Capacity of Hybrid Cognitive Radio Networks

--A possible role of cognitive radio in B4G systems

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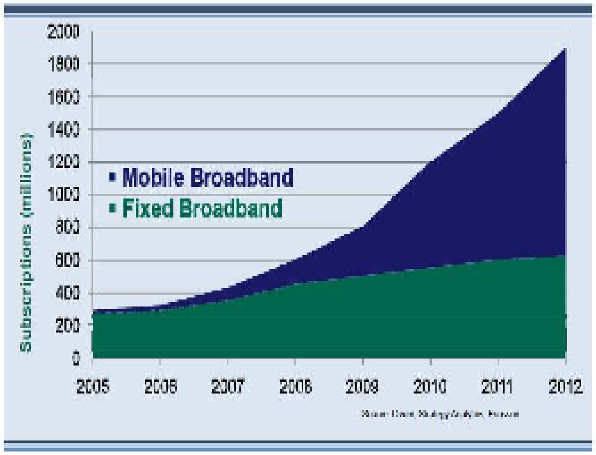
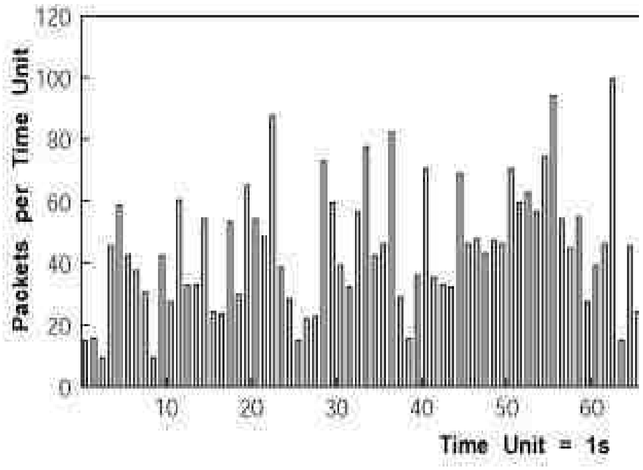
1. Introduction
2. Non-cooperative Hybrid CR Networks
3. Cooperative Hybrid CR Networks
4. Conclusions

1. Introduction

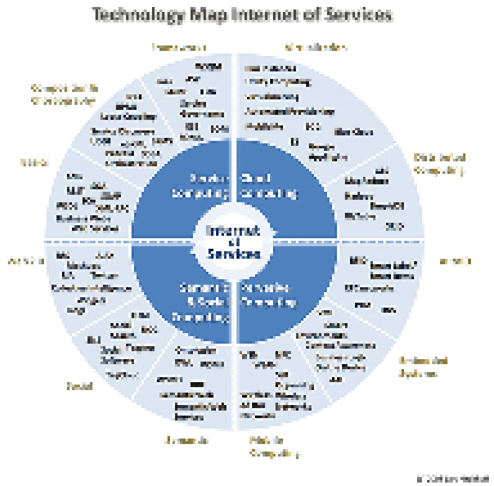
- Challenges in 4G and beyond 4G (B4G) radio access networks
  - Exploding traffic vs. Limited network capacity
  - Random traffic vs. Stable network capacity
  - Diverse traffic vs. Dedicated, reliable expensive network



Exploding traffic



Random traffic



Diverse traffic

A key cause of the above problems: spectrum availability

-- Cellular spectrum is licensed and is **limited**, **fixed**, and **expensive**!

Example of Cellular Spectrum Licensing

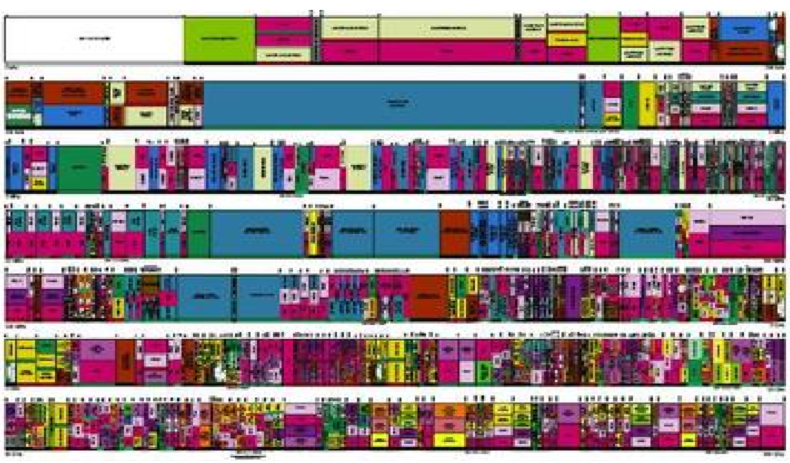
- UK 3G Spectrum Auction, 2000
  - Limited (140 MHz bandwidth), fixed (1900--2170 MHz), expensive (£22.5 billion)

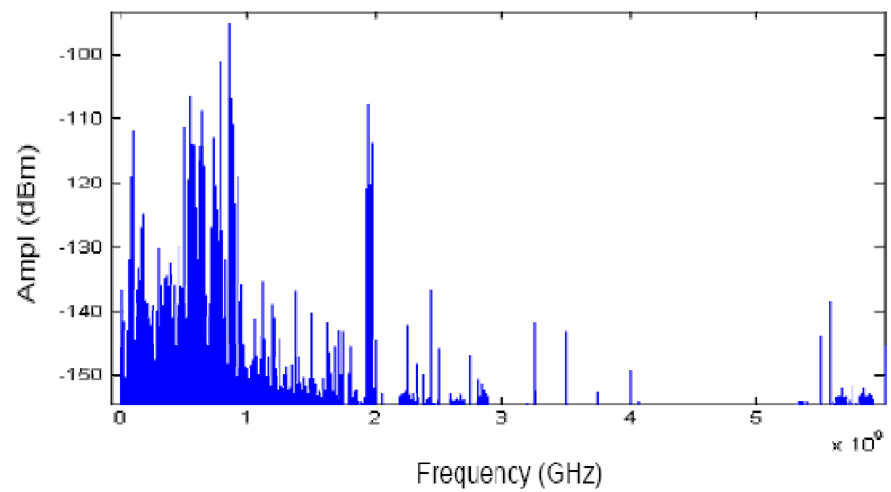
Auction Winners and Winning Bids

	A	B	C	D	E
MHz spectrum	2 x 15	2 x 15	2 x 10	2 x 10	2 x 10
MHz Unpaired	5	0	5	5	5
Price Bidder	T/W	Vodafone	BT	121	Orange
Price Bid (£M)	4,385	5,964	4,030	4,004	4,095
£M/MHz paired	292	398	403	400	410

