Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

6LoWPAN

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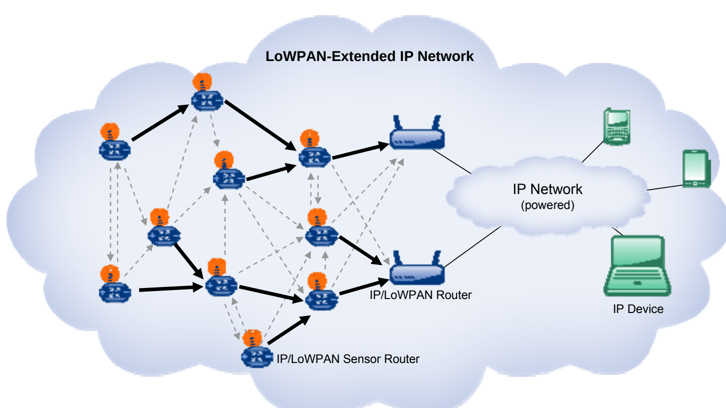
2007 - The IP/USN Arrives



IEEE 802.15.4 – The New IP Link

- http://www.ietf.org/internet-drafts/draft-ietf-6lowpan-format-13.txt
  - Please refer to the internet draft / RFCs for definitive reference
- 1% of 802.11 power, easier to embed, as easy to use.

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THE Question

If Wireless Sensor Networks represent a future of "billions of information devices embedded in the physical world,"

why don't they run ***THE*** standard internetworking protocol?

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The Answer

They should

- Substantially advances the state-of-the-art in both domains.
- Implementing IP requires tackling the general case, not just a specific operational slice
  - Interoperability with all other potential IP network links
  - Potential to name and route to any IP-enabled device within security domain
  - Robust operation despite external factors
    - Coexistence, interference, errant devices, ...
- While meeting the critical embedded wireless requirements
  - High reliability and adaptability
  - Long lifetime on limited energy
  - Manageability of many devices
  - Within highly constrained resources

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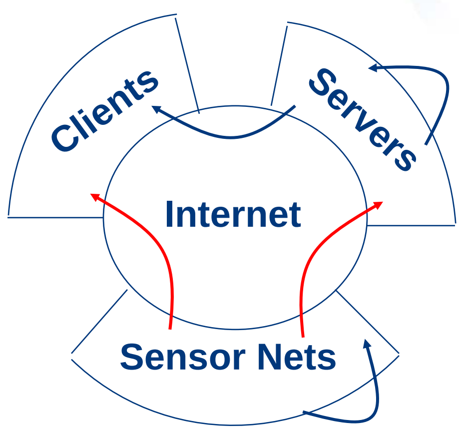
Wireless Sensor Networks
The Next Tier



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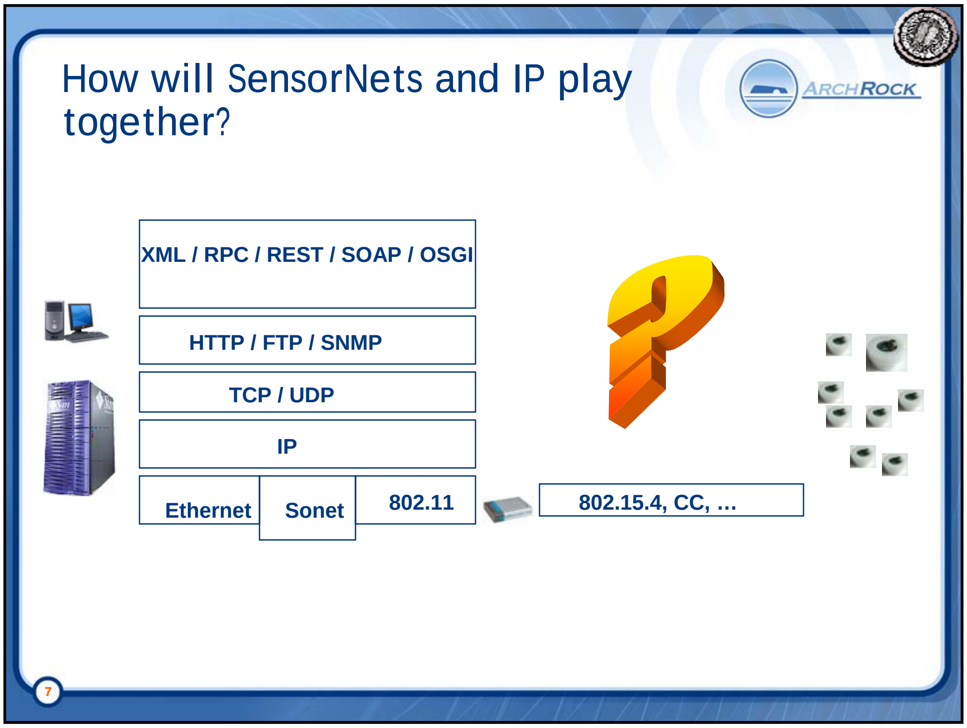
How will SensorNets and IP play together?
ArchRock
XML / RPC / REST / SOAP / OSGI
HTTP / FTP / SNMP
TCP / UDP
IP
Ethernet
Sonet
802.11
802.15.4, CC, …
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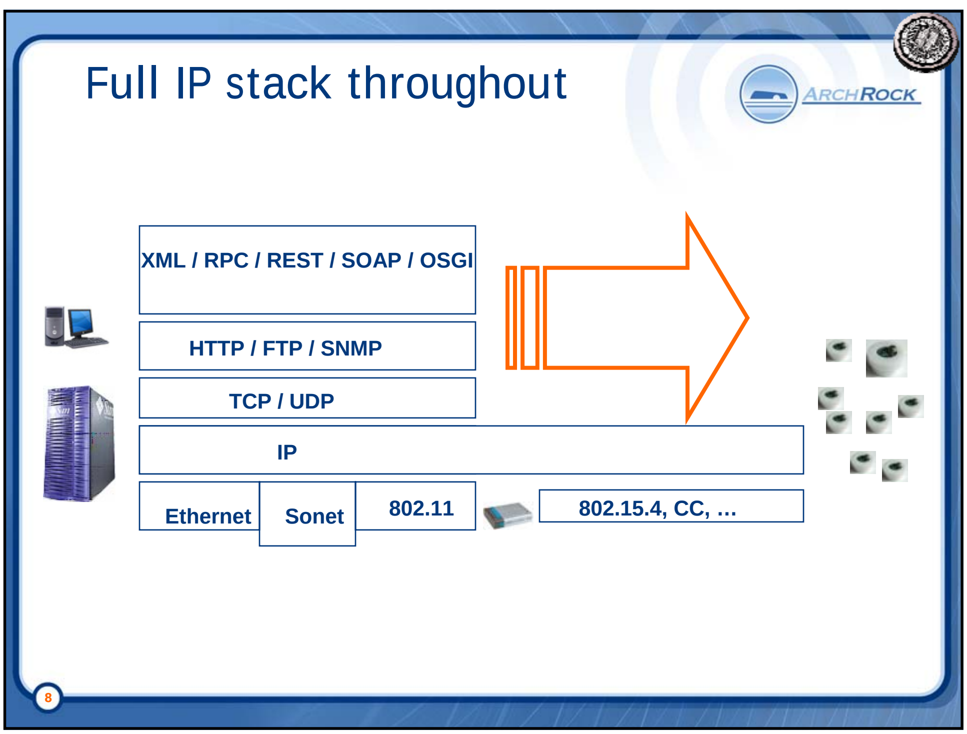
Full IP stack throughout
ArchRock
XML / RPC / REST / SOAP / OSGI
HTTP / FTP / SNMP
TCP / UDP
IP
Ethernet
Sonet
802.11
802.15.4, CC, …
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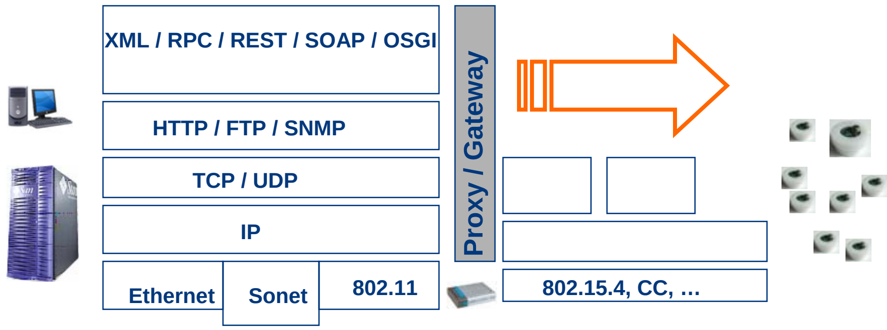
Edge Network Approach

