The Internet of Every Thing - steps toward sustainability

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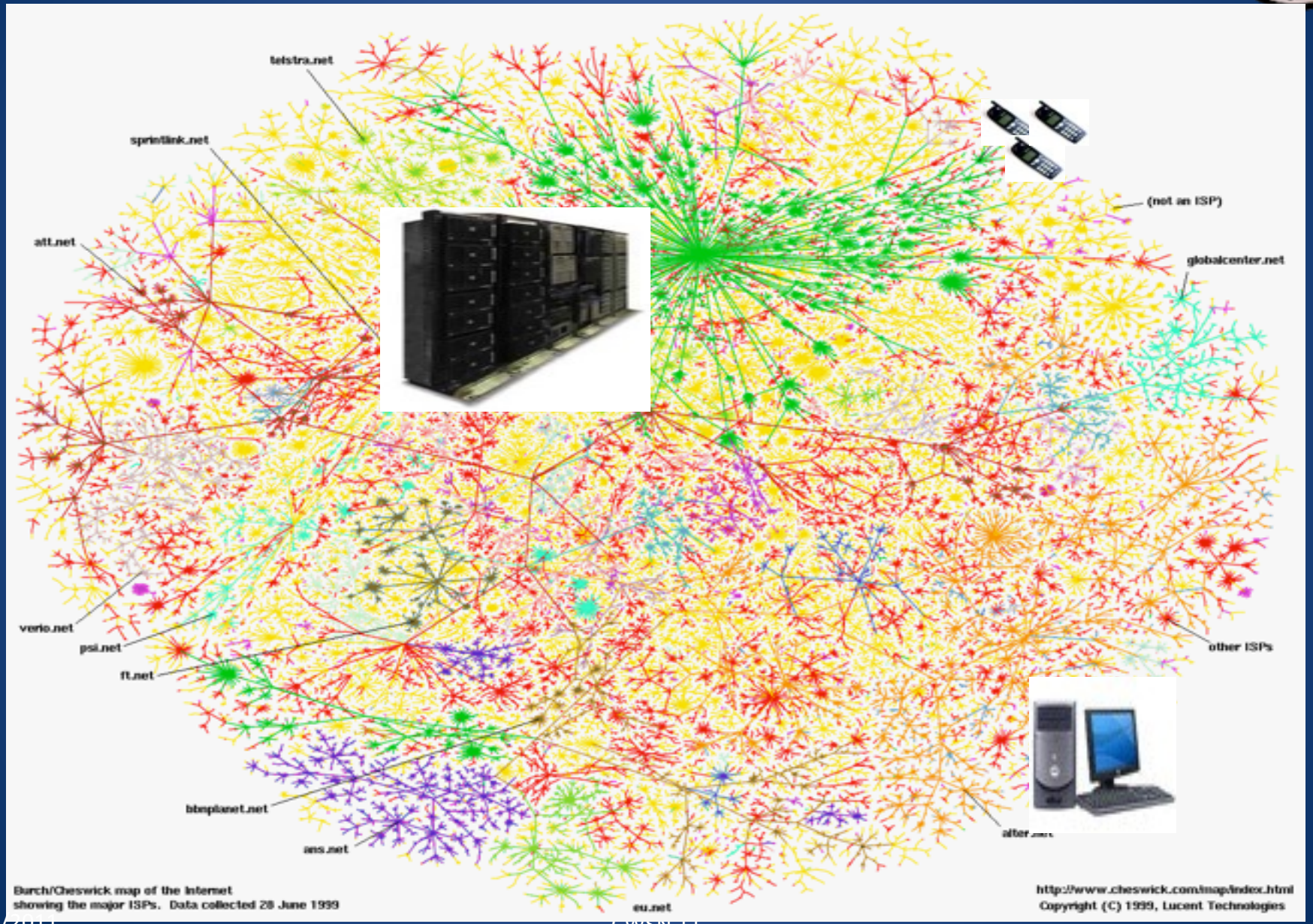
University of California, Berkeley

CWSN Keynote, Sept. 26 2011

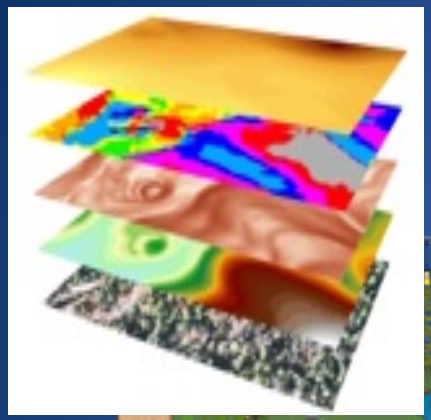
The Internet … a decade ago

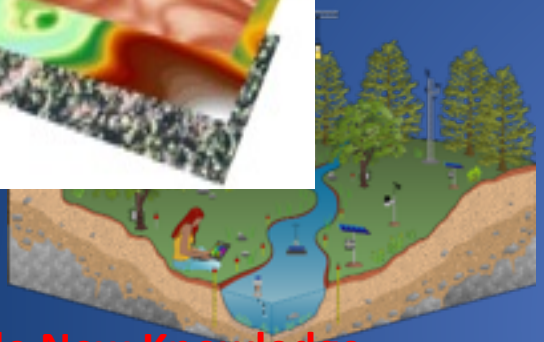


The Internet … that we envisioned

9/26 /[illegible] Cheswick map of the Internet showing the major ISPs. Data collected 28 June 1999

Why “Real” Information is so Important

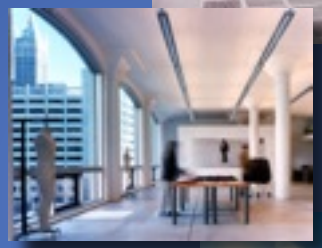




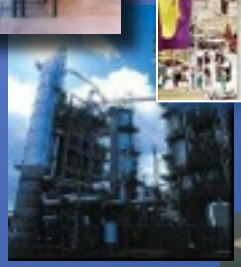
Enable New Knowledge

Save Resources

Improve Productivity



Increase Comfort



Enhance Safety & Security

Preventing Failures

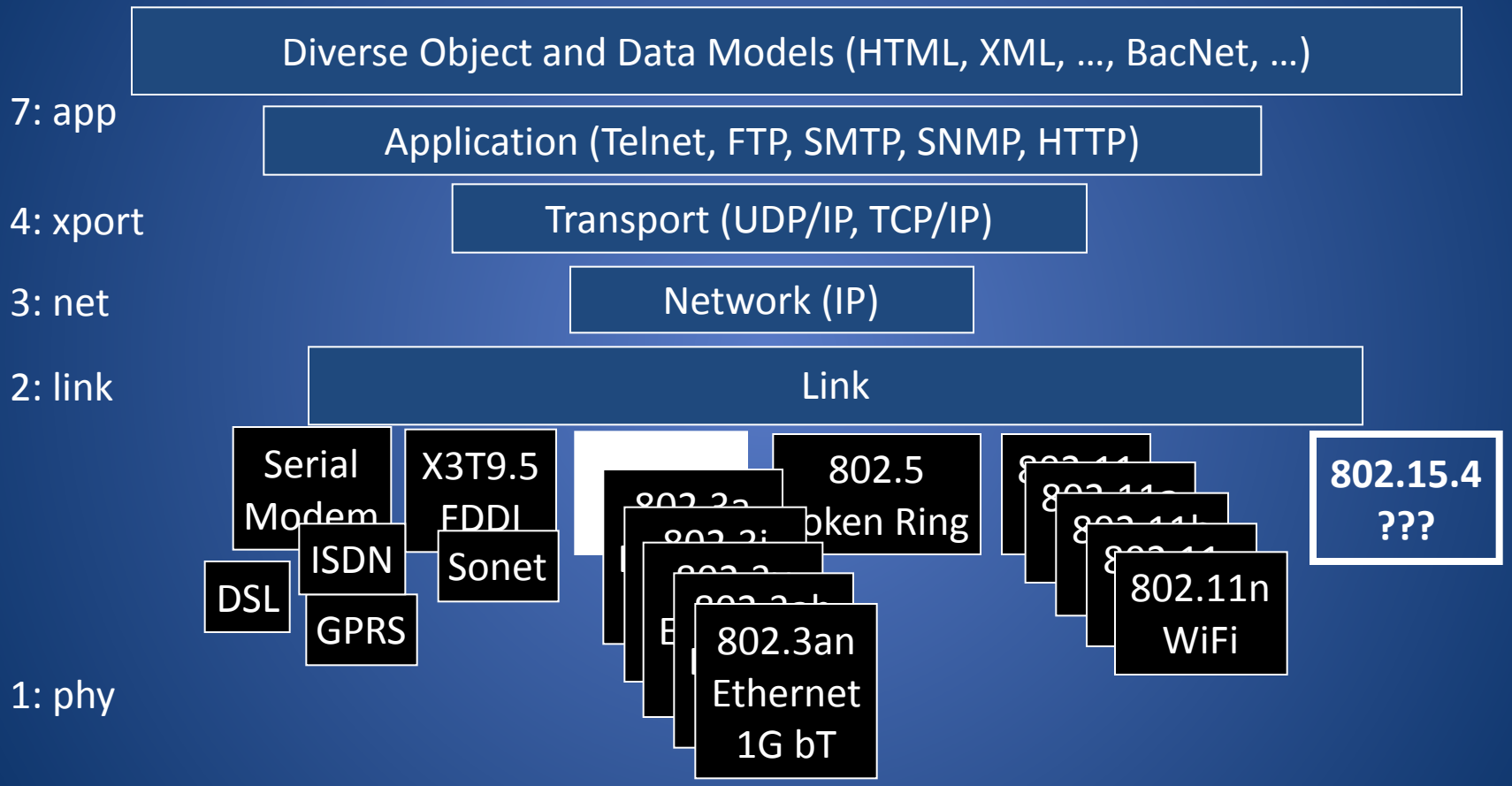
High-Confidence Transport

Improve Food & H20

Protect Health

Enabling Technology

Internet Concepts: Layering…

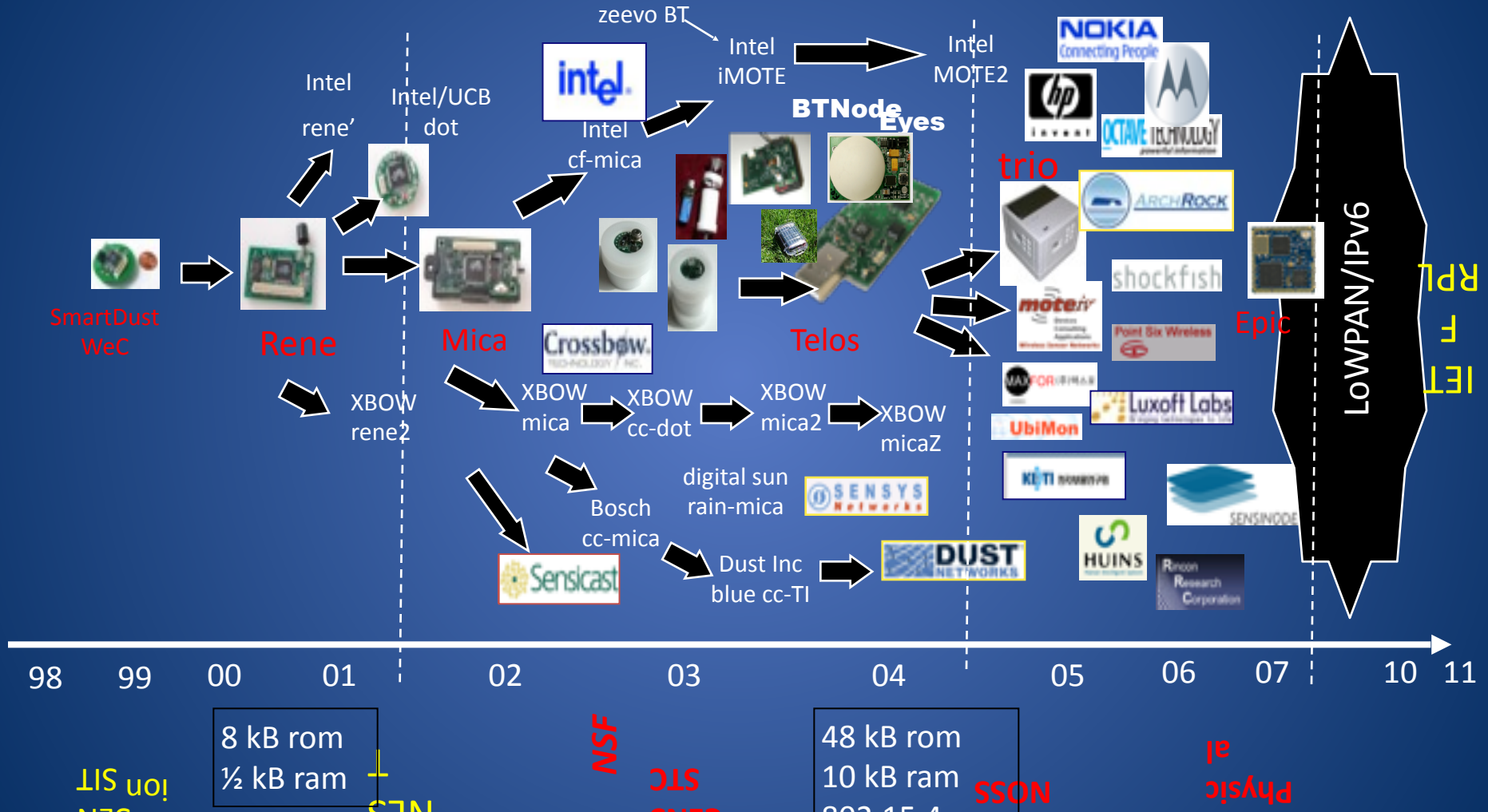


Leading Internet Research Perspective - a decade ago

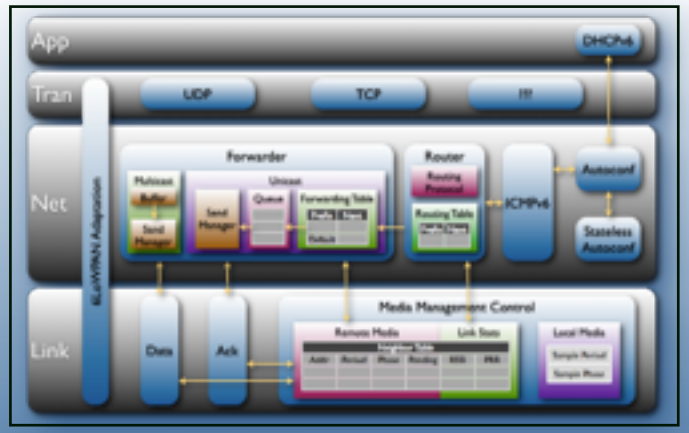
- "Resource constraints may cause us to **give up the layered architecture**."
- "Sheer numbers of devices, and their unattended deployment, will preclude reliance on broadcast communication or the configuration currently needed to deploy and operate networked devices."
- "There are significant robustness 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…

The Mote/TinyOS revolution…



Internet of Every Thing – Realized 2008



24038 ROM

3598 RAM

(including runtime)

	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

* Production implementation on TI msp430/cc2420

- Footprint, power, packet size, & bandwidth
- Open version 27k / 4.6k

ARCH ROCK

Internet of Every Thing – standardized 2010

ROLL
Internet-Draft
Intended status: Standards Track
Expires: April 4, 2011

T. Winter, Ed.

P. Thubert, Ed.
Cisco Systems
A. Brandt
Sigma Designs
T. Clausen
LIX, Ecole Polytechnique
J. Hui
Arch Rock Corporation
R. Kelsey
Ember Corporation
P. Levis
Stanford University
K. Pister
Dust Networks
R. Struik

JP. Vasseur
Cisco Systems
October 1, 2010

RPL: IPv6 Routing Protocol for Low power and Lossy Networks
draft-ietf-roll-rpl-12

Abstract

Low power and Lossy Networks (LLNs) are a class of network in which both the routers and their interconnect are constrained. LLN routers

2008-02-15 charter

Routing Over Low power and Lossy networks (roll)

Charter

Current Status: Active Working Group

Chair(s):
JP Vasseur <jpv@cisco.com>
David Culler <culler@eecs.berkeley.edu>

IPSO Alliance
Enabling the
INTERNET OF THINGS

ZigBee Alliance

ZigBee Smart Energy Version 2.0 Documents

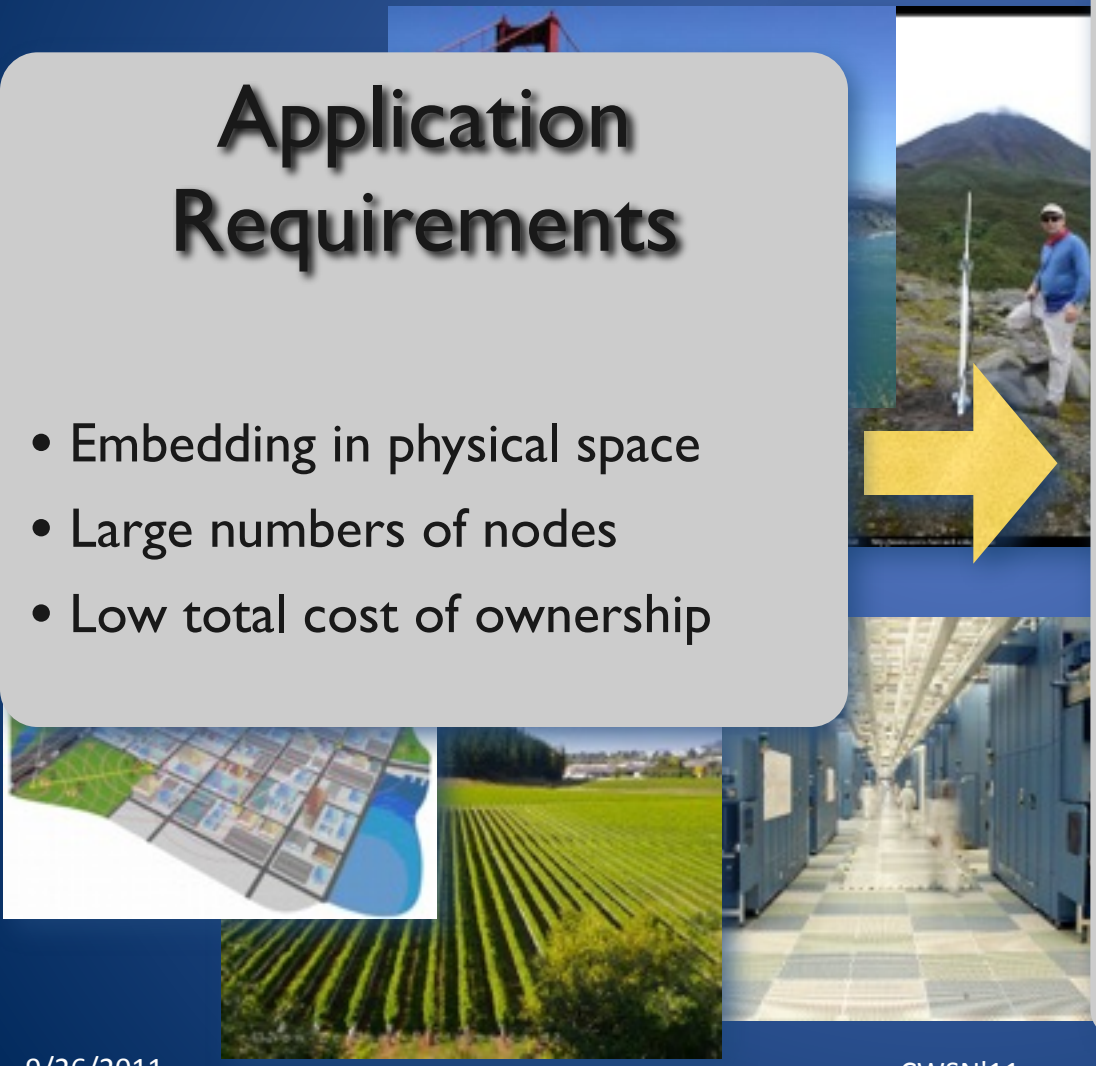
ZigBee Smart Energy version 2.0 will be IP-based and offer a variety of new features.

