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/cse570-21/

Student Questions

Overview

- 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.

Recent Protocols for IoT

Session	MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC, IEEE 1888, …	**Security**	**Management**
Network	Encapsulation 6LowPAN, 6TiSCH, 6Lo, Thread… Routing RPL, CORPL, CARP	IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …	IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856
Datalink	WiFi, 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, …		

Student Questions

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

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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 WiFi 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

❑ More details in CSE 574 wireless networking course
http://www.cse.wustl.edu/~jain/cse574-14/index.html

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)
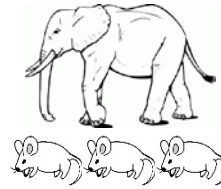 ⇒ U-bit formatted EUI64 addresses

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

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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

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.

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

Student Questions

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							

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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 (assigned by local admin).

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Homework 12A

❑ [8 points] 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 =

Mesh Addressing Header

❑ Dispatch $= 10_2$ (2 bits) $\Rightarrow$ Mesh Addressing Header

❑ MAC header contains per-hop source and destination

❑ Original source and destination addresses are saved in Mesh addressing header

❑ A 4-bit hops-left field is decremented at each hop

| Originator | — | P1 | — | P2 | — | P3 | — | Final |
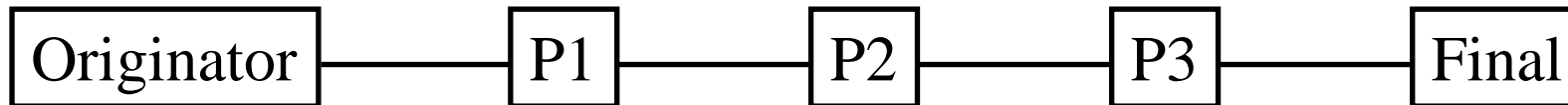
Dispatch 10	V	F	Hops Left	Originator Address	Final Address
2b	1b	1b	4b	16b/64b	16b/64bit

V=0 $\Rightarrow$ Originator address is EUI64, V=1 $\Rightarrow$ 16bit

F=0 $\Rightarrow$ Final address is EUI64, F=1 $\Rightarrow$ 16-bit

6LowPAN Broadcast Header

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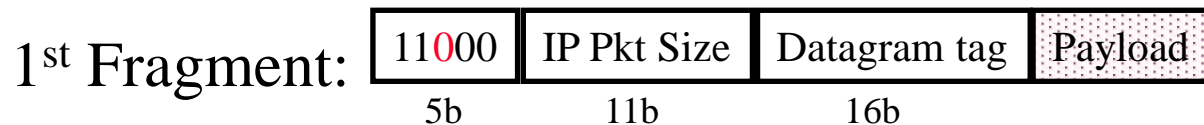❏ A new sequence number is put in every broadcast message by the originator

Dispatch 01010000_2	Sequence Number
8b	8b

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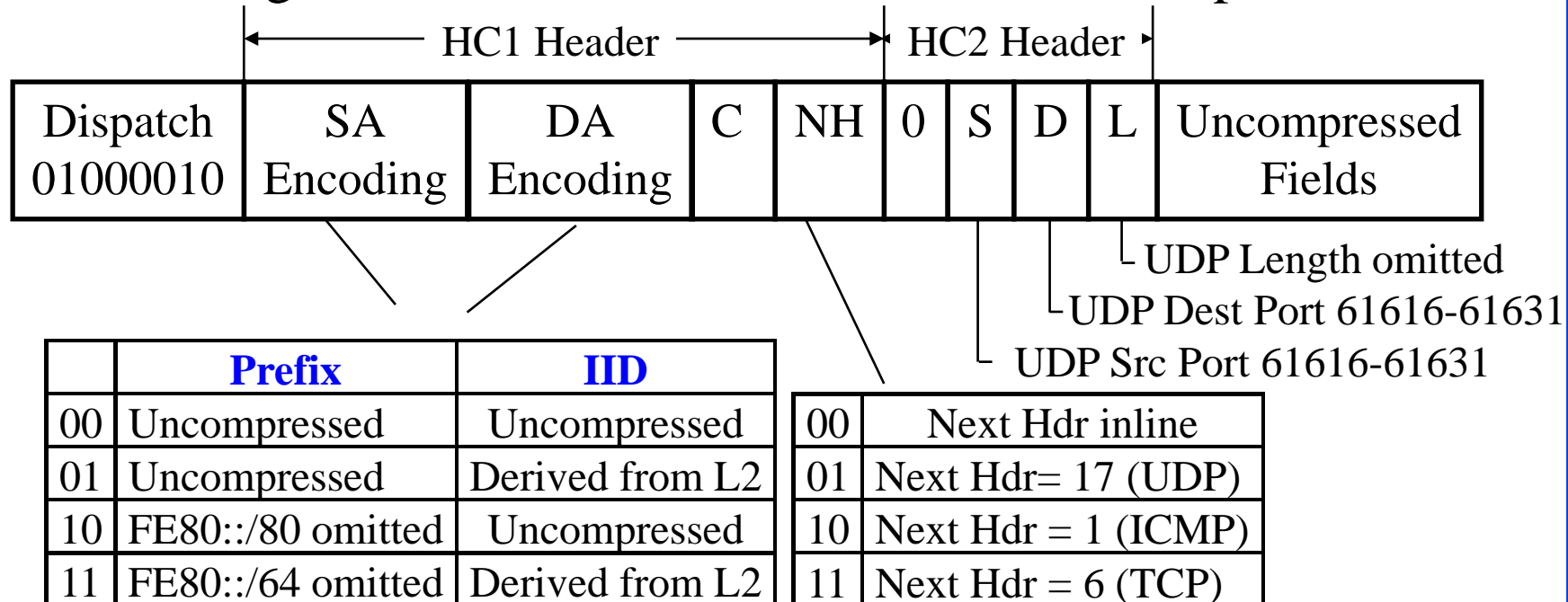©2021 Raj Jain
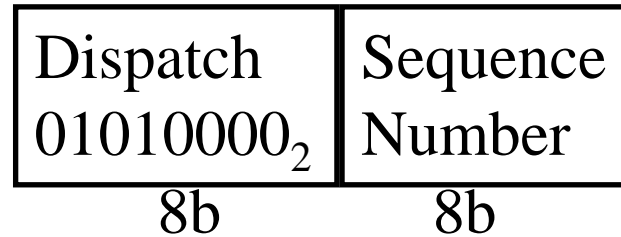
6LowPAN Fragment Header

