

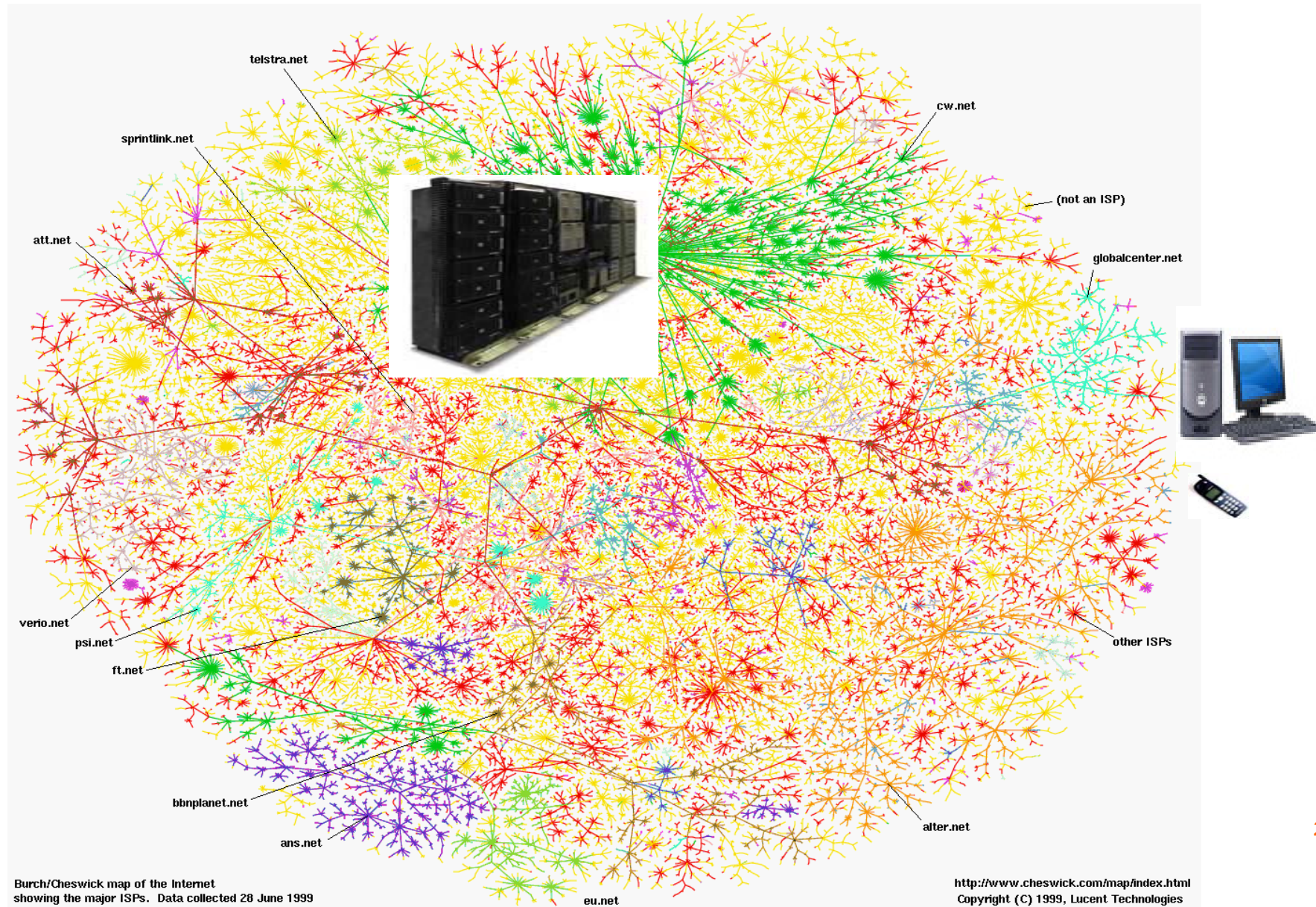


Closing the Cyber-Physical Gap - The Internet of Every Thing

David E. Culler

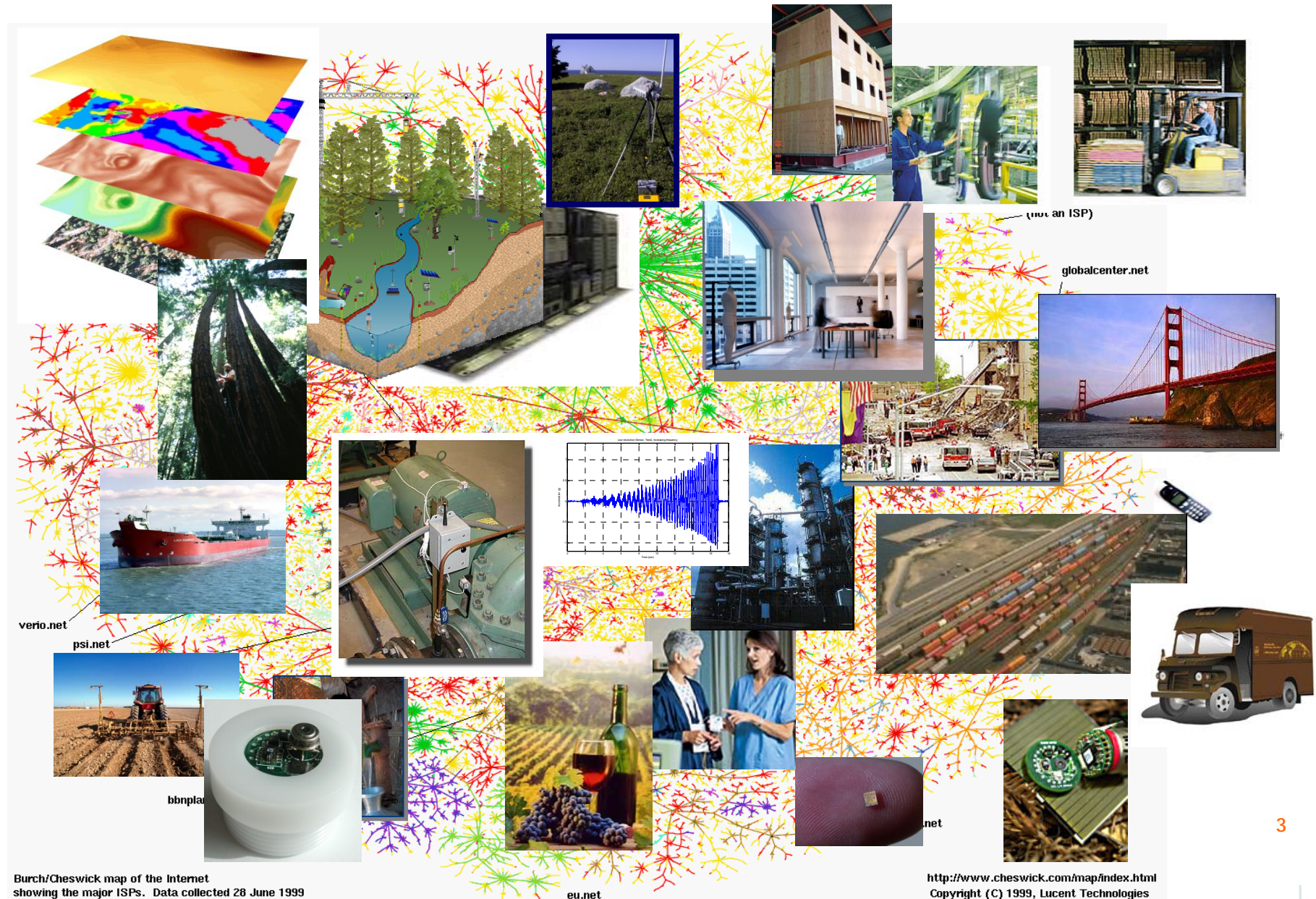
University of California, Berkeley

The Internet - a decade ago





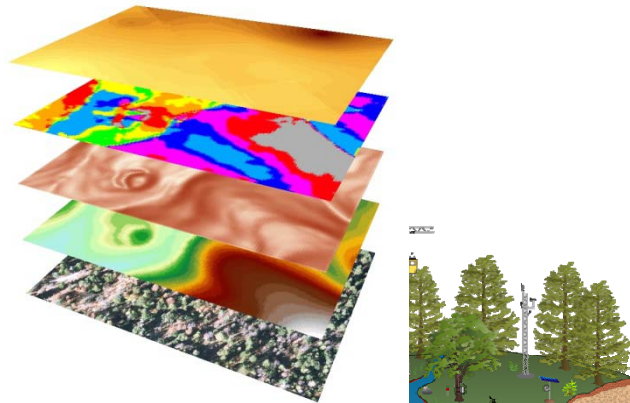
The Internet we envisioned



Burch/Cheswick map of the Internet showing the major ISPs. Data collected 28 June 1999

<http://www.cheswick.com/map/index.html>
Copyright (C) 1999, Lucent Technologies

Why "Real" Information is so Important



Enable New Knowledge



Preventing Failures



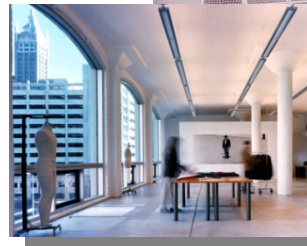
Improve Food & H2O



Save Resources



Improve Productivity



Increase Comfort



Enhance Safety & Security



High-Confidence Transport

Protect Health





Enabling Technology



Microcontroller

Flash Storage

Radio Communication

Sensors

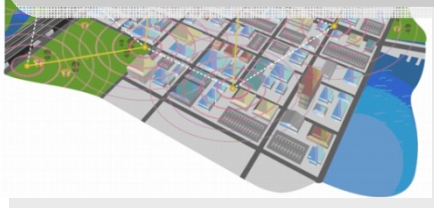
IEEE 802.15.4



Networking in the Physical World

Application Requirements

- Embedding in physical space
- Large numbers of nodes
- Low total cost of ownership

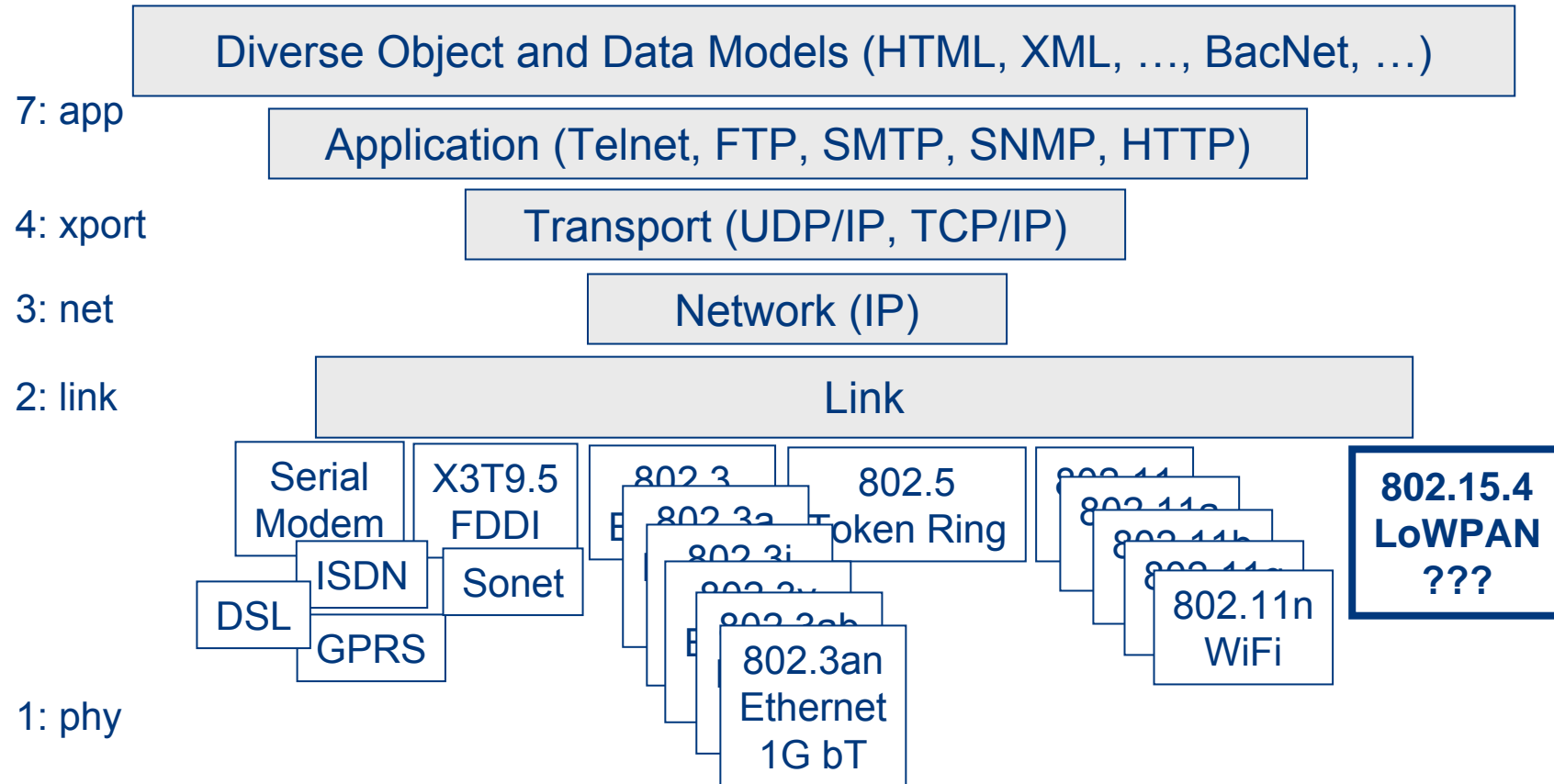


Networking Challenges

- Variable communication
 - Unknown obstacles
 - Variable density and loss
- Constrained resources
 - Limited routing state
 - Limited throughput
 - Limited buffering
- Low power wireless
 - Multihop
 - Low SNR
 - Small MTU