ISA

Networking in the Physical World

Application Requirements

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

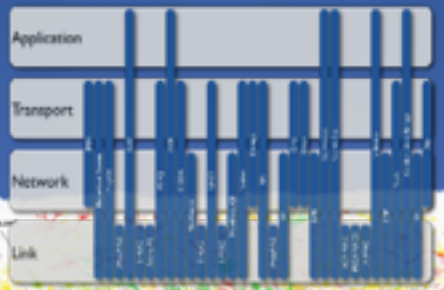


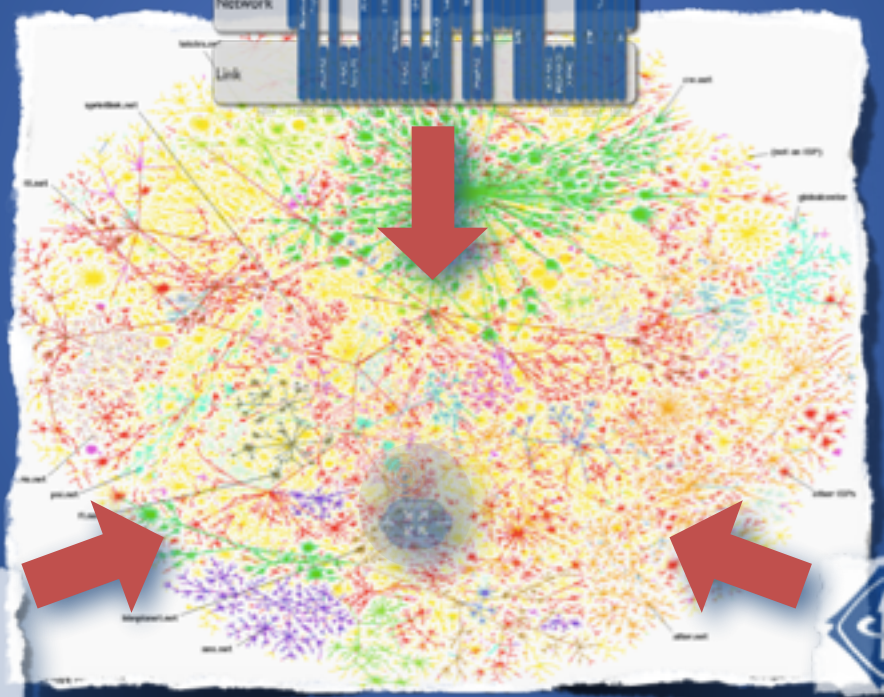
Networking Challenges

- 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

Confluence Research, Industry, and Standards

Research Community

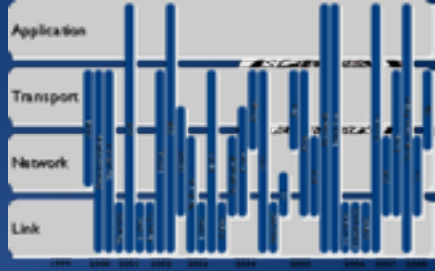




IETF

IEEE

Key Research Developments

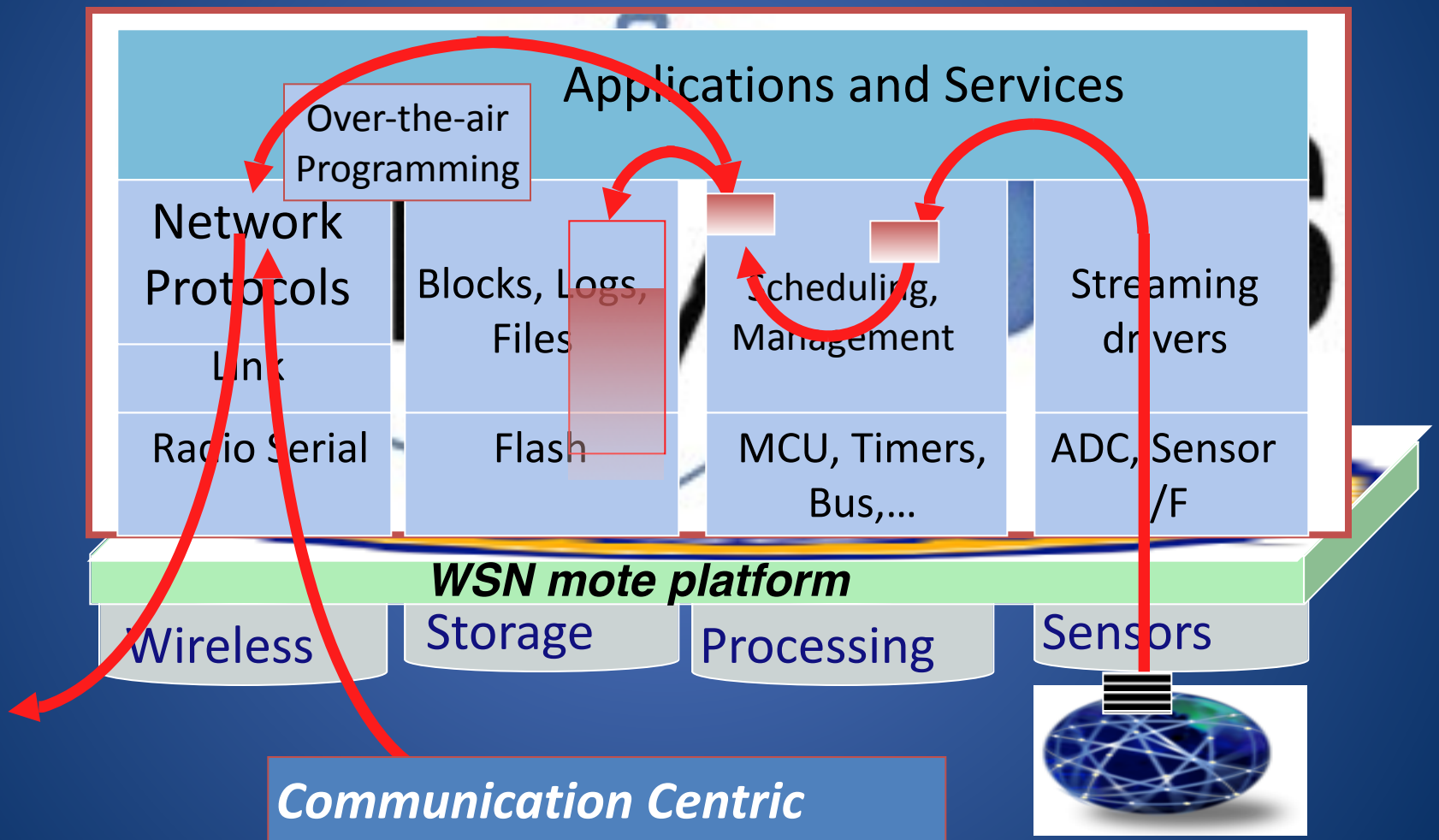


- Event-Driven Component-Base Operating System
  - Framework for building System & Network abstractions
  - Low-Power Protocols
  - Hardware and Application Specific
- Idle listening
  - All the energy is consumed by listening for a packet to receive

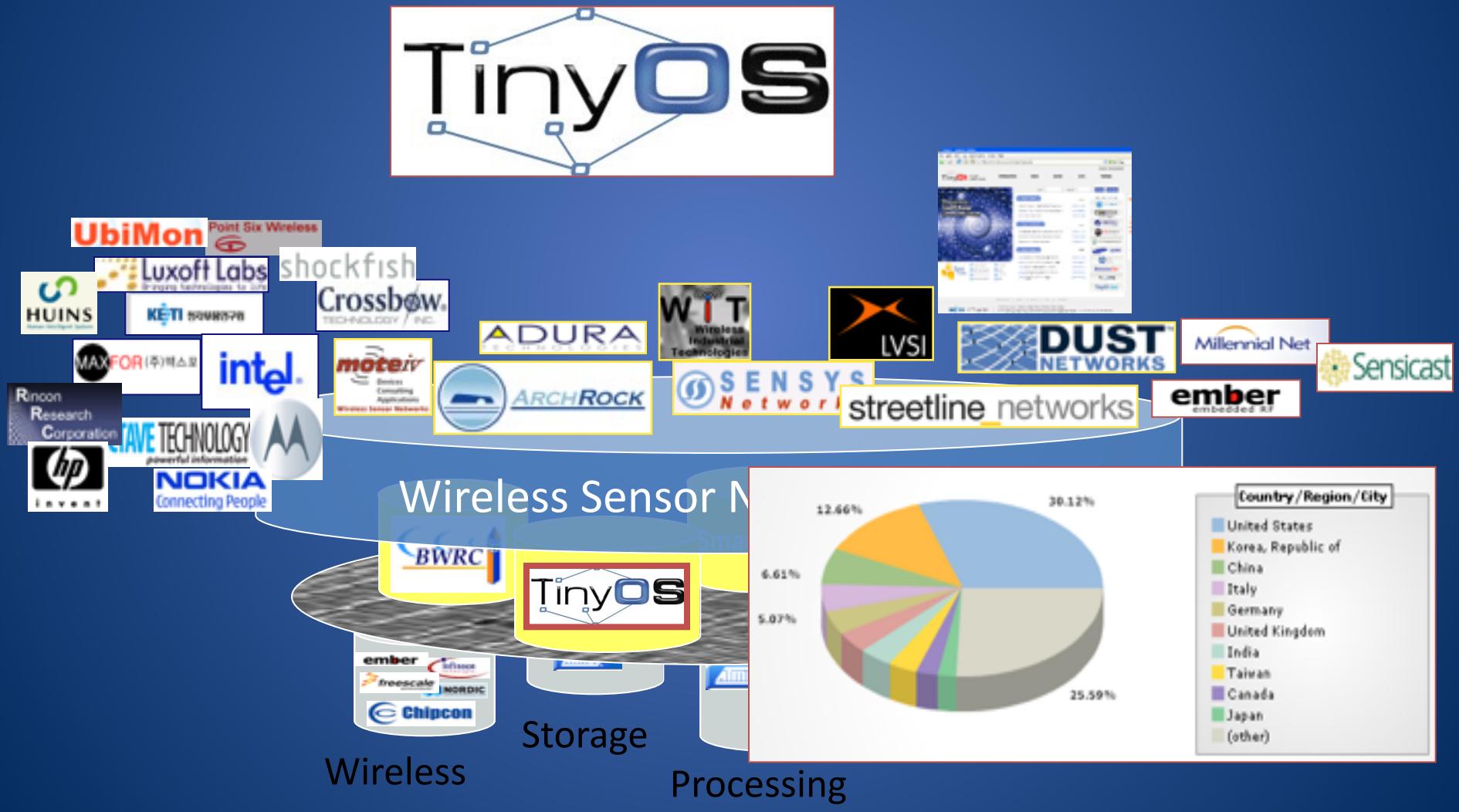
  => Turn radio on only when there is something to hear
- Reliable routing on Low-Power & Lossy Links
  - Power, Range, Obstructions => multi-hop
  - Always at edge of SNR => loss is common

  => monitoring, retransmission, and local rerouting
- Trickle – don't flood (tx rate < 1/density, and < info change)
  - Connectivity is determined by physical points of interest, not network designer.
  - never naively respond to a broadcast
  - re-broadcast very very politely

TinyOS – Framework for Innovation



A worldwide community



Low Power Networking in the Real World

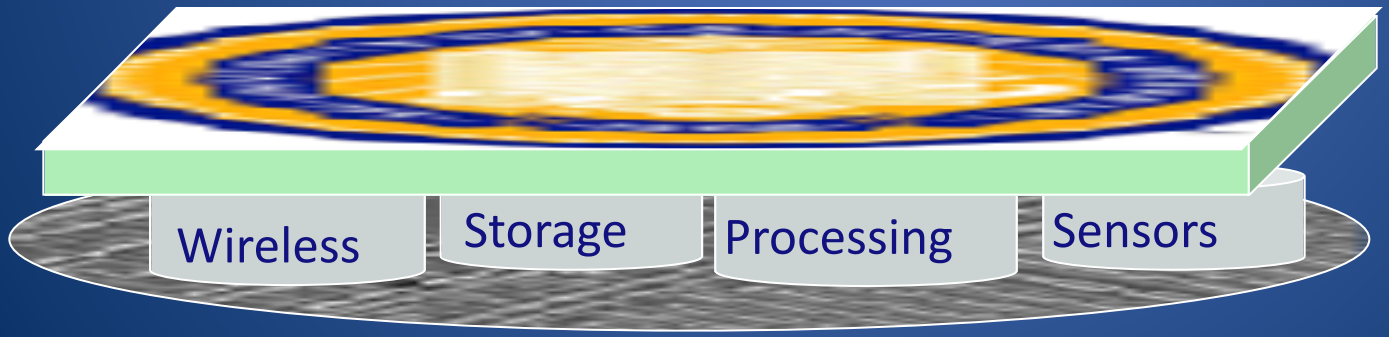
Applications

Network

system

architecture

Technology

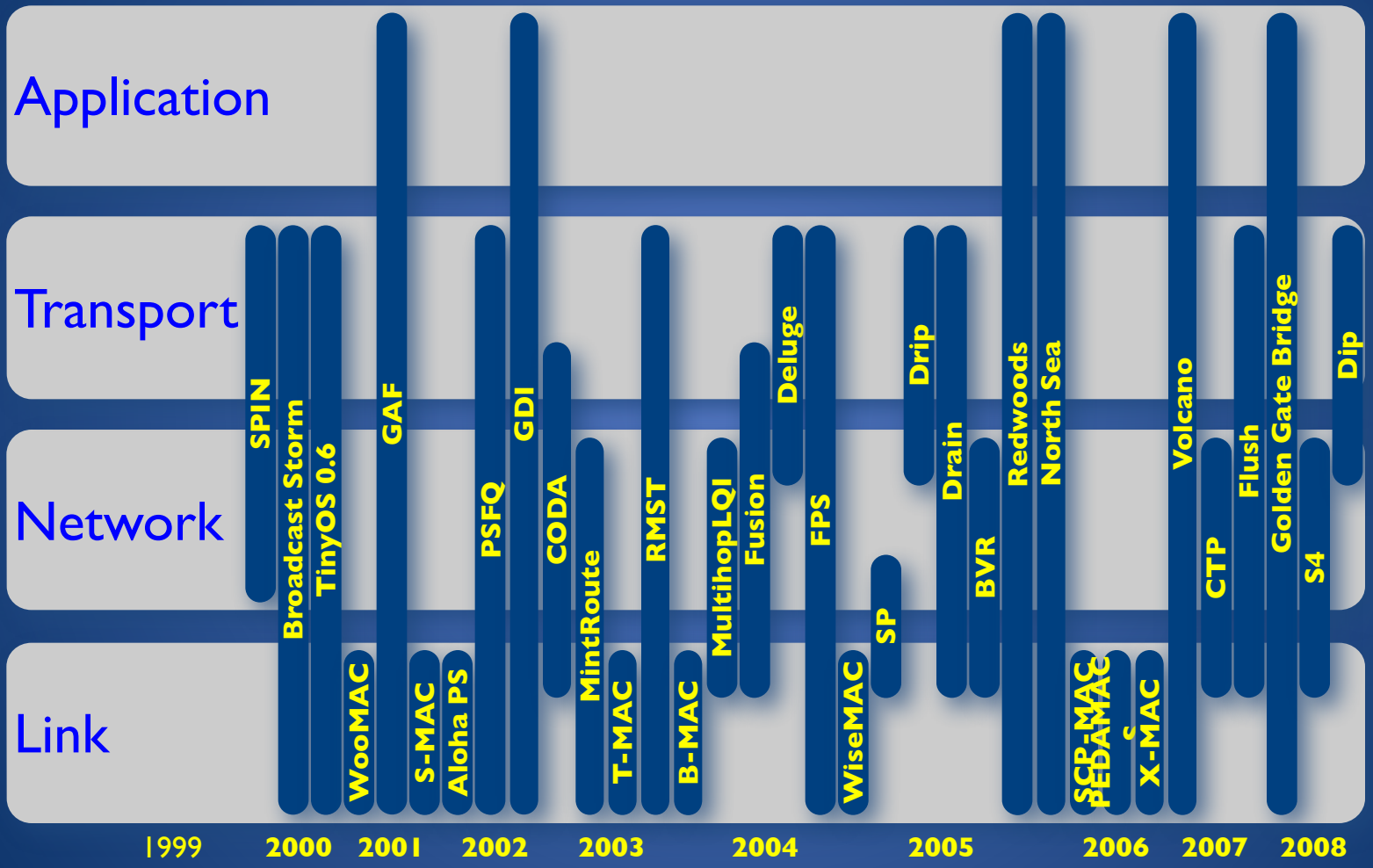


A Low-Power Standard Link

	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 Signal-to-noise Ratio (SNR), modest BW, Little Frames

Decade of Networking (sans Architecture)



