Large Scale Wireless Network Systems: Experience, Observations, and Theories

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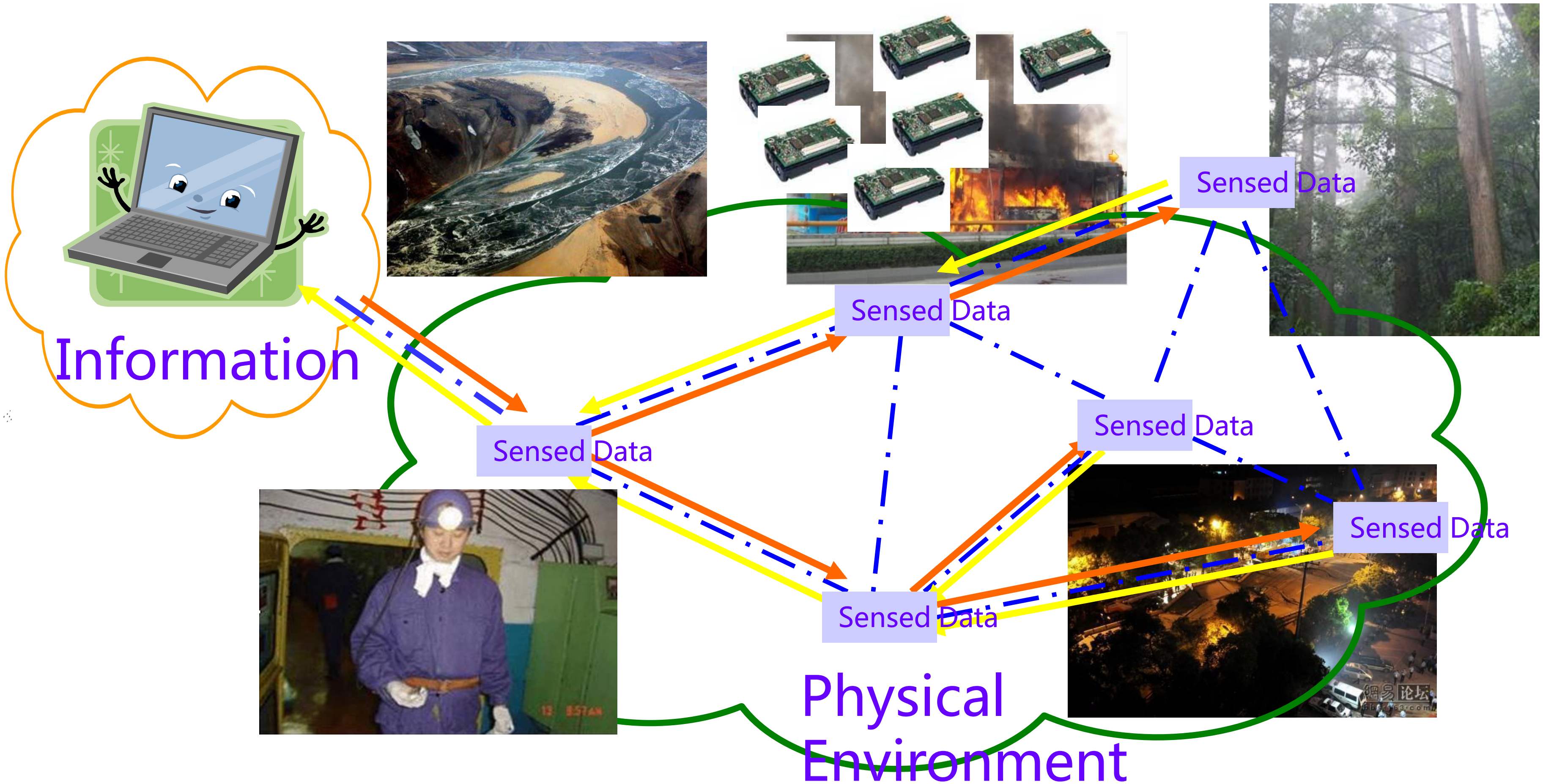
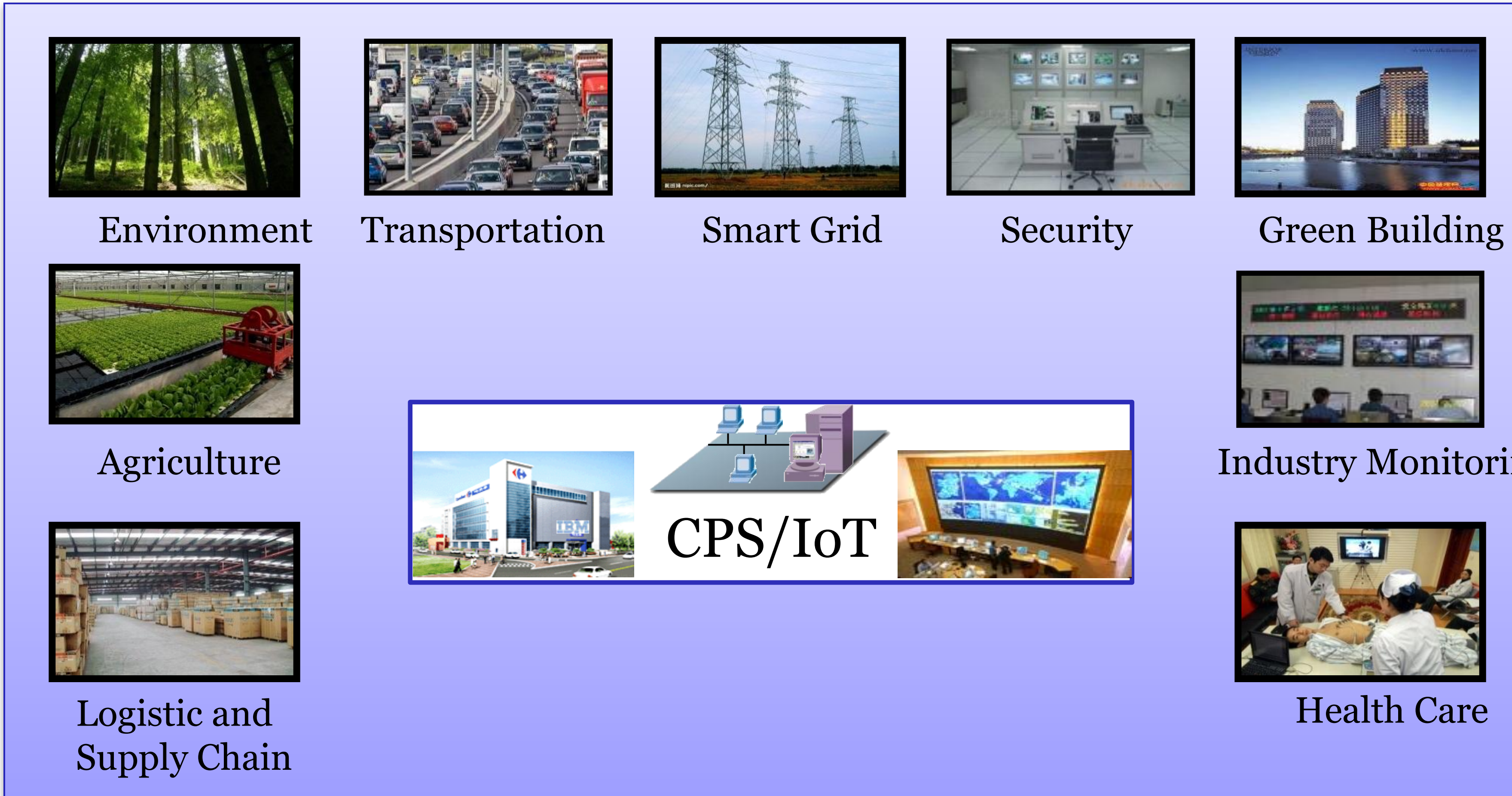
Wireless Sensor/Actuator Networks

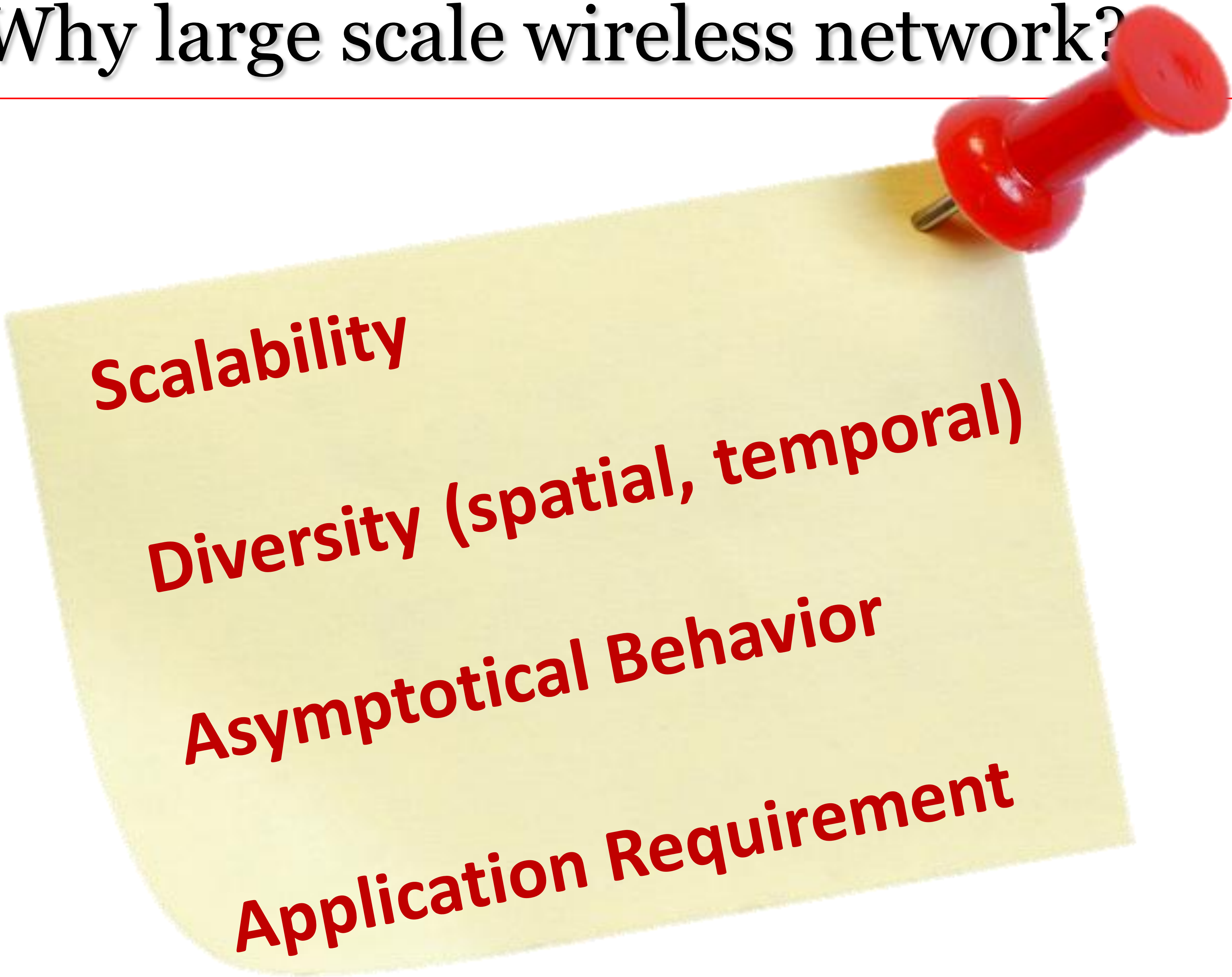
Bridging the digital world and physical world



Wide Applications: CPS, IOT

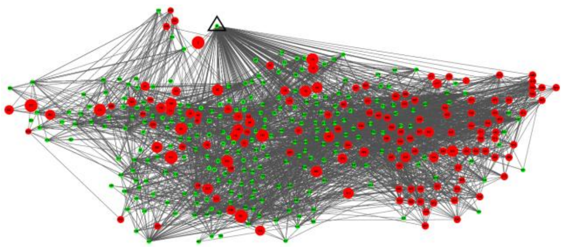


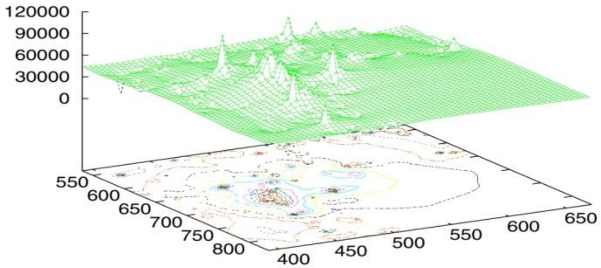
Why large scale wireless network?

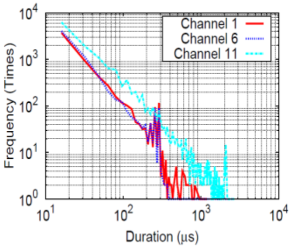


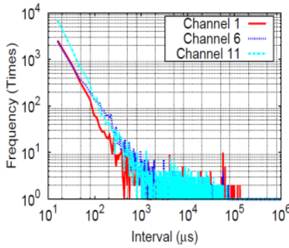
Presentation Outline

OceanSense | **GreenOrbs** | **CitySee**





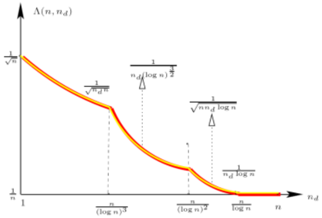




Networking observations

ZIMO: Coexistence

Capacity: the Limit



Real World Systems

1. OceanSense (2007)

2. GreenOrbs (2009-)

3. CitySee (2011-)

OceanSense

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Motivation

❖ Silt Deposition problem of Qingdao Port:

– Qingdao port :

➢ one of the ten busiest ports in the world

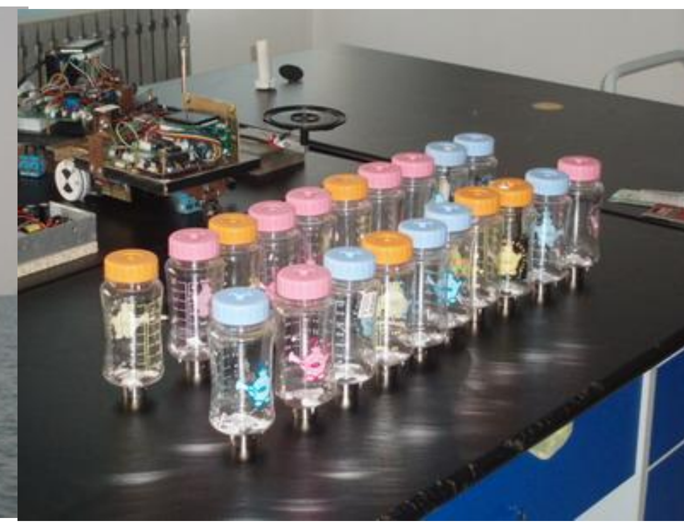
– Silt Deposition:

➢ Affect the water depth

➢ High uncertainty and high instant uncertainty (tide, wind, etc.)

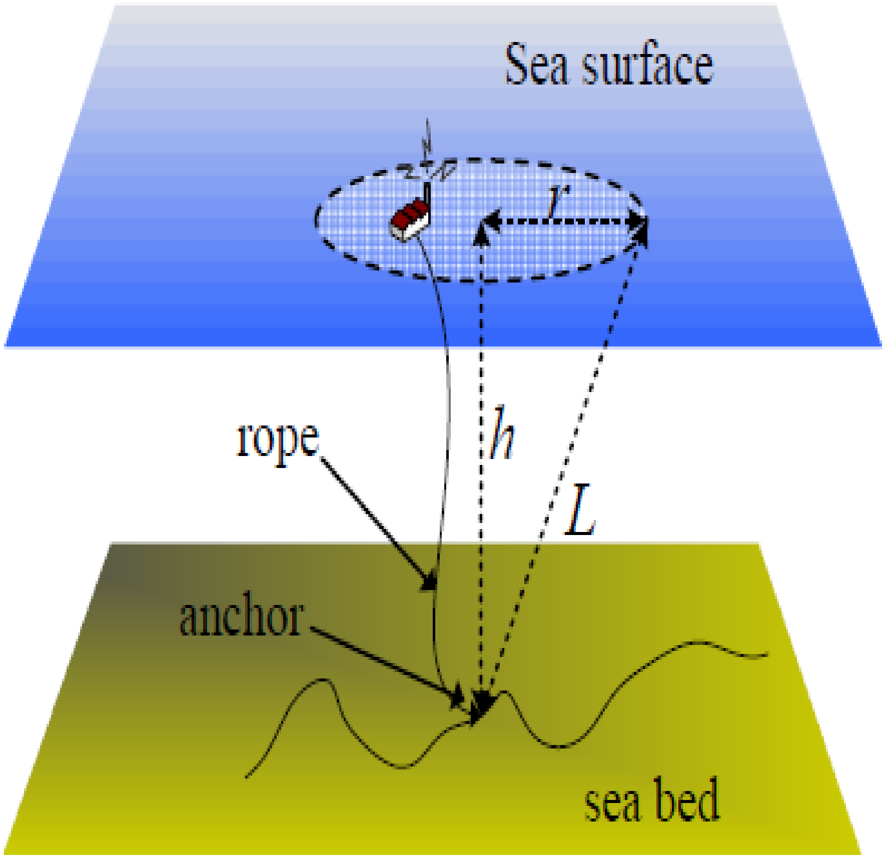
OceanSense

- Monitor the sea!
  - The first sea environment monitoring sensor network system in China
  - More than 120 sensor nodes
  - Temperature, Light, Sea depth



Deployment

- Deployed in the Yellow sea near Qingdao, China



GreenOrbs

http://www.greenorbs.org/

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Motivation

Carbon sequestration

Canopy closure estimates

Study on biodiversity

Fire risk evaluation

GreenOrbs

- Go to the wild!
  - Supporting forestry research and applications
  - Multiple deployments, each> 330 sensor nodes
  - Temperature, Light, CO2

Deployment: Overview

Place	Area	Duration	Battery	Scale	Network Diameter	Duty Cycle	Data Volume
University woodland #1	20,000 m^2	1 month (2008)	800 mAh 1.5V	50	6 hops	No	15 Mbytes
University woodland #2	20,000 m^2	10 months (2009)	2200 mAh 1.2V	120	10 hops	5%	272 Mbytes
University woodland #2 and #3	40,000 m^2	1 year (2009.12~)	~8000mAh, 1.5V	330	**12 hops**	8% or No	140 Mbytes
Tianmu Mountain	200,000 m^2	1.5 months (2009)	~8000mAh, 1.5V	50	10 hops	5%	3 Mbytes
Tianmu Mountain	200,000 m^2	1.5 year (2009.10~)	~8000mAh, 1.5V	200	**~ 20 hops**	5%	10 Mbytes

Campus

TianMu Mountain

Deployment: Nodes in the Wild

CitySee

City-Wide Urban Sensing

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Motivation: Global Warming

- Starting from Global Climate Changes
  - Emission of large volume of greenhouse gases is the main reason for global warming
    - CO_2, N_2O, CH_4, HFCs,PFCs,SF_6
  - The most greenhouse gases is CO_2
  - CO_2 generation of human activities: in the city

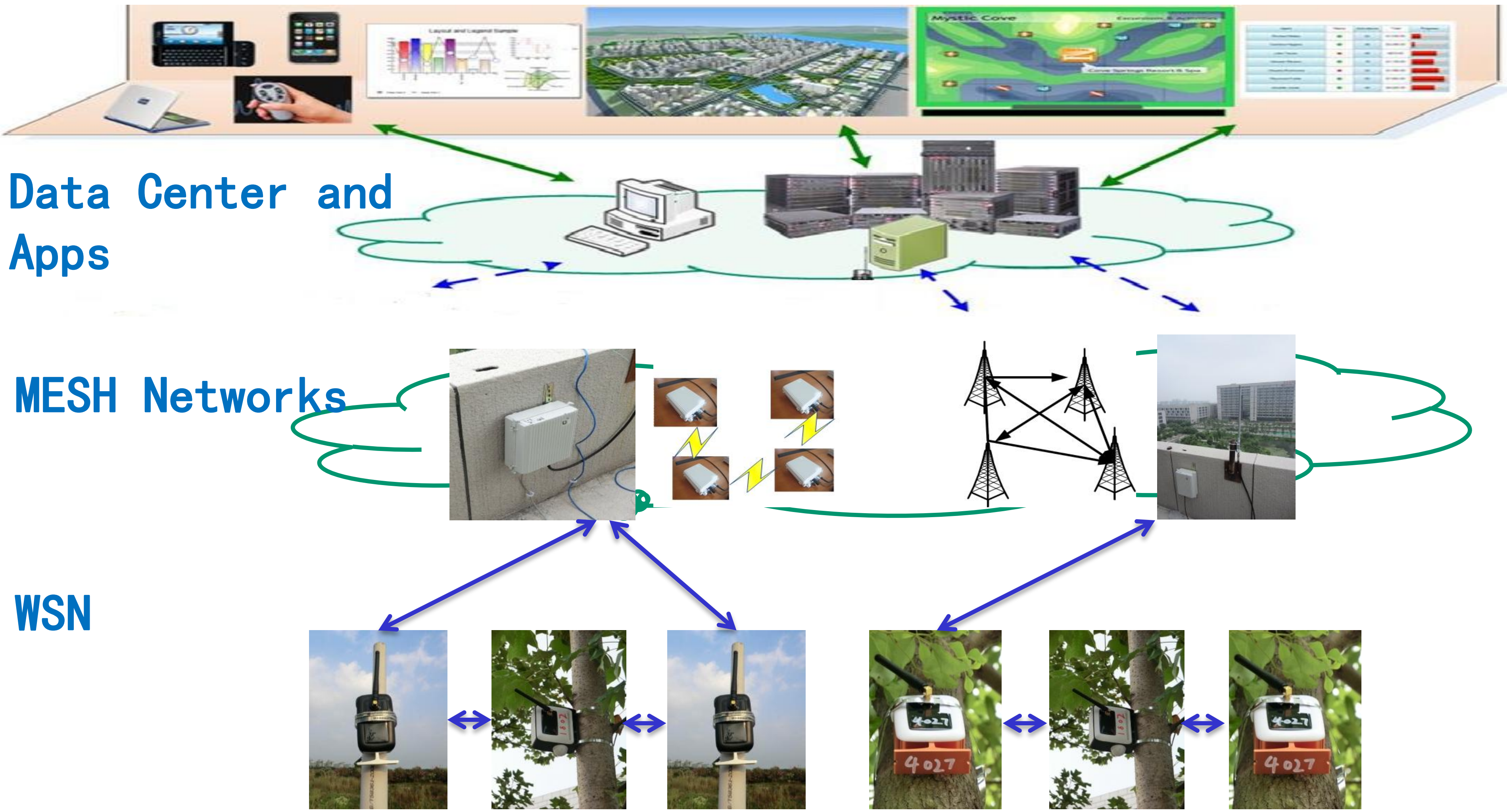





CitySee

- ❖ Back in the city!
  - Large scale indoor/outdoor environment monitoring
  - More than 1200 sensor nodes
  - Temperature, Light, CO_2
  - Mesh routers

