Networked Embedded Systems: 6LoWPAN

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Benefits of 6LoWPAN Technology

• Low-power RF + IPv6 =
  The Wireless Embedded Internet
• 6LoWPAN makes this possible
• The benefits of 6LoWPAN include:
  – Open, long-lived, reliable standards
  – Easy learning-curve
  – Transparent Internet integration
  – Network maintainability
  – Global scalability
  – End-to-end data flows
Evolution of Wireless Sensor Networks

- **1980s**: Any vendor, cabling, increased productivity
- **2000**: Z-Wave, proprietary ISM, increased productivity
- **2006**: ZigBee and WHART, complex middleware
- **2008+**: 6LoWPAN, ISA100, open development and portability

**Price**
- Radio + network

**Scalability**
- Increased productivity

**Evolution Timeline**
- 1980s: Any vendor
- 2000: ZigBee and WHART
- 2008+: 6LoWPAN, ISA100
Relationship of Standards

- OGC
- IPSO Alliance
- IETF
- 6LoWPAN
- ROLL
- IPv6
- IP500 Alliance
- ISA SP100.11a
- ZigBee
- IEEE 802.15.4
6LoWPAN Applications

• 6LoWPAN has a broad range of applications
  – Facility, Building and Home Automation
  – Personal Sports & Entertainment
  – Healthcare and Wellbeing
  – Asset Management
  – Advanced Metering Infrastructures
  – Environmental Monitoring
  – Security and Safety
  – Industrial Automation

• Examples from the SENSEI project
  – http://www.sensei-project.eu/
Facility Management

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What is 6LoWPAN?

- IPv6 over Low-Power wireless Area Networks
- Defined by IETF standards
  - RFC 4919, 4944
  - draft-ietf-6lowpan-hc and -nd
  - draft-ietf-roll-rpl
- Stateless header compression
- Enables a standard socket API
- Minimal use of code and memory
- Direct end-to-end Internet integration
  - Multiple topology options
Protocol Stack

TCP/IP Protocol Stack

- HTTP
- RTP
- TCP
- UDP
- ICMP
- IP
- Ethernet MAC
- Ethernet PHY

6LoWPAN Protocol Stack

- Application
- UDP
- ICMP
- IPv6 with LoWPAN
- IEEE 802.15.4 MAC
- IEEE 802.15.4 PHY

Application
- Transport
- Network
- Data Link
- Physical
Features

• Support for e.g. 64-bit and 16-bit 802.15.4 addressing
• Useful with low-power link layers such as IEEE 802.15.4, narrowband ISM and power-line communications
• Efficient header compression
  – IPv6 base and extension headers, UDP header
• Network autoconfiguration using neighbor discovery
• Unicast, multicast and broadcast support
  – Multicast is compressed and mapped to broadcast
• Fragmentation
  – 1280 byte IPv6 MTU -> 127 byte 802.15.4 frames
• Support for IP routing (e.g. IETF RPL)
• Support for use of link-layer mesh (e.g. 802.15.5)
Architecture
Architecture

- LoWPANs are stub networks
- Simple LoWPAN
  - Single Edge Router
- Extended LoWPAN
  - Multiple Edge Routers with common backbone link
- Ad-hoc LoWPAN
  - No route outside the LoWPAN
- Internet Integration issues
  - Maximum transmission unit
  - Application protocols
  - IPv4 interconnectivity
  - Firewalls and NATs
  - Security

IPv6-LoWPAN Router Stack
6LoWPAN Headers

- Orthogonal header format for efficiency
- Stateless header compression
The Internet

- A global, publicly accessible, series of interconnected computer networks (made up of hosts and clients) using the packet-switched Internet Protocol
- Consists of millions of small network domains
- ICANN, the Internet Corporation for Assigned Names and Numbers
  - Unique identifiers, domain names, IP addresses, protocol ports etc.
  - Only a coordinator, not a governing body
- These days an Internet Governance Forum (IGF) has been formed to discuss global governance
- Internet-related protocols are standardized by the Internet Engineering Task Force (IETF)
IP Protocol Stack

- **Application (L5-7)**
  - HTTP
  - RTP
- **Transport (L4)**
  - TCP
  - UDP
  - ICMP
- **Network (L3)**
  - IP
- **Data Link (L2)**
  - Ethernet MAC
- **Physical (L1)**
  - Ethernet PHY
Internet Architecture