ARCHROCK



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"Hacking it in" may not be so bad

ARCHROCK

- Security
  - No IP to the nodes, attacks have to get through the gateway or be physically close
- Namespace management
  - Name nodes, networks, services
- Mask intermittent connectivity
  - Terminate IP on the powered side
  - Loosely couple, energy aware protocols on the other
- Distillation proxies
  - Small binary packets where constrained
  - Expanded to full text, XML, HTML, web services
- Mobility, Aggregate communication, …
- Rich suite of networking techniques in the Patch unimpeded by the "ossification" of the core

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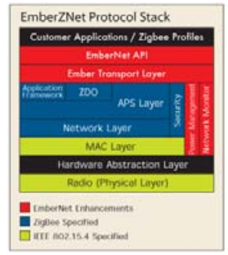
SensorNets need the Wisdom of the "Internet Architecture"

- **Design for change!**
- Network protocols must work over a wide variety of links
  - Links will evolve
- Network protocols must work for a variety of applications
  - Applications will evolve
- **Provide only simple primitives**
  - Don't confuse the networking standard with a programming methodology
- Don't try to lock-in your advantage in the spec
- Open process
- Rough consensus AND running code



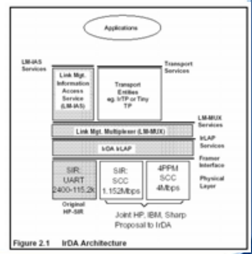


Figure 2.1 IrDA Architecture

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Characteristics of SensorNets?

- *Not Universal pt-pt file transfer and keystrokes between hosts!*
- Aggregate communication
  - dissemination, data collection, aggregation
- Resource constraints
  - Limited bandwidth, limited storage, limited energy
- In-network processing and storage
  - Really
- Intermittent connectivity
  - Low-power operation, out of range, obstructions
- Communicate with data or logical services, not just devices
  - Datacentric
- Mobility
  - Devices moving, tags, networks moving through networks

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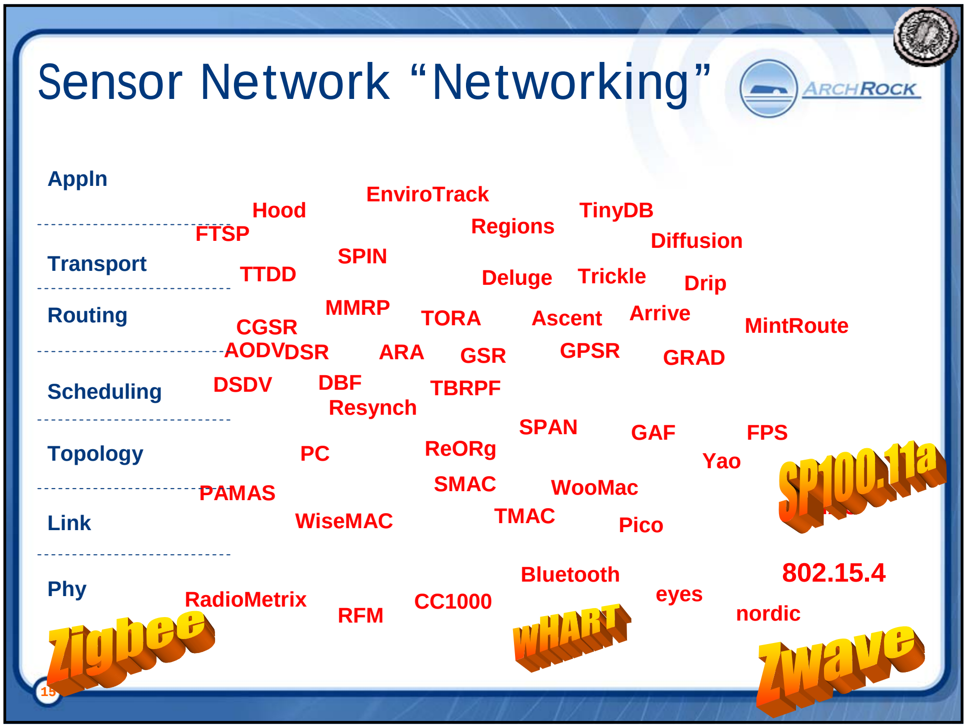
Where has Internet Architecture Struggled?