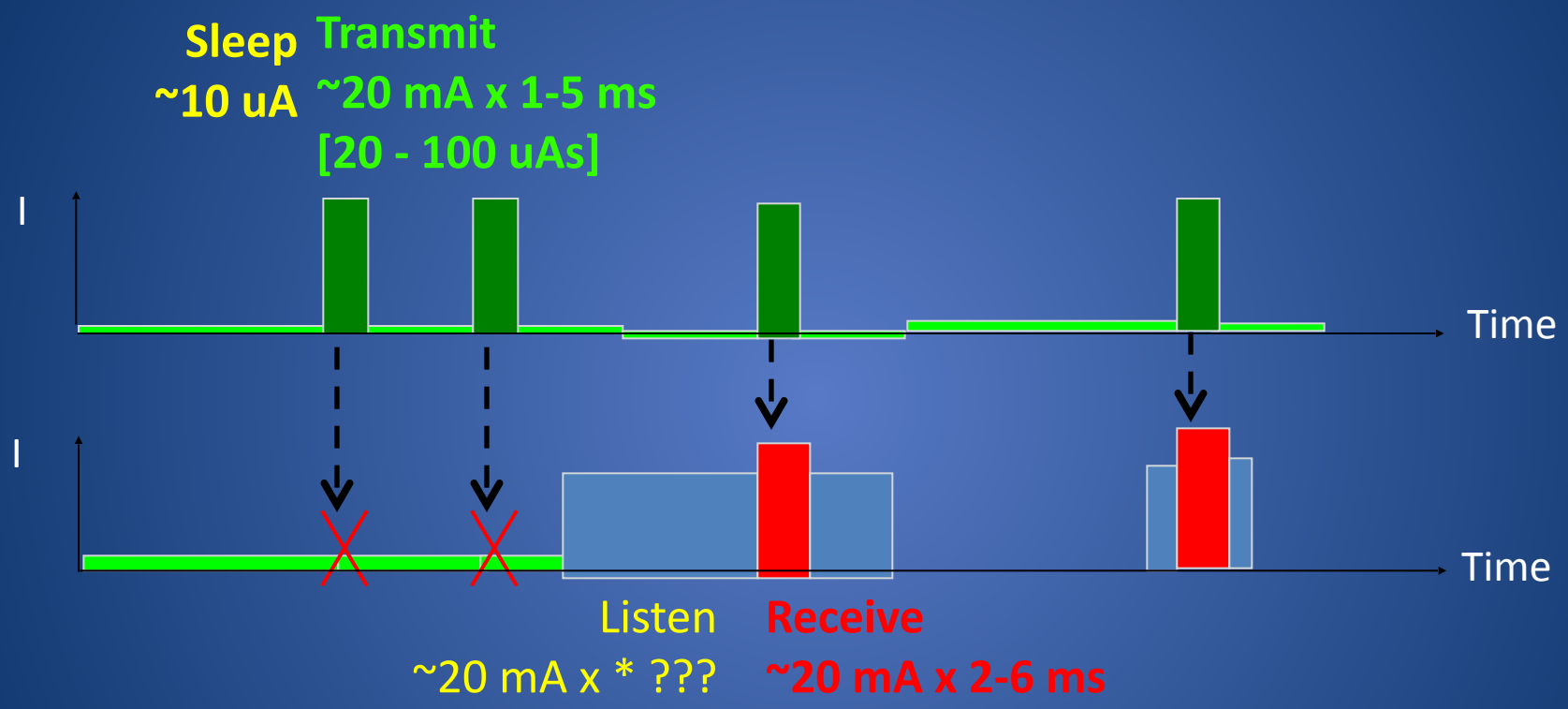
The “Idle Listening” Problem

- The power consumption of “short range” (i.e., low-power) wireless communications is roughly the same when
  - transmitting,
  - receiving,
  - or simply ON, “listening” for potential reception.
  - IEEE 802.15.4, Zwave, Bluetooth, …, WiFi
- Radio must be ON (listening) in order receive anything.
  - Transmission is rare
  - Listening happens all the time

⇒ Energy consumption dominated by *idle listening*

⇒ *Do Nothing Well*

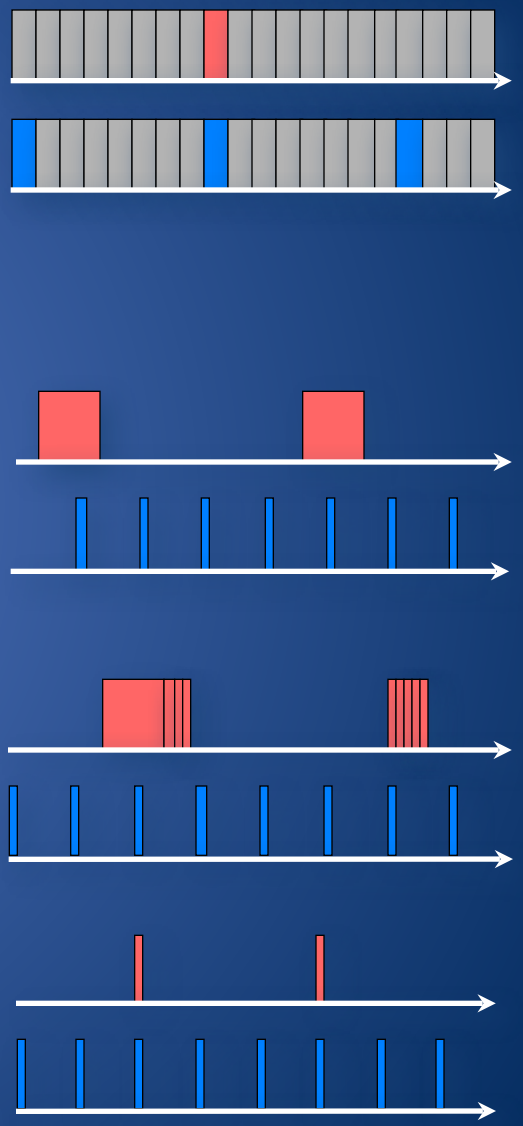
Communication Power – Passive Vigilance



- Listen just when there is something to hear …

3 Basic Solution Techniques

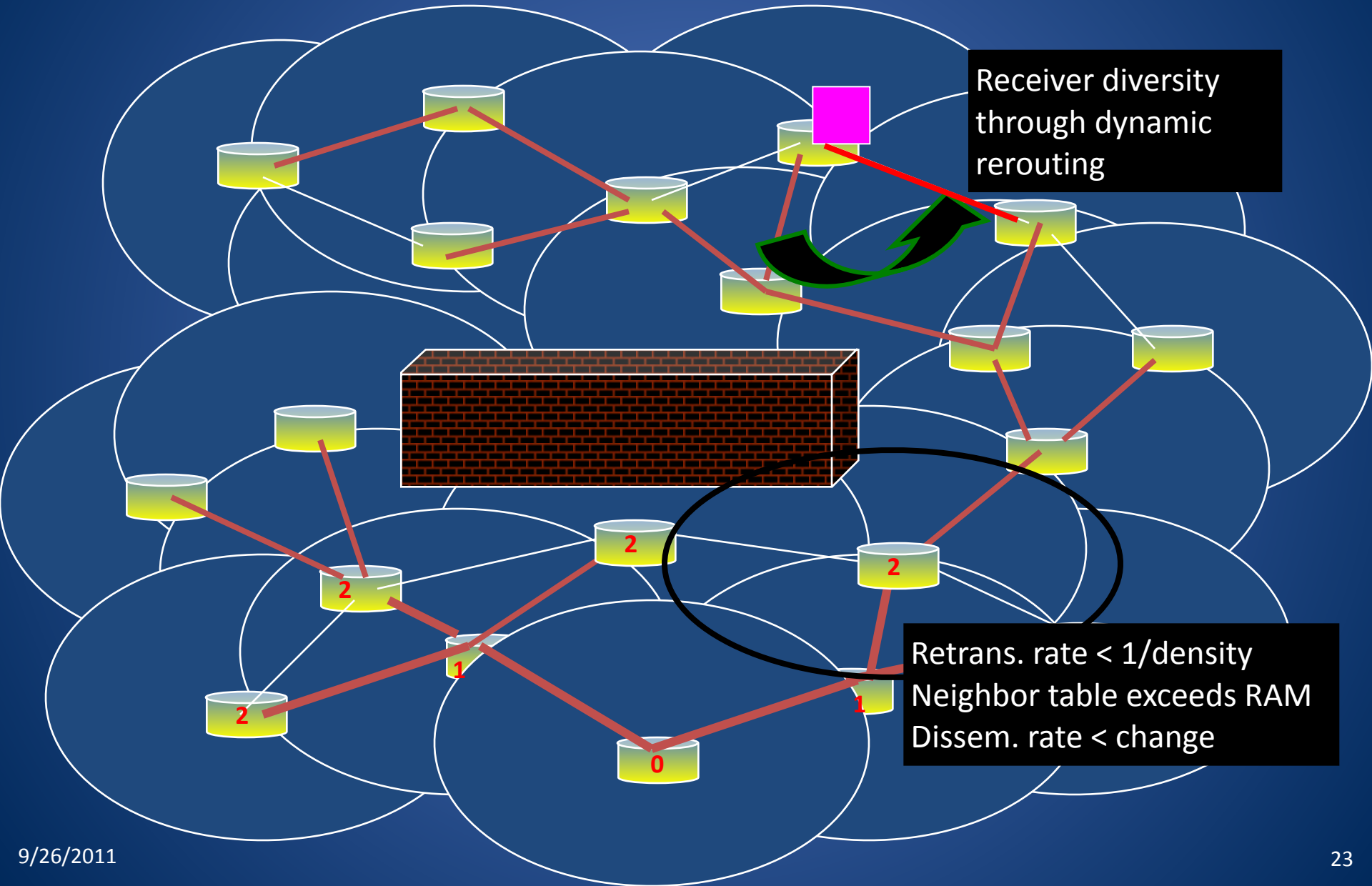
- Scheduled Listening
  - Arrange a schedule of communication Time Slots
  - Maintain coordinated clocks and schedule
  - Listen during specific “slots”
  - Many variants:
    - Aloha, Token-Ring, TDMA, Beacons, Bluetooth piconets, …
    - S-MAC, T-MAC, PEDAMACS, TSMP, FPS, …
- Sampled Listening
  - Listen for very short intervals to detect emin transmissions
  - On detection, listen actively to receive
  - DARPA packet radio, LPL, BMAC, XMAC, …
  - Maintain “always on” illusion, Robust
- Listen after send (with powered infrastructure)
  - After transmit to a receptive device, listen for a short time
  - Many variants: 802.11 AMAT, Key fobs, remote modems, …
- Many hybrids possible



Routing in Low Power Wireless Networks

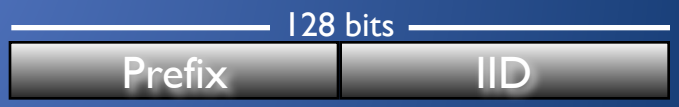
- Classic View
  - Network = Graph of routers and links
    - Like a street map
  - Routing is a (distributed) algorithm for finding good paths in this (slowly changing) graph
  - Realized (hop by hop) by tables and addressing
- But, … there is no graph
  - Discover it by attempting to communicate
  - Changes due to environment

Self-Organized Routing - nutshell

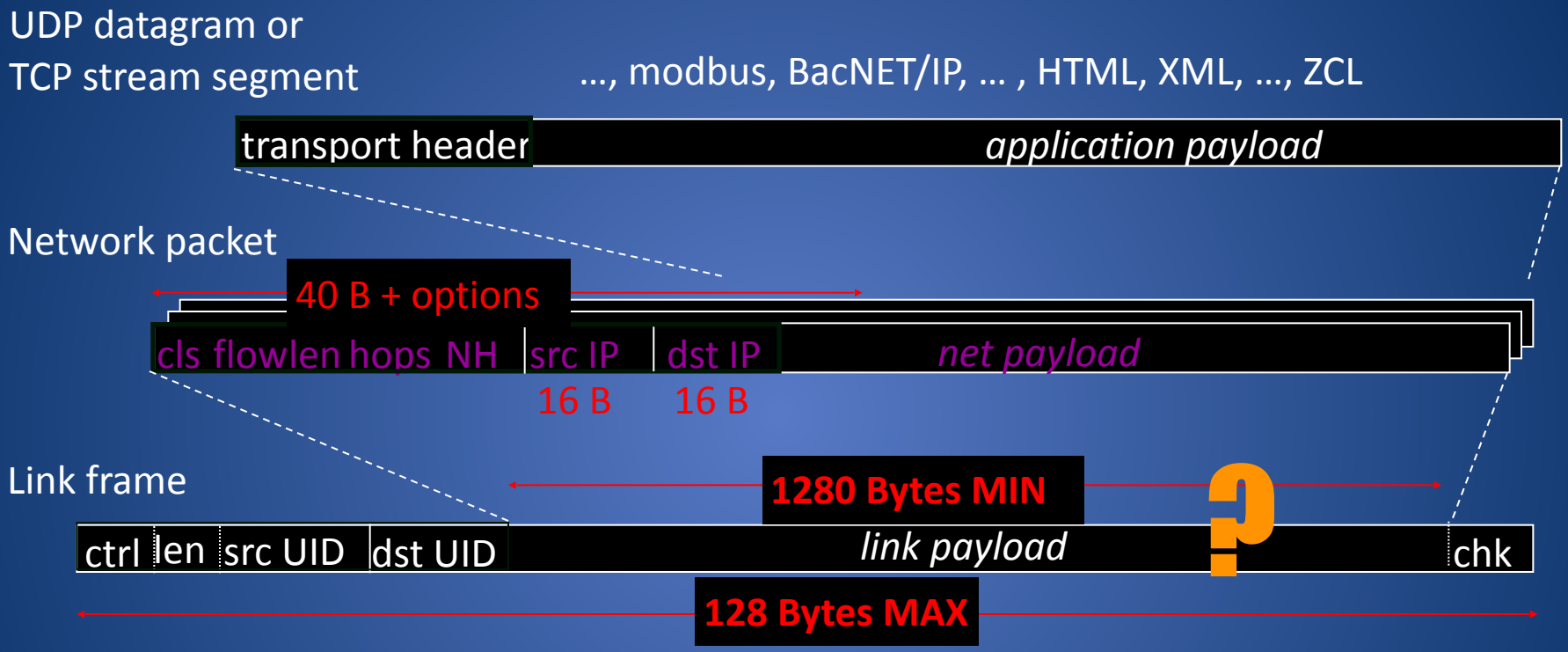


Key IPv6 Contributions

- 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

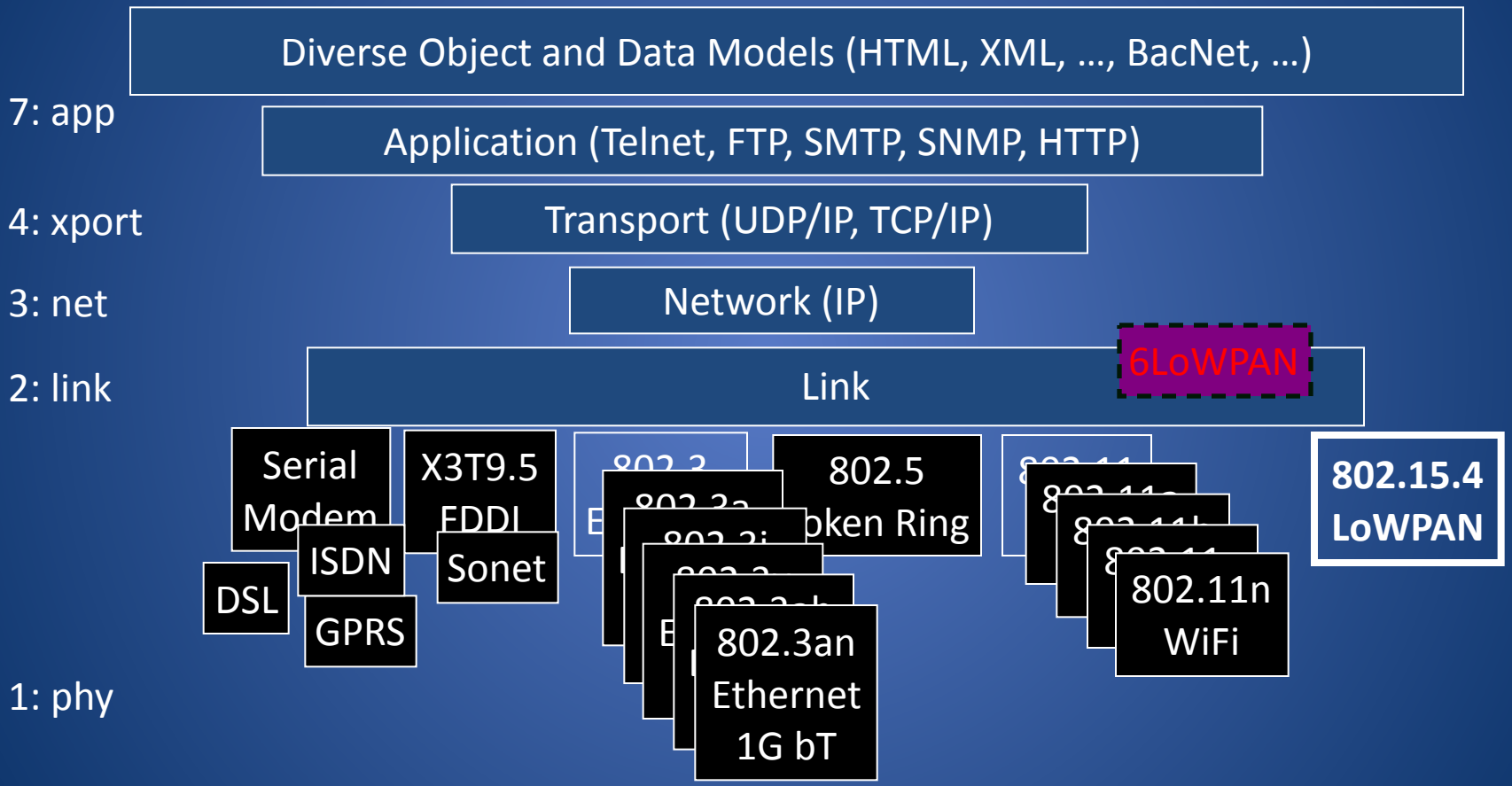


6LoWPAN – IPv6 over 802.15.4

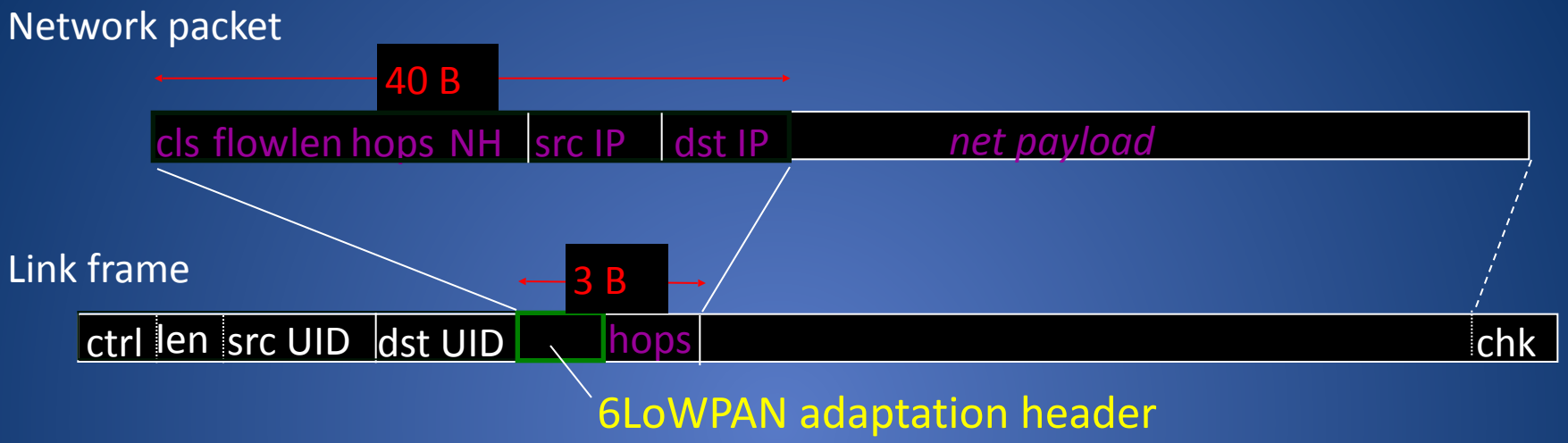


- Large IP Address & Header => 16 bit short address / 64 bit EUID
- Minimum Transfer Unit => Fragmentation
- Short range & Embedded => Multiple Hops

