Cooperative Information Fusion and Inference (CIFI):
Enabling M2M wireless communications in the Swarm

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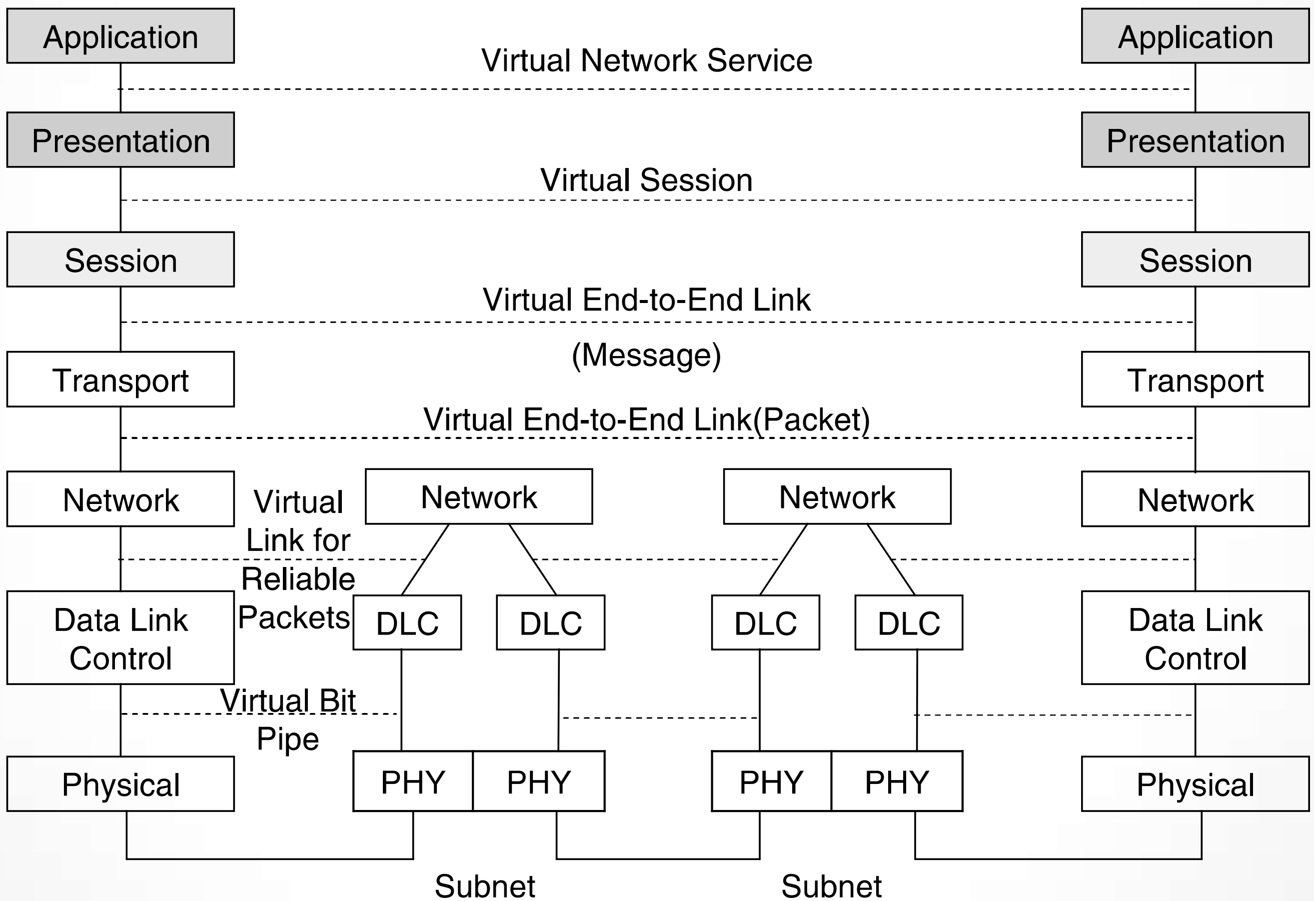
OSI Network Architecture



Radio Communications

Guglielmo Marconi Karl Ferdinand Braun

The Nobel Prize in Physics 1909 was awarded jointly to Guglielmo Marconi and Karl Ferdinand Braun *"in recognition of their contributions to the development of wireless telegraphy"*

A Few Pioneers to Thank in Communication Theory

- ❑ A.N. Kolmogorov
  - ✓ Probability theory
  - ✓ Stochastic processes
- ❑ John von Neumann
  - ✓ Game theory
  - ✓ Later generalized to statistical decision theory
- ❑ Claude Shannon
  - ✓ Information theory

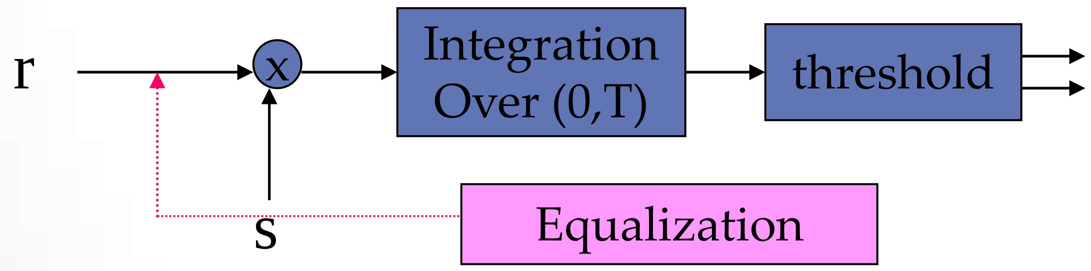
Optimal Receiver: Wozencraft & I. Jacobs "Principles of Comm. Eng.", 1965

Criterion: (statistical decision theory)

1. Bayes: *a priori* probability, cost function, both known
2. Minimax: only cost function known
3. Neymann-Pereson: neither known (most likely radar)

Matched filter: s(T-t), optimal in AWGN channel

Correlation receiver: to compute $|r-s|^2$, r: received waveform, s: signal



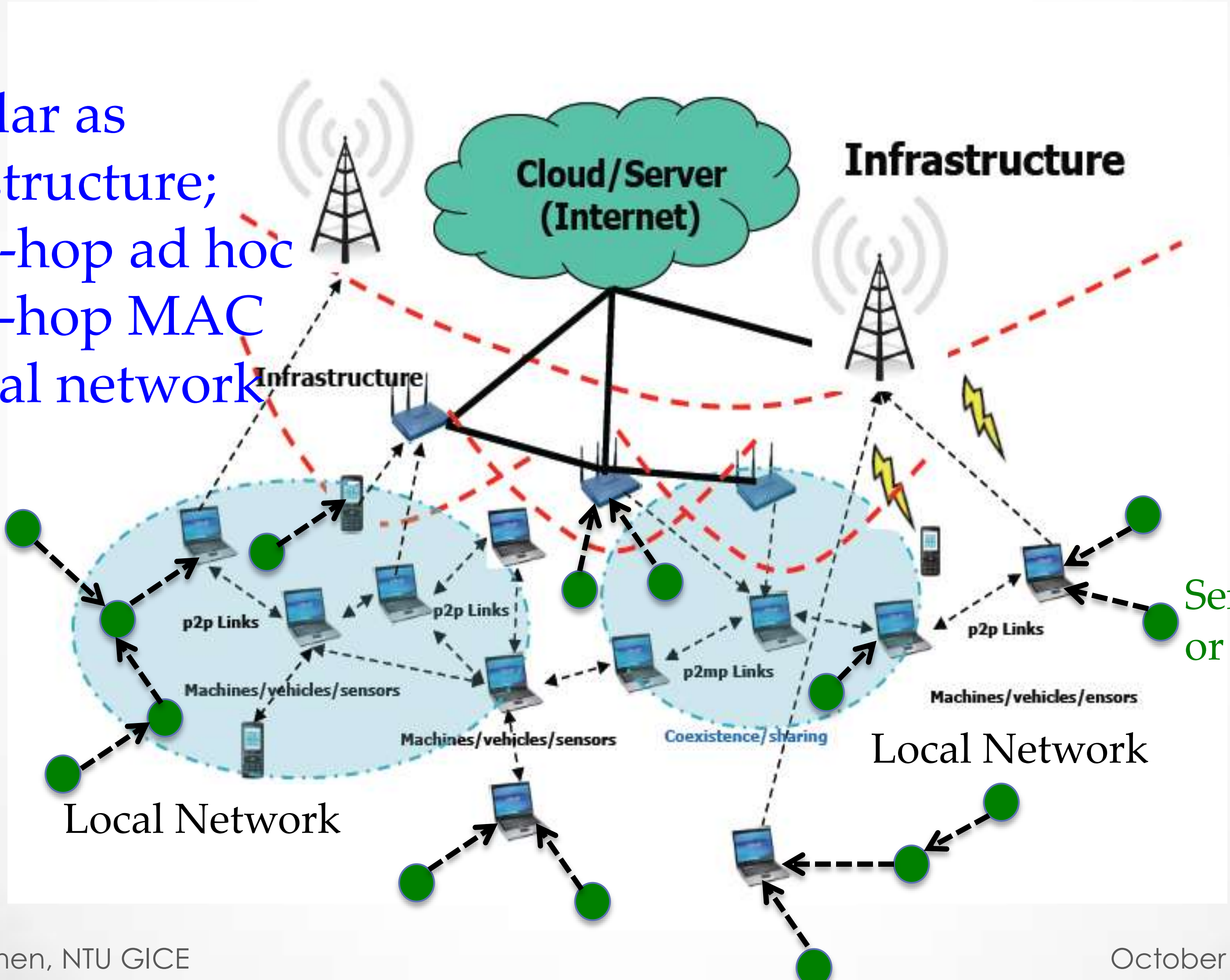
Correlation receiver is optimal in AWGN channel too.

Carrier recovery, timing recovery, …

Scope and Vision of SIGARC

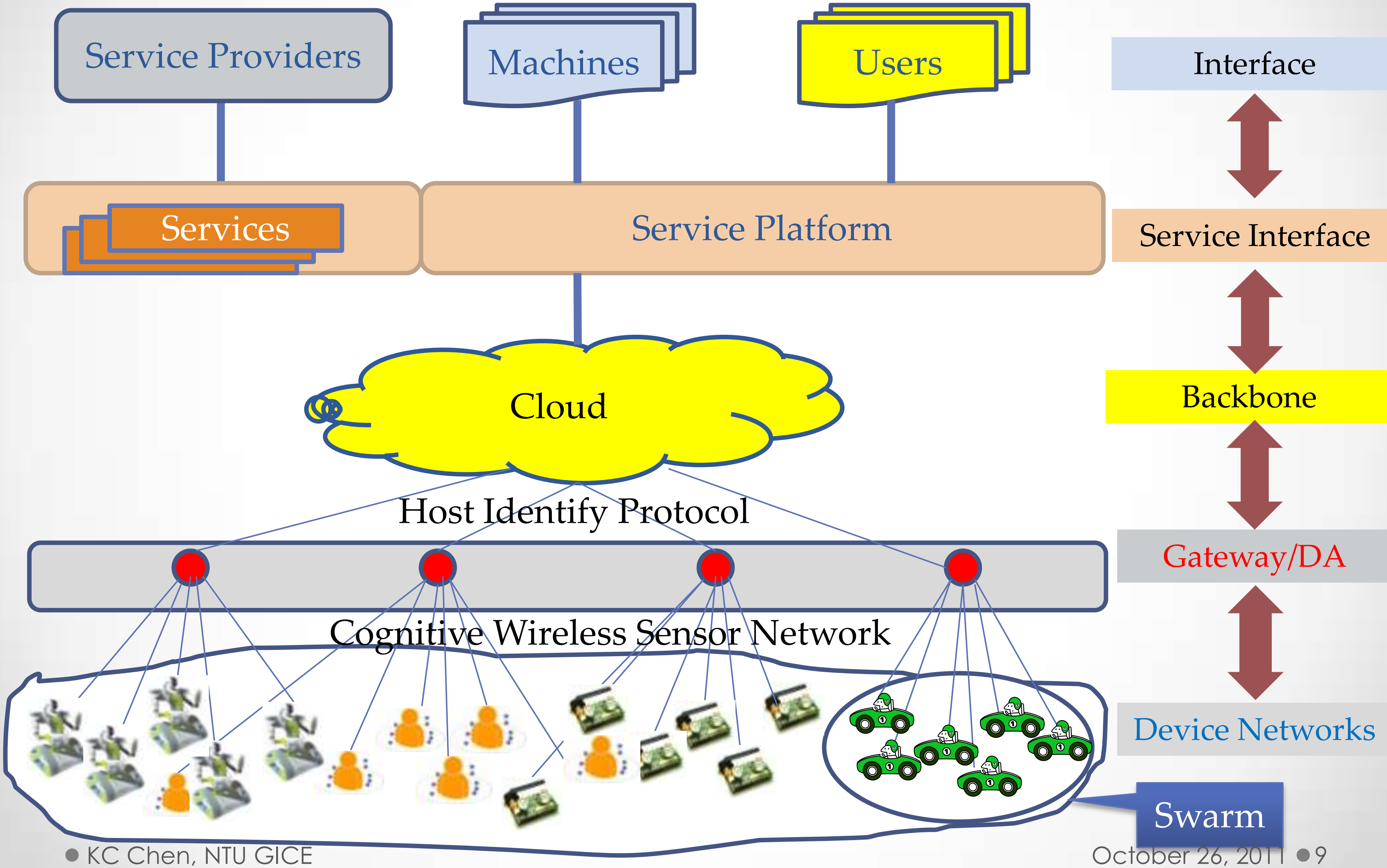
M2M Inter-connected Vision

Cellular as infrastructure; Multi-hop ad hoc and 1-hop MAC as local network




Transparent communications
between machines and cloud
Even with mobility

M2M Network Interface & Architecture

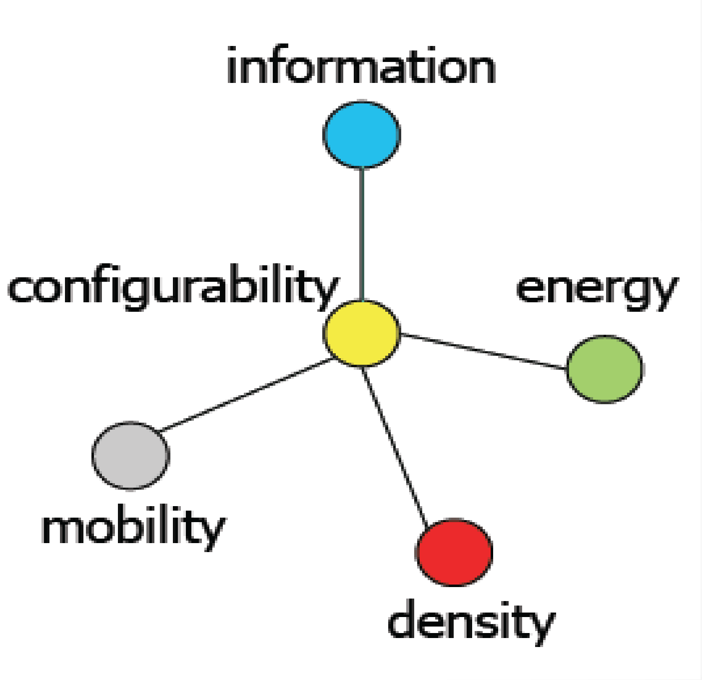


Technology Challenges in Front of SIGARC

- ❑ Large-scale and dense networks
  - ✓ From billions devices in wireless personal communications to trillions devices in M2M communications
  - ✓ Addressing and indexing; IPv6
  - ✓ Scalability and self-organizing
- ❑ Limited radio spectrum
  - ✓ Spectrum allocation to H2H with priority
  - ✓ Tolerance on packet errors in some (not all) M2M communications
  - ✓ M2M communications toward data aggregator may have to adopt the strategy of spectrum sharing, though infrastructure would be likely to enjoy spectrum-dedicated technology such as cellular
  - ✓ Mother Nature determines which frequency bands are good to use
- ❑ Heterogeneity
  - ✓ Ubiquitous and autonomous heterogeneous wireless networks
- ❑ Energy efficiency
  - ✓ Communication may consume more battery energy than processing
- ❑ Mobility
  - ✓ Vehicular or mobile applications
  - ✓ Autonomous re-configurability transparent to applications