- Aggregate communication => Multicast
- Resource constraints => QoS, DIFFSERV
- In-network processing and storage => ActiveNets
- Intermittent connectivity => DTN
- Communicate with data or logical services, not just devices => URNs (DHTs?)
- Mobility => MobileIP, MANET
- … but never underestimate IP

Facing these challenges

- Today, we use a wide range of ad hoc, application specific techniques in the SensorNet patch
  - Zillion different low-power MACs
  - Many link-specific, app-specific multihop routing protocols
  - Epidemic dissemination, directed diffusion, synopsis diffusion, …
  - All sorts of communication scheduling and power management techniques
- Building consensus and influencing the future internet architecture



Many Advantages of IP

- **Extensive interoperability**
  - Other wireless embedded 802.15.4 network devices
  - Devices on any other IP network link (WiFi, Ethernet, GPRS, Serial lines, …)
- **Established security**
  - Authentication, access control, and firewall mechanisms
  - Network design and policy determines access, not the technology
- **Established naming, addressing, translation, lookup, discovery**
- **Established proxy architectures for higher-level services**
  - NAT, load balancing, caching, mobility
- **Established application level data model and services**
  - HTTP/HTML/XML/SOAP/REST, Application profiles
- **Established network management tools**
  - Ping, Traceroute, SNMP, … OpenView, NetManager, Ganglia, …
- **Transport protocols**
  - End-to-end reliability in addition to link reliability
- **Most "industrial" (wired and wireless) standards support an IP option**

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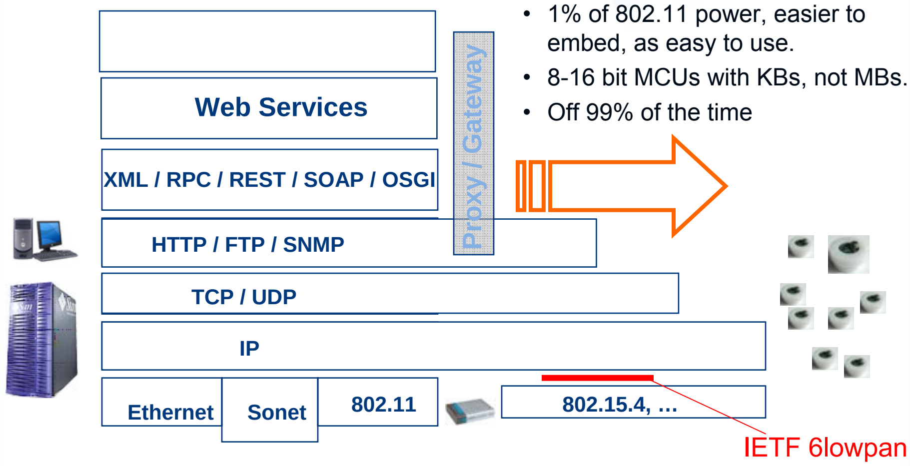
Making sensor nets make sense

LoWPAN – 802.15.4

- 1% of 802.11 power, easier to embed, as easy to use.
- 8-16 bit MCUs with KBs, not MBs.
- Off 99% of the time



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Leverage existing standards, rather than "reinventing the wheel"

- RFC 768 UDP - User Datagram Protocol [1980]
- RFC 791 IPv4 – Internet Protocol [1981]
- RFC 792 ICMPv4 – Internet Control Message Protocol [1981]
- RFC 793 TCP – Transmission Control Protocol [1981]
- RFC 862 Echo Protocol [1983]
- RFC 1101 DNS Encoding of Network Names and Other Types [1989]
- RFC 1191 IPv4 Path MTU Discovery [1990]
- RFC 1981 IPv6 Path MTU Discovery [1996]
- RFC 2131 DHCPv4 - Dynamic Host Configuration Protocol [1997]
- RFC 2375 IPv6 Multicast Address Assignments [1998]
- RFC 2460 IPv6 [1998]
- RFC 2463 ICMPv6 - Internet Control Message Protocol for IPv6 [1998]
- RFC 2765 Stateless IP/ICMP Translation Algorithm (SIIT) [2000]
- RFC 3068 An Anycast Prefix for 6to4 Relay Routers [2001]
- RFC 3307 Allocation Guidelines for IPv6 Multicast Addresses [2002]
- RFC 3315 DHCPv6 - Dynamic Host Configuration Protocol for IPv6 [2003]
- RFC 3484 Default Address Selection for IPv6 [2003]
- RFC 3587 IPv6 Global Unicast Address Format [2003]
- RFC 3819 Advice for Internet Subnetwork Designers [2004]
- RFC 4007 IPv6 Scoped Address Architecture [2005]
- RFC 4193 Unique Local IPv6 Unicast Addresses [2005]
- RFC 4291 IPv6 Addressing Architecture [2006]

- Proposed Standard - "Transmission of IPv6 Packets over IEEE 802.15.4 Networks"

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Key Factors for IP over 802.15.4

- Header
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Options and capabilities already well-defines
  - Various protocols to establish routing tables
- Energy calculations and 6LoWPAN impact

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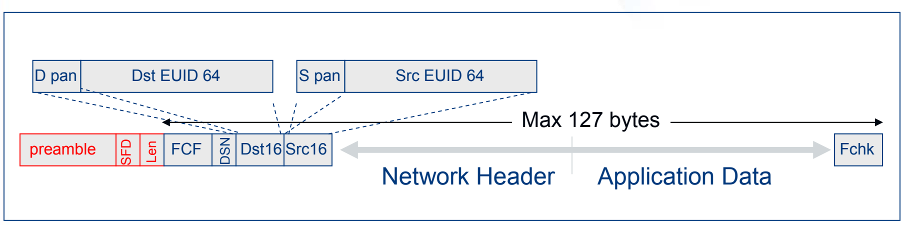
IEEE 802.15.4 Frame Format



- Low Bandwidth (250 kbps), low power (1 mW) radio
- Moderately spread spectrum (QPSK) provides robustness
- Simple MAC allows for general use
  - Many TinyOS-based protocols (MintRoute, LQI, BVR, …), TinyAODV, Zigbee, SP100.11, Wireless HART, …
  - 6LoWPAN => IP
- Choice among many semiconductor suppliers
- Small Packets to keep packet error rate low and permit media sharing

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RFC 3189 – "Advice for Internet Sub-Network Designers"

ARCHROCK

- Total end-to-end interactive response time should not exceed human perceivable delays
- Lack of broadcast capability impedes or, in some cases, renders some protocols inoperable (e.g. DHCP). Broadcast media can also allow efficient operation of multicast, a core mechanism of IPv6
- Link-layer error recovery often increases end-to-end performance. However, it should be lightweight and need not be perfect, only good enough
- Sub-network designers should minimize delay, delay variance, and packet loss as much as possible
- Sub-networks operating at low speeds or with small MTUs should compress IP and transport-level headers (TCP and UDP)

