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

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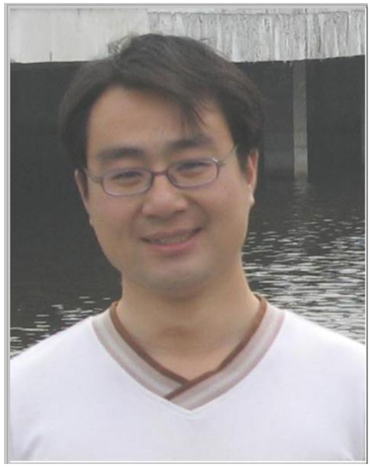
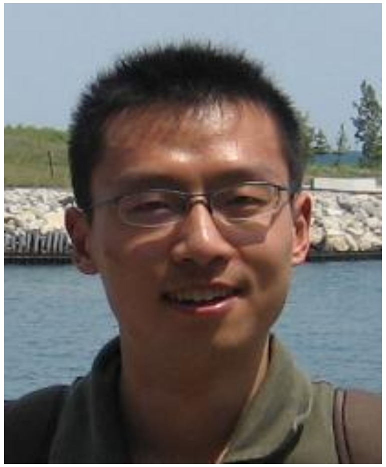
  - With students Cheng Wang, ShaoJie Tang, Xiaohua Xu, XuFei Mao, Wei Dong, Kebin Liu, Shi Li, etc
  - Many collaborators: Prof. Yunhao Liu, and Prof. Zhao

Collaborators

PhD Students (graduated 10)

UNCC

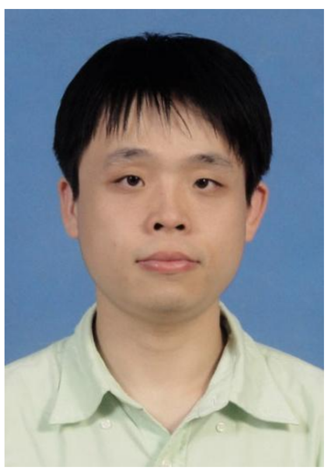
GSU

financial

Google

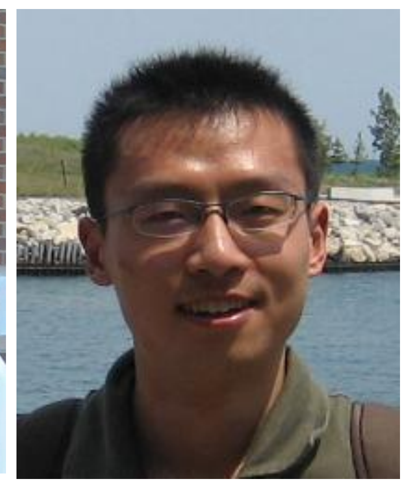
W. Oregon

Tsinghua

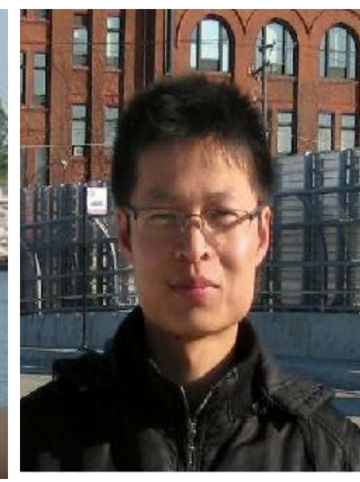


financial

Motorola



Temple

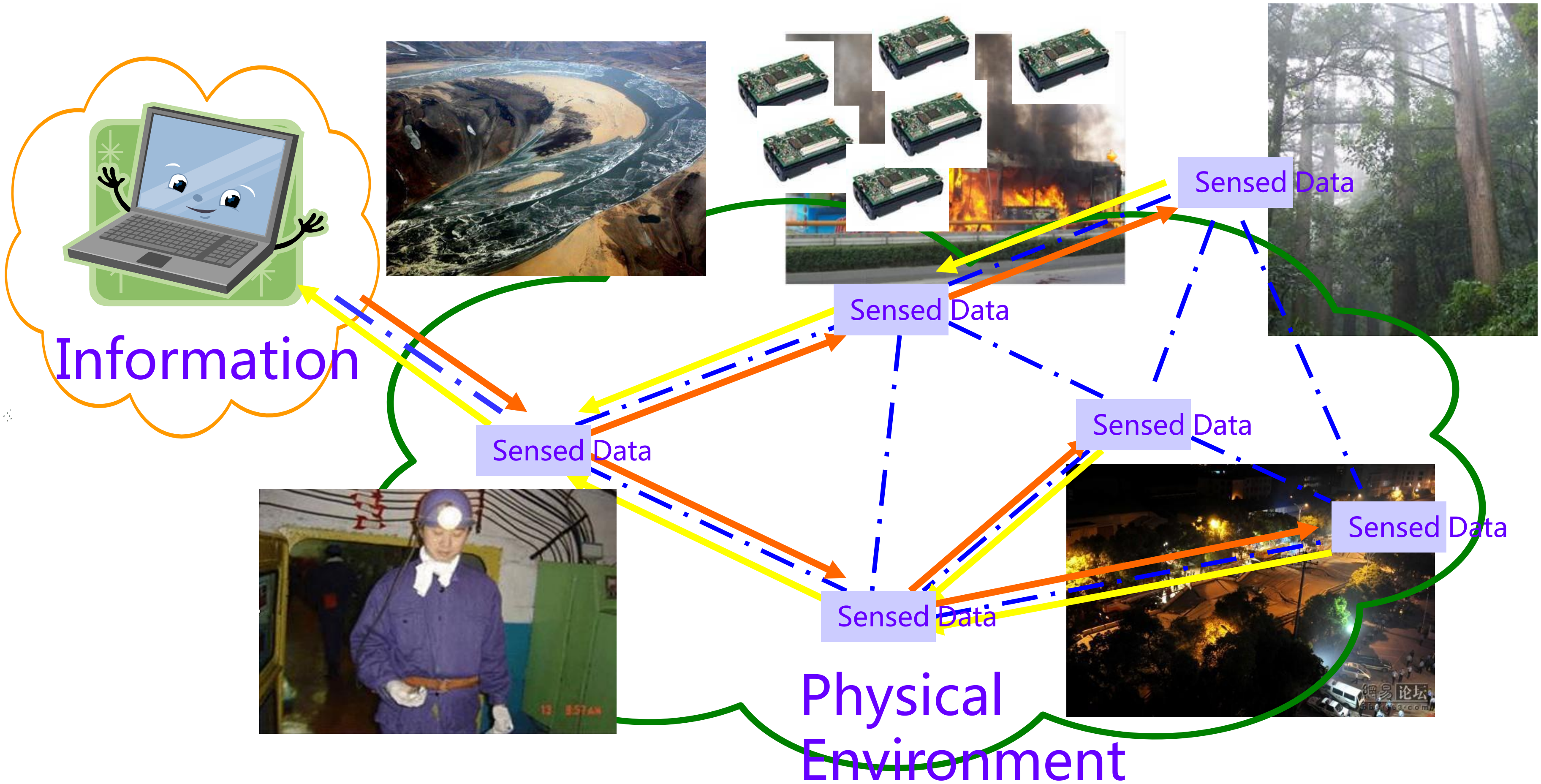


Toledo

PhD and MS Students (current)

Wireless Sensor/Actuator Networks

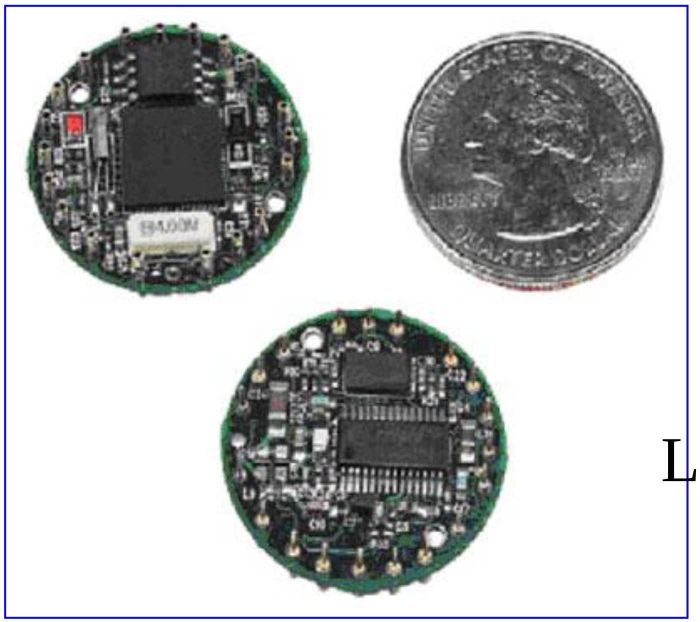
Bridging the digital world and physical world



Challenges

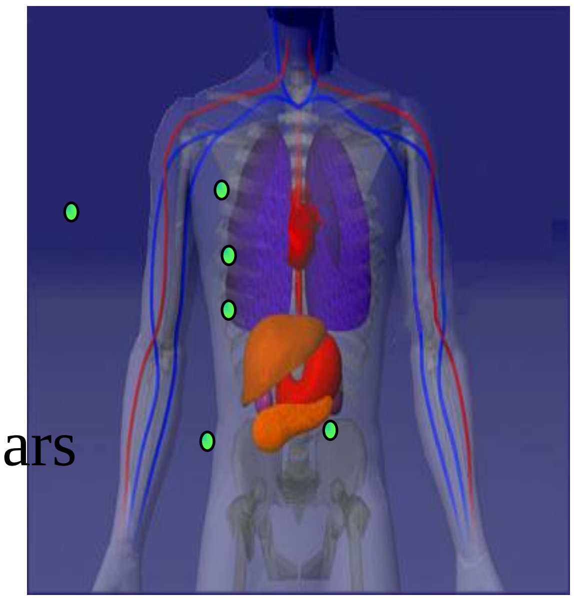
Size of now

Future



Cubic Inch

Log 16387~ 40 years



Cubic Millimeter

More Challenges

- Naming
- Localization
- Energy Supply
- Dynamic programming
- Security
- Fault detection, modeling, diagnosis

Presentation Outline

- ❖ Experience and Lessons from Large Scale WSN System Design and Deployment
  - – OceanSense
  - – GreenOrbs
  - – CitySee
  - – Waste-Water Processing
- ❖ Asymptotical Capacity of Large Scale Wireless Networks
  - – Network model, and asymptotical capacity
  - – Literature review
  - – Our results summary
  - – Our approaches

Experience and Lessons

LARGE SCALE WIRELESS SENSOR NETWORK SYSTEMS

Strategic Plan

Example: “Sensing China” 2009--

Some WSN Systems/ Ours

System (Affiliation)	Deployment manner	System Scale	Duration
Great Duck (2002)	Outdoor, battery	~150	3 months
VigilNet (Uni. of Virginia)	Outdoor Battery power	200	3~6 months
Motelab (Harvard Uni.)	Indoor Tethered power	190	N/A
SensorScope (EPFL)	Outdoor Battery power	97	6 months
Trio (UC Berkeley)	Outdoor Solar-powered	557	4 months
Jindo Bridge	Outdoor Battery power	113 Nodes, 680 sensors	2-4 months
Clemson Intelligent River	Outdoor	N/A	N/A
GreenOrbs (HKUST, IIT,...)	Outdoor/battery	1000	1 year
CitySee (Tsinghua, WuXi...)	Outdoor/battery	1500	>1 year

1. OceanSense (QingDao)
2. GreenOrbs (HangZhou)
3. CitySee (WuXi)

OceanSense

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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

中國海洋大學

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清華大學
Tsinghua University

OceanSense Project (2007-2008, video)

- The first sea environment monitoring sensor network system in China
  - More than 120 sensor nodes
  - Temperature, Light, Sea depth
  - More than one year duration
  - Deployed in the Yellow sea near Qingdao China
- With Prof. Y. Liu, Z. Guo, etc

video

Experiences and Lessons

- ❖ Systems that work in labs fail horribly in practice
  - – System run out of battery in a week (labs run in months)
    - ➢ Routing protocol and system design
    - ➢ Faults detection and diagnosis
  - – Nodes destroyed by water
    - ➢ Fixed deployment? Large flexibility? Tide?
    - ➢ Balance between accuracy, coverage, and sustainability
  - – People factors!
    - ➢ Nodes stolen by people
      - – they are not interested in the node, but the sticks

GreenOrbs 绿野千传

http://www.greenorbs.org/

GreenOrbs (2009-)

About 1000 sensors deployed at multiple phases, places

Joint work with Prof. Liu from HKUST, and Prof. Dai from HDU, Prof. Zhou from ZFU, Prof. Zhao from Xi'An JTU, Prof. Gu from Tsinghua, Prof. Ma from BUPT, and several others

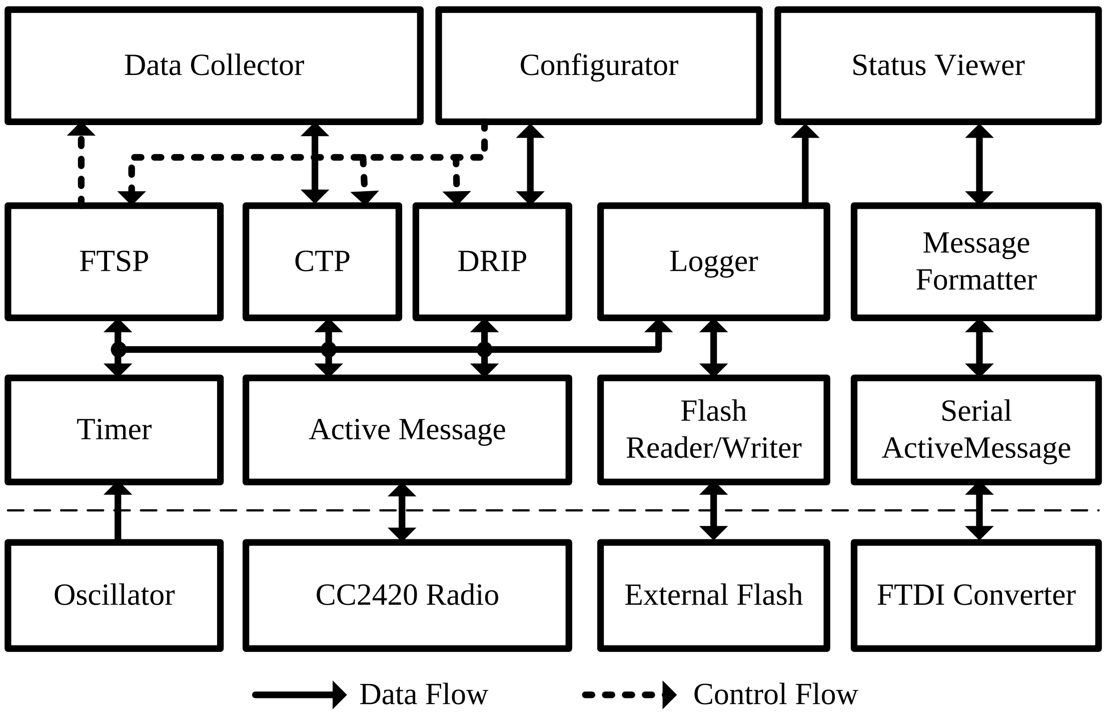
GreenOrbs - building blocks (1)

- Hardware
  - TelosB mote with MSP430 processor and CC2420 transceiver
  - Sensors

Sensor	Function	Software
Sensirion Sht11	Temperature & Humidity	SensirionSht11C
Hamamatsu S1087	Illuminance	HamamatsuS1087ParC
Internal Voltage Sensor	MCU-Internal Voltage	VoltageC
GE Telaire 6004	Content of CO2	Self-developed

GreenOrbs - building blocks (2)

- System based on TinyOS 2.x.
  - Low Power Listening LPL
  - Data collection: CTP
  - Parameter dissemination: DRIP

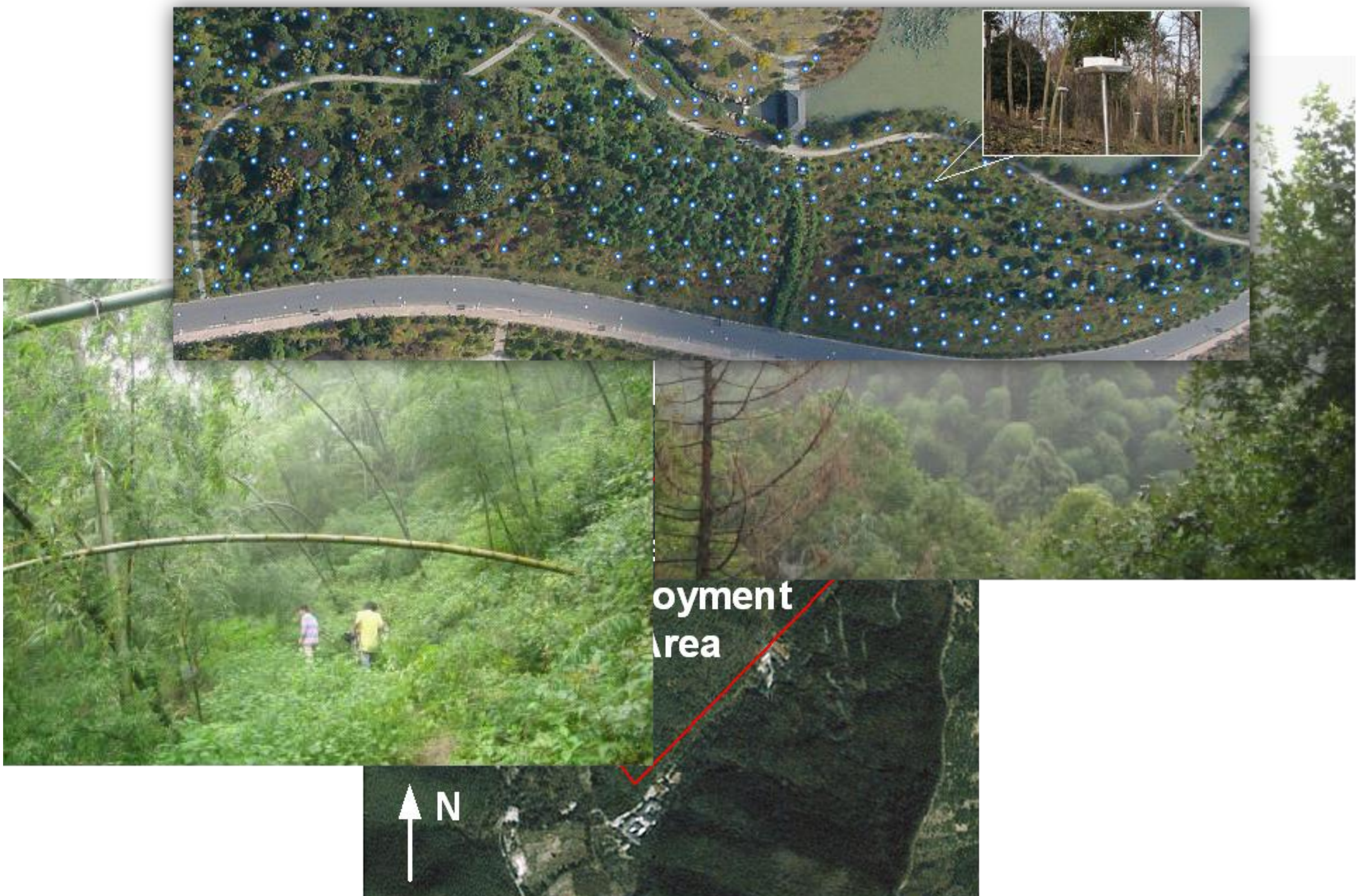


GreenOrbs Deployments

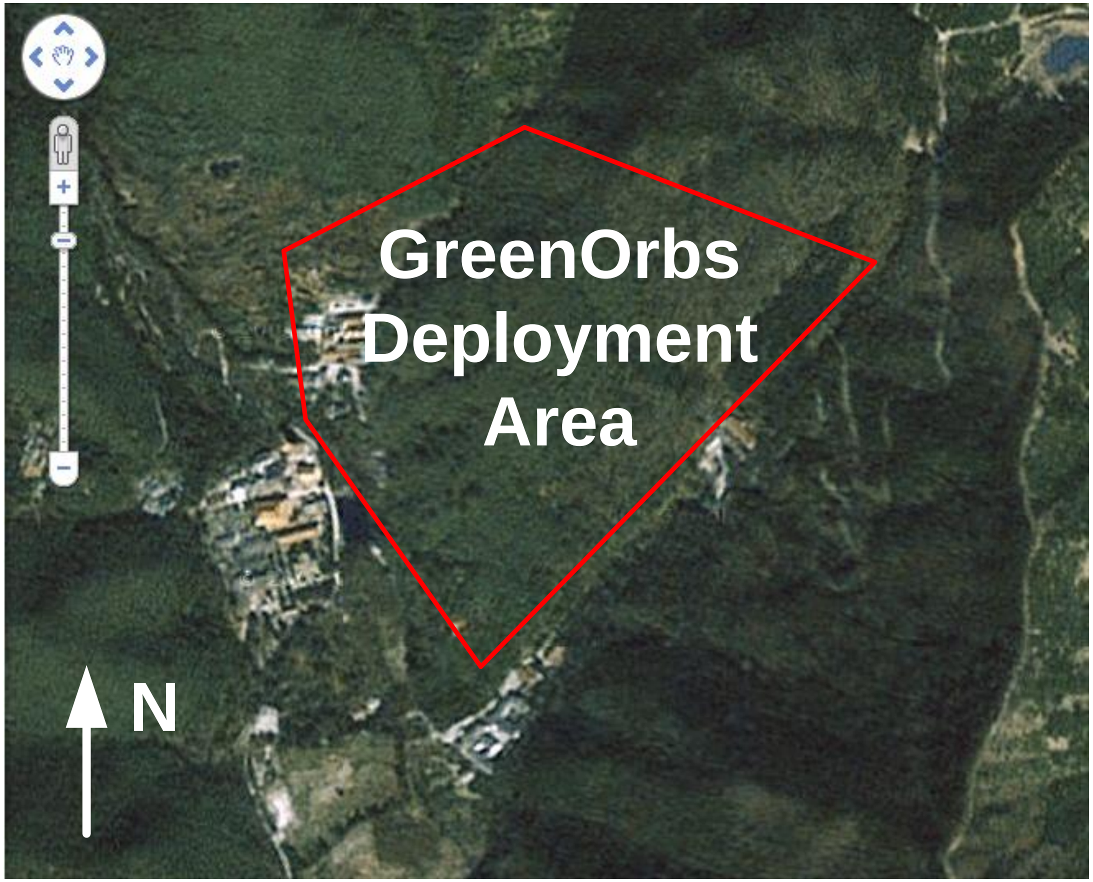
Place	Area	Duration	Battery	Scale	Network Diameter	Duty Cycle	Data Volume
University woodland #1	20,000 m^2	1 month (2008)	800 mAh 1.5V	50	6 hops	No	15 Mbytes
University woodland #2	20,000 m^2	10 months (2009)	2200 mAh 1.2V	120	10 hops	5%	272 Mbytes
University woodland #2 and #3	40,000 m^2	1 year (2009.12~)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

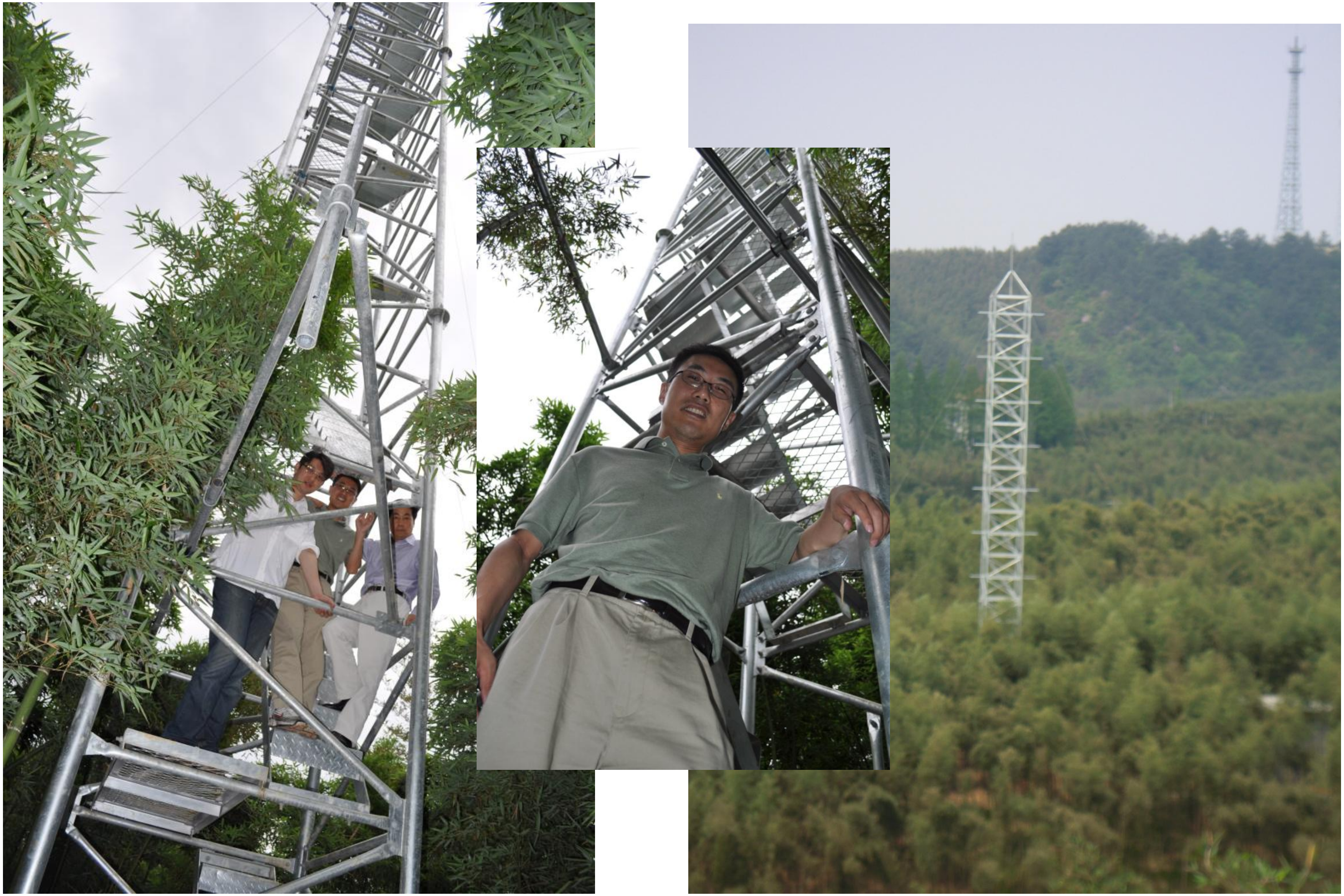
Deployment



Tianmu Mountain Deployment



TianMu Mountain Deployment



Real Deployment

Working station

Deployment in Forest

29

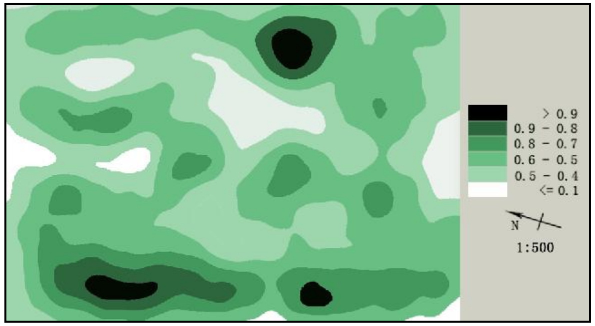
WSN Nodes

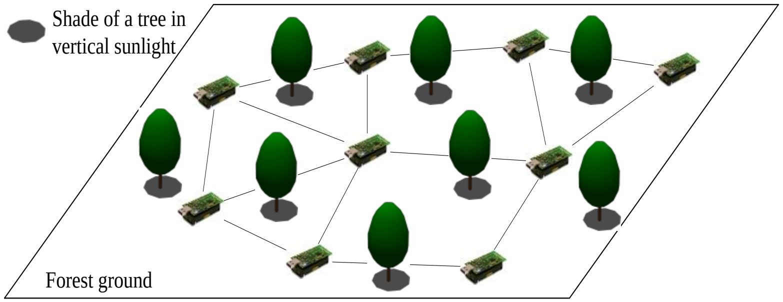
GreenOrbs Deployments

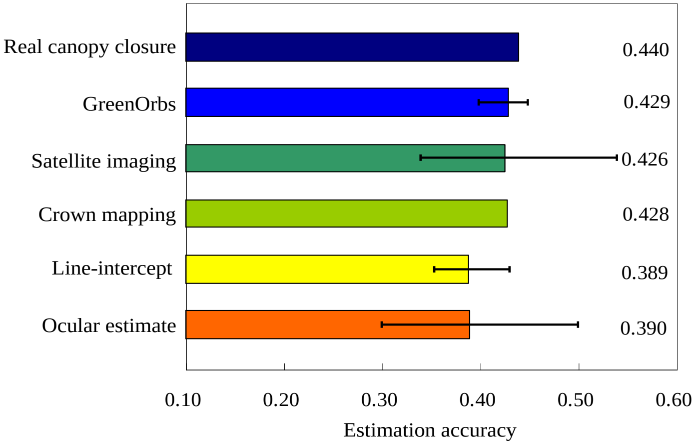
Screen capture from our video

App 1: Canopy Closure Estimates

❖ Using WSN for forestry measurements



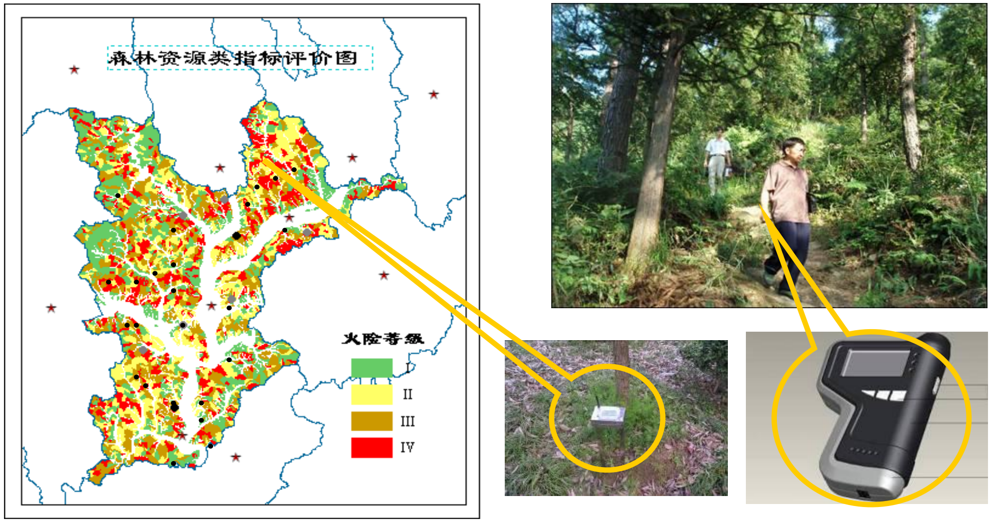




Lufeng Mo, Yuan He, Yunhao Liu, Jizhong Zhao, Shaojie Tang, Xiangyang Li, Guojun Dai, "Canopy Closure Estimates with GreenOrbs: Sustainable sensing in the Forest," **ACM SenSys 2009**.

