GreenOrbs

Lessons Learned from Large Scale Sensor Network Deployment

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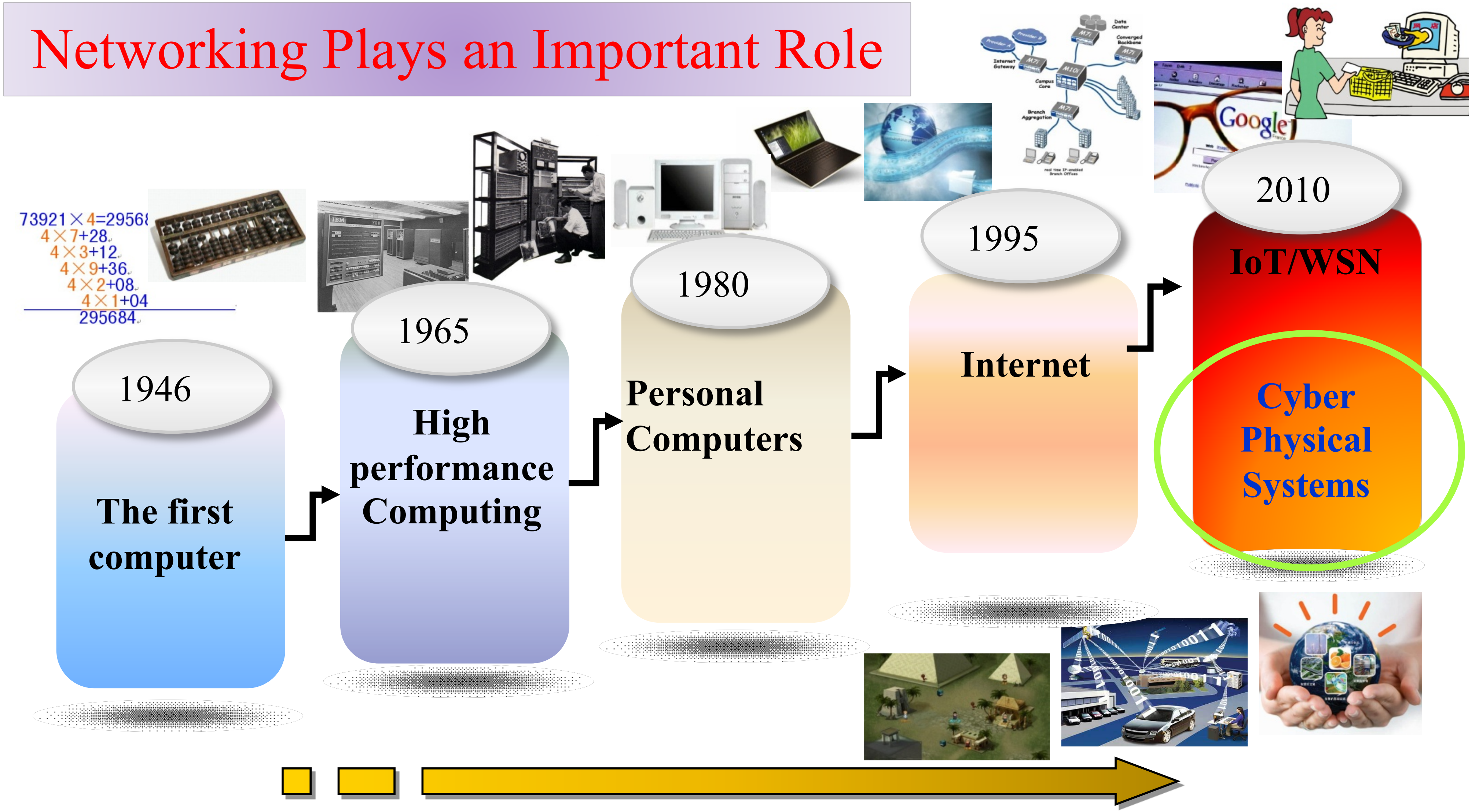
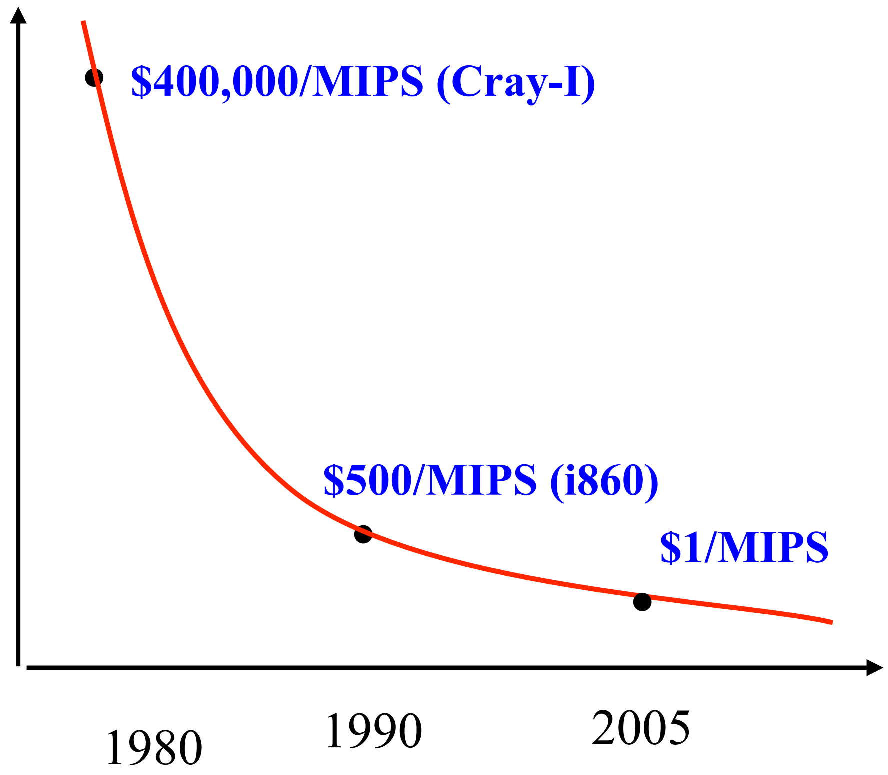
Networking Plays an Important Role

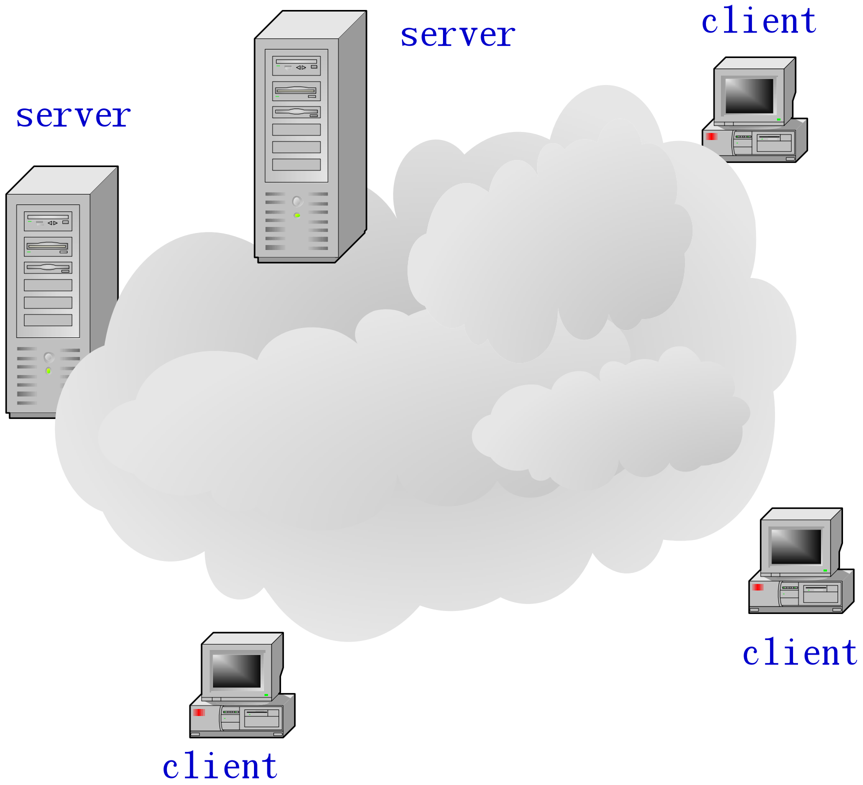


Computers are faster and cheaper



Client-Server Model

- Clients send request to servers
- Servers finish work and send back response to clients
- Small number of servers serve for large number of clients
- Example: web service

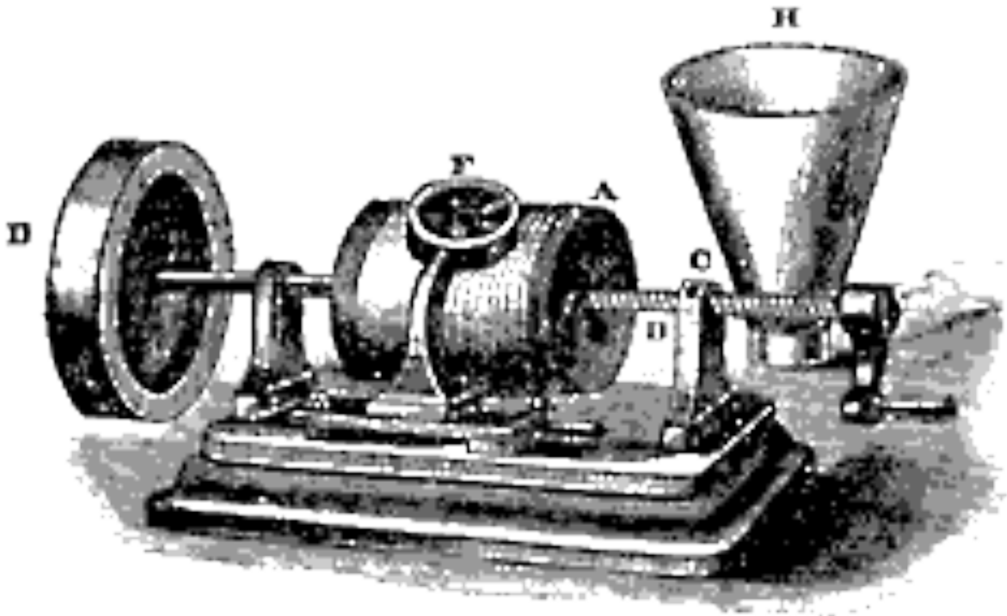


Peer-to-Peer Model

- P2P
  - Link the resources of all peers
  - Resources: storage, CPU cycles, content, etc.
  - All peers are servers and equal – highly scalable
  - All peers are autonomous (different owners)
  - Peers are both clients and servers
- Examples: Napster, Gnutella, KaZaA, Bit-Torrent, E-Donkey…

Why P2P popular…

- 150 years ago…all performance was live!
- If you wanted music, the best way is you do it yourself… and almost everyone did.
- This all changed in 1877.


H
F
A
D
C


I want to see a Phonograph
in every American Home
Thomas A. Edison

Arthur Sullivan: The Lost Chord

I can only say that I am astonished and somewhat terrified at the results of this evening's experiment -- astonished at the wonderful power you have developed, and terrified at the thought that so much hideous and bad music may be put on record forever.

But all the same I think it is the most wonderful thing that I have ever experienced, and I congratulate you with all my heart on this wonderful discovery

London, October 5, 1888





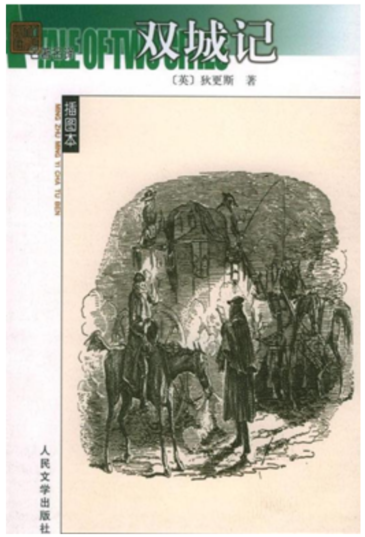

WESTERN UNION
TELEGRAPH
AND
CABLE OFFICE


Culver Pictures, Inc.

BELL SYSTEM

"People mutht be amuthed. They can't be alwayth a learning, nor yet they can't be alwayth a working, they an't made for it."

Mr. Sleary,
in Charles Dickens'
Hard Times, Book 3, Chapter 8,
1834

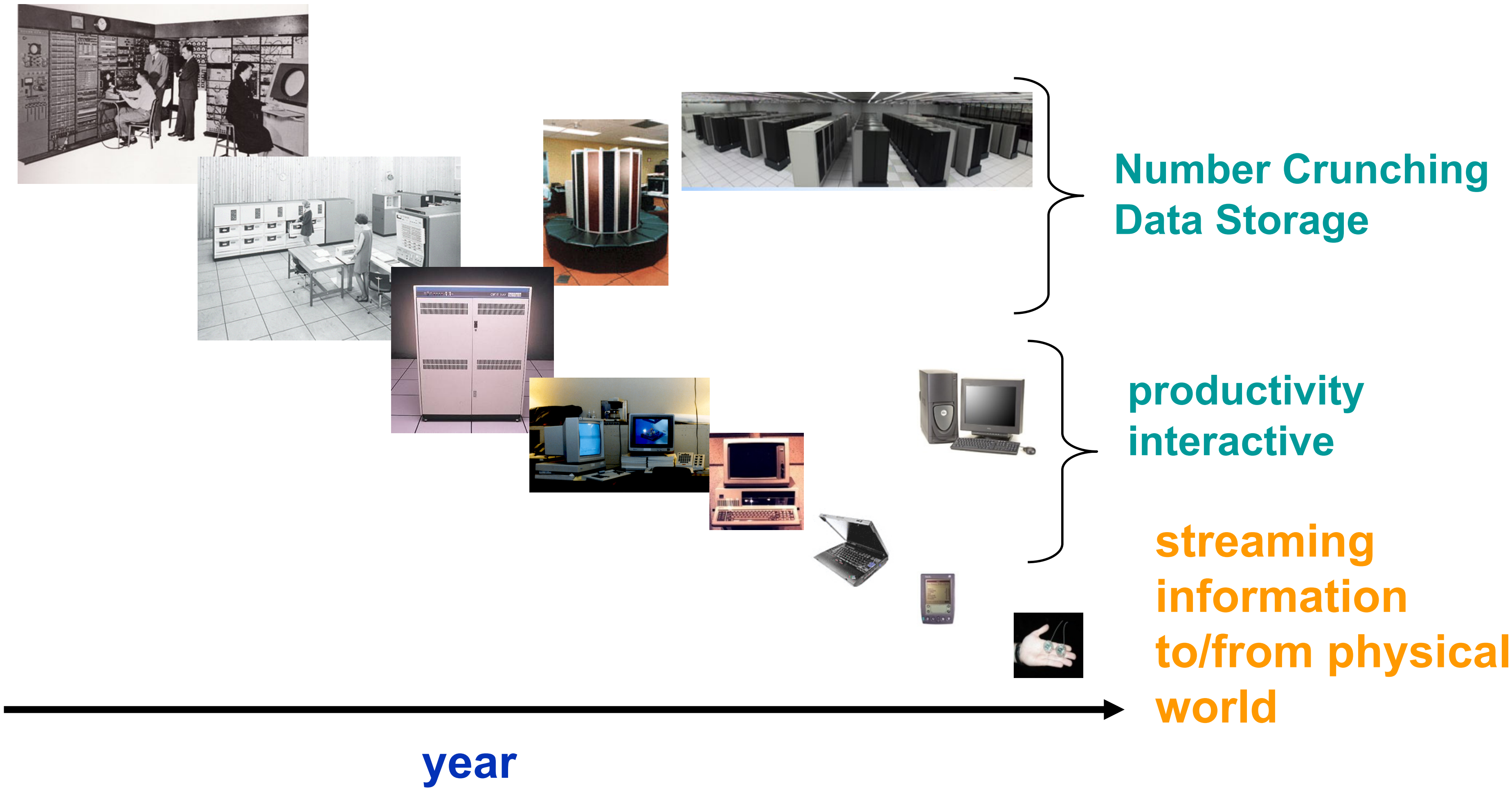


Pervasive Computing

Mark Weiser 1988

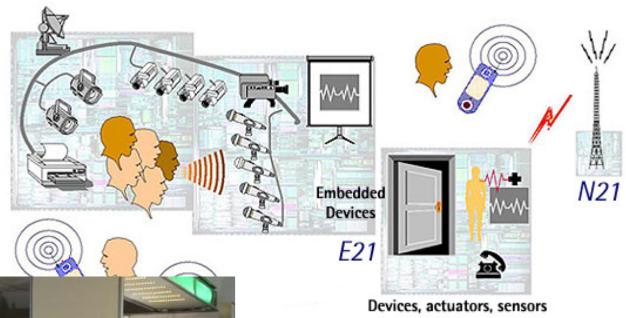
- From Mark Weiser's paper
  - …making many computers available throughout the physical environment, but making them effectively **invisible** to the user.
  - The most profound technologies are those that disappear.
  - **4A** Service: **A**nytime, **A**nywhere, **A**ny device, **A**ny data!!

Where Computing is Done



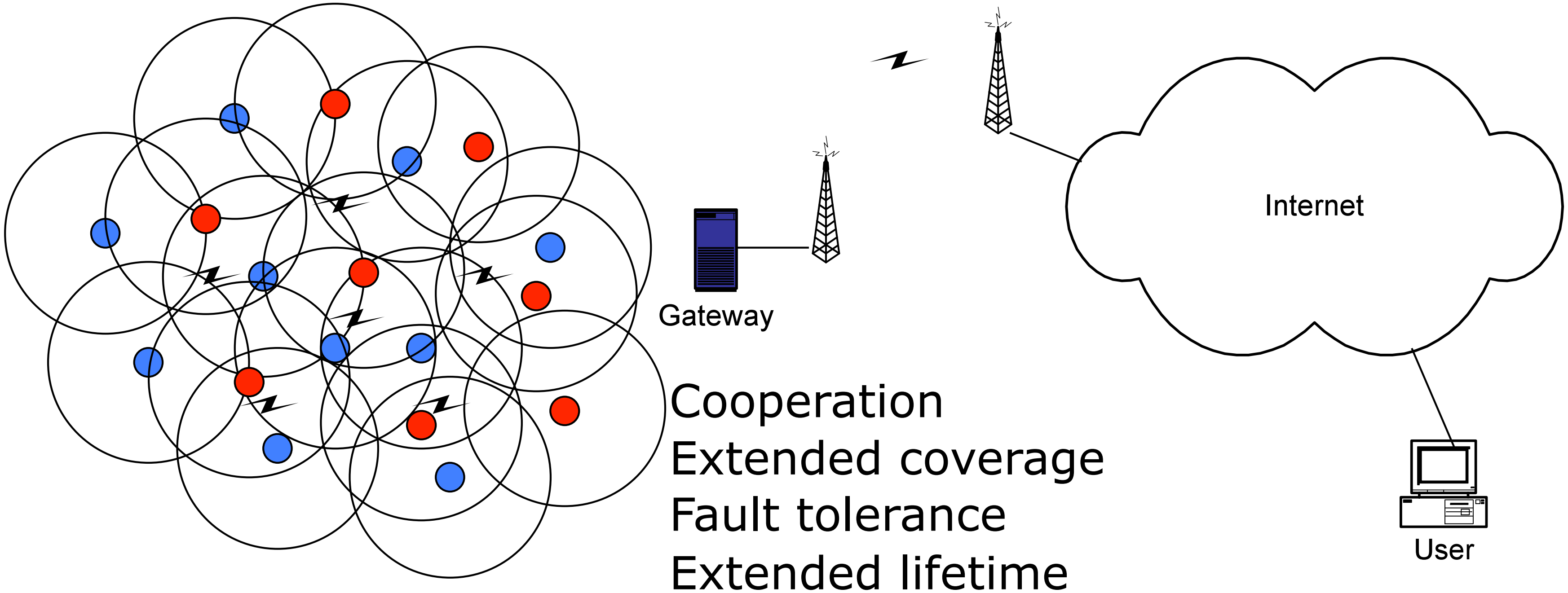
Many Active Projects

- MIT Oxygen Project
- Microsoft EasyLiving
- Stanford Interactive Workspaces Project
- IBM Blue Space
- IBM Dream Space
- …



What is a WSN?

- Wireless Sensor Network (WSN) is a wireless network consists of hundreds or even thousands of sensors



Cooperation
Extended coverage
Fault tolerance
Extended lifetime

China National Strategic Plan

"Sensing China": national focus!

IoT V.S. Sensor Network

Instrumented:
Every item has an address

Interconnected:
Every item communicates

Intellectual:
Every item can be controlled

Not every item has sensing ability…

Research Projects at our Group

1, Coal Mine Monitoring

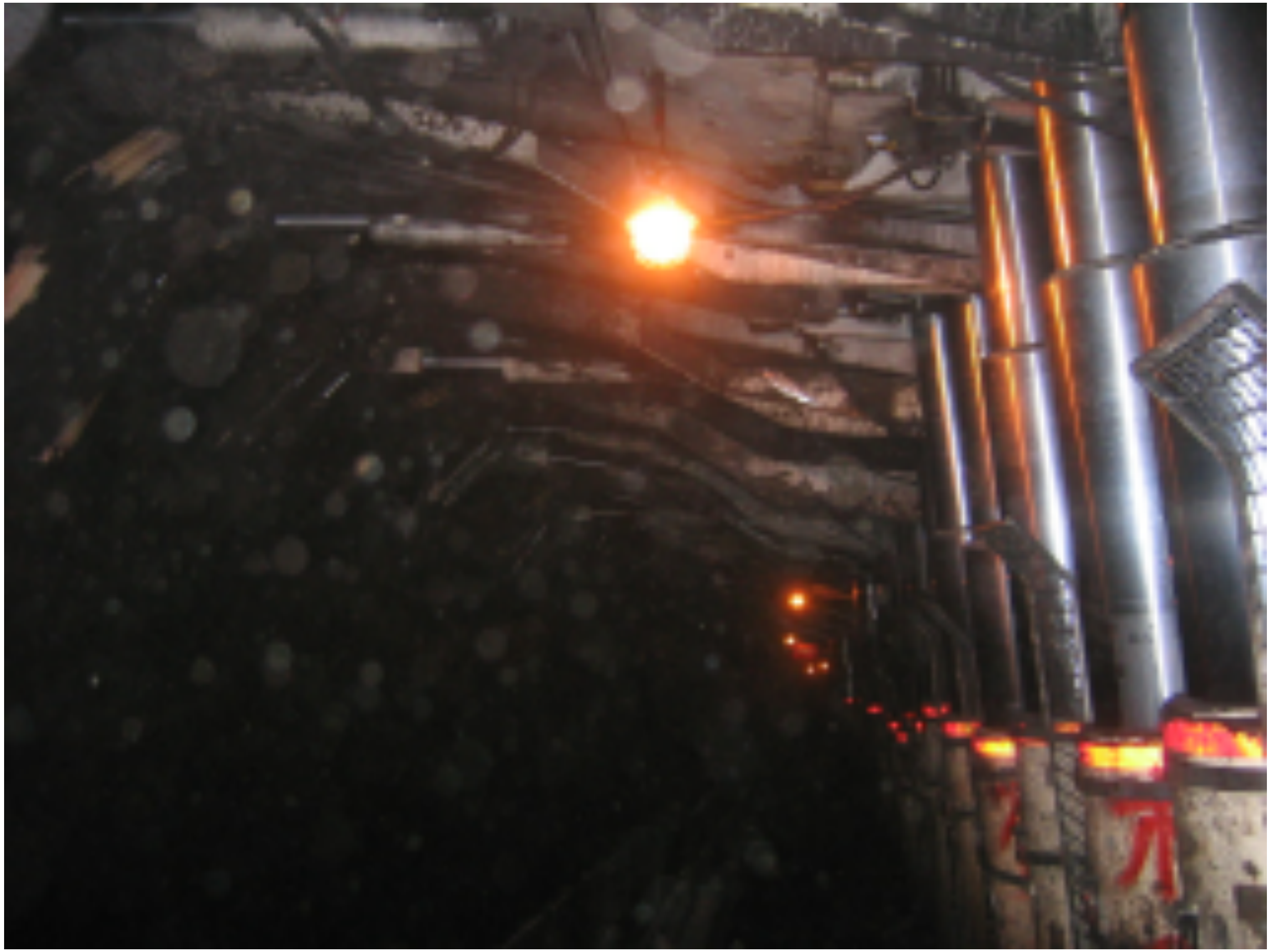
Across the desert (2004-2005)

Ready to go (2005)

14 kilometer dark tunnel (D.L. Coal Mine)

Mining Machines

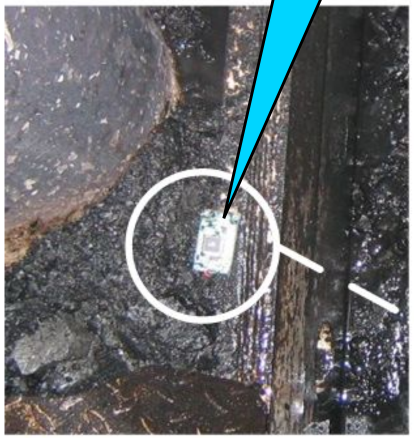
Mining Field

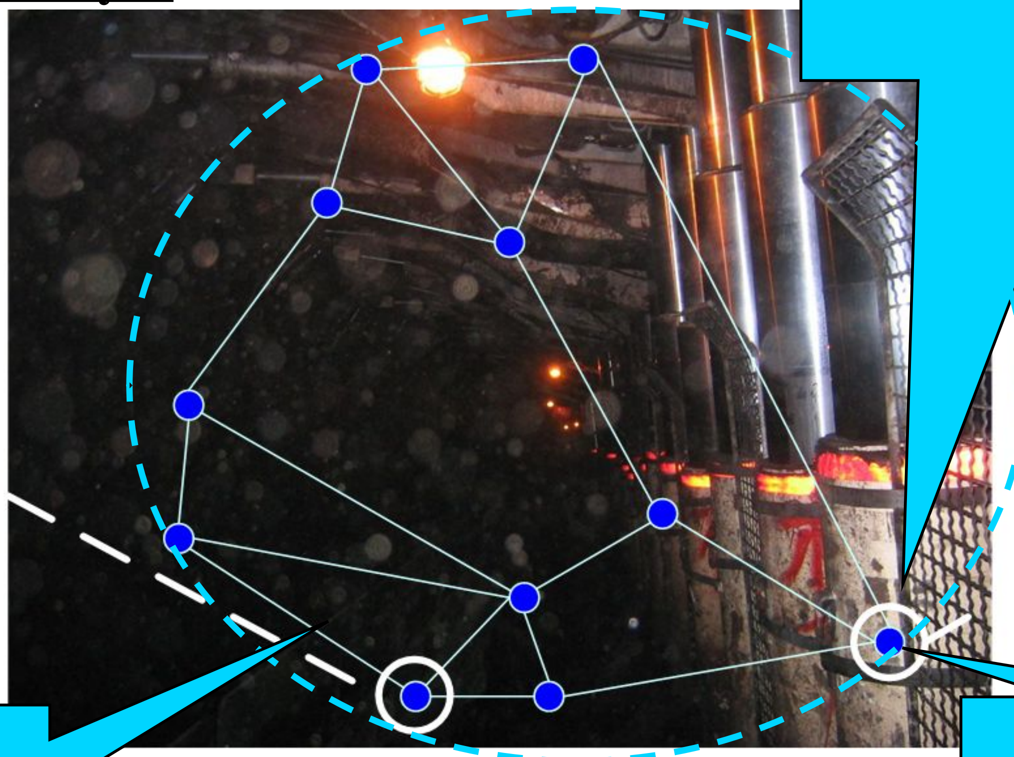


Issues Addressed

Energy Efficiency

Reliable Routing
Multi-Sink Deployment
Geocasting





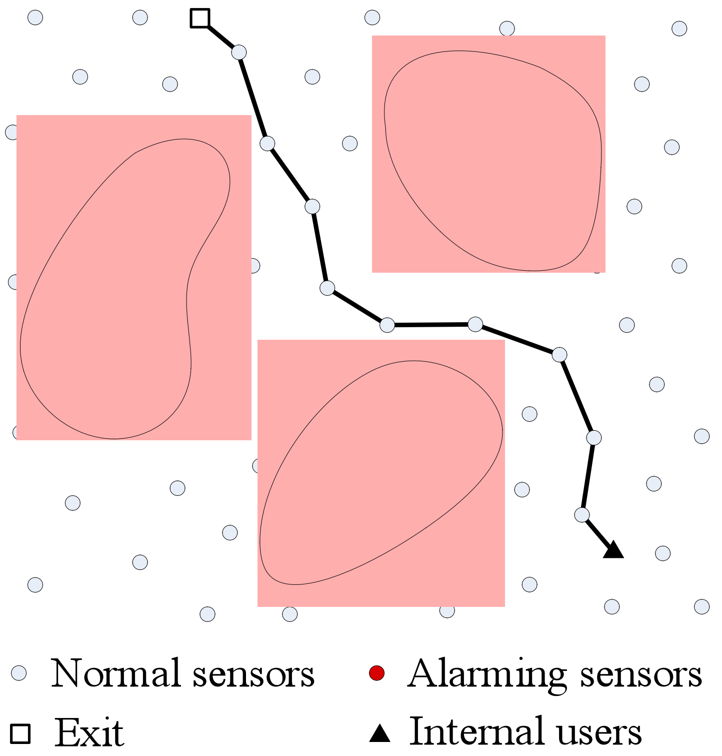
Location Sensing
Human Navigation

27 node WSN Prototype

Data Aggregation
Compression Event Detection

Human navigation

- Navigate human beings out of field of emergent events
  - gas leakage, fire, water seepage, etc.



Human navigation

- Human navigation v.s. packet routing
  - packet loss
    - retransmission
    - human loss?
  - multipath routing
    - packet copies
    - human clone?
  - opportunistic routing
    - wireless multicast
    - human multicast?

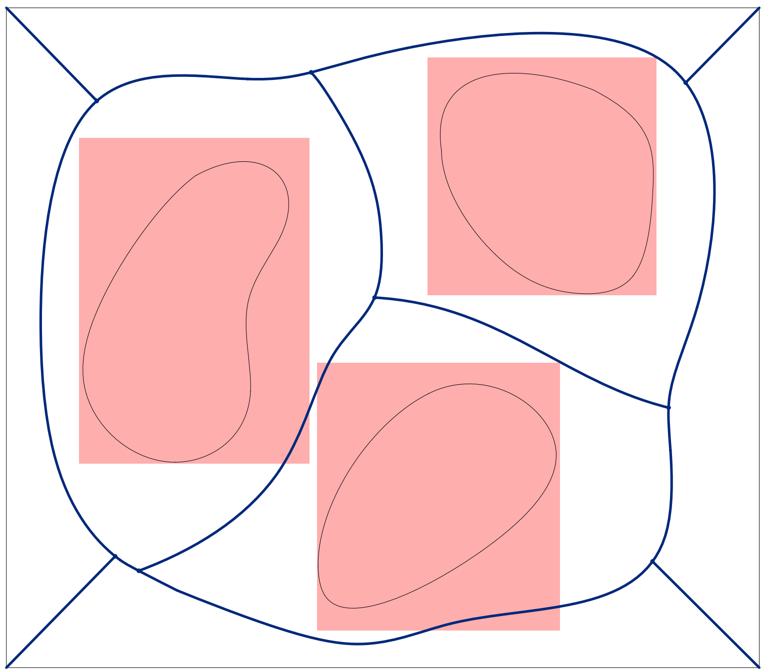
Human navigation

- Human movement v.s. packet delivery
  - limited human speed
  - dynamic conditions

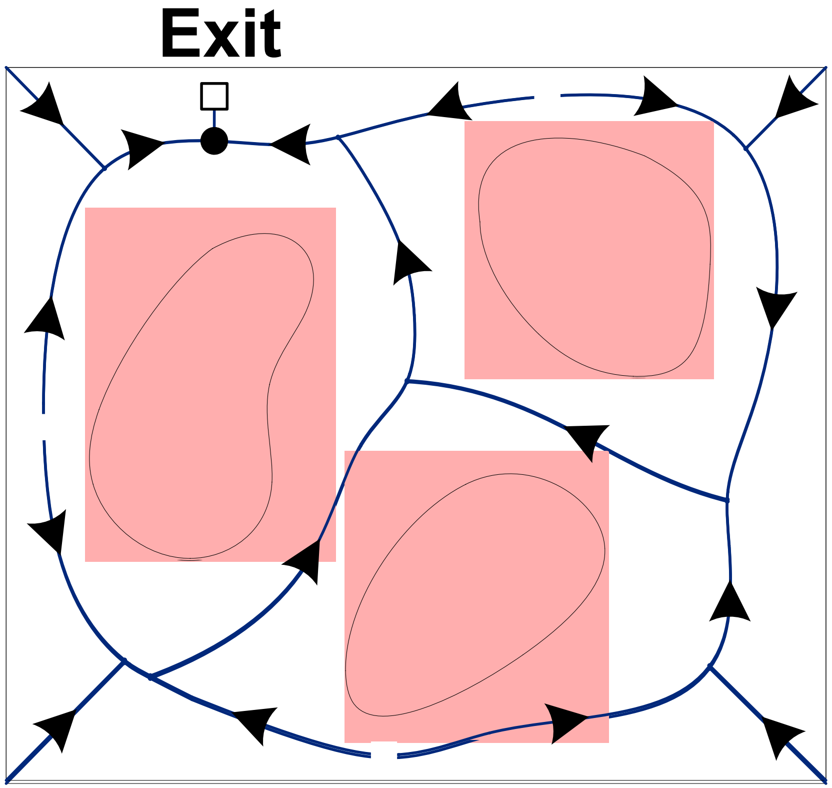
Human beings may even move backwards to seek for safe paths.