SIGARC Key Technological Components

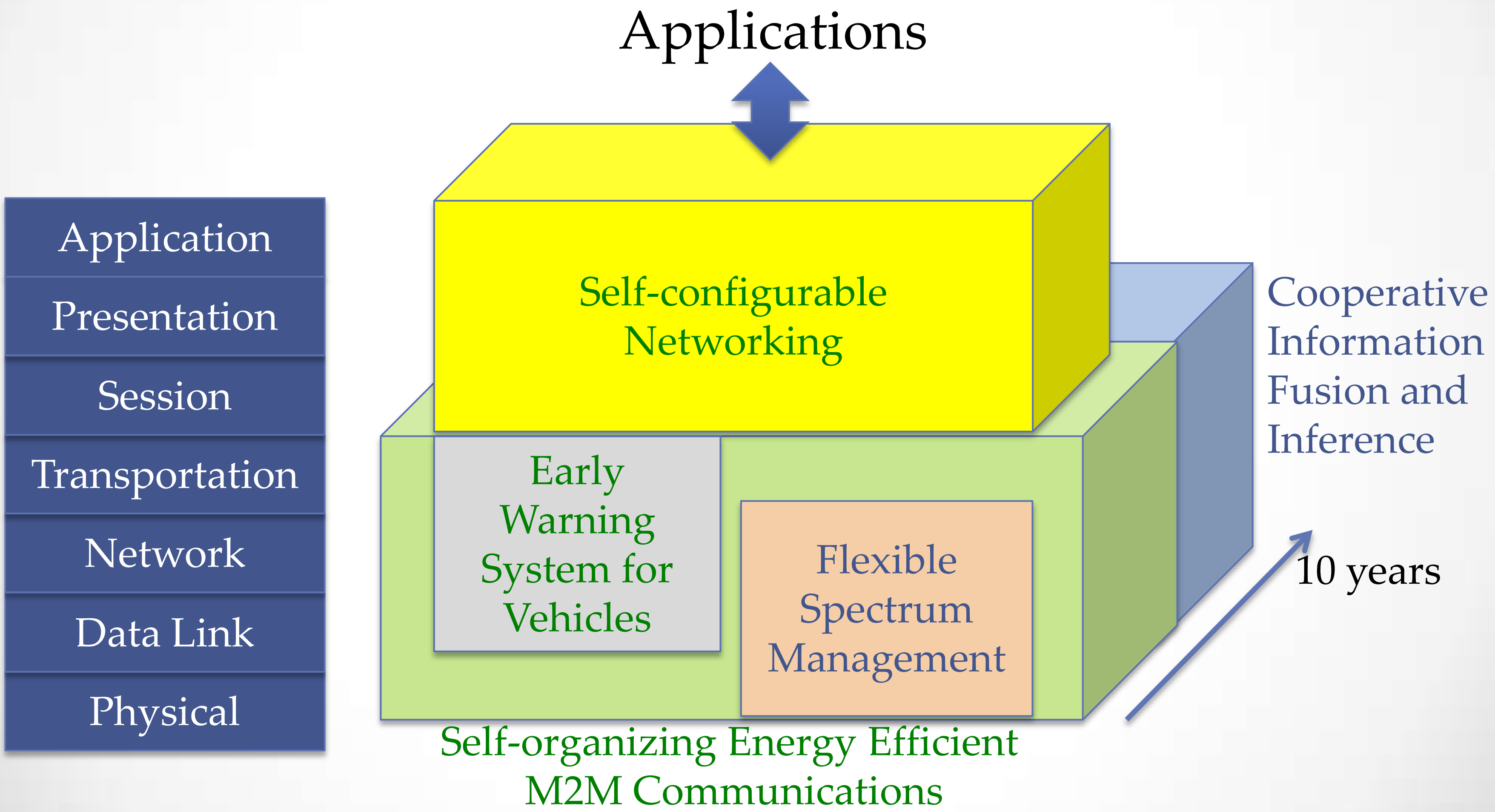
- Density of machines
  - ✓ Infrastructure
  - ✓ Flexible spectrum usage
- Mobility
  - ✓ Unique feature in SIGARC
  - ✓ Vehicular application scenario
- Energy efficiency
  - ✓ Not just device
  - ✓ Optimization over system/network
- Re-configurability
  - ✓ Transparent to applications based on IPv6
  - ✓ Addressing and indexing
- Information driven networking
  - ✓ Collection and fusion
  - ✓ Traffic reduction



Cooperation to Goal

- ❑ Flexible Spectrum Management (HJ Su, HY Hsieh)
  - ✓ Density
- ❑ Cooperative Information Fusion and Inference (KC)
  - ✓ Information
- ❑ Extend the Safety Shield – Early Warning System for Vehicles (Hsinmu Tsai, AC Pang)
  - ✓ Mobility
- ❑ Self-organizing Energy Efficient M2M Communications (HY Wei)
  - ✓ Energy
- ❑ Self-configurable Networking (Phone Lin, CT Chou)
  - ✓ Configurability

SIGARC Organization

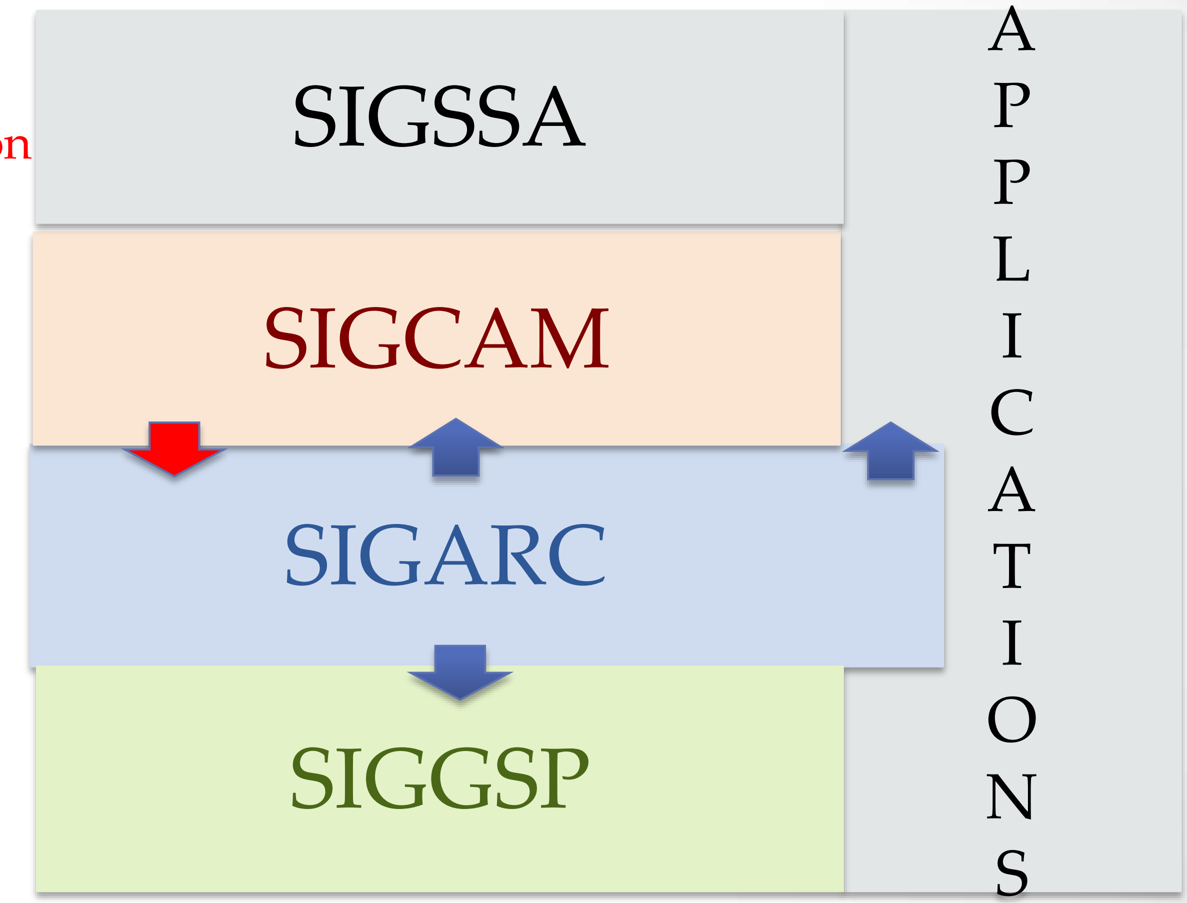


SIGARC Interaction with other SIGs

What is useful information rather than data from SIGCAM/SSA?

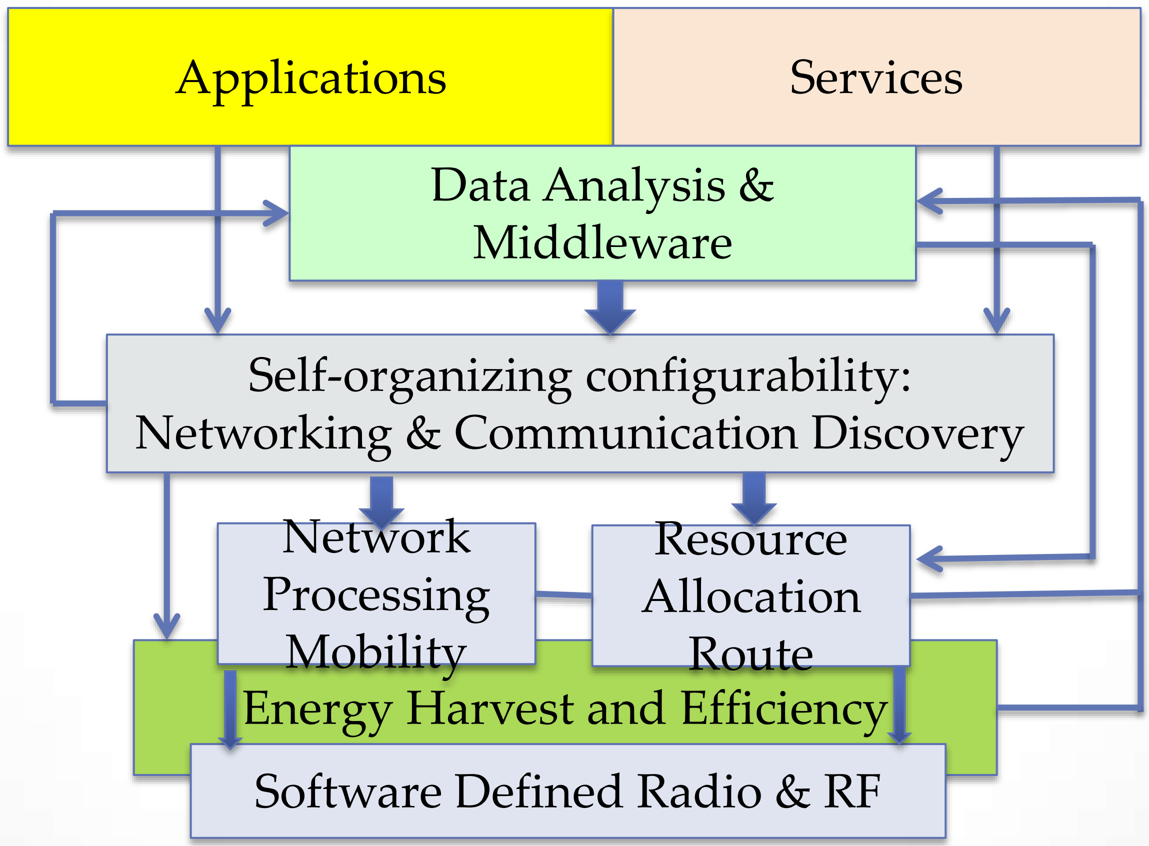
Transparent Supporting To SIGCAM/SSA

System/Network Optimality To SIGGSP



The success of SIGARC to the center is "look-like non-existing", to minimize communications through effective computations.

