Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks

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Outline

- **Network Capacity in Classic Ad Hoc Networks**

- **Research Progress in CRAHNs**

- **Network Capacity of CRAHNs: PU Activity**

- **Next Research Plan**

The capacity of wireless networks

[1]P. Gupta and P. Kumar, *"The capacity of wireless networks,"* *IEEE Trans. on Info. Theory, vol. 46, no. 2, pp. 388.404, Mar 2000.*

- **The seminal work is conducted by Gupta and Kumar in 2000.**

- **The aim of this research is to study the achievable throughput capacity for large scale wireless ad hoc networks.**

- **Scenario: n identical randomly located nodes distributed in a wireless network, each capable of transmitting at W bits per second and using a fixed range.**

  - Dense Network Model: **n** nodes distributed in a unit square region.

  - Extended Network Model: nodes with density **1** distributed in a **n** square meter region.

The capacity of wireless networks

[1]P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Trans. on Info. Theory, vol. 46, no. 2, pp. 388.404, Mar 2000.*

- Nodes Distribution: randomly or arbitrarily

  For random distribution, usually, it assumes two distribution functions: P.P.P or uniformly distribution; this does not change the capacity scaling results.

■ Conclusion:

- The throughput $\lambda(n)$ for each node in the **randomly distribution** scenario is $\theta\left(\dfrac{W}{\sqrt{n\log n}}\right)$

- The throughput $\lambda(n)$ for each node in the **arbitrarily distribution** scenario is $\theta\left(\dfrac{W}{\sqrt{n}}\right)$

■ The per-node throughput capacity is decreasing with the increase of nodes density, which means the wireless ad hoc networks are unscalable in large network deployment.

Mobility Increases the Capacity of Wireless Networks

[2]M. Grossglauser and M. D. Tse, "Mobility increases the capacity of ad hoc wireless networks," in Proc. of *IEEE INFOCOM 2001.*

- It is shown in [2] that significant gains in per-node throughput capacity can be achieved by allowing nodes to move independently and uniformly with the store-carry-and-forward paradigm.

- In particular, a 2-hop relaying scheme is proposed in [2], which can achieve a constant per-node throughput capacity $\theta(1)$.

Mobility Increases the Capacity of Wireless Networks/Architecture

[2]M. Grossglauser and M. D. Tse, "Mobility increases the capacity of ad hoc wireless networks," in Proc. of *IEEE INFOCOM 2001*.
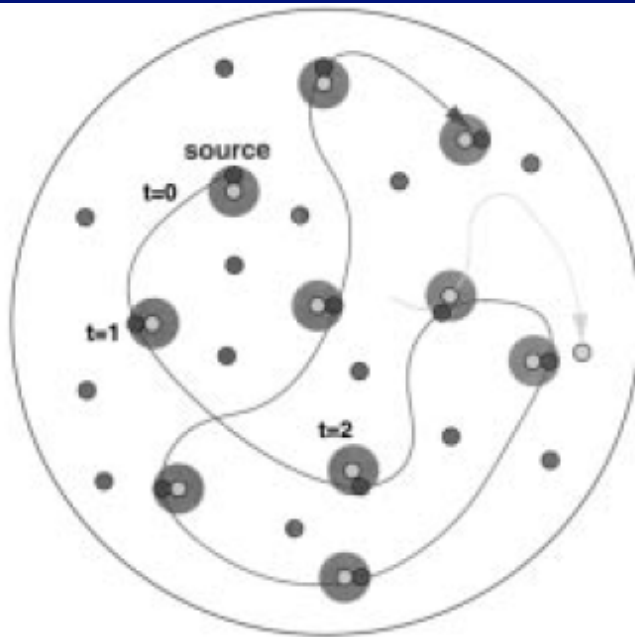