Navigation on a road map

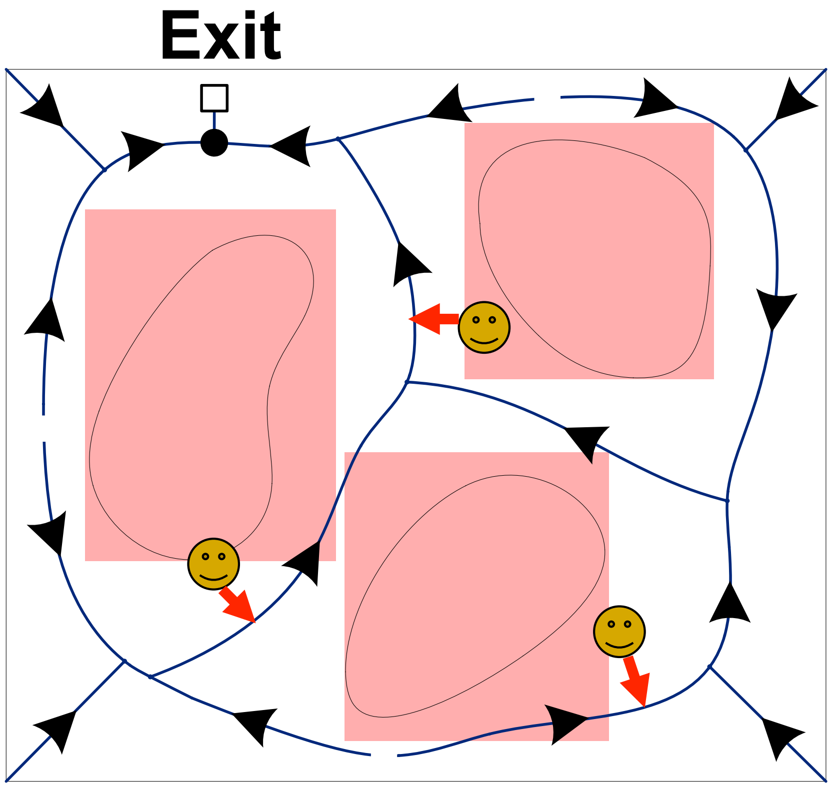
- Building the road map



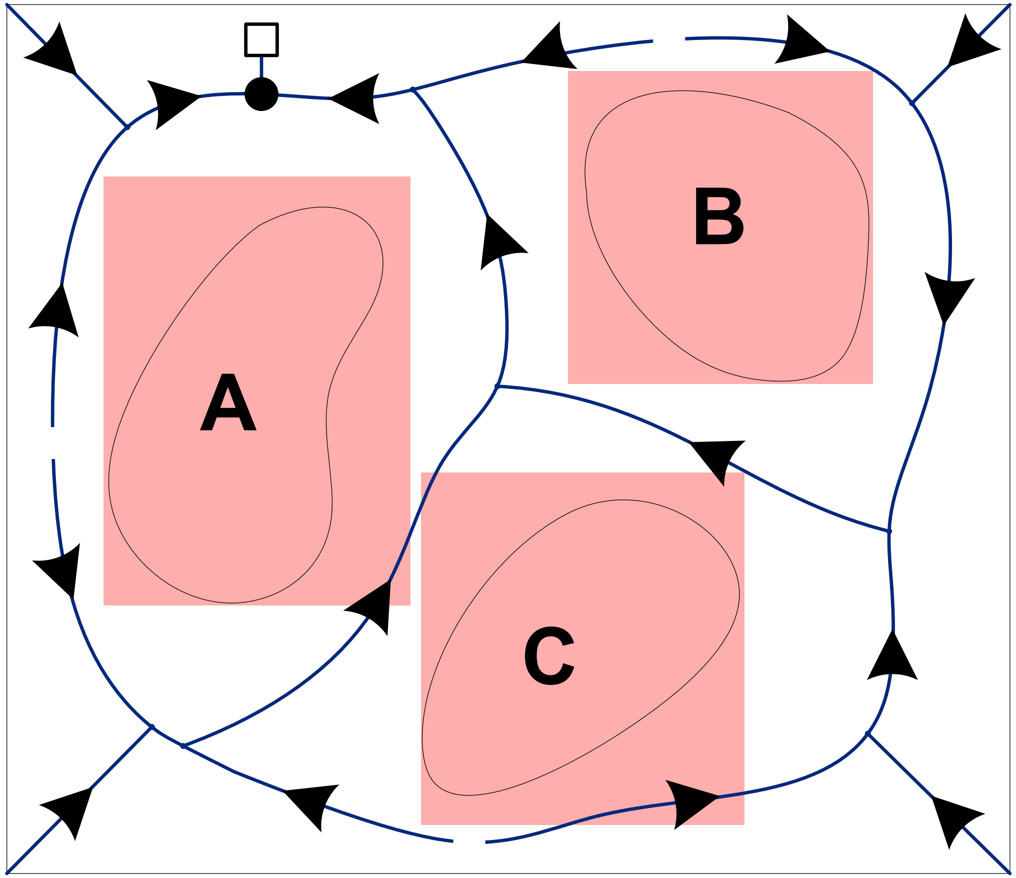
Navigation on a road map



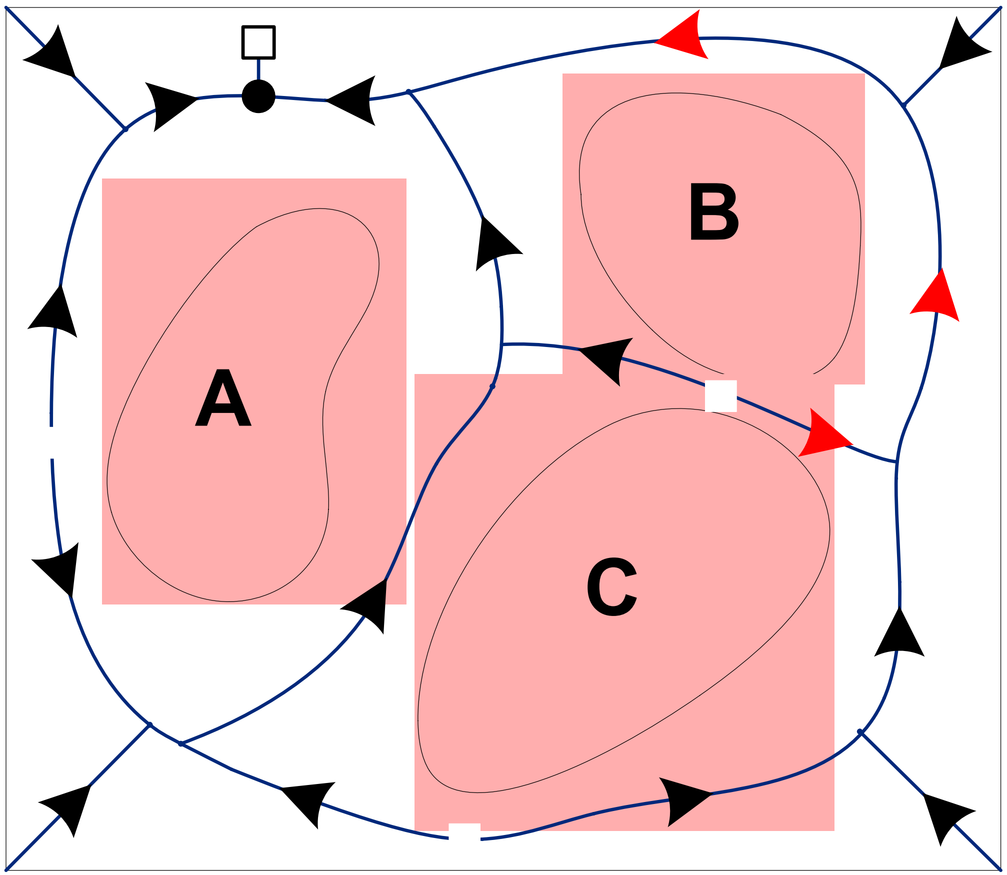
Navigation on a road map



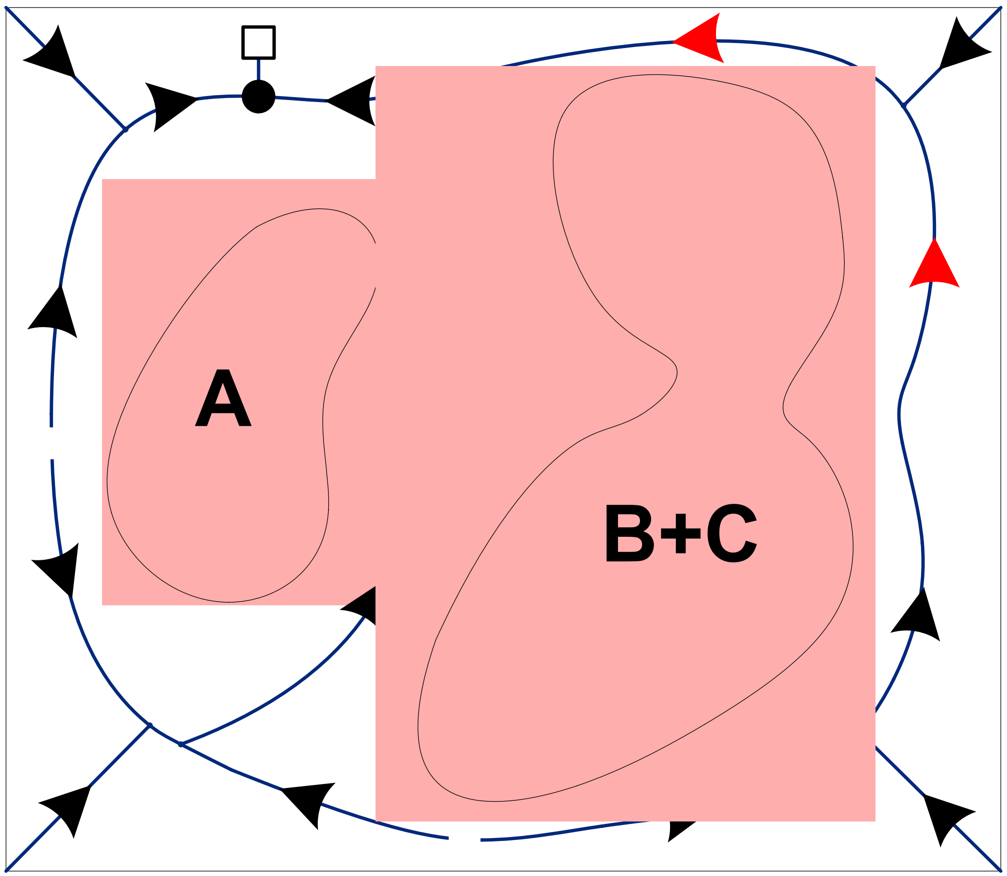
Maintenance of the road map



Maintenance of the road map



Maintenance of the road map



Publications

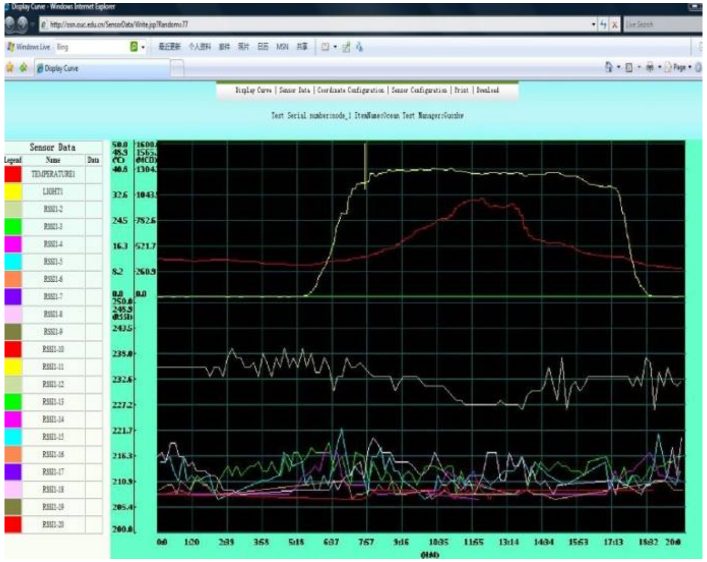
- Mo Li, and Yunhao Liu, "Rendered Path: Range-Free Localization in Anisotropic Sensor Networks with Holes", **IEEE/ACM Transactions on Networking**
- Mo Li, and Yunhao Liu, "Underground Coal Mine Monitoring with Wireless Sensor Networks", **ACM Transactions on Sensor Networks**
- Mo Li, Yunhao Liu, and Lei Chen, "Non-Threshold based Event Detection for 3D Environment Monitoring in Sensor Networks", **IEEE Transactions on Knowledge and Data Engineering**
- Mo Li, Yunhao Liu, Jiliang Wang, and Zheng Yang, "Sensor Network Navigation without Locations", **IEEE INFOCOM**
- Mo Li and Yunhao Liu, "Rendered Path: Range-Free Localization in Anisotropic Sensor Networks with Holes", **ACM MobiCom**
- Mo Li and Yunhao Liu, "Underground Structure Monitoring with Wireless Sensor Networks", **ACM/IEEE IPSN**

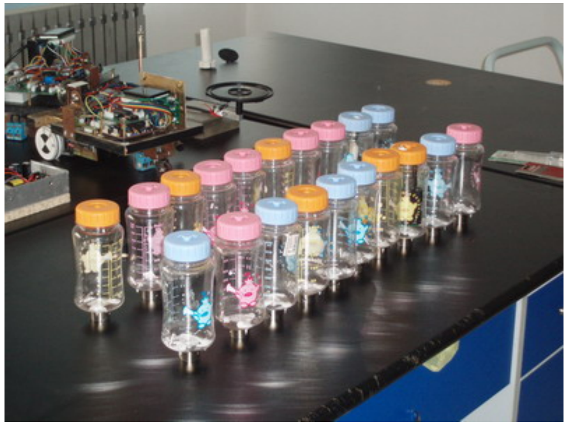
Best Innovation & Research

2，OceanSense

OceanSense Project (07-08)

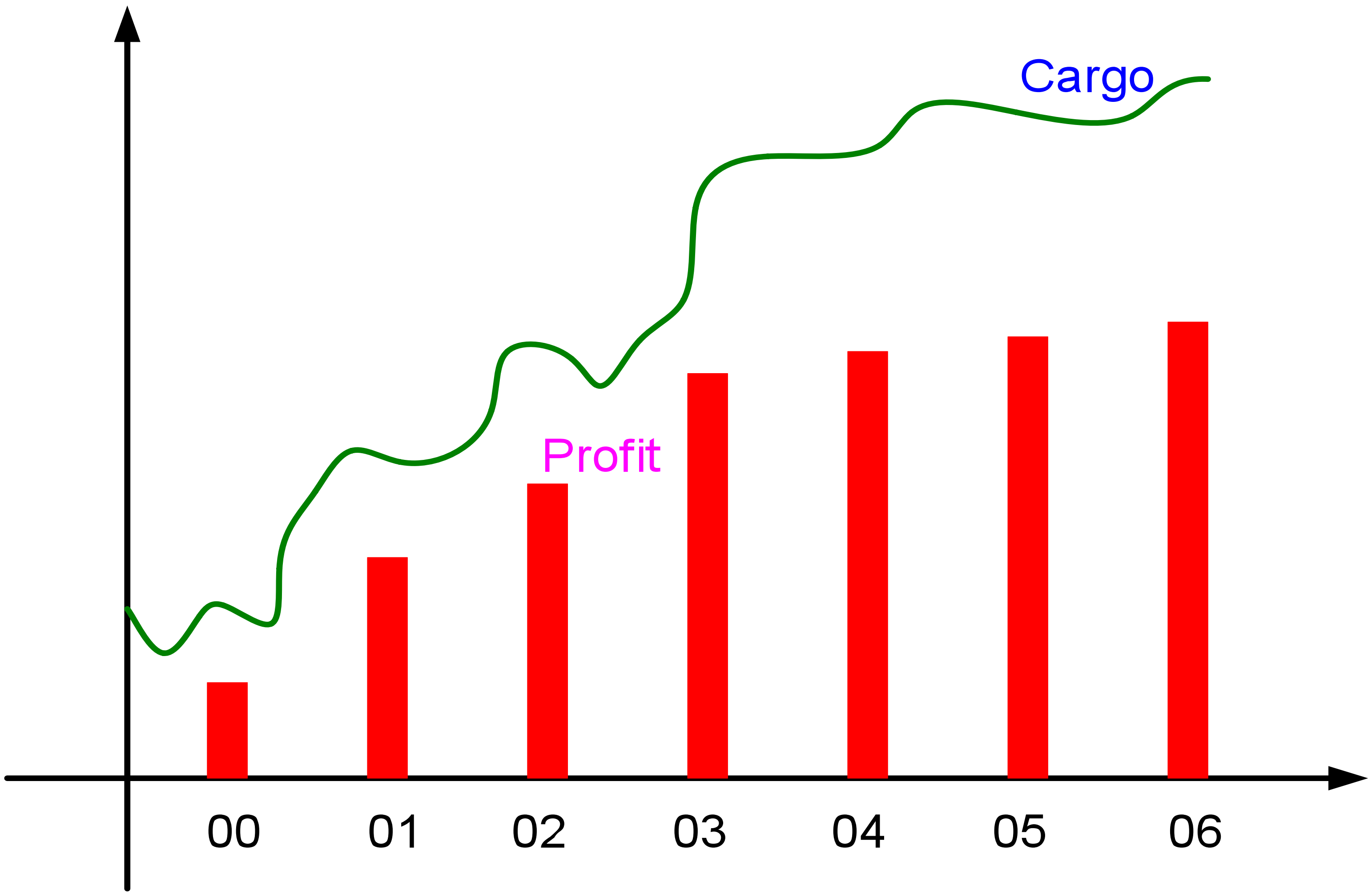
- The first sea environment motoring sensor network system in China
  - More than 120 sensor nodes
  - Temperature, Light, Sea depth and the like
  - More than one year duration
  - Deployed on the Yellow sea near Qingdao

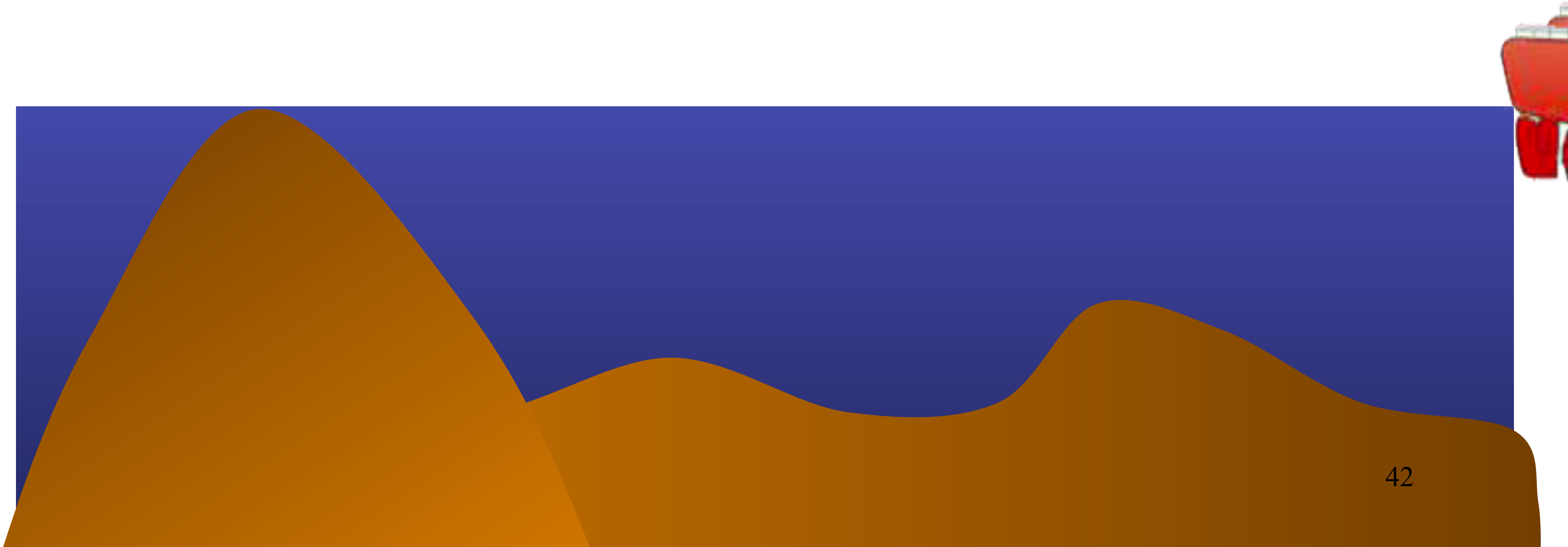


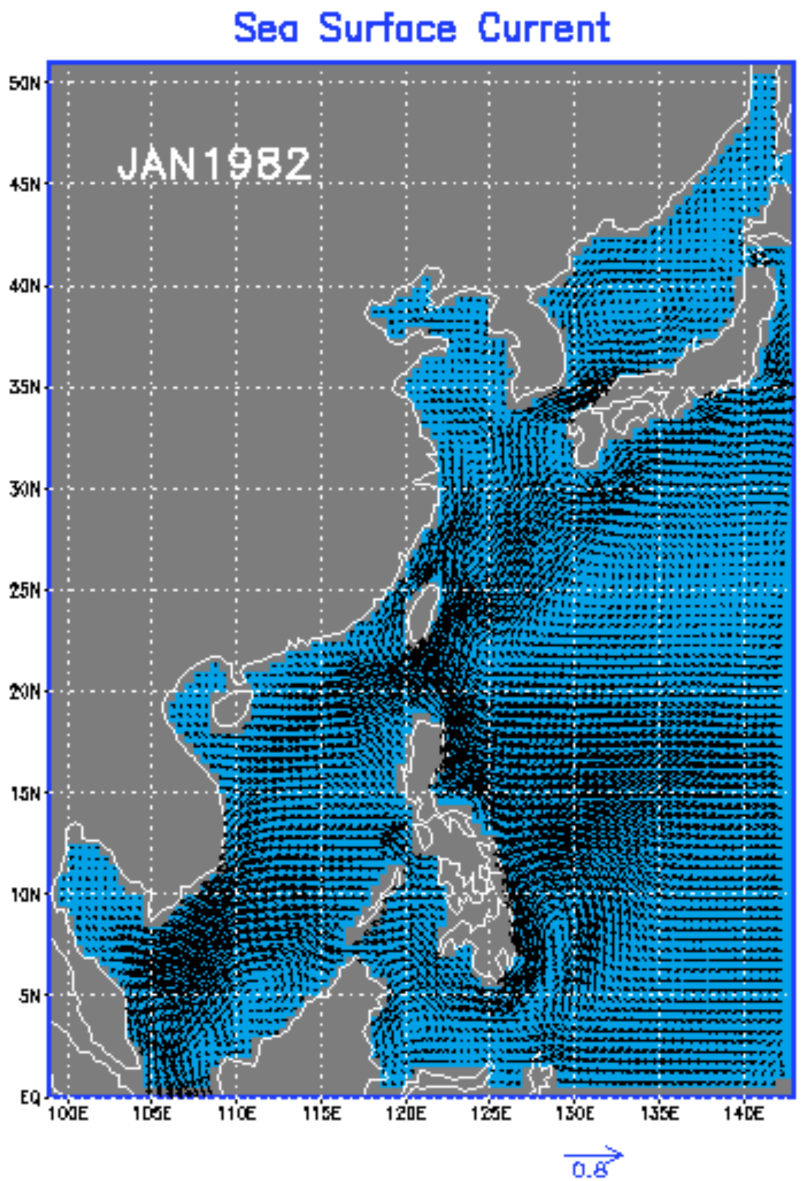


Sea Monitoring

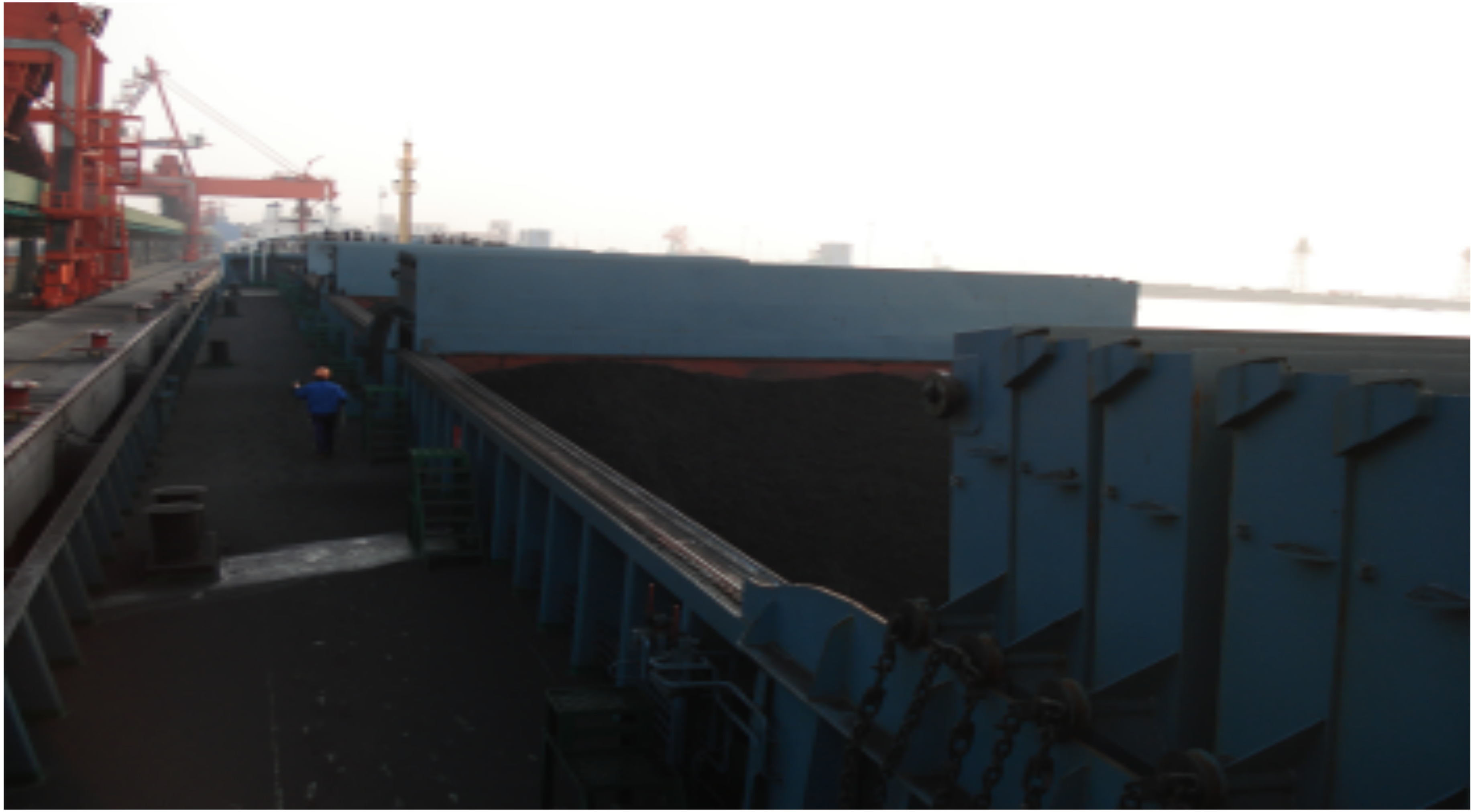
Where is money



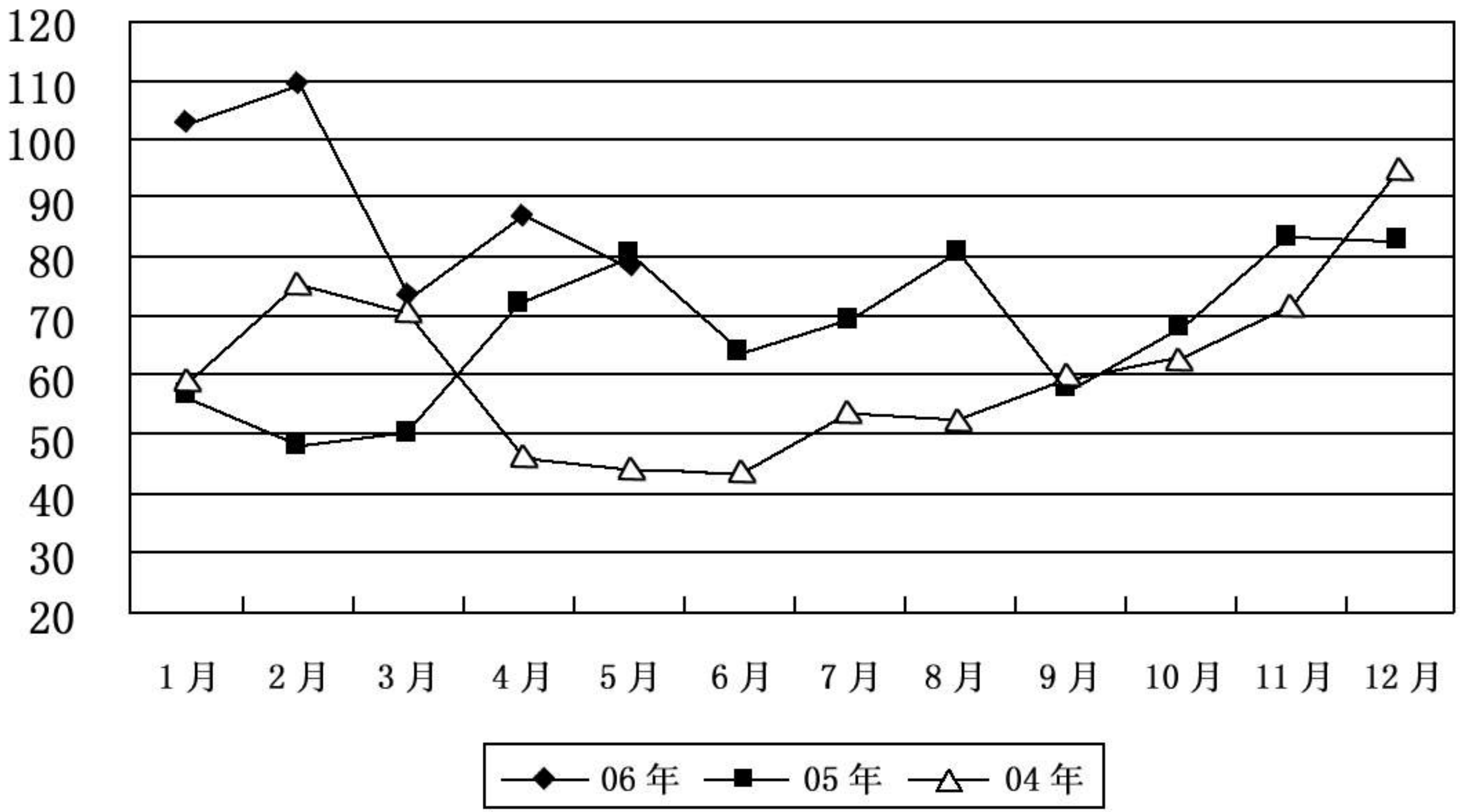



Sea Surface Current
JAN1982
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
100E
105E
110E
115E
120E
125E
130E
135E
140E
0.8

Ships need to wait…



Waiting Time Dominates Profit



Waiting ship; Digging ship; Detecting ship (watch a short video)

Publications

- Jie Lian, Yunhao Liu, K. Naik, and Lei Chen, "Virtual Surrounding Face Geocasting with Guaranteed Message Delivery for Ad Hoc and Sensor Networks", **IEEE/ACM Transactions on Networking**
- Zheng Yang, and Yunhao Liu, "Quality of Trilateration: Confidence based Iterative Localization", **IEEE Transactions on Parallel & Distributed Systems**
- Zheng Yang, Yunhao Liu, XiangYang Li, “Beyond Trilateration: On the Localizability of Wireless Ad-hoc Networks”, **IEEE INFOCOM**
- Shi Li, Yunhao Liu, and XiangYang Li, "Capacity of Large Scale Wireless Networks Under Gaussian Channel Model", **ACM MobiCom** (**Best Paper Award Candidate**)
- Kebin Liu, Mo Li, Yunhao Liu, et al, "Passive Diagnosis for Wireless Sensor Networks", **ACM SenSys**
- Zheng Yang, Mo Li, and Yunhao Liu, "Sea Depth Measurement with Restricted Floating Sensors", **IEEE RTSS**

GreenOrbs 绿野千传

清華大學 Tsinghua University

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

西安交通大學 XI'AN JIAOTONG UNIVERSITY

浙江林学院

杭州電子科技大學 HANGZHOU DIANZI UNIVERSITY

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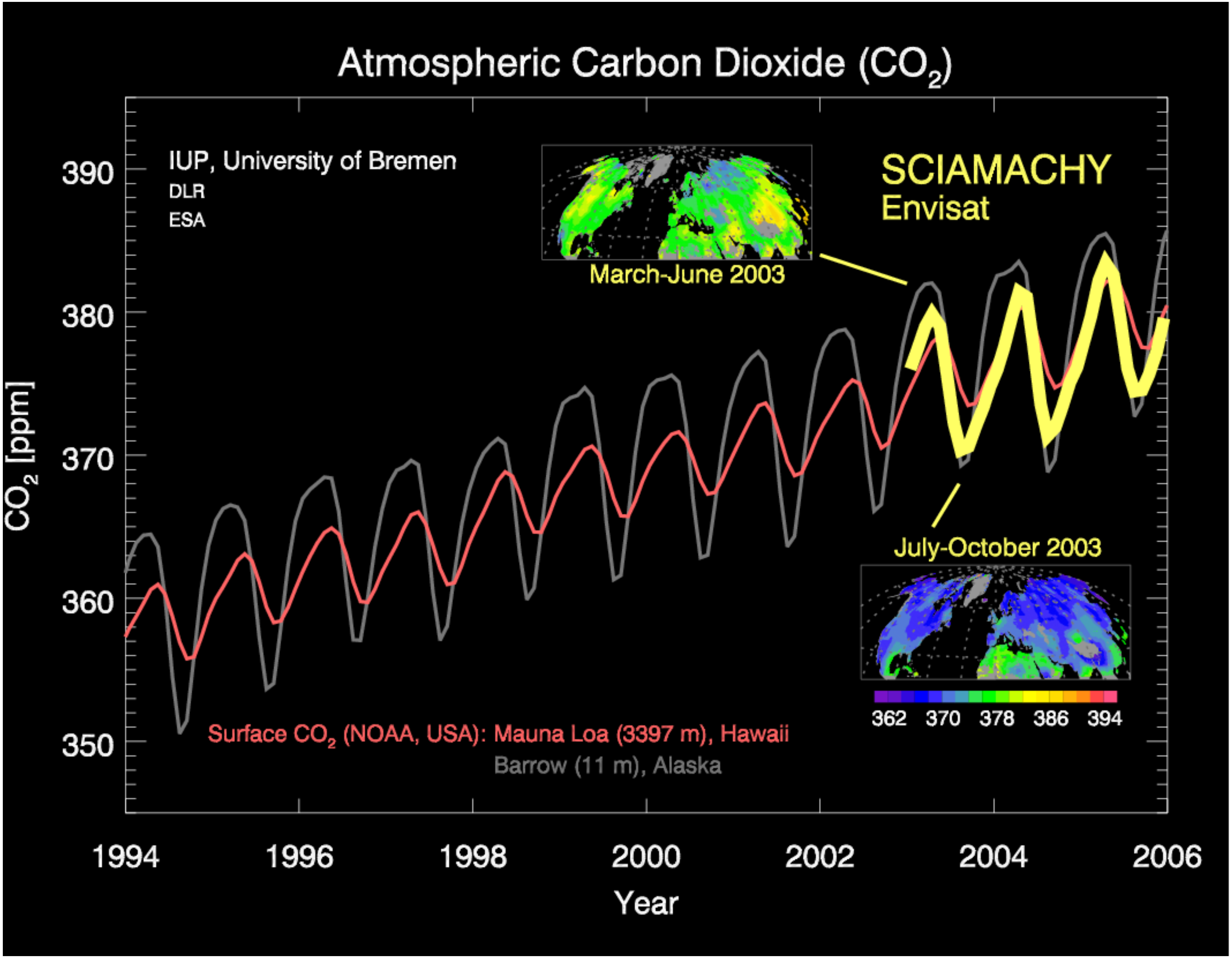
JACK
Columbia



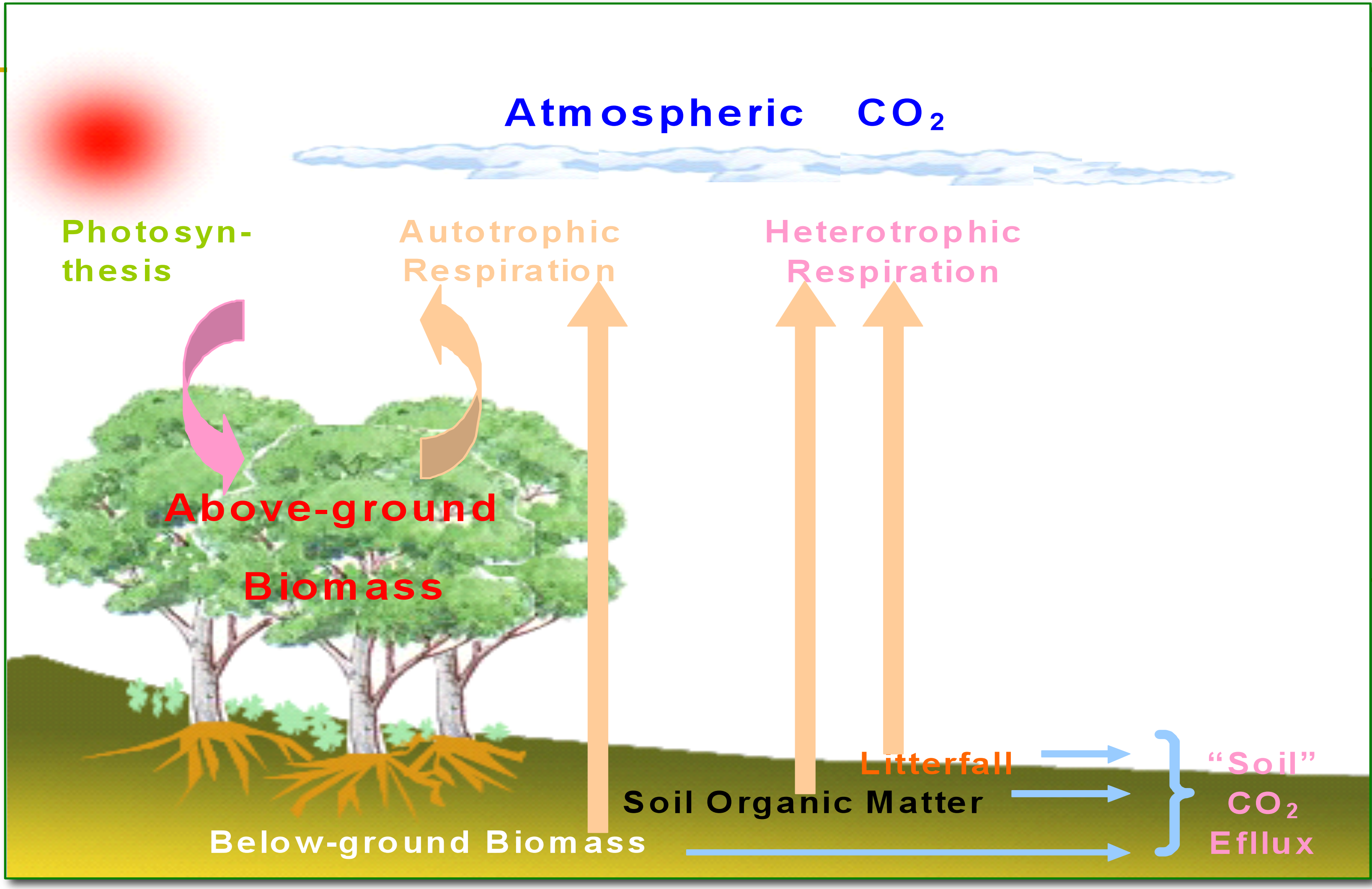
Atmospheric Carbon Dioxide (CO_2)
IUP, University of Bremen
DLR
ESA
SCIAMACHY
Envisat
March-June 2003
July-October 2003
362 370 378 386 394
Surface CO_2 (NOAA, USA): Mauna Loa (3397 m), Hawaii
Barrow (11 m), Alaska
CO_2 [ppm]
390
380
370
360
350
1994 1996 1998 2000 2002 2004 2006
Year

Forestry background

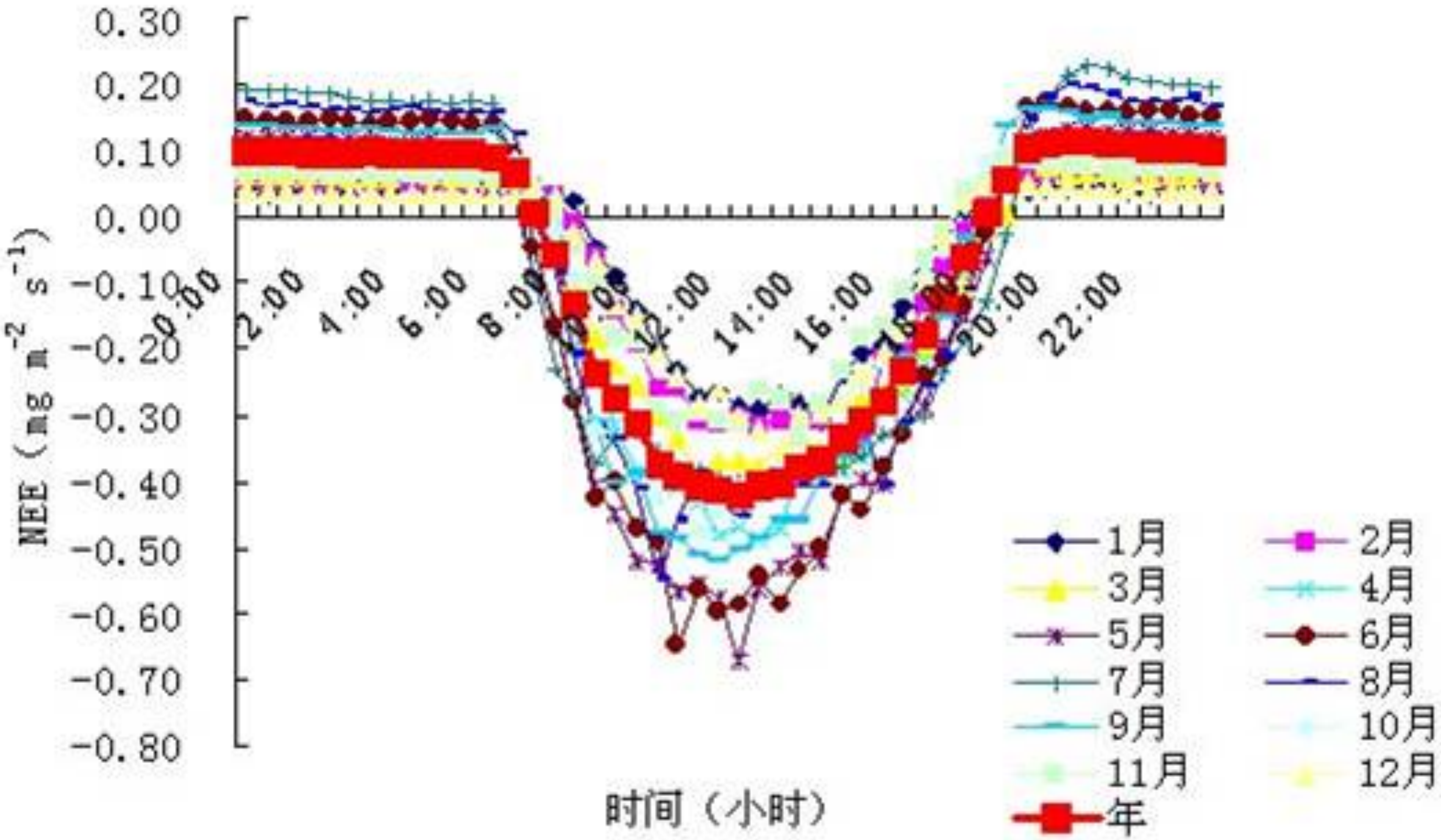
- Global climate change

  "The world has just ten years to bring greenhouse gas emissions under control before the damage they cause become irreversible."

