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/cse574-24/

Student Questions

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Next Q 9



- 6LowPAN
  - Adaptation Layer
  - Address Formation
  - Compression
- RPL
  - RPL Concepts
  - RPL Control Messages
  - RPL Data Forwarding
- Note 1: This is part 3 of a series of class lectures on IoT.
- Note 2: If you are unfamiliar with IPv6, please watch our CSE473 class video on IPv6 first. It is at http://www.cse.wustl.edu/~jain/cse473-24/ftp/i_4nld3/i_4nld3.html

Student Questions

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Recent Protocols for IoT

		Security	Management
Session	MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC, IEEE 1888, …	IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …	IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856
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, …		

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

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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

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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

- Does U-bit formatted just mean the version of the address where Local=0? So the U-bit format of an EUI address would just flip the second bit?

Yes.

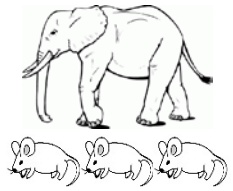
- Some of them were not updated in time may cause misunderstanding right?

I am not aware of the issue.

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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



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.

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

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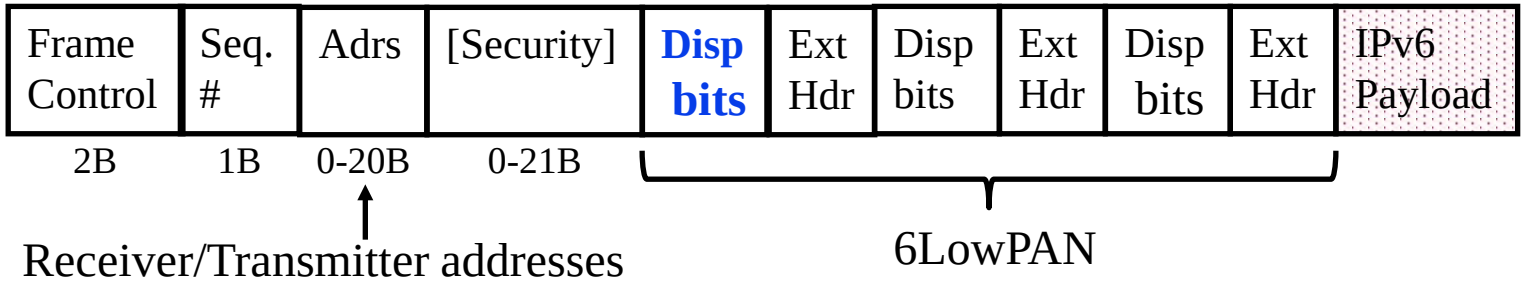
Student Questions

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

See 7 issues in this slide and next.

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**



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

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Student Questions

- What is the reason behind 6LowPAN Header compression?

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

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**.
  1st bit of Short address and PAN ID is Unicast/Multicast
  The 2nd 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.
  2nd bit of PAN ID should always be zero since it is always local.
  2nd most significant = 6th 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.

- 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.

- 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.

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Student Questions

- In the review question U-bit formatted EUI64 addresses were designed by IEEE, I thought it is defined by IETF, but when I select false it says wrong, am I misunderstand or the answer were wrong?

The quiz answer was wrong. We will manually correct the grading.

- If the IPv6 Link address example was universal, would it have been 1111111010000000::11?

No.

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IPv6 Address Formation

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  2nd most significant = 6th bit from right)

Student Questions

- When two separate LR-WPAN networks with identical PAN IDs enter each others vicinity, which will change their PAN ID?

Vicinity ≠ join

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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?

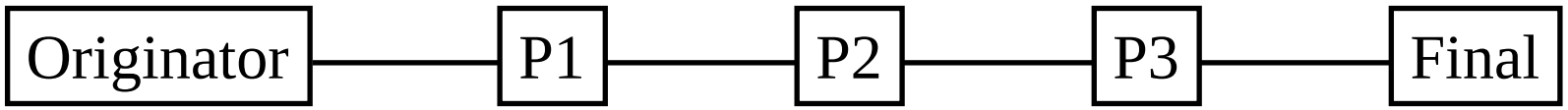
Sure.