App 2: Fire Risk Prediction

- ❖ Fire prediction vs. fire detection
- ❖ Microscopic vs. macroscopic prediction
- ❖ Devices designed for rangers
  - – ranger’s trace, collect data



App 3: Ecological Study (Video)

- ❖ Study on the classical forestry theory of climax community
  - – Equilibrium broken after declaring Tianmu mountain as forest preserve (bamboo prevails)




Experience and Lessons

- Ensuring Performance of Large Scale Multi-Hop WSN is extremely challenging
  - The data packet loss ratio is higher initially for ~20 hops WSN
  - The network capacity is limited to support all nodes with large sampling frequency
  - Environment Factors
    - Deployment difficulty --- trees, and bamboos.
    - Flooding destroy some nodes
    - 4-season weather-proof?

CitySee

City-Wide Urban Sensing

清華大學 Tsinghua University

西安交通大學 XI'AN JIAOTONG UNIVERSITY

ILLINOIS INSTITUTE OF TECHNOLOGY
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杭州電子科技大學 HANGZHOU DIANZI UNIVERSITY

香港科技大學 THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

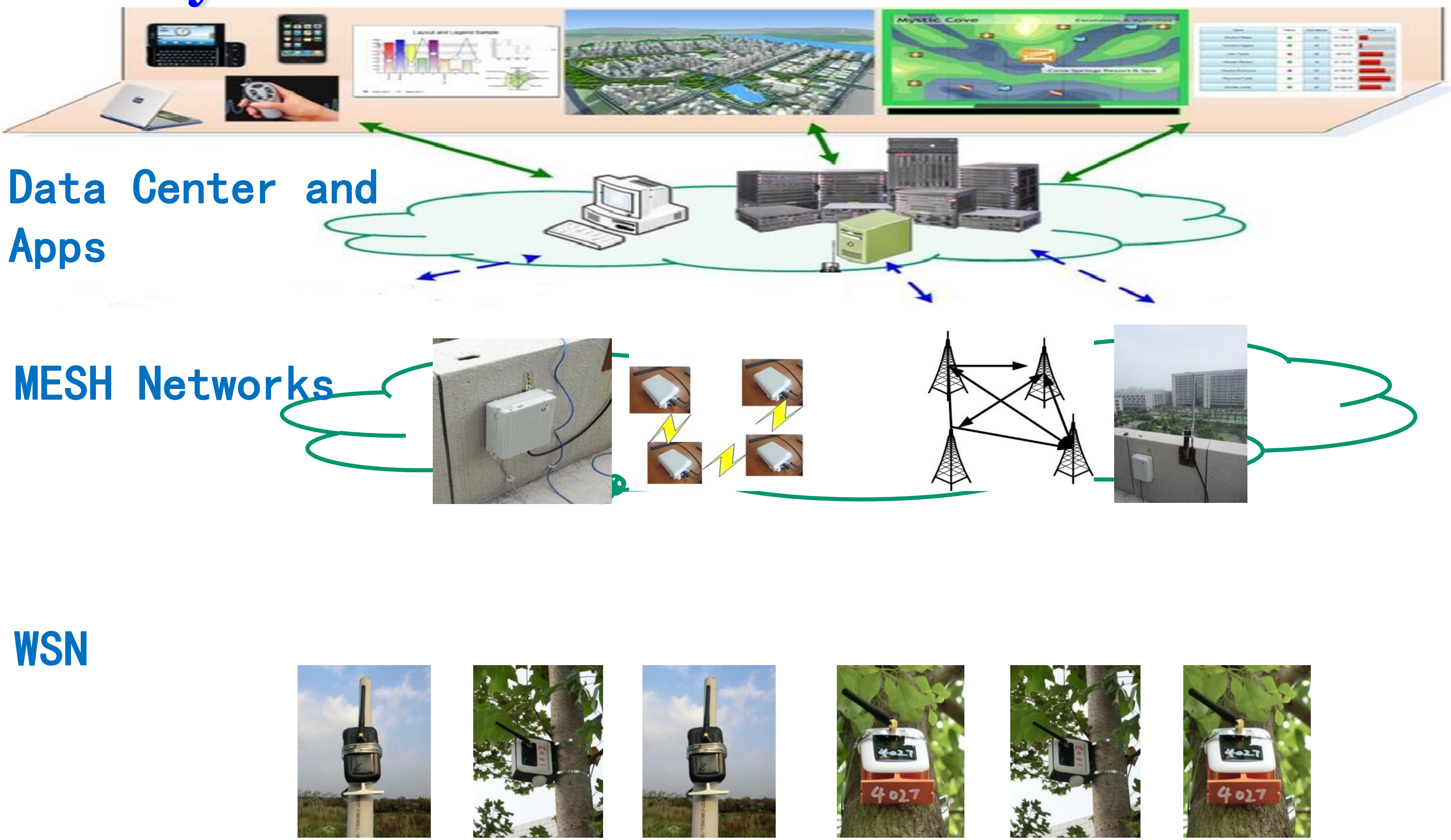
浙江林学院

CitySee (2011-present)

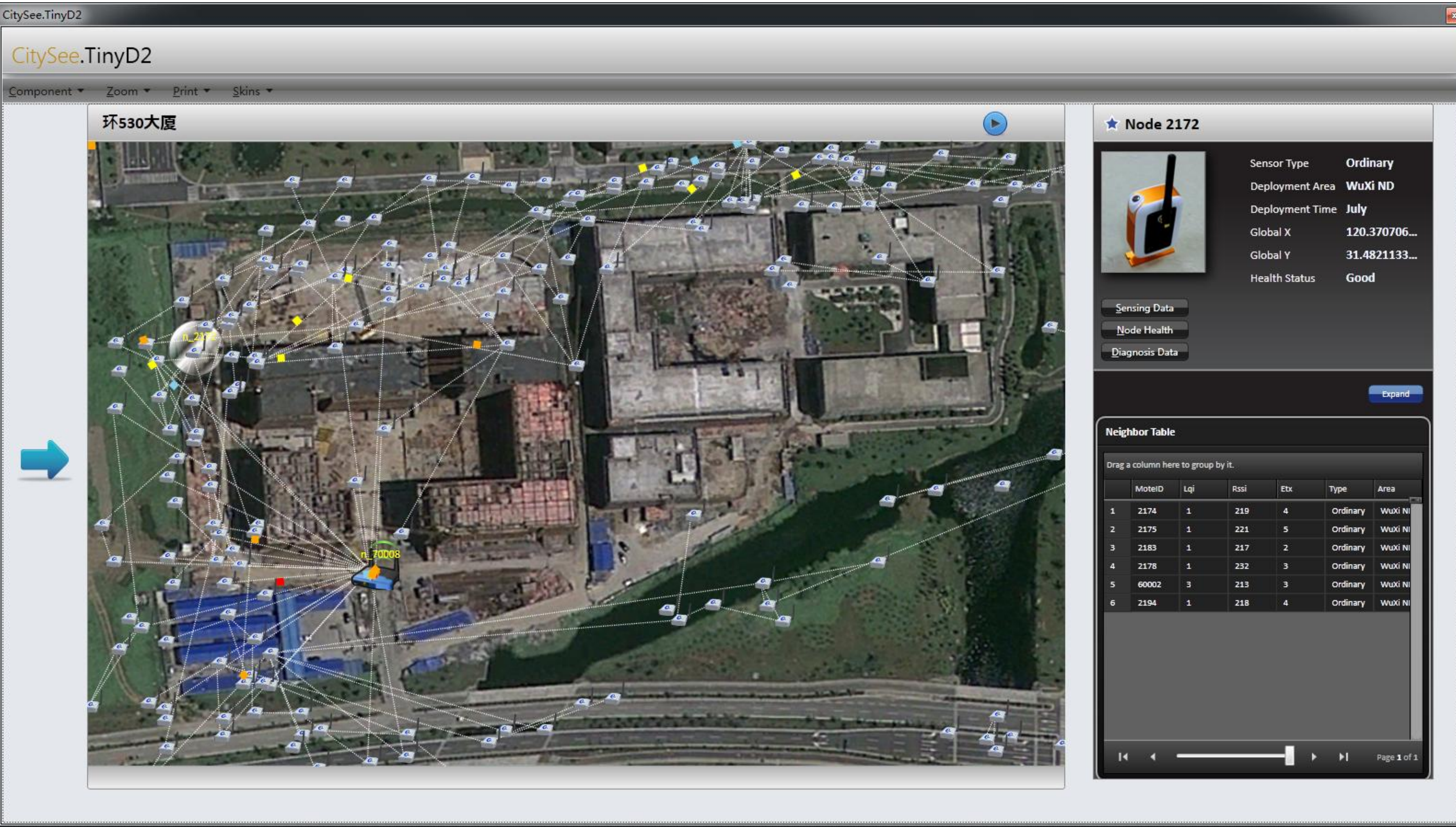
In the process of deploying **10,000** sensors in city environment.
A project that needs wide range of domain experts→


JACK
Columbia

System Architecture

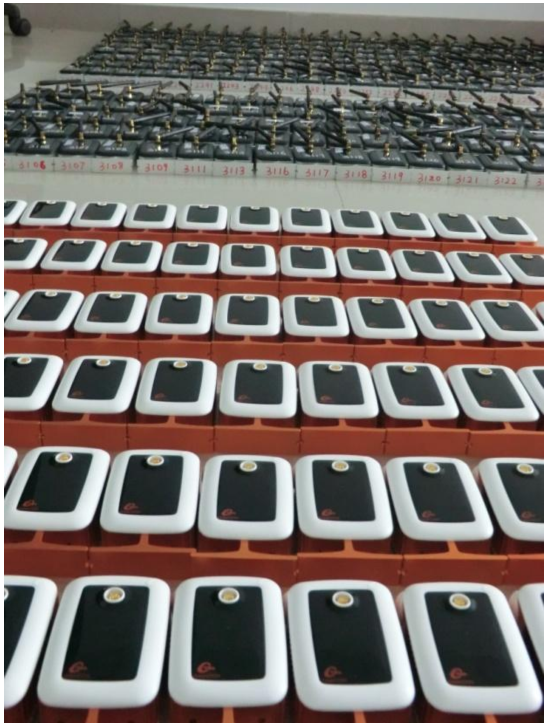


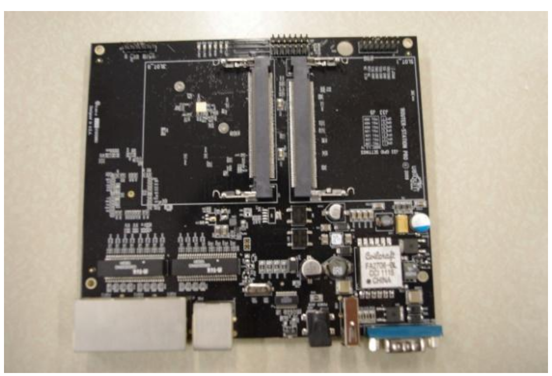
1500 Sensor Nodes Deployed



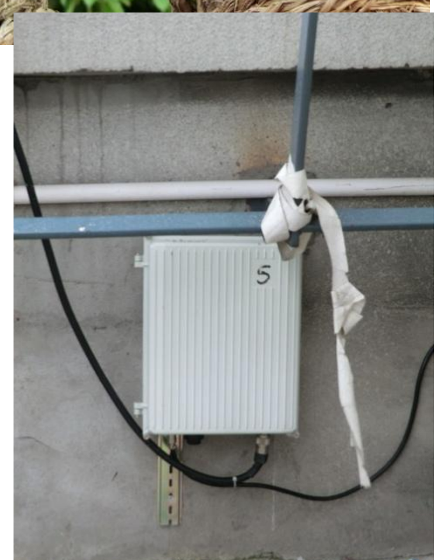
A snapshot of part of the deployment

Wireless Sensor, Mesh Nodes Designed





Sensor nodes, mesh routers deployed



CitySee: City-Wide Urban Sensing

- First phase deployment at Wuxi City (2011.5 to 2012.9)
  - 1100 nodes with temperature, humidity, light
  - 100 CO2 nodes
  - 4 Mesh nodes
  - 1.2 KM^2
- Missions: ~2013.6
  - 4000+ sensor nodes with temperature/humidity and light sensors
  - 500+ nodes with CO_2 sensor
  - Some new nodes with other GHG measurements
  - Cover 20KM^2 urban area in Wuxi City, China
- Eventually: **10,000 nodes, 100 KM^2**

CitySee – Monitoring Areas

Power Plant

Industry Zone

Residential Quarter

The Tai Lake

High-tech Park

Railway Station

Applications

Environmental monitoring, Carbon sink/emission measurement, pollution detection

CitySee Monitoring/Visualizatin System

- Network monitoring (video)
  - Network scale
  - Link scale
  - Node scale
  - Fault management
  - Localization, syn,

- Data visualization (video)
  - Spatial
  - Temporal
  - Anomaly, outlier,

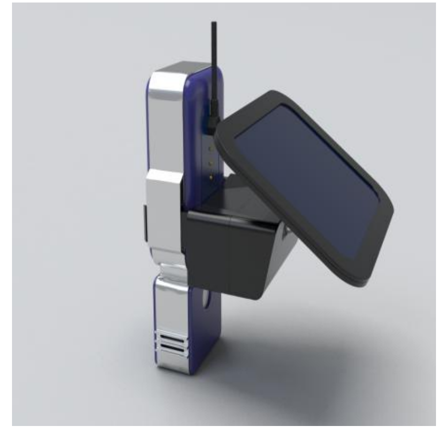
Experiences and Lessons

- It is extremely difficult and complicated to deploy in city environment
  - Need coordination with and approve from almost all government departments
  - Functionality is not enough
    - Need a nice-looking design to be approved for city
    - Cost reduction is a must when you need so many nodes
      - Node cost
      - Labor cost
    - Location constraints of deployment
      - physical constraints for placement and signal quality
      - quality of service constraints for quality of monitoring, and
      - Cost constraints
  - Co-existence with other wireless technologies
    - WiFi Interference

Some New Devices Designed Recently

Temp, Light

Outdoor CO2



CO2, Solar

Dust

Indoor CO

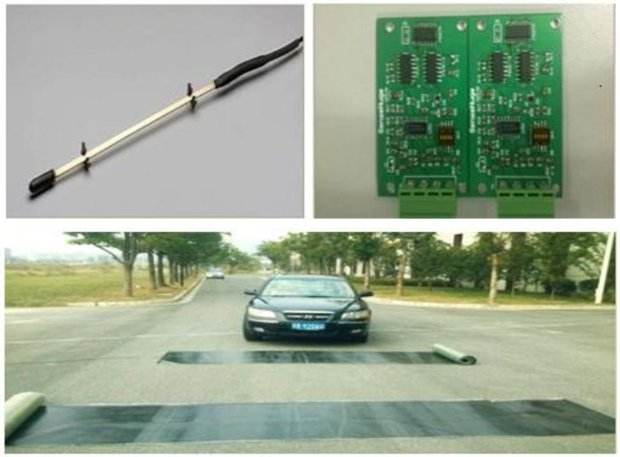
Indoor SO2

Indoor CO2

Mesh Nodes, Solar panel

Mobile Terminal

Some New Devices Designed Recently

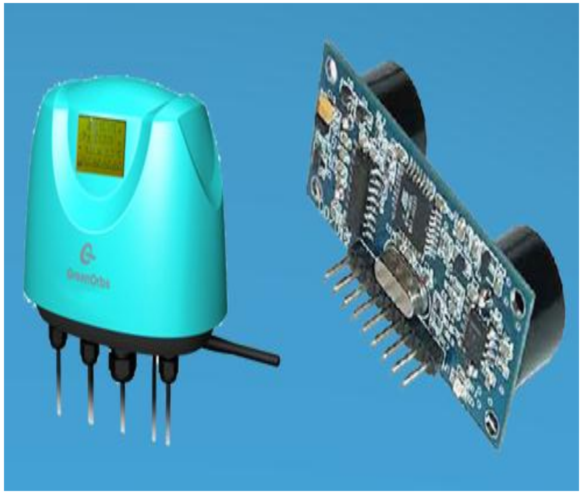


Pressure Sensor

Oil Pressure Terminal

Water Depth Sensor

Magnet Sensor



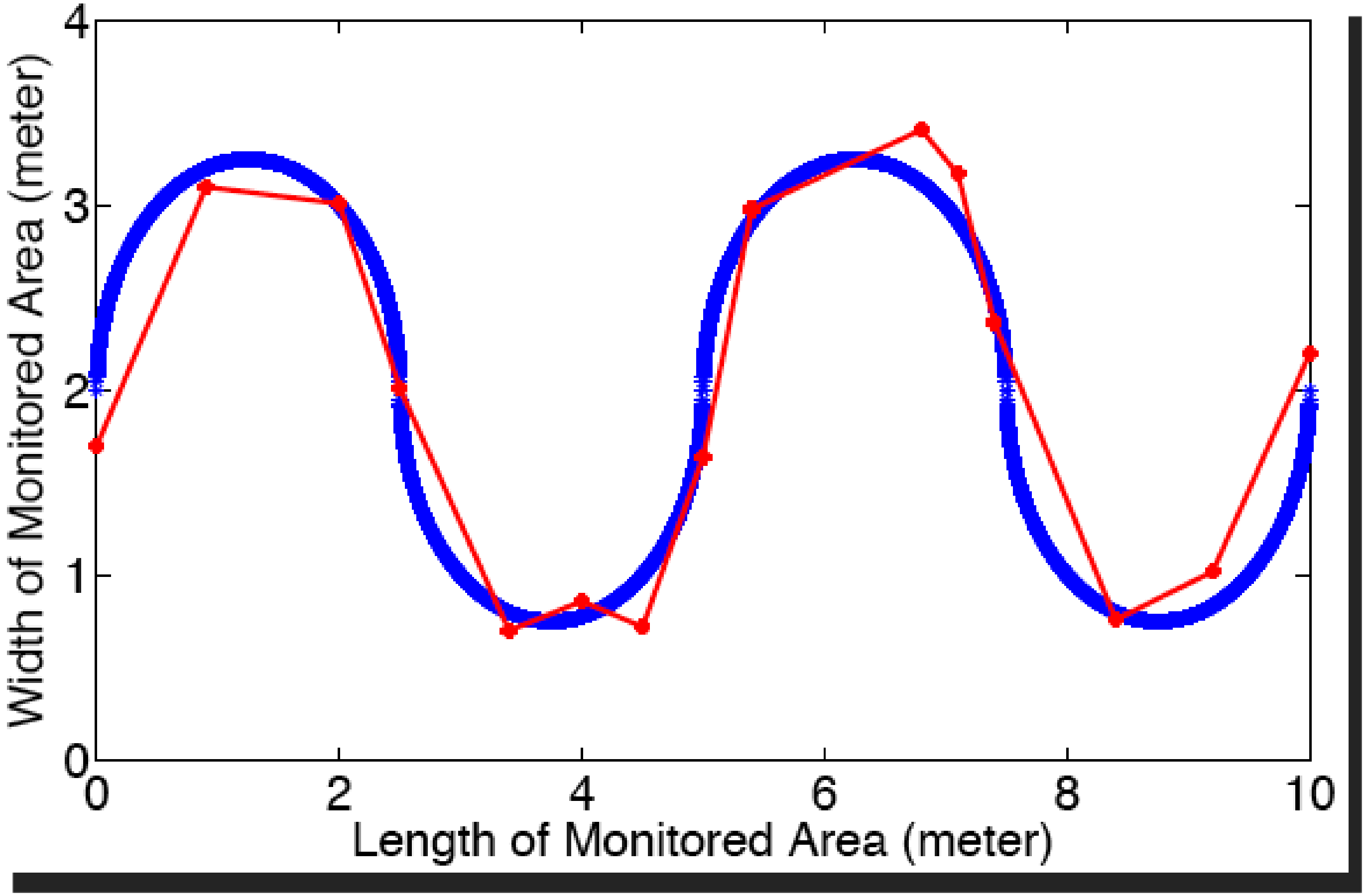
Water level

ILIGHT

iLight

System examples (iLight)

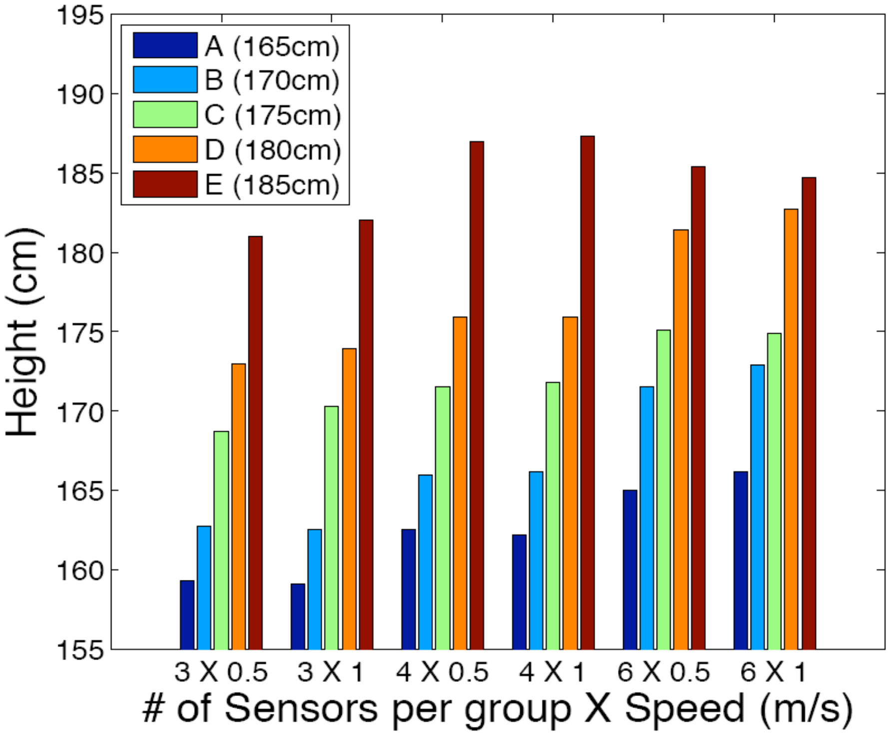
Track Objects



Blue line: real trace

Red line: computed trace

Estimating heights



Testing environment and estimated height

Estimation error at most 2 cm w.h.p

WASTE WATER PROCESS

Managing Loosely Coupled Networked Control Systems with External Disturbances

This is a joint project with
Professor ShangPing Ren (CS),
Professor Fouad Teymour (ChE) and
Professor Paul Anderson (CE).

Professor Xiangyang Li is the lead.

Managing Loosely Coupled Networked Control Systems with External Disturbances

- Characteristics and challenges of the targeted problem domain
  - Widely distributed physical systems
  - Has historical data, but also has large unpredictable factors
  - Wide range of timing granularities
  - Large spectrum of abstraction levels for events
- Research Focus

  Develop algorithms and timing analysis approaches to ensure that loosely coupled networked control systems satisfy timing constraints with different timing granularities; and develop event model to model and reason about events at different abstraction levels, ranging from simple sensor signals, to human control actions.

General Overview

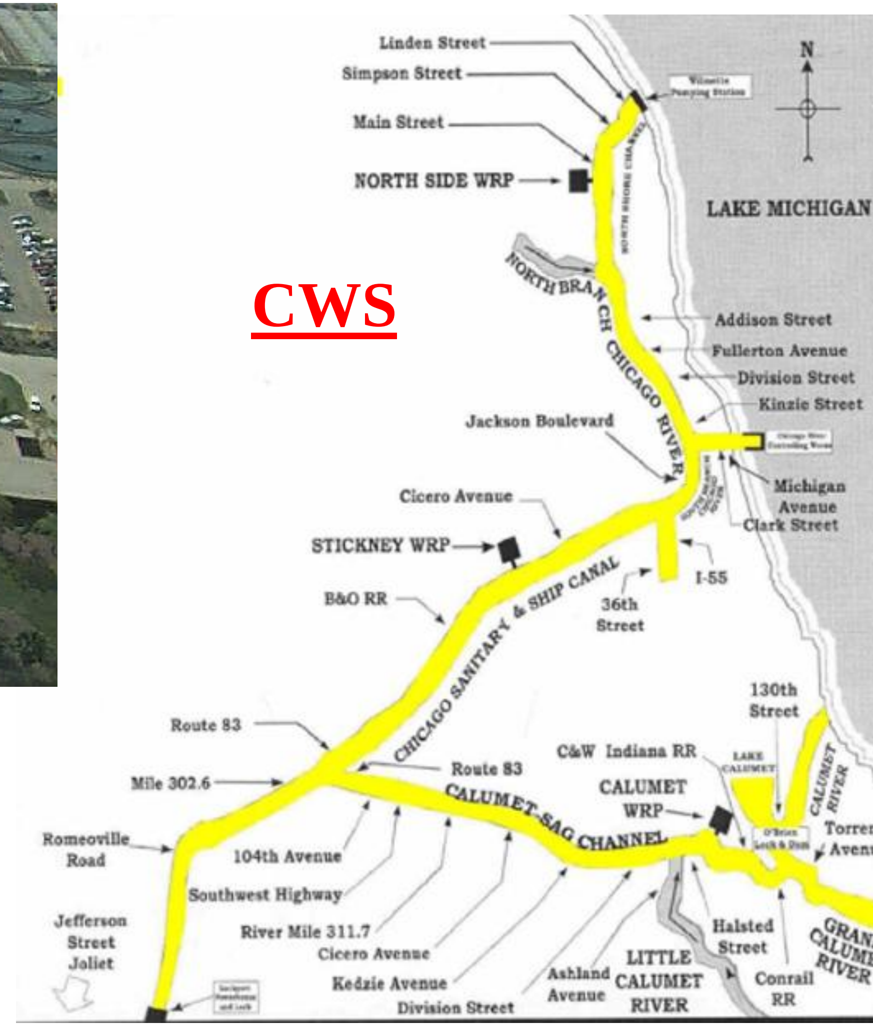
- The goal of this research is to
  - understand the waterway as a Cyber-Physical System (CPS),and
  - to provide a set of strategies and tools for meeting new U.S. Environmental Protection Agency standards for ammonia regulation scheduled to take effect in 2014.
- Plan to update the waterway's systems by
  - extending the systems with available technologies such as wireless sensors and networks, and
  - by providing real-time, on-line monitoring and process control to minimize energy demands and carbon footprint associated with nutrient control.