System Architecture



Deployment: Locations

Cover more than 1.2 KM^2 urban area of the Wuxi City

Thermal Power Plant

High emission Factories

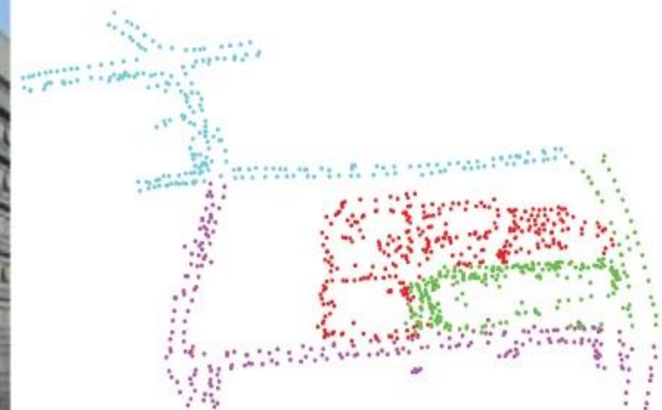
Residential Area

Water Source

Development Zone

Railway Station

System Deployment



Deployment: Nodes Deployed

	Normal node	Carbon node	Mesh node
Microcontroller	MSP430f1611	MSP430f1611	ARM7
Type of sensor reading	Temperature, humidity, light.	CO_2	N/A
Radio module	IEEE 802.15.4 CC2420 2.4GHz	IEEE 802.15.4 CC2420 2.4GHz	IEEE 802.11b NetCard 5.8GHz
Communication range (m)	150~200	150~200	5000~6000
Power	2 AA batteries (3V)	12V Rechargeable battery	110V~220V AC
Power consumption - sleeping (mW)	0.6~1.2	2.4~4.8	N/A
Power consumption - sensing (mW)	60~90	~2160	N/A
Power consumption - communication (mW)	60~90	60~90	3000~25000
Manufactory cost (USD)	~80	~260	~800

Presentation Outline

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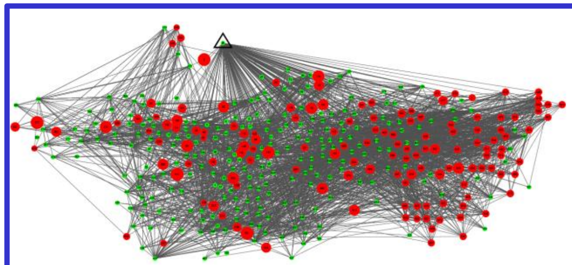
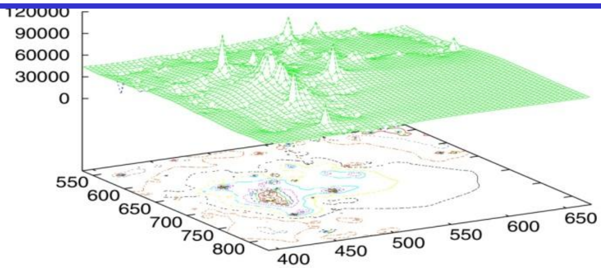
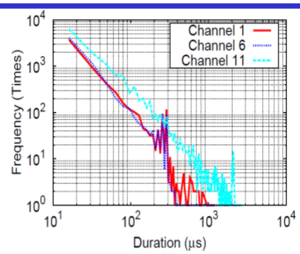
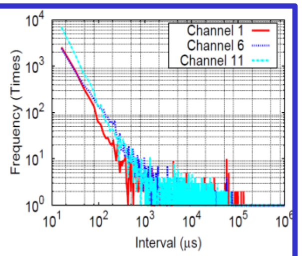
GreenOrbs

CitySee









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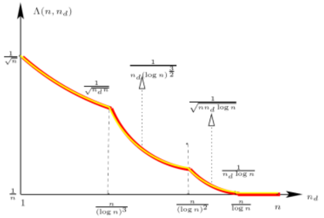


LESSONS

Lesson 1

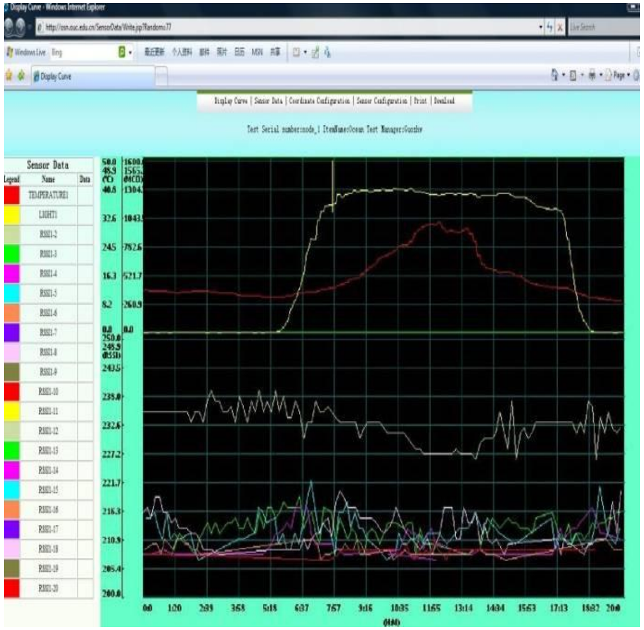
- System that work in labs fails horribly in practice
  - OceanSense:
    - System run out of battery in a week (labs run in months)
    - Nodes destroyed by water
    - Devices stolen by people: they are interested in the sticks!
  - GreenOrbs:
    - Nodes destroyed by flooding
  - CitySee:
    - Installation needs the coordination of various government departments
    - Require nice encapsulation

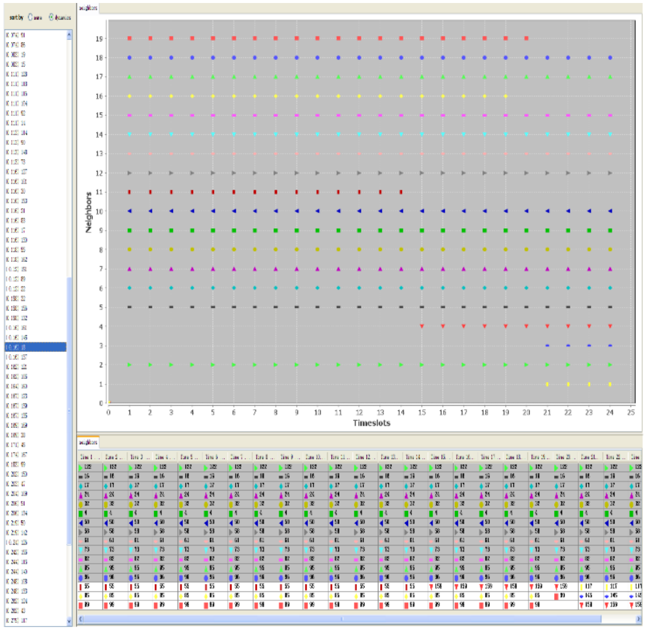
Lesson 2

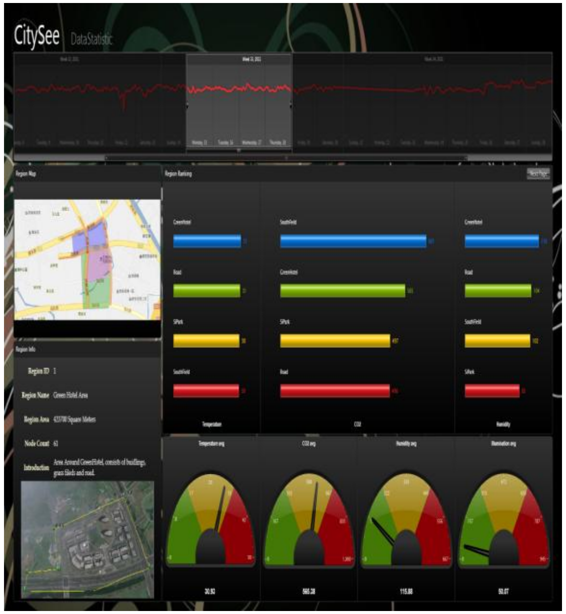
- Encapsulation? Encapsulation!
  - Solutions to many of the previously mentioned problems
  - OceanSense:
    - Waterproof, considering factors such as tide, wind, etc.
  - GreenOrbs:
    - Waterproof, allow accurate collection of humidity and luminosity
  - CitySee:
    - Made the nodes nice-looking!

Lesson 3

- Need good visualization tools
  - Allow diagnostics
  - Easy to interpret the data and locate the problems







Lesson 4

❖ Deployment

– Balance between accuracy, coverage, sustainability and cost

– Regions that doesn't allow deployment

➢ Not allowed by the nature (physically infeasible)

➢ Not allowed due to bad signal (interference, obstruction, etc)

➢ Forbidden by the government

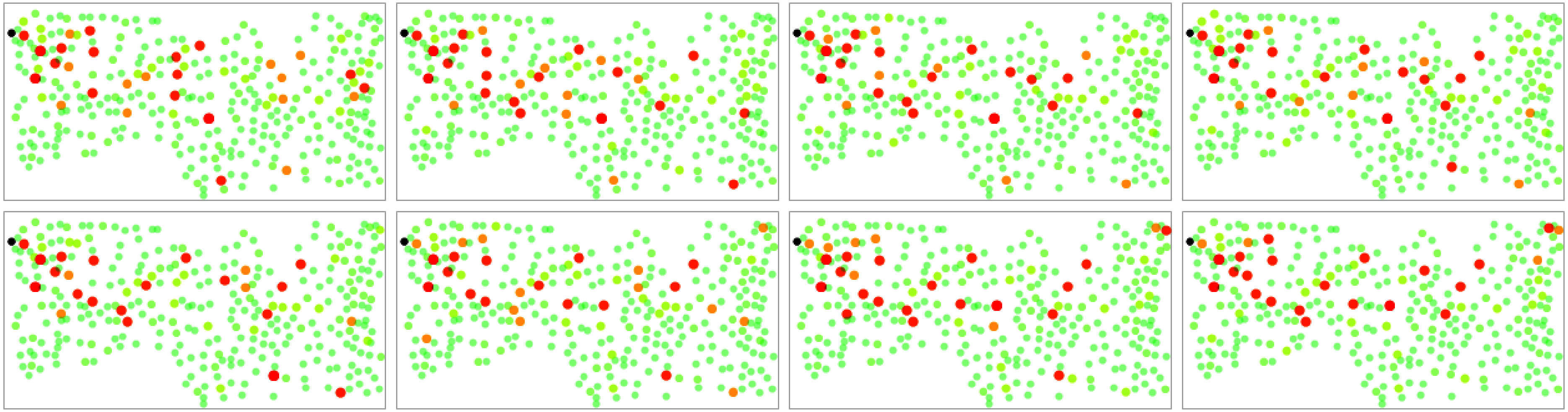
– Deployment challenges: bamboo, large trees

Lesson 5

- Control the cost!
  - Cost reduction is a must when you need so many nodes
    - Node cost
    - Labor cost

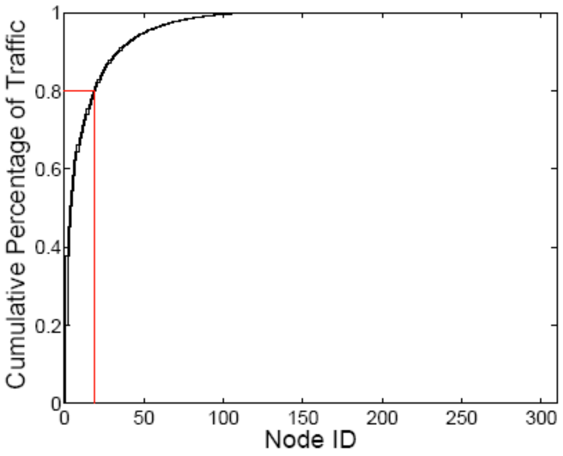
NETWORK OBSERVATIONS: GREENORBS

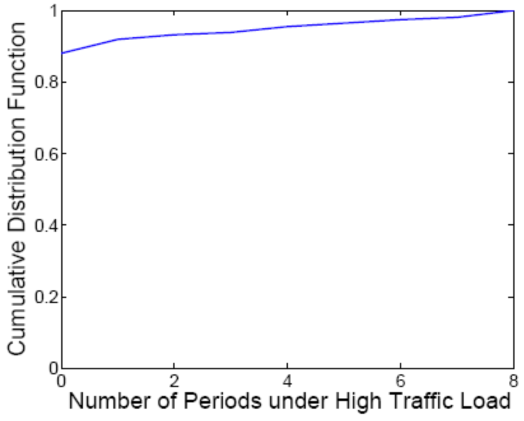
Traffic distribution : balanced in CTP?



5% nodes account 80% traffic.

90% nodes have very low traffic.

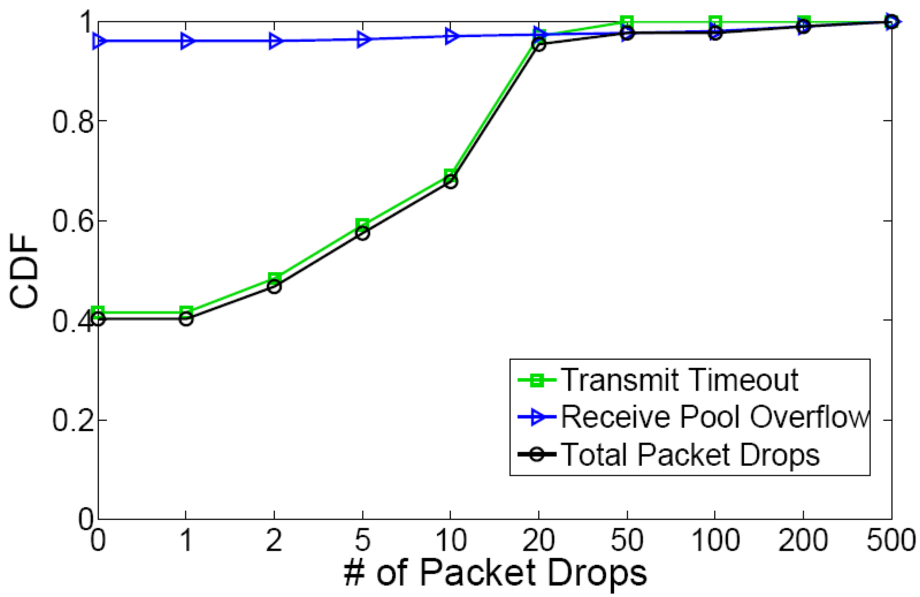




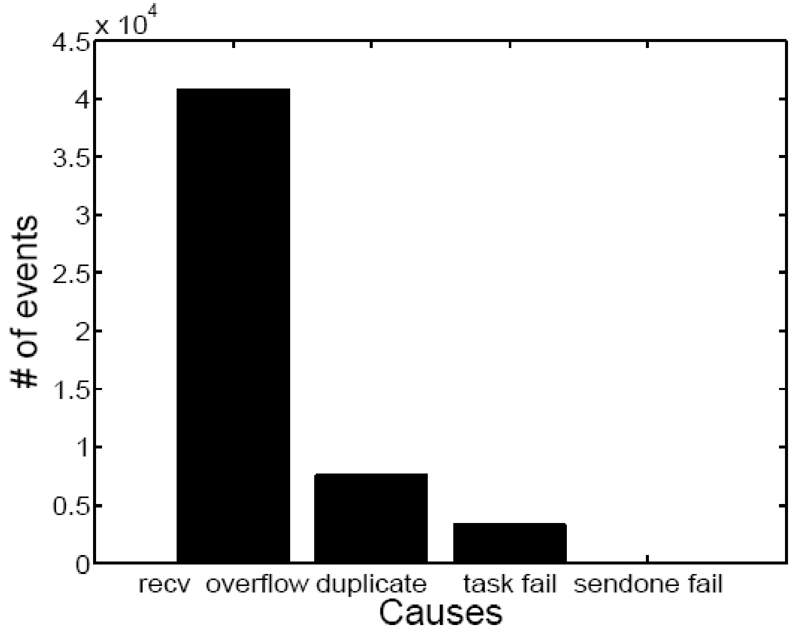
The traffic distribution is relatively stable over time

Causes of Packet Losses

- Packet Delivery Ratio (PDR) about 85%
  - Link loss (61%) vs. Node drops (39%)
- Faulty behavior on forwarding nodes



Cumulative distribution of packet loss

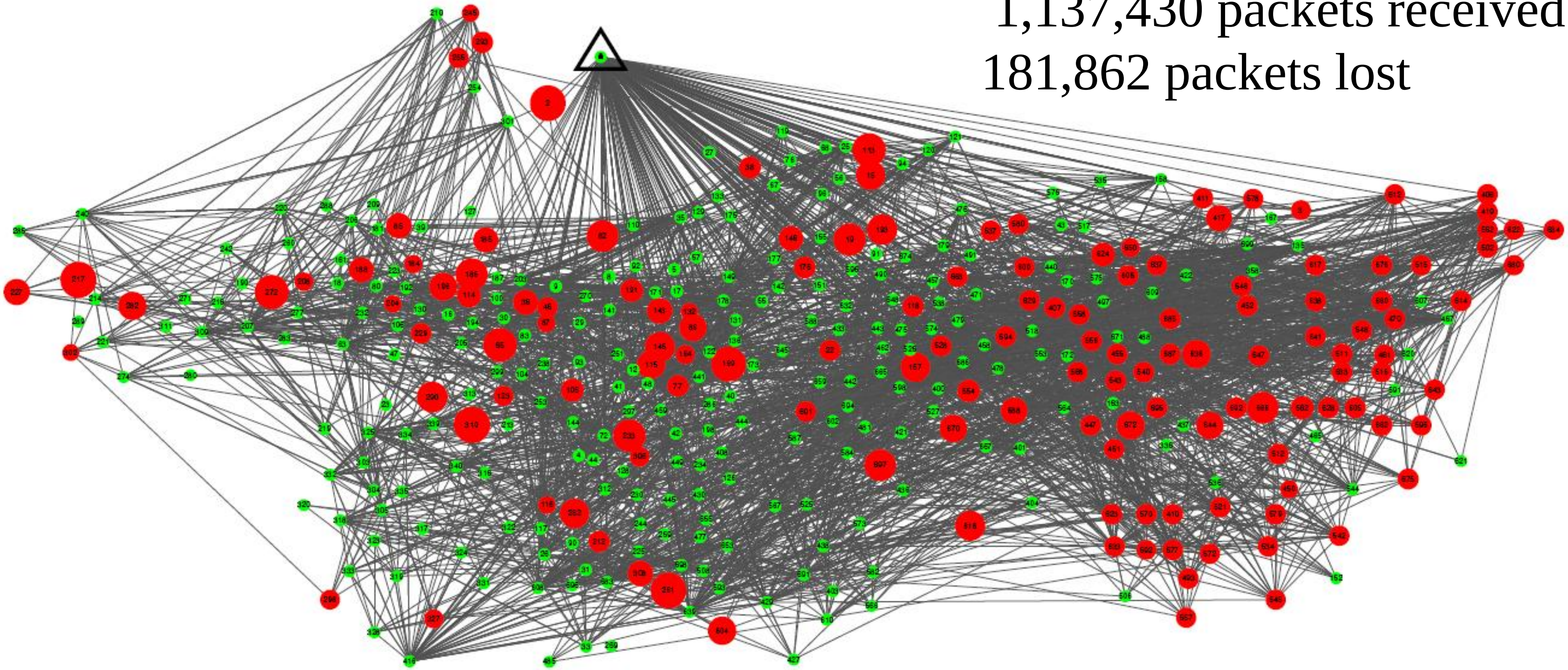


Causes of packet drops on sensor nodes

Packet Loss Diagnosis

December 10, 2010; 400 nodes, 60,000m^2

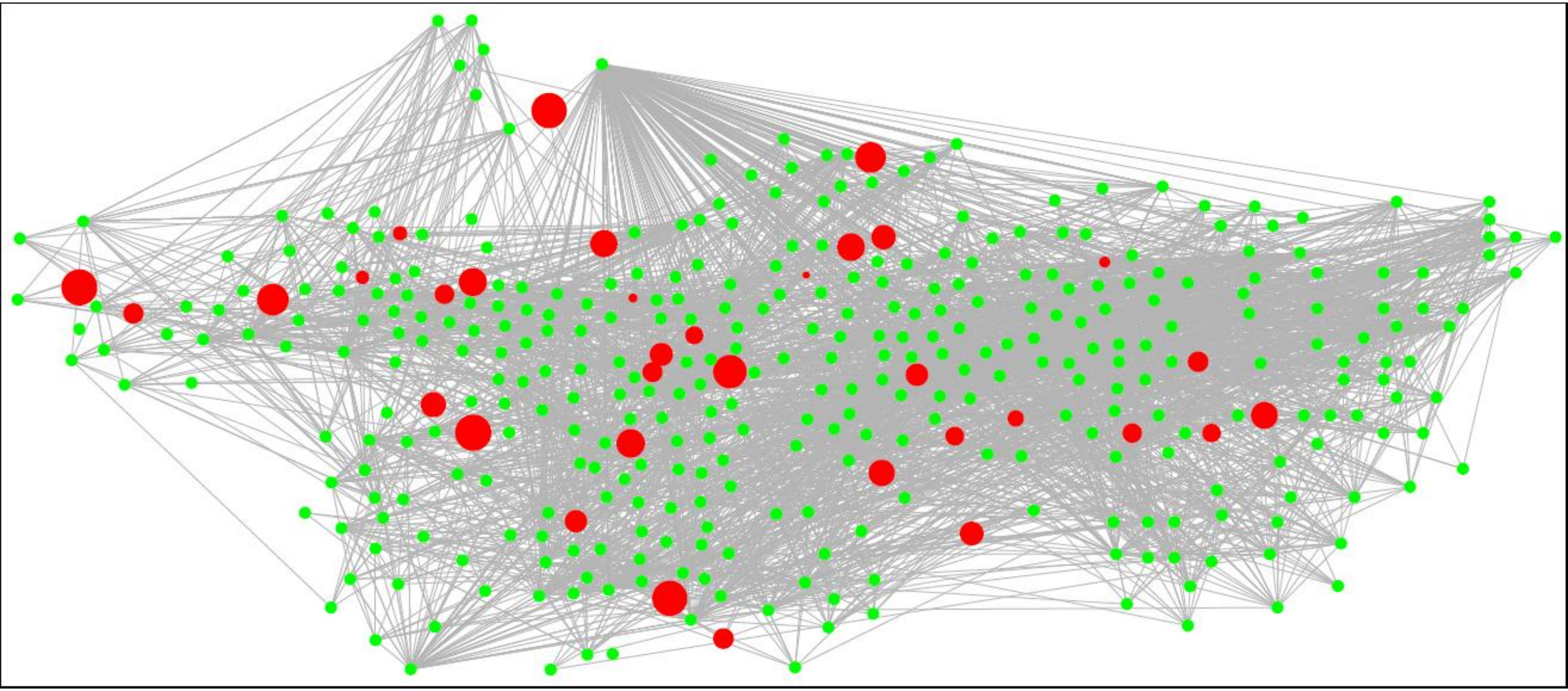
Data of 10 days:
1,137,430 packets received
181,862 packets lost



- The green nodes with PRR > 90%.
- The red nodes with PRR < 90%,
- The radius indicates the number of lost packets