Network Connections

Stack Connections

Image source: (Wikipeida) GFDL
Internet Protocol v6

• IPv6 (RFC 2460) = the next generation Internet Protocol
  – Complete redesign of IP addressing
  – Hierarchical 128-bit address with decoupled host identifier
  – Stateless auto-configuration
  – Simple routing and address management
• Majority of traffic not yet IPv6 but...
  – Most PC operating systems already have IPv6
  – Governments are starting to require IPv6
  – Most routers already have IPv6 support
  – So the IPv6 transition is coming
  • 1400% annual growth in IPv6 traffic (2009)
IPv4 vs. IPv6 Addressing

An IPv4 address (dotted-decimal notation)

172 . 16 . 254 . 1

\[10101100.00010000.11111110.00000001\]

One byte = Eight bits

Thirty-two bits (4 * 8), or 4 bytes

An IPv6 address (in hexadecimal)

2001:0DB8:AC10:FE01:0000:0000:0000:0001

\[2001:0DB8:AC10:FE01:0000:0000:0000:0000\]

Zeroes can be omitted

Image source: Indeterminant (Wikipeida) GFDL
IPv4 vs. IPv6 Header

Image source: Bino1000, Mkim (Wikipeida) GFDL
IPv6 Neighbor Discovery

- IPv6 is the format - ND is the brains
  - “One-hop routing protocol” defined in RFC4861
- Defines the interface between neighbors
- Finding Neighbors
  - Neighbor Solicitation / Neighbor Acknowledgement
- Finding Routers
  - Router Solicitation / Router Advertisement
- Address resolution using NS/NA
- Detecting Duplicate Addresses using NS/NA
- Neighbor Unreachability Detection using NS/NA
- DHCPv6 may be used in conjunction with ND
IPv6 Neighbor Discovery

![Diagram showing the process of IPv6 Neighbor Discovery]

- Host
  - Router Discovery
    - Router Solicitation
  - DAD
    - Neighbor Solicitation
    - Neighbor Advertisement
  - Address Resolution
    - Neighbor Solicitation
    - Neighbor Advertisement
  - Router Advertisement
- Router
ICMPv6

- The Internet Control Message Protocol (ICMPv6)
  - Defined by RFC2463
  - Used for control messaging between IPv6 nodes
- ICMPv6 Error Messages
  - Destination Unreachable Message
  - Packet Too Big Message
  - Time Exceeded Message
  - Parameter Problem Message
- ICMPv6 Informational Messages
  - Echo Request Message
  - Echo Reply Message
### ICMPv6

The ICMPv6 messages have the following general format:

<table>
<thead>
<tr>
<th>0</th>
<th>8</th>
<th>16</th>
<th>24</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICMPv6 type</td>
<td>ICMPv6 code</td>
<td>ICMPv6 checksum</td>
<td>ICMPv6 data</td>
<td></td>
</tr>
</tbody>
</table>

The type field indicates the type of the message. Its value determines the format of the remaining data.

The code field depends on the message type. It is used to create an additional level of message granularity.

The checksum field is used to detect data corruption in the ICMPv6 message and parts of the IPv6 header.
TCP

• The Transmission Control Protocol (TCP) (RFC 793)
  – A reliable, ordered transport for a stream of bytes
  – TCP is connection oriented, forming a pairing between 2 hosts using a 3-way handshake
  – Positive ack windowing is used with flow control
  – Congestion control mechanism critical for the Internet
• TCP is not suitable for every application
  – Support for unicast communications only
  – Reacts badly to e.g. wireless packet loss
  – Not all protocols require total reliability
  – TCP connection not suitable for very short transactions
The TCP Header