Chicago Waterway System (NSF)

Joint work with Prof. Ren, Prof. Anderson and Prof. Teymour

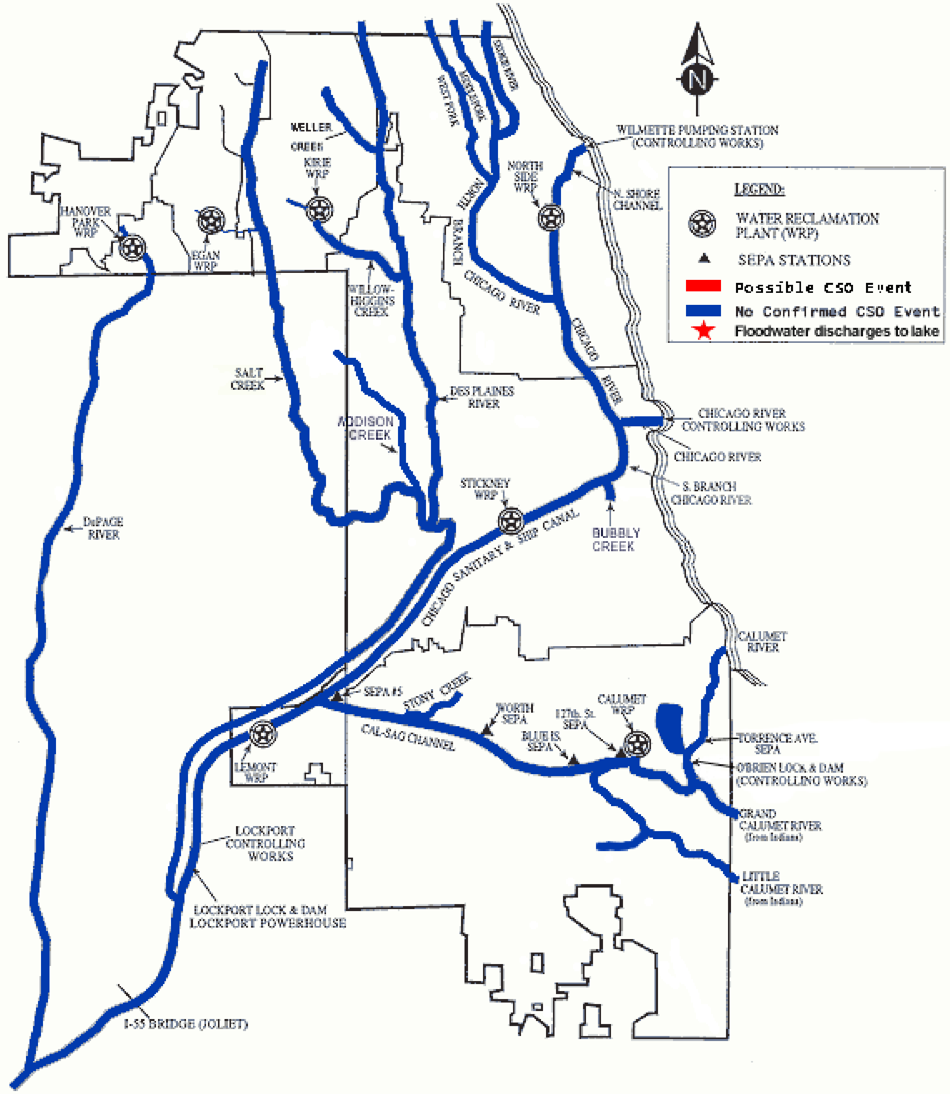
Stickney WRP (world largest)

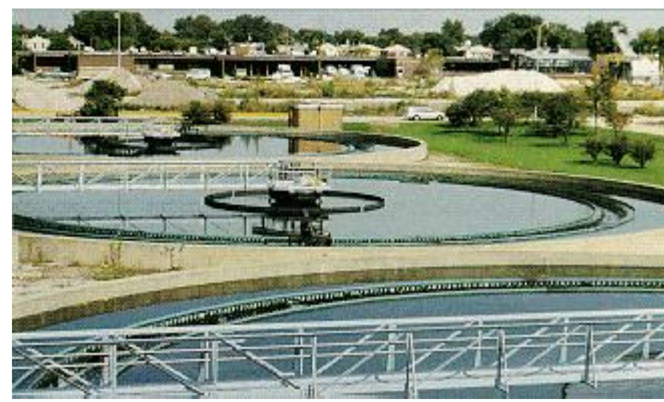
CWS



Ammonia sensor

Dissolved Oxygen sensor


N
WILMETTE PUMPING STATION (CONTROLLING WORKS)
LEGEND:
WATER RECLAMATION PLANT (WRP)
SEPA STATIONS
Possible CSO Event
No Confirmed CSO Event
Floodwater discharges to lake
WELLER CREEK
KIRIE WRP
NORTH SIDE WRP
N. SHORE CHANNEL
HANOVER PARK WRP
EGAN WRP
WILLOW-HIGGINS CREEK
CHICAGO RIVER
SALT CREEK
DES PLAINES RIVER
ADDISON CREEK
CHICAGO RIVER CONTROLLING WORKS
CHICAGO RIVER
S. BRANCH CHICAGO RIVER
STICKNEY WRP
BUBBLY CREEK
DuPAGE RIVER
CHICAGO SANITARY & SHIP CANAL
CALUMET RIVER
SEPA #5
STONY CREEK
WORTH SEPA
127th. St. SEPA
CALUMET WRP
BLUE IS. SEPA
CAL-SAG CHANNEL
TORRENCE AVE. SEPA
O'BRIEN LOCK & DAM (CONTROLLING WORKS)
LEMONT WRP
GRAND CALUMET RIVER (from Indiana)
LOCKPORT CONTROLLING WORKS
LITTLE CALUMET RIVER (from Indiana)
LOCKPORT LOCK & DAM LOCKPORT POWERHOUSE
I-55 BRIDGE (JOLIET)

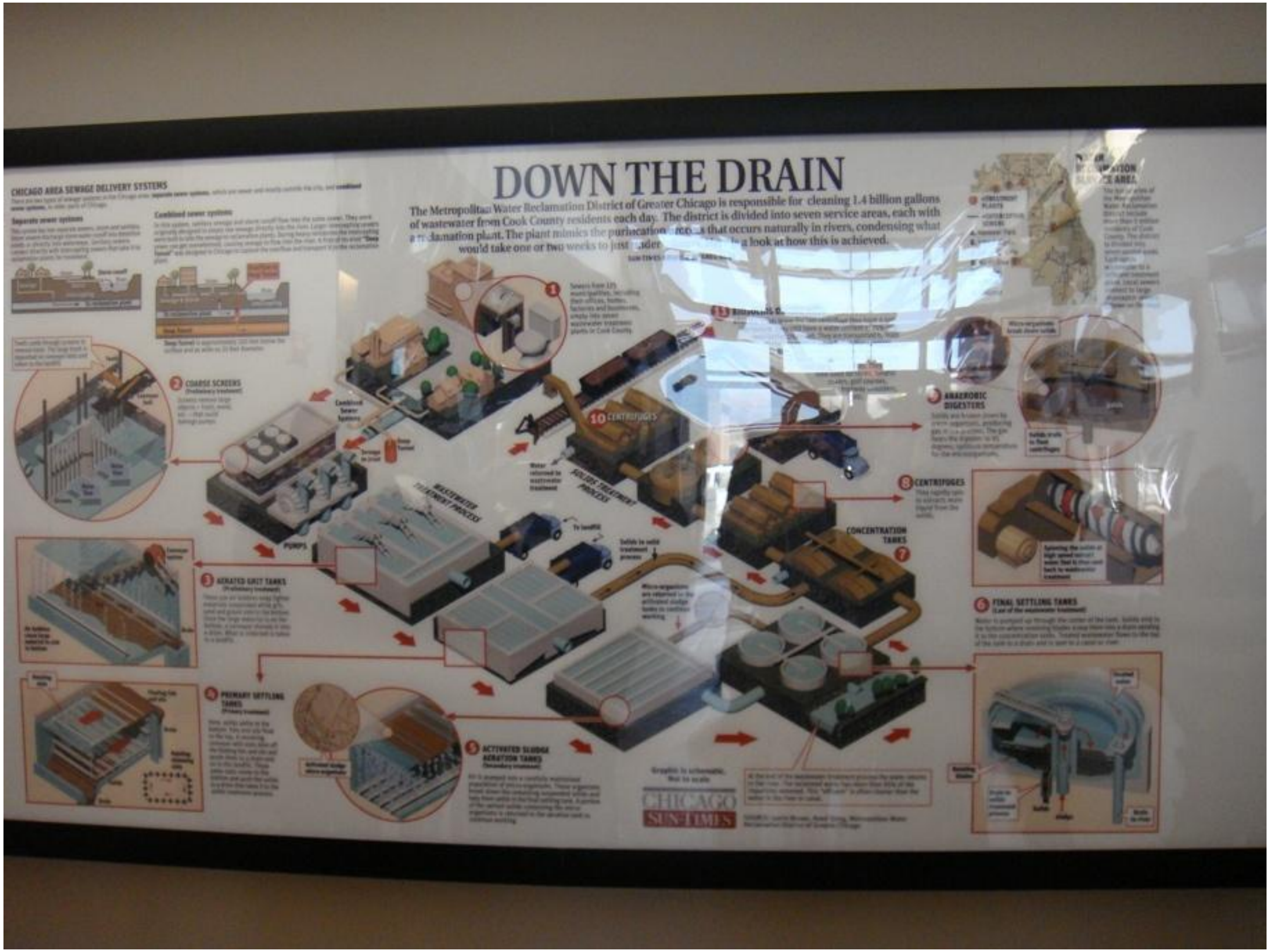


Visiting Stickey WRP

Prof. XiangYang Li and 15 students visit Stickney WRP on March 17th, 2011.

One of the many visiting and meetings with local WRPs

Overview


DOWN THE DRAIN
CHICAGO AREA SEWAGE DELIVERY SYSTEMS
CHICAGO SUN-TIMES

Tanks

DO Sensors

Lab-used Sensors


2

Wind Blower


KNAACK


5

Secondary Processing

Control Room

Control room

Key water quality indicators

- Chemical assessment
  - Oxygen saturation or dissolved oxygen (DO)
  - Chemical oxygen demand (COD)
  - Biochemical oxygen demand (BOD)
  - PH
  - Nitrate
  - Phosphate
- Physical assessment
  - Temperature
  - Total suspended solids (TSS)
  - Turbidity
- Biological assessment

Water resource systems

- Source waters
  - Lakes
  - Rivers
  - Groundwater
- Water treatment systems
  - Municipal treatment
  - Industrial treatment
- Wastewater treatment systems
  - Municipal wastewater
  - Industrial wastewater
- Stormwater

Cyber physical systems

- Intelligent sensor networks and software applied to more efficient and effective operations
- Information from the network/software system results in a change in operations
  - Range in the response times:
    - Real-time response for water/wastewater treatment
    - Long-term response times for watershed management

Optimization problem

- Minimize the cost of the system required to realize more efficient and effective operations
- Subject to:
  - Human health
  - Environmental quality
  - Commerce & industry
  - Other constraints…

Specific issues

- Network design
- Simulation and control models
- CPS operations

Illinois DO Water Quality Criteria

- General Use Water
  - March to July
    - >5.0 mg L-1 minimum at all times
    - > 6.0 mg L-1 7-day mean(2)
  - August to February
    - > 3.5 mg L-1 minimum at all times
    - > 4.0 mg L-1 7-day mean
    - > 5.5 mg L-1 30-day mean

- Secondary Contact and Indigenous Aquatic Life Use
  - >4.0 mg L-1 / 3.0 mg L-1 minimum at all times

Is Continuous DO Monitoring Necessary to Determine Compliance with Standards?
Are perpetual CDOM programs practical and reasonable ?

Current MWRDGC DO Monitoring

- October 1994 to May 1996 weekly DO surveys in the Chicago River System. Water samples collected manually, chemically fixed in field, returned to laboratory for titration.
- 1998 initiated a comprehensive CDOM program to characterize Chicago River System
  - Initial focus on the Chicago River System for a two-year period
  - Program expanded to Calumet River System in 2001
  - Program further expanded to wadeable streams in 2005.
- Subsequently, resulting data have been used for calibration and verification of a water quality model for the CAWS used in IEPA's UAA study.

Successful CDOM Program Requires Intensive QA

- Currently, Thirty-Two Locations Monitored
- DO, Water Temperature, and Specific Conductivity Measured Hourly at All Locations, pH and Turbidity at Selected Locations
- Monitors Deployed for Seven Continuous Days in Protective Enclosures
- Monitors Exchanged over Period of 3 Days /Week (Tuesday To Thursday)
- Calibrated and Serviced Monitors Deployed Weekly to Replace Monitors Retrieved from Field
- Winkler DO Check Sample Taken During Monitor Exchanges
- Housings Cleaned Weekly April Through November, Monthly December Through March
- Cross-Sectional DO Measured at Each Monitoring Location During April, August, and November

CDOM Program QA (Cont’d)

- Eighty Monitors Purchased
- Retrieved Monitors Cleaned Weekly With Laboratory Detergent Solution
- Battery Compartment, Cable Connector Inspected for Water Leakage
- Batteries Checked with Voltmeter
- O-Rings Cleaned, Inspected and Lubricated
- DO, Specific Conductivity, Temperature Calibration Checked Daily in Holding Tanks
- Polarographic DO Sensor Membrane and Electrodes Observed Daily Under Microscope

SOME KEY CHALLENGE ISSUES

Network design

- Spatial resolution for the sensor network
- Required network communication distance
- Required network communication capacity
- What sensor array provides the most useful integrated system information?

CPS operations

- Temporal resolution for the sensor network
- Temporal resolution for process control
- Network maintenance requirements
- Balancing network costs and process control confidence

Process and control models

- Two very different model requirements
  - Simulation model to assess network design
  - Control model links sensor input to process control

Water resource examples

- Watershed
- Municipal water treatment
- Wastewater treatment

Watershed management

- ❖ Federal and state programs
- ❖ Data to calibrate watershed model
- ❖ Asynchronous process control
- ❖ Link development to water quality

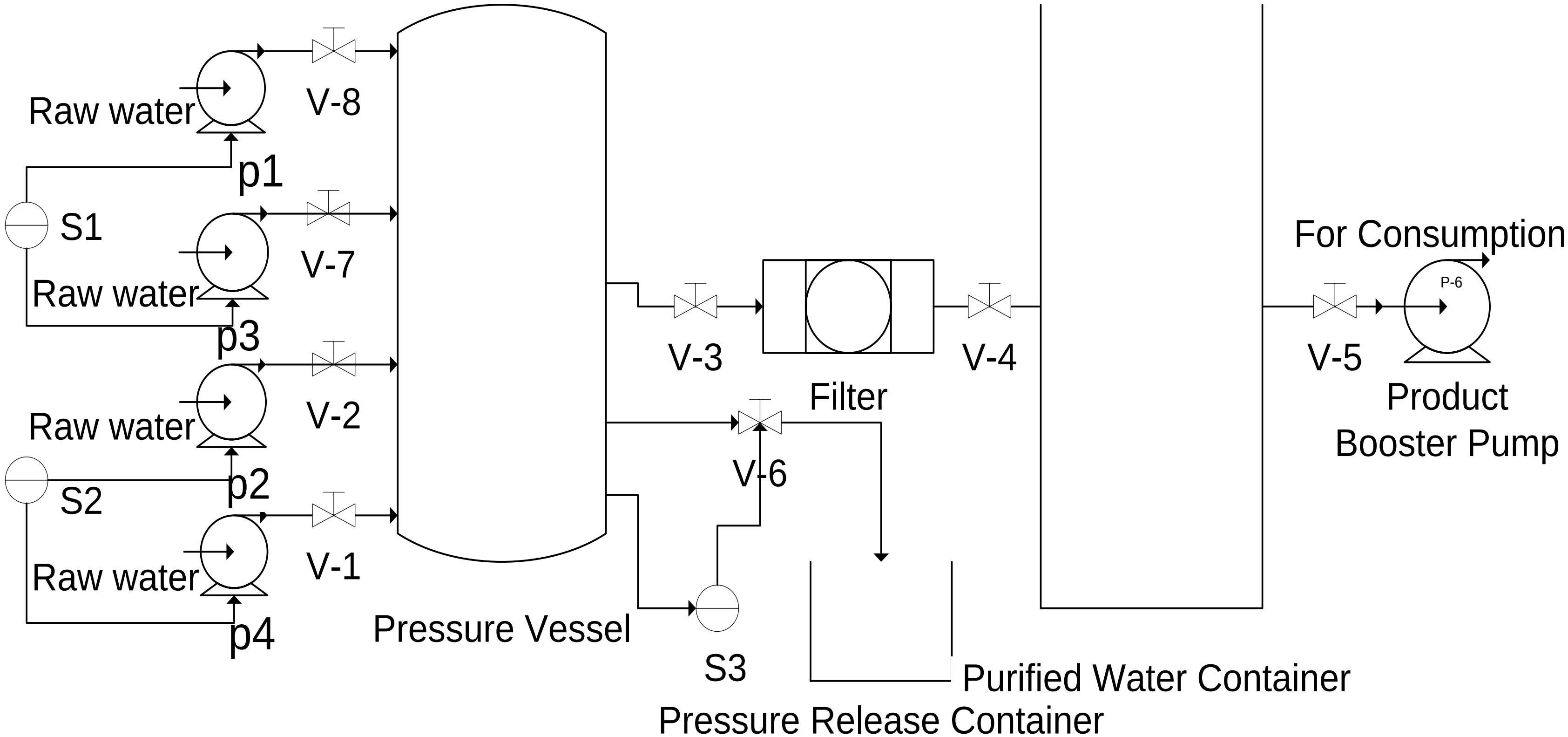
Municipal & industrial process water treatment

- Security
- Groundwater versus surface water
- Changes in water quality
  - Seasonal (algal blooms)
  - Storm events
- Monitor
  - Source water
  - Processes
  - Distribution system
- Real-time process control

Wastewater treatment

- ❖ Effluent quality is regulated
- ❖ Influent quality varies
  - – Seasonal (temperature)
  - – Storm events (flow, loading)
- ❖ Monitor
  - – Influent
  - – Processes
- ❖ Real-time control

Protecting legacy critical Infrastructures against coordinated attacks



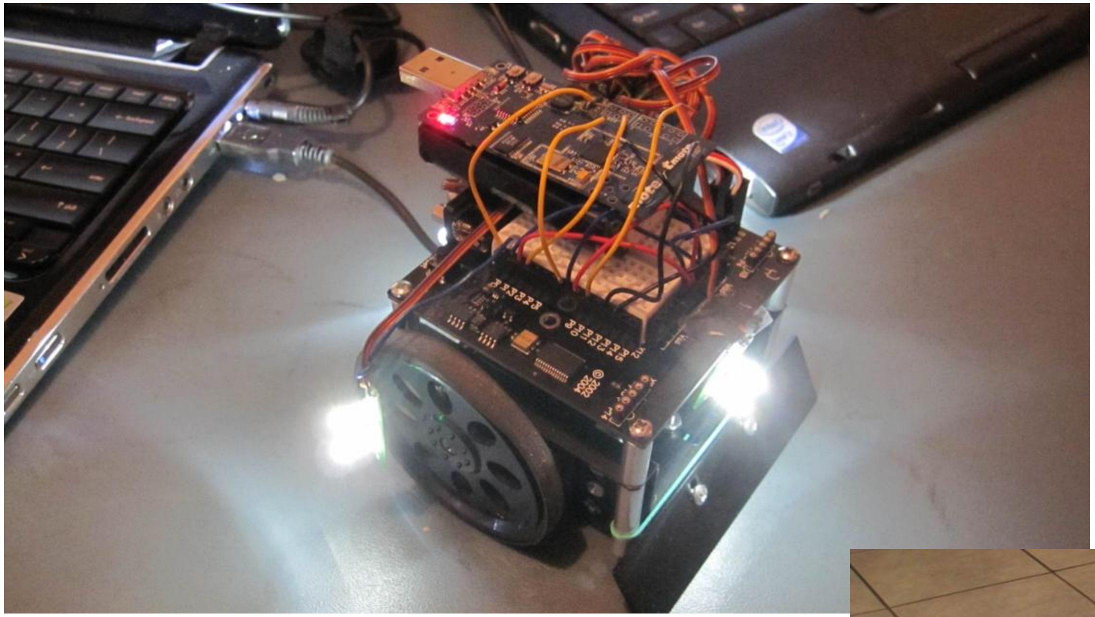
Behavior-Based Coordination for Open Distributed Real-Time and Embedded Computing

- Characteristics and challenges of the targeted problem domain
  - Open
  - Dynamic
  - Large scale of autonomous and concurrent entities
  - Hard QoS requirements
  - Running in a real world environment which is sometimes unpredictable
- Research Focus

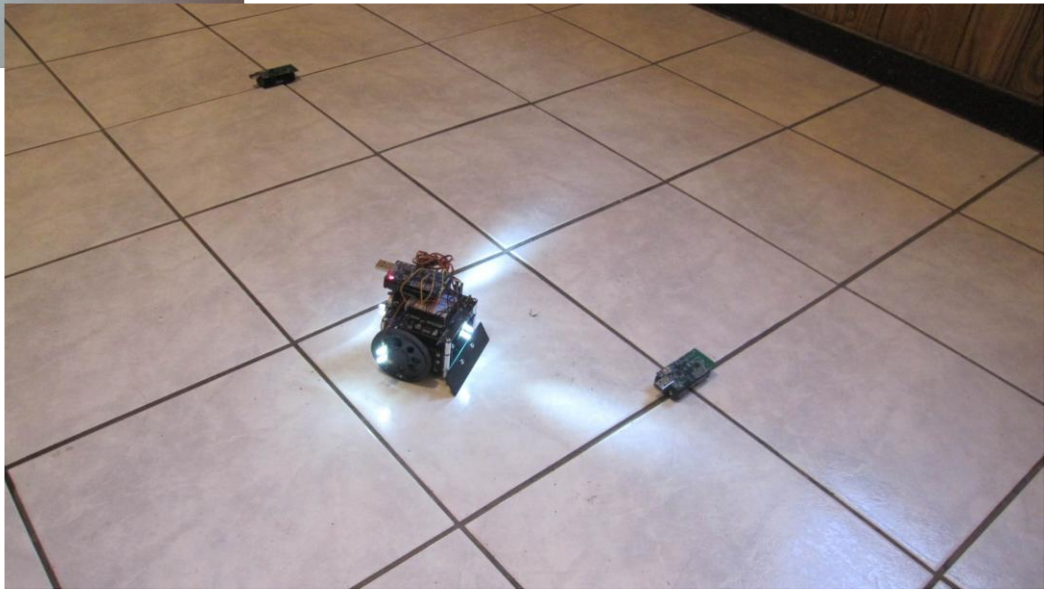
  Develop models, software architecture and programming language support to facilitate the design and development of such systems and further be able to verify the correctness of the systems.

