org/doc/rfc5867/
- "The Trickle Algorithm," IETF RFC 6206, Mar 2011, https://datatracker.ietf.org/doc/rfc6206/
- "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar 2012, https://datatracker.ietf.org/doc/rfc6550/
- "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks," IETF RFC 6551, Mar 2012, https://datatracker.ietf.org/doc/rfc6551/
- "Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)," IETF RFC 6552, Mar 2012, https://datatracker.ietf.org/doc/rfc6552/


**Student Questions**

# References (Cont)


- "The Minimum Rank with Hysteresis Objective Function," IETF RFC 6719, Sep 2012, https://datatracker.ietf.org/doc/rfc6719/
- "Reactive Discovery of Point-to-Point Routes in Low-Power and Lossy Networks," IETF RFC 6997, Aug 2013, https://datatracker.ietf.org/doc/rfc6997/
- "A Mechanism to Measure the Routing Metrics along a Point-to-Point Route in a Low-Power and Lossy Network," IETF RFC 6998, Aug 2013, https://datatracker.ietf.org/doc/rfc6998/


**Student Questions**

# Acronyms

| | |
|---|---|
| 6LowPAN | IPv6 over Low Power Wireless Personal Area Network |
| AODV | Ad-hoc On-demand Distance Vector |
| AQMP | Advanced Queueing Message Protocol |
| ARC-EM4 | Name of a product |
| ARM | Acorn RISC Machine |
| CC | Consistency Check |
| CID | Context ID |
| CoAP | Constrained Application Protocol |
| CoRE | Constrained Restful Environment |
| DA | Destination Address |
| DAC | Destination Address Compression |
| DAG | Directed Acyclic Graph |
| DAM | Destination Address Mode |
| DAO | DODAG Advertisement Object |
| DCI | Destination Context ID |
| DDS | Data Distribution Service |





**Student Questions**

# Acronyms (Cont)

| | | |
|---|---|---|
| ❑ | DECT | Digital Enhanced Cordless Telecommunication |
| ❑ | DIO | DODAG Information Object |
| ❑ | DIS | DODAG Information Solicitation |
| ❑ | DODAG | Destination Oriented Directed Acyclic Graph |
| ❑ | DSCP | Differentiated Services Control Point |
| ❑ | DSR | Dynamic Source Routing |
| ❑ | DTLS | Datagram Transport Level Security |
| ❑ | ECN | Explicit Congestion Notification |
| ❑ | EID | IPv6 Extension Header ID |
| ❑ | EUI | Extended Unique Id |
| ❑ | GP | GreenPHY |
| ❑ | HC | Header Compression |
| ❑ | HC1-HC2 | Header Compression 1 and Header Compression 2 |
| ❑ | ICMP | IP Control Message Protocol |
| ❑ | ID | Identifier |
| ❑ | IEEE | Institution of Electrical and Electronic Engineers |

**Student Questions**

# Acronyms (Cont)

- IETF Internet Engineering Task Force
- IID Interface Identifier
- IoT Internet of Things
- IP Internet Protocol
- IPHC IP Header Compression
- IPv6 Internet Protocol Version 6
- ISASecure Security certification by
- LLN Low-Power and Lossy Networks
- LoRaWAN Long Range Wide Area Network
- LTE Long-Term Evolution
- MAC Media Access Control
- MTU Maximum Transmission Unit
- NFC Near Field Communication
- NH Next Header
- NHC Next Header Compression
- OLSR On-Demand Link State Routing

## Student Questions

# Acronyms (Cont)

| | |
|---|---|
| OSPF | Open Shortest Path Forwarding |
| PAN | Personal Area Network |
| RFC | Request for Comments |
| RIP | Routing Information Protocol |
| ROLL | Routing over Low-Power and Lossy Networks |
| RPL | Routing Protocol for Low-Power and Lossy Networks |
| SA | Source Address |
| SAC | Source Address Compression |
| SAM | Source Address Mode |
| SASL | Simple Authentication and Security Layer |
| SCI | Source Context ID |
| SMACK | Simplified Mandatory Access Control Kernel |
| TCG | Trusted Computing Group |
| TCP | Transmission Control Protocol |
| TF | Traffic Class, Flow Label |
| TinyOS | Tiny Operating System |





