Digital eco-systems, Wireless sensor networks, Internet of Things

Beirut, Lebanon

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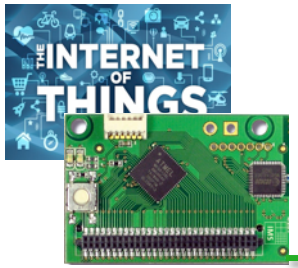
Université de Pau, France

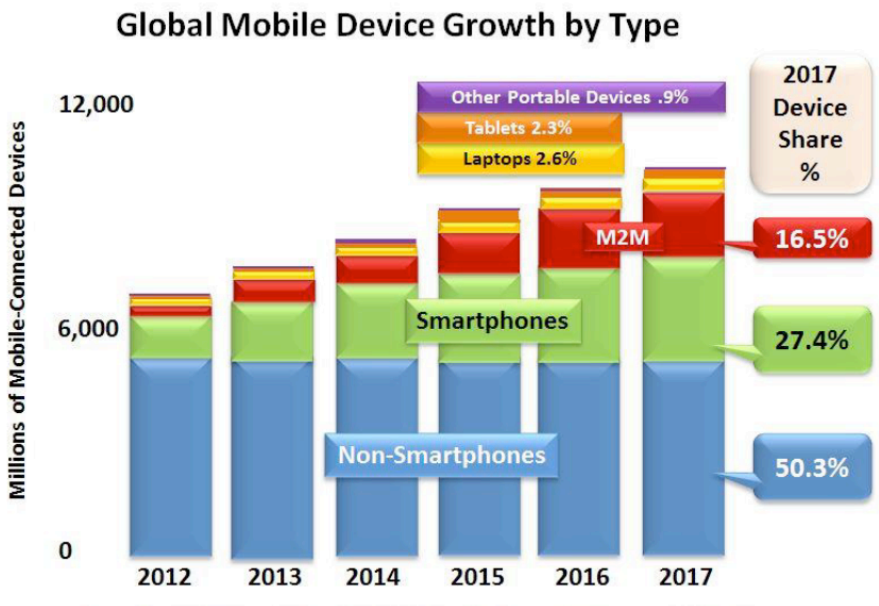


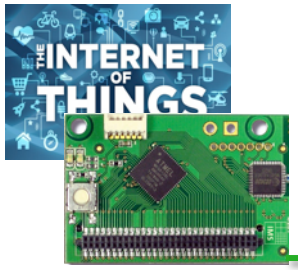
Digital devices...

... and why we called it an ecosystem

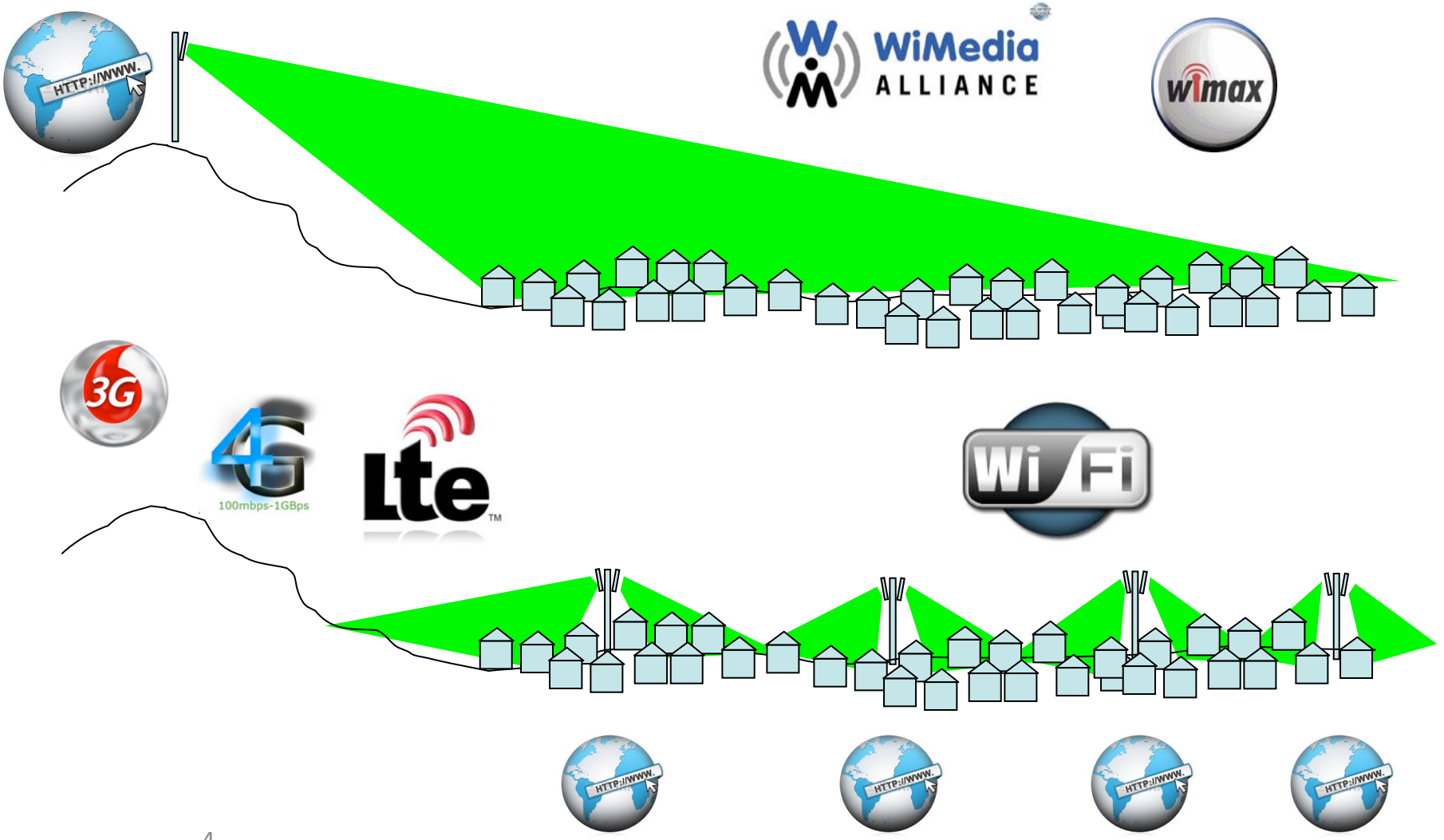
Mobile devices

4G Americas / **4G Mobile Broadband Evolution: 3GPP Release 11 & Release 12 and Beyond** / February 2014





Cellular model



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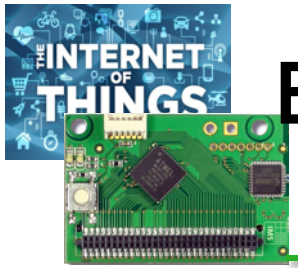
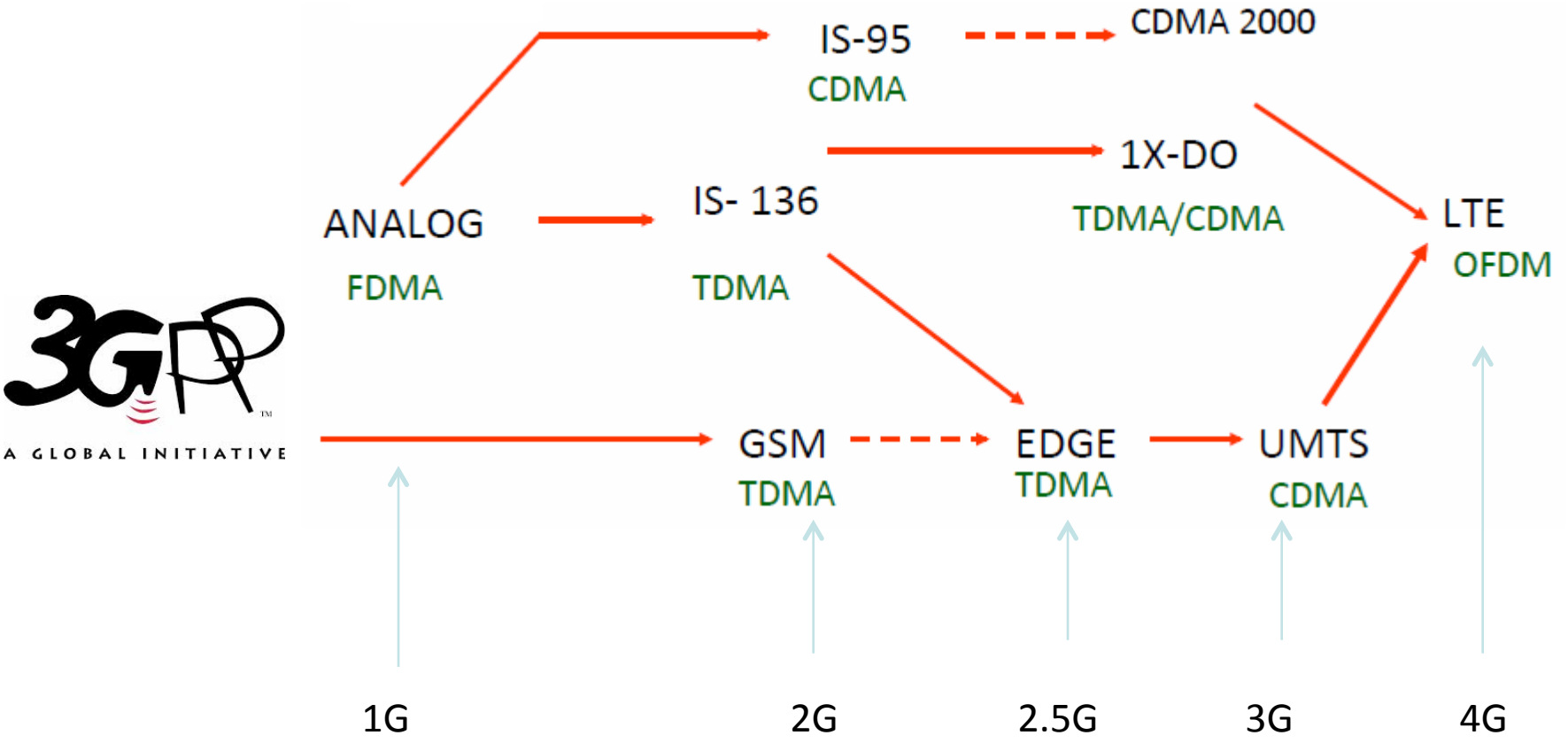


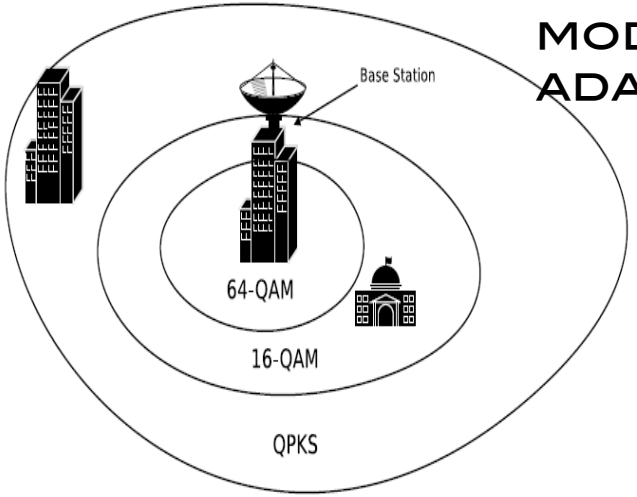
Evolution of Cellular Networks

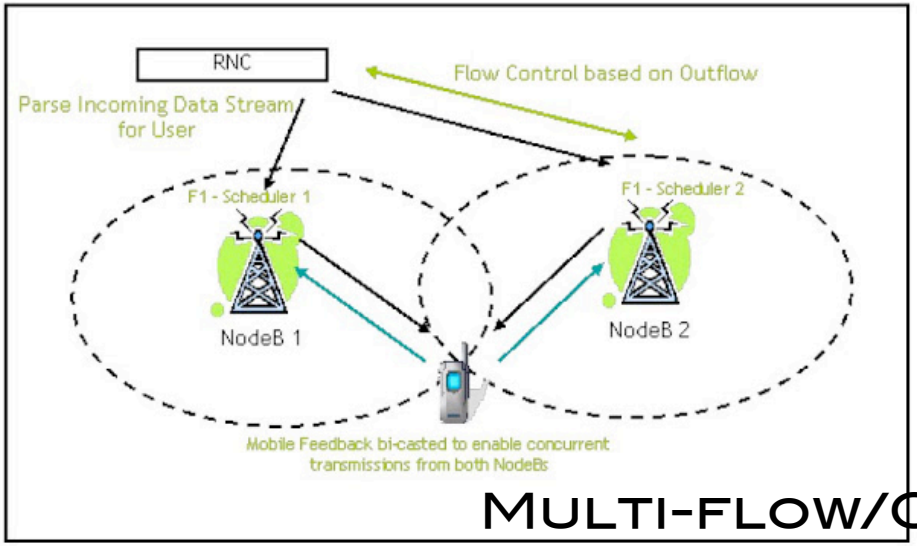


CDMAone->CDMA2000
EGDE: Enhanced Data Rates for GSM Evolution
UMTS:Universal Mobile Telecommunications System (W-CDMA)

(SOME) KEY TECHNOLOGIES

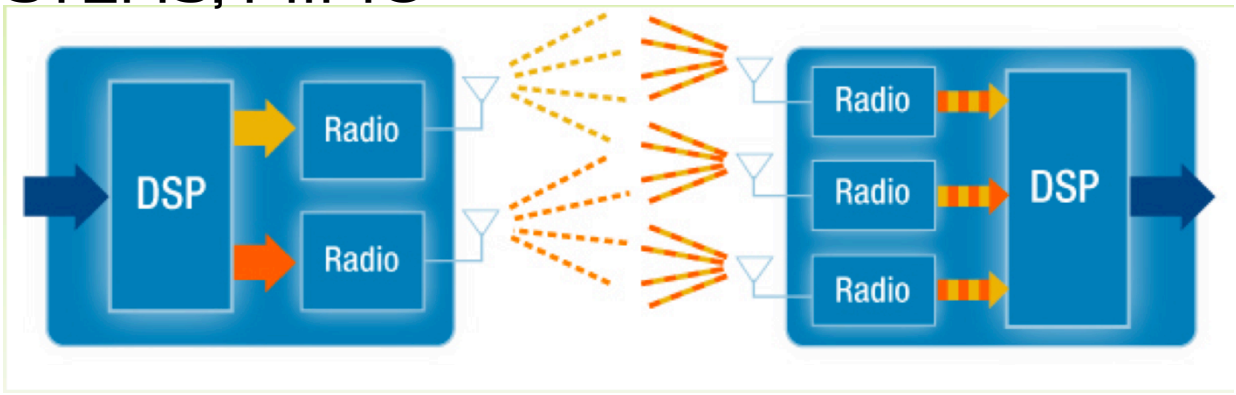
HIGHER ORDER MODULATION AND ADAPTIVE MODULATION

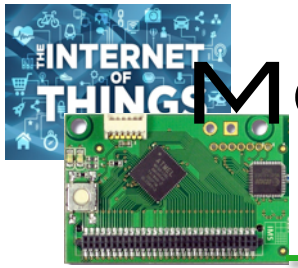




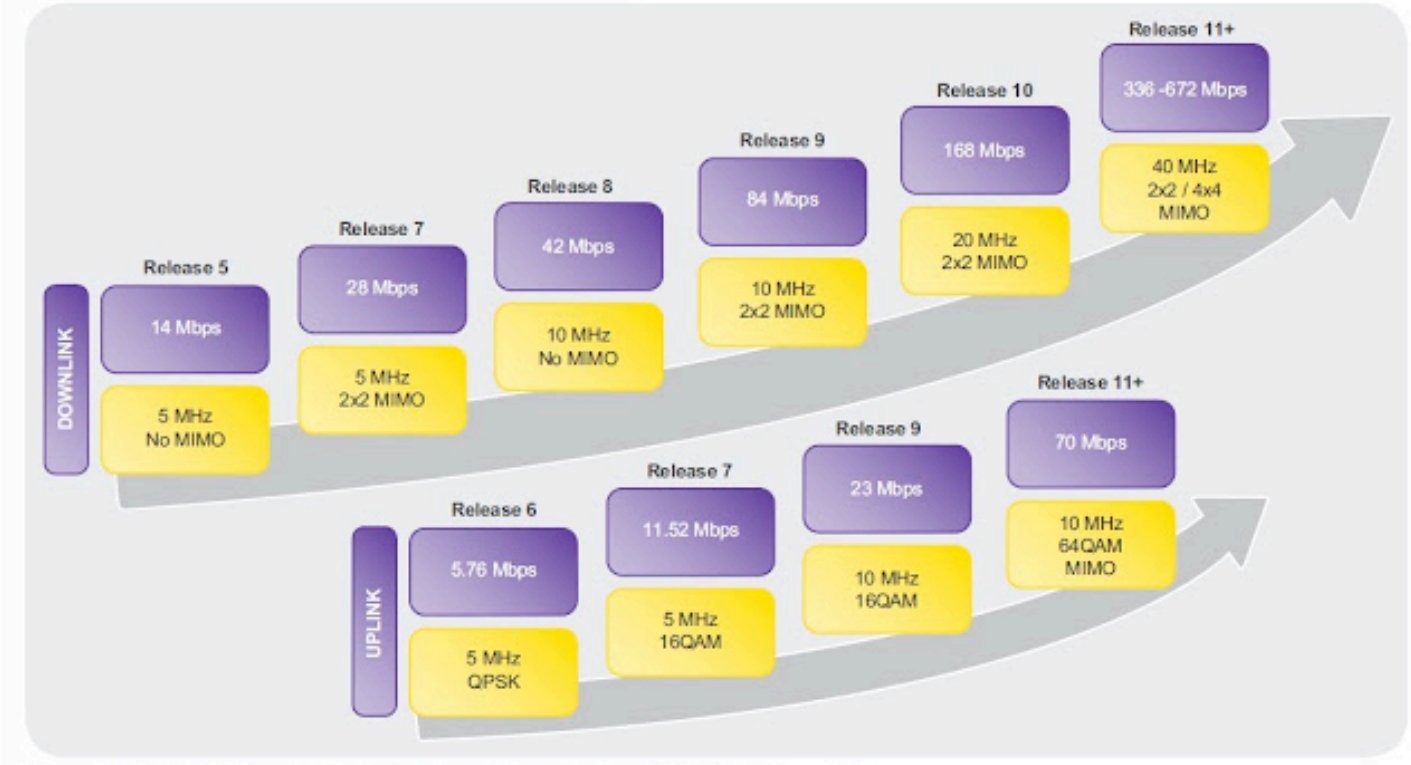
MULTIPLE ANTENNA SYSTEMS, MIMO

MULTI-FLOW/CELL SYSTEM

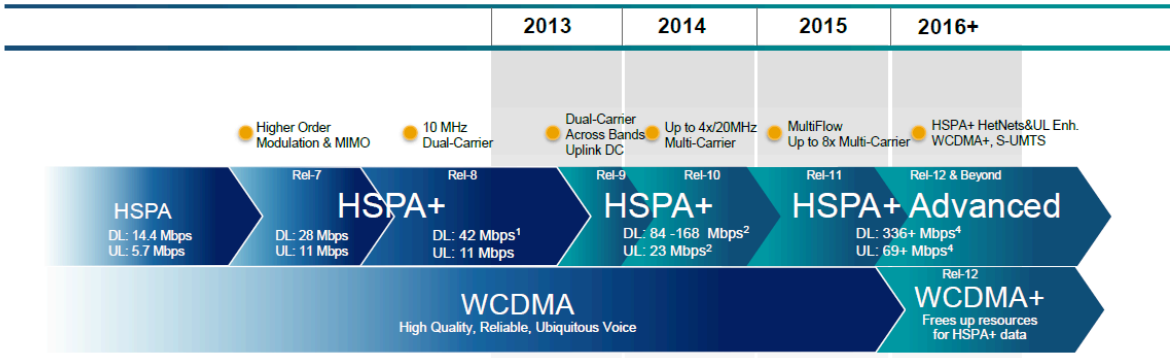




More throughput in near future!

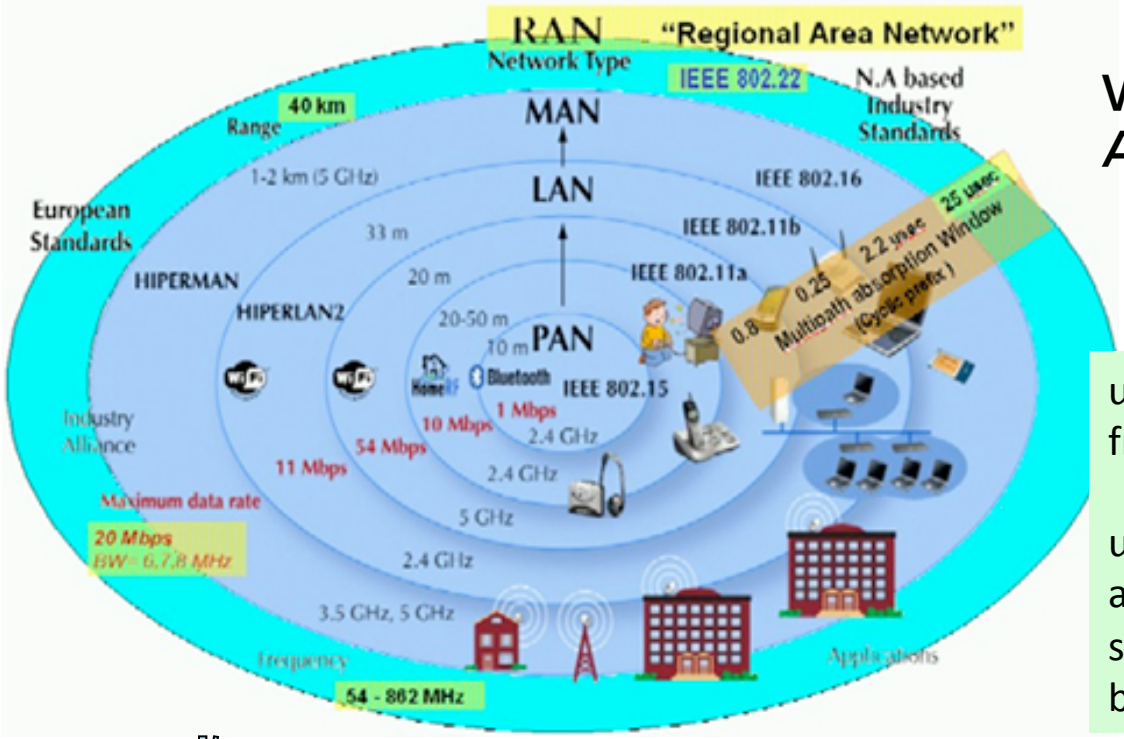


FROM NSN WHITE PAPER ON HSPA EVOLUTION



From QualComm

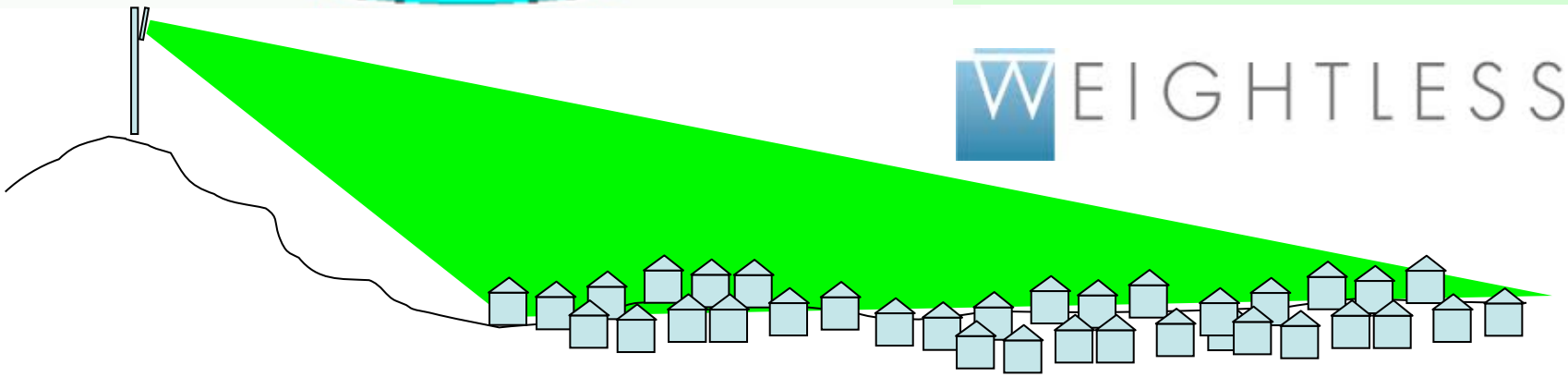
Towards 802.22 WRAN



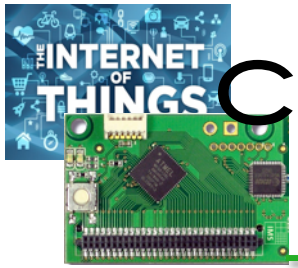
Wireless Regional Area Networks

uses white spaces in the television (TV) frequency spectrum.

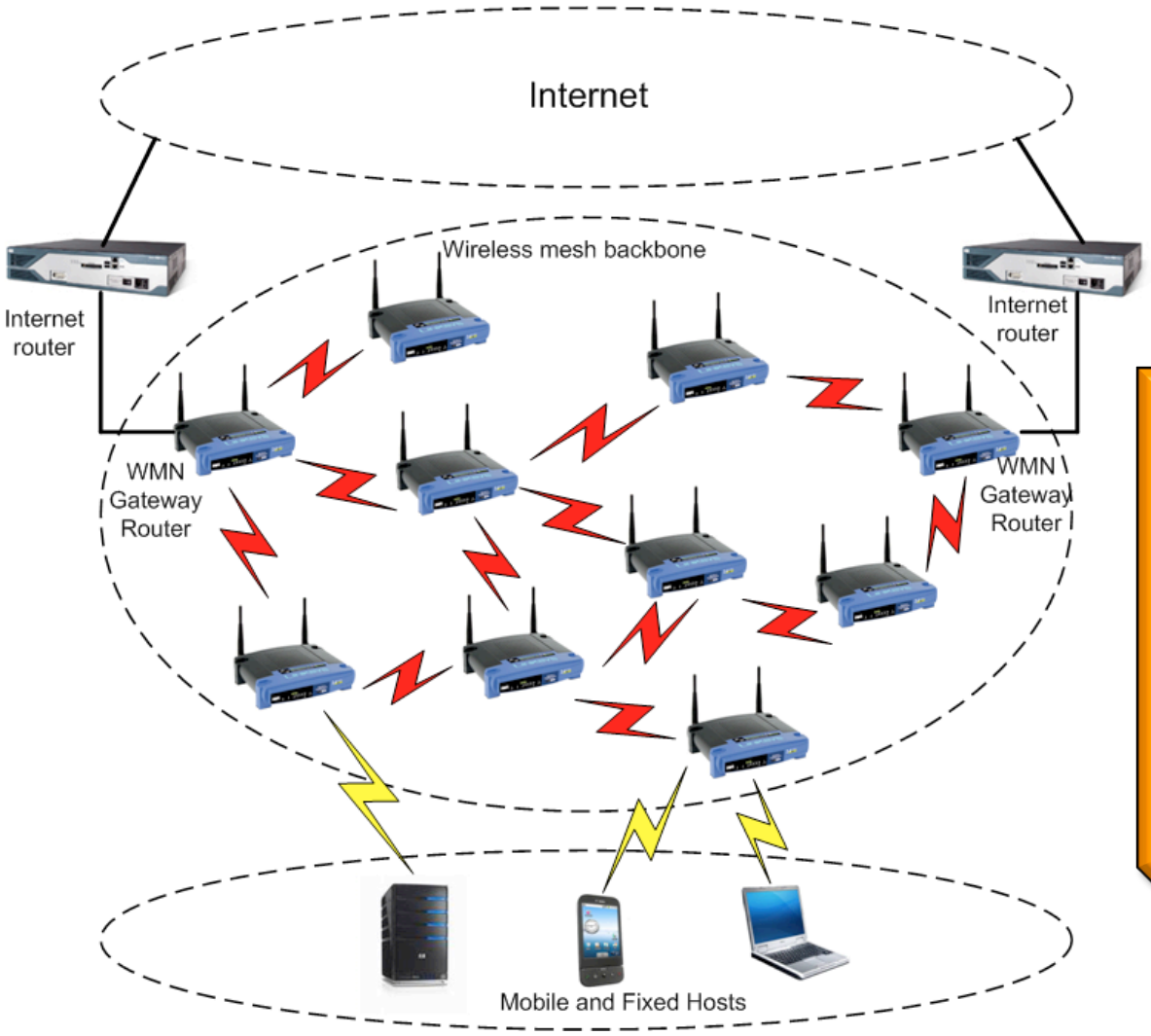
using cognitive radio (CR) techniques to allow sharing of geographically unused spectrum allocated to the television broadcast service.



WEIGHTLESS™



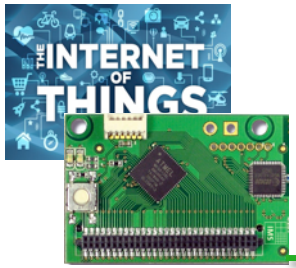
COGNITIVE RADIO WIRELESS MESH NETWORKS



Cognitive, opportunistic, multi-channel radio for large-scale wireless infrastructures

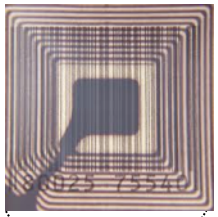
Everything, everywhere

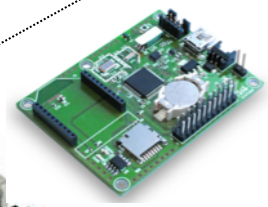
Take into account that in a near future, we will have more throughput with our mobile wireless devices than our wired home internet access



More digital devices!



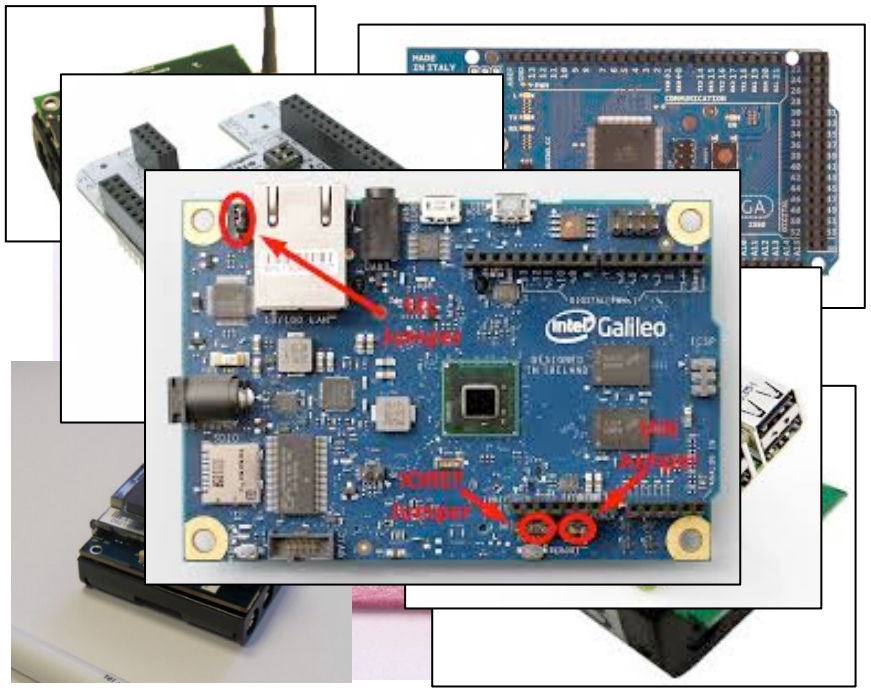



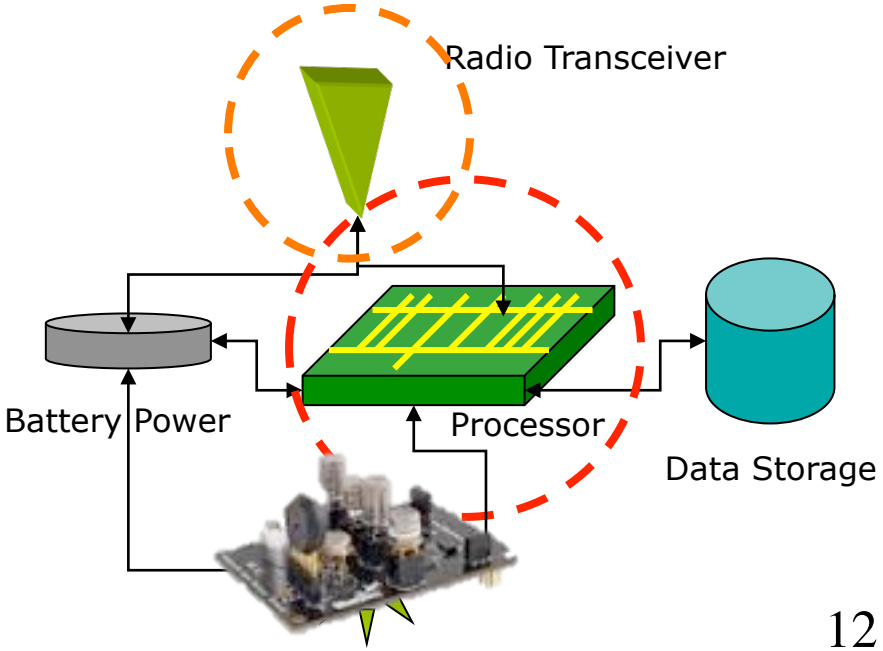




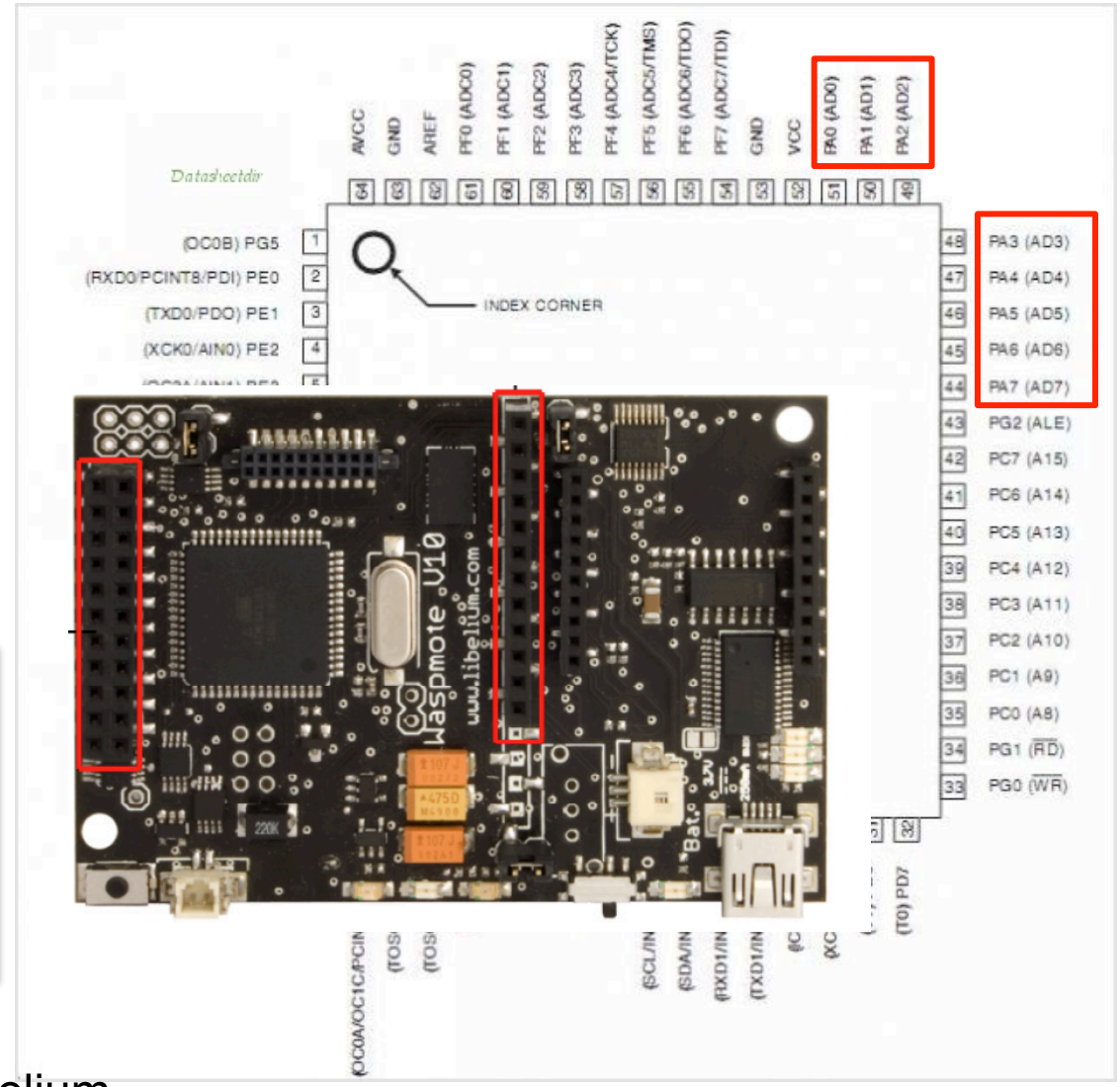
Wireless autonomous sensor

- Wireless Sensor Nodes or embedded Linux still remain the main IoT development platform
- In general: low cost, low power (the battery may not be replaceable), small size, prone to failure, possibly disposable





Micro-controller vs micro-processor

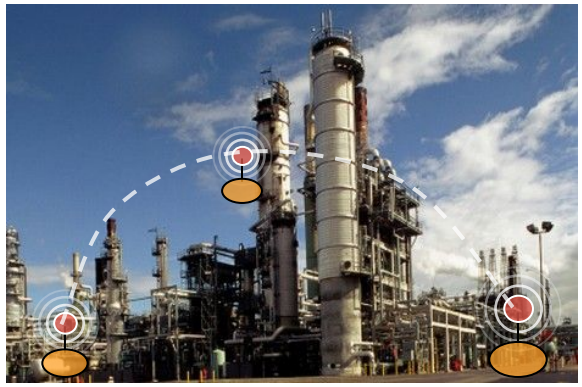


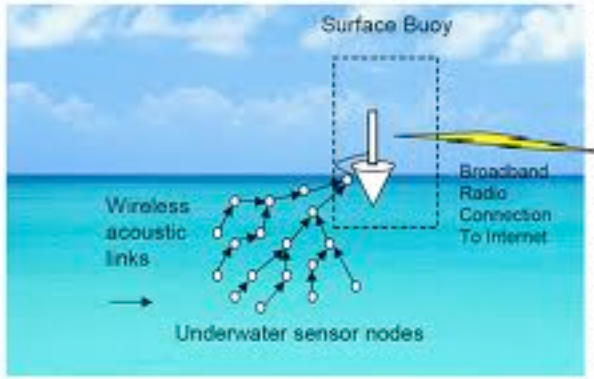
Input voltage between 0 and Vref (e.g. 3.3V). ADC usually have 10-bit resolution:

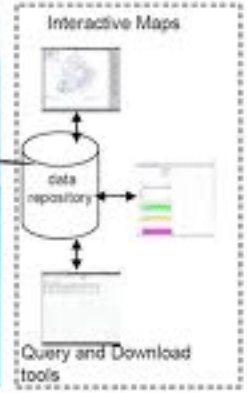
0 is for 0V
1014 is for 3.3V

WaspMote figure from Libelium

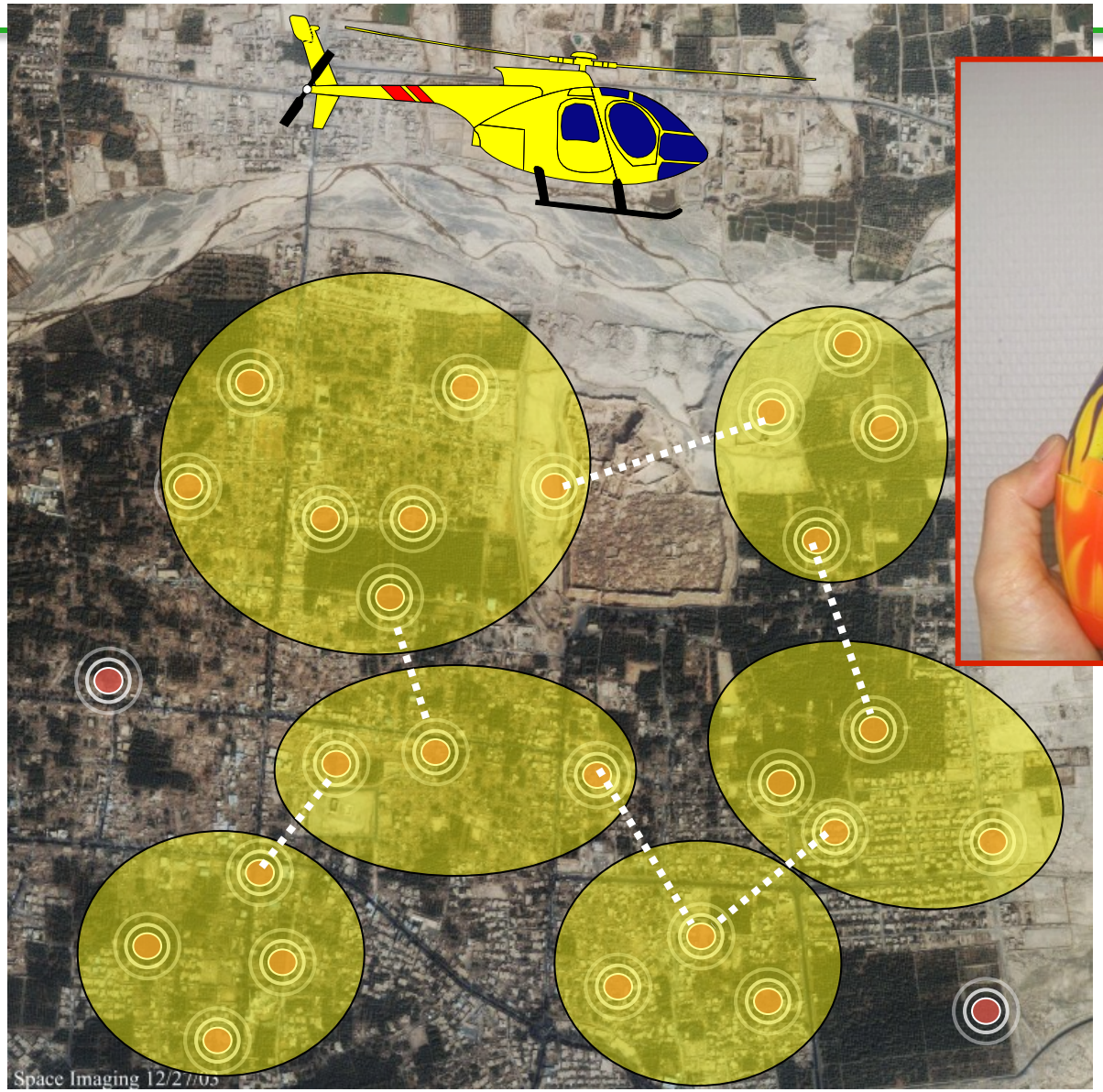
« Naturally » well suited for Monitoring/Surveillance

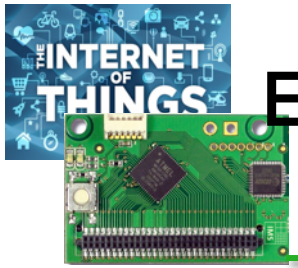






Safety, disaster relief





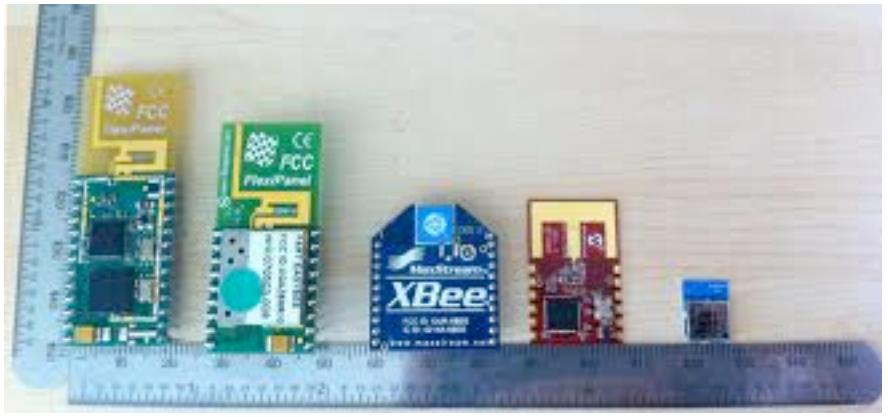
Beyond Sensor Networks: Communicating Objects!

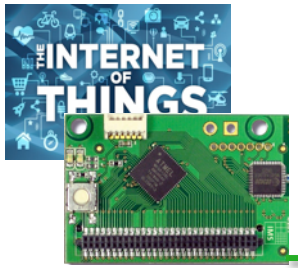
- Native communication:

- Added communication
  - Active communication

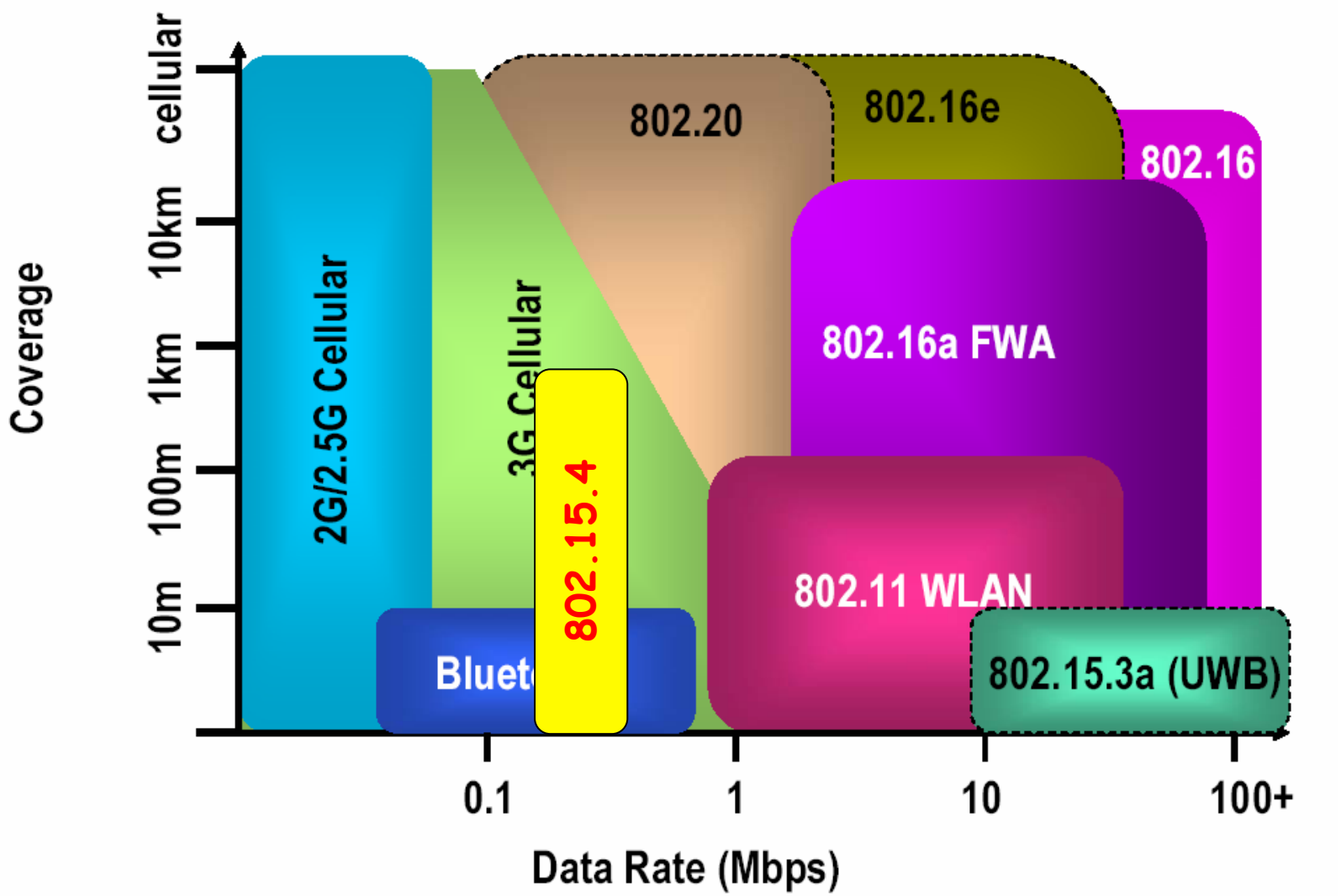
- Passive communication

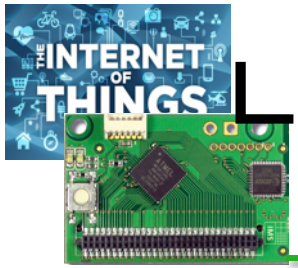
Wireless Communication made easy





Summary of Wireless Technologies

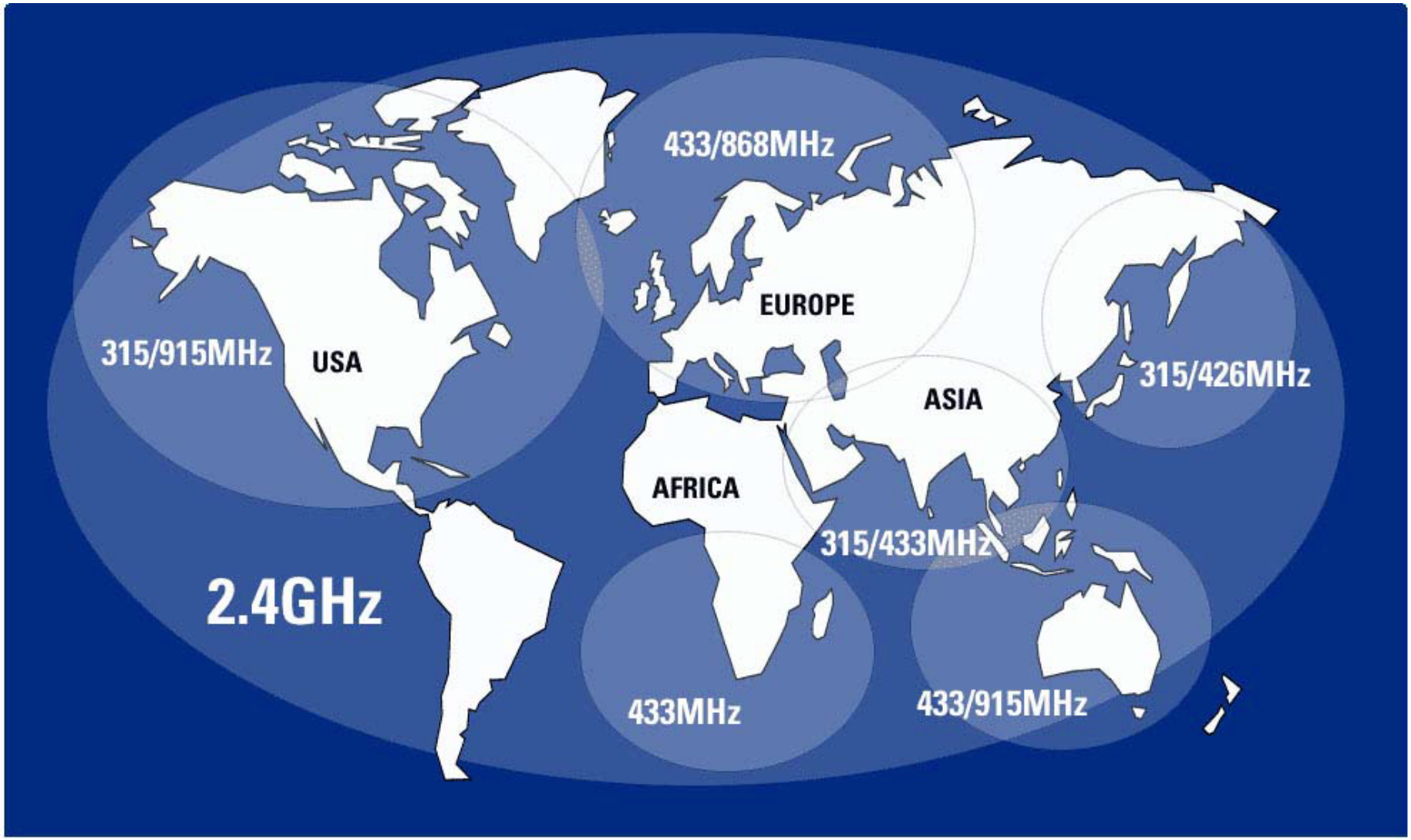




LICENSE-FREE FREQUENCY ALLOCATION

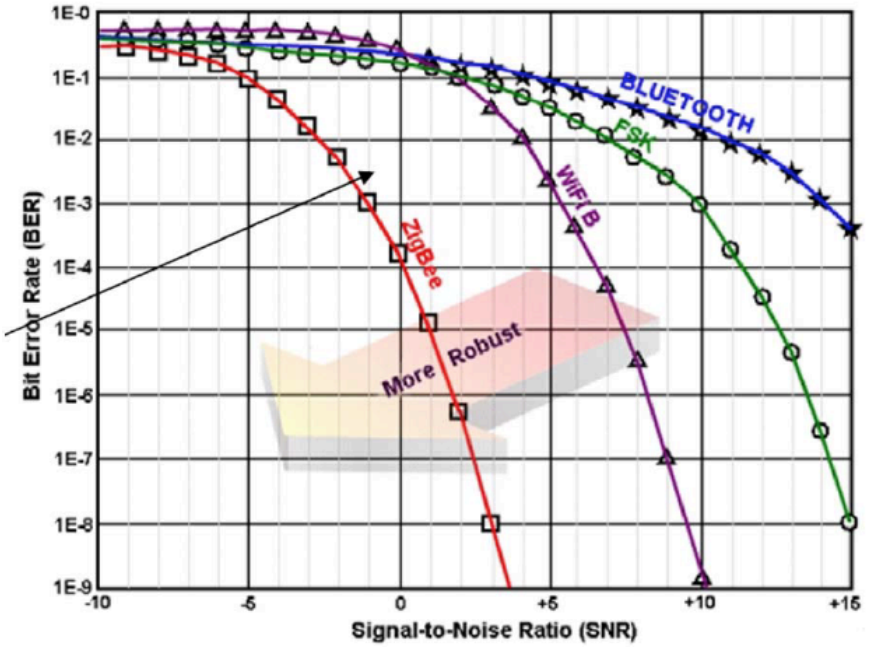
- The ISM/SRD License-Free Frequency Bands
  - Global 2.4 GHz band and regional Sub-1GHz bands
- The global 2.4 GHz ISM band
  - USA
  - Europe
  - Japan/Korea
- Sub-1GHz ISM bands
  - USA
  - Europe
  - Japan/Korea

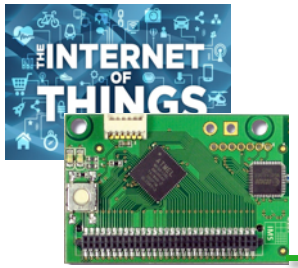
The ISM/SRD License-Free Frequency Bands