Architecture of Transparent M2M Communications



Why Spectrum Sharing

- ❑ Limited spectrum, particularly under 3-6G Hz
  - ✓ Hard to get new spectrum
- ❑ Great success at 2.4GHz ISM band
  - ✓ Namely, WiFi, Bluetooth, etc.
- ❑ Large network to support trillions wireless devices
  - ✓ Most of devices are QoS insensitive
  - ✓ Mobility and its tradeoff with bandwidth
- ❑ Reality: H2H has high priority in spectrum utilization
- ❑ M2M has to heavily rely on spectrum sharing
  - ✓ To steal "unused" spectrum of H2H or primary systems, that is, cognitive radio
    - Most widely applied spectrum sharing technology: adaptive frequency hopping in Bluetooth and IEEE 802.15
  - ✓ Multiple heterogeneous wireless networks to share the spectrum
  - ✓ How to realize above two scenarios are pretty open engineering problems now, also open scientific problems

Spectrum Efficiency

- Networking throughput per bandwidth as spectrum efficiency
  - ✓ Not just traditional physical layer spectral efficiency
- Spectrum efficiency is one of the key technologies supporting trillions devices for M2M
  - ✓ For easy deployment, mother nature prefers frequency bands within several GHz
  - ✓ H2H communications keep occupying most of these valuable bandwidth
  - ✓ M2M communications, in spite of huge volume (number of devices and traffic load), should unlikely obtain enough dedicated spectrum
    - M2M infrastructure could leverage cellular-type systems with dedicated spectrum
- Spectrum sharing networks would be an evitable technology
  - ✓ Although wide usage at ISM bands, extremely limited study on this technology, until J. Mitola III's proposal of cognitive radios in IEEE Personal Communications 1999; FCC approves this technology in 2002
    - IEEE 802.11, Bluetooth, UWB, etc. all implement the concept of "cognitive radio", later 802.22
  - ✓ Unfortunately (fortunately as a researcher), people still know little on spectrum sharing communications and networks, except CDMA, MUD, MIMO

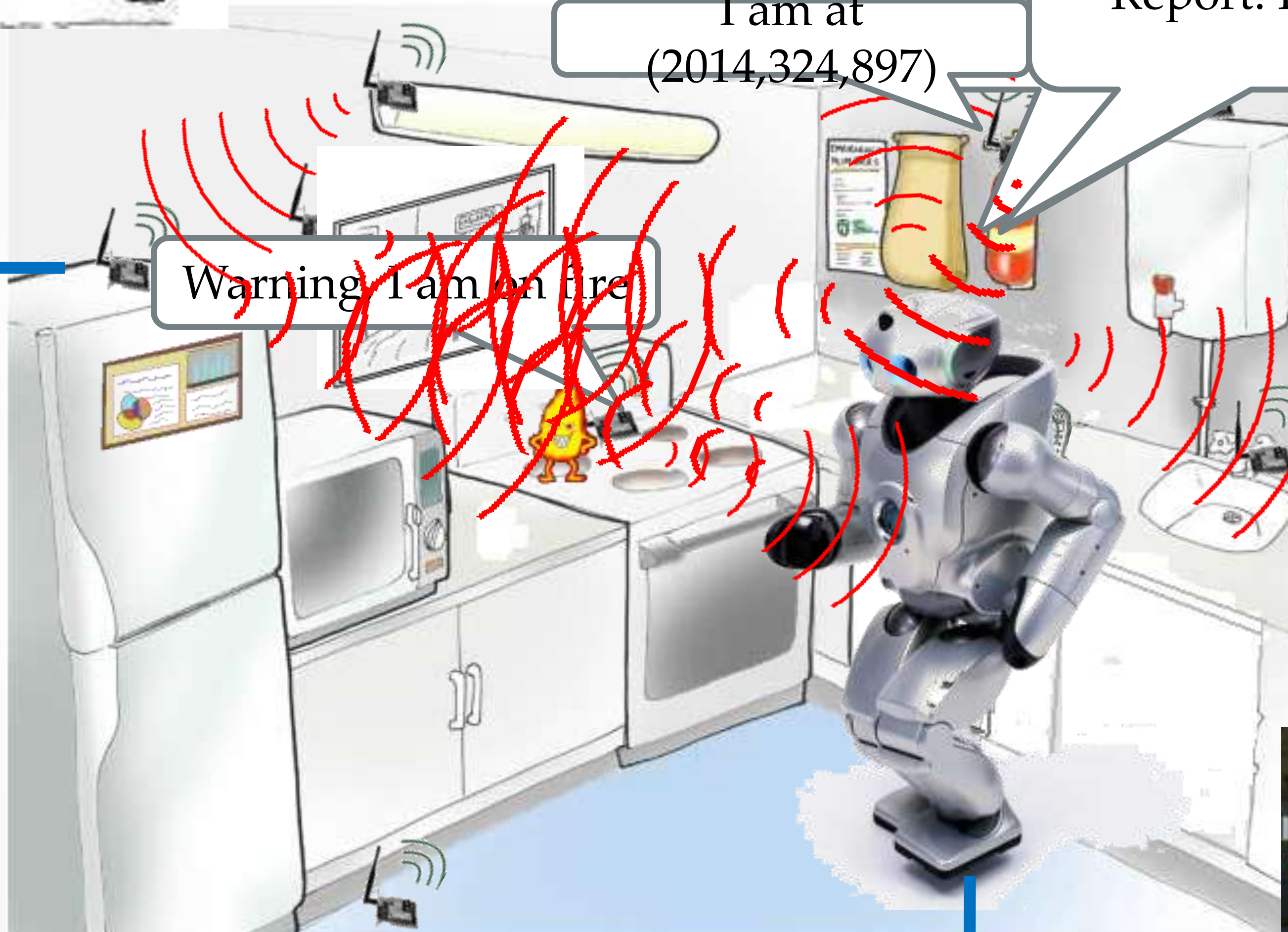
To Change the landscape of Communications

- Telephone (circuit switching)
  - ✓ State-of-the-art cellular is still under this structure
- Asynchronous transfer mode (ATM)
- Internet (packet switching)
  - ✓ Webs
  - ✓ Clouds
  - ✓ Social networks
  - ✓ ....
- What's next? Swarm intelligence?

New Landscape of Painting

Sma

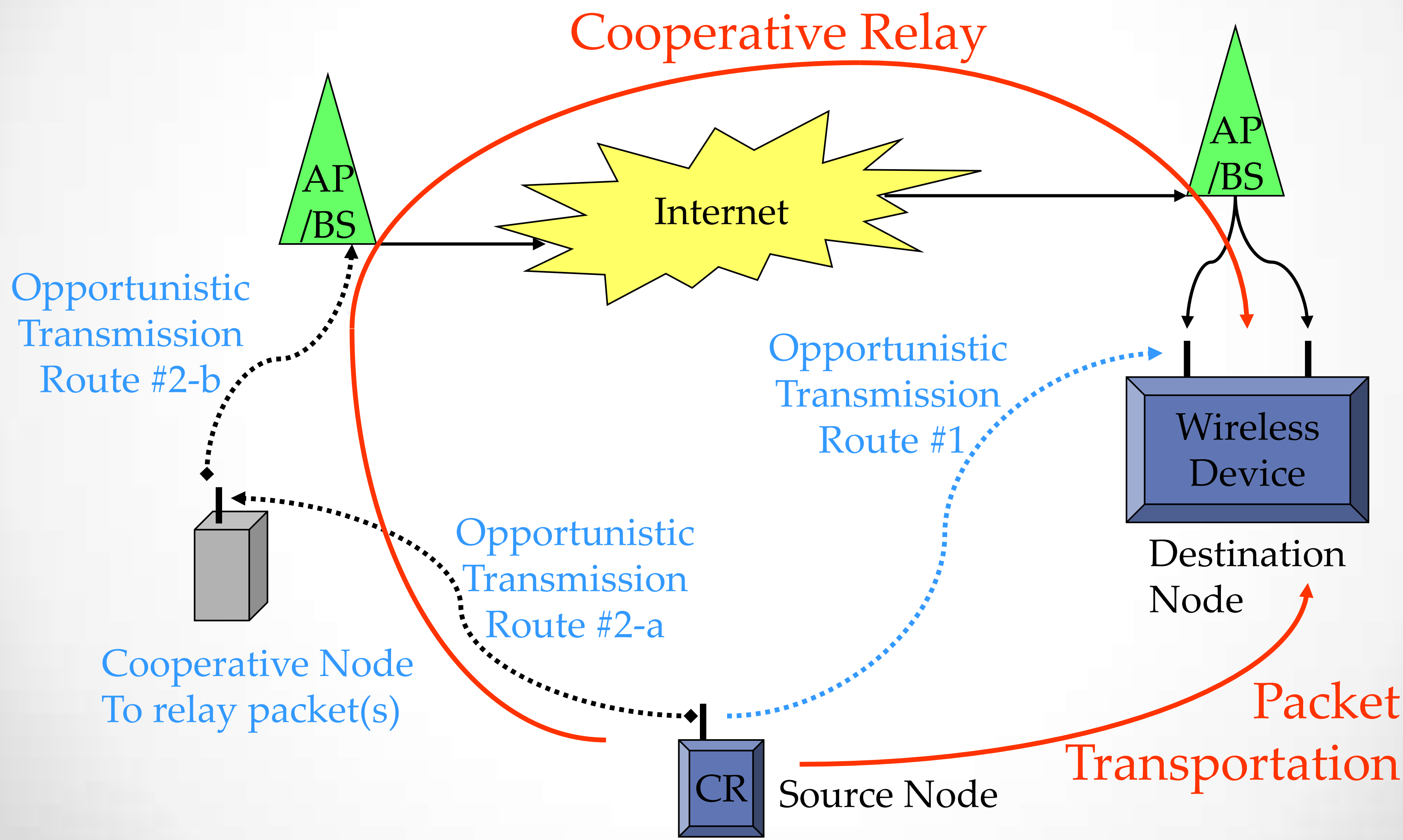
Internet



Internet

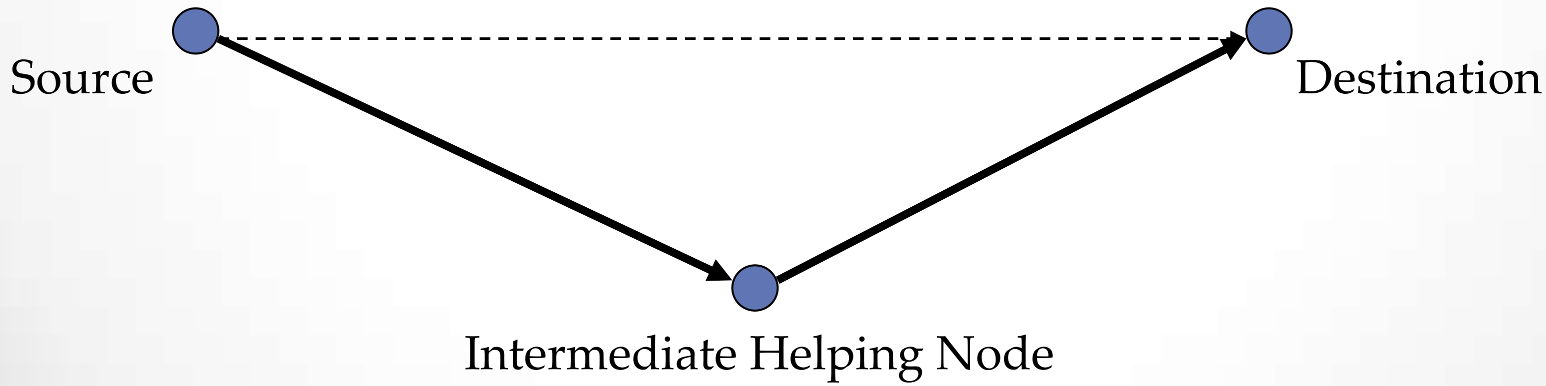
It is impossible for you to set/program the new home robot to link all these devices. They should learn to cooperate by all means.

CRN via Cooperative Networking



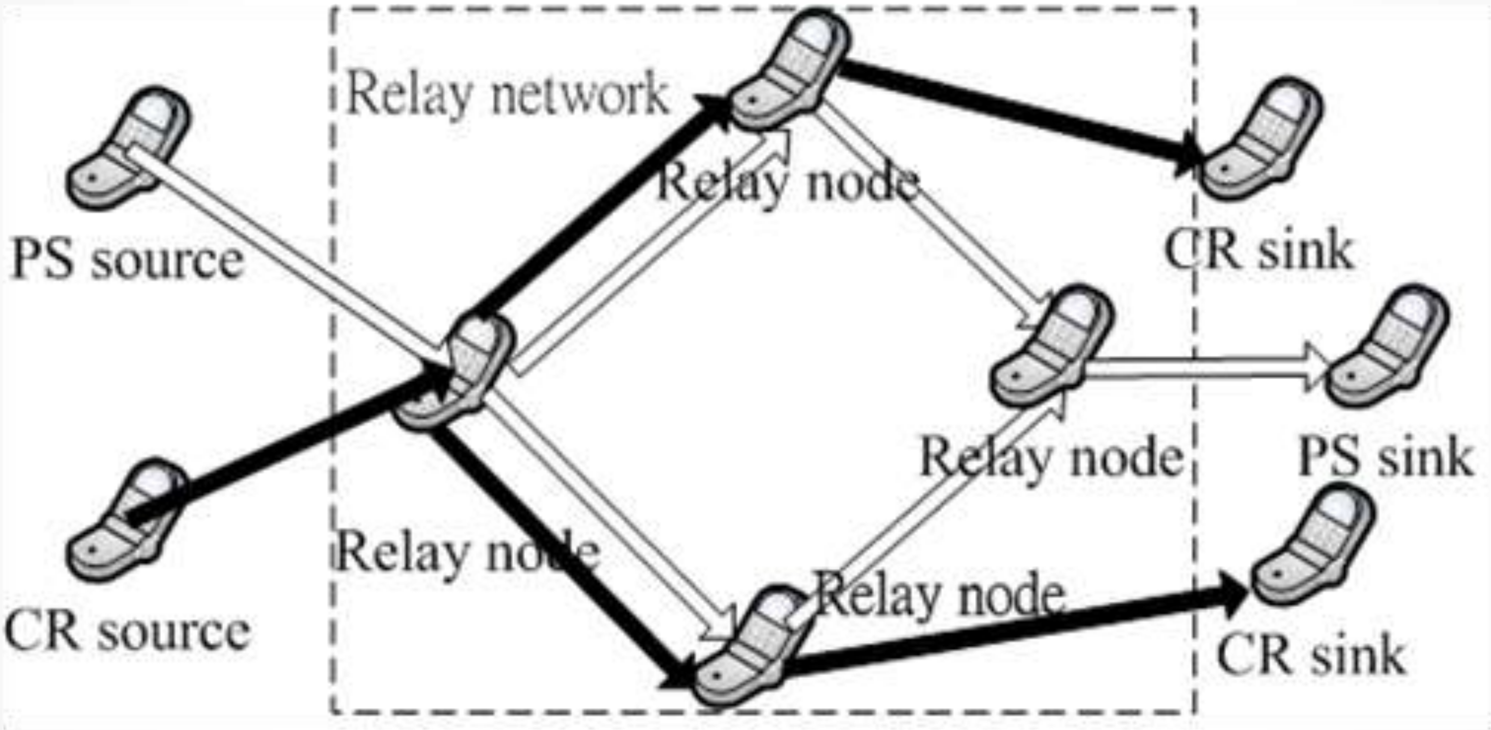
Cooperative Communications and Networks

- ❑ Origin from diversity
  - ✓ Microscopic: MIMO is a kind of antenna cooperation
  - ✓ Macroscopic: cooperation among (network) nodes to have better signal reception
  - ✓ Nodes can cooperate to relay packets (routing)
    - Amplify-and-forward (AF)
    - Decode-and-forward (DF)
    - Compress-and-forward (CF)



Cognitive Radio Relay Network (CRRN)

As cooperative relay is the fundamental operation of CRN, CRRN shall be explored.