6LoWPAN adaptation layer

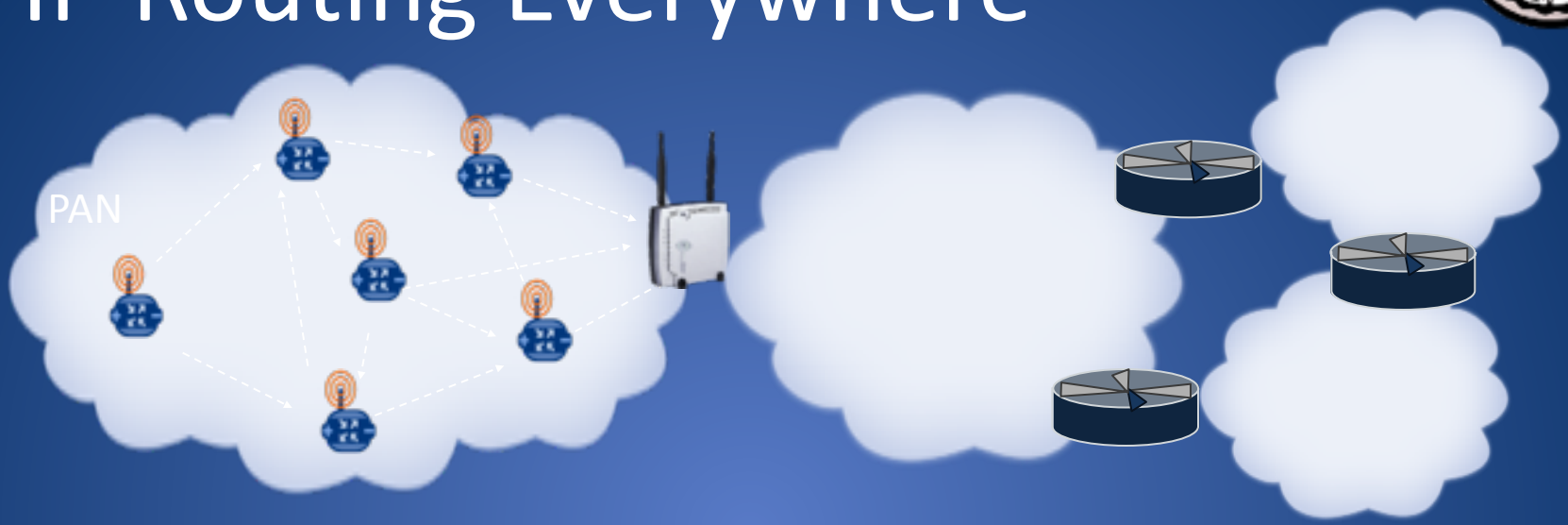


6LoWPAN – IP Header Optimization



- 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

IP Routing Everywhere



- Conventional IP link is a full broadcast domain
  - Routing connects links (i.e, networks)
- Many IP links have evolved from a broadcast domain to a “mesh” with emulated broadcast
  - ethernet => switched ethernet
  - 802.11 => 802.11s
- Utilize high bandwidth on powered links to maintain the illusion of a broadcast domain
- 802.15.4 networks are limited in bandwidth and power so the emulation is quite visible.

Embedded IPv6 in Concept

Structured Decomposition

- ✓ Retain strict modularity
- ✓ Some key cross-layer visibility

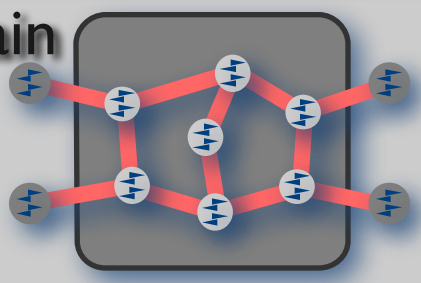
IP Link ⇒ Always On

- ✓ Retain illusion even when always off

IP Link ⇒ "Reliable"

- ✓ Retain best-effort reliability over unreliable links

IP Link ⇒ Broadcast Domain

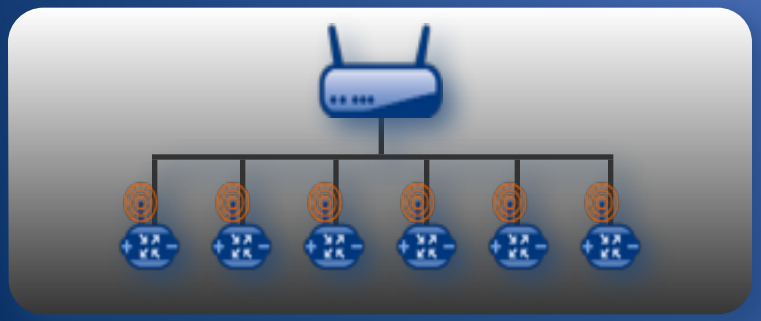


- ✗ IPv6 can support a semi-broadcast link with few changes

Example: Autoconfiguration

Configuring Large Numbers of Interfaces

RFC 4861 – Neighbor Discovery
RFC 4862 – Stateless Addr Autoconf
RFC 3315 – DHCPv6

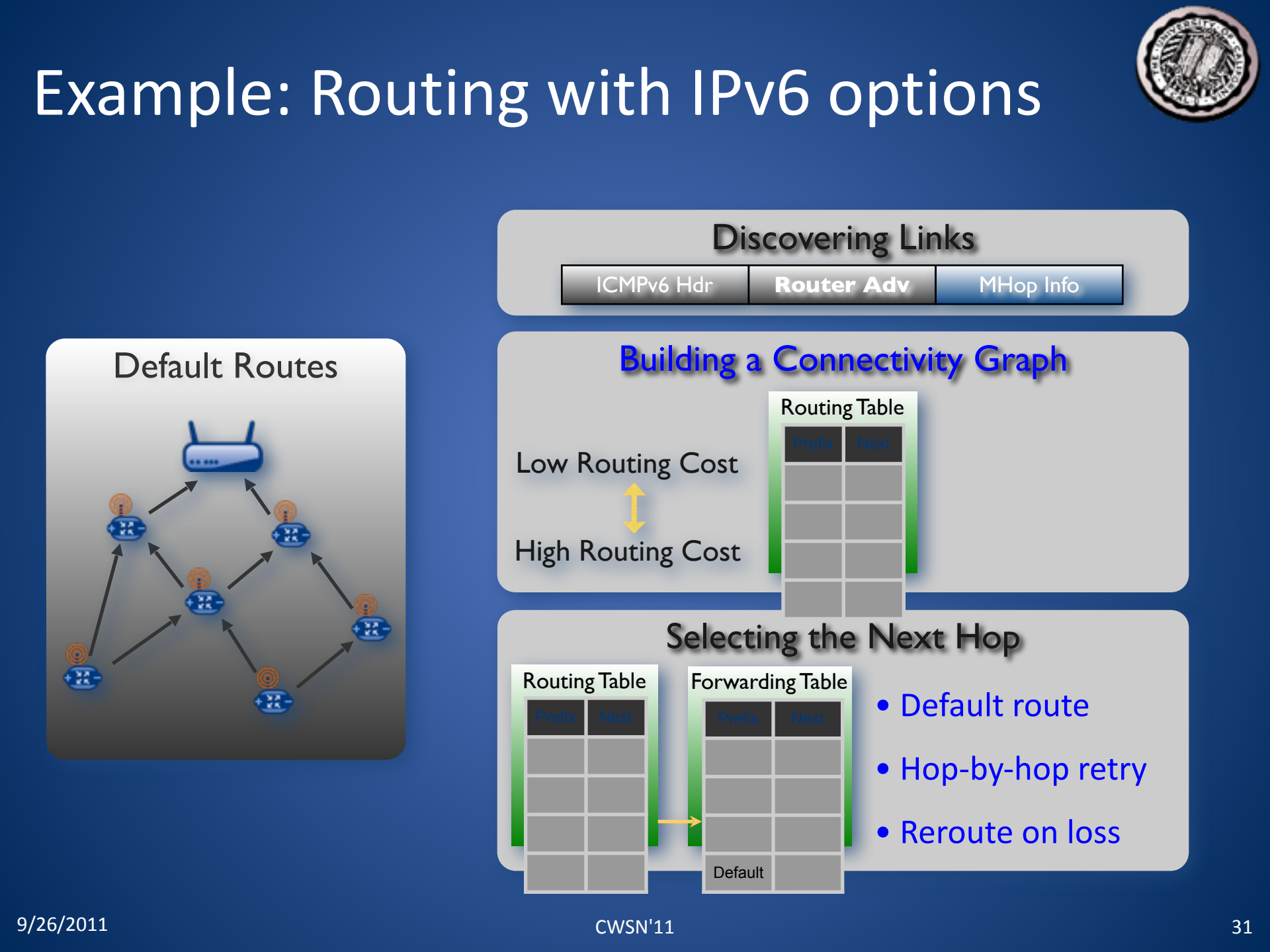


Existing Options

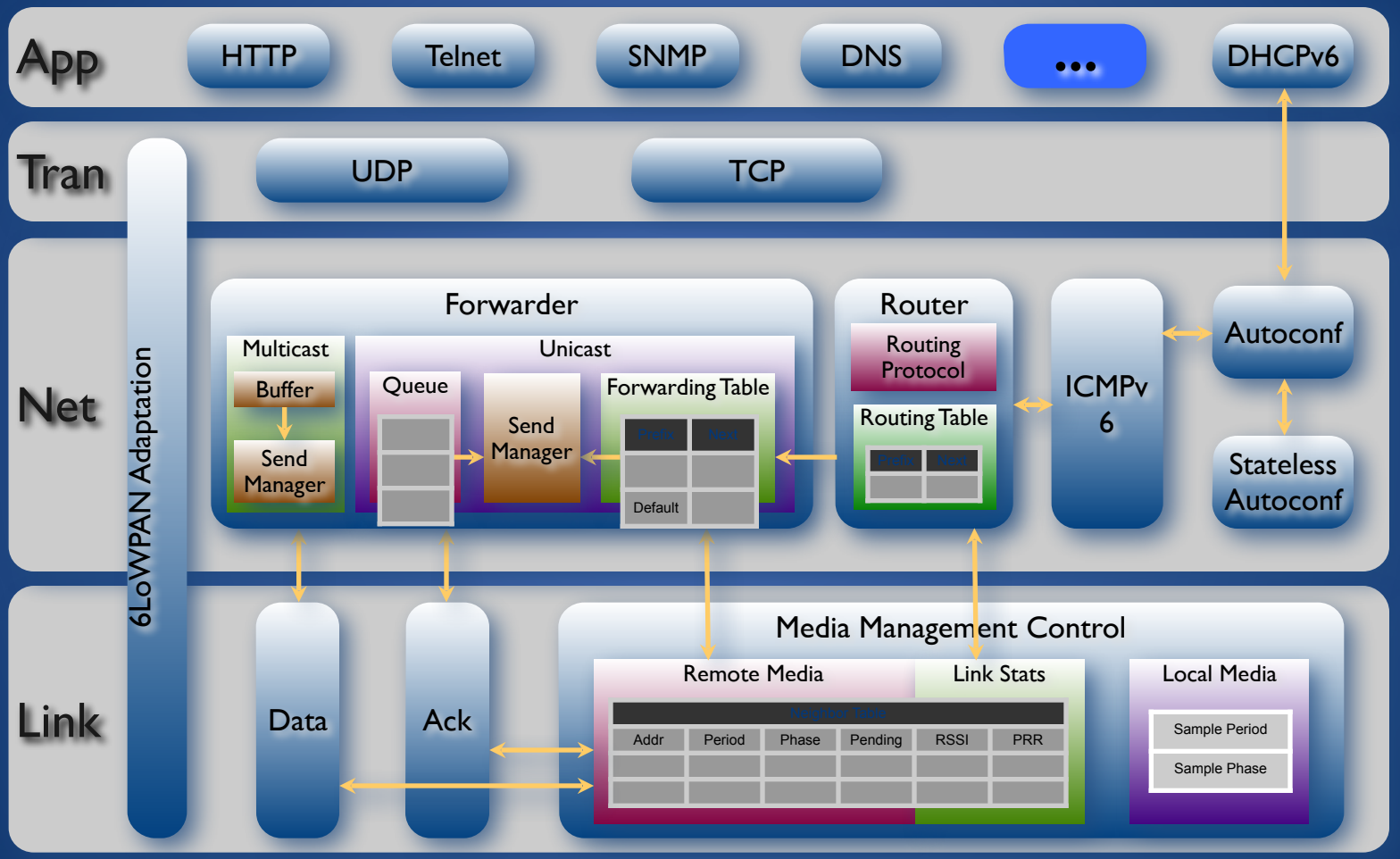
New Options

ICMPv6 Hdr	Router Adv	Prefix Info	MHop Info
	Cur Hop Limit	Prefix Length	Network ID
	Managed Addr Config	Autonomous Config	Sequence Number
	Other Config	Valid Lifetime	Router Hops
	Router Lifetime	Preferred Lifetime	Flags
	Reachable Time	Prefix	

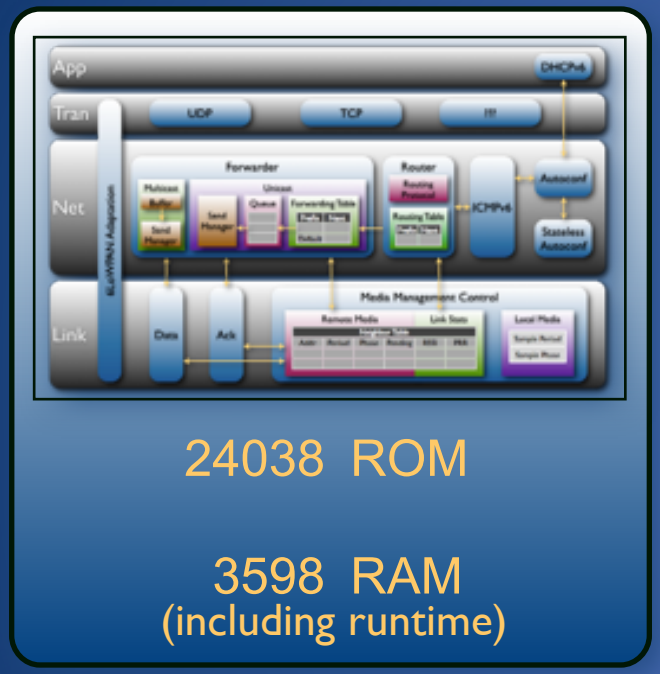
Example: Routing with IPv6 options



Complete Embedded IPv6 Stack



Adding up the pieces



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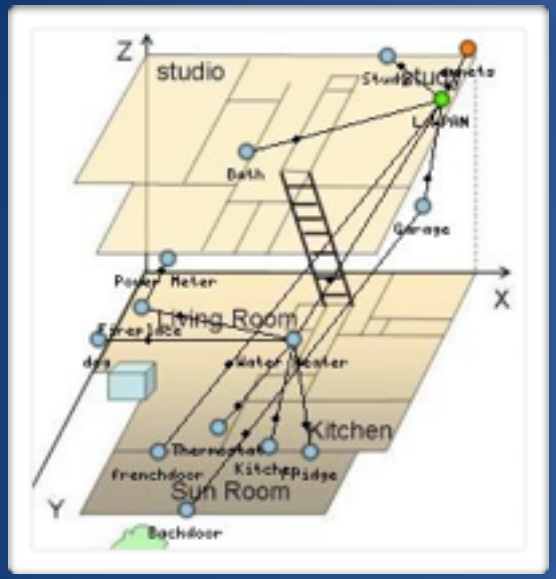
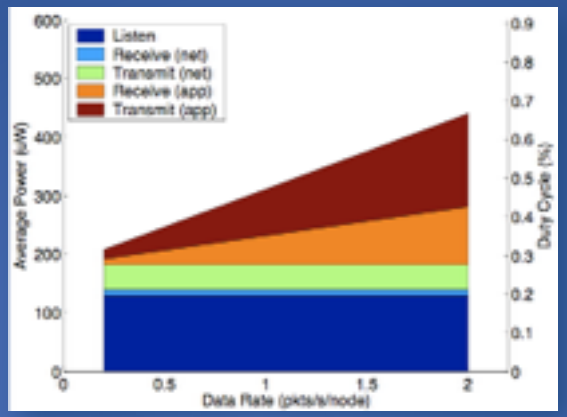
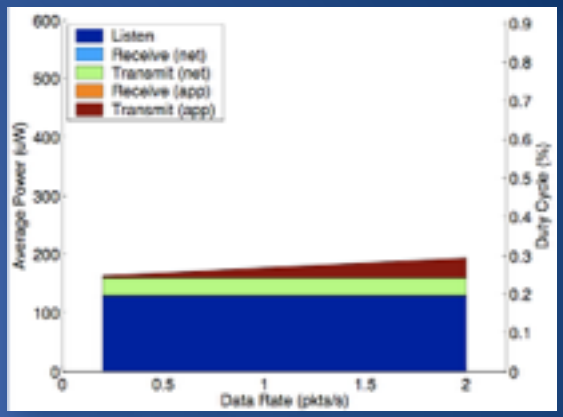
and Power and reliability …

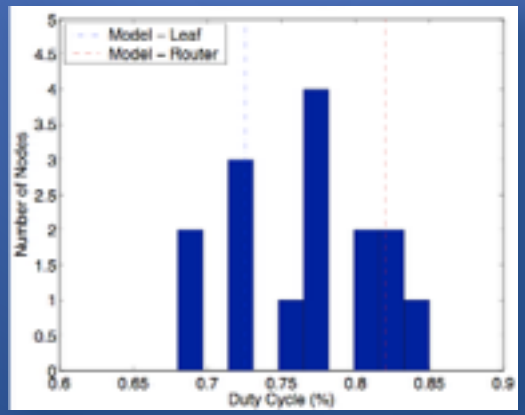




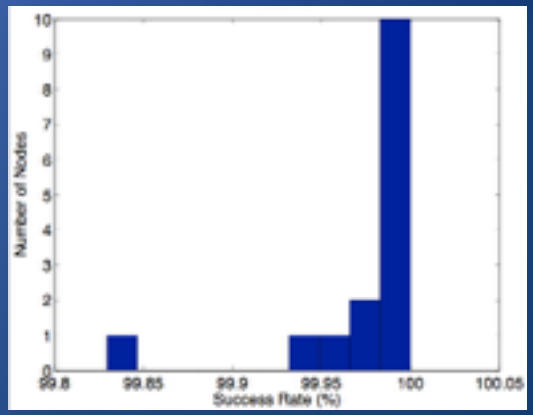
Data Rate Sensitivity
(Router)



Data Rate Sensitivity
(Edge)



Deployment Duty Cycle



Deployment Reliability

What has Changed with ROLL ?