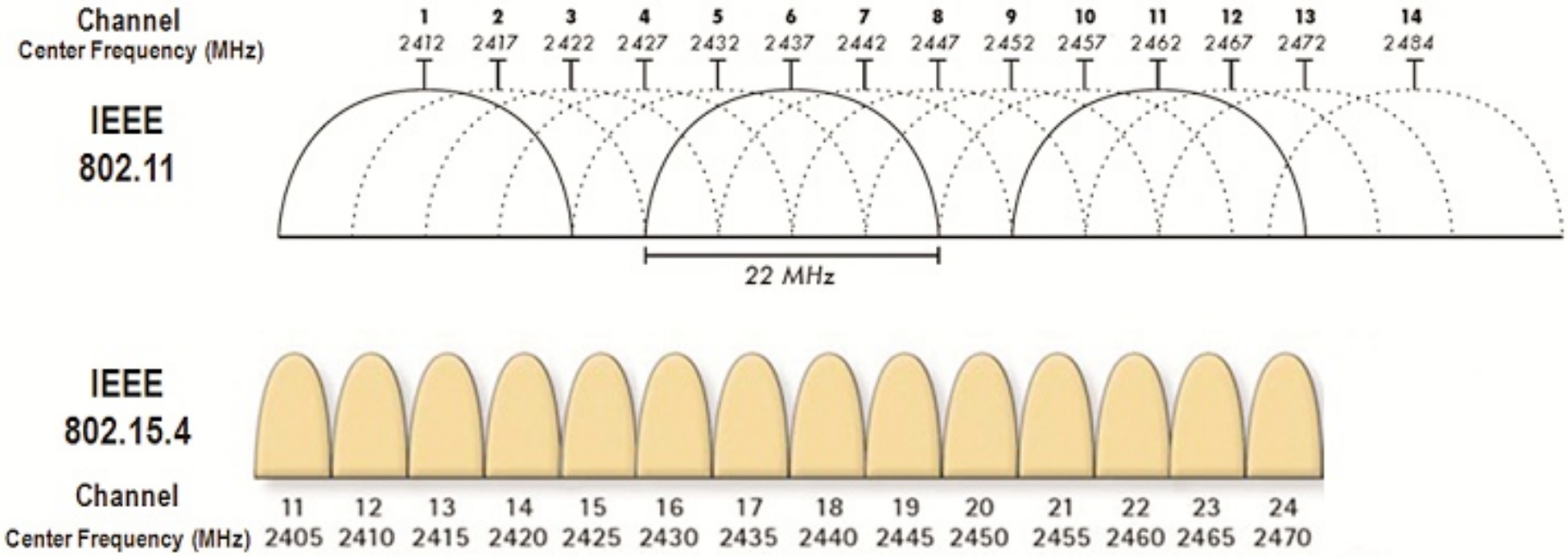
IEEE 802.15.4 in ISM 2.4GHz

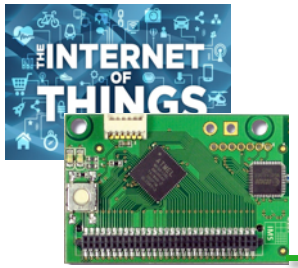
- Low-power radio in the 2.4GHz band offering 250kbps throughput at physical layer
- Power transmission from 1mW to 100mW for range from 100m to about 1km is LOS
- CSMA/CA (beacon & non beacon)
- Used as physical layer in ZigBee





Spectrum band





MAC FRAME FORMAT

Max size = 127 bytes

Max=102 bytes

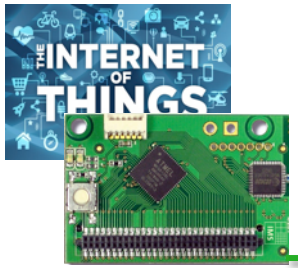
Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN	Destination Address	Source PAN	Source Address	Auxiliary Security Header	Frame Payload	FCS
CC61	58	3332	0013A200 40922078	3332	0013A200 4086D834		HELLO	2B32
		Addressing fields						
MHR							MAC Payload	MFR

HELLO

64-bit 0x0013A2004086D834
16-bit 0x0010
CHANNEL 0x0C
PANID 0x3332

Can broadcast if sent to 0x000000000000FFFF

64-bit 0x0013A20040922078
16-bit 0x0020
CHANNEL 0x0C
PANID 0x3332



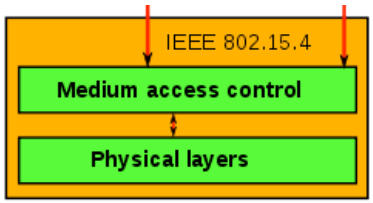
IEEE 802.15.4

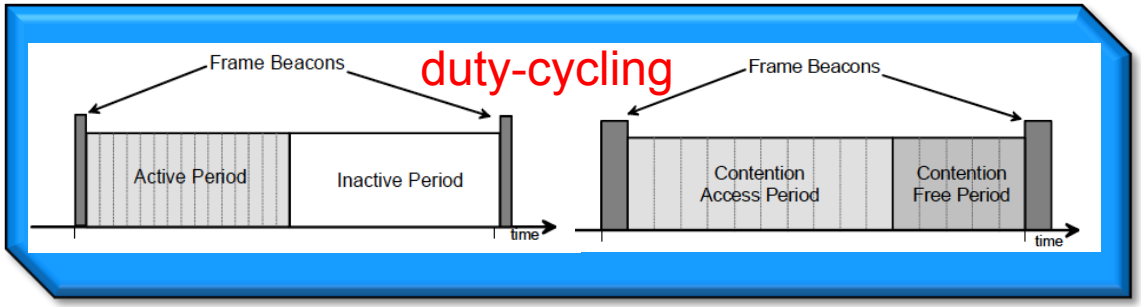
ZigBee Member

WirelessHART

ISA 100 WIRELESS

OSI 3 & 4

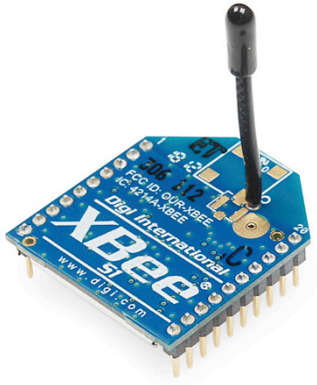




OSI 2

OSI 1

CC2420 (TI)

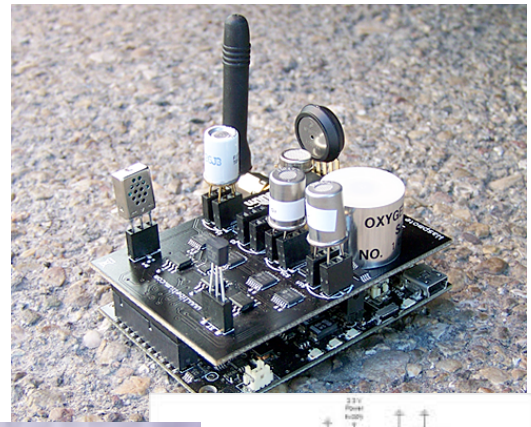


XBee (Digi)

MRF24J40MA (Microchip)

ZigBit AT86RF230 (ATMEL)

Energy consideration



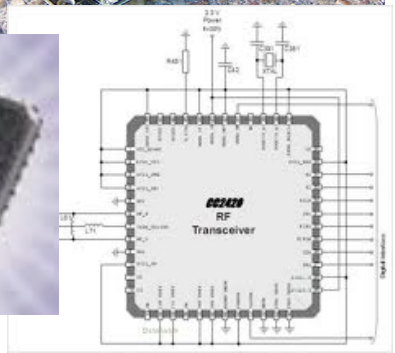
18720 Joules

TX power 0dbm: 17.4mA

P = I x V = 17.4 x 3.3 = 57.42mW

E = P x t -> t = E/P

326018s or 90.5h



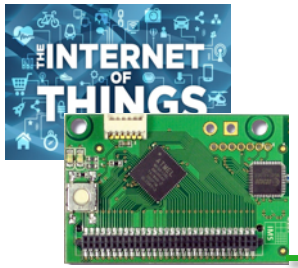
Chipcon Products
from Texas Instruments

CC2420

Parameter	Min.	Typ.	Max.	Unit	Condition / Note
Current Consumption, transmit mode:					
P = -25 dBm		8.5		mA	The output power is delivered differentially to a 50 Ω singled ended load through a balun, see also page 55.
P = -15 dBm		9.9		mA	
P = -10 dBm		11		mA	
P = –5 dBm		14		mA	
P = 0 dBm		17.4		mA	

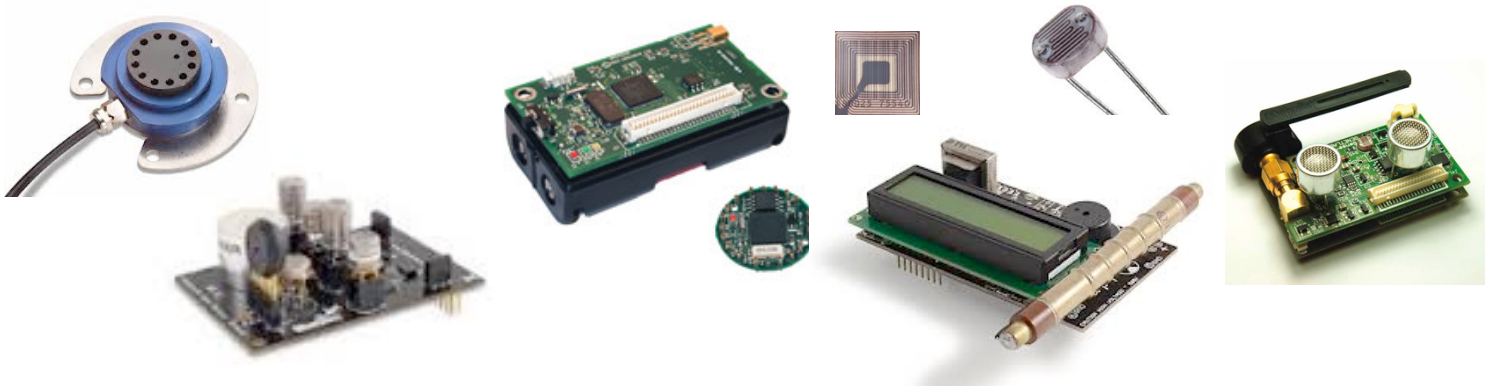
Haven't considered:

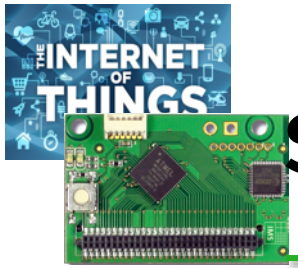
- Baseline power consumption of the sensor board
- RX consumption: 18.8mA!
- Event capture consumption
- Event processing consumption



Step 1: measuring the physical world

Sensing

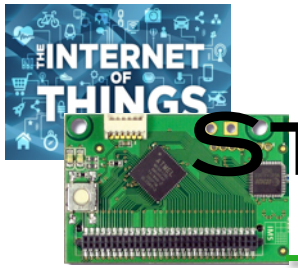




Step 2: store, process

Pervasive Systems

Sensing

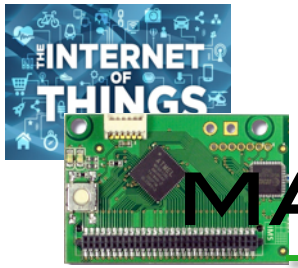


Step 3: connect, interact

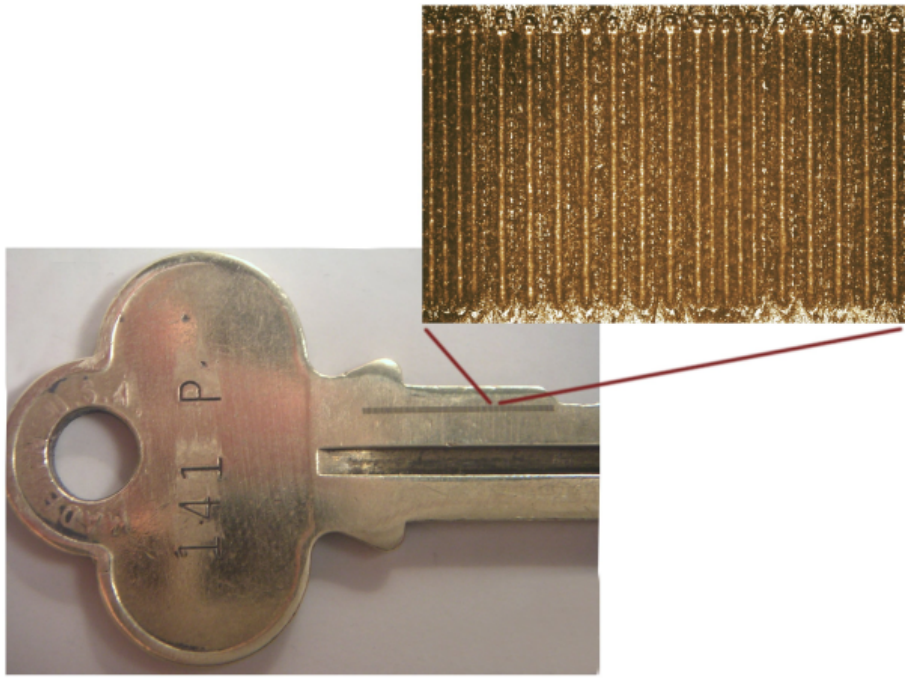
Pervasive Systems

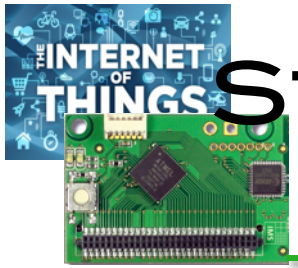
Sensing

PEOPLES,
INFRASTRUCTURES,
BUILDINGS, VEHICULES,...



Interaction can takes many (unexpected) forms!





Step 4: control, optimize & instrument !

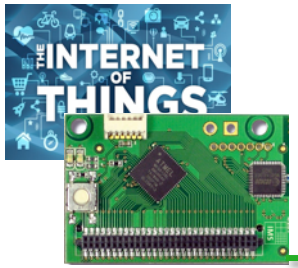
DATA ANALYSIS, OPTIMIZATION & CONTROL

PERVASIVE SYSTEMS

SENSING

PEOPLES, INFRASTRUCTURES, BUILDINGS, VEHICULES

Towards WSN mass-market

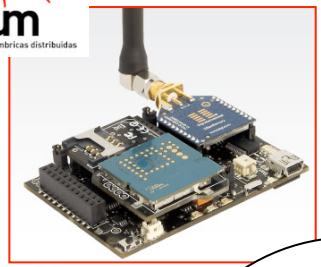


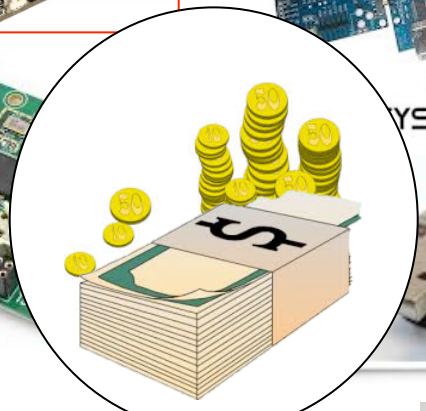
NOW

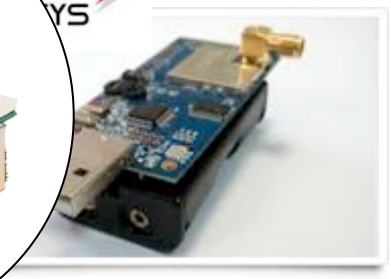
Zolertia

ARDUINO

libelium
comunicaciones inalámbricas distribuidas







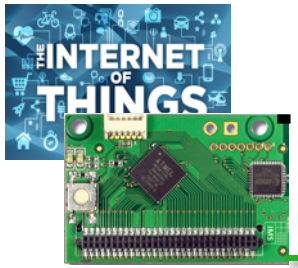
TST

MICROCHIP

Genet
Generation Next
Technology Laboratories

Jennic
TECHNOLOGY FOR A CHANGING WORLD

2000-2007



...AND CHEAP POWERFULL EMBEDDED SYSTEMS

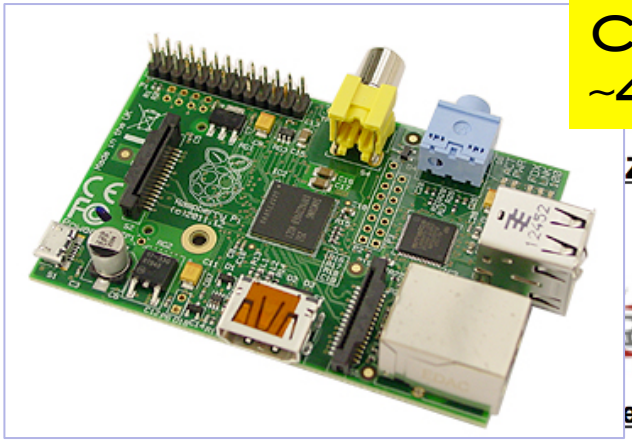
Arduino™

CUBLOC

beagle board.org

Beagleboard

Raspberry Pi



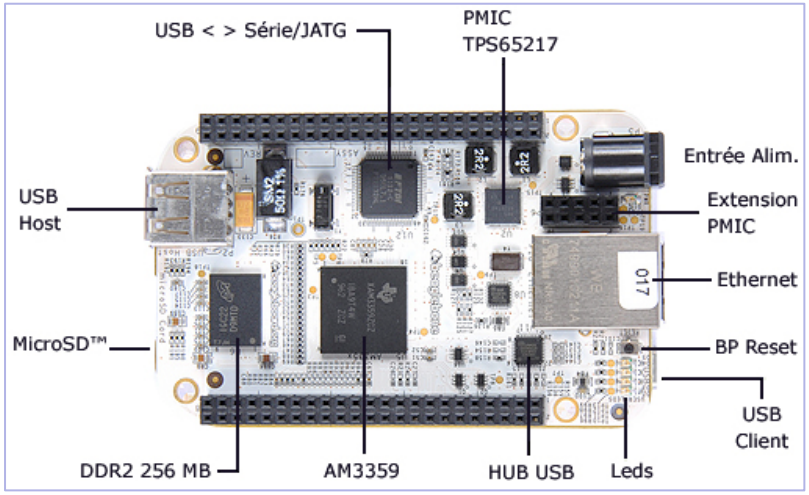
Cost: ~40€

Z/Gadgeteer

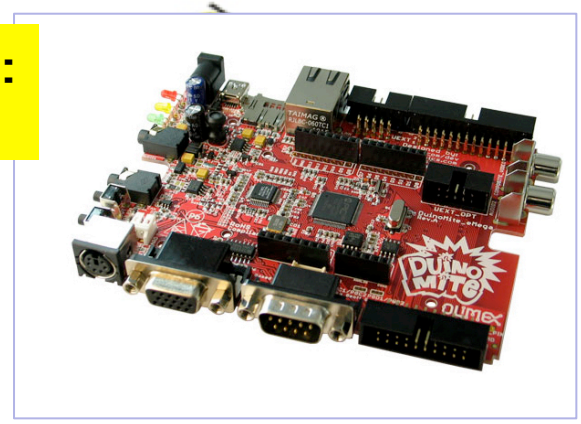
Embedded Artists

edded Artists

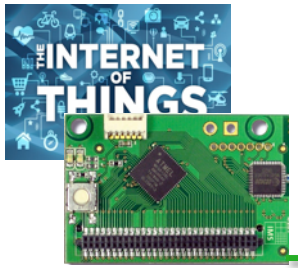
Cost: ~80€



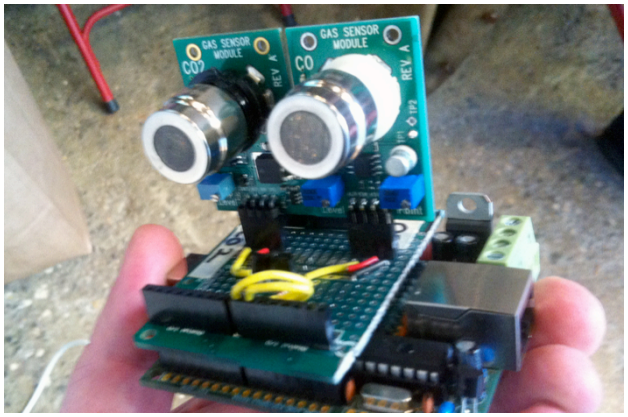
Cost: ~50€

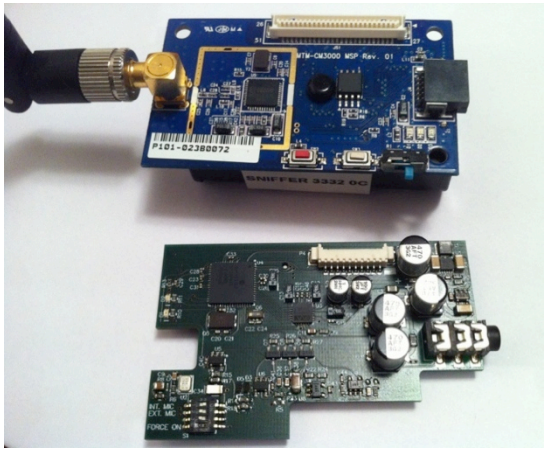


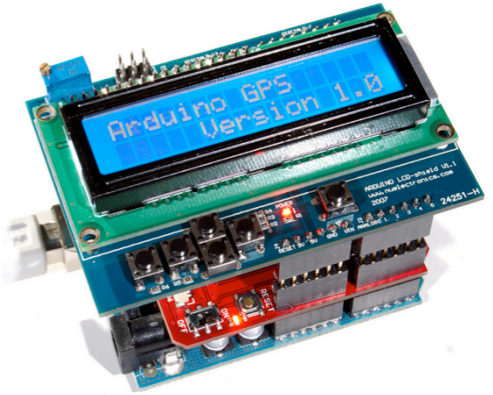
DuinoMite

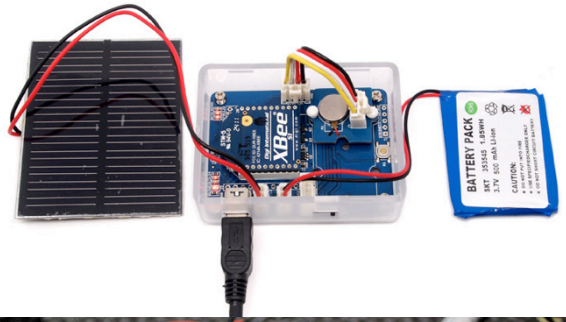


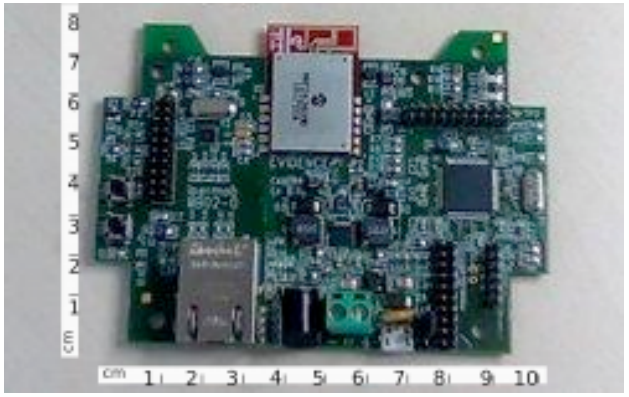
From custom developments...

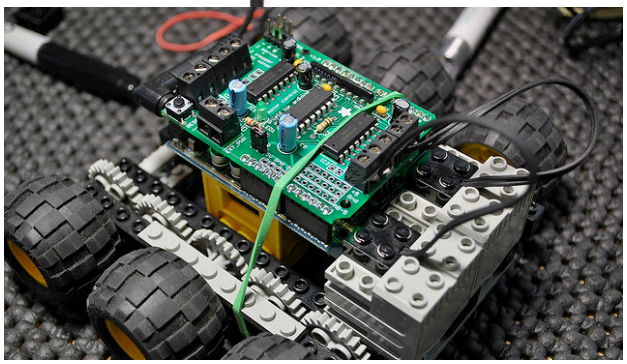


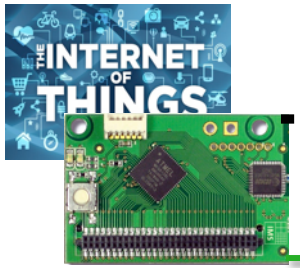




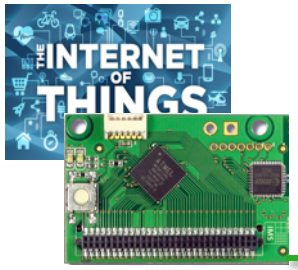




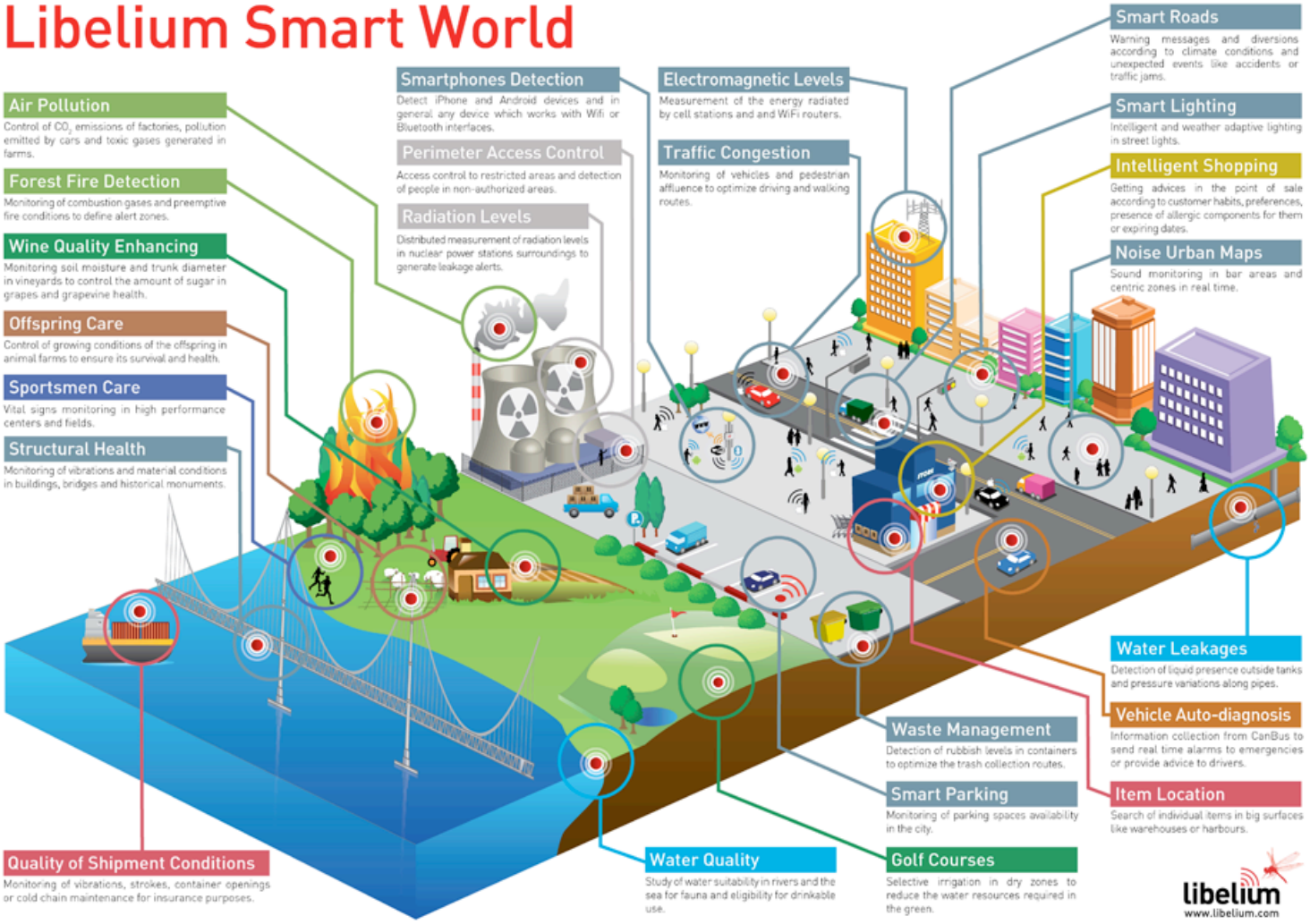


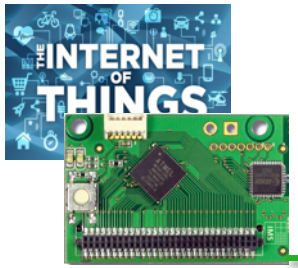


...To maturation of the market: WSN→IoT



Smart Cities



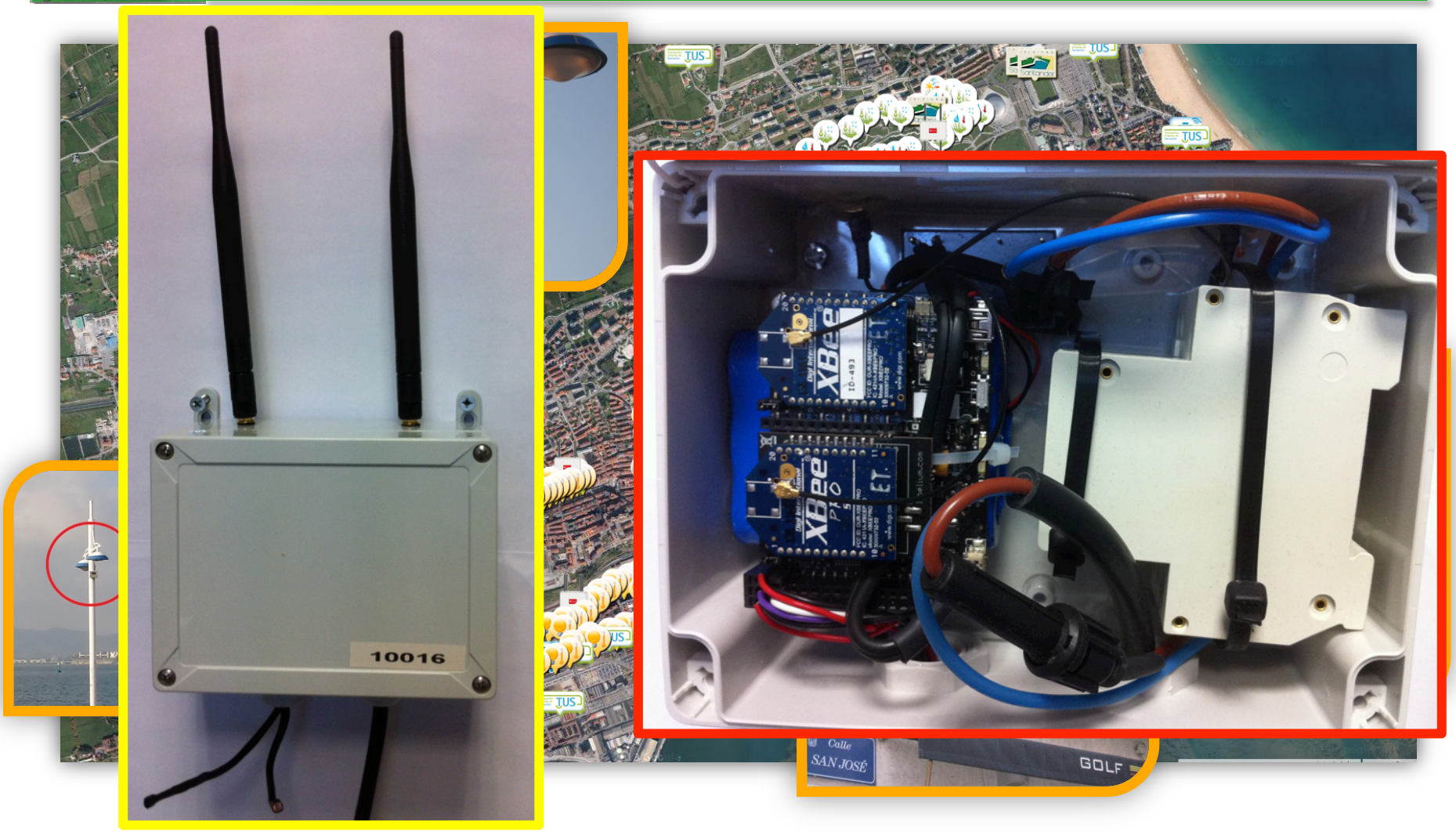


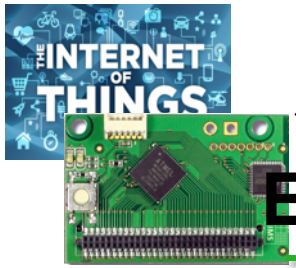
SmartSantander

www.smartsantander.eu

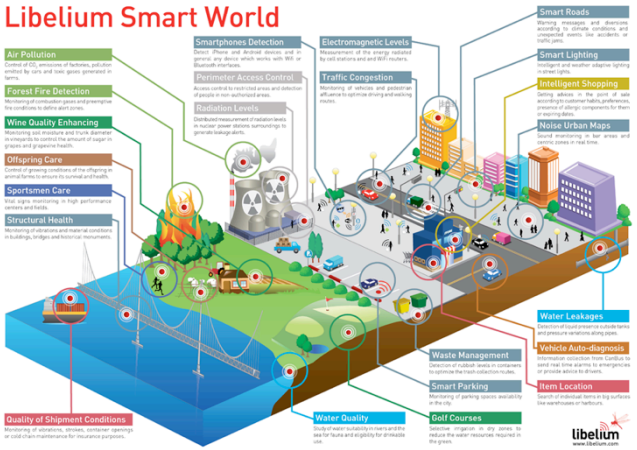
SmartSantander test-bed

Sensor network deployment



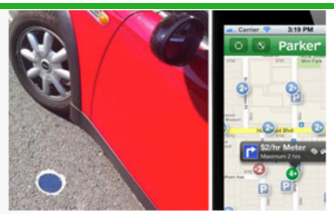


Smart Cities with real business model behind!



KEEP STREETS CLEAN

Products like the cellular communication enabled Smart Belly trash use real-time data collection and alerts to let municipal services know when a bin needs to be emptied. This information can drastically reduce the number of pick-ups required, and translates into fuel and financial savings for communities service departments. // Visit



STOP DRIVING IN CIRCLES

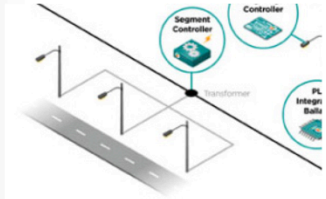
With the use of installed sensors, mobile apps, and real-time web applications like those provided in Streetline's ParkSight service, cities can optimize revenue, parking space availability and enable citizens to reduce their environmental impact by helping them quickly find an open spot for their cars. // Visit

RECEIVE POLLUTION WARNINGS

The DontFlushMe project by Leif Percifield is an example that combines sensors installed in Combined Sewer Overflows (CSOs) with alerts to local residents so they can avoid polluting local waterways with raw sewage by not flushing their toilets during overflow events. // Visit

USE ELECTRICITY MORE EFFICIENTLY

The SenseNET system uses battery-powered clamp sensors to quickly measure current on a line, calculate consumption levels, and send that data to a hosted application for analysis. Significant financial and energy resources are saved as the clamps can easily identify meter tampering issues, general malfunctions, and any installation issues in the system. // Visit



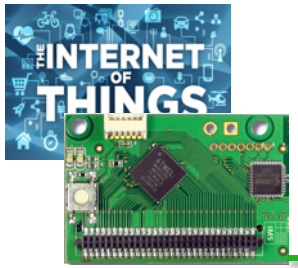
LIGHT STREETS MORE EFFECTIVELY

This smart lighting system from Echelon allows a city to intelligently provide the right level of lighting needed by time of day, season, and weather conditions. Cities have shown a reduction in street lighting energy use by up to 30% using solutions like this. // Visit

SHARE YOUR FINDINGS

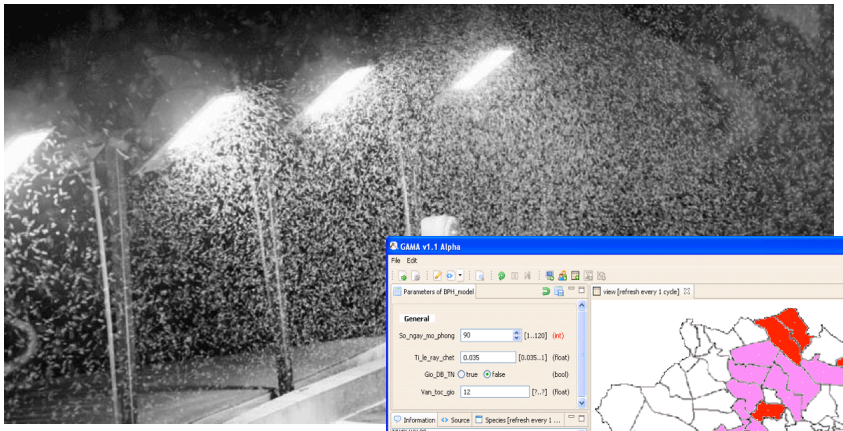
AirCasting is a platform for recording, mapping, and sharing health and environmental data using your smartphone. Each AirCasting session lets you capture real-world measurements (Sound levels recorded by their phone microphone; Temperature, humidity, carbon monoxide (CO) and nitrogen dioxide (NO2) gas concentrations), and share it via the CrowdMap with your community. // Visit

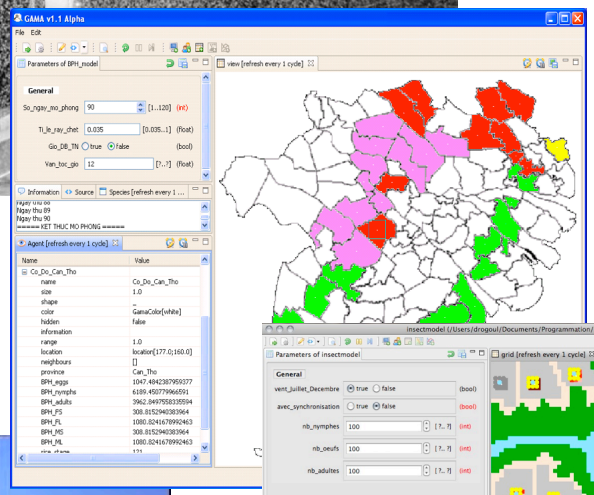
http://www.postscapes.com/internet-of-things-examples/

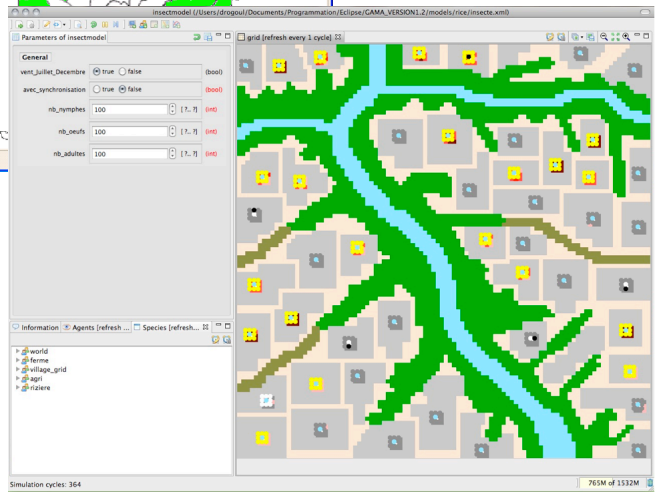


Who is concerned?

Developing countries have huge needs

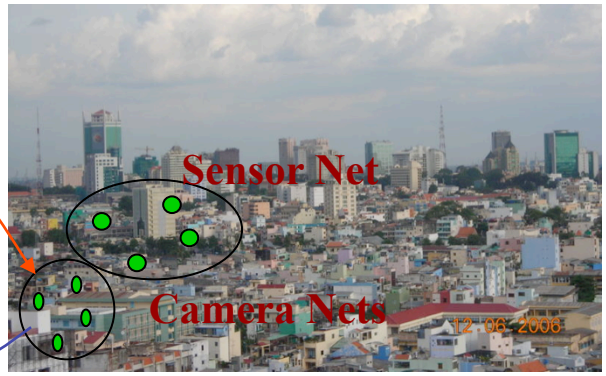






TOWARDS GLOBAL SENSING

Activating



Intelligent Agent

Sending

Activating

Intelligent Agent

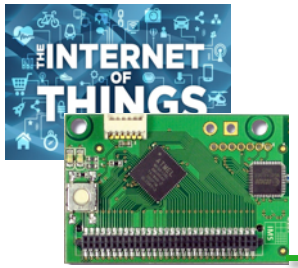
Sending

Activating

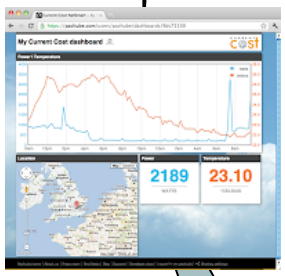
Intelligent Agent

Sensor Net

Sending



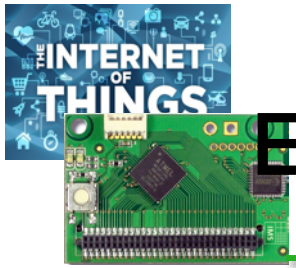
Control, optimize & Instrument



Pervasive Systems

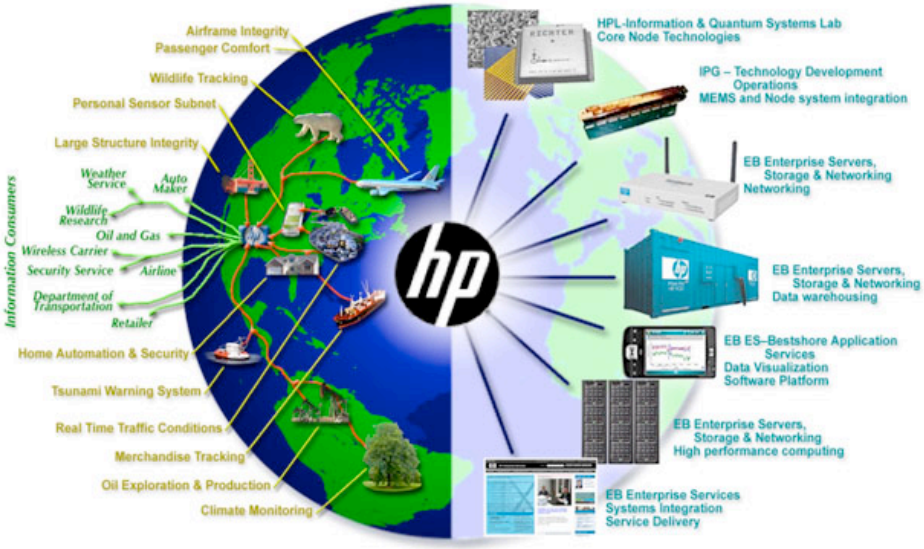
Sensing

PEOPLES, INFRASTRUCTURES, BUILDINGS, VEHICULES

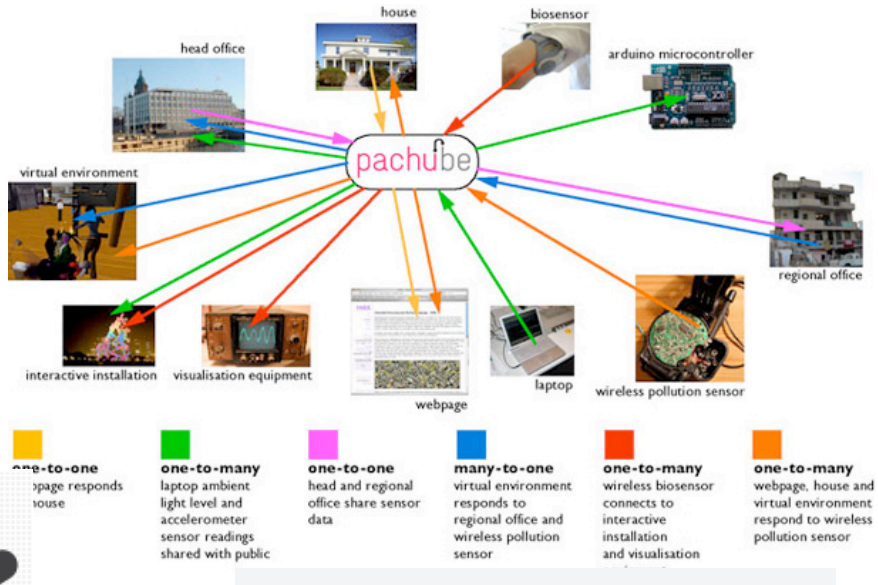


Big actors for big data

HP CeNSE



Pachube/Cosm



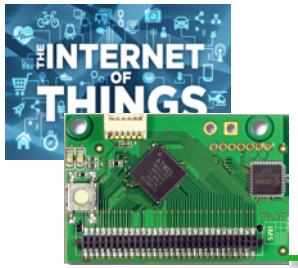
IBM Smarter Planet

IBM

cosm™ BETA

Connect to your world

http://readwrite.com/2010/12/15/top_10_internet_of_things_developments_of_2010

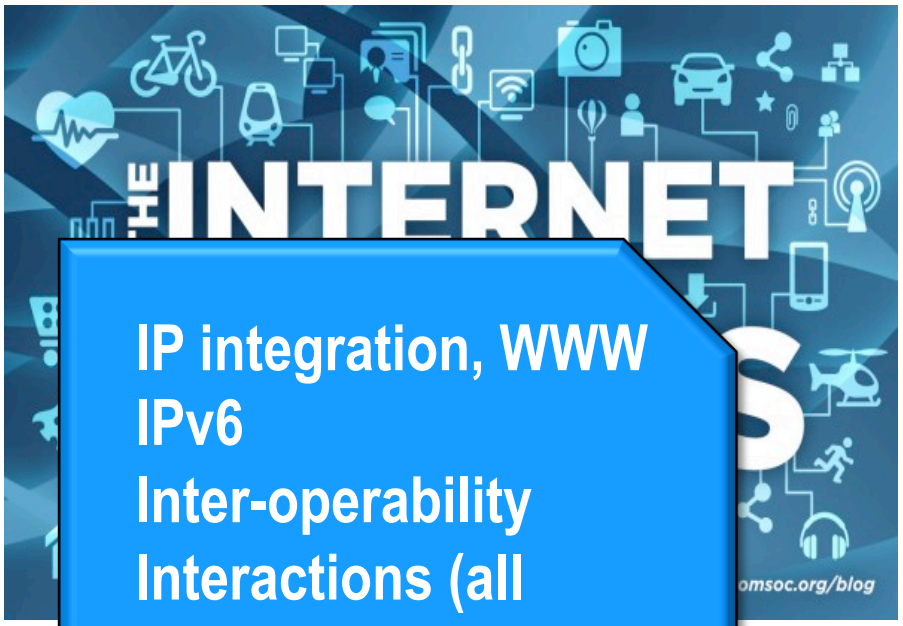


OPENIoT

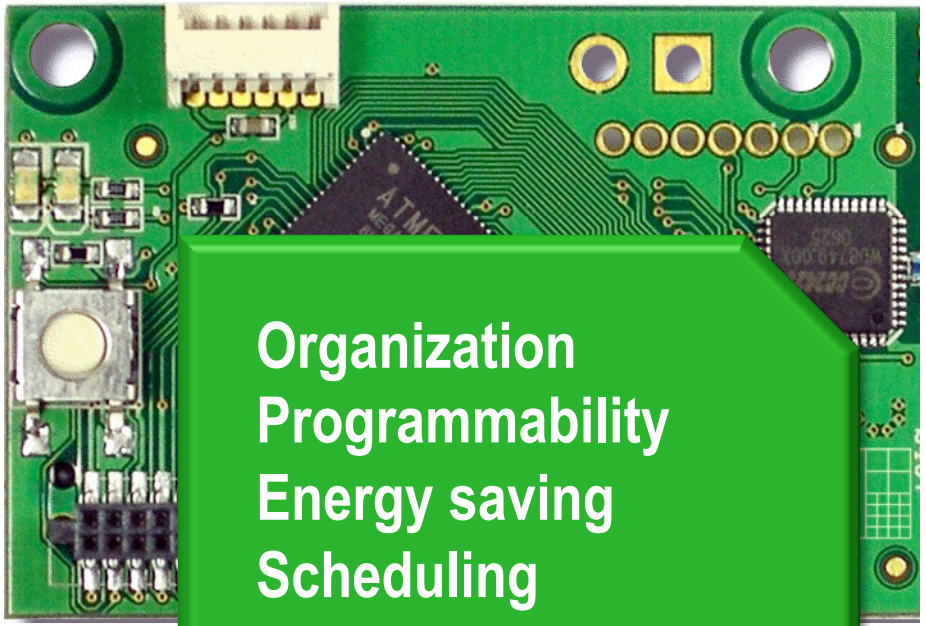
COOPERATION

- open source middleware for getting information from sensor clouds, without having to worry about what exact sensors are used.
- explores efficient ways to use and manage cloud environments for IoT "entities" and resources (such as sensors, actuators and smart devices) and offering utility-based, pay-as-you-go, IoT services.
- enables the concept of "Sensing-as-a-Service", via an adaptive middleware framework for deploying and providing services in cloud environments

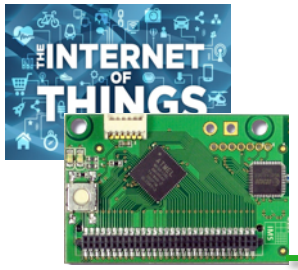
Are you I-o-T or WSN?



IP integration, WWW
IPv6
Inter-operability
Interactions (all kind)
Semantic, Ontology
Data representation
Data logging
WebServices, RDF, OWL, …



Organization
Programmability
Energy saving
Scheduling
Efficient MAC, routing
Congestion control
Data transmission



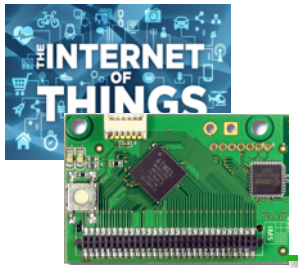
1ST ISSUE: COLLECT DATA

DATA ANALYSIS, OPTIMIZATION & CONTROL

PERVASIVE SYSTEMS

SENSING

PEOPLES, INFRASTRUCTURES, BUILDINGS, VEHICULES



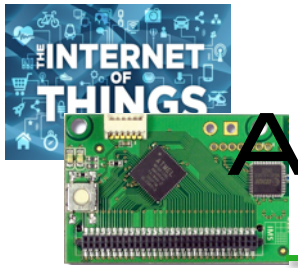
Connectivity is a challenge

Internet of Objects 80% of volume

Requirements:

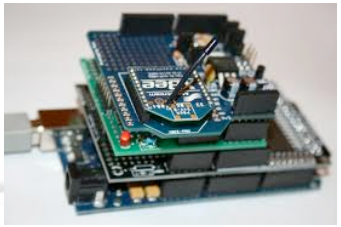
- How to connect Low Cost Assets or having no Energy source, non rechargeable?
- Low Cost communication
- Low Cost Infrastructure
- Low Power Technology
- Robust Communication
- Allowing Mobility
- Scalability

Slide from Semtech

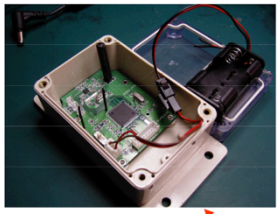


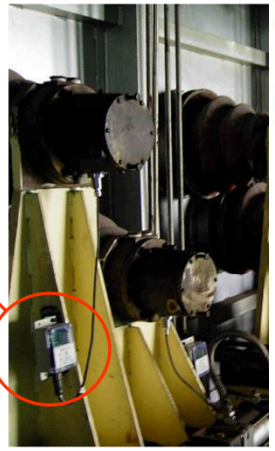
Academics vs Industries

Millions of sensors, self-organizing, self-configuring, with QoS-based multi-path routing, mobility, and …



50 sensors, STATIC deployment, but need to have RELIABILITY, GUARANTEED LATENCY for monitoring and alerting. MUST run for 3 YEARS. No fancy stuff! CAN I HAVE IT?

