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/cse570-23/

Student Questions

Q on 7b, 9

- 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

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

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
- The coordinator assigns a 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/cse574-20/j_12wpn.htm

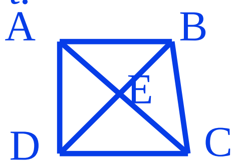
Student Questions

- IEEE 802.15.4 is about personal area networks. Isn't a 64-bit address too large? Is it possible to have such a huge number of nodes in a personal area network?

The number of unique PAN objects in the world is large. So we need a large global address. For any one network, the number is small and so we use a 16-bit short address.

- What are the "Full-function nodes"?

In 802.15.4, there are two kinds of nodes. Full-function nodes can forward other's packets. Other nodes can't.



EUI64 Addresses

- **Ethernet addresses**: 48-bit MAC

0=Unicast 1=Multicast	0=Universal 1=Local	Organizationally Unique ID (OUI)	Manufacturer Assigned
1b	1b	22b	24b

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

0=Unicast Multicast	0=Universal 1=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

0=Unicast 1=Multicast	0=Local 1= Universal	Organizationally Unique ID (OUI)	Manufacturer Assigned
1b	1b	22b	40b

Student Questions

- So, to sum up, in EUI 64, local = 0; in Ethernet 48-bit MAC, local = 1, except for the all-broadcast address. Is it correct?

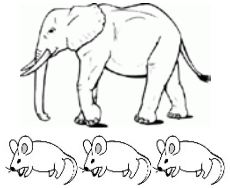
Yes.

- So the second bit of an EUI frame means local when set to 0, universal when set to 1?

Yes, see the corrected figures.

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

- Around how much energy is saved per bit?

It is not about energy. The number of fragments and their headers is large. Shorter headers save computing and transmission time.

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							

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

Student Questions

- Which extension headers are always present in the 6LowPan packet, and which are optional?

All of the extension headers in IPv6 are optional. However, some are necessary for certain situations. 6LowPAN simply compresses whatever is present in the IPv6 header.

- How does the security part work? Does it contain something like a private key?

Any secret or private information cannot be included in the headers that are not encrypted. It is open information that can be used by the receiver but has no meaning for others without complete context, e.g., an initialization vector (IV).

- Do 0-20B and 0-21B mean it can be any number of bytes from 0 to 21?

Yes.

6LowPAN Adaptation Layer

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Student Questions

- So, the length of the extension header determines what type of header it is? So then the maximum number of different headers would be 8?

No. The number of headers could be up to 2^8. But, it only sometimes uses all 8 bits.

- For the ACK feature 802.15.4, how do retransmissions on layer two overlap with layer 4?

Datalink layer retransmissions are short distance and therefore quick. Layer 4 retransmissions are long-distance, hence delayed and consume more resources. In datalinks with rare losses, e.g., Ethernet, it is not worth the cost to do datalink retransmissions.

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 the local admin).

Student Questions

- Based on RFC 4291, the EUI64 is generated by adding two octets (FF: FE) in the middle of a MAC address, and the seventh bit in EUI64 is the bit that indicates if it's local or universal. Is it the case in this example? If this is the case, should I assume that when solving HW 12A?

RFC4291 explains a way to get EUI address from a 48-bit MAC address. In HW 12A, EUI is given and you do not need to construct it. Use it exactly as given. IEEE introduced EUI by simply making it larger bit similar to MAC addresses. IETF uses U-Bit formatted EUI. IEEE writes bits as seen on the wire. IETF writes bits as stored inside "their" computer. We use IEEE bit order but when talking about IETF protocols, we use U-bit encoded EUI.

- Could you explain about example one more time? *Sure.*
- Is it possible to abbreviate '0::1' as '::1'?*Yes.*
- How many bits are there in EUI64 Address, U-bit formatted EUI64, IPv6 Link-local address? Is that 64, 64, 128? *Yes.*

IPv6 Address Formation

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Student Questions

- How to change EUI64 Address into U-bit formatted EUI64? Is that just simply set second bit into 0, or there is any other rules? *Complement the 2nd bit.*

- To change from EUI64 to U-bit and link-local, we change the 2nd bit in EUI64 to its complement and add a FE80 prefix to get link-local.

Yes.

- Where is the 16-bit "short address"/ "PAN ID" in IPv6 link-local Address?

Last 32 bits of the link-local address.

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
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  1st bit of Short address and PAN ID is Unicast/Multicast
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- IPv6 Link Local Address = FE80 :: PAN ID : Short Address
  Use 0 if PAN ID is unknown.
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Student Questions

- How are the short addresses unique?

Short addresses are unique within a single net, like private IP addresses.