- Forest is "lung of the earth"
  - A critical component in global carbon cycle
  - Significant in resisting natural disasters



Atmospheric CO_2
Photosyn-
thesis
Autotrophic
Respiration
Heterotrophic
Respiration
Above-ground
Biomass
Litterfall
Soil Organic Matter
Below-ground Biomass
"Soil"
CO_2
Efflux



0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
NEE（mg m-2 s-1）
0:00
2:00
4:00
6:00
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
时间（小时）
1月
2月
3月
4月
5月
6月
7月
8月
9月
10月
11月
12月
年

CO_2

Existing WSN Systems

System (Affiliation)	Deployment manner	System Scale	Duration
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

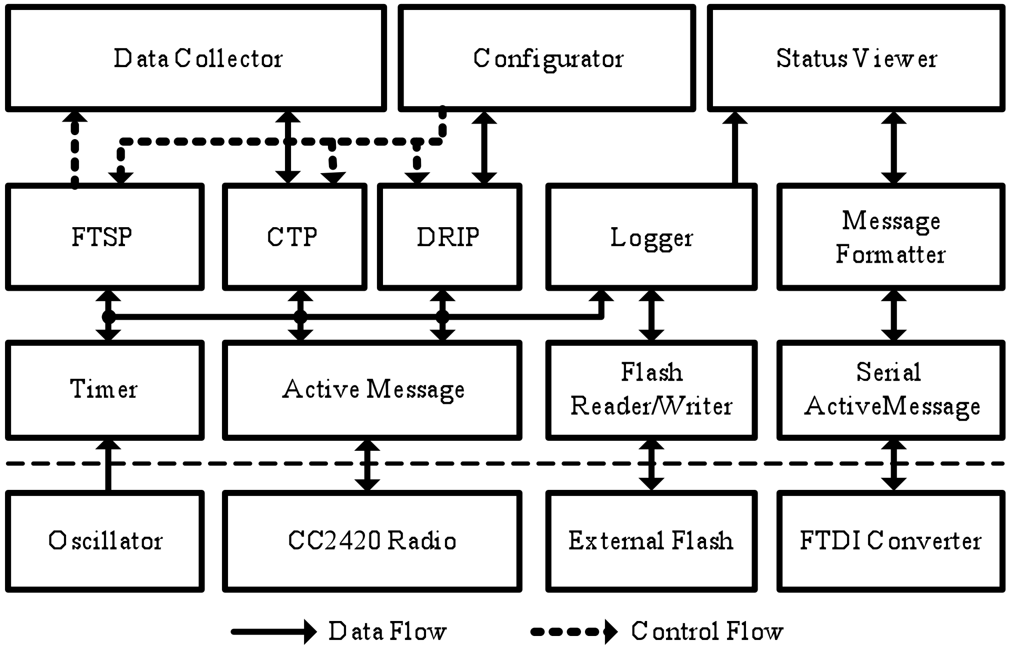
GreenOrbs - building blocks (1)

- 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)

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

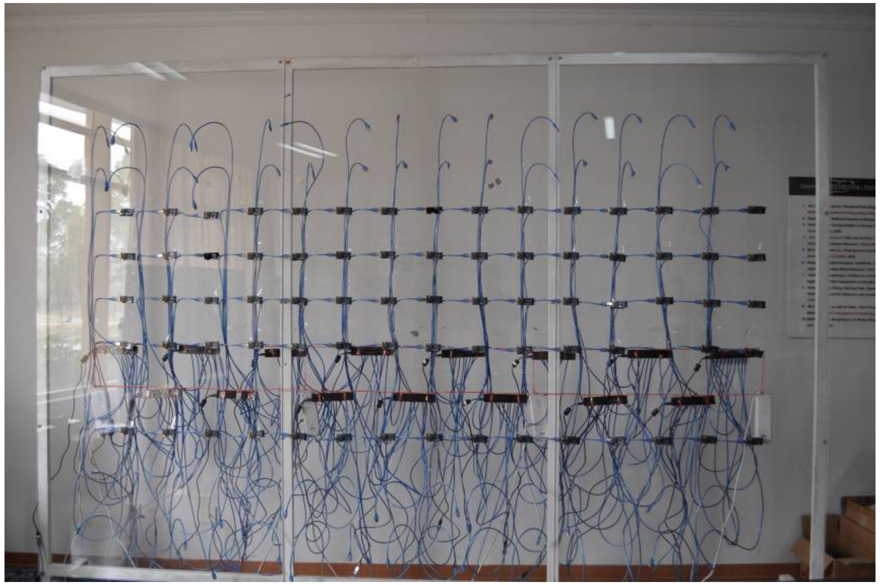


GreenOrbs - deployments

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	Ongoing (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	Ongoing (2009.10~)	~8000mAh, 1.5V	200	~ 20 hops	5%	10 Mbytes

GreenOrbs testbed

- 50~150-node indoor experiments
- High speed serial programming
- Find-grained network configurations
- Testing, debugging, and diagnosis



W200P

HMP45C

A100R

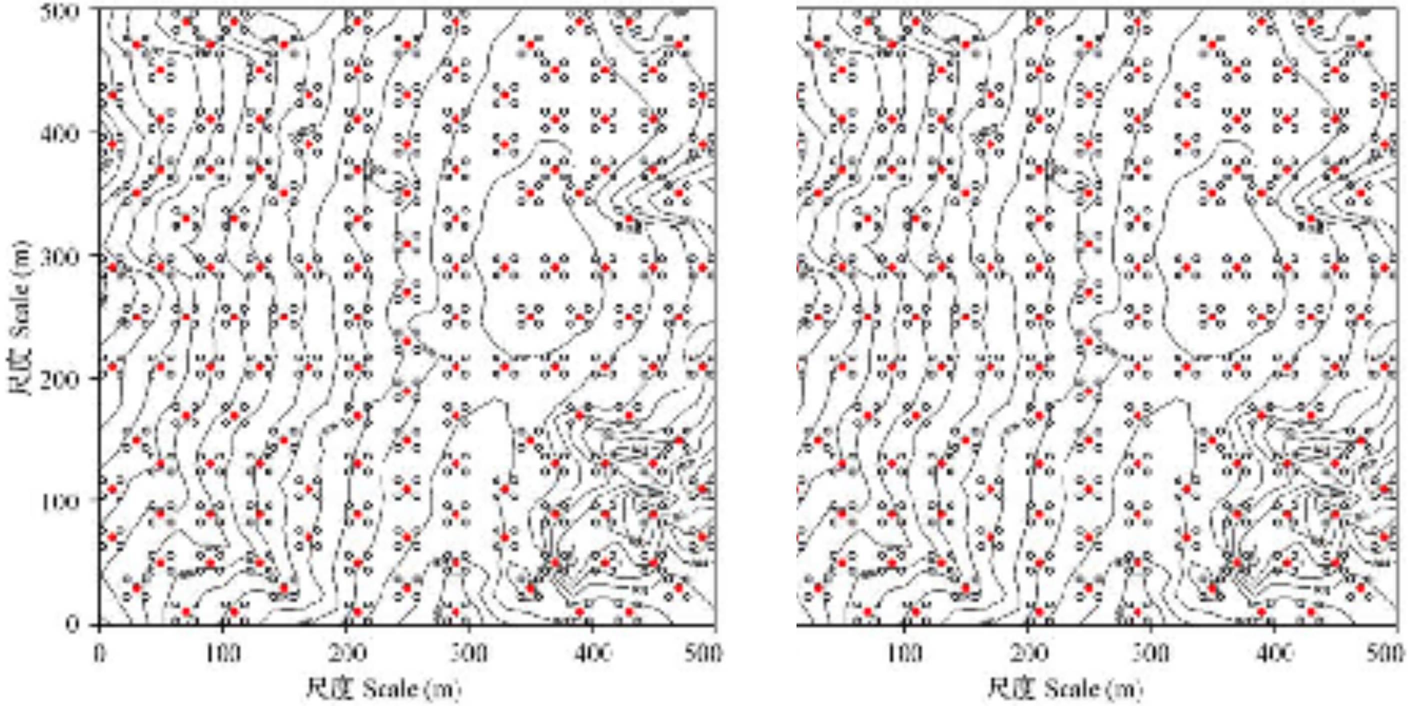
LI820

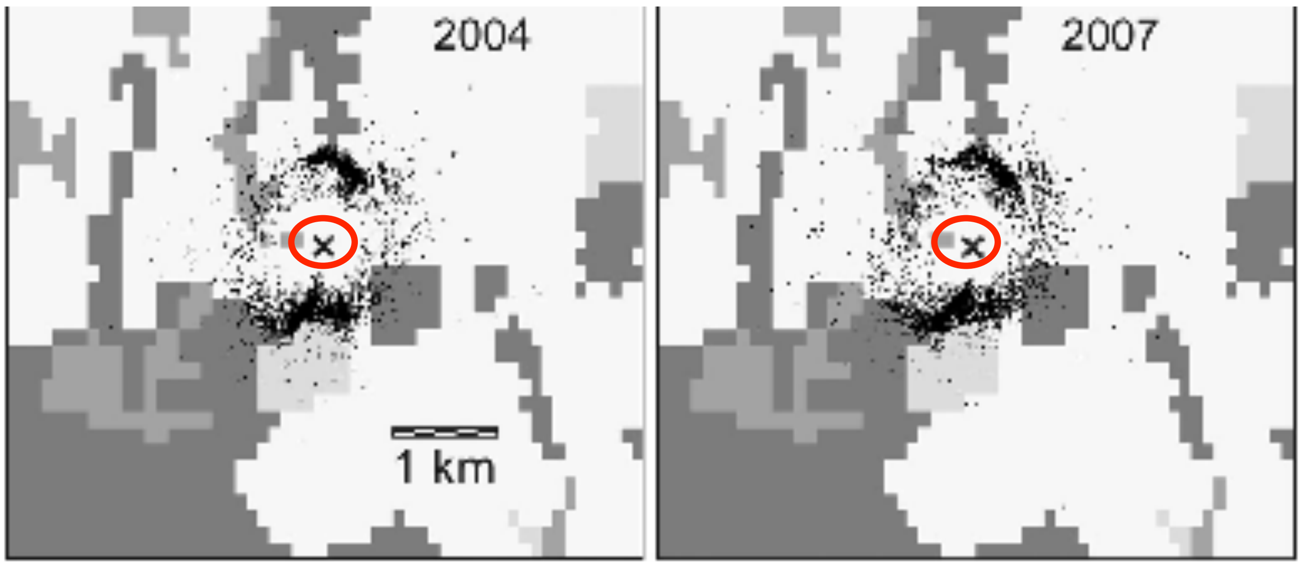
LI6262

CM11, CNR-1, LI190SB

SLSCWA-140

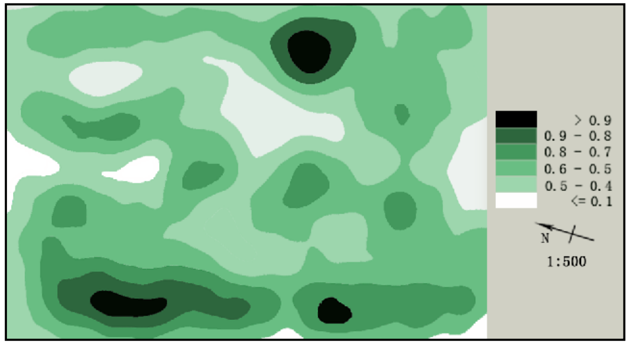
CR5000

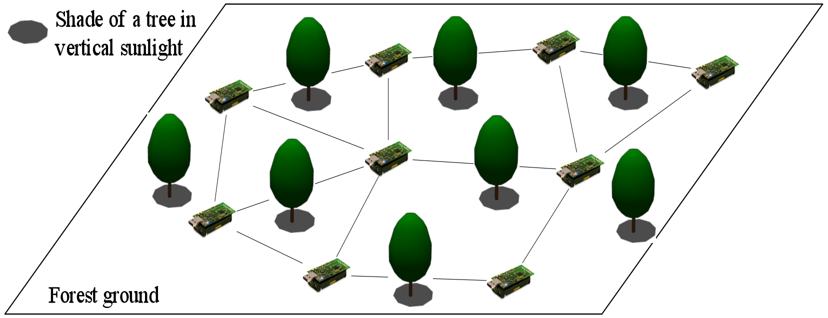

500
400
300
200
100
0
0
100
200
300
400
500
尺度 Scale (m)
尺度 Scale (m)
100
200
300
400
500
尺度 Scale (m)

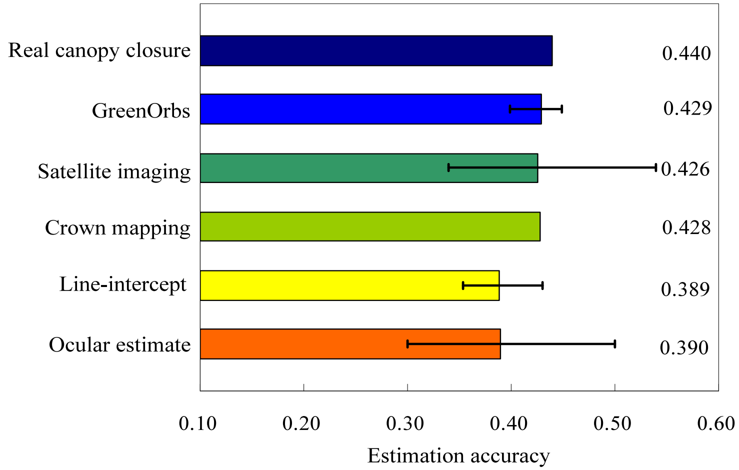

2004
2007
1 km

Canopy Closure Estimates

- Using WSN for forestry measurements



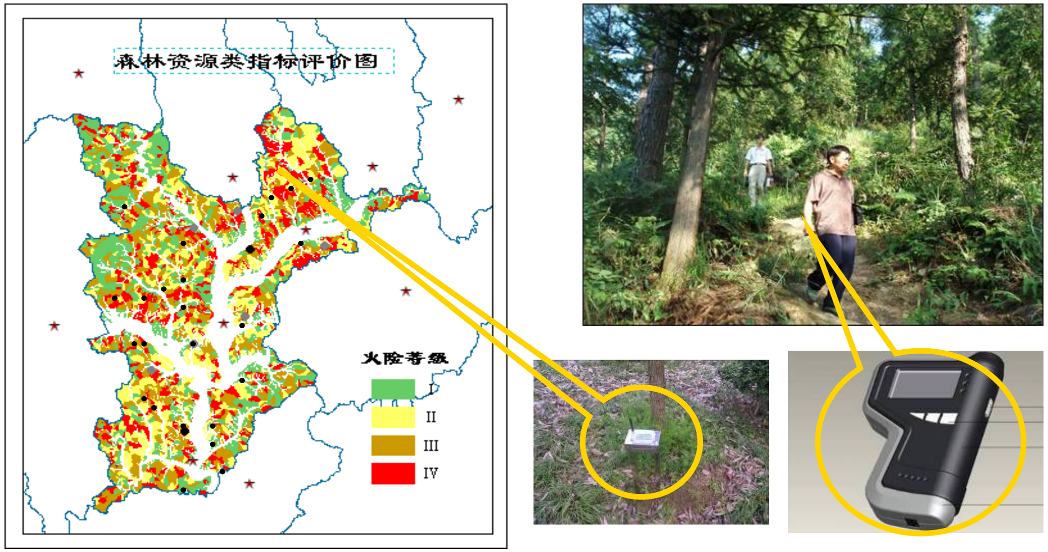




Lufeng Mo, Yuan He, Yunhao Liu, Jizhong Zhao, Shaojie Tang, Xiangyang Li, Guojun Dai, "Canopy Closure Estimates with GreenOrbs: Sustainable sensing in the Forest," **ACM SenSys 2009**.

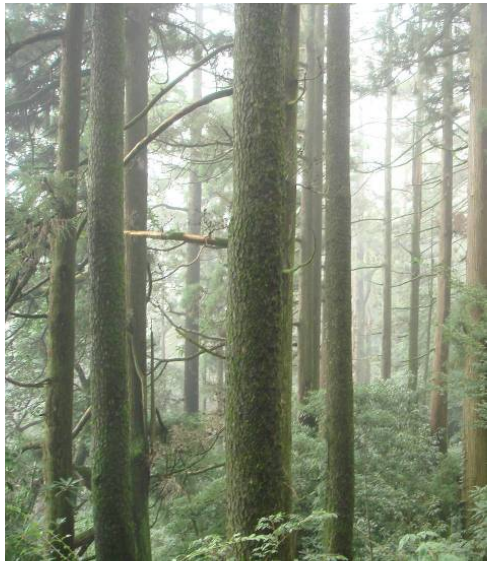
Fire Risk Prediction

- Fire prediction vs. fire detection
- Microscopic vs. macroscopic prediction



Ecological Observation(Video)

- Study on the classical forestry theory of climax community



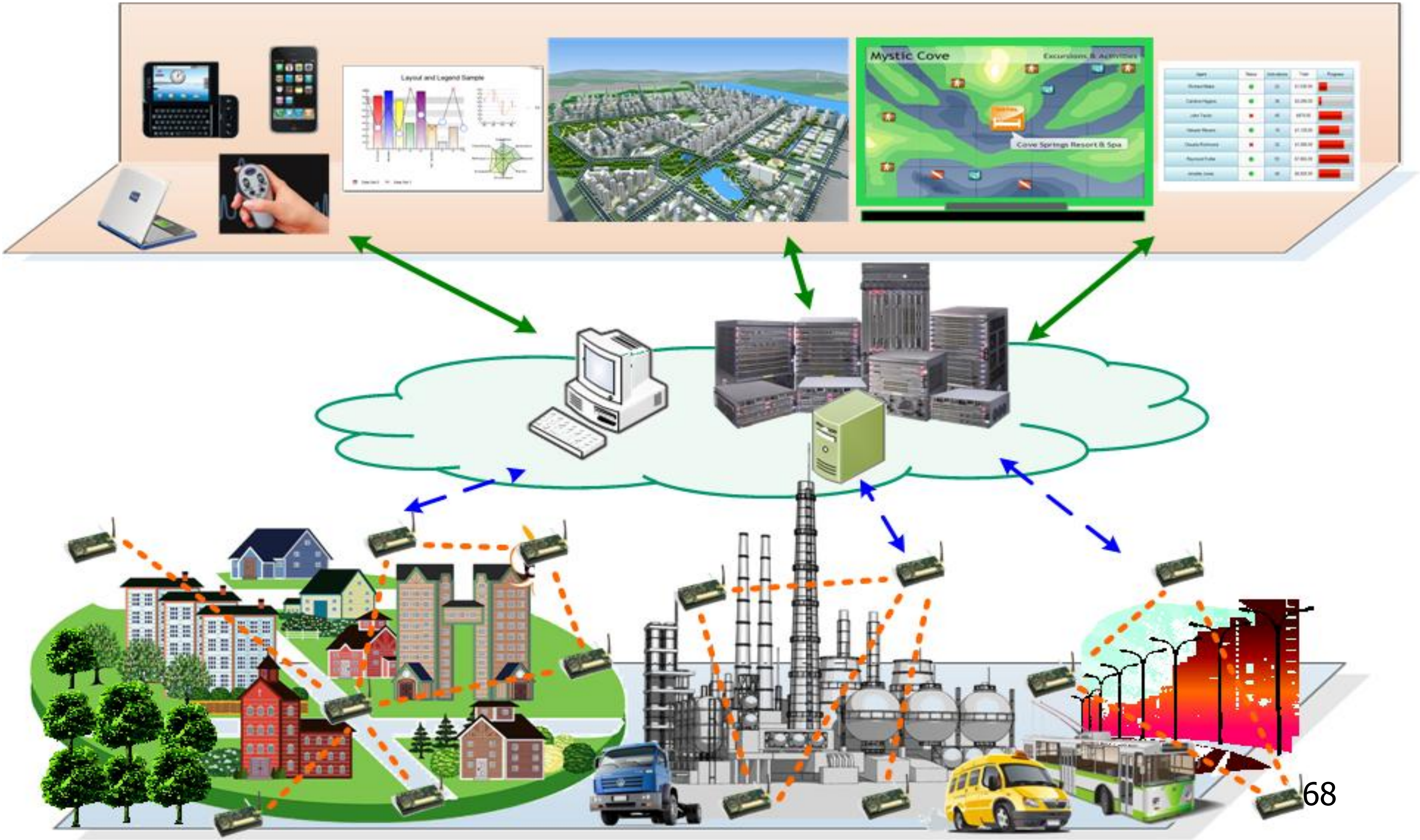

City Forest Planning

- City forest plays the role of
  - Natural cleaning-air machines
  - Noise barriers

Disasters Forecast

- Monitor the environment to forecast disasters like mud-rock flows and floods.

CitySee：City-Wide Urban Sensing



4000 Sensors in a City this year…

CitySee: City-Wide Urban Sensing

- First Phase deployment at Wuxi
  - 1100 nodes with temperature, humidity, light
  - 100 CO2 nodes
  - 4 Mesh nodes
  - 1.2 KM^2
- Missions: ~2011.12
  - 4000+ sensor nodes with temperature/humidity and light sensors
  - 500+ nodes with CO_2 sensor
  - Cover 20KM^2 urban area in Wuxi, China
- Eventually: **10,000 Nodes, 100 KM^2**

CitySee - Monitoring Areas

Power Plant

Industry Zone

Residential Quarter

The Tai Lake

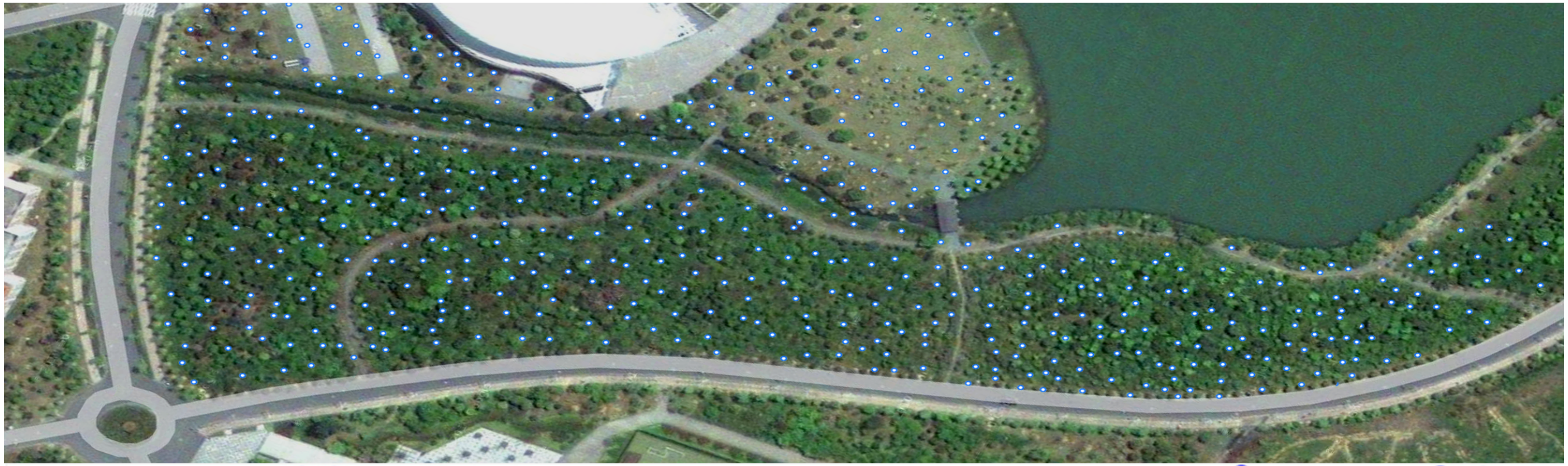
High-tech Park

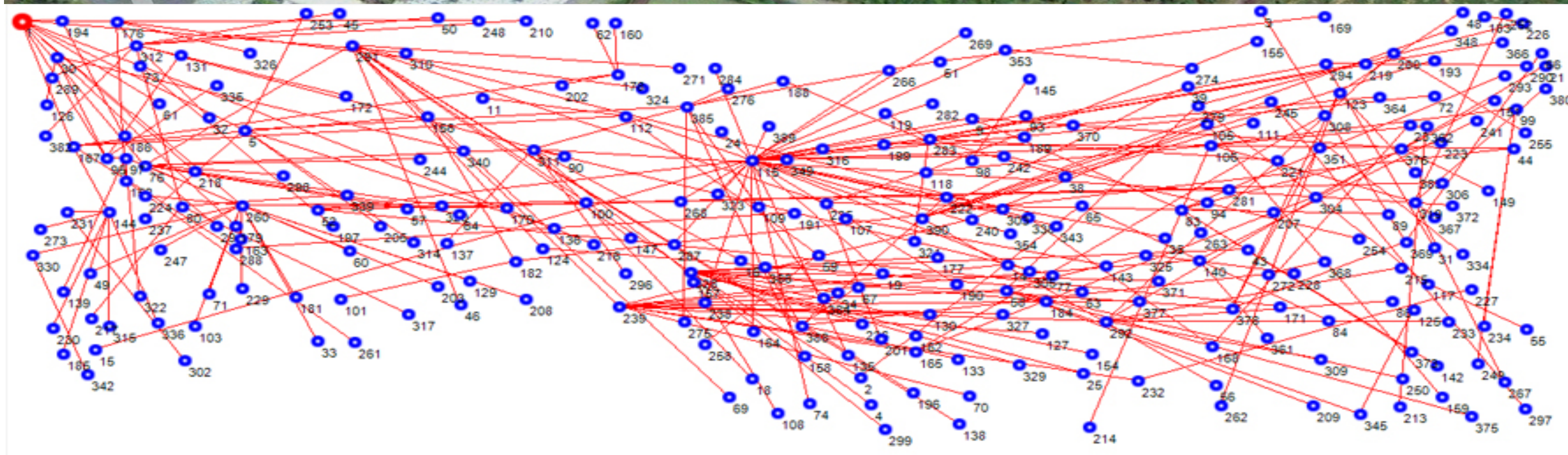
Railway Station

Applications

Environmental monitoring, Carbon sink/emission measurement, pollution detection

1, Measurement Study





72

Data Set

December 2009, 29 consecutive days, 2540000 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 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

Measures

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

What limits the system scale?

- What is the dominant resource that is at the first depleted when the network workload scales?
- Is such resource appropriately used?
- Where are the places of resource depletion that bottleneck the entire network?
- How should existing protocols be improved to adapt to large-scale sensor network characteristics?

Three conjectures

- A small portion of nodes bottlenecks the entire network, and most of the existing network indicators may not accurately capture them
- The network dynamics mainly come from the inherent concurrency of network operations instead of environment changes
- The environment, although the dynamics are not as significant as we assumed, has an unpredictable impact on the sensor network

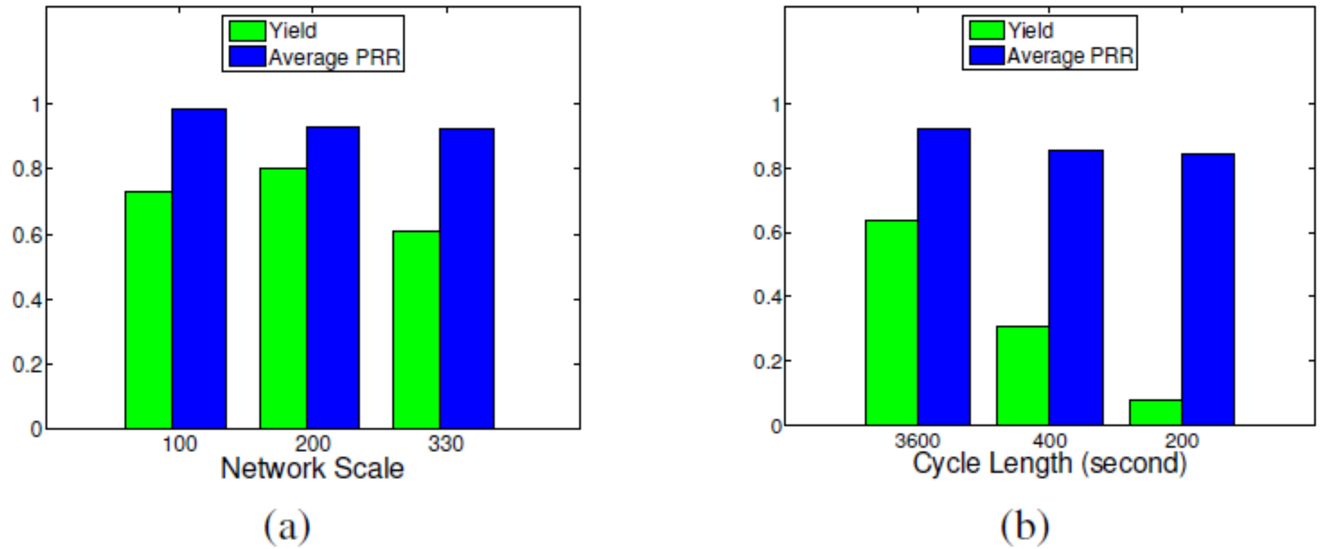
Three conjectures #1

- A small portion of nodes bottlenecks the entire network, and most of the existing network indicators may not accurately capture them

- The network dynamics mainly come from the inherent concurrency of network operations instead of environment changes

- The environment, although the dynamics are not as significant as we assumed, has an unpredictable impact on the sensor network

Does sink hole exist?

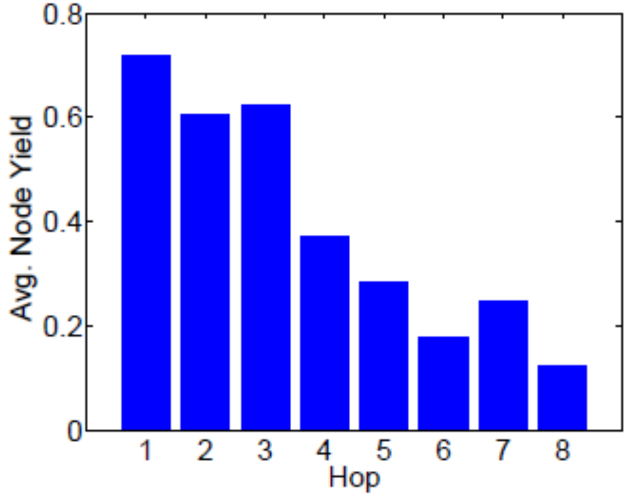


Network yield and PRR

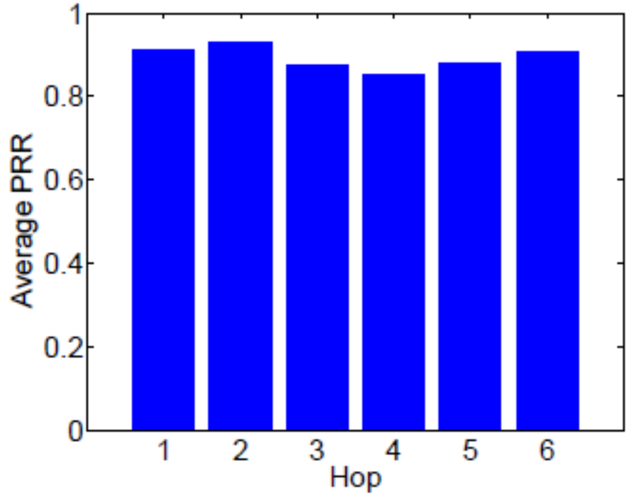
Throughput bottleneck around the sink?

- Current goodput of data reception is far less than 250 Kbps (the upper bound data rate of TelosB mote)

Does sink hole exist?



(a) Packet reception ratio



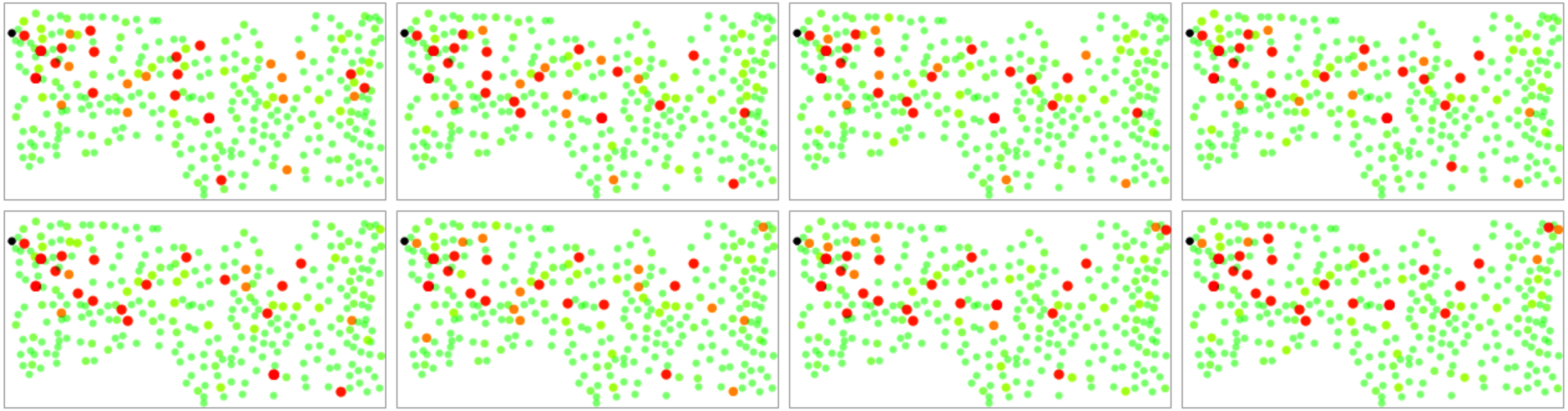
(b) Link PRR

System performance for
different categories of nodes

A large portion of the packet losses occur around the sink?

- If sink hole exists, all the packets are likely to be equally dropped around the sink, due to the contention or congestion.

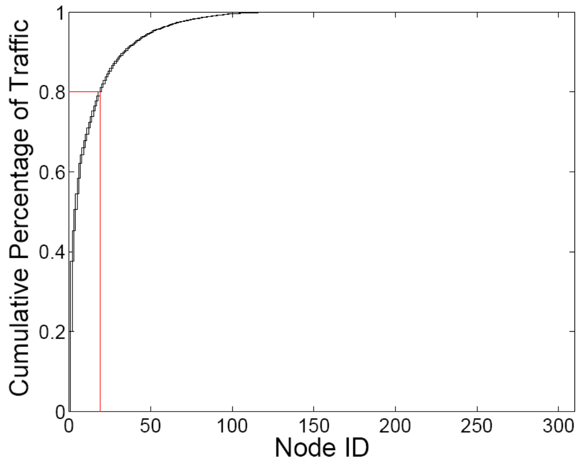
Traffic distribution : balanced in CTP?

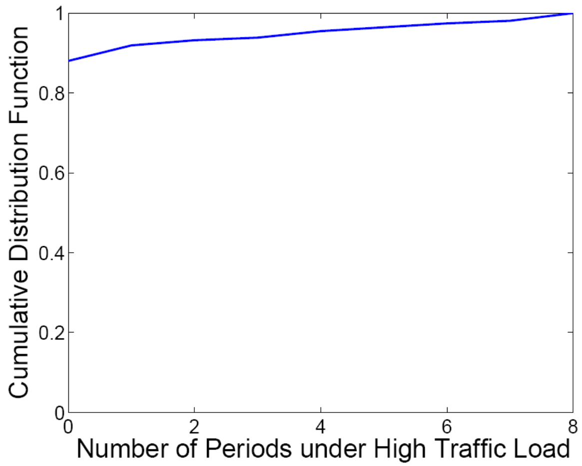


5% nodes account 80% traffic.

90% nodes have low traffic.

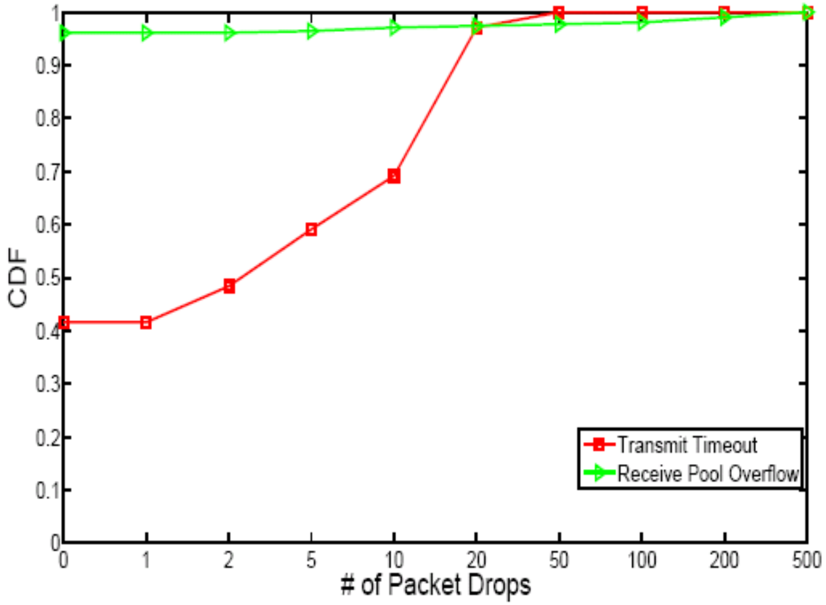
The traffic distribution is relatively stable over time.



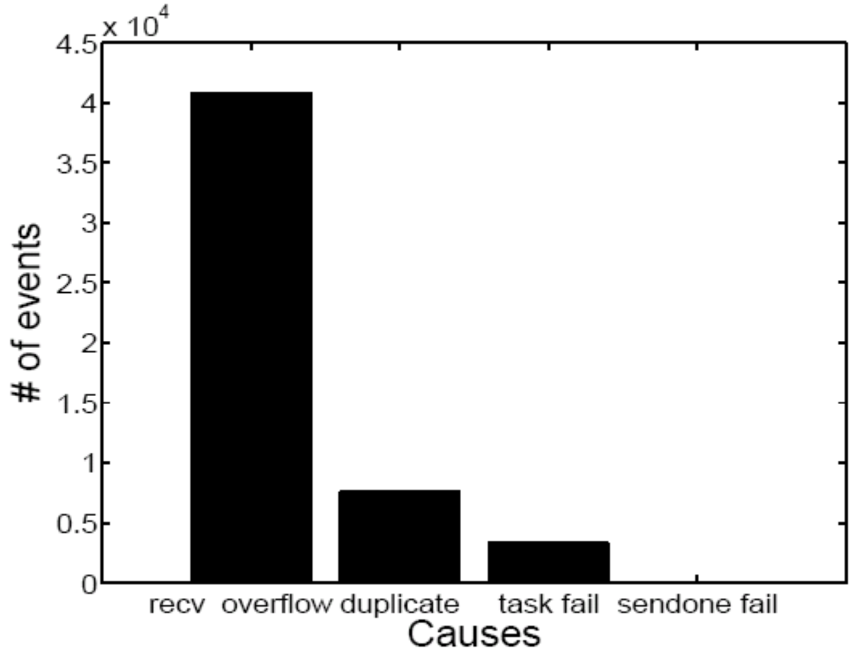


Causes of packet loss

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



Cumulative distribution of packet loss



Causes of packet loss on sensor nodes

Limitations of Network Indicator (ETX)

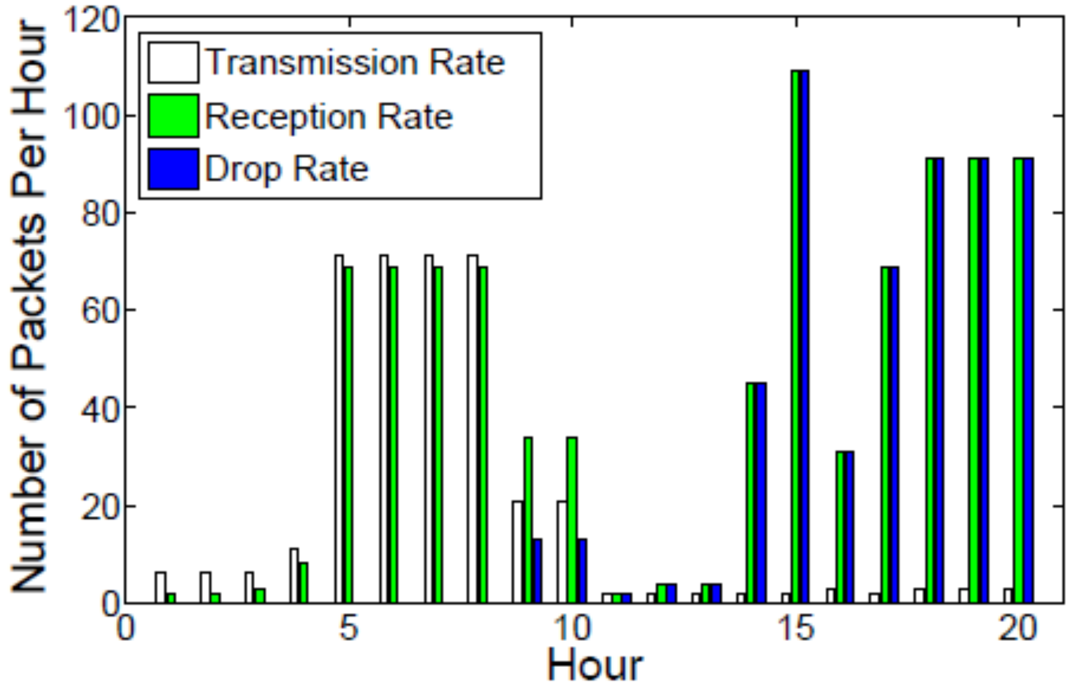
- Current network indicators, e.g. ETX only focuses on link quality

- The result :

  Cannot capture nodes dr

  packet behavior

- Consider more:
  - –Accurate link estimator
  - –Node's forwarding quality
  - –...