❑ Dispatch = 11x00 (5 bits) $\Rightarrow$ Fragment Header

❑ Full packet size in the first fragment's fragment header

❑ Datagram tag = sequence number
  $\Rightarrow$ 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	

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 (F0Bx)
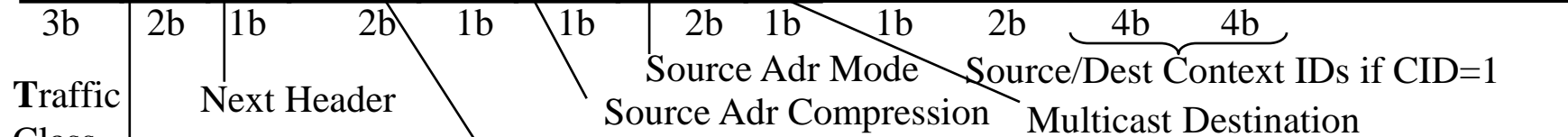- UDP length field is omitted. IP addresses are compressed.

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

HC1 Header ← SA Encoding ... NH → HC2 Header → 0 S D L

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

	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

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, Flow Label

Next Header uses LowPAN_NHC

Source Adr Mode

Source Adr Compression

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

Source/Dest Context IDs if CID=1

Multicast Destination

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

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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		
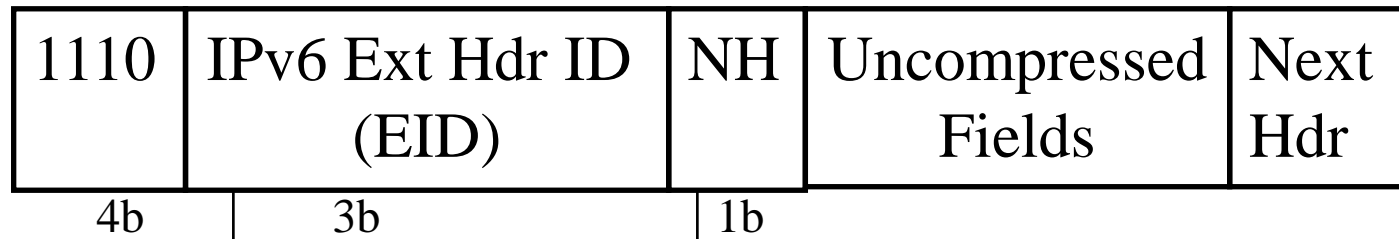
0 = Uncompressed
1 = LowPAN_NHC encoded

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:
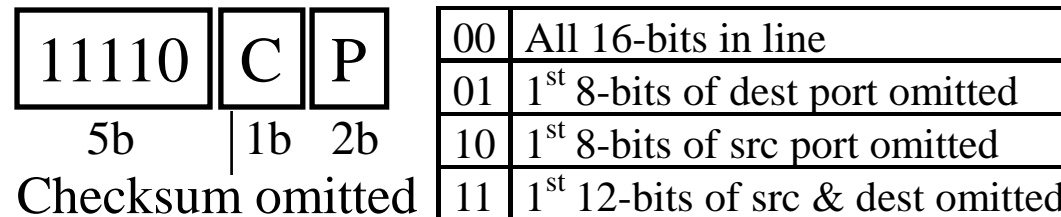
11110	C	P
5b	1b	2b