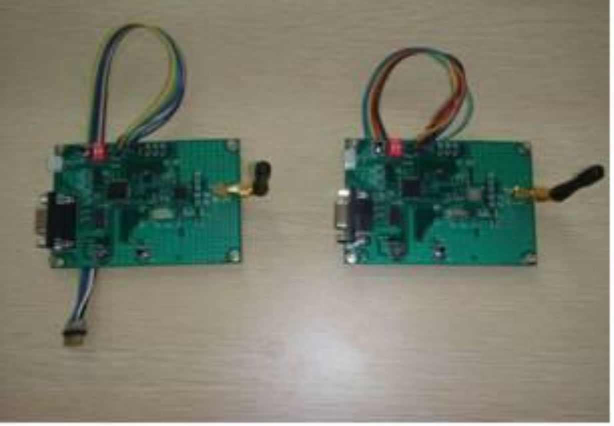
HARDWARES

WSN Controlled Mobile Car



ShaoJie Tang
XuFei Mao
XiaoHua Xu





V1 2007.12

V2 2008.6

V3 2009.3

Solar Powered Node

Camera Sensor Node

Temperature Sensor

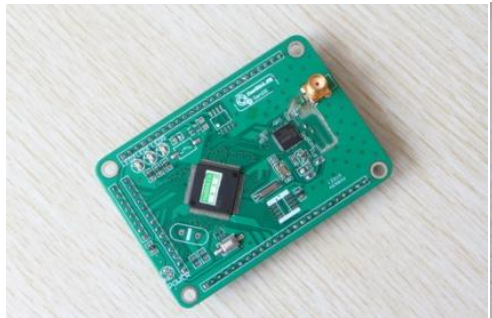
RFID Nodes

Encapsulation

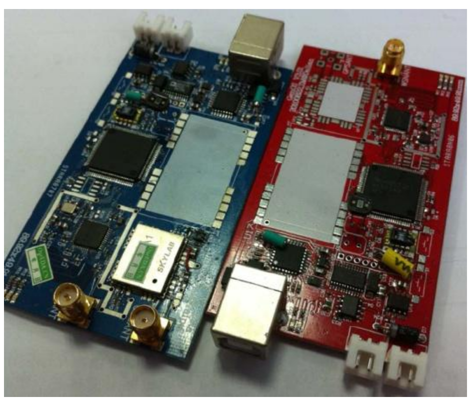
Encapsulation

Sensor nodes

❖General

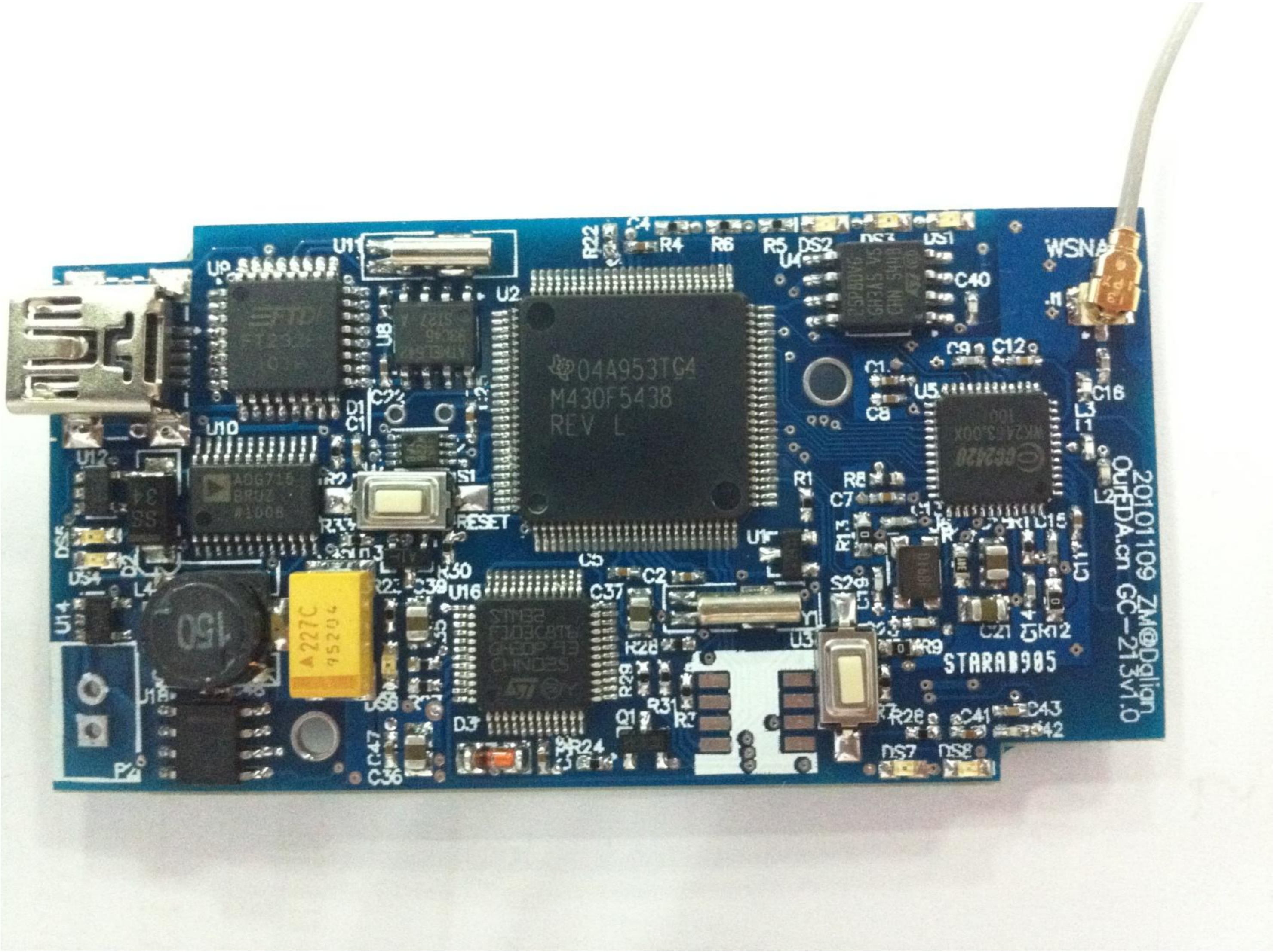




❖Co2，GPRS，GPS

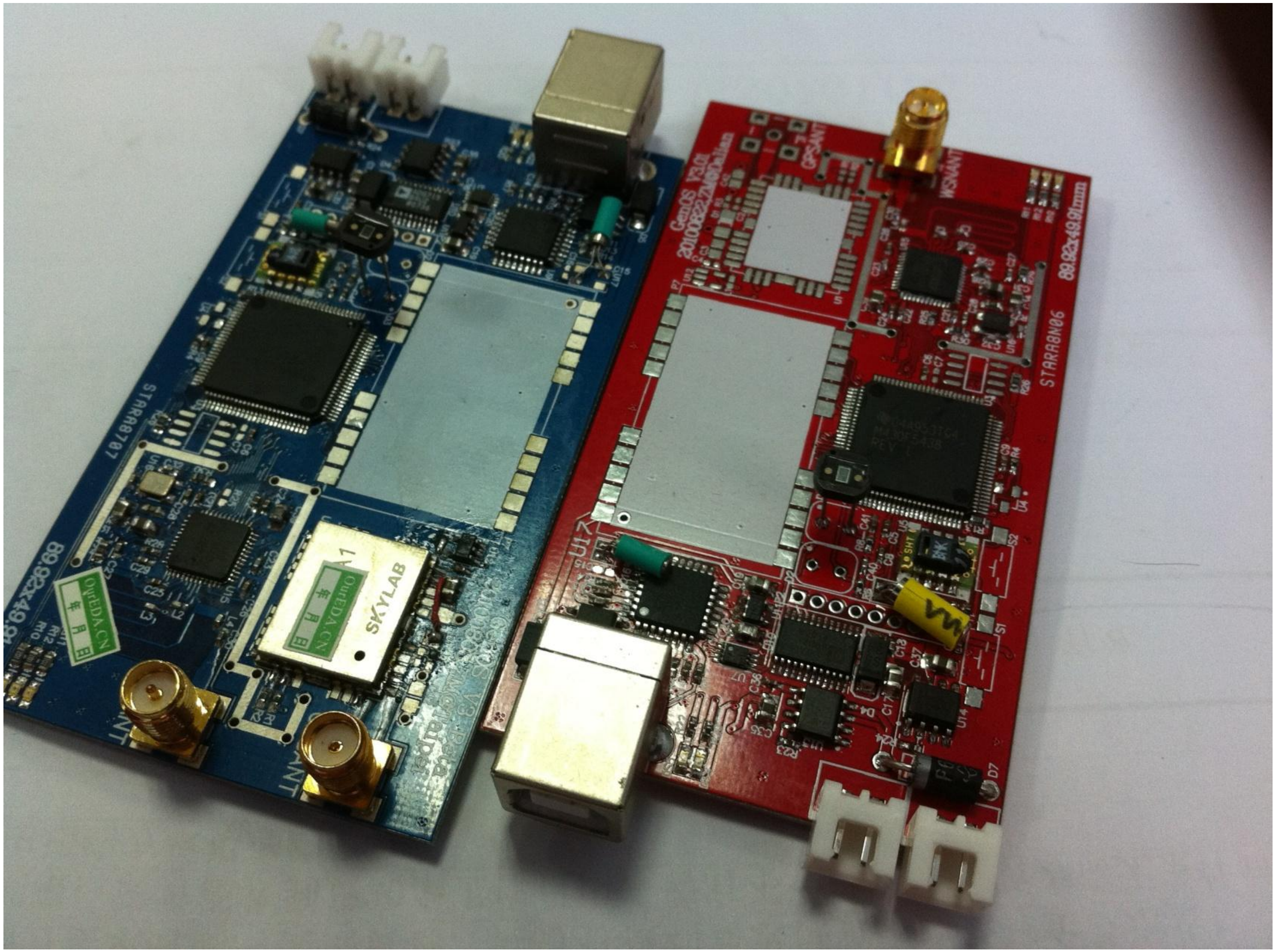



- TI MSP430 MCU 低功耗
- IEEE 802.15.4 兼容
- Tinyos 2.x 操作系统
-

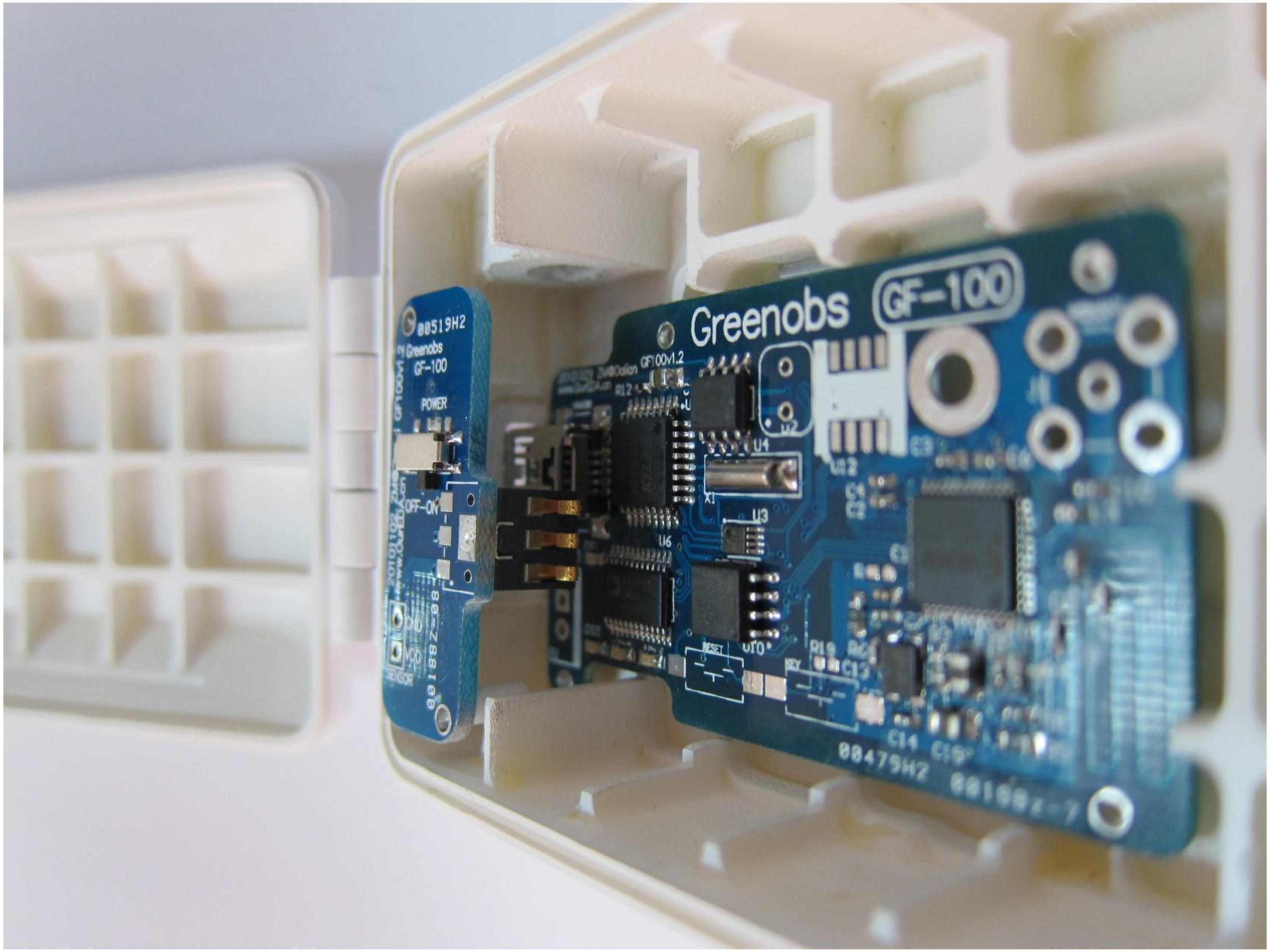
More sensor nodes



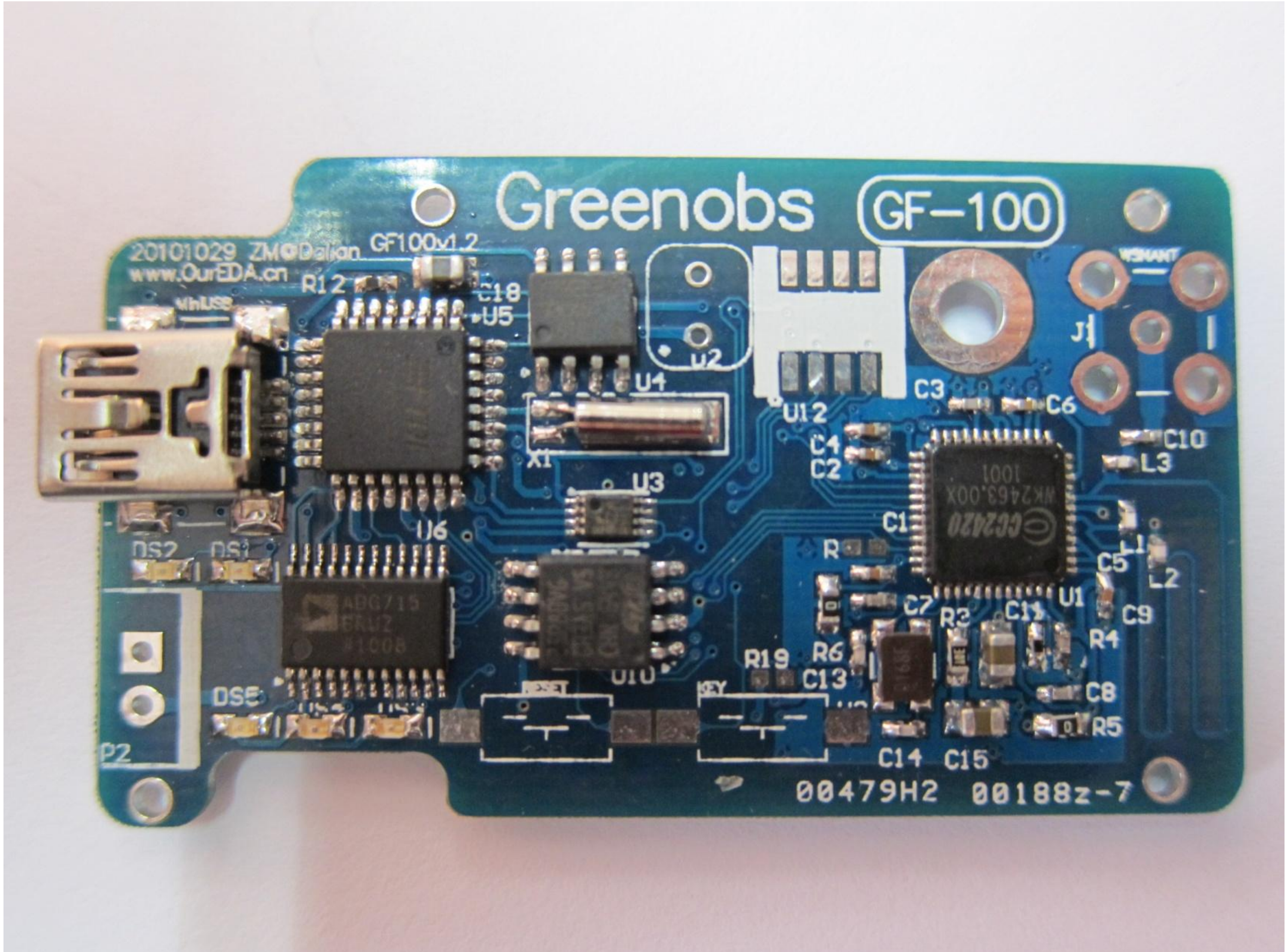
Sensor nodes



Sensor nodes



Sensor nodes



CO2 Sensor node

Encapsulated Node

Another one

Many nodes

Wireless **Mesh** Nodes

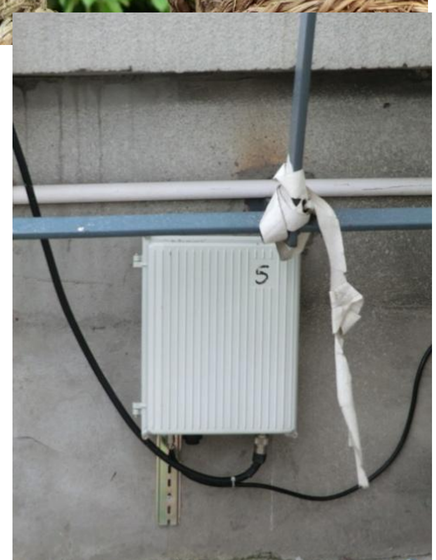
- IEEE 802.11g/a
- 30Mbps , 1km
- Distance 7km ,

- MultiHop
- Auto-Routing
- Security

Mesh Nodes

- Solar Panel and Wind Energy

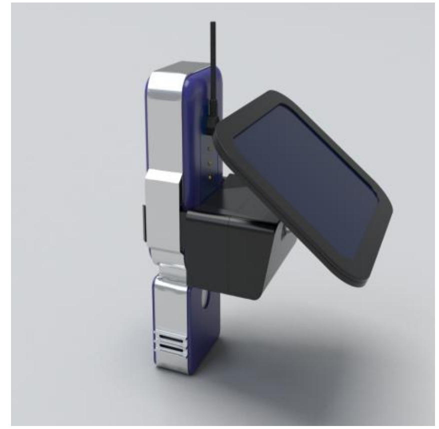
Sensor nodes, mesh routers deployed



Some New Devices Designed Recently

Temp, Light

Outdoor CO2



CO2, Solar

Dust

Indoor CO

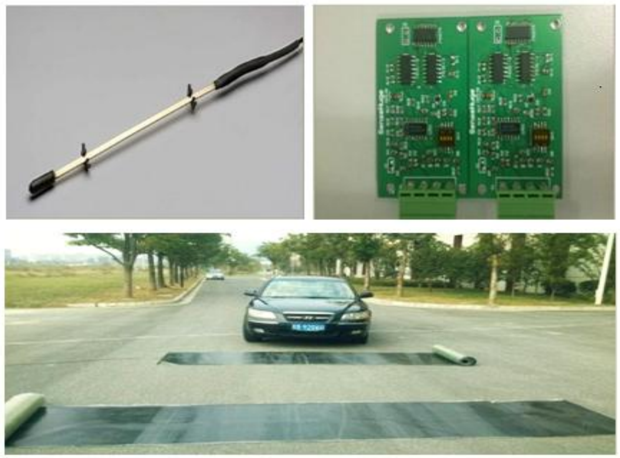
Indoor SO2

Indoor CO2

Mesh Nodes, Solar panel

Mobile Terminal

Some New Devices Designed Recently

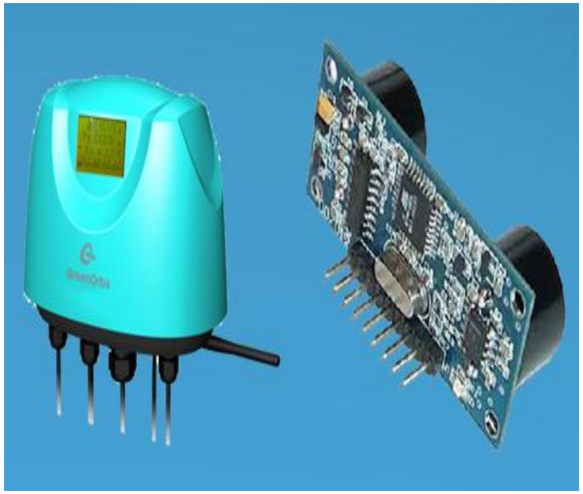


Pressure Sensor

Magnet Sensor

Oil Pressure Terminal

Water Depth Sensor



Water level

OBSERVATIONS, EXPERIENCES, LESSONS

Approaches

deployment

measurement

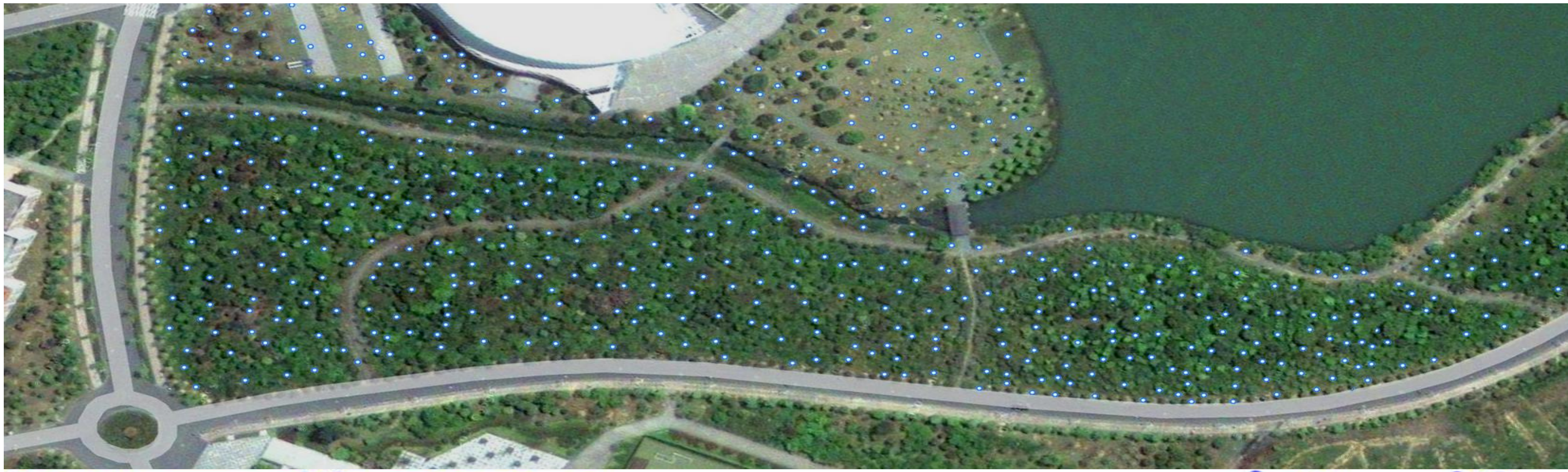
Improvement

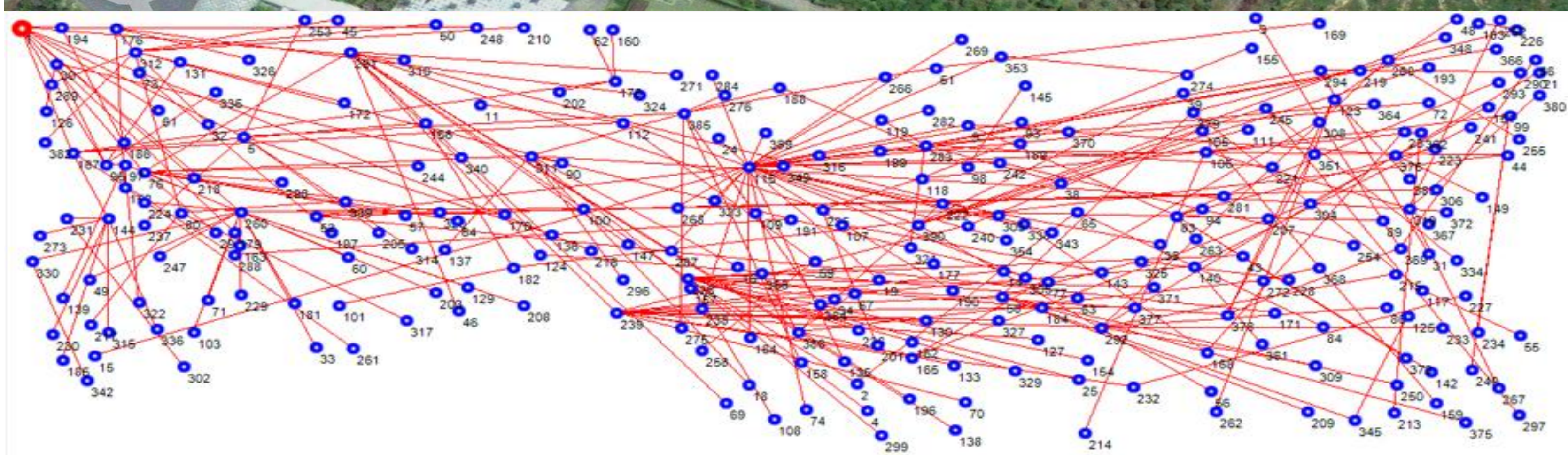
Design and protocol

analysis

Measurement Study

multiple testing deployments at a campus forest





First: Network "topology" varies over time and space

Multiple Network Scenarios

December 2009, 29 consecutive days, 2,540,000 data packets

Trace No.	Network Scale	Power level	Data Rate (pkts/hour)	Duration (hour)	Duty cycle
1	100	15	3	60	No
2	200	15	3	25	No
3	330	15	3	300	No
4	330	15	12	24	No
5	330	15	18	100	No
6	330	15	27	30	No
7	330	15	54	3	No
8	330	15	108	3	No
9	330	31	12	1	No
10	330	21	12	1	No
11	330	15	12	1	No
12	330	8	12	1	No
13	330	15	3	150	8%
14	330	15	60	12	8%

Back-end Collected Data Set

Routing trace

- Routing path
- Sensor reading

Link trace

- List of neighbor nodes
- RSSI, LQI, and ETX

Node statistic trace

- A large set of statistical information on each node

Out-band Measurement

Overhearing

- Multiple sniffers in the network to overhear the network traffic

Beaconing

- Each node actively broadcast beacons periodically

Local logging

- The fine-grained local events on the nodes are recorded as a backup data set for diagnosis

Measurements

Yield

- Measure the quantity of the collected data

Packet Reception Ratio / Loss Ratio

- Measure the quality of a link

Packet Delivery Ratio(PDR)

- The ratio of the amount of packets received by the destination to those sent by the source

Measures and Derivations

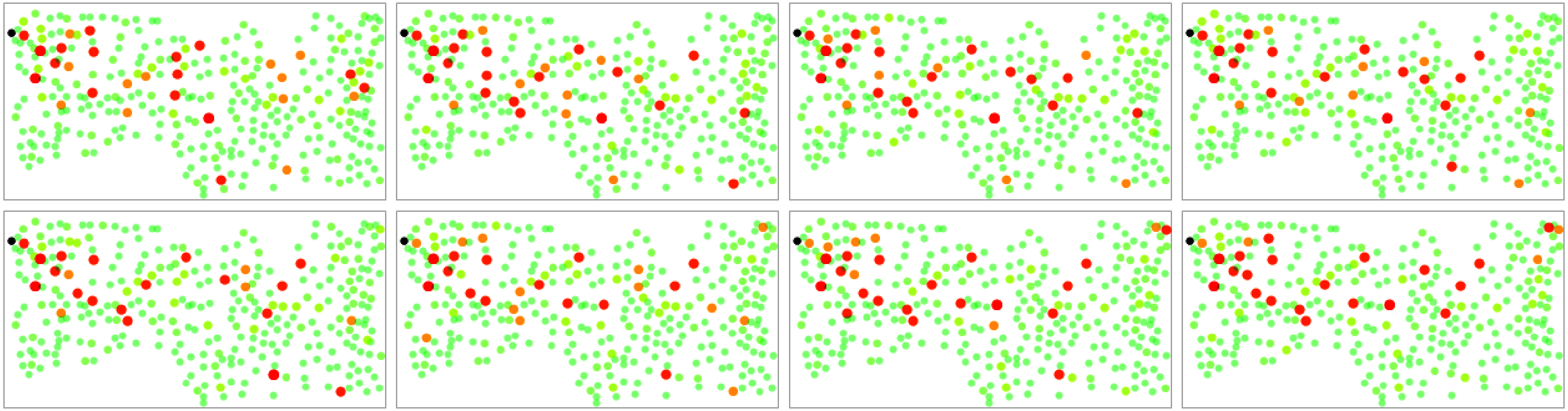
End-to-end delay

- The time difference between the sending time at the source node and the reception time at the sink

Correlation Coefficient

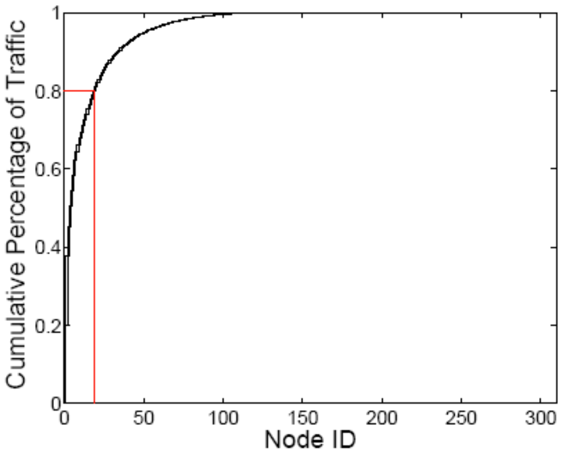
- A statistical measure of association between two variables
- This is often used for fault diagnosis of sensor networks

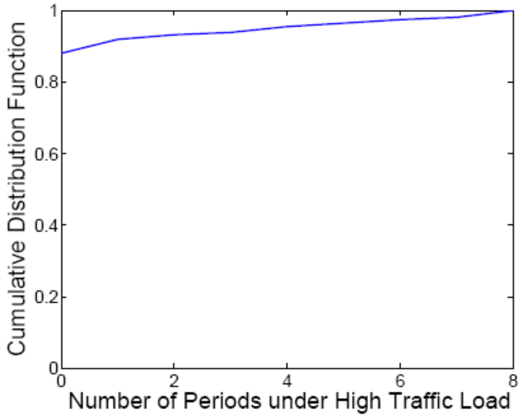
Traffic distribution : balanced in CTP?



5% nodes account 80% traffic.

90% nodes have very low traffic.

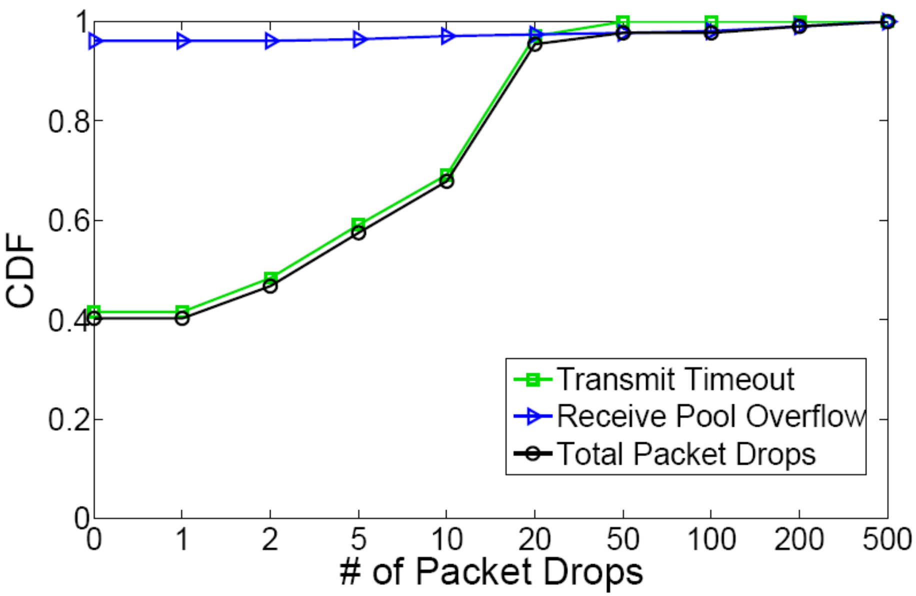




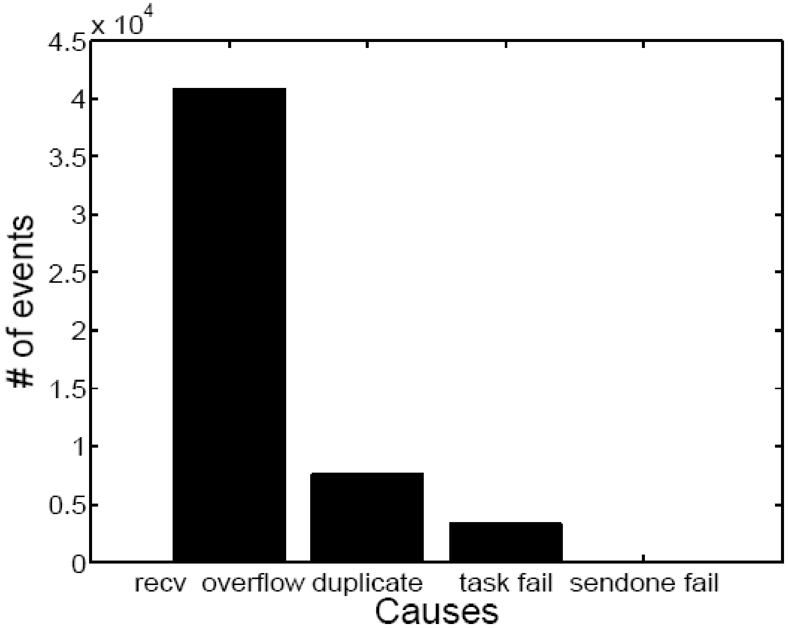
The traffic distribution is relatively stable over time

Causes of Packet Losses

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



Cumulative distribution of packet loss

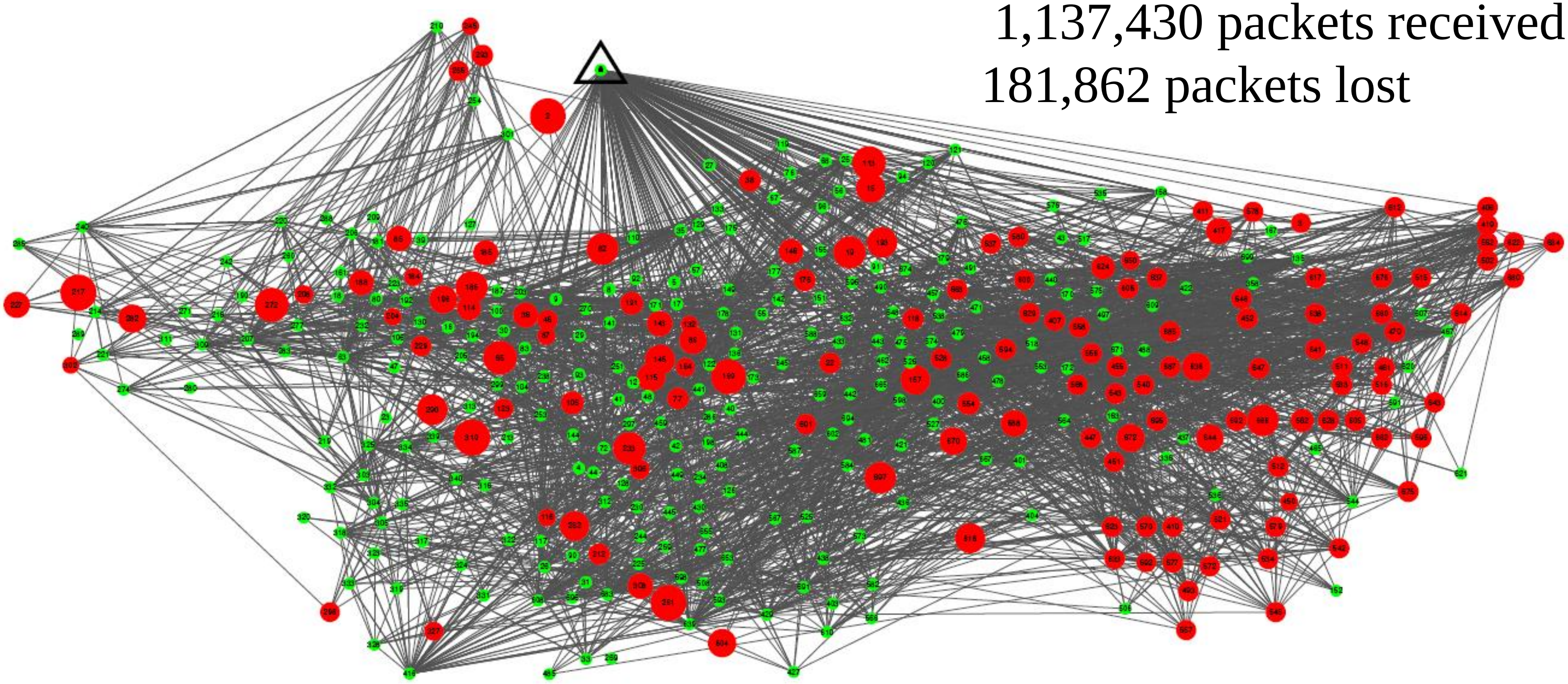


Causes of packet drops on sensor nodes

Packet Loss Diagnosis

December 10, 2010; 400 nodes, 60,000m²

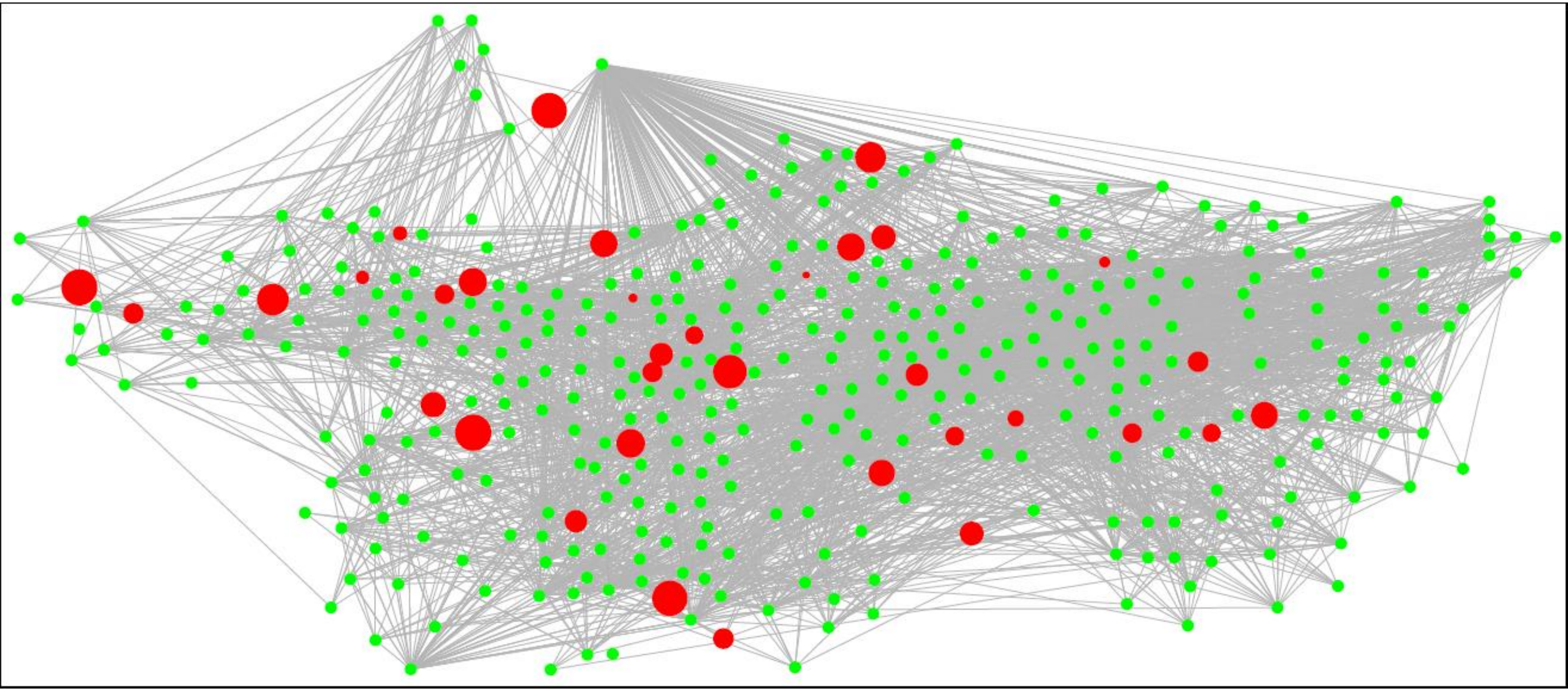
Data of 10 days:
1,137,430 packets received
181,862 packets lost