The Internet Architecture





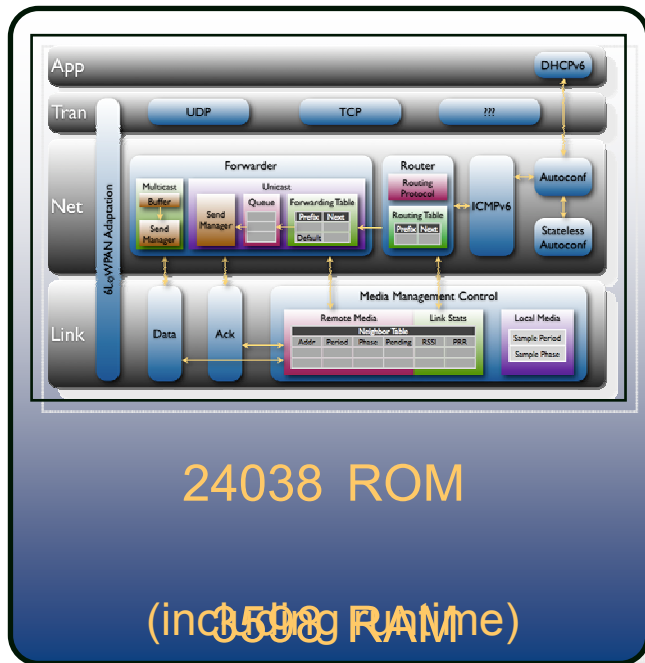
Leading Internet Research Perspective - a decade ago

- “Resource constraints may cause us to give up the layered architecture.”
- “Sheer numbers of devices, and their unattended deployment, will preclude reliance on broadcast communication or the configuration currently needed to deploy and operate networked devices.”
- “There are significant robustness and scalability advantages to designing applications using localized algorithms.”
- “Unlike traditional networks, a sensor node may not need an identity (e.g. address).”
- “It is reasonable to assume that sensor networks can be tailored to the application at hand.”

We were wrong...



Complete IPv6 on “dishwasher-scale” computing and “candy bar” power



* Production implementation on TI msp430/cc2420

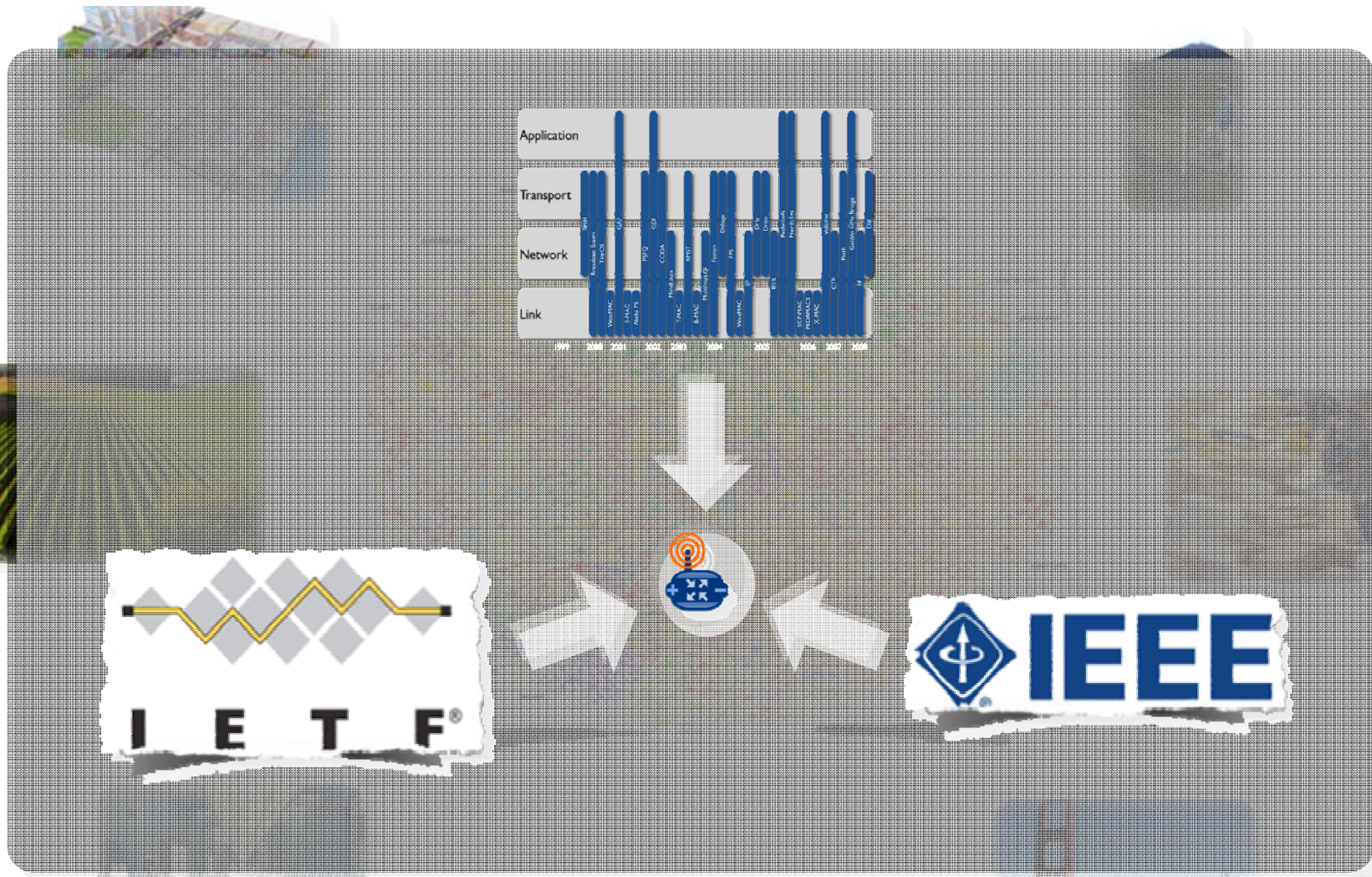
- Footprint, power, packet size, & bandwidth

	ROM	RAM
CC2420 Driver	3149	272
802.15.4 Encryption	1194	101
Media Access Control	330	9
Media Management Control	1348	20
6LoWPAN + IPv6	2550	0
Checksums	134	0
SLAAC	216	32
DHCPv6 Client	212	3
DHCPv6 Proxy	104	2
ICMPv6	522	0
Unicast Forwarder	1158	451
Multicast Forwarder	352	4
Message Buffers	0	2048
Router	2050	106
UDP	450	6
TCP	1674	50



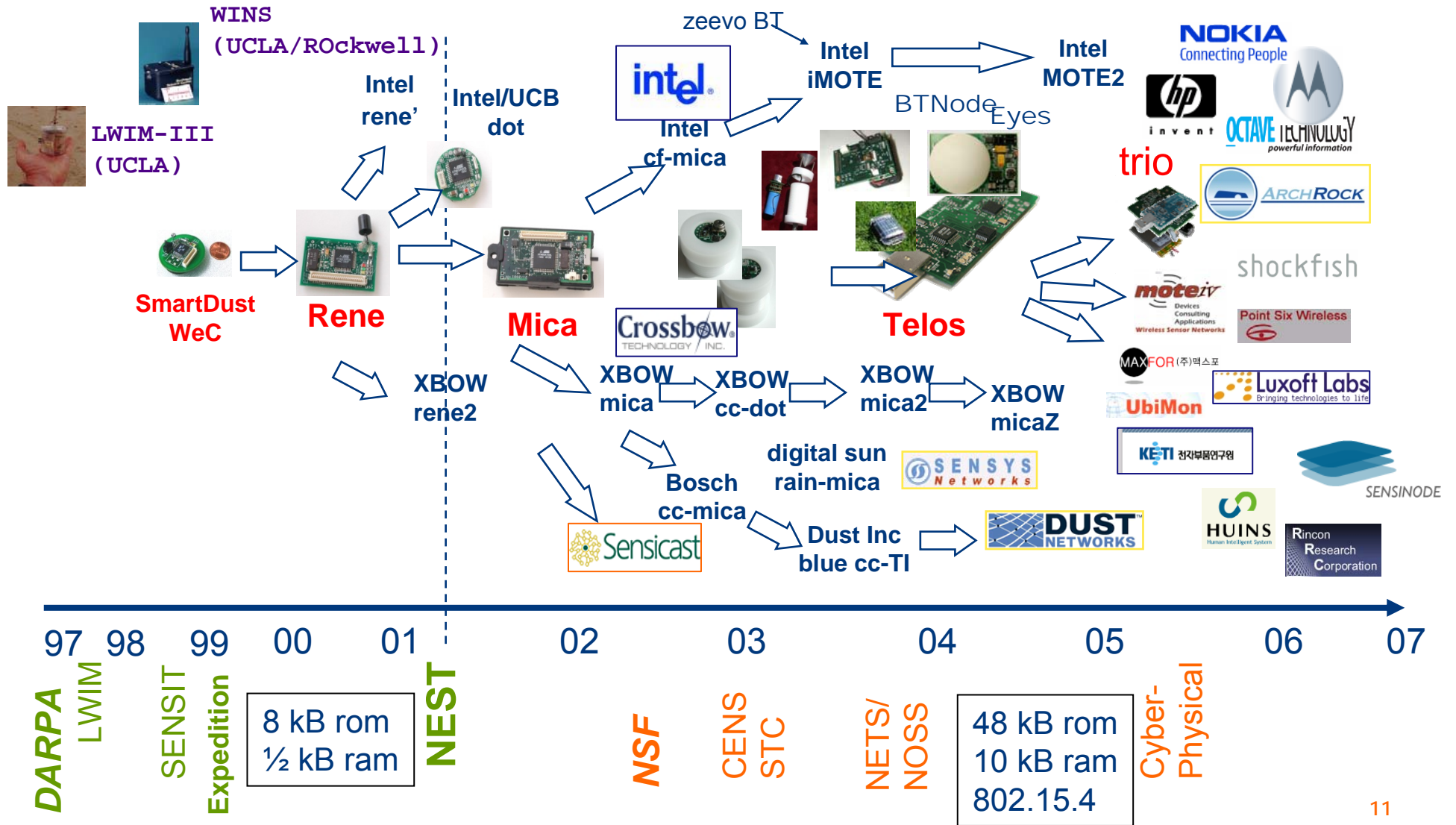


Confluence on three fronts





Mote/TinyOS - rethink from scratch



A Low-Power Standard Link

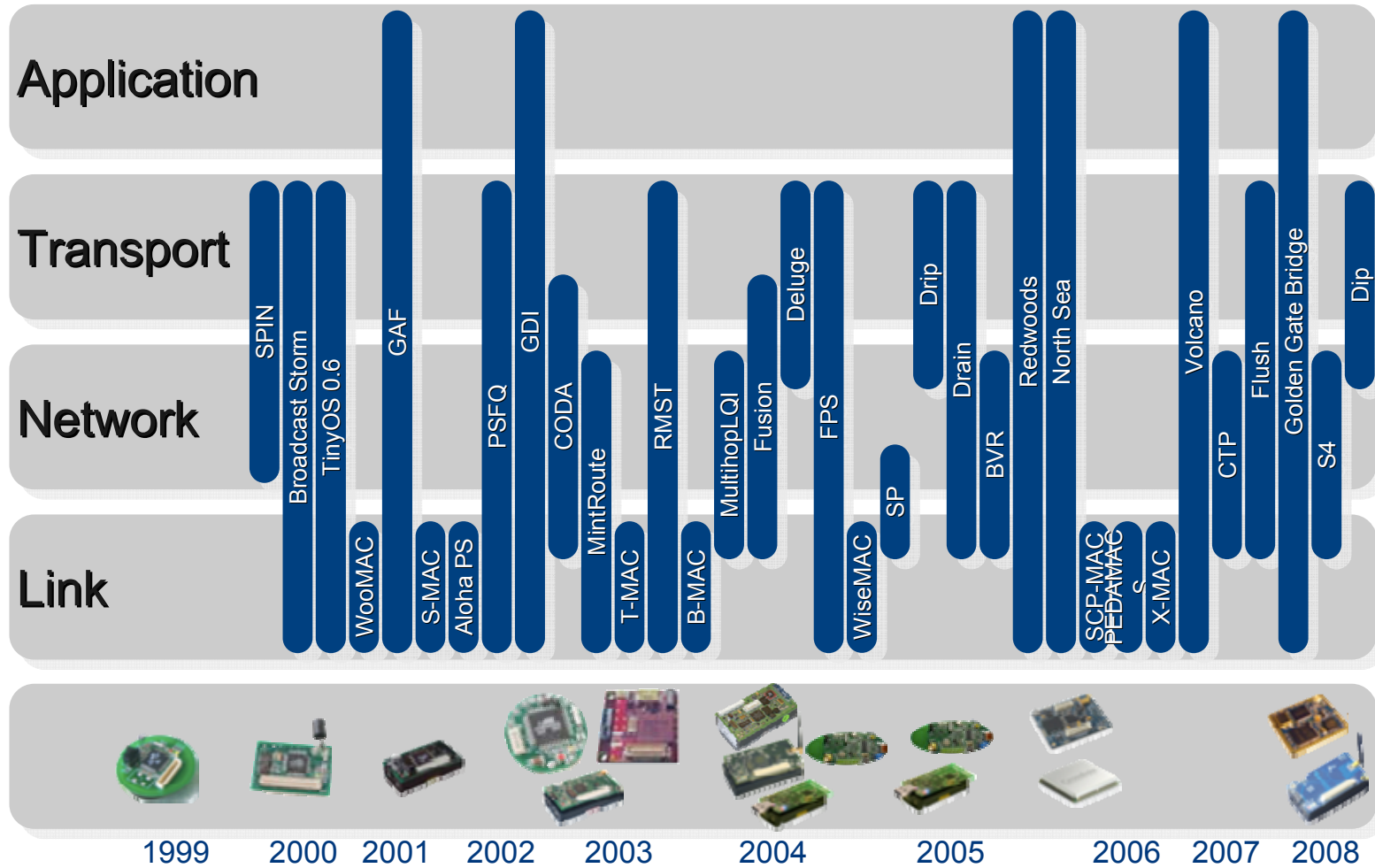


	802.15.4	802.15.1	802.15.3	802.11	802.3
Class	WPAN	WPAN	WPAN	WLAN	LAN
Lifetime (days)	100-1000+	1-7	Powered	0.1-5	Powered
Net Size	65535	7	243	30	1024
BW (kbps)	20-250	720	11,000+	11,000+	100,000+
Range (m)	1-75+	1-10+	10	1-100	185 (wired)
Goals	Low Power, Large Scale, Low Cost	Cable Replacement	Cable Replacement	Throughput	Throughput