Spectrum Is A Scarce Resource

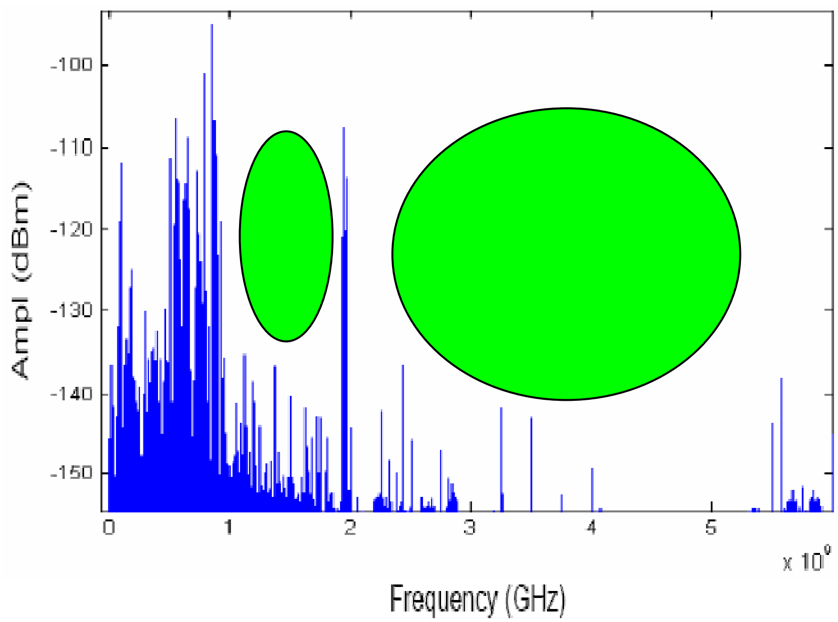
- More licensed cellular spectrum?
  - It will be expensive!
  - Most suitable spectrum has been allocated/licensed to different applications.
- **Secondary spectrum** and **cognitive radio** (CR)
  - A large portion of the spectrum is significantly underutilised.
  - CR networks can use underutilised spectrum as secondary spectrum without interfering with the incumbents (i.e., primary networks).

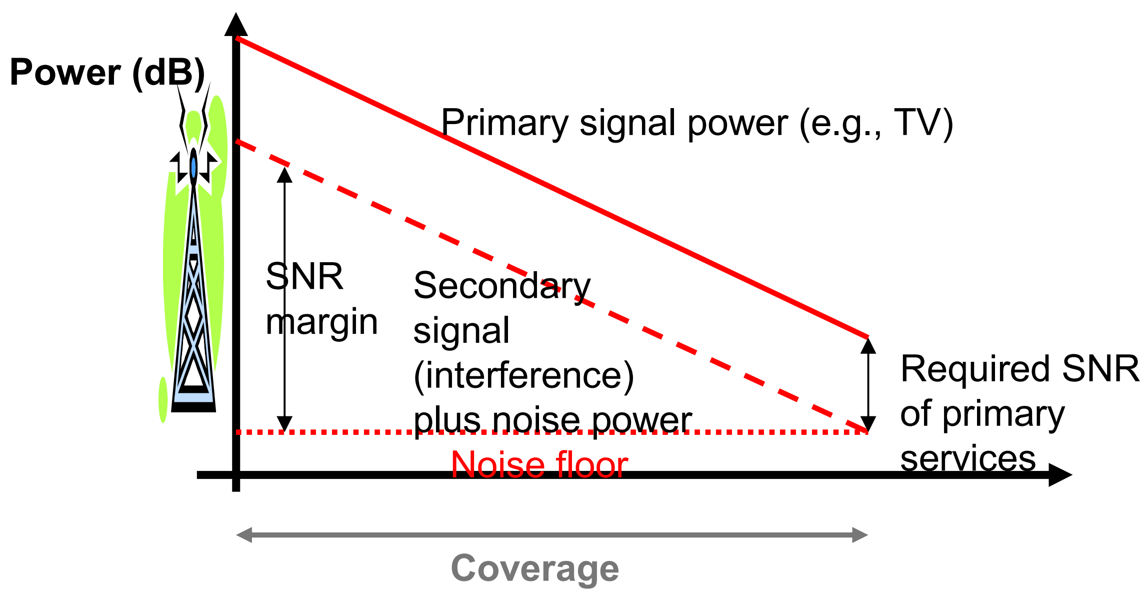




Classification of CR Networks

- Interweave CR network – practical, early CR system
  - Exploit temporal or spatial frequency voids – white spaces/spectrum holes.
- **Overlay CR network** – long term vision of CR system
  - Operate to keep the signal-to-interference-and-noise ratios (SINR) at primary receivers above a certain threshold.





Hybrid CR Networks for B4G

- Definition of hybrid CR networks: A network that integrates both **dedicated licensed spectrum** as well as **secondary spectrum** to serve the users.

- Secondary spectrum vs. Dedicated licensed spectrum
  - Wide bandwidth vs. Small bandwidth
  - Adaptable vs. Fixed
  - Inexpensive vs. Expensive
  - Low power vs. High power
  - Unreliable? vs. Reliable

- Hybrid CR networks can be the future architecture for B4G cellular networks.
  - Growing traffic → Use secondary spectrum to expand capacity.
  - Random traffic → "Borrow" secondary spectrum on demand.
  - Diverse traffic → High-cost, reliable licensed network for high-value services; Low-cost, less reliable CR network for low-value services.

Motivation for Capacity Analysis

- The purpose and importance of capacity analysis
  - Understand the performance limits of CR networks.
  - Provide basic guidelines for the planning and design of CR networks.
- Why capacity analysis of CR networks is different from conventional ones
  - Conventional wireless networks: intra-network (self) interference constraint
  - CR networks: inter-network interference constraint (protect primary systems)
    - Peak / Average /Outage interference power constraints
- Previous work: link capacity analysis
  - Consider a CR link.
  - Information-theory-oriented: provide guidelines for transmission scheme design.
- Our work: system capacity analysis
  - Consider multiple CR links, user distribution, and channel propagation.
  - Network-engineering-oriented: provide guidelines for network planning.