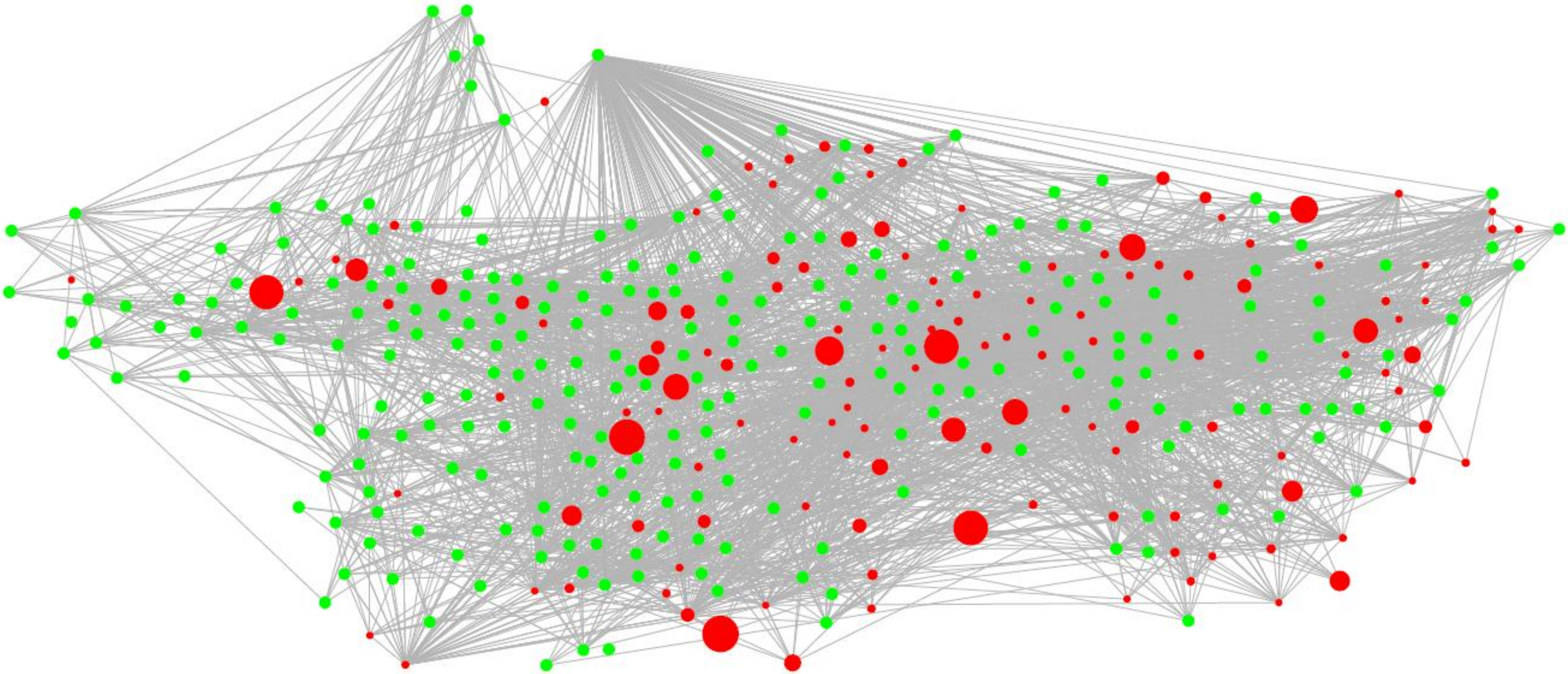
Packet Losses: Non-ACK

- 84,030 packet loss due to non-ack
  - 46.2% of total losses
  - 68,444 caused by physical environment (bad links)



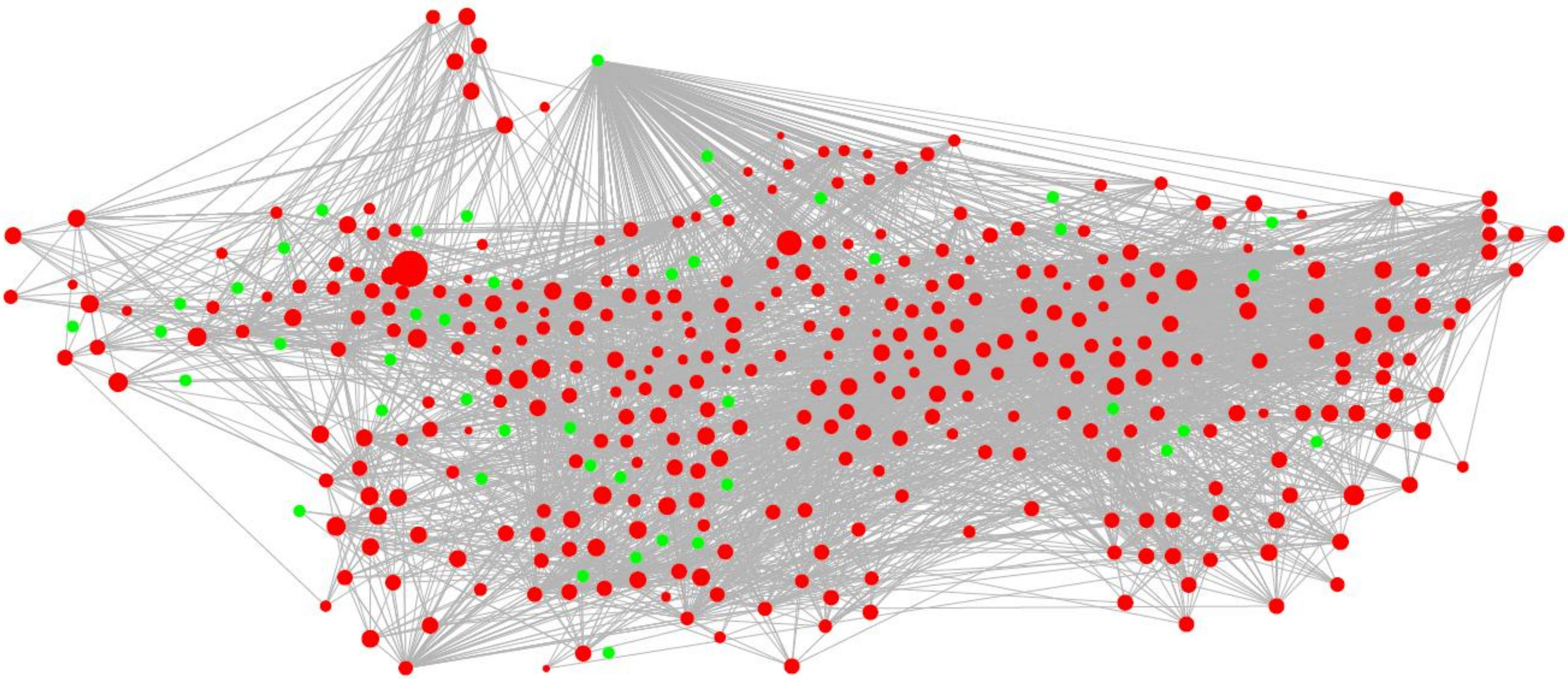
Packet Losses: Non-ACK

- 84,030 packet loss due to non-ack
  - 46.2% of total losses
  - 4,361 caused by interferences (contention <--reboot, loop)



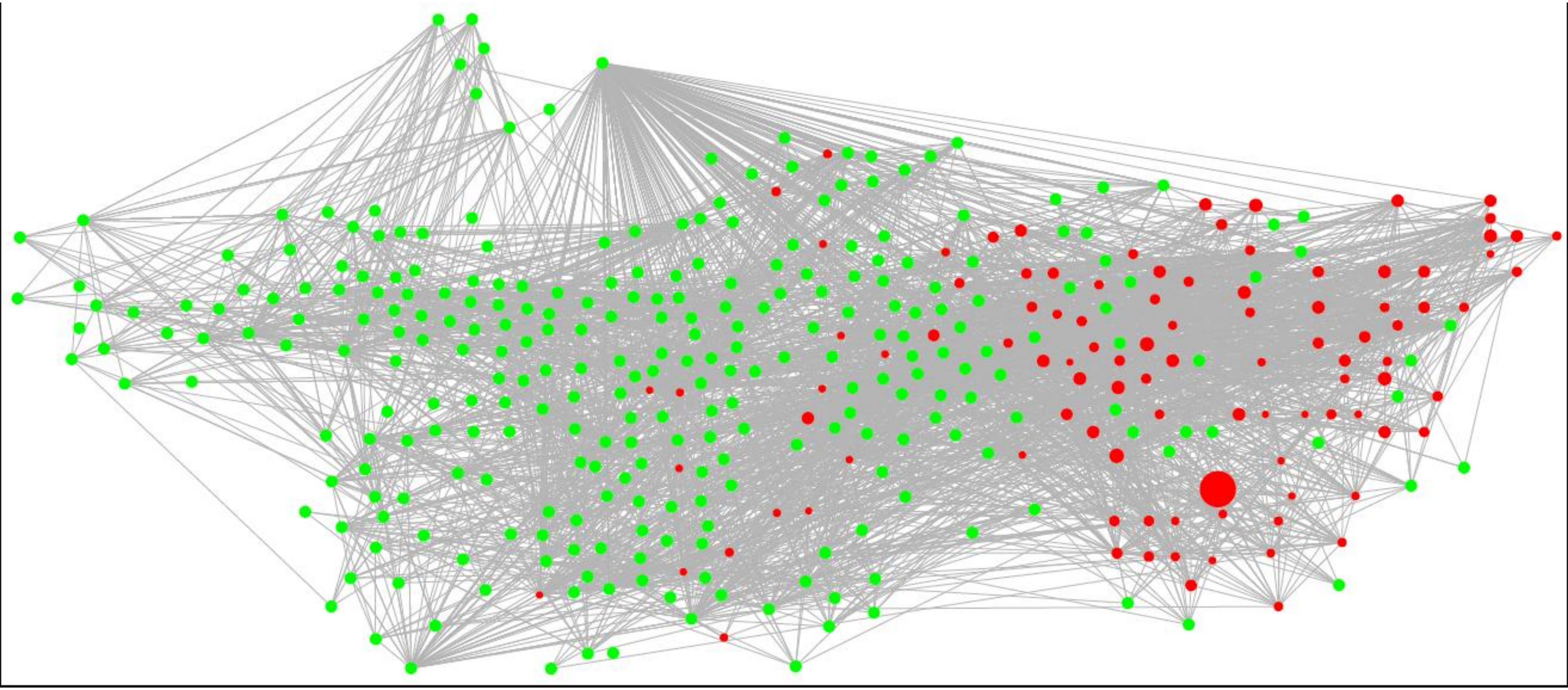
Packet Losses: Corrupted Packets

- 9,511 corrupted packets
  - 9037 real losses (after consider retransmission)
  - ~ 5% of total loss



Packet Losses: Routing Loop

- 5,178 packet loss due to overflow from routing loop
  - 2.9% of total losses
  - 93% of overflow events did not result in packet loss



Packets Loss Summary

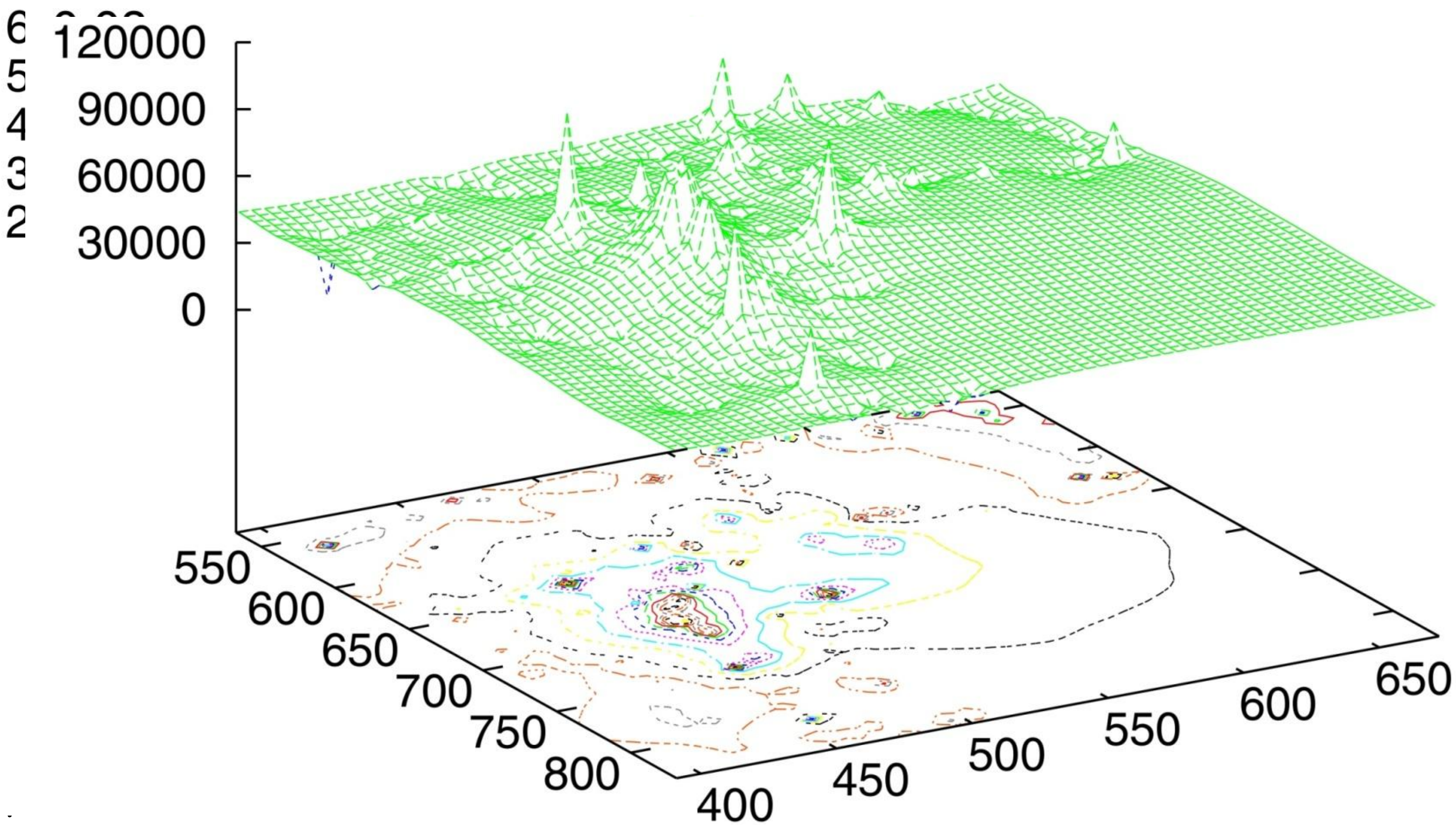
Root cause	%
1. sink-side failure	12.5%
1.1 vertical banding	12.45%
2. corruption	5%
3. overflow drops	2.87%
3.1 loop overflow drops	2.85%
3.2 non-loop overflow drops	0.02%
4. no-ack drops	46.2%
4.1 env-no-ack drops	37.6%
4.2 interference-no-ack drops	2.4%
5. reboot (direct impact on loss)	∼0

About 35% packet losses are unidentified now.

NETWORK OBSERVATIONS: CITYSEE

Where Packets are Lost ?

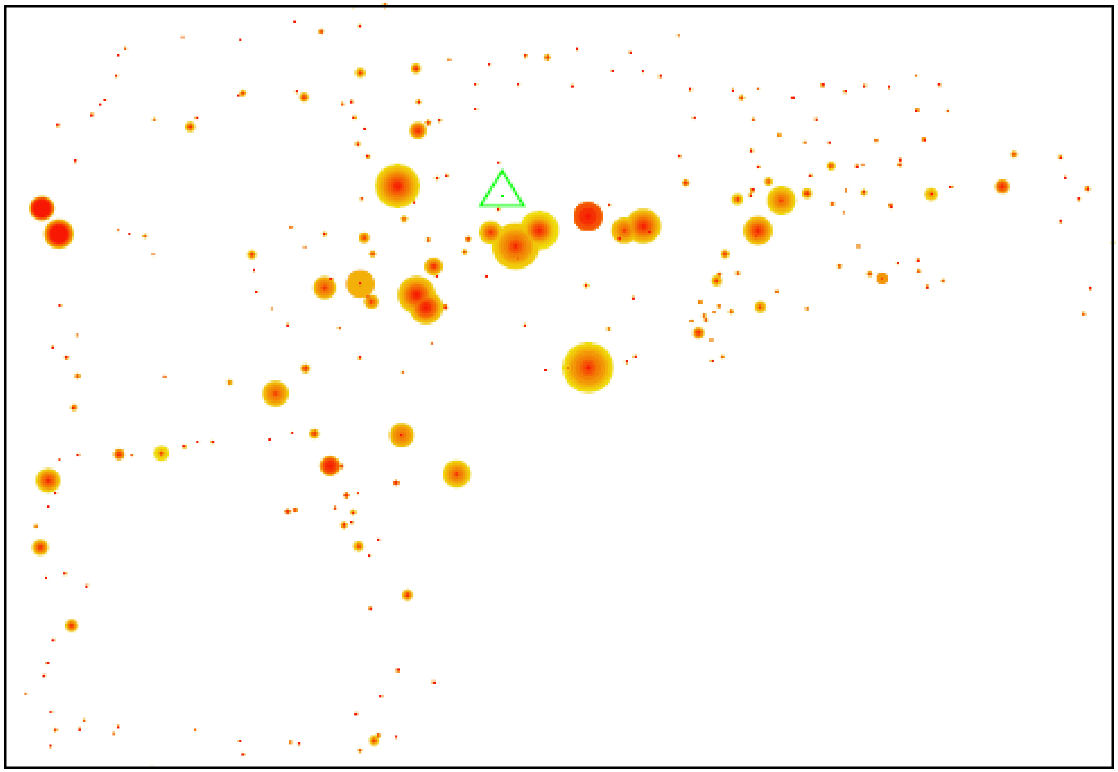
- From f… betwe…



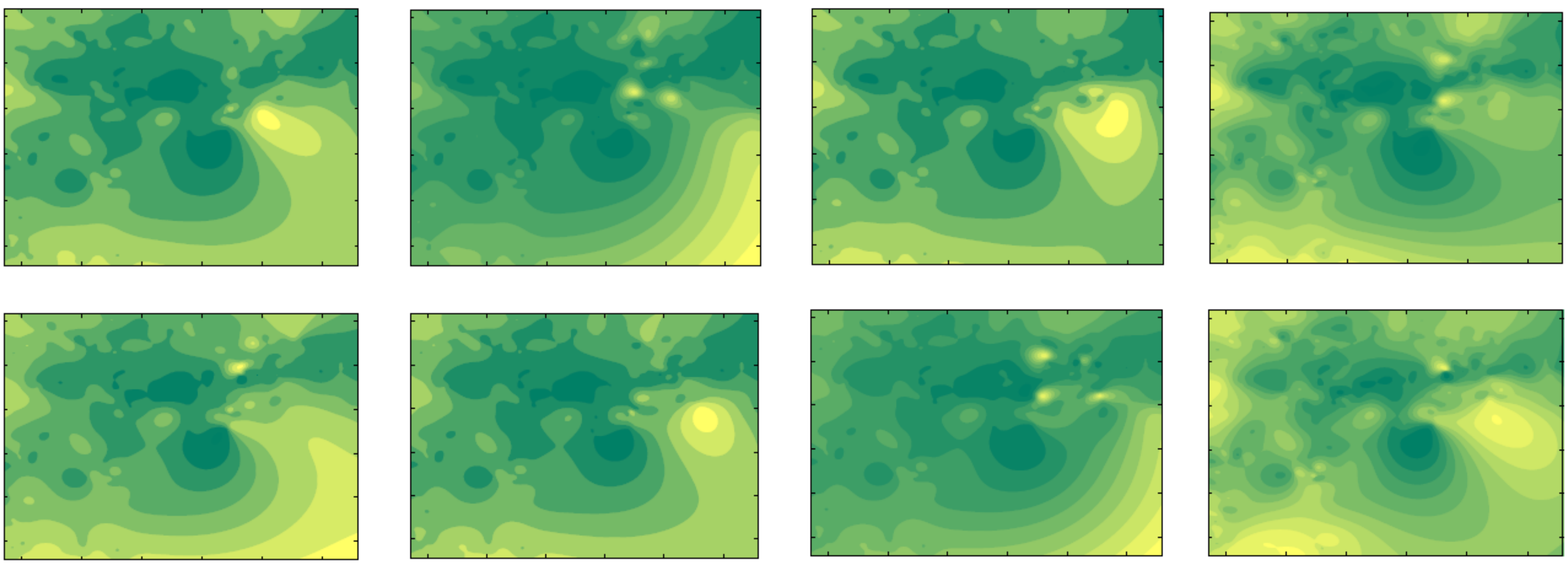
- Fro… distribution is closely related … the spatial property of the deployment.

Traffic Distribution

- Small portion of "critical nodes", verifies the same finding observed from GreenOrbs
- Traffic dynamics exhibits different pattern, e.g. burstness on some nodes



Network Topology



Nodes closer to the sink have a more stable topology than nodes that are far away.

Summary

Many challenges to make it

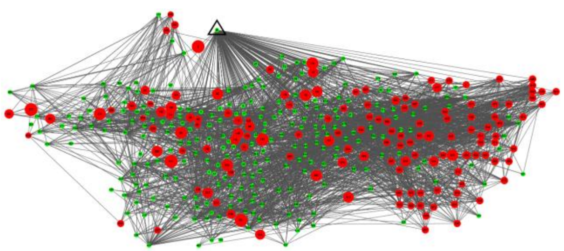
1. **Sustainable** --- energy efficiency and fault diagnosis?
2. **Robust** --- co-existence?
3. **Scalable** ---large scale performance?
4. **Predictable** ---- under varying environment?