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6LoWPAN Format Design

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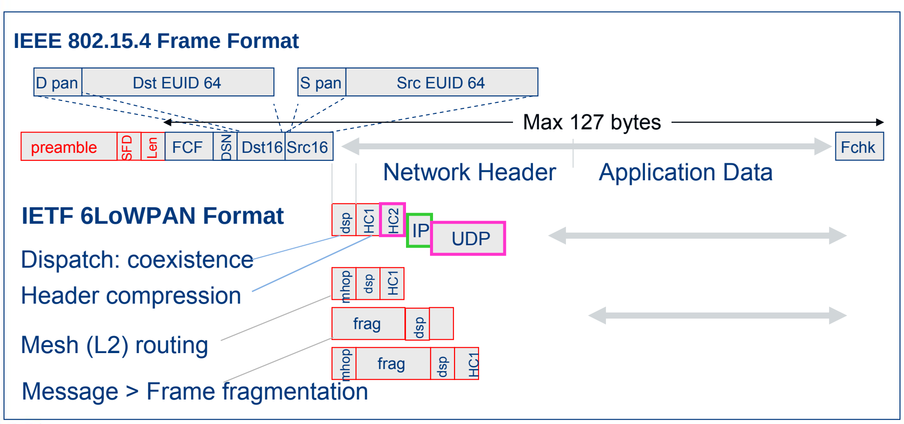
- Orthogonal stackable header format
- Almost no overhead for the ability to interoperate and scale.
- Pay for only what you use



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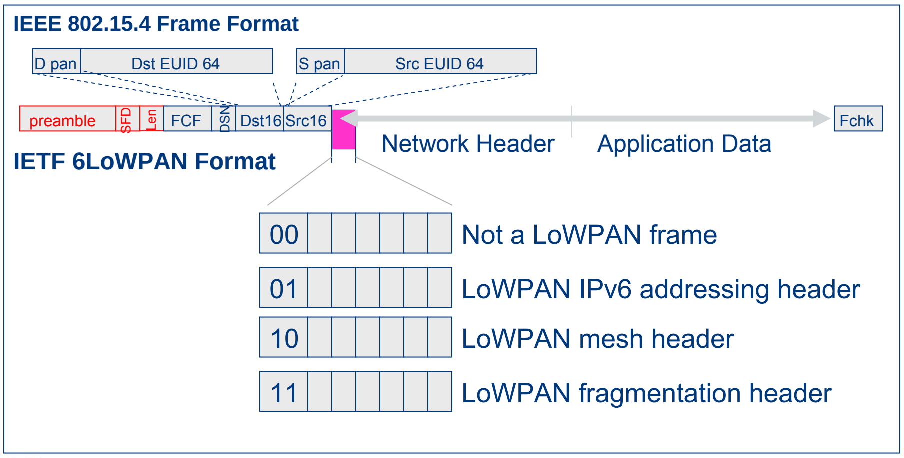
6LoWPAN – The First Byte

- Coexistence with other network protocols over same link
- Header dispatch - understand what's coming



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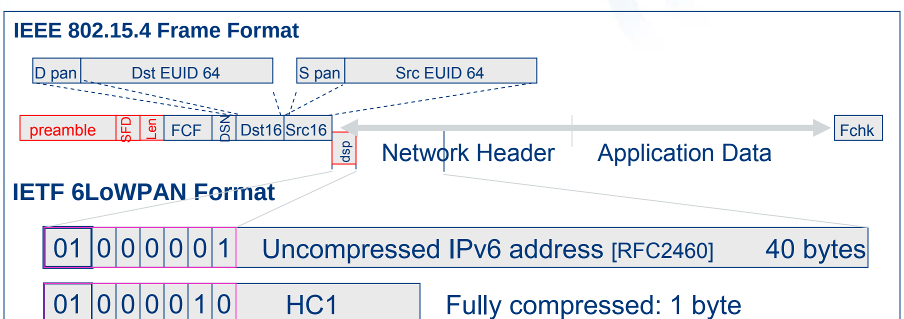
6LoWPAN – IPv6 Header



Source address	: derived from link address
Destination address	: derived from link address
Traffic Class & Flow Label	: zero
Next header	: UDP, TCP, or ICMP

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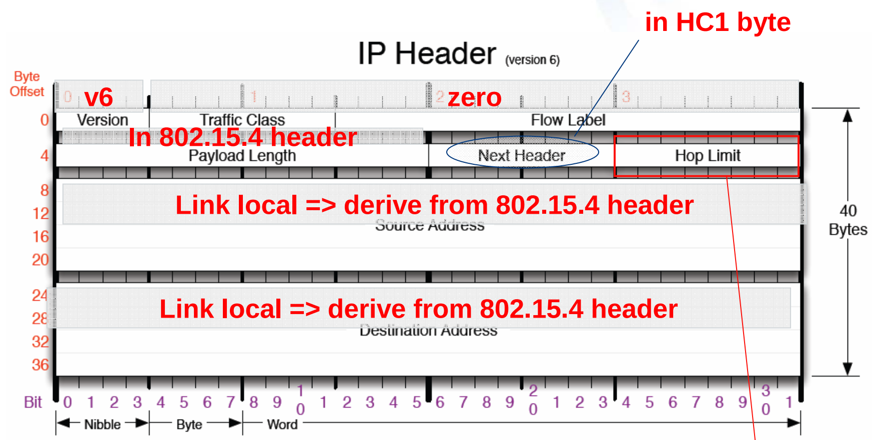
IPv6 Header Compression