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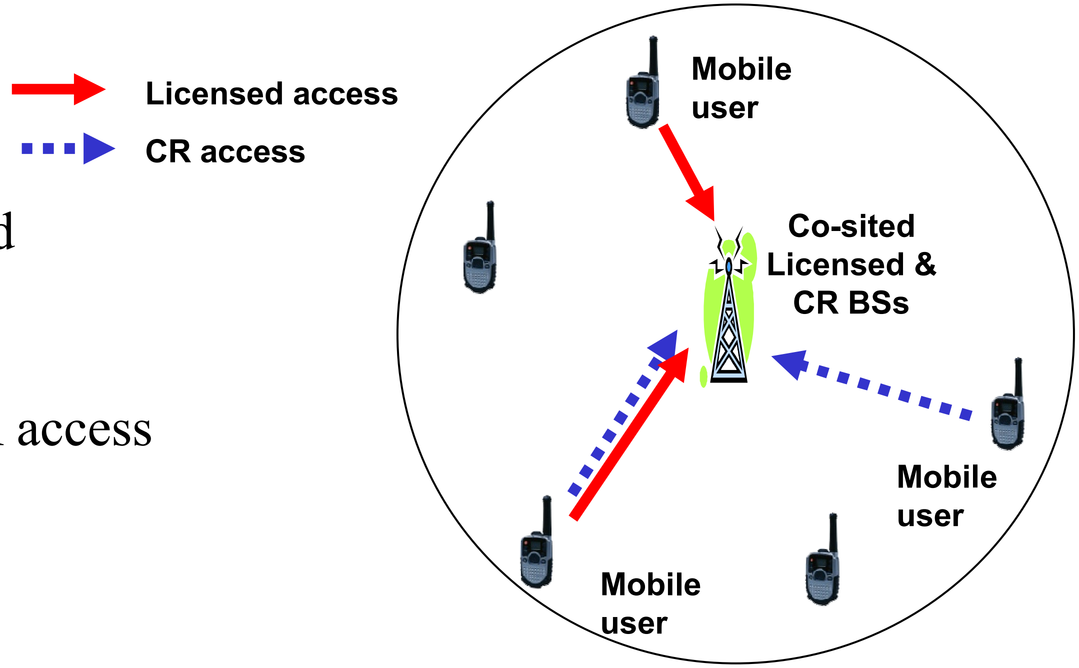
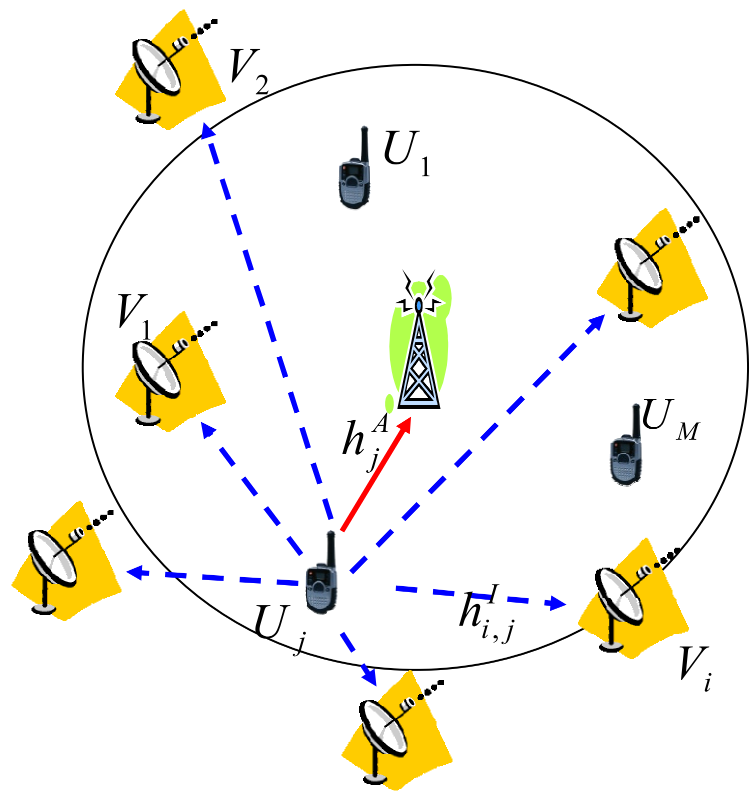
2. Non-cooperative Hybrid CR Networks

- System description
  - Separated PHY layers in the licensed band and the secondary band.
  - Dual-mode BSs and mobile users.
  - Users are served by either the licensed or secondary bands.
- Advantages
  - Simple
  - Relatively less signalling overhead
- Disadvantages
  - May not support long distance CR access
  - Require modification to the BS
- Capacity analysis
  - Licensed network capacity + pure CR network capacity