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

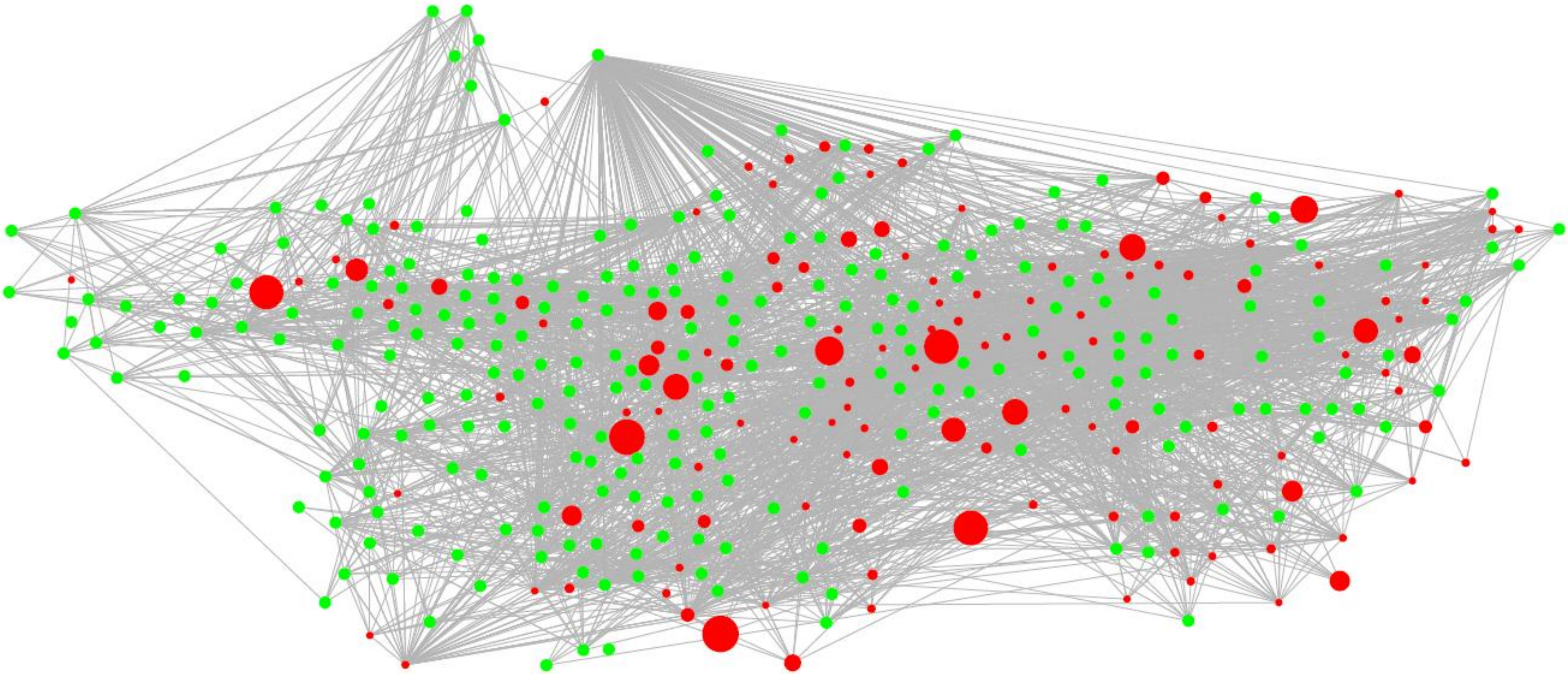
Packet Losses: Non-ACK

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



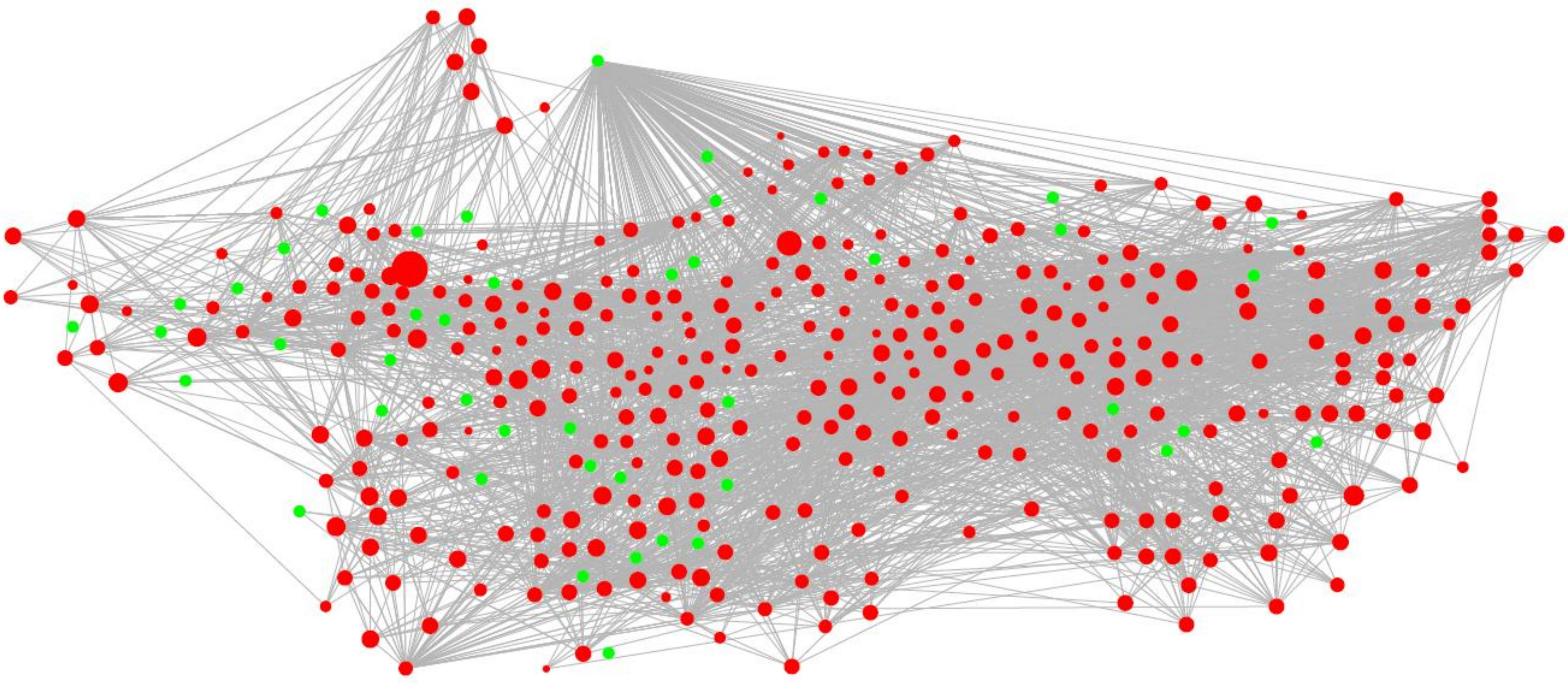
Packet Losses: Non-ACK

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



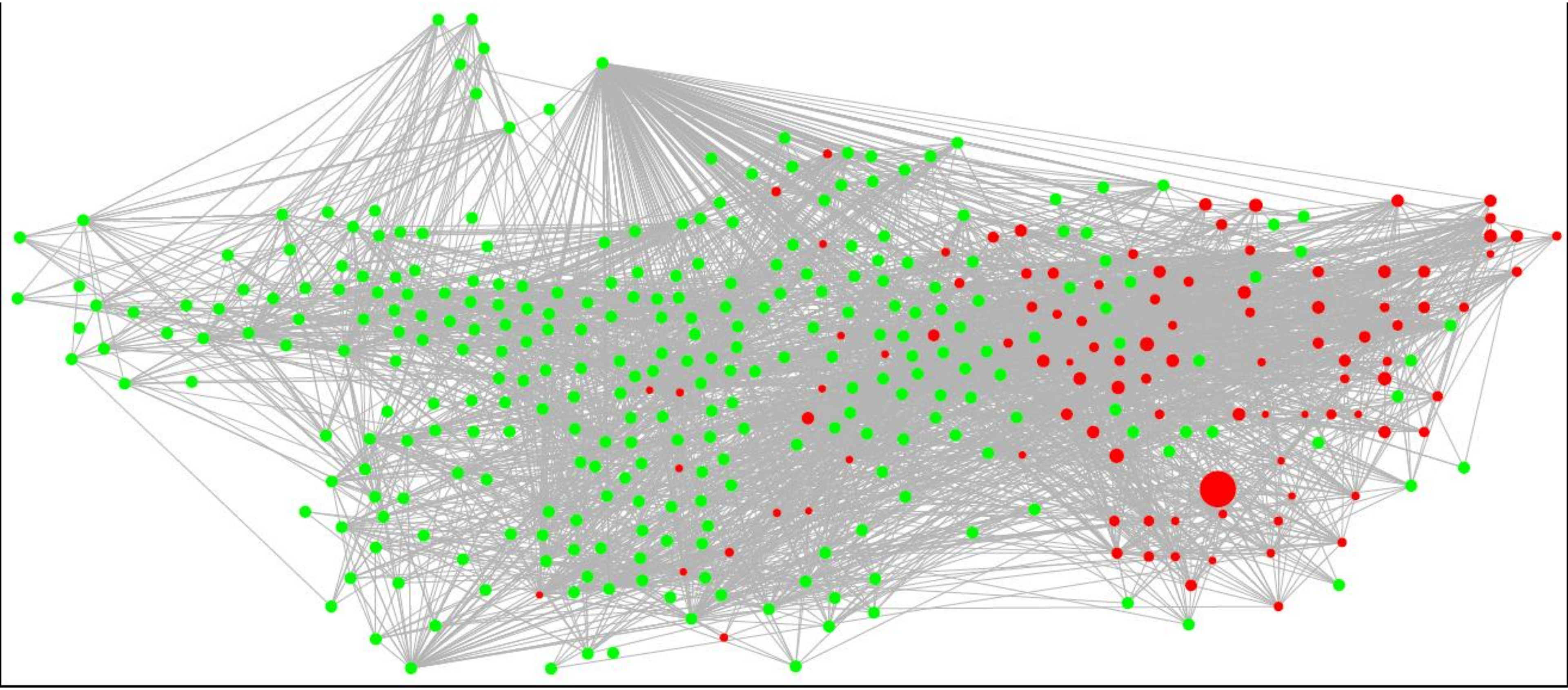
Packet Losses: Corrupted Packets

- 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)	$\sim$0

About 35% packet losses are unidentified now.

Summary of Some Observations

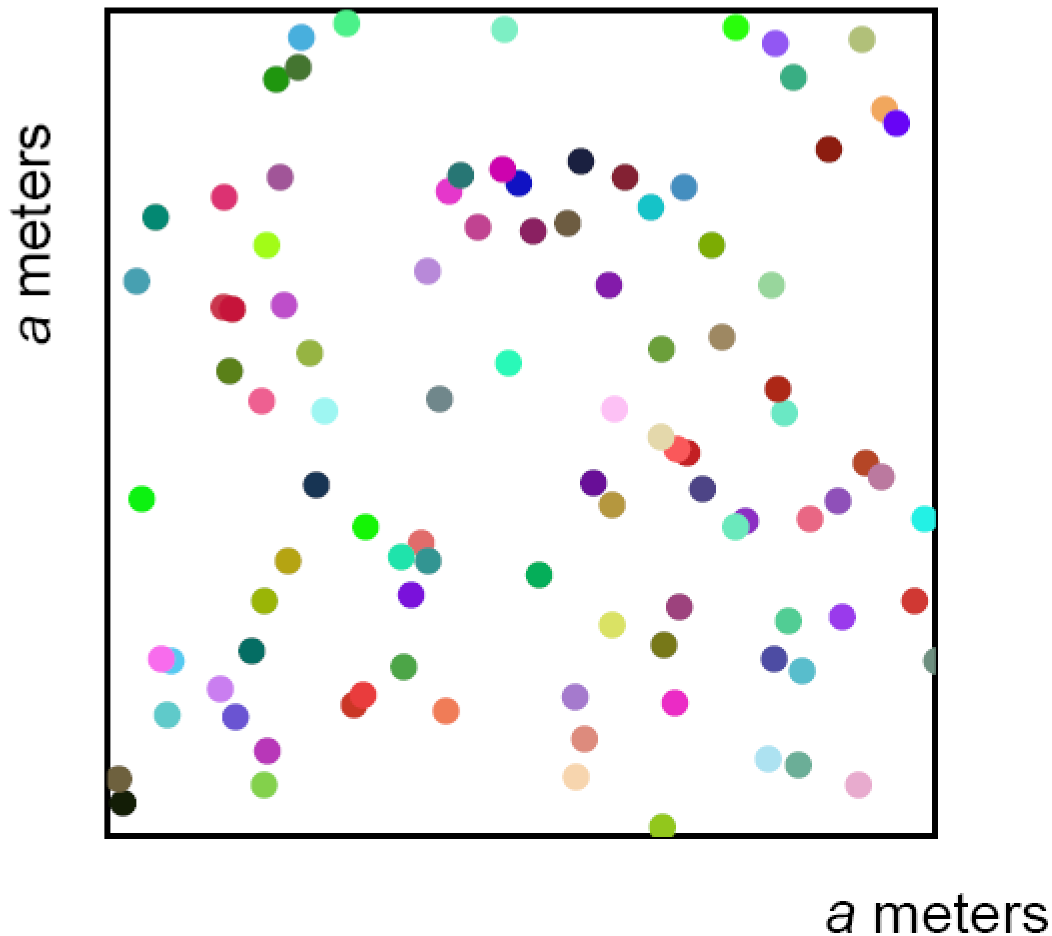
1. A small portion of nodes bottleneck the entire network, most of the existing network indicators may not accurately capture them
2. The environment, although the dynamics are not as significant as we assumed, has an unpredictable impact on the sensor network performances
3. By adjusting the operation parameters of various protocols (e.g., MAC), performance greatly improved
4. Many challenges to make it
   1. **Sustainable** --- energy and fault diagnosis?
   2. **Scalable** ---performance bottleneck?
   3. **Robust** --- co-existence?
   4. **Predictable** ---- system stable points?

What limits the system scale?

- What is the dominant resource, first depleted when the network workload scales?
- Is such resource appropriately used?
- Where and when does resource depletion happen?
- How should existing protocols be improved to adapt to large-scale sensor network characteristics?
- How much information a network can support? How do networks scale?

CAPACITY OF LARGE SCALE WIRELESS NETWORKS

Large Scale WSN



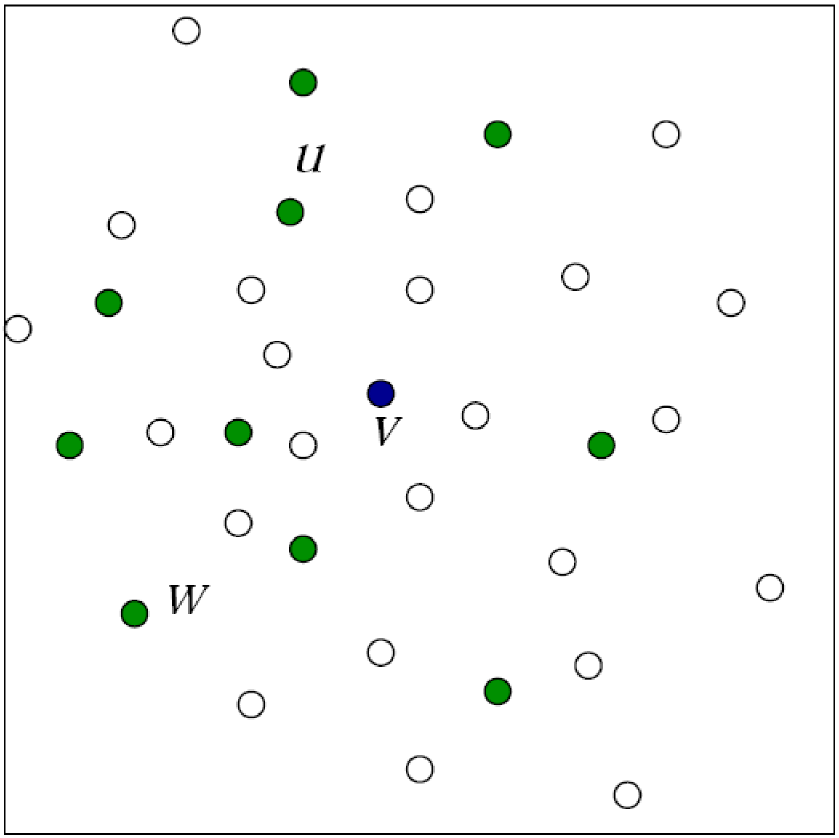
Large Scale WSN: *n* nodes randomly placed in a square or nodes follow Poisson distribution with density ζ

Asymptotical Capacity

❖ How much information a large WSN can support

- – Impact of network size n, and deployment size a
- – Impact of network model and interference model
- – Impact of different sessions, number of sessions, size of a session,

Network Model



- $N_p(\zeta, n)$: place nodes in 2-D plane according to a Poisson point process of density ζ
  - focus on a square $[0,(n/\zeta)^{1/2}]^2$
- n_s sources *S for* n_s multicast flows, each with n_d nodes
  - Each source node randomly selects $n_d - 1$ points and closest $n_d - 1$ nodes to these points as receivers
- Each source v_i *sends* λ_i bits/second to all receivers.

General Network Model

- General Node Density $\zeta \in [1, n]$
  - random dense network (RDN, $\zeta = n$).
  - random extended network (REN, $\zeta = 1$).

- General Session
  - multicast capacity $n_d \in [1, n]$
  - unicast capacity $n_d = 1$.
  - broadcast capacity $n_d = n$.

- General Number of Sessions $n_s \in (1, n]$
  - $n_s = \Theta(n)$

Capacity

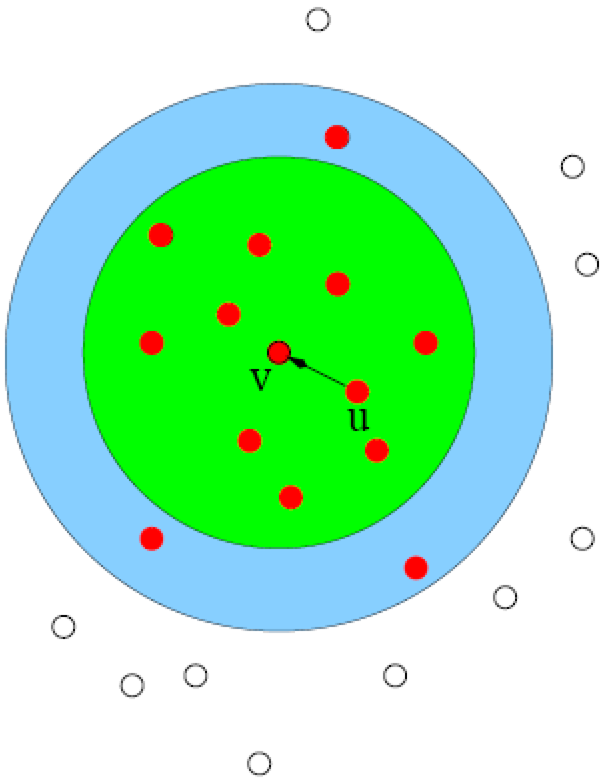
❖ Various network capacities for multicast

– **Total Capacity**: $\sum_{v_i \in S} \lambda_i$

– **<u>Minimum Capacity</u>**: $\phi_{n_d}(n) = \min_{v_i \in S} \lambda_i$

– **Average Capacity**: $\sum_{v_i \in S} \lambda_i / n_s$

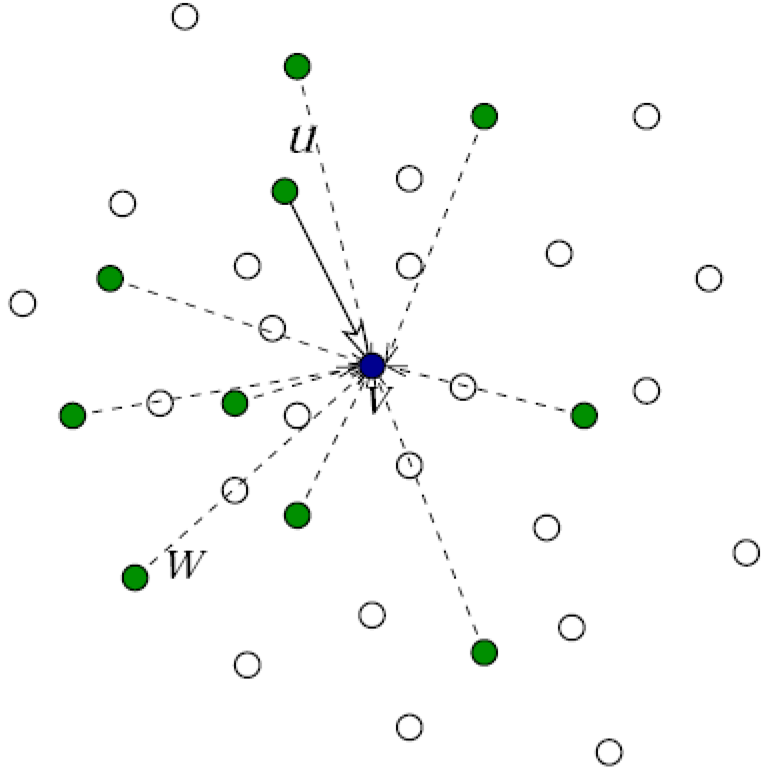
Interference and Link Models



- Fixed Range Protocol Interference Model (PrIM)
  - Link rate w bps
  - Transmission range r
  - Interference range R
  - Receiver v should not be interfered by other senders

Idealistic, but give us a reasonable scenario to study

Physical Interference Model



- Node u can send to v successfully at a given data rate only if

$$SINR = \frac{P_u \ell(u,v)}{\sigma + \sum_{w \in sending} P_w \ell(w,v)}$$

at node v is at least a threshold value

Gaussian Link Model

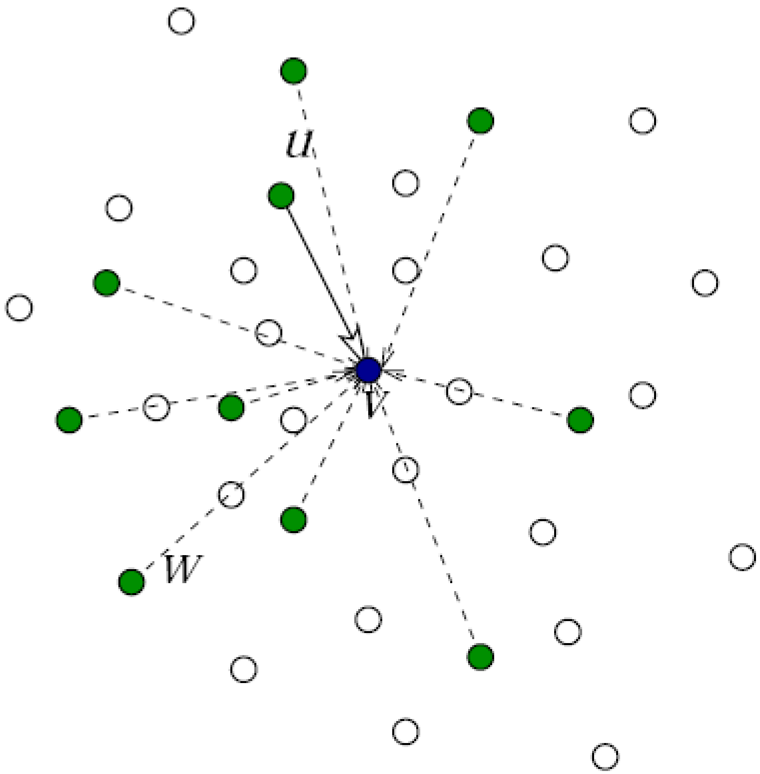


Figure: Gauss Channel

The capacity of link $u \longrightarrow v$ is

$$B \log(1 + SINR), \text{ where}$$

$$SINR = \frac{P_u \ell(u, v)}{\sigma + \sum_{w \in sending} P_w \ell(w, v)}$$

Assume that all nodes have same power P_u, and

$$\ell(u, v) = \min(1, \|u - v\|^{-\beta}),$$

for a constant $\beta > 2$

Feasible Rate Vector

- ❖ A data rate vector

$$\lambda = (\lambda_1, \lambda_2, \cdots, \lambda_{n-1}, \lambda_n)$$

is feasible if there is a spatial and temporal scheme for scheduling transmissions such that by operating the network in a multi-hop fashion and buffering at intermediate nodes when awaiting transmission, every node v_i can send λ_i bits/sec average to its chosen destination nodes.

Capacity for Random Networks

- The per flow multicast capacity of a class of random networks is of order $\Theta(f(n))$ bits/sec
  - if there are deterministic constants $c > 0$ and $c < c' < +\infty$ such that

$$\lim_{n\to\infty} \Pr(\min \lambda_i(n) = c \cdot f(n) \text{ is feasible}) = 1$$

$$\lim_{n\to\infty} \inf \Pr(\min \lambda_i(n) = c' \cdot f(n) \text{ is feasible}) < 1$$

Factors affecting capacity, but not studied here

- Noise Strength and Distribution,
- Dynamic Power Adjustment,
- Traffic Profile, Topology,
- Latency, Heterogeneity,
- Mobility,

- Channel diversity, multi-user, MIMO,
- Network Coding (application layer, physical layer)
- Successive Interference Cancelation
- Cognitive radio
- …..

RESULTS REVIEW AND OUR RESULTS SUMMARY

Some Milestone Results for Unicast

Unicast Capacity

$\Theta(\frac{W}{\sqrt{n \log n}})$ random $\Rightarrow \Theta(W)$ $\Rightarrow \Theta(\frac{W}{\sqrt{n \log n}})$ NC $\Rightarrow \Theta(\frac{W}{\sqrt{n}})$ GC

A Scare, 00-01 Gupta, Kumar: Per-flow unicast throughput under PrIM is $\Theta(W/\sqrt{n \log n})$

Unicast Capacity

$\Theta(\frac{W}{\sqrt{n \log n}})$ random $\Rightarrow \Theta(W)$ $\Rightarrow \Theta(\frac{W}{\sqrt{n \log n}})$ NC $\Rightarrow \Theta(\frac{W}{\sqrt{n}})$ GC

Mobility Matters, 2002 Grossglauser and Tse, $\Theta(W)$ via mobility and power-adjustment, large delay.