- http://www.visi.com/~mjb/Drawings/IP_Header_v6.pdf

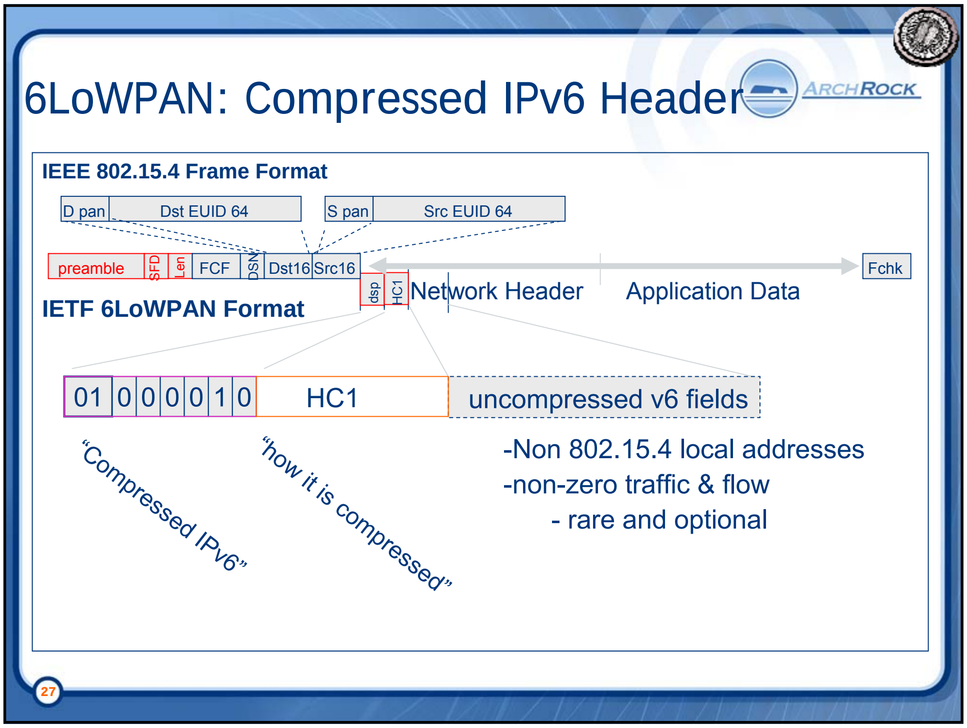
HC1 Compressed IPv6 Header

- Source prefix compressed (to L2)
- Source interface identifier compressed (to L2)
- Destination prefix compressed (to L2)
- Destination interface identified compressed (to L2)
- Traffic and Flow Label zero (compressed)
- Next Header
  - 00 uncompressed, 01 UDP, 10 TCP, 11 ICMP
- Additional HC2 compression header follows

HC1 | Zero or more uncompressed fields follow in order

0 7

- IPv6 address <prefix64 || interface id> for nodes in 802.15.4 subnet derived from the link address.
  - PAN ID maps to a unique IPv6 prefix
  - Interface identifier generated from EUID64 or Pan ID & short address
- Hop Limit is the only incompressible IPv6 header field


6LoWPAN: Compressed IPv6 Header
ArchRock
IEEE 802.15.4 Frame Format
D pan
Dst EUID 64
S pan
Src EUID 64
preamble
SFD
Len
FCF
DSN
Dst16
Src16
Fchk
dsp
HC1
Network Header
Application Data
IETF 6LoWPAN Format
01 0 0 0 0 1 0
HC1
uncompressed v6 fields
"Compressed IPv6"
"how it is compressed"
-Non 802.15.4 local addresses
-non-zero traffic & flow
- rare and optional
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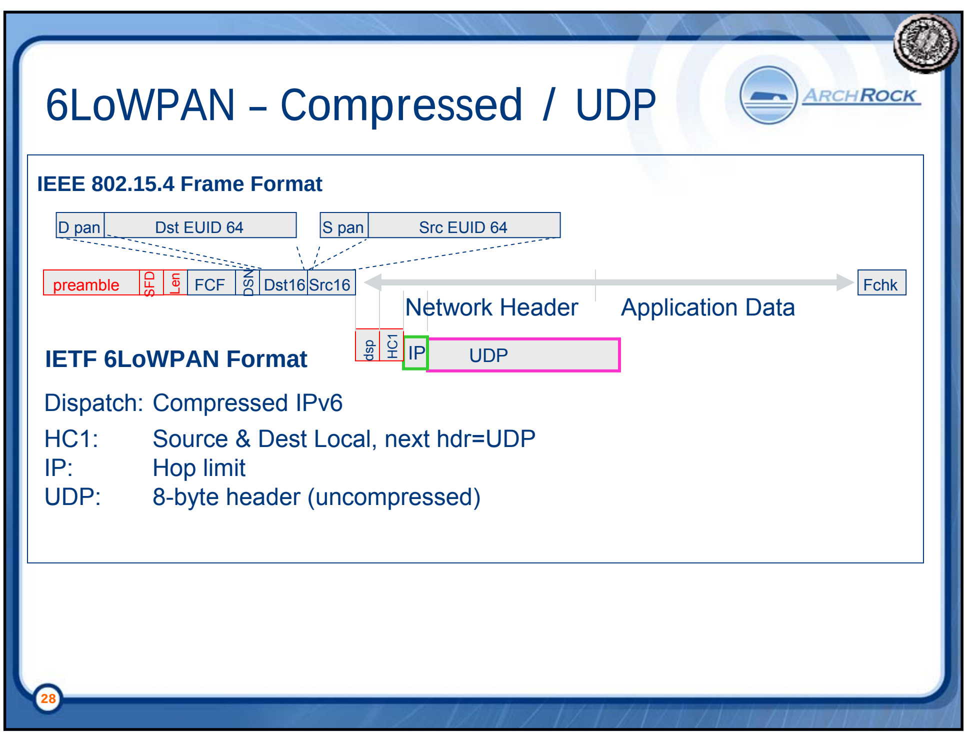
6LoWPAN – Compressed / UDP
ArchRock
IEEE 802.15.4 Frame Format
D pan
Dst EUID 64
S pan
Src EUID 64
preamble
SFD
Len
FCF
DSN
Dst16
Src16
Fchk
Network Header
Application Data
IETF 6LoWPAN Format
dsp
HC1
IP
UDP
Dispatch: Compressed IPv6
HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: 8-byte header (uncompressed)
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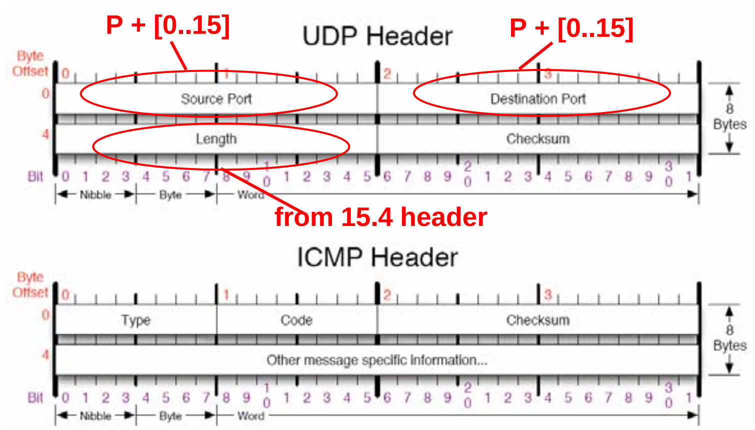
L4 – UDP/ICMP Headers (8 bytes)