<table>
<thead>
<tr>
<th>Field</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>source port</td>
<td></td>
</tr>
<tr>
<td>destination port</td>
<td></td>
</tr>
<tr>
<td>sequence number</td>
<td></td>
</tr>
<tr>
<td>acknowledgment number</td>
<td></td>
</tr>
<tr>
<td>data offset</td>
<td></td>
</tr>
<tr>
<td>reserved</td>
<td></td>
</tr>
<tr>
<td>URG</td>
<td></td>
</tr>
<tr>
<td>ACK</td>
<td></td>
</tr>
<tr>
<td>PSH</td>
<td></td>
</tr>
<tr>
<td>RST</td>
<td></td>
</tr>
<tr>
<td>SYN</td>
<td></td>
</tr>
<tr>
<td>FIN</td>
<td></td>
</tr>
<tr>
<td>window</td>
<td></td>
</tr>
<tr>
<td>checksum</td>
<td></td>
</tr>
<tr>
<td>urgent pointer</td>
<td></td>
</tr>
<tr>
<td>options</td>
<td>(0 oder mehr 32-Bit-Wörter)</td>
</tr>
<tr>
<td>data</td>
<td>(Nutzdaten)</td>
</tr>
</tbody>
</table>
UDP

- The User Datagram Protocol (UDP) (RFC 768)
  - Used to deliver short messages over IP
  - Unreliable, connectionless protocol
  - Can be used with broadcast and multicast
  - Common in streaming and VoIP, DNS and network tools

<table>
<thead>
<tr>
<th>Source Port</th>
<th>Destination Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDP Length</td>
<td>UDP Checksum</td>
</tr>
<tr>
<td></td>
<td>Data</td>
</tr>
</tbody>
</table>
The Link-Layer and IP

- The Internet Protocol interconnects heterogeneous links
- Key link-layer features to support IP:
  - Framing
  - Addressing
  - Error checking
  - Length indication
  - Broadcast and unicast
- RFC3819 discusses IP subnetwork design
- 6LoWPAN enables IPv6 over very constrained links
  - Limited frame size and bandwidth
  - Wireless mesh topologies and sleeping nodes
  - No native multicast support
IEEE 802.15.4

- Important standard for home networking, industrial control and building automation
- Three PHY modes
  - 20 kbps at 868 MHz
  - 40 kbps at 915 MHz
  - 250 kbps at 2.4 GHz (DSSS)
- Beaconless mode
  - Simple CSMA algorithm
- Beacon mode with superframe
  - Hybrid TDMA-CSMA algorithm
- Up to 64k nodes with 16-bit addresses
- Extensions to the standard
  - IEEE 802.15.4a, 802.15.4e, 802.15.5
Other Link-Layers for 6LoWPAN

• Sub-GHz Industrial, Scientific and Medical band radios
  – Typically 10-50 kbps data rates, longer range than 2.4 GHz
  – Usually use CSMA-style medium access control
  – Example: CC1110 from Texas Instruments

• Power-Line Communications
  – Some PLC solutions behave like an 802.15.4 channel
  – Example: A technology from Watteco provides an 802.15.4 emulation mode, allowing the use of 6LoWPAN

• Z-Wave
  – A home-automation low-power radio technology
The 6LoWPAN Format
Architecture
The 6LoWPAN Format

- 6LoWPAN is an adaptation header format
  - Enables the use of IPv6 over low-power wireless links
  - IPv6 header compression
  - UDP header compression
- Format initially defined in RFC4944
- Updated by draft-ietf-6lowpan-hc (work in progress)
The 6LoWPAN Format

- 6LoWPAN makes use of IPv6 address compression
- RFC4944 Features:
  - Basic LoWPAN header format
  - HC1 (IPv6 header) and HC2 (UDP header) compression formats
  - Fragmentation & reassembly
  - Mesh header feature (deprecation planned)
  - Multicast mapping to 16-bit address space
- draft-ietf-6lowpan-hc Features:
  - New HC (IPv6 header) and NHC (Next-header) compression
  - Support for global address compression (with contexts)
  - Support for IPv6 option header compression
  - Support for compact multicast address compression
IPv6 Addressing

- 128-bit IPv6 address = 64-bit prefix + 64-bit Interface ID (IID)
- The 64-bit prefix is hierarchical
  - Identifies the network you are on and where it is globally
- The 64-bit IID identifies the network interface
  - Must be unique for that network
  - Typically is formed statelessly from the interface MAC address
    - Called Stateless Address Autoconfiguration (RFC2462)
- There are different kinds of IPv6 addresses
  - Loopback (0::1) and Unspecified (0::0)
  - Unicast with global (e.g. 2001::) or link-local (FE80::) scope
  - Multicast addresses (starts with FF::)
  - Anycast addresses (special-purpose unicast address)
6LoWPAN Addressing

• IPv6 addresses are compressed in 6LoWPAN
• A LoWPAN works on the principle of
  – flat address spaces (wireless network is one IPv6 subnet)
  – with unique MAC addresses (e.g. 64-bit or 16-bit)
• 6LoWPAN compresses IPv6 addresses by
  – Eliding the IPv6 prefix
    • Global prefix known by all nodes in network
    • Link-local prefix indicated by header compression format
  – Compressing the IID
    • Elided for link-local communication
    • Compressed for multihop dst/src addresses
  – Compressing with a well-known “context”
  – Multicast addresses are compressed
Addressing Example
48 Bytes!