- Low Transmit power, Low SNR, modest BW, Little Frames
- Reined in the Phy Chaos, allowed MAC chaos to Reign

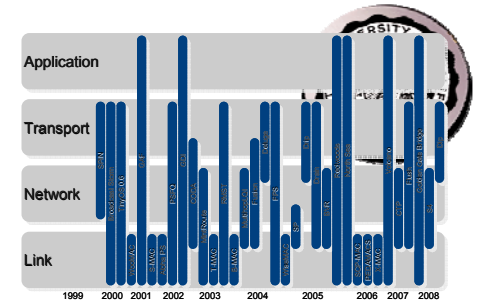


Decade of Networking (sans Architecture)



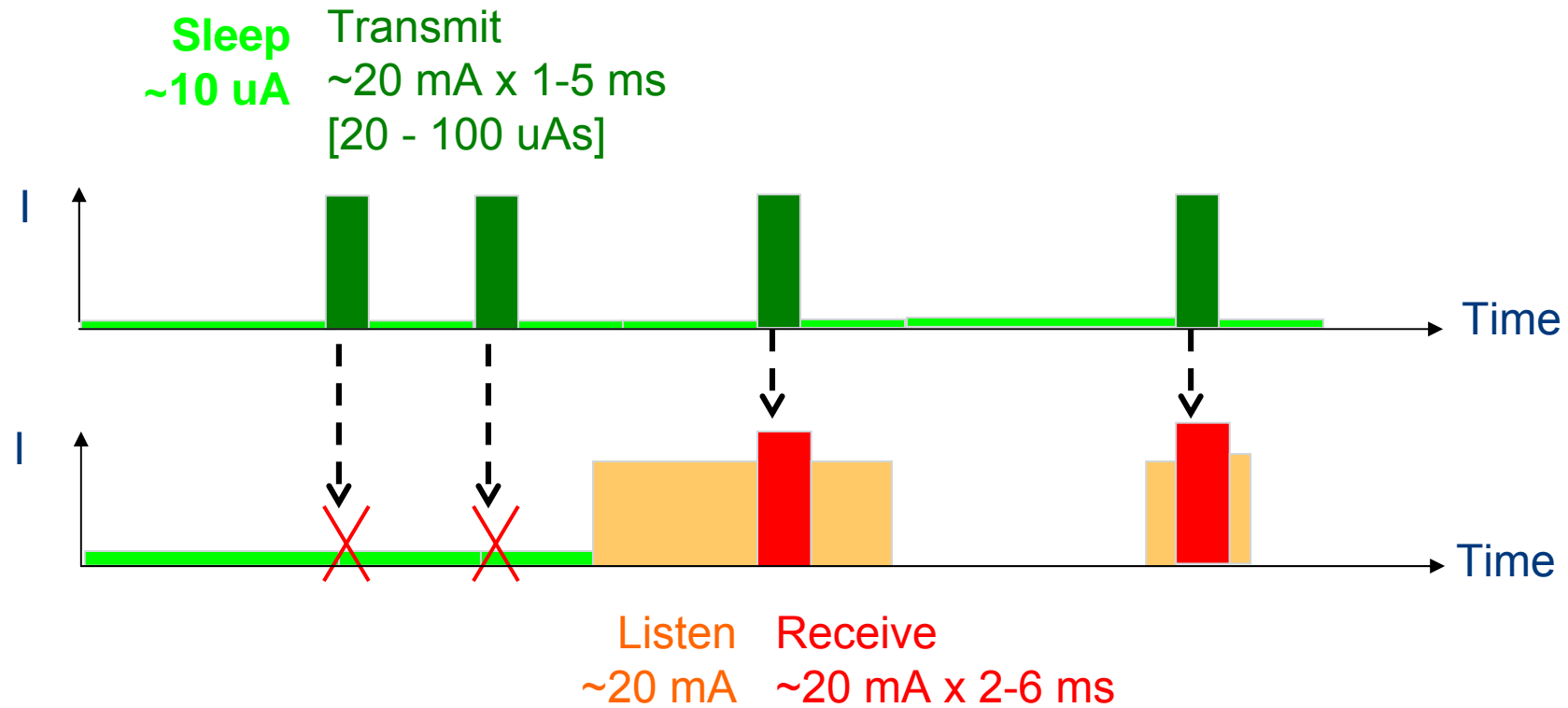
Three Key Developments

- Idle listening
 - Radio power: transmit \approx receive \approx just listening
 - All the energy is consumed by listening for a packet to receive
 - $E = P \cdot \text{Time}$
 - => Turn radio on only when there is something to hear
- Reliable routing on Low-Power & Lossy Links
 - Power, Range, Obstructions => multi-hop
 - Always at edge of SNR => loss happens
 - => monitoring, retransmission, and local rerouting
- Trickle – don't flood (tx rate $< 1/\text{density}$, and $< \text{info change}$)
 - Connectivity is determined by physical points of interest, not network designer. May have huge number of neighbors, so ...
 - never naively respond to a broadcast
 - re-broadcast very very politely



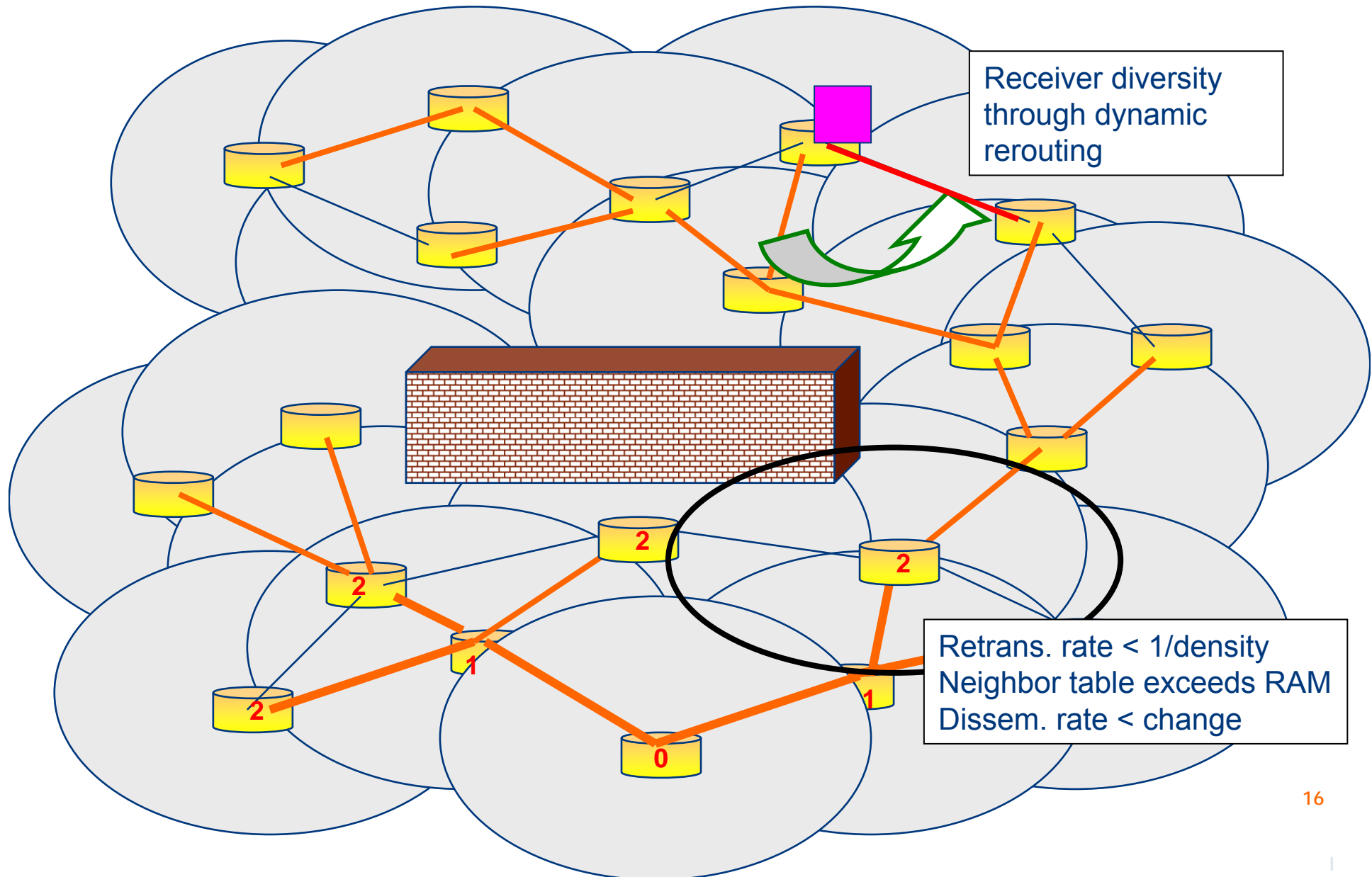


Communication Power - Passive Vigilance

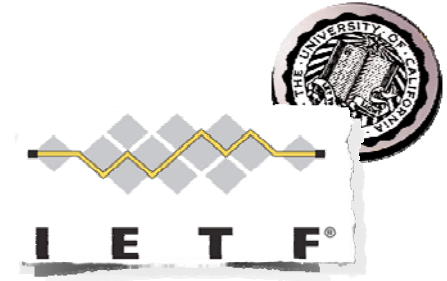




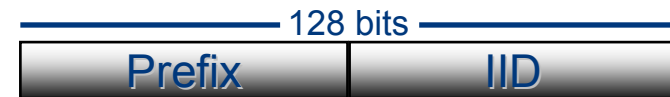
Self-Organized Routing - nutshell



Meanwhile: Key IPv6 Contributions



- Large simple address
 - Network ID + Interface ID
 - Plenty of addresses, easy to allocate and manage
- Autoconfiguration and Management
 - ICMPv6
- Integrated bootstrap and discovery
 - Neighbors, routers, DHCP
- Protocol options framework
 - Plan for extensibility
- Simplify for speed
 - MTU discovery with min
- 6-to-4 translation for compatibility