Unicast Capacity

$\Theta(\frac{W}{\sqrt{n \log n}})$ random $\Rightarrow \Theta(W)$ $\Rightarrow \Theta(\frac{W}{\sqrt{n \log n}})$ NC $\Rightarrow \Theta(\frac{W}{\sqrt{n}})$ GC

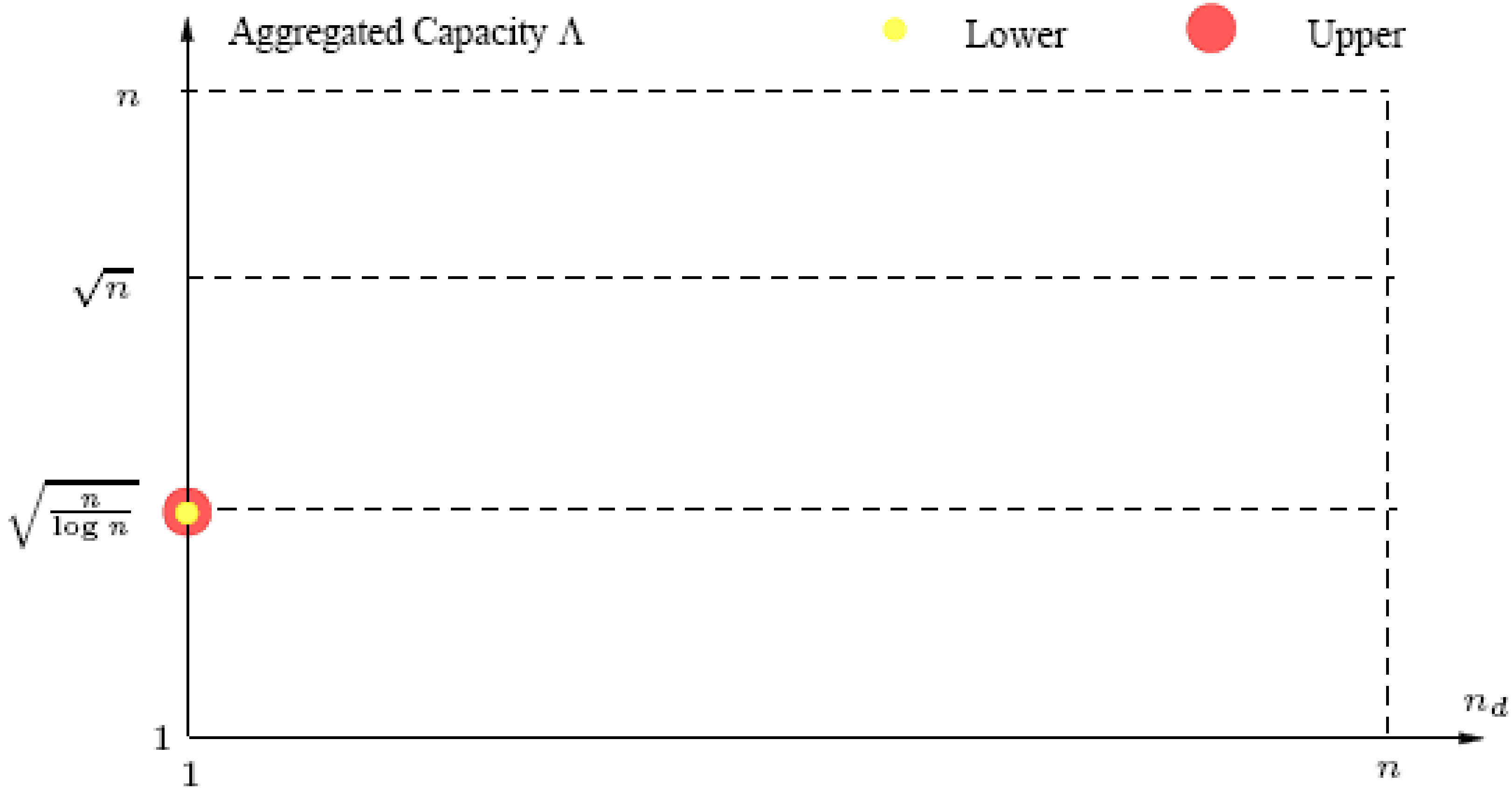
Network Coding Does Not Matter, 2006 Li, Goeckel and Towsley: $\Theta(1/\sqrt{n \log n})$ with NC & PrIM.

Unicast Capacity

$\Theta(\frac{W}{\sqrt{n \log n}})$ random $\Rightarrow \Theta(W)$ $\Rightarrow \Theta(\frac{W}{\sqrt{n \log n}})$ NC $\Rightarrow \Theta(\frac{W}{\sqrt{n}})$ GC

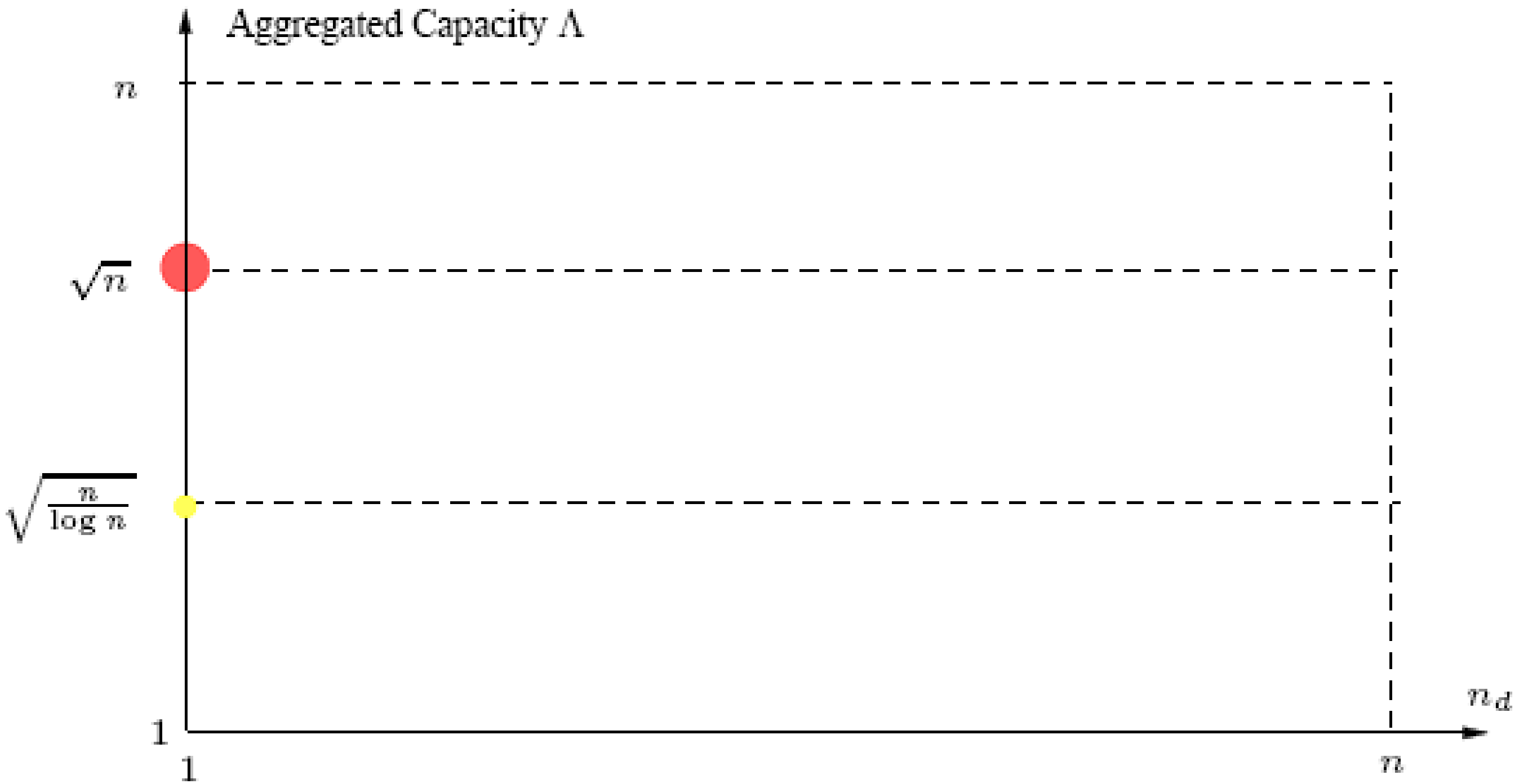
Channel Model Does Matter, 2007 Franceschetti *et al.*, $\Omega(W/\sqrt{n})$ when using Gaussian Channel.

Milestone Results: Unicast



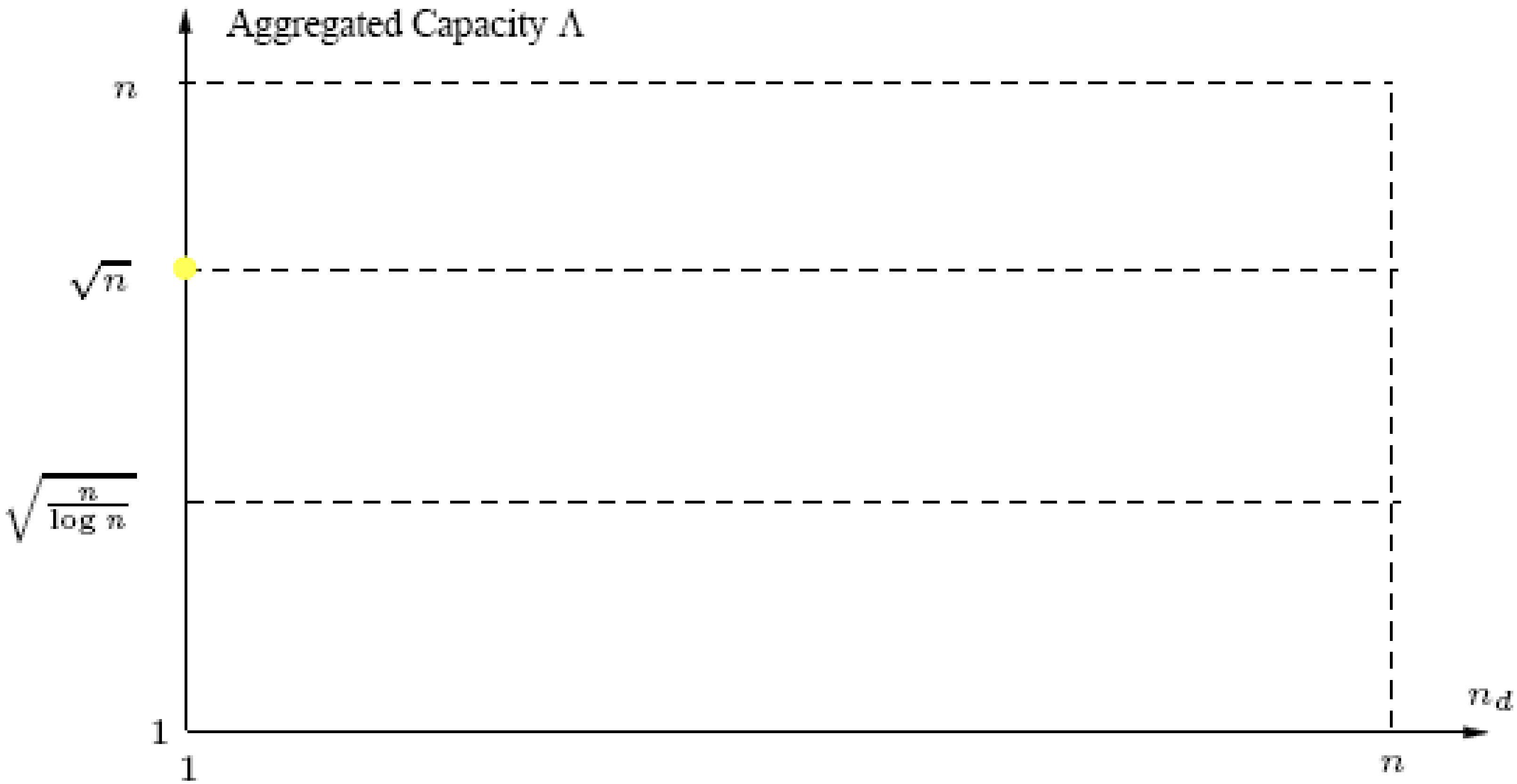
Total Unicast Capacity for RDN under Protocol Model, $n_s = \Theta(n)$, *Gupta and Kumar [IEEE TIT 2000].*

Milestone Results: Unicast



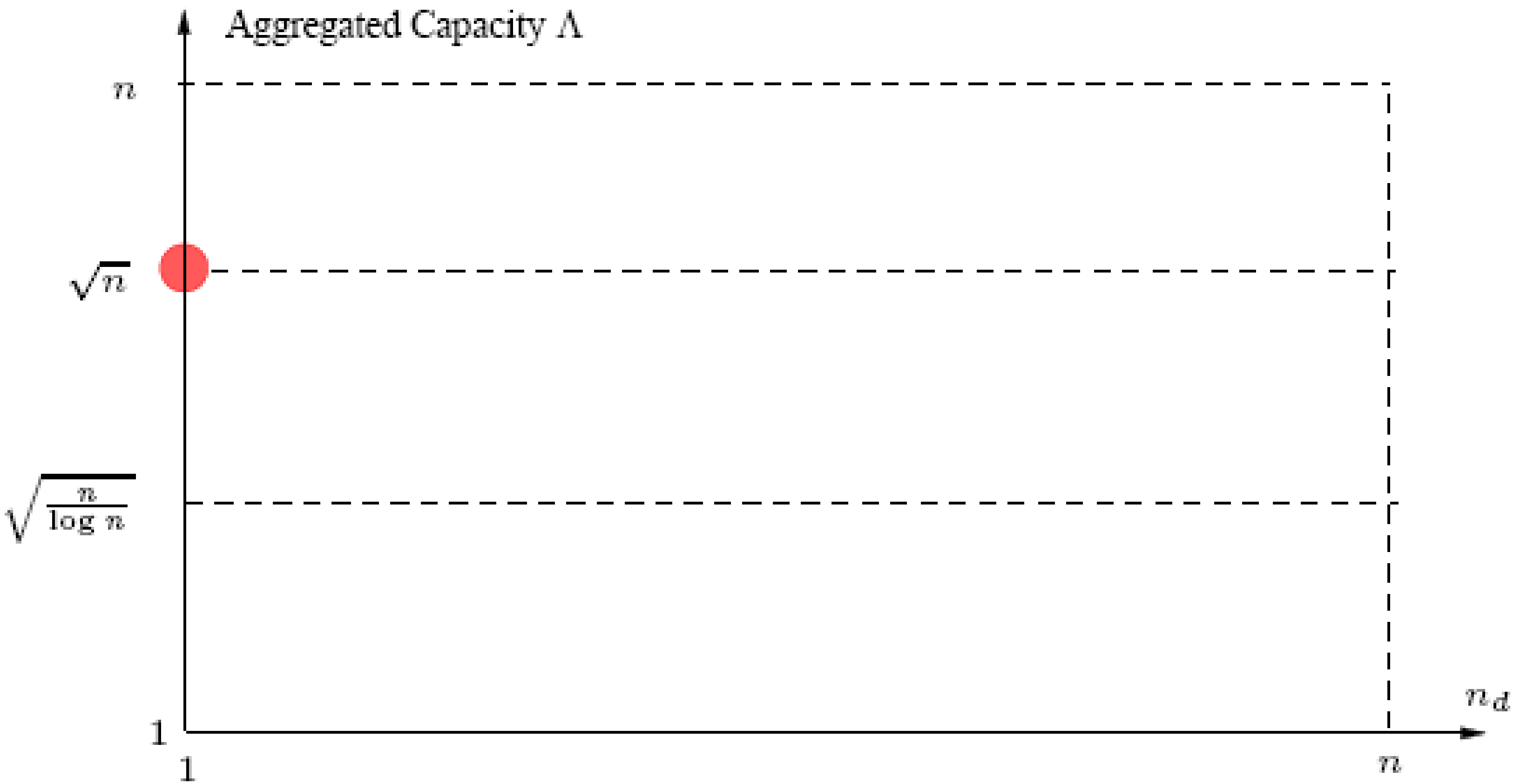
Unicast Capacity for RDN under Physical Model,
$n_s = \Theta(n)$, *Gupta and Kumar [IEEE TIT 2000].*

Milestone Results: Unicast



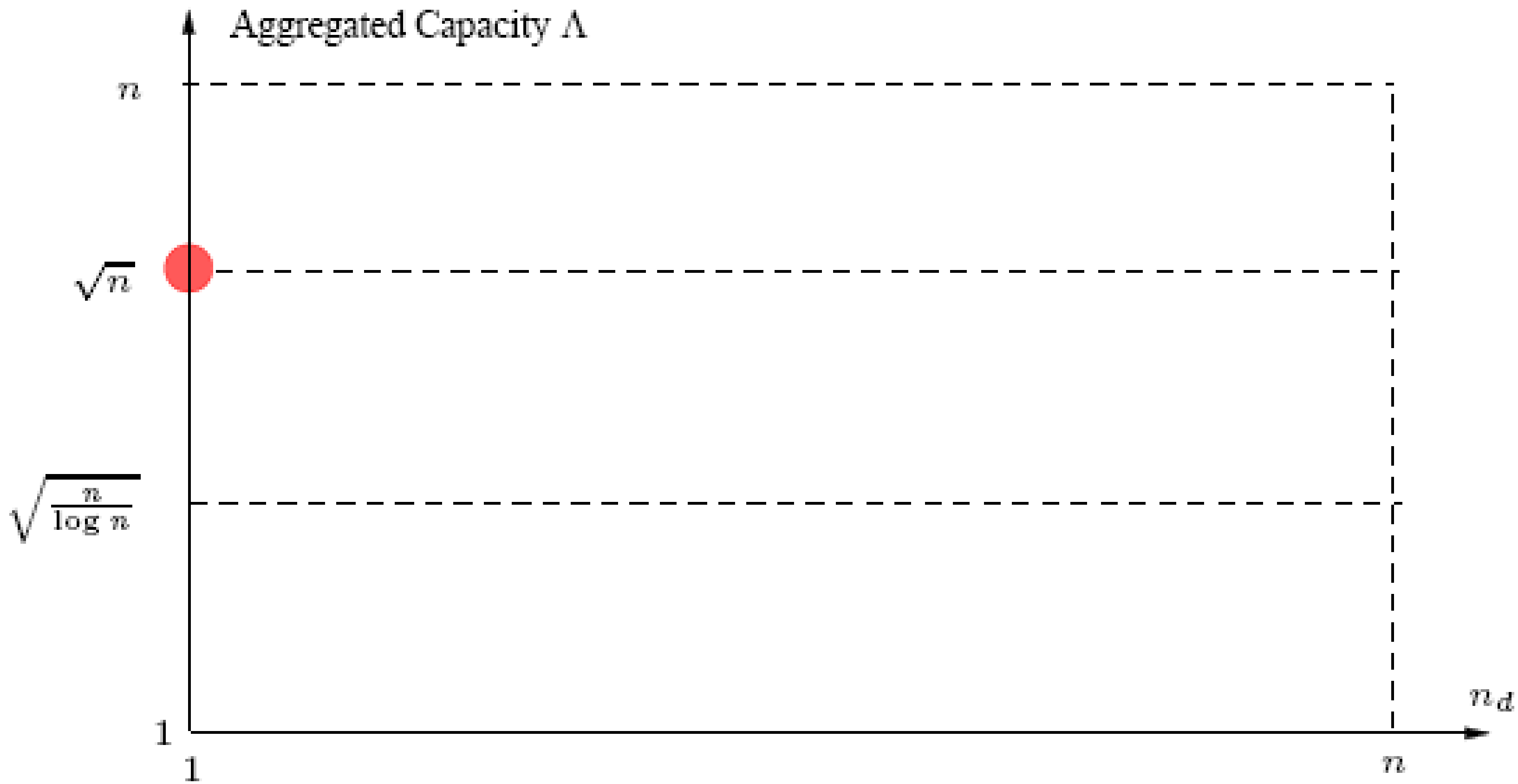
Total Unicast Capacity for RDN, REN under Gaussian Model, $n_s = \Theta(n)$, Franceschetti et al. [IEEE TIT 2007].

Milestone Results: Unicast



Total Unicast Capacity for RDN under Gaussian Model,
$n_s = \Theta(n)$, *Keshavarz-Haddad and Riedi [WiOPT2007].*

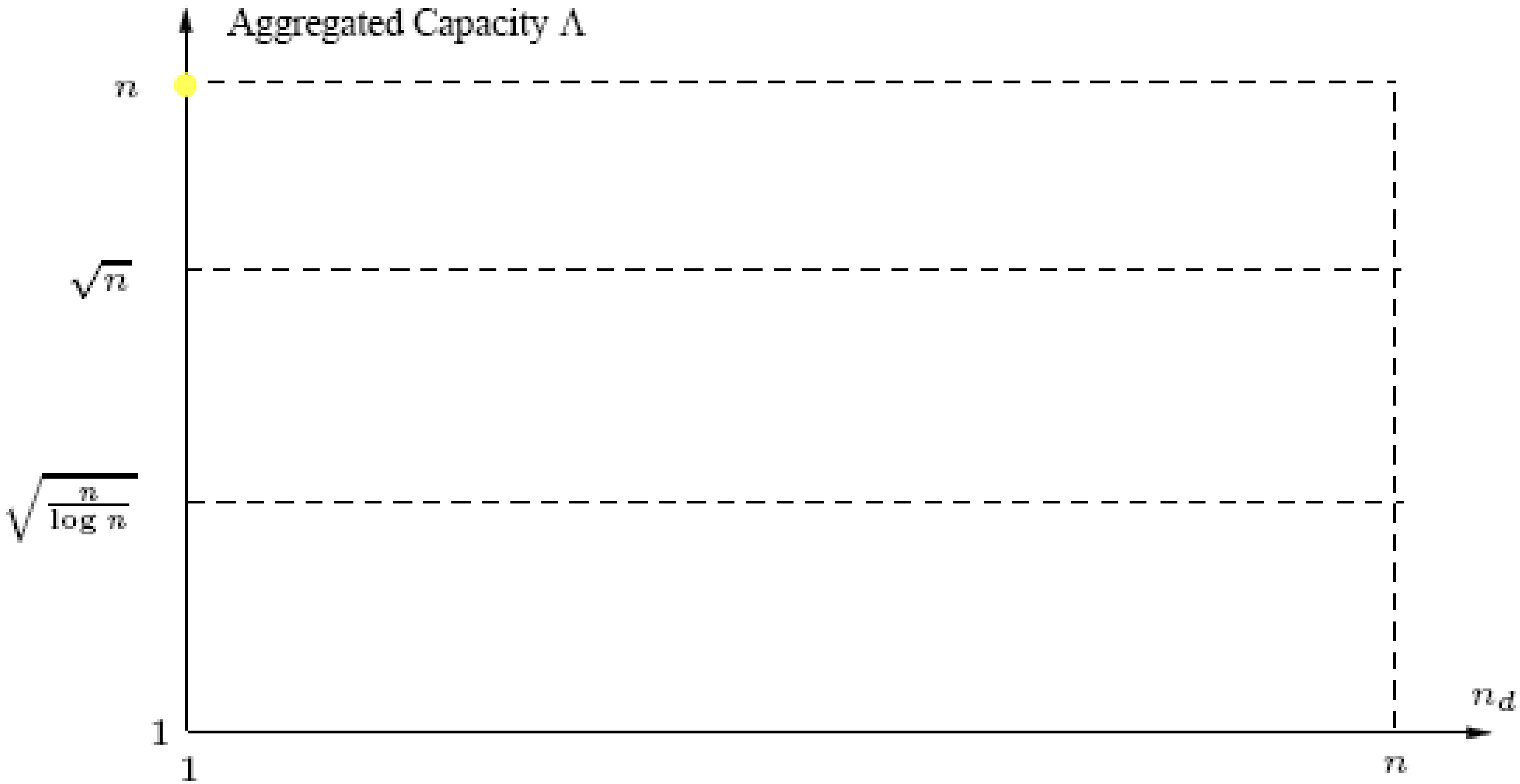
Our Results: Unicast



Total Unicast Capacity for REN under Gaussian Model,

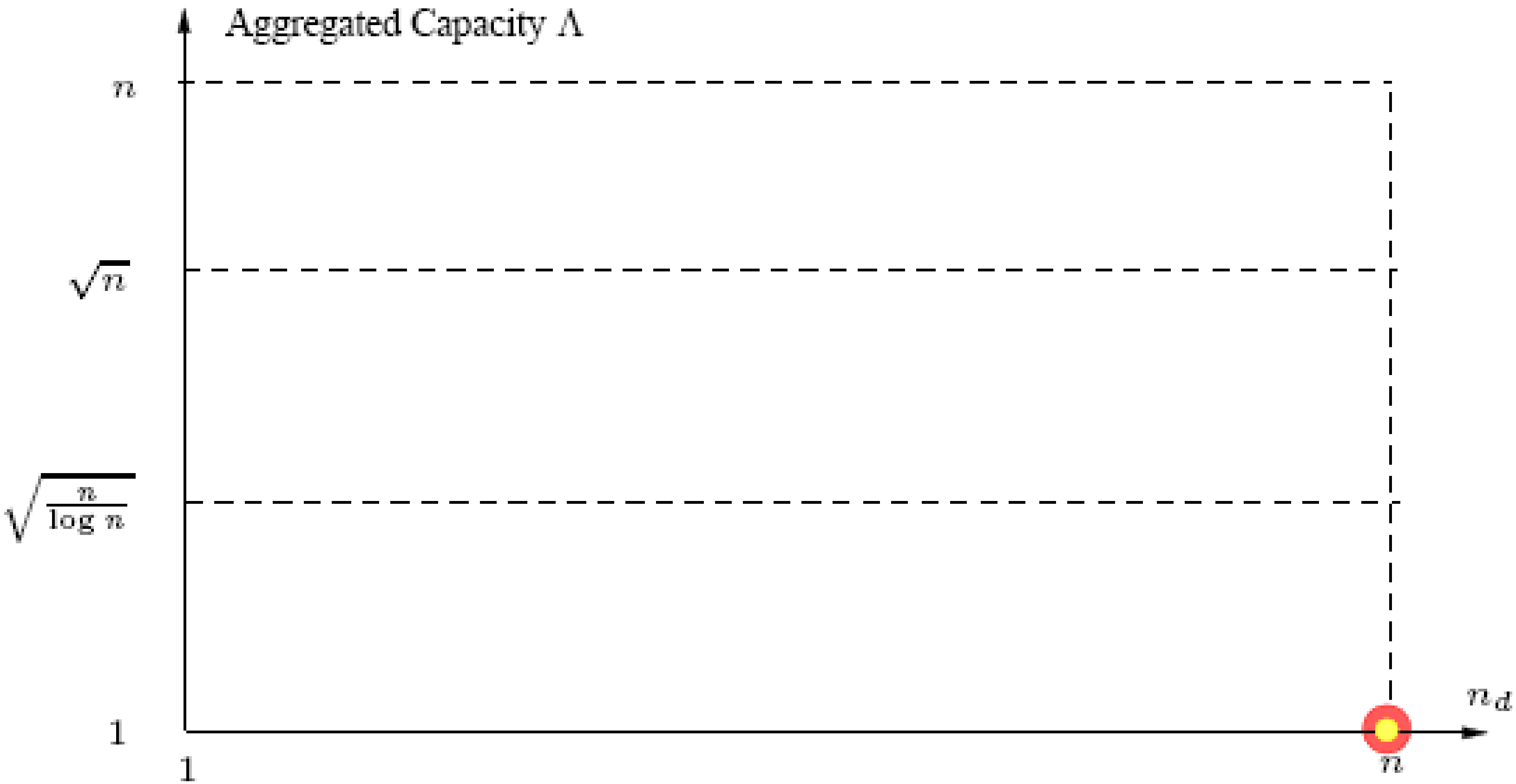
$n_s = \Theta(n)$, *Li et al [MobiCom2008].*

Milestone Results: Unicast



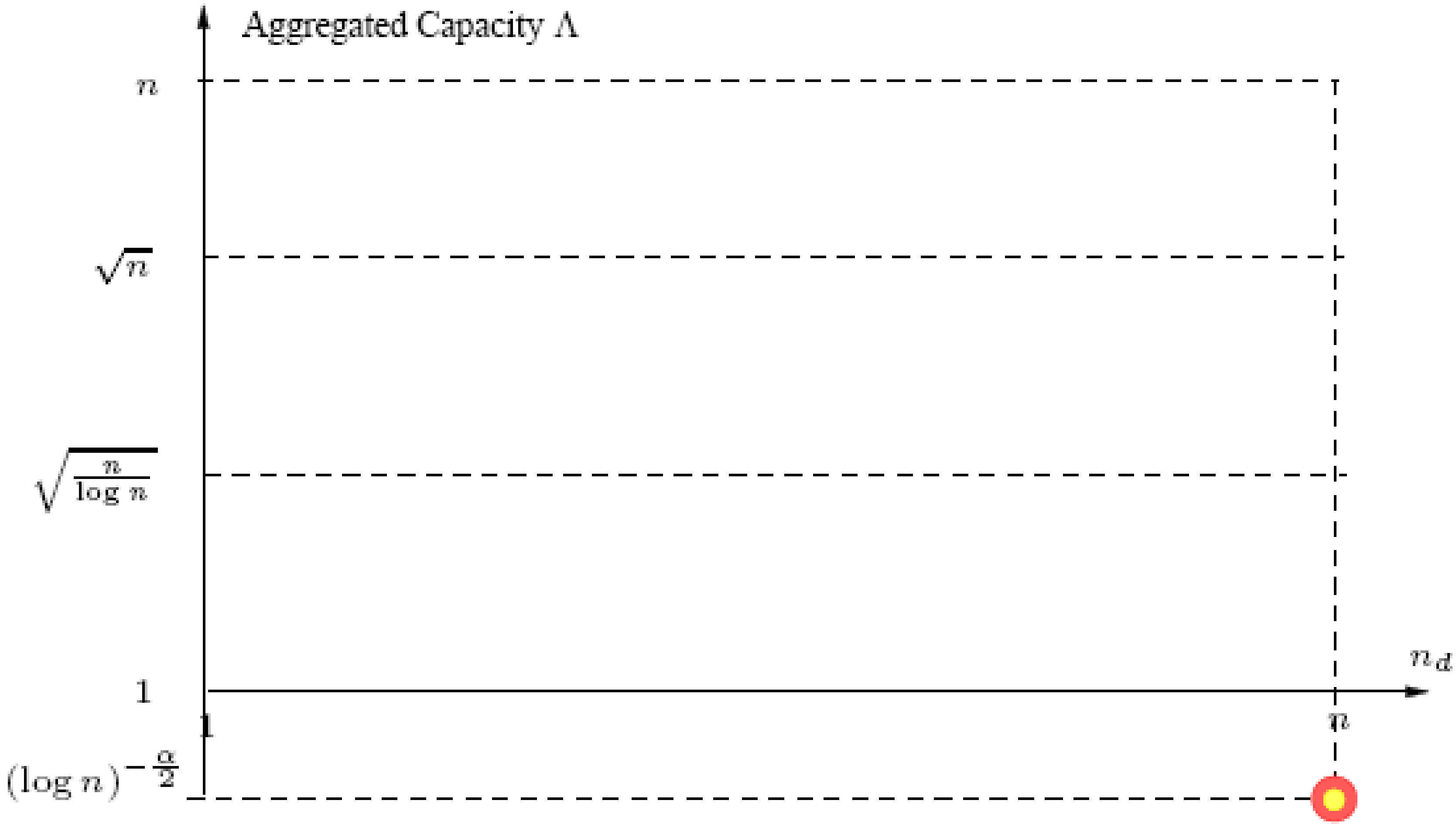
Total Unicast Capacity for mobile RDN under Physical Model (i.i.d. mobility model), $n_s = \Theta(n)$, Grossglauser and Tse [INFO2002],