- Three routing requirements case studies
  - Buildings [RFC 5867], Industrial [RFC 5673], Urban [RFC 5548], and home [RFC 5826]
  - Narrow the domain, establish constraints
- IETF Routing Protocol Survey
  - Useful study, unpublished for political reasons
- Three Initial Proposals
  - HYDRO: simple merger of well-established techniques (CTP, TSMP, …)
  - TD: repurpose of MANEMO proposal
  - Backtrack
- Design Team to produce unification: RPL
  - 1+ year, inter-related suite of design choices

Elements of RPL

- Retains carefully-formed, low-complexity muti-path routing
  - DAG constructed and maintained via discovery and use of links
  - Roots route to/from “powered Internet”
  - Multiple ‘upward’ default routes
  - Source-based downward routing via reversal
    - State-free: routing table at root
    - State-full: tables may be in any node
- Imposes some structure on DAG
  - Collection of single-rooted DAGs (DODAG)
  - Local-repair within constraints
  - Roots may initiate global repair through seq # advance
  - Avoids count-to-infinity via split-horizon emulation

Elements (cont)

- Arbitrary point-to-point via up/down
- Multiple RPL instances over common physical topology
- Elaborate metric container mechanism (OF)
  - Support multi-objective, constraint-based routing
  - OF0 essentially shortest path (with threshold)
  - MRHOF: generalization of ETX (estimated transmission cost)
- Proposed lower-stretch P2P via instance formation

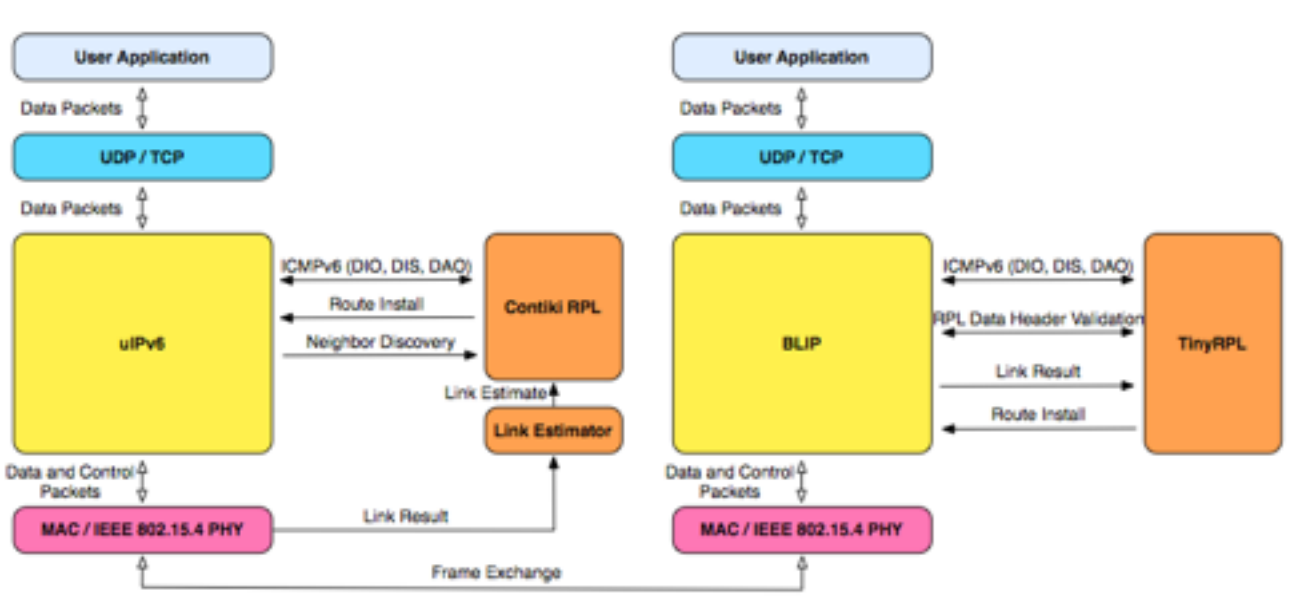
Many Important Details

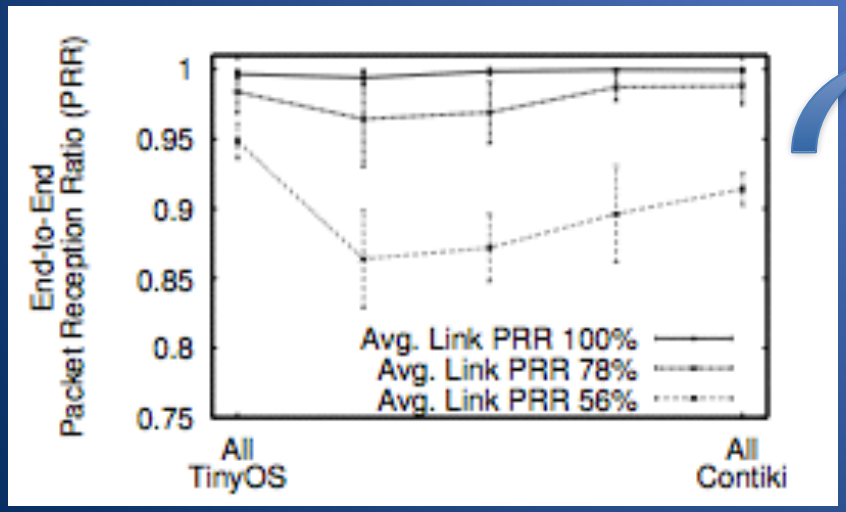
- Header format specifics and trade-offs
- ICMPv6 ND (RA etc.) replaced with RPL ND
  - DIS, DIO, DAO
- Routing Security framework from the start
- Limited Tolerance for Routing Inconsistency
- Source routing as compact hop-by-hop option
  - 6MAN
- Not limited to 802.15.4 or LoWPAN
  - PLC
- …

Rough Consensus and Running Code

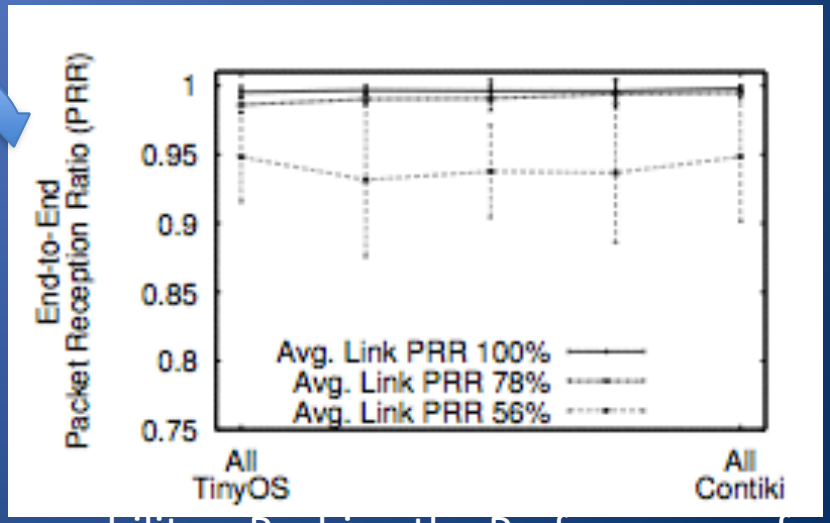
- IETF Standard requires multiple independent interoperable implementations
  - Two major open-source ones already (next)
  - Many commercial and research ones of varying quality
- Standards bodies in transformation
  - ZIGBEE has become compliance body
  - 802.15.4 | 6LoWPAN |RPL ipv6 | TCP/UDP | … ??
  - IETF CORE developing compact http over UDP
  - IEEE 802.15.4e/g wrapping up low power MAC
- Lots of vested interest positioning & cruft

Open InterOp …





MAC Parameter alignment



Beyond Interoperability – Pushing the Performance of Sensor Network IP Stacks, Sensys 2011

Opportunities and Open Problems

- Quantitative Analysis and Design of WSNs in context of layered IPv6 architecture
  - Objective function trade-offs, utility, table management algorithms, …
- Classic issues in new context
  - Transport protocol, compression, cross-layer optimization, …
- Ideas set aside for lack of knowledge
  - Piecewise source routing, reactive backtracking, …
- “Let chaos Reign, then Rein in the Chaos”

The “Killer App” for WSNs

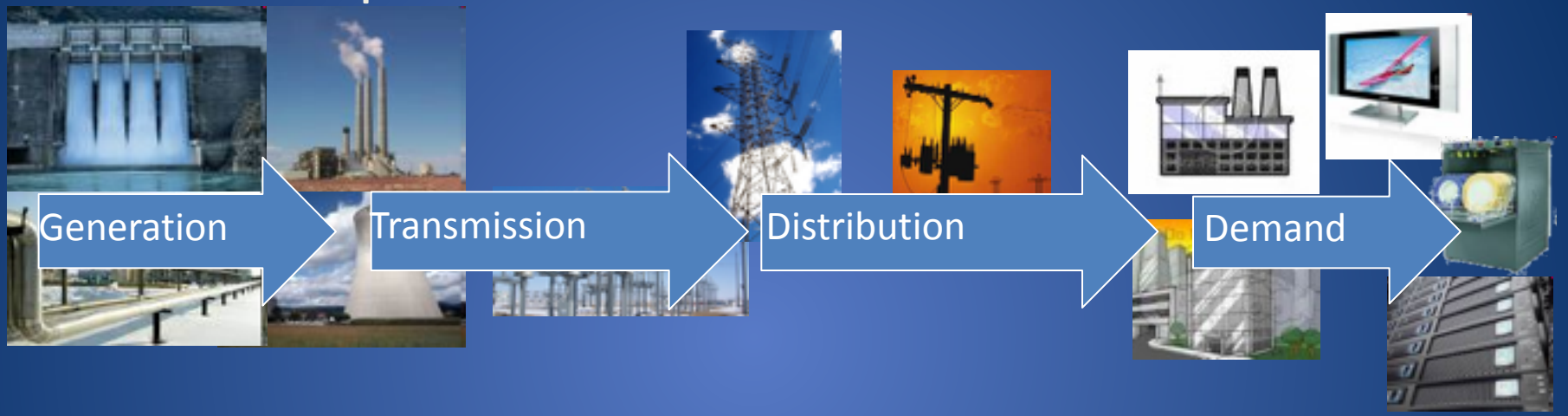
- Energy and the environmental impact of extraction, use, and disposal
- THE problem of the Industrial Age
- We need to find Information Age solutions to THE Industrial Age Problem

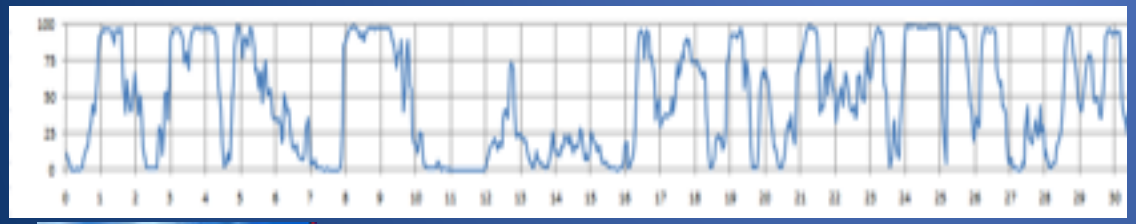
- => Fundamental transformation in the architecture of the electric grid

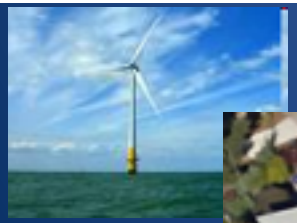
Traditional Load-Following Grid

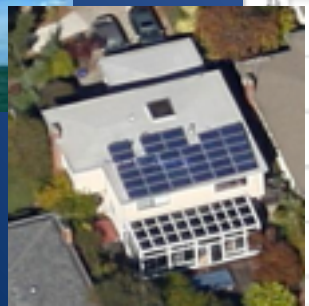
Baseline + Dispatchable Tiers

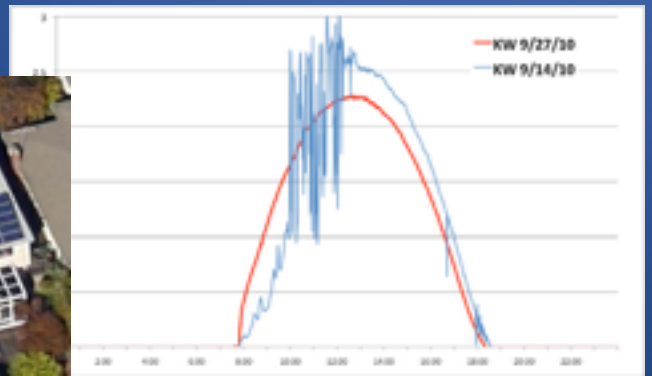
Oblivious Loads

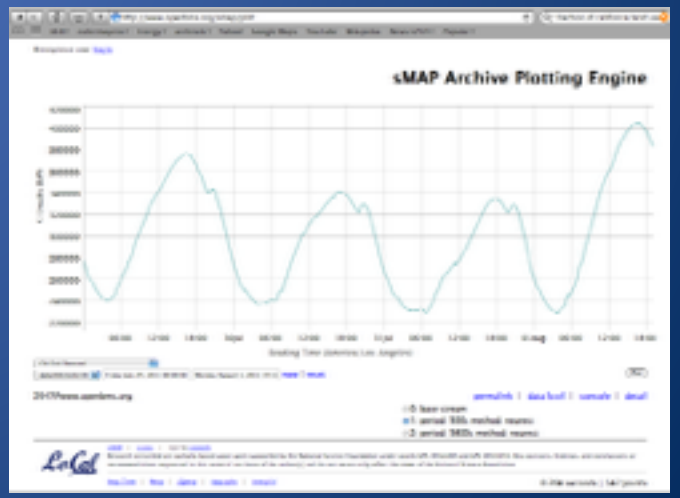








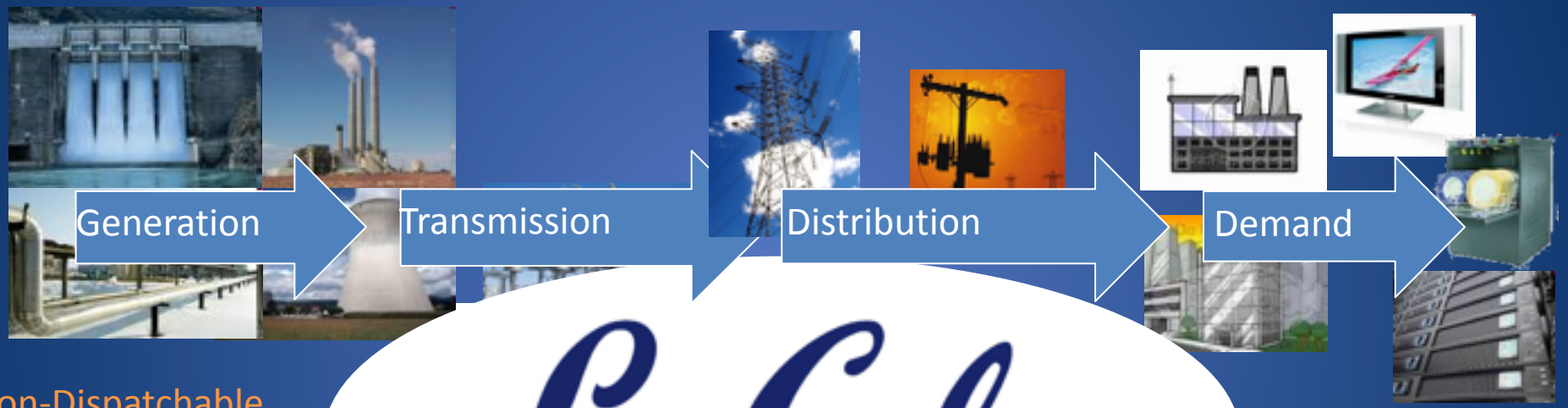




Towards an 'Aware' Energy Infrastructure

Baseline + Dispatchable Tiers

Oblivious Loads



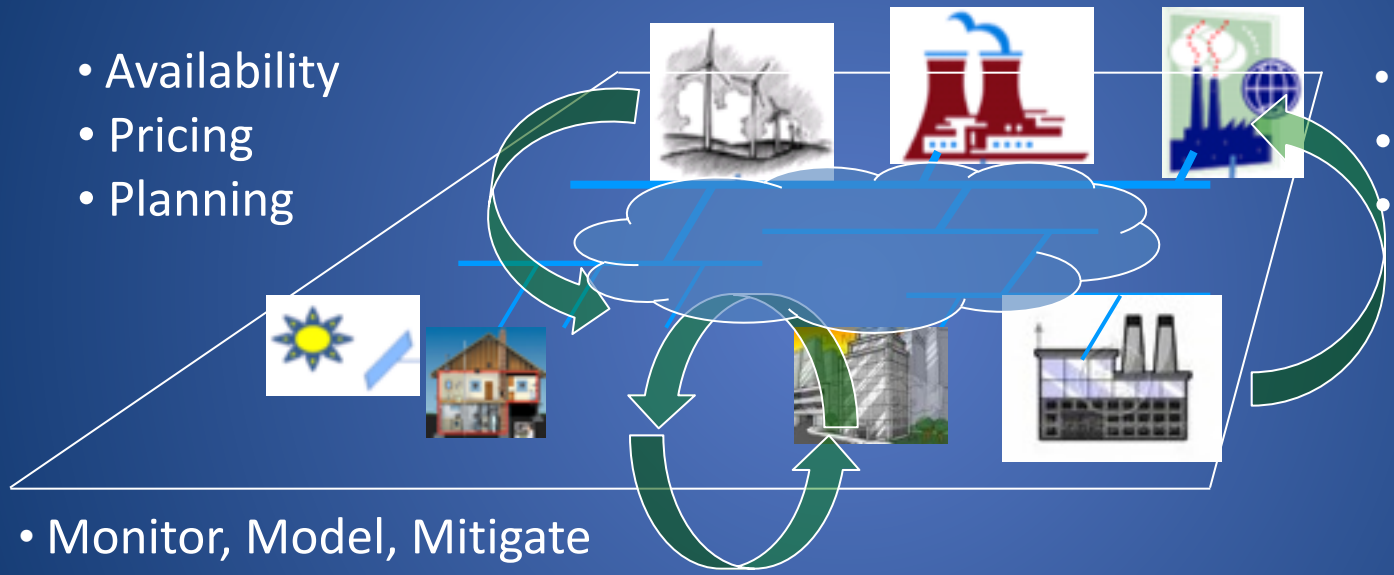
LoCal

Non-Dispatchable Sources

Aware Interactive Loads

Aware Co-operative Grid

- Availability
- Pricing
- Planning

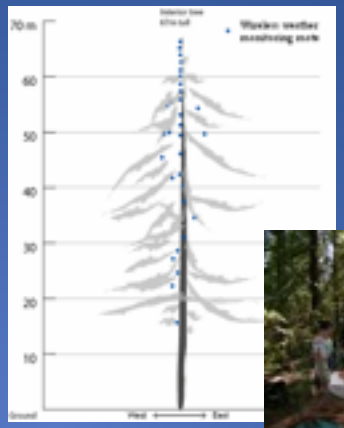


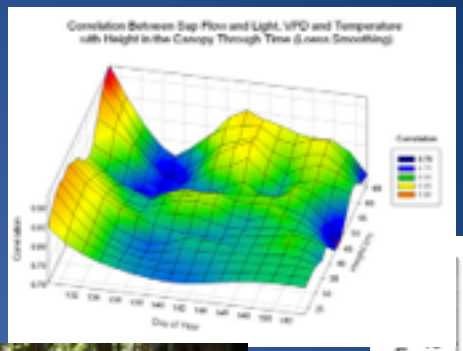
- Forecasting
- Tracking
- Market

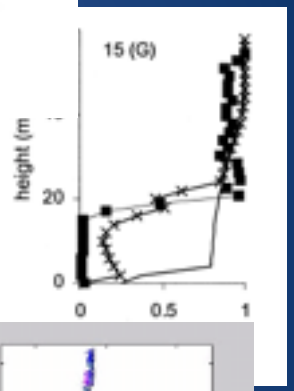
- Monitor, Model, Mitigate
  - Deep instrumentation
  - Waste elimination
  - Efficient Operation
- Shifting, Scheduling, Adaptation