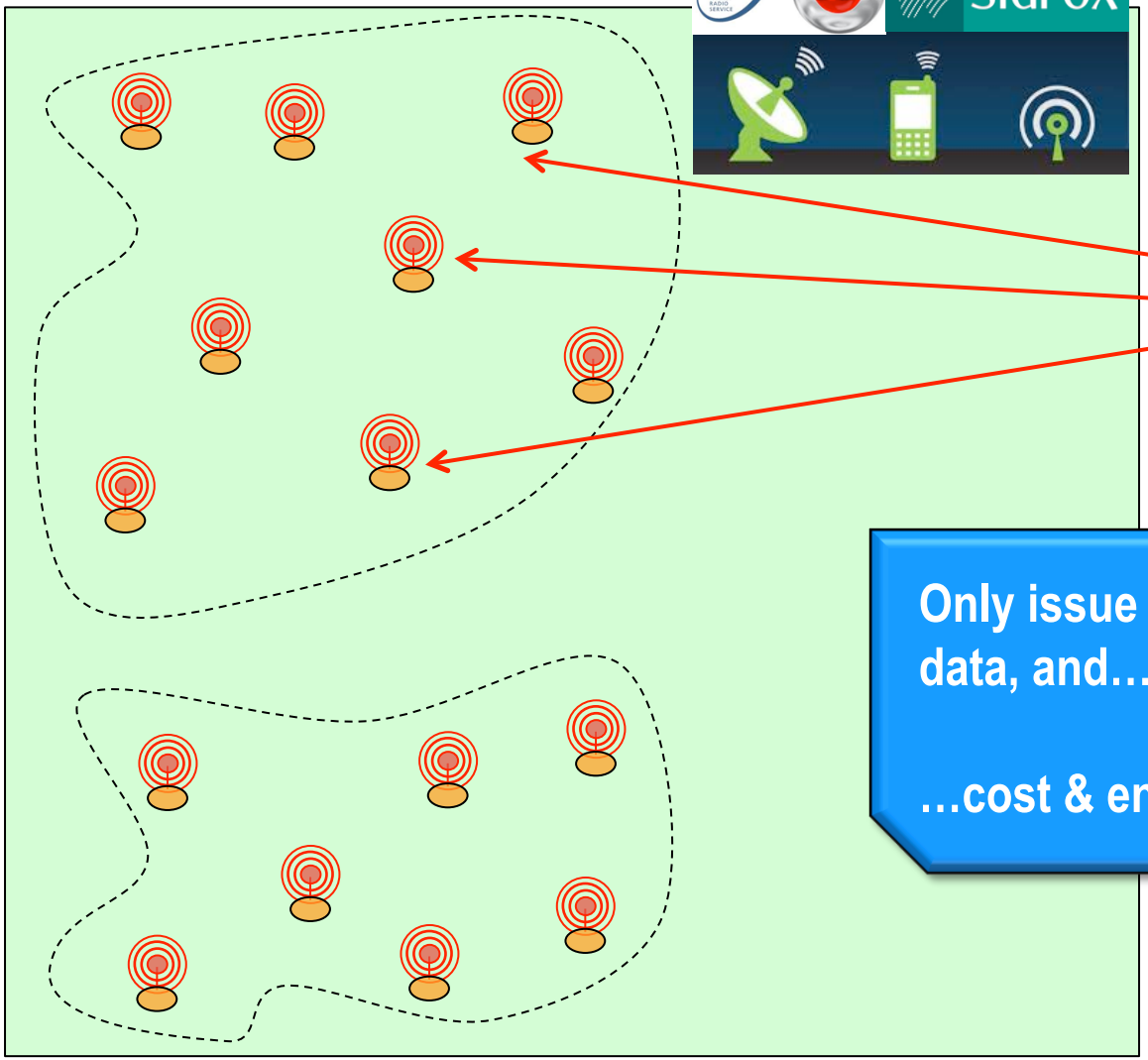




- Placement constraints
- Lifetime constraints

From Peng Zeng & Qin Wang

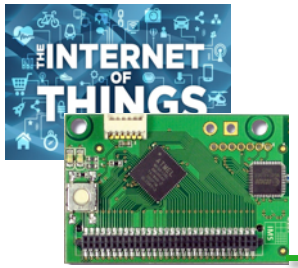
1-HOP COMMUNICATION



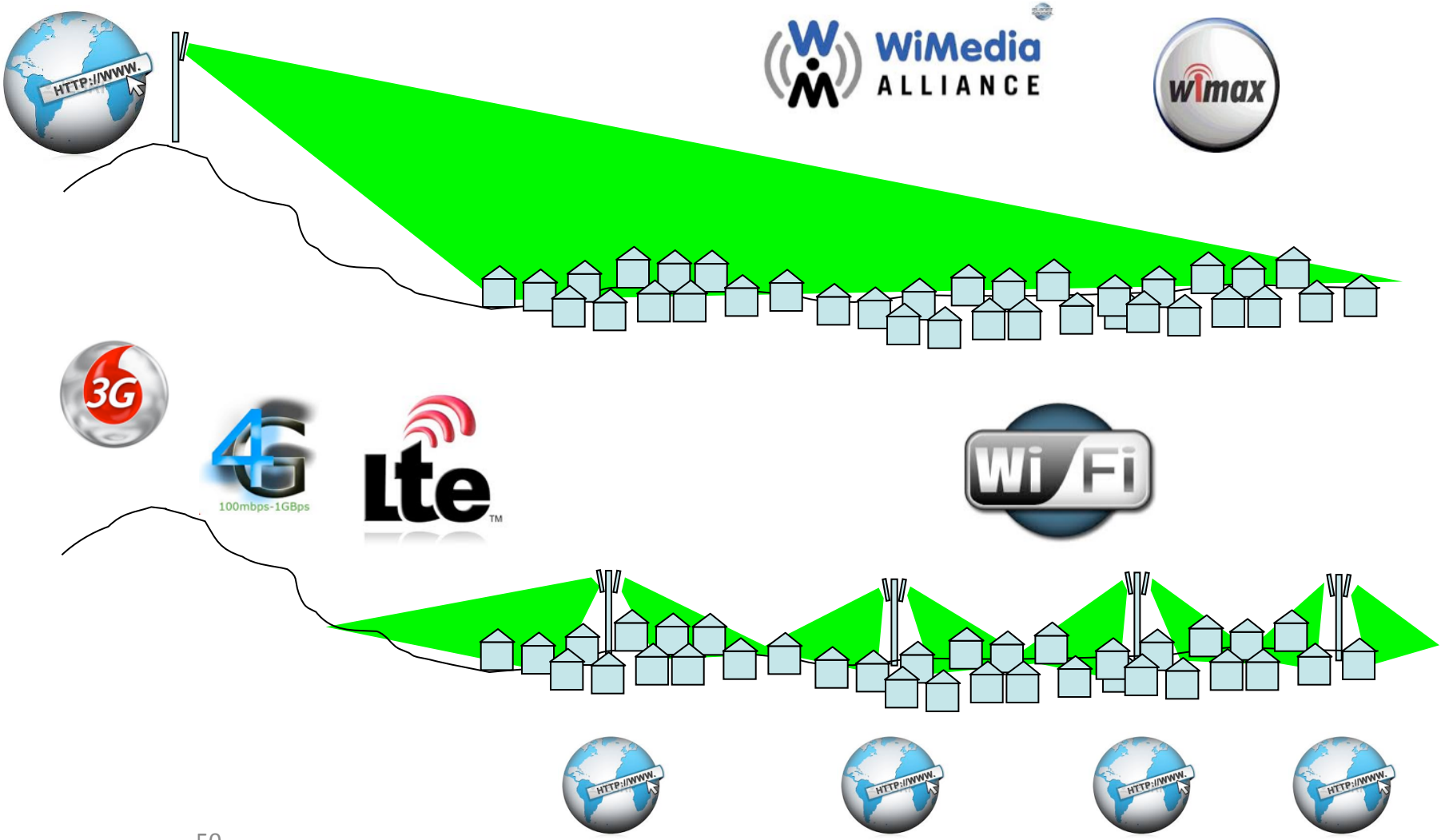
Most of telemetry systems

Only issue is to process data, and…

…cost & energy

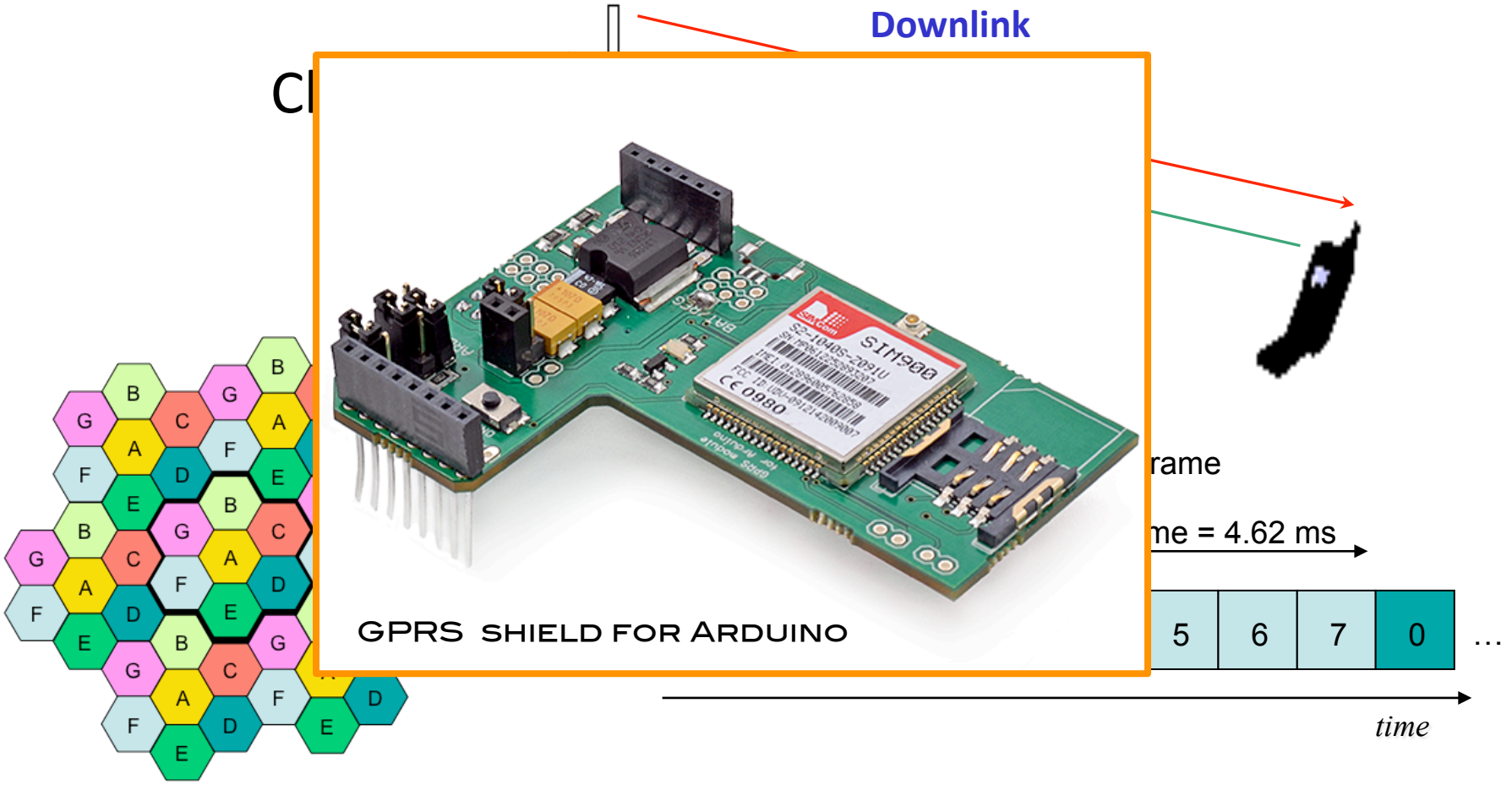


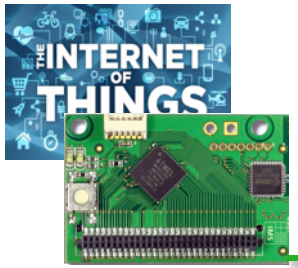
Cellular model



50

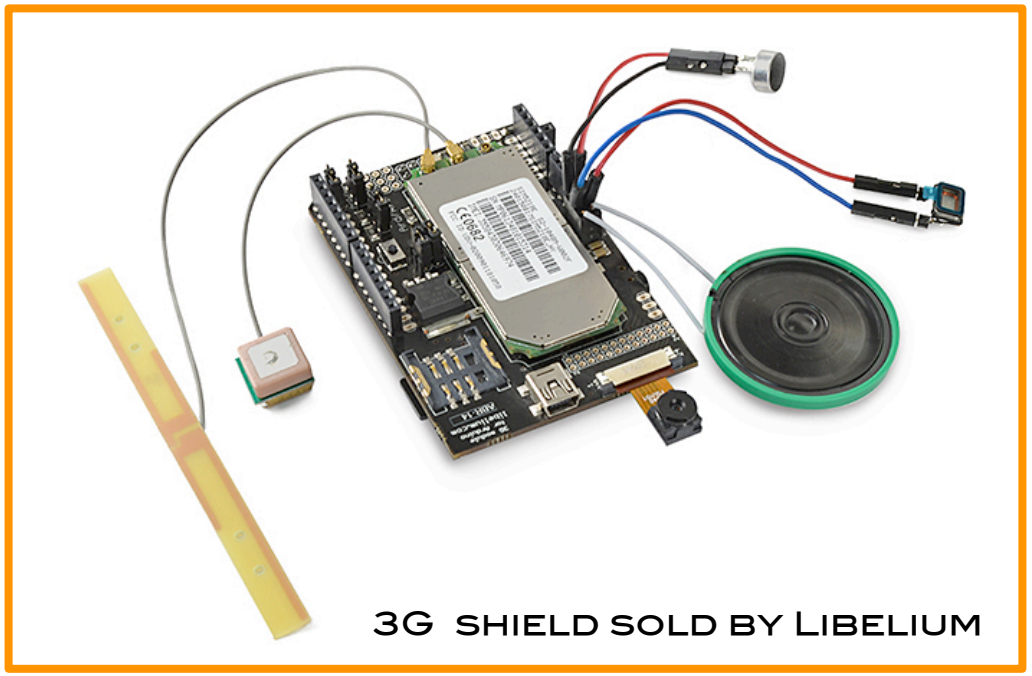
GSM (2G)/GPRS



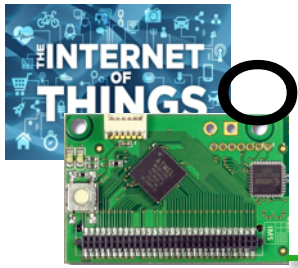


3G AND BEYOND

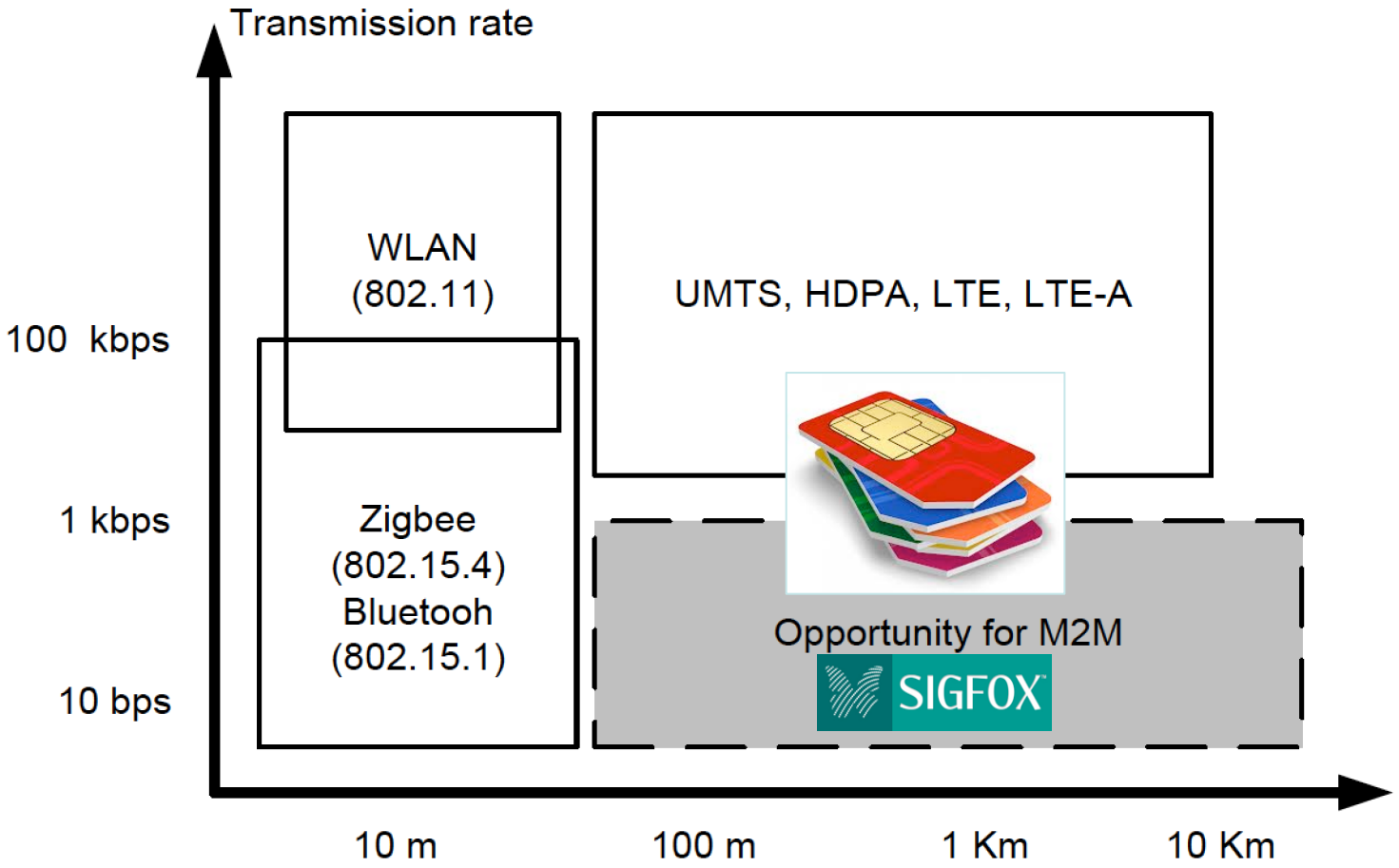
- 3G and beyond use CDMA techniques



3G SHIELD SOLD BY LIBELIUM



Opportunities for Telco operators & more...

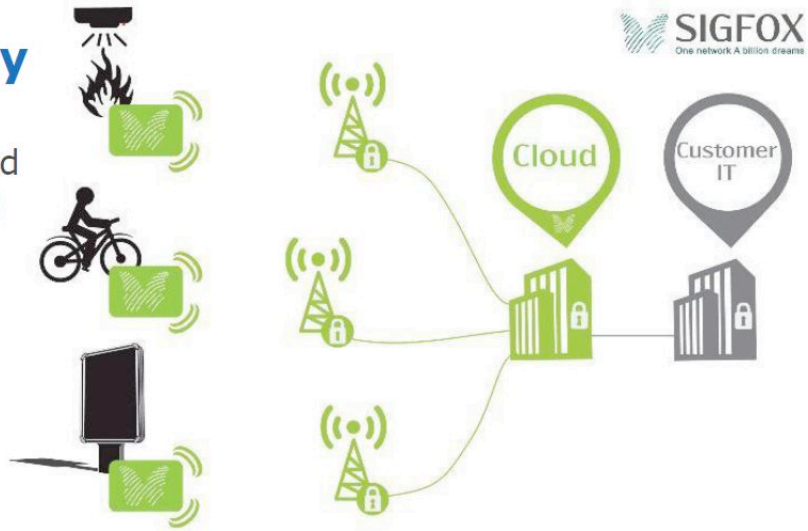


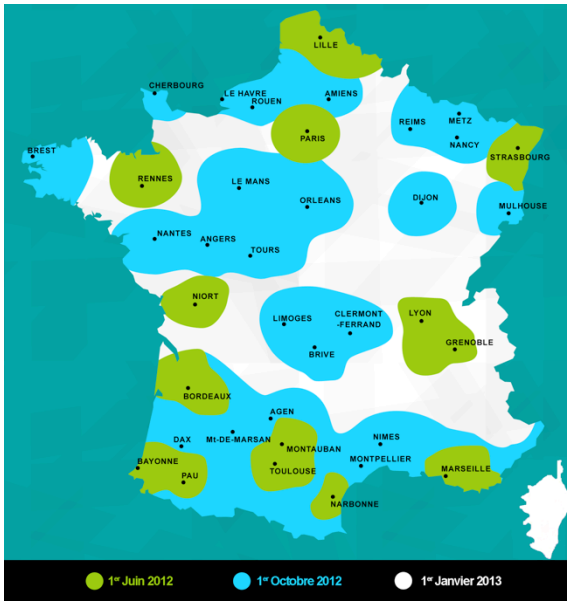
Enhanced from M. Dohler "M2M in SmartCities"

SigFox model for M2M

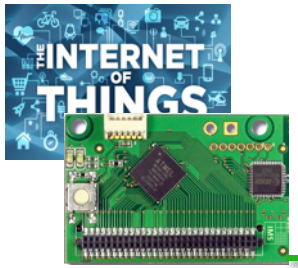
SIGFOX–Technology

- Wireless technology for Internet of Things (IoT) and Machine-to-Machine (M2M)
- Long Range
- Low Power Consumption
- Very Low Cost
- Existing Global Cloud architecture





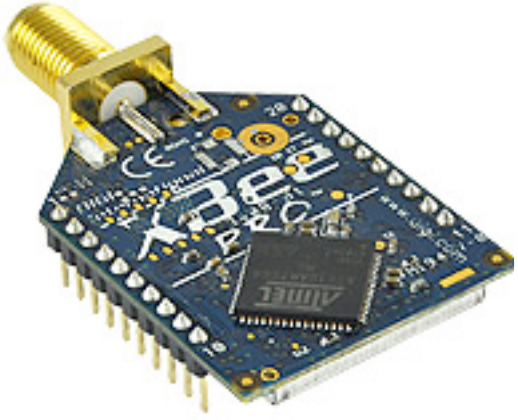
Figures from SigFox



Private long range communications

License-free sub-GHz band

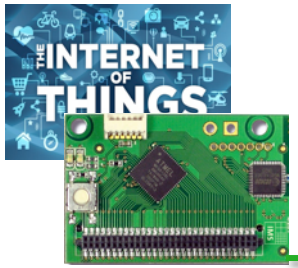
Several kilometers (20-80kms) can be achieved in a single hop!



XBEE—PRO 868
868 MHz short-range device
G3 band for Europe
Data rate of 24 Kbps

Libelium LoRa is based on Semtech SX1272 LoRa
863-870 MHz for Europe
Data rate from 200bps to 20kbps

DORJI DRF1278DM is based on Semtech SX1278 LoRa 433MHz



Semtech's LoRa

dBm – power referred to 1 mW,

$P_{dBm}=10\log(P/1mW)$

- Parameters
  - Bandwidth: 125kHz, 250kHz, 500kHz
  - Coding rate: 4/5, 4/6, 4/7, 4/8
  - Spreading factor: 6 to 12

Sensitivity: lowest input power with acceptable link quality, typically 1% PER

SpreadingFactor (RegModemConfig2)	Spreading Factor (Chips / symbol)	LoRa Demodulator SNR
6	64	-5 dB
7	128	-7.5 dB
8	256	-10 dB
9	512	-12.5 dB
10	1024	-15 dB
11	2048	-17.5 dB
12	4096	-20 dB

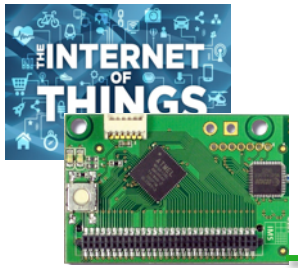
Bandwidth (kHz)	Spreading Factor	Nominal Rb (bps)	Sensitivity (dBm)
125	6	9380	-122
125	12	293	-137
250	6	18750	-119
250	12	586	-134
500	6	3750	-116
500	12	1172	-131

Rule of thumb

6dB increase = twice the range

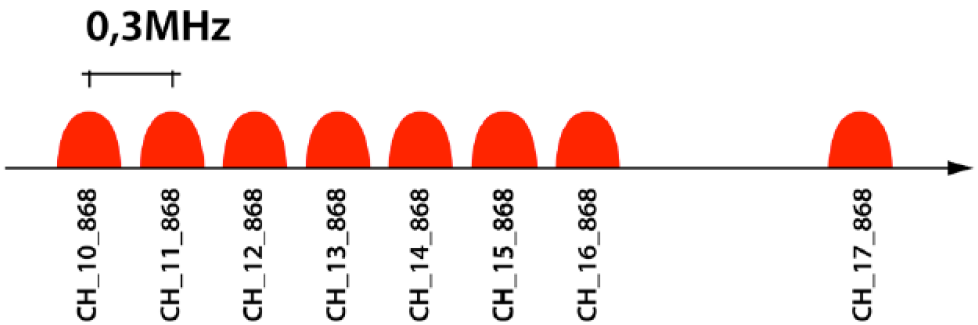
Bandwidth (kHz)	Spreading Factor	Coding rate	Nominal Rb (bps)	Sensitivity (dBm)
125	12	4/5	293	-136
250	12	4/5	586	-133
500	12	4/5	1172	-130

Tables from Semtech



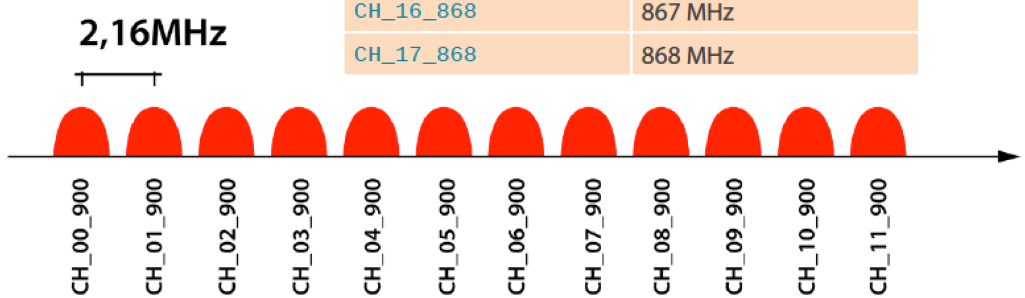
Libelium LoRa

863-870 MHz Band



Channel Number	Central Frequency
CH_10_868	865.20 MHz
CH_11_868	865.50 MHz
CH_12_868	865.80 MHz
CH_13_868	866.10 MHz
CH_14_868	866.40 MHz
CH_15_868	866.70 MHz
CH_16_868	867 MHz
CH_17_868	868 MHz

902-928 MHz Band



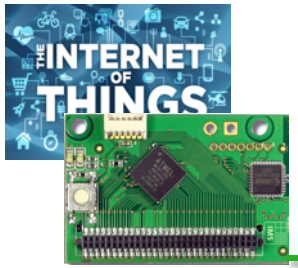
Mode	BW	CR	SF	Sensitivity (dB)
1	125	4/5	12	-134
2	250	4/5	12	-131
3	125	4/5	10	-129
4	500	4/5	12	-128
5	250	4/5	10	-126
6	500	4/5	11	-125,5
7	250	4/5	9	-123
8	500	4/5	9	-120
9	500	4/5	8	-117
10	500	4/5	7	-114

Figures and table from Libelium

Tests from Libelium

Pictures from Libelium

HTTP://WWW.LIBELIUM.COM



LoRa vs SigFox

SigFox uses ultra-narrow band (UNB) of about 100Hz!

Figure show Semtech LoRa band of 125kHz

SigFox's band is 1000 time smaller!
Can create less interference,
« hide » in noise at the cost of much lower data rate, i.e 100bps

Figure from Semtech

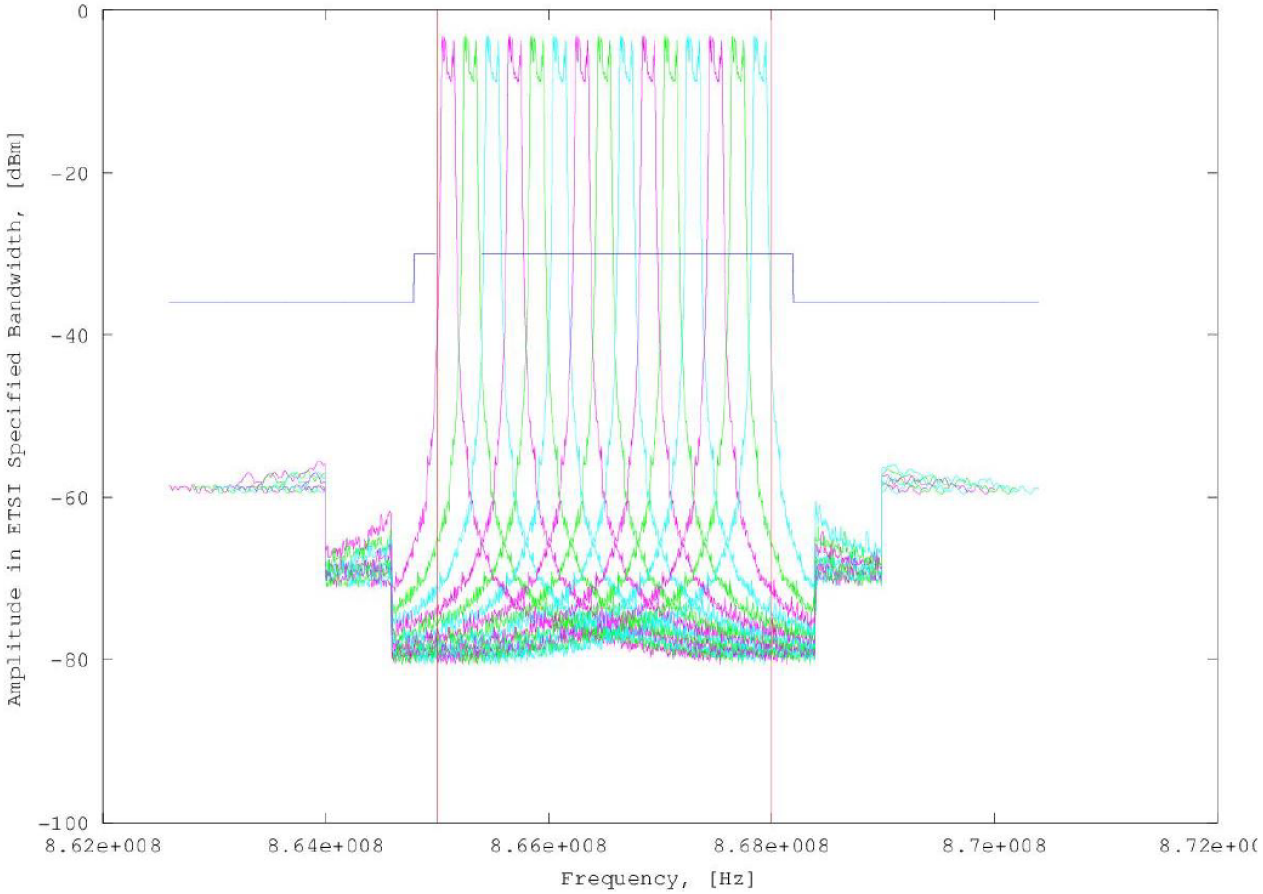
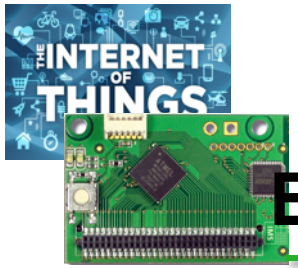
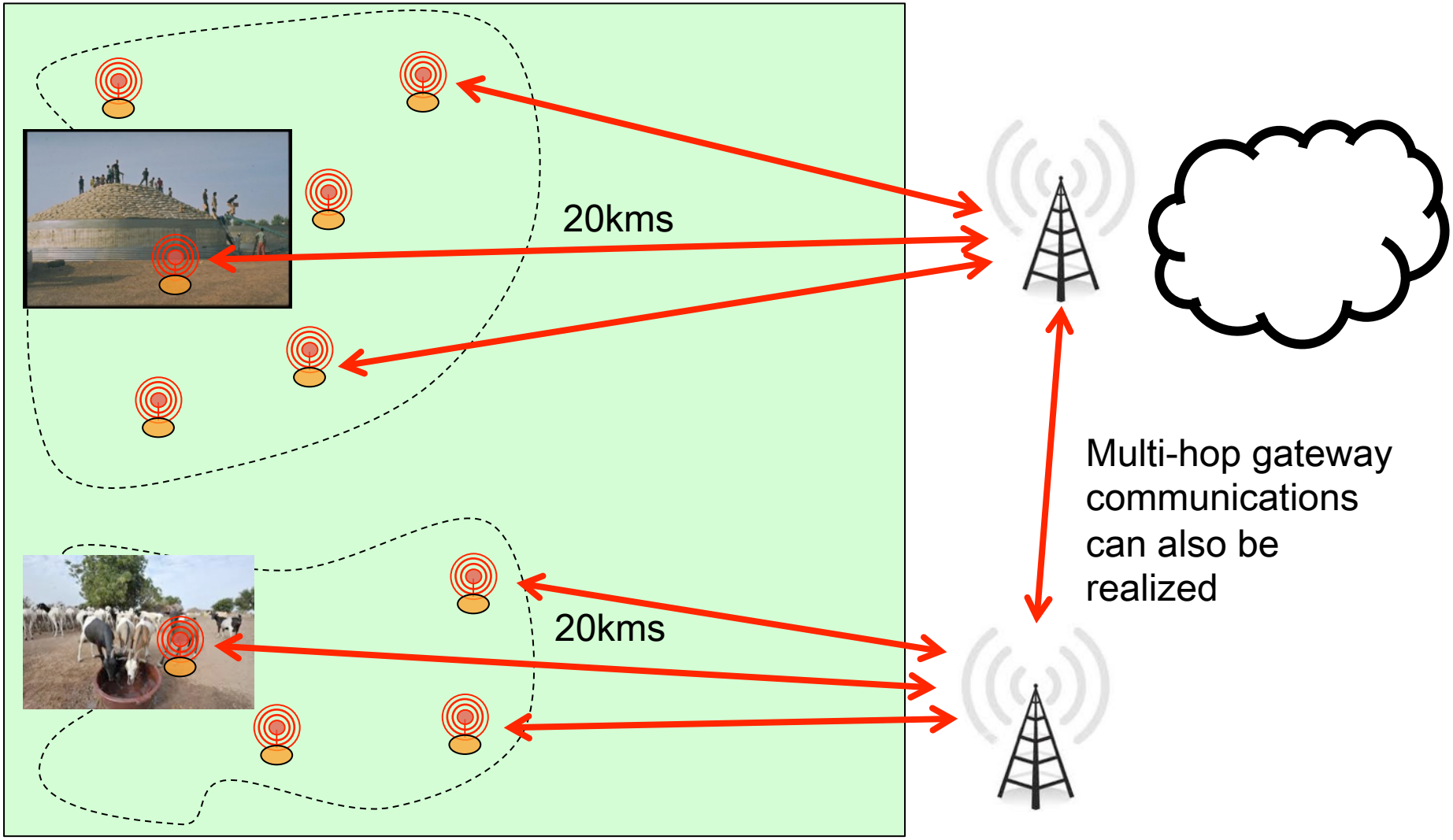
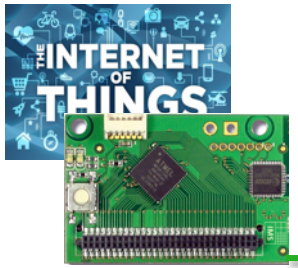


Figure 3. Band G (Note 7) 6 dBm RF Output Power 125 kHz Bandwidth



IoT deployment made easier: Low Power WAN

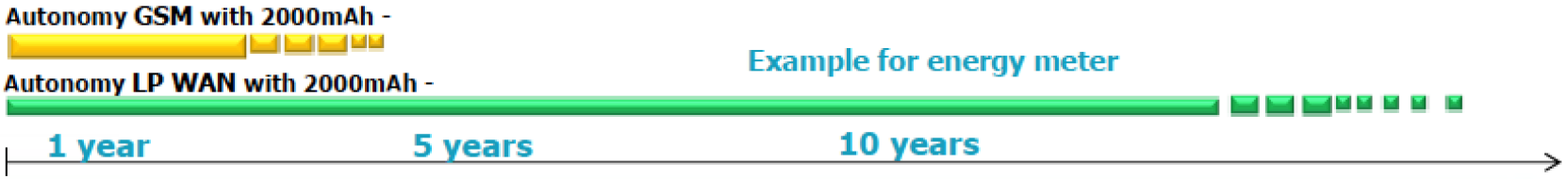




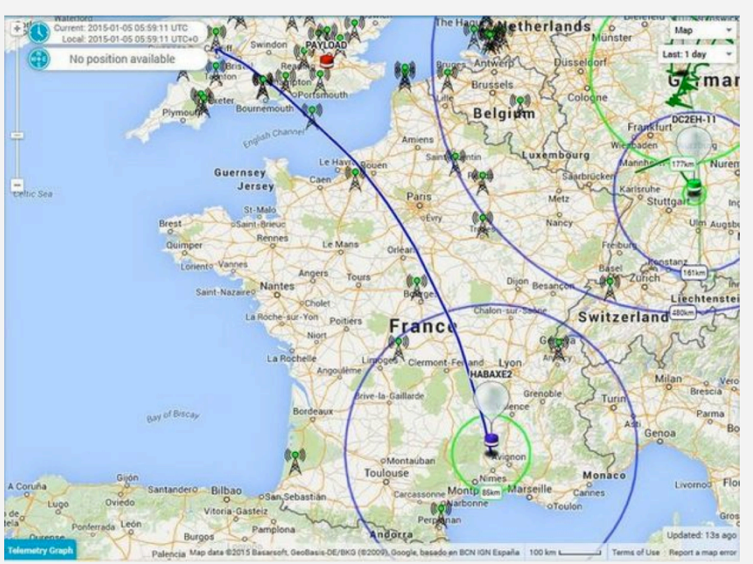
Power consumption rough comparison

Tables from Semtech

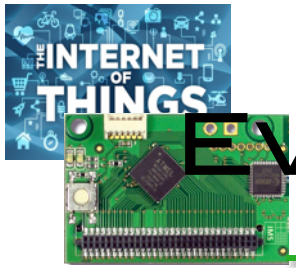
Technology	2G	3G	LAN	ZigBee	Lo Power WAN
Range (I=Indoor, O=Outdoor)	N/A	N/A	O: 300m I: 30m	O: 90m I: 30m	Same as 2G/3G
Tx current consumption	200mA-500mA	500mA – 1000mA	50mA	35mA	18mA
Standby current	2.3mA	3.5mA	NC	0.003mA	0.001mA
Energy harvesting (solar, other)	No	No	No	Possible	Possible
Battery 2000mAh (LR6 battery)	4-8 hours(com) 36 days(idle)	2-4 hours(com) X hours(idle)	50 hours(com) X hours(idle)	60hours (com)	120 hours(com) 10 year(idle)
Module Revenue Annually	12 $	20 $	4 $	$3	3 $



Extreme long-range!



UK HAB (High Altitude Ballooning) trials gave 2 way LoRa™ coverage at up to 240 km. Lowering the data rate from 1000bps to 100bps should allow coverage all the way to the radio horizon, which is perhaps 600 km at the typical 6000-8000m soaring altitude of these balloons. Balloon tracking can be made



EVERYBODY WANTS TO BE IN!

SIGFOX

SIGFOX OPERATOR

LoRa

SEMTECH

TST

LoRa Alliance
Wide Area Networks for IoT

IBM

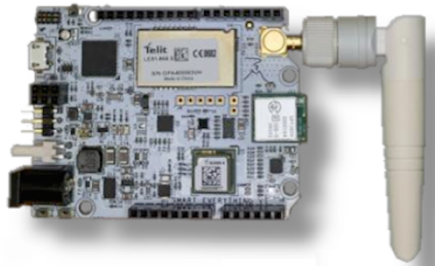
Texas Instruments

libelium

Froggy Factory

actility
Making Things Smart

INTERNET OF THINGS
Atmel

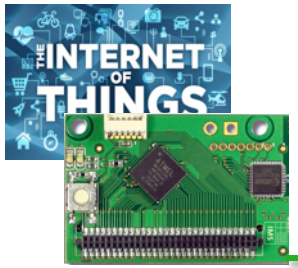


Wi6Labs

ThingPark Wireless

Bouygues Telecom

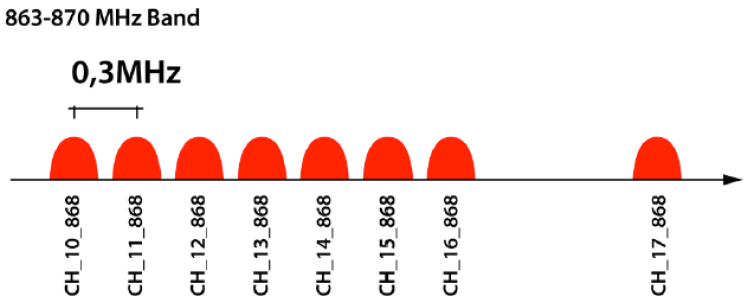
kerlink
m2m technologies



License-free Sub-GHz constraints

- Shared medium so long-range transmission in dense environments can create lots of interference!
- Activity time is constrained from 0.1% to 1% duty-cycle depending on frequency: 3.6s to 36s/hour

Band	Edge Frequencies		Field / Power	Spectrum Access	Band Width
	Fe-	Fe+			
g(Note 7)	865 MHz	868 MHz	+6.2 dBm /100 kHz	1 % or LBT AFA	3 MHz
g(Note 7)	865 MHz	870 MHz	-0.8 dBm / 100 kHz	0.1% or LBT AFA	5 MHz
g1	868 MHz	868.6	14 dBm	1 % or LBT AFA	600 kHz
g2	868.7 MHz	869.2 MHz	14 dBm	0.1% or LBT AFA	500 kHz
g3	869.4 MHz	869.65 MHz	27 dBm	10 % or LBT AFA	250 kHz
g4	869.7 MHz	870 MHz	7 dBm	No requirement	300 kHz
g4	869.7 MHz	870 MHz	14 dBm	1 % or LBT AFA	300 kHz



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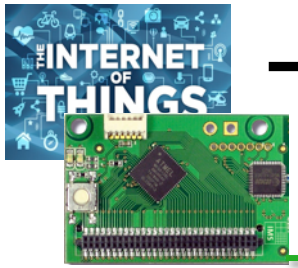
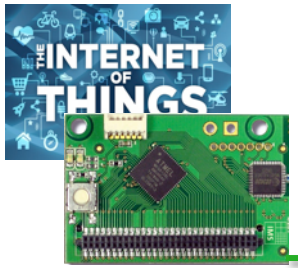


Time on air for various Libelium LoRa mode

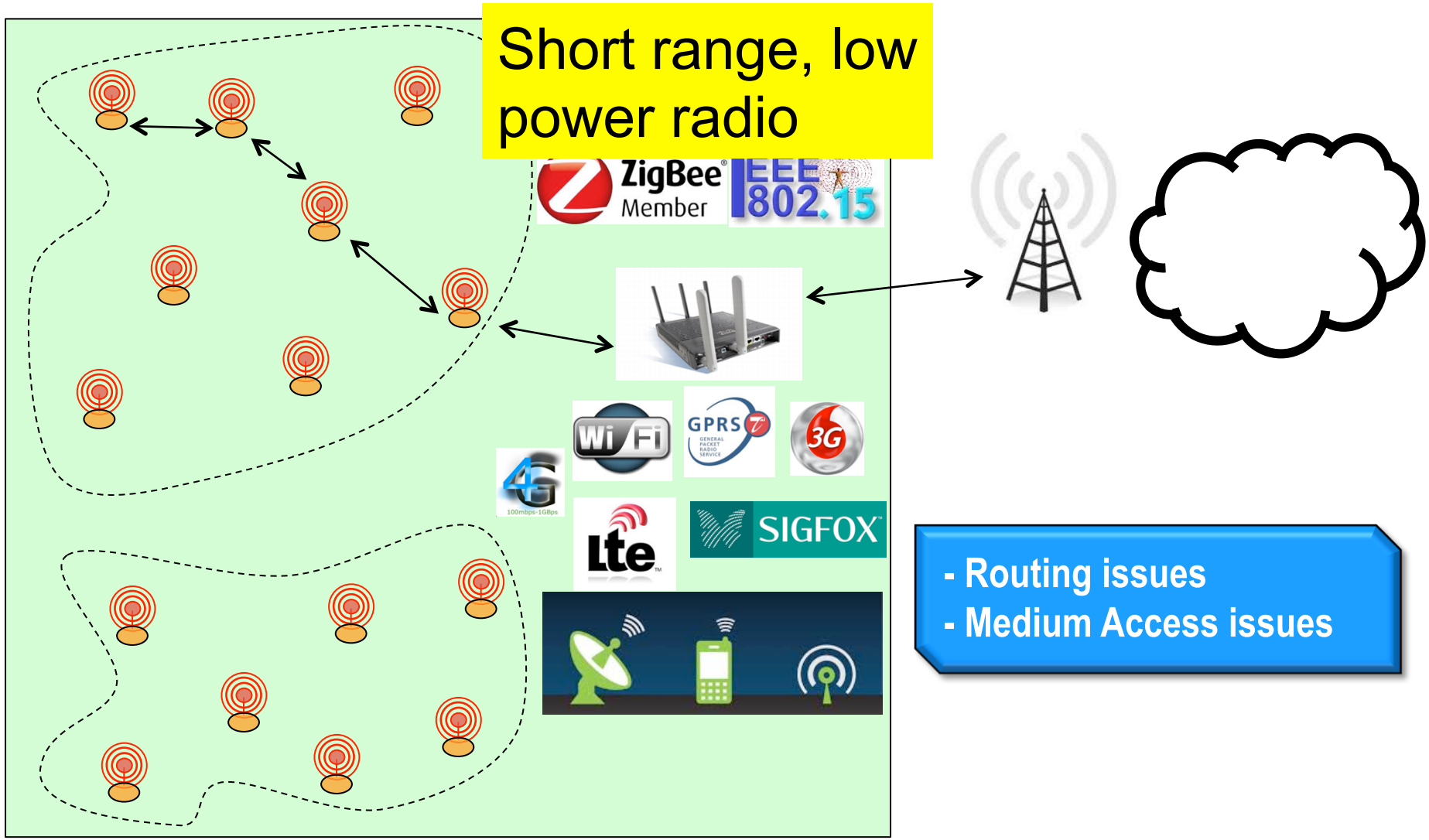
				time on air in second for user payload size of					
LoRa mode	BW	CR	SF	1 bytes	50 bytes	100 bytes	150 Bytes	200 Bytes	250 Bytes
1	125	4/5	12	0.9257	2.30195	3.67821	5.0217	6.39795	7.77421
2	250	4/5	12	0.46285	1.15098	1.8391	2.51085	3.19898	3.8871
3	125	4/5	10	0.24781	0.65741	1.06701	1.47661	1.88621	2.29581
4	500	4/5	12	0.23142	0.57549	0.91955	1.25542	1.59949	1.94355
5	250	4/5	10	0.1239	0.3287	0.5335	0.7383	0.9431	1.1479
6	500	4/5	11	0.11981	0.30413	0.49254	0.67686	0.86528	1.0496
7	250	4/5	9	0.064	0.17869	0.29133	0.40602	0.51866	0.63334
8	500	4/5	9	0.032	0.08934	0.14566	0.20301	0.25933	0.31667
9	500	4/5	8	0.01702	0.04877	0.08102	0.11277	0.14502	0.17677
10	500	4/5	7	0.00877	0.0272	0.04538	0.06381	0.08198	0.10042



LBT+AFA

- Listen Before Talk and Adaptive Frequency Agility can remove the duty-cycle constraints…
- … but still
  - 100s / hour on every 200kHz BW
  - no more than 1s for a single transmission

Multi-hop to gateways



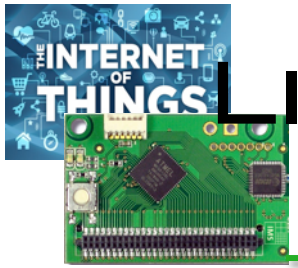
SmartSantander testbed

www.smartsantander.eu

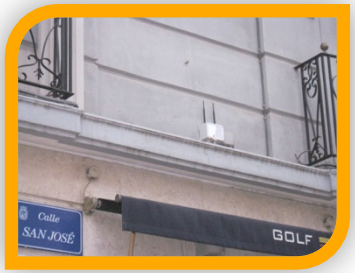
SmartSantander test-bed

Gateways

Pictures are taken in the context of the EAR-IT project

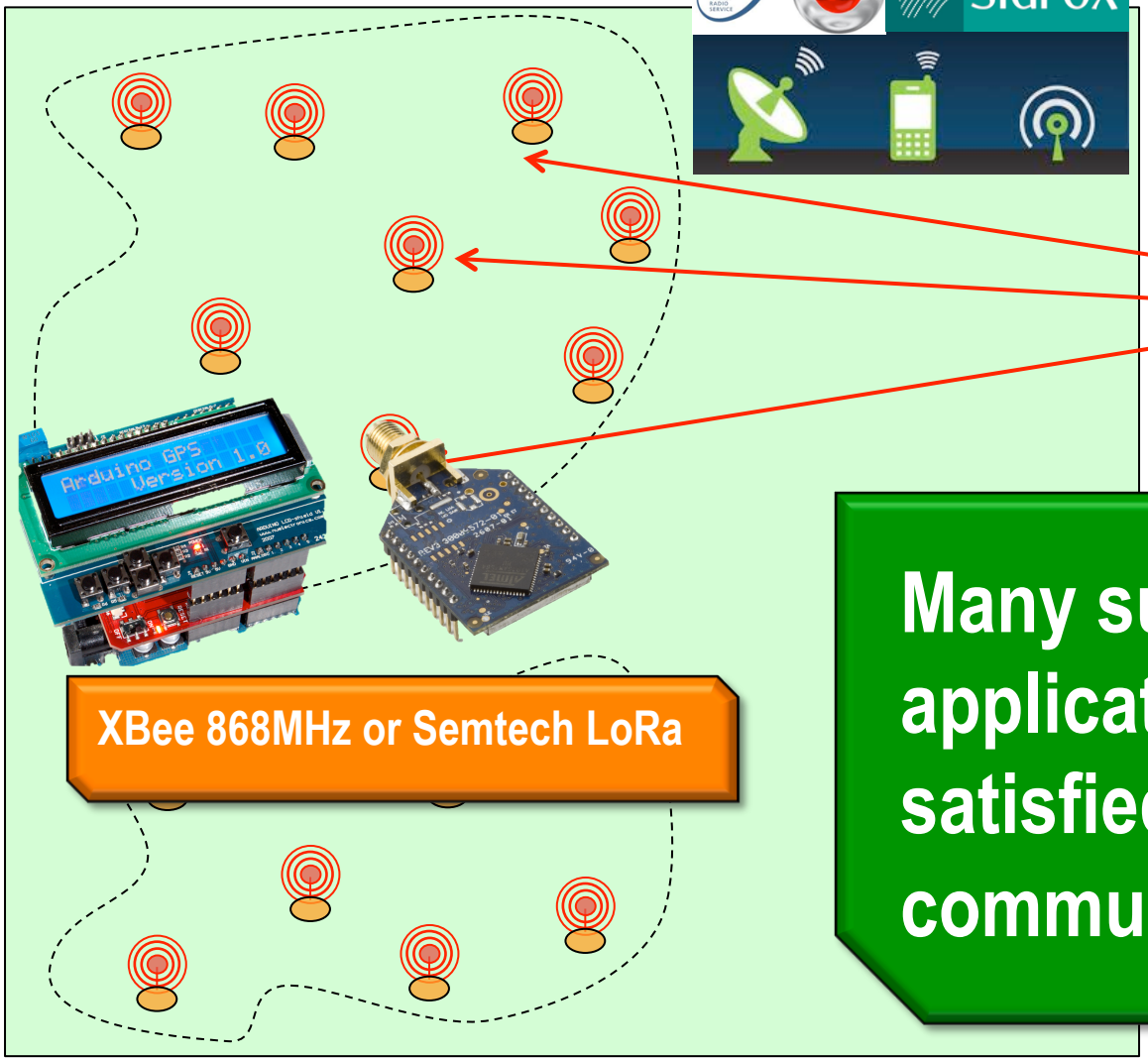


LIMIT THE NUMBER OF HOPS TO GATEWAYS

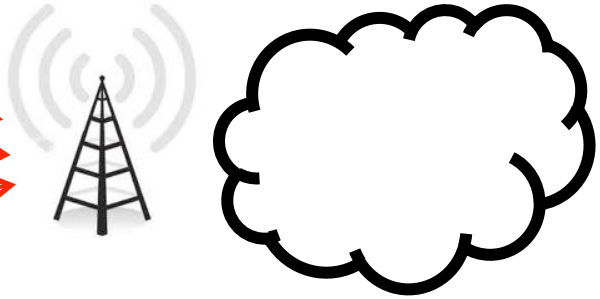


3 TO 5 HOPS MAXIMUM

Do I need multi-hop for my app?

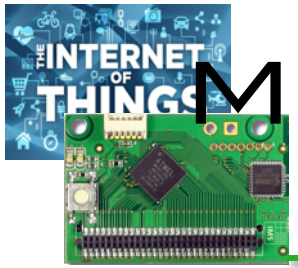


Most of telemetry systems



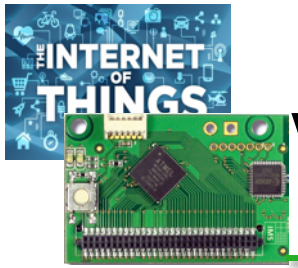
XBee 868MHz or Semtech LoRa

Many surveillance applications can be satisfied with the 1-hop communication model!!!



Multi-hop routing is still interesting!

- 1-hop model is not economically tractable in large scale deployment
- 1-hop model is usually not energy-efficient
- 1-hop model is hard to optimize in terms of radio access methods
- Routing in WSN is fundamentally different from routing in other type of networks, even other wireless networks

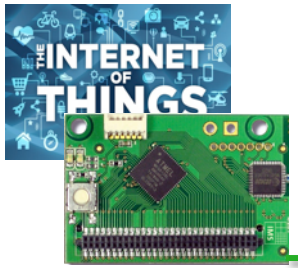


Why is it so different?

1. WSN/IoT are mainly deployed for surveillance ➔coverage & Latency is important

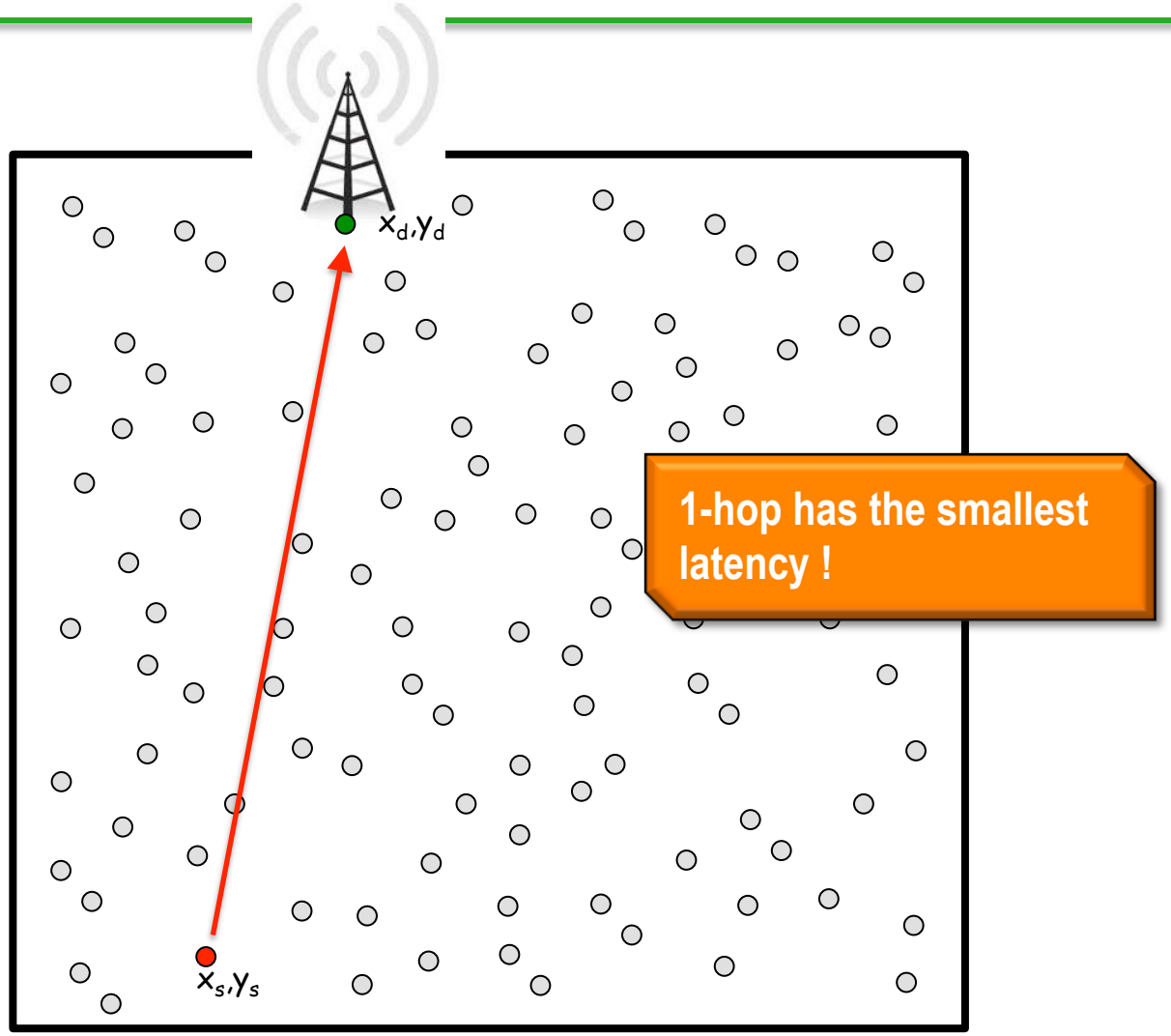
2. WSN/IoT are deployed to get data from remote areas or to react to events ➔ mainly data-centric

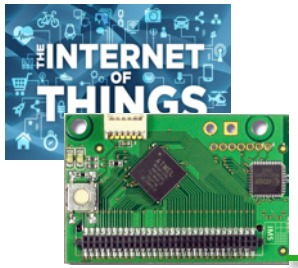
3. WSN/IoT run on battery ➔ energy saving is important, if not managed correcty, see item 1



Energy vs Latency

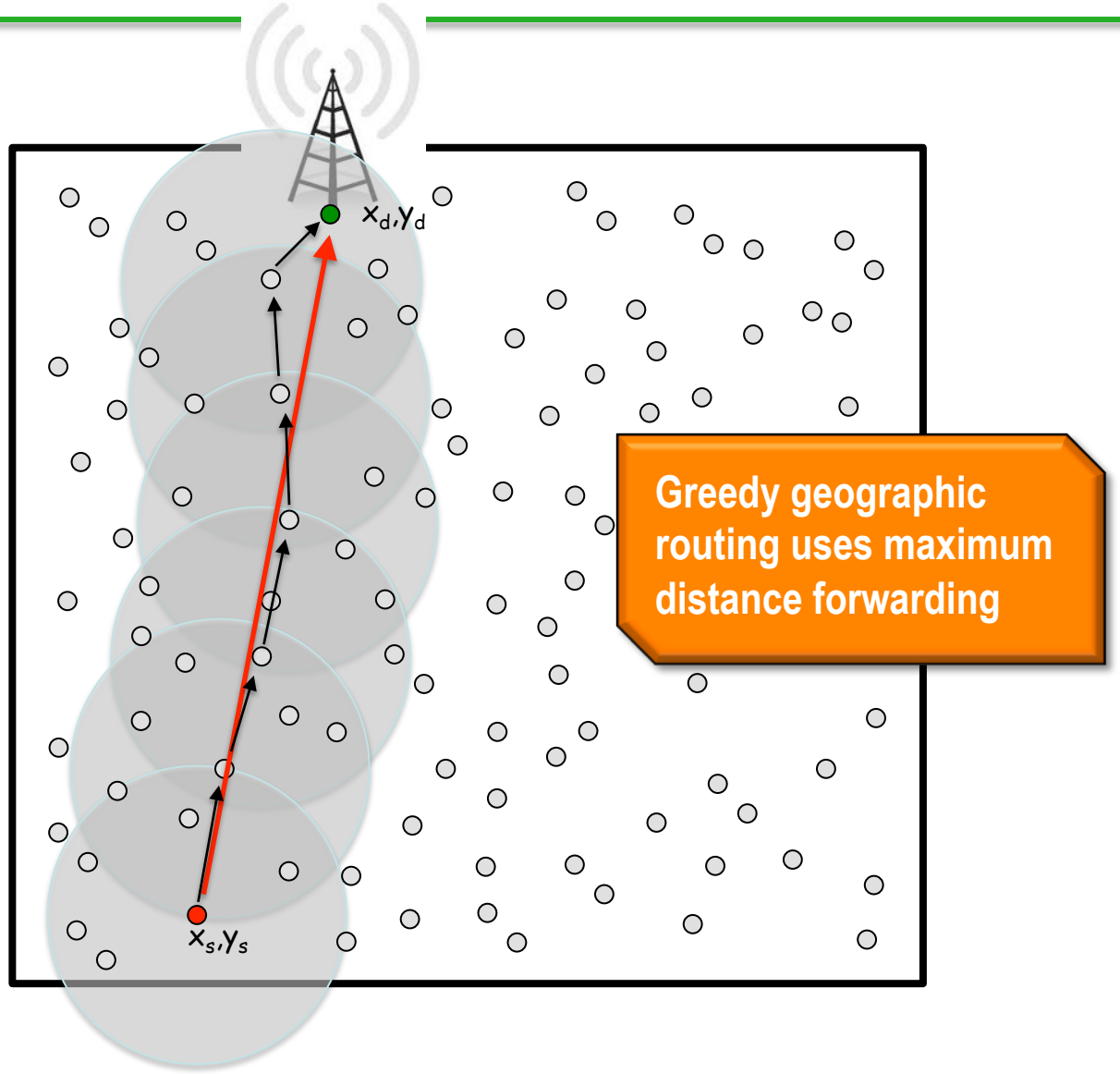
1-hop

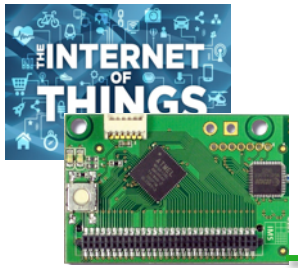




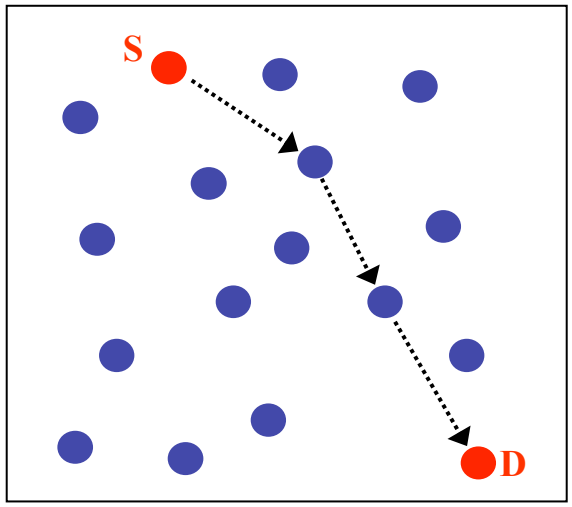
Energy vs Latency

Multi-hop - greedy

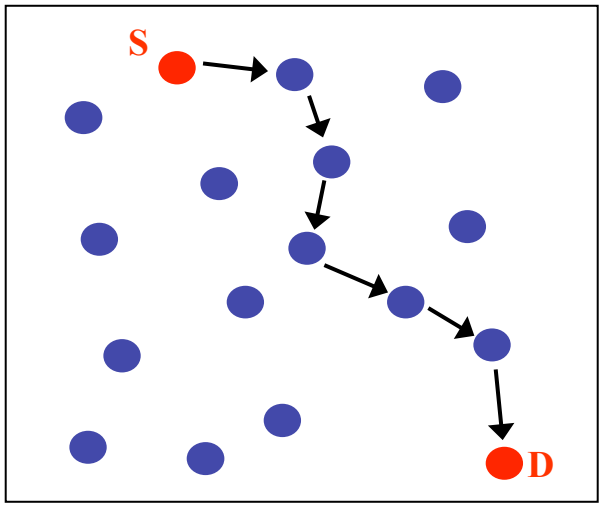




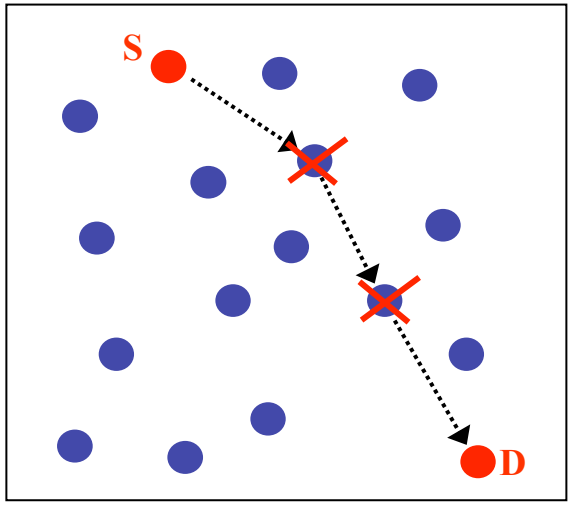
Is maximum distance always good?