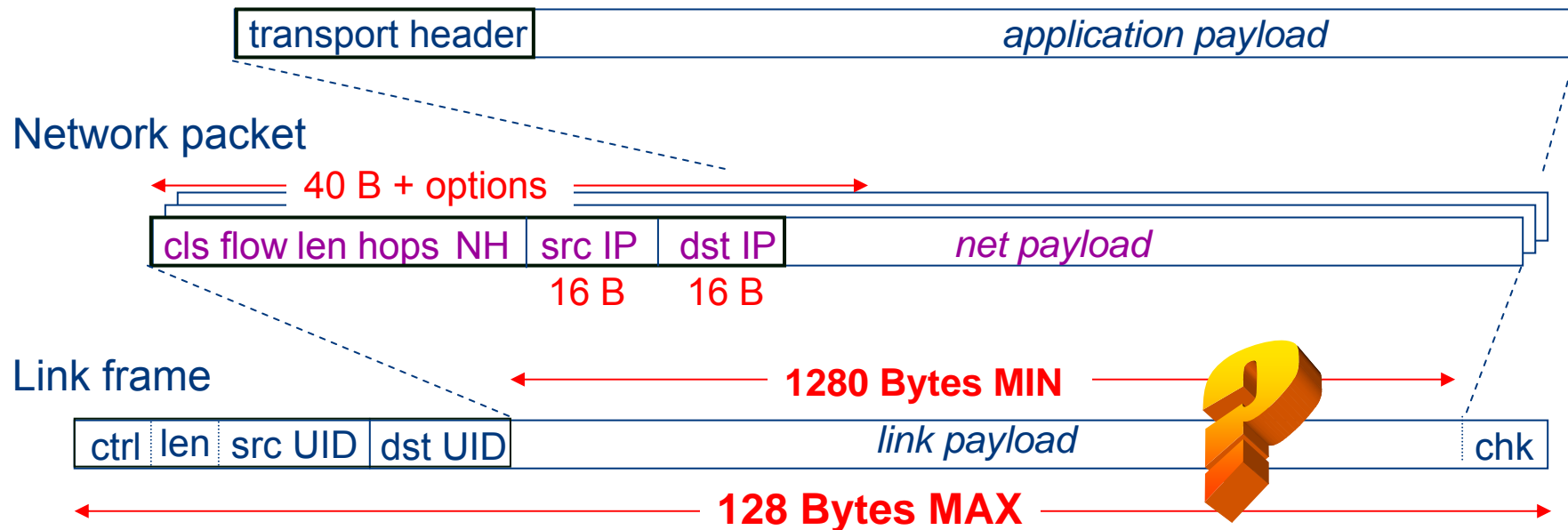




IPv6 over 802.15.4: Not an obvious fit

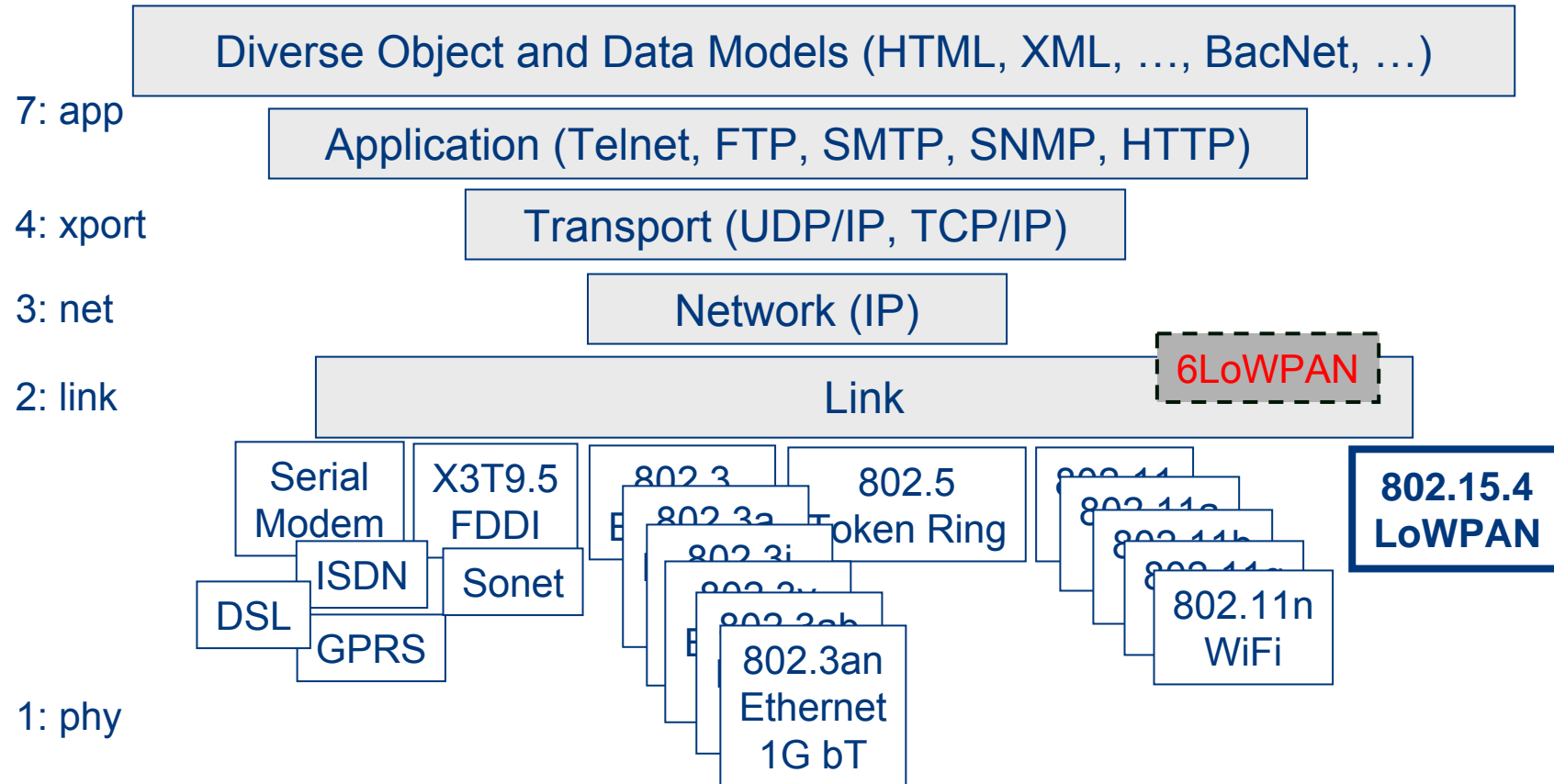
UDP datagram or
TCP stream segment

..., modbus, BacNET/IP, ... , HTML, XML, ..., ZCL





6LoWPAN adaptation layer





6LoWPAN - IP Header Optimization

Network packet



Link frame



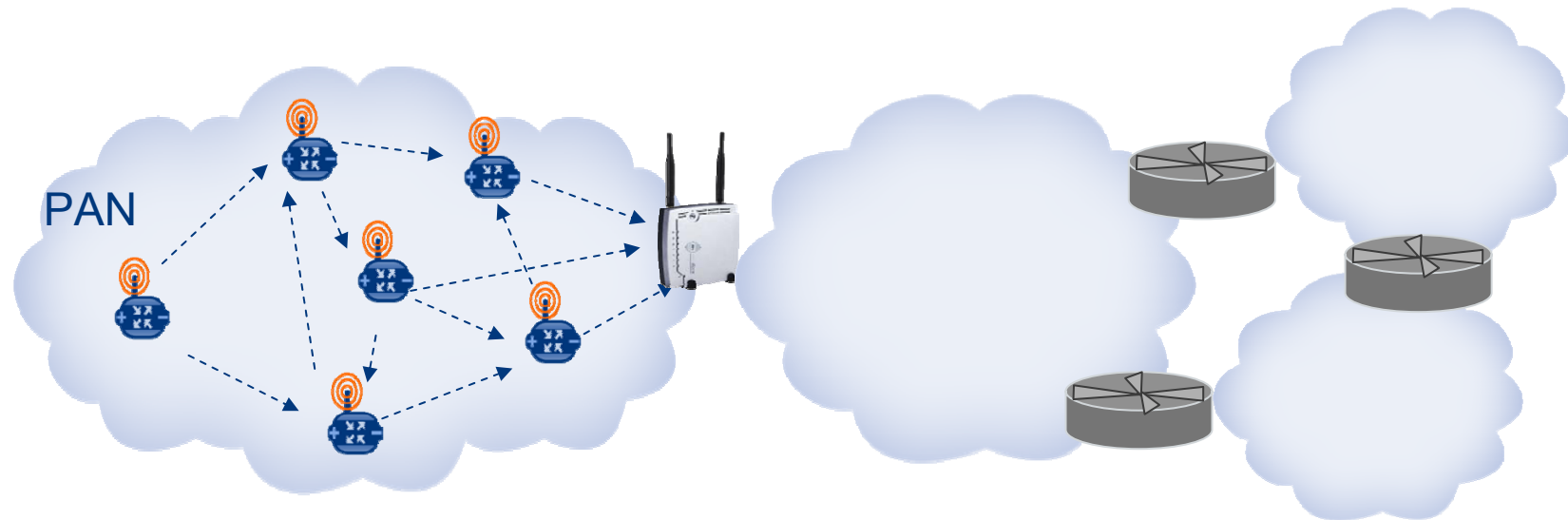
6LoWPAN adaptation header

- Eliminate all fields in the IPv6 header that can be derived from the 802.15.4 header in the common case
 - Source address : derived from link address
 - Destination address : derived from link address
 - Length : derived from link frame length
 - Traffic Class & Flow Label : zero
 - Next header : UDP, TCP, or ICMP
- Additional IPv6 options follow as options





Multi-Hop Communication => Routing



- Short-range radios & Obstructions => Multi-hop Communication is often required
 - i.e. Routing and Forwarding
 - That is what IP does!
- “Mesh-under”: multi-hop communication at the link layer
 - Still needs routing to other links or other PANs
- “Route-over”: IP routing within the PAN => ROLL

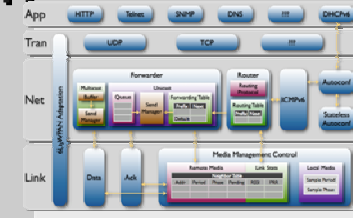


Embedded IPv6 in Concept

Structured Decomposition



Retain strict modularity
Some key cross-layer visibility



IP Link Always On

Retain illusion even when always off



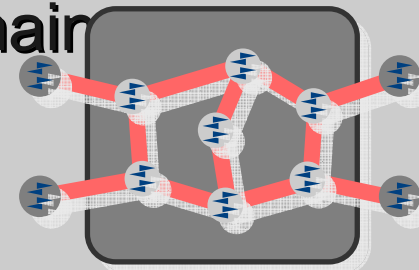
IP Link “Reliable”