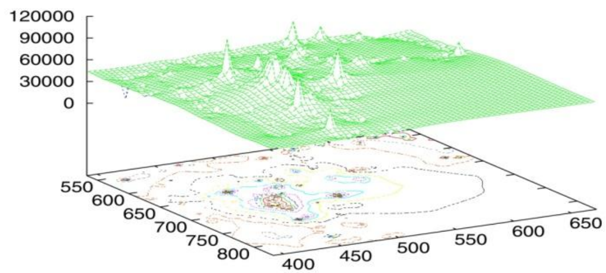
Presentation Outline

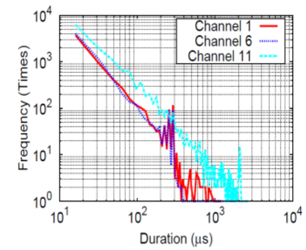
OceanSense

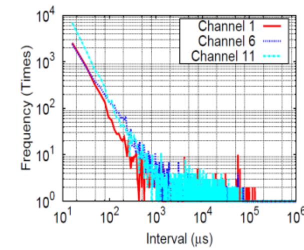
GreenOrbs

CitySee









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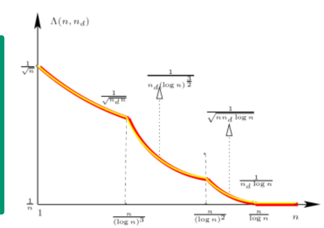
ZIMO: Coexistence

Capacity: the Limit



ZIMO: CROSS-TECHNOLOGY MIMO TO HARMONIZE COEXISTENCE OF ZIGBEE WITH WIFI

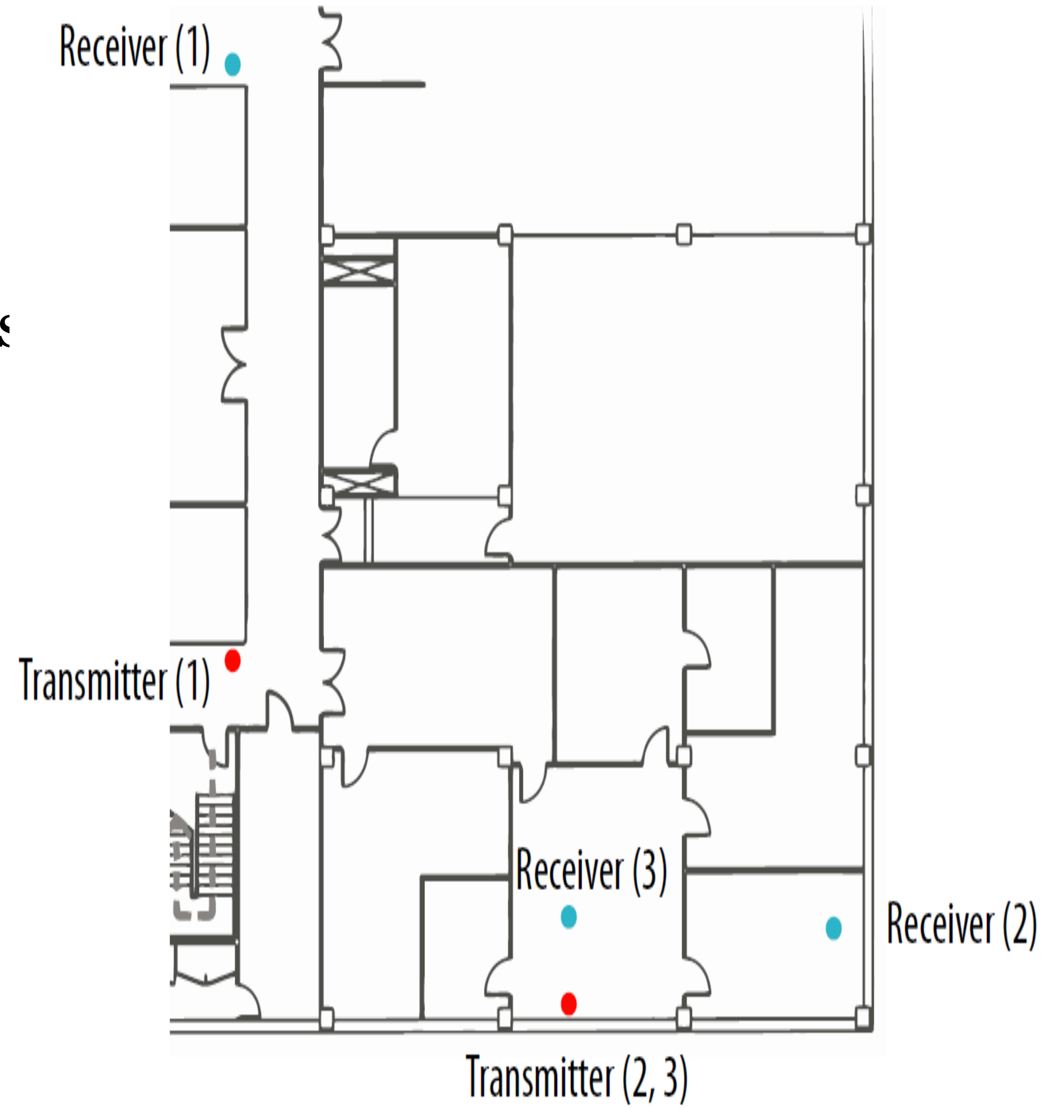
Coexistence in ISM Band

ISM band interferences are pervasive and crowded
WiFi signal is the primary and first class passenger

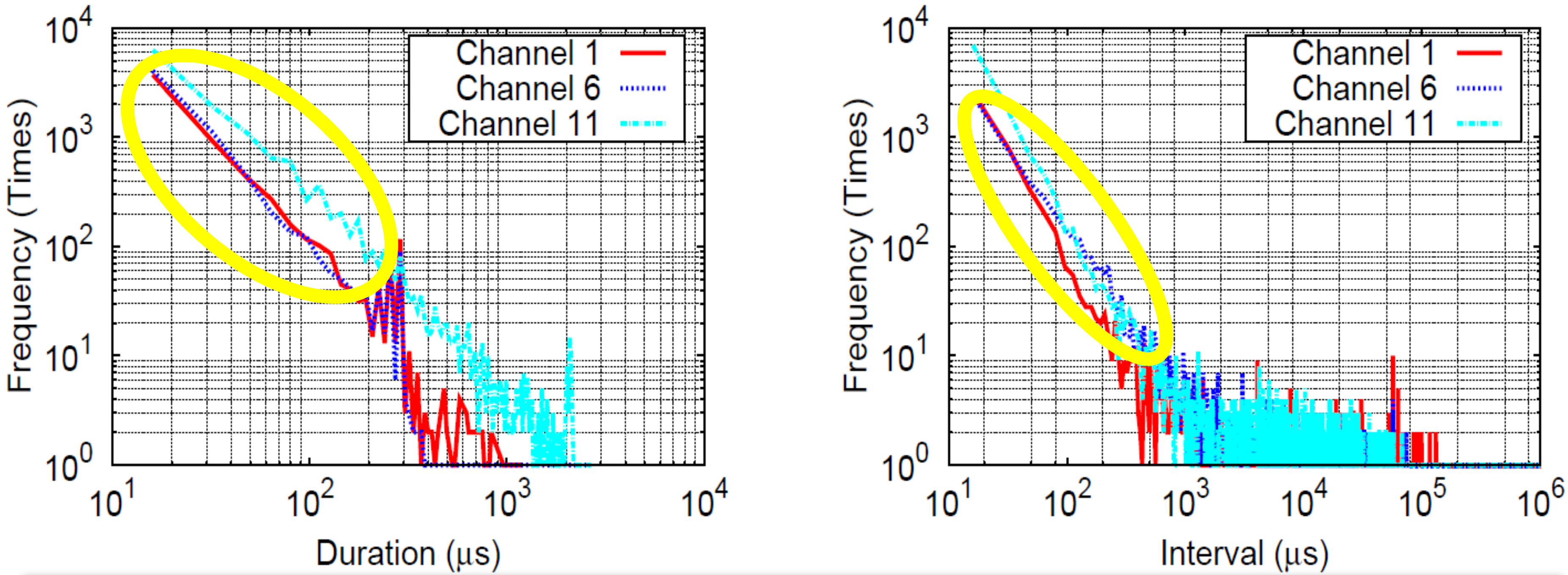
- Existing Works mainly protect WiFi signal and mitigate cross technology interference [TIMO]
- Some ZigBee signal protection works need modifications or degrade WiFi [Sensys10, Liang]

Experiment Setup

- Two ZigBee Nodes (TX&RX)
- WiFi APs are in IIT campus
- ZigBee nodes are configured to receive full spectrum interference in full time scale
- Adding controllable AP for tunable interference



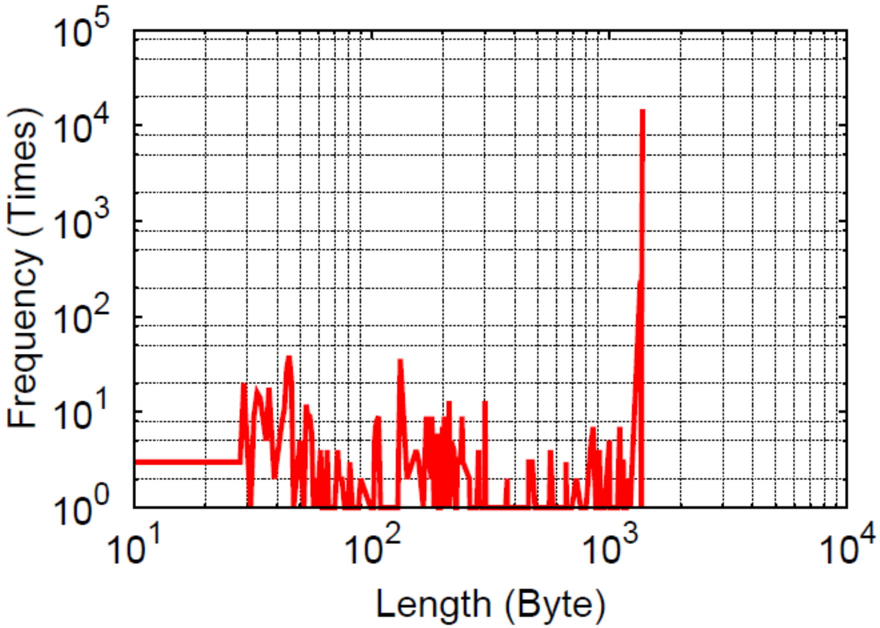
Effect of WiFi interference on ZigBee



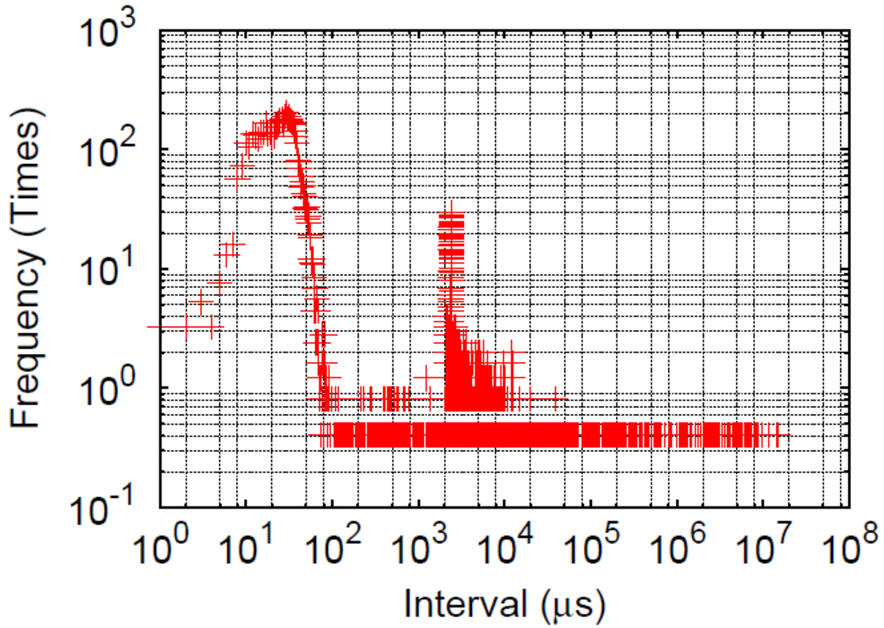
✓Short and frequent WiFi data transmission (i.e., flash) play the main role of WiFi interference on ZigBee.

✓Power-law like distribution indicates the shorter flashes interfere ZigBee signal with exponentially increasing probability, which is a drastic threat for ZigBee signal.

Effect of WiFi interference on ZigBee



(a) Length statistics



(b) Interval statistics

✓ The WiFi interference is distributed across ZigBee symbols, rather than concentrated on particular positions.

✓ We need to resort to the signal processing techniques for fundamental solutions.

ZIMO: Sink Based Design

Cons No.1: ZIMO has more antennas than WiFi AP (N+1)
Cons No.2: ZIMO needs at least one preamble is clear
Cons No.3: Can work with one ZigBee and multiple WiFi

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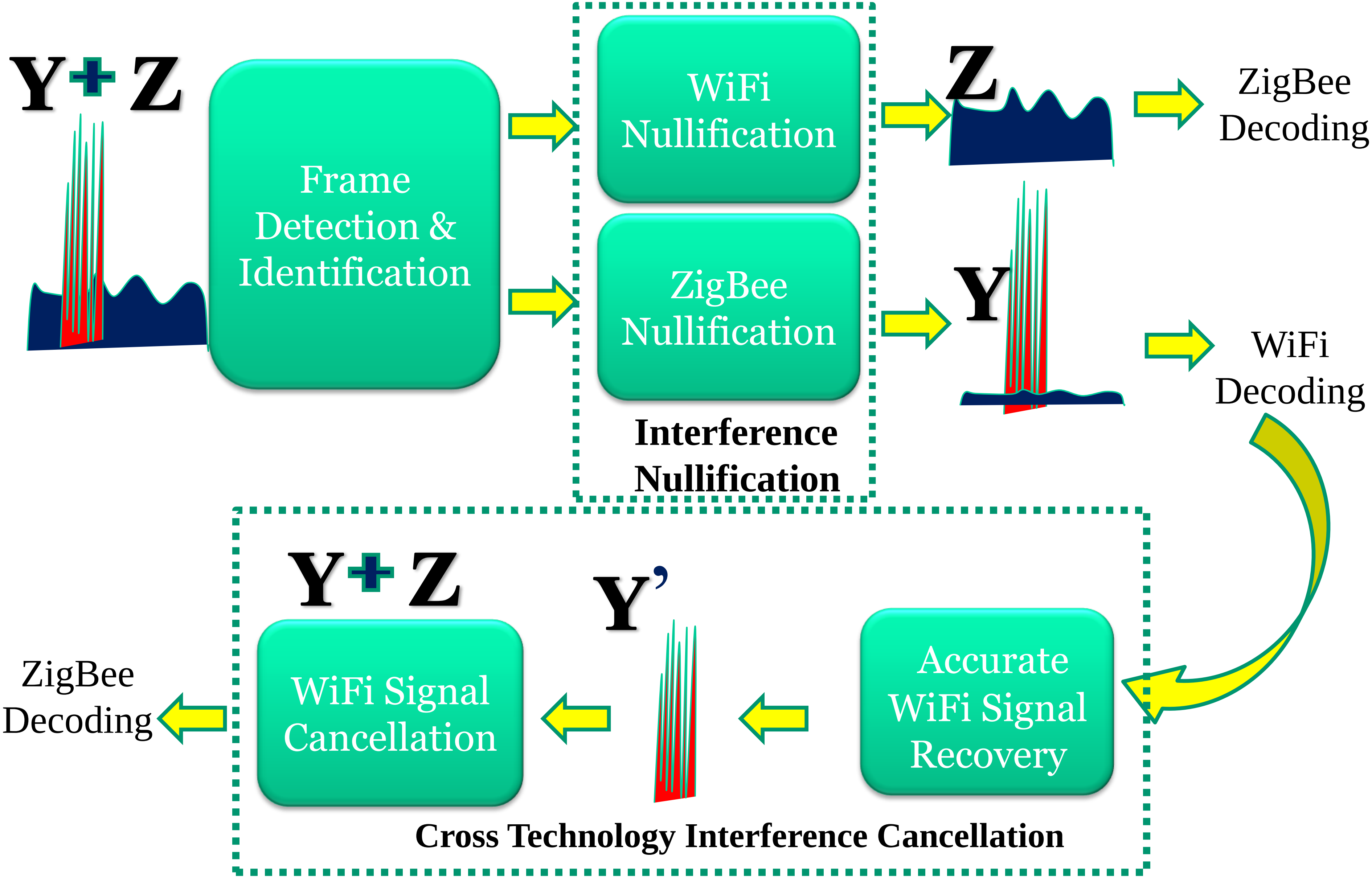
How ZIMO works?

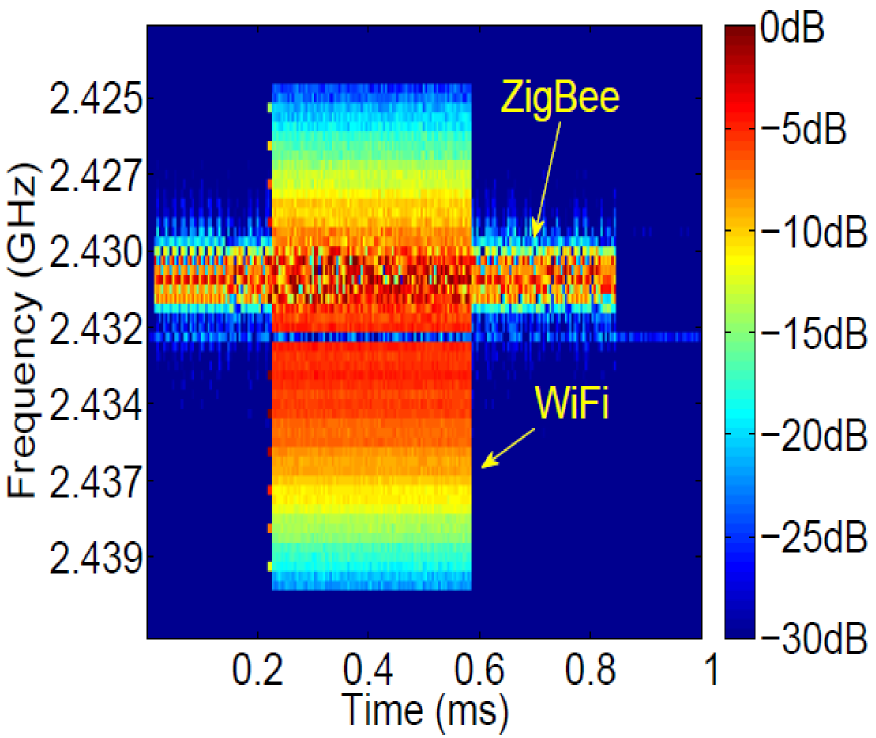


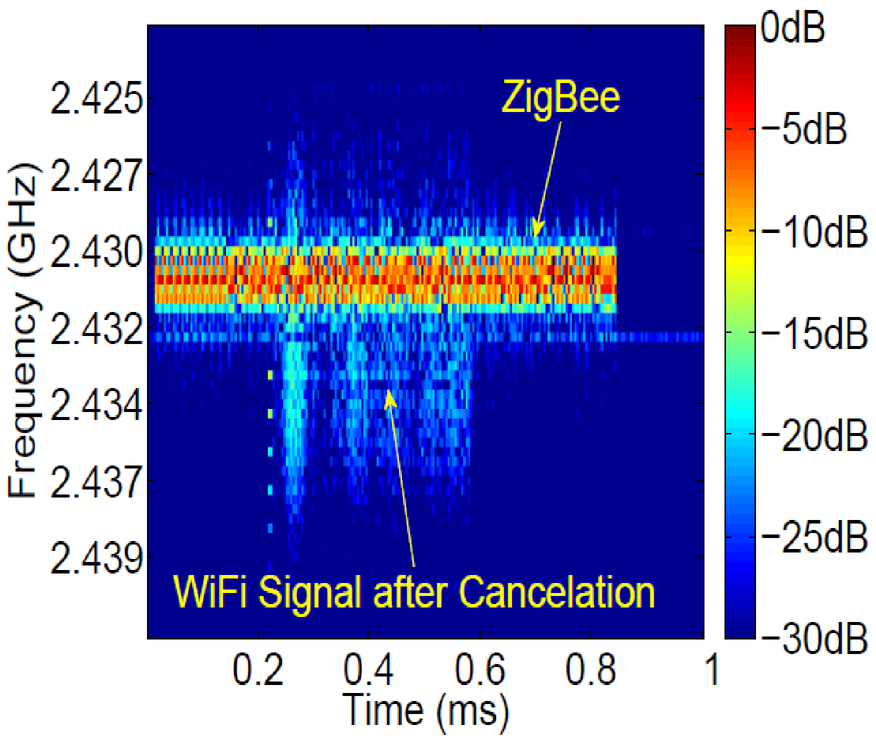
Main challenges

- Channel Coefficient Recovery
  - Interference in frequency domain
  - Sufficient for decoding, insufficient for accurate signal recovery
- CFO Compensation
  - Well done for preamble, insufficient for whole data scale
  - Extremely large with the increasing packet length

Where are opportunities?

- Frequency domain is partially overlapped
- Time domain also partially overlapped
- Power domain shows significant difference





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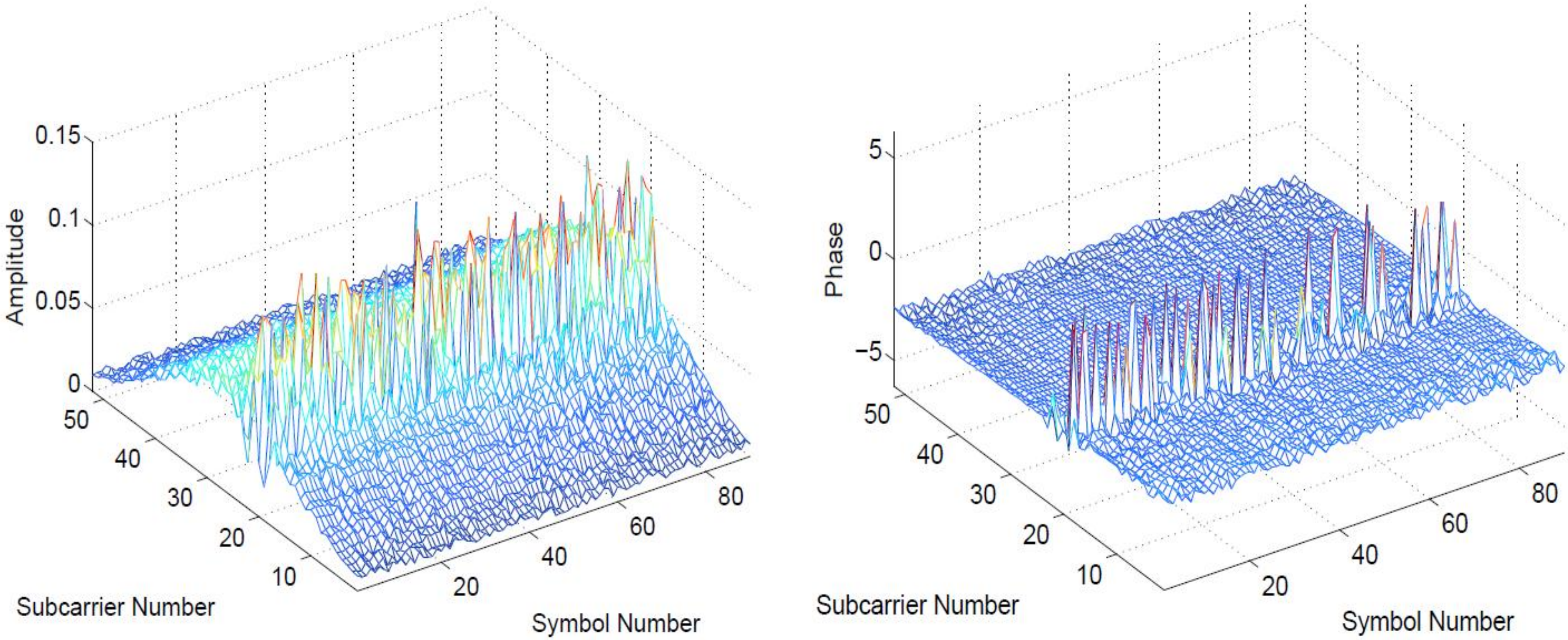
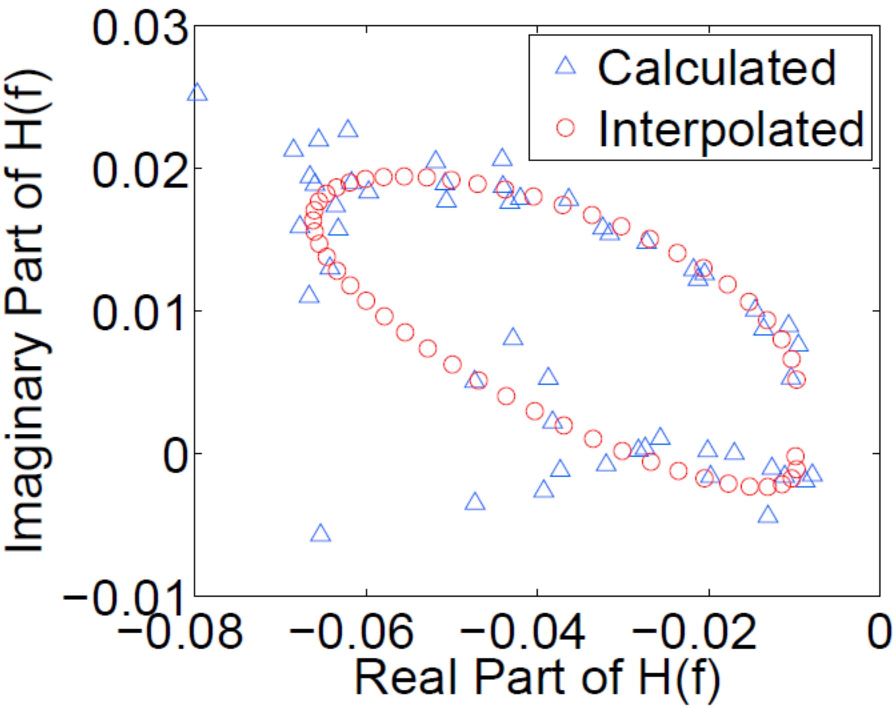
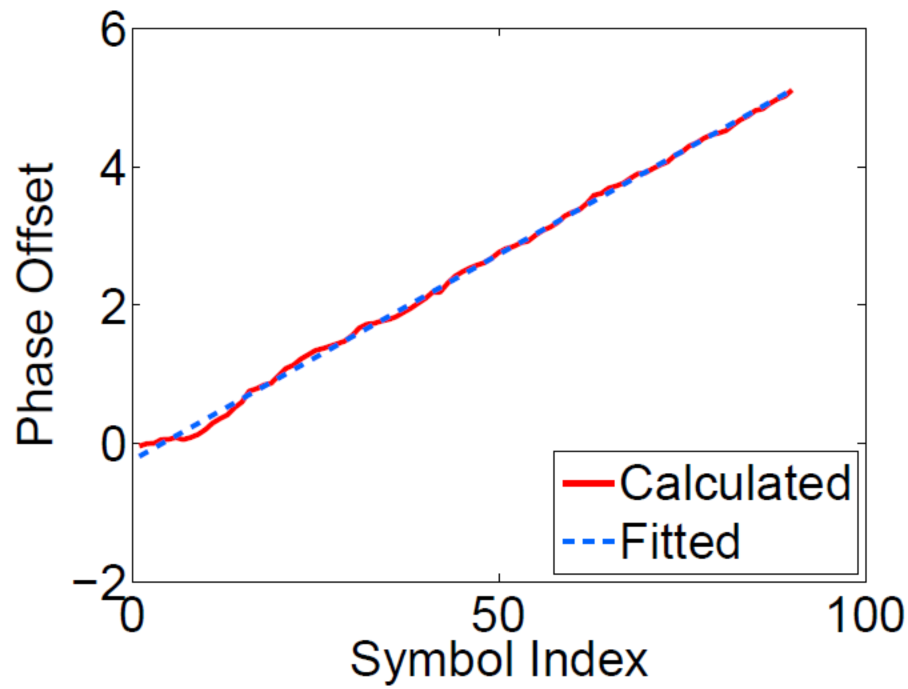


For channel coefficient:
Interpolation is simple, effective

Where are opportunities?