Few long links with low quality

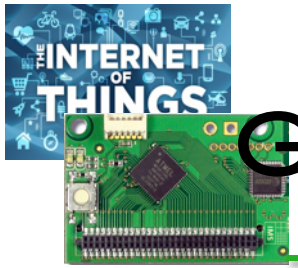


Many short links with high quality

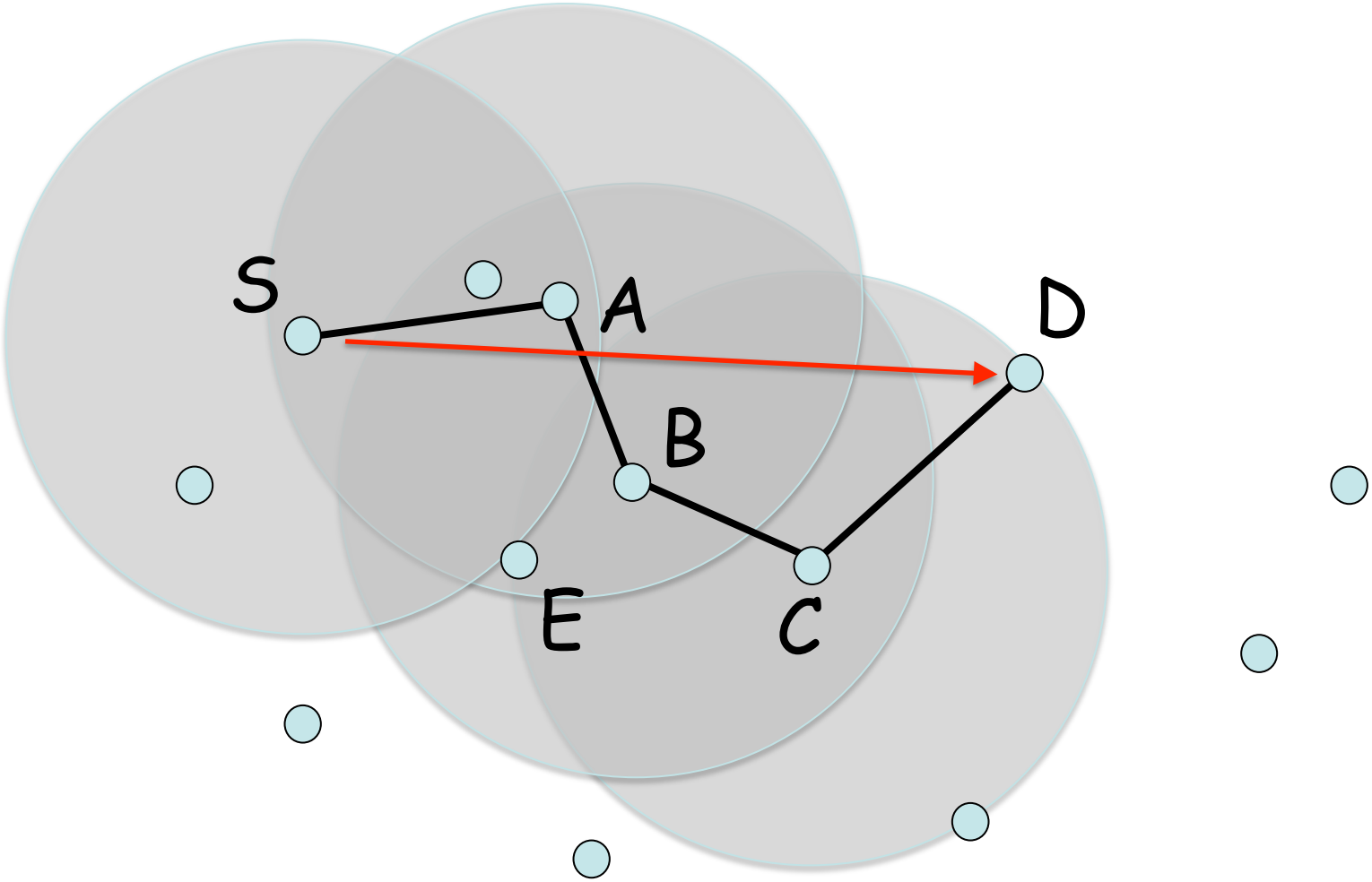


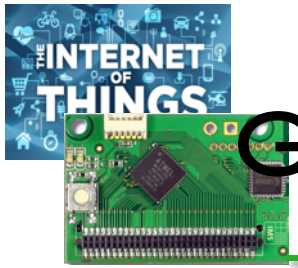
Intermediate nodes that are more sollicited die first

Adapted from Ahmed Helmy, "Robust Geographic Routing and Location-based Services"

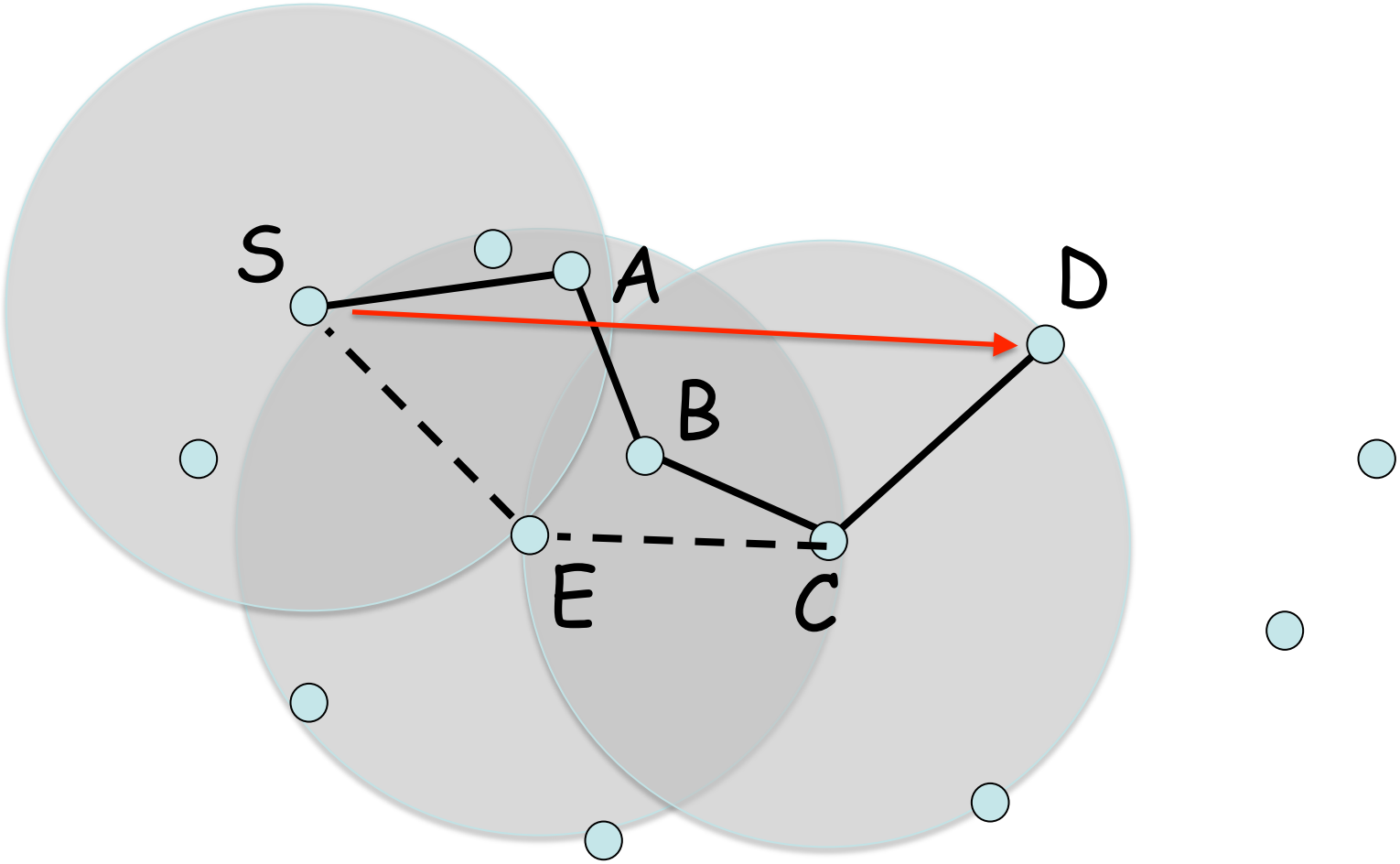


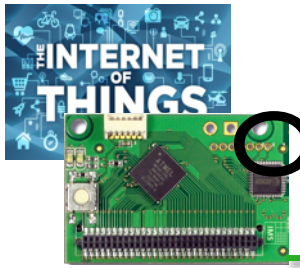
GREEDY=SHORTEST PATH?





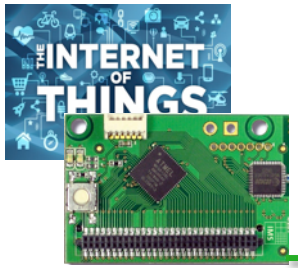
GREEDY=SHORTEST PATH?





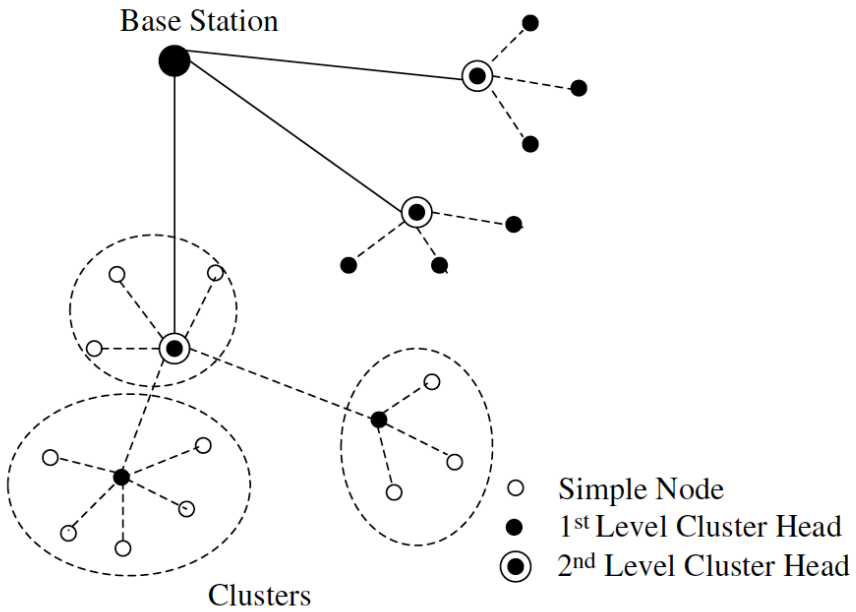
ORGANIZING THE NETWORK

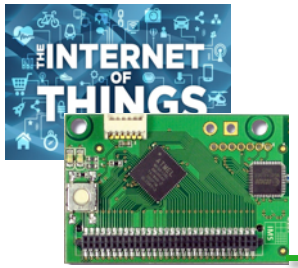
- The network is no longer useful when node's battery dies
- Organizing the network allows for spacing out the lifespan of the nodes
- Hierarchical routing protocols often give priority to energy
- Ex: Low-Energy Adaptive Clustering Hierarchy (LEACH)



Clustering

- A cluster-head collect data from their surrounding nodes and pass it on to the base station
- The job of cluster-head rotates





LEACH CLUSTER-HEAD

- Cluster-heads can be chosen *stochastically* (randomly based) on this algorithm:

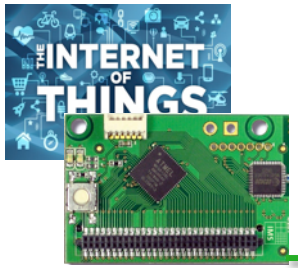
$$T(n) = \frac{P}{1 - P \times (r \bmod P^{-1})} \quad \forall n \in G$$

$$T(n) = 0 \quad \forall n \notin G$$

Where n is a random number between 0 and 1
P is the cluster-head probability and
G is the set of nodes that weren't cluster-heads the previous rounds

- If n < T(n), then that node becomes a cluster-head
- The algorithm is designed so that each node becomes a cluster-head at least once

W.B. Heinzelman, A.P. Chandrakasan, H. Balakrishnan, Application specific protocol architecture for wireless microsensor networks, IEEE Transactions on Wireless Networking (2002).

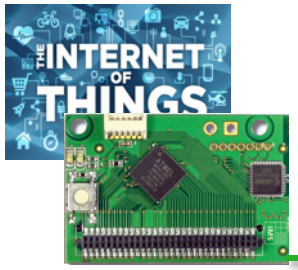


Example

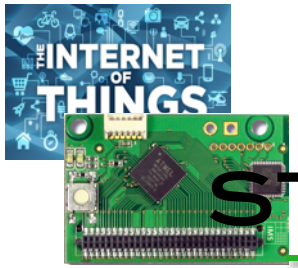
```
p=0.05, r=0 initially
draw N a random number [0,1[ at each
round

N < 0.0500 = 0.05/(1-0.05*0) ?
N < 0.0526 = 0.05/(1-0.05*1) ?
N < 0.0555 = 0.05/(1-0.05*2) ?
N < 0.0588 = 0.05/(1-0.05*3) ?
N < 0.0625 = 0.05/(1-0.05*4) ?
N < 0.0666 = 0.05/(1-0.05*5) ?
N < 0.0714 = 0.05/(1-0.05*6) ?
N < 0.0769 = 0.05/(1-0.05*7) ?
N < 0.0833 = 0.05/(1-0.05*8) ?
N < 0.0909 = 0.05/(1-0.05*9) ?
N < 0.1000 = 0.05/(1-0.05*10) ?

N < 0.5000 = 0.05/(1-0.05*18) ?
N < 1.0000 = 0.05/(1-0.05*19) ?
```

- Number of clusters may not fixed in any round.

$$T(n) = \begin{cases} \dfrac{P}{1 - P[r \bmod (1/P)]} & \text{if } n \in G, \\ 0 & \text{otherwise,} \end{cases}$$



IoT: « I » for Internet



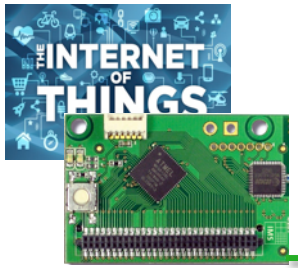
From ad-hoc to standardized protocols


Don't reinvent 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 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]
RFC 4443	ICMPv6 - Internet Control Message Protocol for IPv6	[2006]
RFC 4861	Neighbor Discovery for IP version 6	[2007]
RFC 4944	Transmission of IPv6 Packets over IEEE 802.15.4 Networks	[2007]

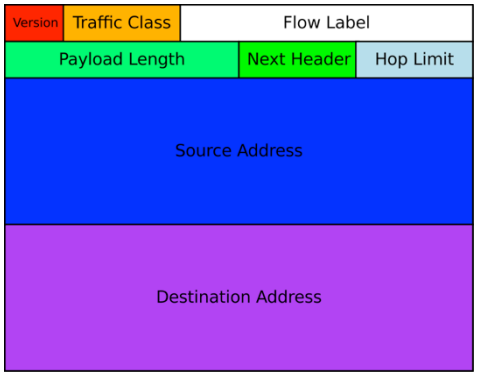
RFC6282 Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks [2011]

From ArchRock "6LowPan tutorial"

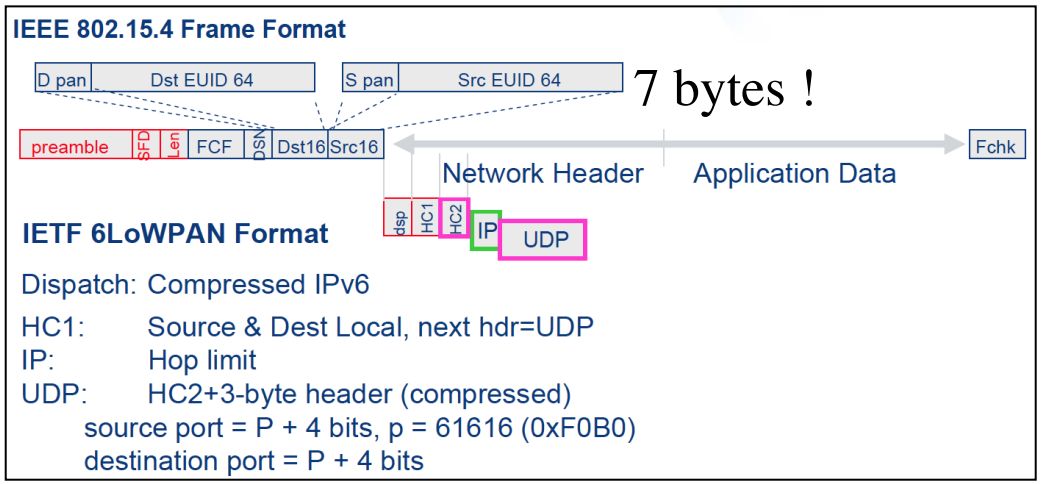


IP NEED IP ADDRESSES!

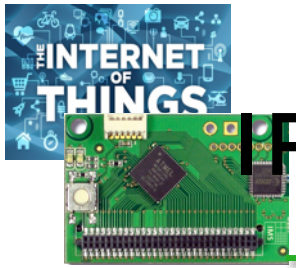
- IPv4 has no more addresses!
- IPv6 gives plenty of addresses
  - 128bit address=16bytes!
- 6LowPan adapts IPv6 to resource-constrained devices
  - Compressed IPv6 header



40 bytes



From ArchRock "6LowPan tutorial"



IPv4 vs. IPv6 Addressing

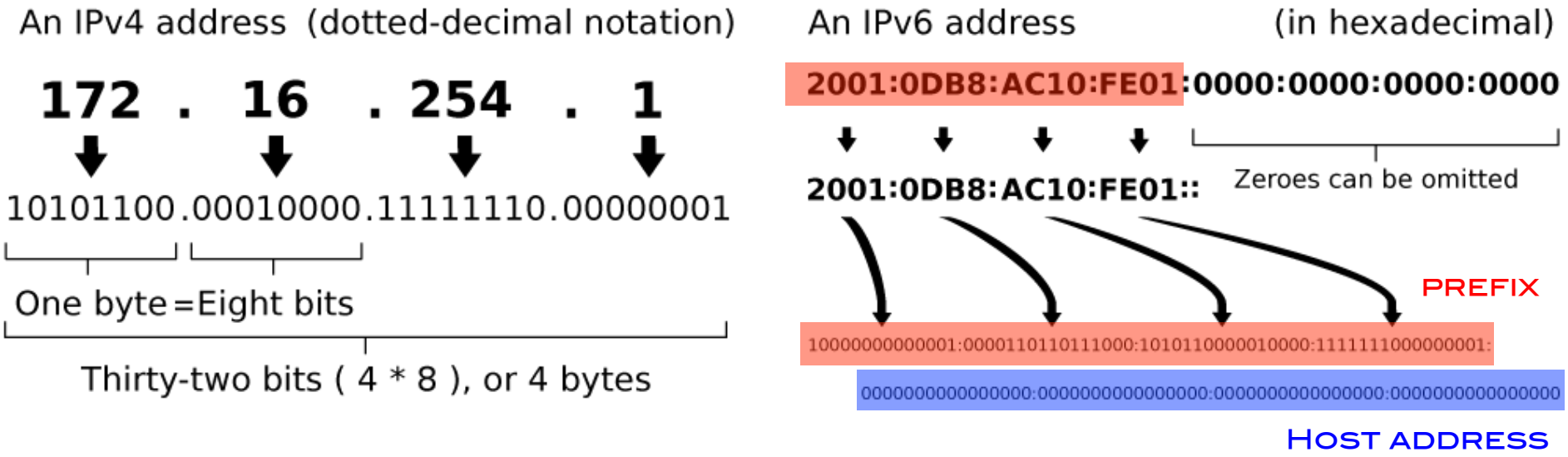
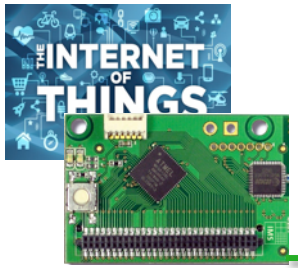


Image source: Indeterminant (Wikipeida) GFDL

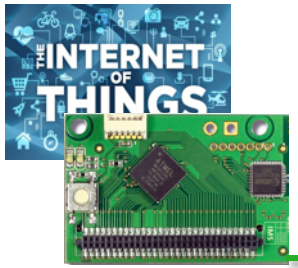
From "6LoWPAN: The Wireless Embedded Internet, Shelby & Bormann"



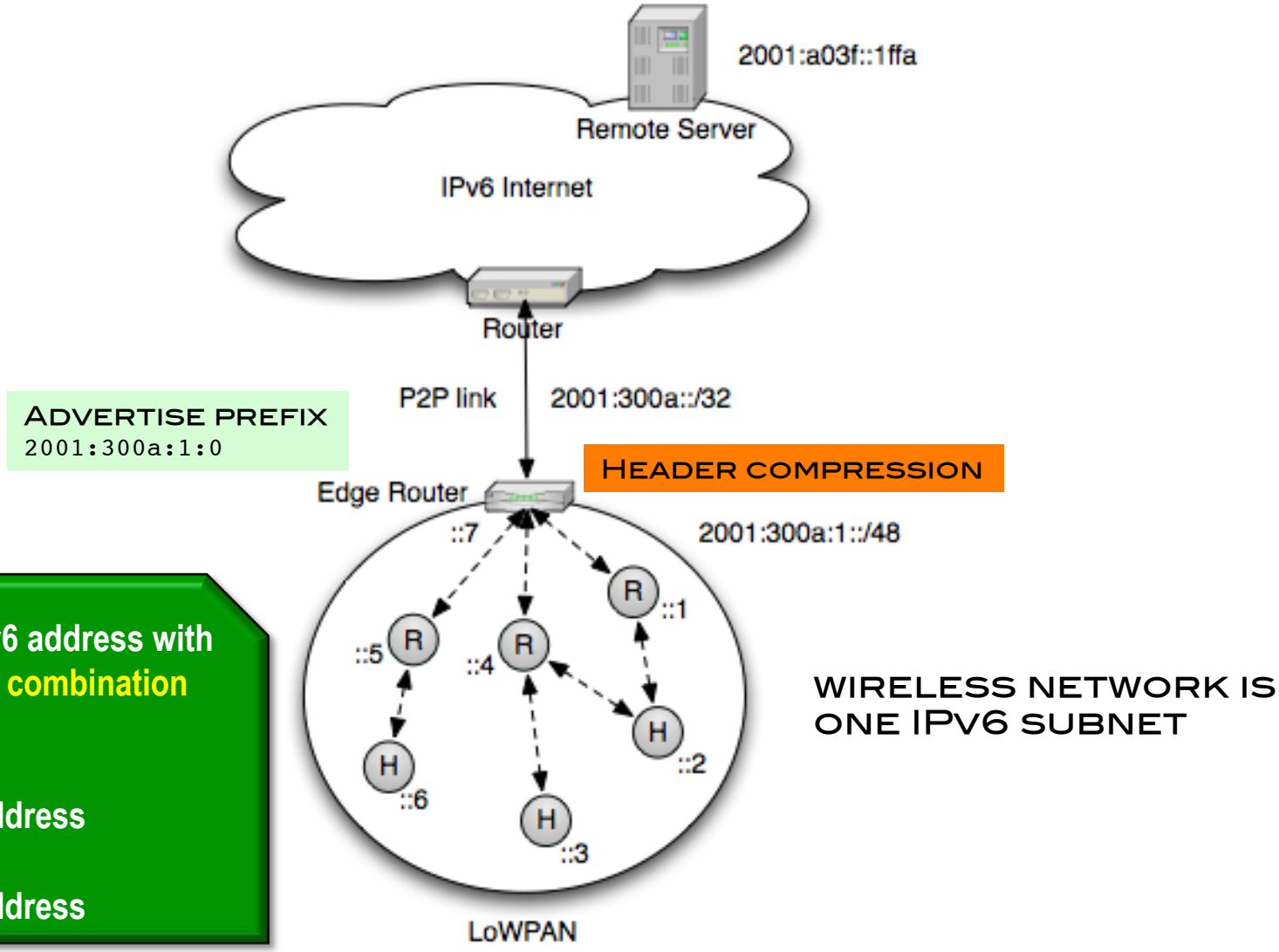
6LoWPAN Addressing

- IPv6 addresses are compressed in 6LoWPAN
- A LoWPAN works on the principle of
  - flat address spaces (wireless network is one IPv6 subnet)
  - with unique MAC addresses (e.g. 64-bit or 16-bit: 0x0013A20040568B34 or 0x0220)
- 6LoWPAN compresses IPv6 addresses by
  - Eliding the IPv6 prefix
    - Global prefix known by all nodes in network
    - Link-local prefix indicated by header compression format
  - Compressing the Interface ID
    - Elided for link-local communication
    - Compressed for multihop dst/src addresses
  - Compressing with a well-known "context"
  - Multicast addresses are compressed

From "6LoWPAN: The Wireless Embedded Internet, Shelby & Bormann"



Addressing Example



Build an IPv6 address with prefix and a combination of 802.15.4:

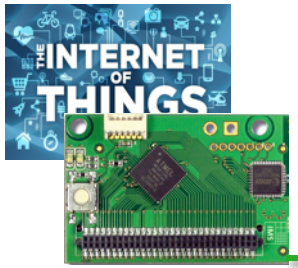
- PANID
- 16-bit address

or

- 64-bit address

WIRELESS NETWORK IS ONE IPV6 SUBNET

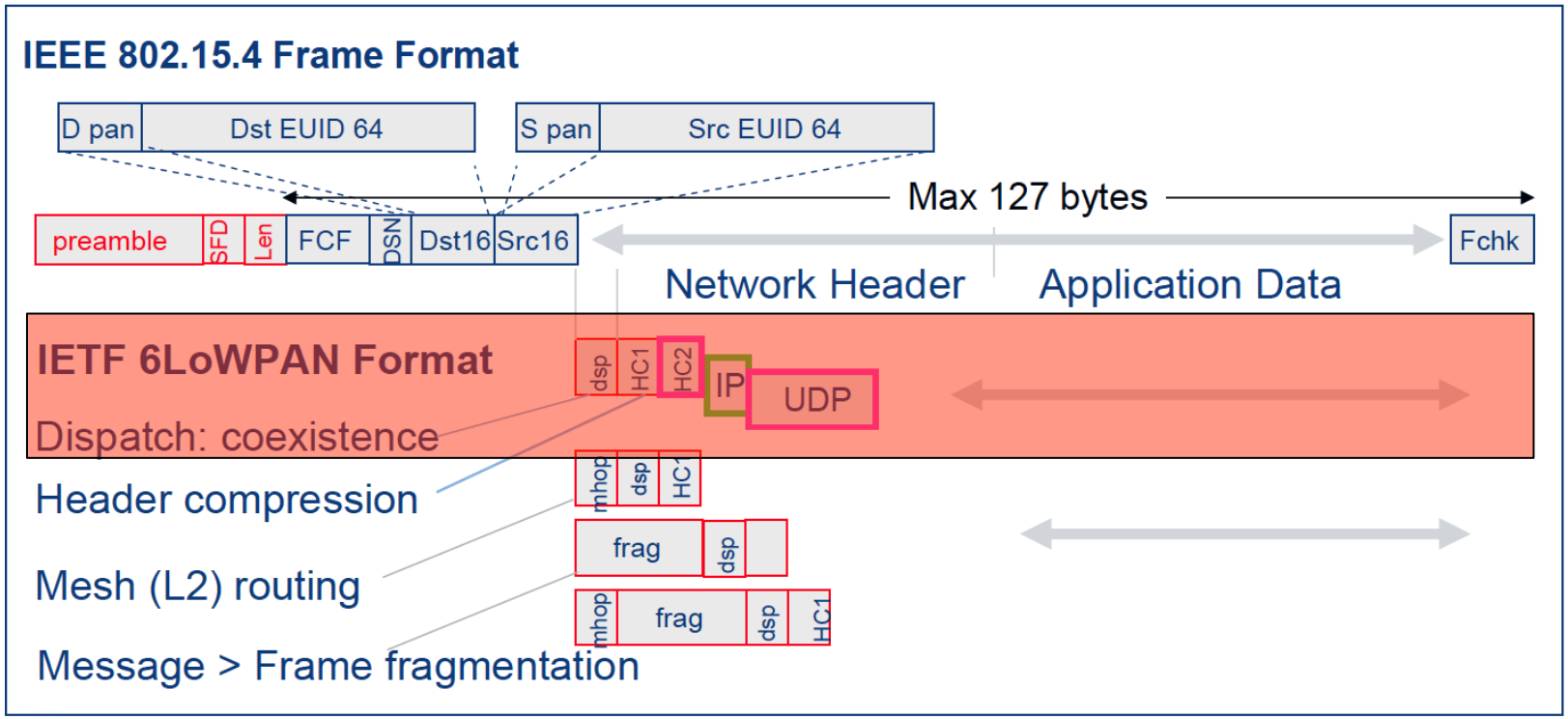
Based from "6LoWPAN: The Wireless Embedded Internet, Shelby & Bormann"



Use RFC4944 compression scheme for simplicity. New scheme should follow RFC6282

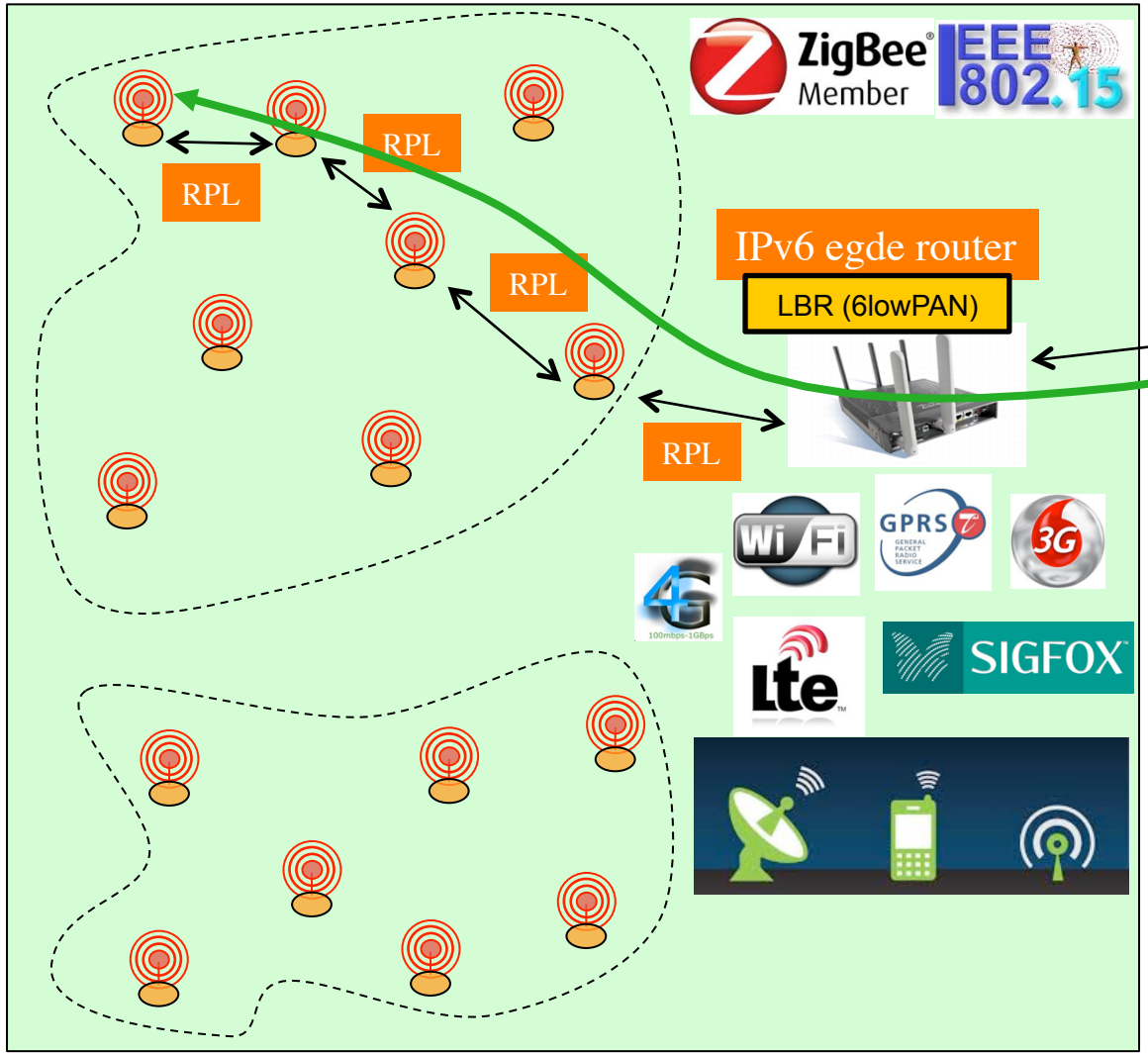
6LoWPAN Format Design

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



From ArchRock "6LowPan tutorial"

Routing over Low Power & Lossy Networks (RPL)



RPL is the 4th protocol standardized by IETF (RIP, OSPF, BGP)

Provides end-to-end IPv6 connectivity

UDP can be used to transport sensor data

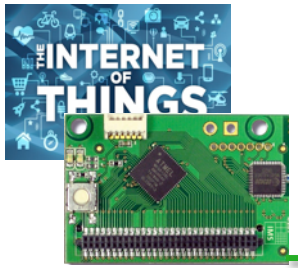
RPL (ripple)
Routing Protocol for Low Power and Lossy Networks

Walkthrough

`draft-dt-roll-rpl-01.txt`

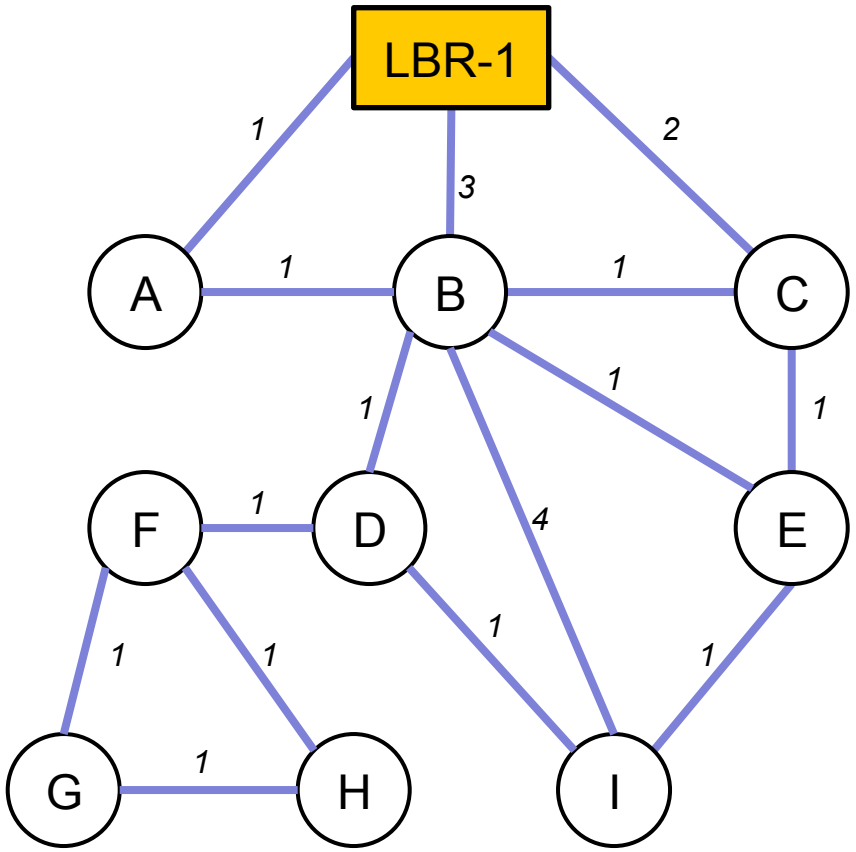
Anders Brandt
Thomas Heide Clausen
Stephen Dawson-Haggerty
Jonathan W. Hui
Kris Pister
Pascal Thubert
Tim Winter

IETF 75 – Roll WG – July 2009



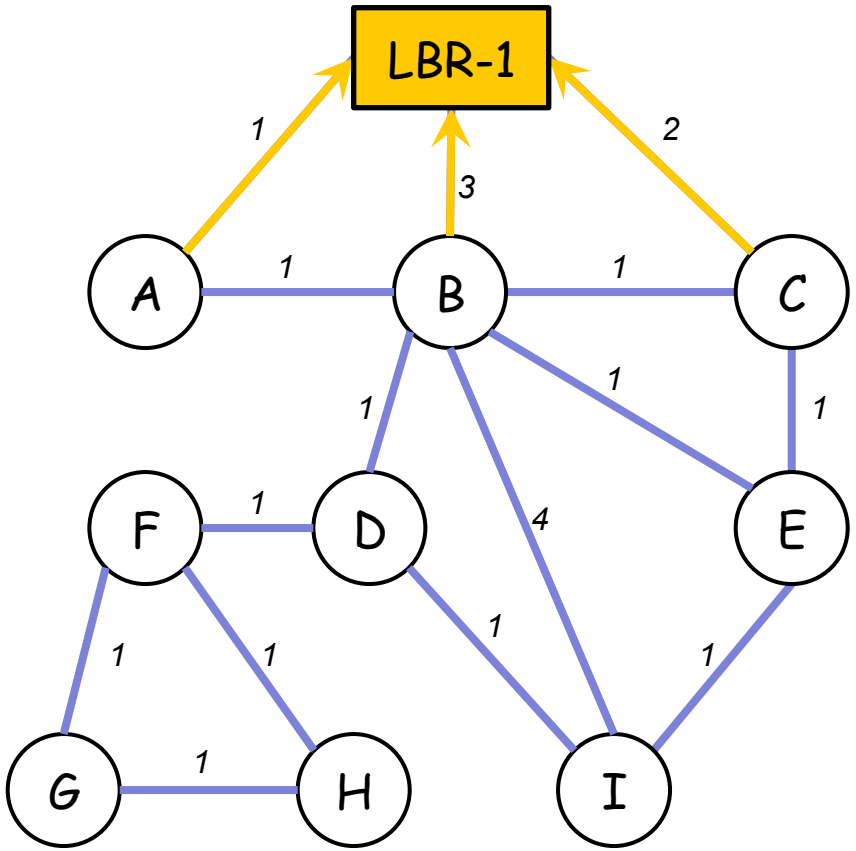
DAG Construction

Low power and lossy network Border Router

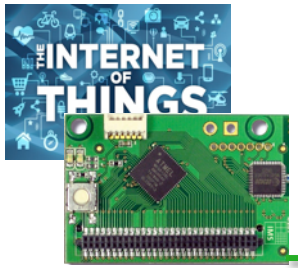


- LLN links are depicted
- LBR form a Destination Object DAG (DODAG)
- Links are annotated w/ ETX (Expected Transmission Count)
- It is expected that ETX variations will be averaged/filtered as per [ROLL-METRICS] to be stable enough for route computation

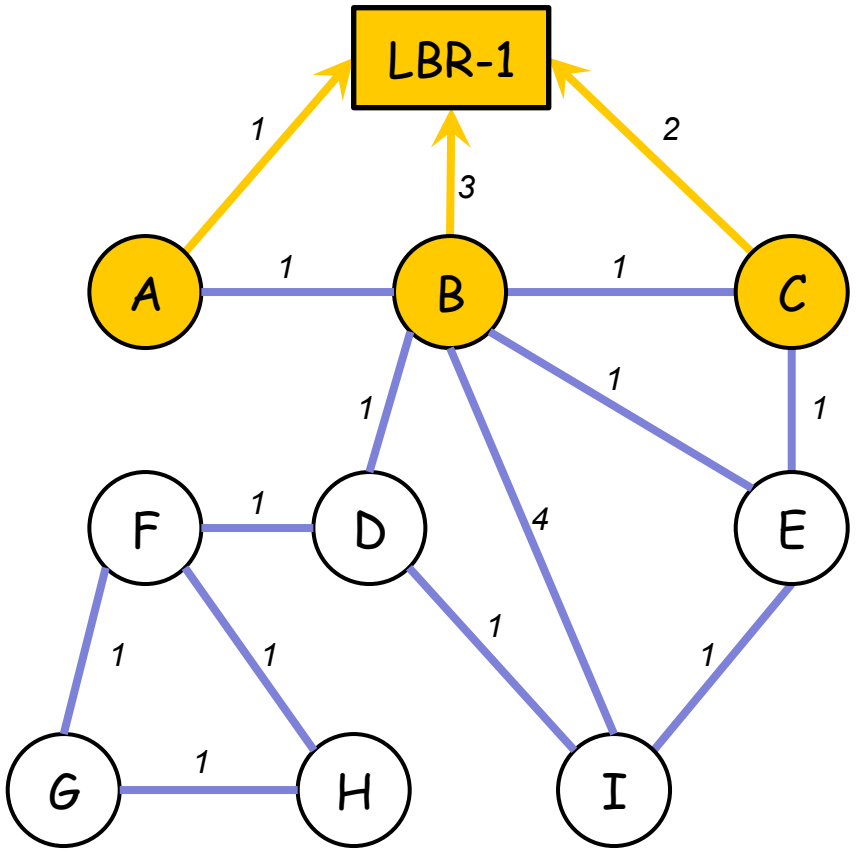
DAG Construction



- LBR-1 multicasts RA-DIO (Router Advertisement DODAG Information Object)
- Nodes A, B, C receive and process RA-DIO
- Nodes A, B, C consider link metrics to LBR-1 and the optimization objective
- The optimization objective can be satisfied by joining the DAG rooted at LBR-1
- Nodes A, B, C add LBR-1 as a DAG parent and join the DAG

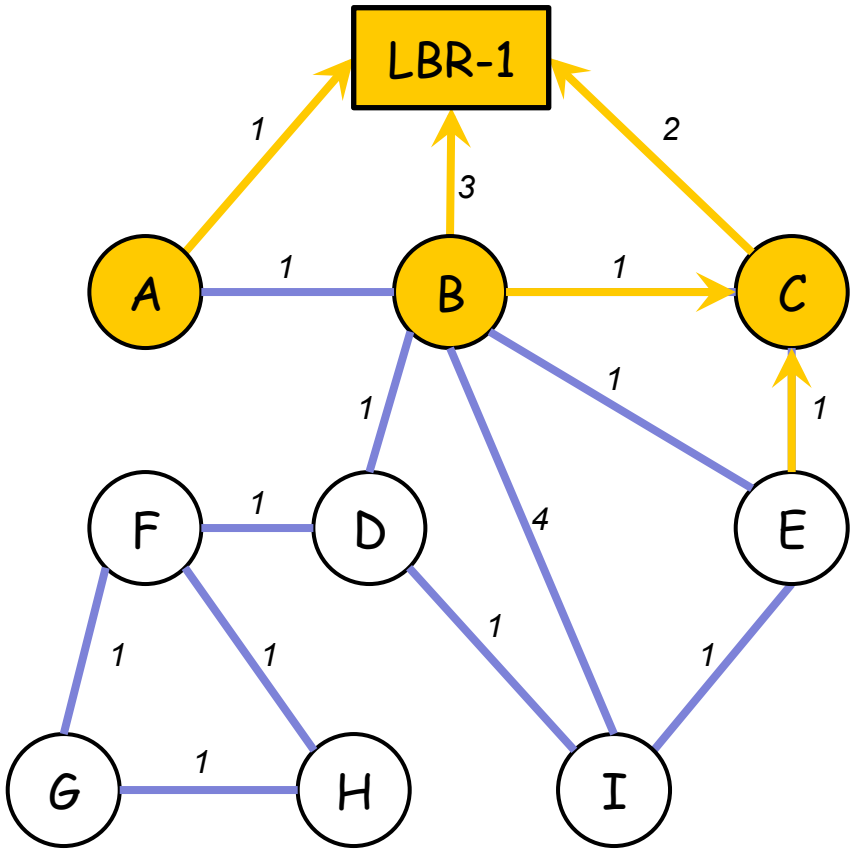


DAG Construction



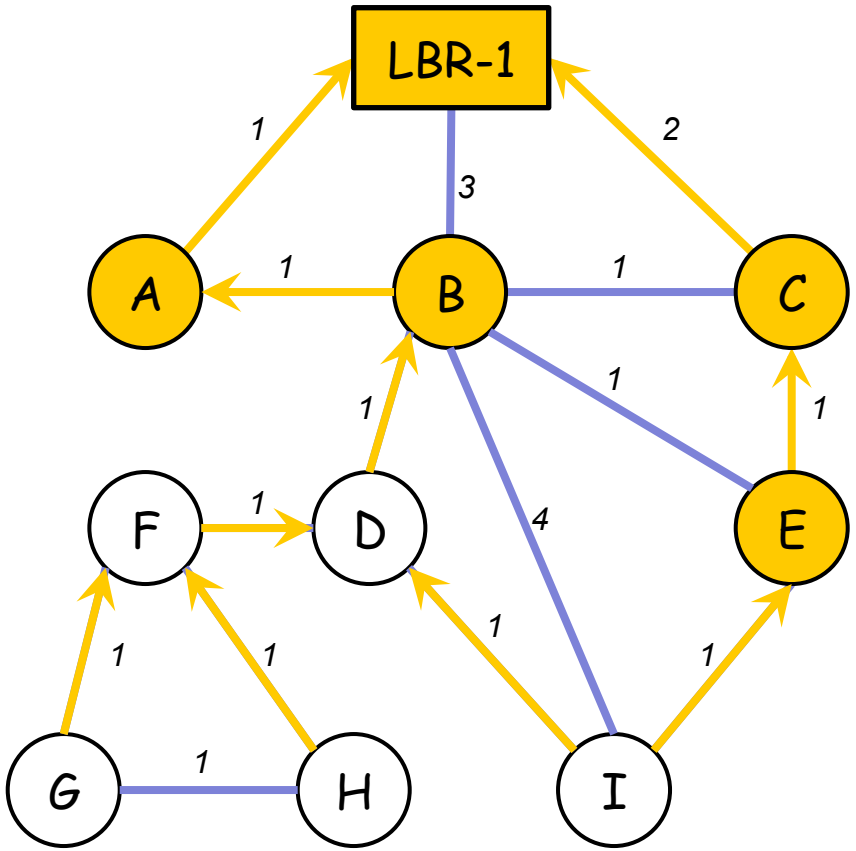
- Node A is at Depth 1 in the DAG, as calculated by the routine indicated by the example OCP (Depth ~ ETX)
- Node B is at Depth 3, Node C is at Depth 2
- Nodes A, B, C have installed default routes (::/0) with LBR-1 as successor

DAG Construction

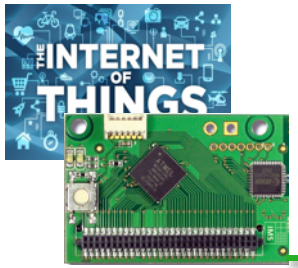


- The RA timer on Node C expires
- Node C multicasts RA-DIO
- LBR-1 ignores RA-DIO from deeper node
- Node B can add Node C as *alternate* DAG Parent, remaining at Depth 3
- Node E joins the DAG at Depth 3 by adding Node C as DAG Parent

DAG Construction



- DAG Construction continues…
- And is continuously maintained



INTERNET FOR THINGS

UDP, TCP?

RPL
Routing Protocol for Low power & Lossy Networks

6LowPan
802.15.4

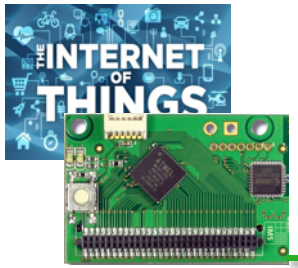
IPv6 egde router

LBR (6lowPAN)

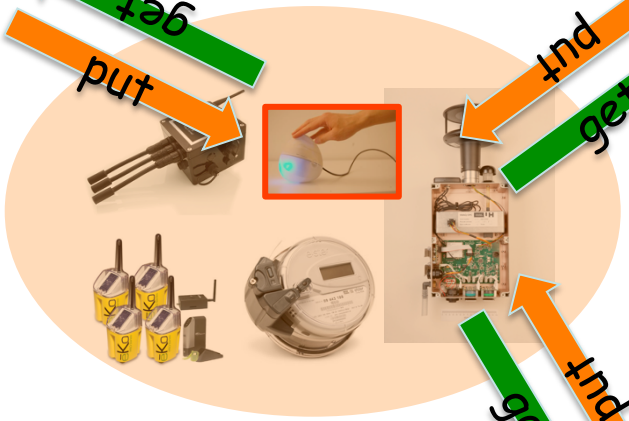
TCP, UDP

Internet Routing Protocols: RIP, OSPF, BGP,…

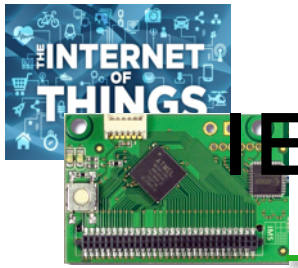
IPv4, IPv6



IoT FOR HUMAN



Internet of Things for you & me



IETF Internet for Things

CoAP: Constrained Application Protocol

UDP, TCP?