Retain best-effort reliability over unreliable links

IP Link Broadcast Domain

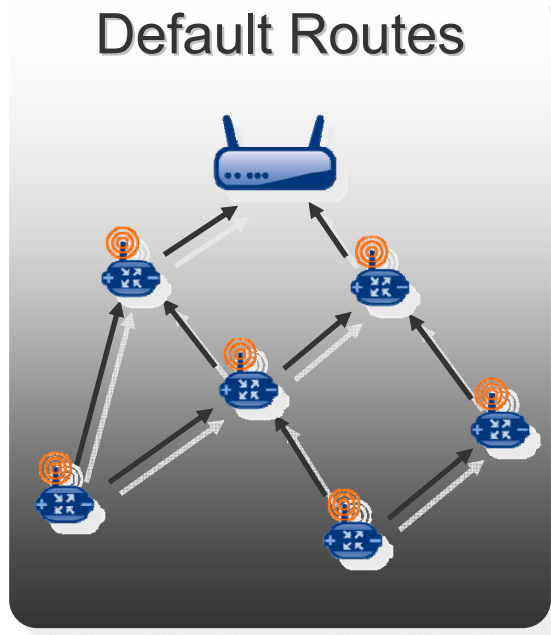


IPv6 can support a semi-broadcast link with few changes





Cross-Fertilization of WSN and IETF ideas



Discovering Links

ICMPv6 Hdr	Router Adv	MHop Info
------------	------------	-----------

Building a Connectivity Graph

Low Routing Cost ↔ High Routing Cost

Routing	
Prefix	Next

Selecting the Next Hop

Routing	
Prefix	Next

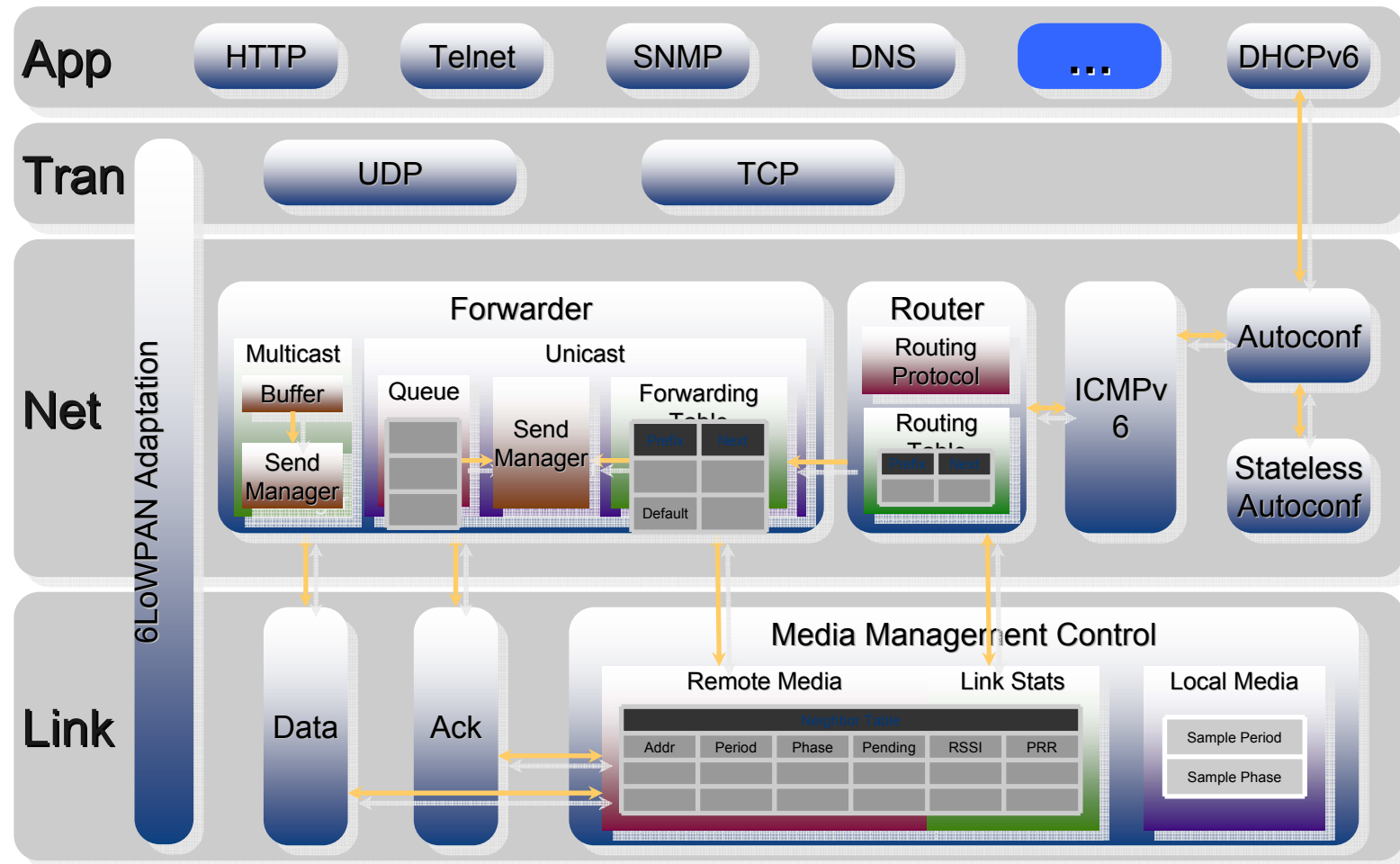
 →

Forwarding	
Prefix	Next
	Default

- Default route
- Hop-by-hop retry
- Reroute on loss

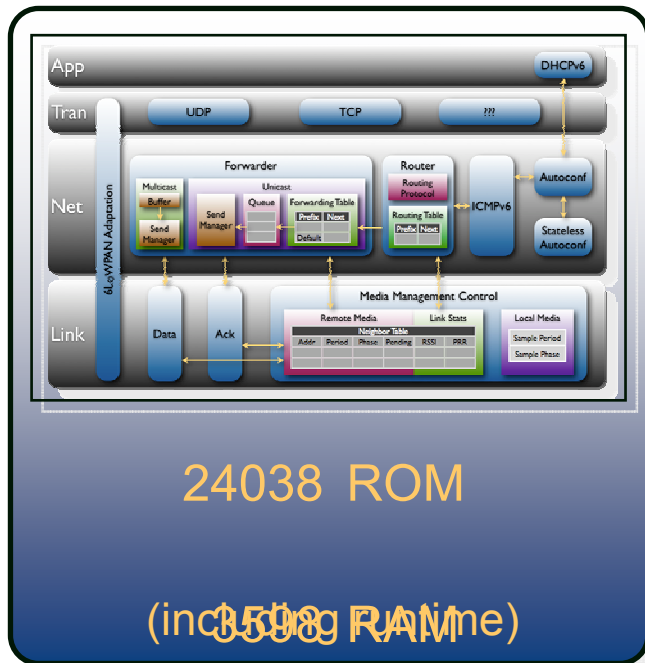


Complete Embedded IPv6 Stack





Adding up the pieces

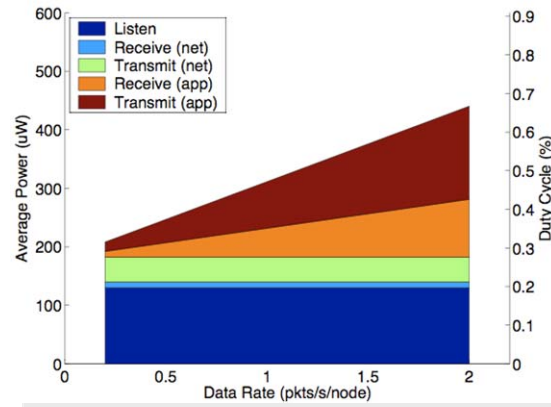
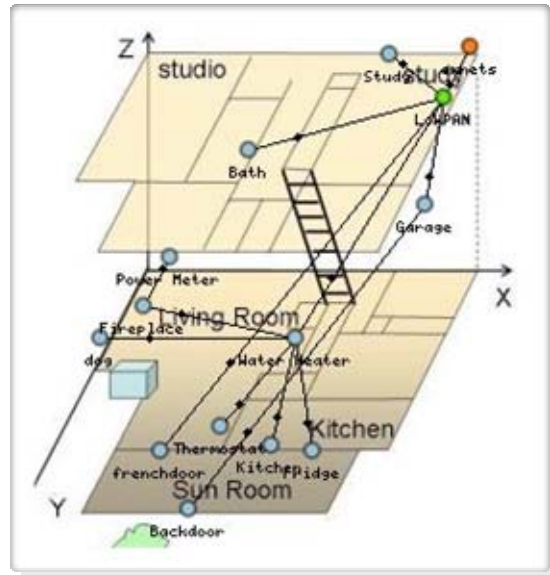


* Production implementation on TI msp430/cc2420

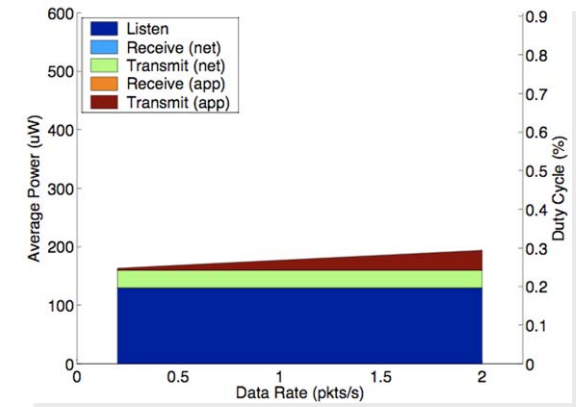
	ROM	RAM
CC2420 Driver	3149	272
802.15.4 Encryption	1194	101
Media Access Control	330	9
Media Management Control	1348	20
6LoWPAN + IPv6	2550	0
Checksums	134	0
SLAAC	216	32
DHCPv6 Client	212	3
DHCPv6 Proxy	104	2
ICMPv6	522	0
Unicast Forwarder	1158	451
Multicast Forwarder	352	4
Message Buffers	0	2048
Router	2050	106
UDP	450	6
TCP	1674	50



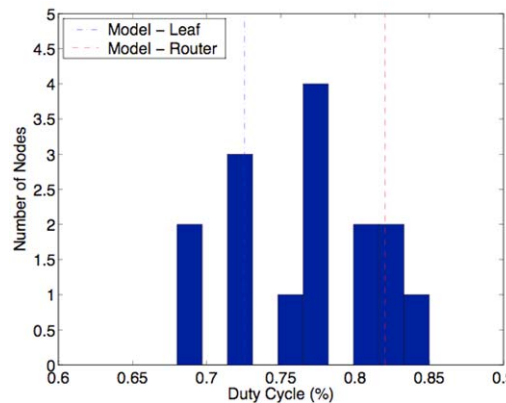
and Power and reliability ...



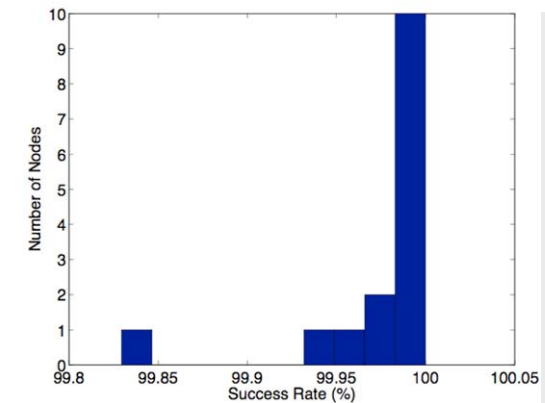
Data Rate Sensitivity (Router)



Data Rate Sensitivity (Edge)



Deployment Duty Cycle

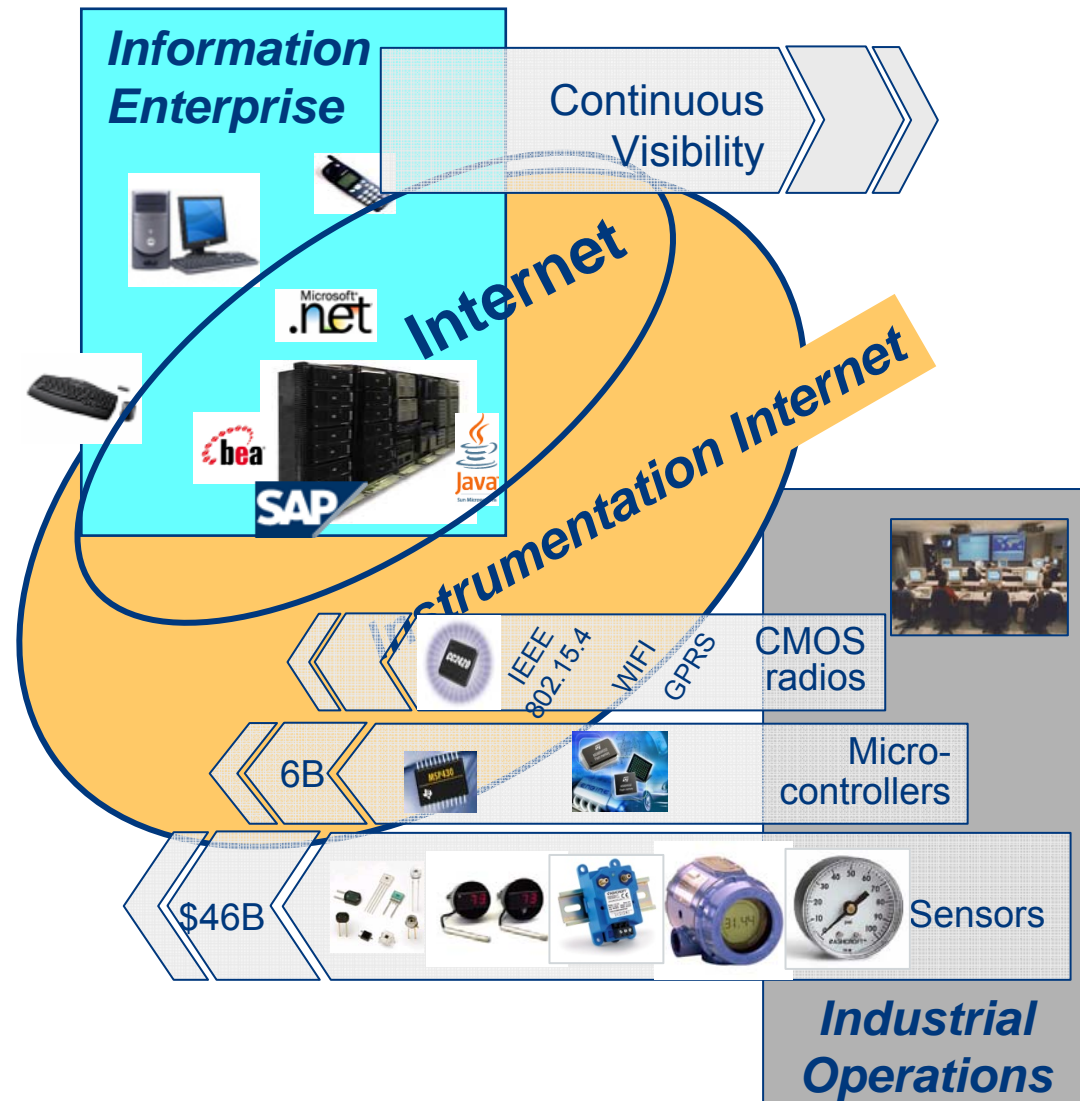


Deployment Reliability













Instrumentation Internet

- **Billions** of devices today sensing their environment
 - Homes, offices, factories, streets, hospitals, autos, ...
 - **Data is dropped** or local
- Demand for **operational visibility** throughout the Enterprise
 - Supply chain, work flow, ...
- Opportunity:
 - **Extend reach** and lower cost through wireless embedded networks
 - **Provide global visibility** by bringing sensors to the IP Network and Web



Most Real World Information goes “down the drain”



											
Security and Access Control	Gas and Electric Usage	Heating, AC, and Ventilation	Water Usage, Temp., Quality	Smoke, Fire, CO, Radon	Smart Appliances	Digital Health Devices	Baby Monitor (Elder care)	Entertainment System	Video Game Consoles	Exercise Units	Clocks and Calendars



The Web Today

Integrates the World's Human Generated Information

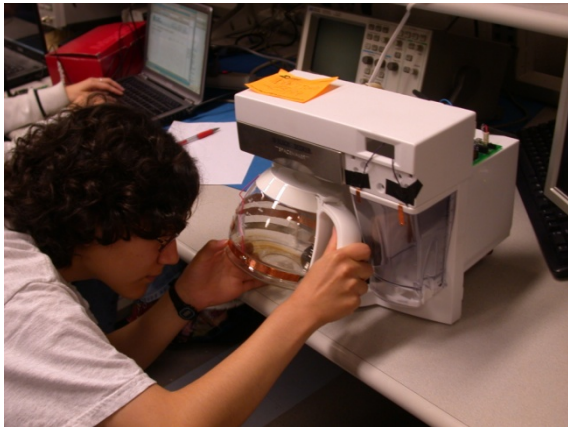
The central monitor displays a glowing 'X' on a blue background. Six orange lines radiate from the monitor to six different web browser screenshots, each representing a different category of human-generated information:

- Shopping:** PriceGrabber.com - Comparison Shopping Beyond Compare - Mozilla Firefox
- Science:** NASA - Missions - Highlights - Mozilla Firefox
- Sports:** Oakland Athletics: The Official Site - Mozilla Firefox
- Weather:** The Weather Channel - Local weather: Enter zip or US/MI or...
- News:** CNN.com - Breaking News, U.S., World, Weather, Entertain...
- Financial:** The NASDAQ Stock Market - Mozilla Firefox

Below the monitor, there is a screenshot of a Korean website for '2006 한국전자전' (2006 Korea Electronics Show) with the word 'Technology' overlaid in large blue letters.