- How are the PAN ID's unique?

These are unique only inside a context. For global uniqueness, you need 64-bit IDs.

- Can you explain the address calculation process again?

Flip the 2nd bit and add FE80 in the front.

Homework 12A

- [8 points] What is the IPv6 Link-Local address for a IEEE 802.15.4 node whose EUI64 address in hex is 4000::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

- The answer for IPV6 Local address should be in Hex, correct?

Yes.

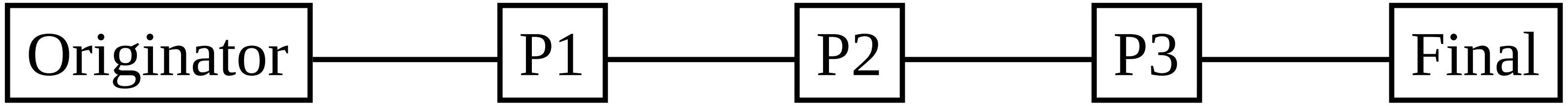
- Can we do another example of this?

Sure.

End of Q

Mesh Addressing Header

- Dispatch = 10_2 (2 bits) ⇒ 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



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

- Why 10 indicates the end of the mesh header? What other cases might we have?

Shannon coding: Most frequent items should be coded with the least bits. Other dispatch items will be 11… or 01…

- Does the "number of hops" limit the IOT device's reach?

The hop limit comes from the IP header.

- Why do we need "hops-left" field?

All IP packets have a time-to-live field. It is kept as the number of hops.

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

- A fragment offset of 8 bytes indicates that no fragment size can be larger than 8 bytes?

*No. Offset = Distance from the beginning of the datagram. X*8 is the maximum offset. X is encoded in 8 bits and so the maximum offset is (2^8-1)*8 bytes.*

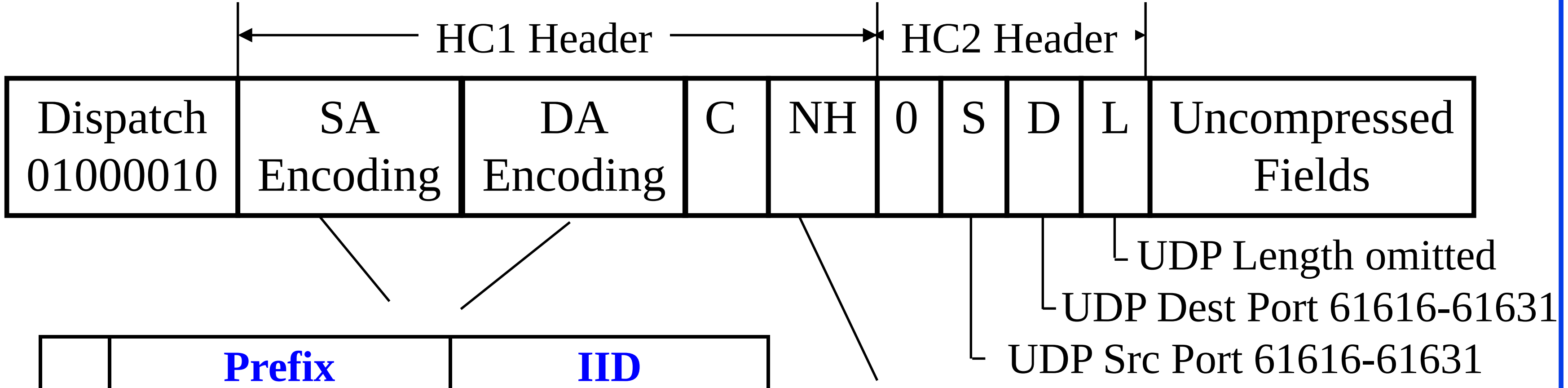
- A Datagram offset of 8 bits means that we can't have more than 2^8 fragments per packet? *See above.*
- Does fragment offset correspond to datagram offset in the image? *Yes.*

- What do the red bits in the first section of the address mean? For example, if a fragment had 11100, does it mean it is the second fragment?

It is any fragment, 2nd, 3rd, etc.

IP+UDP Header Compression: Stateless

- Called **HC1-HC2 compression** (not recommended)
- The 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*)
- The 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

- If the flow label is not omitted would it be within HC1 or HC2 header?

It is omitted iff it is zero. Otherwise, it will be in "Uncompressed fields"

- The *x* in "F0B*x*" is 4 bits? If so, then how can we represent the 61631-61616= 16 ports with 4 bits?

61631-61616= $15_{10}=1111_2$

- Does the dispatch number 0100 0010 mean anything here?

This indicates the type of 6LowPAN header.