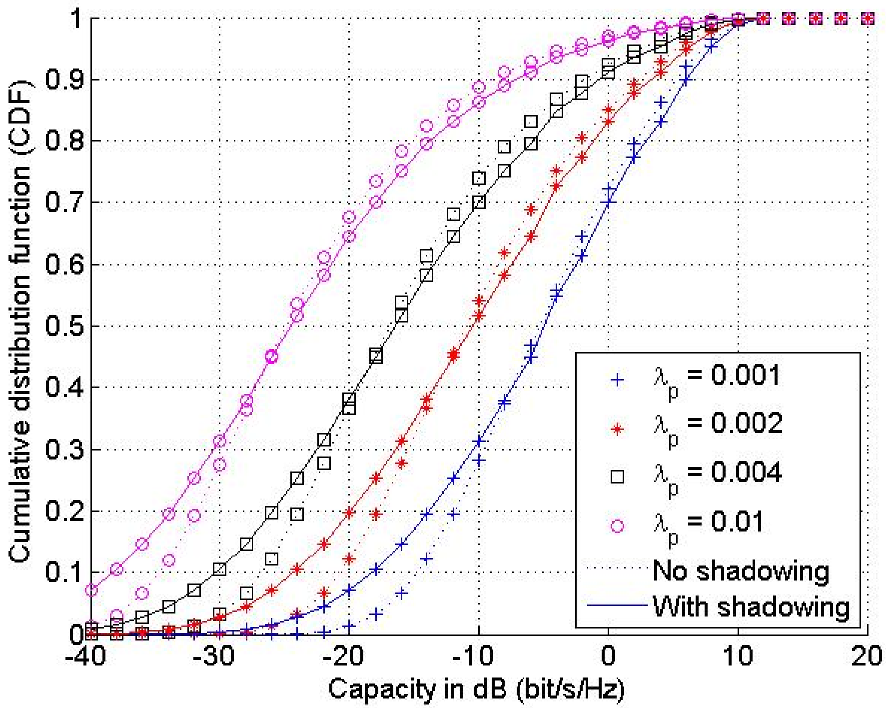
A Centralised CR Network

- System model
  - Primary user locations follow Poisson point distribution with certain density
  - A circular CR cell with a central base station (BS) and a radius *R*
  - Uniformly distributed secondary users
  - Time division multiple access (TDMA)
  - Channel model: Pathloss + Log-normal shadowing + Nakagami fading
  - Power control:
    - Peak interference power constraint
  - Opportunistic scheduling:
    - The BS choose one among M secondary users to communicate in each time slot.
  - Capacity as a random variable: "best effort"



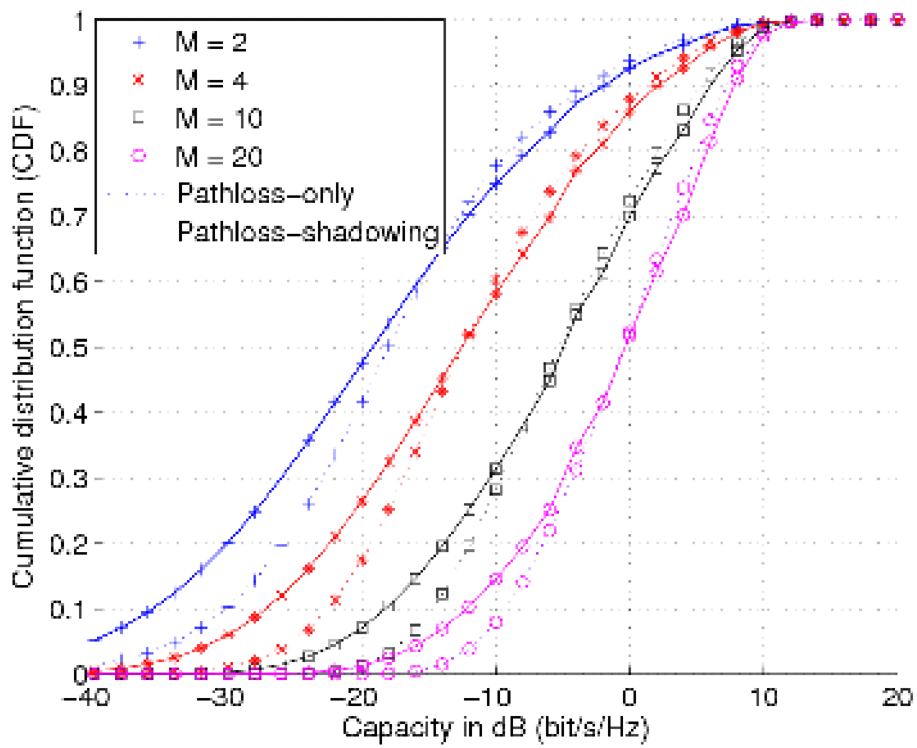
Capacity vs. Primary Receiver Density

- Impacts of the primary receiver density on the capacity
  - Capacity has a large dynamic range.
  - Capacity is sensitive to primary receiver density.
  - Shadowing has limited impacts on the capacity distribution.



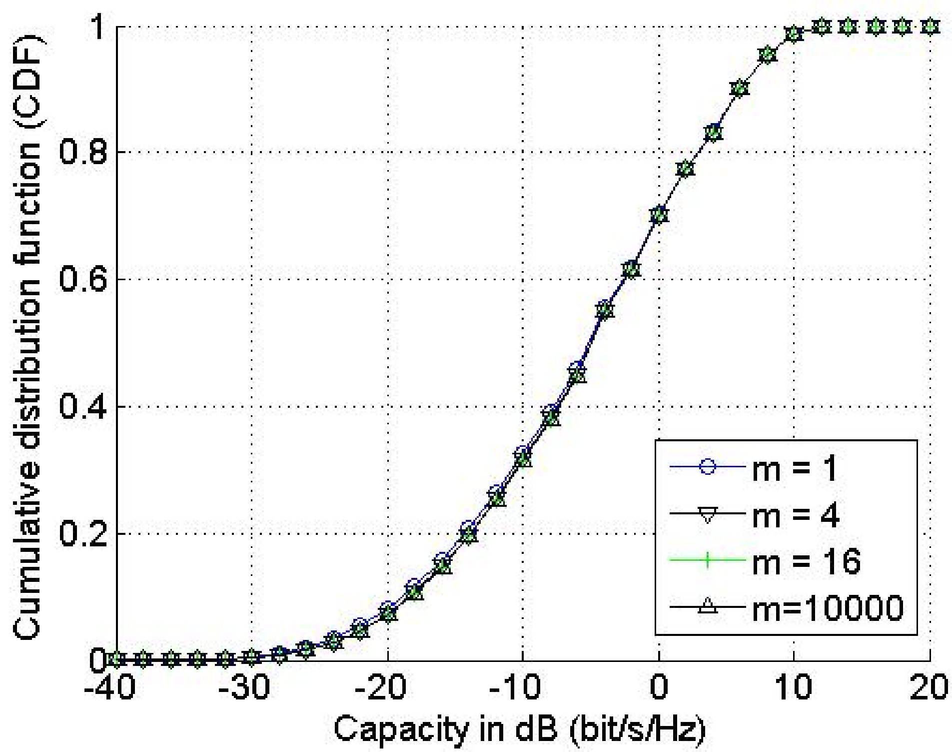
Benefit of Opportunistic Scheduling

- Impacts of the number of scheduled users *M* on the capacity
  - Increasing *M* can significantly increase the capacity.
  - Shadowing has limited impacts on the capacity distribution.
  - Capacity has a large dynamic range even with a large value of *M*.