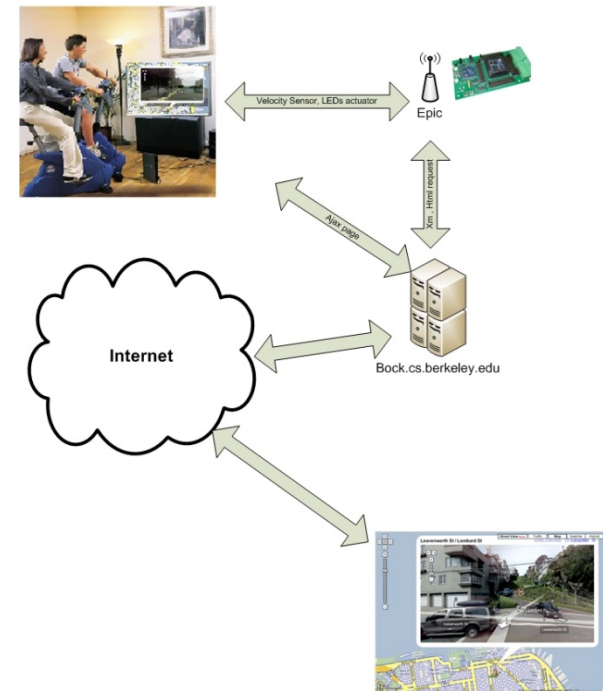


Every Day Internet Things



Bike on Google Maps!!

Developers: Uyen Nguyen, Trung Tran, Lary Ly, Ami Domadia



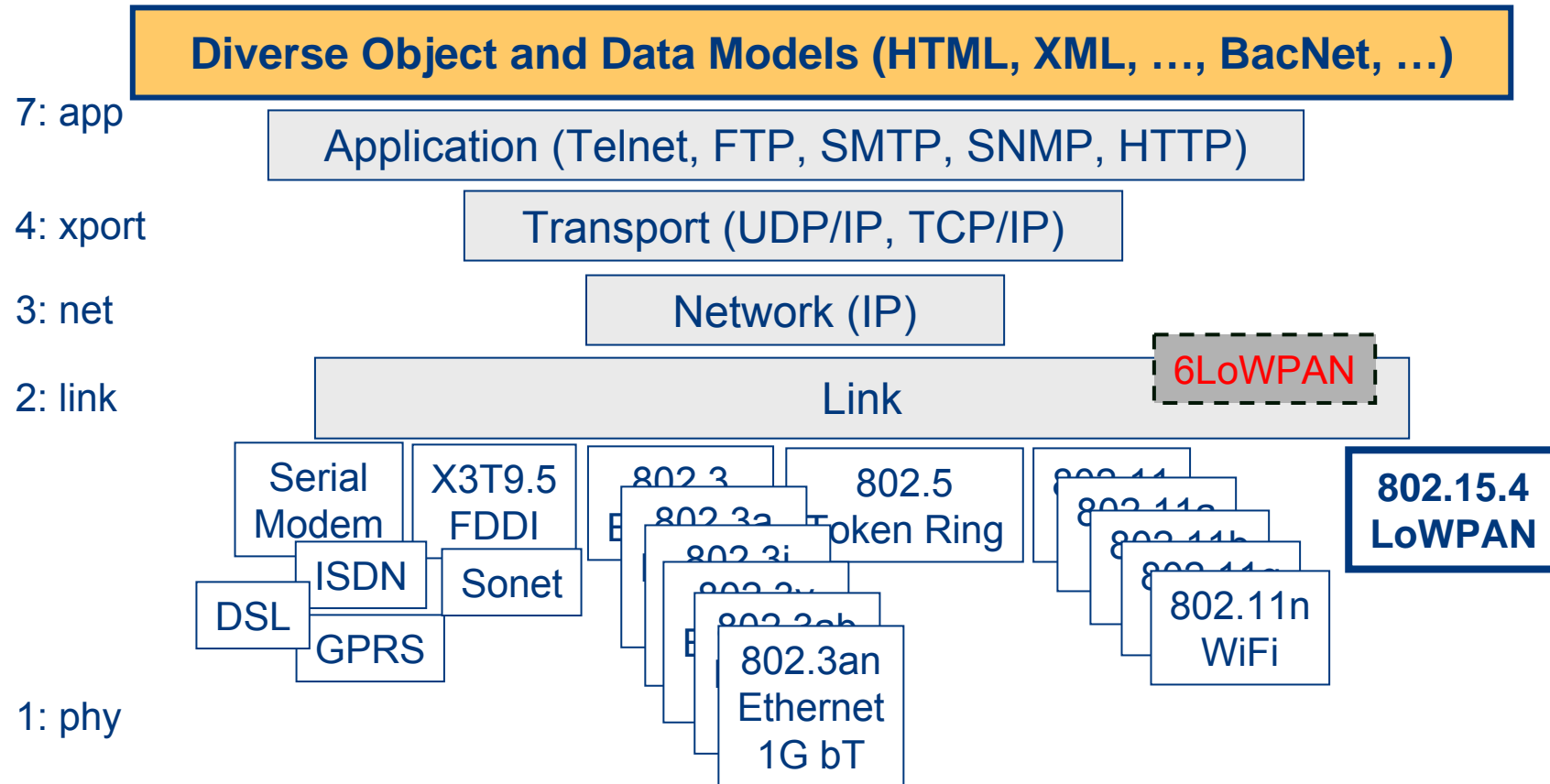


The Core Question Ahead

- Integrating the “non-HGI” from the internet of physical things into useful and meaningful applications
 - Extracting features from Signals
 - Classifying, Indexing, Searching
 - Semantic Content
 - Integration of Devices into Collections



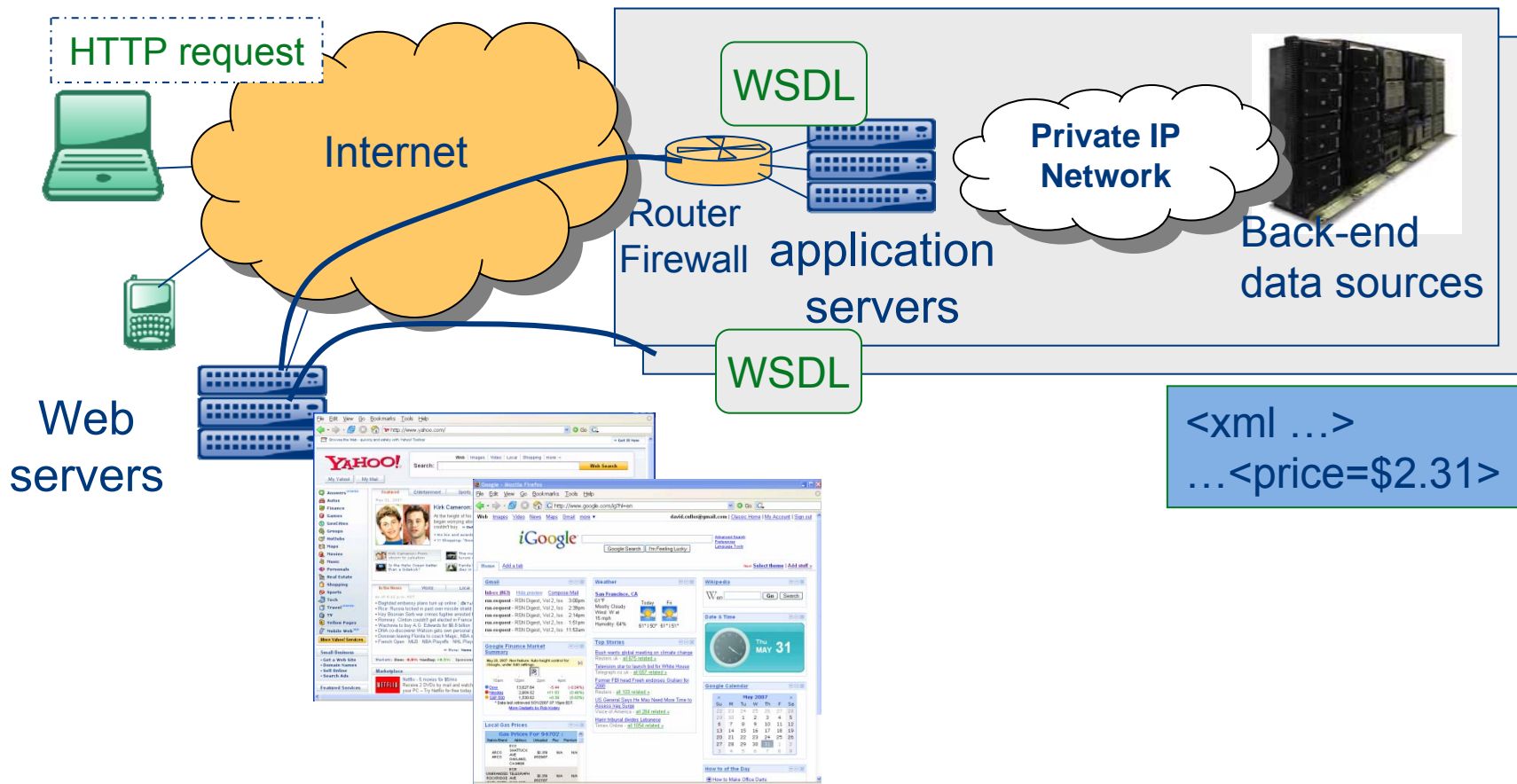
The New Focus





Internet Service Architecture

Clients





Example 1: geocoding

File Edit View Go Bookmarks Tools Help

http://maps.yahoo.com/broadband#mvt=m&tp=1&tt=Coffee&q1=don. Go sensor expo 2007

sensor expo 2007 - Google Sea... Yahoo! Maps, Driving Direc... Search: Web Search

YAHOO! LOCAL Maps Sign In New User? Sign Up Maps Home - Dial-Up Map (Original) - Help

GET MAP AND DIRECTIONS Clear

Printable Version Send Save Live Traffic NEW! Better Directions Help

donald stevens convention center, rosemont, illinois

FIND ON THE MAP Clear

Coffee Search

Browse by Category

Search Results: Coffee Refine

- Executive Coffee Service Incorporated
- Dunkin' Donuts
- Starbucks
- Dunkin' Donuts
- Krispy Kreme Doughnuts
- Dunkin' Donuts
- Hyatt Rosemont
- American Orthopedic Association
- Wyndham O'Hare Rosemont
- Hilton Chicago O'hare Airport
- Rosemont Target
- Embassy Suites Hotel Chicago-O'hare Rosemont
- Target

Results 1-14 of 14

© 2007 Yahoo! Inc. Data © 2007 Navteq, TeleAtlas

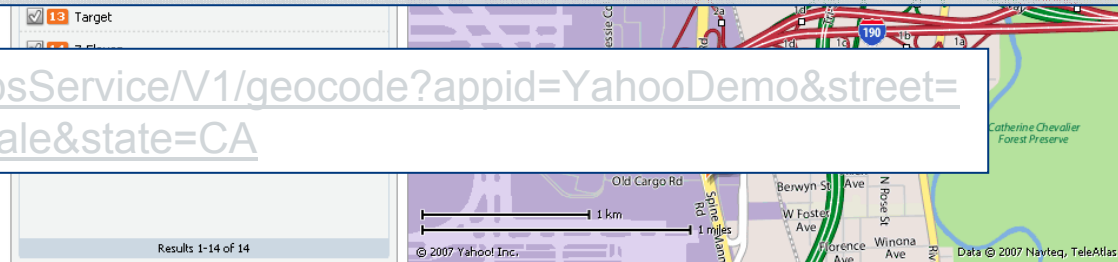
<http://local.yahooapis.com/MapsService/V1/geocode?appid=YahooDemo&street=701+First+Street&city=Sunnyvale&state=CA>



Example 1: geocoding

```
<?xml version="1.0" ?>
-<ResultSet xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xmlns="urn:yahoo:maps"
  xsi:schemaLocation="urn:yahoo:maps
  http://api.local.yahoo.com/MapsService/V1/GeocodeResponse.xsd">
  <Result precision="address">
  <Latitude>37.416384</Latitude>
  <Longitude>-122.024853</Longitude>
  <Address>701 FIRST AVE</Address>
  <City>SUNNYVALE</City>
  <State>CA</State>
  <Zip>94089-1019</Zip>
  <Country>US</Country>
  </Result>
  </ResultSet>
<!-- ws05.search.scd.yahoo.com compressed/chunked Fri Jun 8 17:16:24 PDT 2007 -->
```

<http://local.yahooapis.com/MapsService/V1/geocode?appid=YahooDemo&street=701+First+Street&city=Sunnyvale&state=CA>