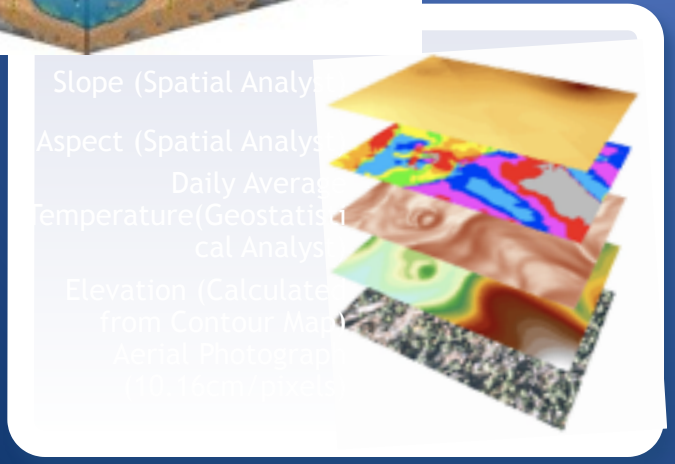
The “Macroscope”

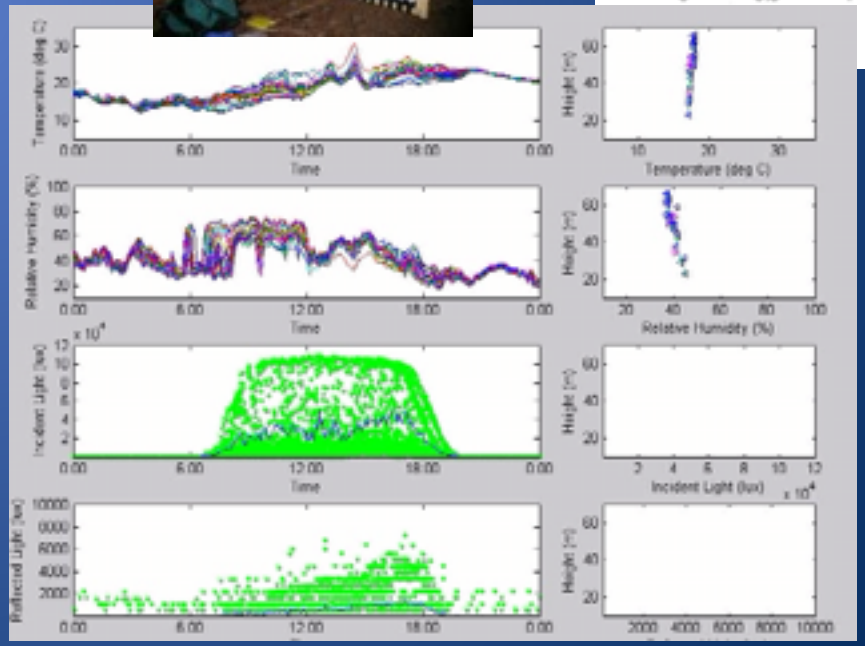
- Observe complex interactions over time and space





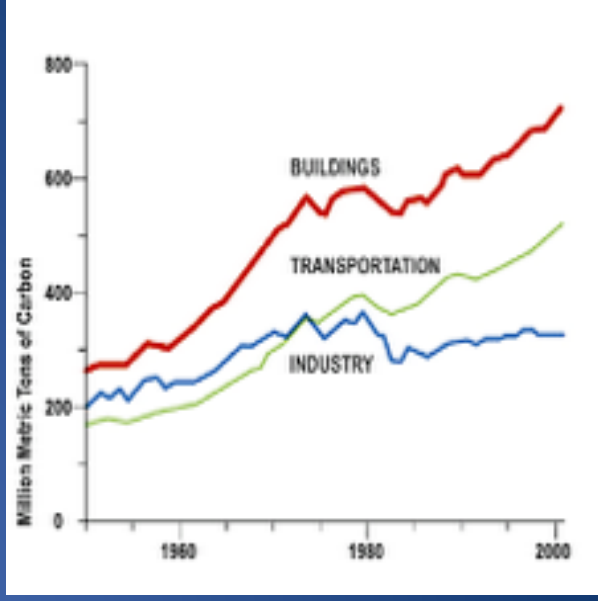


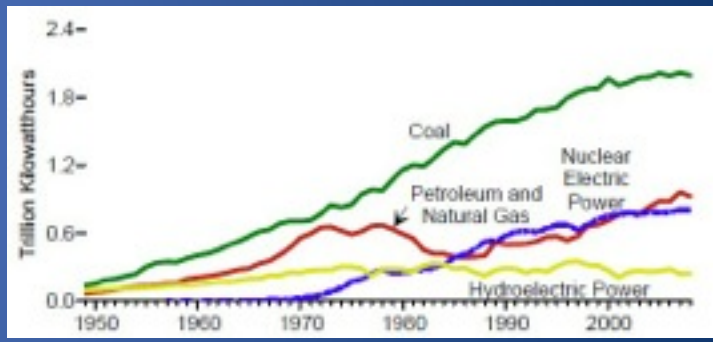




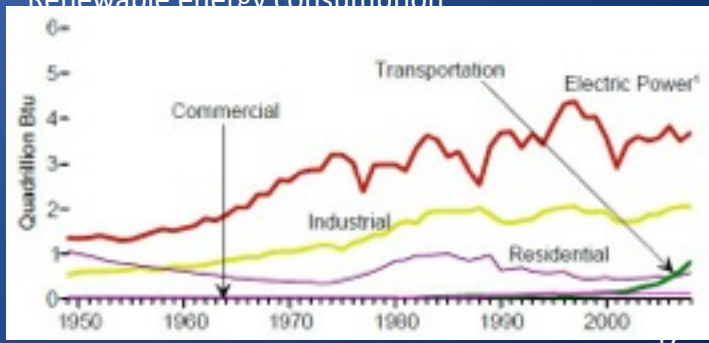
Where to Start?

- Buildings
  - 72% of electrical consumption (US),
  - 40-50% of total consumption,
  - 42% of GHG footprint
  - US commercial building consumption doubled 1980-2000, 1.5x more by 2025 [NREL]
- Where Coal is used
- Prime target of opportunity for renewable supplies