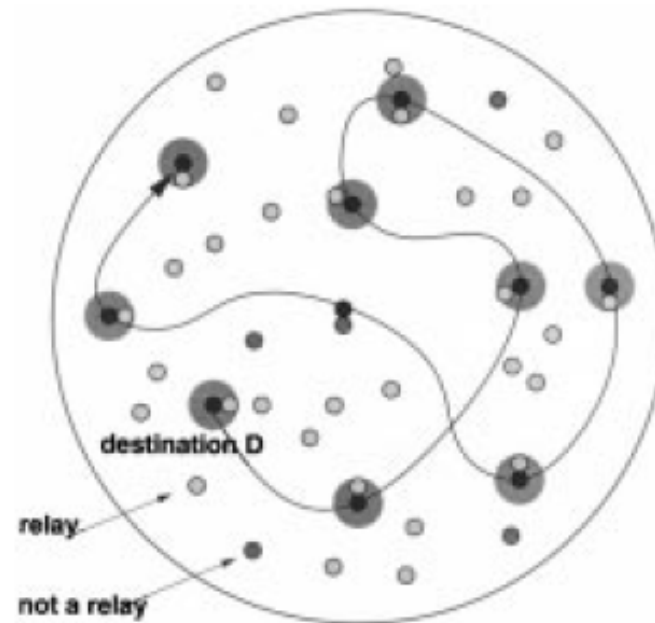Fig. 1. In phase 1, each packet is transmitted by the source to a close-by relay node.

Fig. 2. In phase 2, a packet is handed off to its destination if the relay node is close by.

Mobility Increases the Capacity of Wireless Networks/Delay

[2] M. Grossglauser and M. D. Tse, "Mobility increases the capacity of ad hoc wireless networks," in Proc. of *IEEE INFOCOM 2001*.

[3] A. E. Gamal, J. Mammen, B. Prabhakar and D. Shah, "Throughput-delay trade-off in wireless networks," In *Proc. IEEE Infocom 2004.*

- The per-node throughput capacity in mobile case is $\theta(1)$, which is larger than the *static wireless ad hoc* networks case $\theta\left(\dfrac{W}{\sqrt{n \log n}}\right)$

- Although higher network throughput capacity can be achieved by counting more on mobility, but this has negative effect as significantly increasing the network delay.

- In [3], the optimal delay-throughput tradeoff is established for both static and mobile wireless networks.

Throughput-Delay Trade-off in Wireless Networks

[3]A. E. Gamal, J. Mammen, B. Prabhakar and D. Shah, "Throughput-delay trade-off in wireless networks," In *Proc. IEEE Infocom 2004.*

- **Throughput and delay are important network performance metrics, and, consequently, significant effort has been devoted to research their trade-off in wireless networks on different mobility model, such as Brownian, linear, random walk mobility models, etc.**

- **It is shown that the optimal delay-throughput tradeoff for static networks is given by $D(n) = \theta(n\lambda(n))$, where $D(n)$ and $\lambda(n)$ are the delay and throughput per S-D pair, respectively.**

- **Using the 2-hop relaying scheme in [2], it is shown that an extremely long delay of $\theta(n)$ is associated with the higher throughput of $\theta(1)$**

$$D(n) = \theta\left(\sqrt{\frac{n}{\log n}}\right)$$

$$\lambda(n) = \theta\left(\frac{W}{\sqrt{n \log n}}\right)$$

Other Important Research Topics in Wireless Ad hoc Network Capacity Analysis

■ **Infrastructure improve the capacity of wireless networks.**

■ **Capacity Analysis of Multi-channel and Multi-radio wireless networks.**

■ **Directional Antenna and Cooperative communications improve the capacity of wireless networks.**

■ **Capacity Analysis for Multicast in Wireless network.**

Research Progress in CRAHNs

[4]S-W Jeon, N. Devroye, M. Vu, S-Y Chung and V. Tarokh, "Cognitive networks achieve throughput scaling of a homogeneous network," submitted to *IEEE Trans. on Info. Theory, Jan. 2008. Available:* http://arxiv.org/pdf/0801.0938.

- In [4], a CRAHN co-located with a primary ad hoc network is considered under the assumption that the primary network must be sparser than the secondary network.

- In this scenario, they claim that the two networks share the same space, time, code and frequency dimensions (*spectrum underlay).*

- It is shown that both CRAHN and primary network can simultaneously achieve the same throughput scaling law as a stand-alone network.

- That means the throughput of each node for both primary network $\lambda(m)$ and secondary network $\lambda(n)$ is $\theta\left(\frac{W}{\sqrt{m\log m}}\right)$ and $\theta\left(\frac{W}{\sqrt{n\log n}}\right)$, respectively.

Research Progress in CRAHNs

■ [5]C-Y. Yin, L. Gao and S. Cui, "Scaling Laws for Overlaid Wireless Networks: A Cognitive Radio Network vs. a Primary Network," Submitted to IEEE trans. on Networking, under revision, May. 2008.