We may use network coding to explore the fundamental properties of (cooperative) relay network for CRs, while most existing research in physical layer rather than networking level

Cognitive Radio Networks (CRN)

- CRN can be considered as spectrum sharing heterogeneous wireless networks, with a priority wireless network
  - ✓ A key to M2M and future high-spectral-efficient wireless networking
  - ✓ When primary system users are not using the spectrum, cognitive radio (CR) nodes can transmit in an opportunistic way, known as interweave.
  - ✓ CRs can access the spectrum as long as no effective interference to primary system operation, known as underlay
  - ✓ Via cooperative multi-hop relay, CRN can be facilitated
    - Average 1.3 times of throughput at 92% chances with gain [Huang, Lai, Chen, PHYCOM 2009]
- To understand underlay CRN operation
  - ✓ Relationship among connectivity, interference, latency and other system parameters of underlay secondary networks
  - ✓ Parameterization of underlay secondary networks
- Percolation theory from statistical physics

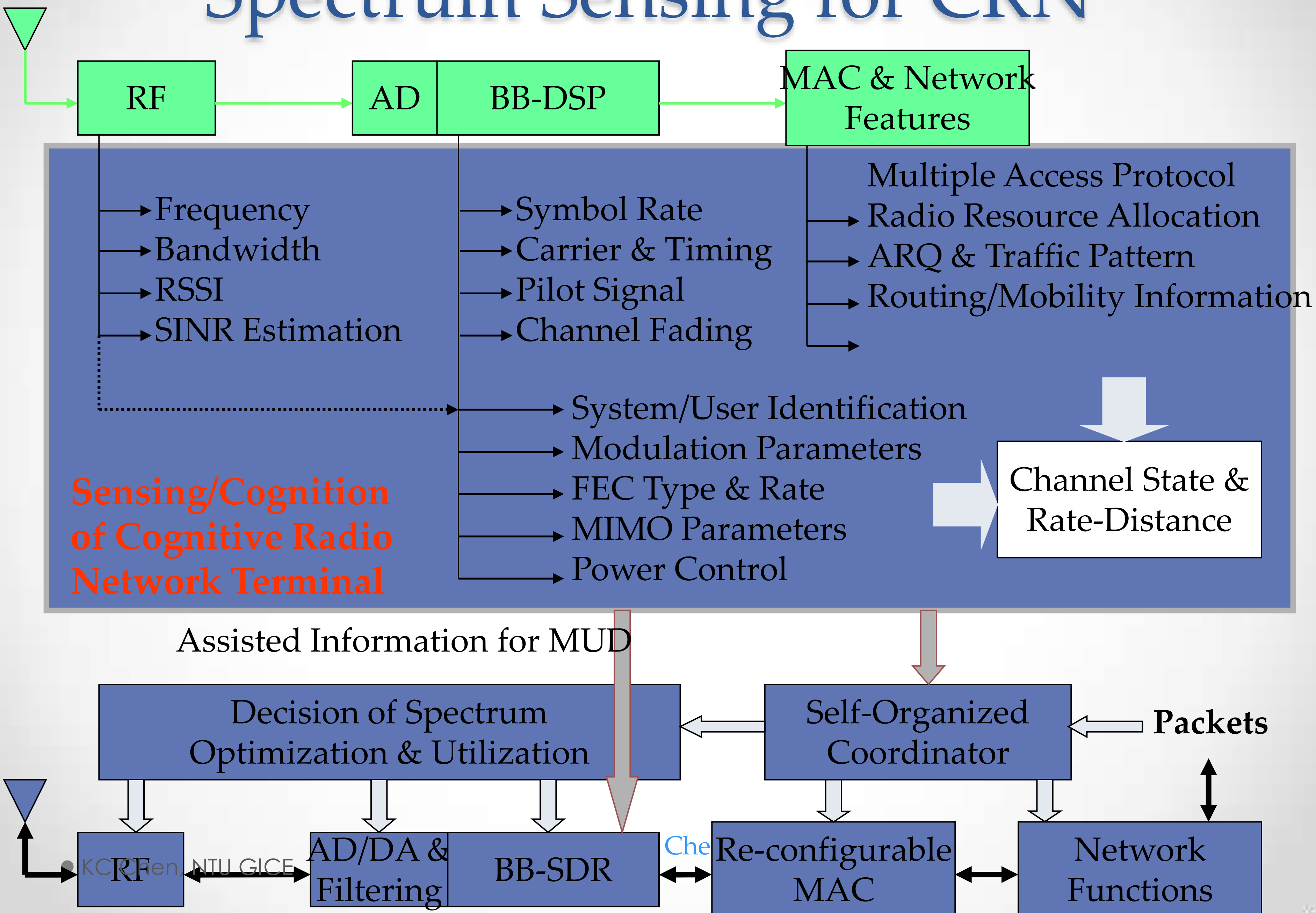
Spectrum Sensing

- The goal of CR spectrum sensing is to identify "available opportunity" to transmit.
  - ✓ Fundamental: Energy detection
    - RSSI from RF
  - ✓ Reliable: Feature extraction
    - Carrier frequency
    - Symbol rate
    - Other spectral correlation methods
  - ✓ Cooperative sensing
  - ✓ Distributed sensing
- More for spectrum sensing in CRN
  - ✓ To identify co-existing systems possibly to cooperate in different frequency bands (unlicensed and even licensed)

Well-Known Techniques in Sensing

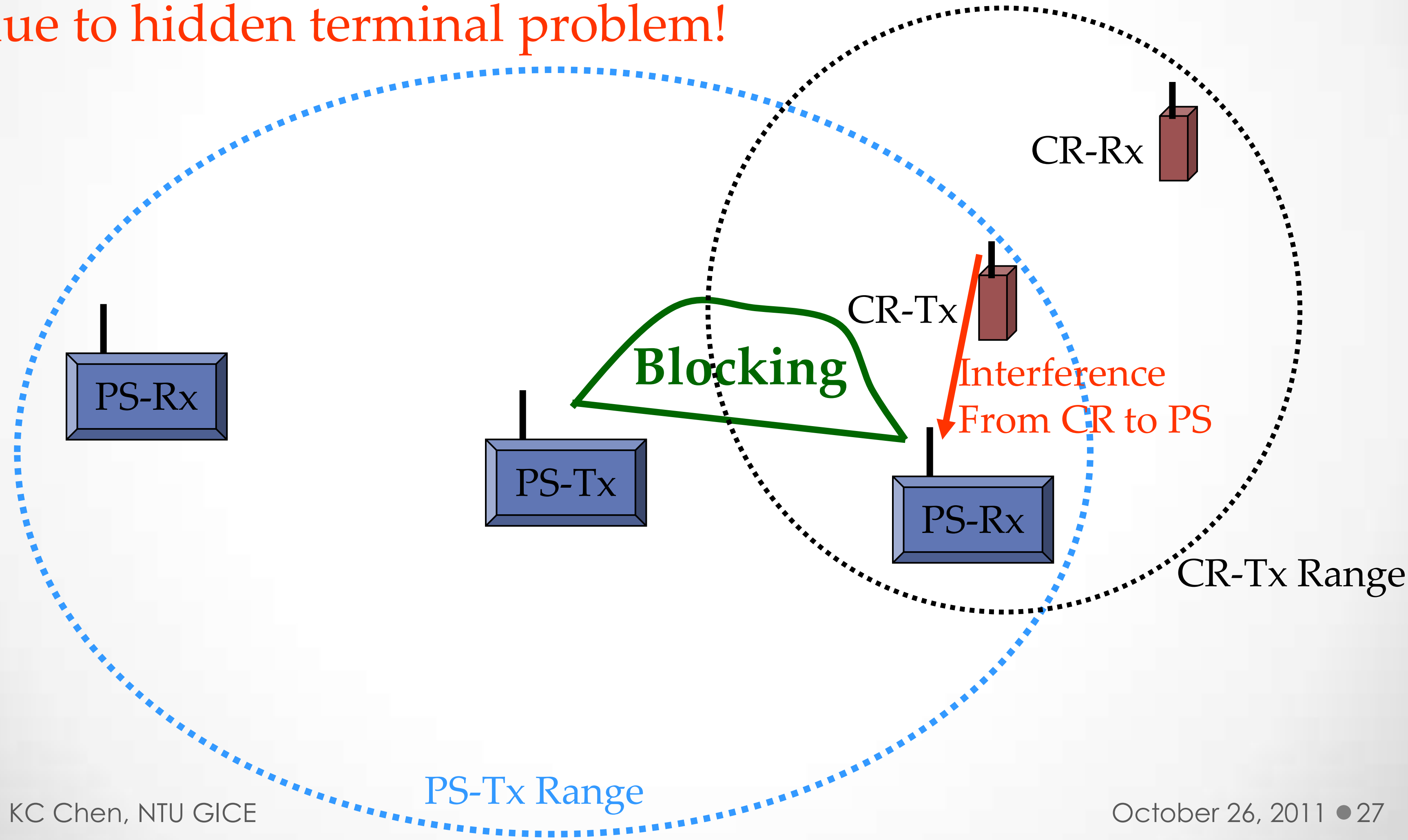
Spectrum Sensing Algorithm	Description
Energy detection	Estimate the energy in a frequency band and compare against a detection threshold.
Cyclostationary detection	Compute the spectral correlation function and detect the peak at multiples of the modulation rate/frequency.
Matched Filter	Coherently detect the pilot signals.
Wavelet detection	Employ a wavelet transform of PSD of the observed signal to locate the singularities of the PSD and identify the vacant frequency bands.
Cooperative Detection	Fuse the observation signal to the fusion center/other nodes and combine them to make decision.

Spectrum Sensing for CRN

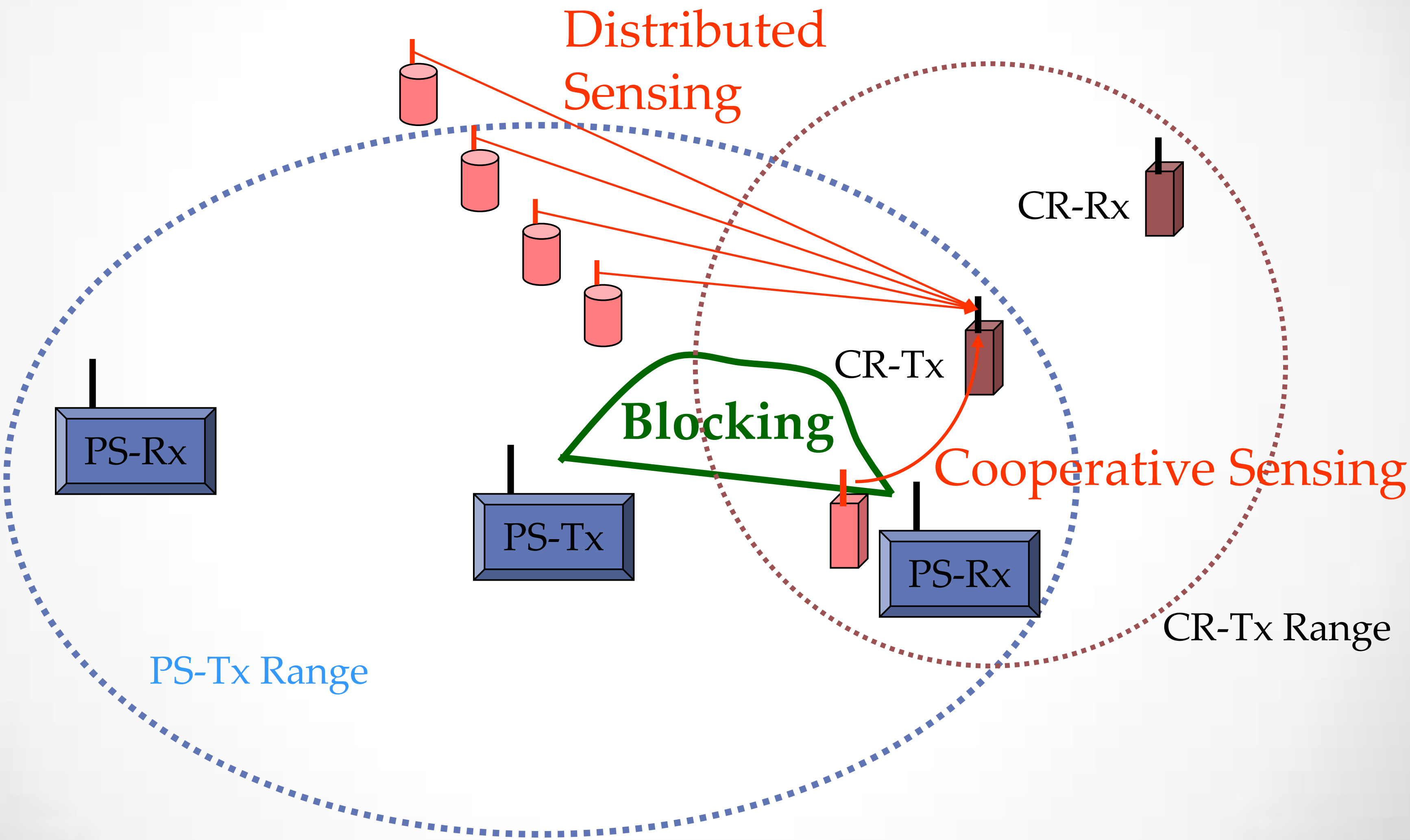


Hidden Terminal Problem

CR's carrier sensing may still be under jeopardy due to hidden terminal problem!



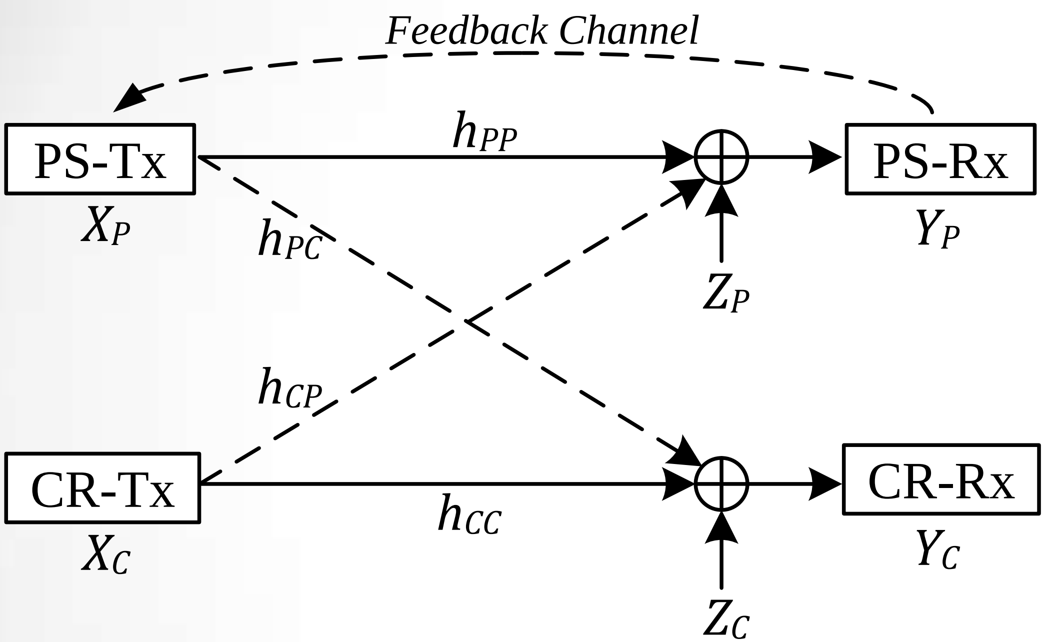
Distributed or Cooperative Sensing



CRN Tomography

- ❑ Spectrum sensing for spectrum hole targets at link-level CR, but CRN requires information beyond.
  - ✓ Only passive detection?
  - ✓ CRN needs information about radio resource, rather than spectrum holes
- ❑ CRN tomography is a sort of statistically measuring and inferring techniques that provide the CRN parameters and traffic patterns without special-purpose cooperation of the radios belonging to heterogeneous systems.
  - ✓ [Yu and Chen, IEEE T-VT 2010]
  - ✓ Inferring not just detection/estimation