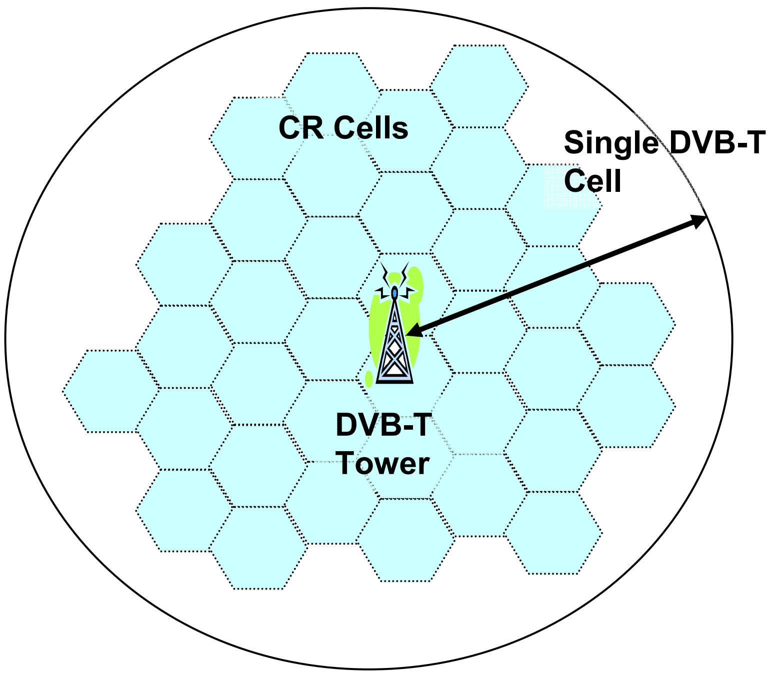
Impacts of Fading

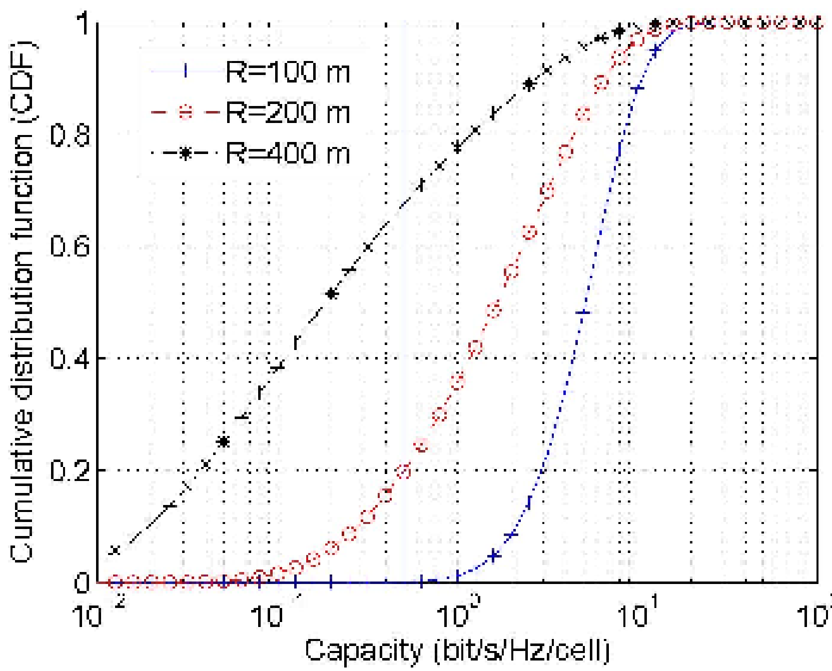
- Impacts of the Nakagami fading parameter *m* on the capacity
  - Small scale fading has trivial impacts on the capacity.
  - The reason is that the access channels and interference channels are assumed to have the same fading properties.



Example: TV and FMC Band Deployments

- DVB receiver density = *0.001/m²*
- DVB receiver antenna gain = *18 dB*
- DVB minimum SIR requirement: = *12 dB*
- CR BS interference suppression gain = *10 dB*
- Number of opportunistic scheduled users M = 20
- Channel model constants KA/KI = 1
- Error tolerance in a 8 MHz channel: 1%





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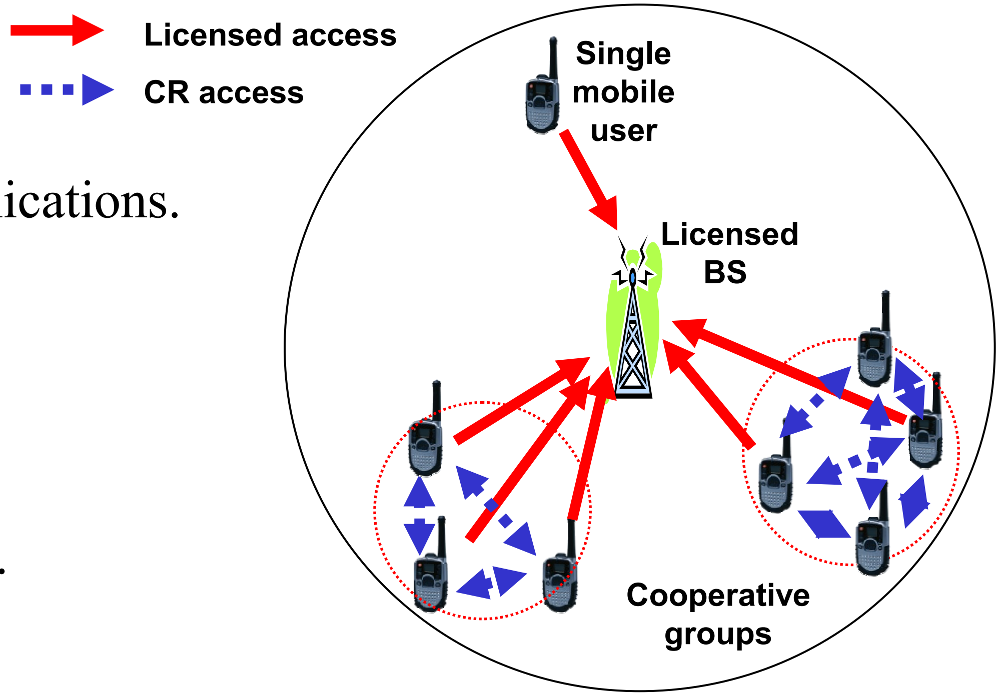
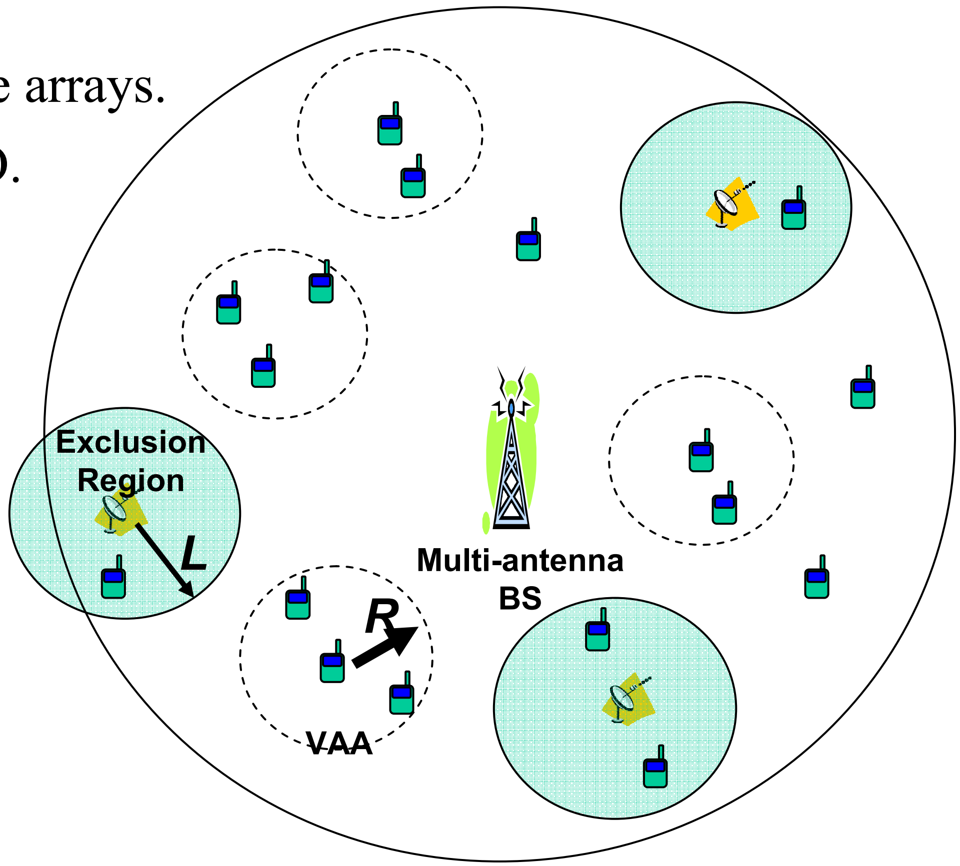
3. Cooperative Hybrid CR Networks