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

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.
   $\Rightarrow$ Can't use OSPF, OLSR, RIP, AODV, DSR, etc

❑ LLN links have high loss rate, low data rates, and instability
   $\Rightarrow$ expensive bits, dynamically formed topology

❑ Covers both wireless and wired networks
   Requires **bidirectional** links. May be symmetric/asymmetric

❑ Ideal for n-to-1 (**data sink**) communications,
   e.g., meter reading
   1-to-n and 1-to-1 possible with some extra work.

❑ Multiple LLN instances on the same physical networks
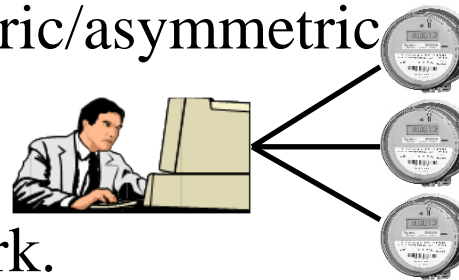
Ref: T. Winder, Ed., et al., "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar 2012,
https://ietf.org/doc/rfc6550/

Student Questions

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

Root

Rank=1

Rank=2

Up

One RPL Instance

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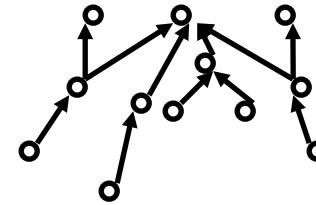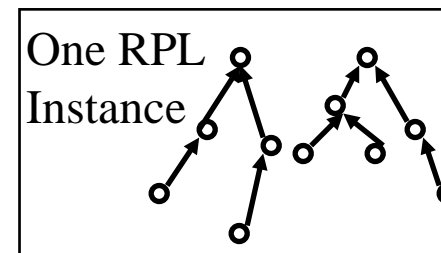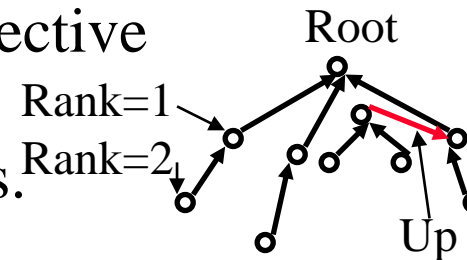
RPL Concepts (Cont)

❑ **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.
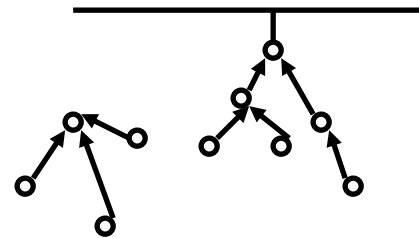
Student Questions

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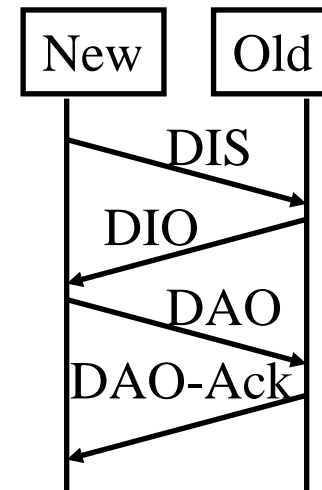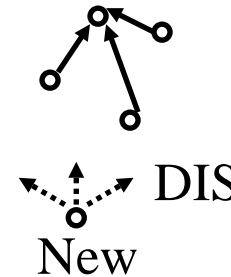
Ref: S. Kuryla, "RPL:IPv6 Routing Protocol for Low Power and Lossy Networks,"
http://cnds.eecs.jacobs-university.de/courses/nds-2010/kuryla-rpl.pdf