Radio Resource Tomography



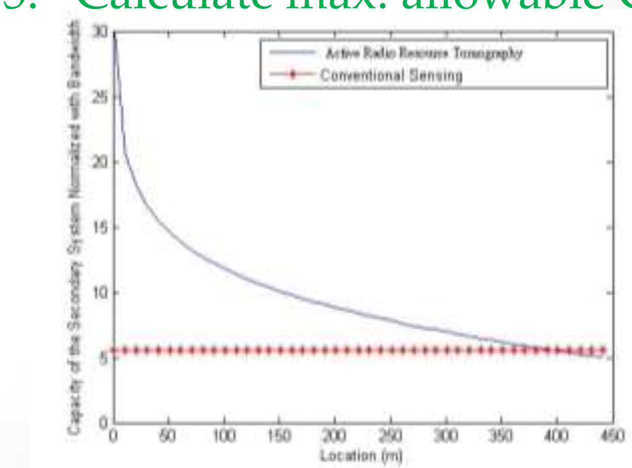
Radio Resource Tomography Algorithm:

Assuming cooperative AMC,

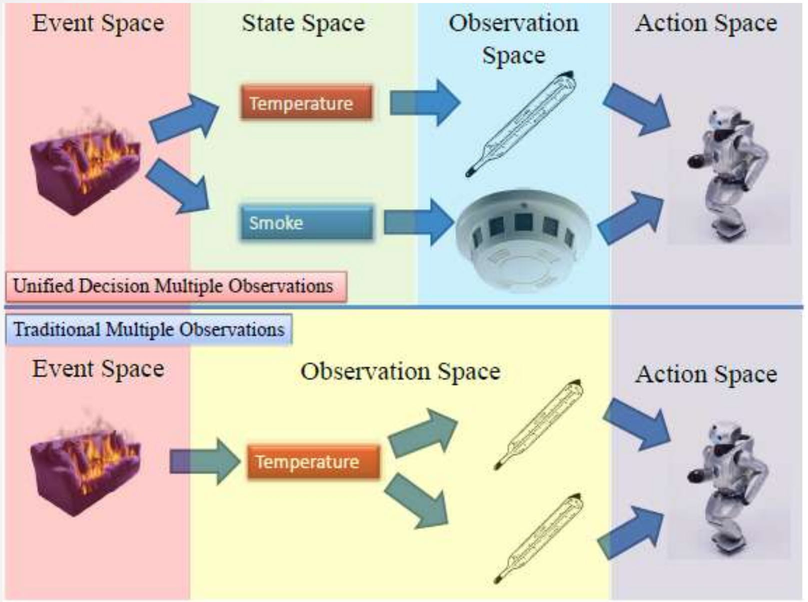
1. Set initial probing power from minimum value
2. Determine AMC of PS
3. Transmit probing signal
4. Adjust probing power based on AMC of PS
5. Calculate max. allowable CR

INR

With above channel model, the purpose of spectrum sensing is actually to identify the maximum transmission power of cognitive radio, subject to regulation and SINR.



Heterogeneous Information Fusion and Inference (HIFI)



Applying heterogeneous information fusion and inference can help more effective construction of spectrum sensing thus spectrum map as well as traffic "shaping", in addition to sensor applications.

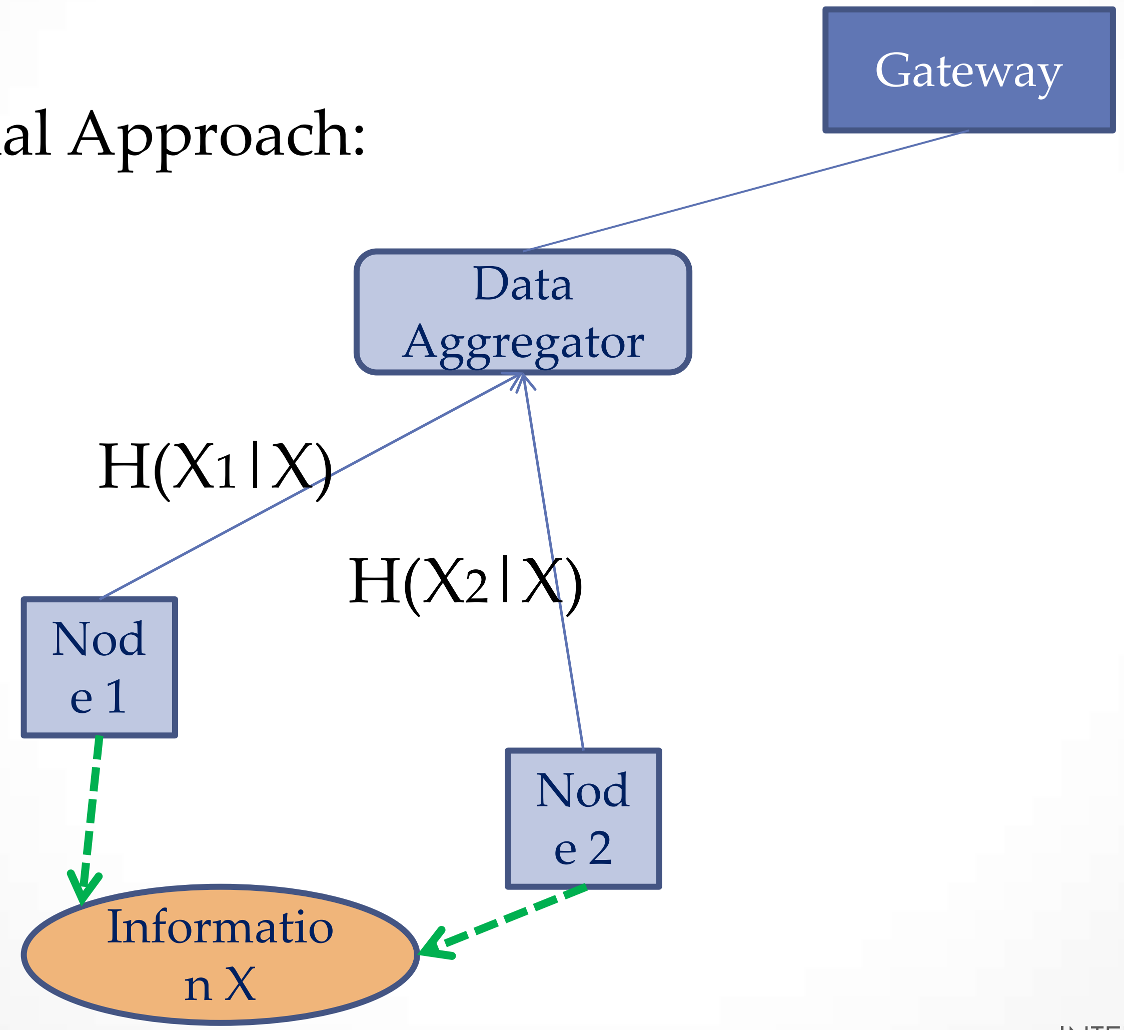
Traditional Approach:
1. Collect information
2. Fuse data
3. Determine control/action using fuzzy logic

Our Approach:
1. [Autonomous reconfigurable] information collection (likely heterogeneous info from multiple types of sources)
2. New decision theory based on fusion/inference/determination (fuzzy logic treated as special case [Huang, Chen, IEEE VTC 2009])
3. Improved HIFI performance using collaborative techniques
4. Autonomous M2M

Effective sensing by single node as cooperative sensing by multiple nodes [Huang and Chen, IEEE T-VT 2011]

Reducing Transferred Data Example

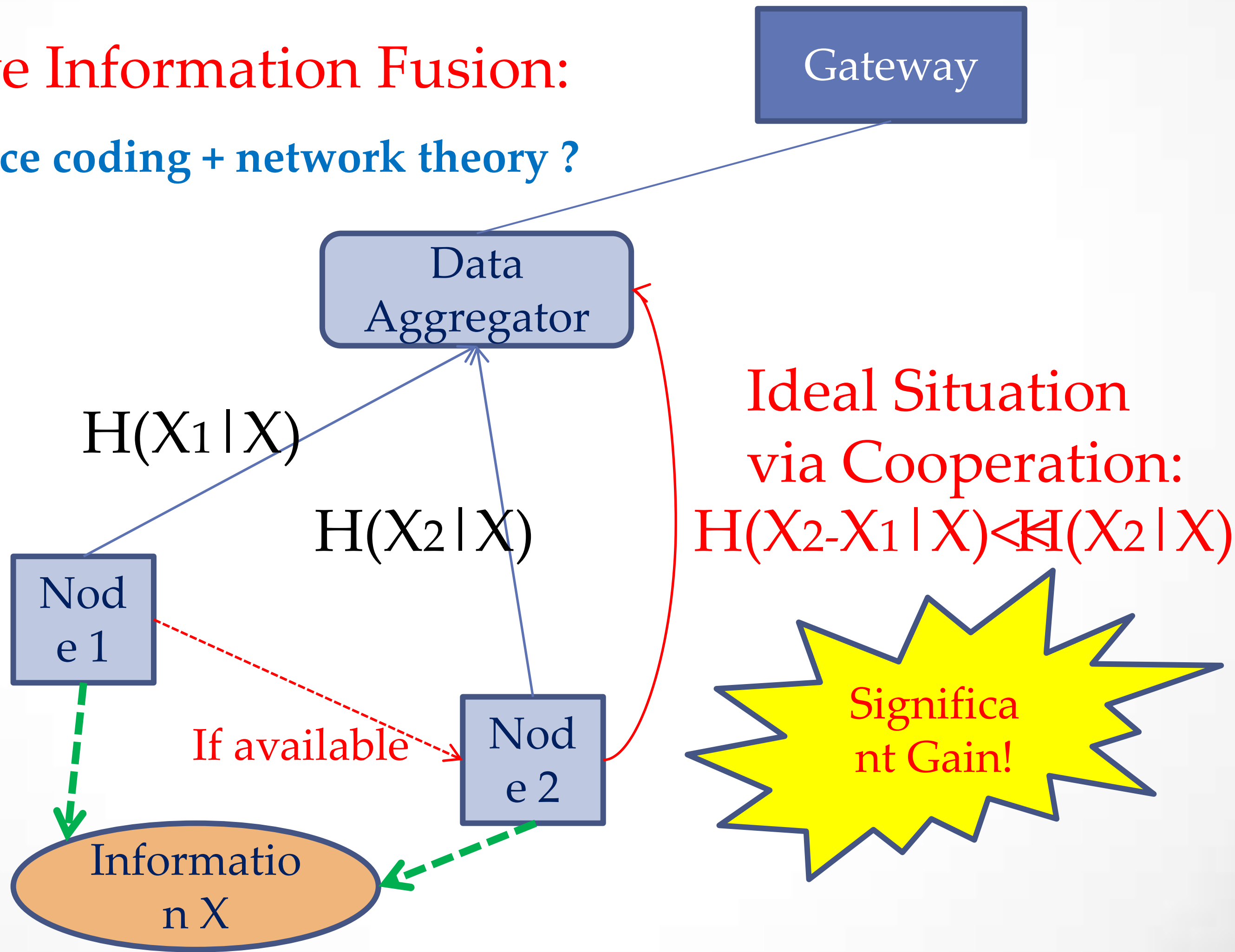
Traditional Approach:



Reducing Transferred Data Example

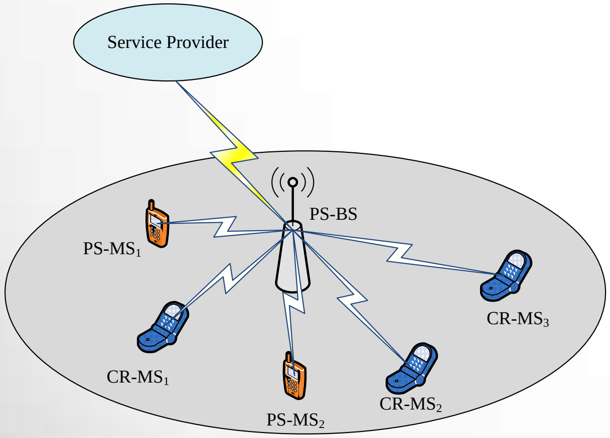
Cooperative Information Fusion:

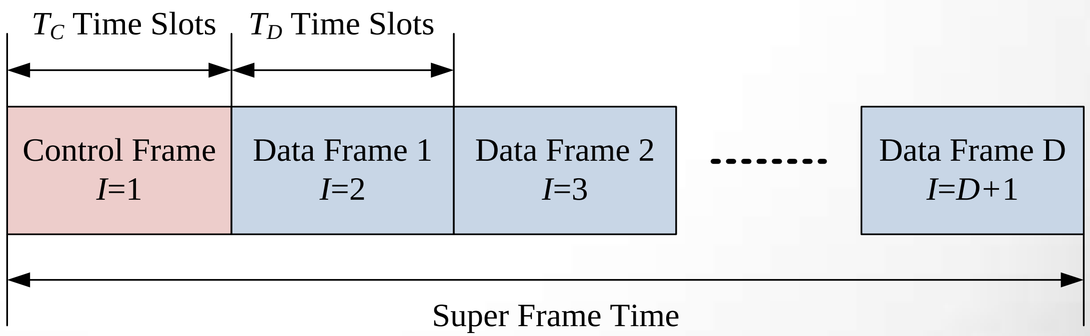
universal source coding + network theory ?



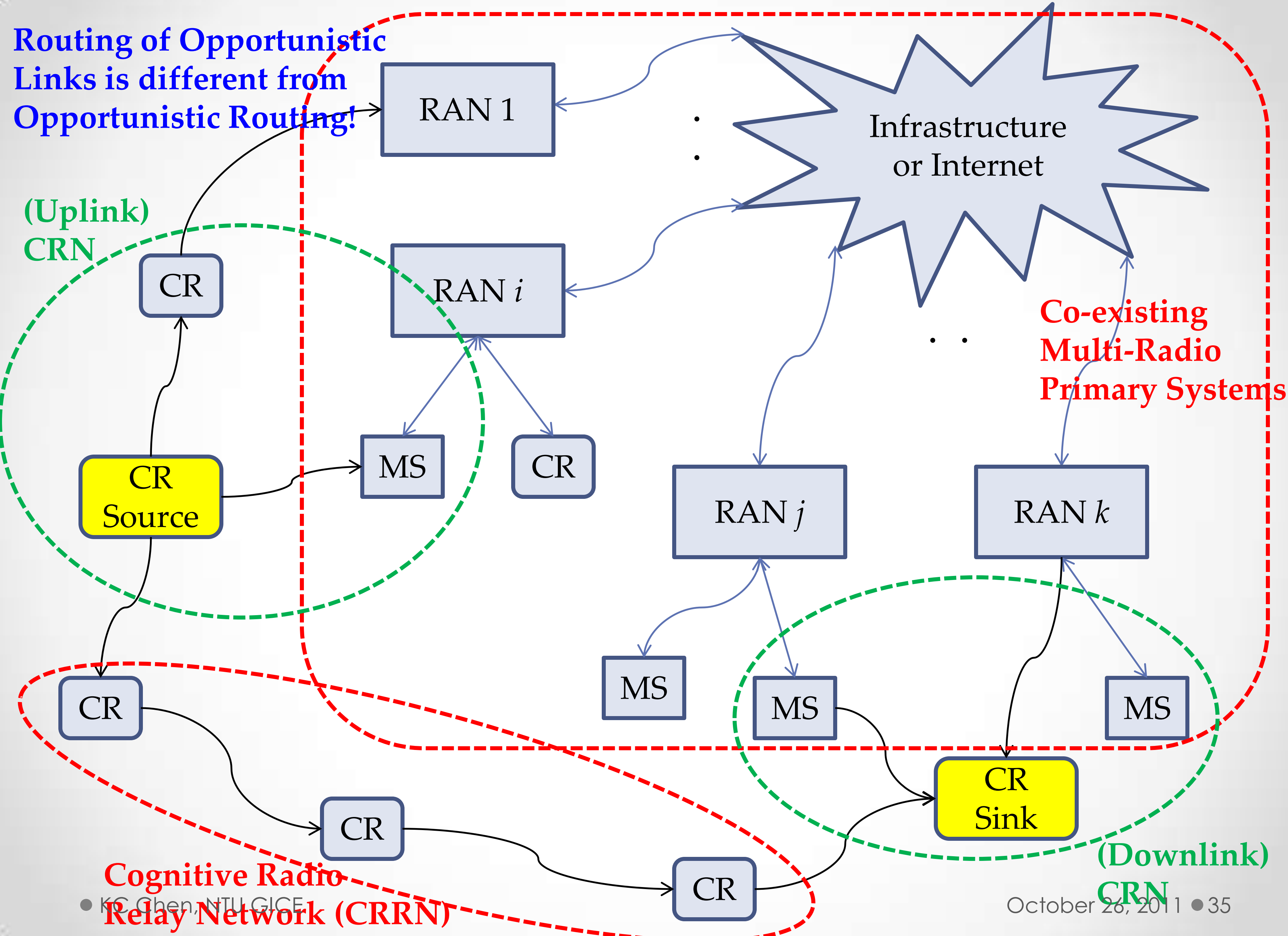
Economy of Cognitive Radio Networks

- Practical realization of cognitive radio technology lies in balanced interests among 4 parties [H.B. Chang, K.C. Chen, IEEE Tr. On Vehicular Technology, 2010]
  - ✓ Incentives to primary users, due to suffering from
  - ✓ Overall spectrum utilization
  - ✓ Interests of service provider(s)
  - ✓ Spectrum access opportunity to cognitive radio users
- Auction mechanism to satisfy above parties and thus economically feasible for spectrum sharing





Routing of Opportunistic Links is different from Opportunistic Routing!