The packet reception, forwarding, and drop at node 25 within 20 hours

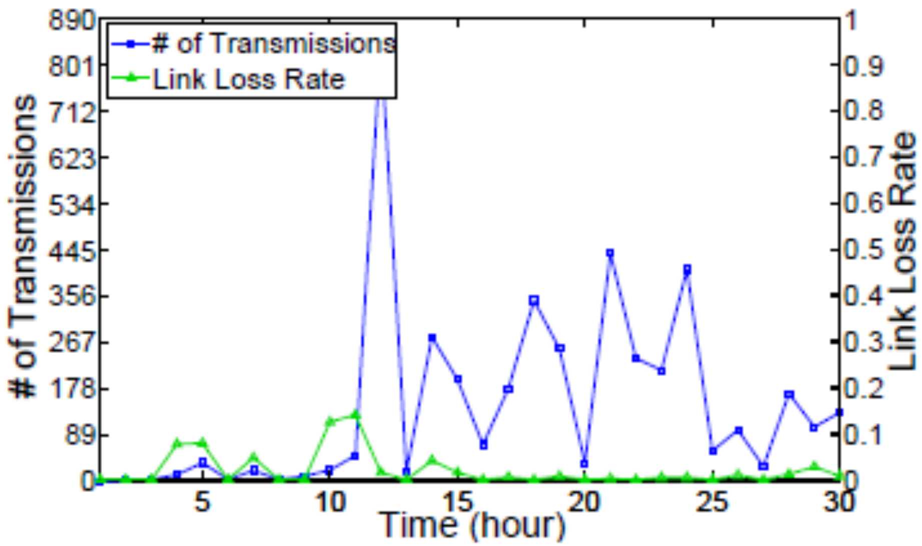
Three conjectures #2

- A small portion of nodes bottlenecks the entire network, and most of the existing network indicators may not accurately capture them

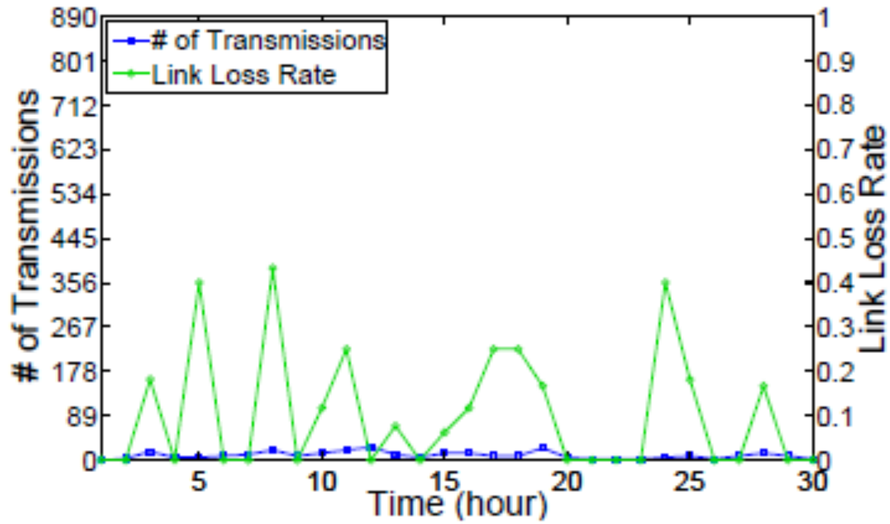
- The network dynamics mainly come from the inherent concurrency of network operations instead of environment changes

- The environment, although the dynamics are not as significant as we assumed, has an unpredictable impact on the sensor network

Dynamics caused by Environment or the Network itself?



(a)



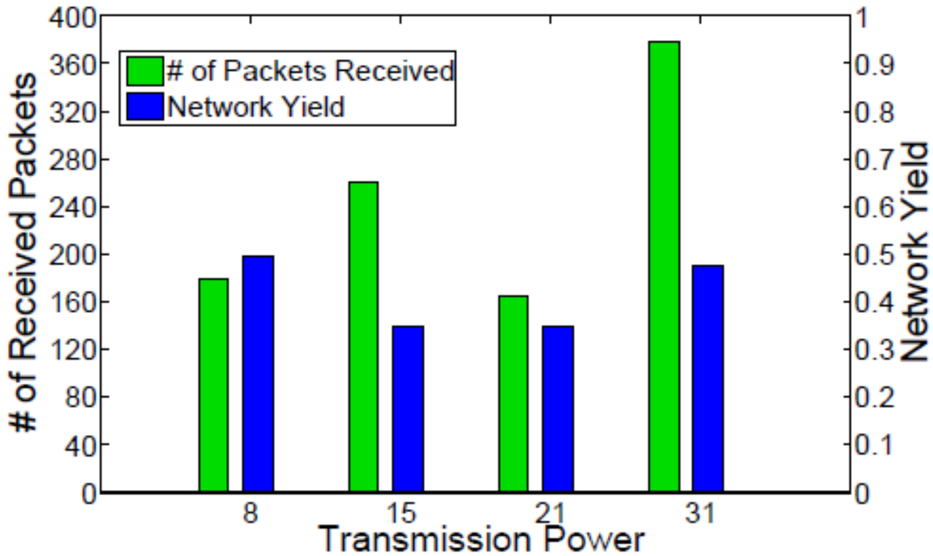
(b)

Link loss rate seems independent from the traffic load.

Question 1:

Caused by environment dynamics?

Dynamics caused by Environment or the Network itself?



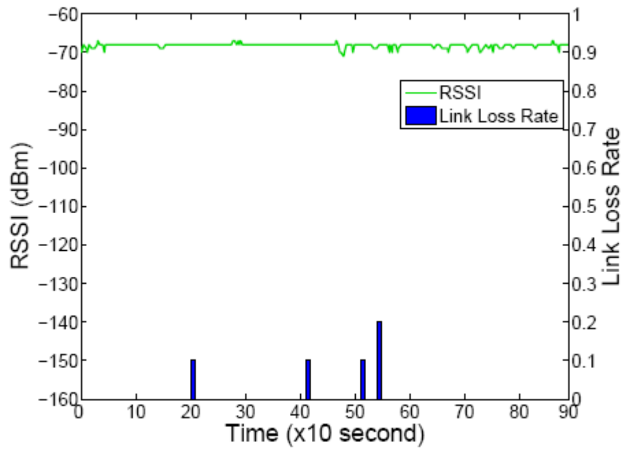
Different settings of transmission power

Increasing power does not show improvement.

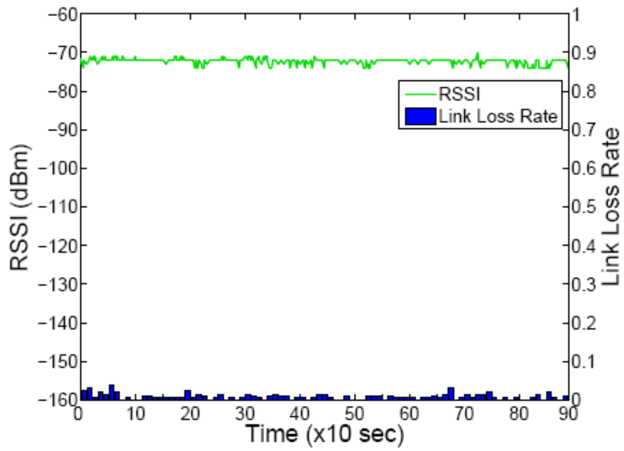
Question 2:
Caused by protocol design?

Link quality in the wild

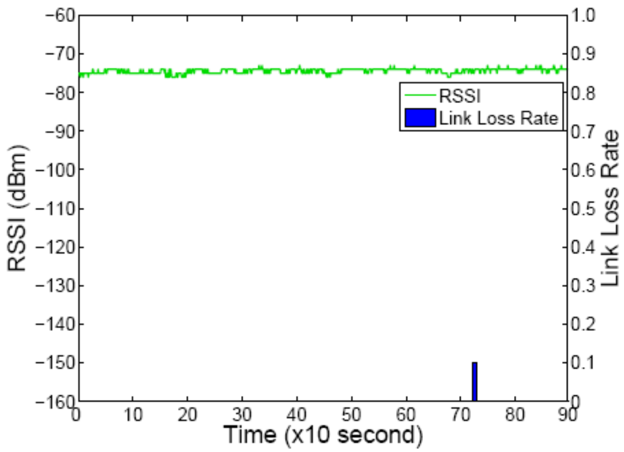
1. Relatively stable in the wild
2. Monotonic with distance
3. Weakly related with RSSI
4. Significant loss near the receive sensitivity



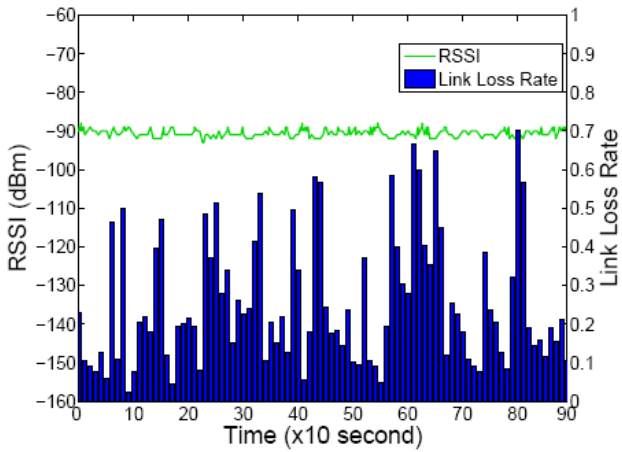
1Hz & 20m



20Hz & 20m

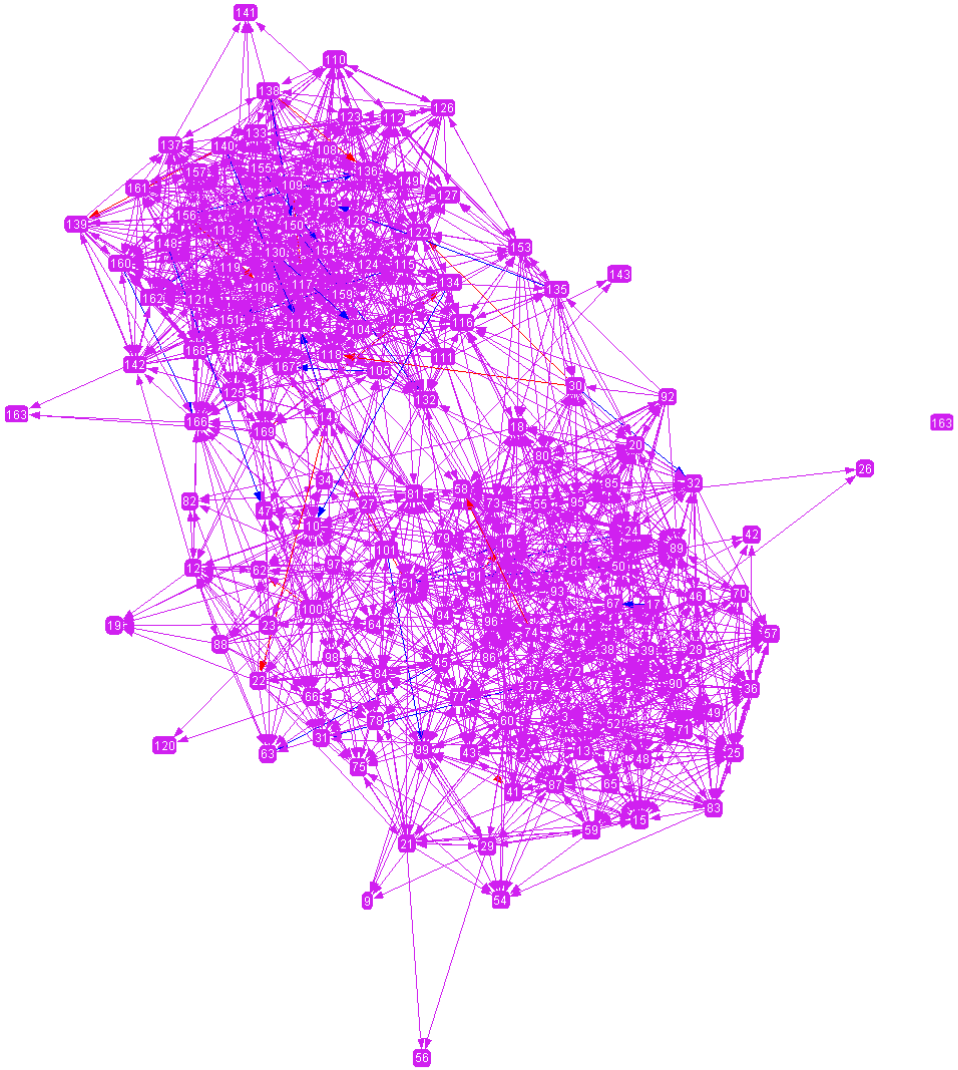


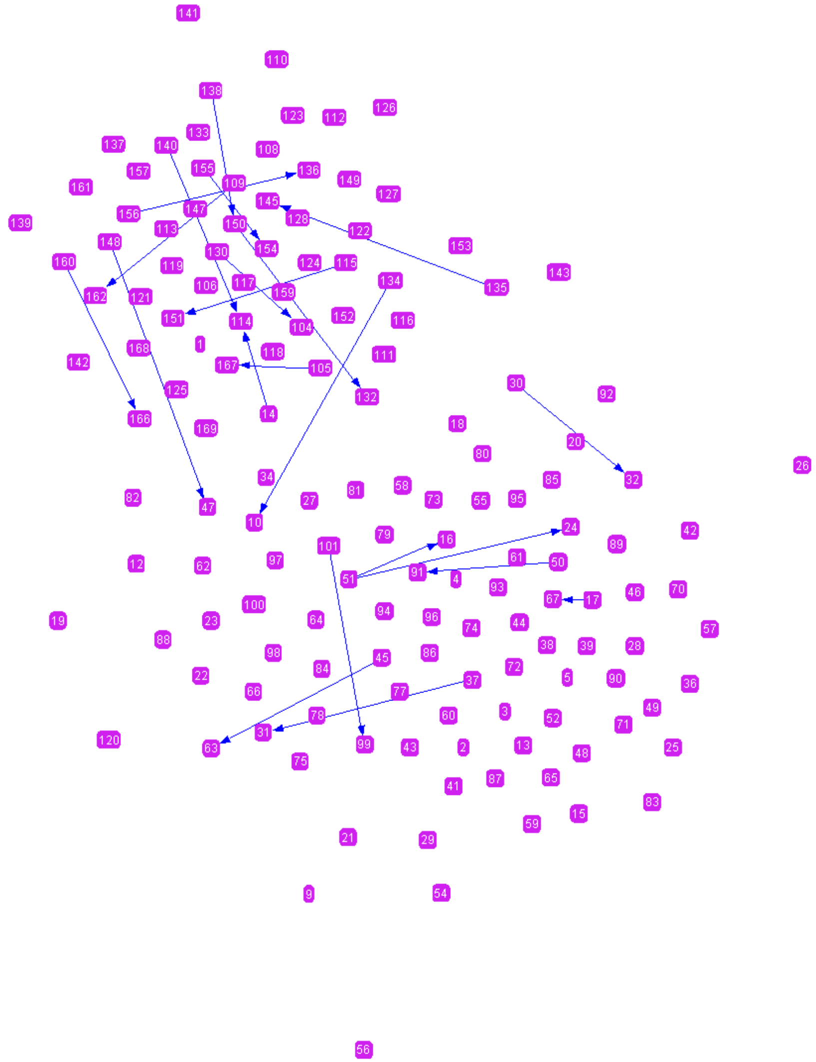
1Hz & 50m



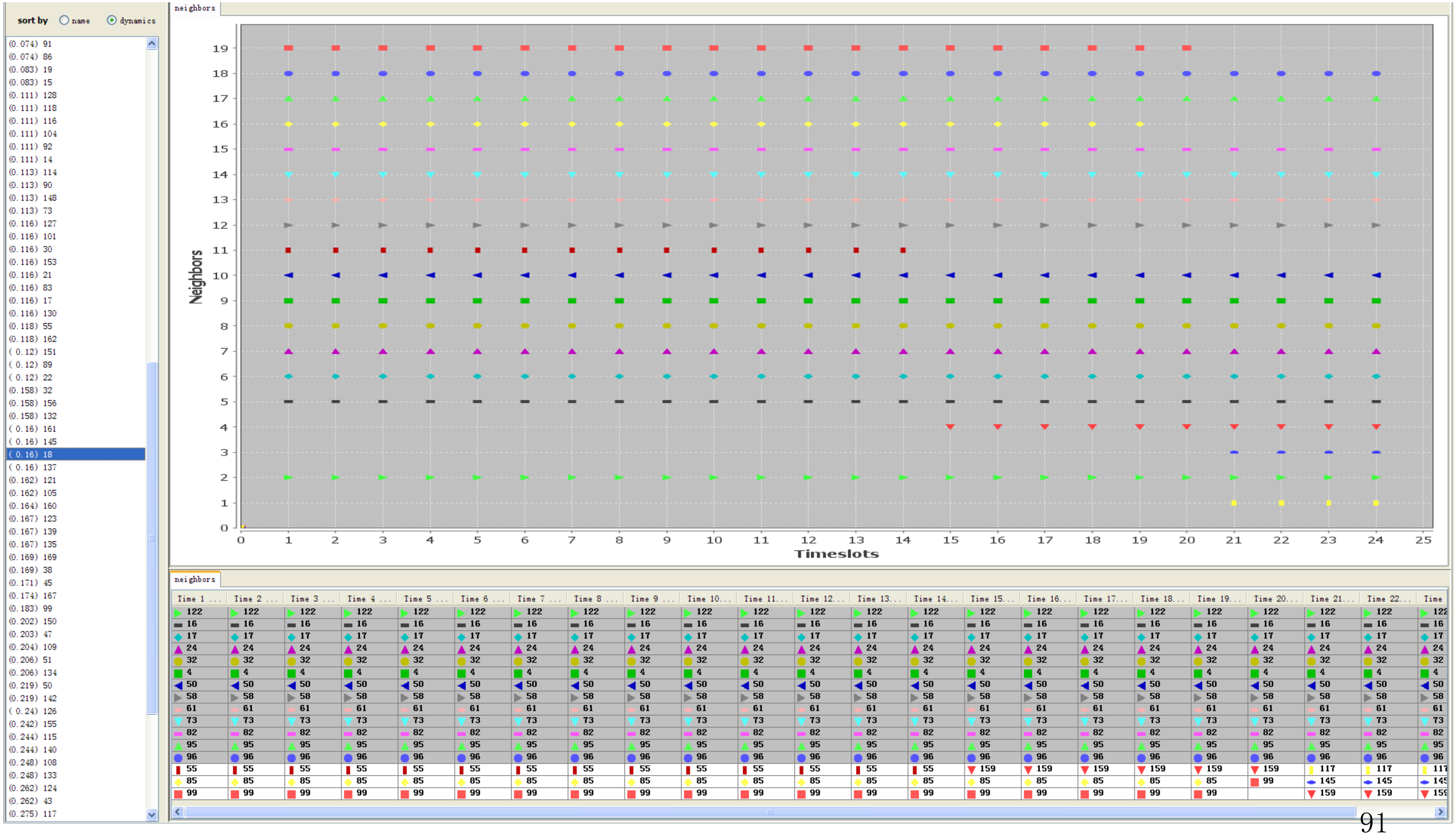
20Hz & 50m

Global view of dynamics





Local view of dynamics



Three conjectures #3

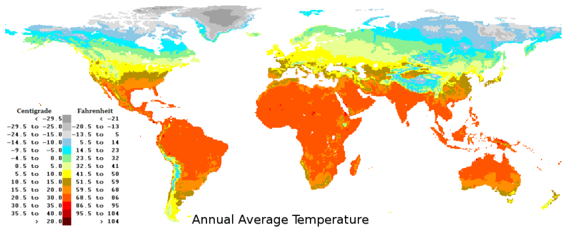
- A small portion of nodes bottlenecks the entire network, and most of the existing network indicators may not accurately capture them

- The network dynamics mainly come from the inherent concurrency of network operations instead of environment changes

- The environment, although the dynamics are not as significant as we assumed, has an unpredictable impact on the sensor network

Environment Characteristics

- Each environment has unique characteristics
  - Inherent irregularity
  - Weather condition
  - External interference
  - …

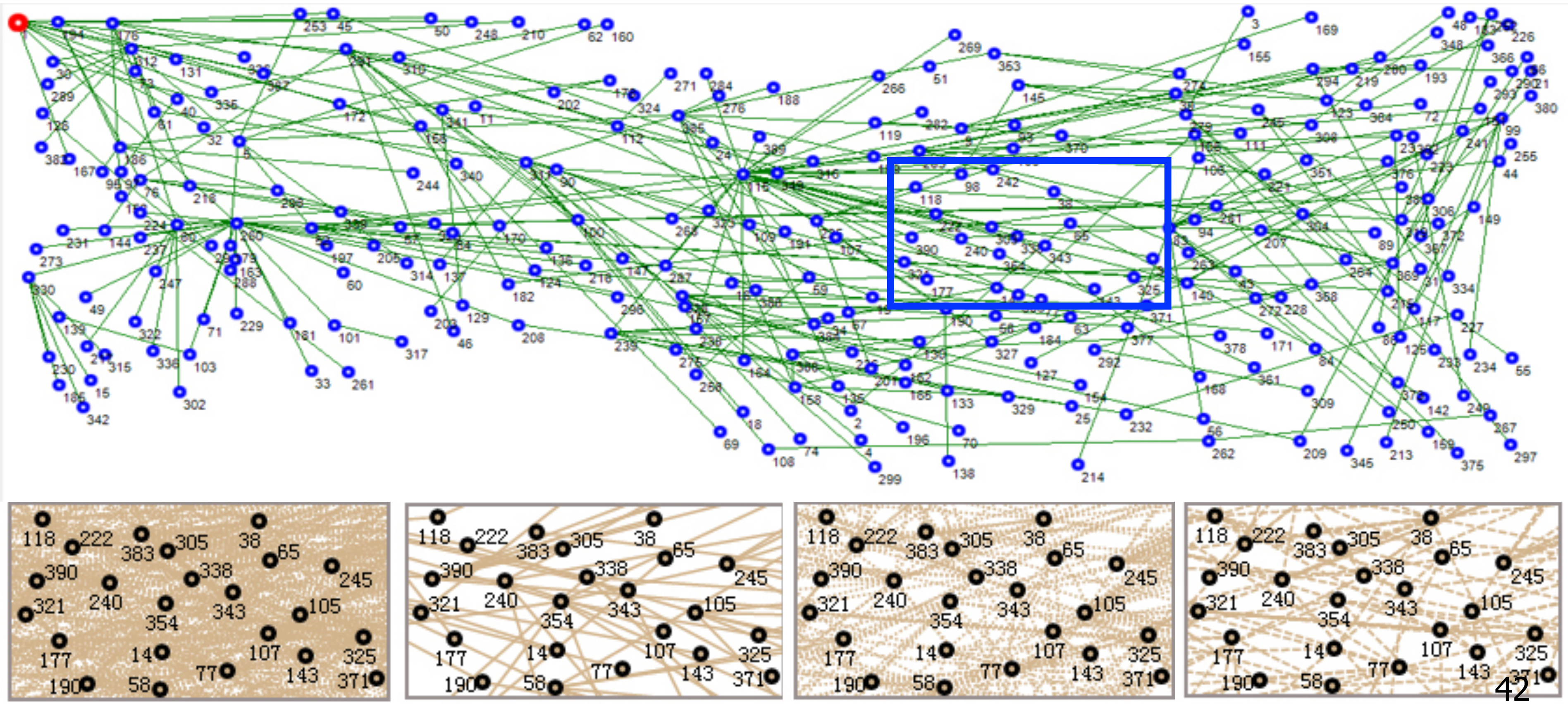


- Adequately learning environments' unique characteristics is helpful to protocols to have better performance
  - Event-based static routing structure

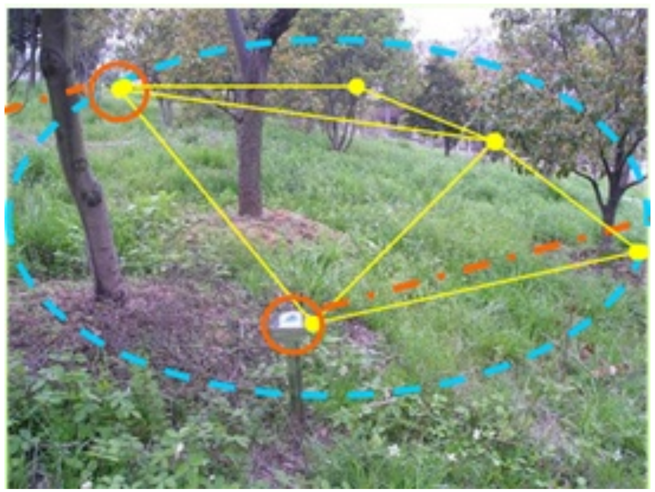
Some Open Issues in Our Mind….

GreenOrbs' Topology

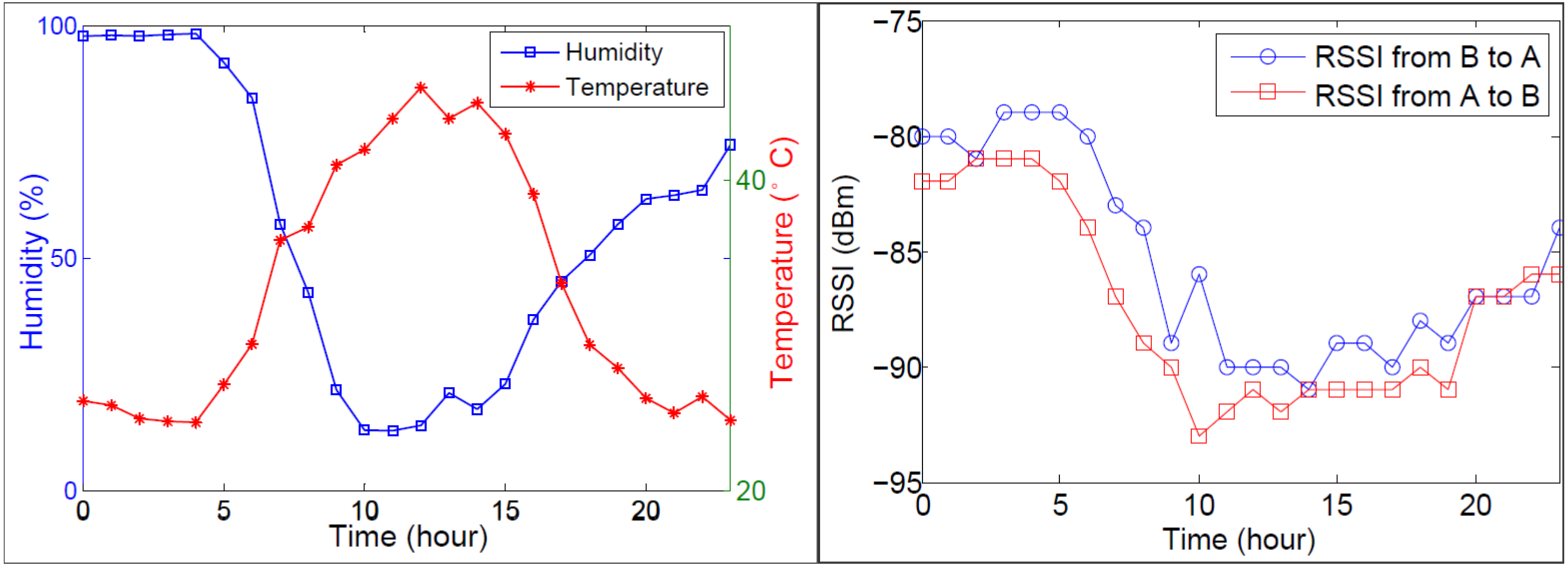
Network-wide routing topology VS Local topology with different criterions



Spatial Dimension of Topology

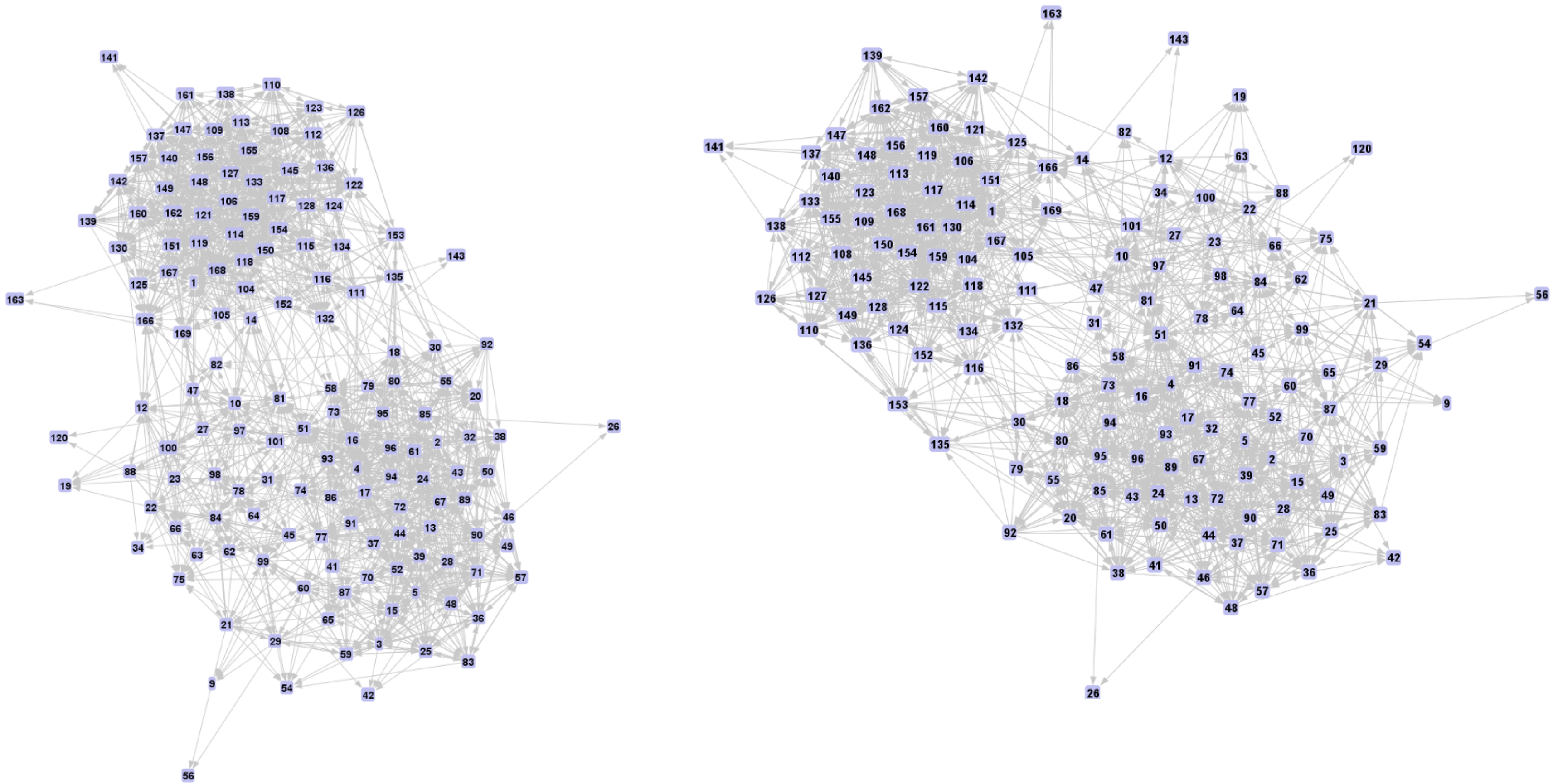


Spatial Dimension of Topology



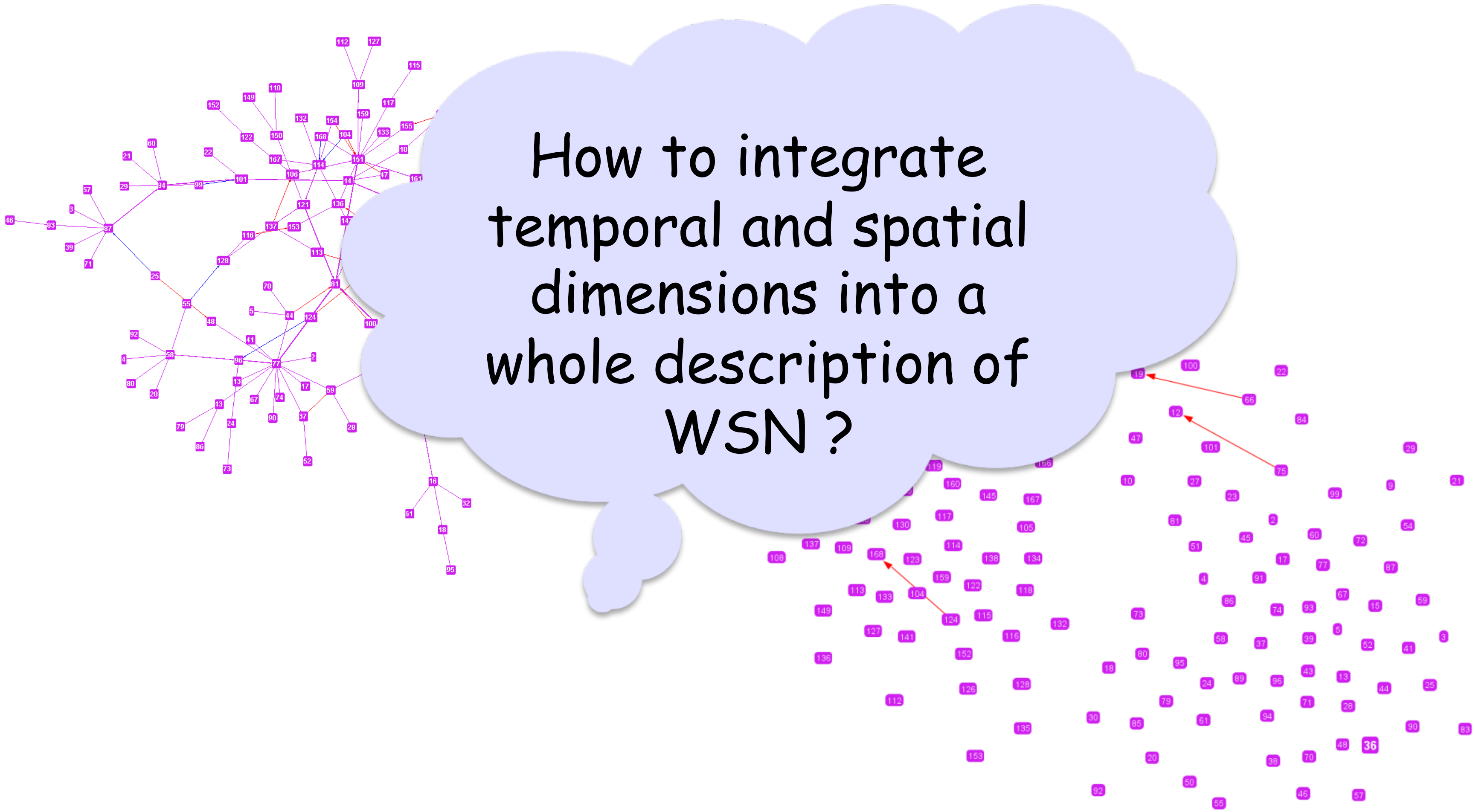
Link quality changes with humidity, temperature and time.

Temporal Dimension of Topology



The logistic topology of reachable links at an interval of two weeks.

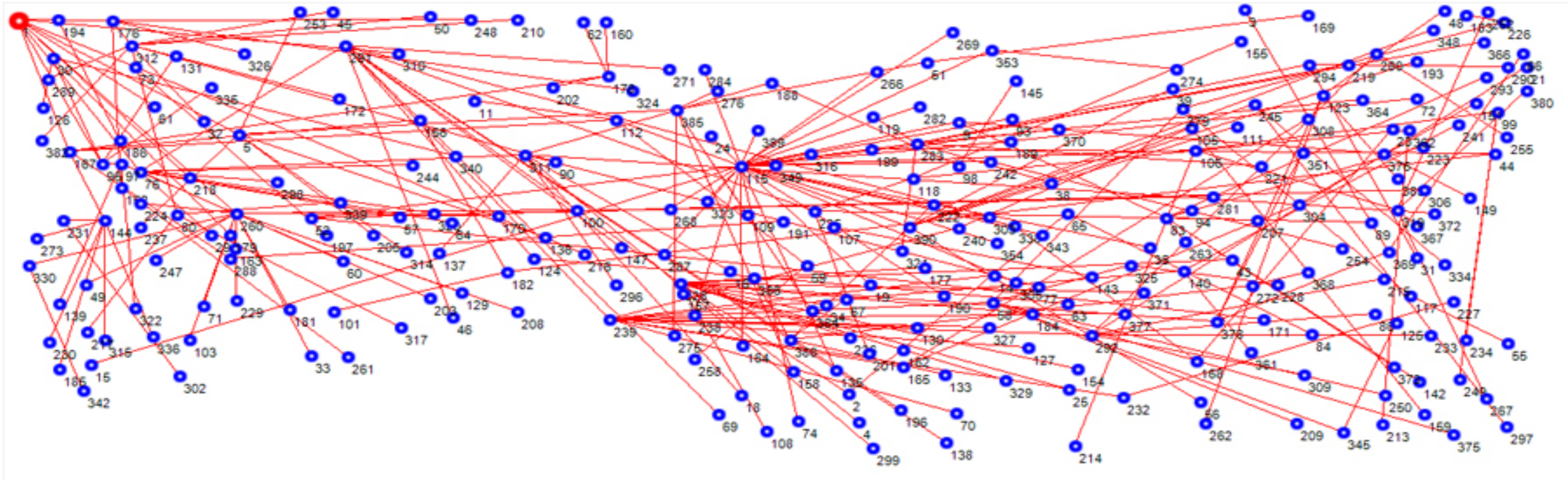
The Dynamics of Routing Topology



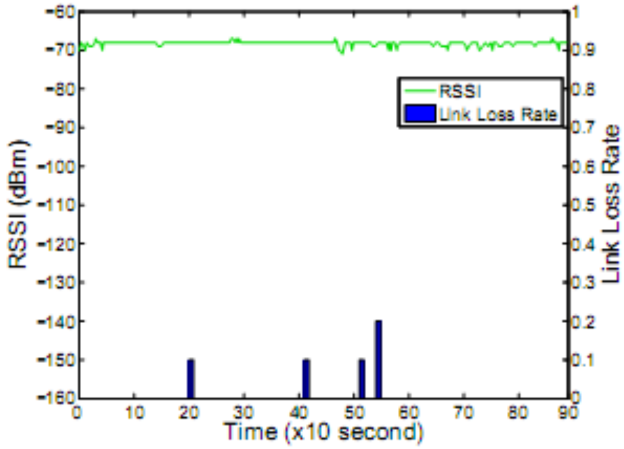
How to integrate temporal and spatial dimensions into a whole description of WSN ?

Relation between the link topology and the dynamics of routing topology.

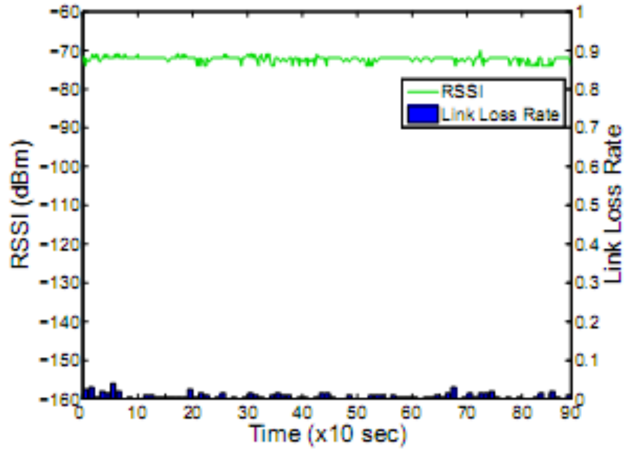
Traditionally:
Routing to transmitting



First sensing, then routing

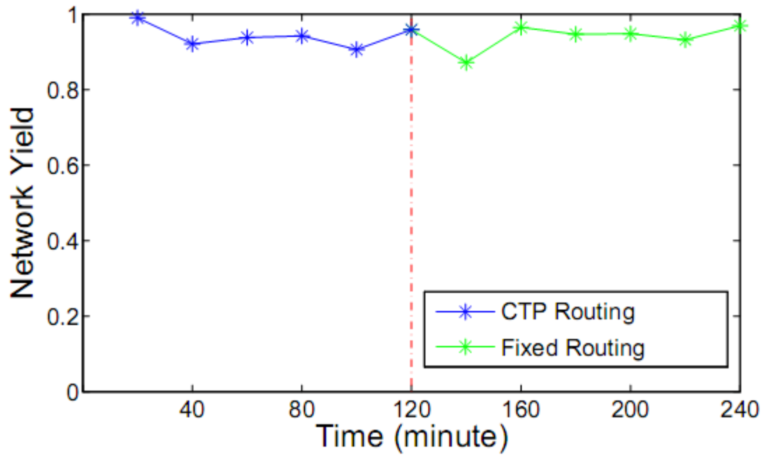


(c) 1Hz and 20m



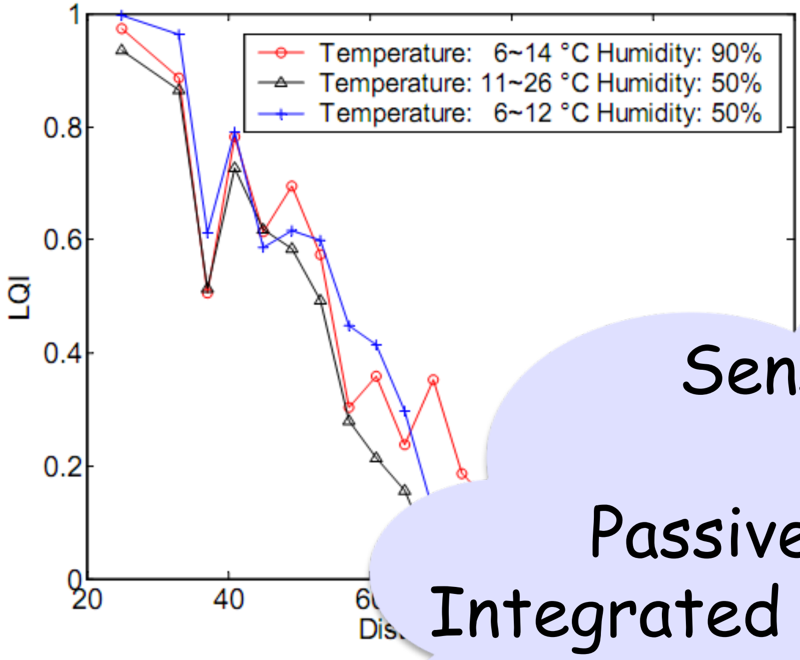
(d) 20Hz and 20m

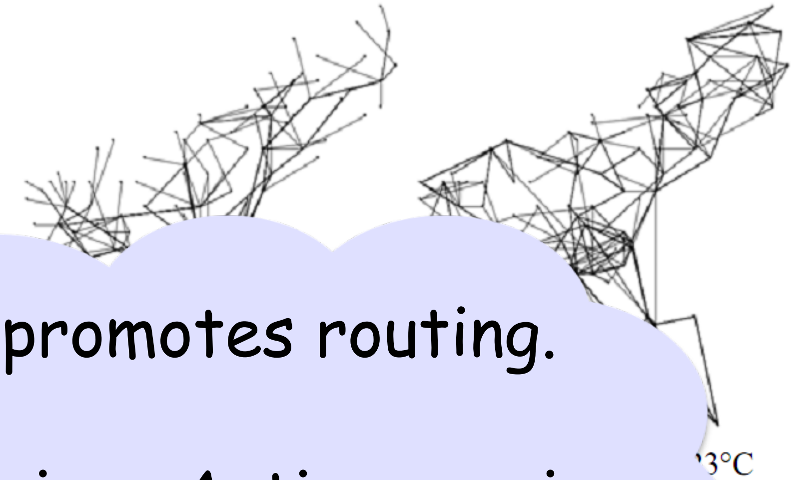
Stable link in uniform environment.