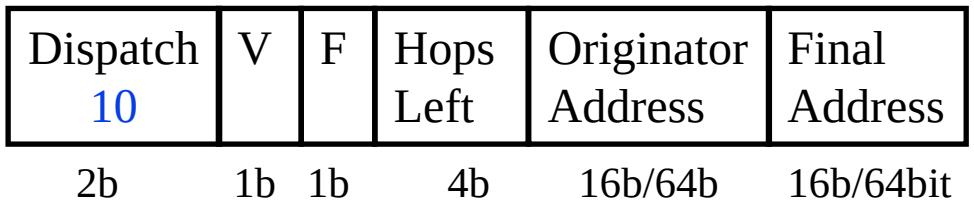
❖Can we go over the homework 14A?

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





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.

- 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.

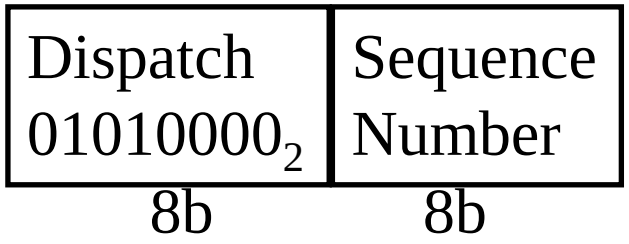
- How is the dispatch header used to identify different types of messages, such as those for mesh addressing?

Dispatch is10 iff mesh. Other values are used for other types of messages.

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6LowPAN Broadcast Header

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

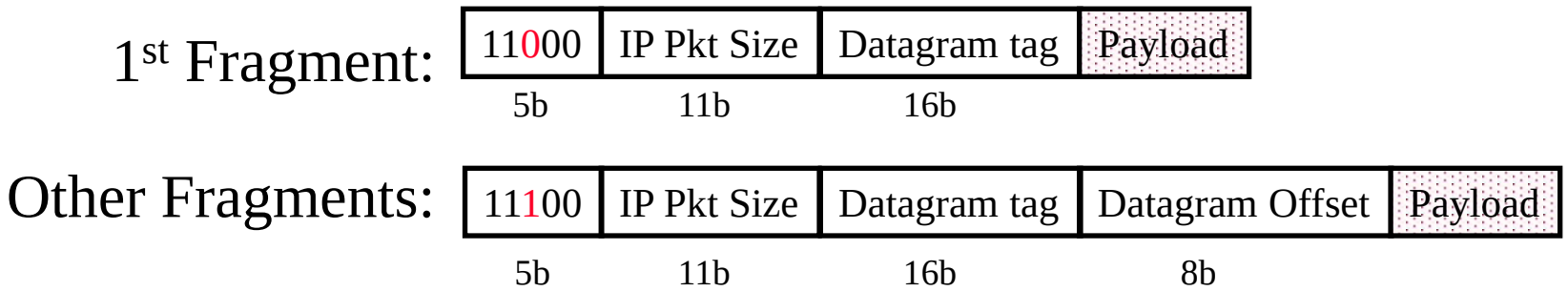


Student Questions

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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