Opportunistic Links and Routing

- To actually realize efficient spectrum utilization, CRN consisting of multi-radio systems
  - ✓ primary and secondary systems under heterogeneous wireless architecture) with the help of cooperative relay technology emerges and supporting a reliable end-to-end transportation over CRN is a must.
- CRN has some properties inherited from CR's DSA and wireless nature.
  - ✓ Spectrum availability: New link paradigm in CR and complex dependence in CRN create large amounts of opportunistic (i.e. highly dynamic available) links in CRN.
  - ✓ Broadcasting and wireless channel fading: These two properties are same with tradition wireless network.
- However, there lacks not only complete understanding of CRN, but also a reliable routing algorithm to deal with these opportunistic links concurrently.
  - ✓ [Lin, Chen, IEEE GLOBECOM 2010]

Spectrum Aware Opportunistic Routing (SAOR)-1

- SAOR studies the origin and property of opportunistic links with the help of spectrum map, employs multi-path and opportunistic routing from cooperative communication, and further concerns QoS guaranteed throughput when deploying itself in CRN.

✓Network topology: CR_S, CR_D, several CRs as cooperative relays CR_Rs, and PS with PS-BS; One-hop path (i.e. direct link) and multi-hop path.

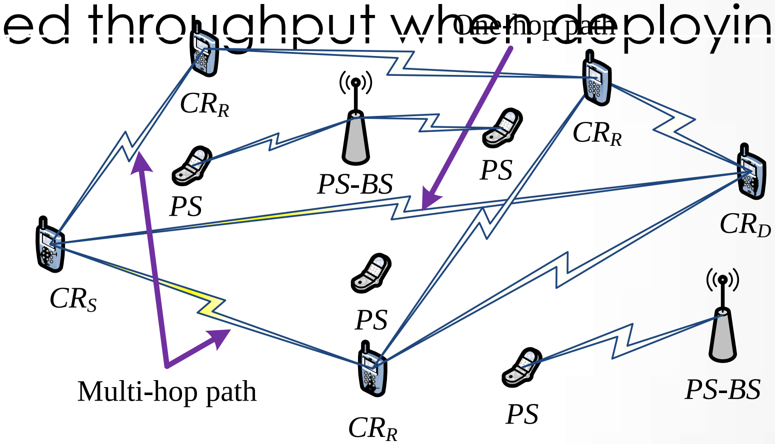


Fig. 1: Network topology of CRN.

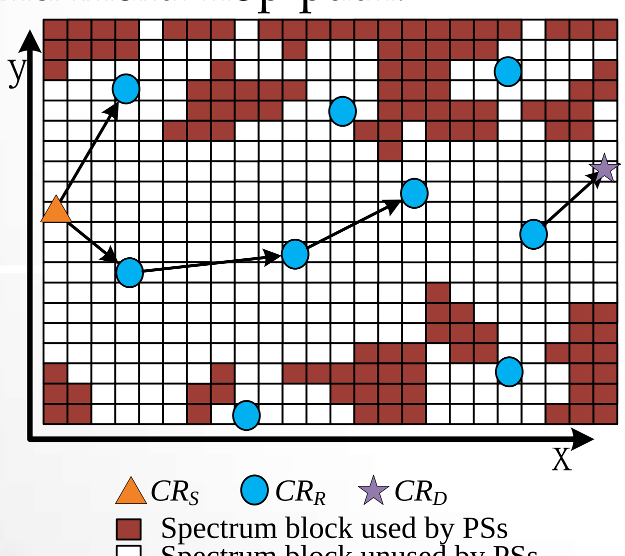


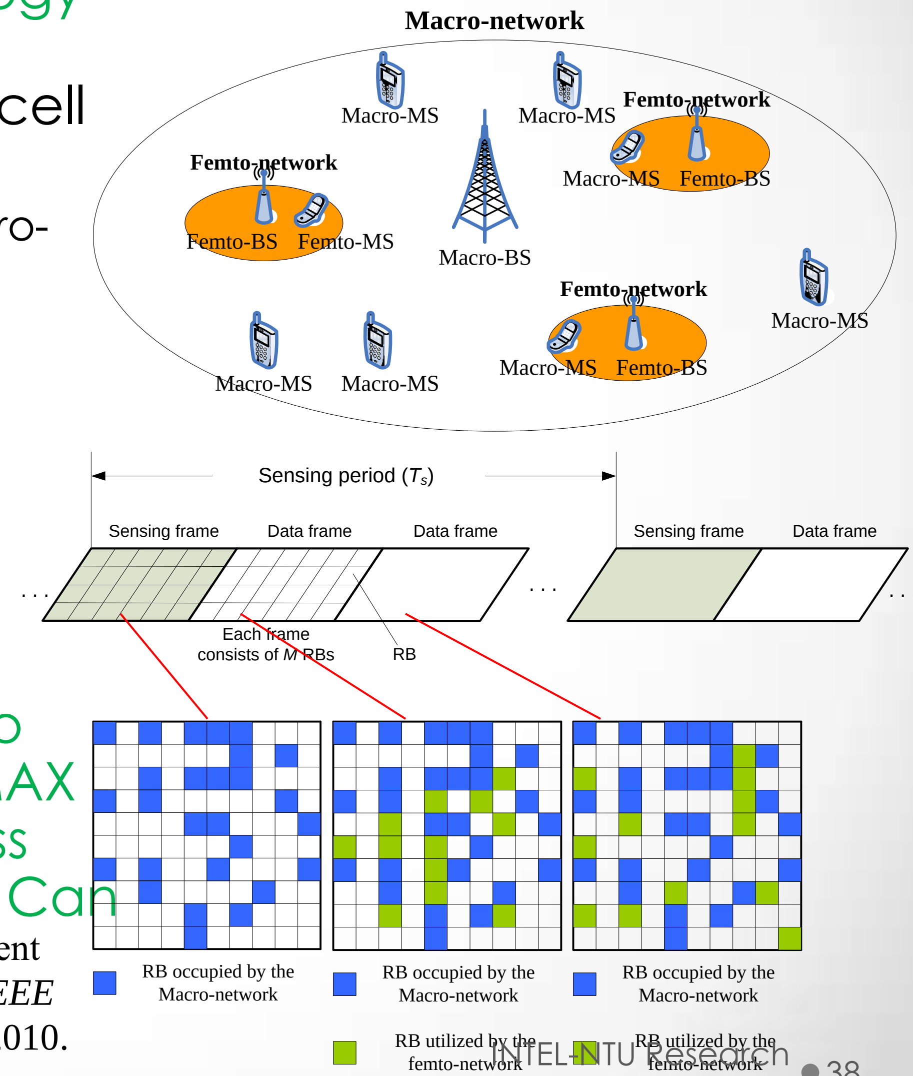
Fig. 2: Spectrum map for PSs' usage of CRN.

✓Spectrum map: For a single block φ

1. Traffic load η
2. Correlated spectrum block ξ for PS
3. Usage dependence for PS

Cognitive Radio Resource Management

- Applying cognitive radio technology to femtocells, CRRM resolves 3 fundamental challenges in femtocell deployments
  - ✓ Interference mitigation between Macro- and femtocell.
  - ✓ Providing statistical QoS guarantees in femtocell
  - ✓ Fully radio resources exploitation
- Fully autonomous
  - ✓ No impacts on Macrocell operations
  - ✓ Provide scalability for highly dense femtocells deployment
- CRRM can be smoothly applied to 3GPP LTE/LTE-Advanced and WiMAX for urgent standardization progress regarding femto-cell technology. Can we do more for M2M?



S.Y. Lien, K.C. Chen, "Cognitive Radio Resource Management for QoS Guarantees in Autonomous Femtocell Networks", *IEEE International Conference on Communications*, Cape Town, 2010. (Best Paper Award)

Scientific Inspired (Wireless) Networking Research

- ❑ It has been quite a few years to exploit biological inspired techniques into (wireless) networking research, namely
  - ✓ Ant routing for ad hoc networks
  - ✓ Epidemic models in ad hoc networks
  - ✓ More .....
- ❑ Ecology and evolutions
  - ✓ Cheng, Chen, Chen, *IEEE Communications Letters*, July 2011
- ❑ Random networks and stochastic geometry have been introduced in past years
  - ✓ For example, award winning review paper, M. Haenggi, J. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, "Stochastic geometry and random graphs for the analysis and design of wireless networks," IEEE J. Sel. Areas Commun., vol. 27, no. 7, pp. 1029–1046, Sept. 2009.
  - ✓ Spectrum sharing induces random/stochastic networks
- ❑ Complex networks or small-world networks have been introduced to Internet research
  - ✓ A-L Barabasi, R. Albert, "Emergence of Scaling in Random Networks", *Science*, vol. 286, no. 5439, pp. 509-512, Oct 15, 1999.
  - ✓ Google citations: 8,700 as of March 24, 2011
  - ✓ Bose-Einstein gas, from statistical mechanics, was employed to networking research

Network Science toward New Frontier in Communications

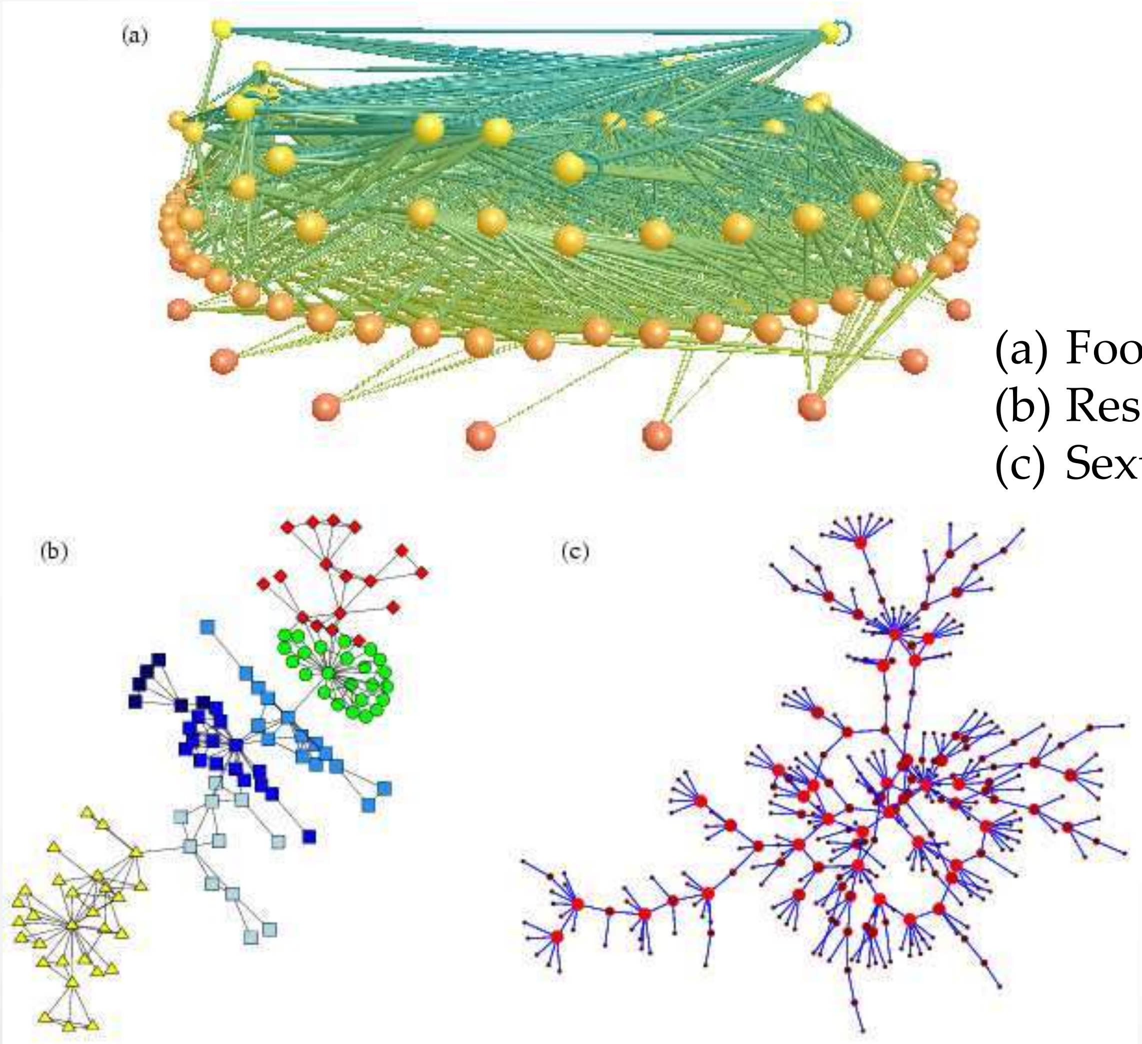
- July 2010, Science introduced a special section, after the first decade of scale-free networking research, to Internet, social science, molecular biology (protein network, regulatory network, …)
- We are interested in emerging (wireless) networking research
  - ✓ Cognitive radio networks
    - co-locating heterogeneous wireless networks sharing the same spectrum, through cooperative multi-hop relay
  - ✓ Social networks
    - Individuals as nodes to form a network, mapping to physically existing networks
  - ✓ M2M communications (INTEL-NTU Lab on M2M technology)
    - Emerging from billions deices for personal communications, to trillions devices for M2M (machine-to-machine) communications
    - Likely spectrum sharing among multiple heterogeneous (cooperative multi-hop relay) wireless networks
  - ✓ Gene regulatory networks

Complex Networks

- Stemming from statistical physics, complex network emerges to quantitatively characterize the real-world behaviors of large-scale networks, e.g. HTTP links of world wide web (WWW), social relation and Internet router topology.
- Many real-world networks are observed to follow some specific attributes instead of totally random nature proposed by Erdös and Rényi back in 1960.
  - ✓ Watts and Strogatz discovered **small-world** feature in social networks.
  - ✓ Barabási and Albert discovered the **scale-free** feature (power-law degree distribution) in various networks.

