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

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse570-19/
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

<table>
<thead>
<tr>
<th>Session</th>
<th>Security</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encapsulation</td>
<td>Encapsulation</td>
<td></td>
</tr>
<tr>
<td>6LowPAN, 6TiSCH, 6Lo, Thread…</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routing</td>
<td>Routing</td>
<td></td>
</tr>
<tr>
<td>RPL, CORPL, CARP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network</td>
<td>DataLink</td>
<td></td>
</tr>
<tr>
<td>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, …</td>
<td>Security</td>
<td></td>
</tr>
<tr>
<td>Datalink</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


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](http://www.cse.wustl.edu/~jain/cse574-14/index.html)
EUI64 Addresses

- **Ethernet addresses**: 48 bit MAC

<table>
<thead>
<tr>
<th>Unicast</th>
<th>Universal</th>
<th>Organizationally Unique ID (OUI)</th>
<th>Manufacturer Assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>1b</td>
<td>22b</td>
<td>24b</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Unicast</th>
<th>Universal</th>
<th>Organizationally Unique ID (OUI)</th>
<th>Manufacturer Assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>1b</td>
<td>22b</td>
<td>40b</td>
</tr>
</tbody>
</table>

- **Local bit** was incorrectly assigned. $L=1 \Rightarrow$ Local but all-broadcast address = all 1’s is not local

  - IETF RFC4291 changed the meaning so that $L=0 \Rightarrow$ Local
  - The 2nd bit is now called Universal bit (U-bit)
  - $\Rightarrow$ U-bit formatted EUI64 addresses
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

<table>
<thead>
<tr>
<th>802.15.4 Header</th>
<th>Security Option</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>25B</td>
<td>21B</td>
<td>81B</td>
</tr>
</tbody>
</table>

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.


Washington University in St. Louis [http://www.cse.wustl.edu/~jain/cse570-19/](http://www.cse.wustl.edu/~jain/cse570-19/)
# 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
   - 102: Mesh addressing header (2-bit dispatch)
   - 11x002: Destination Processing Fragment header (5-bit)
   - 010100002: Hop-by-hop LowPAN Broadcast header (8-bit)

7. **IPv6 and UDP header compression**

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Seq. #</th>
<th>Adrs</th>
<th>[Security]</th>
<th>Disp</th>
<th>Ext Hdr</th>
<th>Disp</th>
<th>Ext Hdr</th>
<th>Disp</th>
<th>Ext Hdr</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B</td>
<td>1B</td>
<td>0-20B</td>
<td>0-21B</td>
<td>bits</td>
<td></td>
<td>bits</td>
<td></td>
<td>bits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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)
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 = 10₂ (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

<table>
<thead>
<tr>
<th>Originator</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>Final</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>V</th>
<th>F</th>
<th>Hops Left</th>
<th>Originator Address</th>
<th>Final Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2b</td>
<td>1b</td>
<td>1b</td>
<td>16b/64b</td>
<td>16b/64bit</td>
</tr>
</tbody>
</table>

V=0 ⇒ Originator address is EUI64, V=1 ⇒ 16bit
F=0 ⇒ Final address is EUI64, F=1 ⇒ 16-bit
6LowPAN Broadcast Header

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

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>Sequence Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>01010000₂</td>
<td>8b</td>
</tr>
<tr>
<td>8b</td>
<td>8b</td>
</tr>
</tbody>
</table>
6LowPAN Fragment Header

- Dispatch = 11x00 (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:

<table>
<thead>
<tr>
<th>5b</th>
<th>11b</th>
<th>16b</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>IP Pkt Size</td>
<td>Datagram tag</td>
<td></td>
</tr>
</tbody>
</table>

Other Fragments:

<table>
<thead>
<tr>
<th>5b</th>
<th>11b</th>
<th>16b</th>
<th>8b</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>11100</td>
<td>IP Pkt Size</td>
<td>Datagram tag</td>
<td>Datagram Offset</td>
<td></td>
</tr>
</tbody>
</table>

Washington University in St. Louis  http://www.cse.wustl.edu/~jain/cse570-19/  ©2019 Raj Jain
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.