Stable routing in uniform environment.

First sensing, then routing





Links chang

envir

Sensing promotes routing.

Passive sensing->Active sensing.
Integrated sensing and transmitting.

-->Event-based routing

Separate Sensing and Routing -> Data supports routing

Traditional routing

- Extra broadcast cost for link quality detection.
- Large routing table.

WSN routing

- Limited link resource. (Transmission data supports routing.)
- Limited node resource.(Week state routing.)

New routing scheme?

- Sensing -> Routing

  Sensing promotes routing.

- Data -> Routing

  Data supports routing.

- Nodes -> Routing

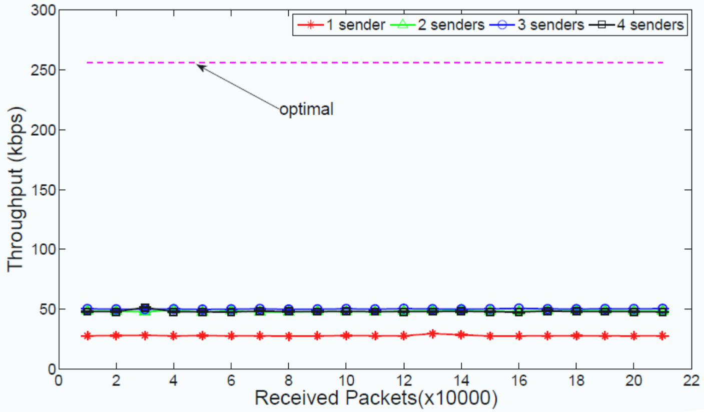
  Links and nodes codetermine routing.

ZigBee
Applications and Characteristics

Zigbee
Low-energy consumption
Low speed
Short range
Low delay
Unlicensed frequency

Can ZigBee satisfies all these requirements?

Is 250Kbps enough?

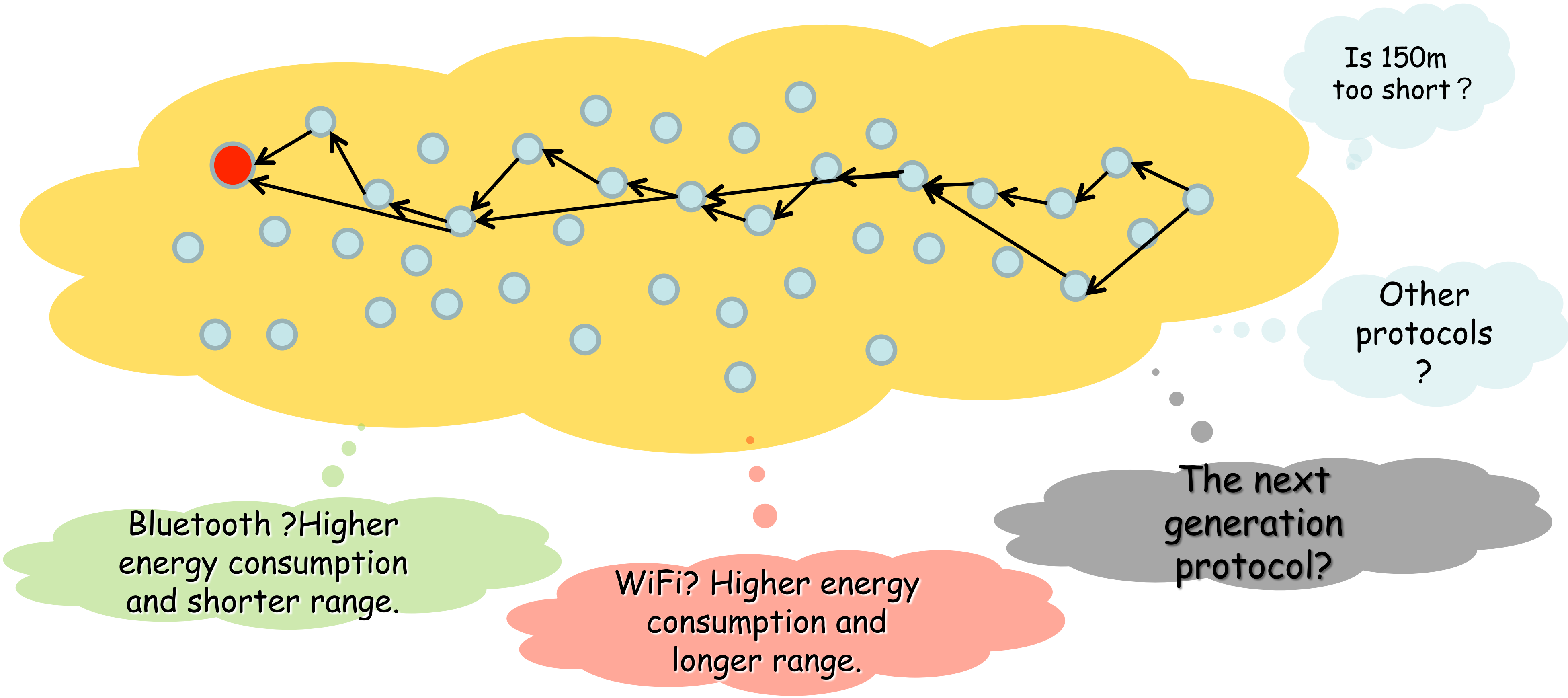


- 250Kbps is just the theoretic peak

- Applications require much more

- Break the flat network structure?
- Seek high-performance data compression methods?
- Design the next generation transfer technology with high data transfer rate and low-energy consumption？
- Design the transfer protocol which increases the throughput? [B. Raman etc., SENSYS 2010],[S. Kim etc., SENSYS 2007]

What is the proper transmission radius?



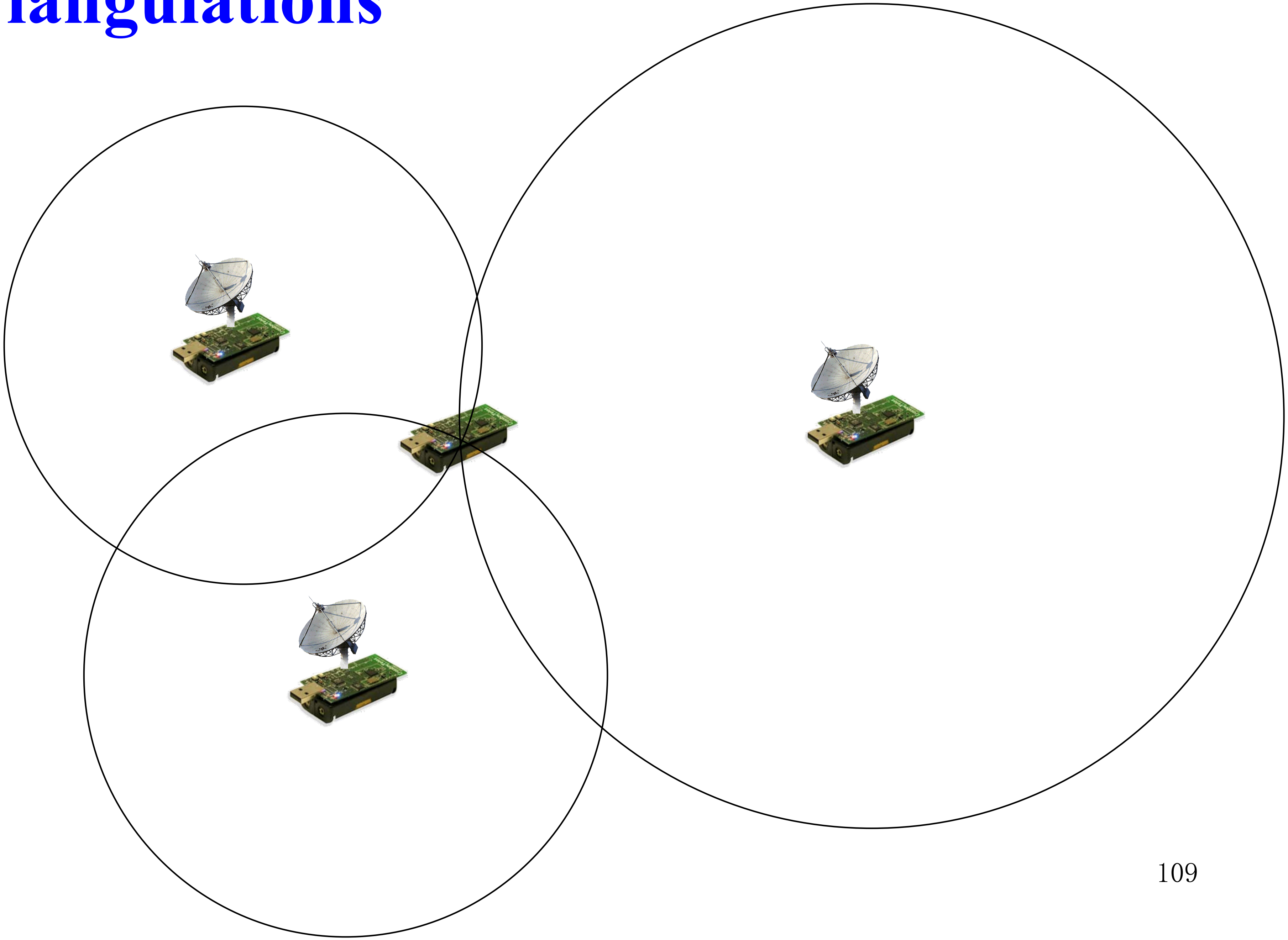
- Separated transmission and sensing
- Layered network structure
- Graded data
- Classified applications

2, Localization

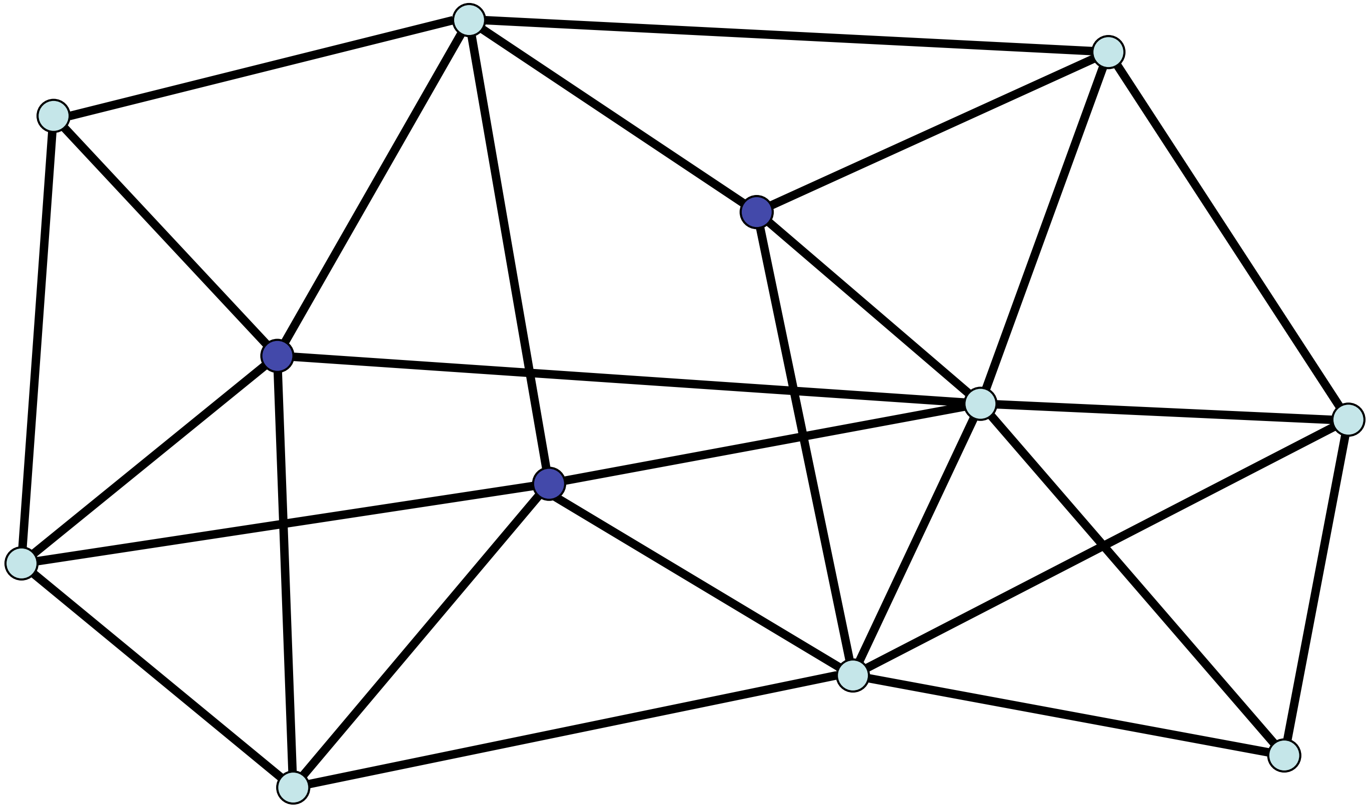
Location, Location, Location

Locating end users may be just another app for wireless technology—or it may be the awaited killer app.

Triangulations



Range-based localization

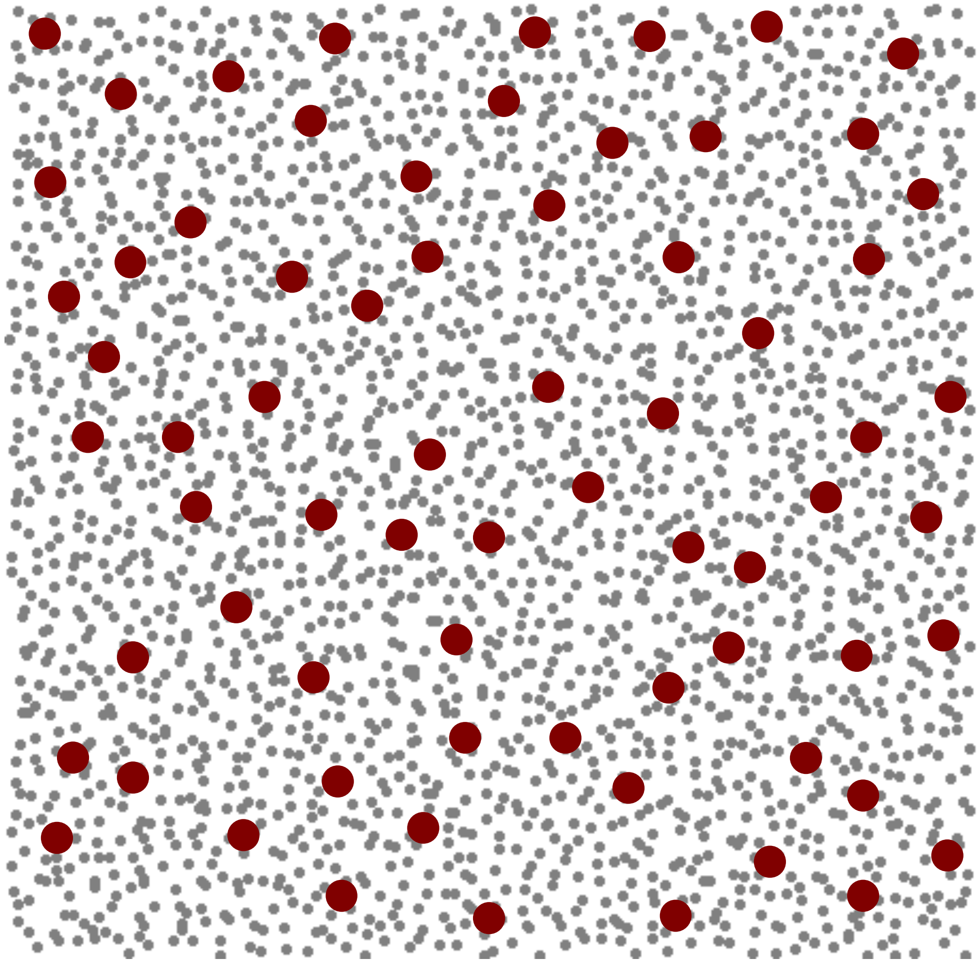


Ranging Techniques

- Time of Arrival (TOA)
  - radio, ultrasound etc.
  - GPS
  - high synchronization
- Time Difference of Arrival (TDOA)
  - light + sound
  - usually directional
- Radio Signal Strength (RSS)
  - receiving signal strength
  - signal irregularity
- Angel of Arrival (AOA)
  - antenna array

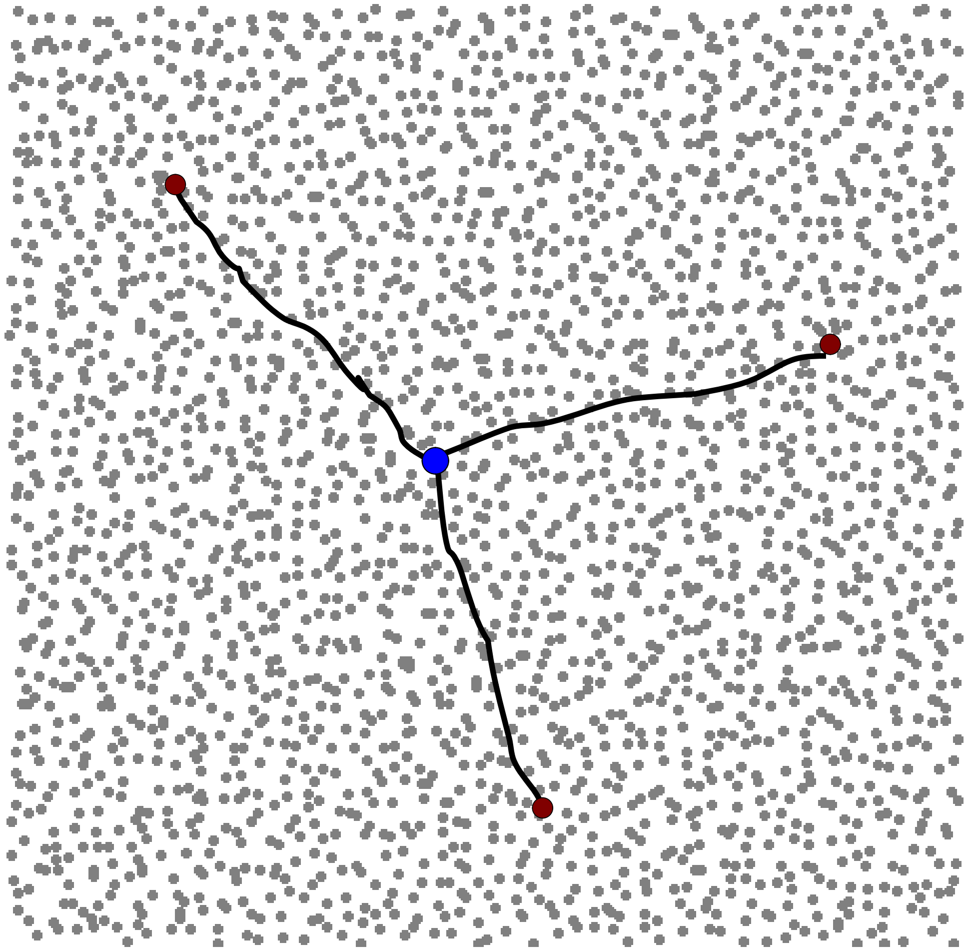
Expensive and Difficult ! !

Rang-free Techniques (1): More Seeds



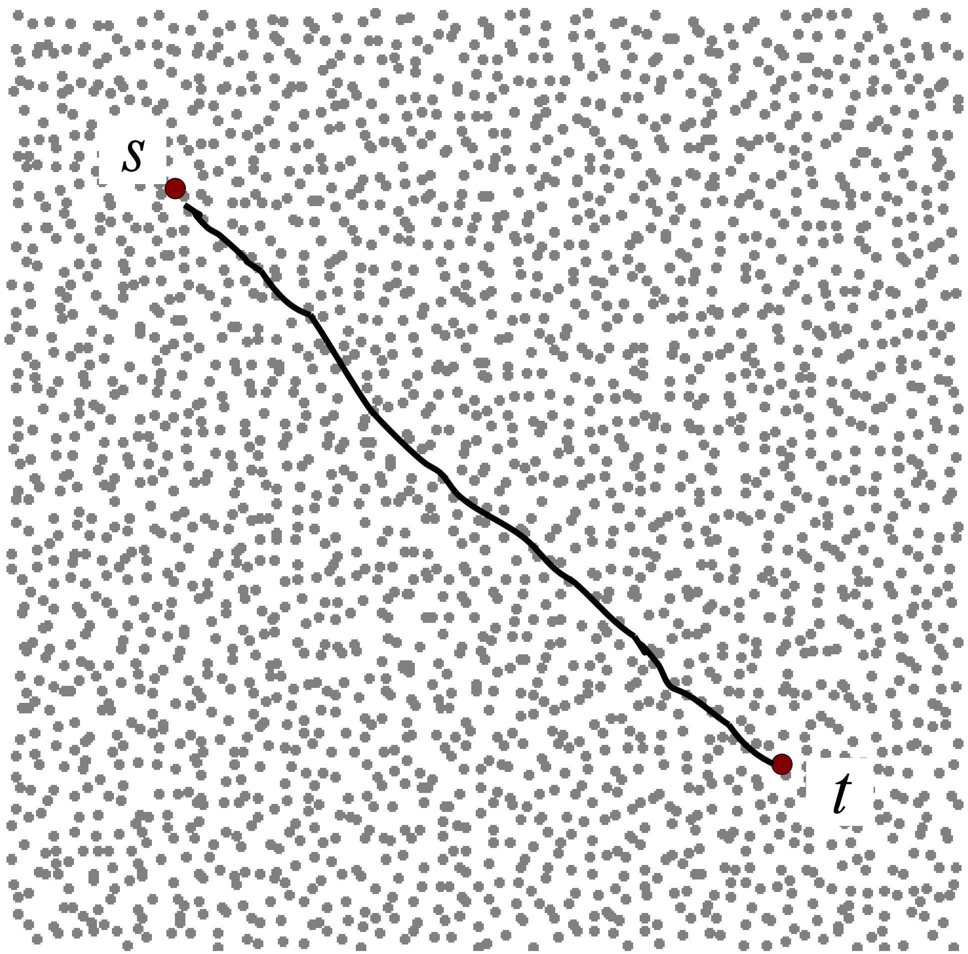
- APIT [MobiCom’ 03]
- MCL [MobiCom’ 04]
- MDS [MobiHoc’ 03]
- SVD [INFOCOM’ 05]

Rang-free techniques (2)

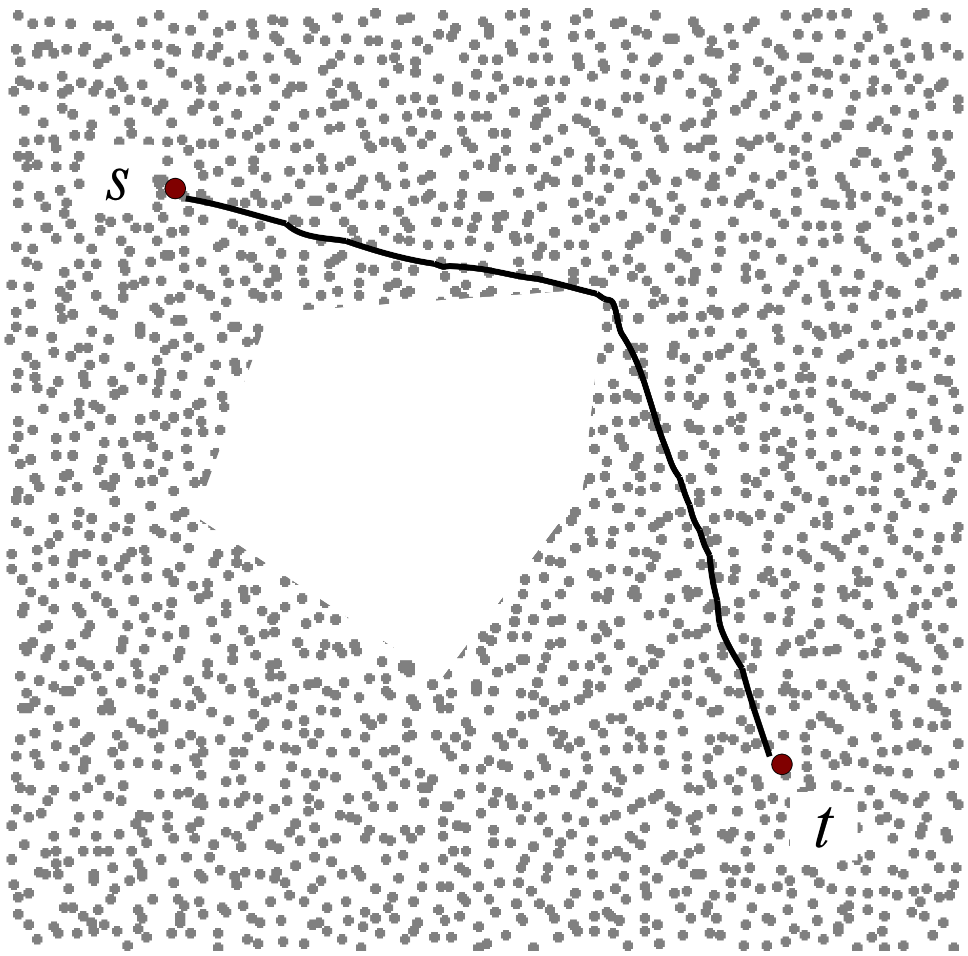


- DV-Hop
  Telecommunication Systems, 2003

Isotropic network



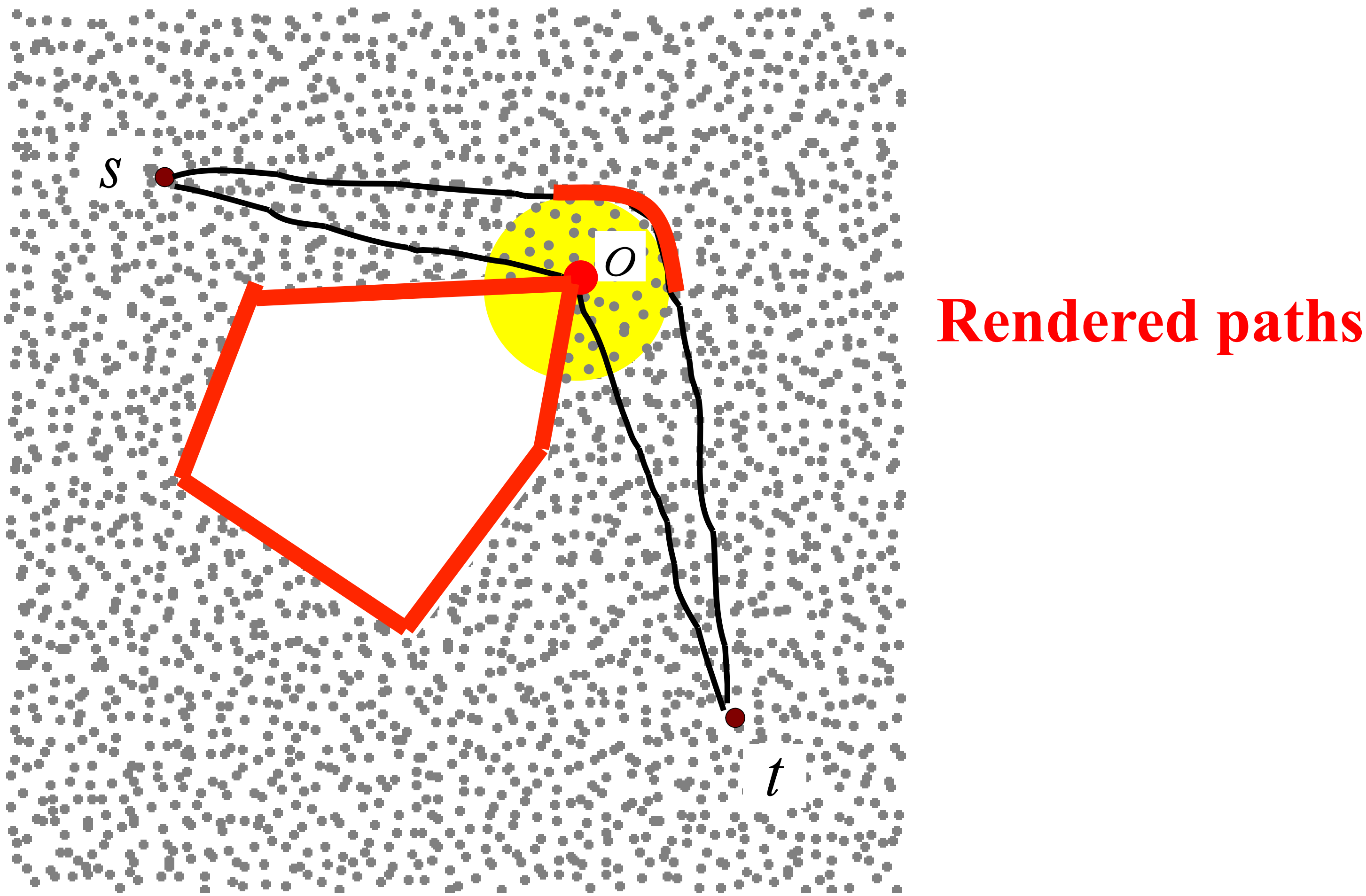
Fail in Anisotropic Networks



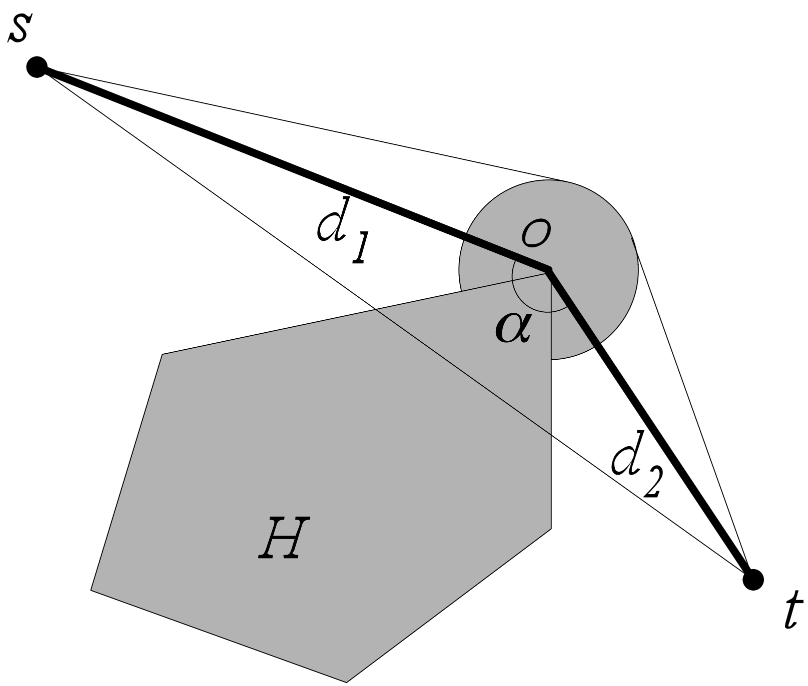
Challenges

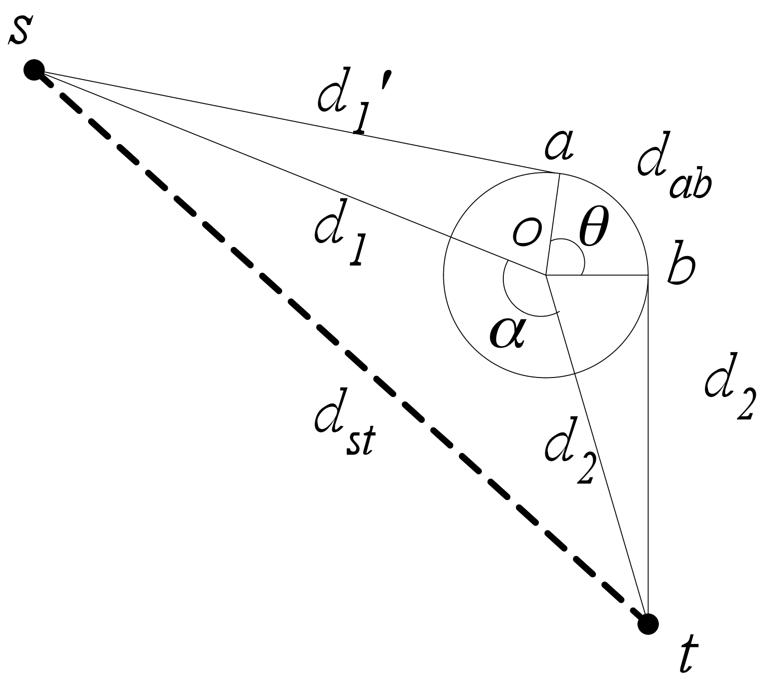
- High link loss rate and poor measurement accuracy: Range-free
- Extremely difficult environment: Constant number of seeds, as few as the lower bound 3 seeds only
- Sensors are not uniformly deployed, or even deployed that way, they might change: Distance mismatch in anisotropic network with holes

Rendered Path (REP)



REP Principle (basic)

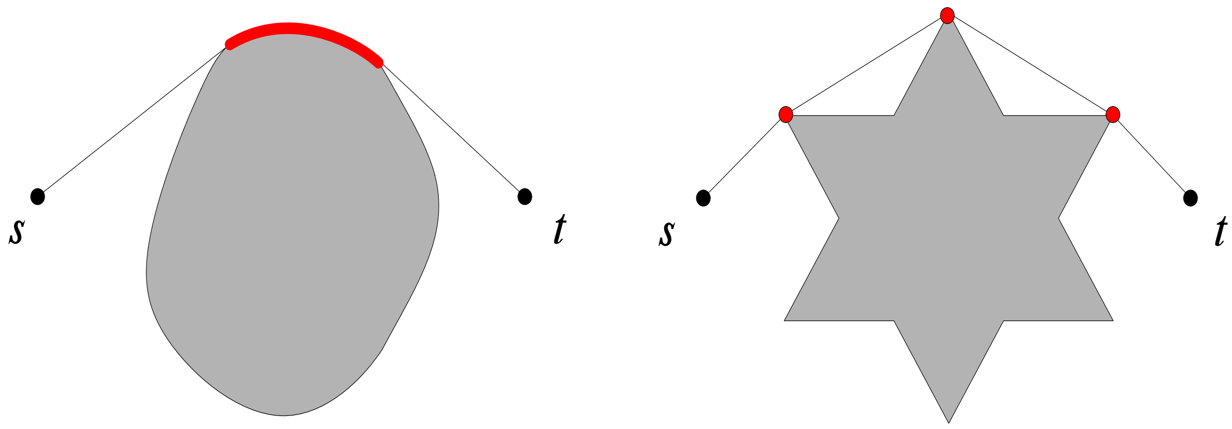




$$\alpha = 2\pi - \frac{d_{ab}}{r} - \arccos\frac{r}{d_1} - \arccos\frac{r}{d_2}$$

$$d_{st} = \sqrt{d_1^2 + d_2^2 - 2d_1 d_2 \cos\alpha}$$

REP Principle

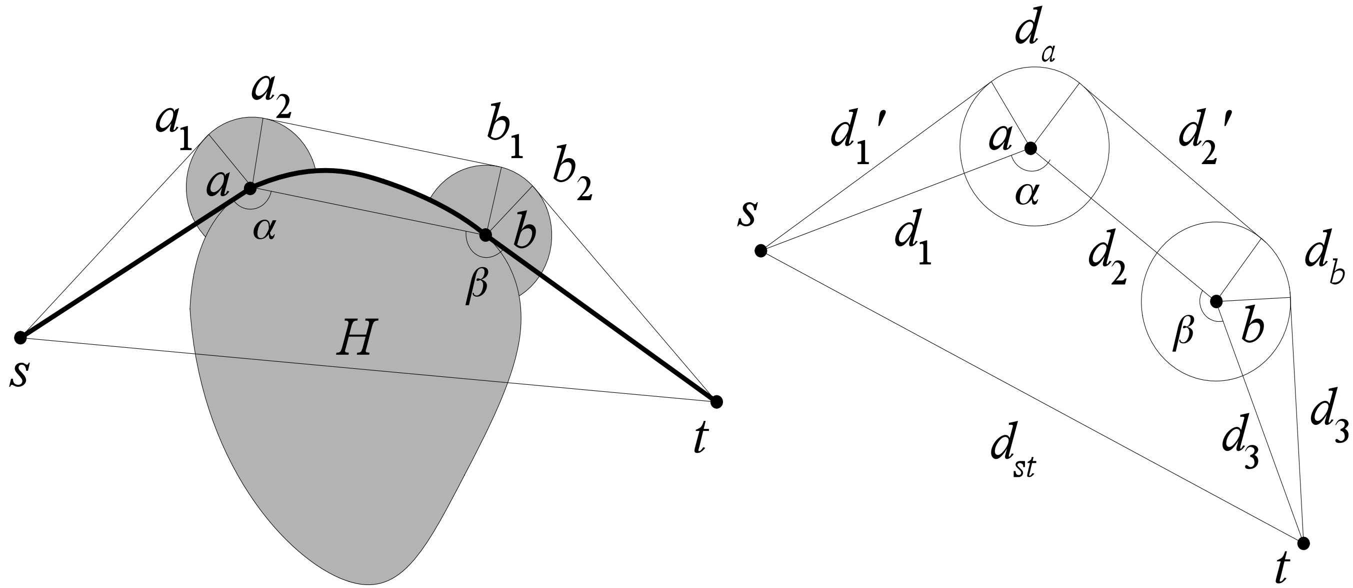


convex hole

concave hole

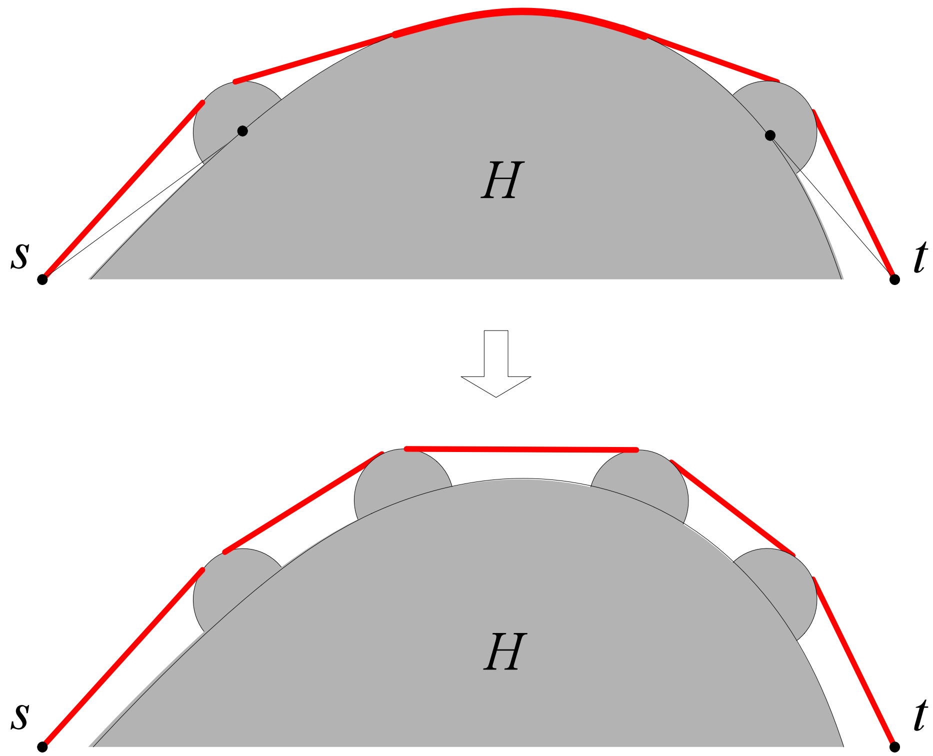
Distinguishable from the path rendering

REP Principle (convex hole)