■ **In [5], the same network scenario and atechetrue is considered as in [4].**

■ **However, the assumption of [4] is relaxed where the secondary nodes do not know the locations of receiving primary nodes.**

■ **They further consider the network delay as introduced in [3] for both CRAHNs and primary networks.**

■ **In conclusion, they show that both the throughput capacity and network delay for either CRAHNs or primary networks scale the same as the stand-alone ad hoc networks.**

Research Progress in CRAHNs

[5]C-Y. Yin, L. Gao and S. Cui, "Scaling Laws for Overlaid Wireless Networks: A Cognitive Radio Network vs. a Primary Network," Submitted to IEEE trans. on Networking, under revision, May. 2008.

[6]V. Bhandari and N. H. Vaidya, "Connectivity and Capacity of Multi-Channel Wireless Networks with Channel Switching Constraints," in *IEEE Infocom 2007*.

- **Specifically, that means, for primary network, we have,**

$$\lambda(m) = \theta\left(\frac{W}{\sqrt{m\log m}}\right) \qquad D(m) = \theta\left(\sqrt{\frac{m}{\log m}}\right)$$

- **For secondary networks, we have,**

$$\lambda(n) = \theta\left(\frac{W}{\sqrt{n\log n}}\right) \qquad D(n) = \theta\left(\sqrt{\frac{n}{\log n}}\right)$$

- **In[6], the capacity of multi-channel ad hoc network was investigated.**

- **The problem is investigated how the asymptotic capacity of a multi-channel network is affected in the presence of constraints on channel switching.**

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Research Progress in CRAHNs

[6]V. Bhandari and N. H. Vaidya, "Connectivity and Capacity of Multi-Channel Wireless Networks with Channel Switching Constraints," in *IEEE Infocom 2007*.

- They introduce a channel assignment model wherein a node can only switch between a set of **f** contiguous channels (2 ≤ f ≤ c), where **c** is the number of total subchannels.

- This model is suitable for *overlay CRAHNs with multi-spectrum feature: given a multi-hop network of secondary* nodes attempting to utilize unused spectrum, some channels may be locally unusable due to the presence of an active PU in the vicinity [6].

- They show that the per-node capacity for the adjacent (c, f) channel assignment model is $\lambda(n) = \theta(W\sqrt{\dfrac{f}{cn\log n}}),$ where $\dfrac{f}{c} \leq 1$.

Network Capacity of CRAHNs: PU Activity

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- As we know, in [4] [5], the throughput scaling is considered for the CRAHNs under the spectrum sharing scheme of *spectrum underlay by enabling secondary (unlicensed)* users to coexist with PUs in the licensed spectrum bands while causing no excessive interference to PUs.

- In [6], the spectrum sharing scheme is spectrum overlay in frequency domain, where the secondary users utilize a portion of the spectrum that is not being used by PUs.

- To the best of our knowledge, the scaling laws which consider the important *time-varying features of spectrum sharing* schemes in CRAHNs due to *PU activity in spectrum overlay* is still not touched in the research community to date.

Network Capacity of CRAHNs: PU Activity/Network Architectures

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- In this research, we focus on the fundamental problem of how the capacity and delay of CRAHNs scale under the impact of PU activity.

- We assume that there are m primary transmit-receive pairs with on-and-off probabilities P_{on} and P_{off} distributed independently in the region of a CRAHN with n secondary nodes and the total bandwidth of W bits per second.

- In this paper, throughput capacity and delay scaling laws are introduced for CRAHNs by capturing the impact of PU activity in dense, and sparse PU deployment conditions.

- Our work differs from the previous studies [4-6] in the following critical points.