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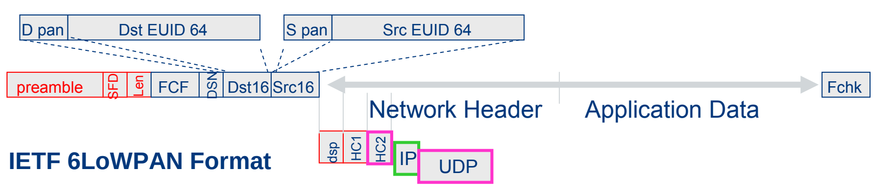
6LoWPAN – Compressed / Compressed UDP

IEEE 802.15.4 Frame Format



Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP

IP: Hop limit

UDP: HC2+3-byte header (compressed)

source port = P + 4 bits, p = 61616 (0xF0B0)

destination port = P + 4 bits

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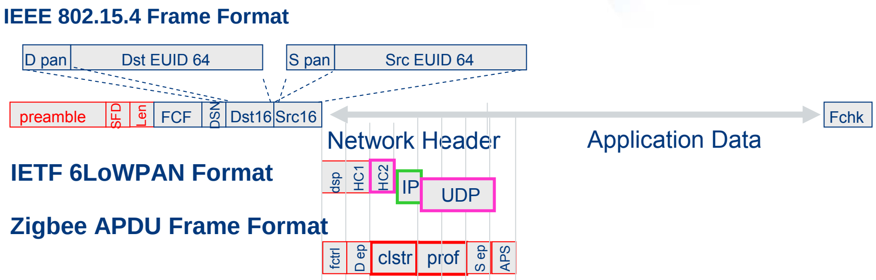
6LoWPAN / Zigbee Comparison

ARCHROCK



fctrl: Frame Control bit fields
D ep: Destination Endpoint (like UDP port)
clstr: cluster identifier
prof: profile identifier
S ep: Source Endpoint
APS: APS counter (sequence to prevent duplicates)
*** Typical configuration. Larger and smaller alternative forms exist.

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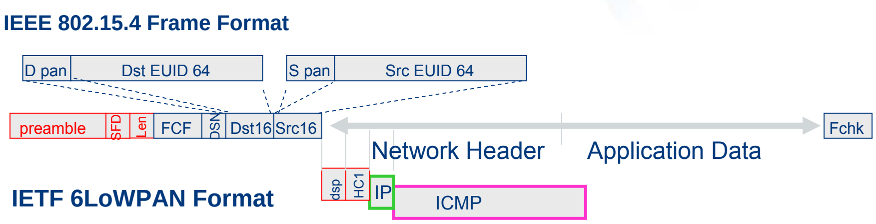
6LoWPAN – Compressed / ICMP

ARCHROCK



Dispatch: Compressed IPv6
HC1: Source & Dest Local, next hdr=ICMP
IP: Hops Limit
ICMP: 8-byte header

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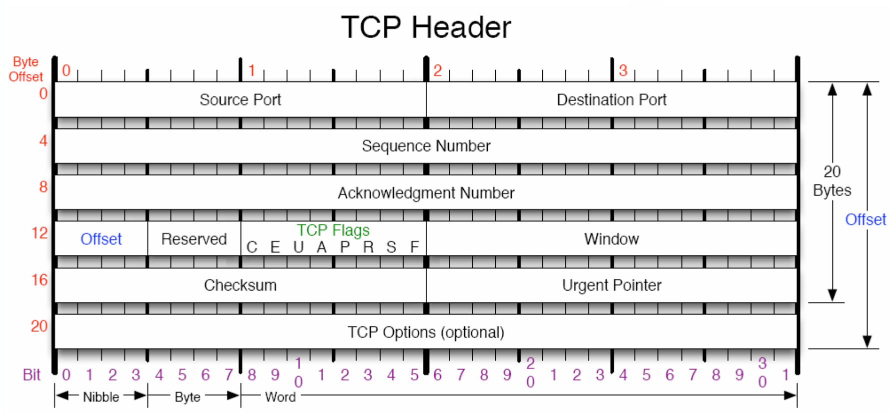
L4 – TCP Header (20 bytes)



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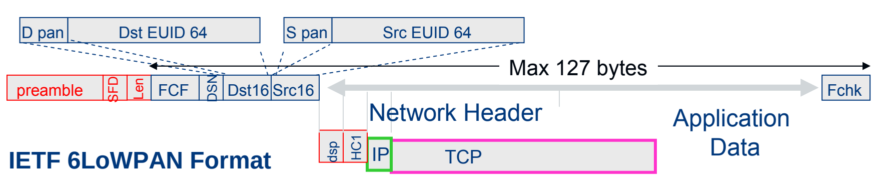
6LoWPAN – Compressed / TCP

IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=TCP
IP: Hops Limit
TCP: 20-byte header

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Key Points for IP over 802.15.4

- Header overhead
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE std]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Localized internet of overlapping subnets
- Energy calculations and 6LoWPAN impact

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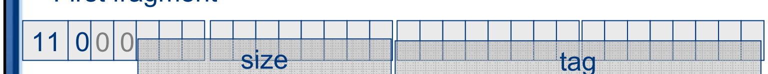
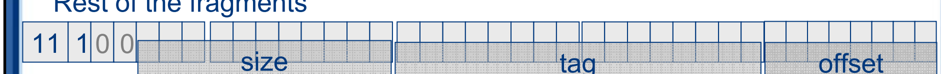
Fragmentation

- All fragments of an IP packet carry the same “tag”
  - Assigned sequentially at source of fragmentation
- Each specifies tag, size, and position
- Do not have to arrive in order
- Time limit for entire set of fragments (60s)

First fragment



Rest of the fragments



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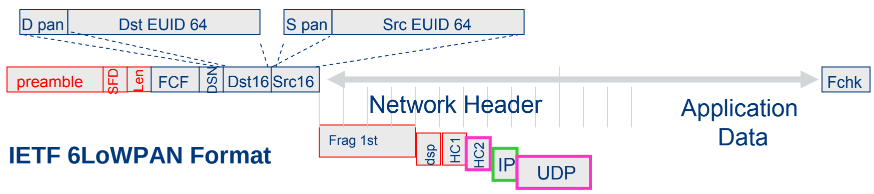
6LoWPAN – Example
Fragmented / Compressed / Compressed UDP

IEEE 802.15.4 Frame Format



Dispatch: Fragmented, First Fragment, Tag, Size

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2+3-byte header (compressed)

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“Mesh Under” Header

- Originating node and Final node specified by either short (16 bit) or EUID (64 bit) 802.15.4 address
  - In addition to IP source and destination
- Hops Left (up to 14 hops, then add byte)
- Mesh protocol determines node at each mesh hop