RPL
Routing Protocol for Low power & Lossy Networks

6LowPan
802.15.4

IPv6 egde router

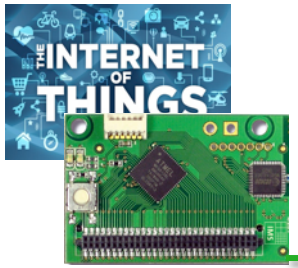
LBR (6lowPAN)

CoAP HTTP

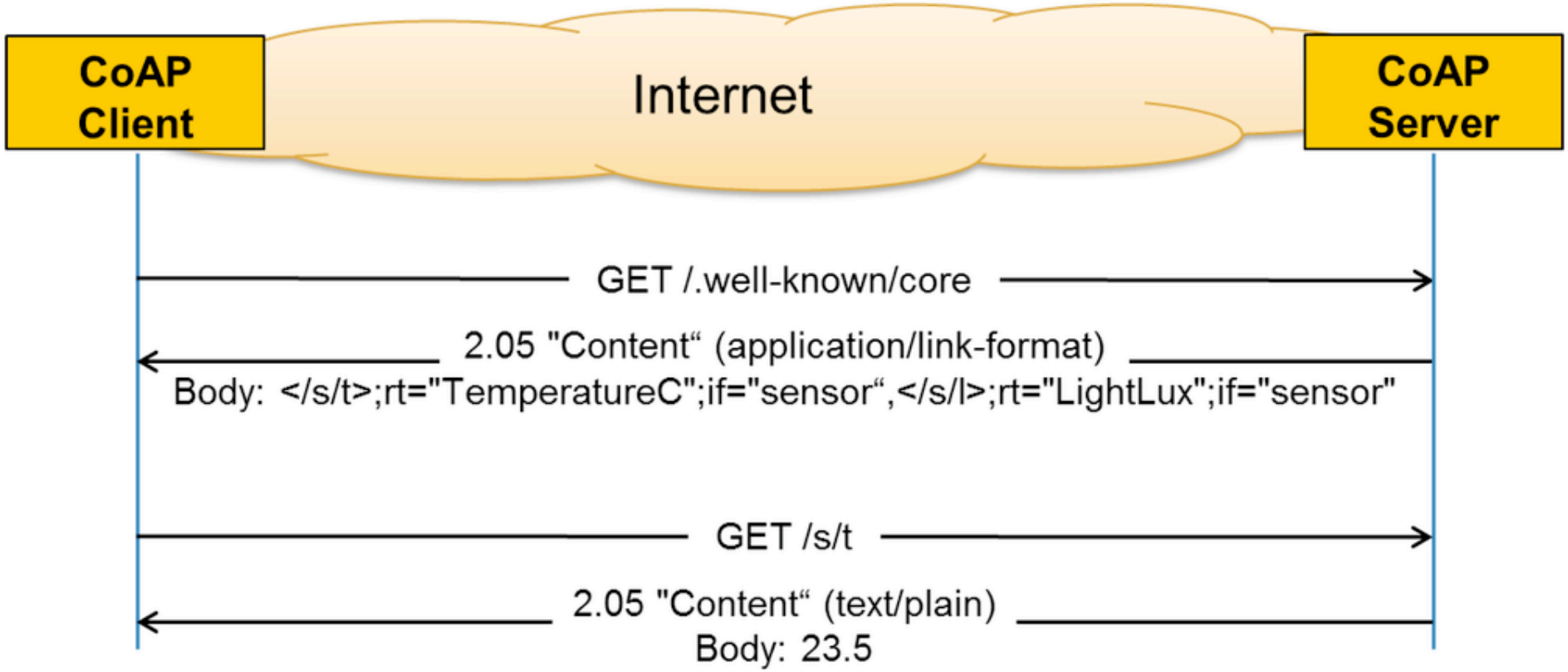
TCP, UDP

Internet Routing Protocols: RIP, OSPF, BGP,…

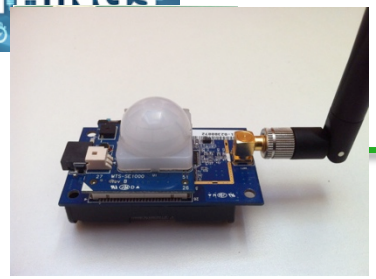
IPv4, IPv6



DATA = RESOURCES

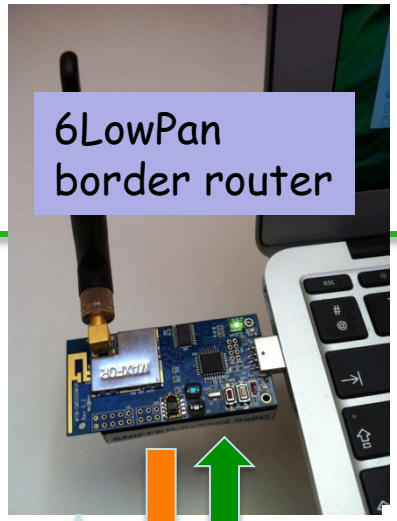


From Isam Ishaq et al. "Flexible Unicast-Based Group Communication for CoAP-Enabled Devices", MDPI *Sensors* **2014**, *14*(6), 9833-9877



get

ack



6LowPan
border router

CoAP/6LowPan/IEEE 802.15.4

RPL routing

ack

get

IPv6

Wi Fi

Client/User-
initiated scenario
(e.g. temp. sensor)

INTERNET

ack

IPv6

get

to actuators

112	106.575520000	fe80::212:6d45:50b7:6a0f	fe80::212:6d45:5026:34cc	ICMPv6	94	RPL Control (Destination Advertisement Object),
113	106.576064000			IEEE 802.15.4	5	Ack, Bad FCS
114	106.576608000			IEEE 802.15.4	5	Ack, Bad FCS
115	113.692576000	fe80::212:6d45:50b7:7575	fe80::212:6d45:5026:34cc	ICMPv6	94	RPL Control (Destination Advertisement Object),
116	114.080416000	fe80::212:6d45:50b7:7575	[illegible]	ICMPv6	94	RPL Control (Destination Advertisement Object),
117	114.[illegible]			IEEE 802.15.4	5	Ack, Bad FCS
118	116.008352000	2001:620:607:5b10::a	::ff:fe00:28	COAP	60	Confirmable, GET, End of Block #15, Bad FCS
119	116.008896000			IEEE 802.15.4	5	Ack, Bad FCS
120	116.292576000	::ff:fe00:28	2001:620:607:5b10::a	COAP	65	Acknowledgement, 2.05 Content, End of Block #[illegible]
121	116.[illegible]			IEEE 802.15.4	5	Ack, Bad FCS
122	116.544800000	fe80::212:6d45:50b7:[illegible]	[illegible]	[illegible]	94	RPL Control (Destination Advertisement Object),
123	116.545344000			IEEE 802.15.4	5	Ack, Bad FCS
124	116.545888000			IEEE 802.15.4	5	Ack, Bad FCS
125	116.546432000			IEEE 802.15.4	5	Ack, Bad FCS
126	121.702624000	fe80::212:6d45:50b7:7e21	fe80::212:6d45:5026:34cc	ICMPv6	94	RPL Control (Destination Advertisement Object),
127	121.703168000			IEEE 802.15.4	5	Ack, Bad FCS
128	123.968480000	fe80::212:6d45:50b7:7575	fe80::212:6d45:5026:34cc	ICMPv6	94	RPL Control (Destination Advertisement Object),
129	123.969024000			IEEE 802.15.4	5	Ack, Bad FCS
130	127.058048000	fe80::212:6d45:50b7:69b3	fe80::212:6d45:50b7:6a0f	ICMPv6	94	RPL Control (Destination Advertisement Object),
131	127.058592000			IEEE 802.15.4	5	Ack, Bad FCS
132	127.344416000	fe80::212:6d45:50b7:6a0f	fe80::212:6d45:5026:34cc	ICMPv6	94	RPL Control (Destination Advertisement Object),

RPL and CoAP exchanges

Browse and run installed applications

k 1.7.2 (SVN Rev 42506 from /trunk)]

File Edit View Go Capture Analyze Statistics Telephony Tools Internals Help

Filter: Expression... Clear Apply Save

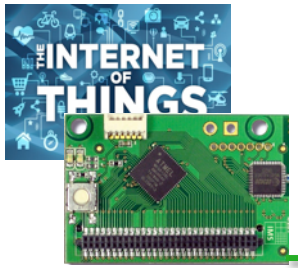
No.	Time	Source	Destination	Protocol	Length	Info	SN	Time
1	0.000000000	0x0078	0x0000	IEEE 802.15.4	35	Data, Dst: 0x0000, Src: 0x0078, Bad FC	1	0.000000000
2	3.253408000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	55	3.253408000
3	3.253952000			IEEE 802.15.4	5	Ack, Bad FCS	55	0.000544000
4	13.642912000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	56	10.388960000
5	13.643456000			IEEE 802.15.4	5	Ack, Bad FCS	56	0.000544000
6	24.023584000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	57	10.380128000
7	24.024128000			IEEE 802.15.4	5	Ack, Bad FCS	57	0.000544000
8	25.457824000	::ff:fe00:100	::ff:fe00:3	COAP	39	Confirmable, PUT (text/plain), Bad FCS	12	1.433696000
9	25.458368000			IEEE 802.15.4	5	Ack, Bad FCS	12	0.000544000
10	25.479296000	::ff:fe00:3	::ff:fe00:100	COAP	41	Acknowledgement, 2.04 Changed (text/pl	58	0.020928000
11	25.479840000			IEEE 802.15.4	5	Ack, Bad FCS	58	0.000544000
12	34.462976000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	59	8.983136000
13	34.463520000			IEEE 802.15.4	5	Ack, Bad FCS	59	0.000544000
14	45.451072000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	60	10.987552000
15	45.451616000			IEEE 802.15.4	5	Ack, Bad FCS	60	0.000544000
16	56.289696000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	61	10.838080000
17	56.290240000			IEEE 802.15.4	5	Ack, Bad FCS	61	0.000544000
18	64.688096000	::ff:fe00:100	::ff:fe00:3	COAP	37	Confirmable, PUT (text/plain), Bad FCS	13	8.397856000
19	64.688640000			IEEE 802.15.4	5	Ack, Bad FCS	13	0.000544000
20	64.707744000	::ff:fe00:3	::ff:fe00:100	COAP	39	Acknowledgement, 2.04 Changed (text/pl	62	0.019104000
21	64.708288000			IEEE 802.15.4	5	Ack, Bad FCS	62	0.000544000
22	66.698080000	fe80::212:6d45:50cc:16b4	fe80::ff:fe00:1	ICMPv6	88	RPL Control (Destination Advertisement	63	1.989792000

▸ Frame 1: 35 bytes on wire (280 bits), 35 bytes captured (280 bits) on interface 0
▸ IEEE 802.15.4 Data, Dst: 0x0000, Src: 0x0078, Bad FCS
▸ Data (24 bytes)

```
0000  41 88 01 34 12 00 00 78  00 3f 00 77 69 72 65 73   A..4...x .?.wires
0010  68 61 72 6b 20 66 6f 6e  63 74 69 6f 6e 6e 65 20   hark fon ctionne
0020  21 ab 00                                          !..
```

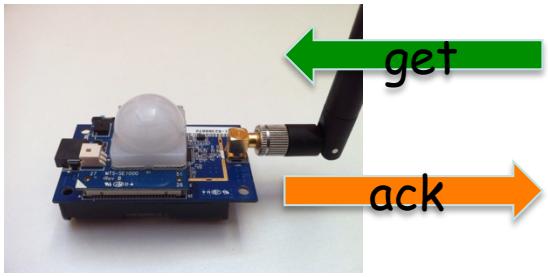
File: "/tmp/wireshark_-_20140327... ... Profile: Default

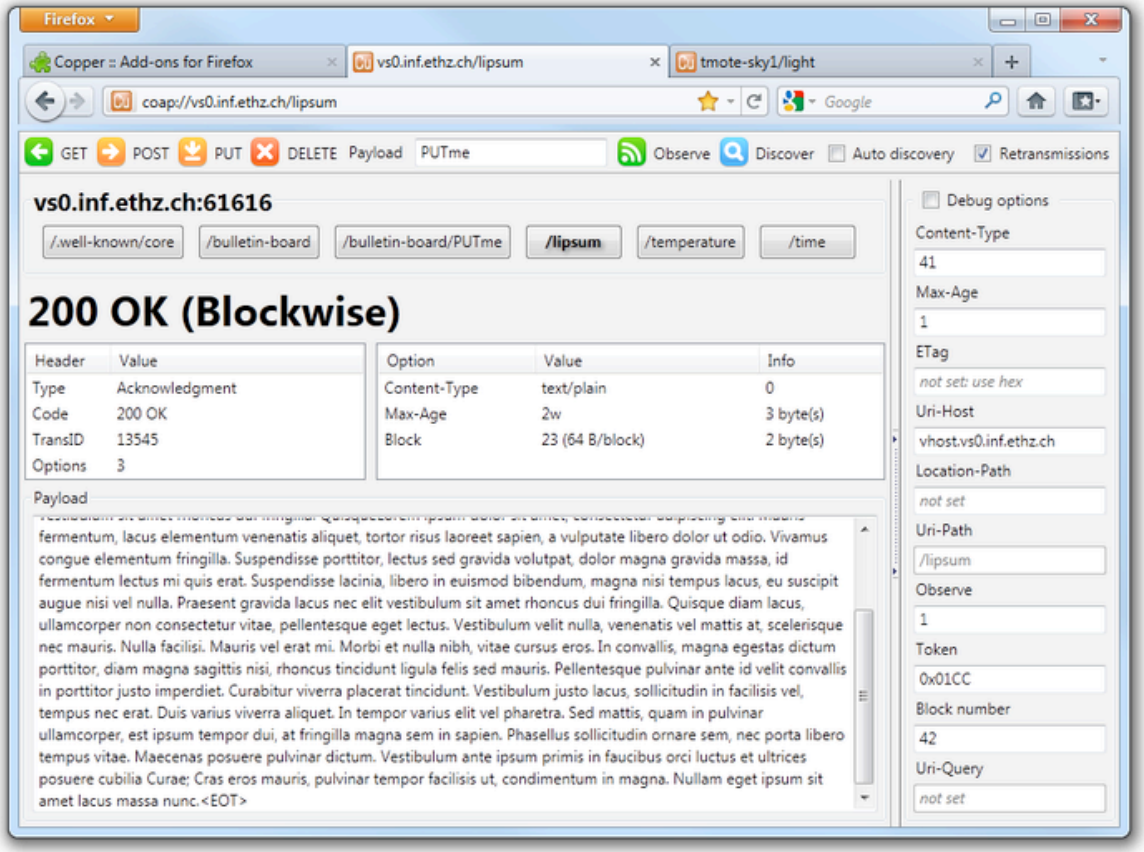
user@instant-contiki: ... Standard input [Wire...

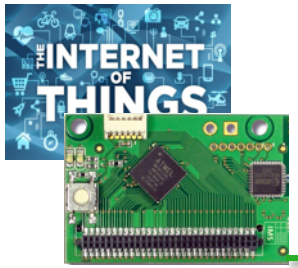


Copper for Firefox

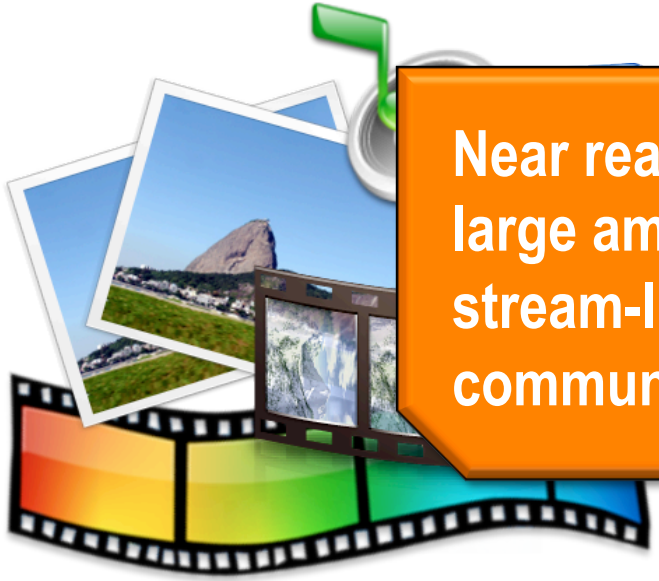
- CoAP pluggin to query CoAP nodes in an http-like fashion







Towards Multimedia Information



Near real-time constraints, large amount of data, stream-like communication,…

Search & Rescue, Situation awareness

EAR-IT: audio surveillance in SmartCities and SmartBuildings

Play/store received Audio data

See http://www.ear-it.eu

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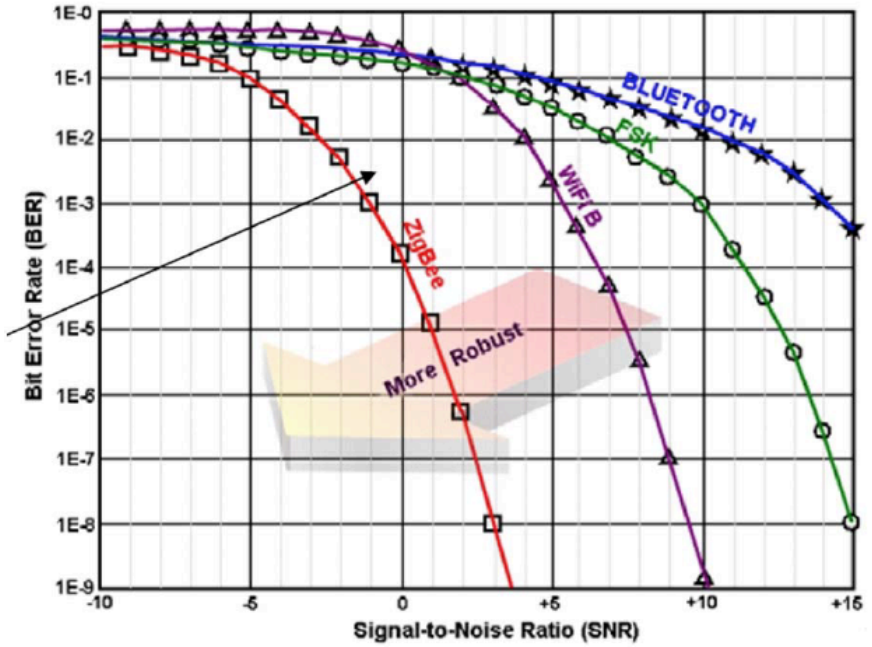
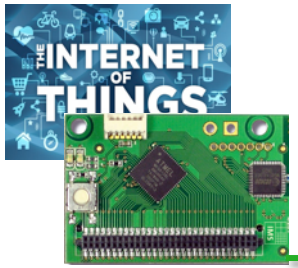
IEEE 802.15.4 in ISM 2.4GHz

- Low-power radio in the 2.4GHz band offering 250kbps throughput at physical layer
- Power transmission from 1mW to 100mW for range from 100m to about 1km is LOS
- CSMA/CA (beacon & non beacon)
- Used as physical layer in ZigBee



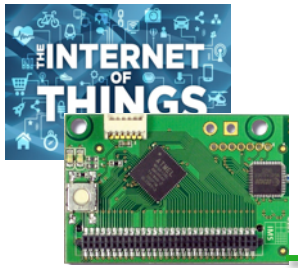


Communication performances

- Application level performances depends on OS, API, hardware architecture
- Usually much lower than radio performances!
- What are min. latencies & max. throughput?
  - For sending?
  - For receiving?
  - For relaying?

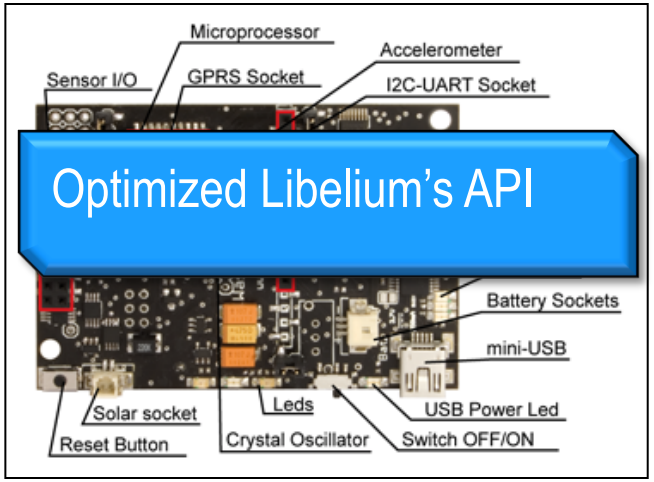
C. Pham, "Communication performance of low-resource sensor motes for data-intensive applications ", Proceedings of the IFIP Wireless Days International Conference (WD'2013), Valencia, Spain, November 2013.

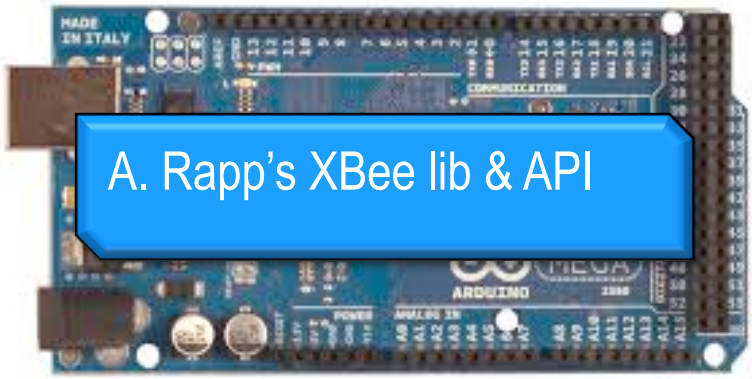
C. Pham, "Communication performances of IEEE 802.15.4 wireless sensor motes for data-intensive applications: a comparison of WaspMote, Arduino MEGA, TelosB, MicaZ and iMote2 for image surveillance", Journal of Network and Computer Applications (JNCA), Elsevier, Vol. 46, Nov. 2014



Sensor's HW&SW

Libelium WaspMote



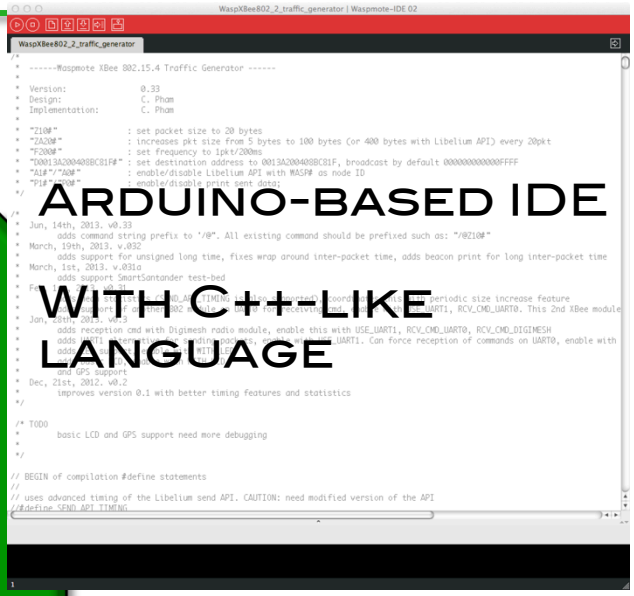


Arduino Mega2560

UART-based connection to micro-controller

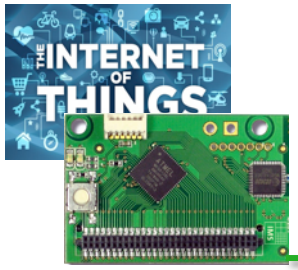
Default speed is usually 38400 bauds

Higher baud rate are possible but…

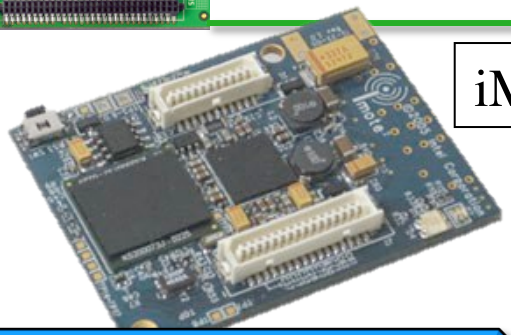


Arduino-based IDE with C++-like language

XBee 802.15.4



« Academic » sensors



iMote2

8MHz Atmega128L
4kB SRAM, 128kB Flash
CC2420 radio

13-416MHz PXA271 X
Wireless MMX DSP
256kB SRAM, 32MB
32MB SDRAM
CC2420 radio

Radio module

Motes are programmed under the TinyOS or the Contiki operating system & lib

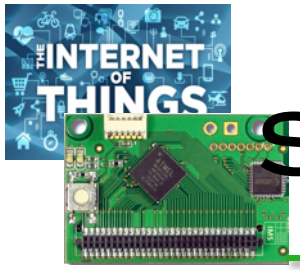
AdvanticSys CM5000 & CM3000
TelosB-like mote

iMote2 with IMB400 multimedia board

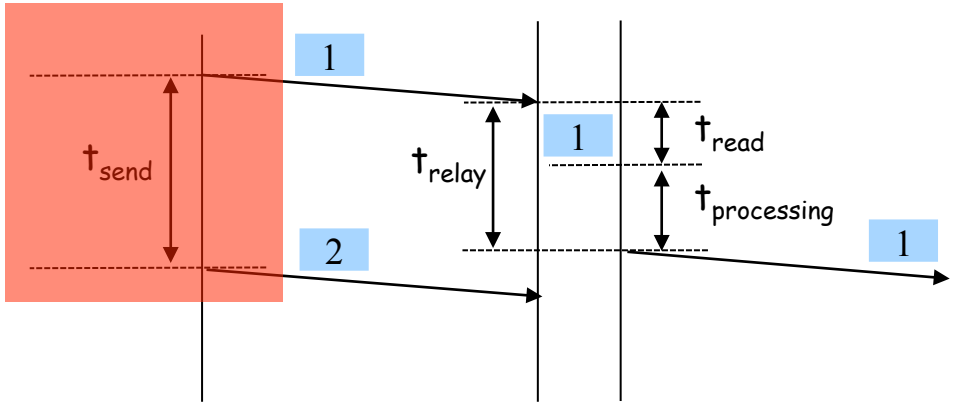
hundredth kbps

TelosB

8Mhz MSP430F1611
10K SRAM, 48K flash
CC2420 radio



Sending performances



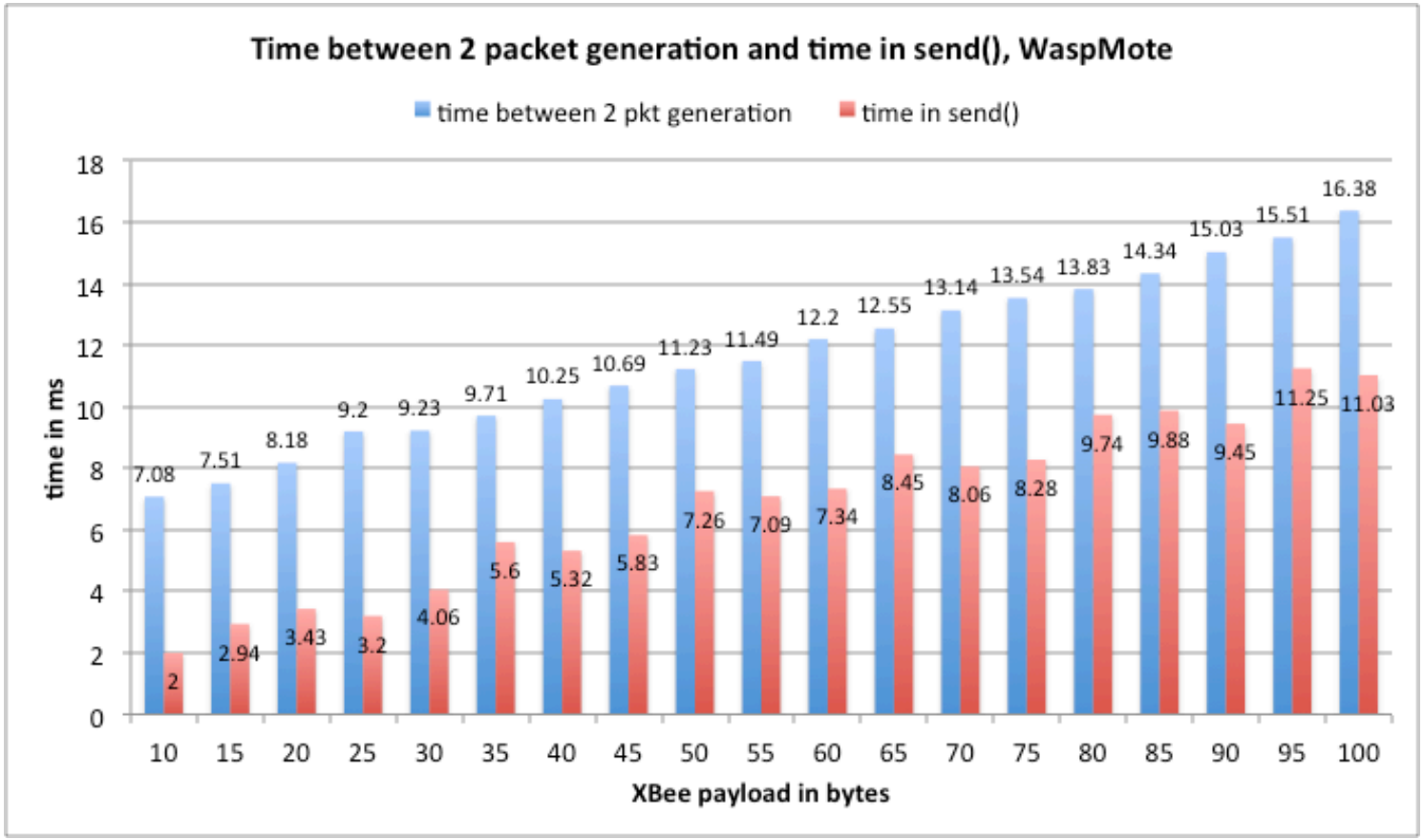
Traffic Generator

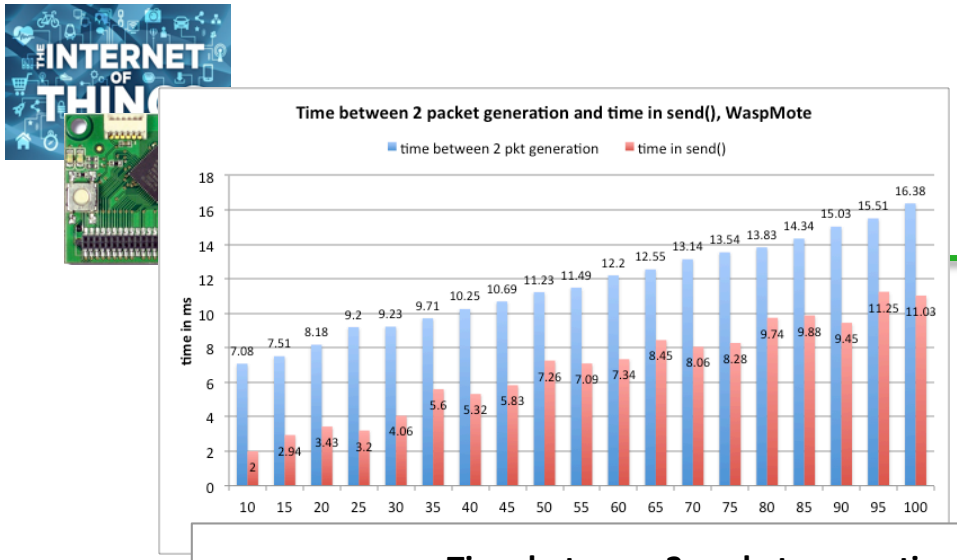
```
void loop() {
        T0;
        L0=T0;
        ...
        T1;
        send(buf);
        T2;
        ...
}
```

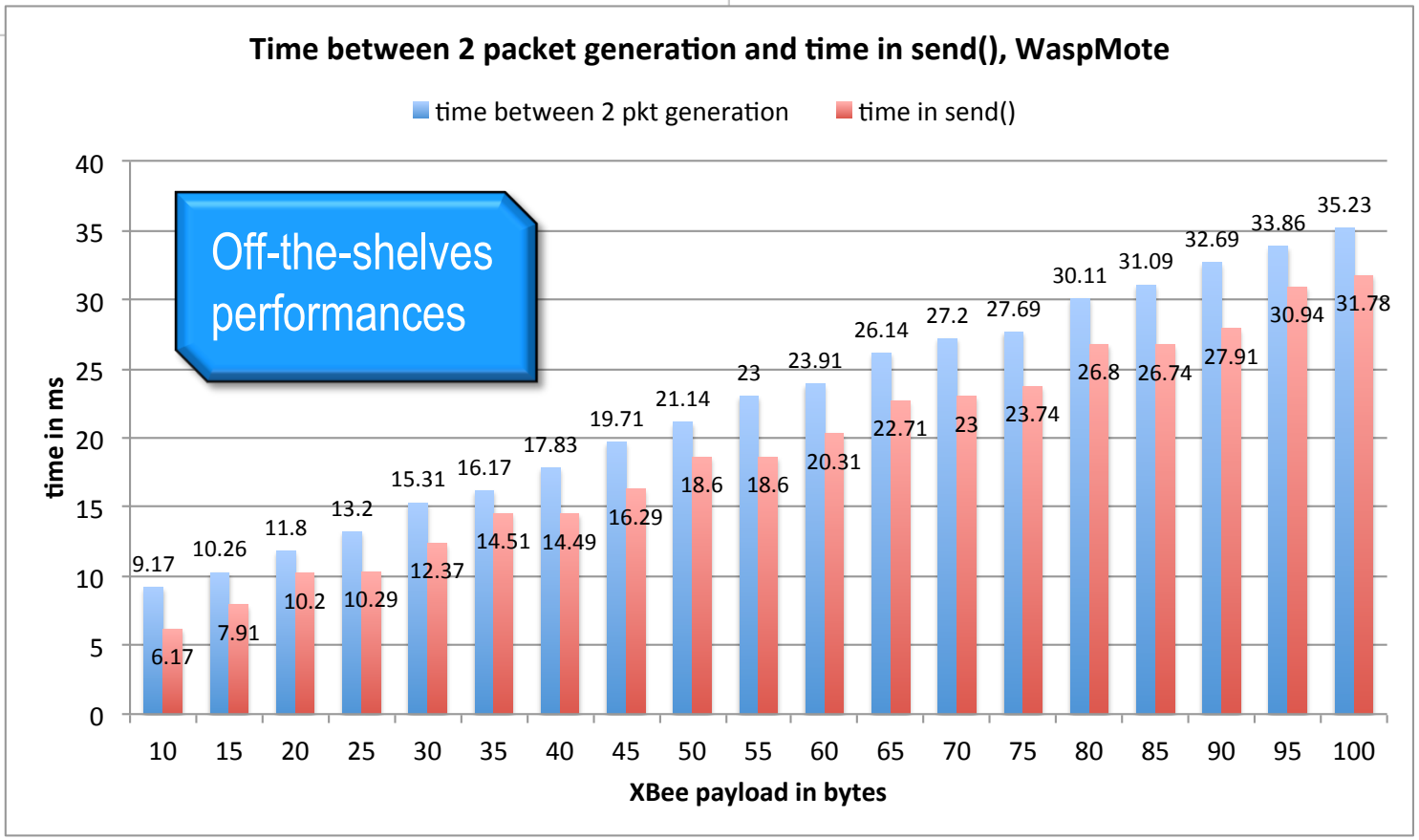
« Time in send() » is T2-T1
« Time between 2 pkt generation » is T0-L0
Time resolution is millisecond
Minimum data manipulation

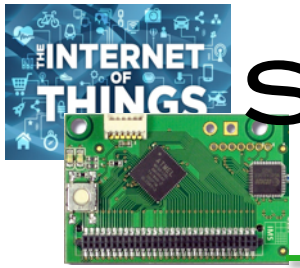
Measure the time in various part of API `send()` when possible.

Sending performances

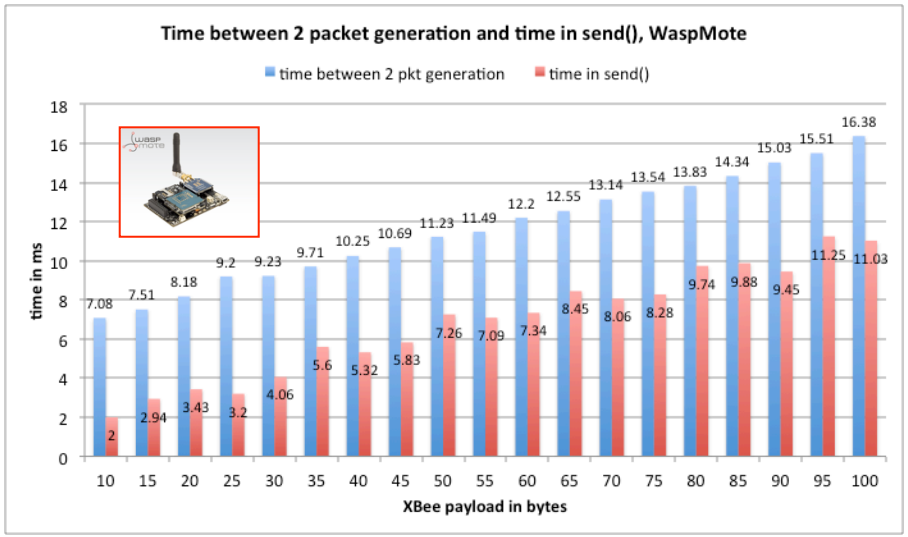


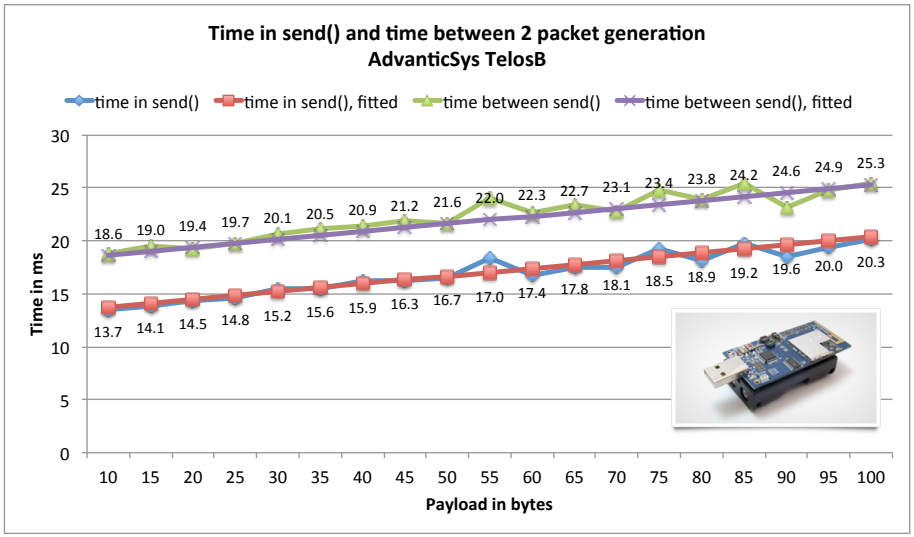

Time between 2 packet generation and time in send(), WaspMote
time between 2 pkt generation
time in send()
time in ms
7.08 2
7.51 2.94
8.18 3.43
9.2 3.2
9.23 4.06
9.71 5.6
10.25 5.32
10.69 5.83
11.23 7.26
11.49 7.09
12.2 7.34
12.55 8.45
13.14 8.06
13.54 8.28
13.83 9.74
14.34 9.88
15.03 9.45
15.51 11.25
16.38 11.03
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

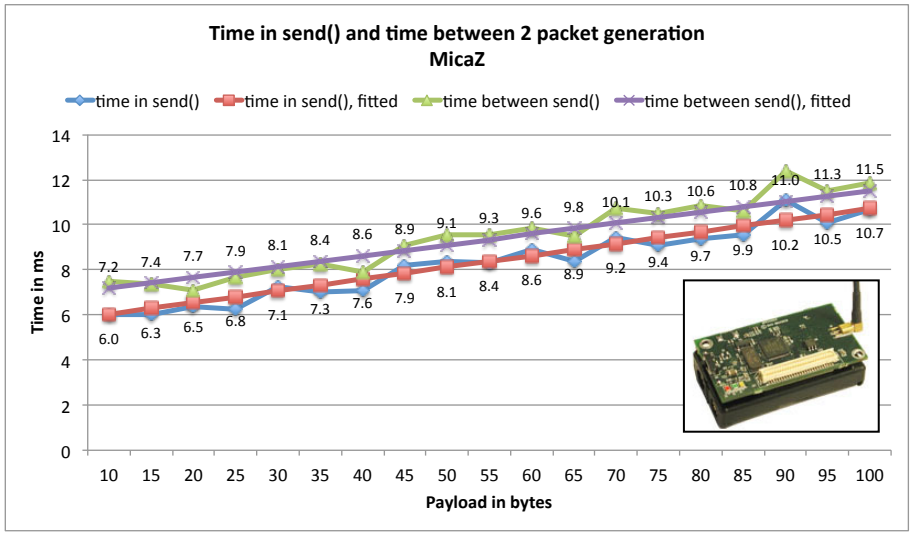

Time between 2 packet generation and time in send(), WaspMote
time between 2 pkt generation
time in send()
Off-the-shelves performances
time in ms
9.17 6.17
10.26 7.91
11.8 10.2
13.2 10.29
15.31 12.37
16.17 14.51
17.83 14.49
19.71 16.29
21.14 18.6
23 18.6
23.91 20.31
26.14 22.71
27.2 23
27.69 23.74
30.11 26.8
31.09 26.74
32.69 27.91
33.86 30.94
35.23 31.78
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
XBee payload in bytes

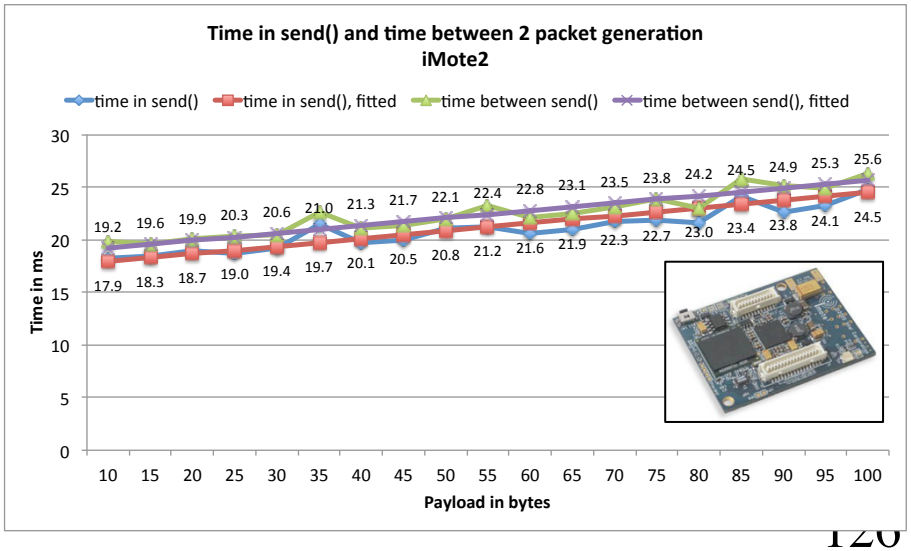


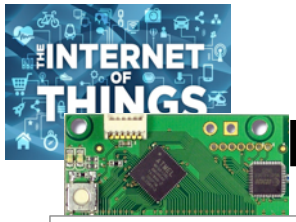
Sending performances: comparison



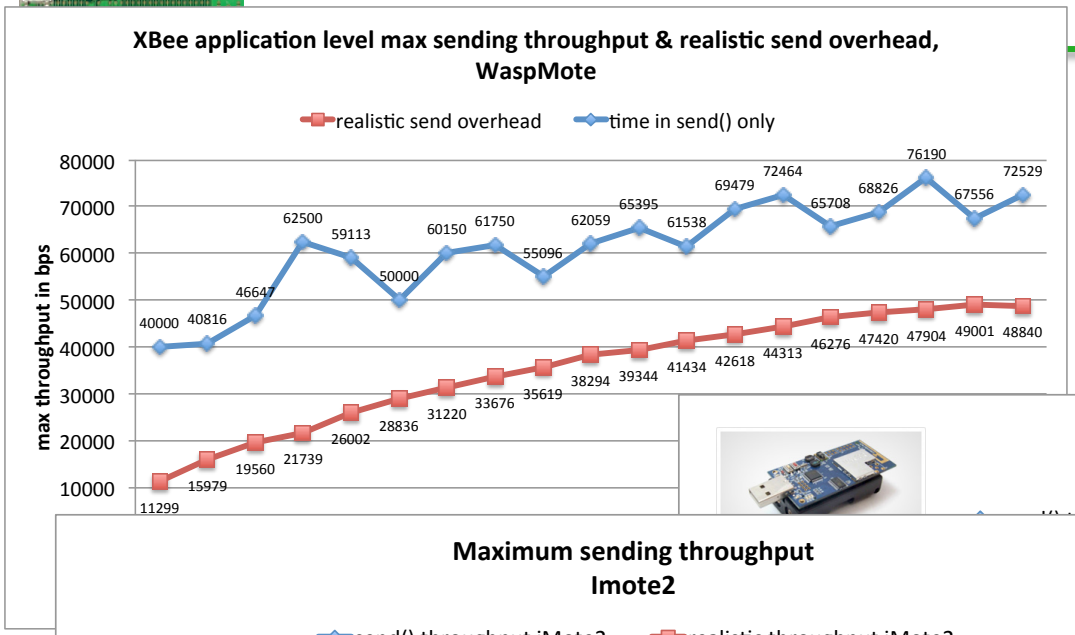


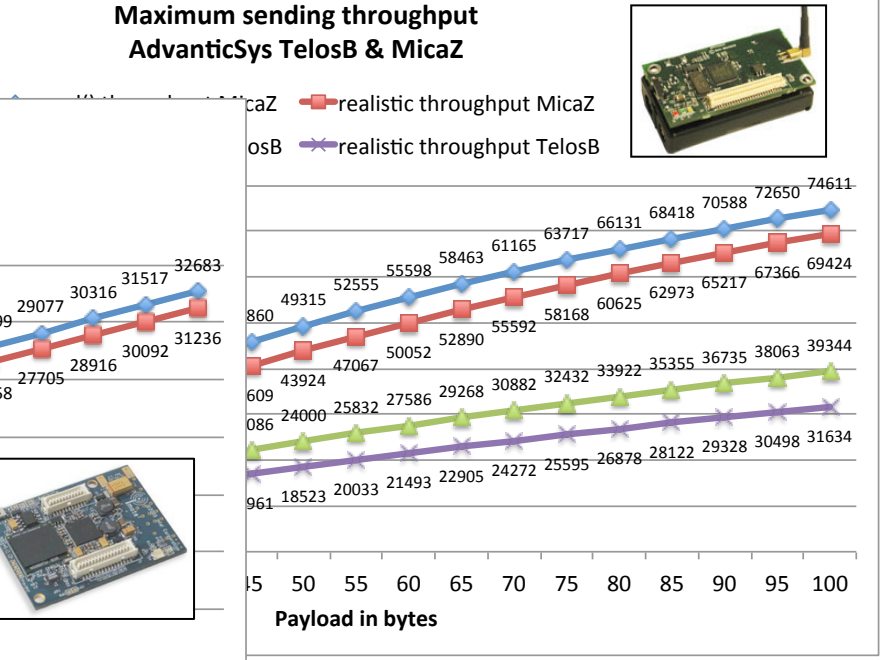


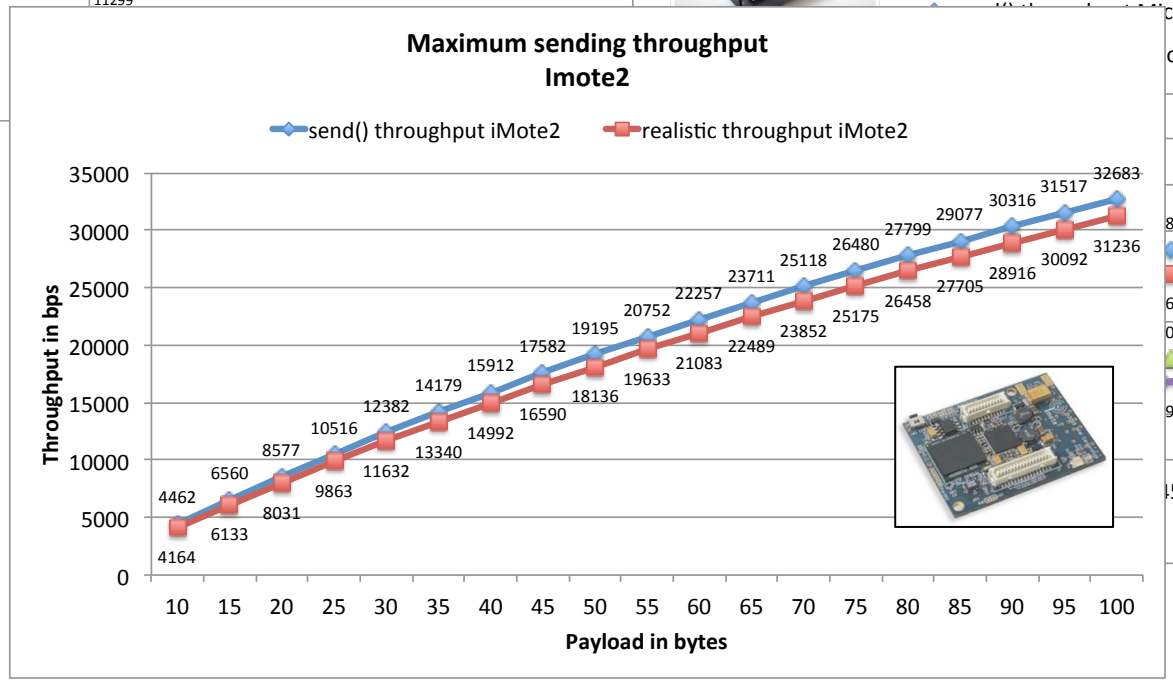




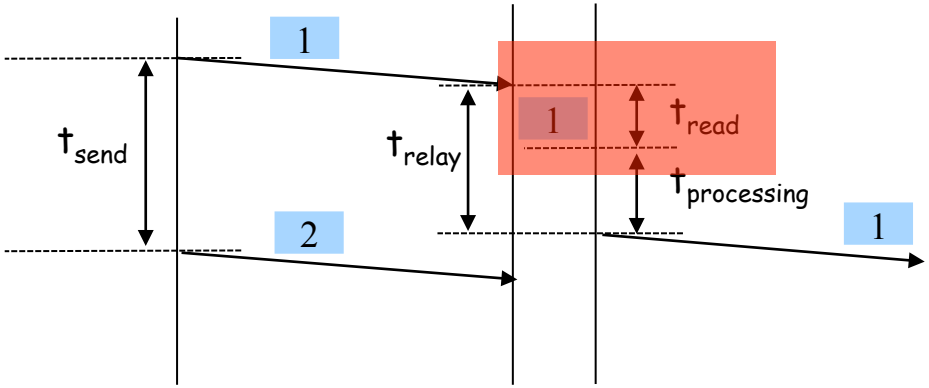
MAXIMUM SENDING THROUGHPUT



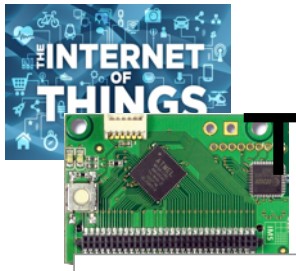




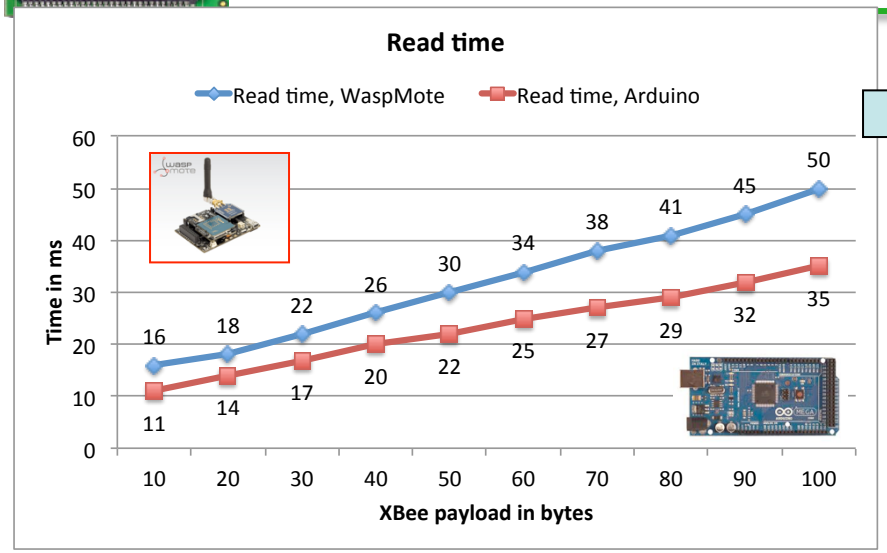
Receive performances

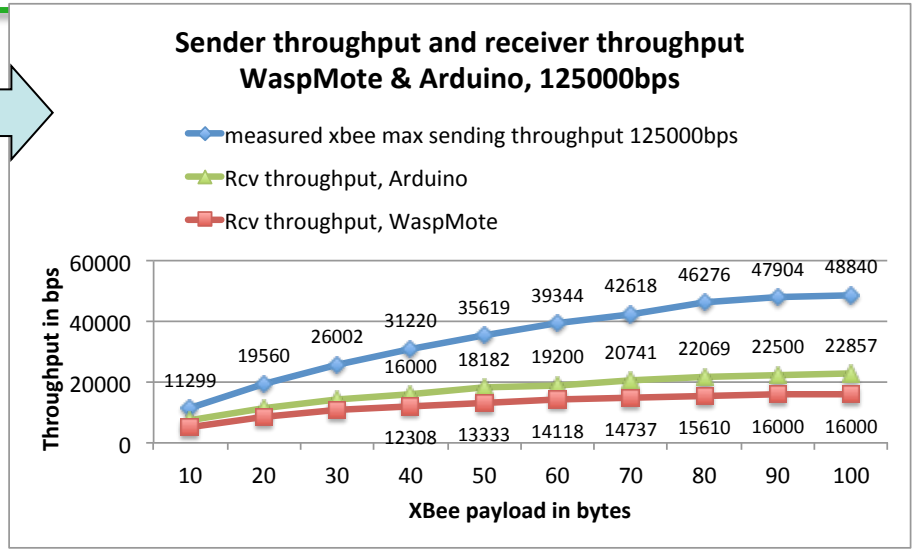


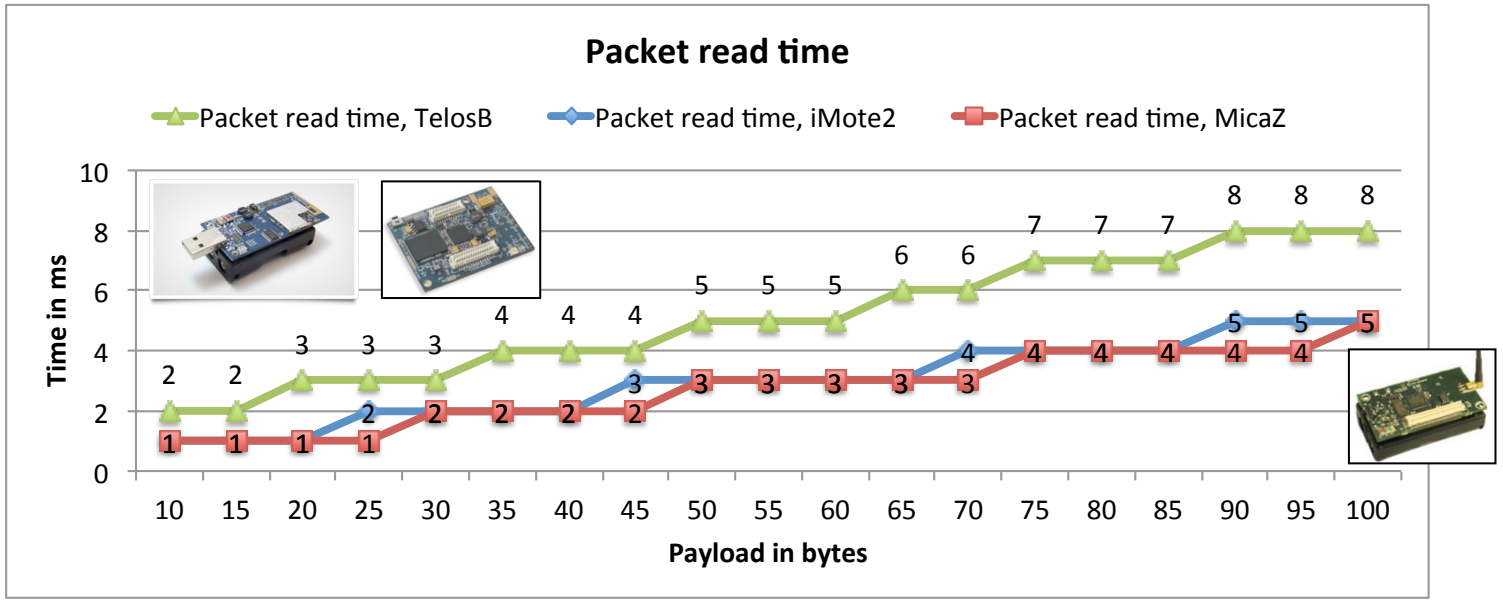
- At sender side, send as fast as possible
- At receiver side, determine t_{read}
- … And also compute the maximum receive throughput per packet size