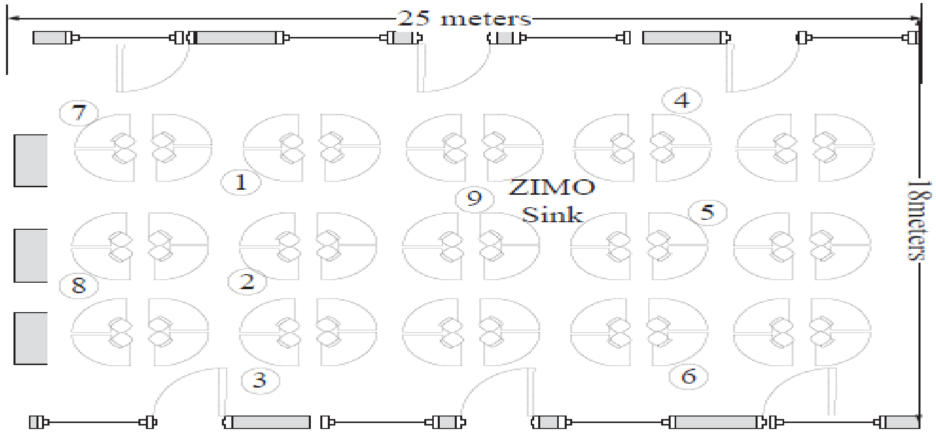


CFO

Linear regression is accurate enough for CFO

enough for CFO

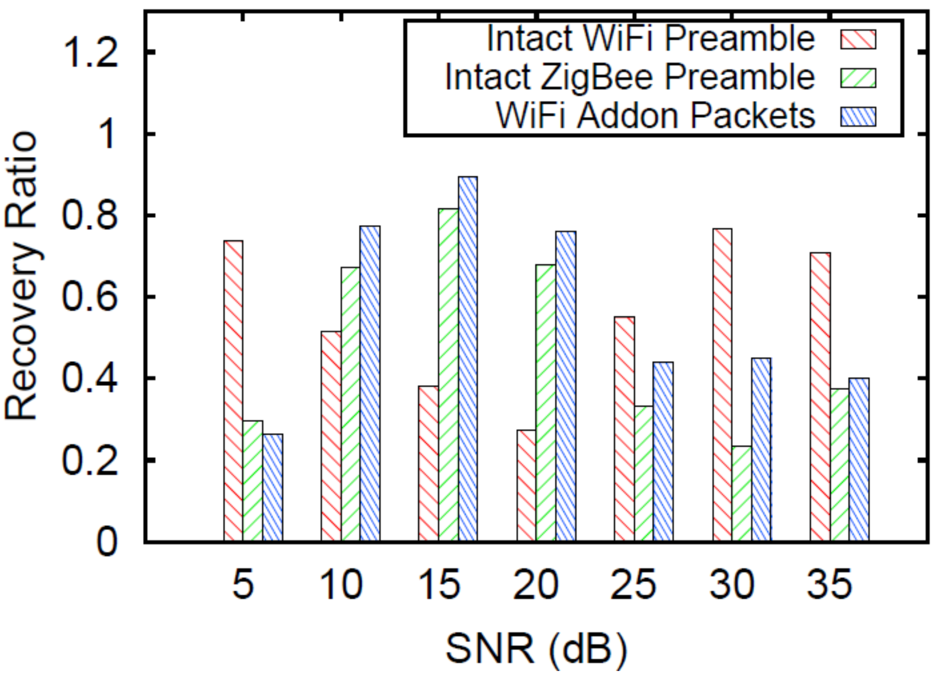
Implementation

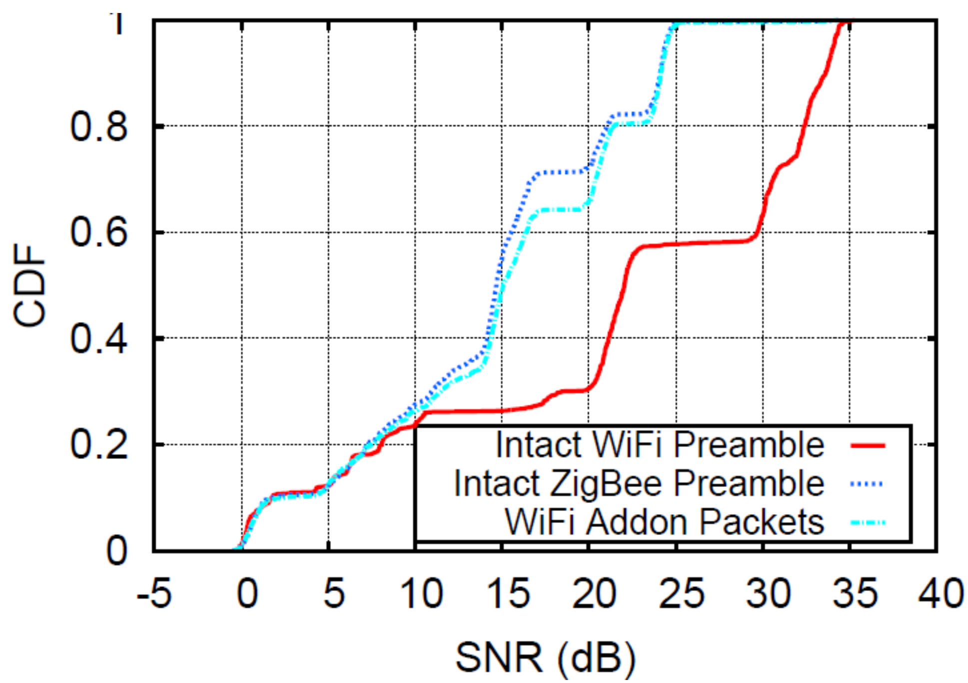


- Implement using USRP2 N200
  - IEEE STD 802.15.4, 2 MHz Bandwidth
  - OFDM is 20 MHz Bandwidth
- Real trace driven ZIMO decoding
- No carrier sense and MAC timing control

Experimental Results: Macro Benchmark

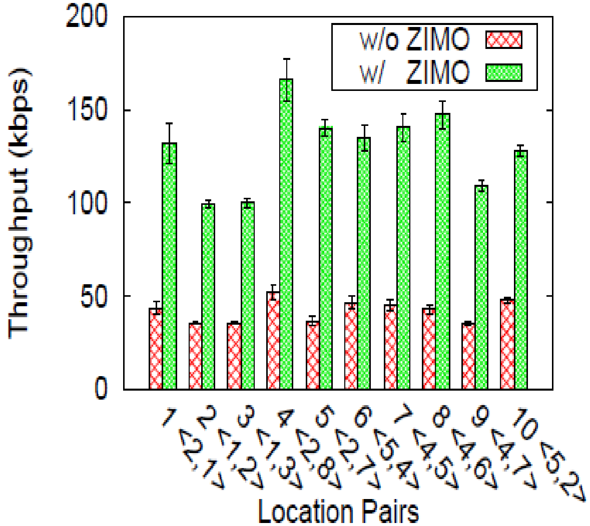
❖ Recovery ratio



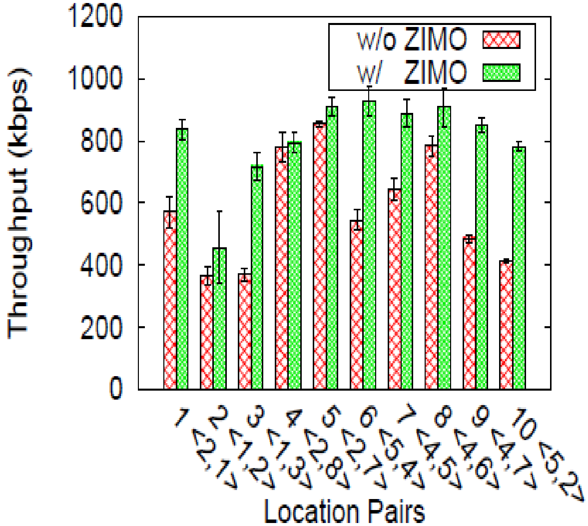


Experimental Results: Macro Benchmark

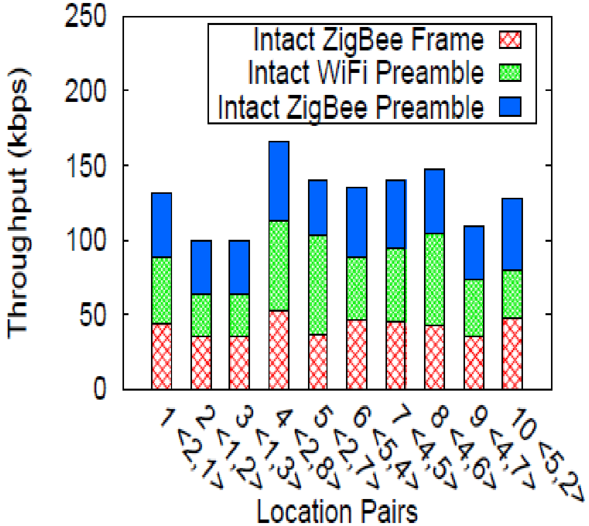
❖ Throughput



Zigbee Baseline



WiFi Baseline



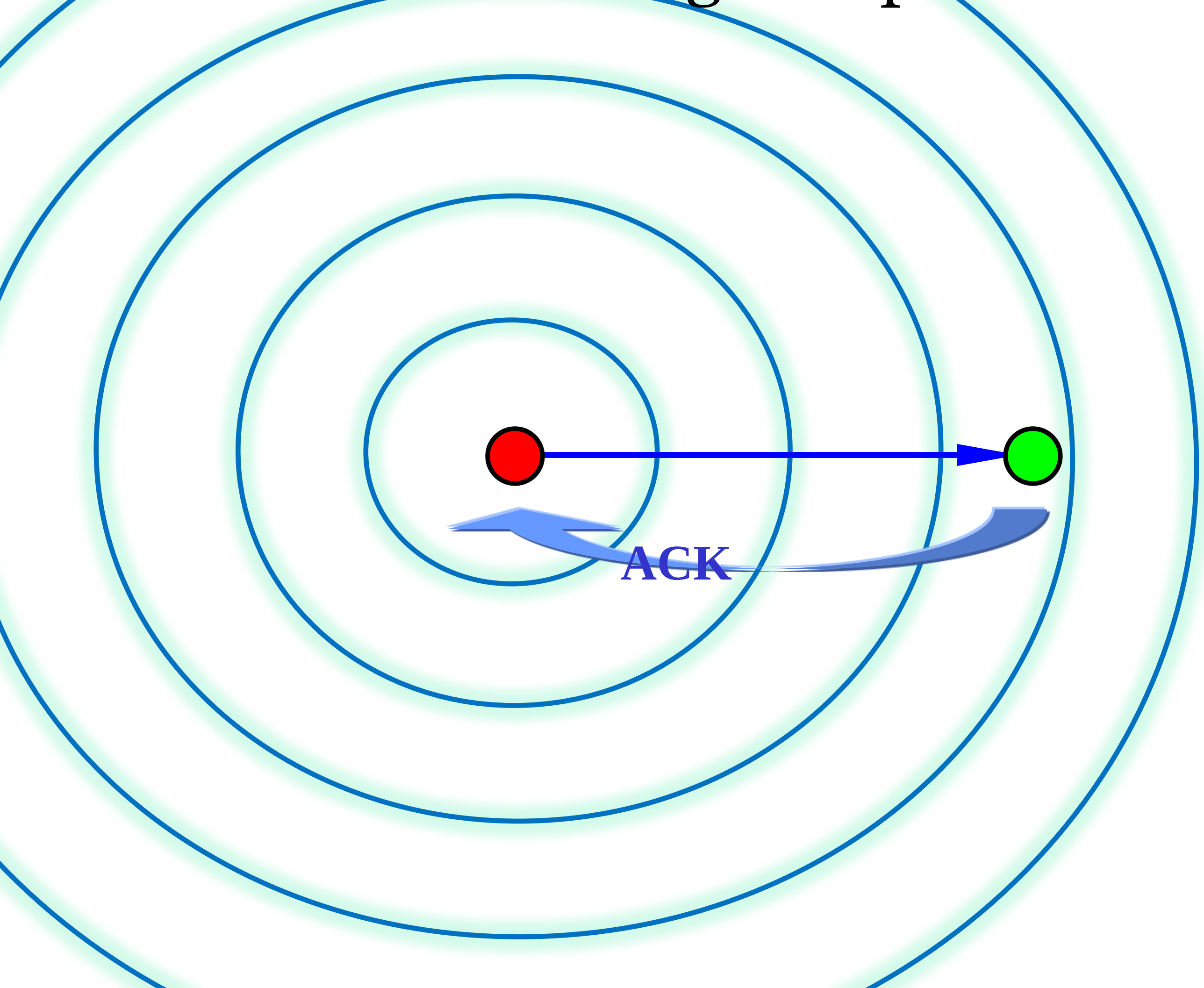
Interference patterns

Asymptotical Capacity

Two Capacity metrics - channel

❖ **Channel capacity**

– achievable single-hop data rate

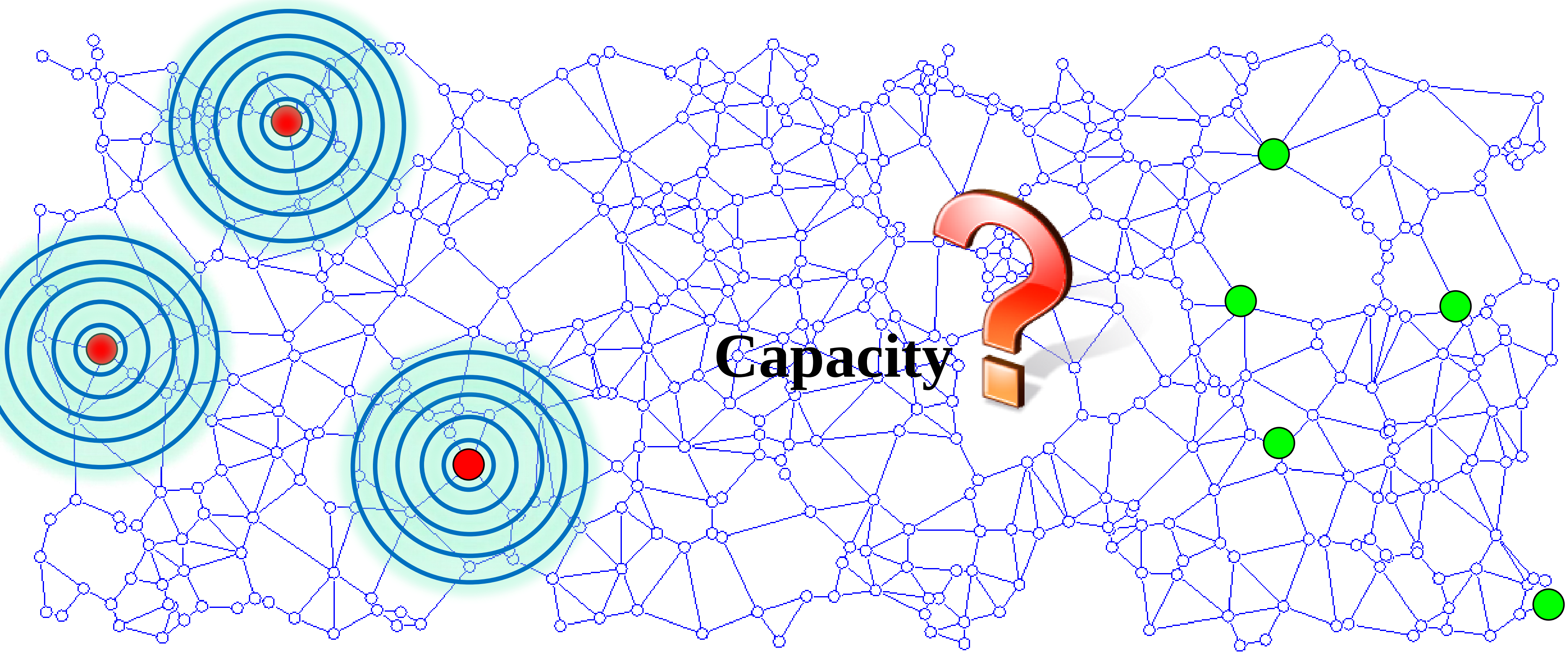


$$C = \log(1 + SINR)$$

Shannon channel theory

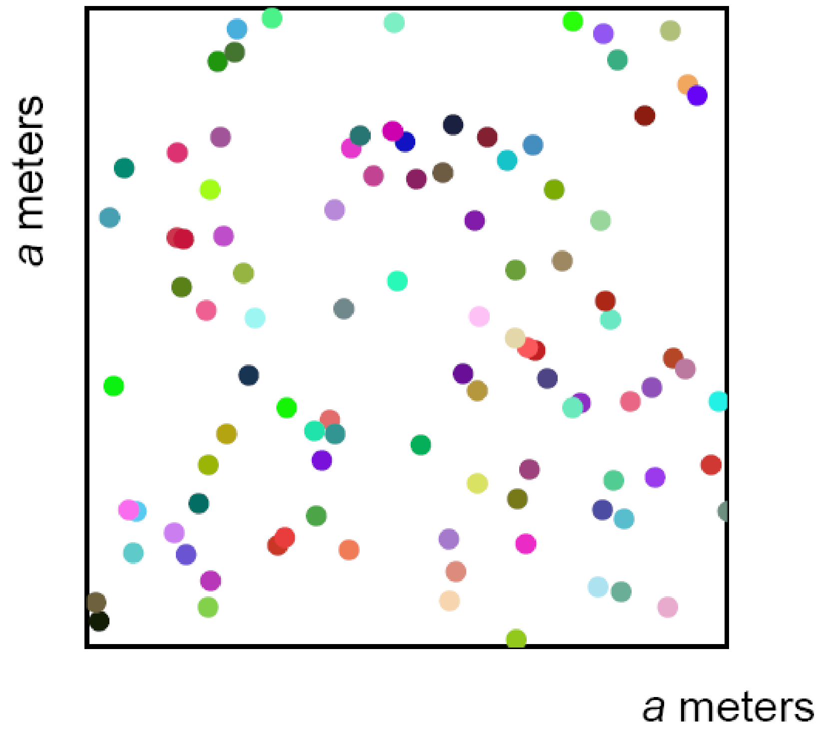
Two Capacity metrics - transport

- **transport capacity**
  - end-to-end multi-hop throughput



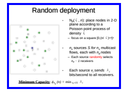
Impact factors :

- ❖ **Network Size**
- ❖ **Networking Models**
- ❖ **Inference Models**
- ❖ **Traffic Models**

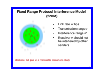


Various Models

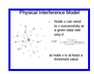
- **deployment models**
  - arbitrary networks
  - random networks



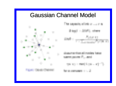
- **network scaling models**
  - dense networks
  - extended networks
- **Communication (Interference) models**
  - the protocol model (PrIM)
  - Fixed Range Protocol Model (fPrIM)



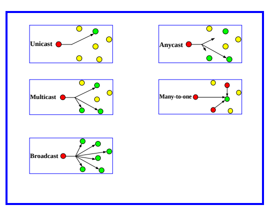
  - physical model (PhIM)



  - generalized physical model (GphM, also called GCM)