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

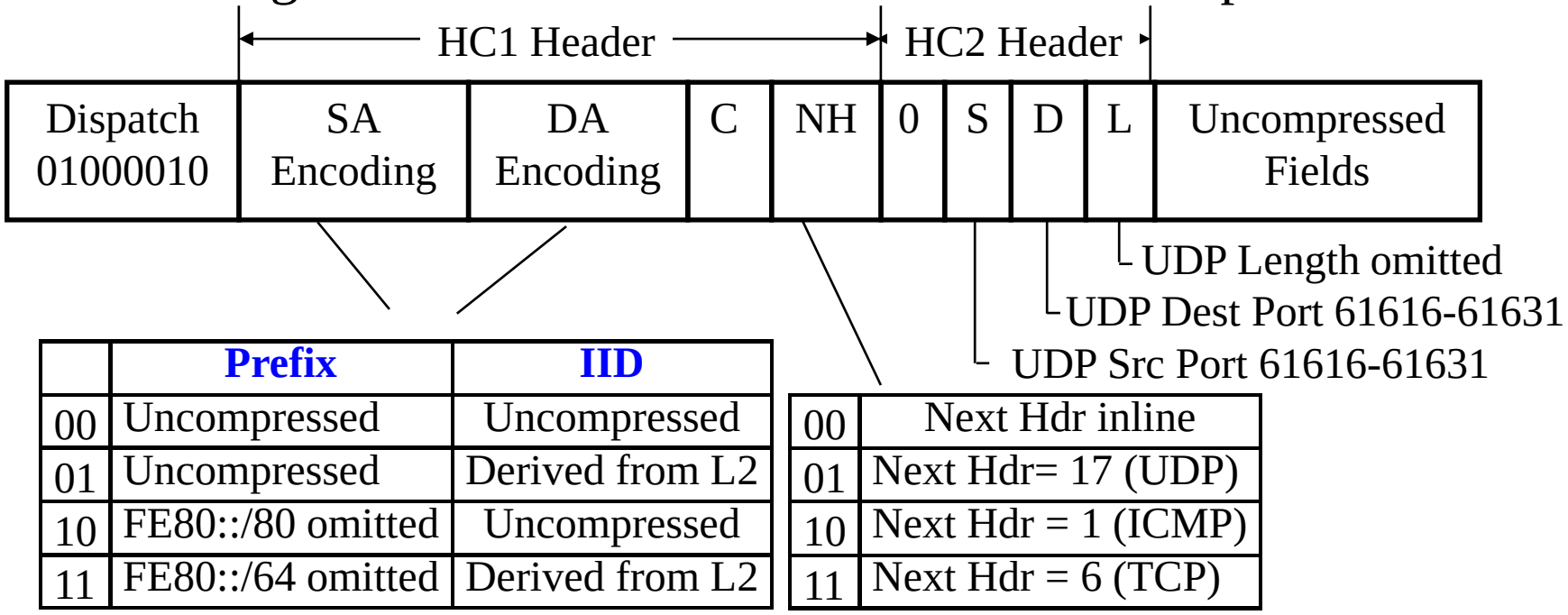
- If there is a datagram tag present already in the header, can the fragments not be put into the correct order based on the sequence number alone? Will it just increase the computational overhead a lot?

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

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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.



	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

- 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.

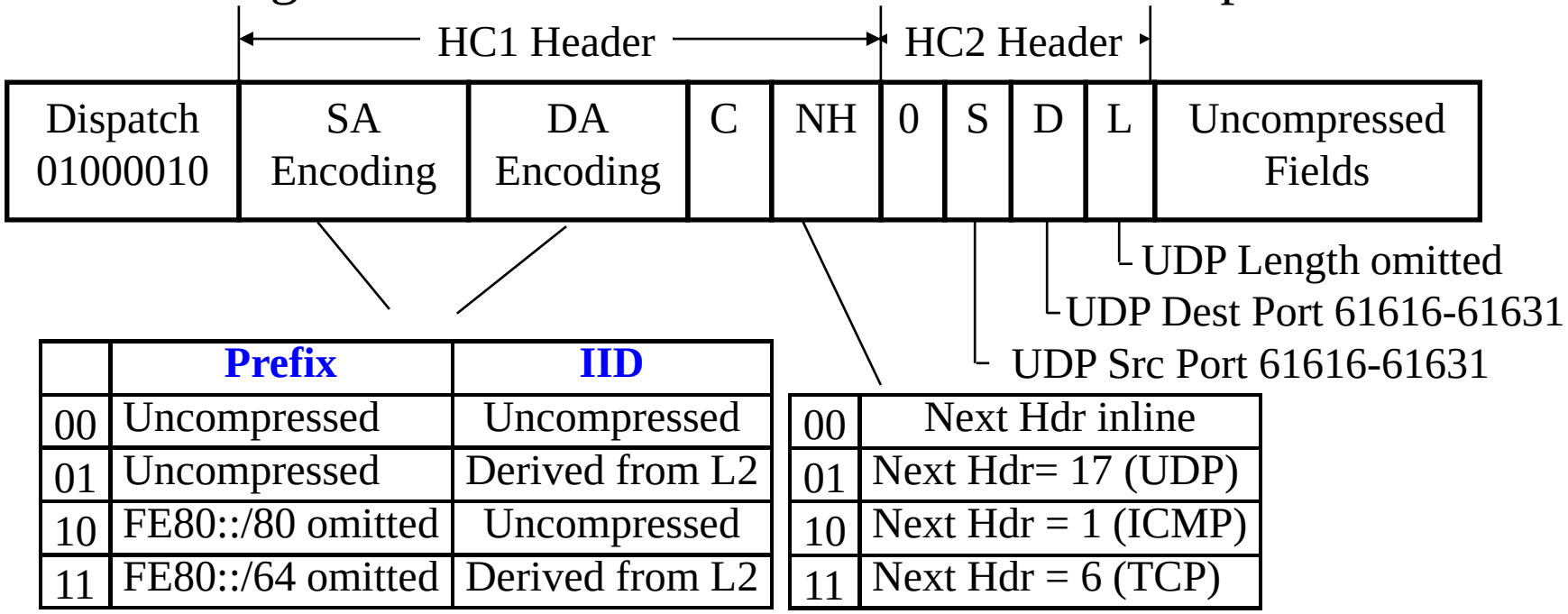
- Does the length of each part of the header change when there is/is not compressing, or it remains the same except for the uncompressed part in the end?