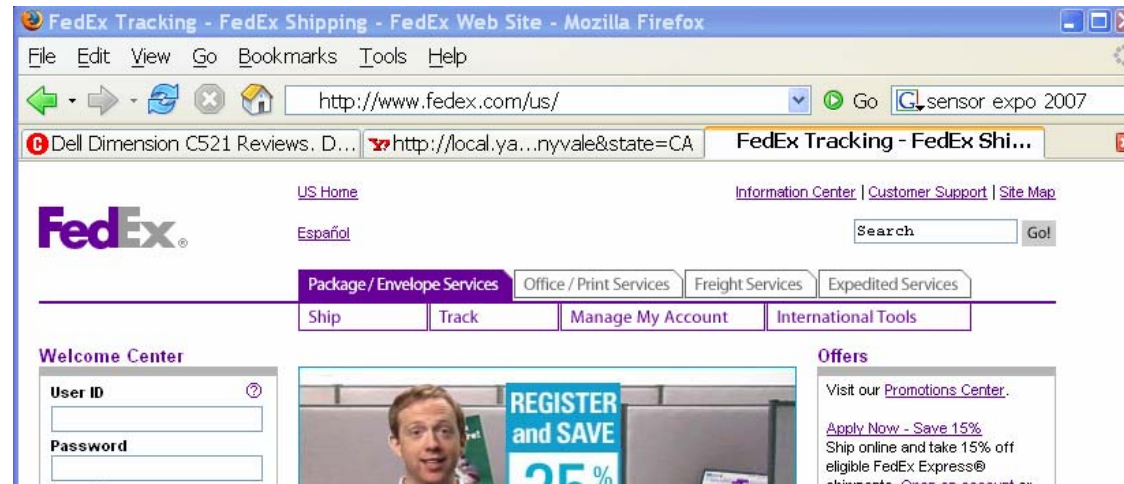


XML Schema for reply in XML too.

```
<xs:schema targetNamespace="urn:yahoo:maps" elementFormDefault="qualified">
  <xs:element name="ResultSet">
    <xs:complexType>
      <xs:sequence>
        <xs:element name="Result" type="ResultType" minOccurs="0" maxOccurs="50"/>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
  <xs:complexType name="ResultType">
    <xs:sequence>
      <xs:element name="Latitude" type="xs:decimal"/>
      <xs:element name="Longitude" type="xs:decimal"/>
      <xs:element name="Address" type="xs:string"/>
      <xs:element name="City" type="xs:string"/>
      <xs:element name="State" type="xs:string"/>
      <xs:element name="Zip" type="xs:string"/>
      <xs:element name="Country" type="xs:string"/>
    </xs:sequence>
    <xs:attribute name="precision" type="xs:string"/>
    <xs:attribute name="warning" type="xs:string" use="optional"/>
  </xs:complexType>
</xs:schema>
```

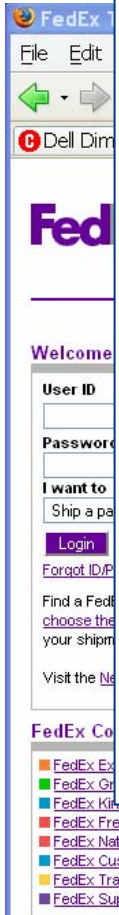
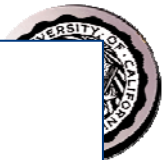


Example 2: logistics



```
<?xml version="1.0" encoding="UTF-8" ?>
<FDXTrack2Request xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="FDXTrack2Request.xsd">
  <RequestHeader>
    <CustomerTransactionIdentifier>String</CustomerTransactionIdentifier>
    <AccountNumber>123456789</AccountNumber>
    <MeterNumber>1234567</MeterNumber>
    <CarrierCode>FDXE</CarrierCode>
  </RequestHeader>
  <PackageIdentifier>
    <Value>987654321987</Value>
  </PackageIdentifier>
  <ShipDateRangeBegin>2006-01-01</ShipDateRangeBegin>
  <ShipDateRangeEnd>2006-01-23</ShipDateRangeEnd>
  <DetailScans>0</DetailScans>
</FDXTrack2Request>
```

Example



```
<?xml version="1.0" encoding="UTF-8"?>
<FDXTrack2Reply xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="FDXTrack2Reply.xsd">
  <ReplyHeader>
    <CustomerTransactionIdentifier>String</CustomerTransactionIdentifier>
  </ReplyHeader>
  <Package>
    <TrackingNumber>123456789123</TrackingNumber>
    <TrackingNumberUniqueIdentifier>1234567890~123456789123</TrackingNumberUn
iqueIdentifier>
    <StatusCode>DL</StatusCode>
    <StatusDescription>Delivered</StatusDescription>
    <CarrierCode>FDXE</CarrierCode>
    <Service>Priority Box</Service>
    <Weight>6.0</Weight>
    ...
    <Description>Delivered</Description>
    <Address>
      <City>PEORIA</City>
      <PostalCode>10402</PostalCode>
      <StateOrProvinceCode>OH</StateOrProvinceCode>
      <CountryCode>US</CountryCode>
    </Address>
  </Event>
</Package>
</FDXTrack2Reply>
```


Putting it together



PackageMapping.com

Enter your Tracking Number below...
 DHL 82416986890
 Track and Map!
 Service provided by: www.PackageMapping.com

Tracking results detail for 82416986890

Tracking summary

Current Status	✓	Shipment delivered.
Shipment delivered:	06/08/2007 12:46 PM	
Est. Delivery Date:	06/05/2007	
Delivered to	Receptionist	
Signed for by	DAVID COLER What is this?	

Tracking history

Date and Time	Status	Location
06/08/2007 12:46 PM	Shipment delivered.	SAN FRANCISCO, CA US Why is this?
06/01/2007 7:25 AM	Arrived at DHL facility.	SAN FRANCISCO, CA US
05/31/2007 5:01 PM	Depart Facility.	WILMINGTON, OH US
10:04 AM	Processed at DHL Location.	WILMINGTON, OH US
05/29/2007 11:45 PM	Transit through sort facility.	ALLENTOWN, PA US
	Processed at DHL	ALLENTOWN, PA US

Distance : 2863.09 miles - Time : 213 hrs 11 mins 0 secs - Avg Speed : 12.49 mph

Copyright © 2007 Robert H., All rights reserved. | Home | Contact Info | Testimonials | Press Release | Privacy Notice | Site Map

You are not authorized to reproduce any portion of this web site without written permission. Google®, UPS®, U.S.P.S.®, FedEx®, nor DHL® in no way endorses the products, services, or information provided on this web site. UPS®, UPS & Shield Design® and UNITED PARCEL SERVICE® are registered trademarks of United Parcel Service of America, Inc.. 'DHL' is a trademark of DHL International GmbH or any other company of the DHL group, registered in at least one jurisdiction. USPS®, United States Postal Service® and the Eagle Logo are trademarks of the United States Postal Service.

UPS Power Protection
 Power protection solutions for many applications.



Making Sense out of Sensors

Semantics and Service Discovery

Object and Data Representation

Communication Media



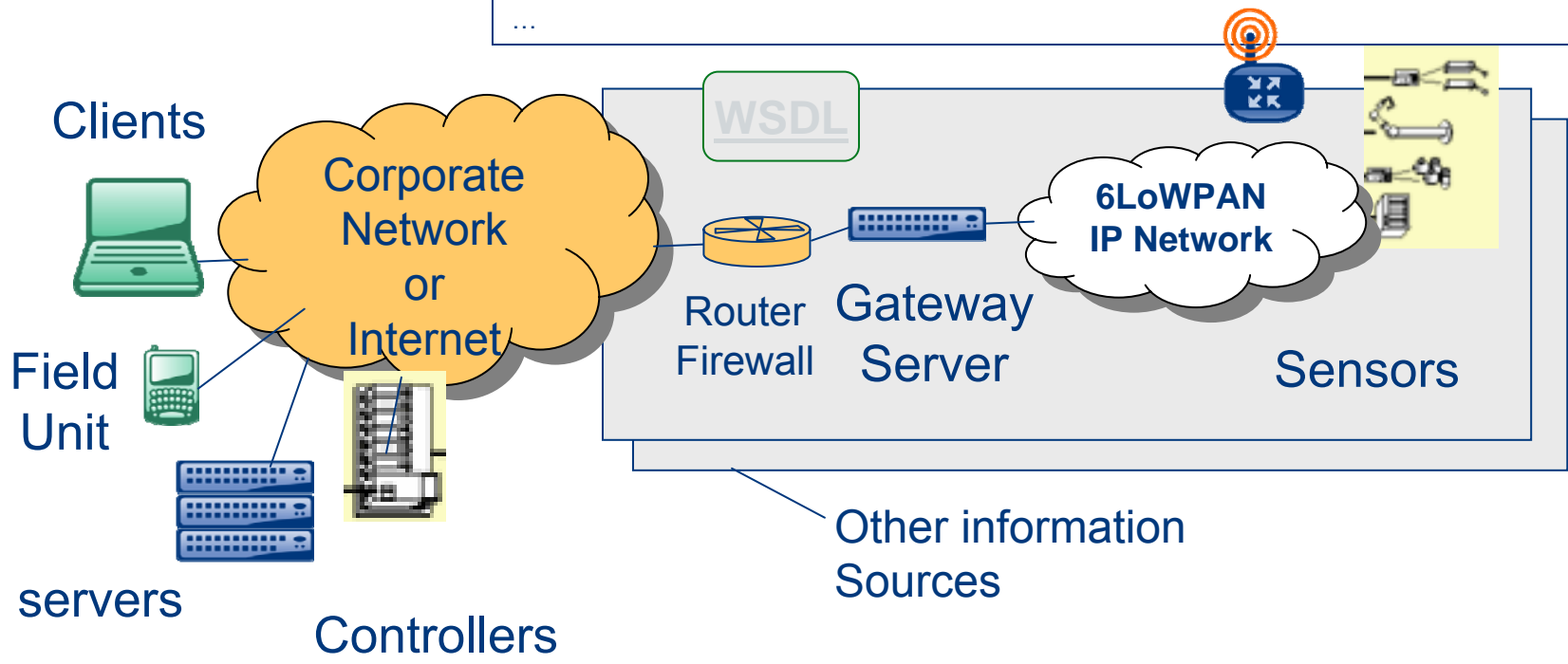
Physical Devices

Sensor Service

```

<?xml version="1.0" ?>
_ <definitions name="GW" targetNamespace="urn:gw"
xmlns="http://schemas.xmlsoap.org/wsdl/" xmlns:gw="urn:gw"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns:soapenc="http://schemas.xmlsoap.org/soap/encoding/"
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
_ <types>
_ <xsd:schema xmlns="http://www.w3.org/2001/XMLSchema" targetNamespace="urn:gw">
_ <xsd:complexType name="GW__attributesList_Result">
_ <xsd:all>
_ <xsd:complexType name="GW__eventsRead_Result">
_ <xsd:all>
_ <xsd:element name="offset" type="xsd:unsignedInt" />
_ <xsd:element name="total" type="xsd:unsignedInt" />
_ <xsd:element name="results" type="gw:GW__Event_Results" />
_ </xsd:all>
...

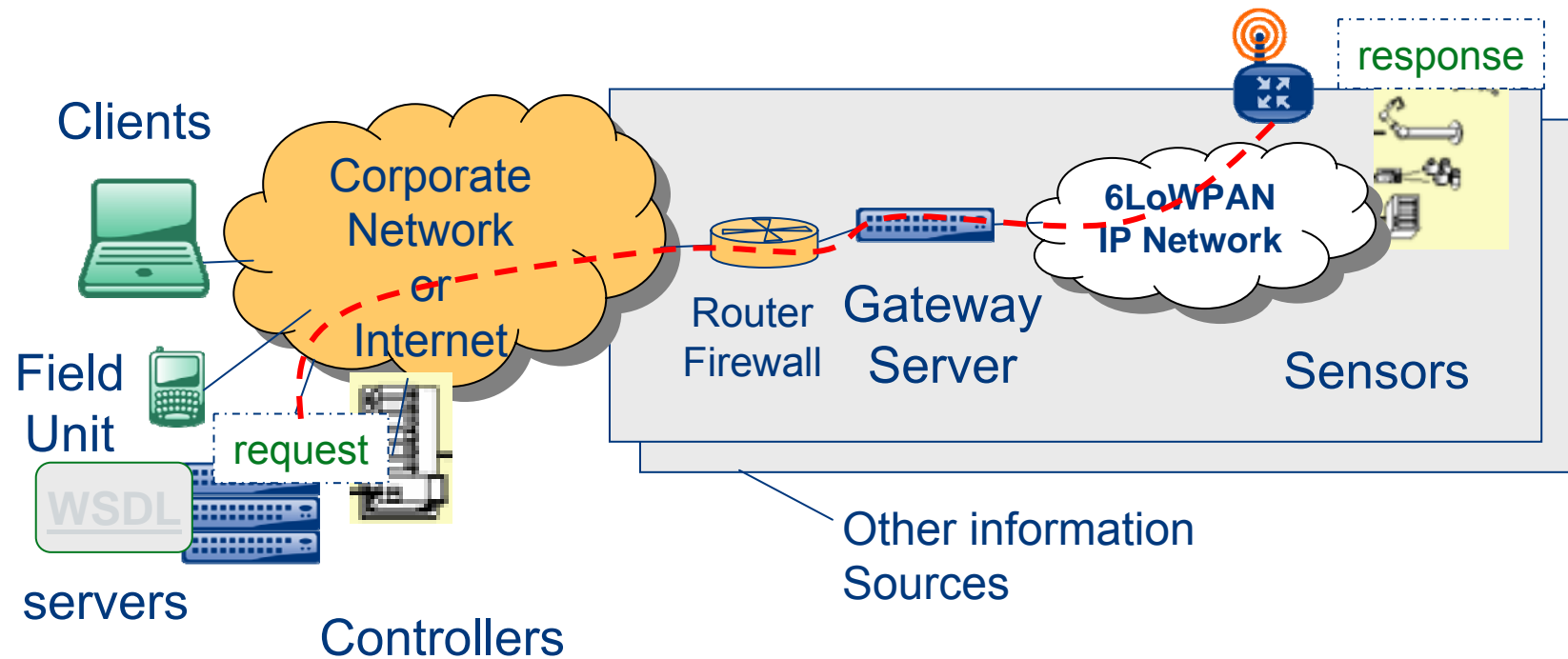
```