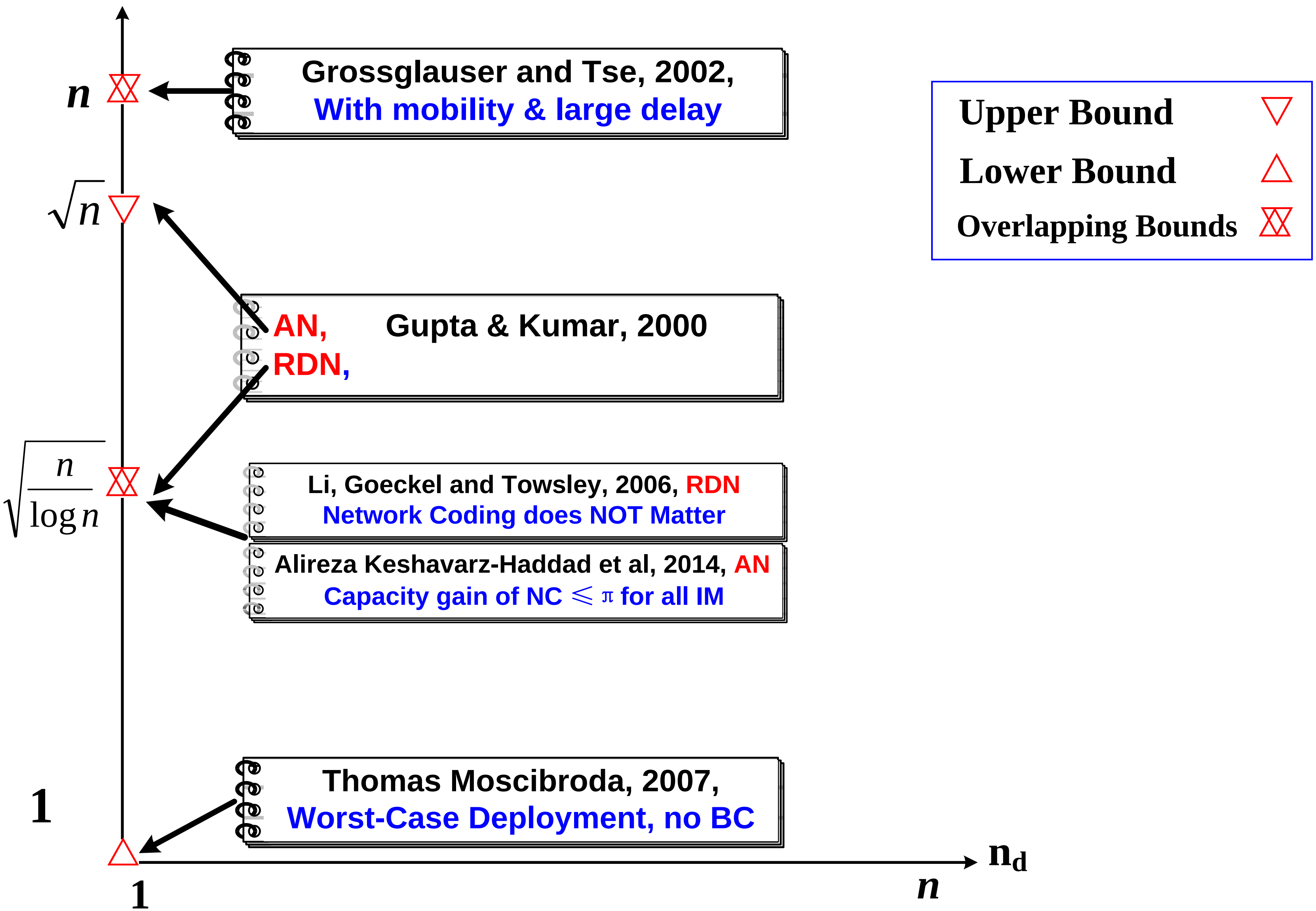
  - Others
- **Traffic models**
  - Unicast
  - Broadcast
  - Multicast
  - Anycast
  - Many-to-one



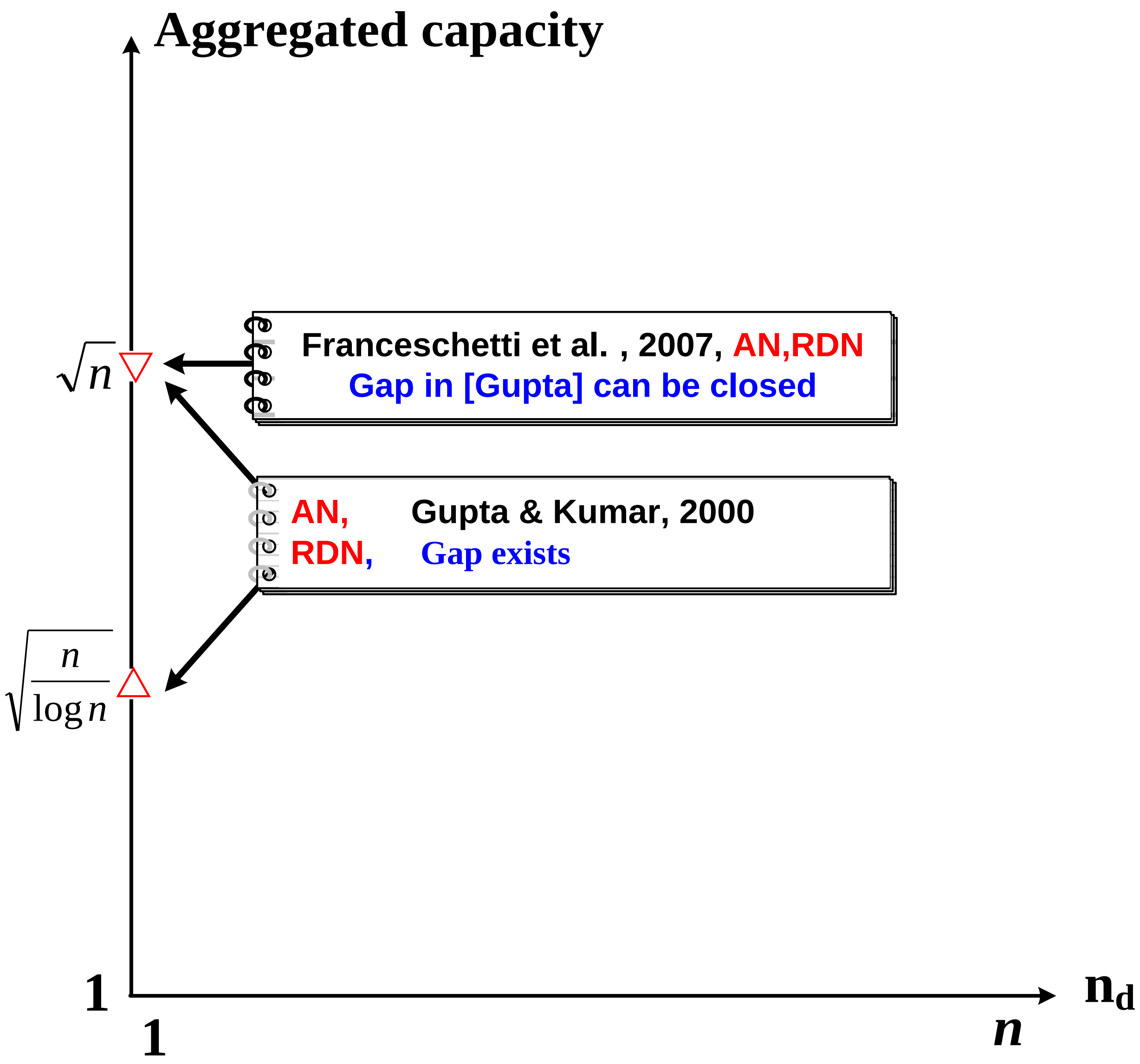
Results Summary

Milestone Results : Unicast, PrIM

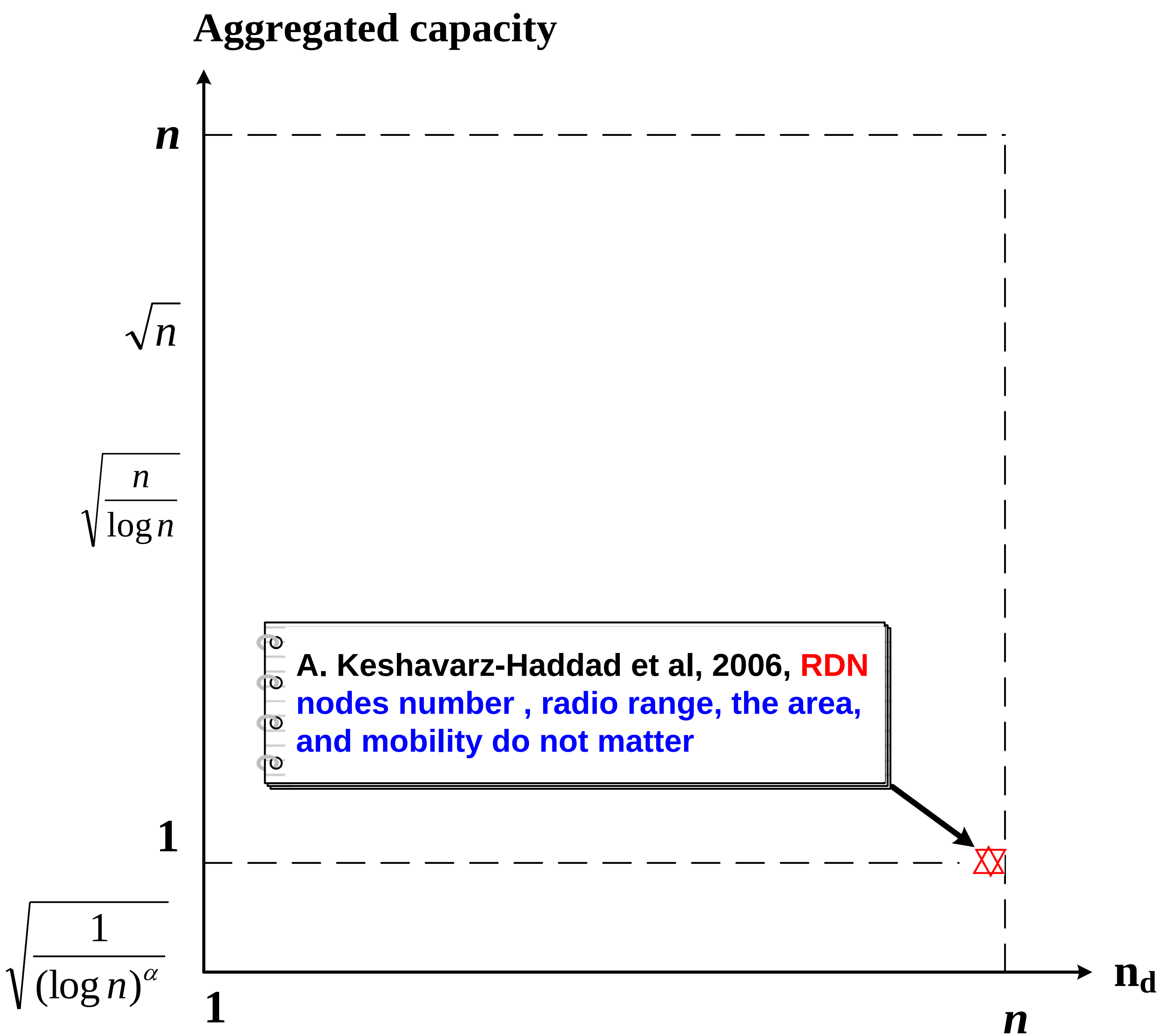
Aggregated capacity: scales n



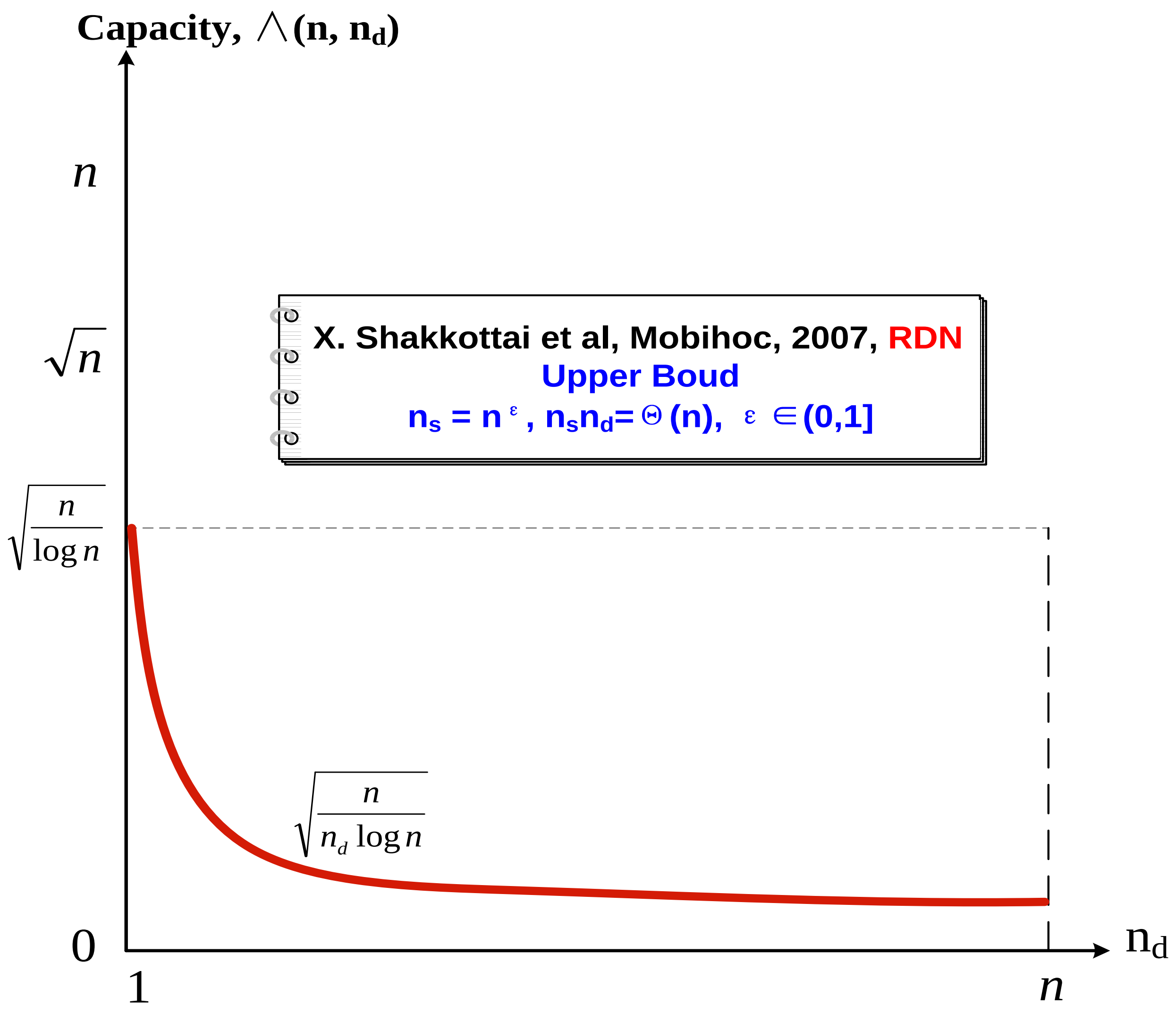
Milestone Results : Unicast, PhIM



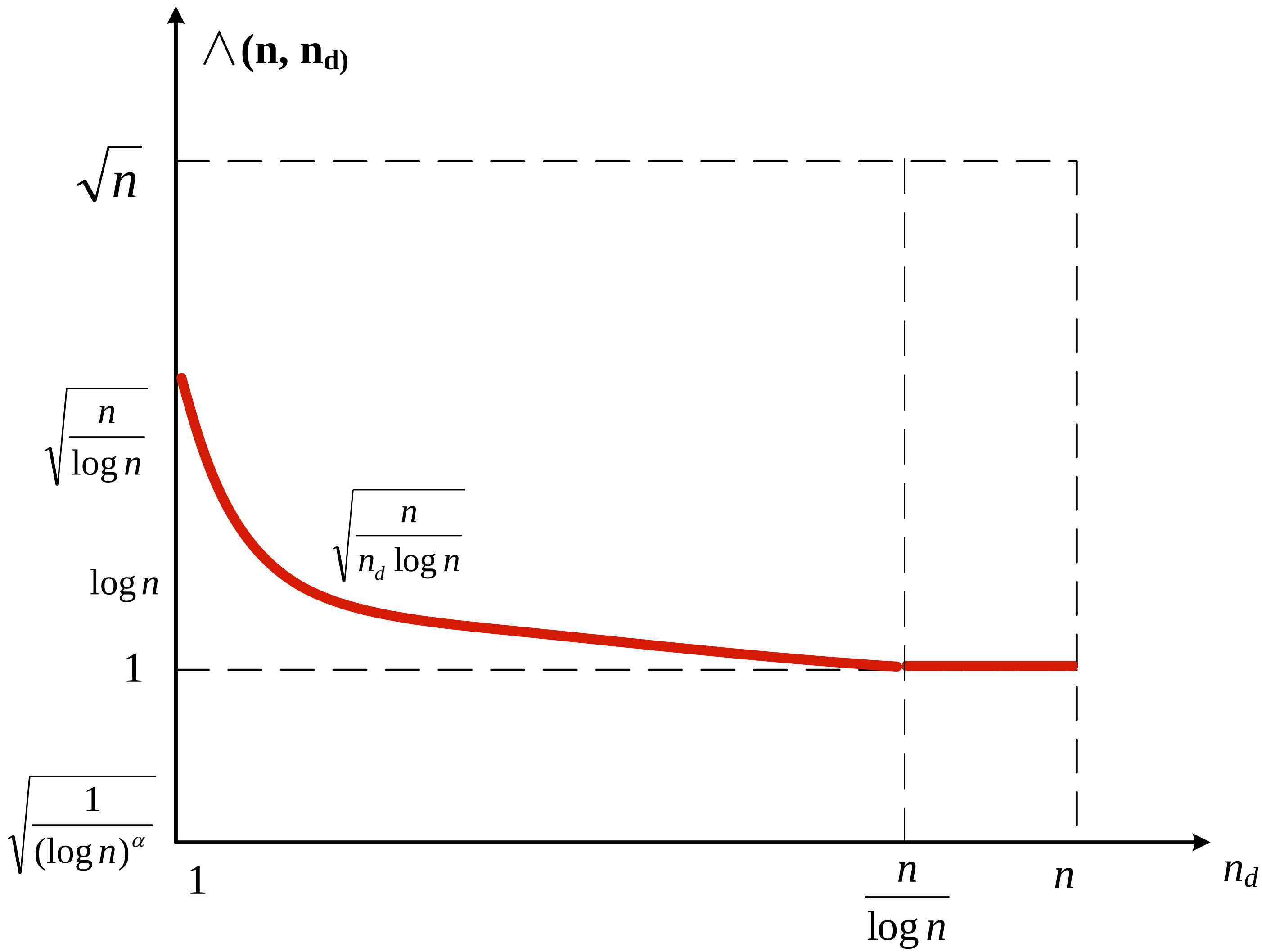
Milestone Results : Broadcast, PrIM



Milestone Results : Multicast, PrIM



Our Results : Multicast, PrIM



Li et al, MobiCom 2007, REN, $n_s = \Theta(n)$

Brief Summary

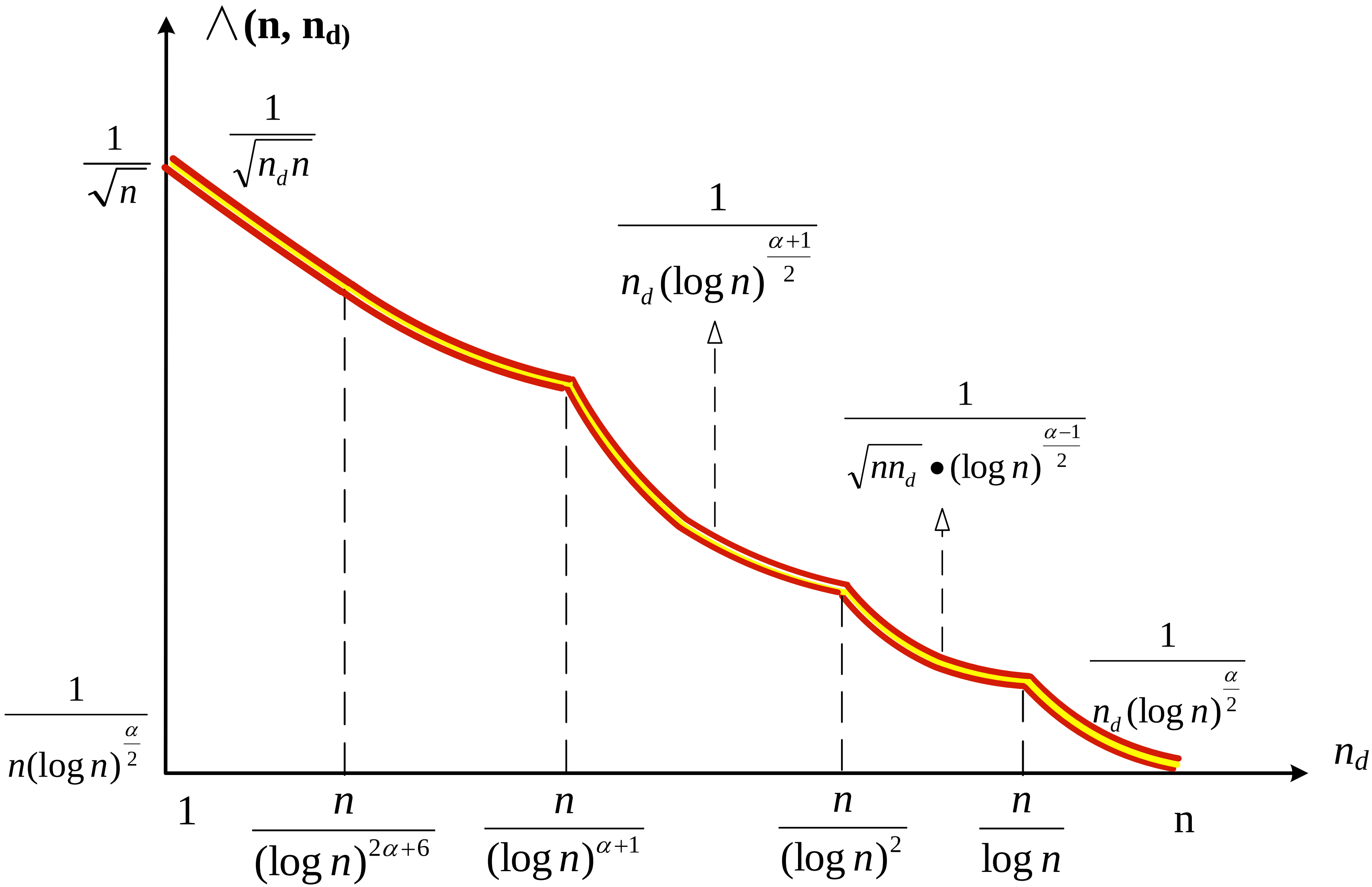
❖ The aggregate multicast capacity of *n* sessions is

$$\Lambda_{n_d}(n) = \begin{cases} \Theta\left(\sqrt{\frac{n}{\log n}} \bullet \frac{W}{\sqrt{n_d}}\right) & when \quad n_d = O\left(\frac{n}{\log n}\right) \\ \Theta(W) & when \quad n_d = \Omega\left(\frac{n}{\log n}\right) \end{cases}$$

❖ Our results unify previous results

1. **Unicast** (when $n_d=2$): $\Theta\left(\sqrt{\frac{n}{\log n}} \bullet W\right)$ by Gupta and Kumar
2. **Broadcast** (when $n_d=n$): $\Theta(W)$ by Keshavarz-Haddad et al., Mobicom'06
3. Multicast ($n_s=n^{\varepsilon}$ and $n_d=n^{1-\varepsilon}$), $O\left(\sqrt{\frac{n}{n_d \log n}}\right)$ by Shakkottai et al., Mobihoc'07

Our Results : Multicast, GCM



Multicast Capacity for REN, $n_s = \Theta(n)$,

Li et al. [MobiCom 2008]. *Wang*, Li et al. [INFOCOM 2010, 2011].