- The 80 and 64 bits are omitted from the LSB, correct?
- In the second table, if the next header=NH =17, then what is 01?

17, 1, 6 are IP payload types. In NH=01 indicates the payload is UDP. When uncompressed, it will be encoded as 17.

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

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

Source Adr Compression

Source Adr Mode

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

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

Student Questions

- The hop limit of 64 is represented as 10? is this correct? What does CID represent?

CID=0 ⇒ SCI/DCI absent

- If I want to broadcast, then what field should I change?

M=1,DAC=0, DAM=11
or M=1,DAC=1, DAM=11

- I am confused why it is compressed. Could you show an example that the uncompressed bits take more space to represent the same information?

Addresses are only a few bits long. IPv4 addresses are 128-bit long.

- SAC and DAC are 1 bit, so 2 bits in total. Why does the table using only 1 bit to represent DAC and SAC?

Their interpretation is the same/similar.

- Same question with SAM and DAM.

Same as above.

- Why is it safe to omit some bits?

Those bits can be reconstructed.

Context Based Compression

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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

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
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0	11	128 bits omitted. Get from L2
1	00	Unspecified Address ::
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Student Questions

- What are the other types of addresses? In what situation would someone want to use HC1 instead of IPHC?

IPv6 has local and global addresses similar to the private and public addresses of IPv4. Private/local addresses can not be used outside the organization.

- Are there any trade-offs or considerations when implementing Context-Based Compression?

Yes, it is more general than IPHC.

- Are there any security risks with this?

It's the same as without compression.

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

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

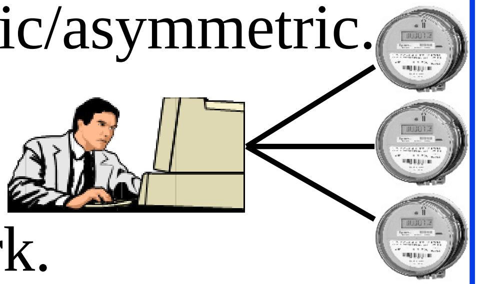
Student Questions

- If the MTU gets bigger and bigger in the future, does that mean 6LowPAN will become useless?

6LowPAN compresses the IPv6 header, which will remain large even if the MTU is larger.

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. Maybe 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

- You stated, "Can’t use OSPF, OLSR, RIP, AODV, DSR" However, ZigBee, which is used in IoT, uses AODV. You also mentioned that in your wireless course (Slide 13-19).

You are right. This slide has been corrected.

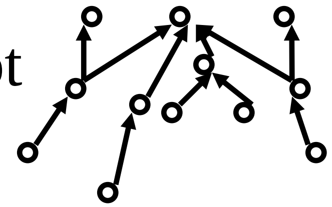
- What do you mean by bidirectional links?

Bidirectional = Traffic can go in both directions.

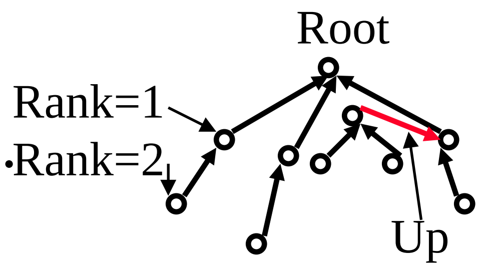
RPL Concepts

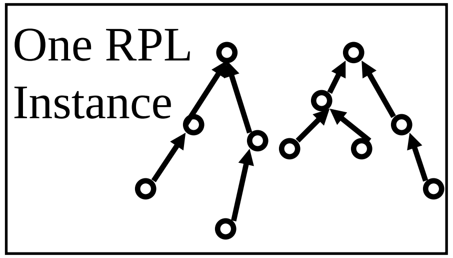
- **Directed Acyclic Graph (DAG)**: No cycles
- **Root**: No outgoing edge
- **Destination-Oriented DAG (DODAG)**: Single root
- **Up**: Towards the root
- **Down**: Away from root
- **Objective Function**: Minimize energy, latency, …
- **Rank**: Distance from the root using specified objective
- **RPL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

- I'm not sure what RPL Instance is.

RPL Instance=DODAG

- Does 'A node may belong to multiple RPL instances' mean 'A node can be in more than one DODAG'?

Yes.

- If it does, are there one more roots?

Yes, each DODAG will have its own root.

- Is the version number used for anything other than saying the DODAG has been changed? Is the DODAG graph also saved with the version number?