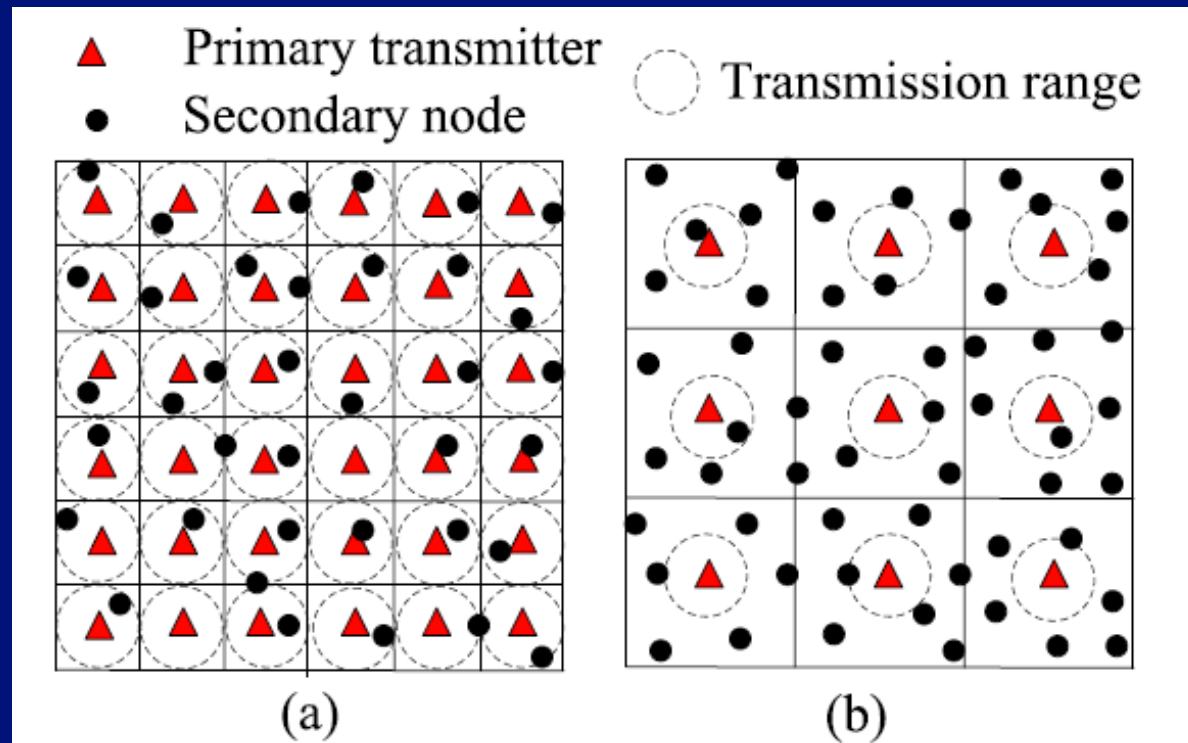# Network Capacity of CRAHNs: PU Activity/Network Architectures

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- In our work, we find that the primary network topology, such as the primary nodes' density, the transmission range and the on-and-off probabilities have great impact on the capacity and delay scaling performance of CRAHNs.

- Especially, the value of P_{on}, P_{off}, m *and primary nodes'* transmission ranges are exactly embodied in our results.

- In classical ad hoc wireless networks [1][2] and CRAHNs [4][5], there is always traffic load in the network all the time.

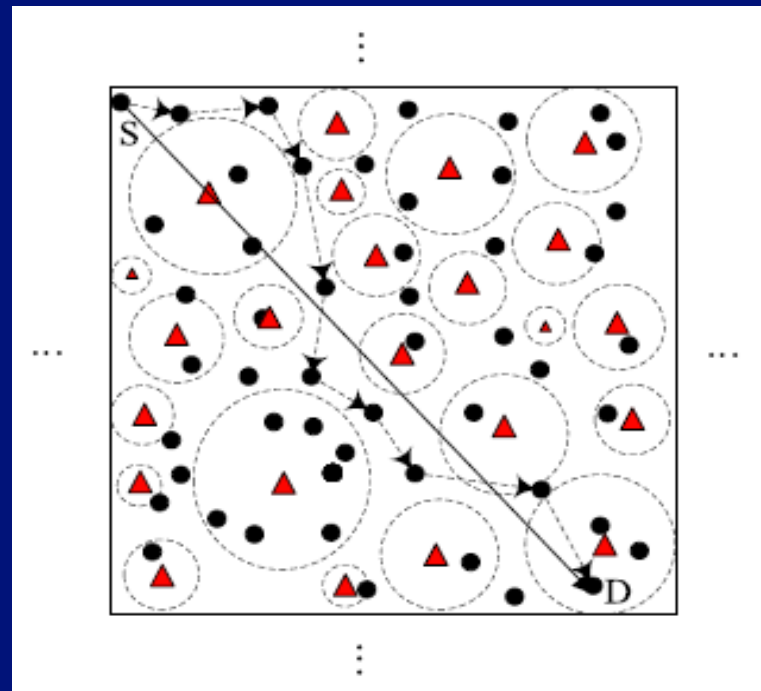# Network Capacity of CRAHNs: PU Activity/Network Architectures

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- However, in our scenario we show that the secondary nodes need to buffer their traffic in order to achieve the maximum throughput capacity due to PU activity.

