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>CoRE, DDS, AMQP, XMPP, CoAP, IEC, IEEE 1888, …</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network</td>
<td>6LowPAN, 6TiSCH, 6Lo, Thread…</td>
</tr>
<tr>
<td>Encapsulation</td>
<td>RPL, CORPL, CARP</td>
</tr>
<tr>
<td>Data Link</td>
<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>
</tr>
<tr>
<td>Security</td>
<td>IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …</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>Multicast</th>
<th>Universal Local</th>
<th>Organizationally Unique ID (OUI)</th>
<th>Manufacturer Assigned</th>
</tr>
</thead>
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<tr>
<td>1b</td>
<td>1b</td>
<td>22b</td>
<td>24b</td>
<td></td>
</tr>
</tbody>
</table>
```

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

```
<table>
<thead>
<tr>
<th>Unicast</th>
<th>Multicast</th>
<th>Universal Local</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>
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</tbody>
</table>
```

- **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
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.


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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 bits</th>
<th>Ext Hdr</th>
<th>Disp bits</th>
<th>Ext Hdr</th>
<th>Disp bits</th>
<th>Ext Hdr</th>
<th>IPv6 Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B</td>
<td>1B</td>
<td>0-20B</td>
<td>0-21B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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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. 2nd most significant = 6th bit from right)
Homework 13A

- 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>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 2b</td>
<td>1b</td>
<td>1b</td>
<td>4b</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

<table>
<thead>
<tr>
<th>1&lt;sup&gt;st&lt;/sup&gt; Fragment:</th>
<th>1100</th>
<th>IP Pkt Size</th>
<th>Datagram tag</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5b</td>
<td>11b</td>
<td>16b</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Fragments:</th>
<th>11100</th>
<th>IP Pkt Size</th>
<th>Datagram tag</th>
<th>Datagram Offset</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5b</td>
<td>11b</td>
<td>16b</td>
<td>8b</td>
<td></td>
</tr>
</tbody>
</table>
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>C</td>
<td>NH</td>
<td>0</td>
<td>S</td>
<td>D</td>
<td>L</td>
<td></td>
</tr>
</tbody>
</table>

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

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

00          | Next Hdr inline |
01          | Next Hdr = 17 (UDP) |
10          | Next Hdr = 1 (ICMP) |
11          | 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 011</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>3b</td>
<td>2b</td>
<td>1b</td>
<td>2b</td>
<td>1b</td>
<td>1b</td>
<td>2b</td>
<td>1b</td>
<td>2b</td>
<td>2b</td>
<td>4b</td>
<td>4b</td>
<td>Source/Dest Context IDs if CID=1</td>
</tr>
<tr>
<td>Traffic Class, Flow Label</td>
<td>Next Header uses LowPAN_NHC</td>
<td>Source Adr Mode</td>
<td>Source Adr Compression</td>
<td>Predefined hop limit = uncompressed (00), 1, 64, 255</td>
<td>Multicast Destination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAC DAC</td>
<td>SAM DAM</td>
<td>Address</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>00</td>
<td>No compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01</td>
<td>01</td>
<td>First 64-bits omitted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>First 112 bits omitted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>128 bits omitted. Get from L2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>00</td>
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<td>Unspecified Address ::</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01</td>
<td>01</td>
<td>First 64 bits from context</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>First 112 bits from context</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>128 bits from context and L2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If the next header uses LowPAN_NHC

- For IPv6 base extension headers:

  ![IPv6 Ext Hdr ID (EID) Table]

  0 = Uncompressed
  1 = LowPAN_NHC encoded

  ![LowPAN_NHC UDP Header Table]

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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
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

https://ietf.org/doc/rfc6550/
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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 Addr 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

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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
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 13B

- 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/IEEE_802.15.4)
- [http://en.wikipedia.org/wiki/Link-local_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
<table>
<thead>
<tr>
<th>Acronyms (Cont)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECT</td>
</tr>
<tr>
<td>DIO</td>
</tr>
<tr>
<td>DIS</td>
</tr>
<tr>
<td>DODAG</td>
</tr>
<tr>
<td>DSCP</td>
</tr>
<tr>
<td>DSR</td>
</tr>
<tr>
<td>DTLS</td>
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<tr>
<td>EID</td>
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<tr>
<td>EUI</td>
</tr>
<tr>
<td>GP</td>
</tr>
<tr>
<td>HC</td>
</tr>
<tr>
<td>HC1-HC2</td>
</tr>
<tr>
<td>ICMP</td>
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<tr>
<td>ID</td>
</tr>
<tr>
<td>IEEE</td>
</tr>
</tbody>
</table>
## 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
<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSPF</td>
<td>Open Shortest Path Forwarding</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Network</td>
</tr>
<tr>
<td>RFC</td>
<td>Request for Comments</td>
</tr>
<tr>
<td>RIP</td>
<td>Routing Information Protocol</td>
</tr>
<tr>
<td>ROLL</td>
<td>Routing over Low-Power and Lossy Networks</td>
</tr>
<tr>
<td>RPL</td>
<td>Routing Protocol for Low-Power and Lossy Networks</td>
</tr>
<tr>
<td>SA</td>
<td>Source Address</td>
</tr>
<tr>
<td>SAC</td>
<td>Source Address Compression</td>
</tr>
<tr>
<td>SAM</td>
<td>Source Address Mode</td>
</tr>
<tr>
<td>SASL</td>
<td>Simple Authentication and Security Layer</td>
</tr>
<tr>
<td>SCI</td>
<td>Source Context ID</td>
</tr>
<tr>
<td>SMACK</td>
<td>Simplified Mandatory Access Control Kernel</td>
</tr>
<tr>
<td>TCG</td>
<td>Trusted Computing Group</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TF</td>
<td>Traffic Class, Flow Label</td>
</tr>
<tr>
<td>TinyOS</td>
<td>Tiny Operating System</td>
</tr>
</tbody>
</table>
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
Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJrKjNAa1n_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=PLjGG94etKypKyvzfVtutHcPFJXumyyg93u

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