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

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IP+UDP Header Compression: Stateless

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Student Questions

- Why is the HC1-HC2 Header Compression called "Stateless"?

State=information about previous messages.

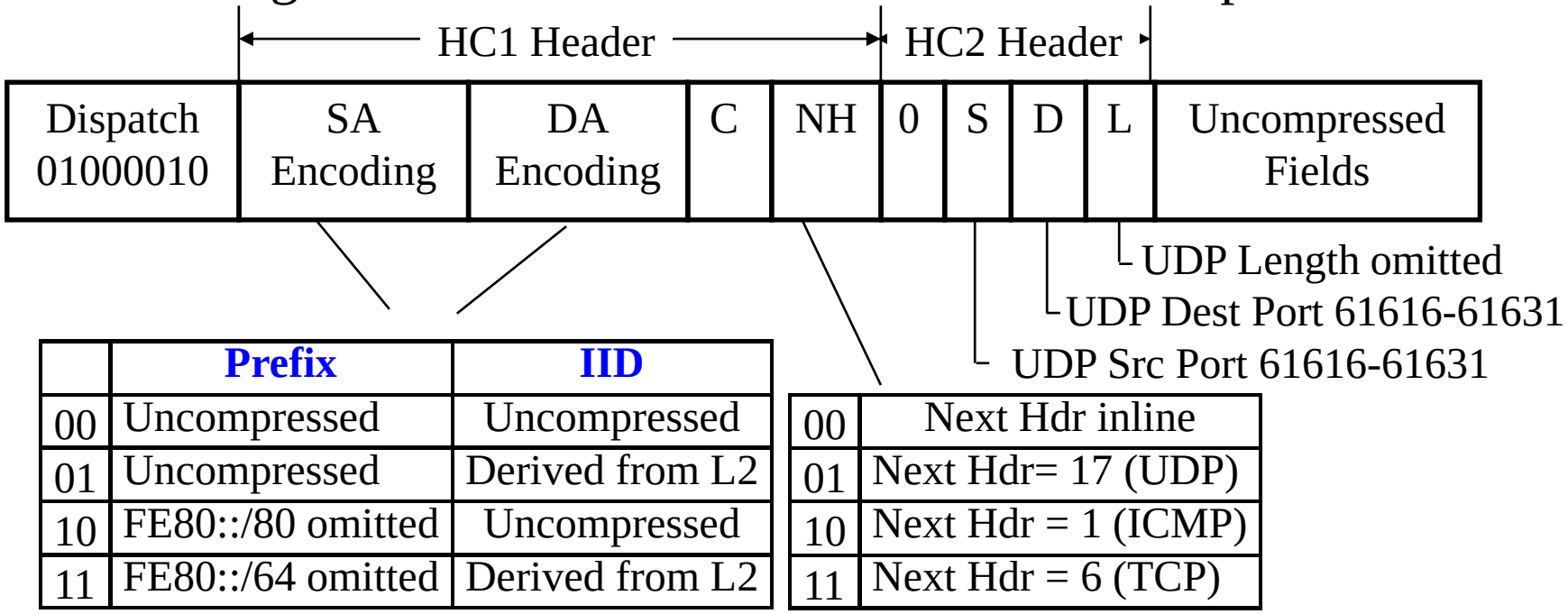
- Can you explain one more time that why HC1-HC2 compression is not recommended? Will it be asked in the exam if its not recommended?

It is not recommended because context-based is better. However, it is still used if a device cannot maintain state. Yes, it may be asked in the exam.

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IP+UDP Header Compression: Stateless

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- IP version field is omitted
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Student Questions

- In the video, it is mentioned that S, D, and L in the HC2 Header are each 1 bit long. How can S and D represent the port range 61616-61631 using only 1 bit?