- As a result, there may not always be traffic in CRAHNs at a specific time and location.

- Based on this reason, we note that the queuing and transmission delays must be involved in the end-to-end delay computation.

- We first consider the typical primary network models: regular dense primary network and regular sparse primary network, then we extend our results to randomly distributed primary networks.

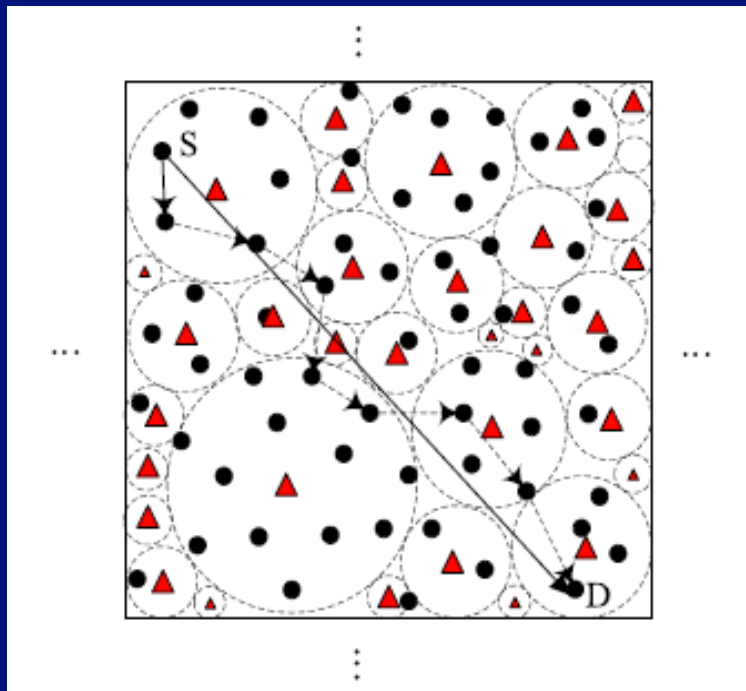# Network Capacity of CRAHNs: PU Activity/Random Primary Networks

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

Network Capacity of CRAHNs: PU Activity/Random Primary Networks

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

Network Capacity of CRAHNs: PU Activity/Main Results 1

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- Under the regular dense primary network, using TDMA-based routing scheme as in [1], the per-node throughput capacity of CRAHN $\lambda(n,m)$ is only $\Theta\left(P_{off}^{\Theta(\sqrt{m})} \dfrac{W}{\sqrt{n \log n}}\right)$

- When secondary nodes consider PU activity, and use additional queue to buffer traffic when primary nodes are active, otherwise they can transmit, then the maximum achievable throughput capacity $\lambda(n,m)$ is improved to $\Theta\left(\dfrac{WP_{off}}{\sqrt{n \log n}}\right)$

- However, to achieve this throughput capacity improvement, the end-to-end delay capturing queuing and transmission delays $D(n,m)$ is increased to $O\left(\sqrt{m}\right)$, which is hold for any value of P_{off} and P_{on} .

Network Capacity of CRAHNs: PU Activity/Main Results 2

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- **The required queue length for each secondary node $Q(n,m)$ becomes**

$$O\left(\sqrt{\frac{m}{n}}P_{off}\right)$$

- **The throughput capacity and delay trade-off for CRAHNs in the regular dense primary network is given by** $\Theta\left(\dfrac{WP_{off}^{\Theta(\sqrt{m})/K}}{\sqrt{n\log n}}\right)$ **vs** $O(K)$ **where** $1 \le K \le \theta\left(\sqrt{m}\right)$

- **Under the regular sparse primary network, both the throughput capacity and delay of CRAHNs will be greatly improved, where the per-node throughput capacity of CRAHN $\lambda(n,m)$ is between** $\Omega\left(\dfrac{WP_{off}}{\sqrt{n\log n}}\right)$ **and** $O\left(\dfrac{W}{\sqrt{n\log n}}\right)$ **. The corresponding end-to-end delay** $D(n,m)$ **is only affected by multihopping delay as in [3],** $\theta\left(\sqrt{\dfrac{n}{\log n}}\right)$

Network Capacity of CRAHNs: PU Activity/Main Results 3

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.