- System description
  - Dual-mode mobile users establish local ad-hoc networks using the secondary spectrum.
  - All users communicate with the BS using only the licensed spectrum.
  - Indirect performance improvement through cooperative communication.
- Advantages
  - Can use short distance CR schemes.
  - Obtain gains of cooperative communications.
  - No modification required to the BSs
- Disadvantages
  - Complex
  - Users may be unwilling to cooperate.



Example: CR Assited Virtual MIMO—System Model

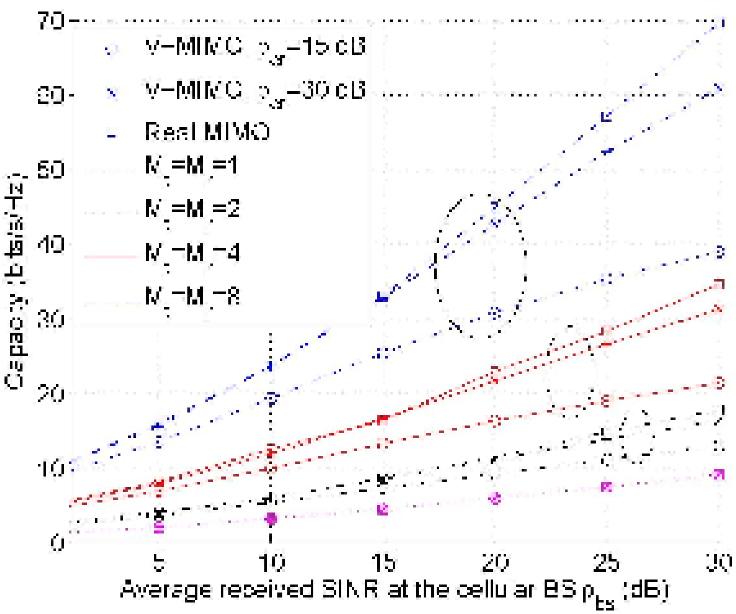
- Virtual MIMO is a promising cooperative scheme.
  - VAA: virtual antenna array
  - Group distributed antennas to cooperative arrays.
  - Exploit MIMO gains using virtual MIMO.



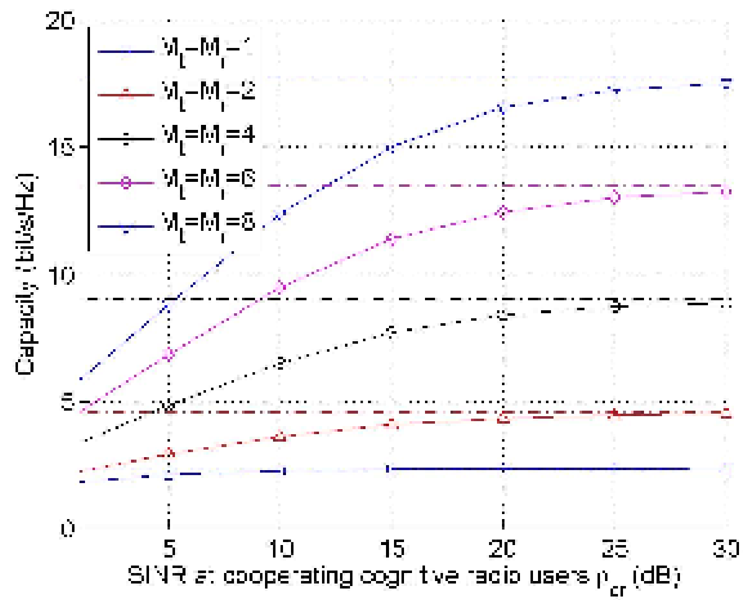
- System model
  - CR band: to form VAA
  - Licensed band: to communicate with BS
  - VAA radius: R
  - Primary exclusion region: L
  - Amplify-and-forward relaying
  - Primary user density λ_p
  - CR user density λ_c
  - Power control to guarantee minimum SINR for communications in the CR band.