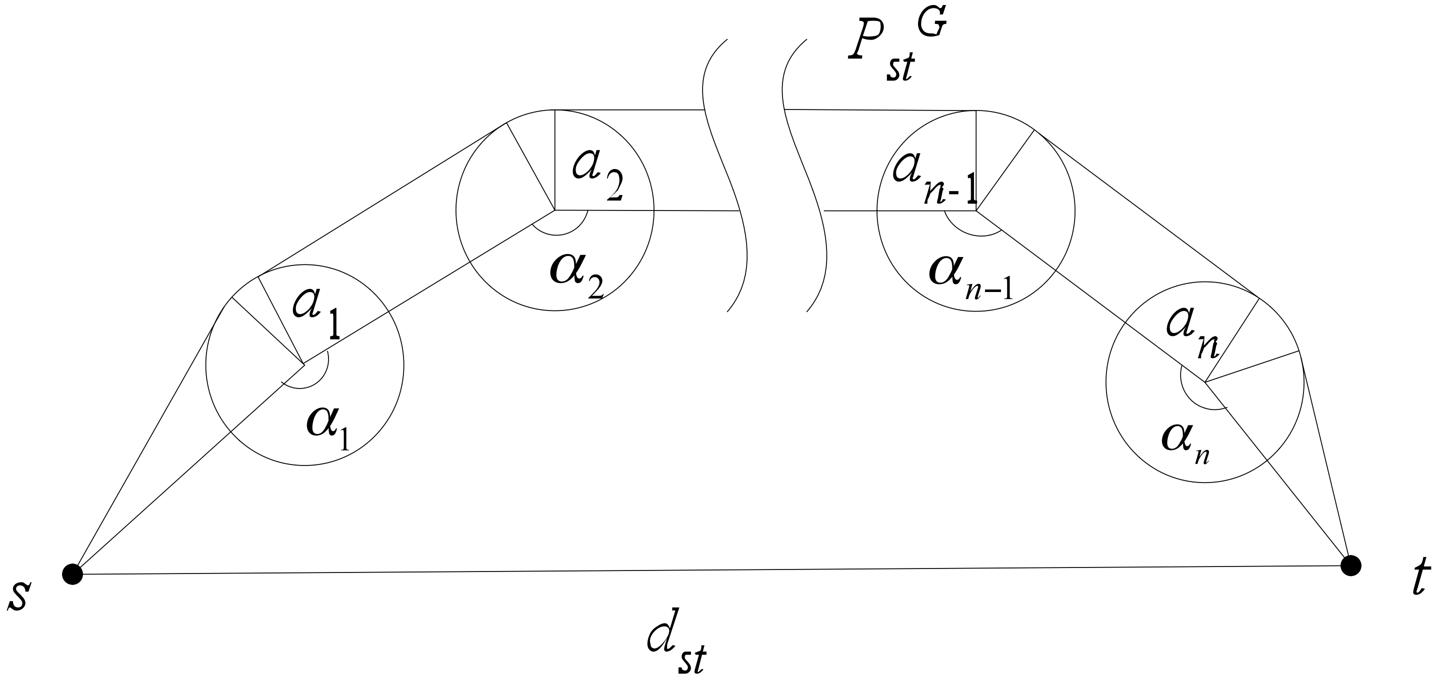


$$\overrightarrow{st} = \overrightarrow{sa} + \overrightarrow{ab} + \overrightarrow{bt}$$

REP Principle (convex hole)

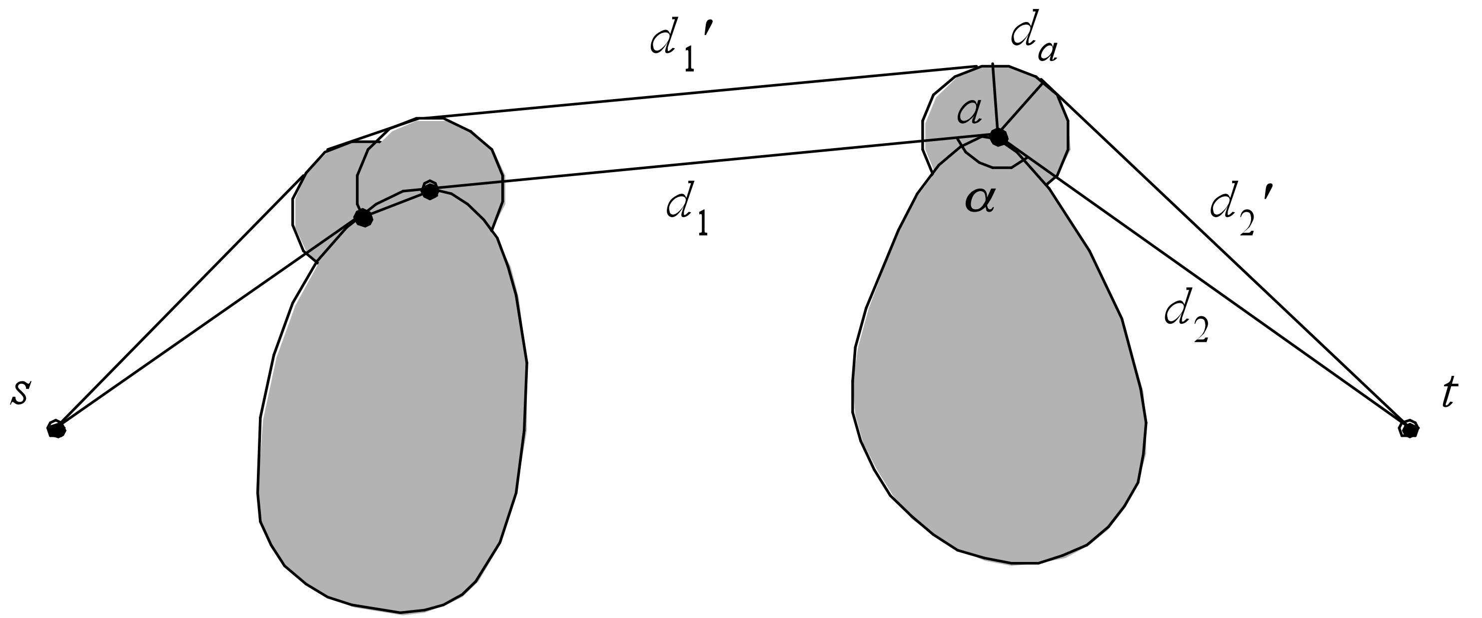


REP Principle (convex hole)



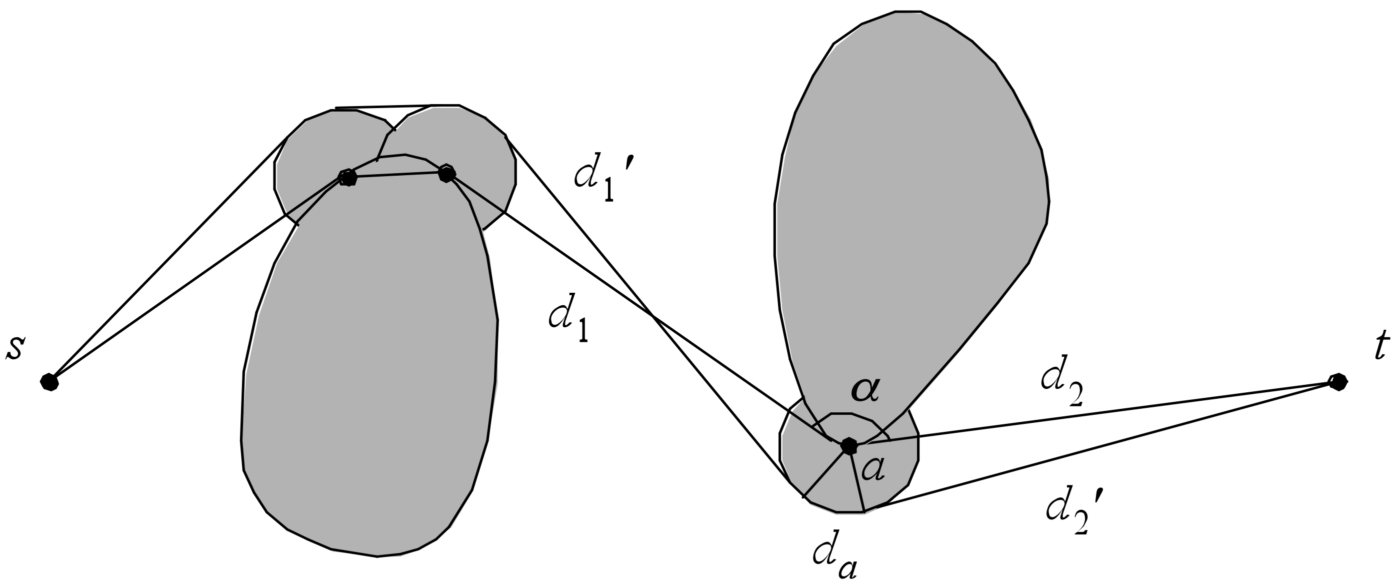
$$\overrightarrow{st} = \overrightarrow{sa_1} + \overrightarrow{a_1a_2} + \cdots + \overrightarrow{a_{n-1}a_n} + \overrightarrow{a_nt}$$

REP Principle (convex holes)



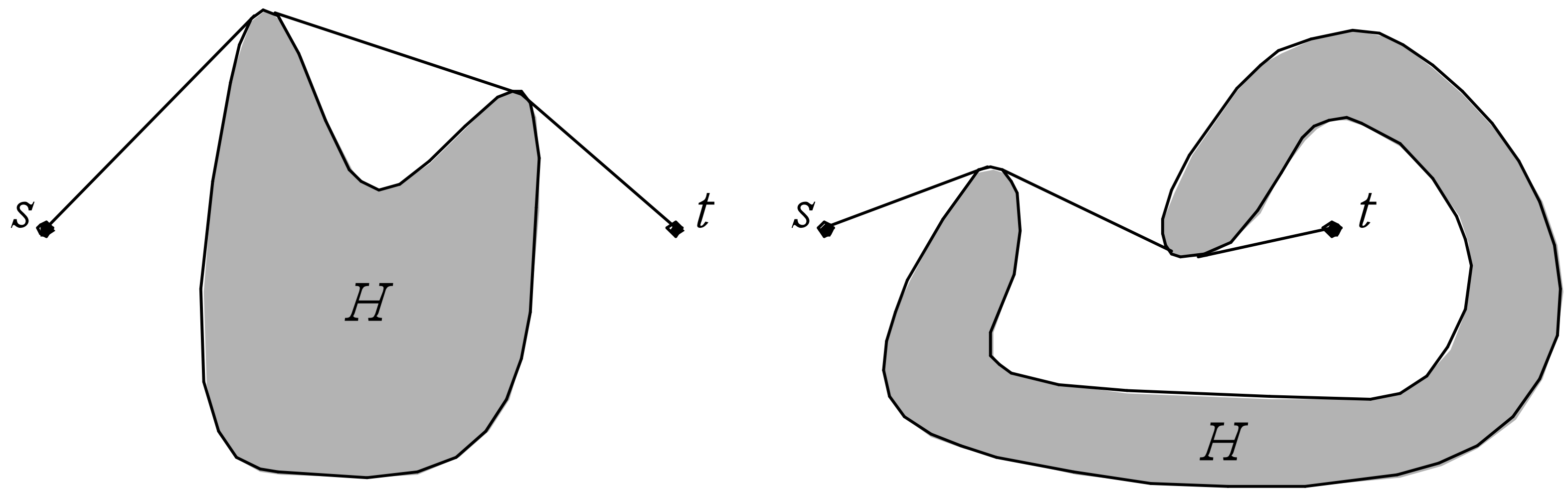
Type 1

REP Principle (convex holes)

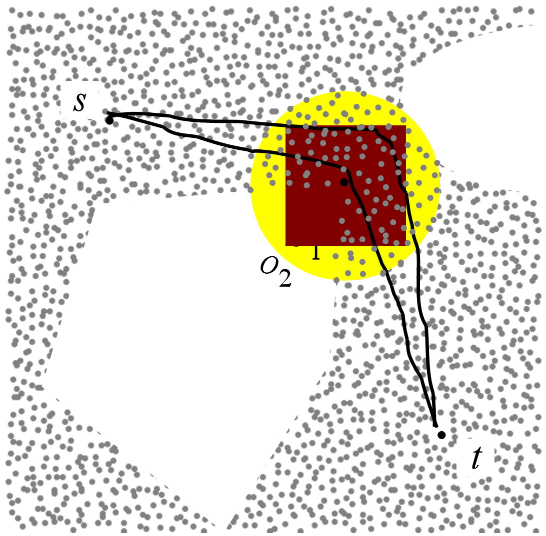


Type 2

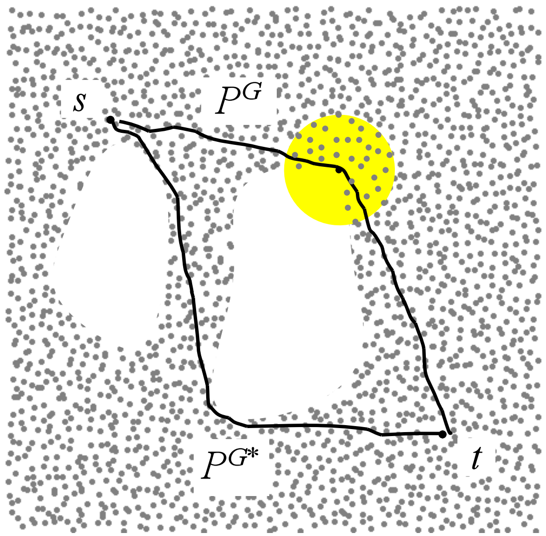
REP Principle (concave holes)



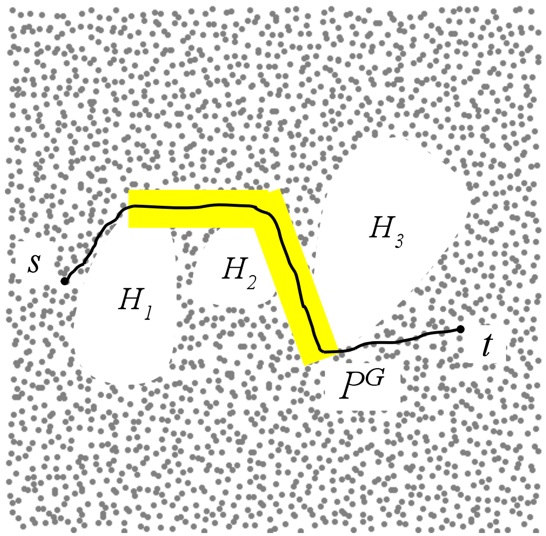
REP in practice (several issues)



The impact of different virtual hole radii

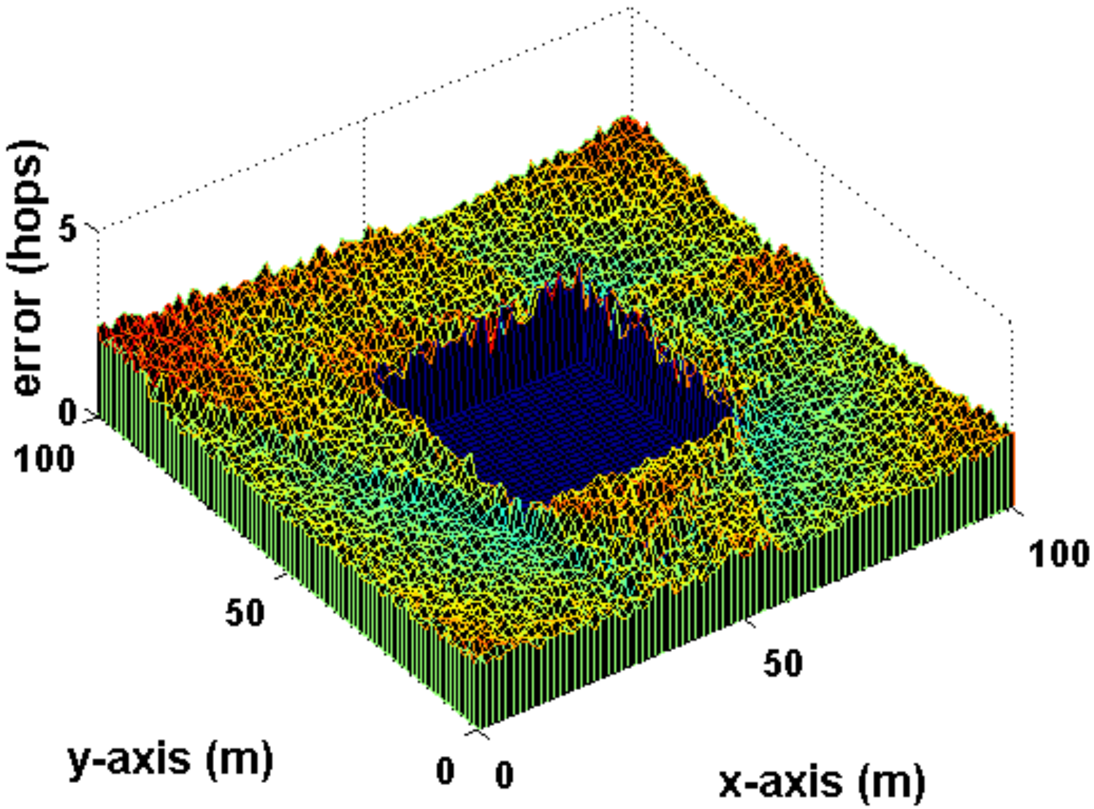


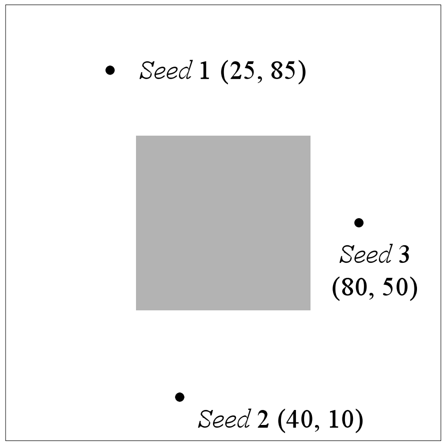
Virtual path alternation



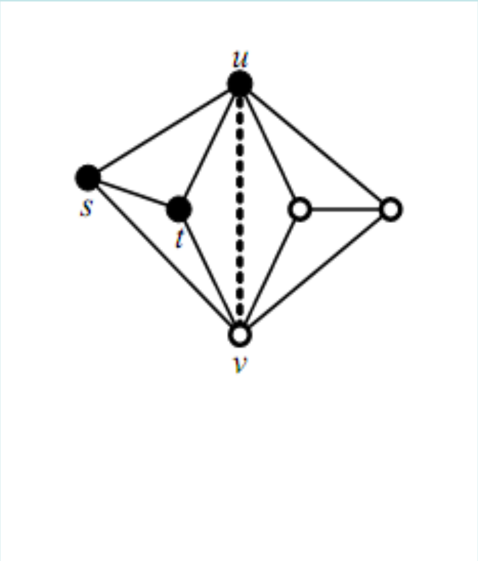
Reducing overhead under multi-hole situations

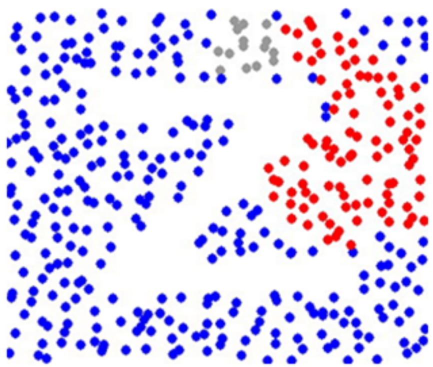
REP Performance (location estimations)



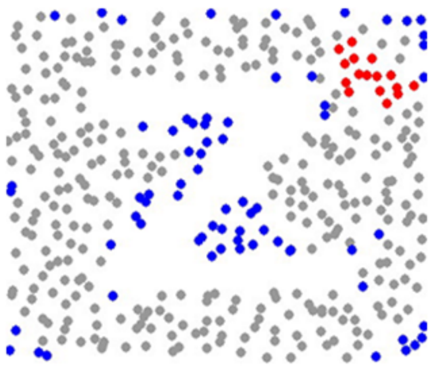


Localizability





Ours

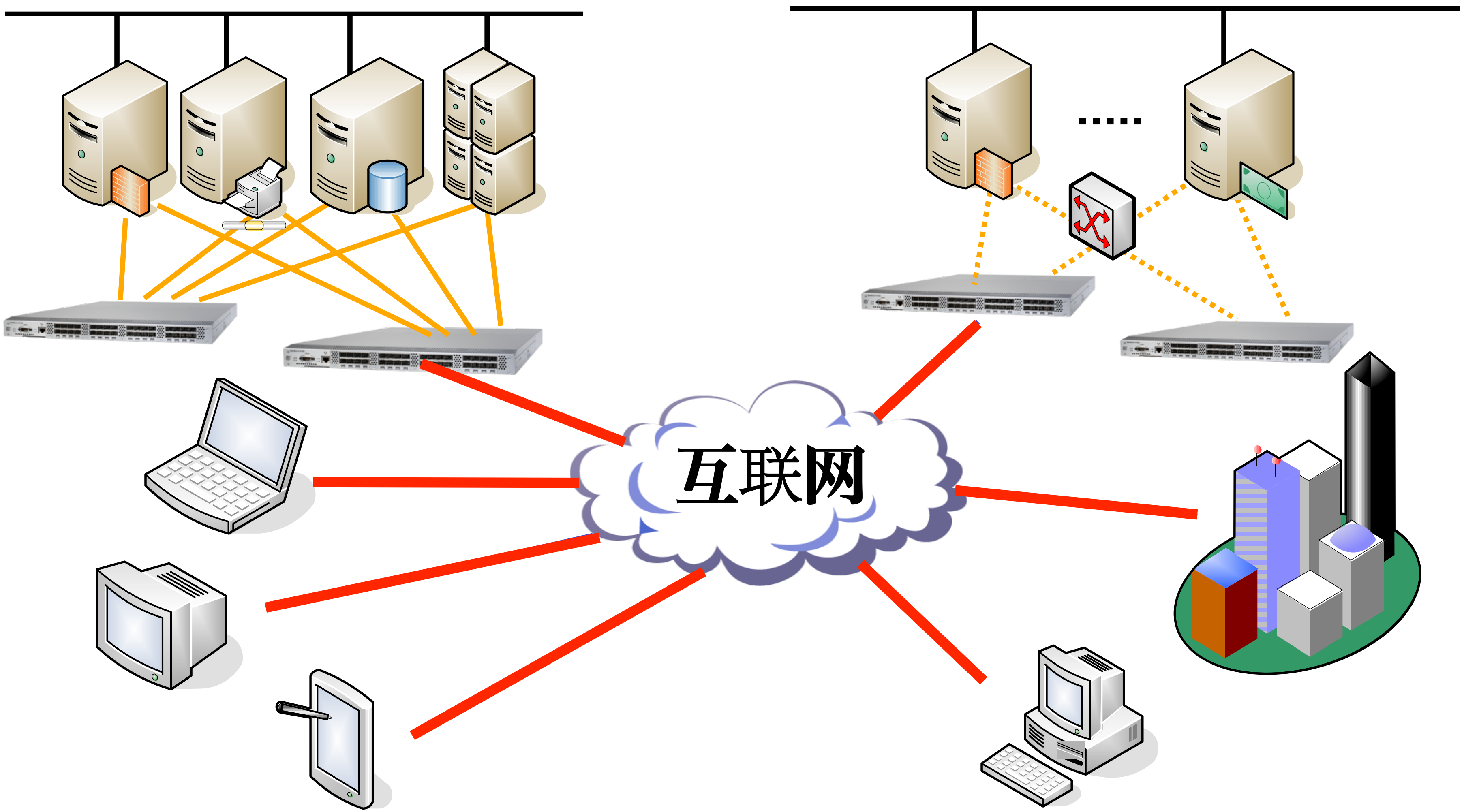


Previous

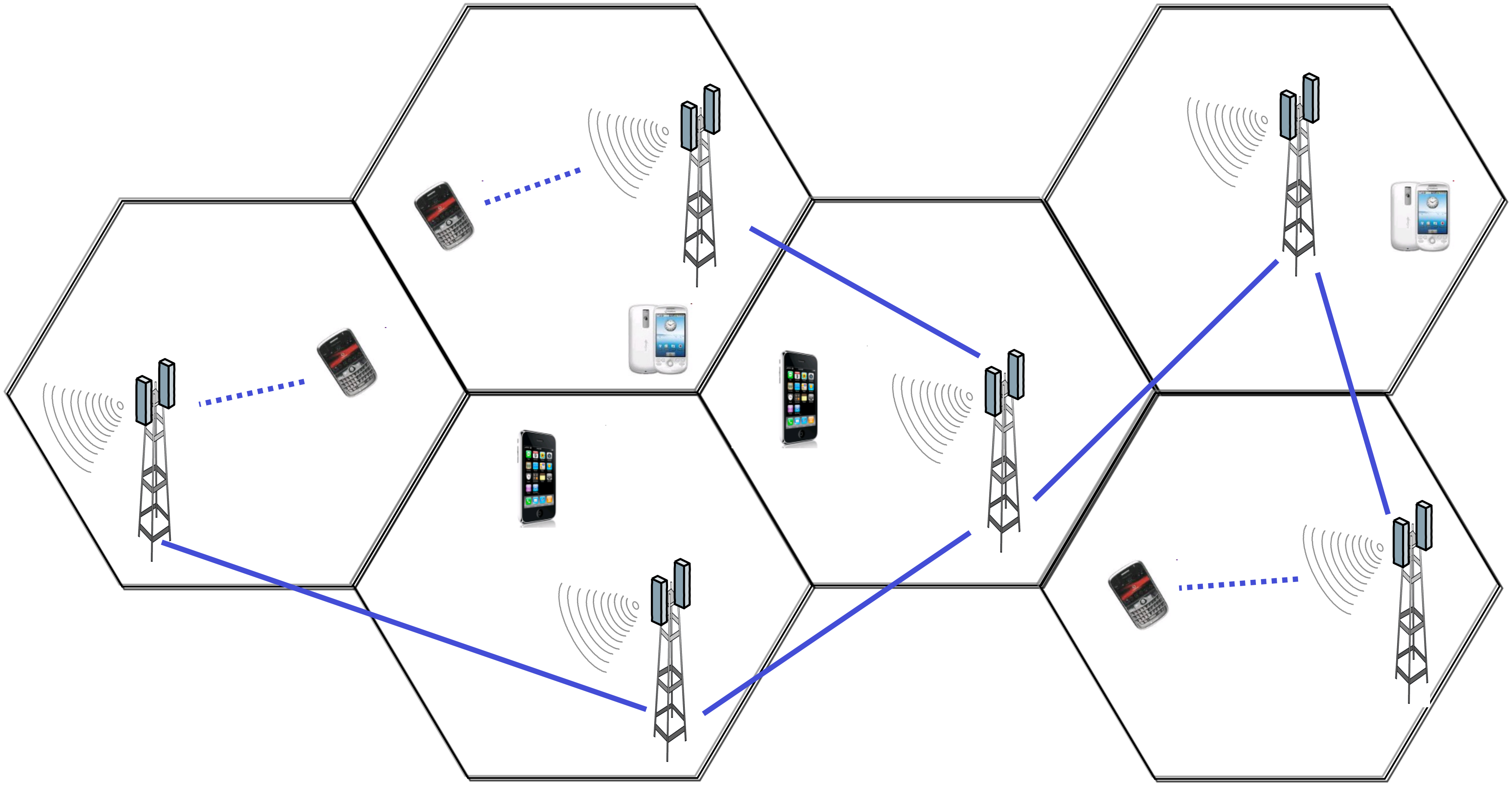
3, Diagnosis and Management

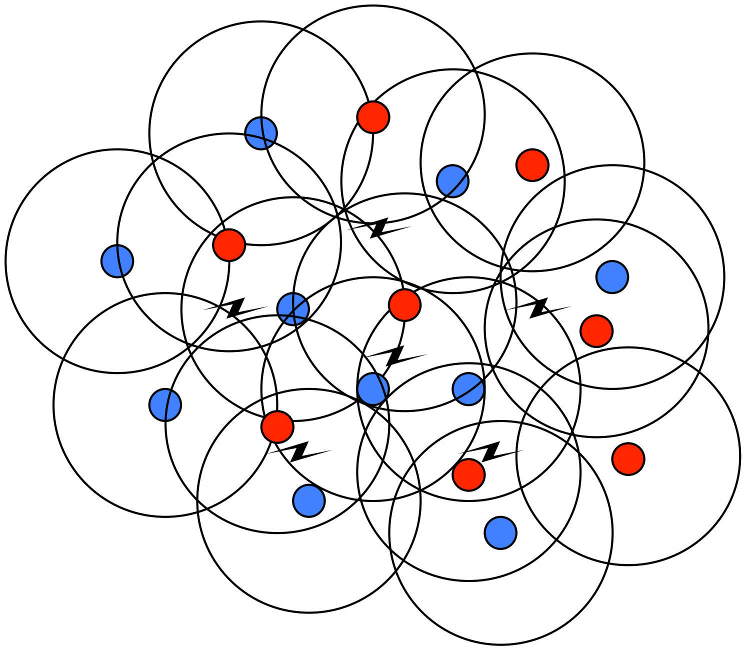
Why difficult compared with Internet?

1, Wireless VS Wired

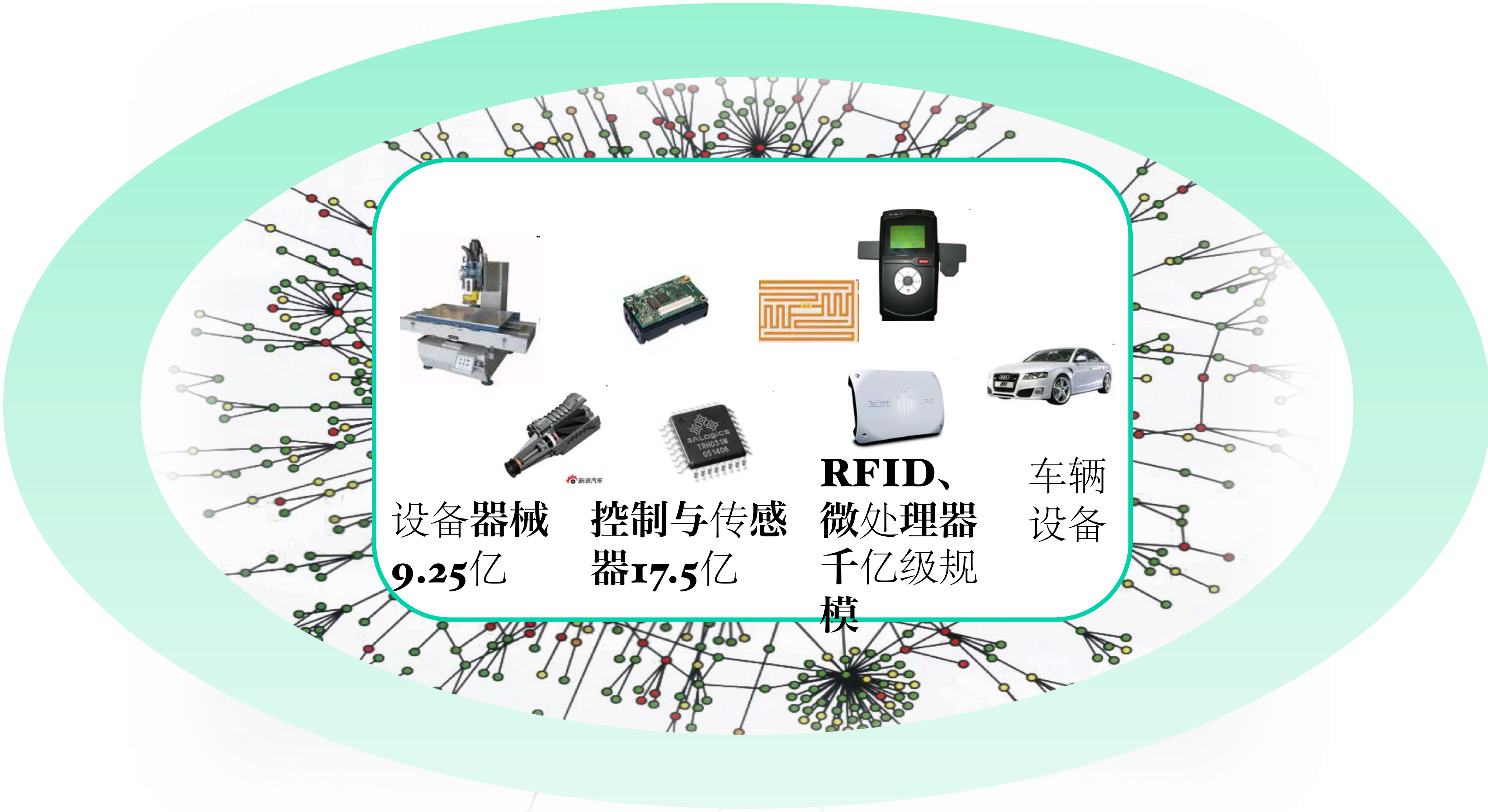


Single hop VS Multi-hop

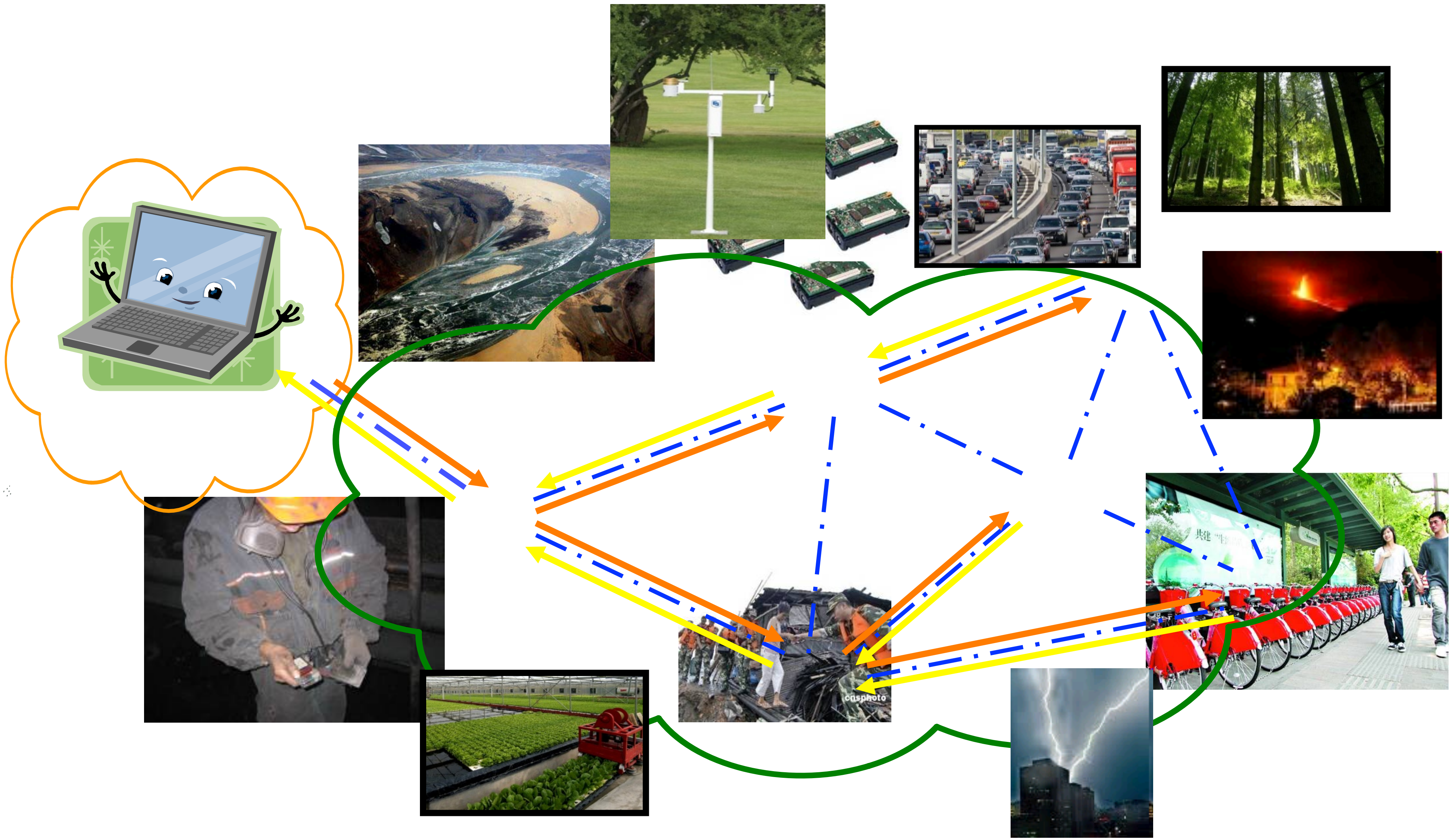




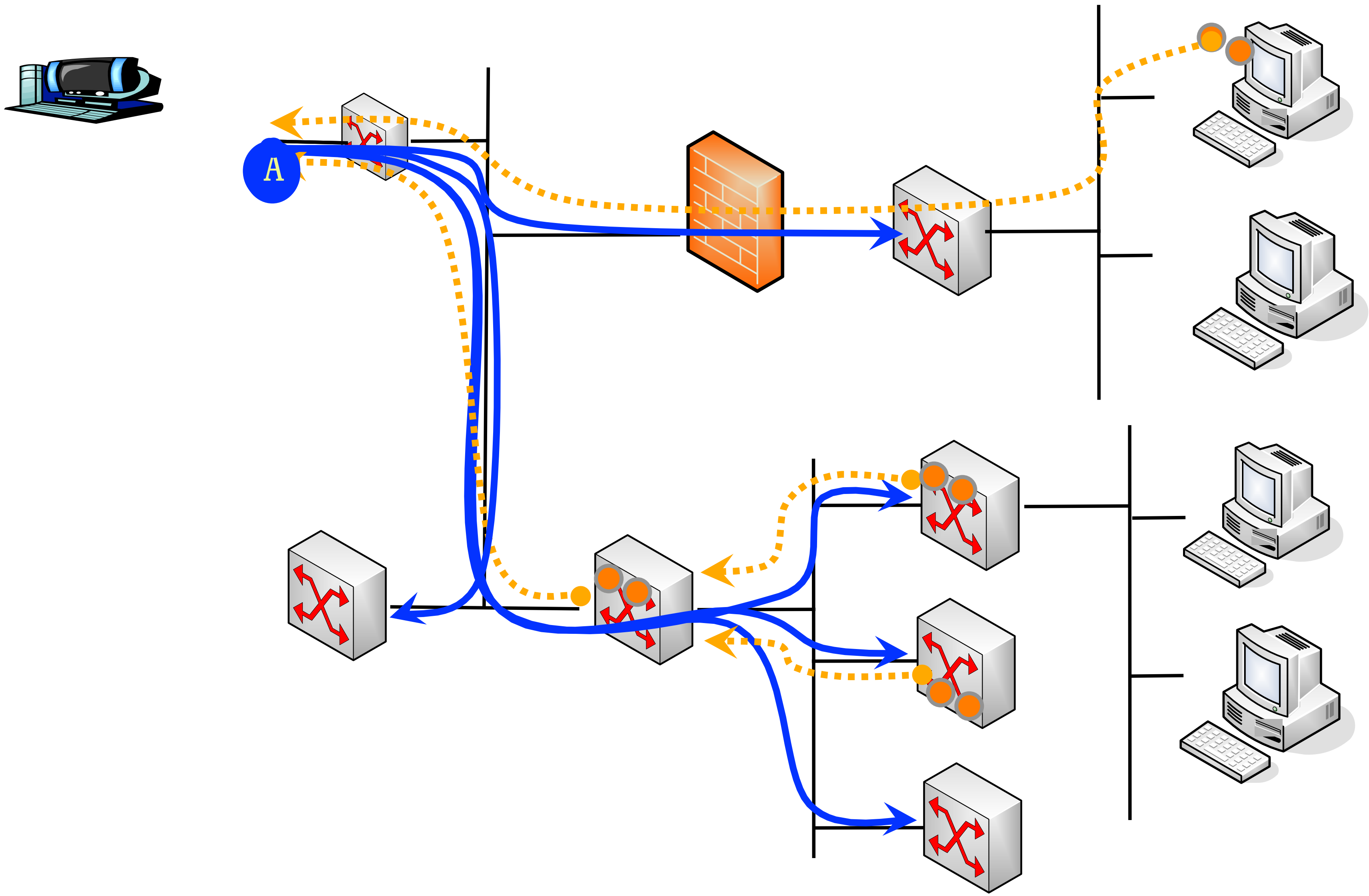
2, Larger number and heterogeneous



3, Tough Application Scenarios

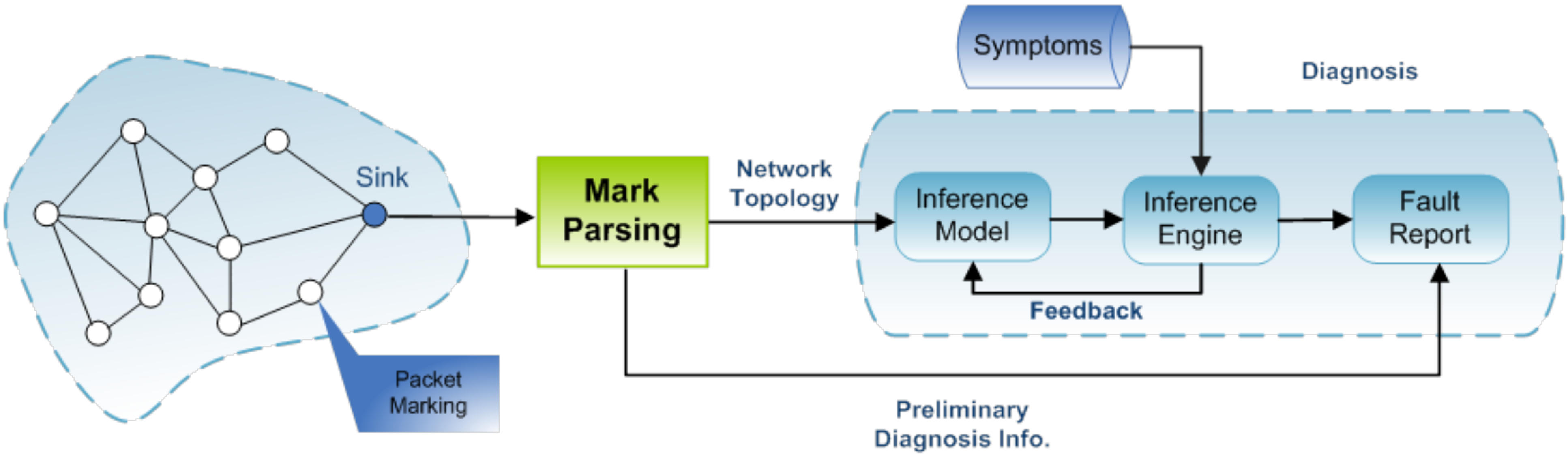


Why not SNMP?