Milestone Results: Broadcast



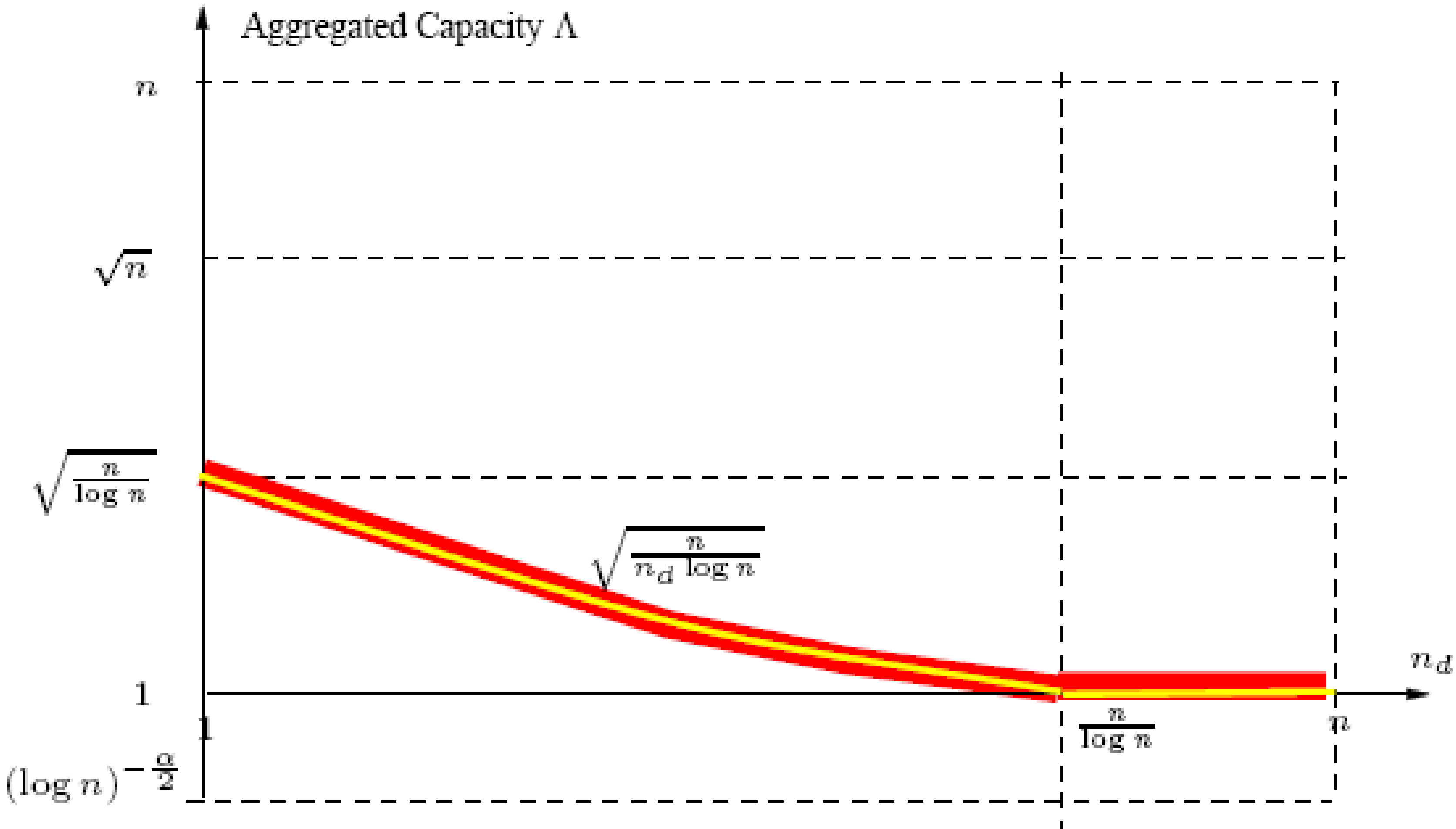
Broadcast Capacity for RDN under Protocol Model, $n_s = \Theta(n)$, Keshavarz-Haddad et al. [MobiCom 2006].

Milestone Results: Broadcast



Broadcast Capacity for REN under Gaussian Model, $n_s = \Theta(n)$, Zheng et al. [INFOCOM 2006].

Our Results: Multicast



Multicast Capacity for REN under Protocol Model, $n_s = \Theta(n)$, Li et al. [MobiCom 2007].

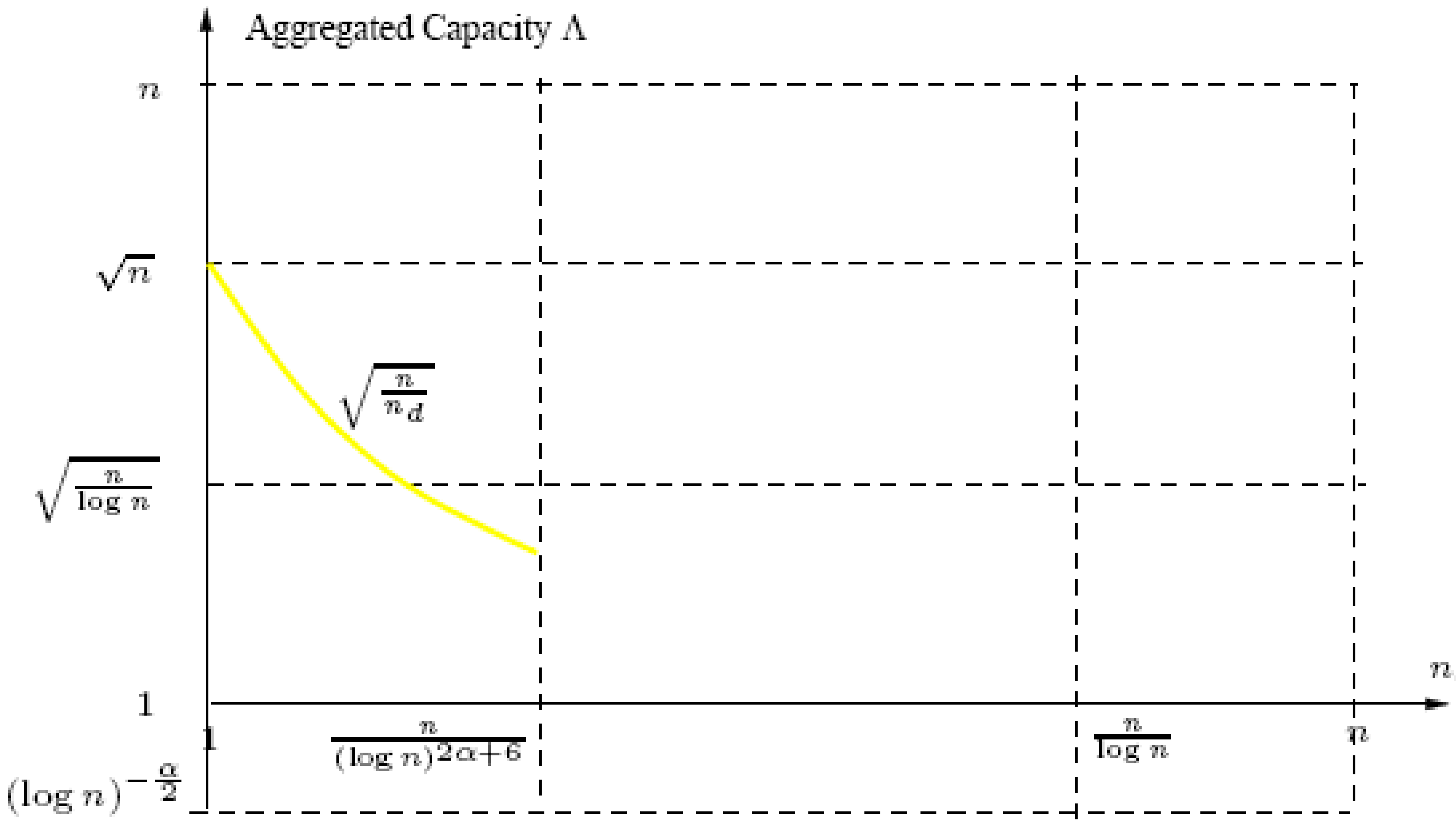
Summary of Our Results

- The aggregate multicast capacity of n sessions is

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

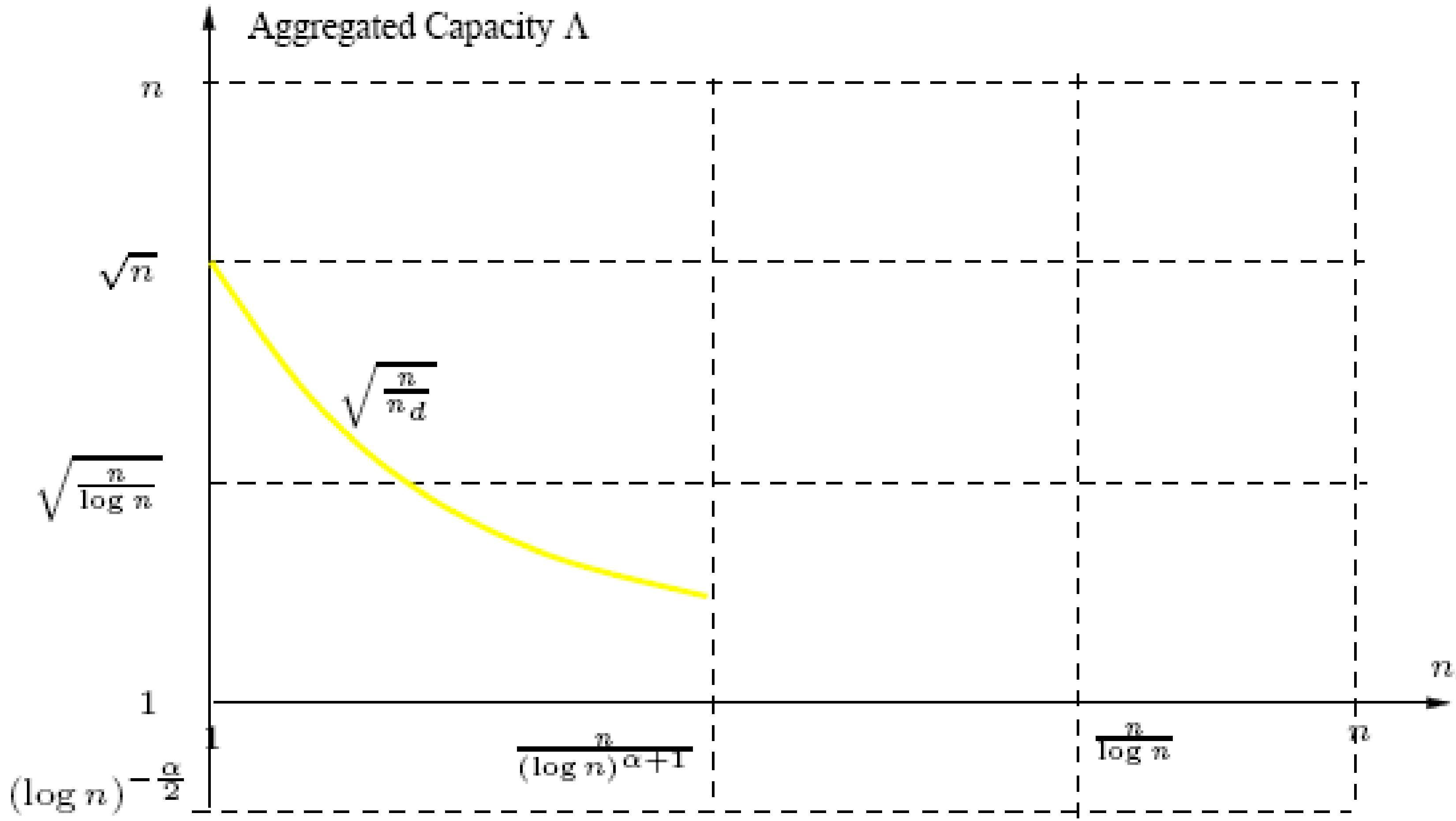
- Our results unify previous results
  1. Unicast (when $n_d = 2$): $\Theta(\sqrt{\frac{n}{\log n}} \cdot W)$ by Gupta and Kumar
  2. Broadcast (when $n_d = n$): $\Theta(W)$ by Keshavarz-Haddad *et al.*, MobiCom'06.
  3. Multicast ($n_s = n^{\epsilon}$ and $n_d = n^{1-\epsilon}$), by Shakkottai, Liu, Srikant, Mobihoc'07.

Our Results: Multicast



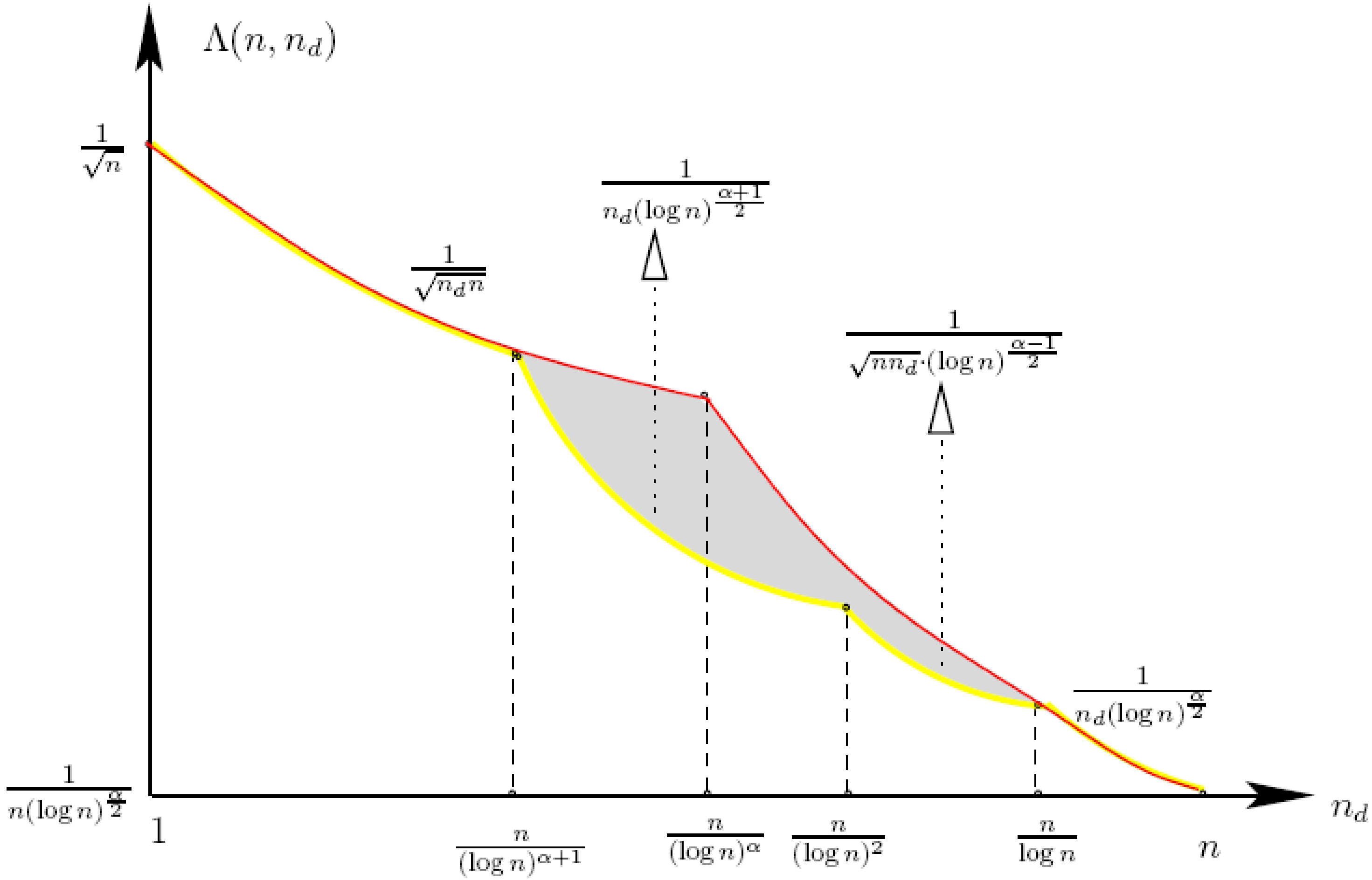
Multicast Capacity for REN under Gaussian Model, $n_s = \Theta(n)$, Li et al. [MobiCom 2008].

Our Results: Multicast



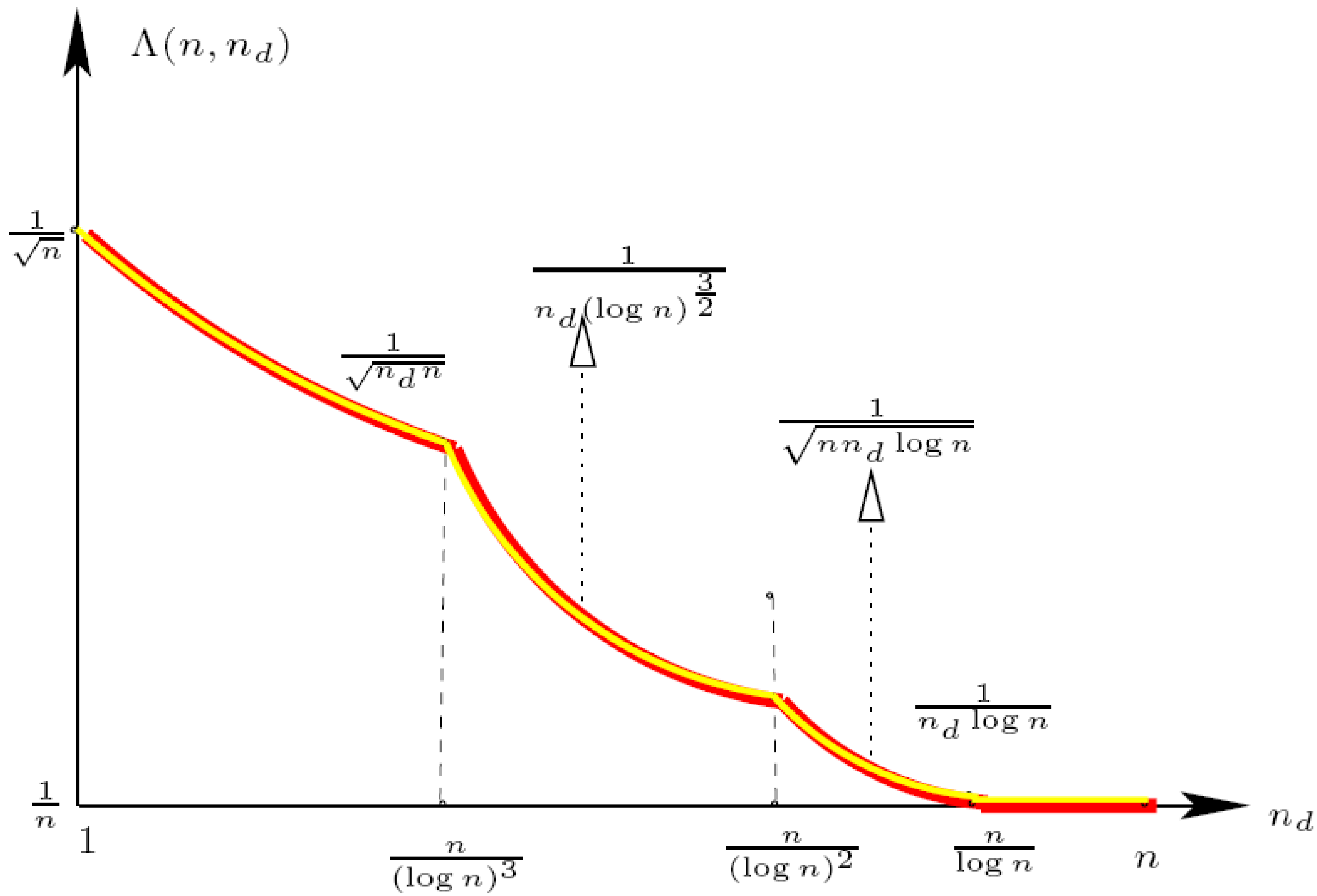
Multicast Capacity for REN under Gaussian Model, $n_s = \Theta(n)$, *Wang*, Li et al. [INFOCOM 2009].

Our Results: Multicast



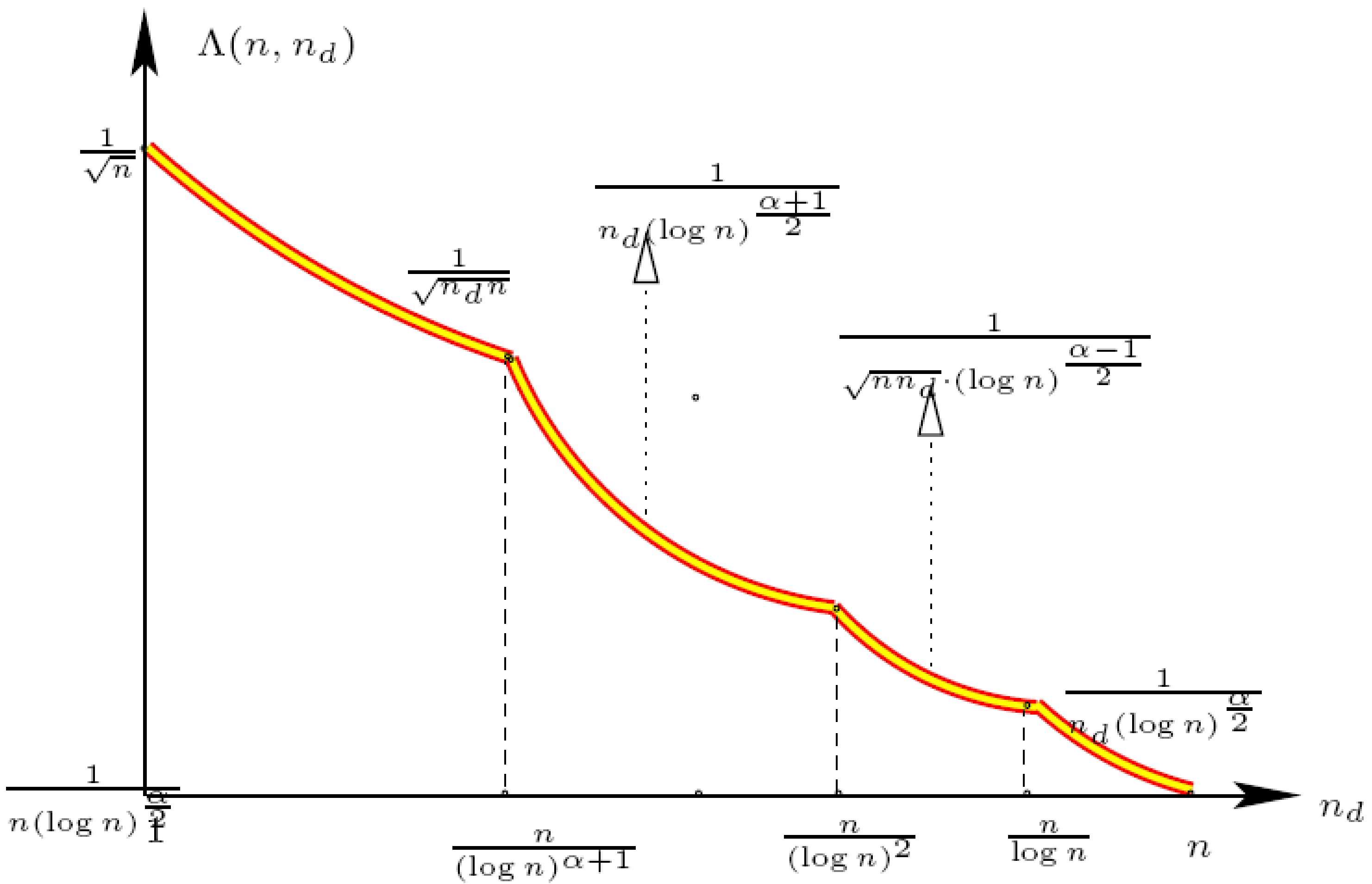
Multicast Capacity for REN under Gaussian Model, $n_s = \Theta(n)$, *Wang*, Li et al. [INFOCOM 2010].

Our Results: Multicast



Multicast Capacity for REN under Gaussian Model, $n_s = \Theta(n)$, *Wang*, Li et al. [INFOCOM 2011].

Our Results: Multicast



Multicast Capacity for RDN under Gaussian Model, $n_s = \Theta(n)$,
Wang, Li et al. [INFOCOM 2011].

Observations:

- There are two typical models in terms of scaling patterns of the network:

- **Criteria of Scaling Patterns:**

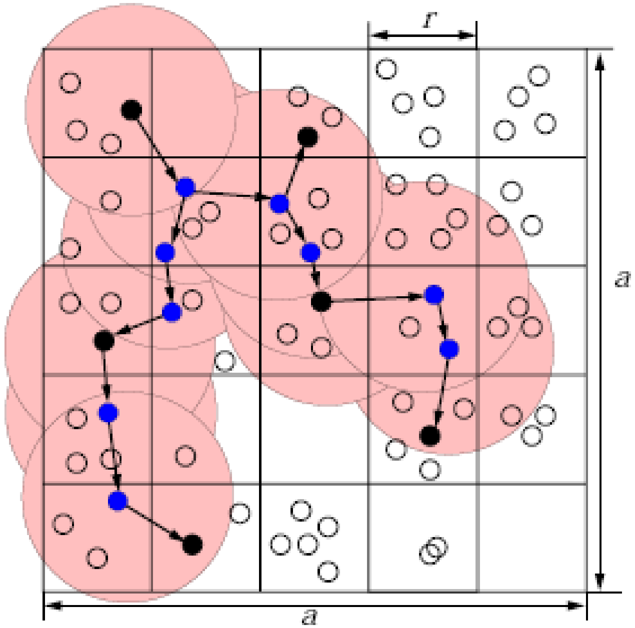
  – Dense Scaling Model: $\zeta = \Omega(\log n)$

  – Extended Scaling Model: $\zeta = o(\log n)$

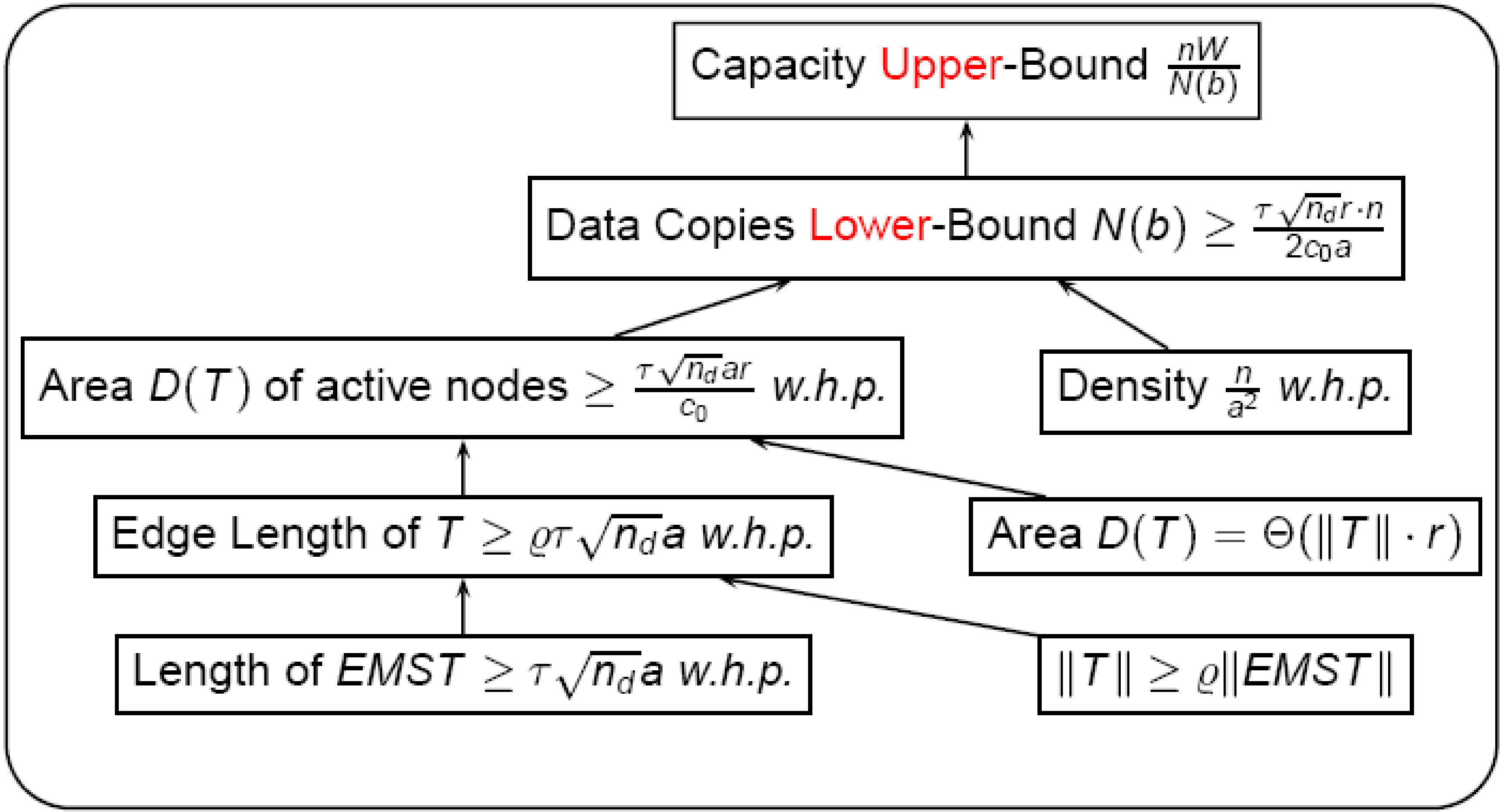
GENERAL APPROACHES

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 $n \cdot W$.