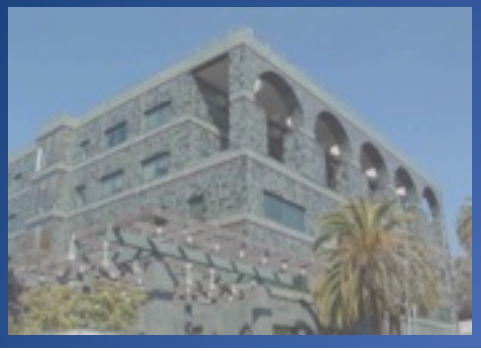


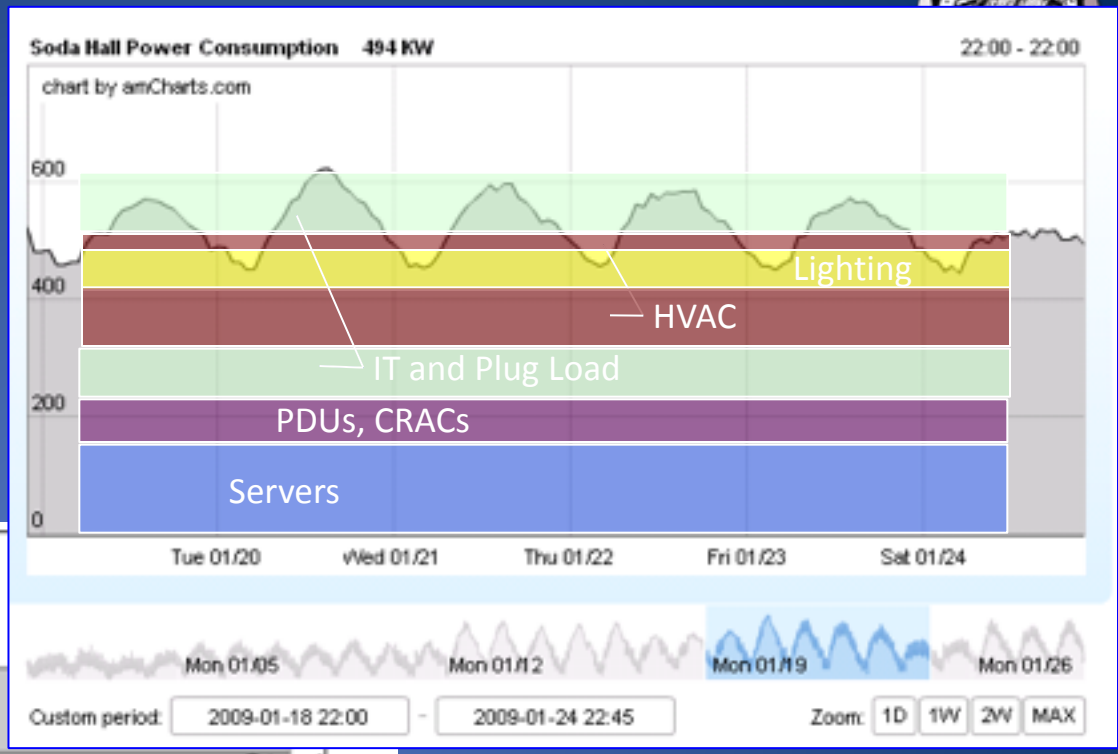


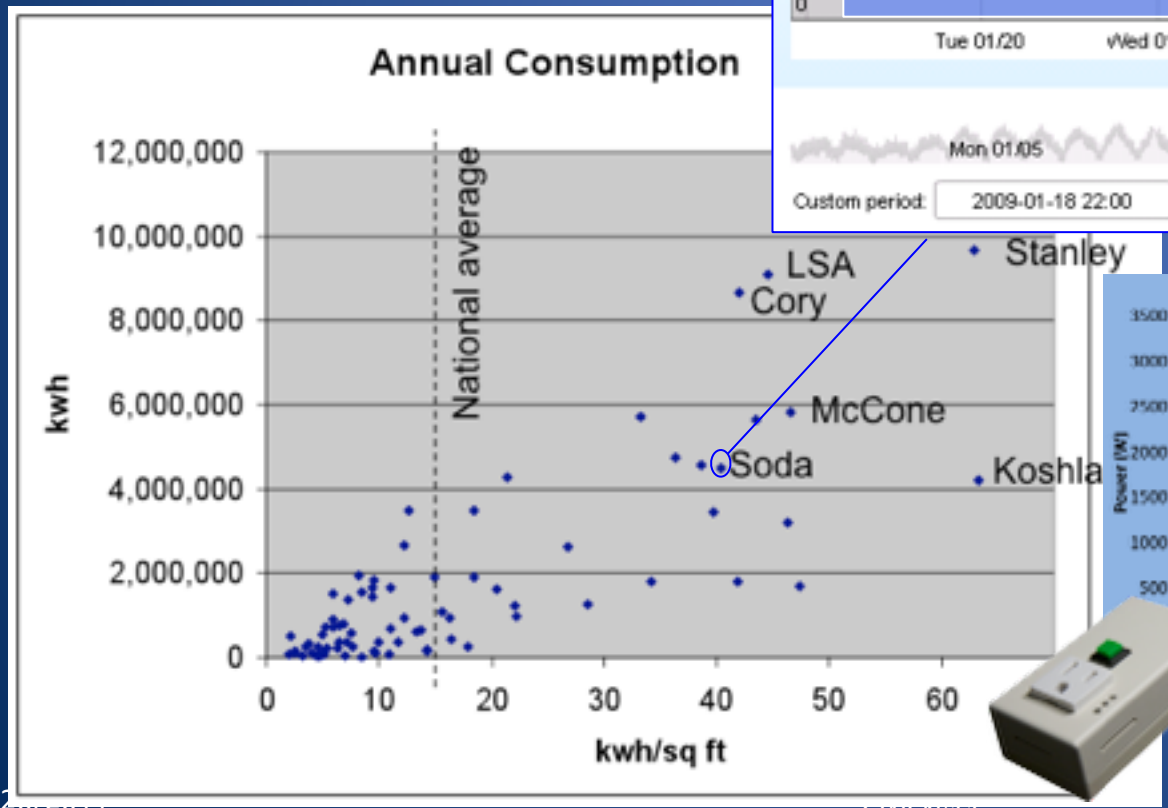
Renewable energy consumption

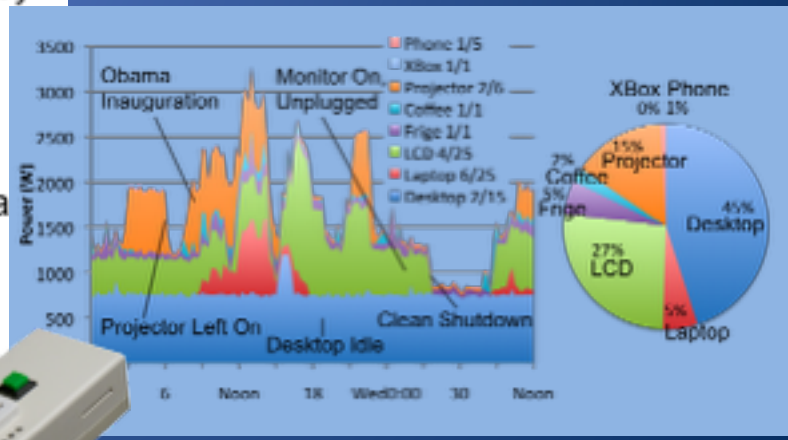


Our Buildings

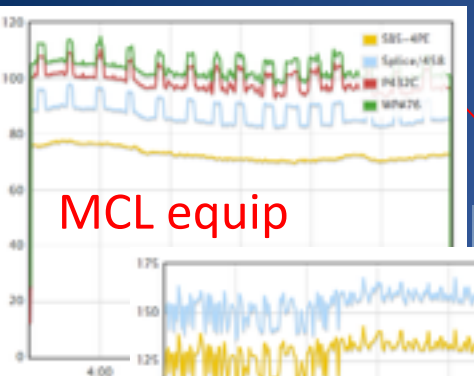


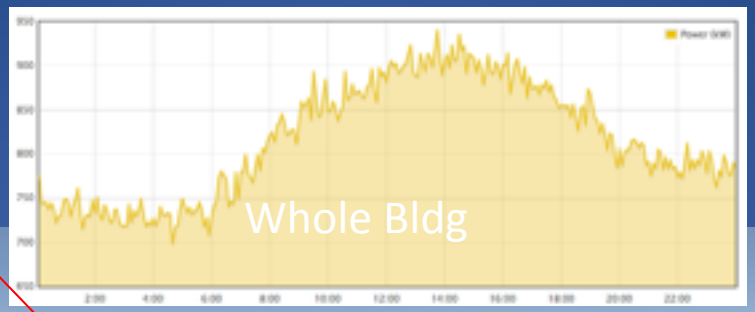


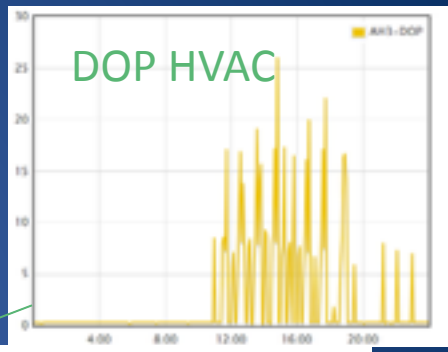


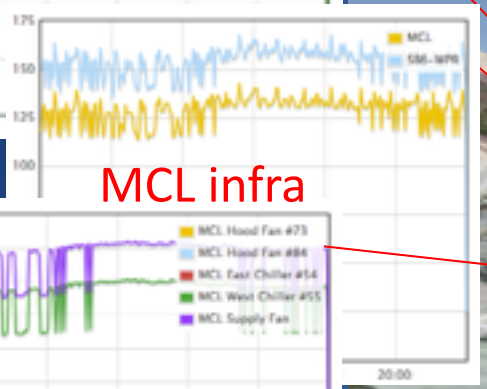


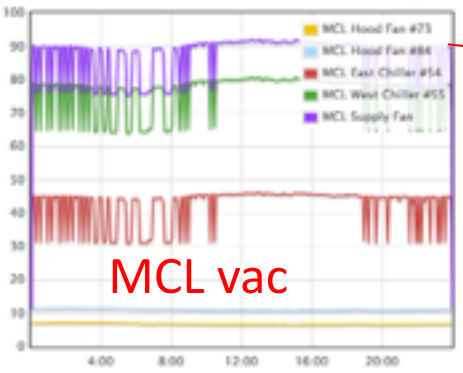
Energy Transparent Building

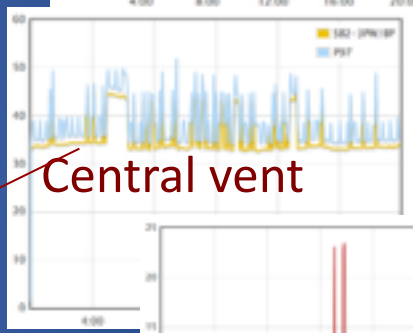


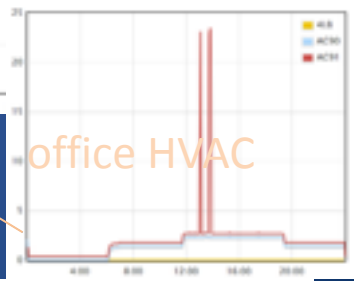


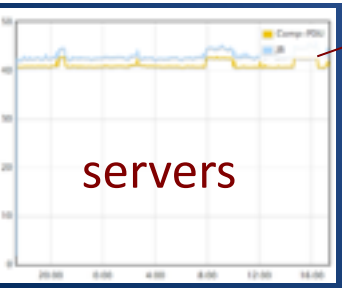


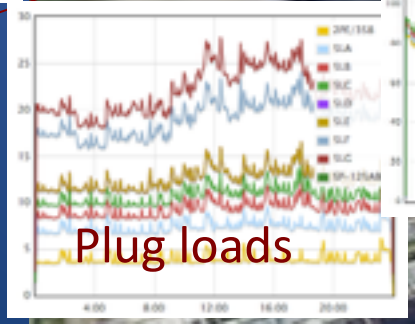


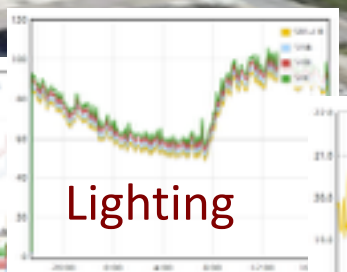


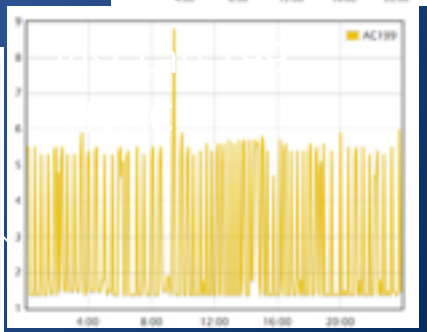




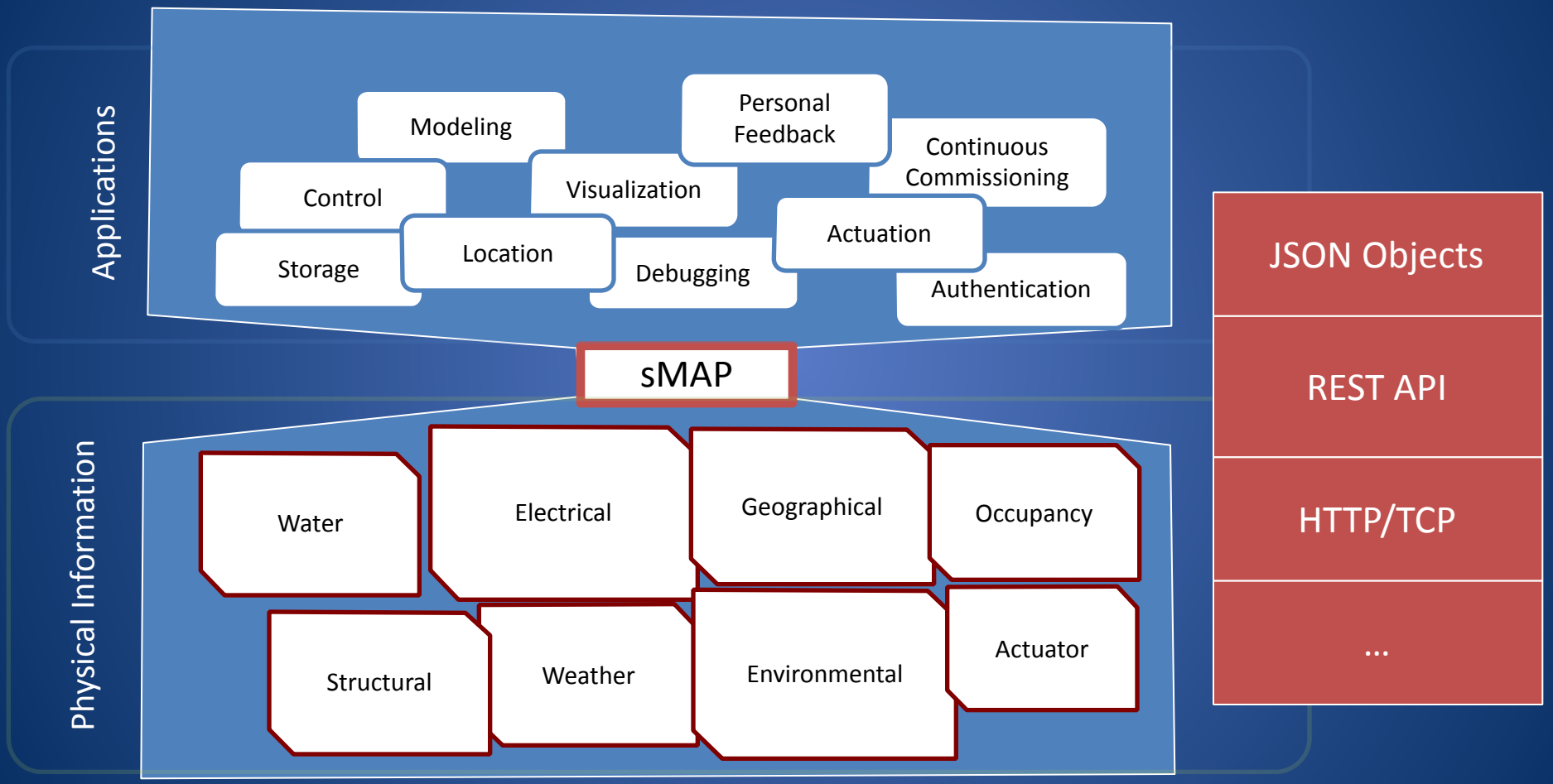




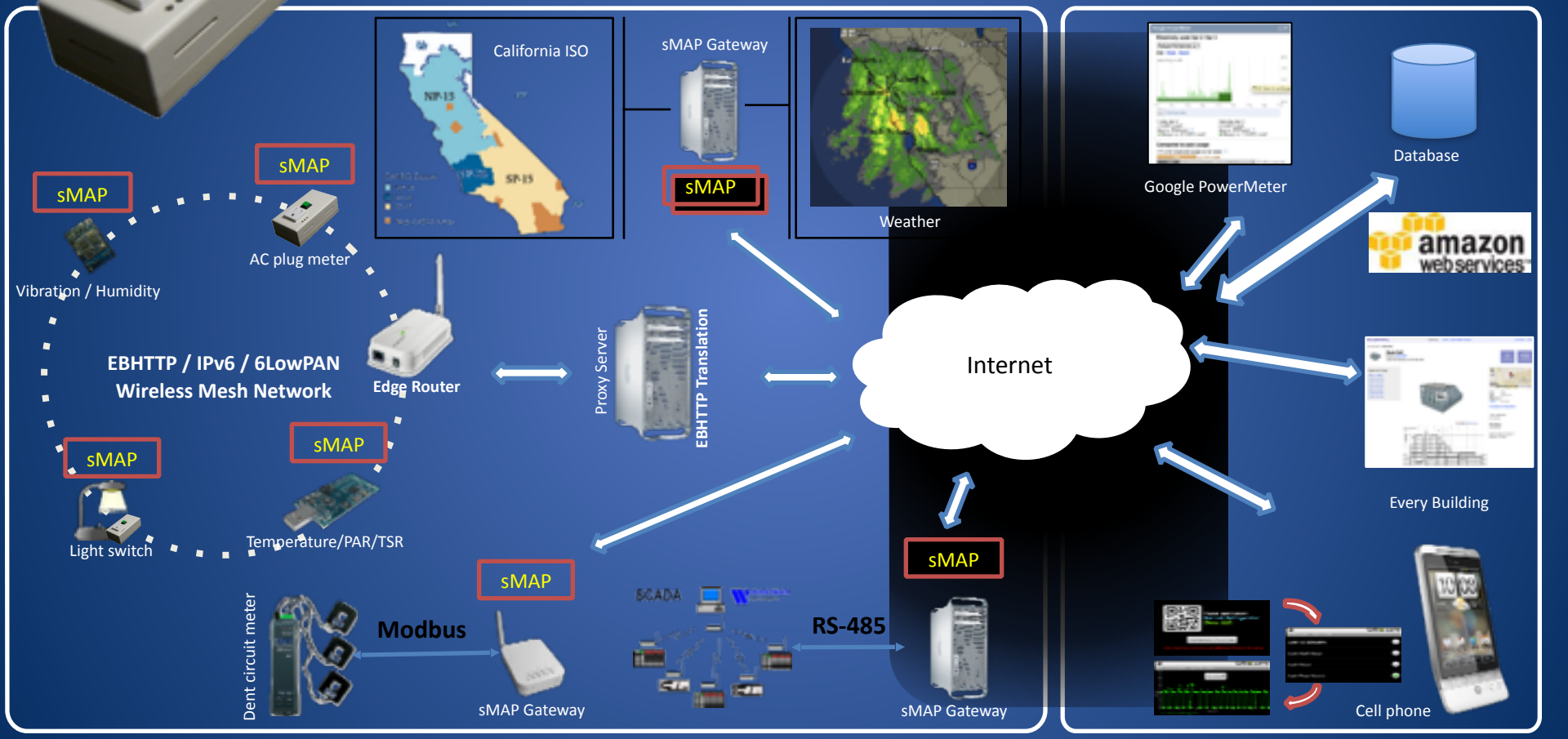




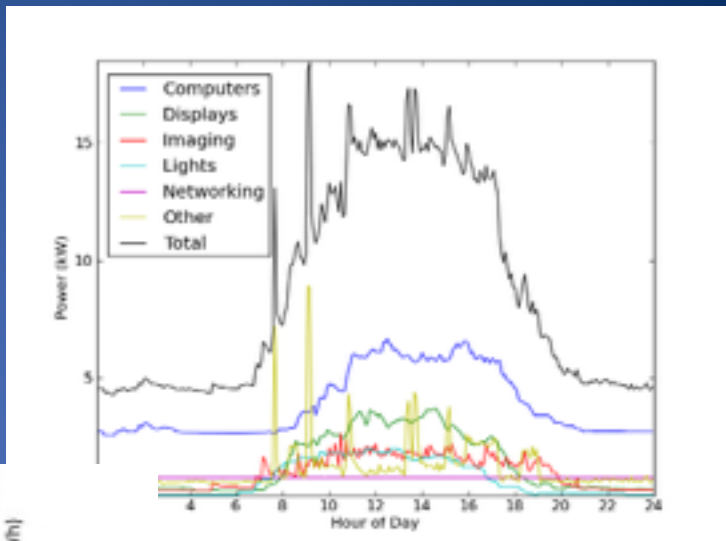
sMAP: Uniform Access to Diverse Physical Information