Our Approach: Passive Diagnosis

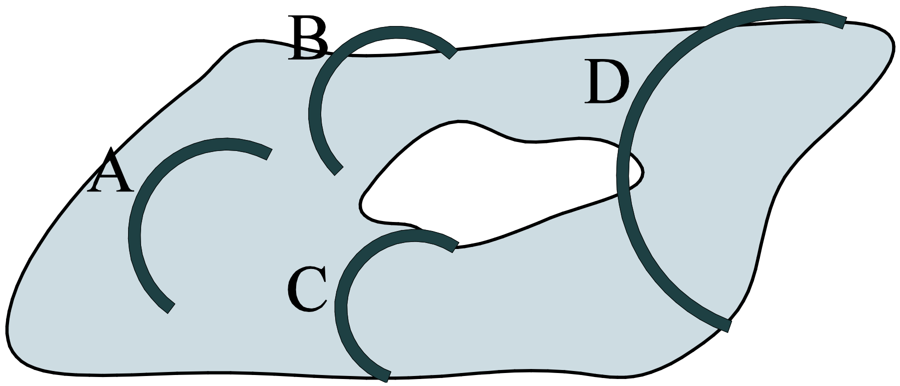
- Sporadically marking the packets
- Probabilistic inference model
- Integrated analysis



4, Security

- Sensitive data
  - Coal Mine: personal security
  - Ocean Sense: national security
- Protect WSNs from attacking
  - Cheating
  - Forging
  - Wormhole attacking

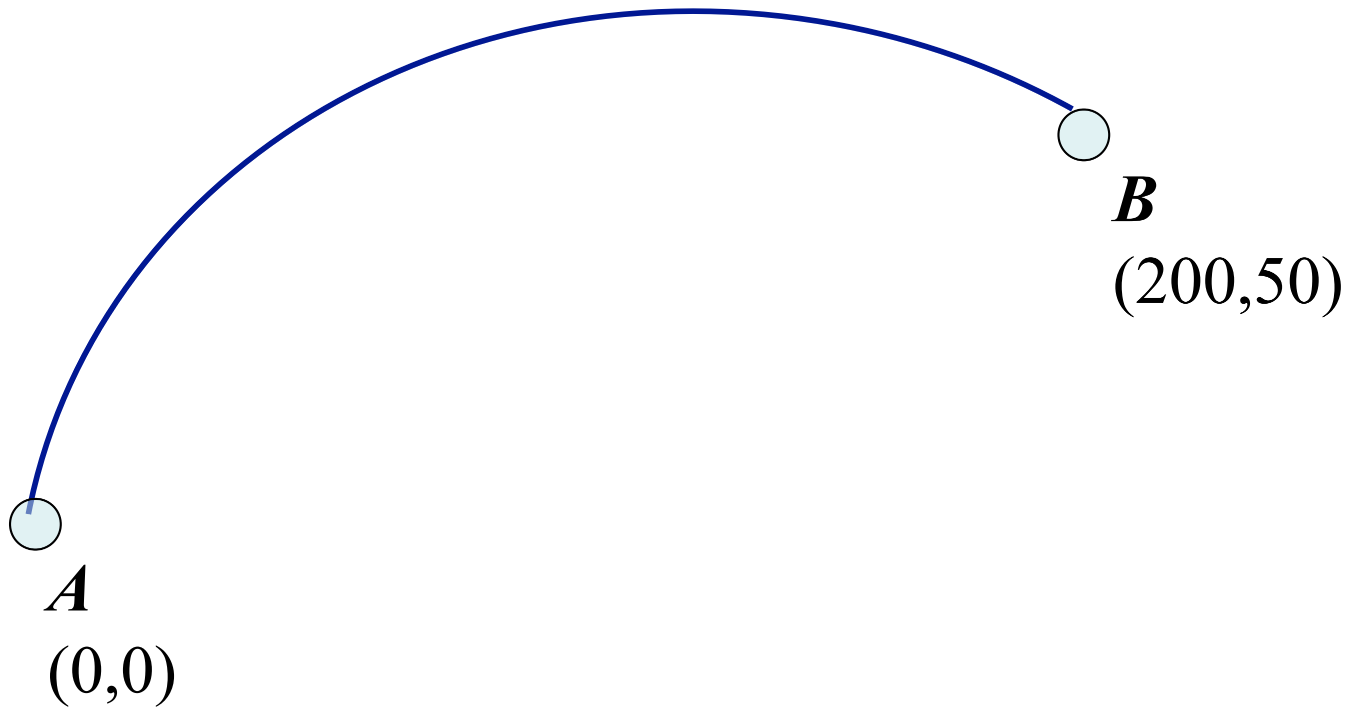
Problem



External channel
Malicious behaviors

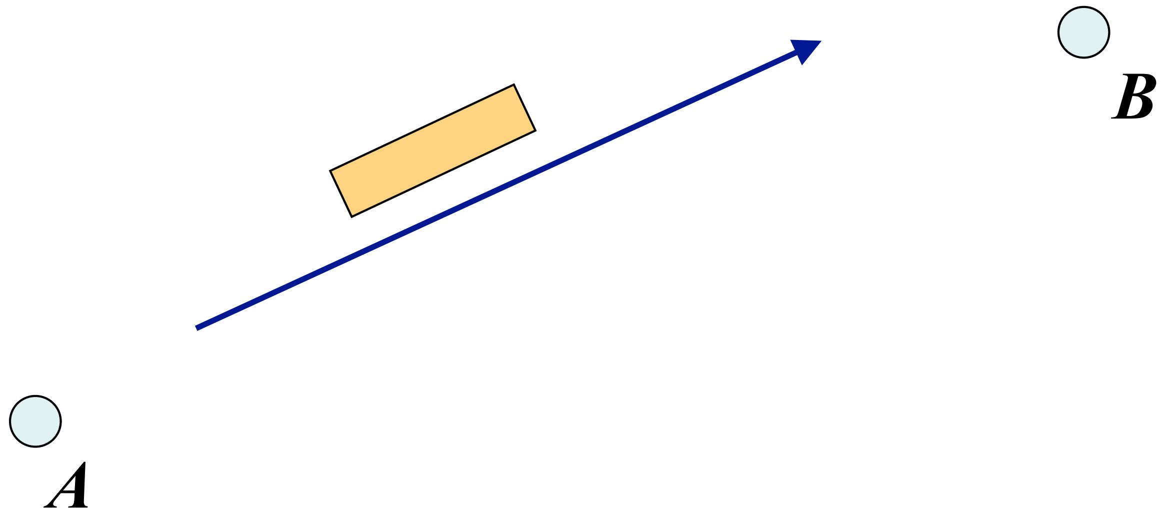
Previous Work

- Symptom of distance mismatch



Previous Work

- Symptom of time mismatch



Previous Work

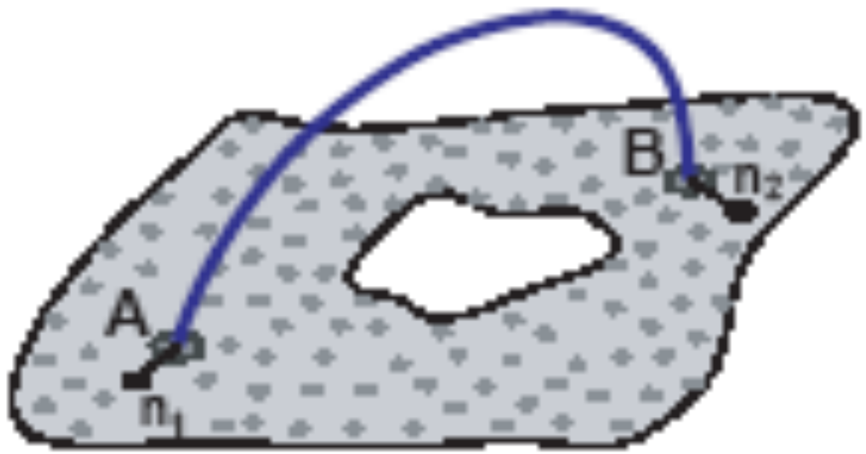
- Symptom of neighborhood mismatch
- Symptom of graph mismatch
- Symptom of traffic flow mismatch

Critical assumptions

Extra cost

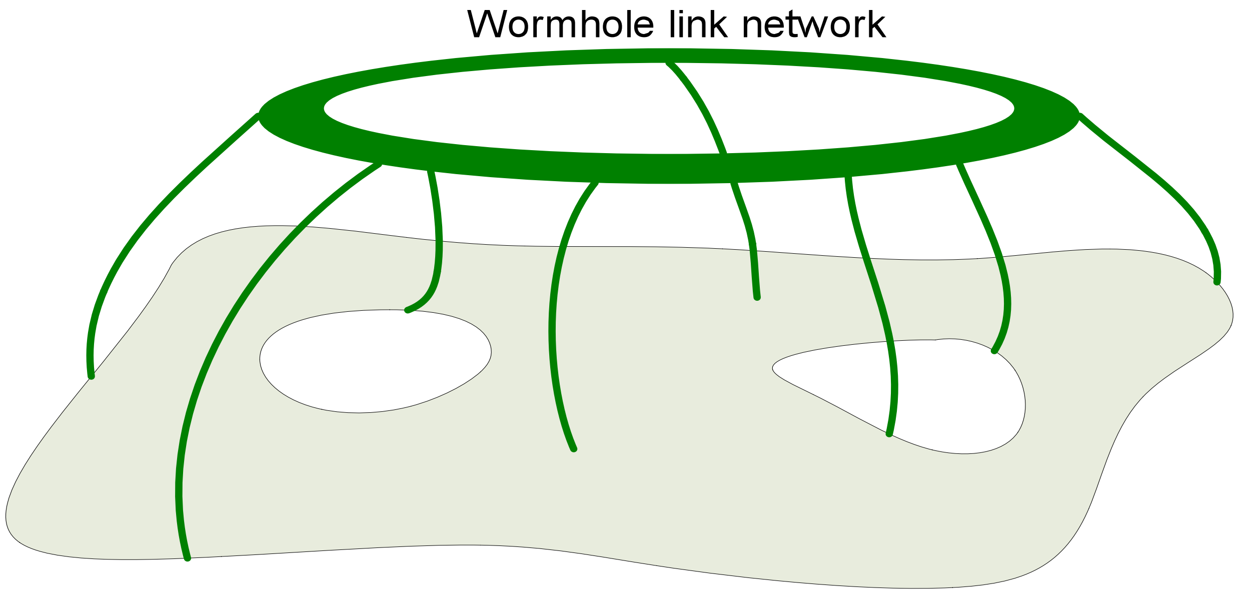
Previous Work

- One hop link v.s. multiple hop link

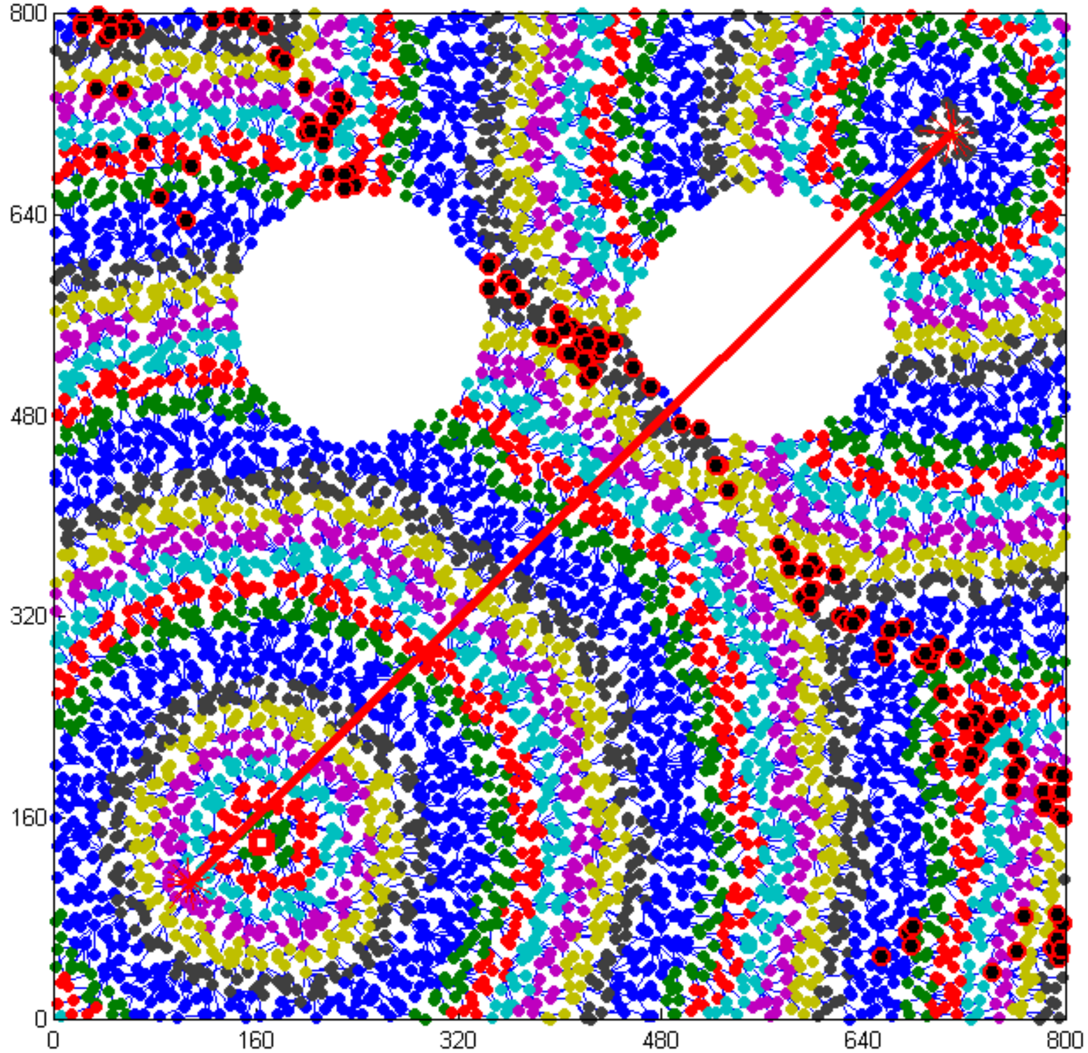


Problem Reformulation

– Two endpoints v.s. multiple endpoints
– “Wormhole mesh“



一个快速的idea!



Topological Method

- Topological impact
- No critical assumptions
  - UDG
  - Location
  - Synchronization
  - etc.
- Accurate detection

Topological Methods

- In computer science
  - Concurrency theory
  - Computational algebraic topology
  - Visualization and image analysis
  - Distributed computing
  - …
- In sensor networks
  - Homotopy of shortest paths in the detection of holes (同伦)
  - Homology for detection of coverage holes (同调)
  - Morse-Smale complex and flow complex in network segmentation and signal analysis
  - …

What is Topology?

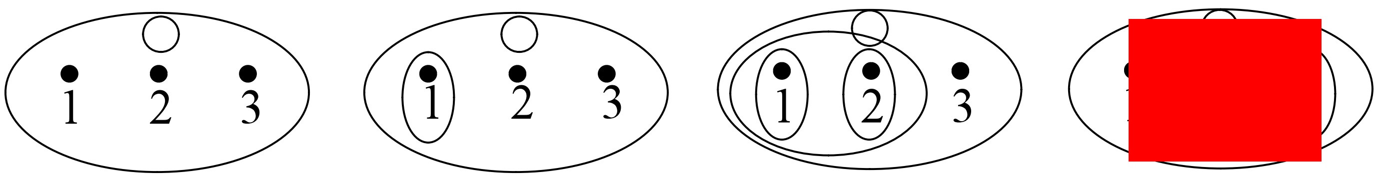
- Informally, **topology** studies ***properties*** of an ***object*** that remain unaffected under **deformation.**

Topological space | *Topological invariant* | *Homeomorphism*

topologically equivalent between a coffee cup and a donut.

Topological Space

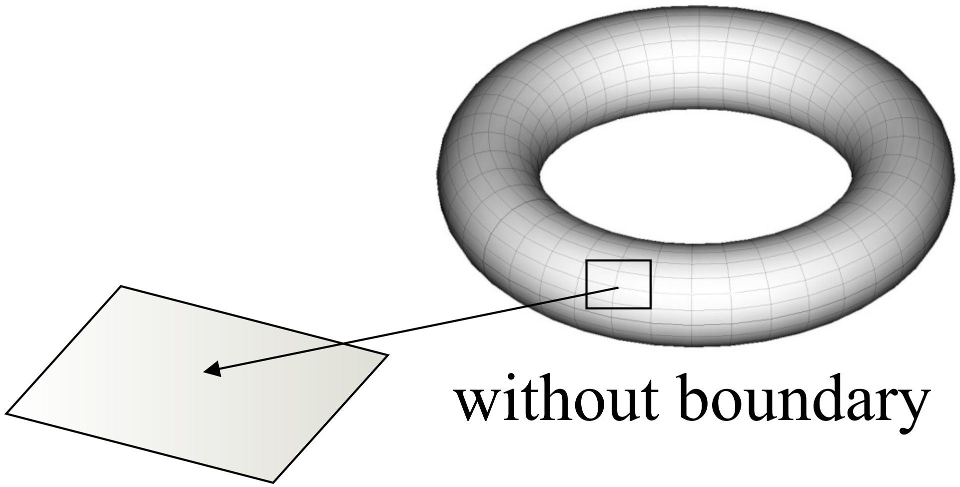
- A ***topological space*** is a pair (X, T), where X a set and a ***topology*** (structure) T on the set.
  - A collection T of subsets of X is a ***topology*** on X , if
  - Empty set and X are in T.
  - Union or intersection of elements of T are in T.

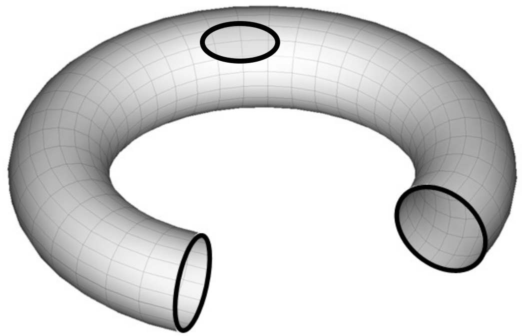


- Examples of topologies:
  - The collection of all subsets of X.
  - If X is the set of real numbers, the collection of all open intervals and unions of intervals. (Euclidean spaces)

Topological Space

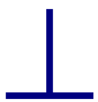
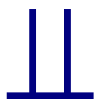
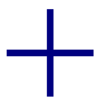
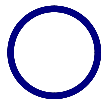
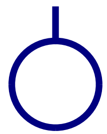
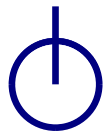
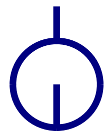
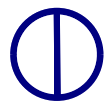
- **Manifolds** are a type of topological space
  - A generalization of Euclidean spaces.
  - Intuitively, a manifold is locally Euclidean.
- Examples: **2-D manifold**
  - A 2-D manifold is *locally flat*: locally, it looks like a plane.
  - Formally, every point has a neighborhood homeomorphic to an open disk





Homeomorphism

- A ***homeomorphism*** f is a function between two topological spaces X and Y.
  - if $f : X \rightarrow Y$ is a bijection, f and f^{-1} is continuous
- Example: classification of the homeomorphic letters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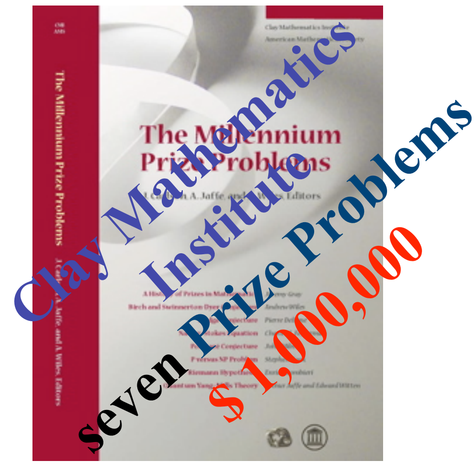
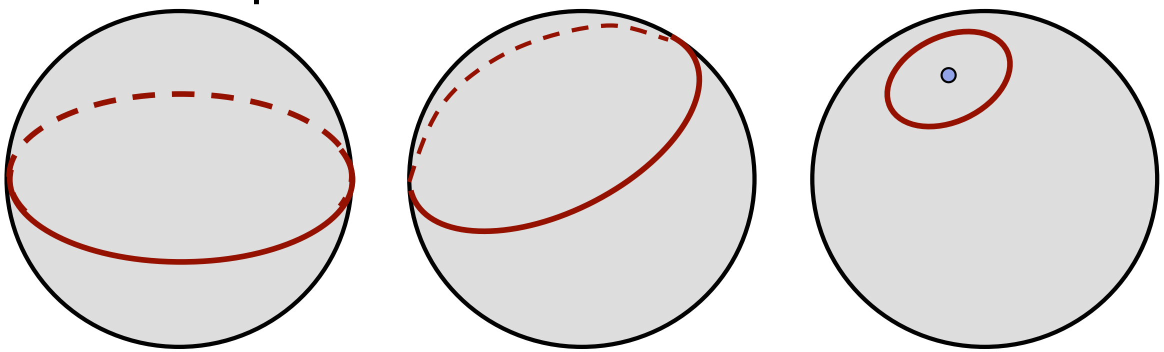
Homeomorphism

- ***Poincaré Conjecture*** is about objects being homeomorphic to a 3-dimensional sphere.
  - If a compact 3-dimensional object has the property that every simple closed curve within the object can be deformed continuously to a point, does it follow that it is homeomorphic to the 3-sphere? Yes.





Poincaré Conjecture, 2-dimensional case

Topological Invariant

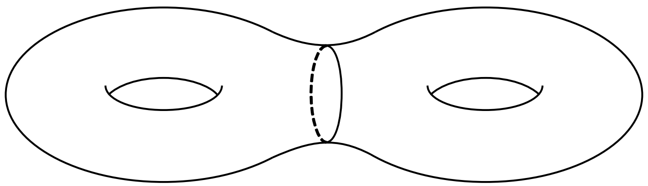
- How to prove whether two objects are topologically equivalent or not?
  - But sometimes it is hard, we need more tools.

Two objects are homeomorphic $\underset{\not\Leftarrow}{\Rightarrow}$ They have the same topological invariants

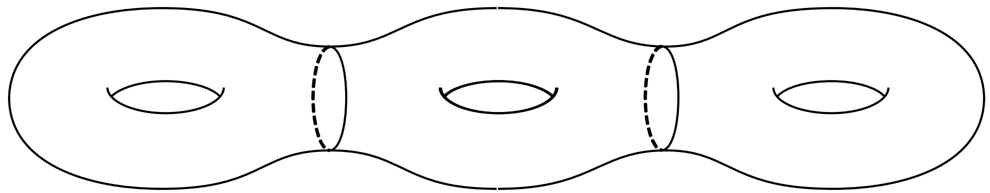
- A ***topological invariant*** is a property which remain unaffected by homeomorphism.
- Examples of topological invariants
  - Euler characteristic, Connectedness, **Betti number**, **Genus**

Topological Invariant

- Genus: “number of holes”
  - Classifying such surfaces
  - Genus of a surface is the maximal number of ***nonintersecting simple closed curves*** that can be drawn on the surface without separating it.
- Example:
  - Genus 0: point, line, sphere
  - Genus 1: torus



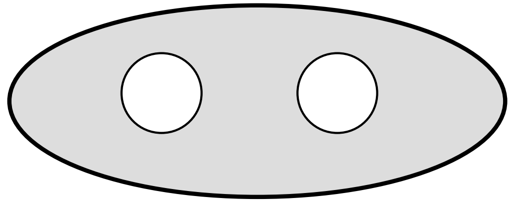
Genus 2



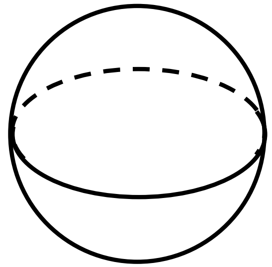
Genus 3

Topological Invariant

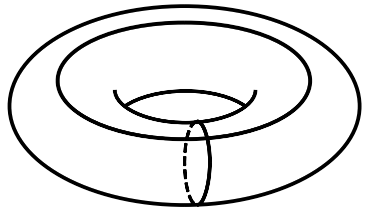
- Betti number
  - give a count of basic topological features: components, holes, etc.
  - for an object in 2-dimensional space
    - b_0 is the number of components
    - b_1 is the number of holes
  - for an object in 3-dimensional space
    - b_0 is the number of components
    - b_1 is the number of tunnels or handles
    - b_2 is the number of voids or cavities
  - in higher dimensions
    - b_k measures the k-dimensional connectivity of X
    - $b_k(X) = \dim(H_k(X))$, $H(X)$ is the homology groups



$b_0 = 1,\ b_1 = 2,\ b_2 = 0$



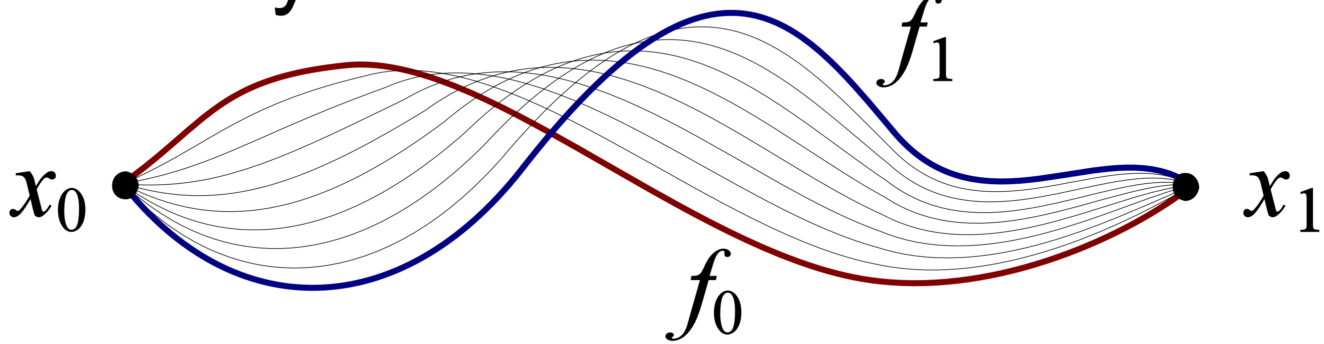
$b_0 = 1,\ b_1 = 0,\ b_2 = 1$



$b_0 = 1,\ b_1 = 2,\ b_2 = 1$

Homotopy

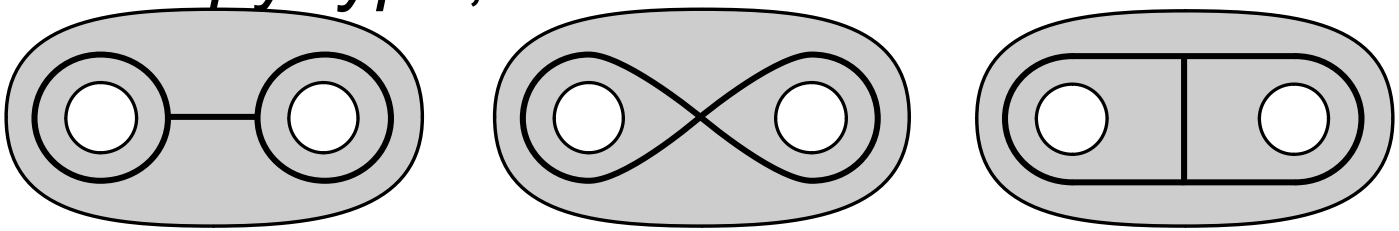
- Two paths f_0 and f_1 are ***homotopic*** (written $f_0 \simeq f_1$) if one loop can be continuously deformed into the other.

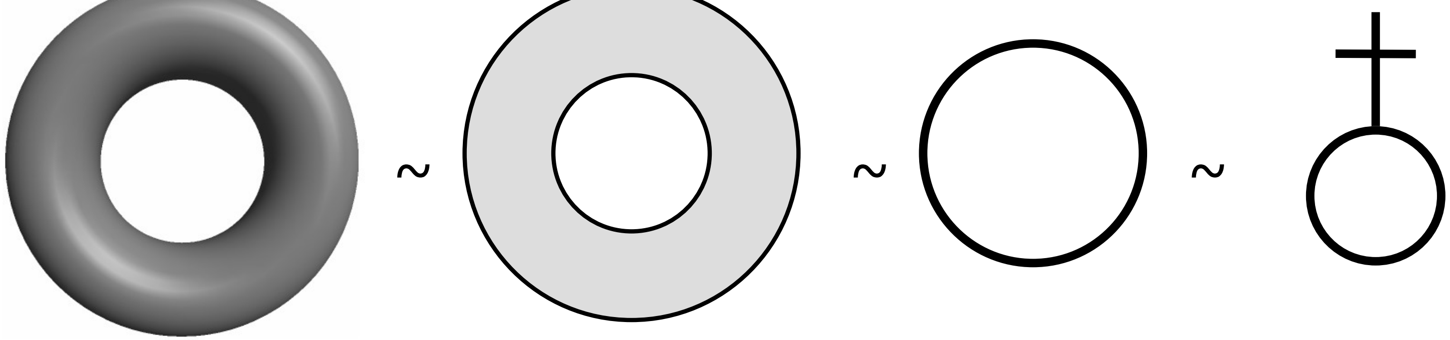


Formally, a ***homotopy*** from f_0 to f_1 is a continuous function h:[0,1]x[0,1]→M where $h(0,t)=f_0(t)$, $h(1,t)= f_1(\mathrm{t})$, and $h(s,0)= x_0$, $h(s,1)= x_1$

Homotopy

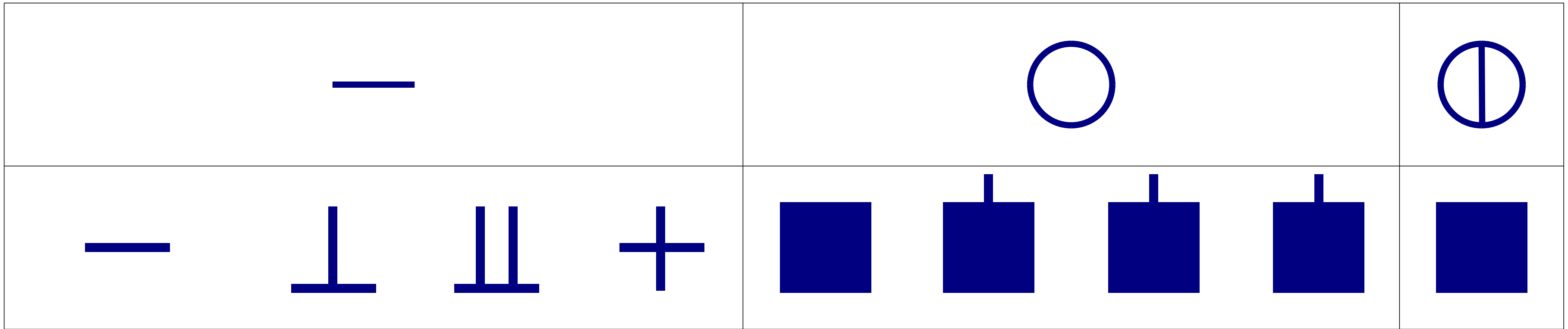
- Homotopy equivalent
  - A map $f : X \to Y$ is called a *homotopy equivalence* if there is a map $g : Y \to X$, such that $f \circ g \simeq 1_Y$ and $g \circ f \simeq 1_X$. Then, X and Y are *homotopy equivalent* and have the same *homotopy type*, denoted as $X \simeq Y$.





Homotopy

- Homotopy equivalent



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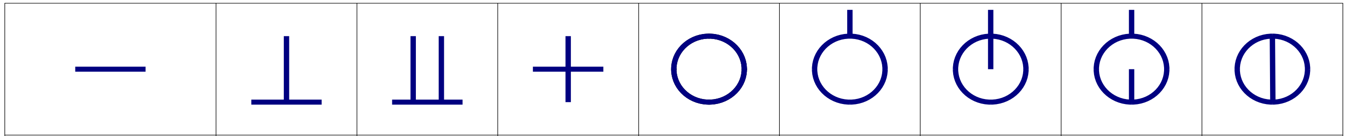
Homotopy



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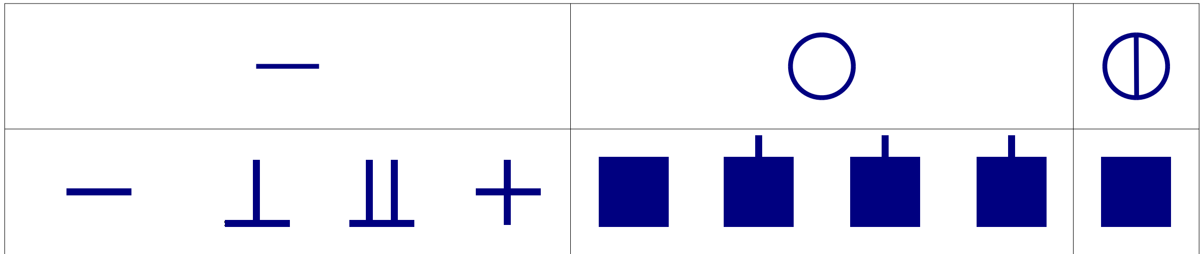

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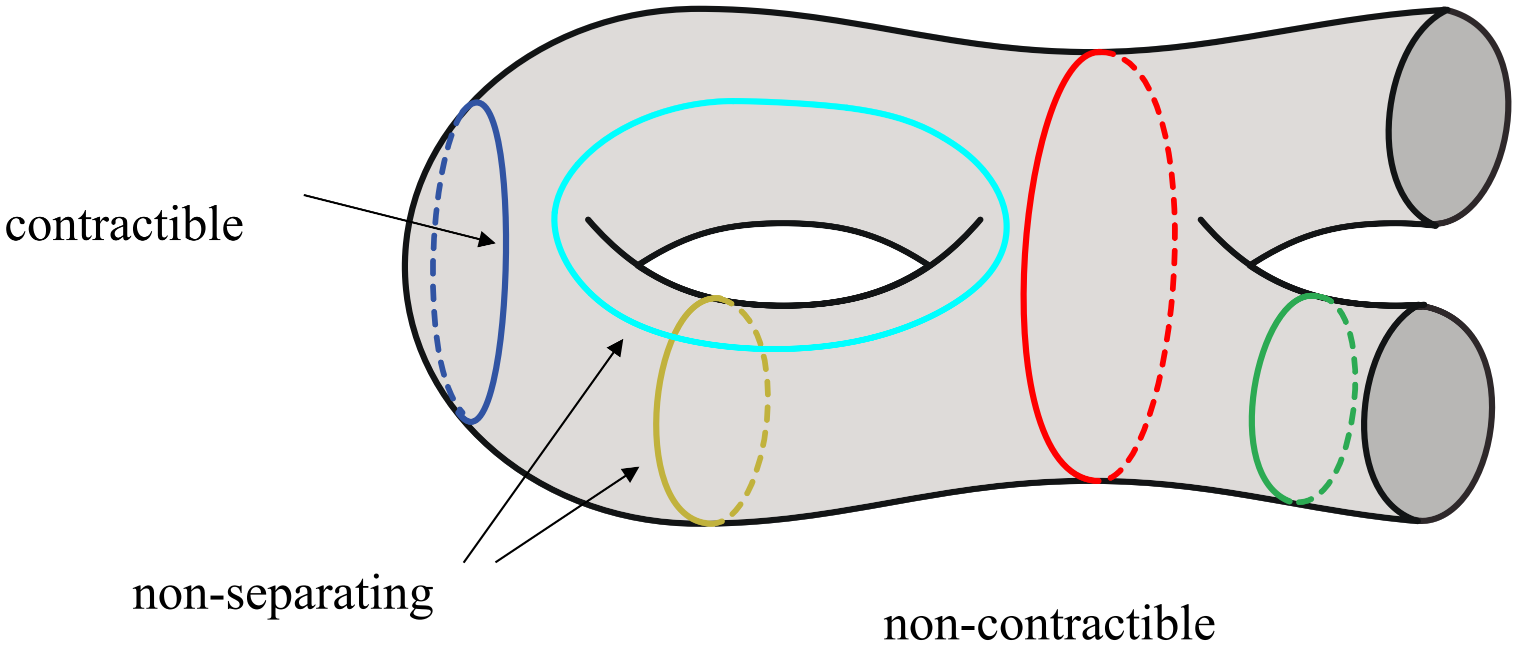
Topologically equivalent

$\subseteq$

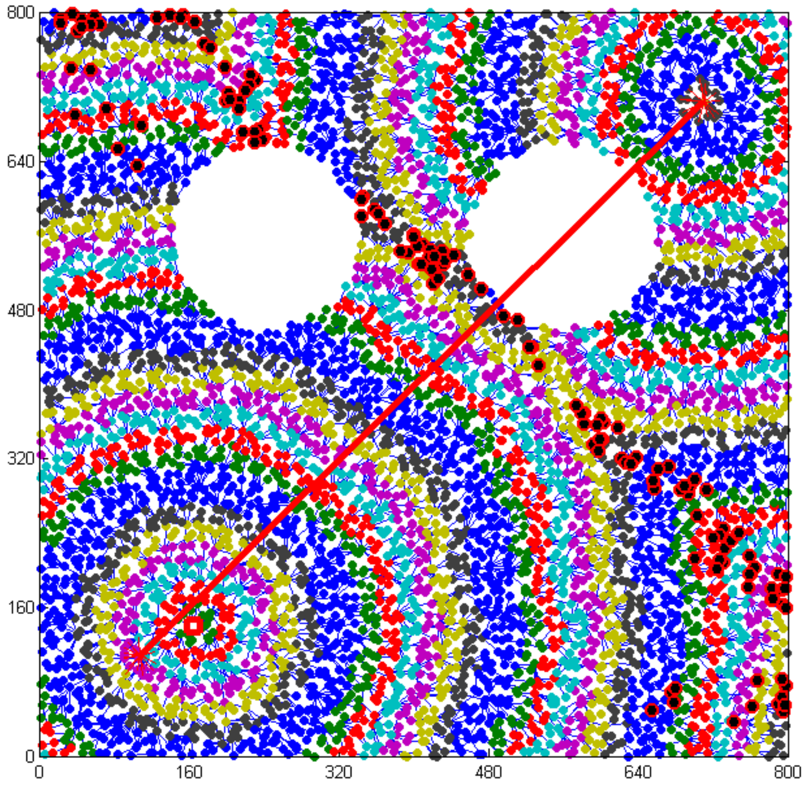
Homotopy equivalent

Homotopy

- Contractible, non-contractible, non-separating cycles in surfaces.
  - A cycle is *contractible* if it is homotopic to a constant a point; otherwise it is *non-contractible*.