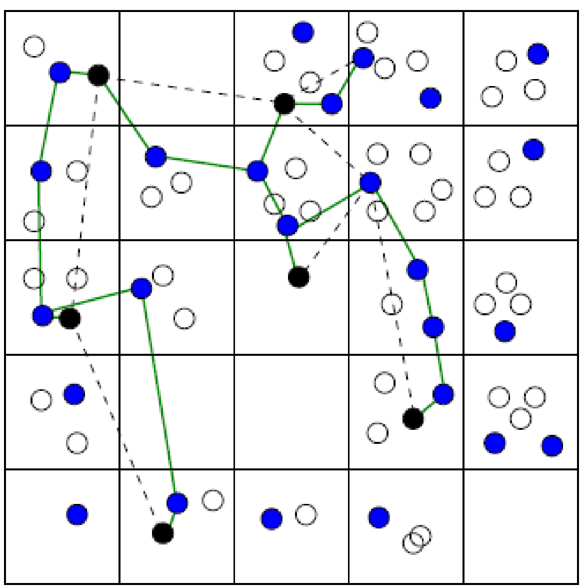


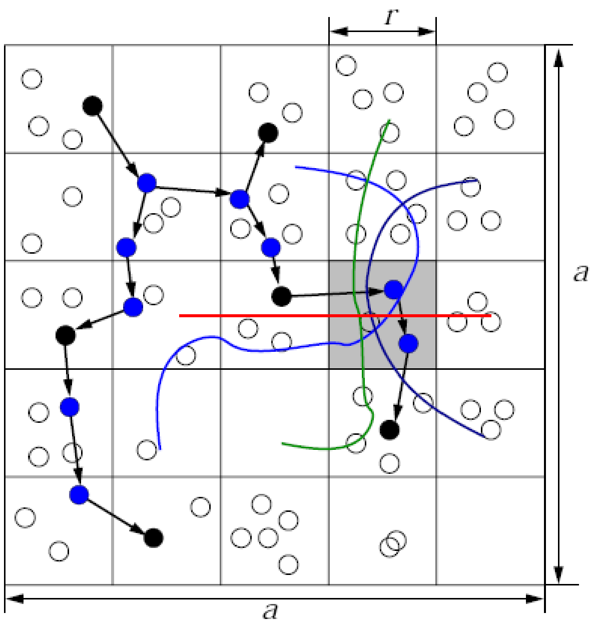
Upper-bound Proof Flow



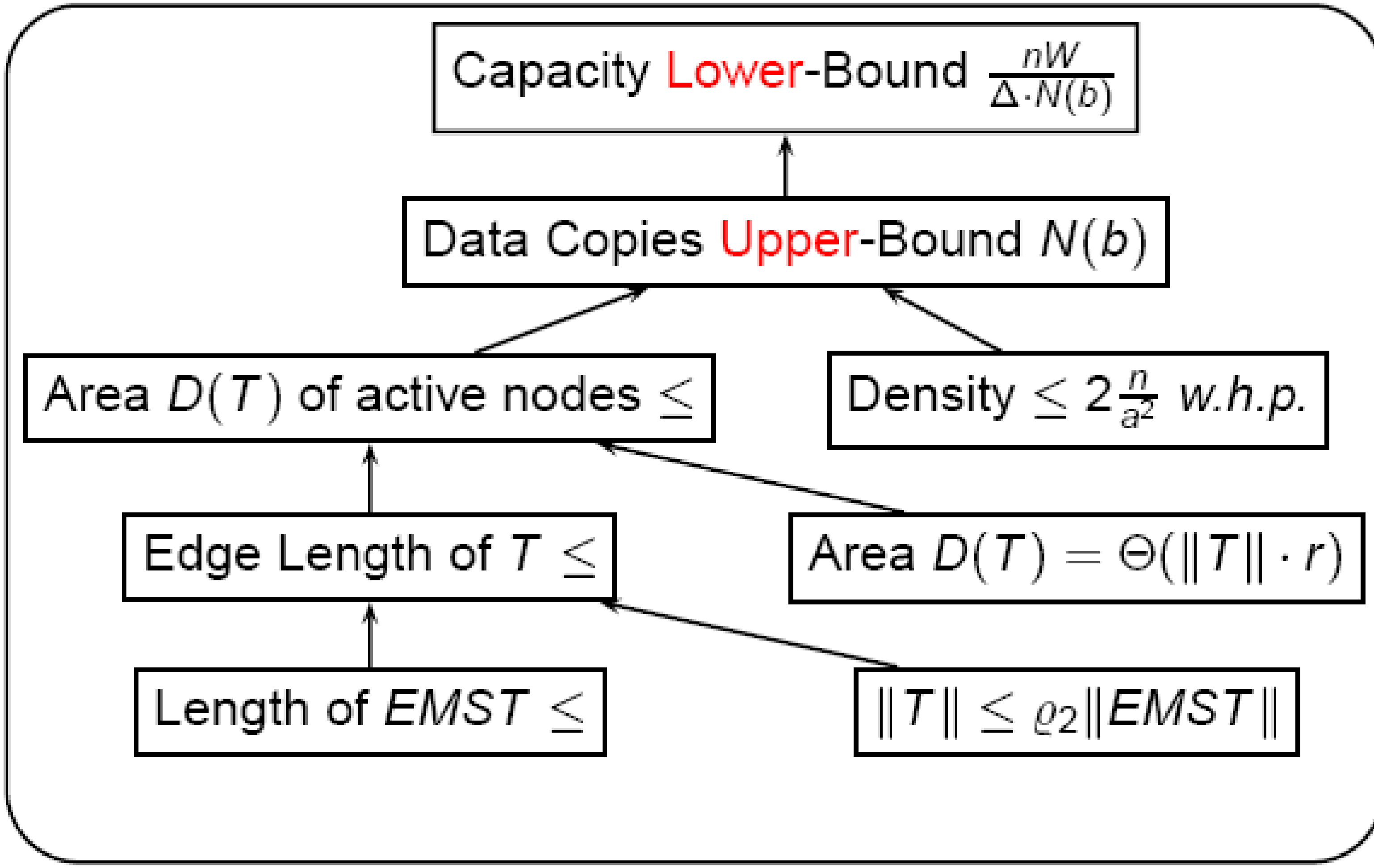
Lower-Bound: Routing and Scheduling

- ❖ 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



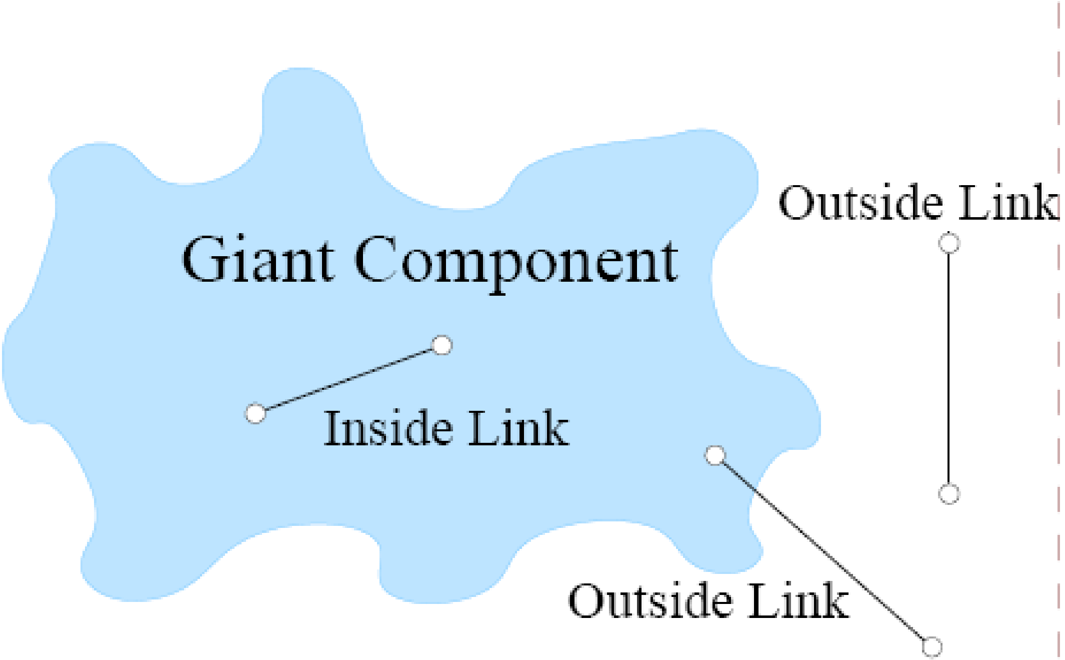


Lower-bound Proof Flow



Multicast under Gaussian Model

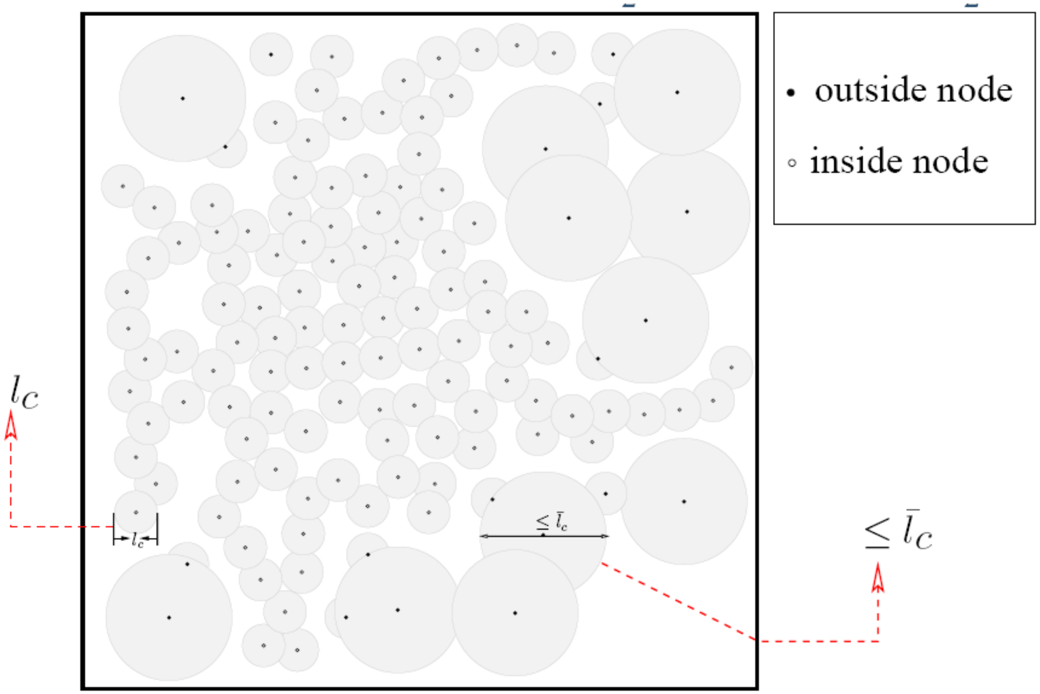
- ❖ Divide the links in multicast into links among giant components (formed by short links), and other links



Relationship between links

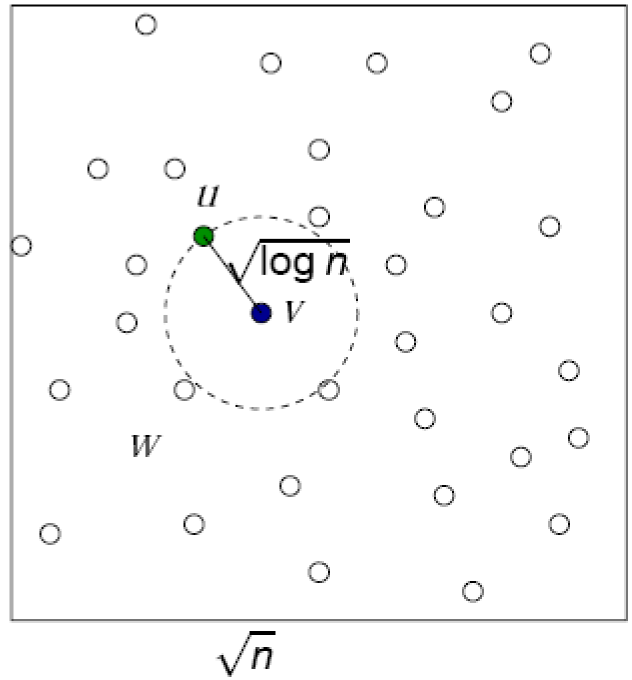
- Consider giant component with link length at most l_c
  - Define the max distance between any node *not in GC and the giant cluster by* $\overline{l}_c$

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



Upper-bound Proof Techniques 1

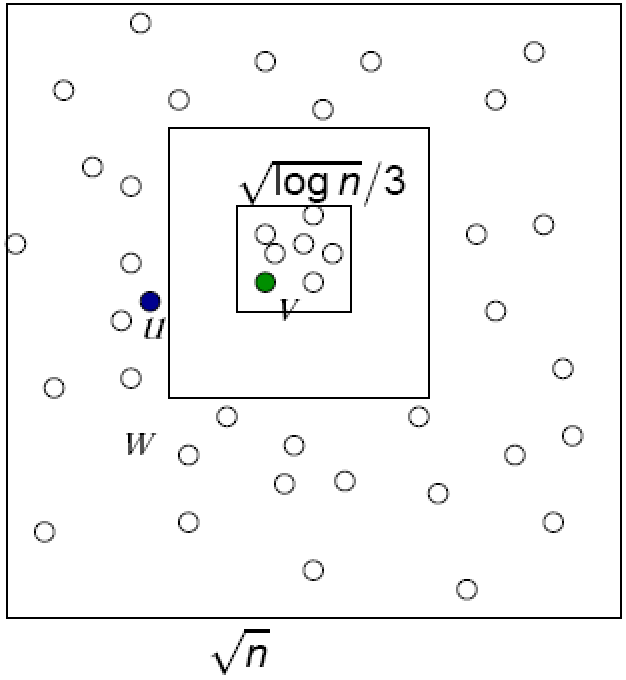
- There is a link *uv, that will be used by many* flows (say f) $\Rightarrow$ *the minimum data rate*
  - – min $\lambda_i \leq$ rate supported by $uv\,/\,f$



Upper-bound Proof Techniques 2

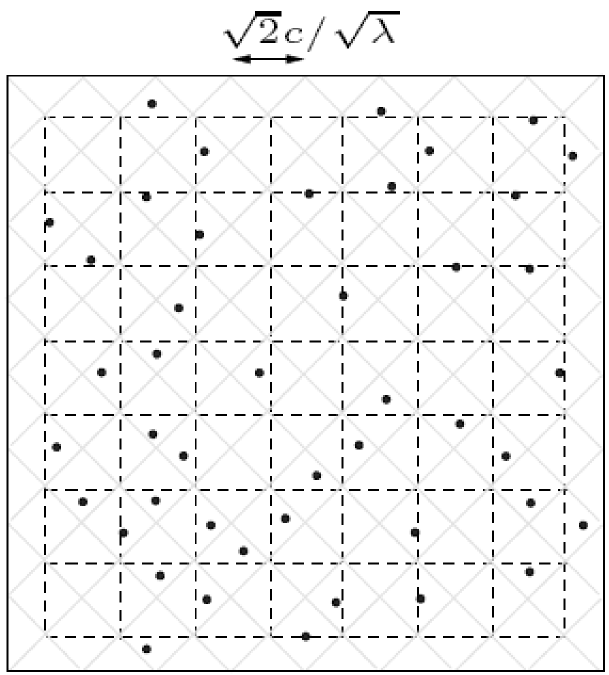
❖ There is an isolated cluster *C of nodes, and f* flows will have links going inside this cluster ⇒ *the minimum data rate*

– min $\lambda_i \leq$ total rate supported by links reaching C / f

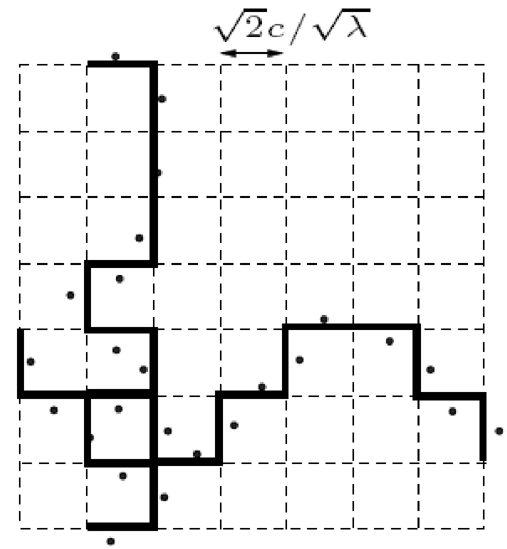


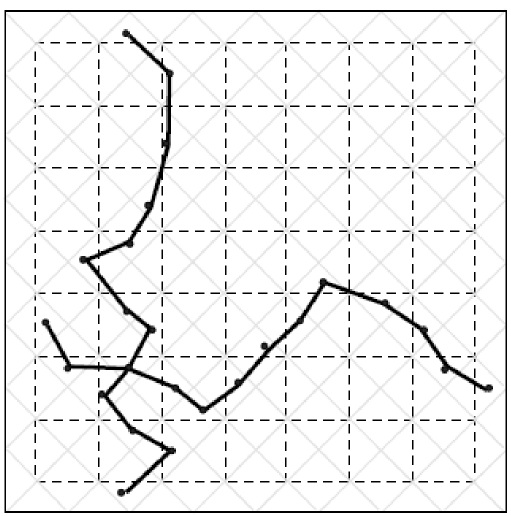
Lower Bounds Techniques

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



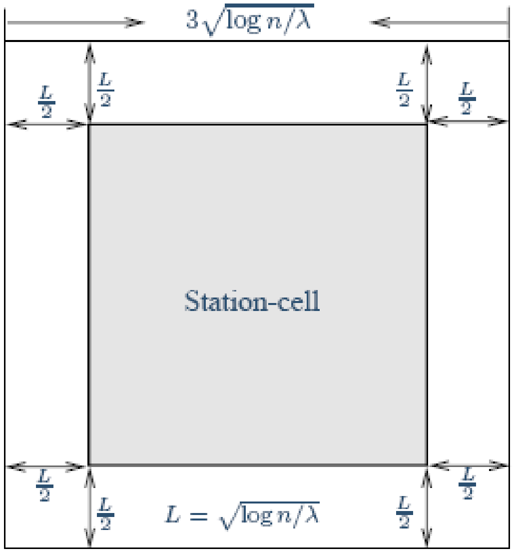
(a) $\mathbb{L}(n, \lambda, \sqrt{c^2/\lambda}, \pi/4)$

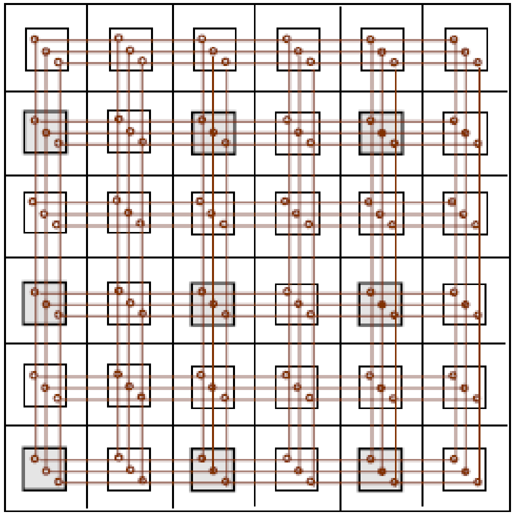




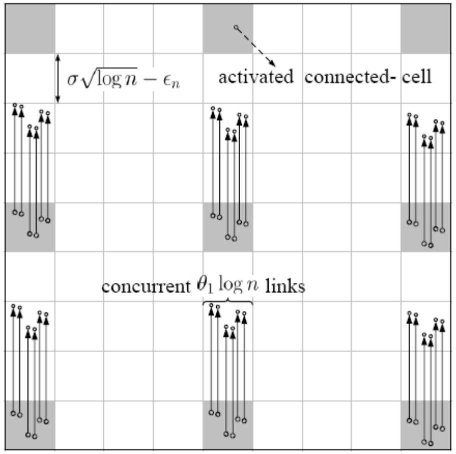
Our New Techniques

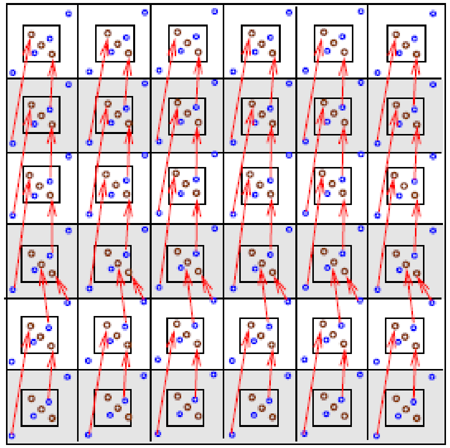
- ❖ Parallel Arterial Road Systems
  - – longer links to connect isolated nodes to highway





- ❖ Parallel Scheduling





Other Capacity Results

- ❖ Hybrid Wireless Networks
  - – Backbone networks + ad hoc networks
  - – Asymptotic capacity for multicast
- ❖ Cognitive Radio Networks
  - – Primary Networks + Secondary Networks
  - – Asymptotic capacity for multicast
- ❖ Mobile Wireless Social Networks
  - – Social Networking + Mobile Networks
- ❖ Capacity for other operations
  - – Data collection and Data aggregation
  - – SelectCast, AnyCast,
  - – Capacity and Delay Tradeoffs

Summary

- Experience and Lessons from Large Scale WSN System Design and Deployment
  - OceanSense
  - GreenOrbs
  - CitySee

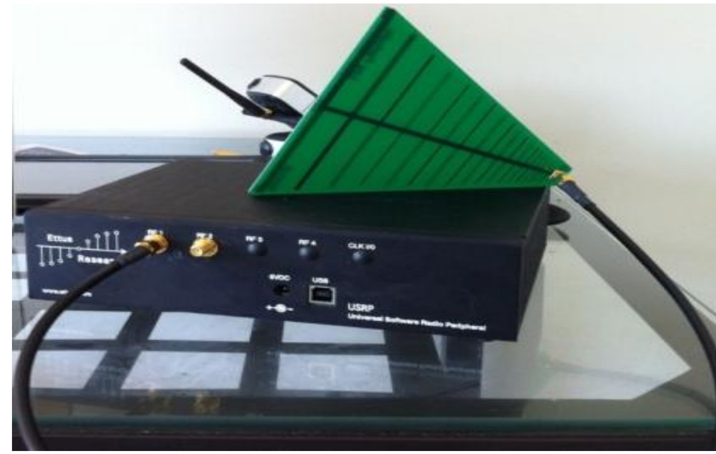
- Asymptotical Capacity of Large Scale Wireless Networks
  - Network model, and asymptotical capacity
  - Literature review
  - Our results summary
  - Our approaches

Other Research Concentrations

- Application of Sensor Networks
  - Wastewater processing (CPS medium project)
  - Mobile health
- Algorithms for wireless networks
  - Offline scheduling,
  - Online scheduling and optimization
  - Game theory and economics
  - Cognitive radio networks
- Social Networks
  - Information propagation
  - Team formation/link predication

Cyber Physical Systems

Cognitive Radio Networks



Mobile, Social Networks

- ❖ Privacy and security
- ❖ Energy saving
- ❖ Location, navigation

- ❖ Influence computation
  - – Churn prediction
- ❖ Relationship learning
- ❖ Sentiment Analysis
- ❖ Spam detection

OUR GROUP

Theoretical Studies

- Algorithm Design and Analysis of Practical Questions
  - Wireless ad hoc networks
  - Wireless sensor networks
  - RFID
  - Cognitive networks
  - **Online optimization (little regret)**
  - Computational geometry
  - Game theory and its applications
  - Information theory (such asymptotical behavior of large scale networks)

Where do we publish?

- Journals
  - IEEE/ACM Transactions on Networking, TPDS, Computers, JSAC, and so on
  - ACM Transactions, and so on
- Conferences
  - ACM MobiCom, ACM Mobihoc, ACM STOC, ACM SODA, ACM EC
  - IEEE INFOCOM, ICNP, ICDCS, and so on
- Well recognized and accepted in the community

Where do our students go?

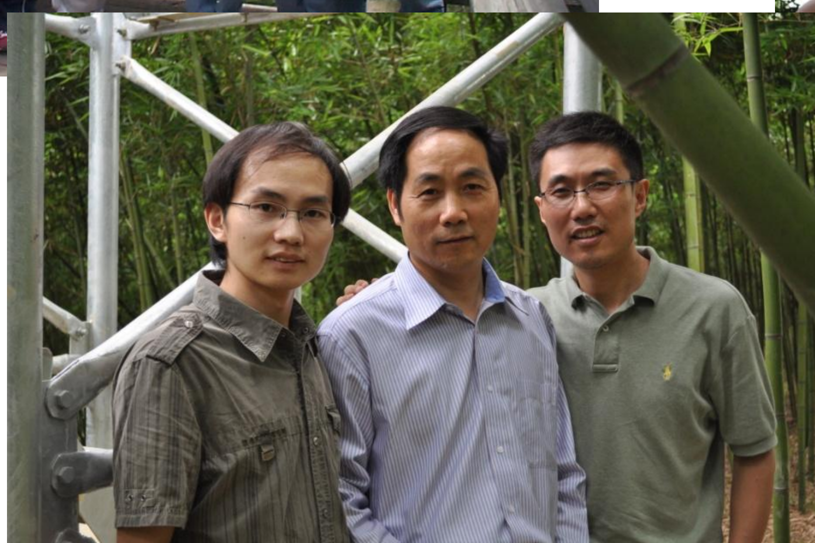
- Graduated students (7 PhDs)
  - (4) Faculty at North Carolina Charlotte, Washington State University, Minnesota State University, BUPT (China)
  - Researcher at Google,
  - Game designer and truck industry
  - Financial industry

Professors, and students

Collaborators


110

Students and Collaborators

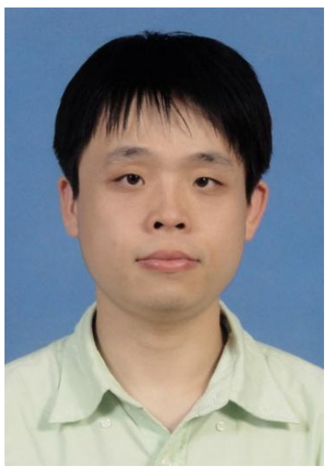
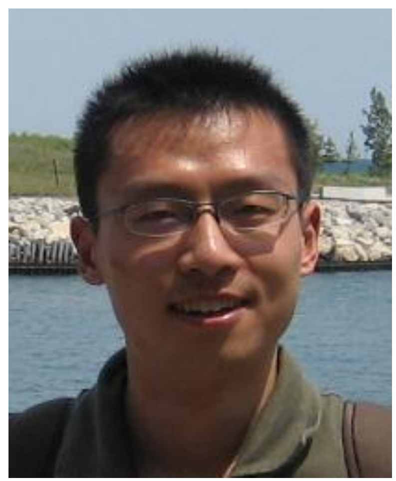


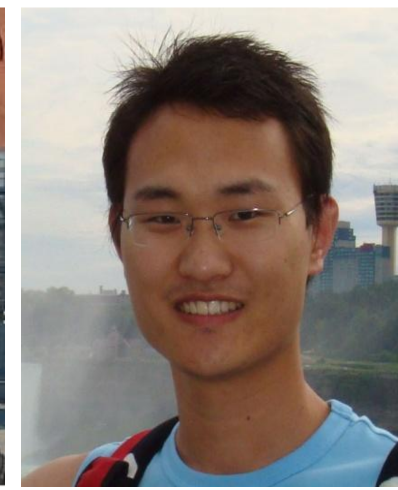
PhD Students (graduated, current)









PhD and MS Students (current)

More PhD students

- TaeHo Jung
- Cheng Bo
- JunZe Han

MS students

- Yue Tao (EE, IIT)
- Eric Sze Ching Duan (CS, IIT)
- SuFeng Niu (EE, IIT)
- PengQian Hu (CS, IIT)
- GuoBiao Yang (CS, IIT)
- YiTian Pan (CS, IIT)
- Chan Guo (CS, IIT)
- YanJie Wang (CS, IIT)
- Hao Bian (CS, IIT)
- Unsuk Heo (CS, IIT, undergraduate)
- Juan Garcia (CS, IIT)
- Siddharth Shankar (CS, IIT)
- Wei Wang
- YiFan Zhu
- Shufan Wang

Thank you !

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