LoWPAN mesh header

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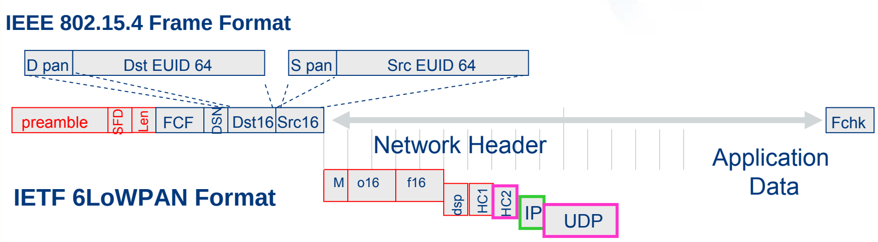
6LoWPAN – Example
Mesh / Compressed / Compressed UDP



Dispatch: Mesh under, orig short, final short

Mesh: orig addr, final addr

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2+3-byte header

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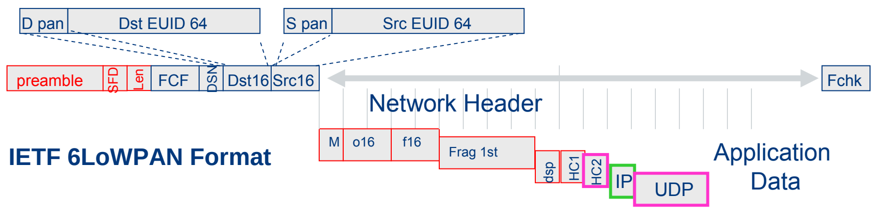
6LoWPAN – Example
Mesh / Fragmented / Compressed / UDP

IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

Dispatch: Mesh under, orig short, final short

Mesh: orig addr, final addr

Dispatch: Fragmented, First Fragment, Tag, Size

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2 + 3-byte header

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IP-Based Multi-Hop Routing

- IP has always done “multi-hop”
  - Routers connect sub-networks to one another
  - The sub-networks may be the same or different physical links
- Routers utilize routing tables to determine which node represents the “next hop” toward the destination
- Routing protocols establish and maintain proper routing tables
  - Routers exchange messages using more basic communication capabilities
  - Different routing protocols are used in different situations
  - RIP, OSPF, IGP, BGP, AODV, OLSR, …
- IP routing over 6LoWPAN links does not require additional header information at 6LoWPAN layer

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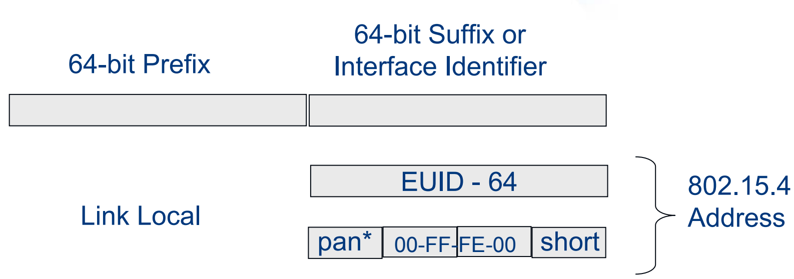
IPv6 Address Auto-Configuration



PAN* - complement the “Universal/Local" (U/L) bit, which is the next-to-lowest order bit of the first octet

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Energy Efficiency

- Battery capacity typically rated in Amp-hours
  - Chemistry determines voltage
  - AA Alkaline: ~2,000 mAh = 7,200,000 mAs
  - D Alkaline: ~15,000 mAh = 54,000,000 mAs
- Unit of effort: mAs
  - multiply by voltage to get energy (joules)
- Lifetime
  - 1 year = 31,536,000 secs
  - ⇒ 228 uA average current on AA
  - ⇒ 72,000,000 packets TX or Rcv @ 100 uAs per TX or Rcv
  - ⇒ 2 packets per second for 1 year if no other consumption

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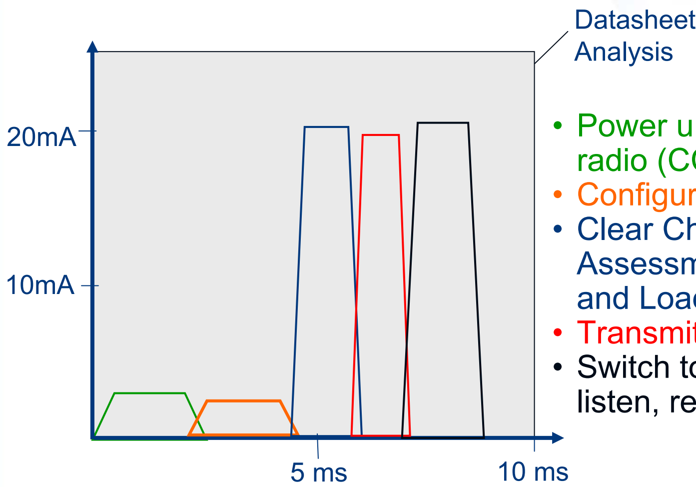
Energy Profile of a Transmission



- Power up oscillator & radio (CC2420)
- Configure radio
- Clear Channel Assessment, Encrypt and Load TX buffer
- Transmit packet
- Switch to rcv mode, listen, receive ACK

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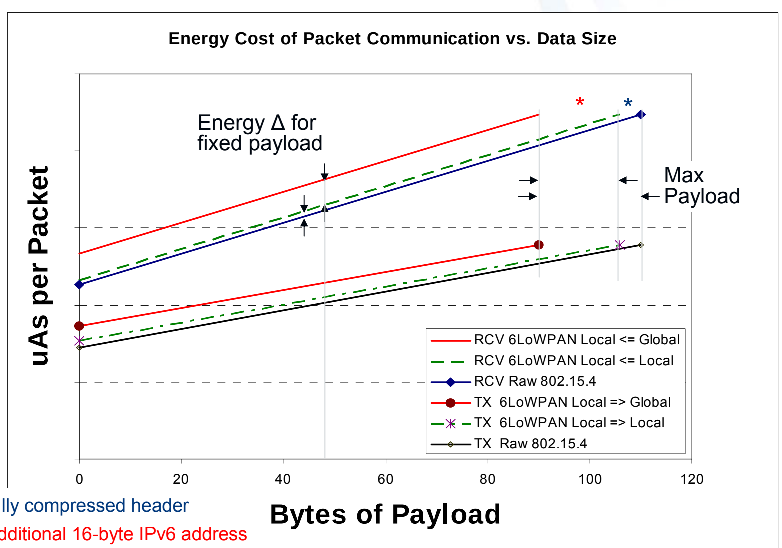
Low Impact of 6LoWPAN on Lifetime – Comparison to *Raw* 802.15.4 Frame



* fully compressed header
* additional 16-byte IPv6 address

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Rest of the Energy Story

- Energy cost of communication has four parts
  - Transmission
  - Receiving
  - Listening (staying ready to receive)
  - Overhearing (packets destined for others)
- The increase in header size to support IP over 802.15.4 results in a small increase in transmit and receive costs
  - Both infrequent in long term monitoring
- The dominant cost is listening! – regardless of format.
  - Can only receive if transmission happens when radio is on, “listening”
  - Critical factor is not collisions or contention, but when and how to listen
  - Preamble sampling, low-power listening and related listen “all the time” in short gulps and pay extra on transmission
  - TDMA, FPS, TSMP and related communication scheduling listen only now and then in long gulps. Transmission must wait for listen slot. Clocks must be synchronized. Increase delay to reduce energy consumption.