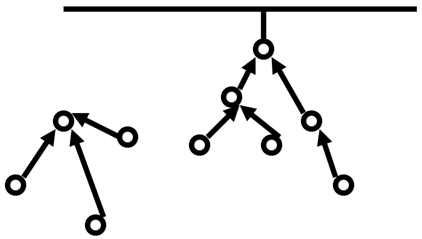
Old DODAGs are not saved. New versions overwrite the old.

- Can you explain the RPL instance again?

Any new node joining or leaving ⇒ New graph ⇒ New instance

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 their parent. Do not keep a routing table.



Student Questions

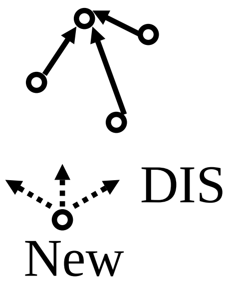
- Could you please explain the concept "parent" and " sub-DODAG" again.

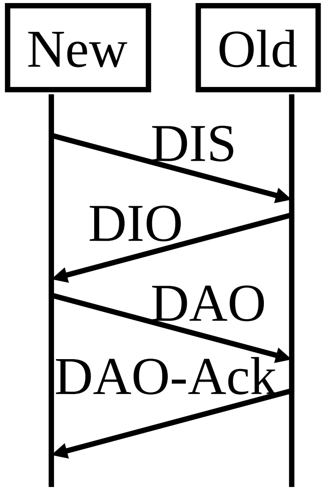
Sub-DODAG = Subtree

Parent=Next node towards the root

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

- DIO: an announcement from above; does this means a parent is acknowledging a child?

DIO=Parent is announcing/ broadcasting. Not acking.

- DIS: request from the bottom. Does this mean a child looking for a parent? *Yes.*
- The image on this slide is confusing! It looks like a 4-way handshake!

It is a 4-way handshake.

- Is RPL a stateful protocol?

No. Stateful=one packet determines the fate of the next.

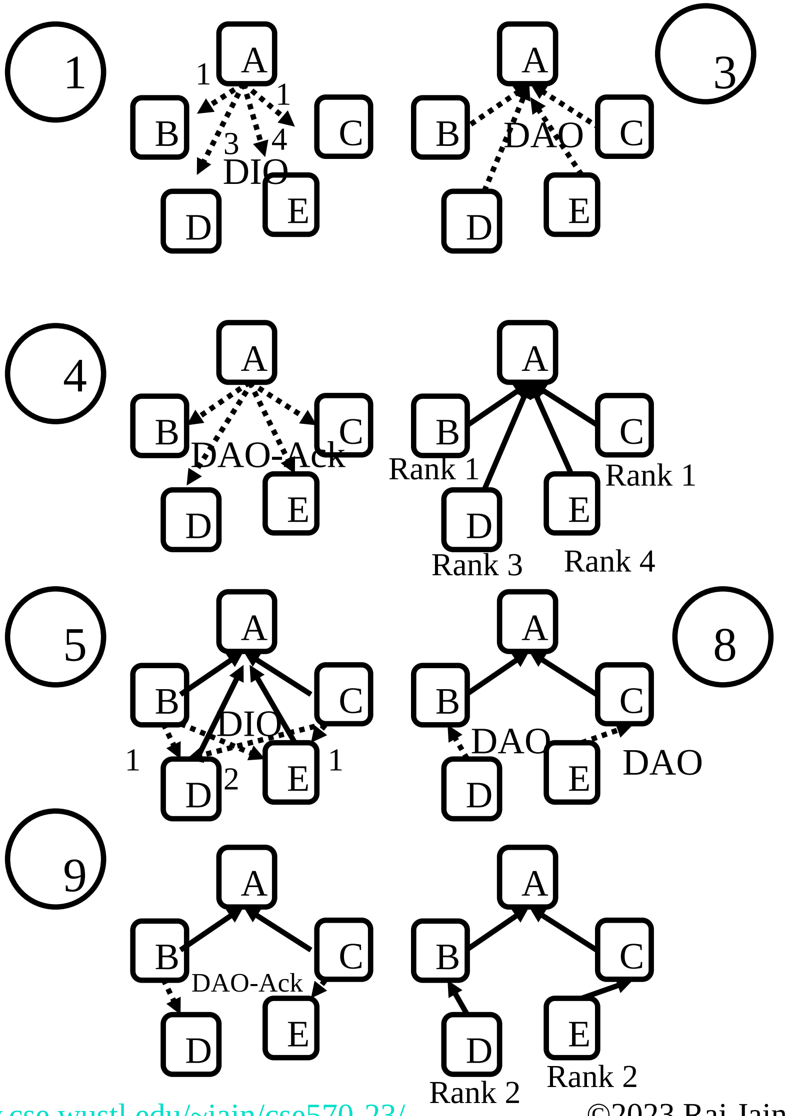
- Can you explain slide 20 again? Sure.