S, D, L are not addresses. They are flags that indicate something about the addresses.

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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	

Traffic Class, **F**low Label

Next Header uses LowPAN_NHC

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

Source Adr Mode

Source Adr Compression

Multicast Destination

Source/Dest Context IDs if CID=1

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

Student Questions

- What is the CID?

Context ID

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

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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		

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

Checksum omitted

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

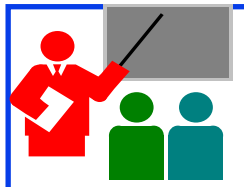
Ref: J. Hui and P. Thubert, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks," IETF RFC 6282, Sep 2011, http://tools.ietf.org/pdf/rfc6282

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.

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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

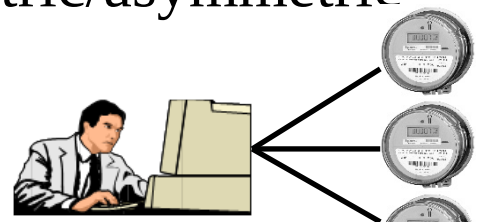
Student Questions

- For 6LoWPAN: are all three headers present in a packet? Or does it depend on the type of message being sent?

Only those headers that are required are present.

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/

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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

- Apart from meter reading, what are some real-world use cases for LLNs?

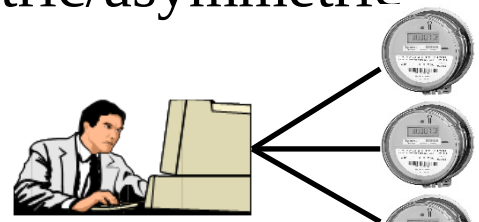
Any data gathering application, e.g., rain in an area.

- What does expensive bit mean? Is it just the energy per bit is expensive relative to the low-power networks?

Low data rate requires that you send only essential information.

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

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Student Questions

- Why RPL requires bidirectional links?

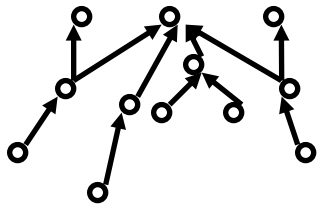
Request-response needs bidirectional links.

Next Q 18b

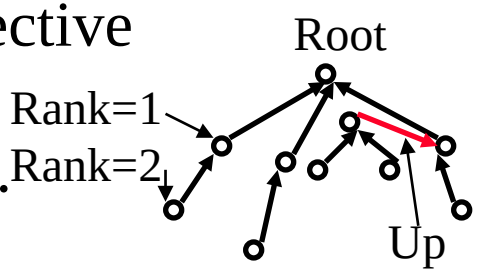
RPL Concepts

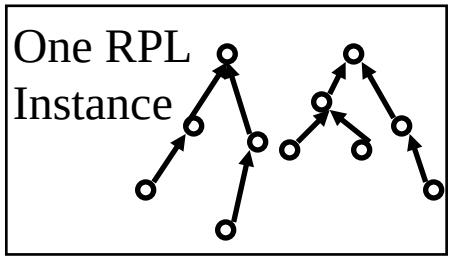
- **Directed Acyclic Graph (DAG)**: No cycles
- **Root**: No outgoing edge
- **Destination-Oriented DAG (DODAG)**: Single root
- **Up**: Towards root
- **Down**: Away from root
- **Objective Function**: Minimize energy, latency, …
- **Rank**: Distance from root using specified objective
- **RPL Instance**: 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

- DODAG version isn't some global version (like IPv6) but is a version that starts counting for each RPL network correct? If so, does it start at 1?

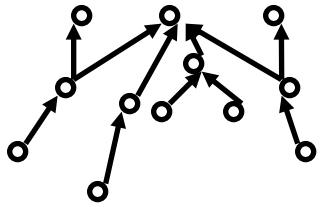
Yes, It is for small number of nodes. Yes, hop distance always starts at 1-hop.