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Conclusion

- 6LoWPAN turns IEEE 802.15.4 into the next IP-enabled link
- Provides open-systems based interoperability among low-power devices over IEEE 802.15.4
- Provides interoperability between low-power devices and existing IP devices, using standard routing techniques
- Paves the way for further standardization of communication functions among low-power IEEE 802.15.4 devices
- Offers watershed leverage of a huge body of IP-based operations, management and communication services and tools
- Great ability to work within the resource constraints of low-power, low-memory, low-bandwidth devices like WSN

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Frequently Asked Questions

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How does 6LoWPAN compare to Zigbee, SP100.11a, …?

- Zigbee
  - only defines communication between 15.4 nodes ("layer 2" in IP terms), not the rest of the network (other links, other nodes).
  - defines new upper layers, all the way to the application, similar to IRDA, USB, and Bluetooth, rather utilizing existing standards.
  - Specification still in progress (Zigbee 2006 incompatible with Zigbee 1.0. Zigbee 2007 in progress.) Lacks a transport layer.
- SP100.11a
  - seeks to address a variety of links, including 15.4, 802.11, WiMax, and future "narrow band frequency hoppers".
  - Specification is still in the early stages, but it would seem to need to redefine much of what is already defined with IP.
  - Much of the emphasis is on the low-level media arbitration using TDMA techniques (like token ring) rather than CSMA (like ethernet and wifi). This issue is orthogonal to the frame format.
- 6LoWPAN defines how established IP networking layers utilize the 15.4 link.
  - it enables 15.4 ⇔15.4 and 15.4 ⇔non-15.4 communication
  - It enables the use of a broad body of existing standards as well as higher level protocols, software, and tools.
  - It is a focused extension to the suite of IP technologies that enables the use of a new class of devices in a familiar manner.

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Do I need IP for my stand-alone network?

- Today, essentially all computing devices use IP network stacks to communicate with other devices, whether they form an isolated stand-alone network, a privately accessible portion of a larger enterprise, or publicly accessible hosts.
  - When all the devices form a subnet, no routing is required, but everything works in just the same way.
- The software, the tools, and the standards utilize IP and the layers above it, not the particular physical link underneath.
- The value of making it "all the same" far outweighs the moderate overheads.
- 6LoWPAN eliminates the overhead where it matters most.

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Will the "ease of access" with IP mean less security?

- No.
- The most highly sensitive networks use IP internally, but are completely disconnected from all other computers.
- IP networks in all sorts of highly valued settings are protected by establishing very narrow, carefully managed points of interconnection.
  - Firewalls, DMZs, access control lists, …
- Non-IP nodes behind a gateway that is on a network are no more secure than the gateway device. And those devices are typically numerous, and use less than state-of-the-art security technology.
- 802.15.4 provides built-in AES128 encryption which is enabled beneath IP, much like WPA on 802.11.

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Does using 6LoWPAN mean giving up deterministic timing behavior?

- No.
- Use of the 6LoWPAN format for carrying traffic over 802.15.4 links is orthogonal to whether those links are scheduled deterministically.
  - Deterministic media access control (MAC) can be implemented as easily with 6LoWPAN as with any other format.
- There is a long history of such TDMA mechanisms with IP, including Token Ring and FDDI.
  - MAC protocols, such as FPS and TSMP, extend this to a mesh.
  - Ultimately, determinacy requires load limits and sufficient headroom to cover potential losses.
  - Devices using different MACs on the same link (TDMA vs CSMA) may not be able to communicate, even though the packet formats are the same.

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Is 6LoWPAN less energy efficient than proprietary protocols?

- No.
- Other protocols carry similar header information for addressing and routing, but in a more ad hoc fashion.
- While IP requires that the general case must work, it permits extensive optimization for specific cases.
- 6LoWPAN optimizes within the low-power 802.15.4 subnet
  - More costly only when you go beyond that link.
  - Other protocols must provide analogous information (at application level) to instruct gateways.
- Ultimately, the performance is determined by the quality the implementation.
  - With IP's open standards, companies must compete on performance and efficiency, rather than proprietary "lock in"

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Do I need to run IPv6 instead of IPv4 on the rest of my network to use 6LoWPAN?

- No.
- IPv6 and IPv4 work together throughout the world using 4-6 translation.
- IPv6 is designed to support “billions” of non-traditional networked devices and is a cleaner design.
  – Actually easier to support on small devices, despite the larger addresses.
- The embedded 802.15.4 devices can speak IPv6 with the routers to the rest of the network providing 4-6 translation.
  – Such translation is already standardized and widely available.

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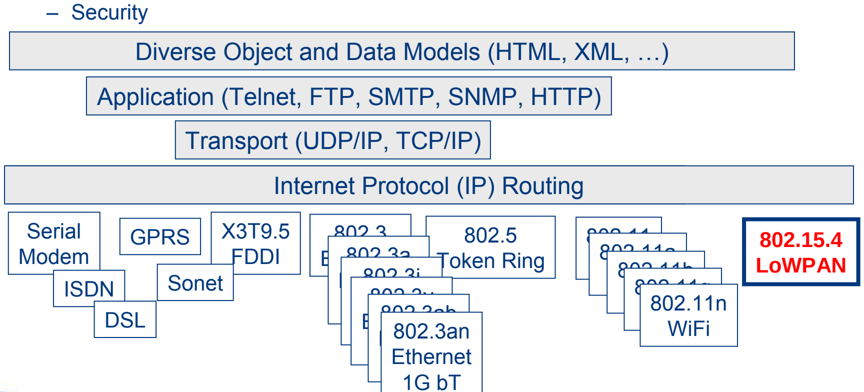
Lesson 1: IP

- Separate the logical communication of information from the physical links that carry the packets.
  – Naming
    - Hostname => IP address => Physical MAC
  – Routing
  – Security



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