Sensor Service Architecture

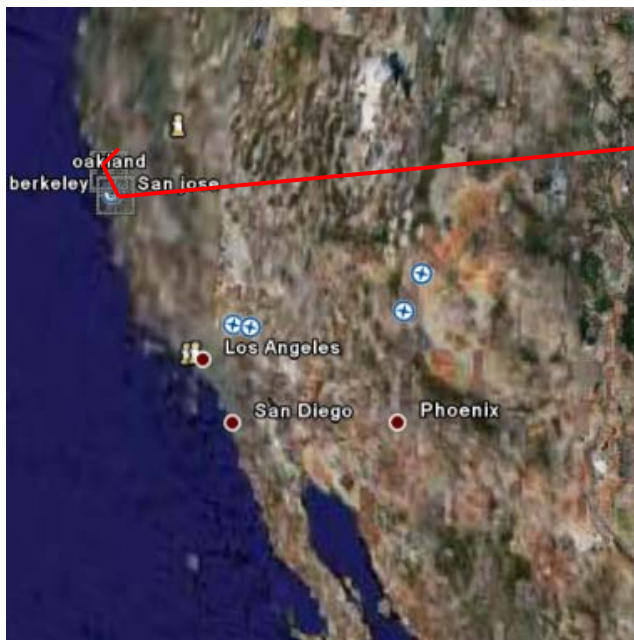
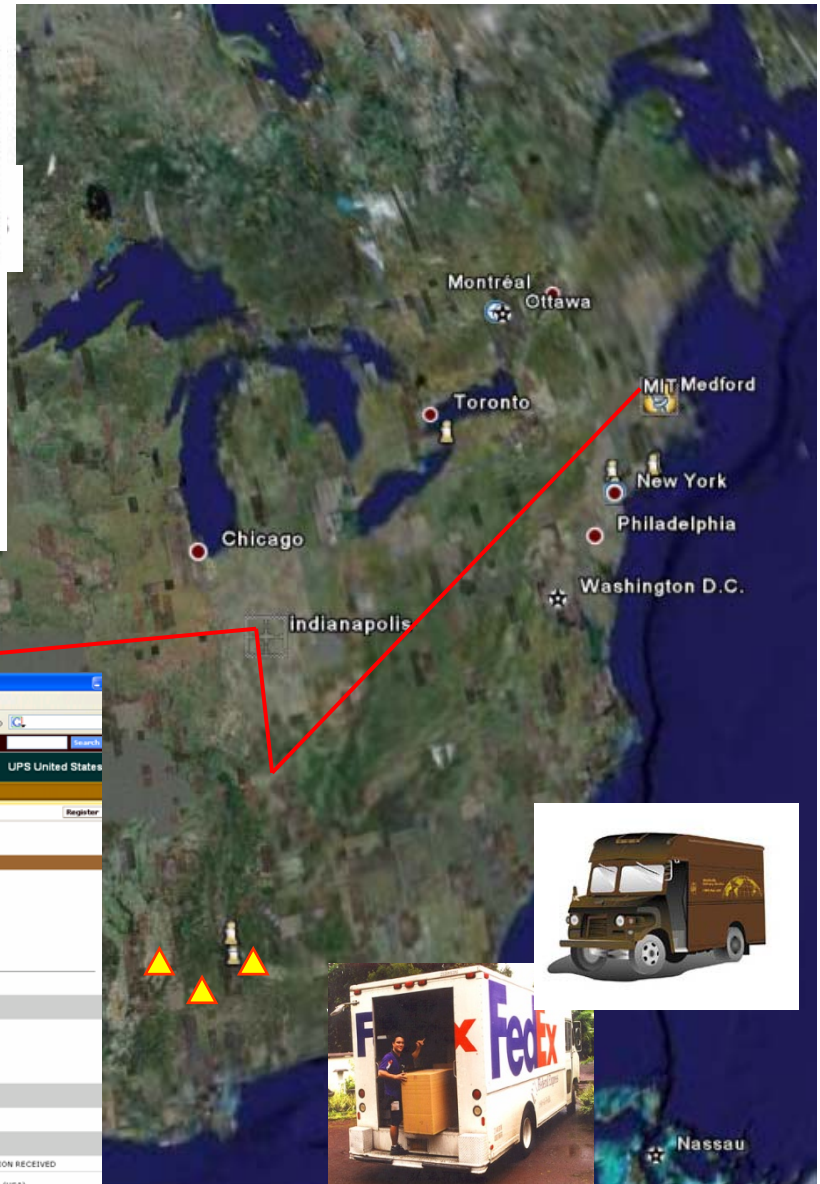
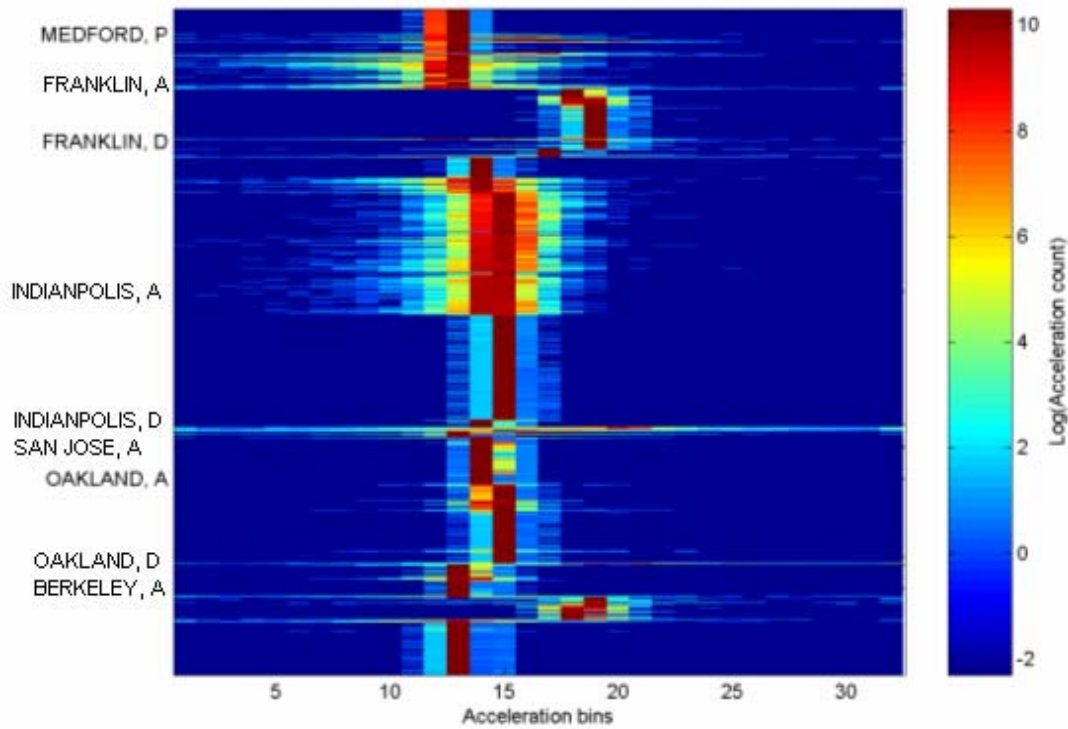
```
<Results>  
  <Result addr="00173b00fed211a" timestamp="1181622351.345968"  
    seqNo="27" name="TemperatureReadEvent">  
    <Value typeName="nx_uint16_t">4240</Value>  
  </Result>  
</Results>
```





Real World ...

Acceleration during the MA to CA FedEx shipment, Mote 7



UPS Package Tracking - Mozilla Firefox

http://wwwapps.ups.com/WebTracking/process

UPS United States

Shipping Tracking Support Business Solutions

Track by Tracking Number

View Details

Status: Delivered
Delivered on: 08/02/2006 2:50 P.M.
Signed by: CULERA
Location: RECEIVER
Delivered to: SAN FRANCISCO, CA, US
Shipped or billed on: 07/27/2006

Tracking Number: 1Z 794 72V 03 4229 772 0
Service Type: GROUND
Weight: 3.08 lbs

Package Progress:

Location	Date	Local Time	Activity
SAN FRANCISCO, CA, US	08/02/2006	2:50 P.M.	DELIVERY
	08/02/2006	7:56 A.M.	OUT FOR DELIVERY
	08/02/2006	4:39 A.M.	ARRIVAL SCAN
SAN PABLO, CA, US	08/02/2006	12:13 A.M.	DEPARTURE SCAN
SAN PABLO, CA, US	07/31/2006	1:42 P.M.	ARRIVAL SCAN
HOOBKINS, IL, US	07/26/2006	8:53 A.M.	DEPARTURE SCAN
US	07/27/2006	10:02 P.M.	BILLING INFORMATION RECEIVED

Tracking results provided by UPS: 08/12/2006 1:03 A.M. Eastern Time (USA)



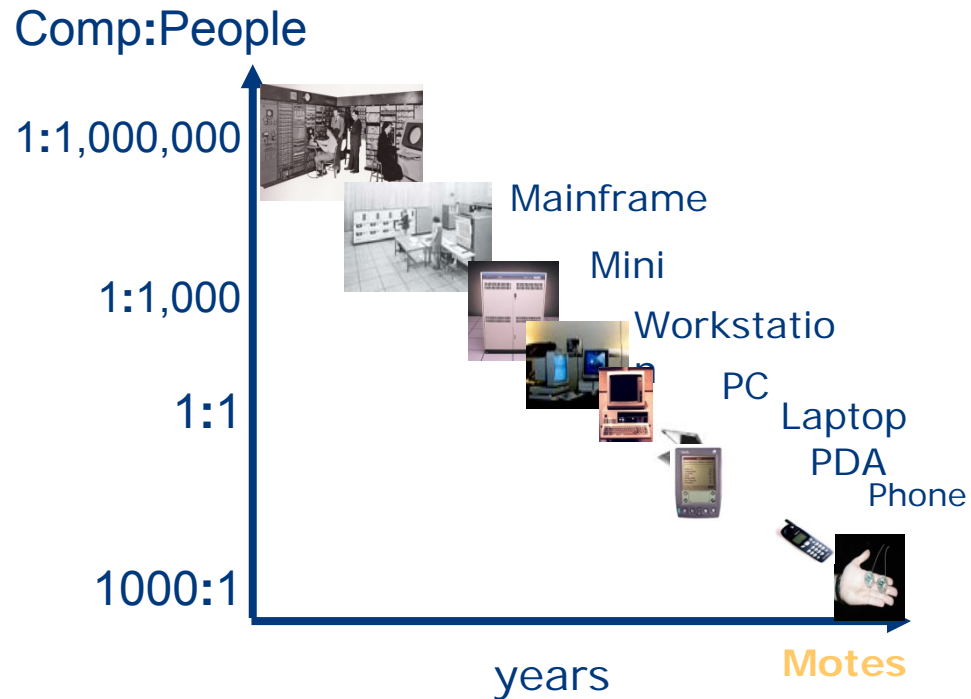
Lessons from the Web

To integrate diverse information sources:

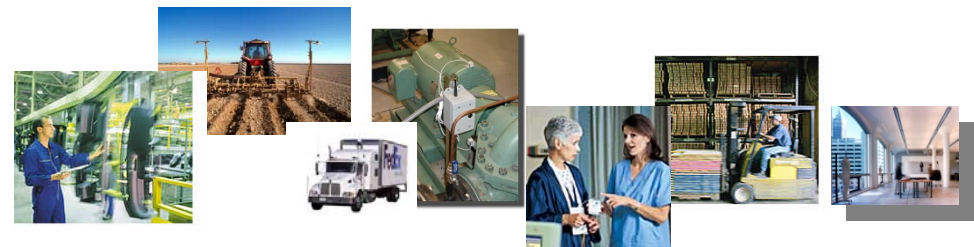
1. IP: separate communication from physical links
 - 6LoWPAN enables efficient low-power, reliable mesh with IP
2. HTML, HTTP, XML: simple self-describing text
 - electronic data sheets that programs understand
3. WSDL: descriptions of services in XML and XML schema
 - Describe what you do so programs can understand it
 - Simple Executable specifications!
 - RESTfull web services may be more appropriate
4. Compress the common case: compact instrumentation and control
 - Simple subset of XML. Automatic translation.



The Next Tier



- Today: we can connect essentially *everybody*
- Tomorrow: we will be able to connect and observe essentially *everything* of value
 - physical spaces, objects, and their interactions
 - physical information, not just keystrokes





Uniting long-lost relatives

Internet

Thanks