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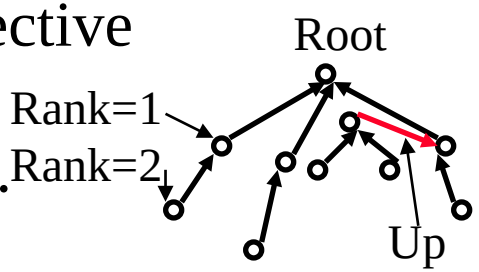
RPL Concepts

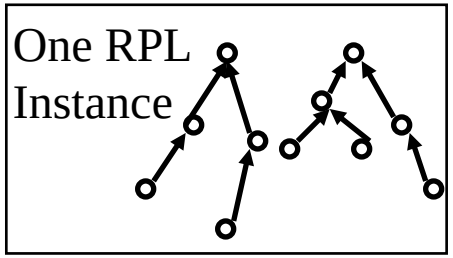
- **Directed Acyclic Graph (DAG)**: No cycles
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- **Destination-Oriented DAG (DODAG)**: Single root
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- **Down**: Away from root
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- **DODAG ID**: IPv6 Adr of the root
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DAG



DODAG





Student Questions

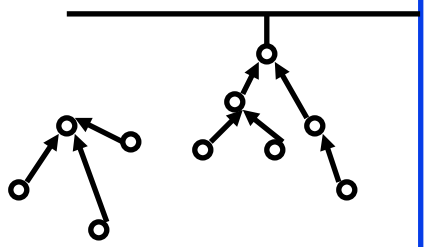
- Can you only have "up" and "down" with DODAG? Or can you describe nodes in this way with regular DAG as well?

In a DAG with multiple destinations, a link may be both up for done destination and down for another.

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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.



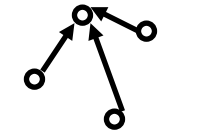
Ref: M. Richardson and I. Robles, "RPL-Routing over Low Power and Lossy Networks," IETF 94 presentation, https://www.ietf.org/proceedings/94/slides/slides-94-rtgarea-2.pdf

Student Questions

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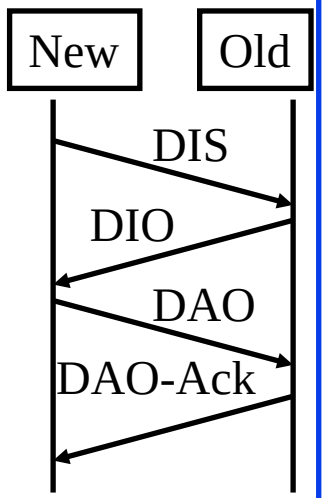
RPL Control Messages

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



DIS

New



Student Questions

- ❑Does the DAO broadcast periodically?

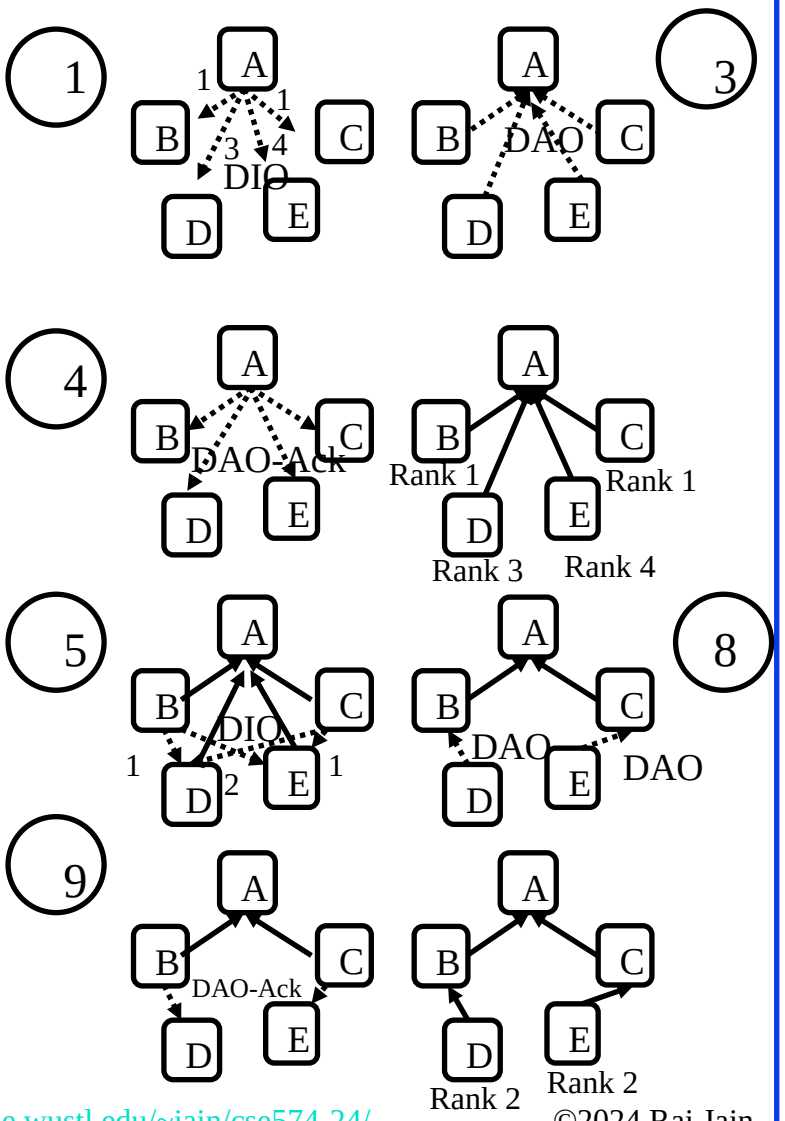
No, DAO is only sent when there is no parent, or they are looking for a better parent.