[D. J. Watts and S. H. Strogatz, *Nature* 1998]
[A. L. Barabási and R. Albert, *Science*1999]

Examples of Complex Networks

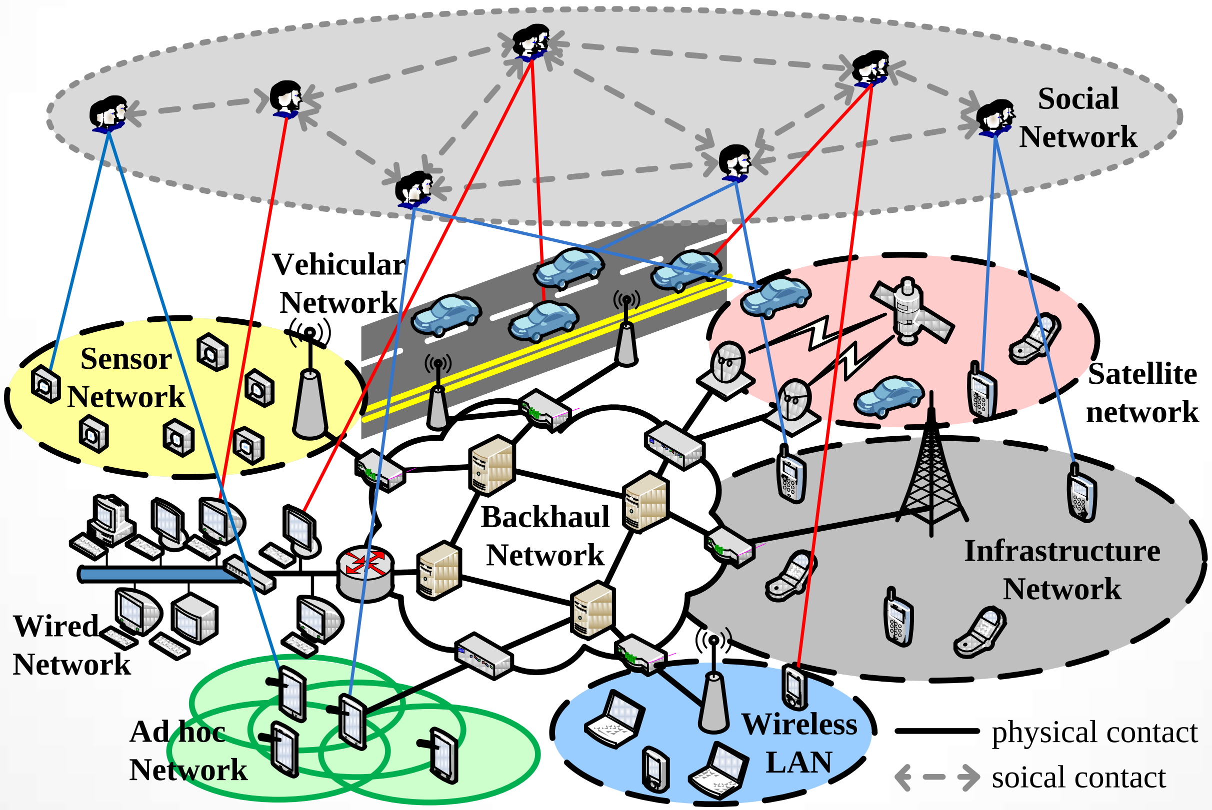


(a) Food web of predator-prey
(b) Research scientists
(c) Sexual contacts

[Newman 2003]

State-of-the-Art Communication Networks

- Combine mobile, ad hoc, peer-to-peer, and sensor/actor network systems
- Massively distributed, large-scale, heterogeneous, and dynamic.



Information Dynamics

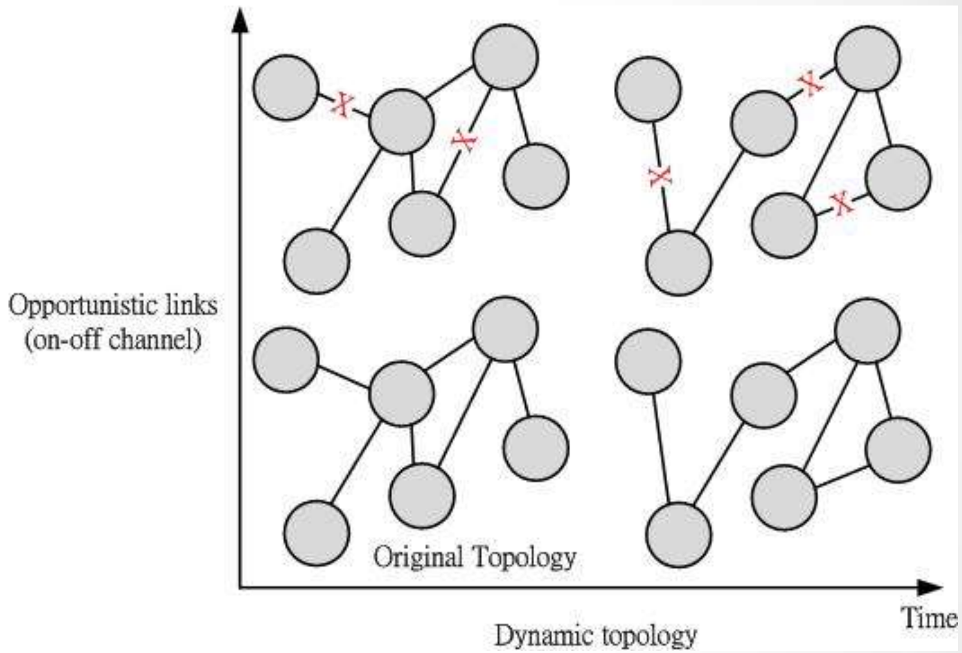
- ❑ Information dynamics is actually not a new terminology
  - ✓ T. Schreiber (Max Planck Institute, Dresden) is one of the pioneers, to introduce transfer entropy for information in dynamic systems [Physical Review Letters 2000]
- ❑ Information dynamics are the information dissemination processes which account for
  - ✓ Routing in communication networks
  - ✓ Power flow in power line/smart grid
  - ✓ Rumor/opinion spreading in social networks
  - ✓ Disease transportation
  - ✓ Virus/malware propagation
    - A generic term that focus on **network synchronization** and **flow/congestion control**.
- ❑ The information dynamics are strongly affected by the underlay network topology.

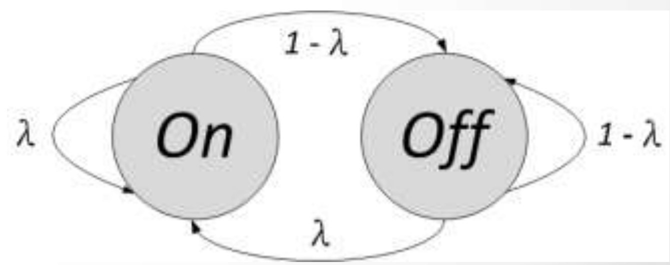
Information Epidemics

- Data transportation much resembles the spread of epidemics
  - ✓ The simplest form of information dynamics
- The mathematical model of epidemics, using differential equations, has existed a century, as a branch in population dynamics
- Inspired from epidemiology, a node is in
  - ✓ Susceptible state: a node does not receive the information
  - ✓ Infected state : a node receives information
  - ✓ Recovered state: a node will not receive the information

Opportunistic Links and Dynamic Topology

- ✓ **Opportunistic link** reflects the pairwise link reliability.
  Ex. Delivery rate
- ✓ **Static network** : Topology does not vary with time.
  Ex. Wireless sensor networks
- ✓ **Dynamic network** : Topology varies with time.
  Ex. Mobile ad hoc networks
- ✓ Spectrum sharing heterogeneous wireless networks and networks of relationship are applied.





Bridging Epidemic Model with Information Dynamics and Complex Networks

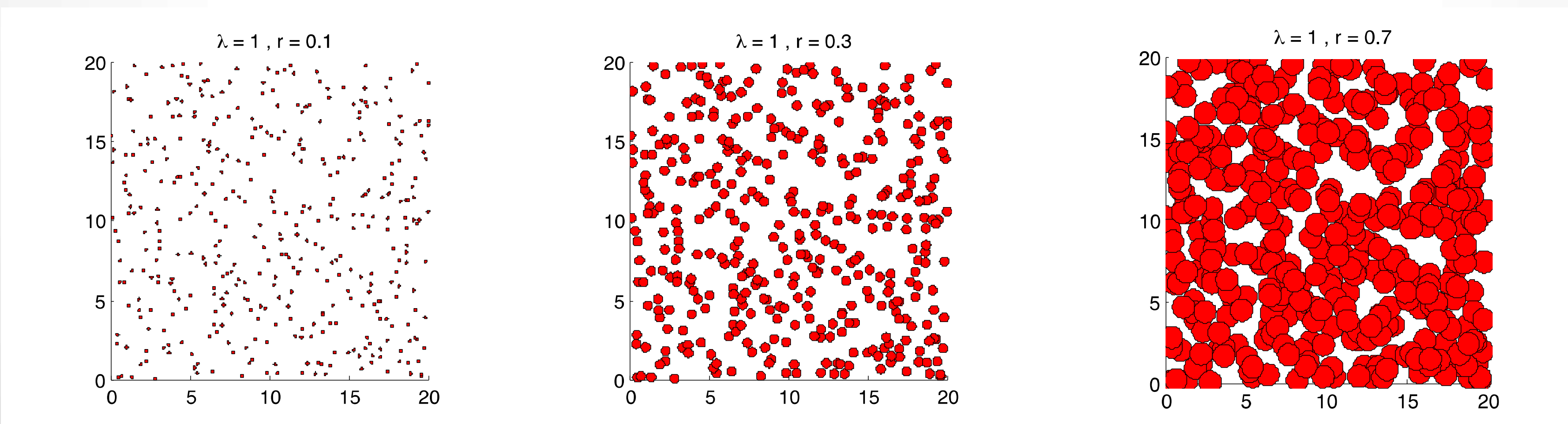
- ✓ The complex network can be expressed by a graph $G(V,E)$.

Network Category	Partially Connectible	Equally Connectible	Unequally Connectible
Homogeneous Mixing	Lattice (regular) network	Random network	Small-world network
Heterogeneous Mixing	Scale-free network	Cellular system	Ad hoc network

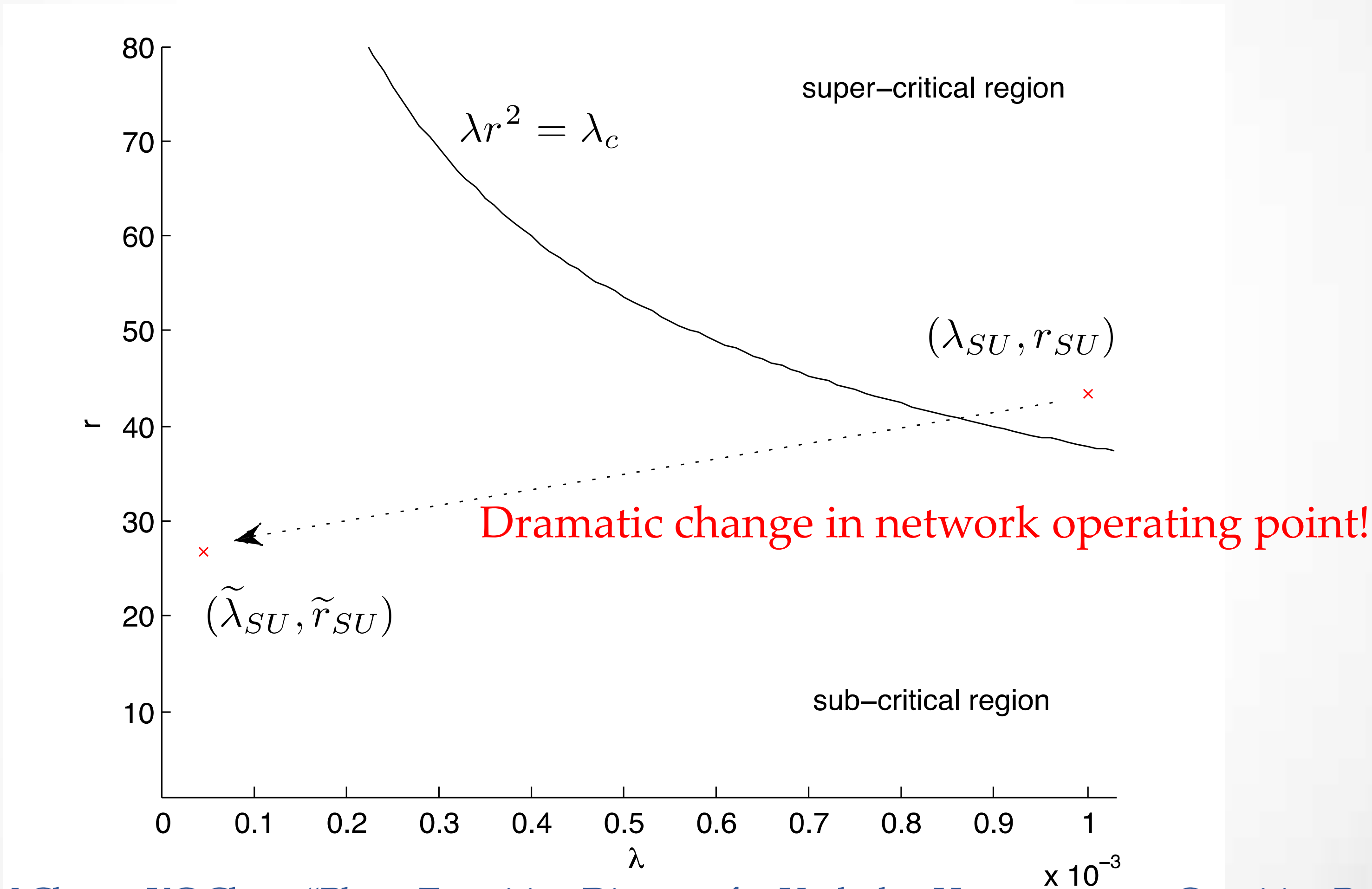
- ✓ The network category also relates to other important network features such as clustering and path length.