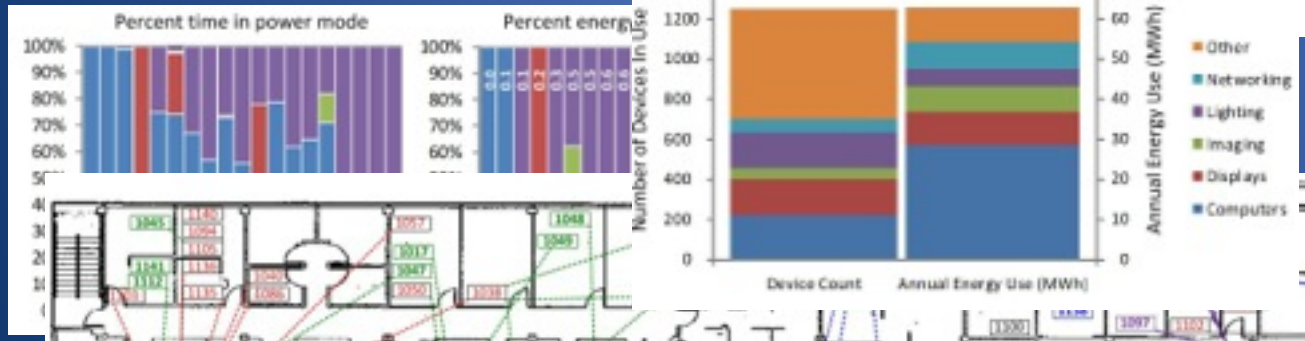


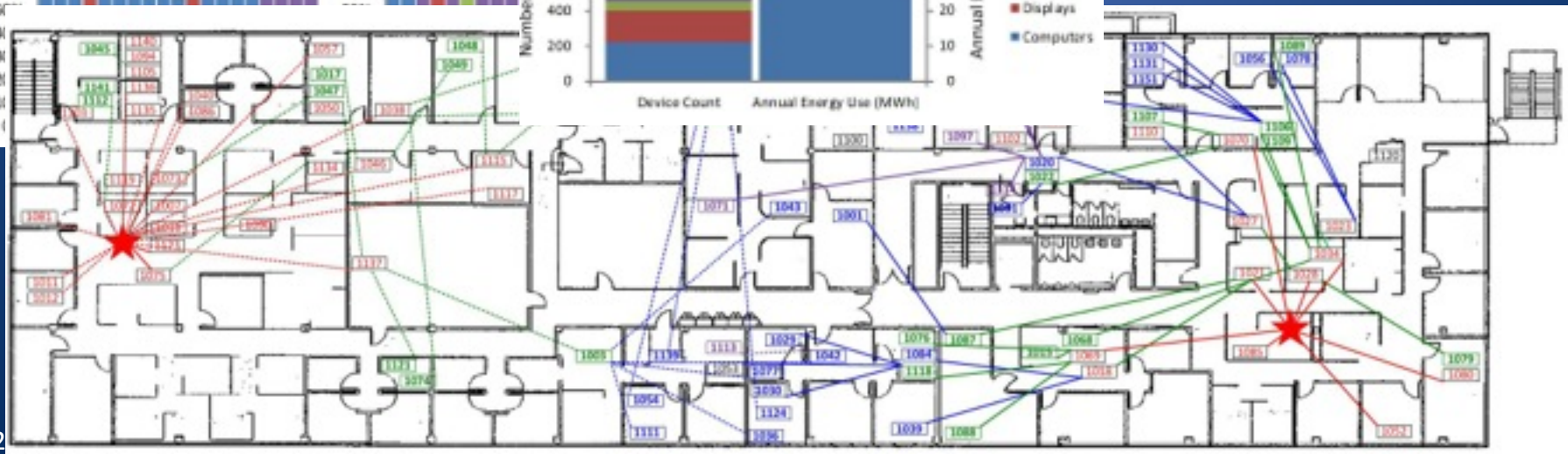
IP everywhere / Real World Web



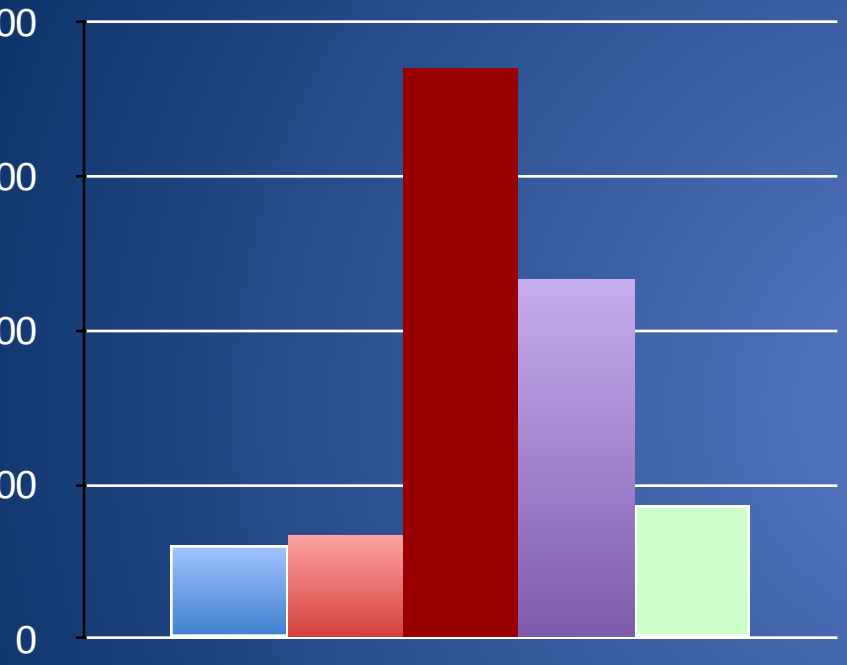
DOE Misc. and Electronic Loads



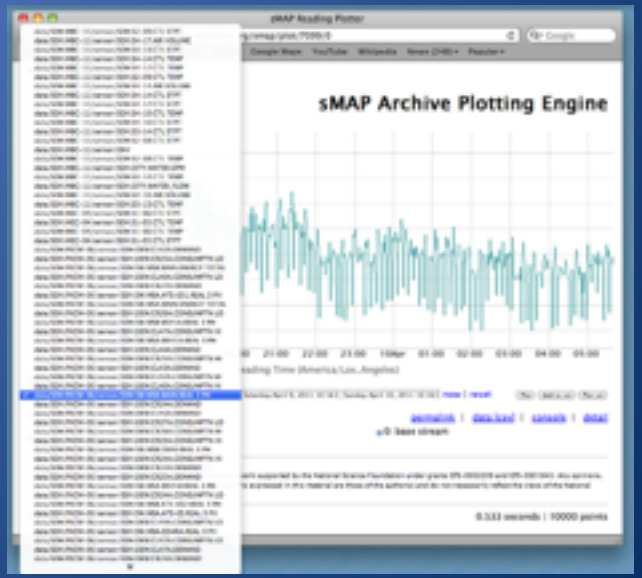




DOE/UCB/Siemens Auto Demand Response



Sutardja Dai Hall



www.openbms.org

BACNet => sMAP

Sensors, Actuators

Controllers

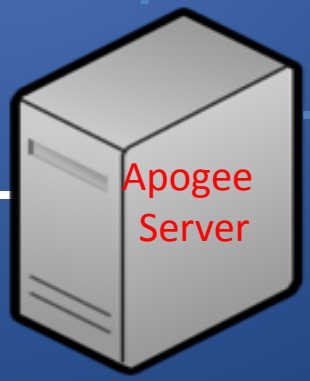
Siemens P2 over RS-485

Modem

Internet

Remote Login

sMAP

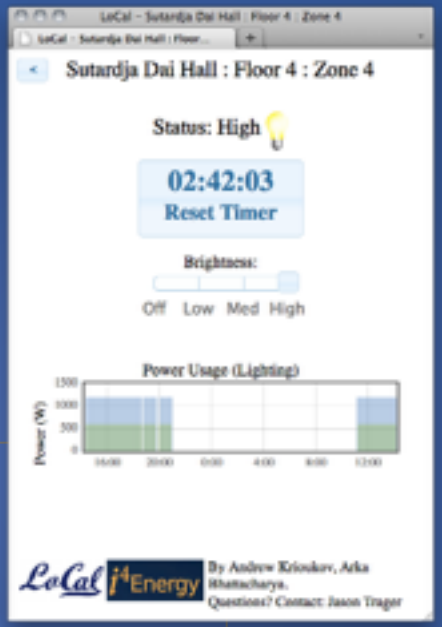


Apogee Server

BACnet/IP

Gateway

Personalized Automated Lighting Control



sMAP

BACnet

Three controllable ballasts per fixture

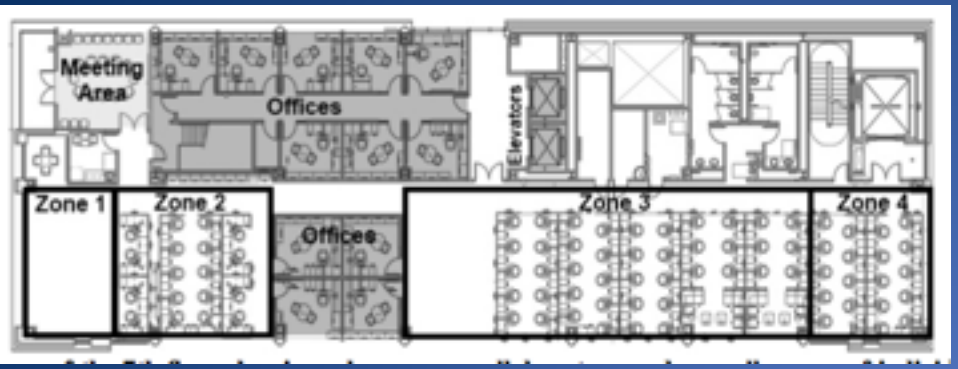
~5 zones per floor

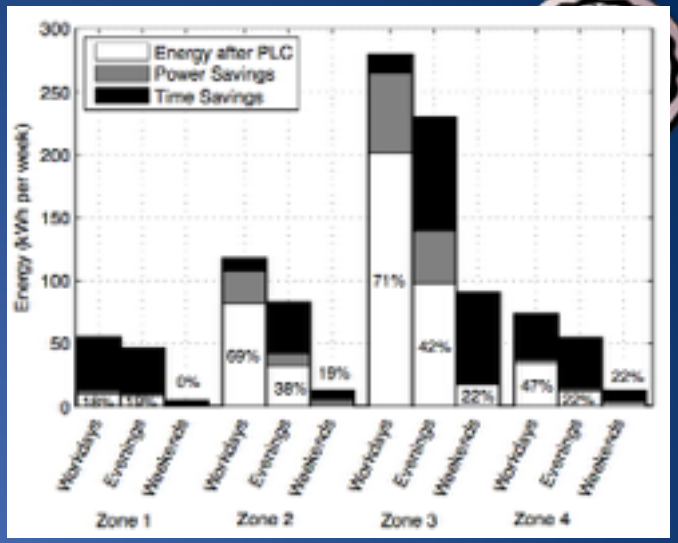
6,000+ Points in 1 Modern Building

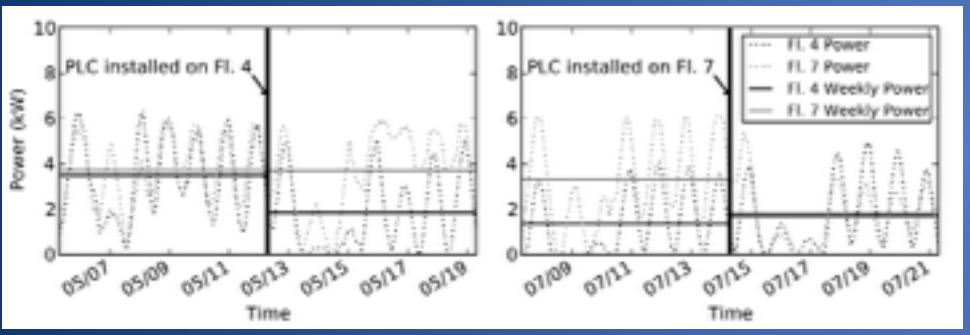
- 1358 control settings
  - Set points, Relays (lights, pumps, etc), Schedules
- 2291 meters/sensors
  - Power (building, floor, lights, chiller, pumps, etc)
    - Current, voltage, apparent, real, reactive, peak
  - Temp (rooms, chilled water, hot water)
  - Air volume
  - Alarms, Errors
- 2165 control outputs
  - Dampers, valves, min/max flow, fan speed, PID parameters
- 72 other

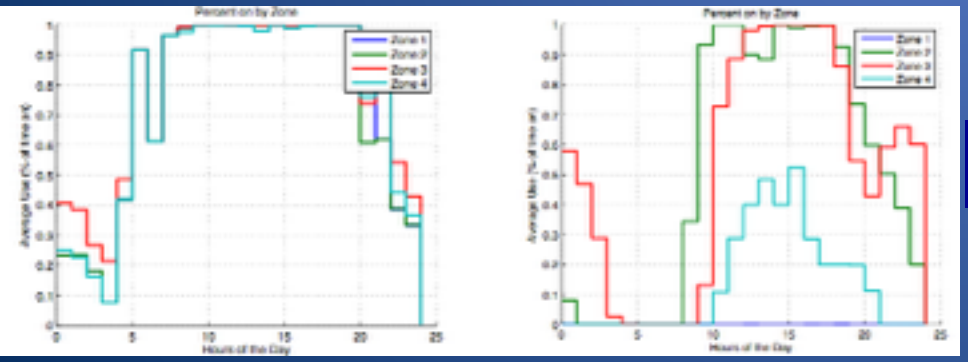
US: 4+ million Commercial, 110+ million Residential

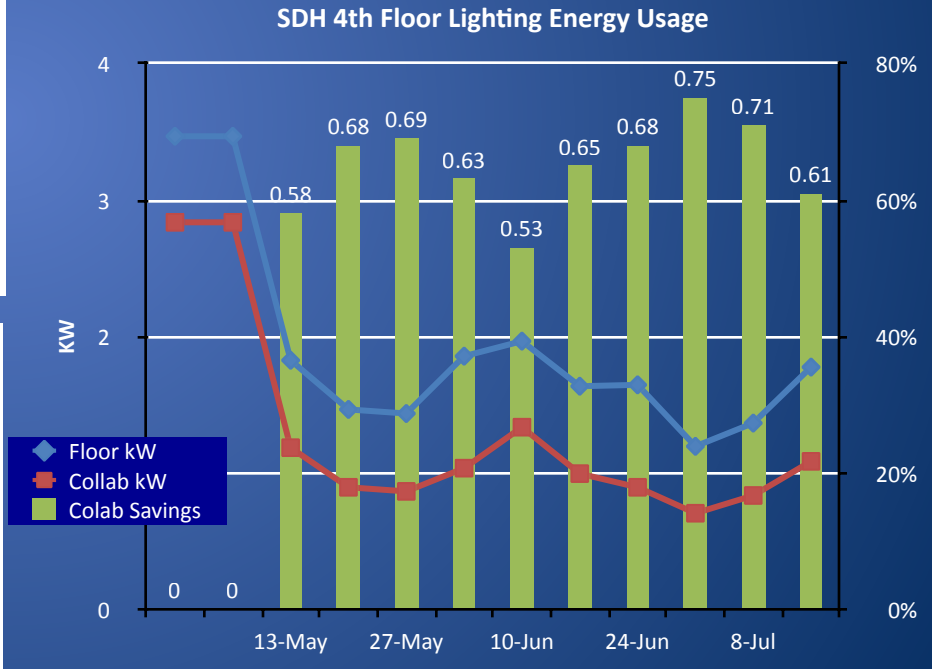
Real Energy Savings



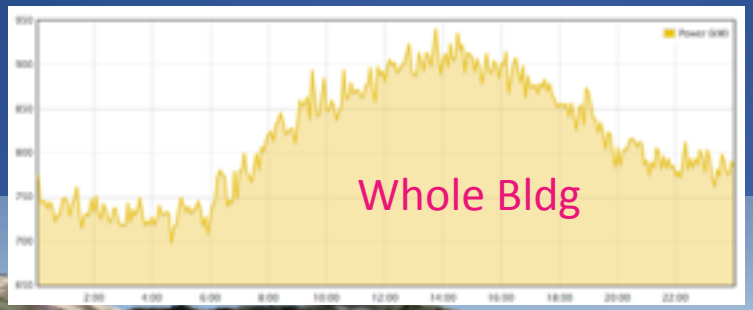




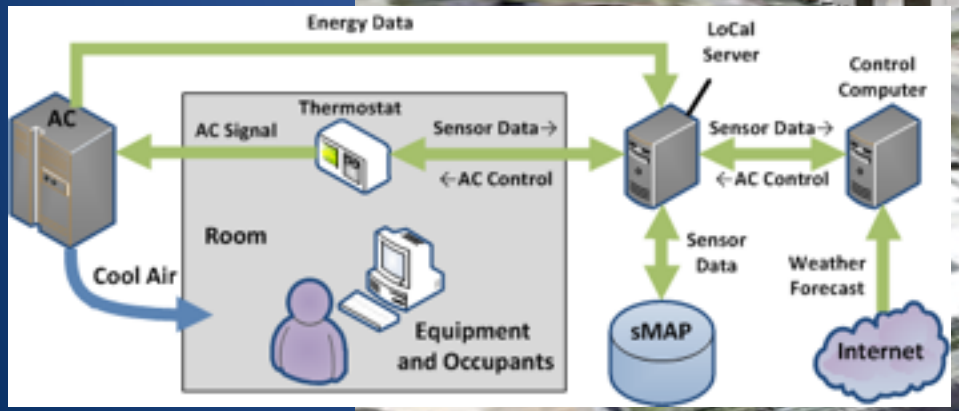


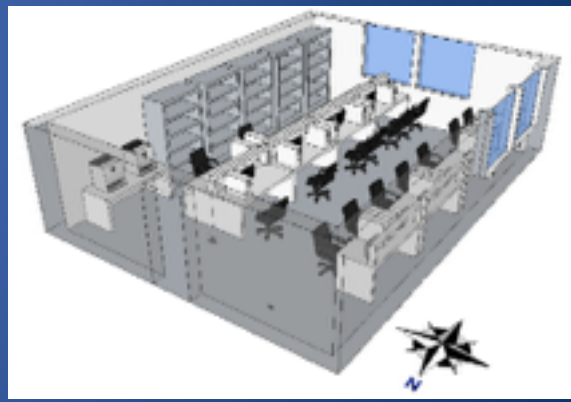


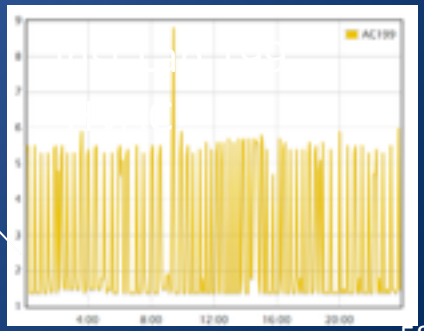
Re-Flash the HVAC …



LoCal + ActionWebs







Learning-based Model Predictive Control

- Mathematical model from Newton's law of cooling

time constant of room

weather

$$dT/dt = -k_r T - k_c u(t) + k_w w(t)) + q(t)$$

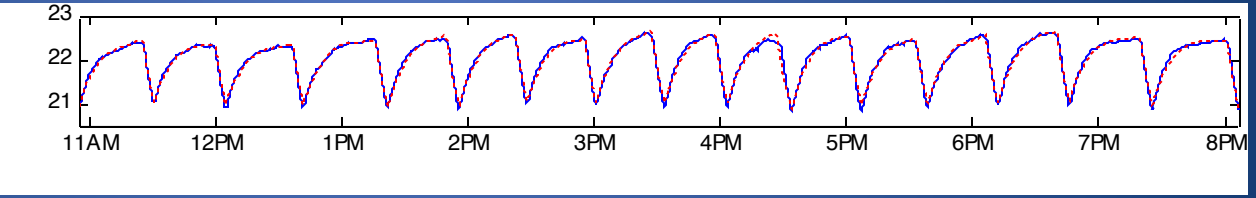
change in temperature over time

AC cooling

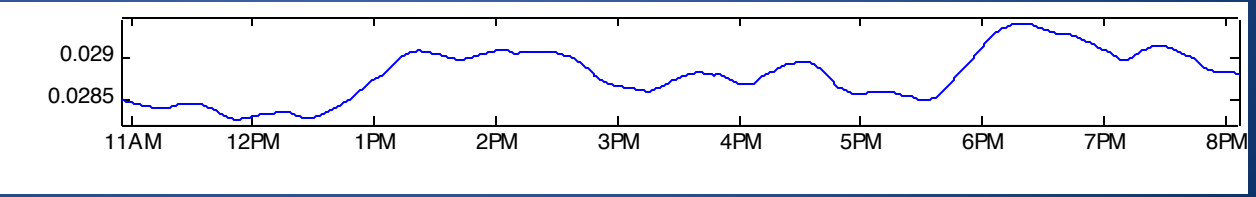
heating from occupants and equipment

- Model identified using semi-parametric regression

Temperature:
Experimental (blue)
Simulated (red)



Heating from occupants and equipment

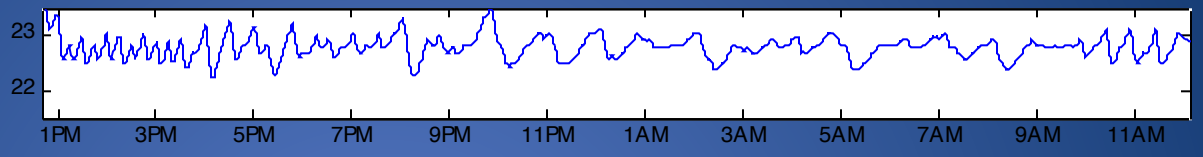


(Aswani, Master, Taneja, Culler, Tomlin, Proc. of IEEE, 2011)

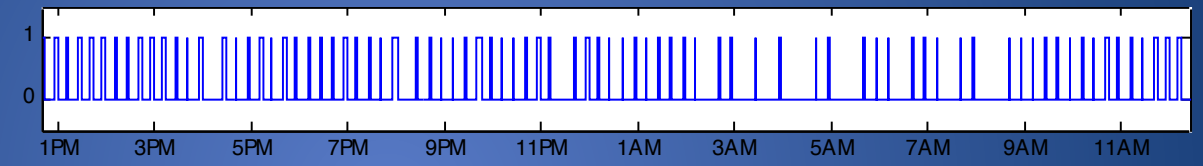
Learning-Based Model Predictive Control

Experimental LBMPC: 12.6kWh Consumed

Temperature

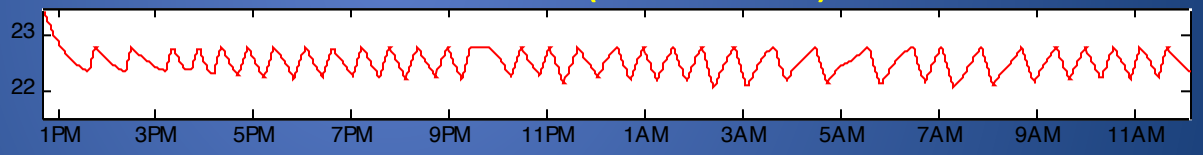


Control Action

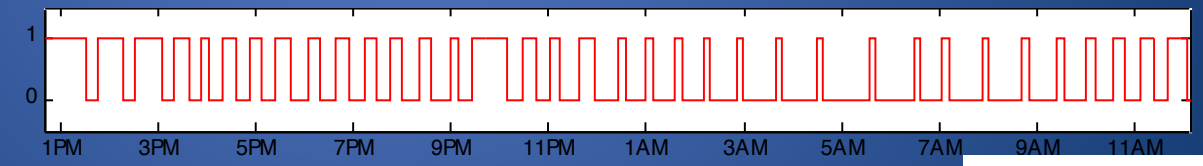


Simulated Hysteresis Control: 29.7kWh Consumed (estimated)

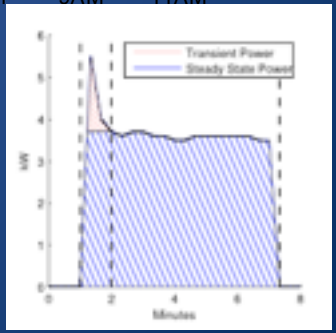
Temperature



Control Action

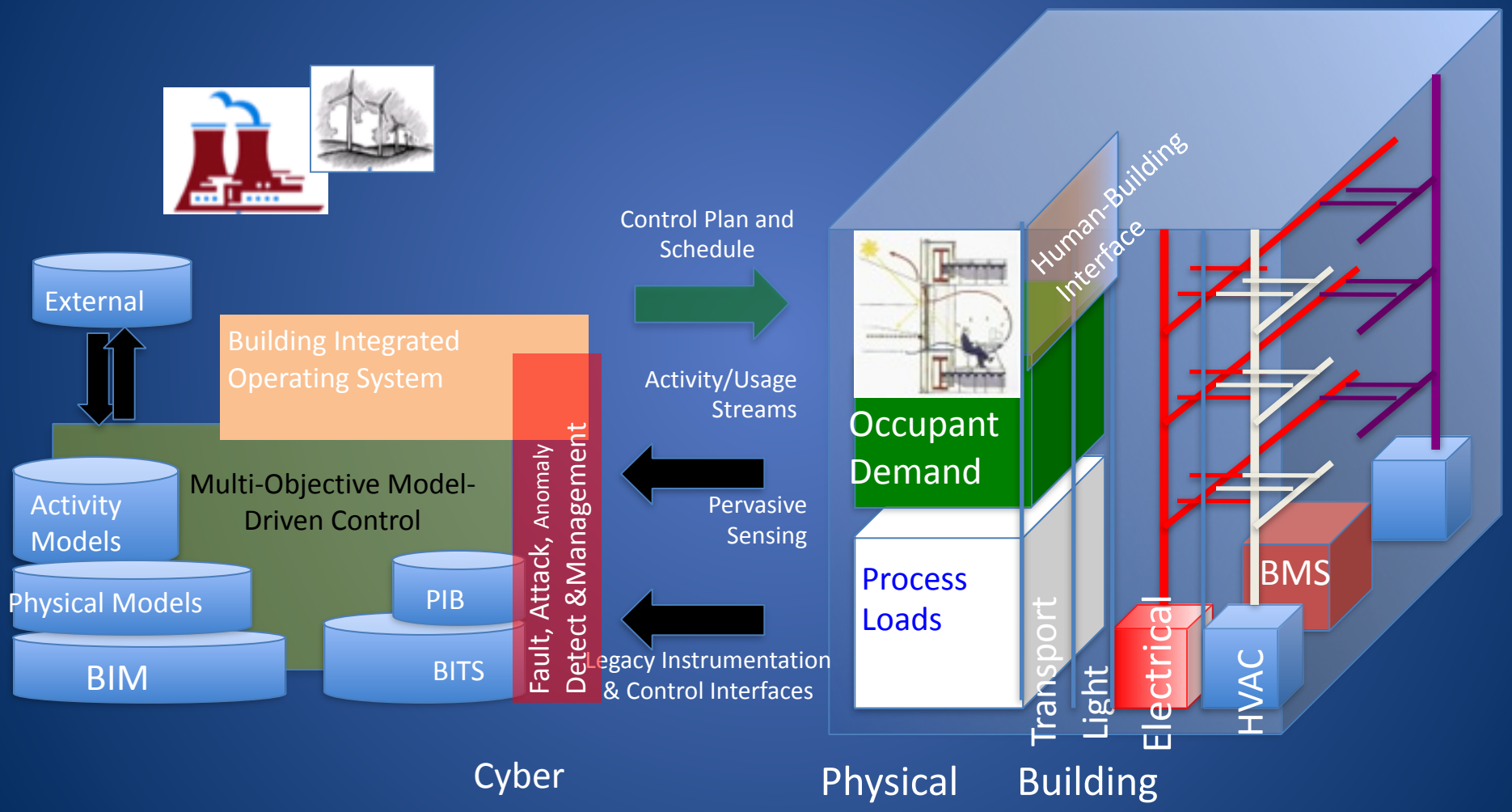


LBMPC adjusts for internal dynamics, avoids over-cooling, trades off duty cycle and switching frequency



(Aswani, Master, Taneja, Culler, Tomlin, 2011)

Cyber / Physical Buildings



Conclusions

- The Internet is Every Thing is Here
- 15 years of deep innovation and research
  - Critical WSN breakthroughs
  - Key IPv6 developments
- Worldwide community of students, faculty, and industry
- Engagement of International organizations
- Fundamentally a new Scientific Instrument
- Focus it on the World's most important problem
  - Energy, productivity, and the environment

Thank You