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

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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?
- ❑ 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?

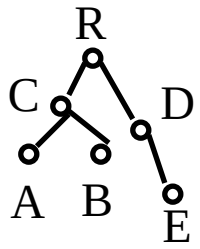
Rank=Distance from the root.

- ❑ 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

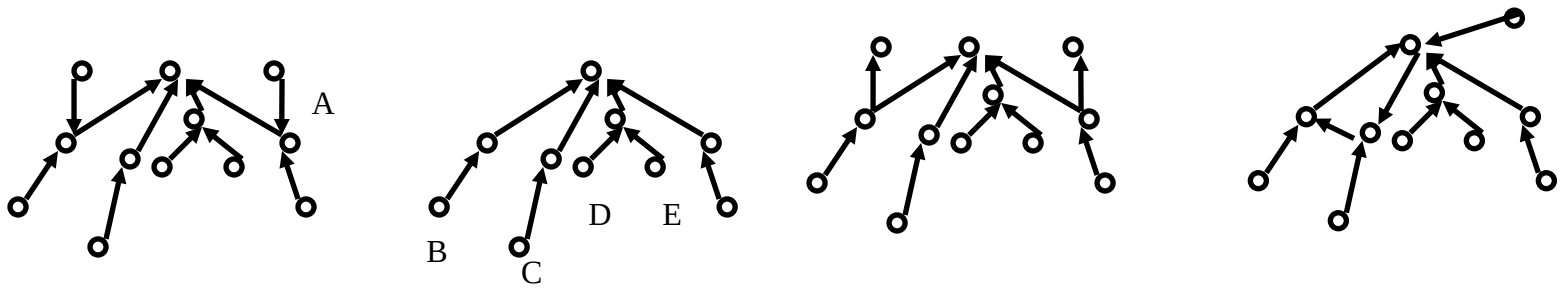


Student Questions

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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.

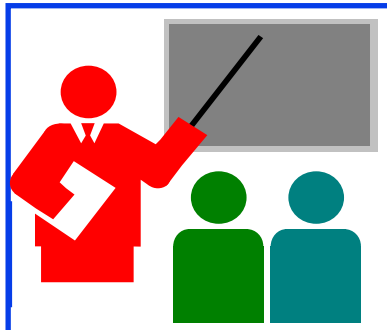


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- How would DODAG formation prevent loops like the one on the far right?

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

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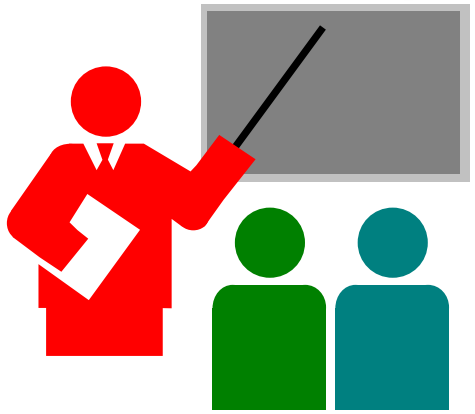
RPL Summary

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

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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

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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

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- 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

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- "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/

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- "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/

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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

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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

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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

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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

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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

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Little Endians vs. Big Endians

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

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

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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

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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:xx
  - Most people are unaware of this notation and use : and – interchangeably and msb is first always.

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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

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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



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

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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-24/j_14lpn.htm

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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

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