Poisson Random Network

- Node density: λ, transmission range: r.
- When $\lambda r^2 > \lambda_c$, the network percolates. A giant connected component exists. Super-critical region.
- When $\lambda r^2 < \lambda_c$, the network breaks down into many finite isolated components. Sub-critical region.

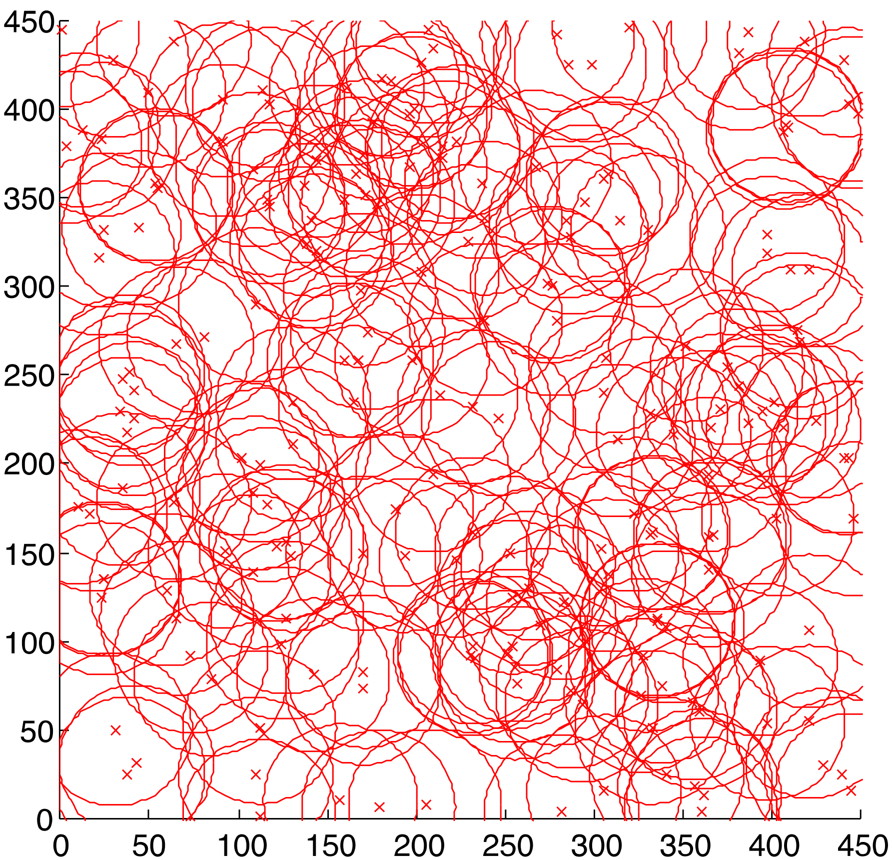


Phase Transition due to Inter-system Interference (I)

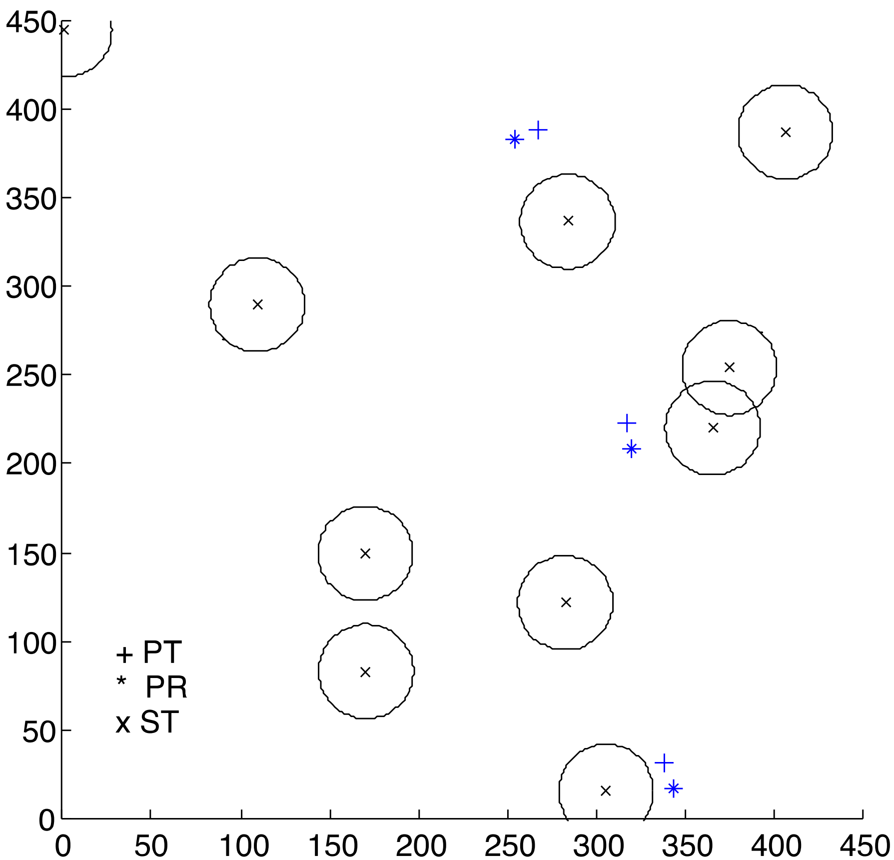


WC Ao, SM Cheng, KC Chen, "Phase Transition Diagram for Underlay Heterogeneous Cognitive Radio Networks", *IEEE GLOBECOM 2010*

Phase Transition due to Inter-system Interference (II)



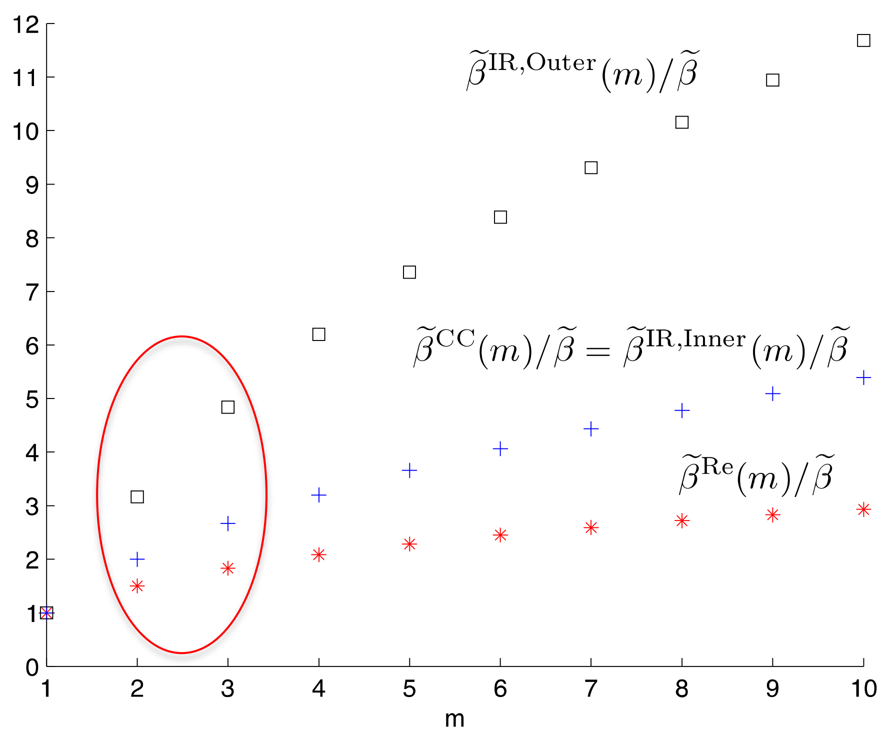
Stand-alone Secondary Network



Underlay Secondary Network

Degree Distribution in Interference-Limited Heterogeneous Wireless Networks

Based on the percolation analysis, error control influences degree distribution.

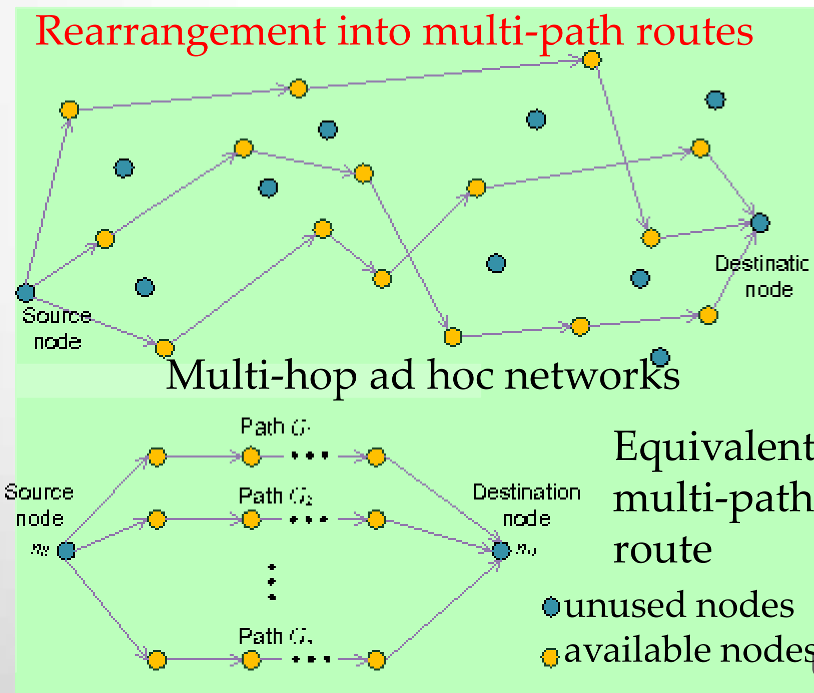


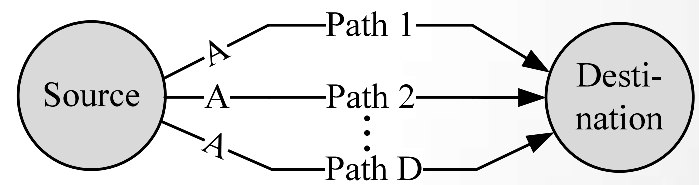
[Ao, Chen, IEEE ICC 2011]

Numerical: lots of normalized average number of neighbors with simple retransmission $\widetilde{\beta}^{\mathrm{Re}}$, retransmission with Chase combining at receiver side $\widetilde{\beta}^{\mathrm{CC}}$, and retransmission with incremental redundancy and code combining at receive side $\widetilde{\beta}^{\mathrm{IR}}$ v.s. the number of retransmissions m.

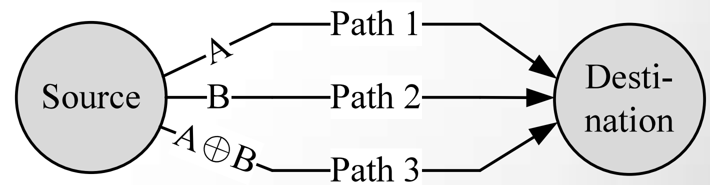
Cooperative Multi-path Networking

- Multi-hop ad-hoc random networks can not guarantee QoS, however, we create multi-path to overcome this challenge in a statistical way
  - ✓ QoS provisioning [IEEE INFOCOM 2011]
    - Using effective bandwidth to obtain guaranteed QoS end-to-end operation
    - Coding aided multi-path routing

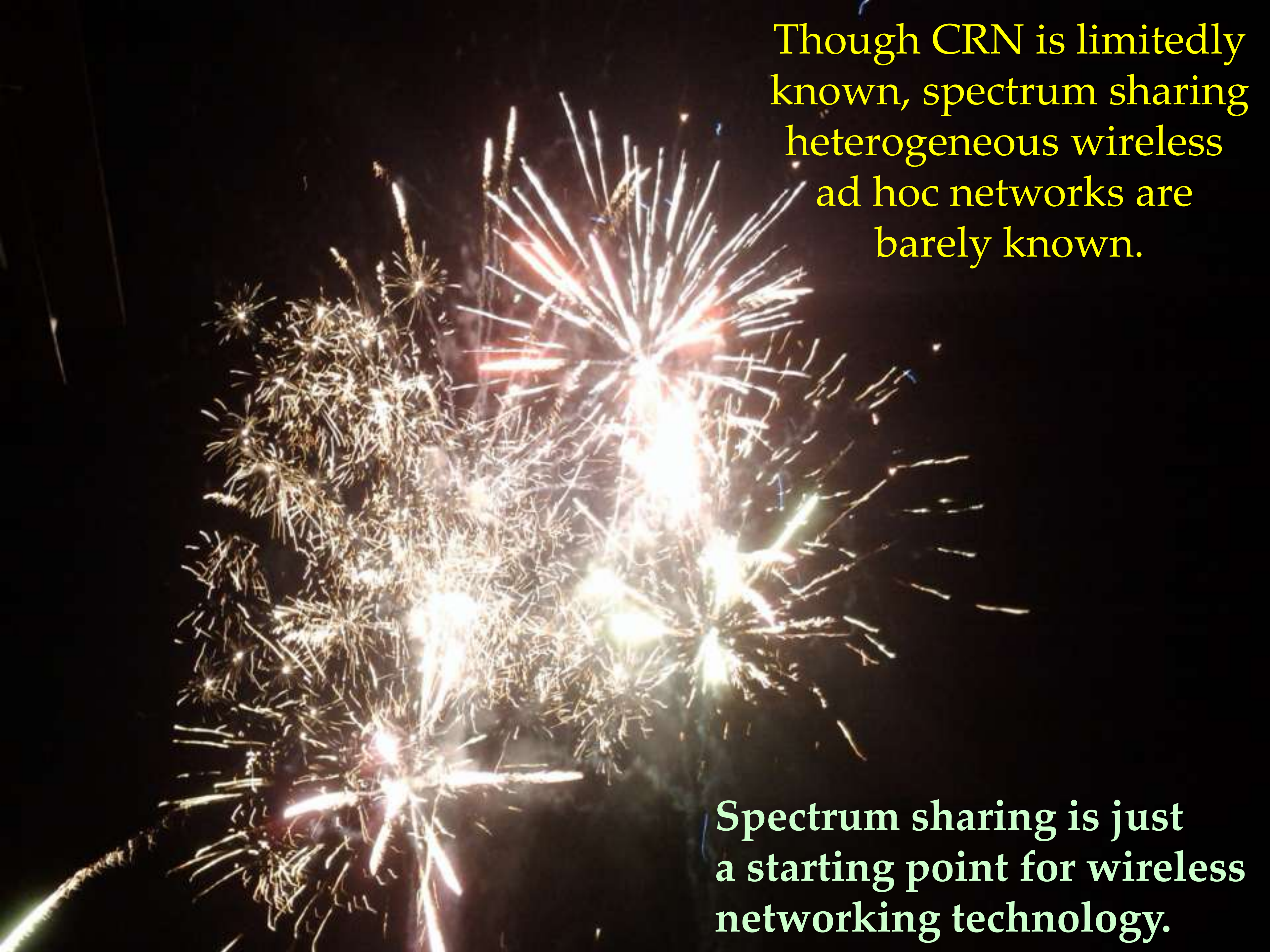




end-to-end throughput = 1/D



end-to-end throughput = 2/3


Though CRN is limitedly known, spectrum sharing heterogeneous wireless ad hoc networks are barely known.
Spectrum sharing is just a starting point for wireless networking technology.

Thank you
for your
attention!
Question?