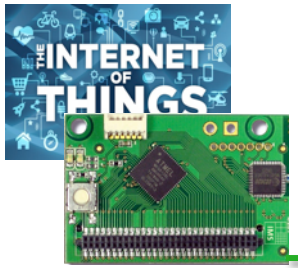


T READ FOR VARIOUS MOTES

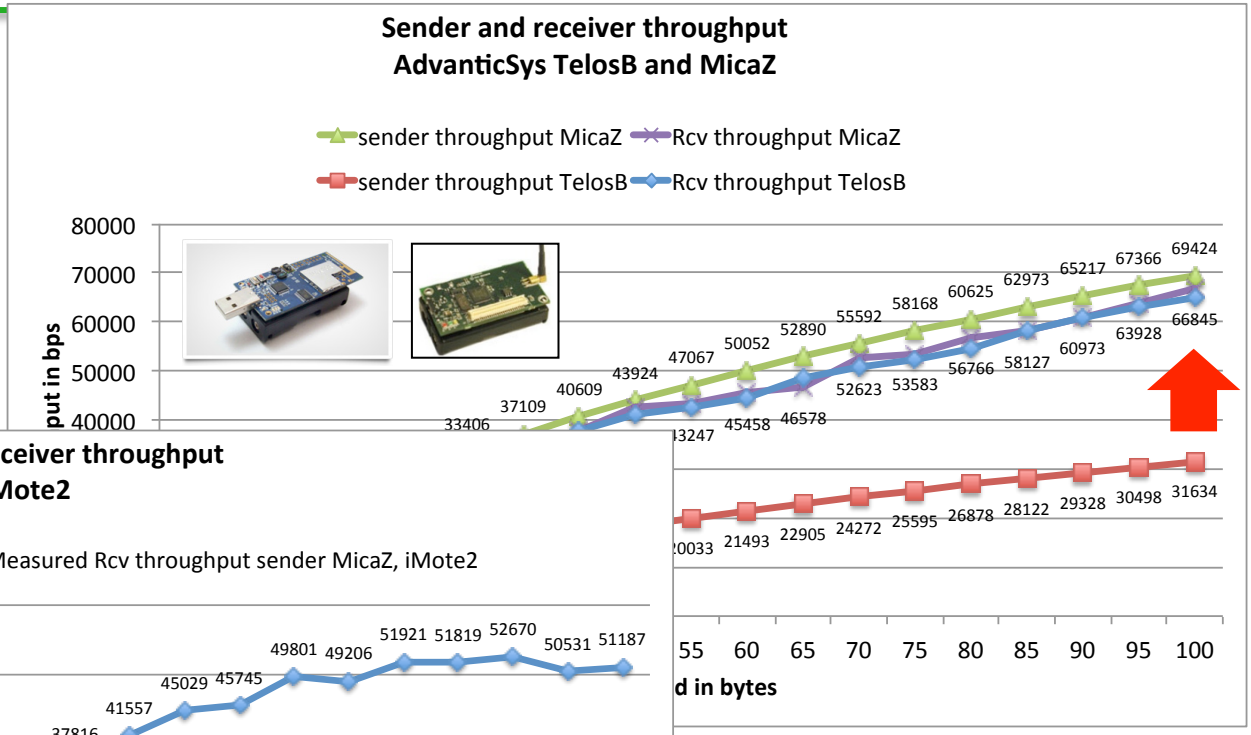


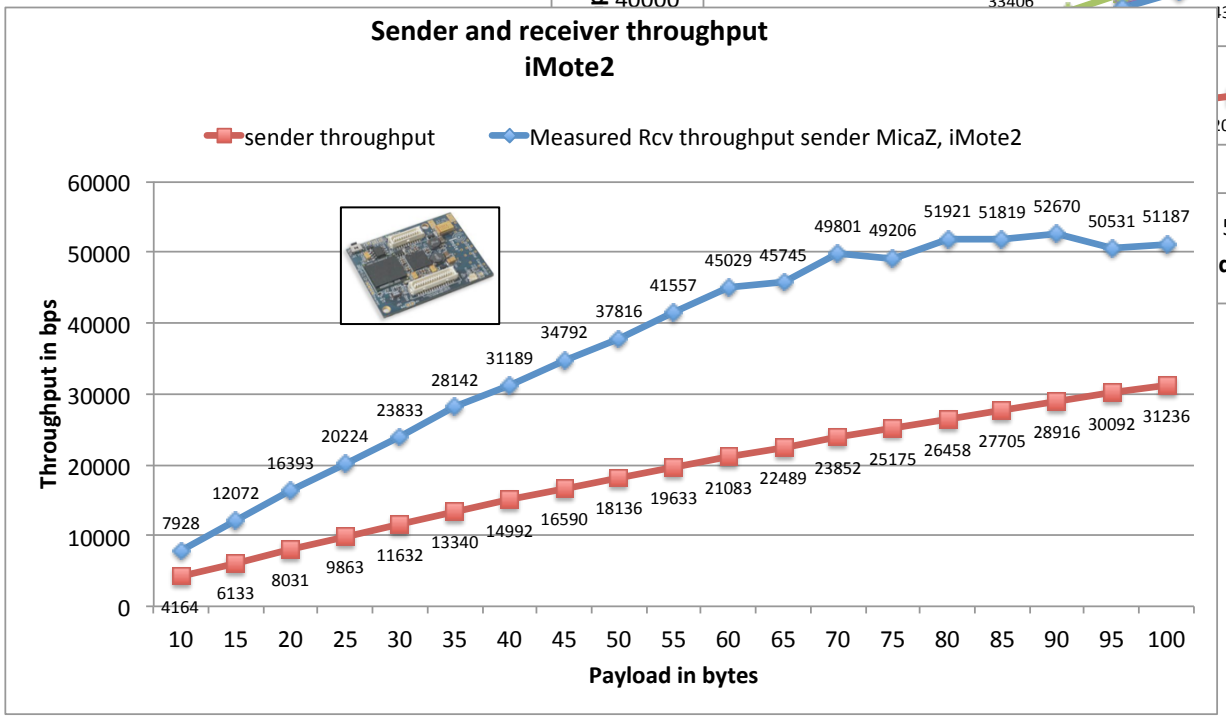


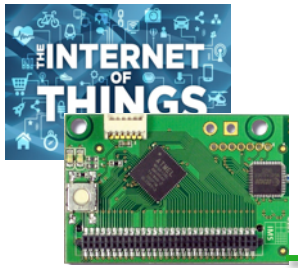




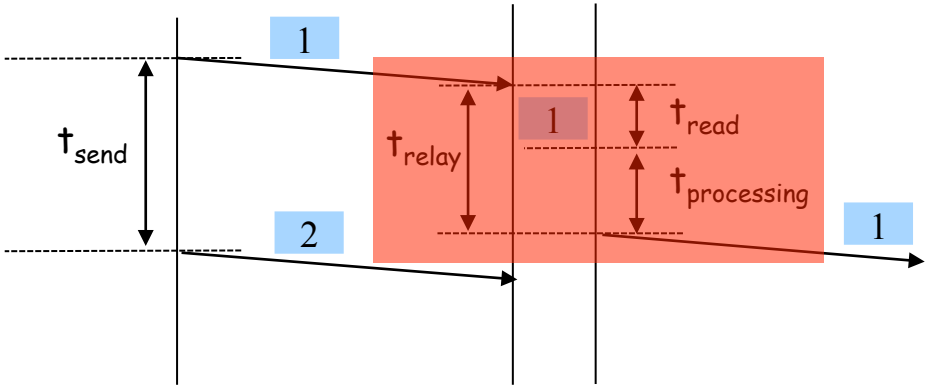
Receiver throughput





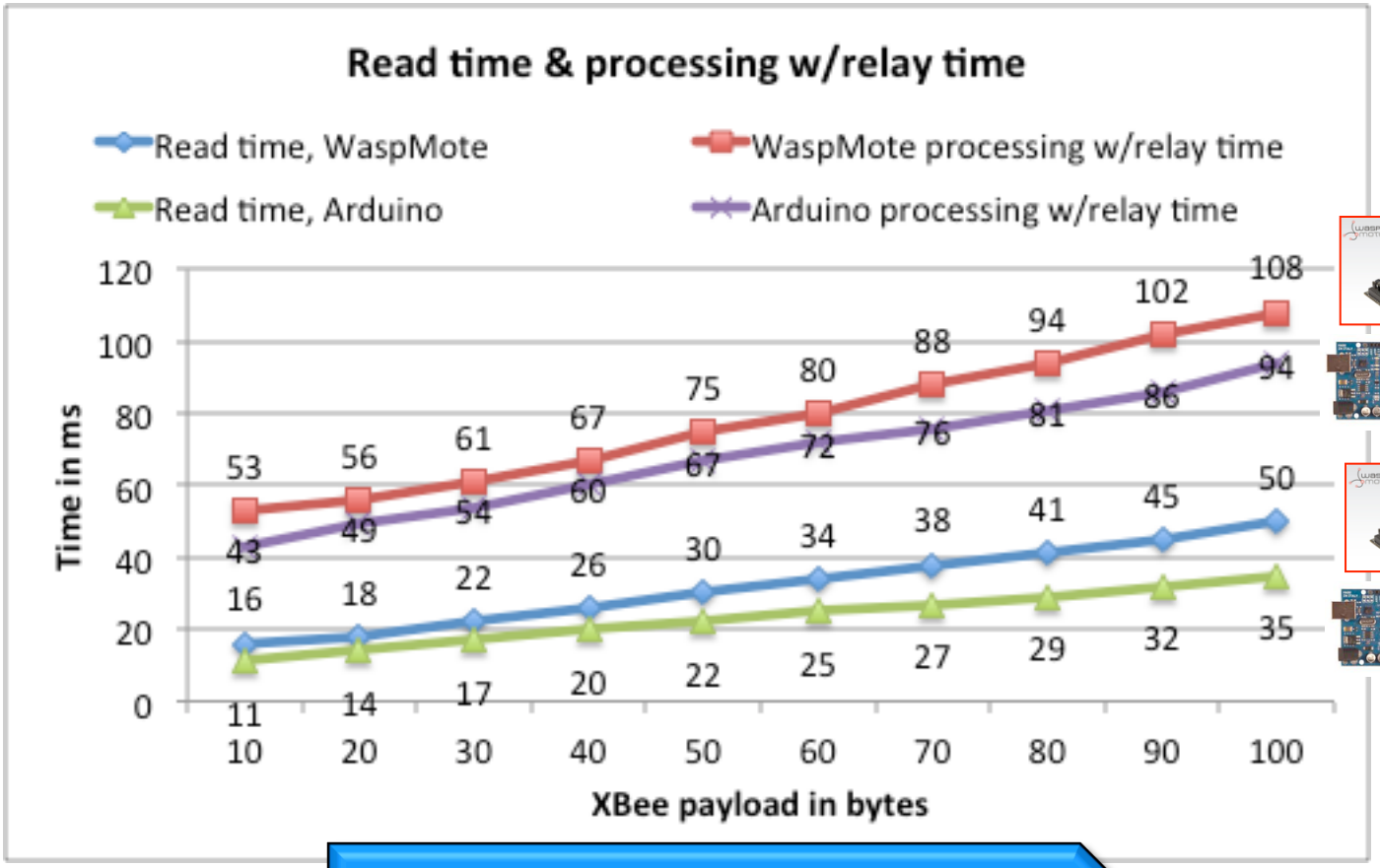


Relay performances



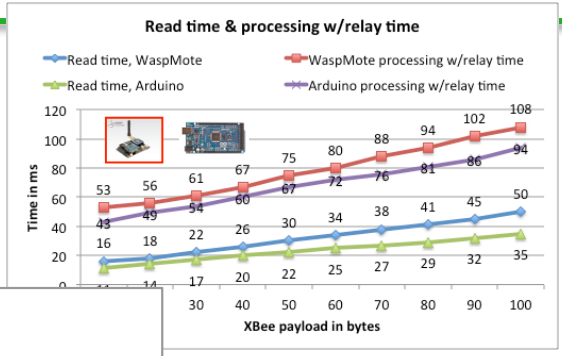
- Relaying are usually done at application-level (even OS level is considered app-level for the mote)
- Relaying means:
  - Read the packet in memory
  - Send the packet to next hop

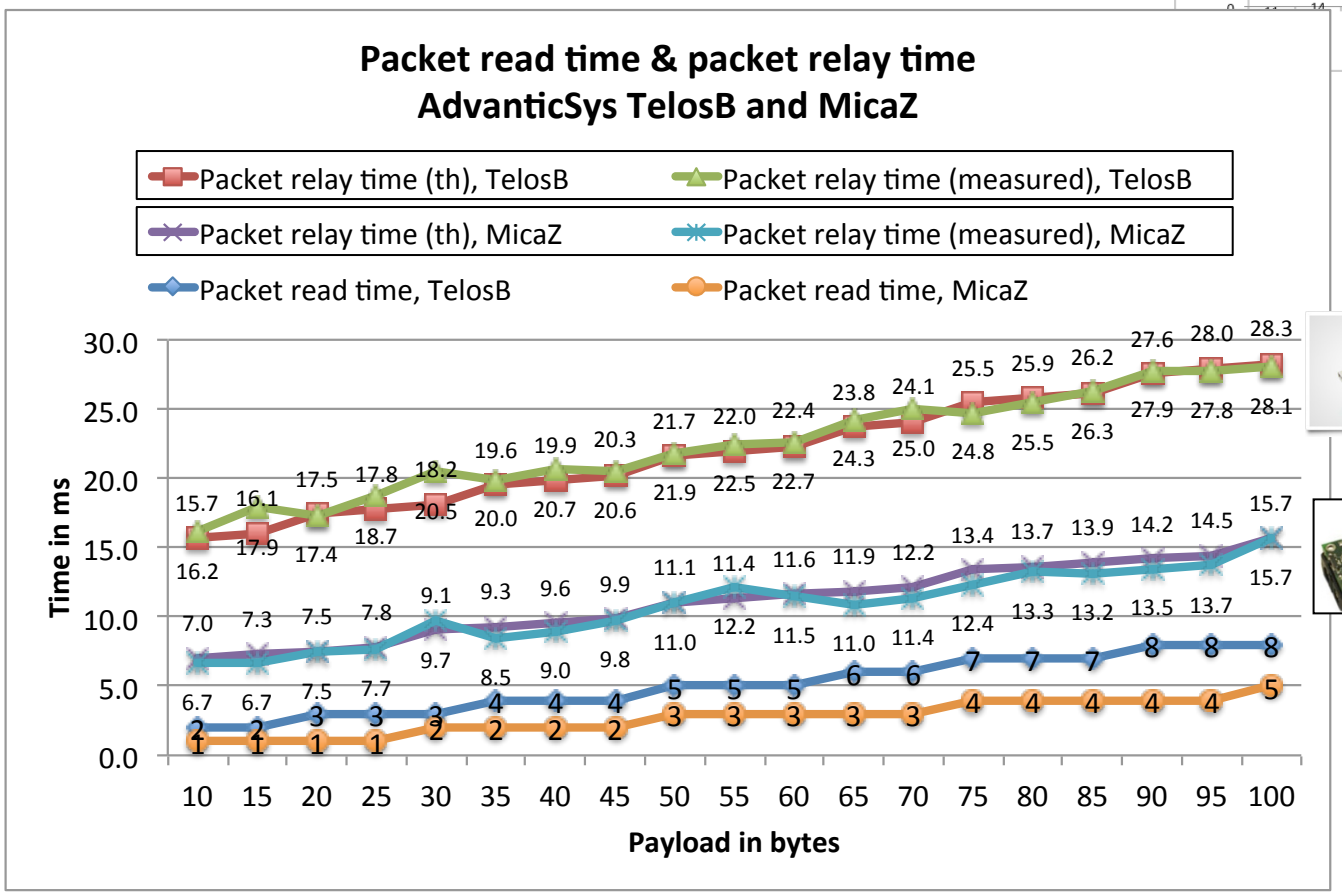
Read time and relay time

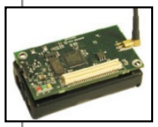


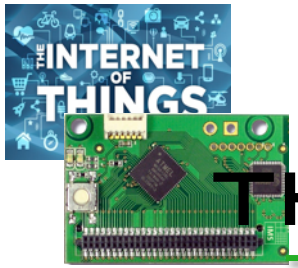
Read time is quite independant from the UART baud rate, but depends on microcontroller frequency

READ TIME AND RELAY TIME

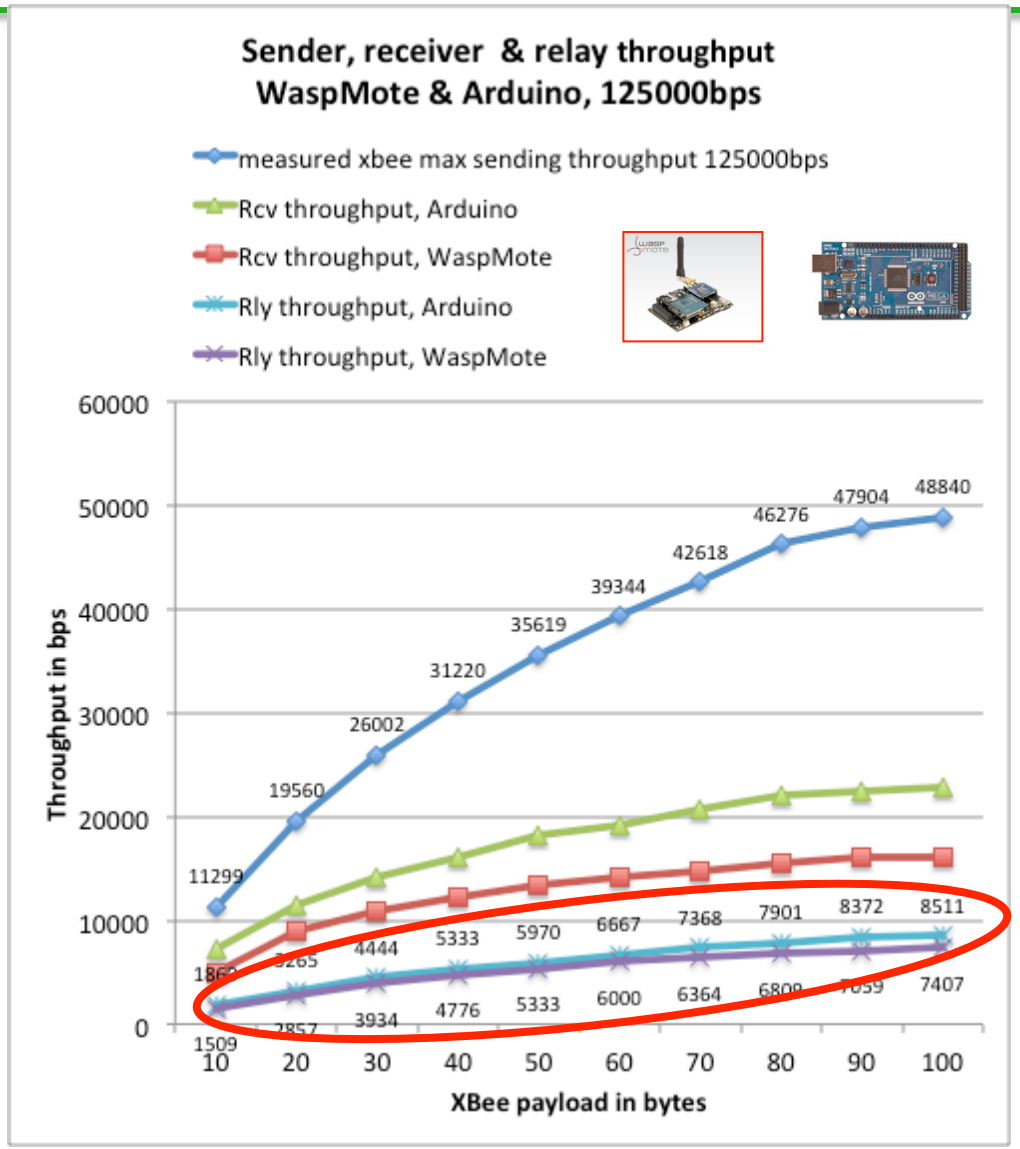




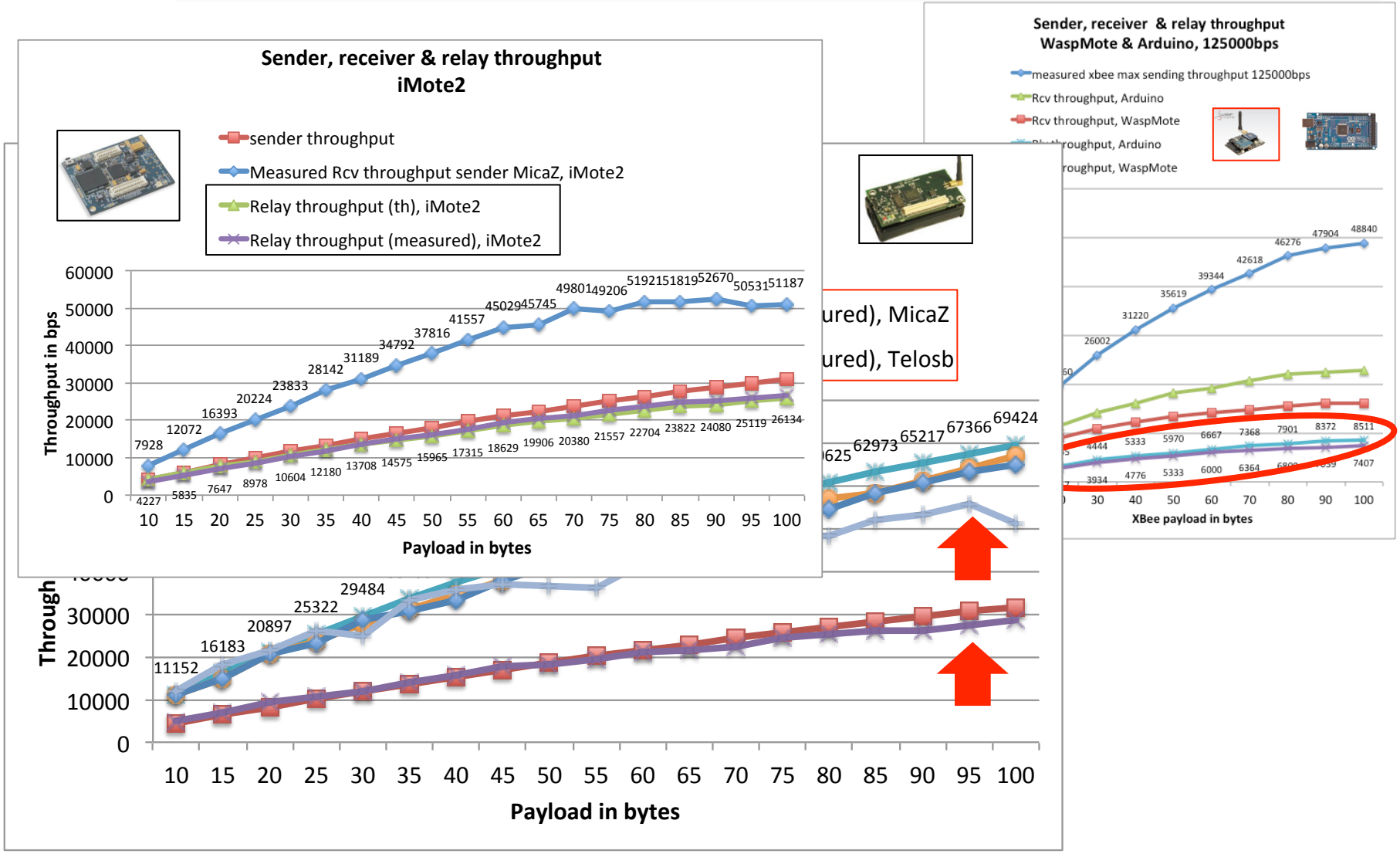


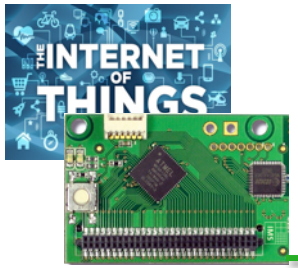


Maximum expected throughput in multi-hop



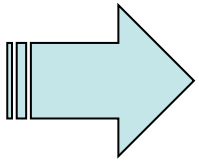
Maximum expected throughput in multi-hop





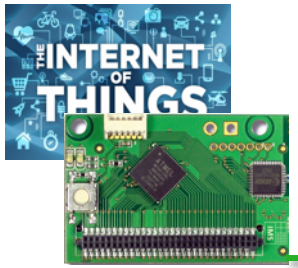
Visual surveillance

for situation-awareness



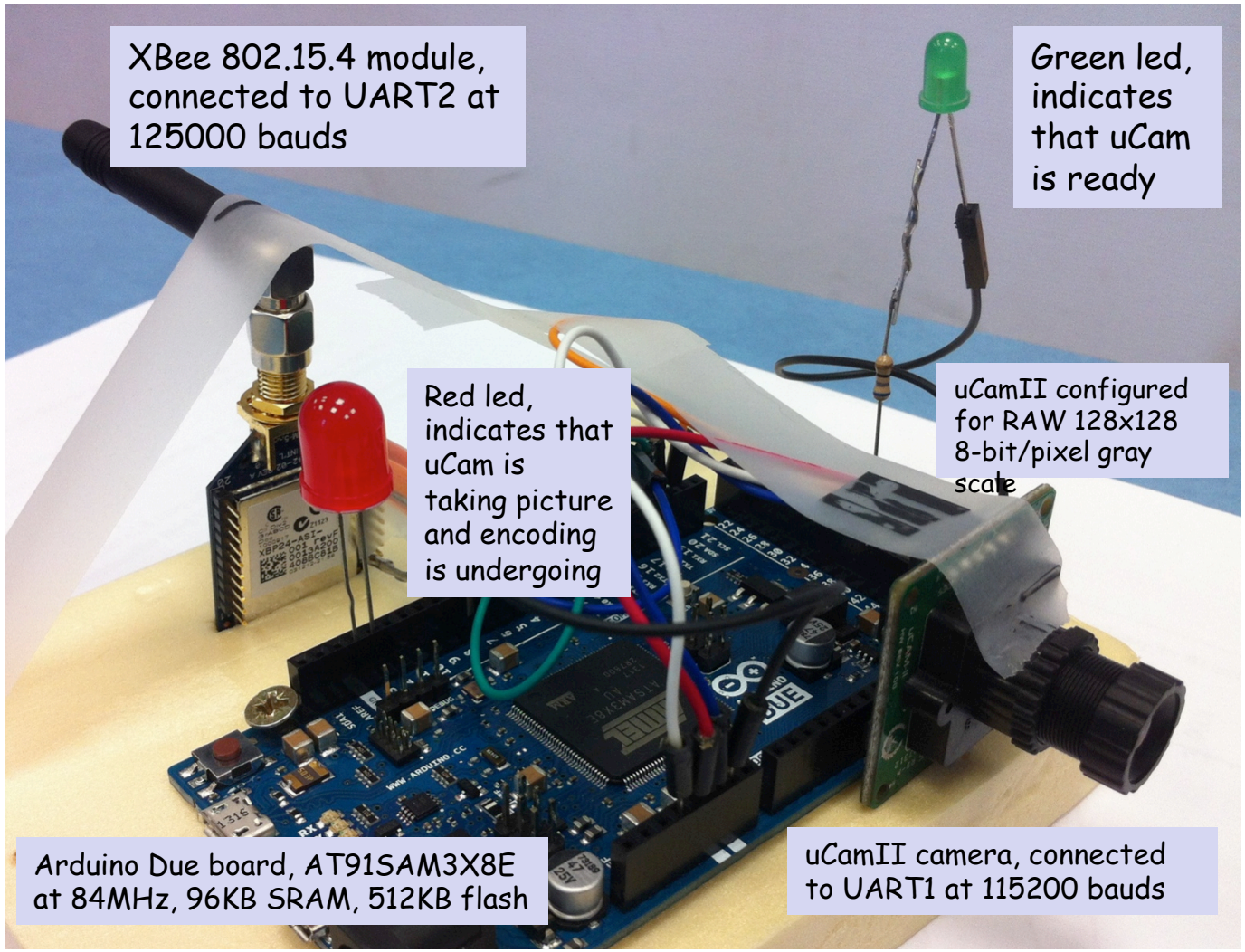
for remote, hard to access areas

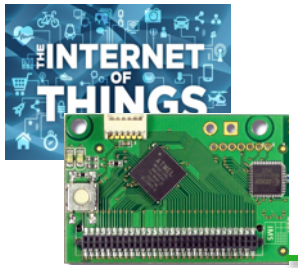
- Infrastructures, pipelines,...
- Leakages, Cracks,...



Arduino + uCamII
128x128 images

Can be controlled wirelessly to capture, take reference image, compare image, transmit image, define packet size, image quality factor,…





ADJUSTABLE IMAGE QUALITY FACTOR Q

raw 16384b

Q=100; 9768b(1.7)
158 pkts PSNR=51.344

Q=90; 5125b(3.2)
70 pkts PSNR=29.414

Q=80; 3729b(4.4)
48 pkts PSNR=28.866

Q=70; 2957b(5.5)
37 pkts PSNR=28.477

Q=60; 2552b(6.4)
32 pkts PSNR=28.024

Q=50; 2265b(7.2)
28 pkts PSNR=27.912

Q=40; 2024b(8.1)
25 pkts PSNR=27.423

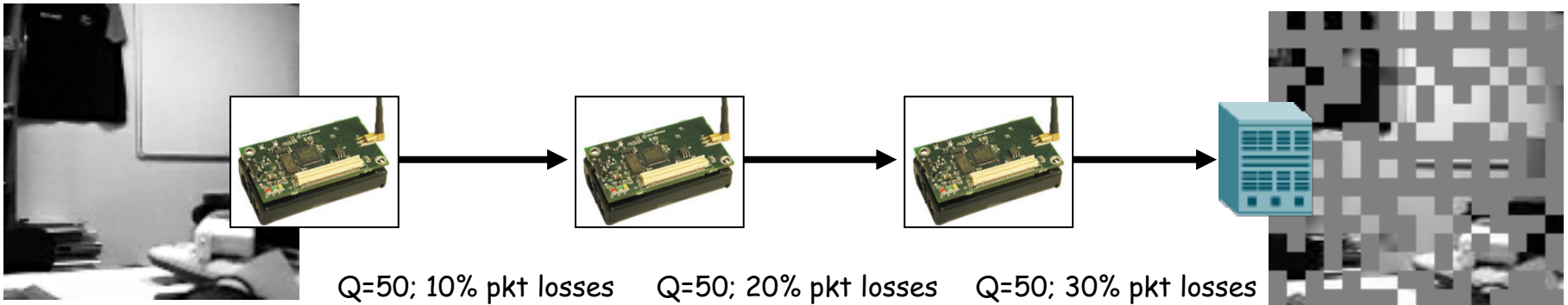
Q=30; 1735b(9.5)
21 pkts PSNR=26.933

Q=20; 1366b(12)
17 pkts PSNR=26.038

Q=10; 911b(18)
11 pkts PSNR=25.283

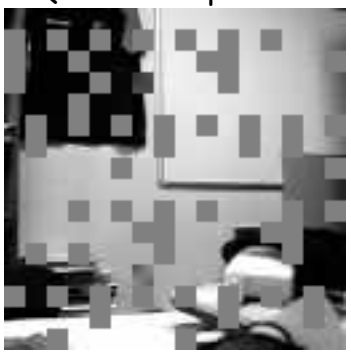
Q=5; 576b(28.4)
7 pkts PSNR=23.507

Robust to packet losses, Out of order reception



Q=50; 10% pkt losses

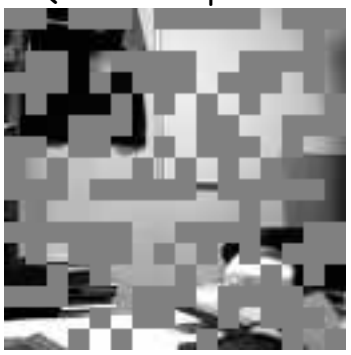
Q=50; 20% pkt losses



Q=50; 30% pkt losses

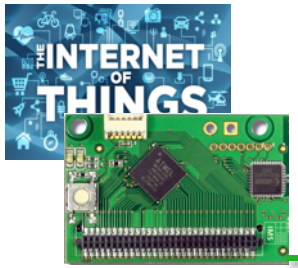
Q=50; 40% pkt losses

Q=50; 50% pkt losses



Q=50; 60% pkt losses

Scientific cooperation with V. Lecuire from CRAN laboratory for the optimized image encoding algorithm



Transmission time

raw 16384b

250kbps: 0.524s

163pkt of 100bytes:
163*0.0115=1.87s

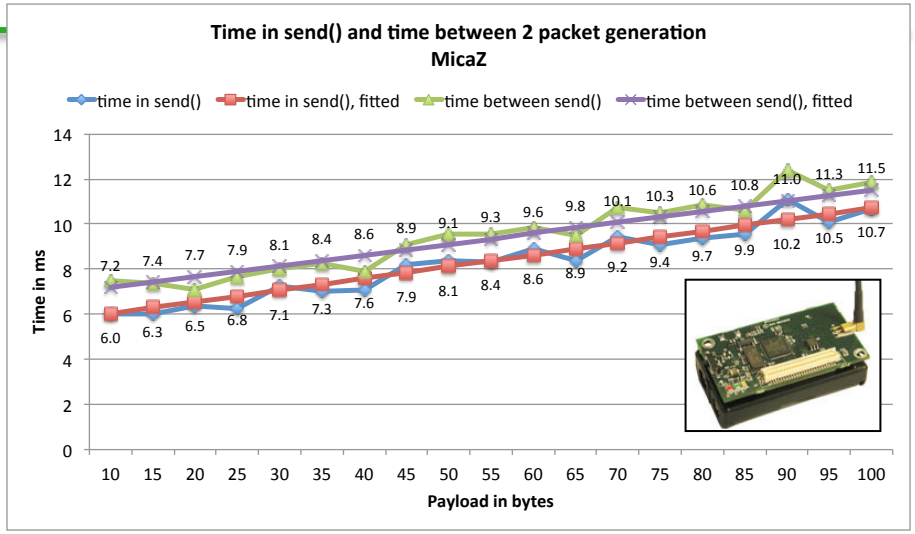
Relay overhead:
163*0.0157=2.55s

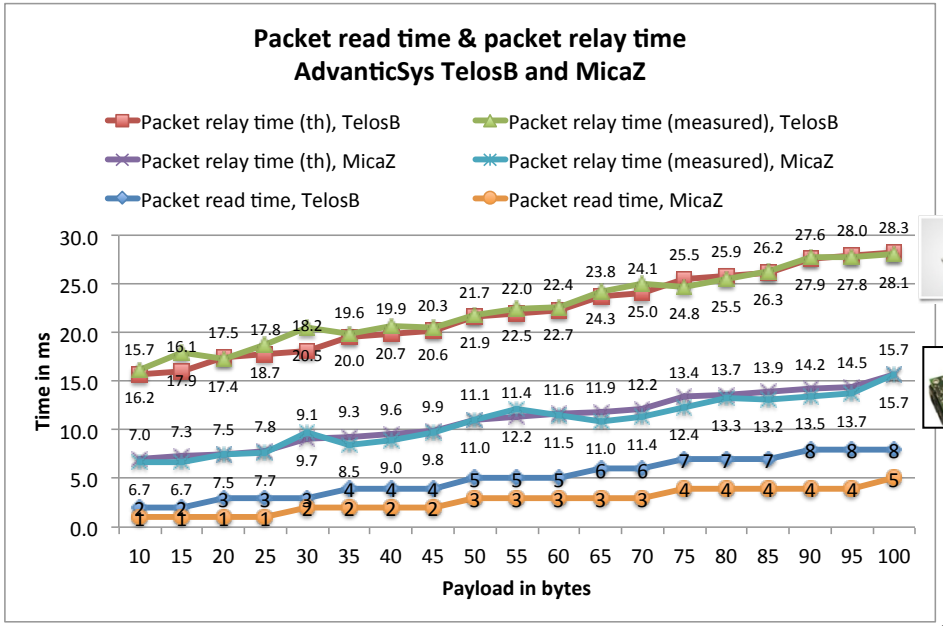
Q=20; 1366b(12)
17 pkts PSNR=26.038

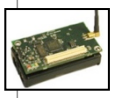
250kbps: 0.043s

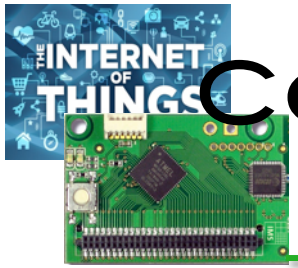
17pkt of 95bytes:
17*0.0115=0.195s

Relay overhead:
76*0.0157=0.266s







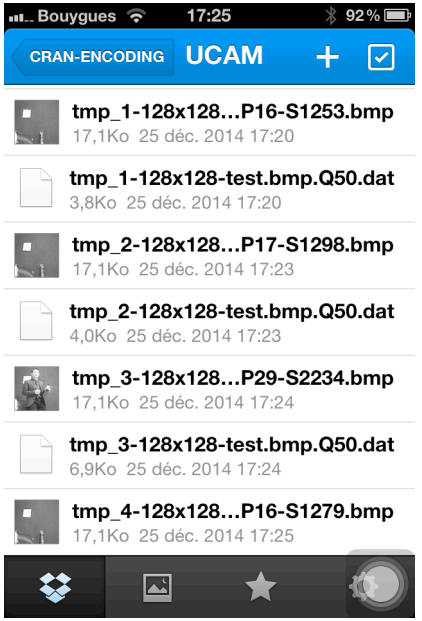


COST OF IMAGE ENCODING & TRANSMISSION

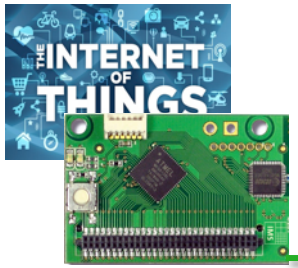
		N	R	A	B	C = D - B	D	E=R+D	F
Quality Factor Q	size in bytes (compression ratio)	number of packets (with MSS=90)	reading time from ucam	encode time	encode + pkt time	transmis-sion time (deduced)	encode + pkt + transmis-sion time	cycle time, with transmis-sion	rcv time at the sink
90	5125 (3.2)	70	1512	512	782	539	1321	2833	799
80	3729 (4.4)	48	1512	511	704	384	1088	2600	599
70	2957 (5.5)	37	1512	519	686	304	990	2502	447
60	2552 (6.4)	32	1512	509	662	263	925	2437	390
50	2265 (7.2)	28	1512	500	646	233	879	2391	349
40	2024 (8.1)	25	1512	516	657	207	864	2376	317
30	1735 (9.5)	21	1512	516	649	177	826	2338	278
20	1366 (12)	17	1512	518	638	140	778	2290	231
10	911 (18)	11	1512	516	628	93	721	2233	177

IMAGE CHANGE DETECTION

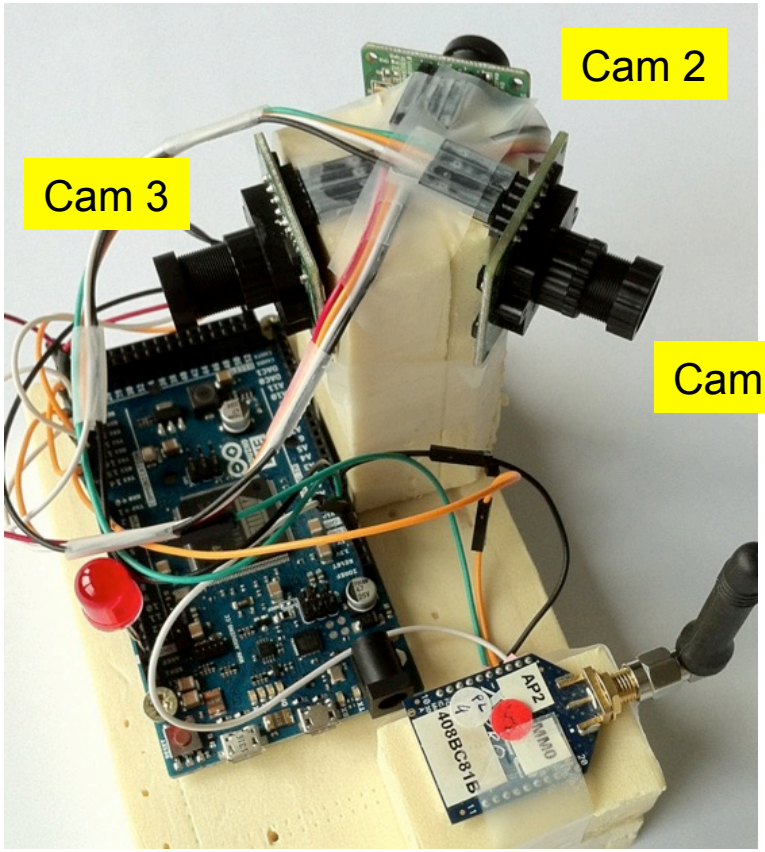
Sends image to gateway on intrusion detection

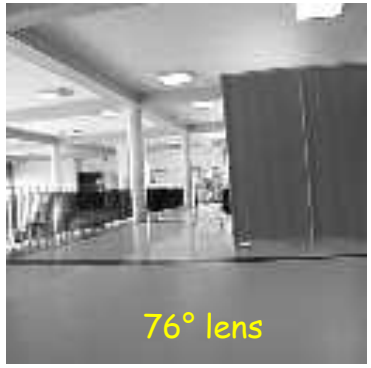


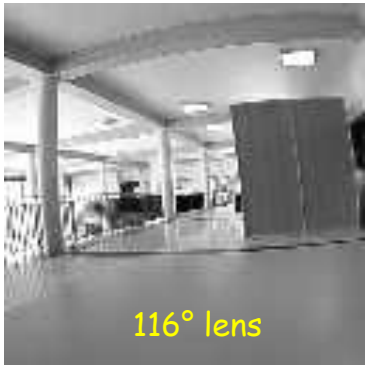
Real-time synchronization with your smartphone through cloud applications, e.g. DropBox



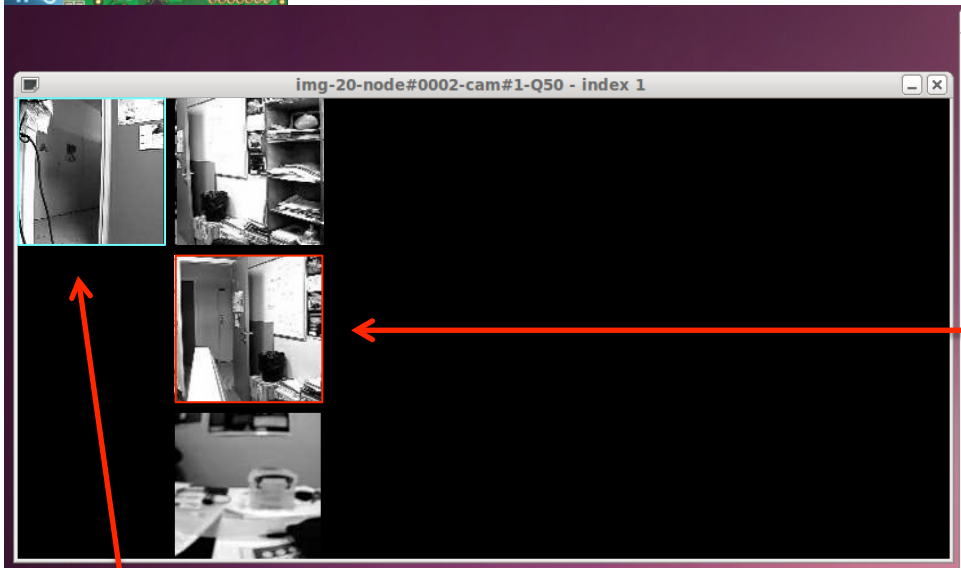
Multi-camera system

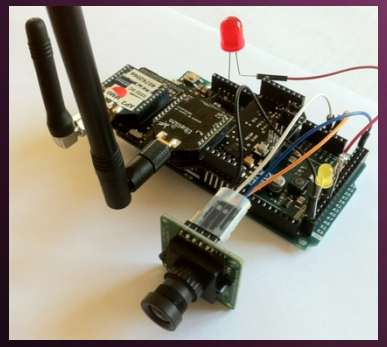




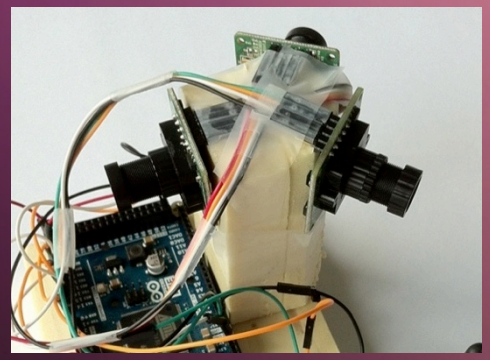


OUT-OF-THE-BOX SURVEILLANCE

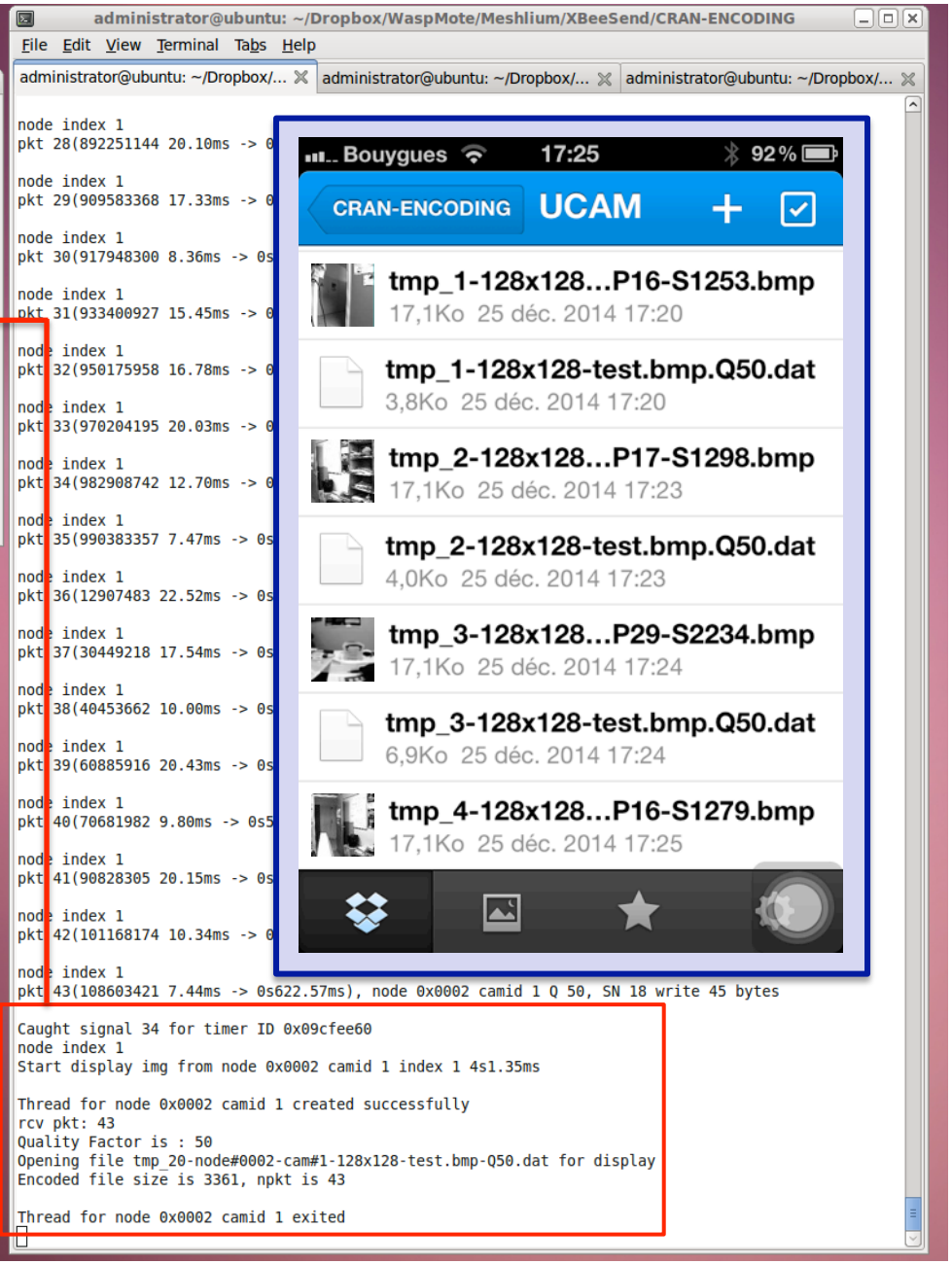


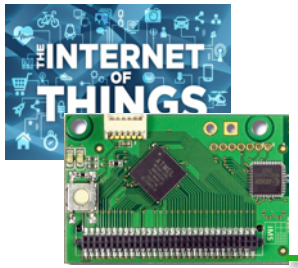


Single camera
addr is 0x0001

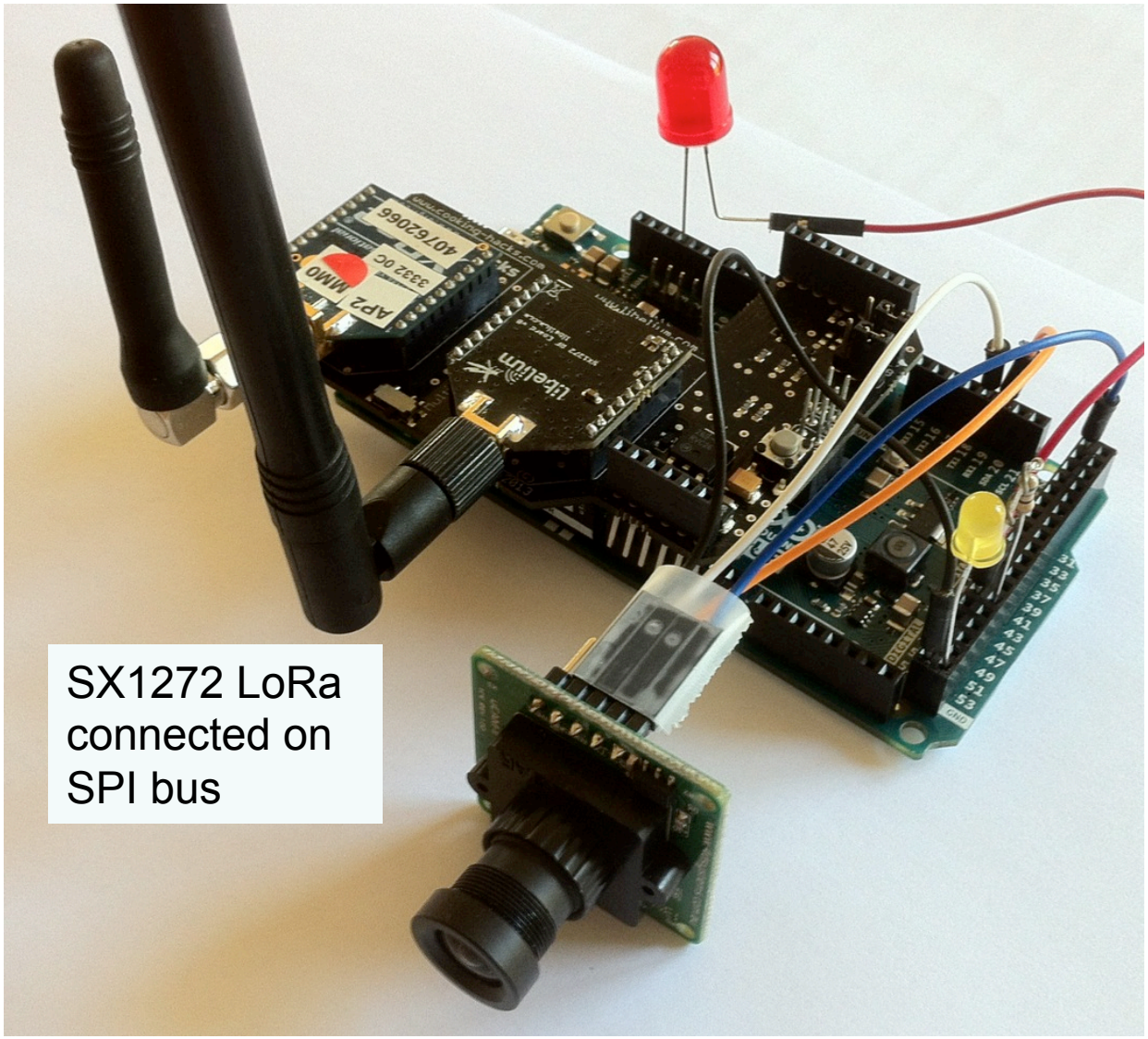


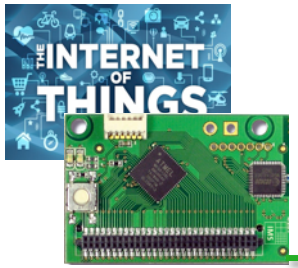
3 cameras
addr is 0x0002





Using long-range transmission (LoRa)

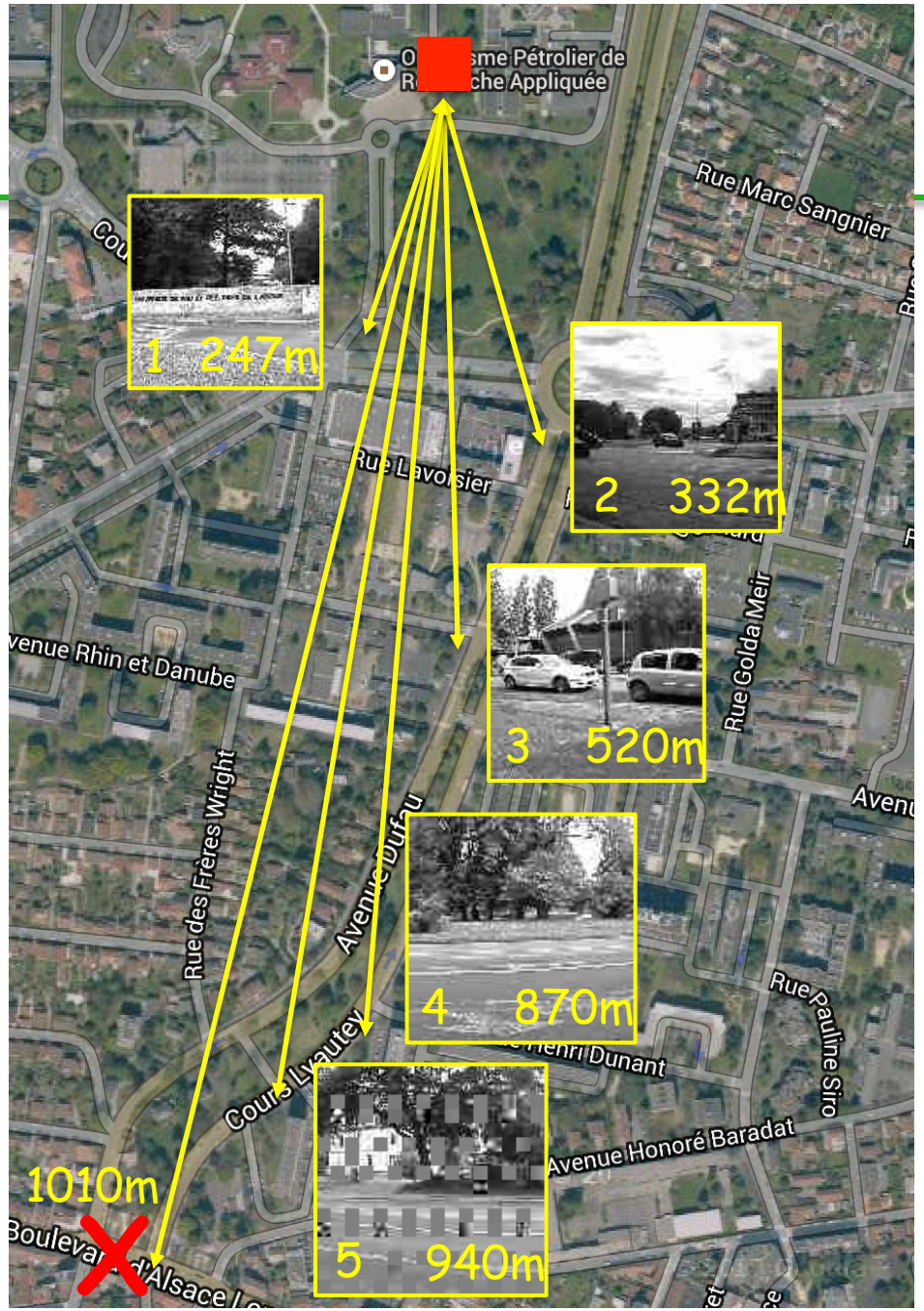


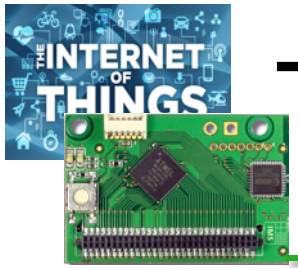


Tests use Libelium LoRa mode 4 in NLOS conditions (many buildings to go through)

Using LoRa mode 1 can increase the NLOS range to 1.8km!