Protocol Interference Model

General Approaches

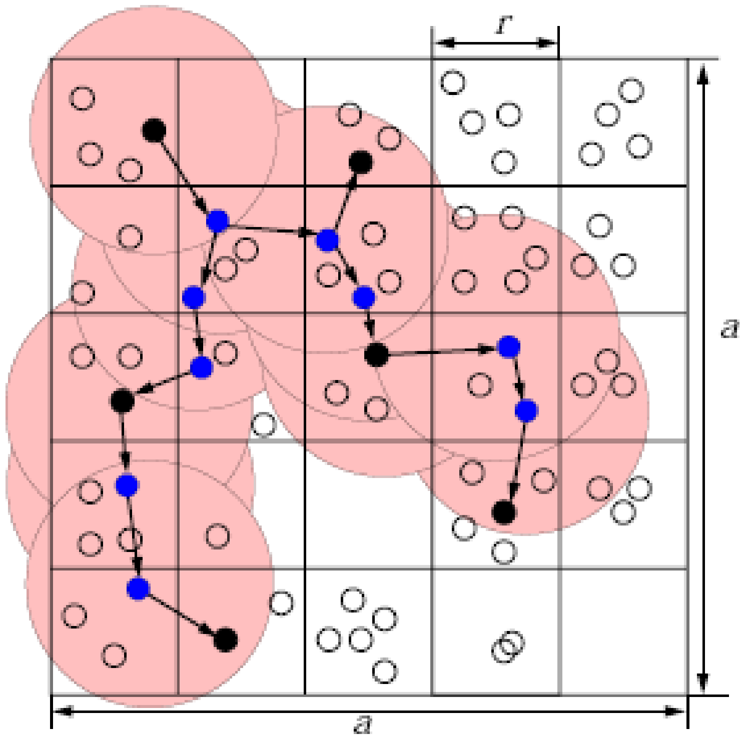
Multicast under Protocol Model

❖ **Data Copies Argument** (upper bound)

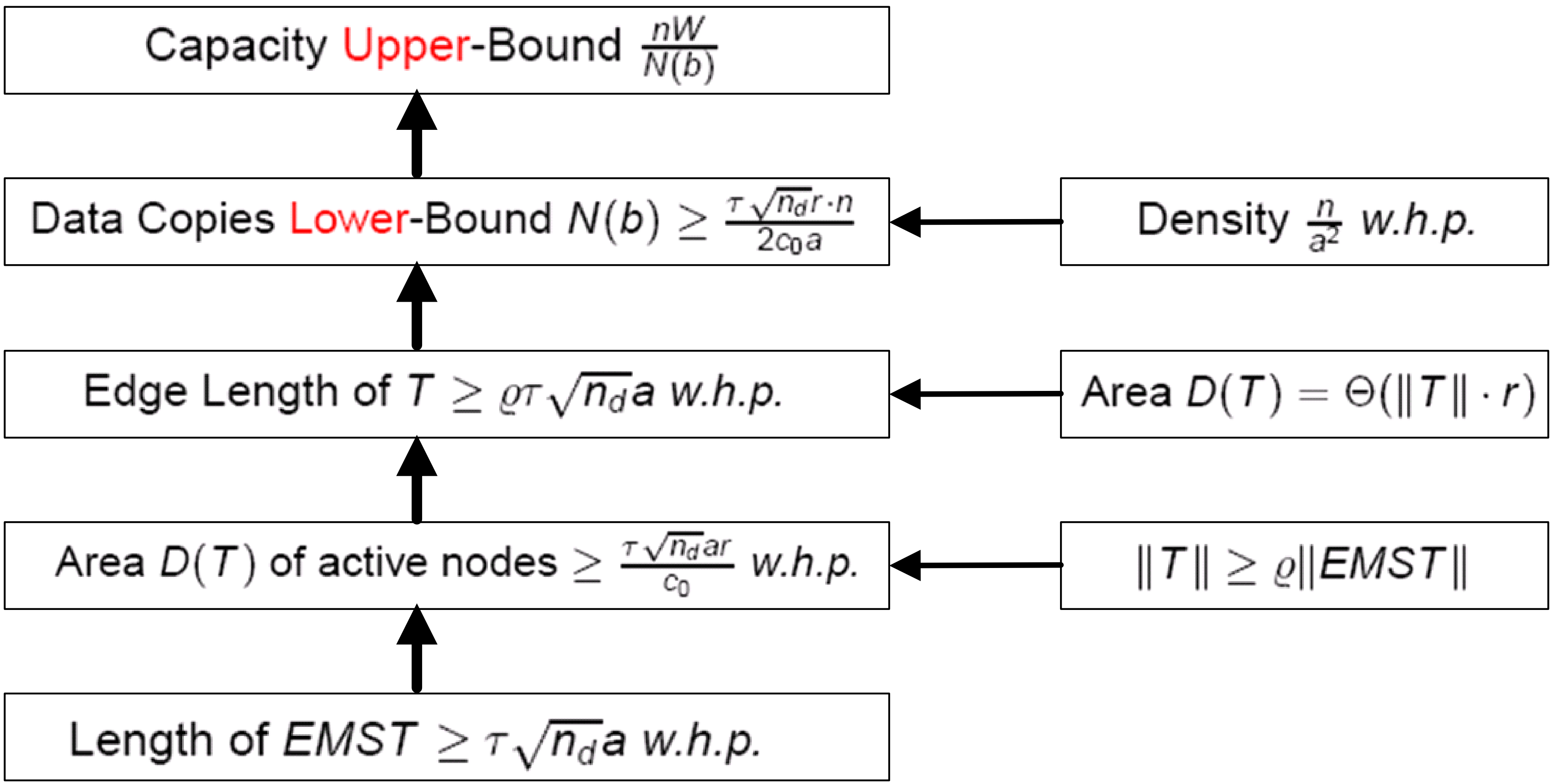
– Estimate the expected (or asymptotic lower bound) number of nodes *N(b) that received (or listened) a bit b*.

– Capacity at most $n \cdot W/N(b)$

➢ *since all nodes receive at rate at* most $n \cdot W$.

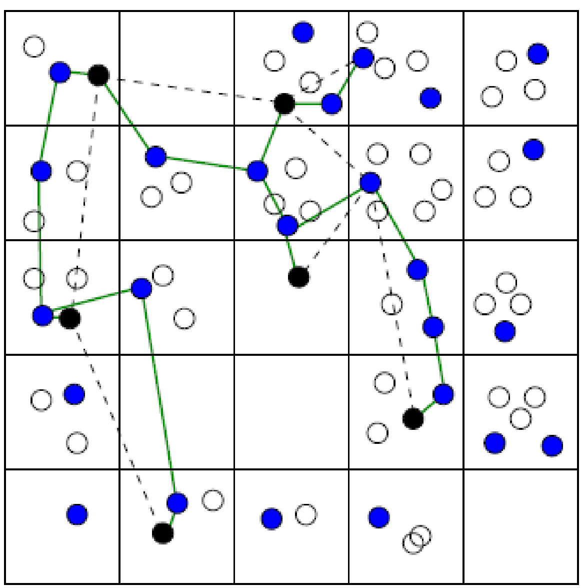


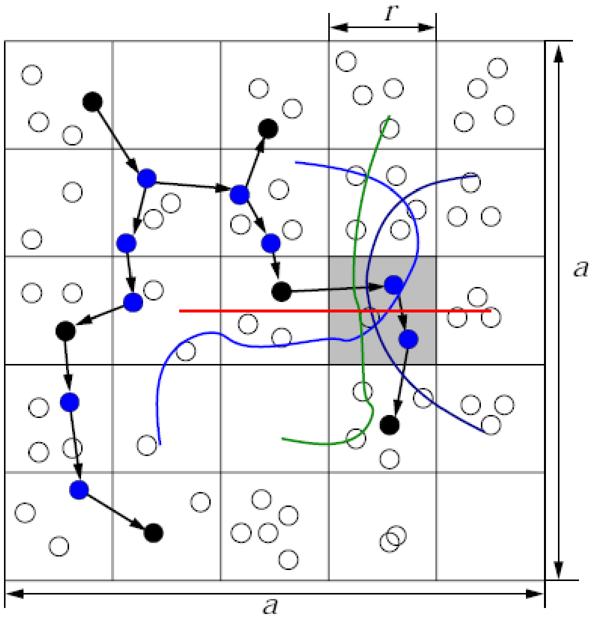
Upper-bound Proof Flow



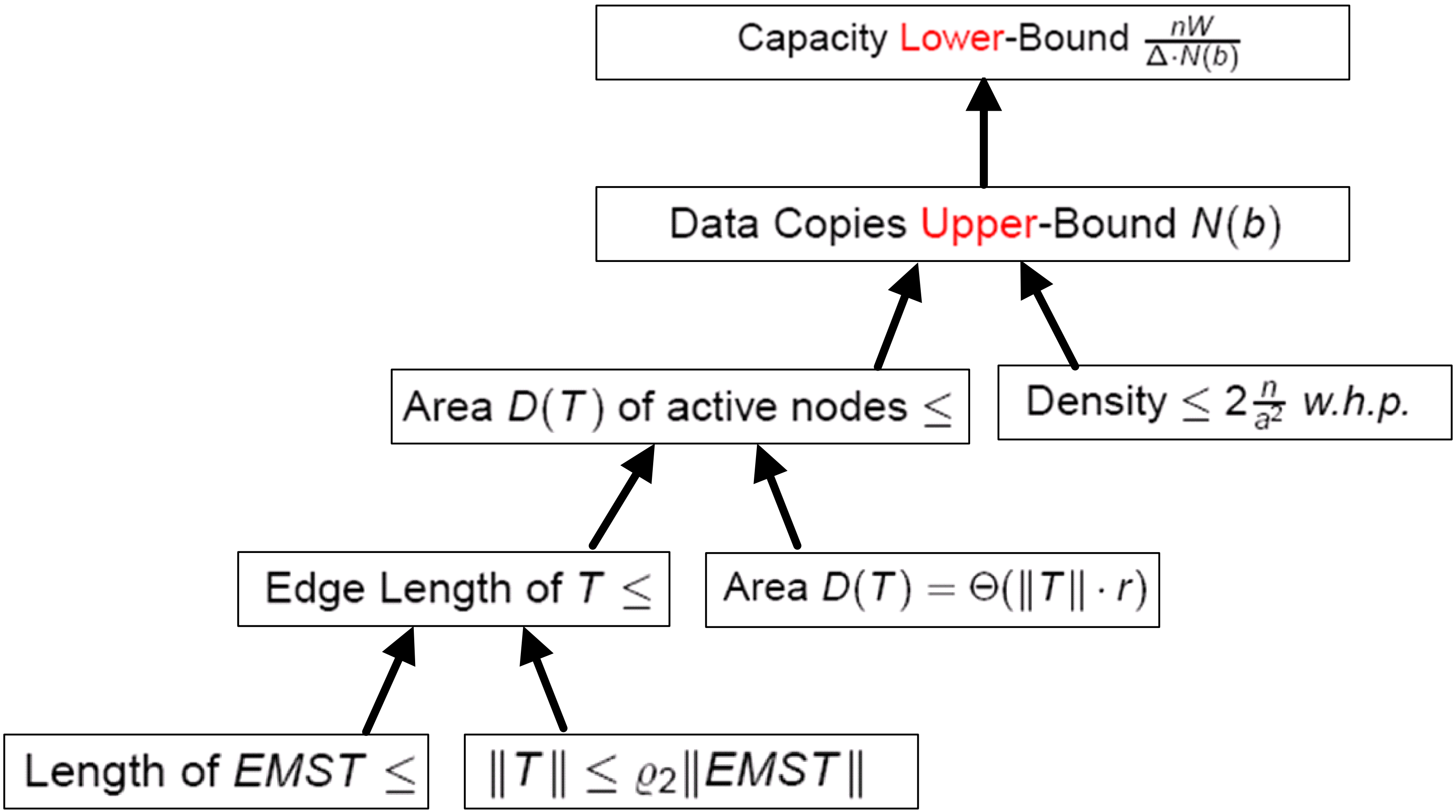
Lower-Bound: Routing and Scheduling

- Build EMST
  - Routing structure using EMST as backbone
  - Need to bound the conflict and total data copies
    - The lower-bound of multicast tree length w.h.p.? EMST?
    - Maximum number conflicting flows in the network w.h.p
      - Using VC dimension (proved to be O(log n_d)), and VC theorem





Lower-bound Proof Flow

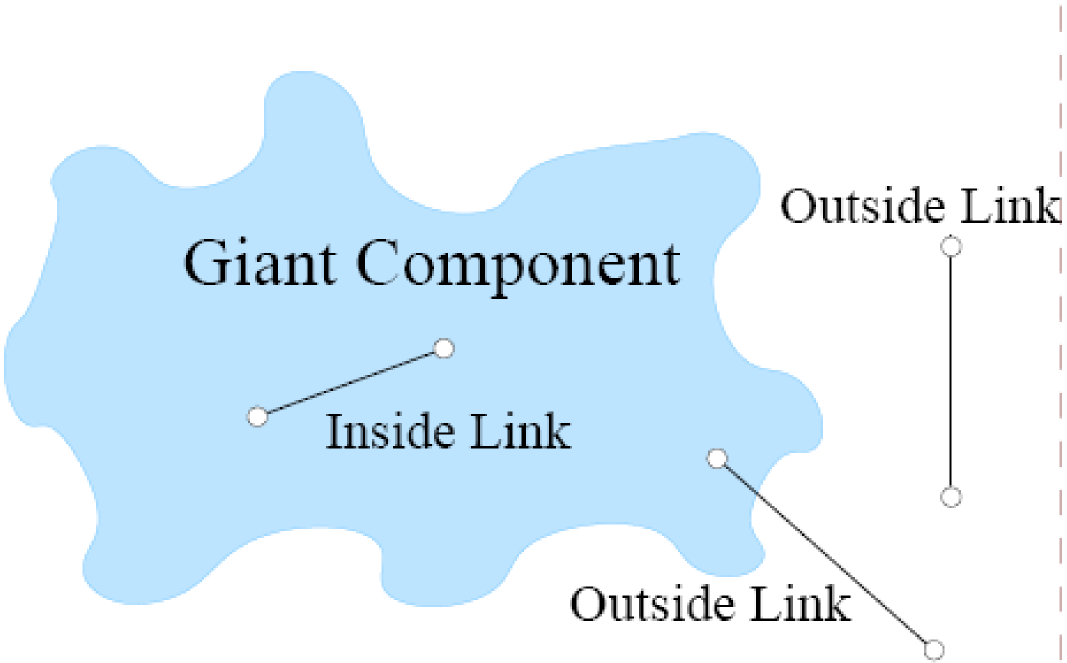


Gaussian Channel Model

General Approaches

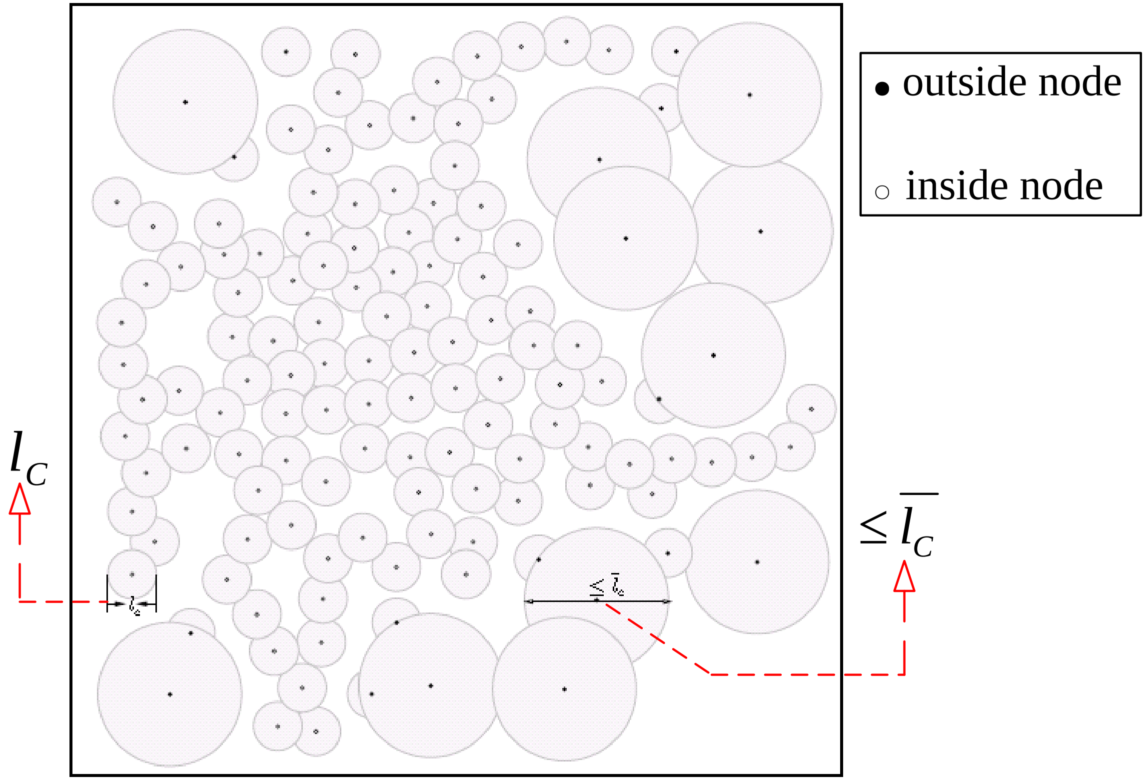
Multicast under Gaussian Model

- Two kind of links
  - Inside Links
  - Outside Links



Relationship between links

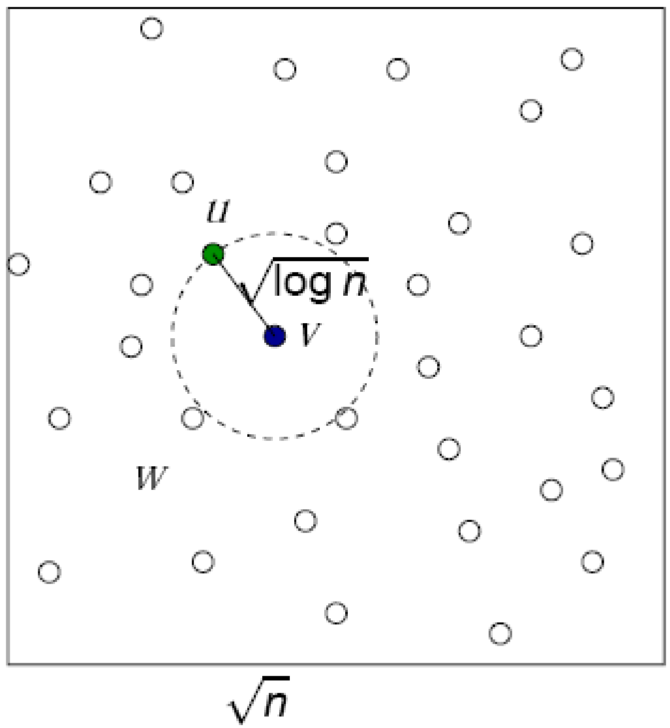
- l_c : max link length in giant component.
- $\overline{l_c}$: the max distance between any node *not in GC and the giant cluster*



$$\text{If } l_c = o(\sqrt{\log n / \zeta}) \text{ then } \zeta \cdot l_c \cdot \overline{l_c} = \Omega(\log n)$$

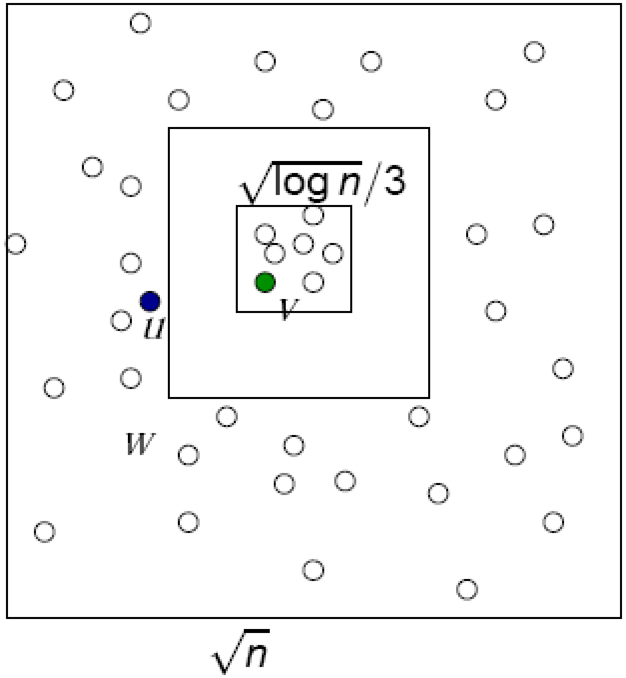
Upper-bound Proof Techniques 1

- There is a link *uv, that will be used by many* flows (say *f*) ⇒ *the minimum data rate*
  - – min $\lambda_i \le$ rate supported by *uv / f*



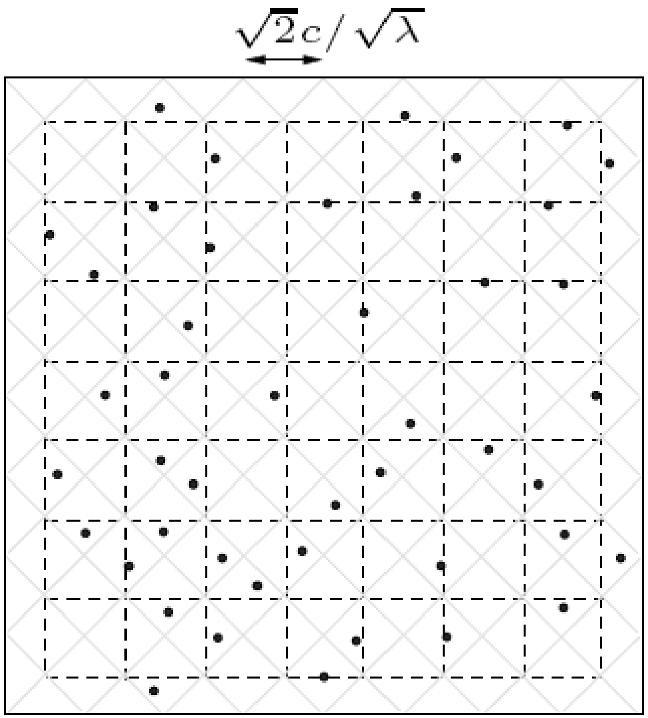
Upper-bound Proof Techniques 2

- There is an isolated cluster *C of nodes, and f* flows will have links going inside this cluster
  - – min $\lambda_i \leq$ total rate supported by links reaching C/f

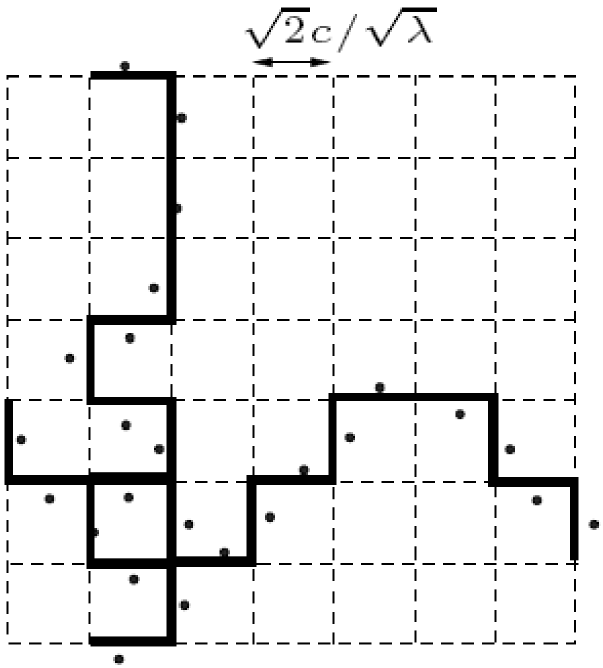


Lower Bounds Techniques

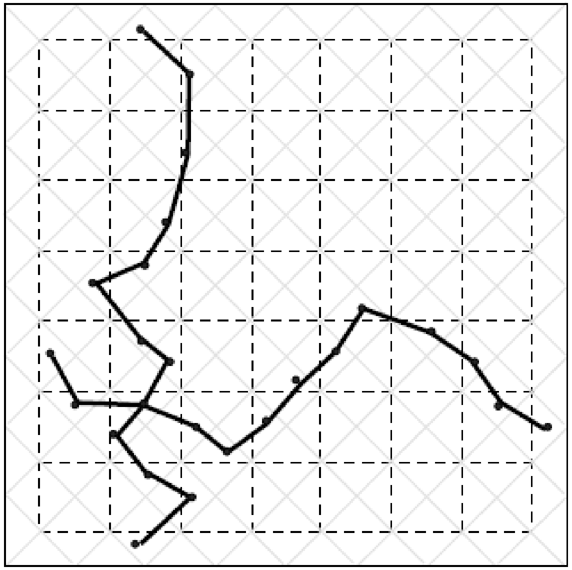
- Highway systems
  - Cell is of O(1) nodes inside
  - from percolation theory
  - First used by Tse et al