- What are some reasons for rejecting a DAO request?

Too many children ⇒ Too few resources left

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

- ❑ Does it really matter how we break the tie here?

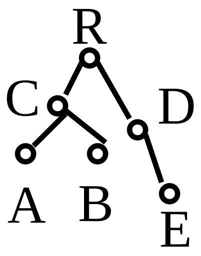
Yes. The final answers will be different. But one answer is not better than the other. For consistency, choose the smaller number or alphabet.

- ❑ Could you explain this example in more detail, please? *Sure.*
- ❑ In number #6, why are the distances from D to B, C 1,2 each? Is it an assumption?

No. Distance is guessed from the signal strength.

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

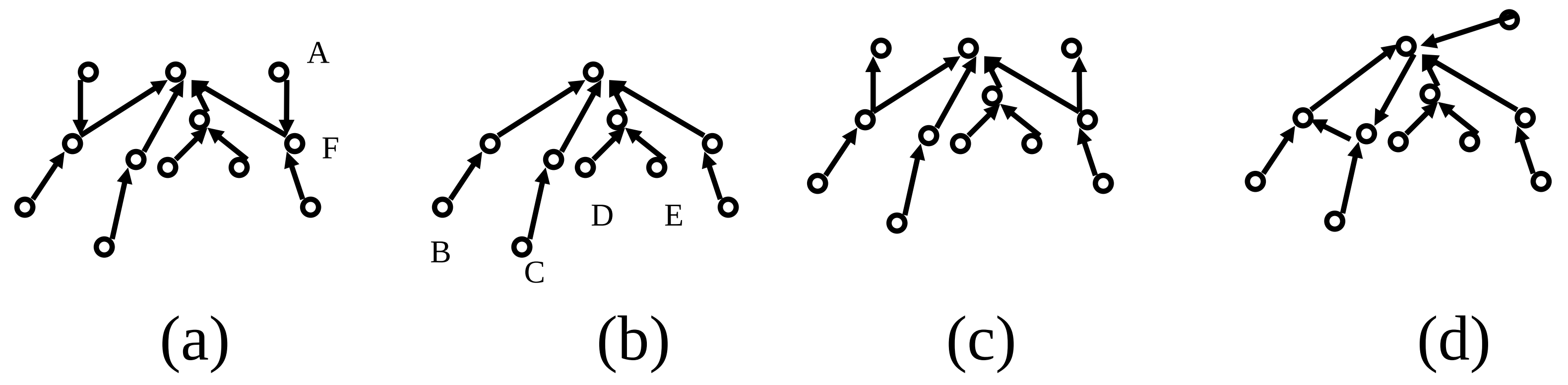
- Could you explain the difference between Storing and Non-Storing in the Broadcast case?

Non-storing ⇒ Alzheimer. You do not know your children or grandchildren. So don't know whether you should forward the packet any further. The root will tell you.

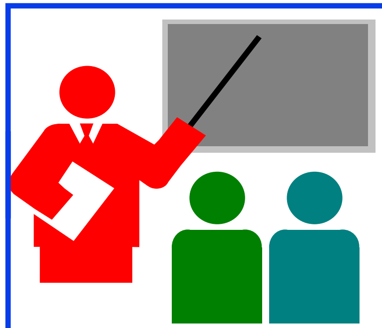
Homework 12B

[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.



Student Questions

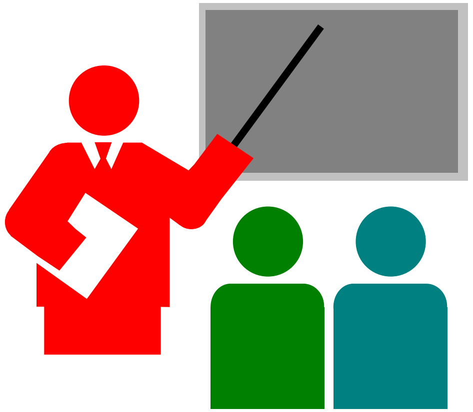


RPL Summary

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

Student Questions

References (Cont)

- "The Minimum Rank with Hysteresis Objective Function," IETF RFC 6719, Sep 2012, https://ietf.org/doc/rfc6719/
- "Reactive Discovery of Point-to-Point Routes in Low-Power and Lossy Networks," IETF RFC 6997, Aug 2013, https://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://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

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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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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse570-23/m_12lpn.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

Wireless and Mobile Networking (Spring 2016),
https://www.youtube.com/playlist?list=PLjGG94etKypKeb0nzyN9tSs_HCd5c4wXF

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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