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>SA Encoding</th>
<th>DA Encoding</th>
<th>C</th>
<th>NH</th>
<th>0</th>
<th>S</th>
<th>D</th>
<th>L</th>
<th>Uncompressed Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>01000010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HC1 Header</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HC2 Header</td>
</tr>
</tbody>
</table>

- **Prefix**
  - 00: Uncompressed
  - 01: Uncompressed
  - 10: FE80::/80 omitted
  - 11: FE80::/64 omitted

- **IID**
  - Uncompressed
  - Derived from L2

- **UDP Length omitted**
  - UDP Dest Port 61616-61631
  - UDP Src Port 61616-61631

- **Next Hdr**
  - Next Hdr inline
  - Next Hdr= 17 (UDP)
  - Next Hdr = 1 (ICMP)
  - Next Hdr = 6 (TCP)
## 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

<table>
<thead>
<tr>
<th>Disp</th>
<th>TF</th>
<th>NH</th>
<th>Hop Limit</th>
<th>CID</th>
<th>SAC</th>
<th>SAM</th>
<th>M</th>
<th>DAC</th>
<th>DAM</th>
<th>SCI</th>
<th>DCI</th>
<th>Uncompressed IPv6 fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>011</td>
<td>2b</td>
<td>1b</td>
<td>2b</td>
<td>1b</td>
<td>1b</td>
<td></td>
<td>1b</td>
<td></td>
<td>2b</td>
<td>1b</td>
<td></td>
<td>4b 4b Source/Dest Context IDs if CID=1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Multicast Destination</td>
</tr>
</tbody>
</table>

**Traffic Class, Flow Label**

<table>
<thead>
<tr>
<th>SAC DAC</th>
<th>SAM DAM</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>0   00</td>
<td>No compression</td>
<td></td>
</tr>
<tr>
<td>0   01</td>
<td>First 64-bits omitted</td>
<td></td>
</tr>
<tr>
<td>0   10</td>
<td>First 112 bits omitted</td>
<td></td>
</tr>
<tr>
<td>0   11</td>
<td>128 bits omitted. Get from L2</td>
<td></td>
</tr>
<tr>
<td>1   00</td>
<td>Unspecified Address ::</td>
<td></td>
</tr>
<tr>
<td>1   01</td>
<td>First 64 bits from context</td>
<td></td>
</tr>
<tr>
<td>1   10</td>
<td>First 112 bits from context</td>
<td></td>
</tr>
<tr>
<td>1   11</td>
<td>128 bits from context and L2</td>
<td></td>
</tr>
</tbody>
</table>


Washington University in St. Louis  
[http://www.cse.wustl.edu/~jain/ece570-19/](http://www.cse.wustl.edu/~jain/ece570-19/)  
©2019 Raj Jain
Context Based Compression (Cont)

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

<table>
<thead>
<tr>
<th>EID</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>IPv6 Hop-by-Hop Options</td>
</tr>
<tr>
<td>1</td>
<td>IPv6 Routing</td>
</tr>
<tr>
<td>2</td>
<td>IPv6 Fragment</td>
</tr>
<tr>
<td>3</td>
<td>IPv6 Destination Options</td>
</tr>
<tr>
<td>4</td>
<td>IPv6 Mobility Header</td>
</tr>
<tr>
<td>5</td>
<td>Reserved</td>
</tr>
<tr>
<td>6</td>
<td>Reserved</td>
</tr>
<tr>
<td>7</td>
<td>IPv6 Header</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IPv6 ExtHdr ID (EID)</th>
<th>NH</th>
<th>Uncompressed Fields</th>
<th>NextHdr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1110</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 0 = Uncompressed
- 1 = LowPAN_NHC encoded

LowPAN_NHC UDP Header:

<table>
<thead>
<tr>
<th>11110</th>
<th>C</th>
<th>P</th>
<th>5b</th>
<th>1b</th>
<th>2b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 00  All 16-bits in line
- 01  1\textsuperscript{st} 8-bits of dest port omitted
- 10  1\textsuperscript{st} 8-bits of src port omitted
- 11  1\textsuperscript{st} 12-bits of src & dest omitted


Washington University in St. Louis [http://www.cse.wustl.edu/~jain/cse570-19/](http://www.cse.wustl.edu/~jain/cse570-19/)

©2019 Raj Jain
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
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
- 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

Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse570-19/ ©2019 Raj Jain
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.
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.
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 can't!

5. **Consistency Check:** Challenge/response messages for security

Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse570-19/
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.

Washington University in St. Louis  http://www.cse.wustl.edu/~jain/cse570-19/  ©2019 Raj Jain
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
Homework 12B

[10 points]

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.
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
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
Reading List

Wikipedia Links

- http://en.wikipedia.org/wiki/IEEE_802.15.4
- http://en.wikipedia.org/wiki/MAC_address
- http://en.wikipedia.org/wiki/Link-local_address
References


References (Cont)

References (Cont)

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
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
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
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
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
Scan This to Download These Slides

Raj Jain
http://rajjain.com
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=PLjGG94etKypJWOSPMh8Azcg5ye_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

Washington University in St. Louis
http://www.cse.wustl.edu/~jain/cse570-19/
©2019 Raj Jain