(a) $\mathbb{L}(n, \lambda, \sqrt{c^2/\lambda}, \pi/4)$



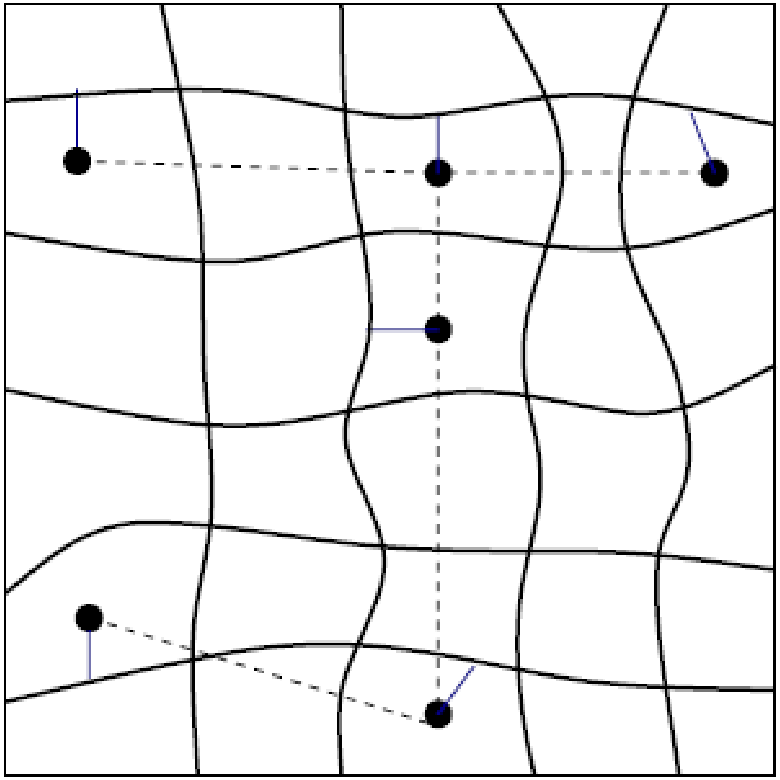
Two paths



Two highways

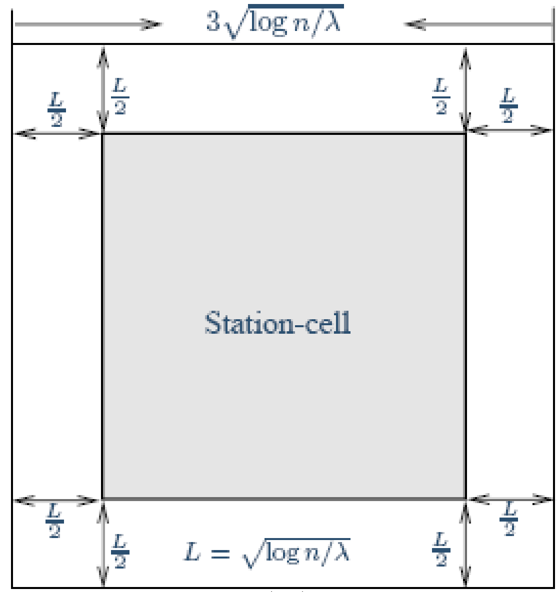
Low Bound: Routing, Scheduling

- First build EMST of receivers
- Build highway using cell size 1
  - Each highway link data rate O(1)
- Build second-class highway using cell size (log n)^1/2
- Node sends its data to highway (solid lines) by multi-hop second class highway (dashed line)

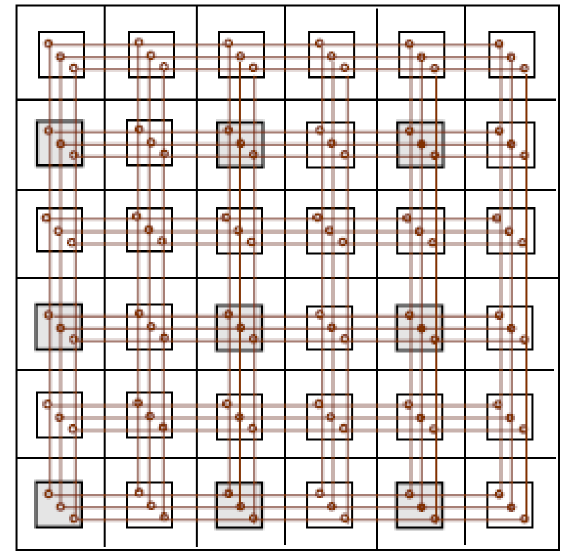


Our New Techniques

- ❖ **Parallel Arterial Road Systems**
  - **– longer links to connect isolated nodes to highway**

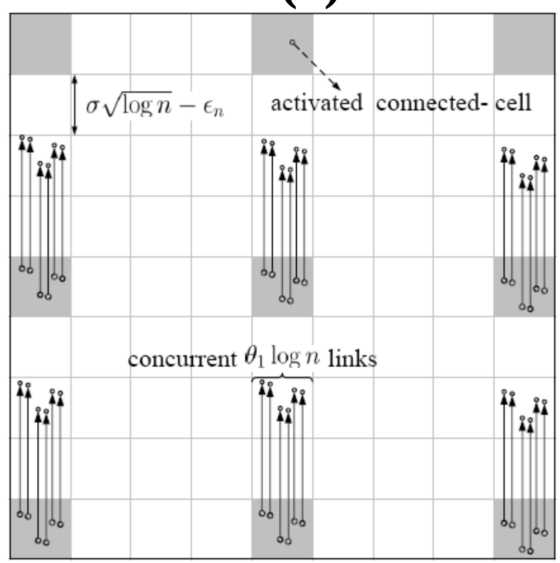


(a)

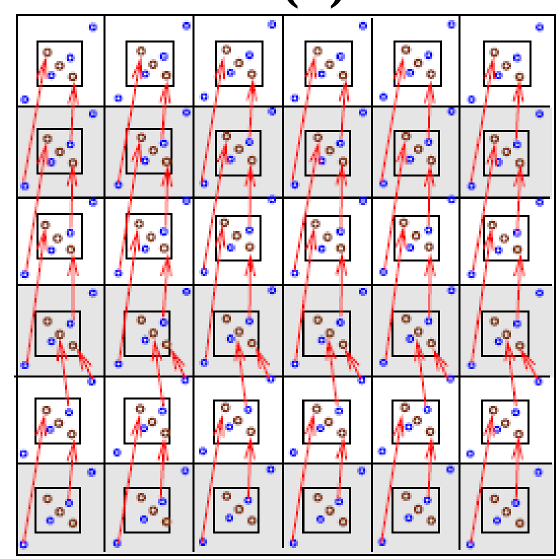


(b)

- ❖ **Parallel Scheduling**



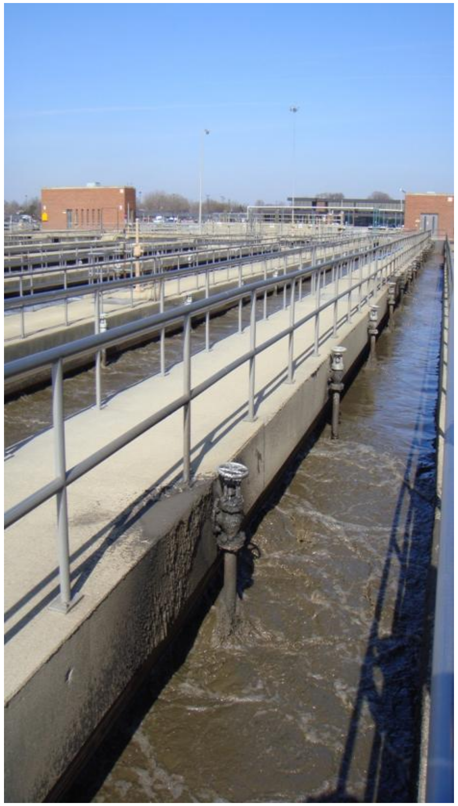
(c)



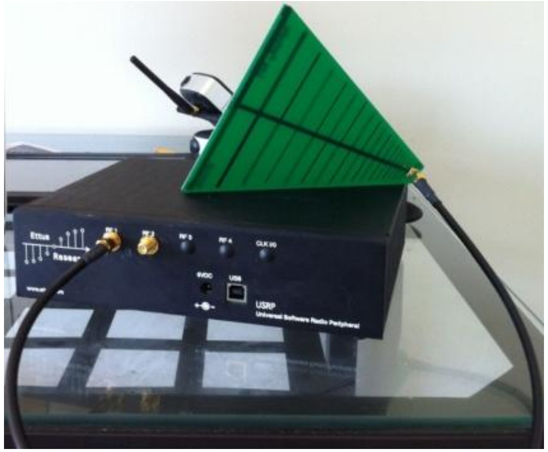
(d)

Other Research

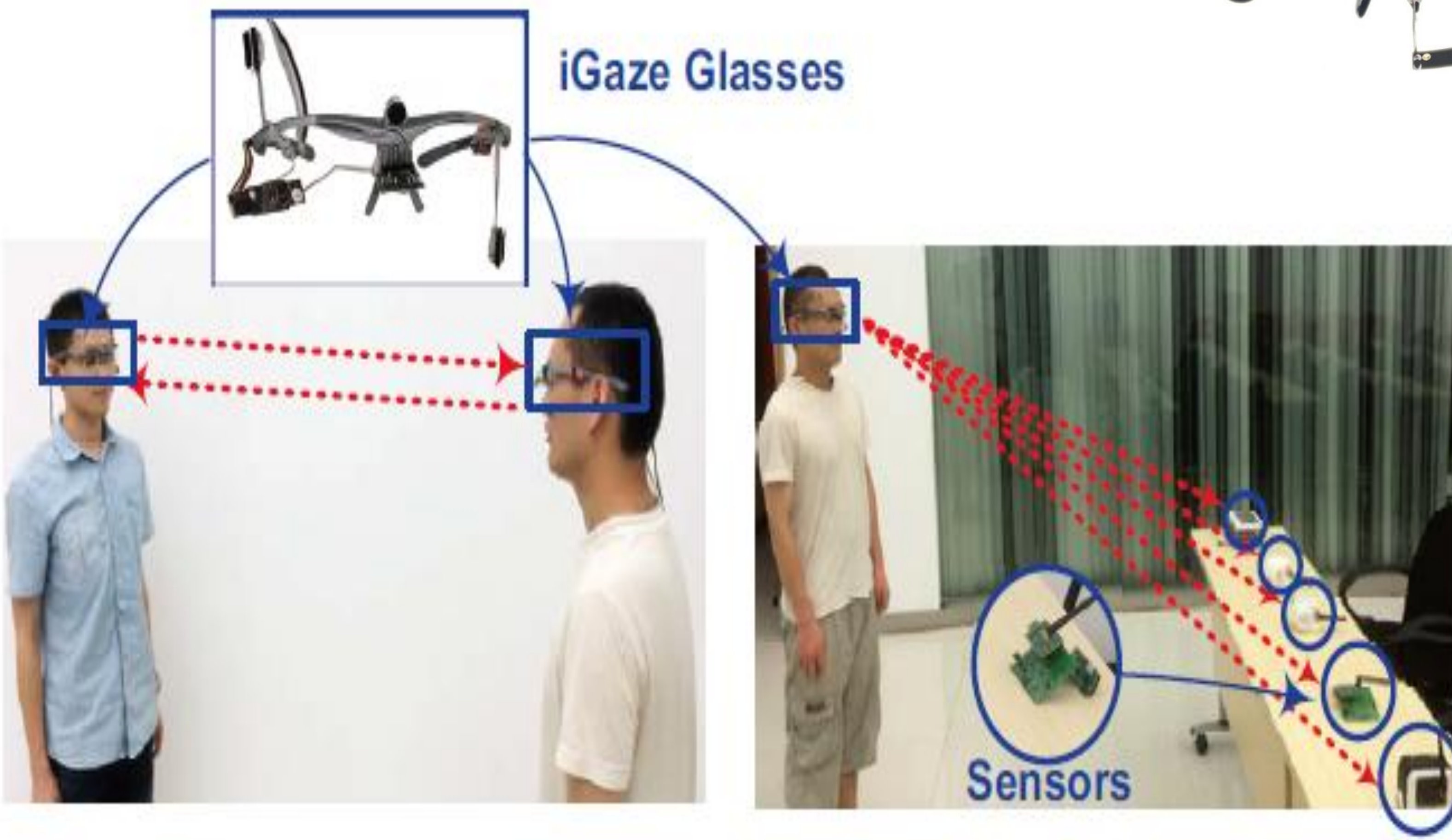
Cyber Physical Systems



Cognitive Radio Networks

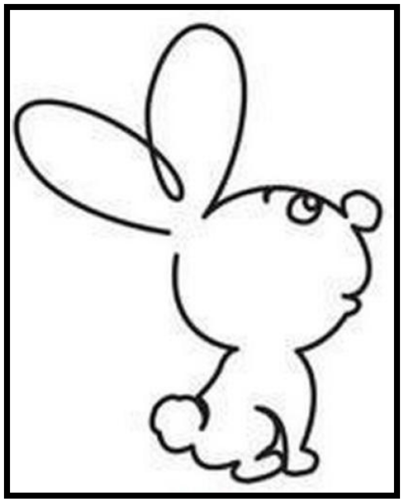


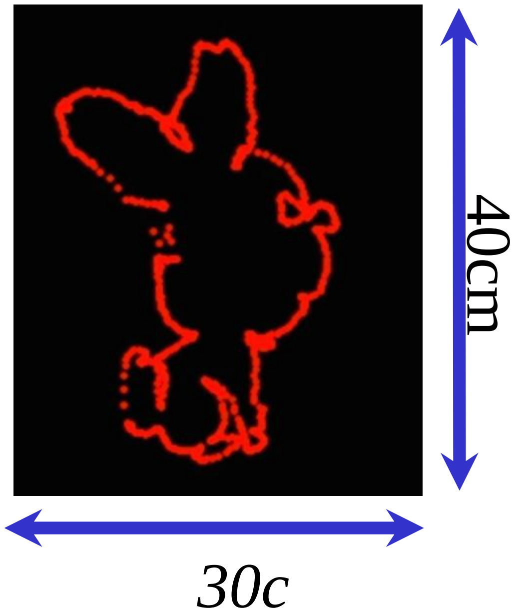
Our iGaze Glasses

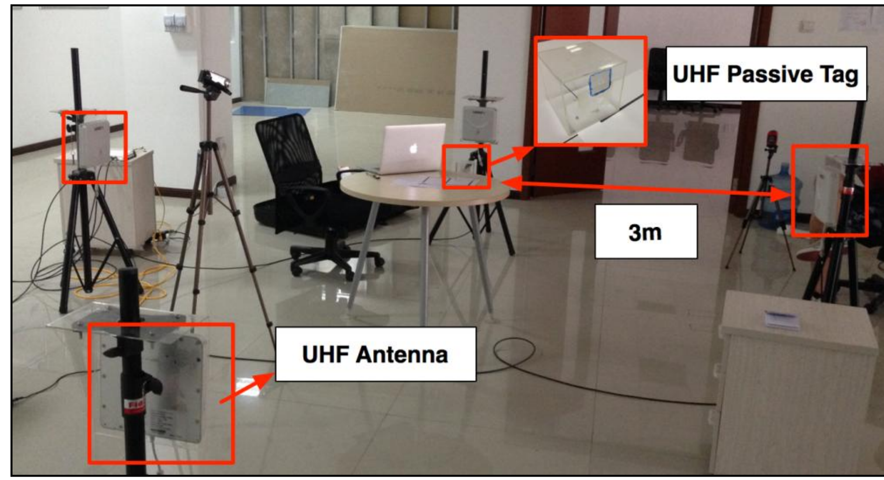


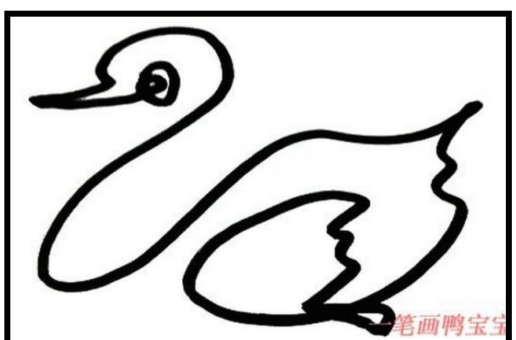
TAGORAM

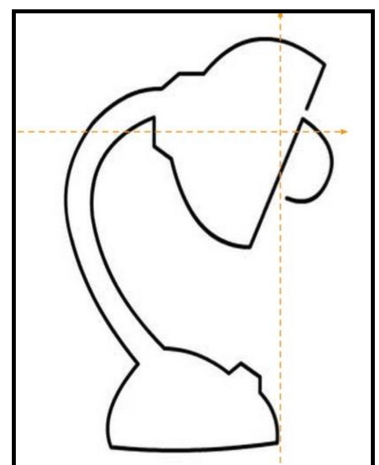
Drawing in the Air

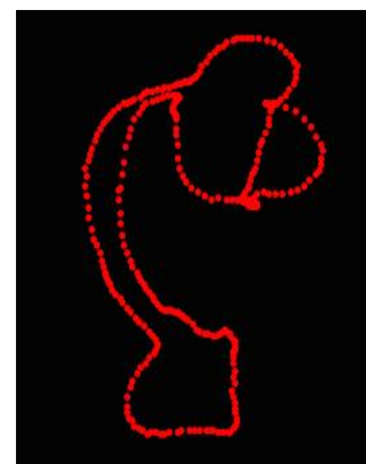












Acknowledgments

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NSFC

Research Grants Council 研究資助局

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UNCC

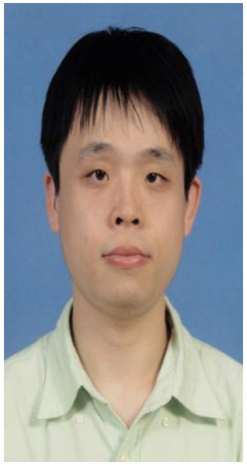
GSU

financial

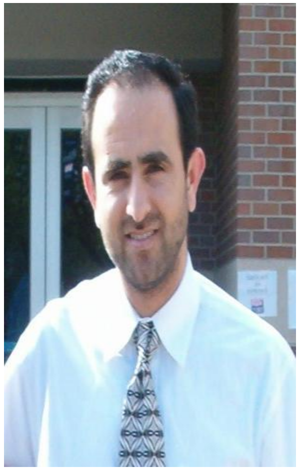
Google

W. Oregon

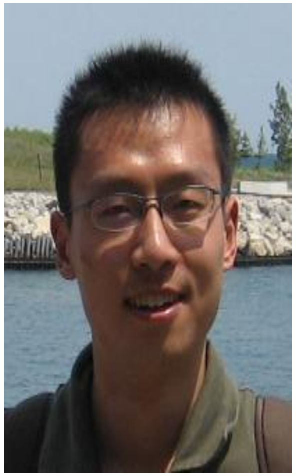
Tsinghua



financial



Motorola



UT Dallas

Toledo

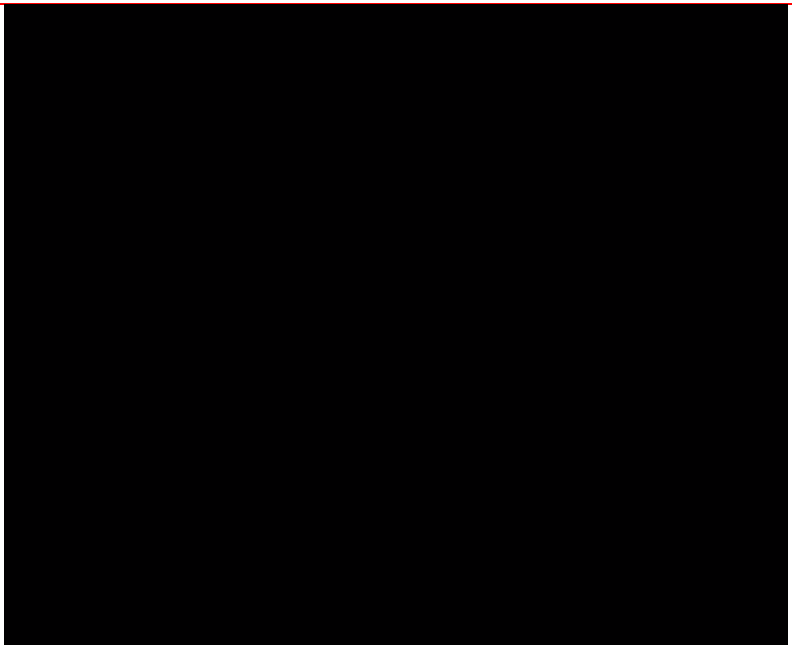
Current PhD Students

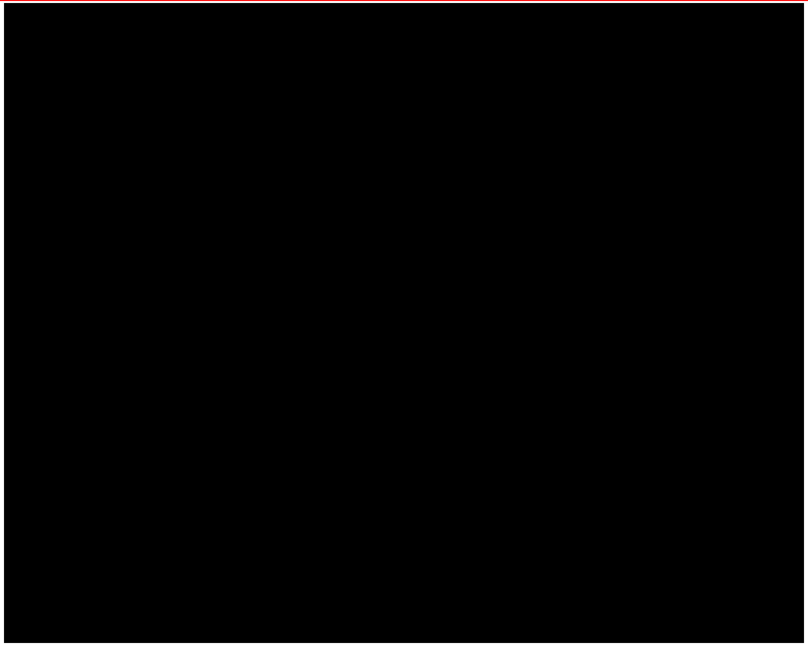
MS Students

Students in IIT

Domestic Students

Deployment Videos





Thank you !

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