Receiver and sender are at 1.5m height. Range greatly increases with elevation



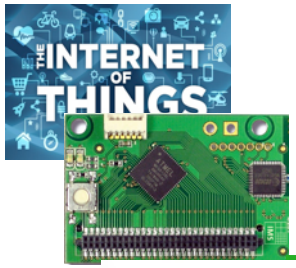


Transmission time with LoRa technology

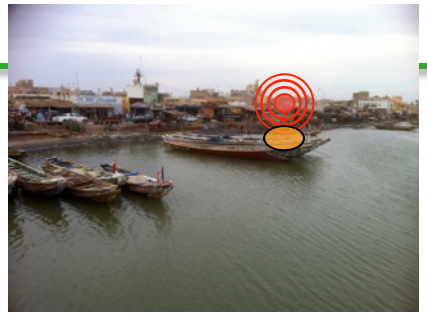
				time in send() in ms for payload size of					
LoRa mode	BW	CR	SF	40 bytes	50 bytes	100 bytes	150 Bytes	200 Bytes	250 Bytes
1	125	4/5	12	2389	2718	4356	5995	7634	9273
2	250	4/5	12	1320	1484	2304	3124	3944	4763
3	125	4/5	10	868	991	1483	2016	2508	3041
4	500	4/5	12	786	868	1278	1688	2098	2509
5	250	4/5	10	559	621	867	1134	1381	1647
6	500	4/5	11	539	580	806	1032	1278	1504
7	250	4/5	9	426	457	601	745	899	1043
8	500	4/5	9	339	354	426	499	576	648
9	500	4/5	8	300	310	352	396	440	482
10	500	4/5	7	279	285	311	337	363	390

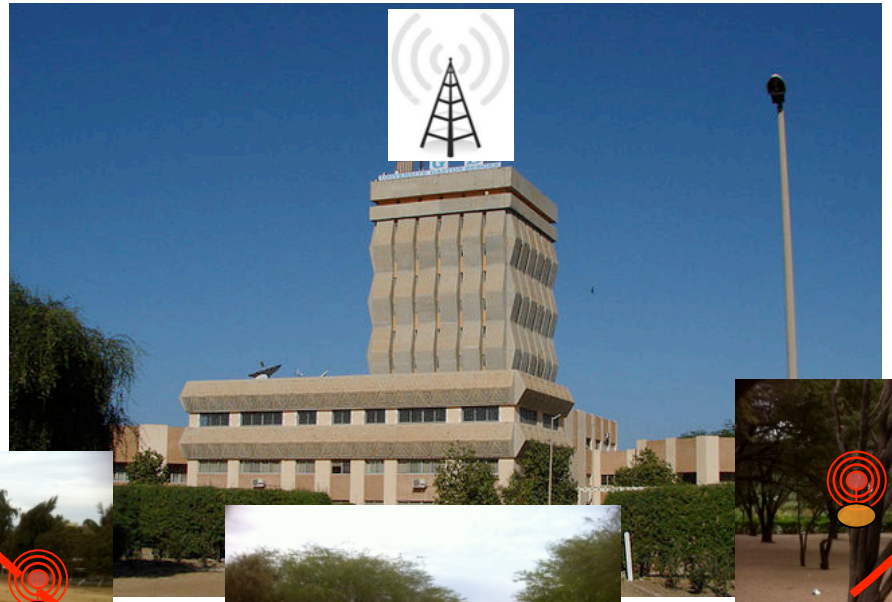
Q=20; 1366b(12)
Will generate 7 pkts using 250 max payload

7*2.5 = 17.5s



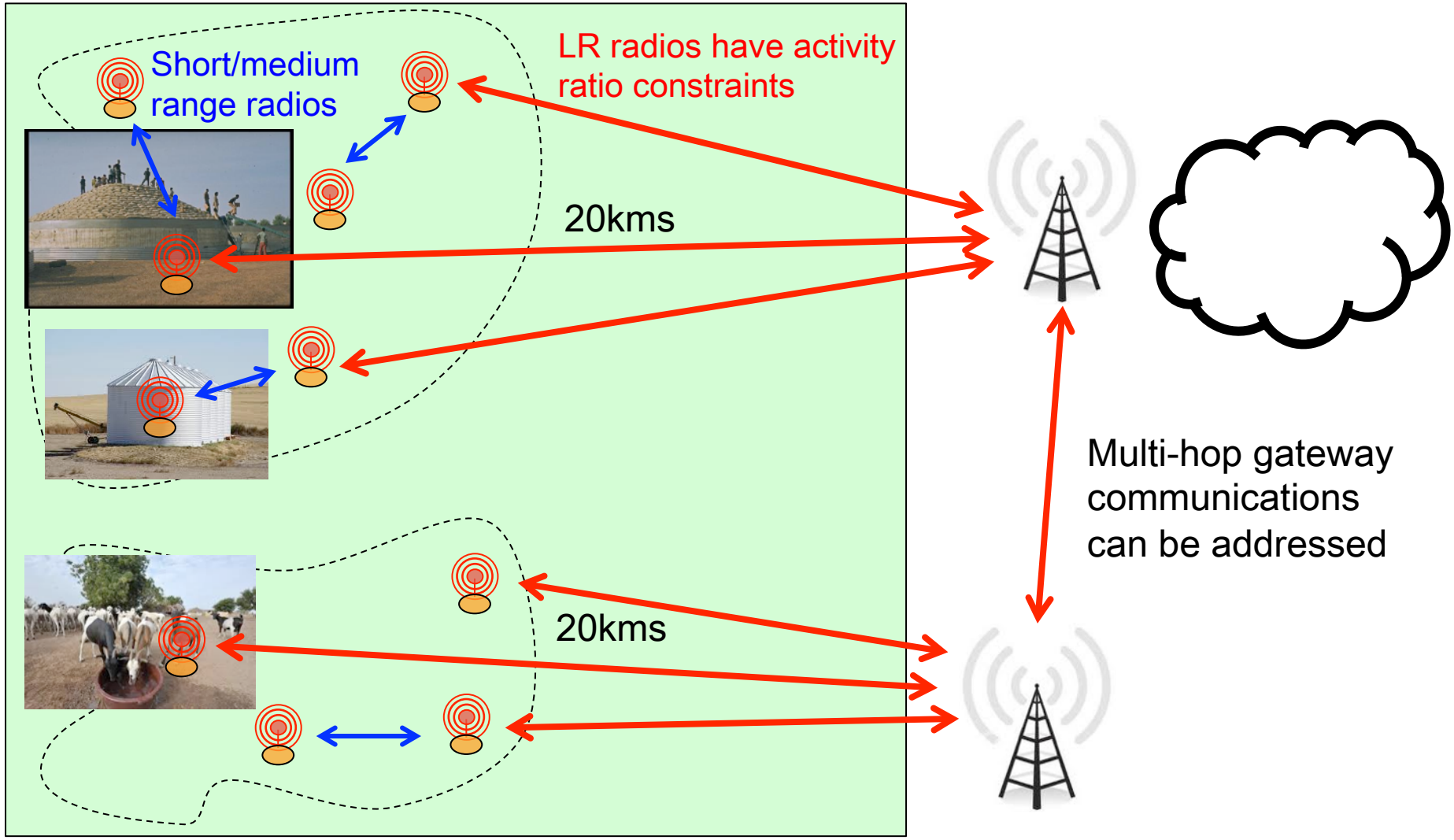
Long-range communication for developing countries, rural areas

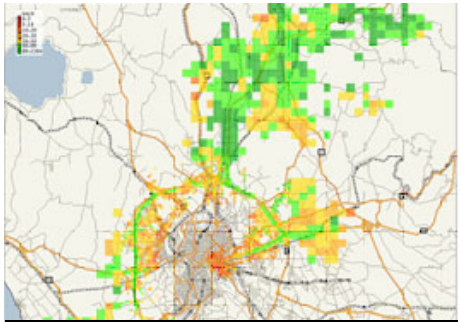





LR and short/medium-range integration

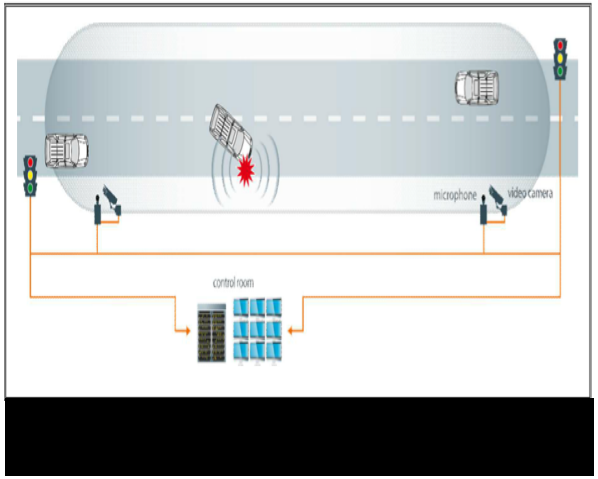


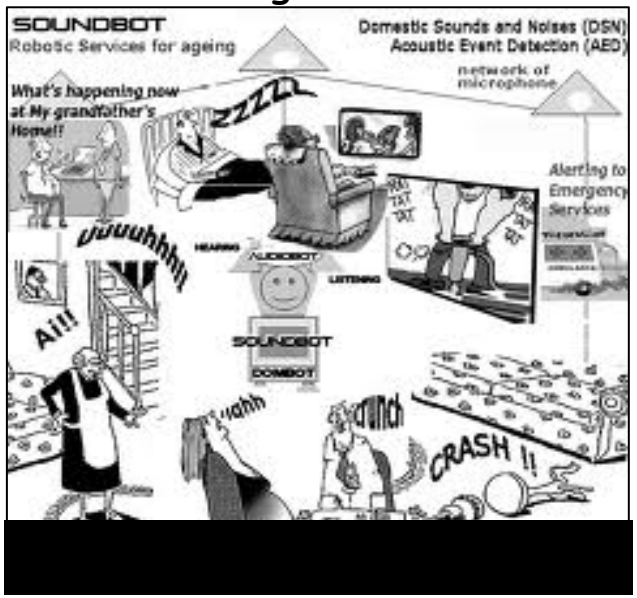
EXPLOITING ACOUSTIC DATA



Management

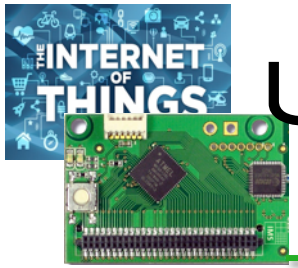
efficiency





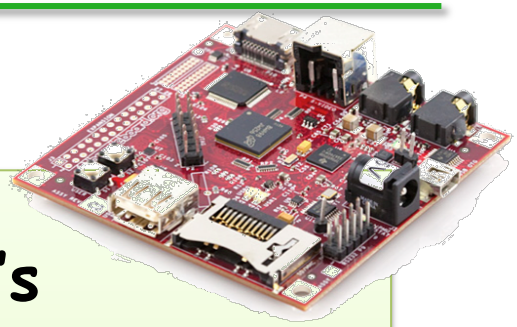
Surveillance

From EAR-IT slides



Use of Complementary Technologies

www.ear-it.eu



Today's audio-ready IoT Technologies

- *Less Capable*
- *Low energy*
- *Cheaper to get*
- *Much deployed*

Today's Acoustic Sensing Technologies

- *Powerful*
- *Power greedy*
- *More costly*
- *Fewer available*

EAR-IT

Combining the complementary Acoustic Sensing and Internet-of-Things technologies of today for value

From EAR-IT slides

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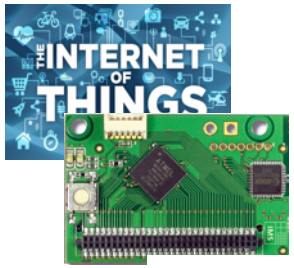


EAR-IT TEST-BEDS

EAR-IT
Future Internet Research Experiment

SmartSantander

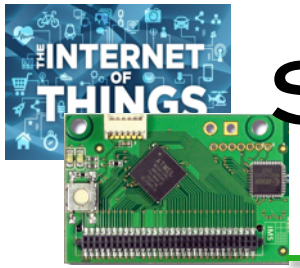
http://www.smartsantander.eu/

HOBNET

www.**hobnet**-project.eu

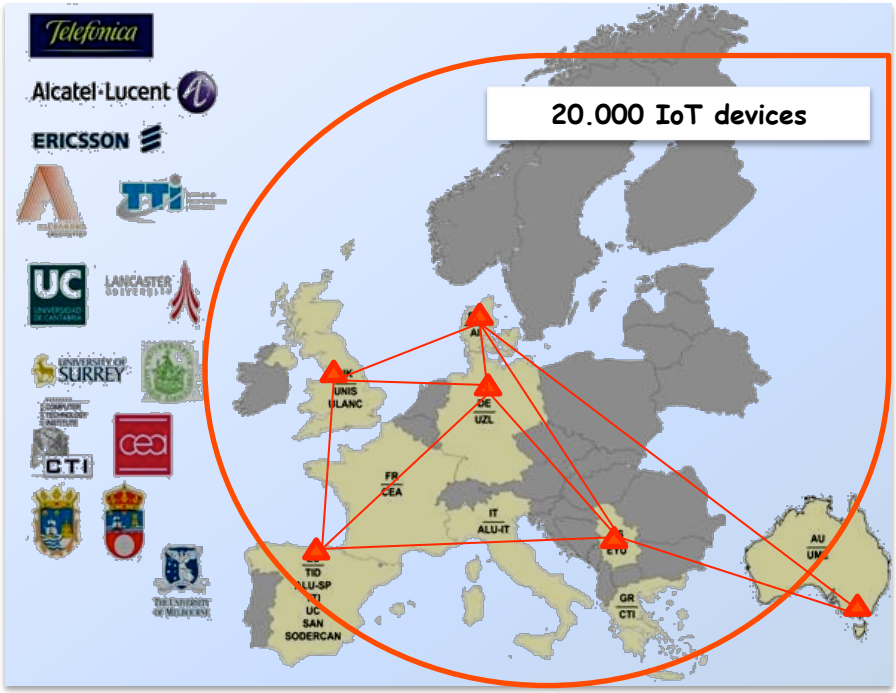
Experimenting Acoustics in Real environment using Innovative Test-beds

From EAR-IT slides



SmartSantander test-bed

SmartSantander aims at providing a European **experimental test facility** for the **research** and **experimentation** of architectures, key enabling technologies, **services** and applications for the Internet of Things (IoT) in the context of the **smart city**.



Smart Santander Highlights

- ❑ **Targeting:**
  - Researchers
  - End users
  - Service providers
- ❑ **Duration**
  - 36 months
- ❑ **Consortium**
  - 15 Organisations
  - 8 EU countries + AU
- ❑ **Budget / Funding**
  - 8.6 M€ / 6 M€
- ❑ **Resources**
  - 746.2 PM

From EAR-IT slides

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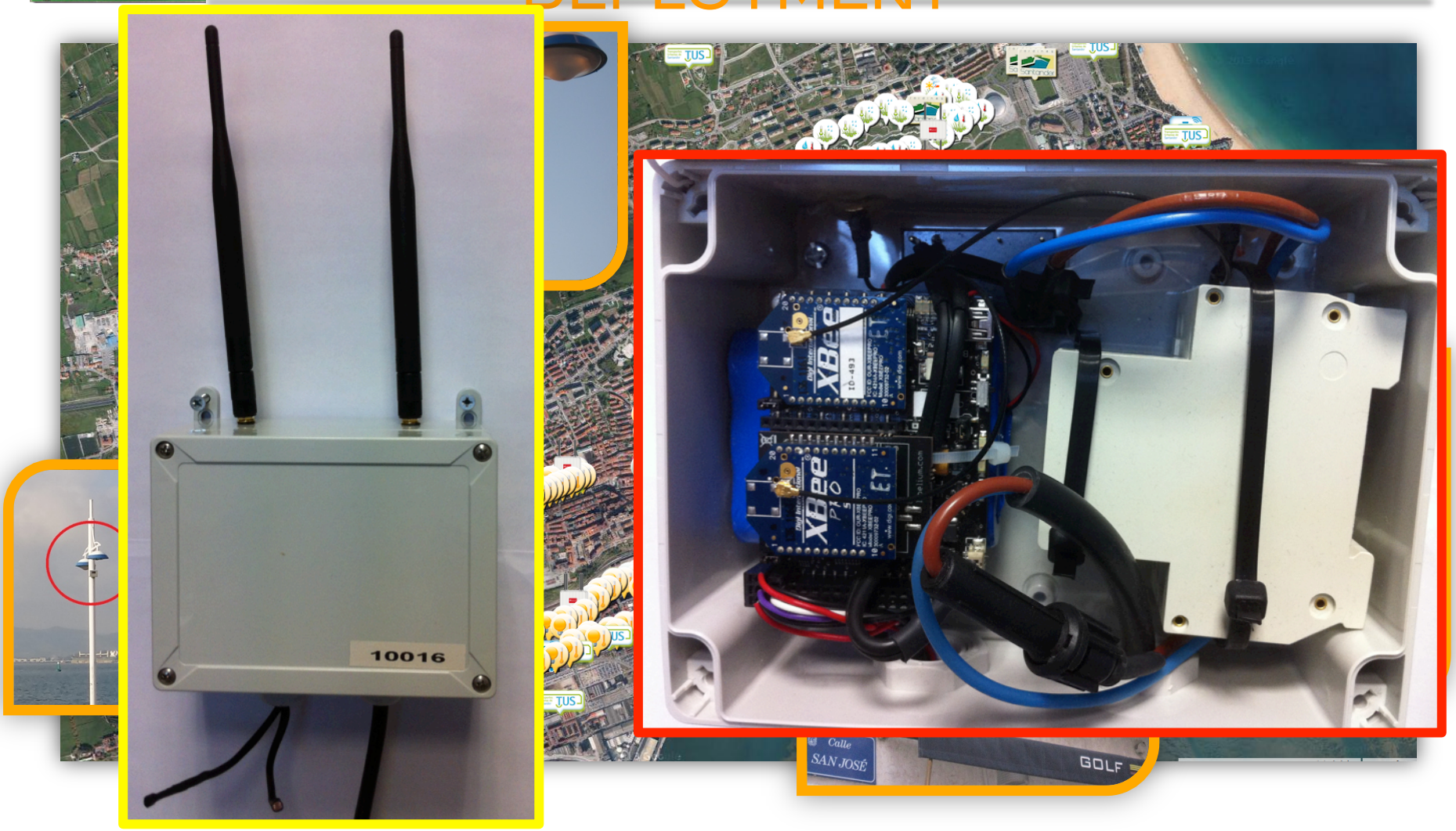
SmartSantander test-bed

Santander's sensor network deployment



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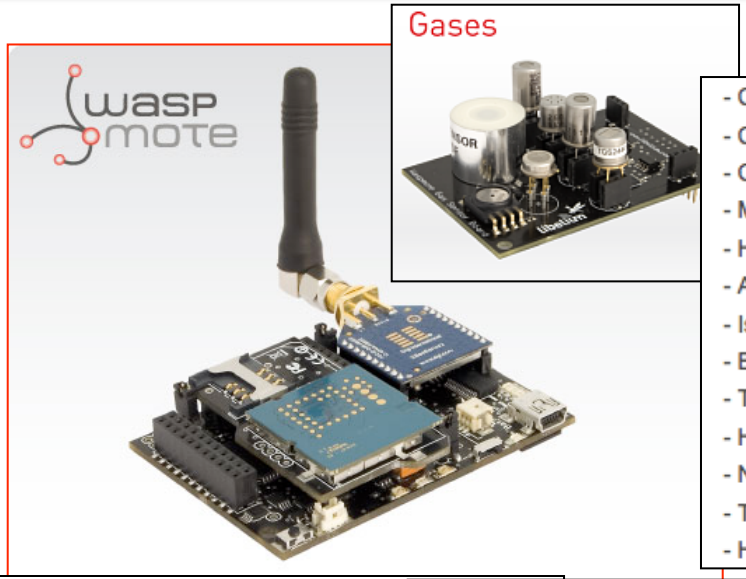
SmartSantander IoT node

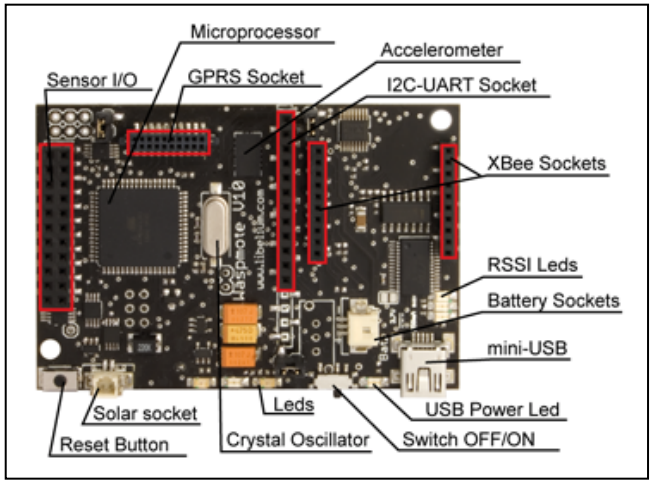
libelium
comunicaciones inalámbricas distribuidas

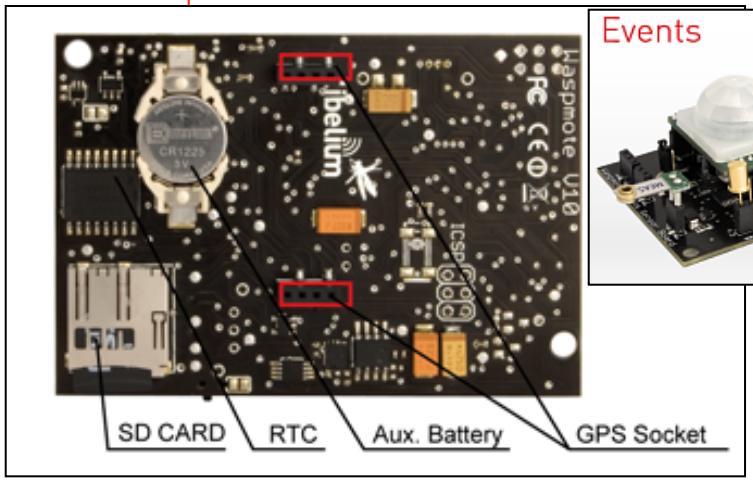
- ATmega1281 microcontroller
- 8Mhz, 4K RAM & 2G SD card.
- 2.4GHz IEEE 802.15.4 XBee
- Libelium API v031



Gases

- Carbon Monoxide – CO
- Carbon Dioxide – CO2
- Oxygen – O2
- Methane – CH4
- Hydrogen – H2
- Ammonia – NH3
- Isobutane – C4H10
- Ethanol – CH3CH2OH
- Toluene – C6H5CH3
- Hydrogen Sulfide – H2S
- Nitrogen Dioxide – NO2
- Temperature
- Humidity

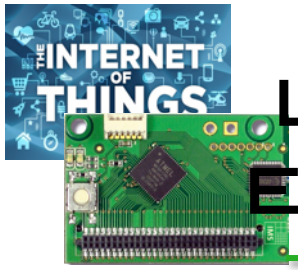




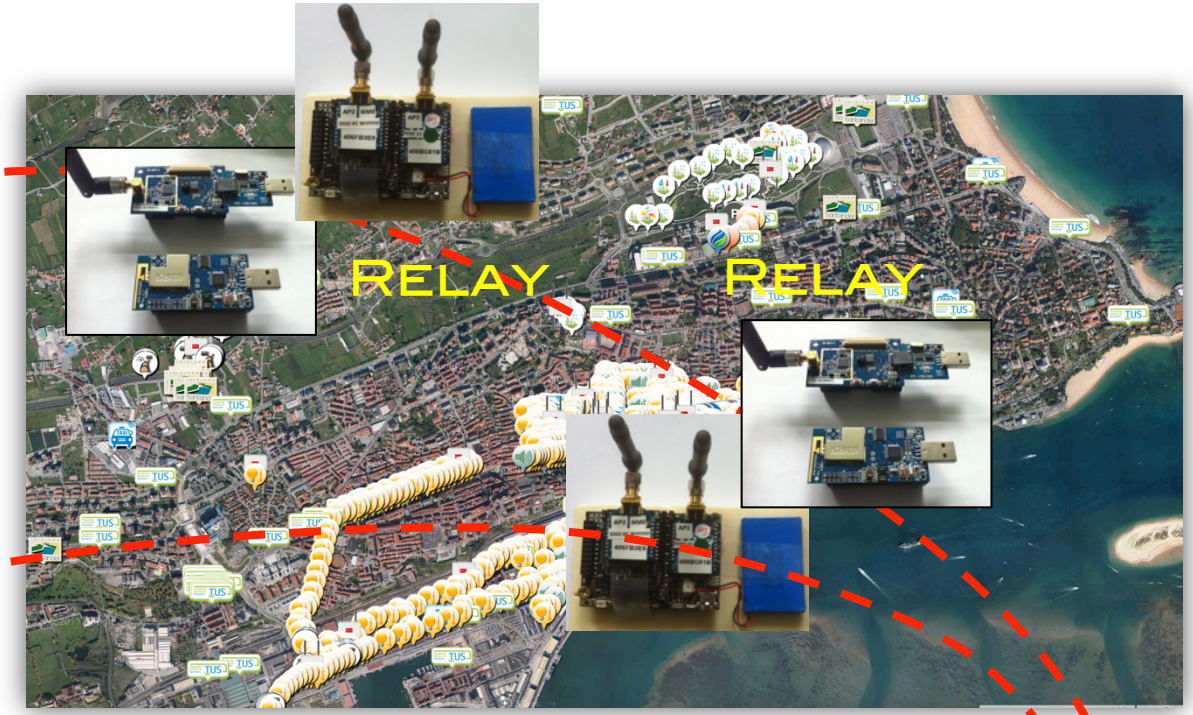
Events

- Pressure/Weight
- Bend
- Vibration
- Impact
- Hall Effect
- Tilt
- Temperature (+/-)
- Liquid Presence
- Liquid Level
- Luminosity
- Presence (PIR)
- Stretch

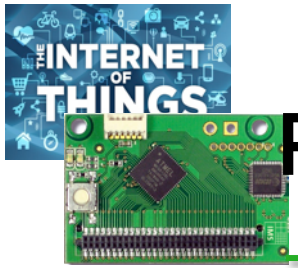
Images are from Libelium company



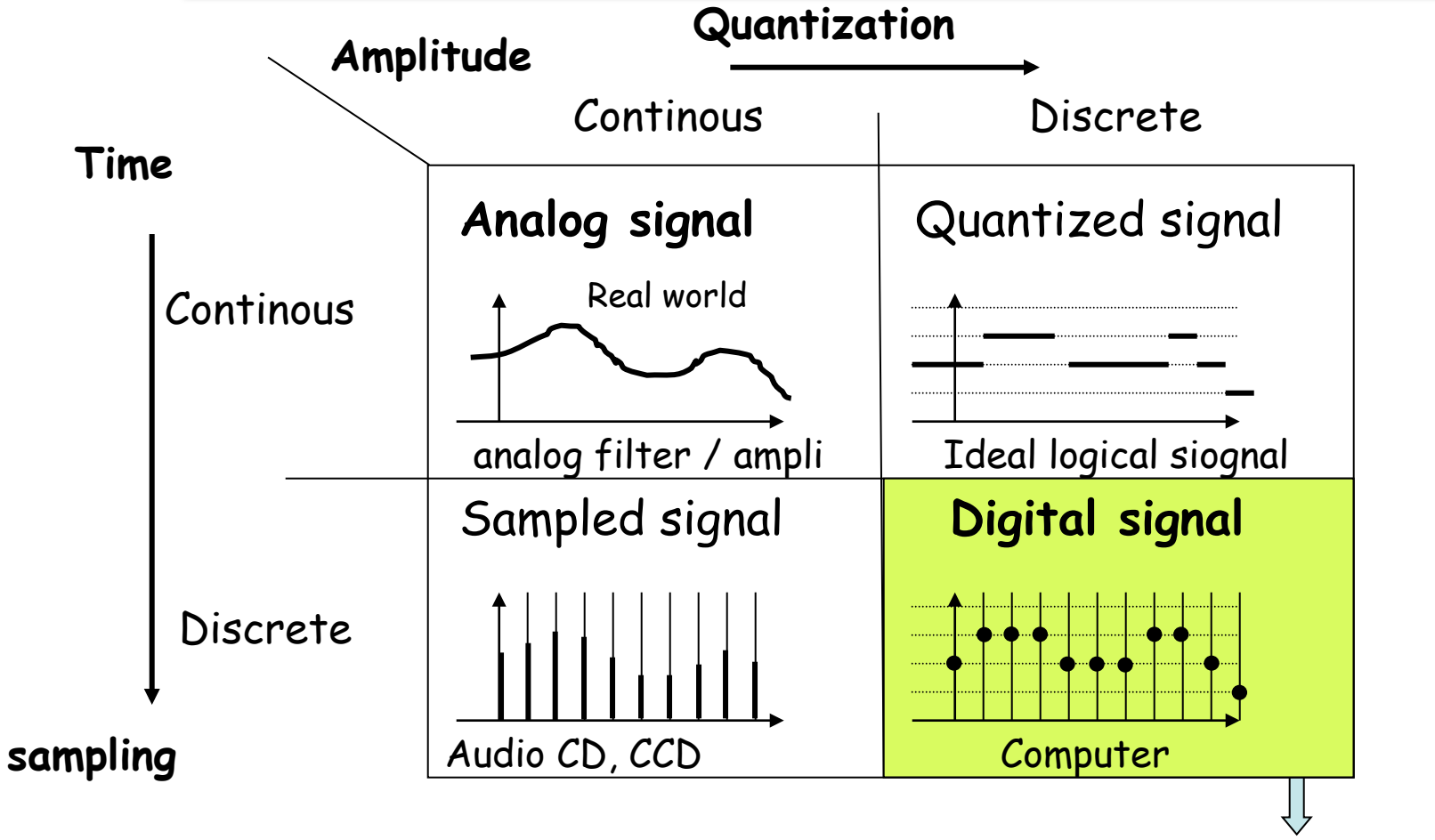
Low-resource IoT node to enhance acoustic services



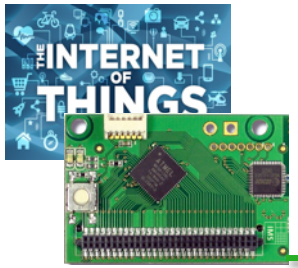
Play/store received audio data



REVIEW OF DIGITAL AUDIO



Only in this case can we associate an integer value to the signal



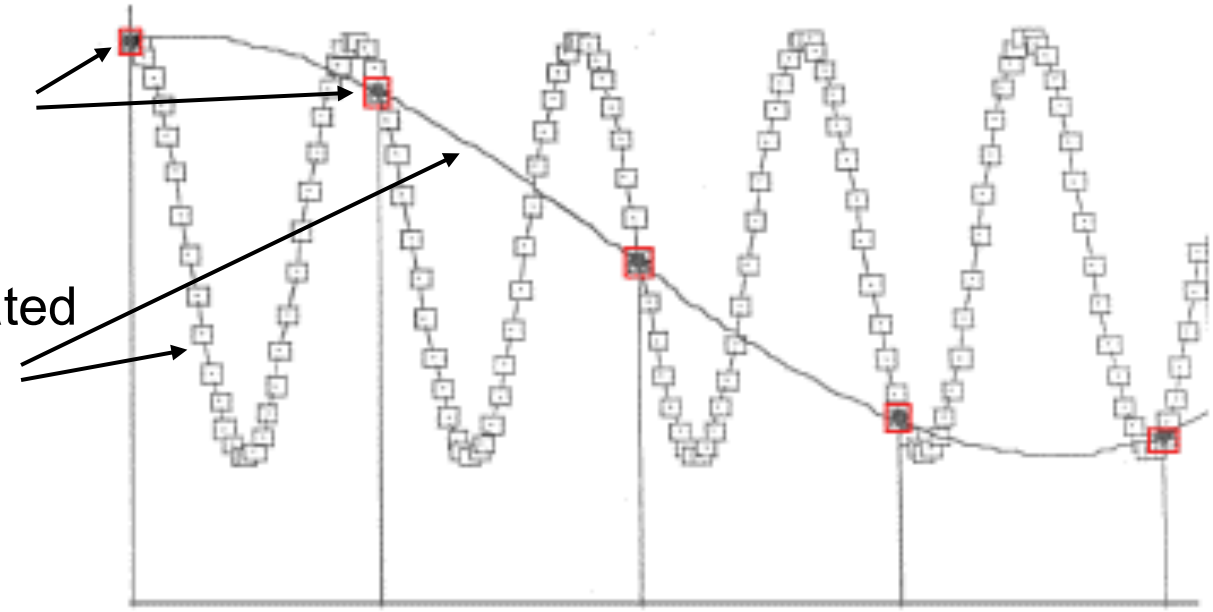
Sampling: Shannon's theorem

Shannon's theorem: Fe > 2 x Fmax(Signal)

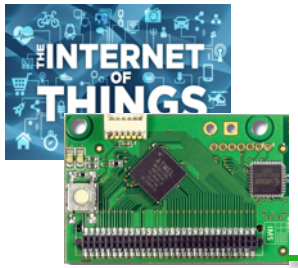
Example :

Samples

Extrapolated signal ?



An incorrectly sampled signal will not be reconstituted



Narrow-band audio

- Sampling rate up to 8kHz
- 1 sample every 1/8000s (125us)
- Sample coded on 8 bits
- Raw throughput of 64kbps
- So-called Pulse Code Modulation (PCM) used in most wired telephony systems
- With 4kHz sampling rate, can reduce to 32kbps

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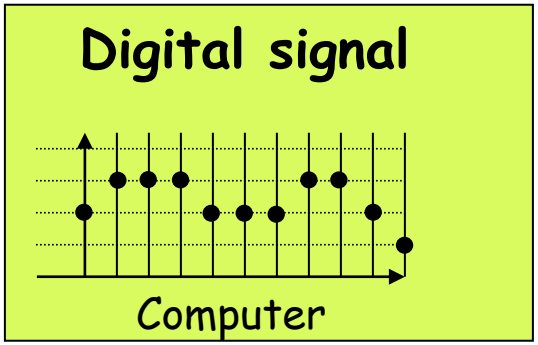
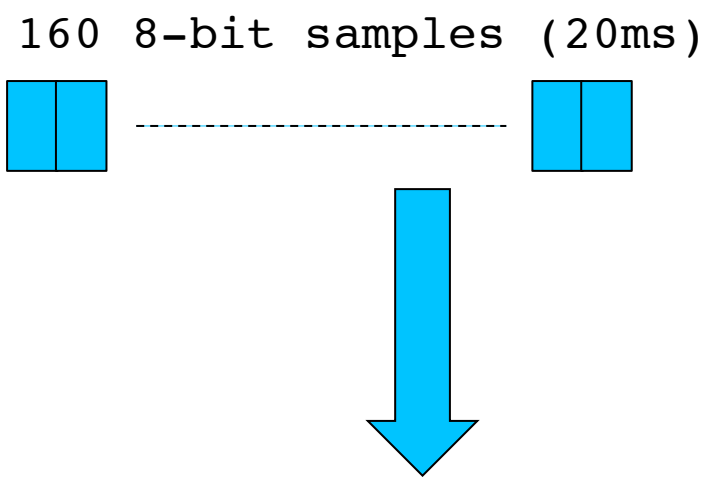
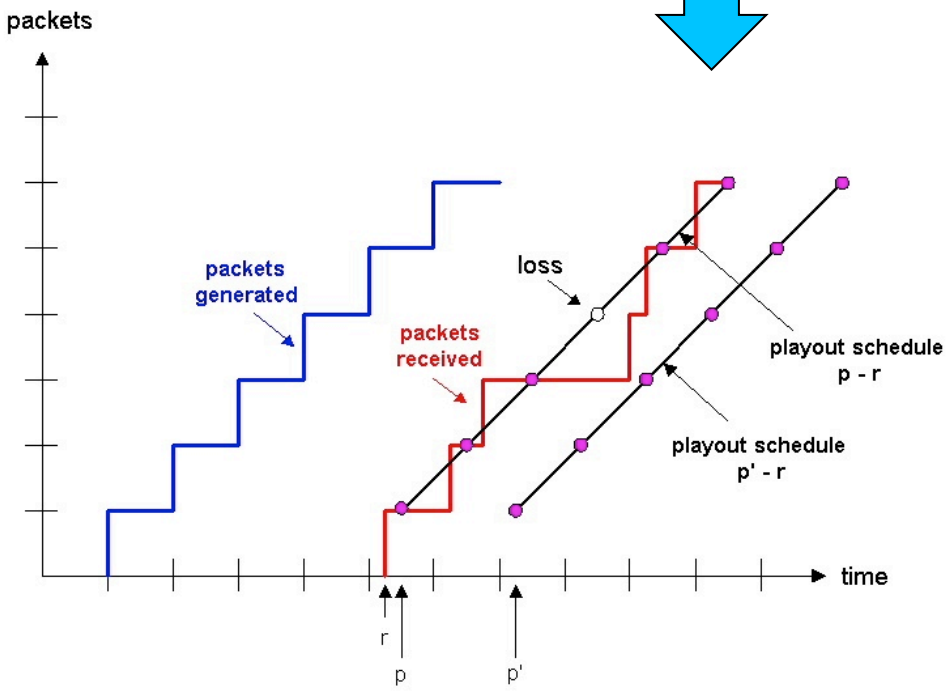
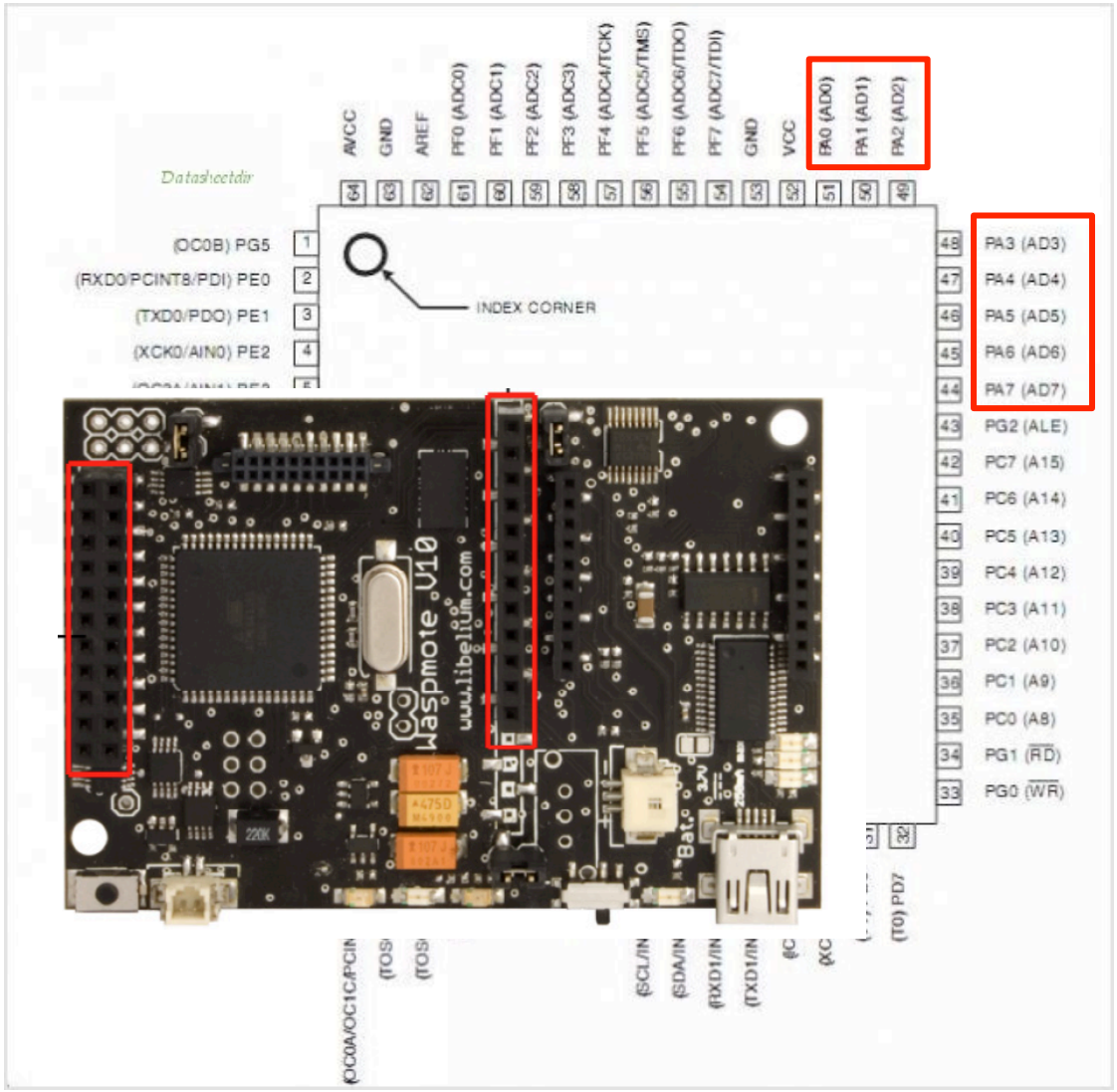
AUDIO STREAMING PRINCIPLE





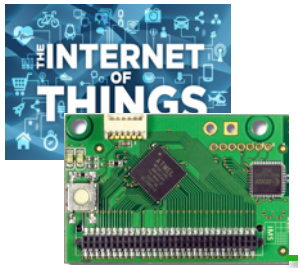


UCONTROLLER VS MICROPROCESSOR



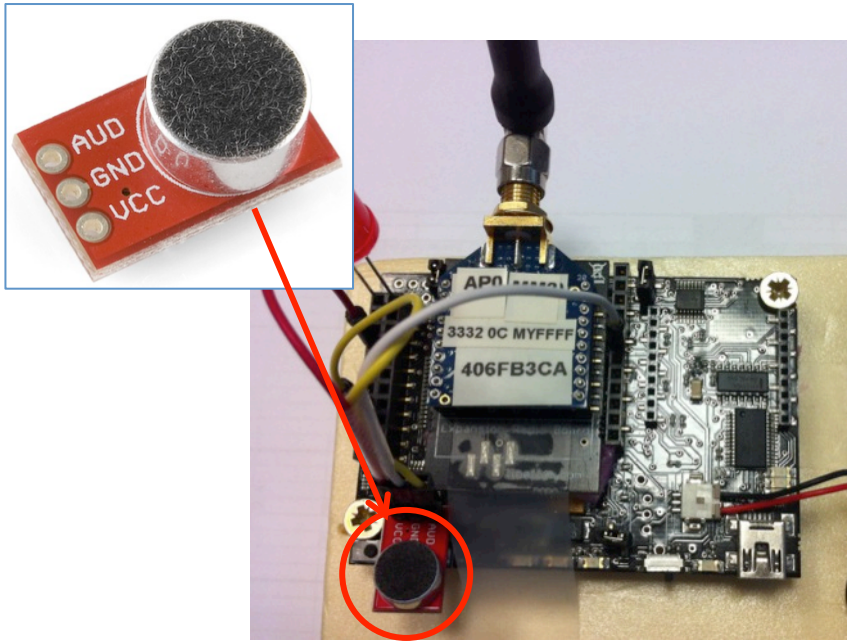
Input voltage between 0 and Vref (e.g. 3.3V). ADC usually have 10-bit resolution:

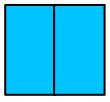
0 is for 0V
1014 is for 3.3V



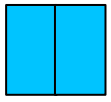
Practical audio

- Electret mic with amplifier on ADC input pin
- Convert from 10-bit to 8-bit sample
- 8Khz sampling gives 64000bps
- 4Khz sampling gives 32000bps





```
100 8-bit samples (12.5ms or 25ms)
-----------------------------------------------------------
```



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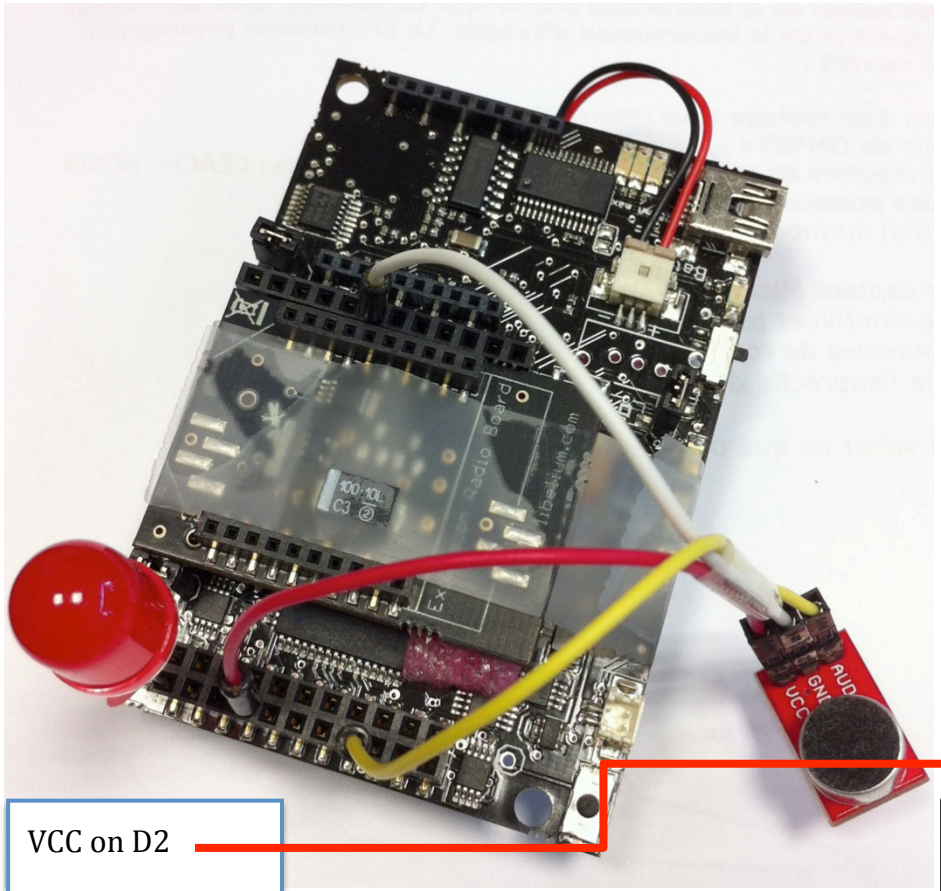
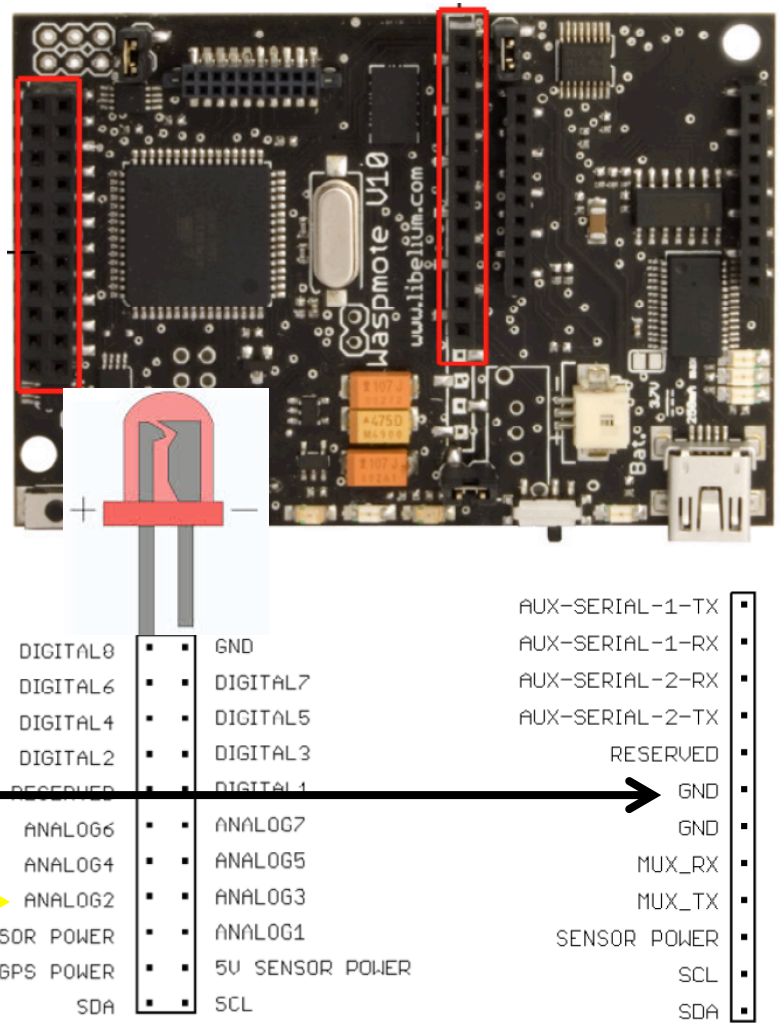
DETAILS OF PIN CONNECTION



VCC on D2

AUDIO on A2

GND on GND



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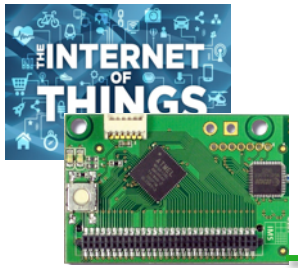
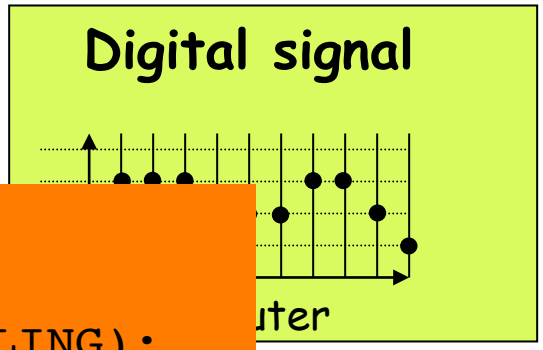


Simple program

```
#define TIMING_SAMPLING 125 // 8000Hz
#define CAPTURE_DURATION 15000000UL // in us 15s
#define SAMPLE_COUNT_CAPTURE CAPTURE_DURATION/TIMING_SAMPLING

void setup() {
  Timer1.initialize(TIMING_SAMPLING);
}

void ca

  sampl

  if (s

    val
    val

    // write on UART1
    ser
  } els

    sto

    Timer1.detachInterrupt();
  }
```

```
void setup() {
  Timer1.initialize(TIMING_SAMPLING);
}
```



of sound pressure level,

Or any other way to put the sample into

```
val = analogRead(ANALOG2) ; // read analog value
val8bit = ((val >> 2) ) ; // convert into 8 bit
```

```
// we have to wake up
if (millis() - lastSleepTime > 15000 && !capturingAudio) {
                sampleCount=0L;
                lastWakeupTime = millis();
                capturingAudio = true;
                    Timer1.attachInterrupt(callback);
}
```

```
                Timer1.attachInterrupt(callback);
    }
}
```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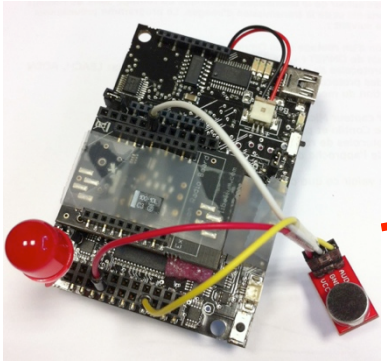
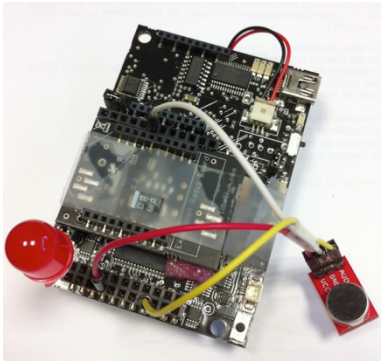
Use deployed low-resource IoT node to enhance acoustic services





To what extend digital audio traffic can be supported by low-resource IoT nodes?

Play/store received Audio data

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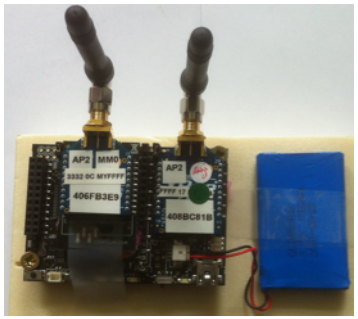
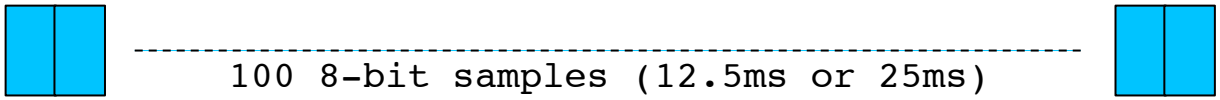
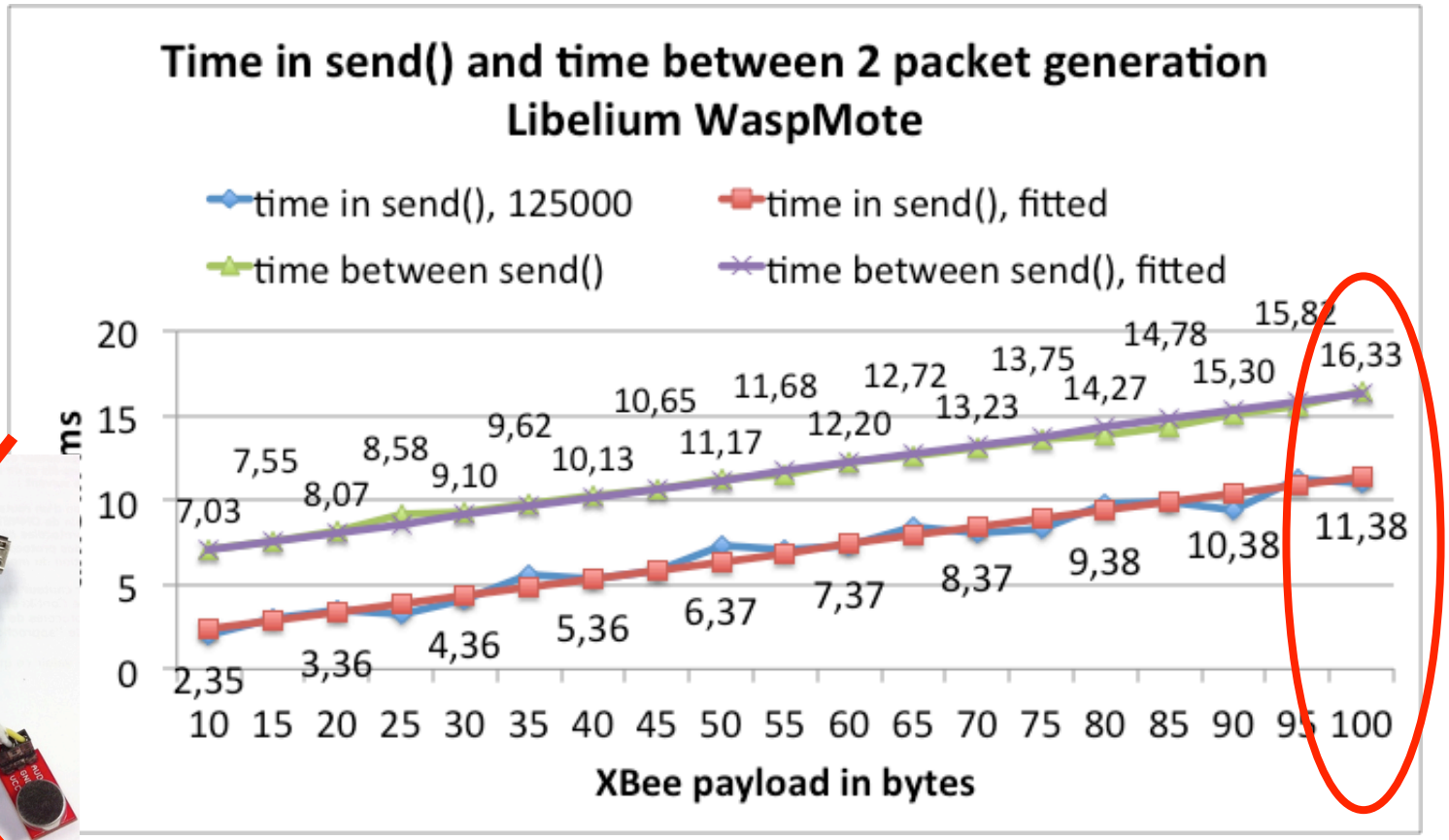
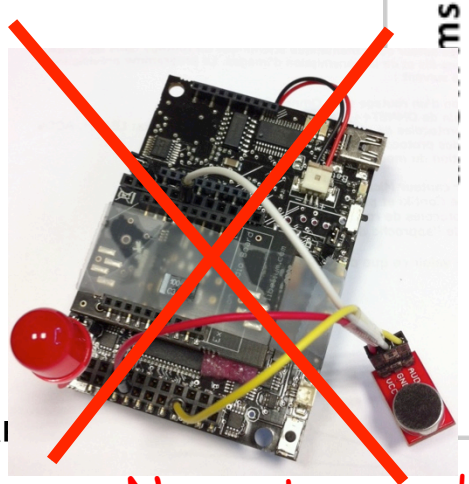
IoT node sending performance



Libelium WaspMote







No capture and transmission at the same time if using only mote ucontroller!