- Finally, the throughput capacity and delay of CRAHNs under random distributed (dense or sparse) primary networks scale the same order as in regular (dense or sparse) primary networks, respectively.

- That means the distribution of the PU locations does not impact the scalability of CRAHNs.

Network Capacity of CRAHNs: PU Activity/Proof Outline 1

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.
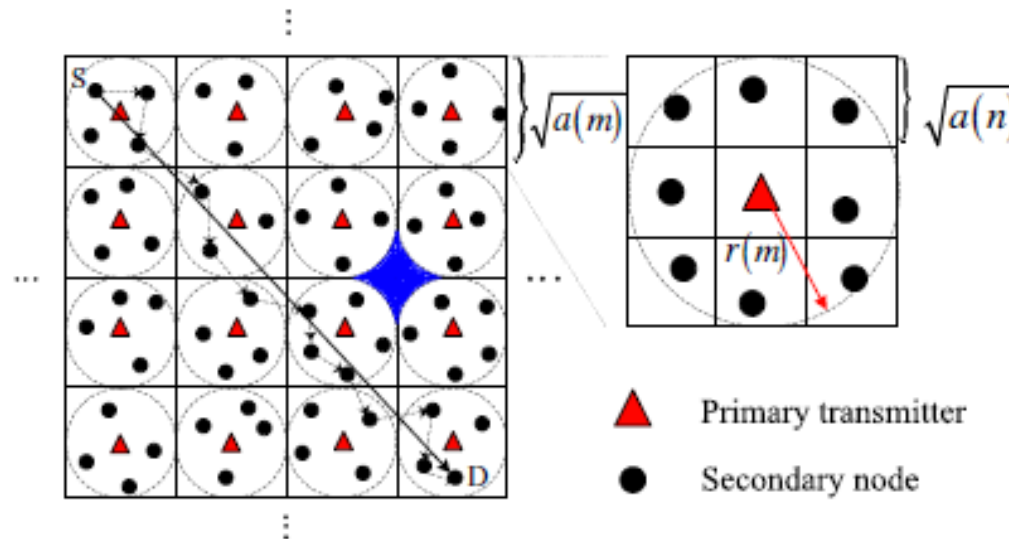

Fig. 2: CRAHN under Regular Dense Primary Network

Network Capacity of CRAHNs: PU Activity/Proof Outline 2

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.
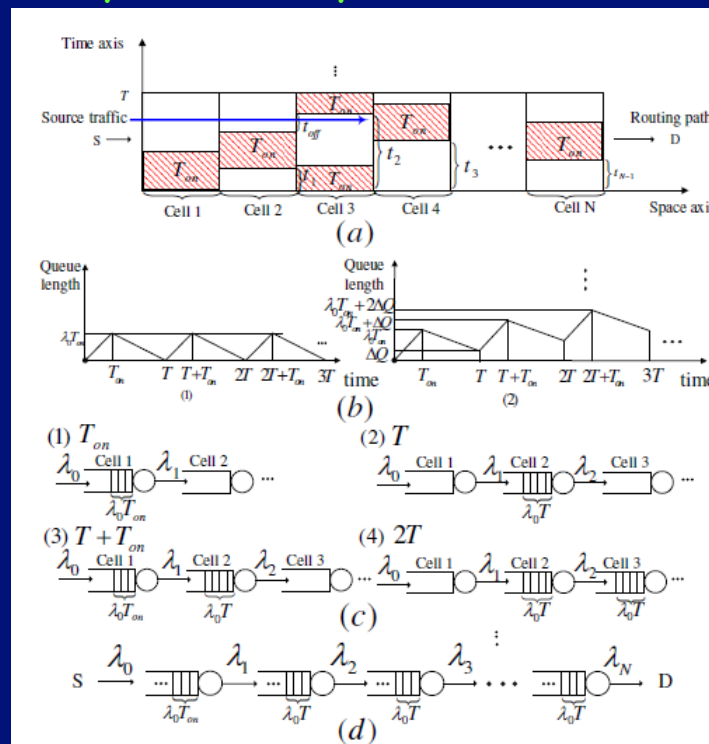