**Student Questions**

# Acronyms (Cont)

- UDP User Datagram Protocol
- ULE Ultra Low Energy
- Wi-Fi Wireless Fidelity
- WirelessHART Wireless Highway Addressable Remote Transducer Protocol
- WPAN Wireless Personal Area Network

**Student Questions**

# Little Endians vs. Big Endians

- Endianness = **B**yte order in a word
- Question 1: How should we write 16,909,060?
  - Answer: $16{,}909{,}060 = 1\times2^{24}+2\times2^{16}+3\times2^{8}+4$

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 4 |

- Question 2: How should we **store bytes in a word** in the memory?
  - Answer 2A:

| | | | |
|---|---|---|---|
| Byte 0 | Byte 1 | Byte 2 | Byte 3 |
| 4 | 3 | 2 | 1 |

  - Answer 2B:

| | | | |
|---|---|---|---|
| Byte 3 | Byte 2 | Byte 1 | Byte 0 |
| 1 | 2 | 3 | 4 |

- Two tribes (Machine Architectures):
  - Big Endians: Most Significant Byte (MSB) first
  - Little Endians: Least Significant Byte (LSB) first

Ref: Raj Jain, "FDDI Handbook: High Speed Networking with Fiber and Other Media," Addison Wesley, Reading, MA April 1994





## Student Questions

# little endians vs. big endians

- endianness = bit order in a Byte
- Question: How should be write $11_{10}$?
- Answer: $11_{10} = B_{16} = 1011_2$
- Question 3: How should we **store bits in a byte** in the memory?
- Answer 3A:

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bit 0 | bit 1 | bit 2 | bit 3 | bit 4 | bit 5 | bit 6 | bit 7 | 1 | 1 | 0 | 1 | … |

- Answer 3B:

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bit 7 | bit 6 | bit 5 | bit 4 | bit 3 | bit 2 | bit 1 | bit 0 | … | 1 | 0 | 1 | 1 |

  - big endians: most significant bit (msb) first
  - little endians: least significant bit (lsb) first

Ref: https://en.wikipedia.org/wiki/Endianness

## Student Questions

# little endians vs. big endians

- Both tribes lived peacefully until they were “networked”
- Networking folks started arguing in IEEE 802 around 1979-80.
- Question 4: How should we **transmit** $11_{10}$ on the wire?
  - Answer 4A:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| bit 0 | bit 1 | bit 2 | bit 3 | bit 4 | bit 5 | bit 6 | bit 7 |

  - Answer 4B:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| bit 7 | bit 6 | bit 5 | bit 4 | bit 3 | bit 2 | bit 1 | bit 0 |

- **Agreement**:
  - MSB, msb on the wire. Store as you like in your computer.
- Question 5: How do we **write the addresses** on paper?
  - lsb use dashes: xx-xx-xx-xx-xx-xx
  - msb use colon: xx:xx:xx:xx:xx
  - Most people are unaware of this notation and use : and – interchangeably and msb is first always.





**Student Questions**

# IPv6

- Colon-Hex Notation: Eight 16-bit words
  FEDC:0000:0000:0000:3243:0000:0000:ABCD
  - Can skip leading zeros of each word
  - Can skip one sequence of zero words, e.g.,
    FEDC::3243:0000:0000:ABCD
    ::3243:0000:0000:ABCD
- Network Prefix: First 64-bit are network address, last 64-bit are host address
- Local Addresses: Provide plug and play
  - Link Local: FE80::xxxx
  - Site Local: FEC0::xxxx

Raj **V6 9IPv6),"** Introduction to Computer Networking, Course Lecture, WUSTL 2005, http://www.cse.wustl.edu/~jain/cse473-05/i_eip6.htm



## Student Questions

- Can you go over point 1?

# IPv6 (Cont)

- IPv6 header has no optional fields.
  - Fields were divided in to groups
  - One group is required (base header)
  - Other groups may or may not be present (Extension headers)
  - All headers have fixed format

| Base Header | Extension Header 1 | ---- | Extension Header *n* | Data |
| --- | --- | --- | --- | --- |

- Extension Headers: Most extension headers are examined only at the destination
- Examples: Fragmentation Header, Routing Header (path routing), …

Raj **V6 9IPv6),”** Introduction to Computer Networking, Course Lecture, WUSTL 2005, http://www.cse.wustl.edu/~jain/cse473-05/i_eip6.htm

## Student Questions

# Scan This to Download These Slides


Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-22/j_14lpn.htm





## Student Questions

# Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw





## Student Questions