Link Level Capacity (Virtual MIMO Uplink)

- As a function of licensed channel SINR
  - With large CR channel SINR, V-MIMO approaches real MIMO capacity.
  - Multiplexing gain is maintained with large relay channel SINR.



- As a function of CR channel SINR
  - With large relay channel SINR, V-MIMO approaches real MIMO capacity.
  - 13+ dB relay channel SINR needed for virtual MIMO to be "useful".



System Capacity of Cooperative Hybrid CR Networks

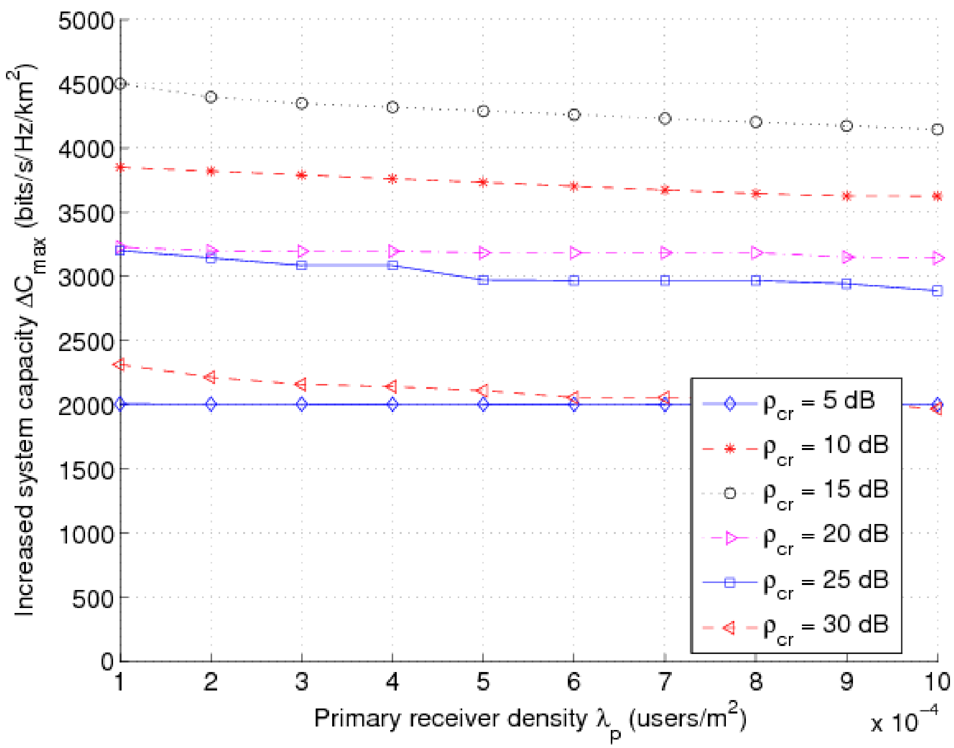
- System capacity (bits/Hz/s/m^2) =

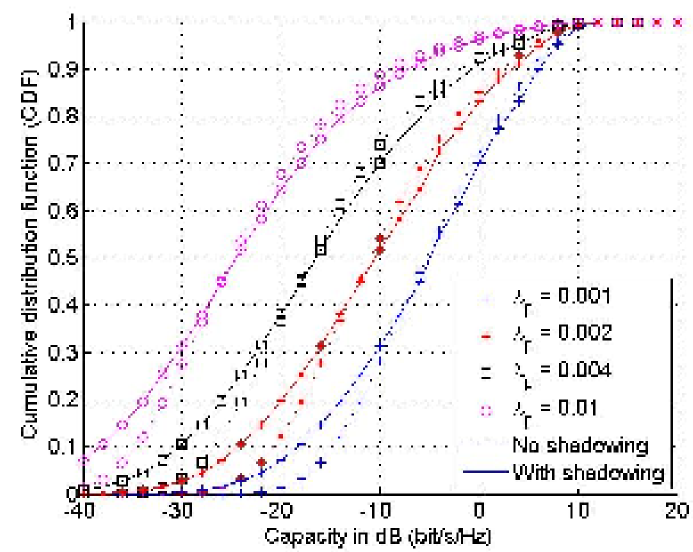
  VAA link capacity (bits/Hz/s) $\times$ Spatial density of VAA (m^{-2})

- Spatial density of CR-based virtual MIMO groups
  - Use physical interference models (Section 2.2)
  - The VAA density can be calculated as a function of
    - The tolerable interference I_{lim}
    - The VAA radius R
    - The primary exclusion region radius L
    - The minimum SINR requirement ρ_{cr}
    - The CR user density λ_c
    - The primary user density λ_p
- There exists complex tradeoffs among various system parameters.
- Optimisation techniques are used to calculate the maxium system capacity.

Capacity vs. Primary Receiver Density

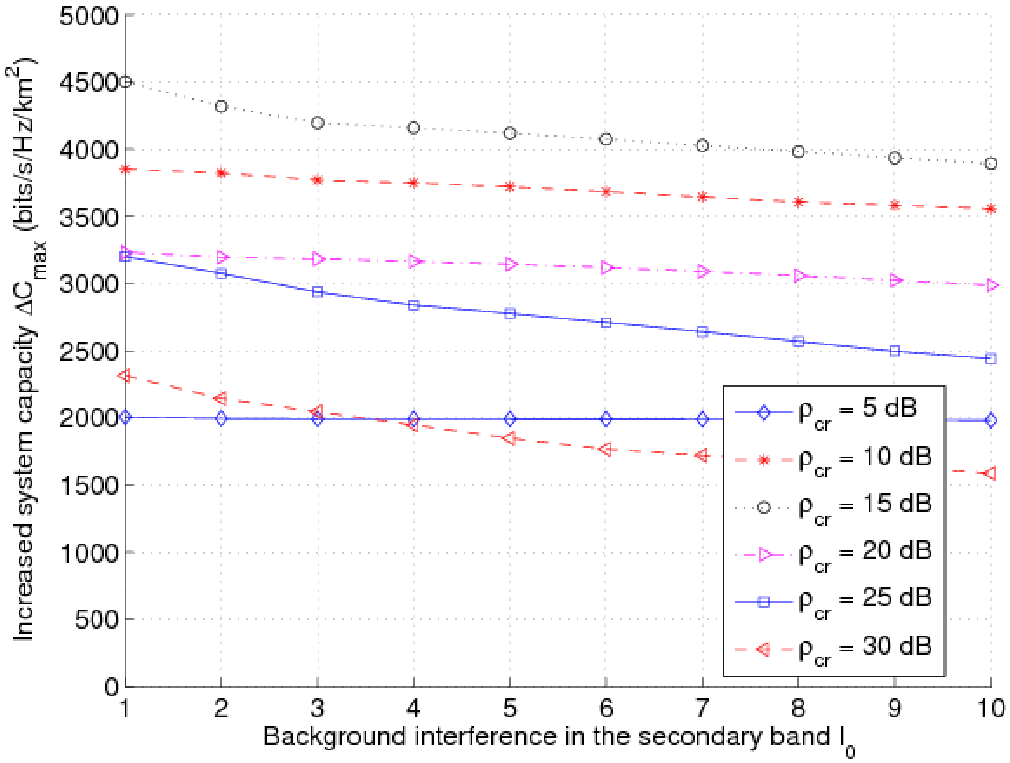
- Impact of primary user density on the capacity of hybrid cooperative CR networks
  - Capacity is **insensitive** to the primary receiver density (left).
  - A major benefit compared with the random capacity of pure CR networks (right).