UDP/IPv6 Headers

![UDP/IPv6 Headers Diagram]
Header Comparison

Full UDP/IPv6 (64-bit addressing)

Minimal UDP/6LoWPAN (16-bit addressing)
LoWPAN UDP/IPv6 Headers

6 Bytes!

draft-ietf-6lowpan-hc
Improved IP Header Compression (IPHC)

Base Header

+-------------------------------------+------------------------
| Dispatch + LOWPAN_IPHC (2-3 octets) | Compressed IPv6 Header |
+-------------------------------------+------------------------

LOWPAN_IPHC Encoding

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 0 | 1 | 2 | 3 |
| 0 | 1 | 1 | TF | NH | HLIM | CID | SAC | SAM | M | DAC | DAM | Uncompressed Fields... |

TF = Traffic Class, Flow Label
NH = Next Header Flag
HLIM = Hop Limit
CID = Context Identifier Extension
SAC = Source Address Compression
SAM = Source Address Mode
M = Multicast Compression
DAC = Destination Address Compression
DAM = Destination Address Mode
Next-header Compression (NHC)

NHC Format

+----------------+---------------------------
| var-len NHC ID | compressed next header... |
+----------------+---------------------------

UDP NHC Encoding

0 1 2 3 4 5 6 7
+-----------+-----------+-----------+-----------+-----------+-----------+
| 1 | 1 | 1 | 1 | 0 | C | P |
+-----------+-----------+-----------+-----------+-----------+

C = Checksum Compression
P = UDP Port Compression
IPHC Examples

IEEE 802.15.4 Header - 22 bytes

<table>
<thead>
<tr>
<th>Length</th>
<th>FCF</th>
<th>DSN</th>
<th>PAN ID</th>
<th>Source Address (00-17-3B-00-11-11-22-22)</th>
<th>Destination Address (00-17-3B-00-33-34-44-44)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compressed UDP/IPv6 Header (fe80::0217:3b00:1111:2222 → fe80::0217:3b00:3333:4444)

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>IPHC</th>
<th>NHC</th>
<th>UDP Ports</th>
<th>UDP</th>
<th>Checksum</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compressed UDP/IPv6 Header (fe80::0217:3b00:1111:2222 → ff02::1)

<table>
<thead>
<tr>
<th>Dispatch</th>
<th>IPHC</th>
<th>Mast Grp</th>
<th>NHC</th>
<th>UDP Ports</th>
<th>UDP</th>
<th>Checksum</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Dispatch</th>
<th>IPHC</th>
<th>CID</th>
<th>Hop Lim</th>
<th>HC ID (0x68)</th>
<th>UDP Ports</th>
<th>UDP</th>
<th>Checksum</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fragmentation

- IPv6 requires underlying links to support Minimum Transmission Units (MTUs) of at least 1280 bytes
- IEEE 802.15.4 leaves approximately 80-100 bytes of payload!
- RFC4944 defines fragmentation and reassembly of IPv6
- The performance of large IPv6 packets fragmented over low-power wireless mesh networks is poor!
  - Lost fragments cause whole packet to be retransmitted
  - Low-bandwidth and delay of the wireless channel
  - 6LoWPAN application protocols should avoid fragmentation
  - Compression should be used on existing IP application protocols when used over 6LoWPAN if possible
- Fragment recovery is currently under IETF consideration
Fragmentation
Bootstrapping
6LoWPAN Setup & Operation

- Autoconfiguration is important in embedded networks
- In order for a 6LoWPAN network to start functioning:
  - 1. Link-layer connectivity between nodes (commissioning)
  - 2. Network layer address configuration, discovery of neighbors, registrations (bootstrapping)
  - 3. Routing algorithm sets up paths (route initialization)
  - 4. Continuous maintenance of 1-3
Link-layer Commissioning