Student Questions

DIS
New

| New | Old |

DIS
DIO
DAO
DAO-Ack

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

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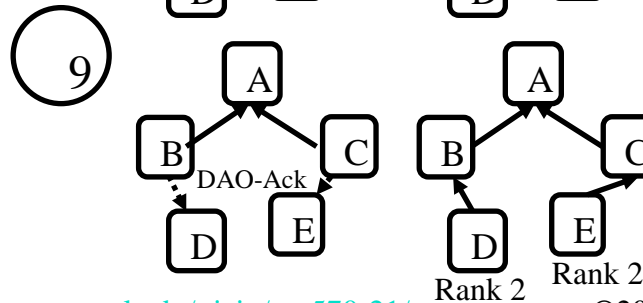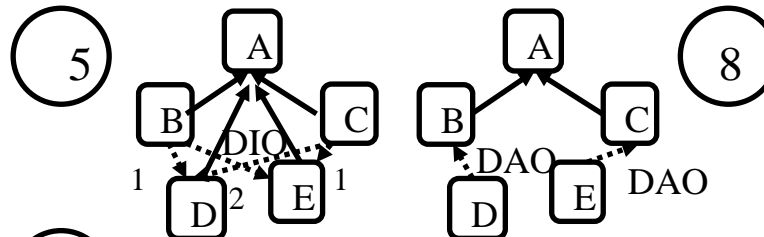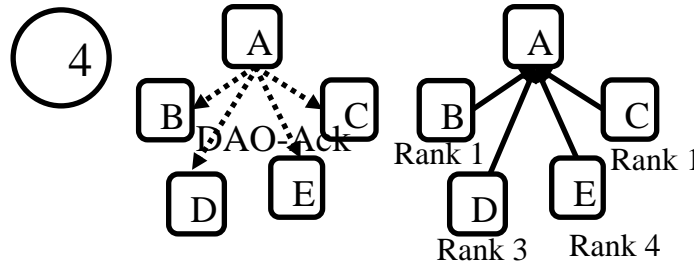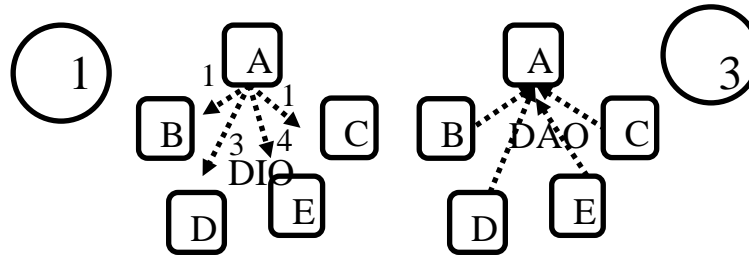
RPL Data Forwarding

❑ 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
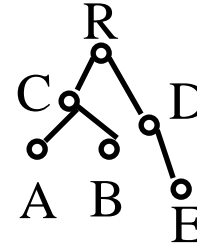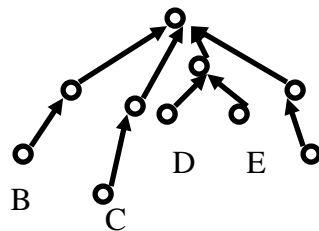
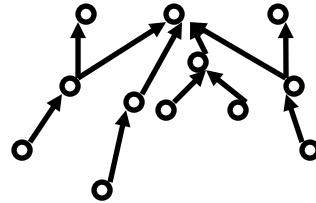**Student Questions**

Homework 12B

[10 points]

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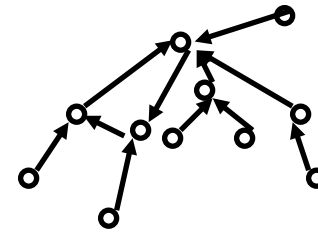5. Show the paths from D to E if the DODAG is storing.
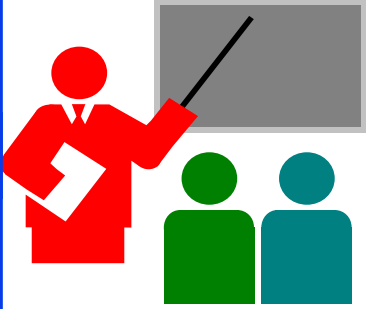

(a)   (b)   (c)   (d)

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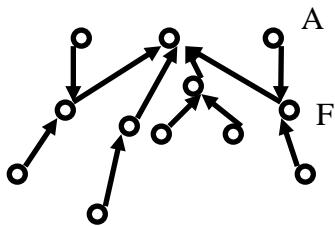
RPL Summary

Student Questions
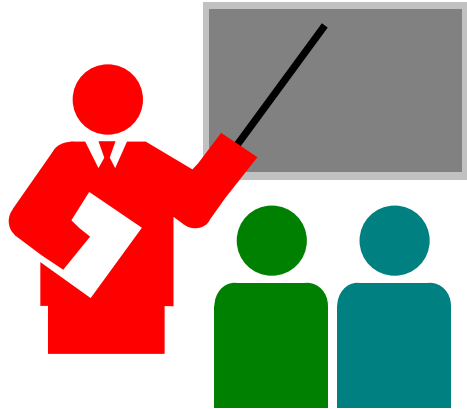
1. An RPL instance consists of one or more DODAGs

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

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://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

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❑ 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

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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
- WiFi   Wireless Fidelity
- WirelessHART Wireless Highway Addressable Remote Transducer Protocol
- WPAN   Wireless Personal Area Network

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