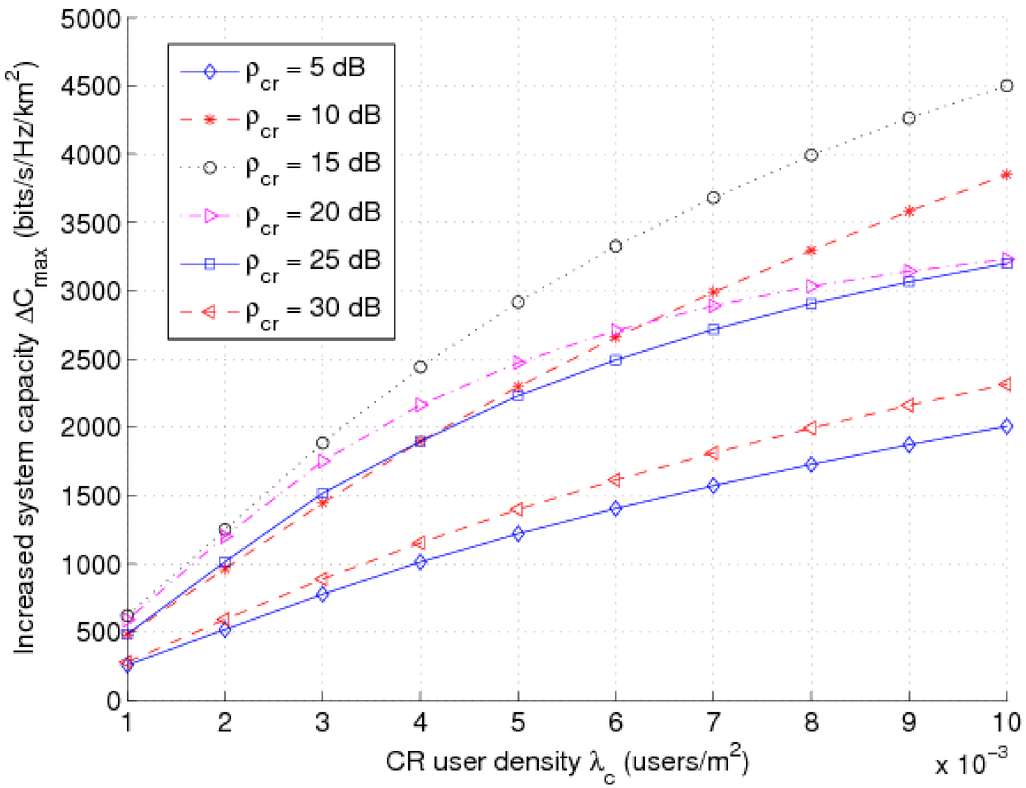
Capacity vs. Interference from Primary to CR Systems

- Impacts of the interference level from primary to CR systems on the capacity of hybrid cooperative CR networks
  - Capacity is **insensitive** to the interference level from primary networks.



Capacity vs. CR User Density

- Impact of CR user density on the capacity of hybrid cooperative CR networks
  - Capacity is very sensitive to the CR user density.



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4. Conclusions

- The concept of hybrid CR networks has been proposed and its capacity studied.
- Non-cooperagtive CR networks
  - Provided analytical framework for capacity evaluation: useful for network planning.
  - The capacity gain is found to be sensitive to the properties of the primary network.
  - In principle, it is possible to deploy such CR networks in the TV band for short to medium range communications.
- Cooperative CR networks
  - Studied a cooperative hybrid CR network based on virtual MIMO.
  - Cooperative hybrid CR networks is found to have a major advantage in that the system capacity is insensitive to the properties of the primary network.

Related Journal/Book Publications

Book chapter

- **X. Hong**, C.-X. Wang, J. S. Thompson, and H.-H. Chen, "Capacity analysis of cognitive radio networks," in *Cognitive Radio Networks: Architectures, Protocols and Standards*, edited by Yan Zhang, Jun Zheng, and Hsiao-Hwa Chen, to be published by Auerbach Publications, CRC Press.

Journals

- **X. Hong**, C.-X. Wang, M. Uysal, X. Ge and S. Ouyang, "Capacity of hybrid cognitive radio networks with distributed VAAs," *IEEE Trans. Vehi. Technol.*, vol. 59, no. 7, Sept. 2010.
- C.-X. Wang, **X. Hong**, H.-H. Chen, and J. S. Thompson, "On capacity of cognitive radio networks under average interference power constraints," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1620-1625, Apr. 2009.
- **X. Hong**, C.-X. Wang, H.-H. Chen, and Y. Zhang, "Secondary spectrum access networks: recent development on the spatial models," *IEEE Vehi. Technol. Mag.*, vol. 4, no. 2, pp. 36-43, June 2008.
- **X. Hong**, Z. Chen, C.-X. Wang, S. A. Vorobyov, and J. S. Thompson, "Interference cancellation for cognitive radio networks," *IEEE Vehi. Technol. Mag.*, vol. 4, no. 4, Nov. 2009.
- C.-X. Wang, H.-H. Chen, **X. Hong**, and M. Guizani, "Cognitive radio network management: tuning in to real time conditions," *IEEE Vehi. Technol. Mag.* vol. 3, no. 1, pp. 28-35, Mar. 2008.

Thank you for your attention!

Questions?