Fig. 3: Secondary traffic passing through S-D line using routing scheme 2

Network Capacity of CRAHNs: PU Activity/Proof Outline 3

[7] P. Zhou and I. F., Akyildiz, "Capacity and Delay Scaling in Cognitive Radio Ad Hoc Networks: Impact of Primary User Activity," Submitted for conference publication, July 2009.
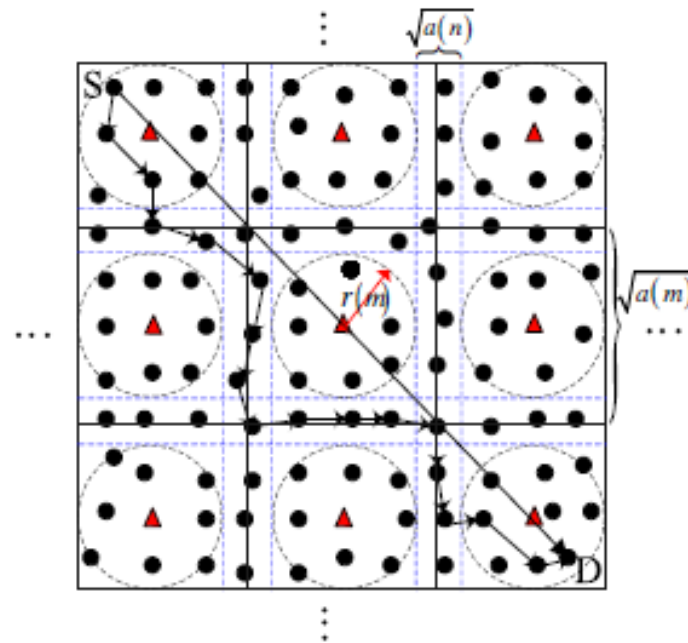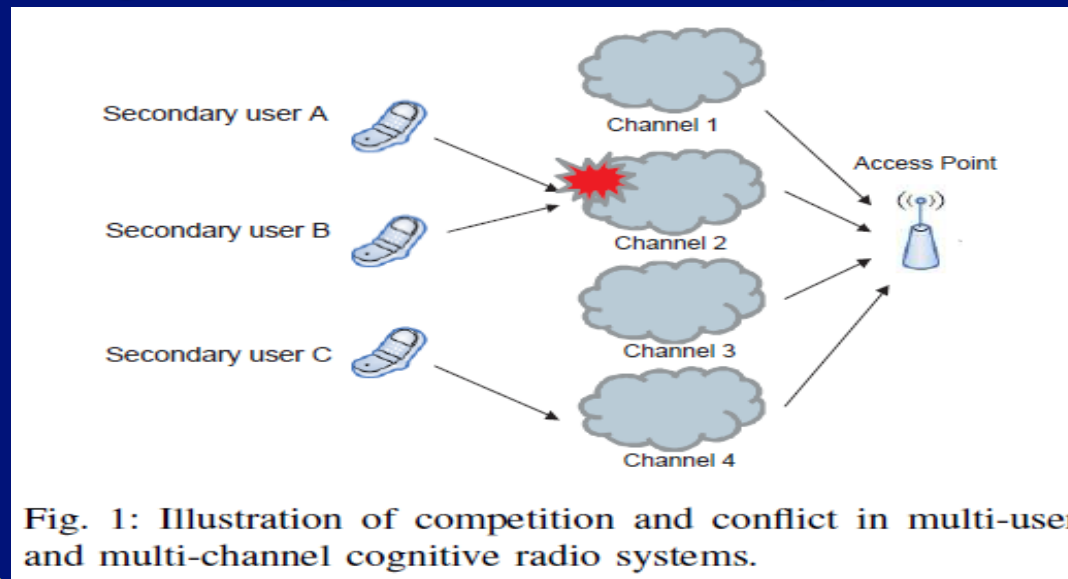

Fig. 5: CRAHN under Regular Sparse Primary Network

Next Research Plan

- **Mobility impact the Capacity of CRAHN under PU Activity?**
- **Scheduling of CRAHN.**
- **Spectrum sensing, sharing, access technology in CRAHNs.**

Fig. 1: Illustration of competition and conflict in multi-user and multi-channel cognitive radio systems.

Acknowledgement

Thank you very much!