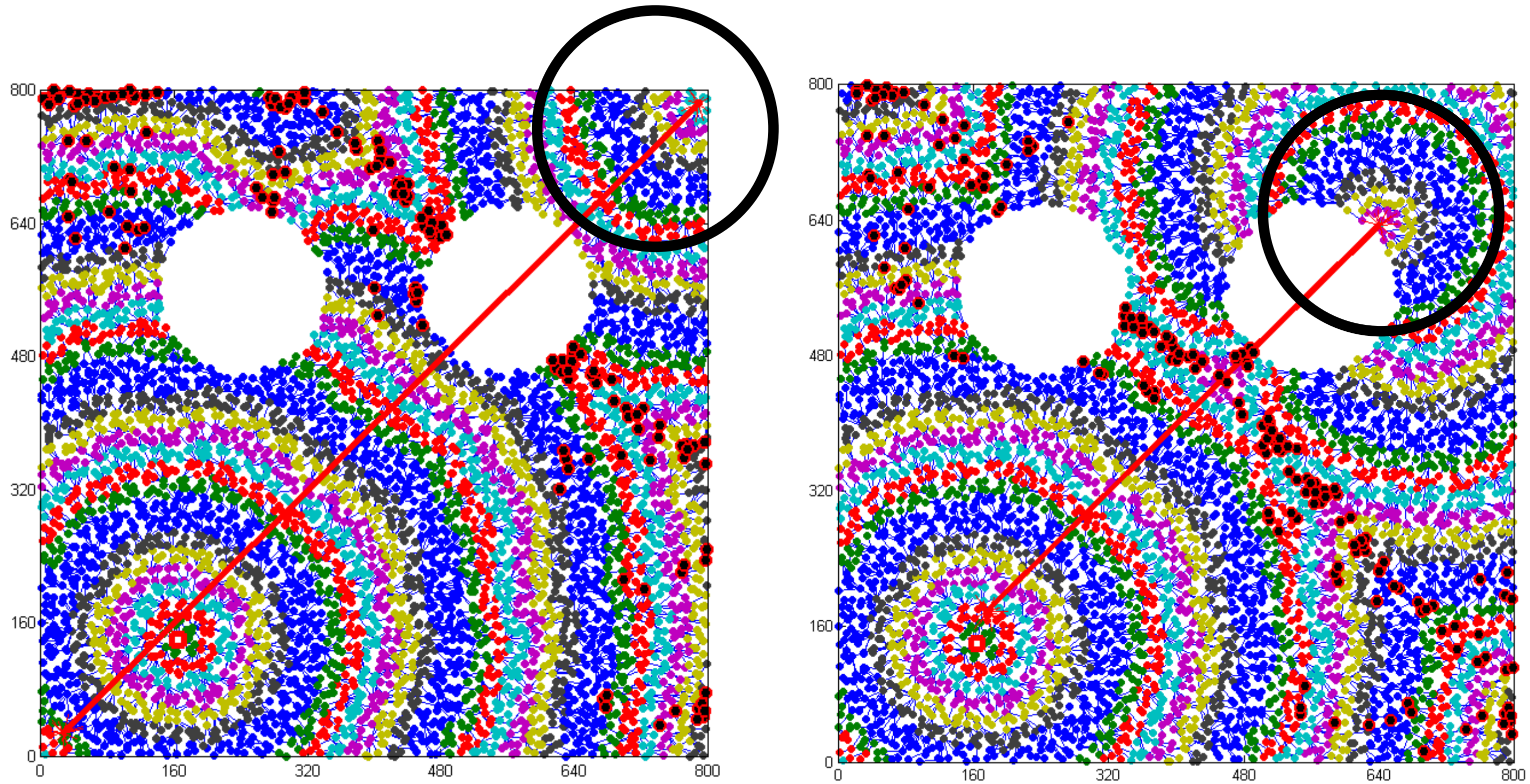


Come Back to Wormhole Detection…



nodes on the same isolines form a circle in the endpoint of wormhole link

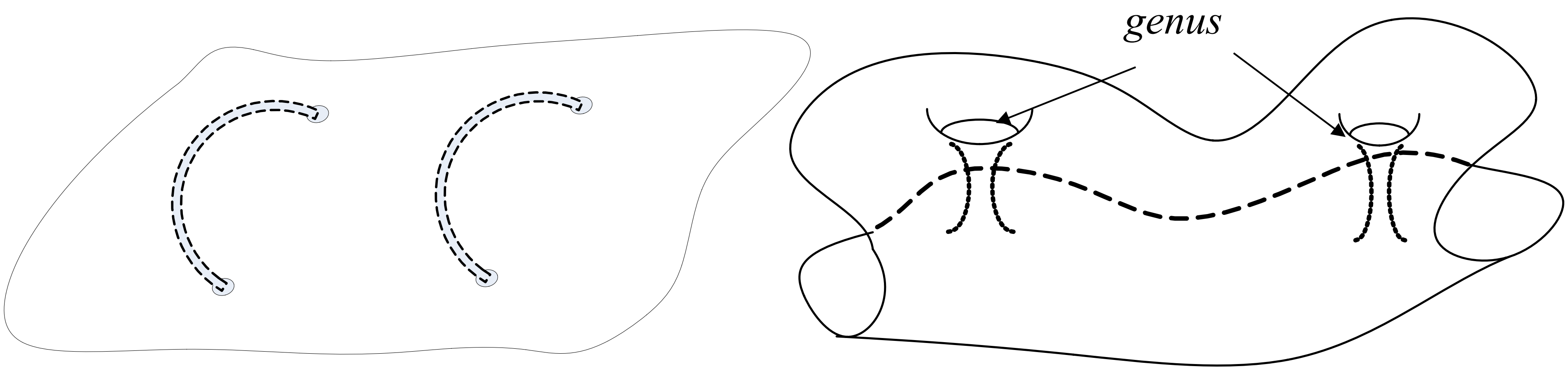
Isoline Detection Fails



When the endpoint of wormhole locate at the inner or outer boundary of the network, it will not form the circle

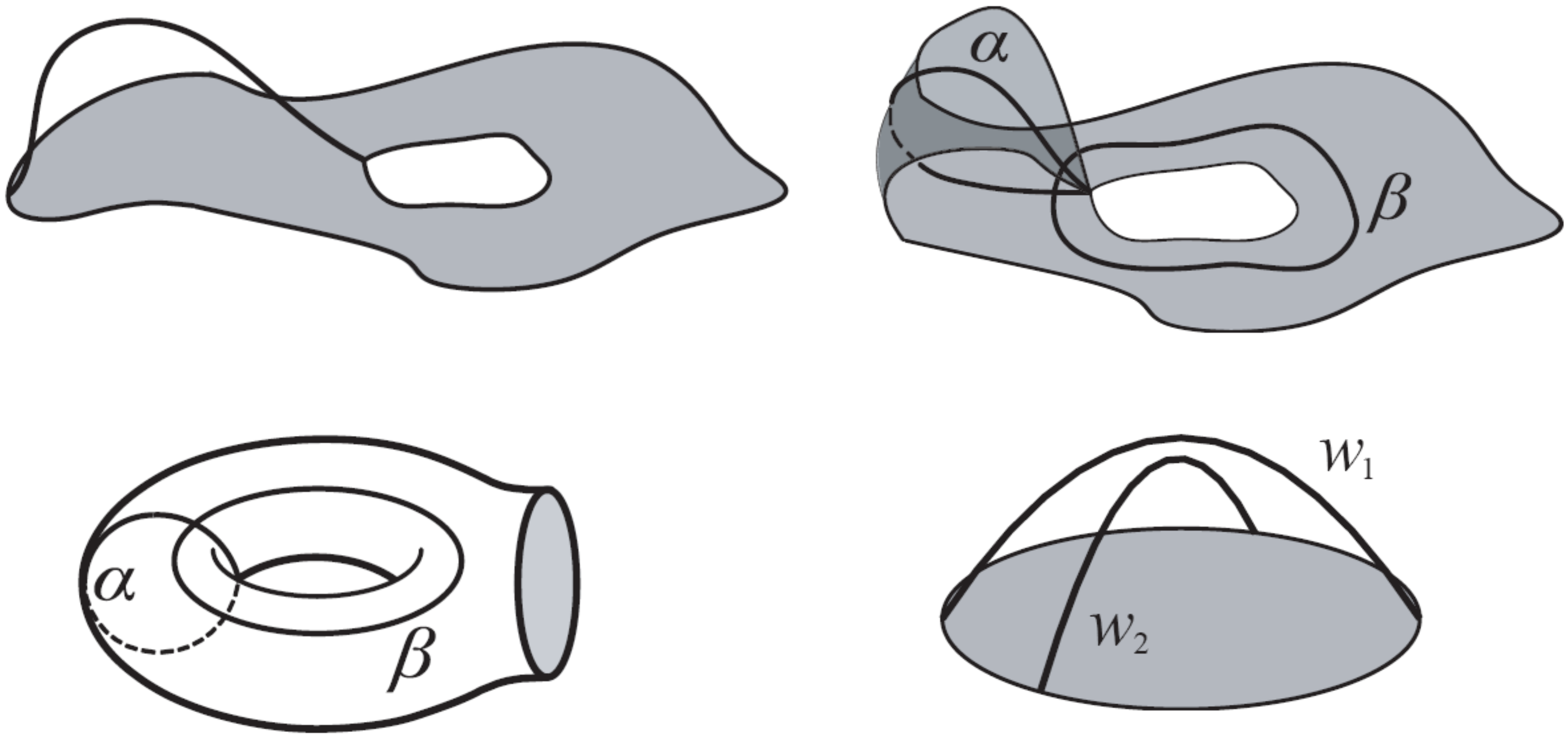
Topological Impact of Wormhole

- *A wormhole will add a genus to the network topology.*



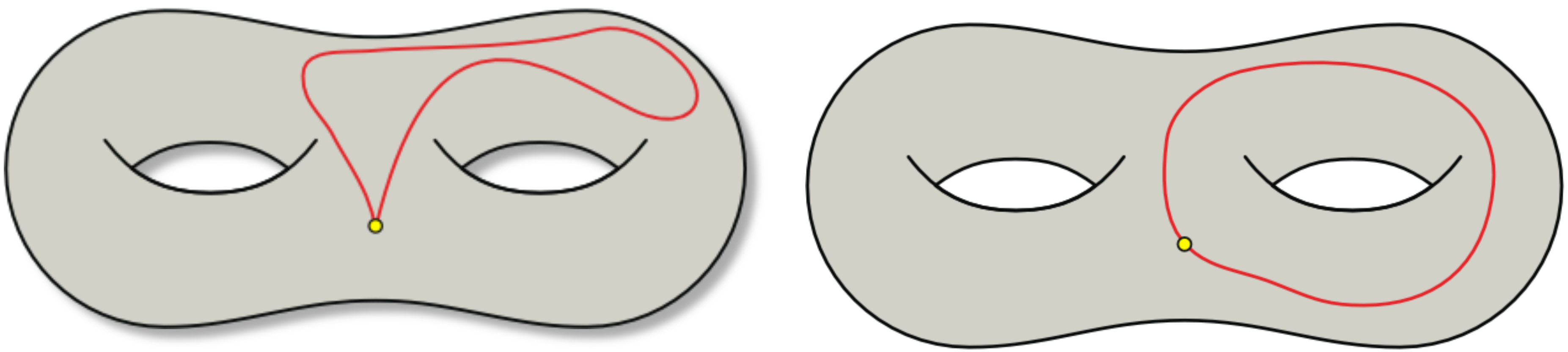
Two simple wormholes add tow genus to original network topology, The right graph shows the real shape of the left graph, which is folded, like a two torus with a big hole.
 "genus" is a topology terminology, "亏格" in chinese.

Characterize Wormholes



Topological Impact of Wormhole

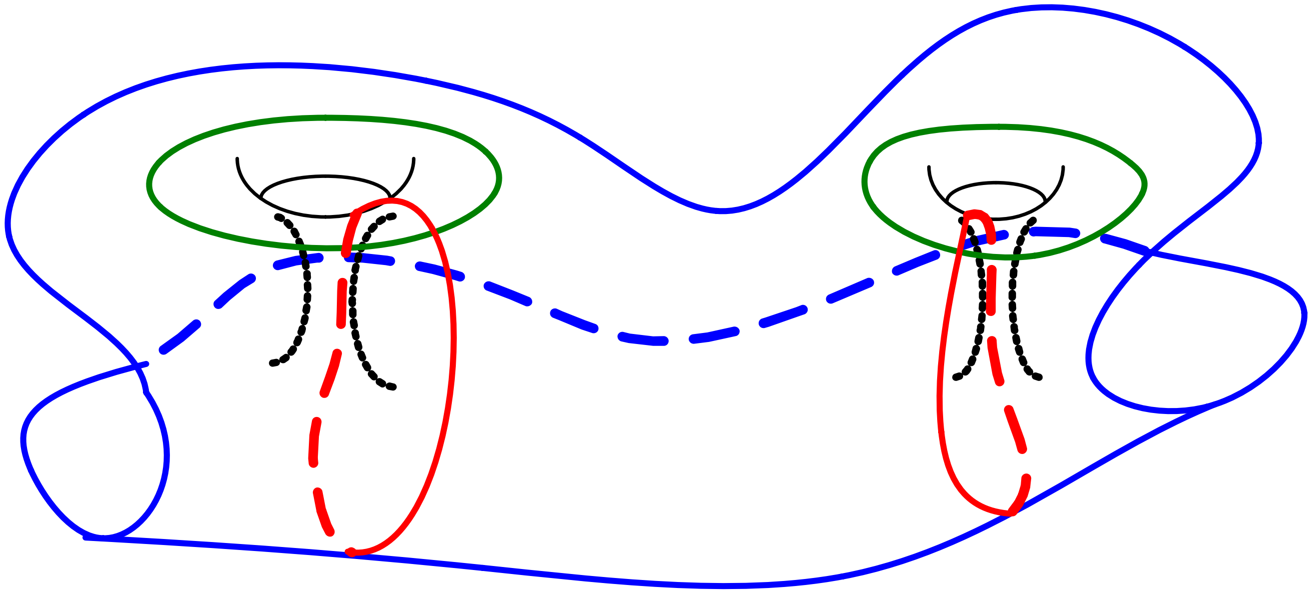
- Non-contractible cycles and contractible cycles



contractible and non-contractible cycles (loops)

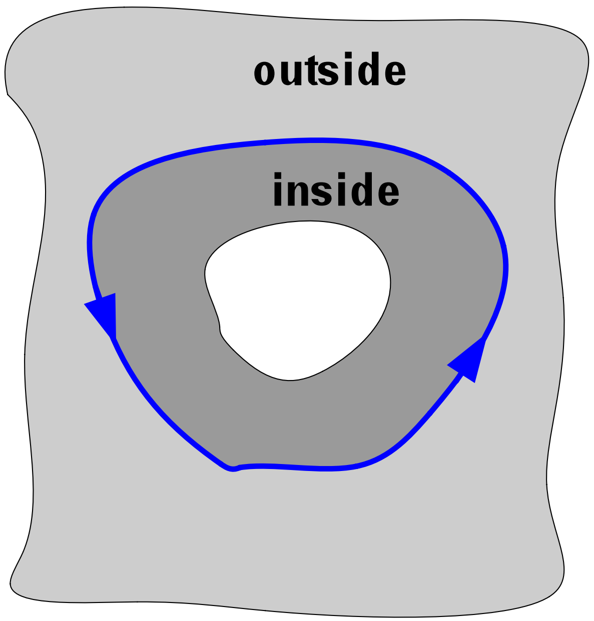
How to Detect and Locate Genus

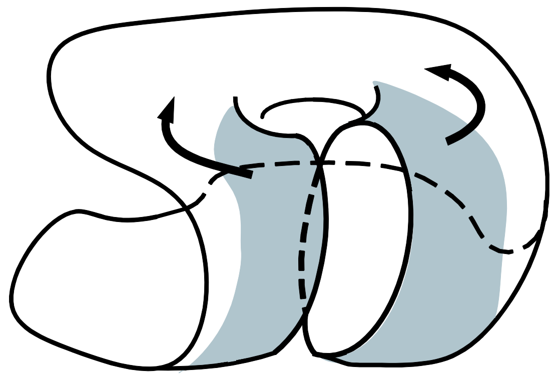
- We need to find the circles that characterize the genera.



There must exist two circles be associated to a genus, the red and green. (homotopy basis or homology basis).

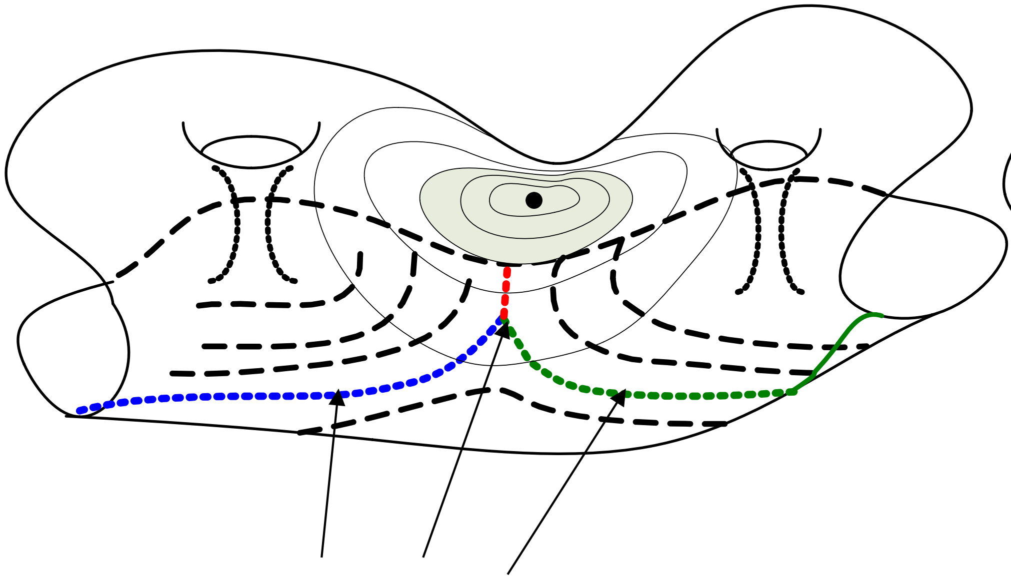
How to Detect and Locate Genus



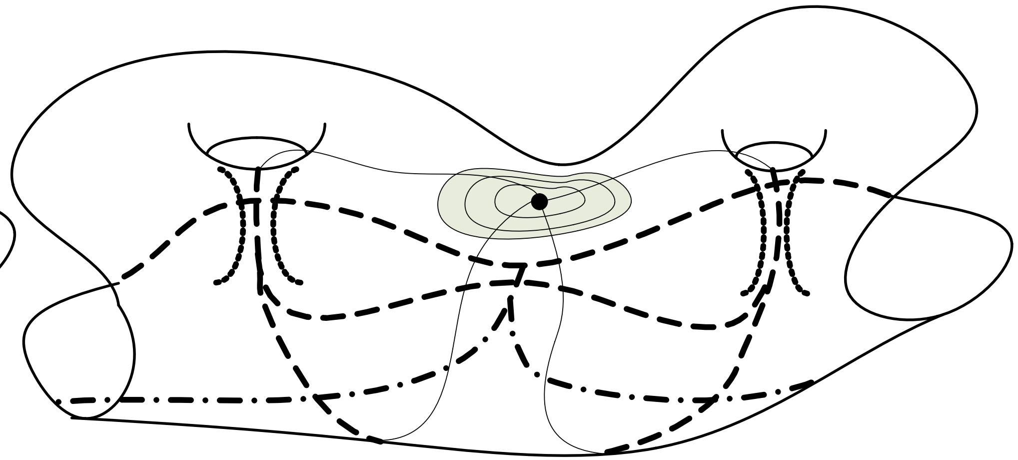


The Method

- 1. flood the network from an arbitrary node
- 2. determine the nodes that form the non-contractible cycles
  (Contract a cycle to be shortest, *maybe optional*)

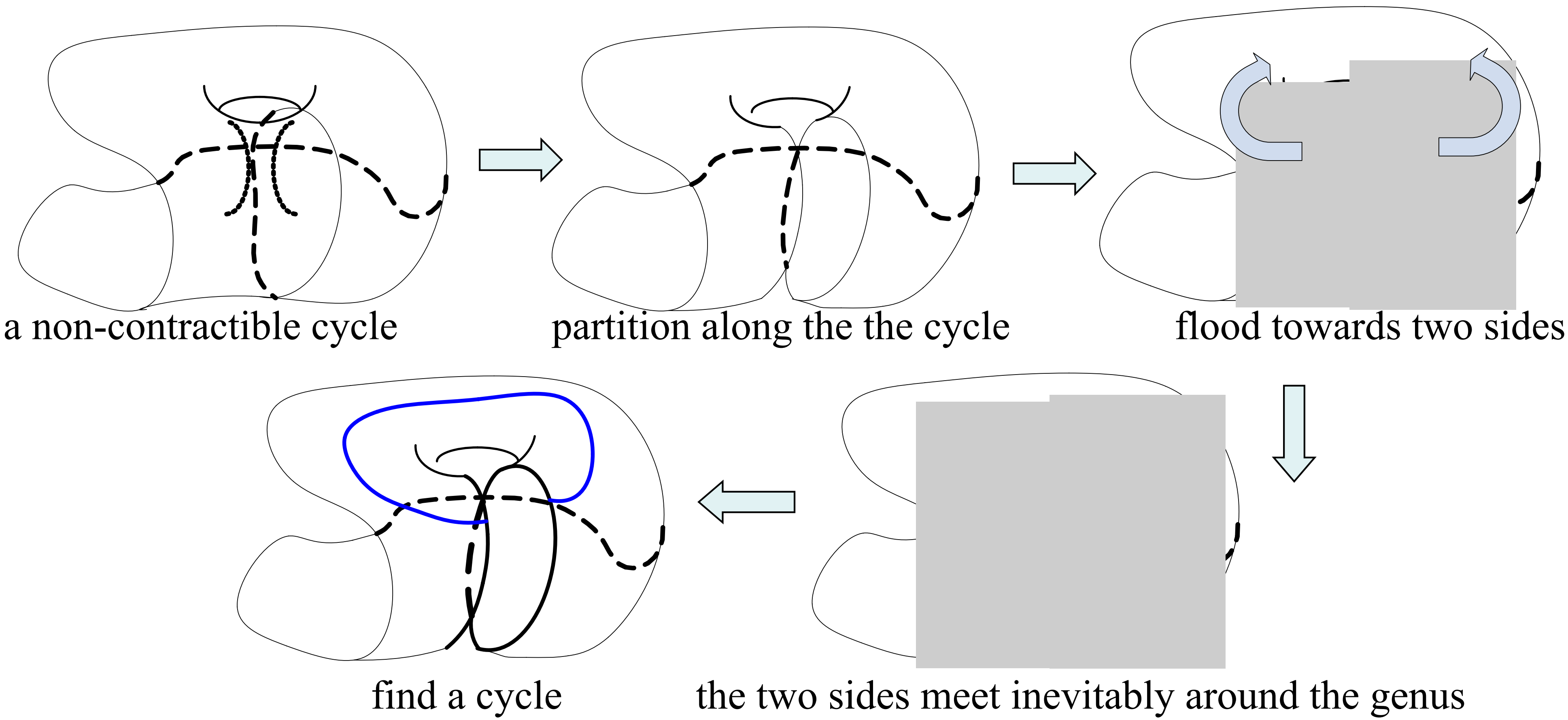


These nodes witness the candidate cycles

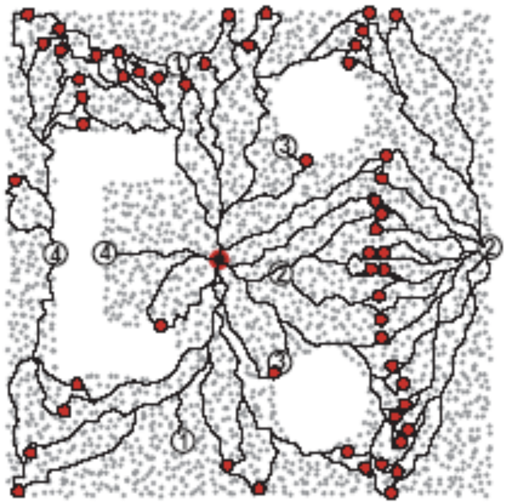


Validate three non-contractible cycles

- 3. select a non-contractible cycle, partition the network along the the cycle.
- 4. flood towards two sides of the non-contractible cycle, they must meet (discuss it later), we get a circle around the genus.



Topological Impact of Wormhole



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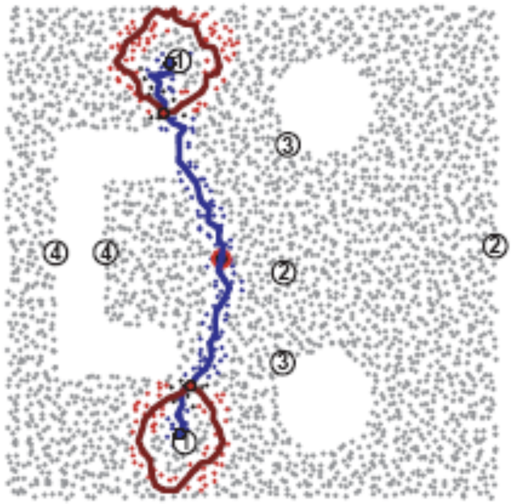
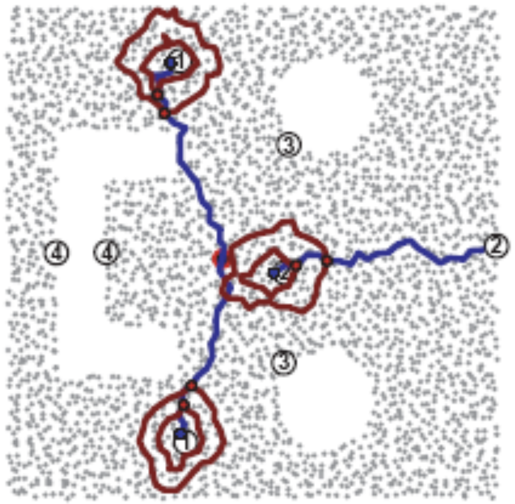
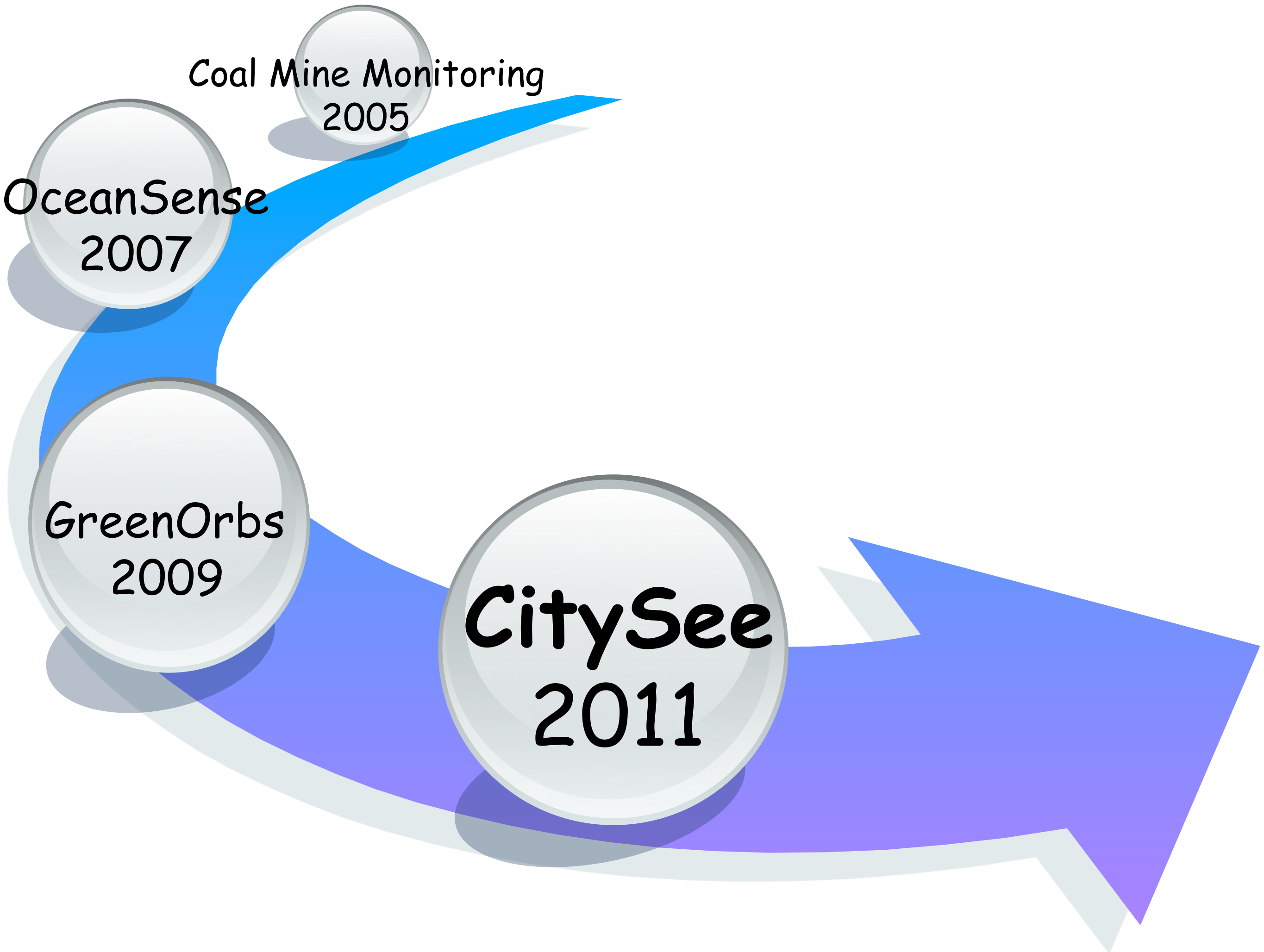


(b)

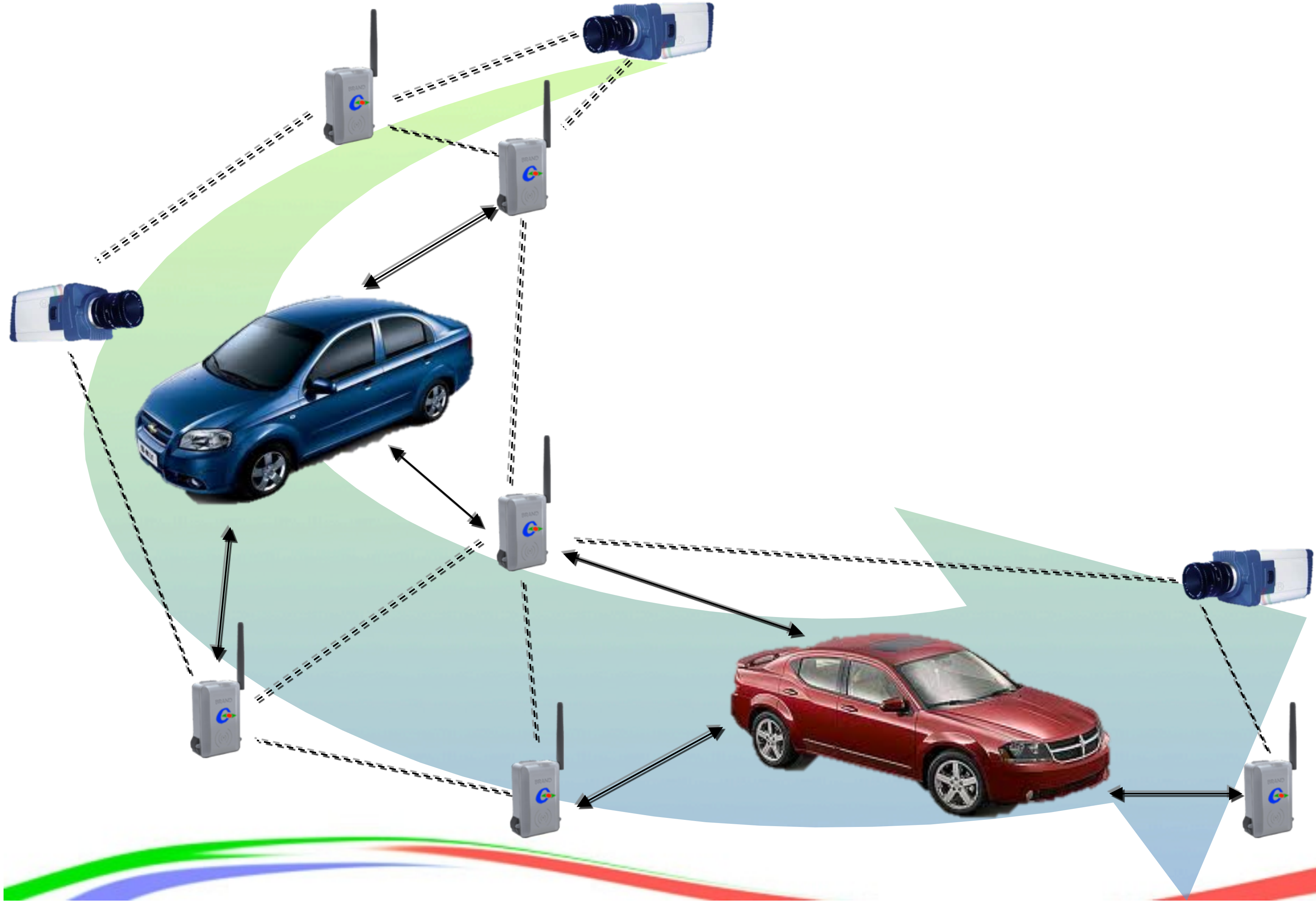


(c)

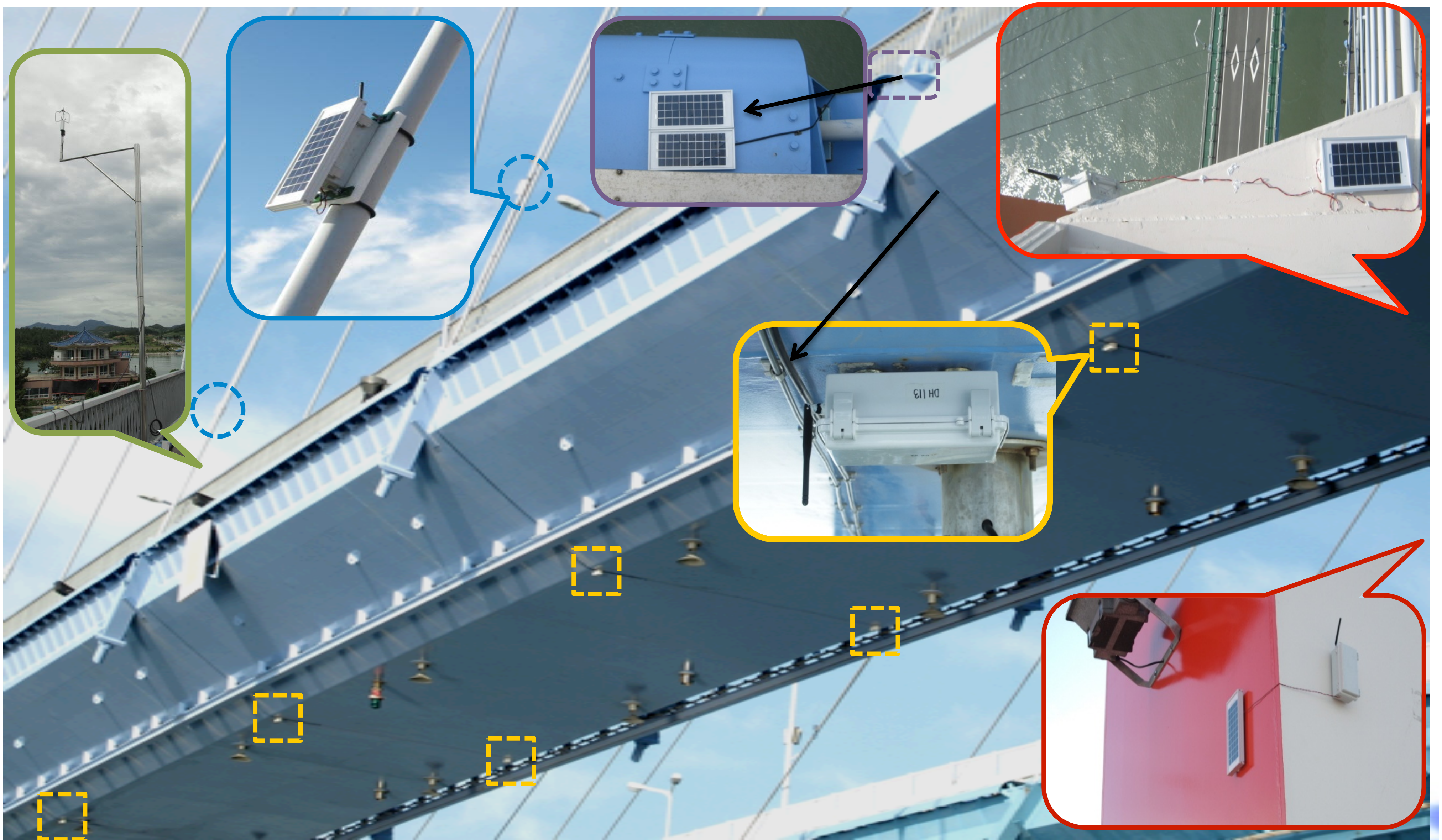
Conclusions



Future Directions: Smart Road



With UIUC: Bridge Monitoring (Borrowed From Bill Spencer)



Thank you !

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