- In order for nodes to communicate with each other, they need to have compatible physical and link-layer settings.
- Example IEEE 802.15.4 settings:
  - Channel, modulation, data-rate (Channels 11-26 at 2.4 GHz)
    - Usually a default channel is used, and channels are scanned to find a router for use by Neighbor Discovery
  - Addressing mode (64-bit or 16-bit)
    - Typically 64-bit is a default, and 16-bit used if address available
  - MAC mode (beaconless or super-frame)
    - Beaconless mode is easiest for commissioning (no settings needed)
  - Security (on or off, encryption key)
    - In order to perform secure commissioning a default key should already be installed in the nodes
6LoWPAN Neighbor Discovery

• Standard ND for IPv6 is not appropriate for 6LoWPAN:
  – Assumption of a single link for an IPv6 subnet prefix
  – Assumption that nodes are always on
  – Heavy use of multicast traffic (broadcast/flood in 6LoWPAN)
  – No efficient multihop support over e.g. 802.15.4

• 6LoWPAN Neighbor Discovery provides:
  – An appropriate link and subnet model for low-power wireless
  – Minimized node-initiated control traffic
  – Node Registration (NR) and Confirmation (NC)
  – Duplicate Address Detection (DAD) and recovery
  – Support for extended Edge Router infrastructures

• ND for 6LoWPAN has been specified in
draft-ietf-6lowpan-nd (work in progress)
Prefix Dissemination

- In normal IPv6 networks RAs are sent to a link based on the information (prefix etc.) configured for that router interface.
- In ND for 6LoWPAN RAs are also used to automatically disseminate router information across multiple hops.
Node Registration

- 6LoWPAN-ND Optimizes only the **host-router** interface
  - RFC4861 = signaling between all neighbors (distributed)
- Nodes register with their neighboring routers
  - Exchange of NR/NC messages
  - Binding table of registered nodes kept by the router
- Node registration exchange enables
  - Host/router unreachability detection
  - Address resolution (a priori)
  - Duplicate address detection
- Registrations are soft bindings
  - Periodically refreshed with a new NR message
NR/NC Format

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

```
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC) |     Code      |           Checksum            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      TID      |     Status    |P|_____________________________|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|        Binding Lifetime       |     Advertising Interval      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Owner Interface Identifier               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Registration option(s)...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
Typical 6LoWPAN-ND Exchange
The Whiteboard

• The whiteboard is used in the LoWPAN for:
  – Duplicate address detection for the LoWPAN (= prefix)
  – Dealing with mobility (Extended LoWPANs)
  – Short address generation
  – Locating nodes
Extended LoWPANs

- Extended LoWPANs consist of two or more LoWPANs:
  - Which share the same IPv6 prefix
  - Which are connected together by a backbone link
- Whiteboards are synchronized over the backbone link
Routing - RPL
Implementation of a Routing Functionality using RPL

- RPL: Routing Protocol for Low-Power and Lossy Networks
- Application in Sensornetworks
  - Optimized for many-to-one communication and networks with high packet error rate
- Only for IPv6 specified
  - IETF Working group ROLL
- Implemented in Contiki 2.5
RPL Functionality

- Target-oriented, directed acyclic graphs (DODAG)
- All nodes contain the route to the DODAG Root
- ICMP Messages:
  - DIO periodical messages: DODAG Information Objects
  - DIS: DODAG Information Solicitation messages
  - Destination Advertisement Object (DAO) - used to propagate destination information upwards along the DODAG.
- DIO period increases exponentially until a change is detected (< overhead).
- Different RPL networks choose different objective functions.
- Node Rank: Defines a node's relative position within a DODAG with respect to the DODAG root.

ETX Metric – node rank (Contiki 2.5)
Comparison between RPL and AODV

Packet delivery ratio vs. node-gateway distance in a metering network [4]

Average end-to-end delay of inward traffic vs. nodes’ distance to the gateway
Bibliography


Additional References:
http://www.contiki-os.org/, Adam Dunkels et al. [Stand: 18.01.2012].
https://github.com/mysmartgrid/hexabus/, GitHub Inc. [Stand: 30.01.2012].