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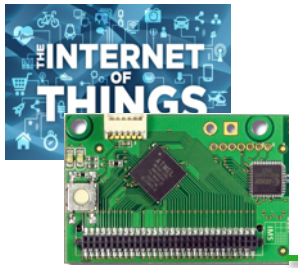
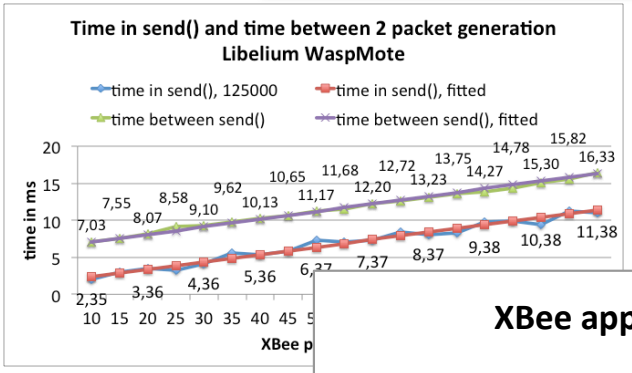
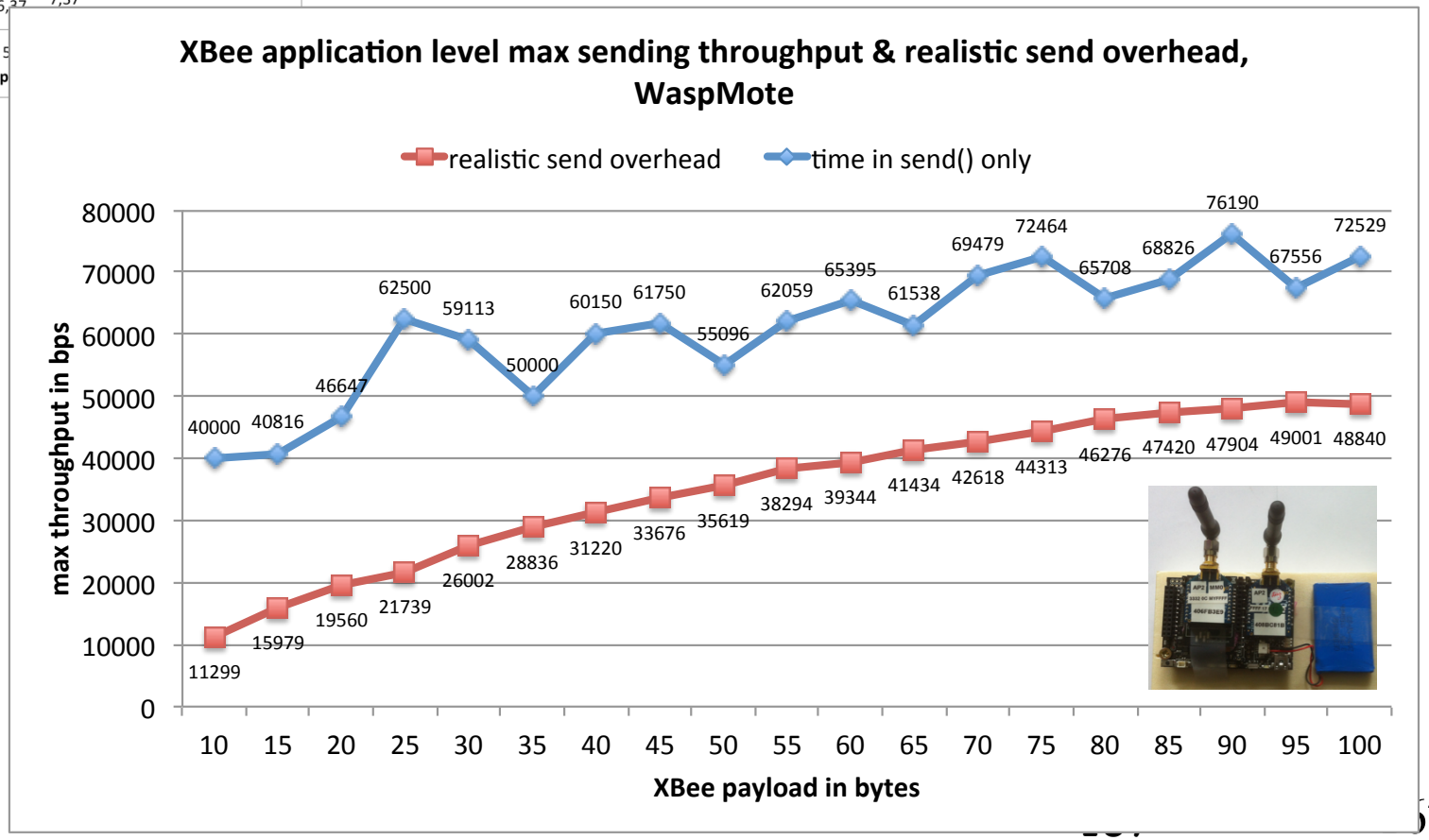
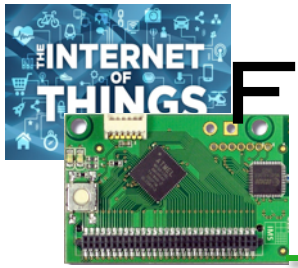


Maximum app. Level throughput







First solution: use XBee ucontroller

- XBee 802.15.4 radio module has an embedded ucontroller that can perform framing tasks
- So called transparent mode or « serial line replacement » mode (AP0)
- Application provides payload, e.g. « hello », and XBee fills-in framing information
- Limitation is no dynamic destination address

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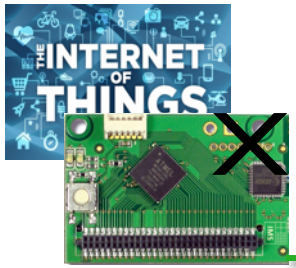


XBee and XBee gateways

IEEE 802.15.4 MAC frame format

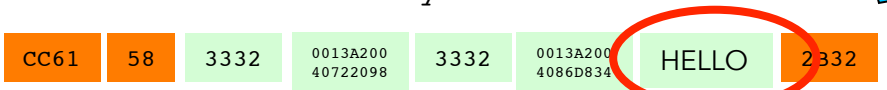
Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN	Destination Address	Source PAN	Source Address	Auxiliary Security Header	Frame Payload	FCS
CC61	58	3332	0013A200 40922078	3332	0013A200 4086D834		HELLO	2B32
		Addressing fields						
MHR							MAC Payload	MFR

HELLO

64-bit 0x0013A2004086D834
16-bit 0x0010
PANID 0x3332

View as a serial port /dev/ttyUSB0

Some hardware give access to Link-layer information

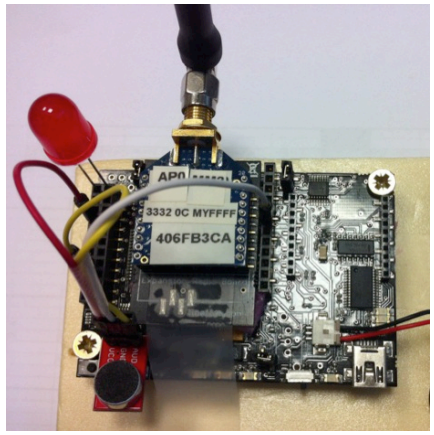


HELLO

Transparent mode
Or Serial line replacement mode

HELLO

Example with XBee & XBee GW APO



```
void loop() {
        val = analogRead(ANALOG2) ; // read analog value
        val8bit = ((val >> 2) ) ; // convert into 8 bit
        // write on UART1, need an XBee module
        // with AP mode 0
}
```

XBee radio in APO mo

Can support up to 8kHz raw audio, but:

1/ quickly saturates the radio medium, i.e. one 100-byte frame every 12.5ms

2/ only 1-hop communication

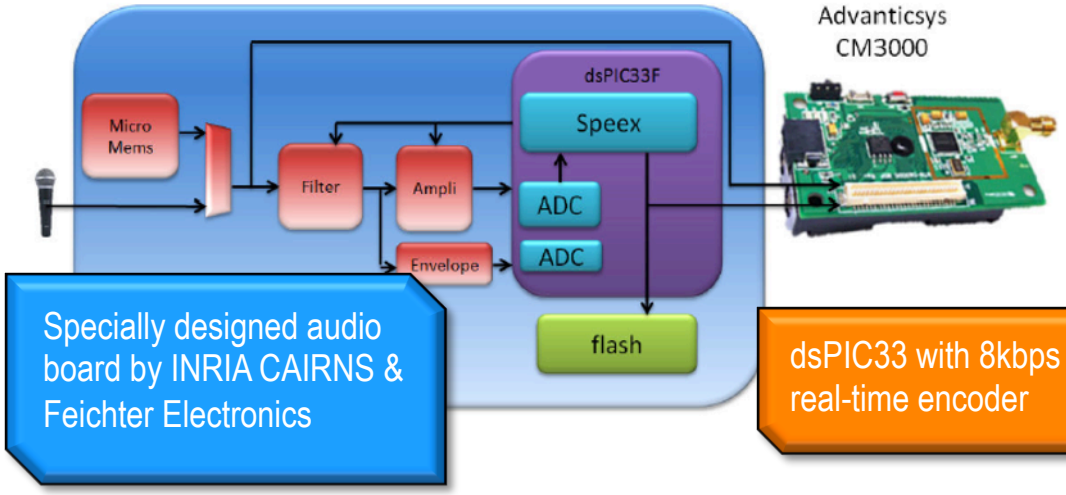
also in APO mode

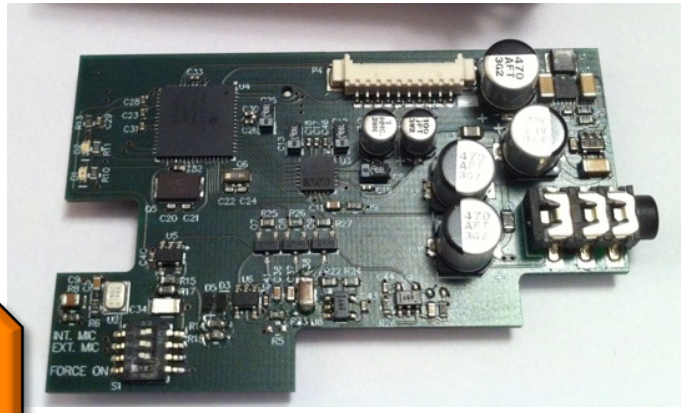
Use python script to read serial port /dev/ttyUSB0

```
> python SerialToStdout | play --buffer 50 -t raw –r 8000 -u -1 –
```

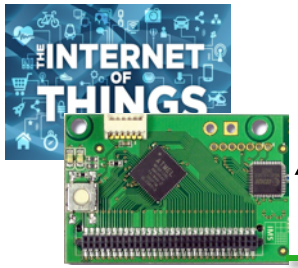
2ND SOLUTION: DEV. OF AUDIO BOARD

- Use dedicated audio board for sampling/storing/encoding



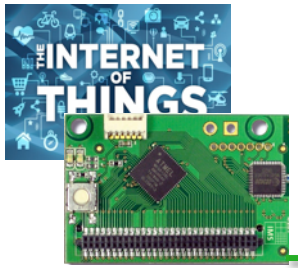


- Encoding scheme is Speex at 8kbps
- Designed for multi-platform motes
- Can be plugged to other boards (UART)

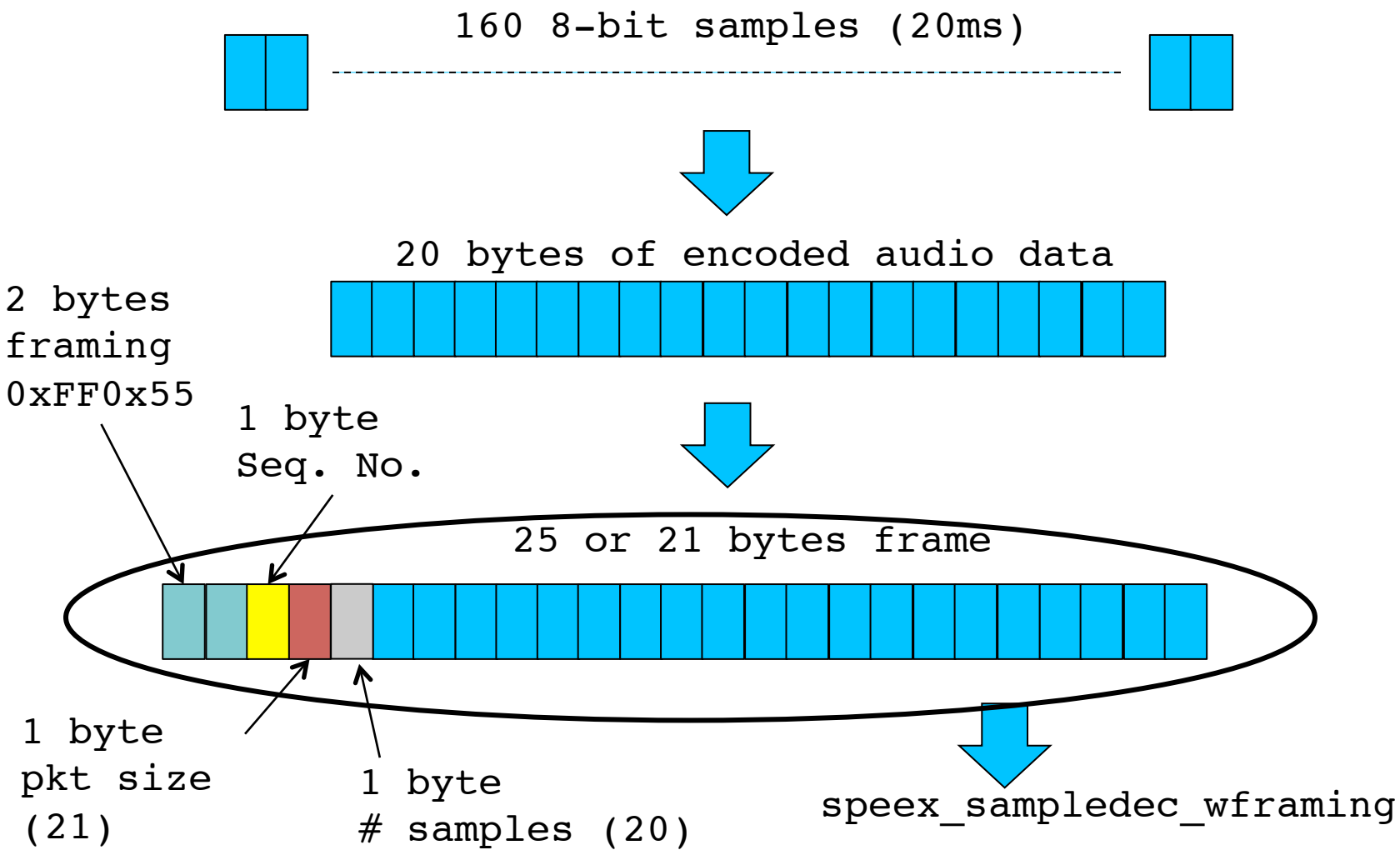


Audio board principle

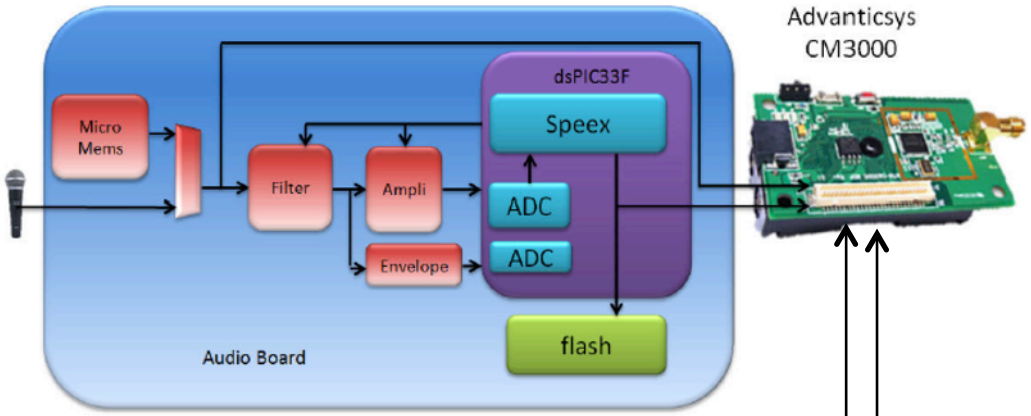
- The audio board captures 160 bytes (20ms) of raw audio and uses speex codec at 8kbps to produce 20 bytes to encoded audio data
- It sends the encoded audio data through an UART line to the host micro-controller
- The host micro-controller receives the encoded data and sends them wirelessly to the next hop
- The last hop is a base station that will forward the encoded audio into a speex audio decoder
- Output of the speex audio decoder is in raw format that can be feed into a player (`play`)



SPEEX AT 8KBPS

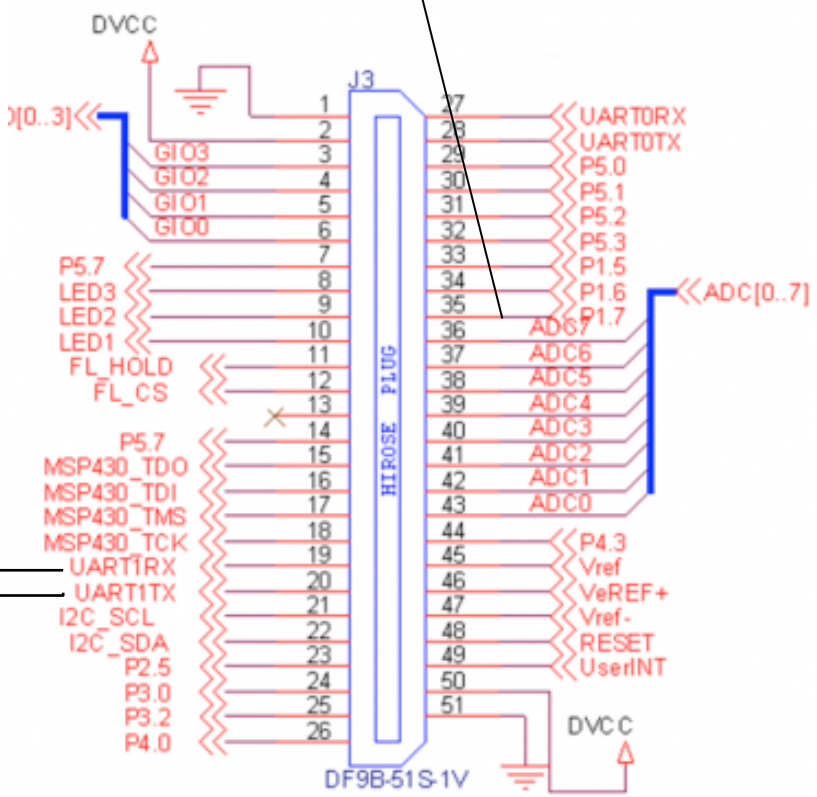


Audio board on TelosB



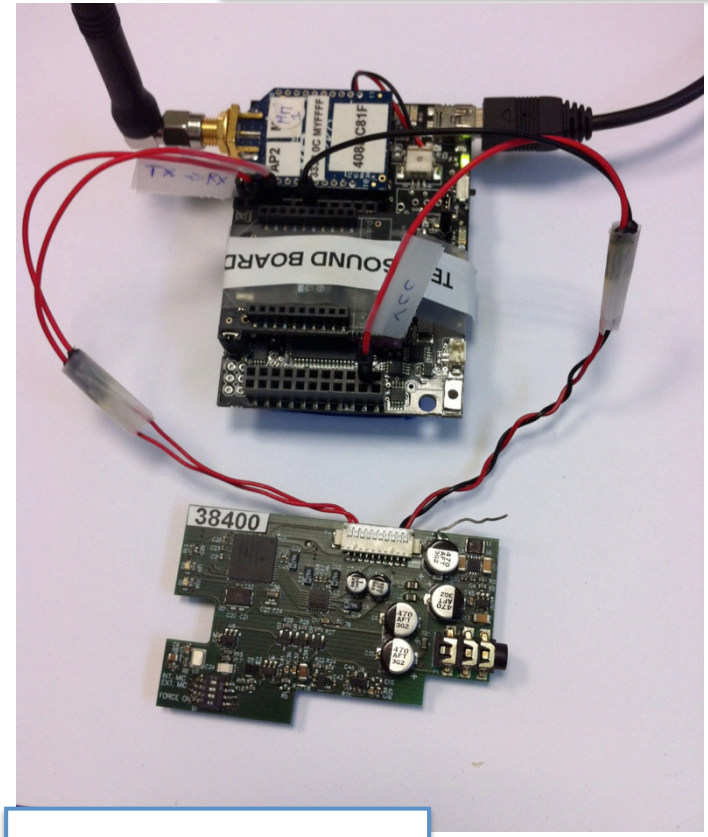
Advanticsys CM3000

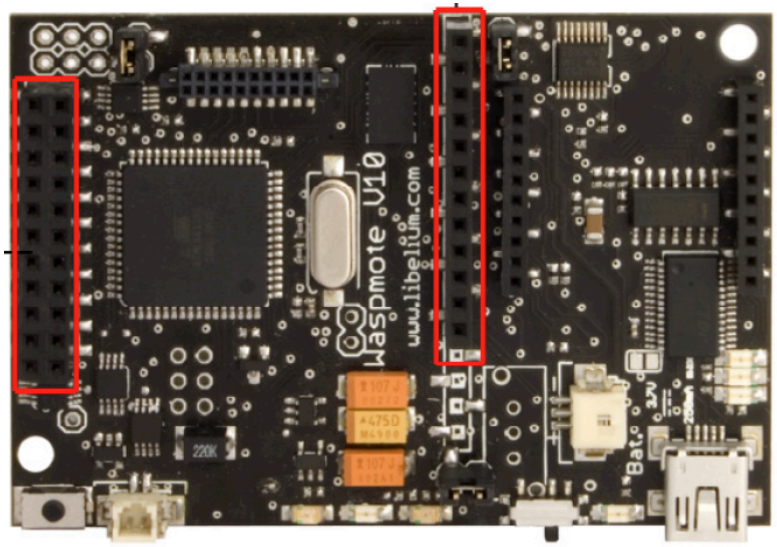
P1.7 can be used to power on/off the audio board

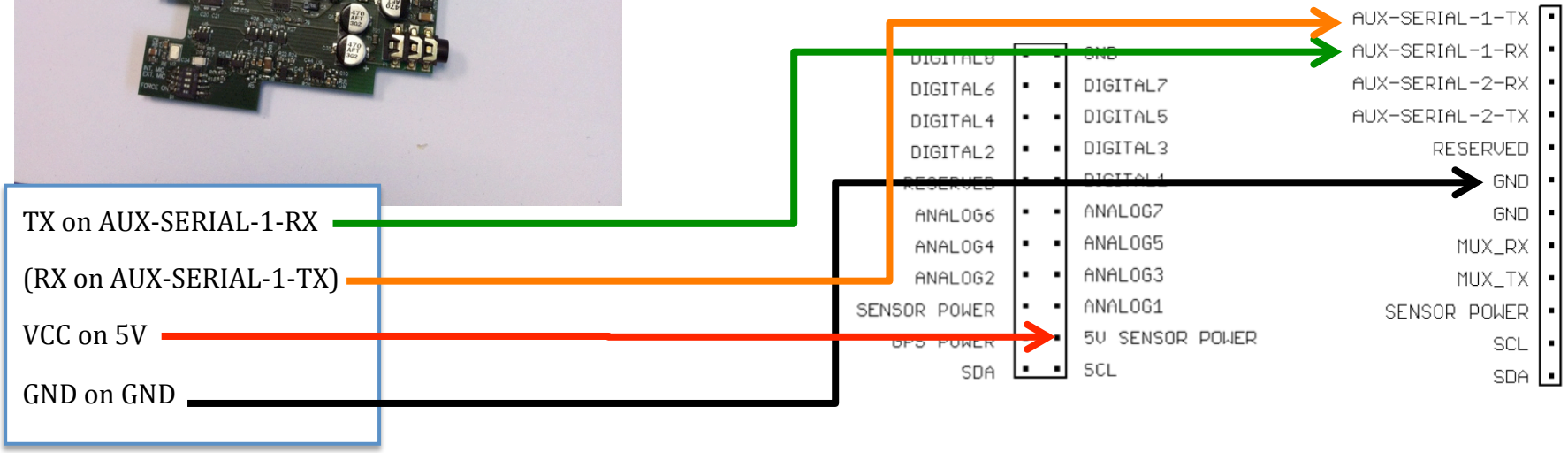


Initial development on AdvanticSys TelosB mote. Encoded audio data transferts are realized with UART (serial) communication so easy to connect to other sensor boards.

Audio board on WaspMote







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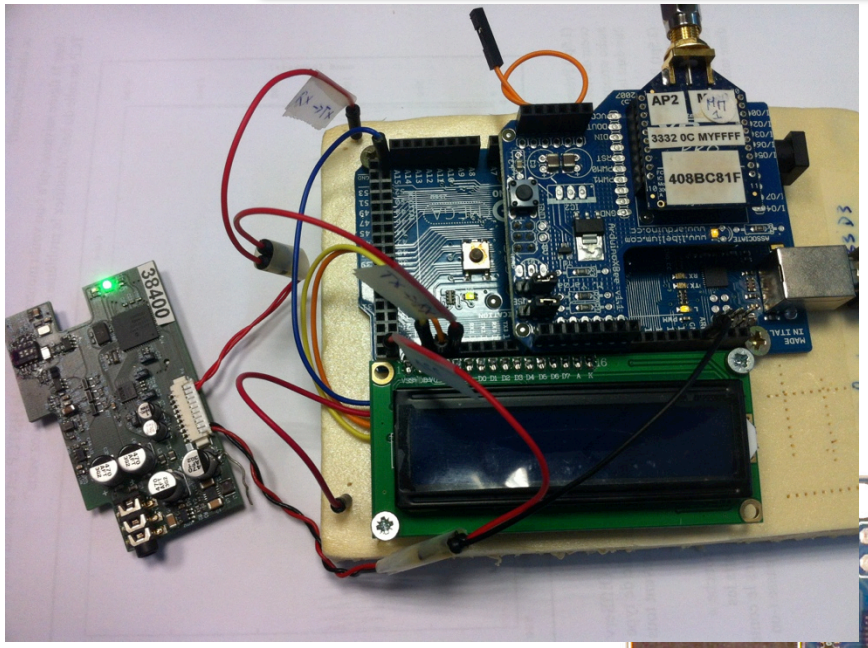
Audio board on Arduino MEGA

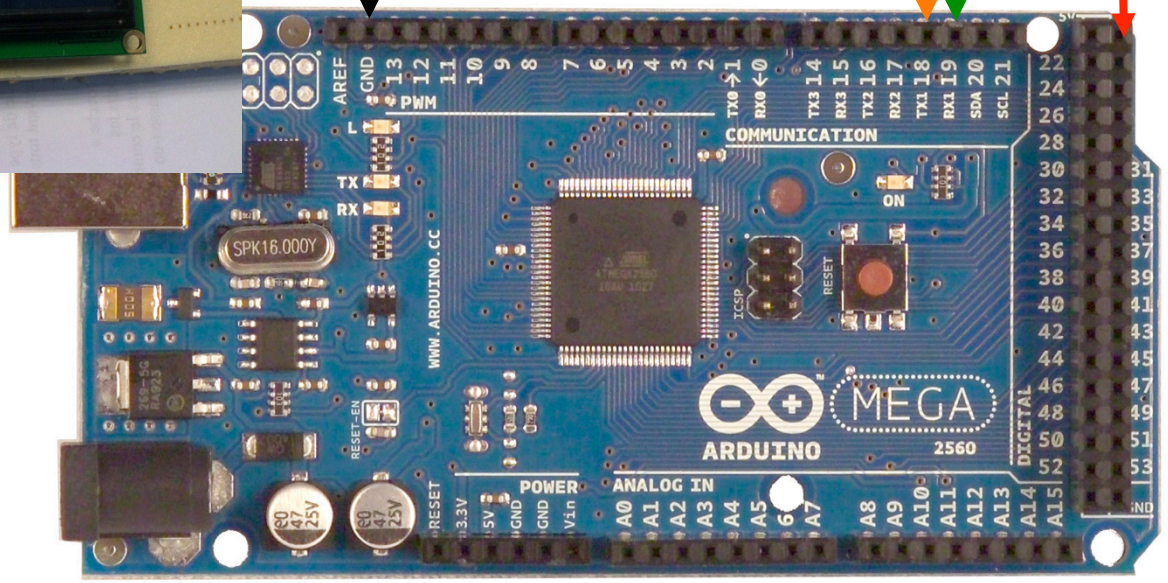


TX on RX1 (pin 19)

(RX on TX1) (pin 18)

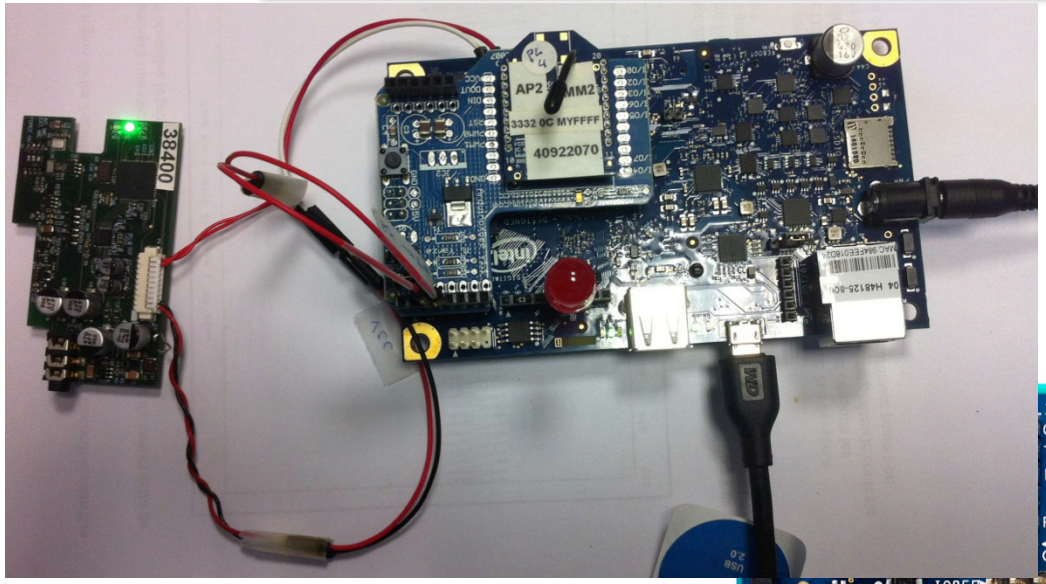
VCC on 5V

GND on GND



Set on FORCE ON, then trigger audio transmission with command /@C1#

Audio board on Intel Galileo v2

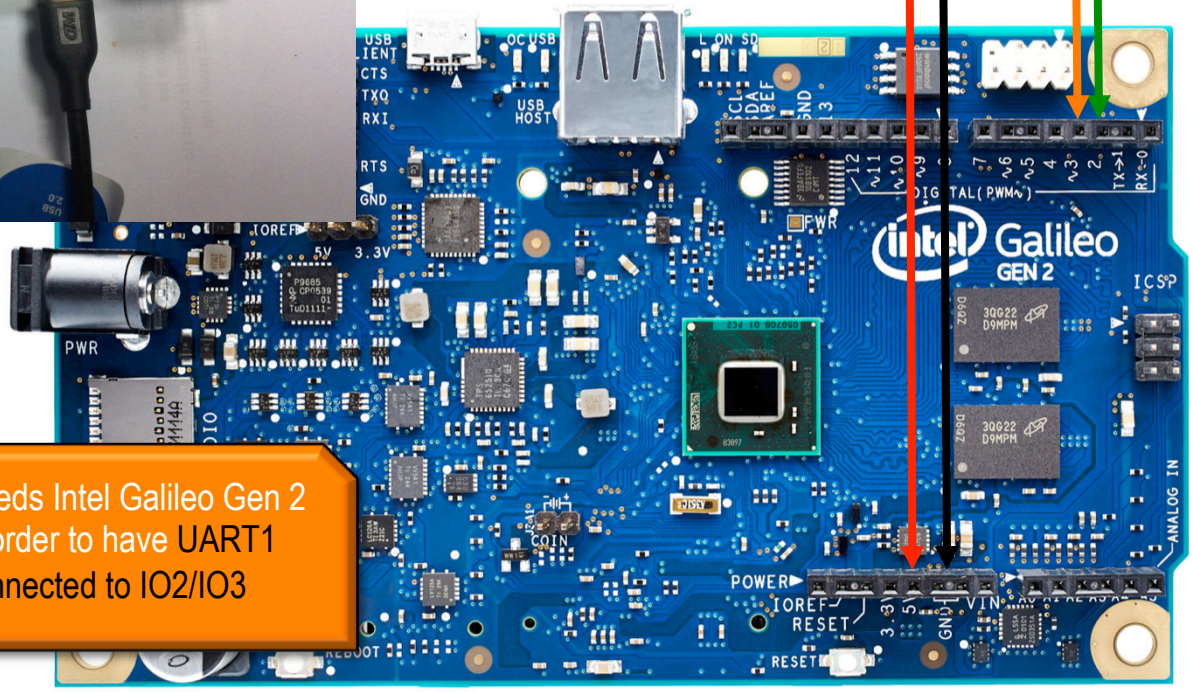


TX on RX (pin 2)

(RX on TX) (pin 3)

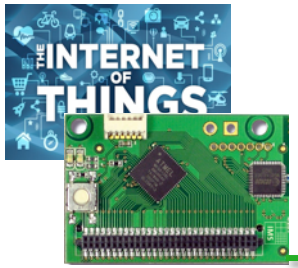
VCC on 5V

GND on GND



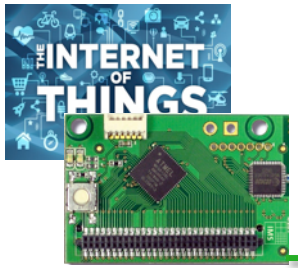
Set on FORCE ON, then trigger audio transmission with command /@C1#

Needs Intel Galileo Gen 2 in order to have UART1 connected to IO2/IO3

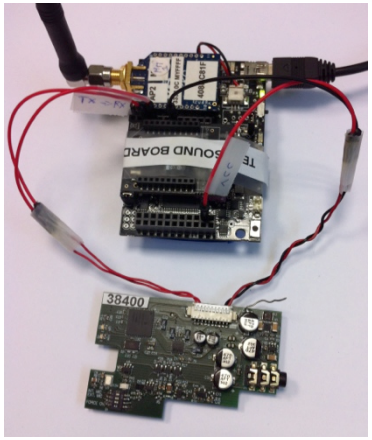


Summary of audio constraints

Codec	Minimum sending rate
Raw 4KHz 8KHz	 100 bytes every 25ms 100 bytes every 12.5ms
Speex 8000bps A1 A2 A3 A4	 24 bytes every 20ms 48 bytes every 40ms 72 bytes every 60ms 96 bytes every 80ms

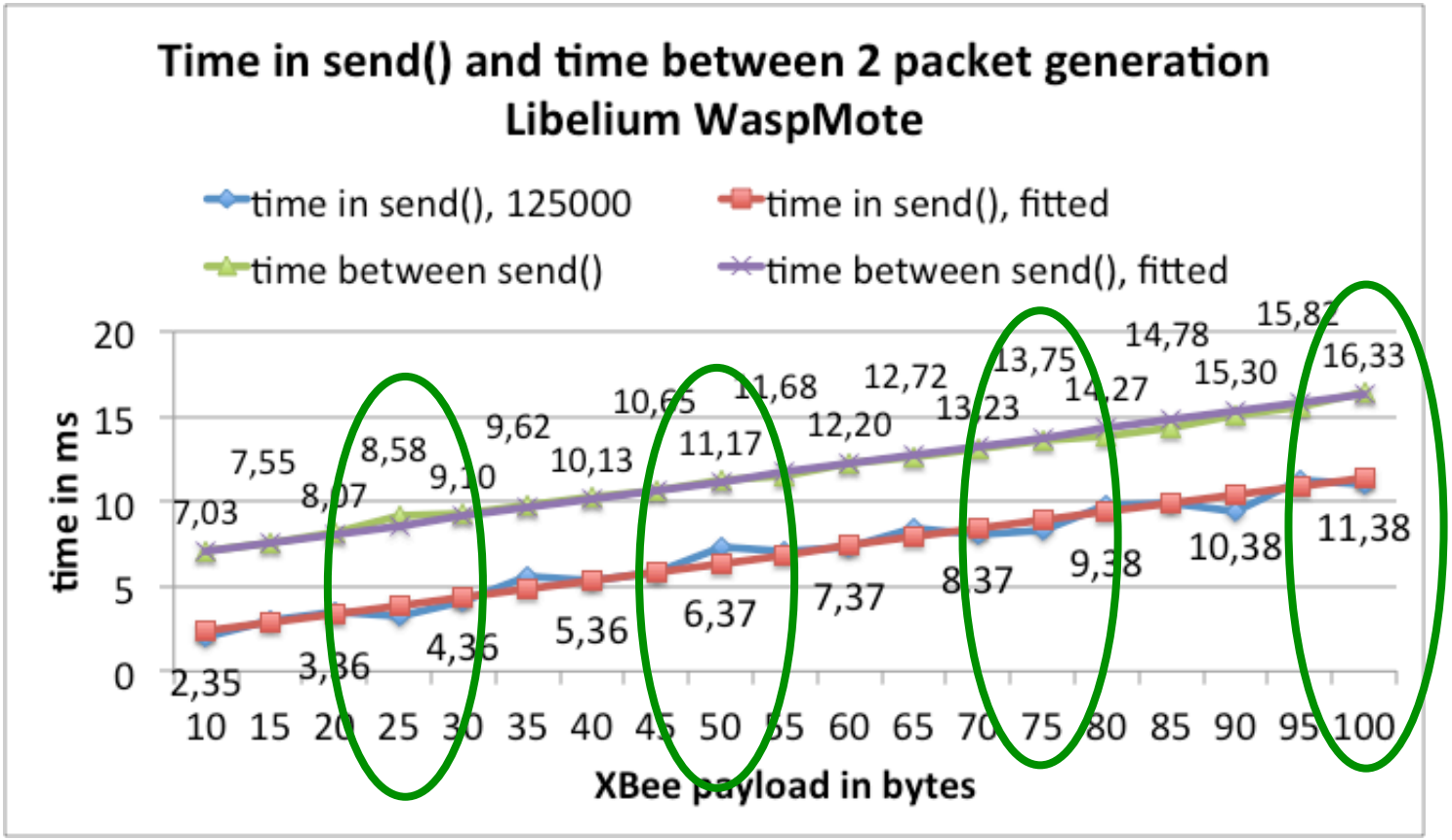


IoT node sending performance

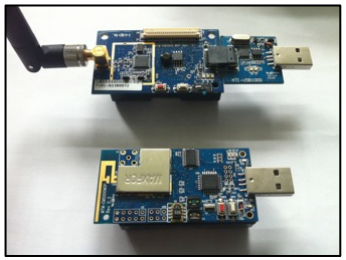


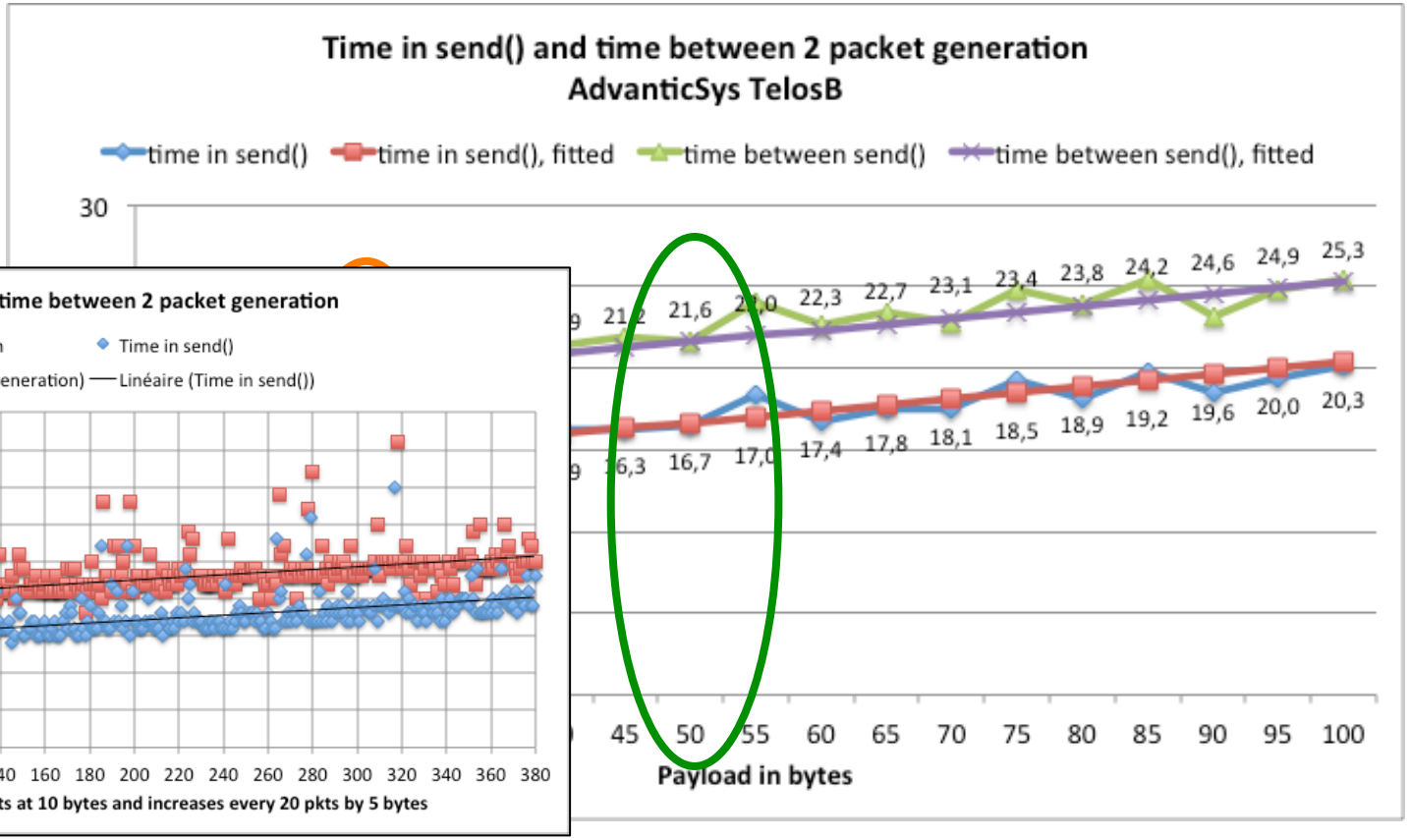
Libelium WaspMote

25 bytes every 20ms



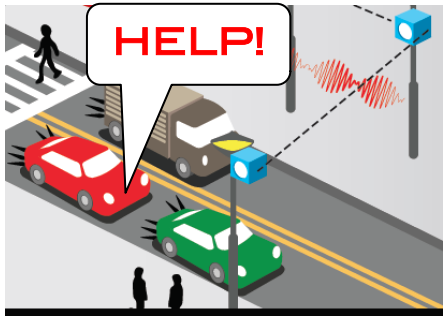
IoT node sending performance

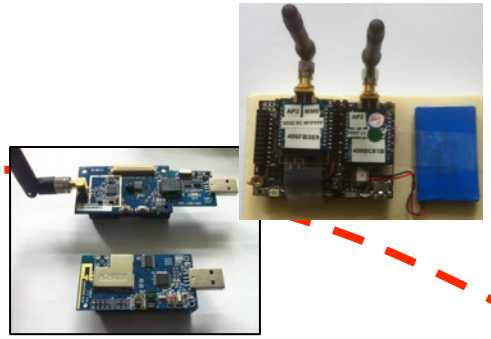


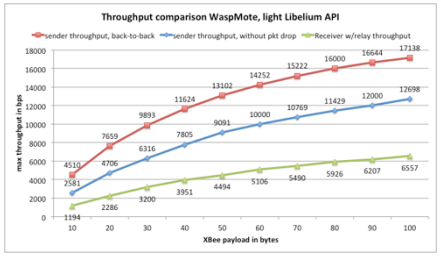


Better with A2 agregation

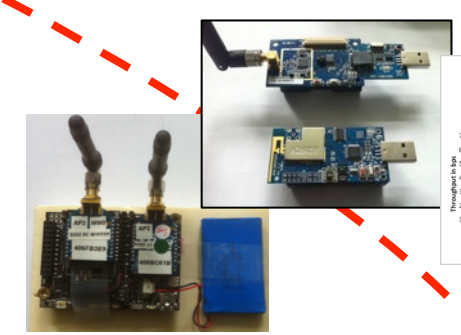
Multi-hop audio constraints

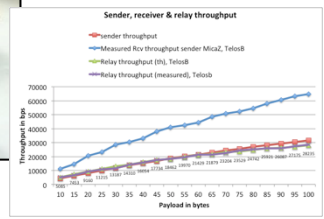




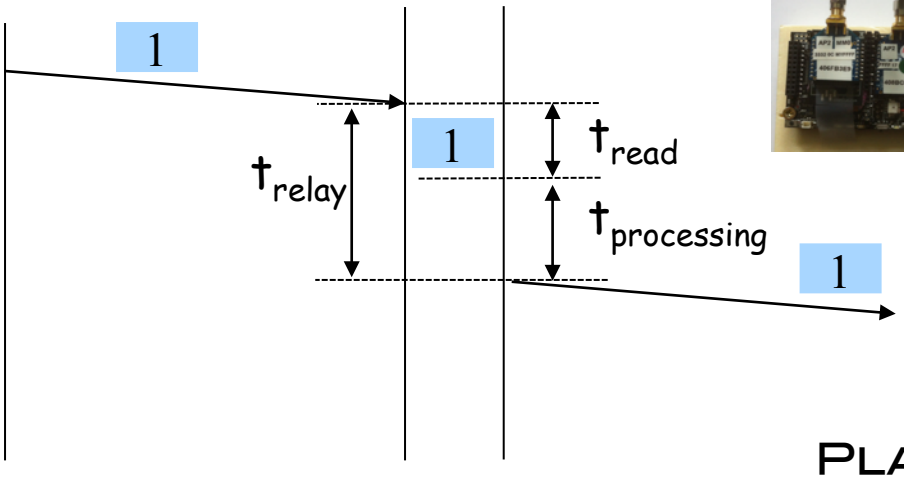


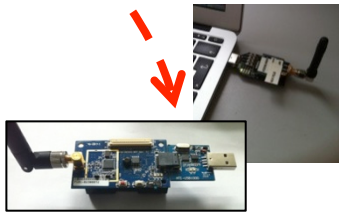
Relay





Relay





Play/store received audio data

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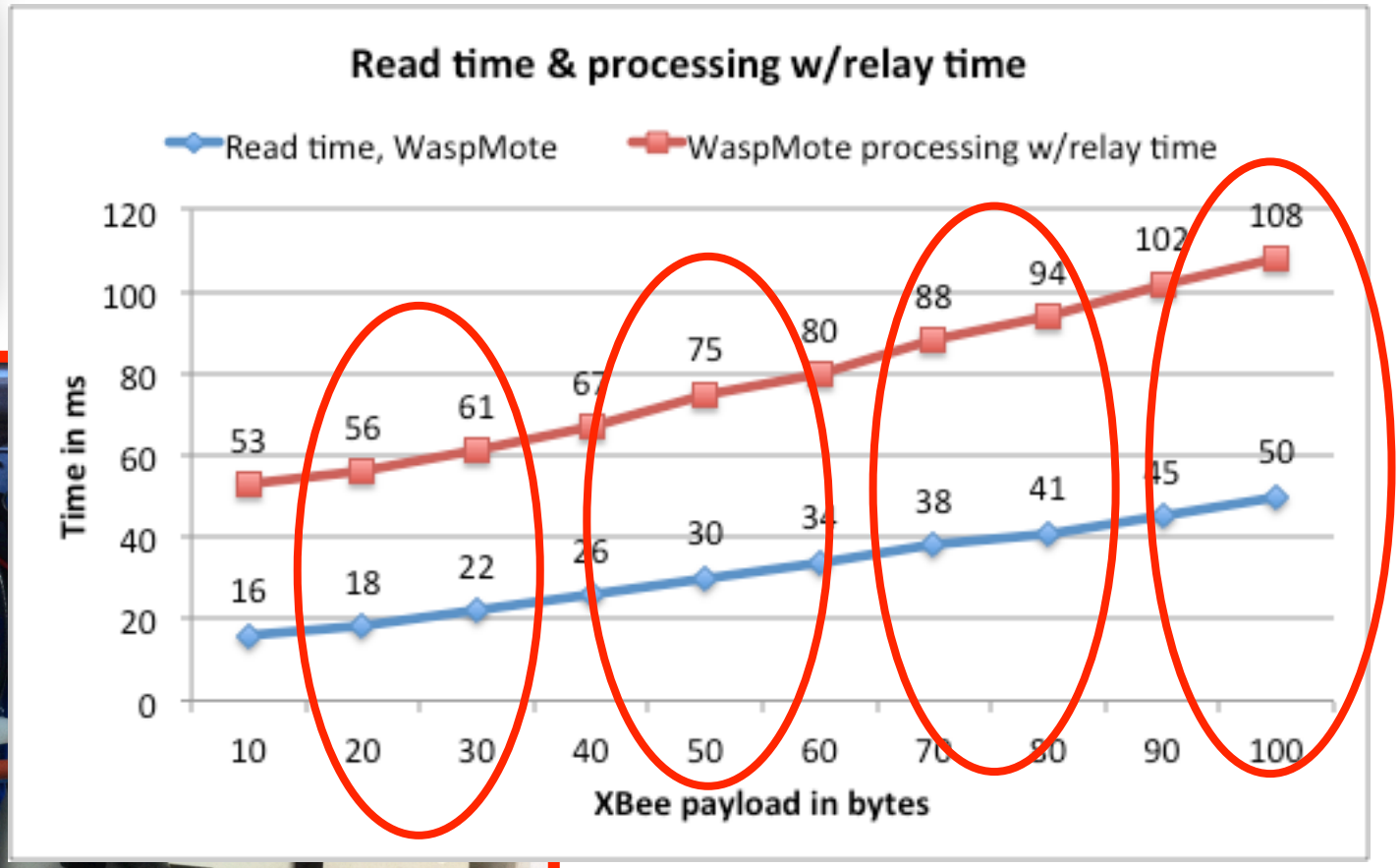
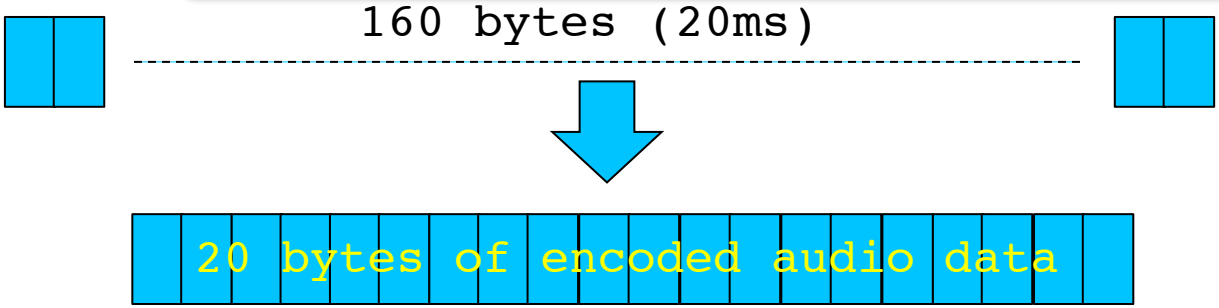
SANTANDER'S LIMITATIONS



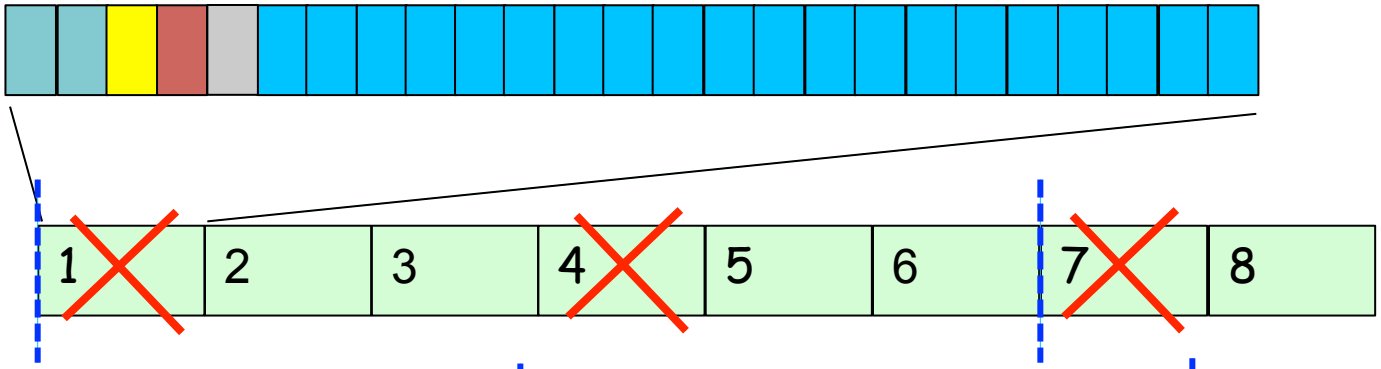
SmartSantander's IoT node uses 38400 baud rate for communication between XBee radio and host ucontroller

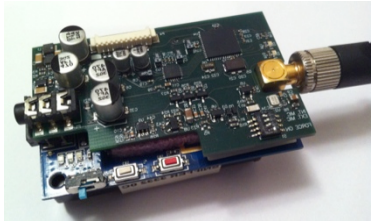
Needs to discard audio frame at the source to increase the time window

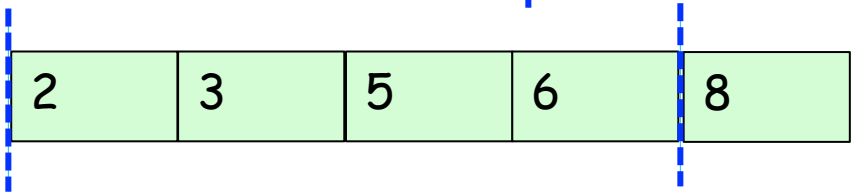
SPEEX AT 8KBPS ON SLOW RELAY NODES



Add framing bytes



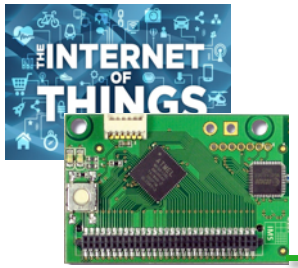




A6 aggregate audio frames

Capture 6 audio frames (120ms) but only send 4

Need to be able to relay 100-byte pkt every 120ms



Conclusions

- Internet of Things, like Wireless Sensor Networks are the foundation of pervasive surveillance infrastructures
- Connecting them, collecting data and providing seamless internet connectivity is challenging but many standards have emerged
- Going beyong « simple » data to multimedia is still challenging on these low-resource platforms