Scaling Laws for Cognitive Radio Network with Heterogeneous Mobile Secondary Users

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***Abstract*—We study the capacity and delay scaling laws for cognitive radio network (CRN) with static primary users and heterogeneous mobile secondary users coexisting in the unit planar area. The primary network consists of n randomly and uniformly distributed static primary users (PUs) with higher priority to access the spectrum. The secondary network consists of $m = (h+1)n^{1+\epsilon}$ heterogeneous mobile secondary users (SUs) which should access the spectrum opportunistically, here $h = O(\log n)$ and $\epsilon > 0$. Each secondary user moves within a circular area centered at its initial position with a restricted speed. The moving area of each mobile SU is $n^{-\alpha}$, where α is a random variable which follows the discrete uniform distribution with $h+1$ different values, ranging from 0 to α_0 ($\alpha_0 > 0$). α_0 and h together determine the mobility heterogeneity of secondary users. By allowing the secondary users to relay the packets for primary users, we have proposed a joint routing and scheduling scheme to fully utilize the mobility heterogeneity of secondary users. We show that the primary network and secondary network can achieve optimal capacity and delay scalings if we increase the mobility heterogeneity of secondary users, i.e., the value of h and α_0, until $h = \Theta(\log n)$ and $\alpha_0 \geq 1 + \epsilon$. In this optimal condition, both the primary network and part of the secondary network can achieve almost constant capacity and delay scalings except for poly-logarithmic factor.**

I. Introduction

The throughput scaling laws for large-scale wireless ad hoc networks has been extensively studied since the seminal work of P. Gupta and P. R. Kumar [1]. They studied the random wireless network with n static nodes randomly located in the unit area and grouped into source-destination (S-D) pairs for transmission. Under the multi-hop relay algorithm, the network could achieve a per-node throughput of $\Theta(1/\sqrt{n \log n})$ [1]. By using percolation theory, Franceschetti *et al.* [2] showed the capacity performance could be $\Theta(1/\sqrt{n})$, even when the nodes are randomly located in the network area.

In contrast to the static wireless network, the capacity performance could be significantly improved when the nodes are mobile. In [3], M. Grossglauser and D. Tse showed the mobile network could achieve a per-node throughput of $\Theta(1)$ under the 2-hop relay algorithm. However, this significant improvement of throughput capacity has been achieved at the cost of huge delay, which is proved to be $\Theta(n)$ by Neely *et al.* [4]. Since mobility could improve the capacity of wireless networks, various mobility models have been studied in later works, such as the i.i.d. mobility model [5]; random way-point mobility model [6]; random walk mobility model [7]; and restricted mobility model [8] [9].

The previous works mainly focus on the capacity and delay scaling for a single network. In recent years, the emergence of the cognitive radio technology has motivated the study of capacity and delay scaling laws of cognitive radio networks (CRN). Due to the coexistence of the licensed primary users, as well as the unlicensed secondary users who can only access the spectrum opportunistically, the study of CRN is more challenging than the traditional single ad-hoc network case. When secondary users have higher node density than primary users, [10] and [11] showed the static primary network and secondary network can simultaneously achieve the same throughput scaling law as a stand-alone network. In [12], Huang *et al.* characterized the general conditions for the cognitive networks to achieve the same throughput and delay scaling as the stand-alone networks.

Those aforementioned results mainly focused on the static CRN and neglected the possible cooperations between two coexisting networks. In [13], Gao *et al.* proposed a supportive cognitive network, in which the secondary nodes may route packets for the primary network. When the secondary users are moving according to the i.i.d. mobility model, the primary users could achieve the per-node throughput scaling of $\lambda_p = \Theta(1/\log n)$ with the delay scaling of $D_p = \Theta(1)$. However, this cooperative scheme requires the number of supportive secondary users m should be at least $\Theta(n^2)$, thus casting a heavy burden on its implementation. Then, Wang *et al.* [14] derived a cooperation scheme which also achieve the near-optimal capacity and delay scaling for primary network, but with less supportive mobile secondary users. This is achieved by dividing the secondary users into h different layers and the mobile secondary users of different layers are associated with different moving areas. However, in order to regulate the moving area of different layer SUs, this network model requires a strict cell partition scheme which arbitrarily partitioned the whole network into h different layer cells.

In this paper, motivated by the fact that cooperation among primary users and secondary users could improve the perfor-

[1]The following asymptotic notations are adopted: $f(n) = O(g(n))$ means $\limsup_{n\to\infty} f(n)/g(n) < \infty$; $f(n) = \Theta(g(n))$ means $f(n) = O(g(n))$ and $g(n) = O(f(n))$; $f(n) = o(g(n))$ means $\lim_{n\to\infty} f(n)/g(n) = 0$; $f(n) = \omega(g(n))$ means $g(n) = o(f(n))$; $f(n) = \Omega(g(n))$ means $g(n) = O(f(n))$.

mance of the CRN, as well as the fact that secondary users could be mobile and have heterogeneous moving areas, we focus on the supportive CRN which has static primary users and heterogeneous mobile secondary users. Specifically, all the $m = (h+1)n^{1+\epsilon}$ secondary users ($h = O(\log n)$, $\epsilon > 0$) will follow a local speed-restricted mobility model, in which they move according to the i.i.d. mobility model within a fixed circular area of radius R. The centers of the circular areas are randomly distributed at the beginning. In addition, the moving area of each mobile SU is $n^{-\alpha}$, where α is a random variable which follows the discrete uniform distribution with $h+1$ different values, ranging from 0 to α_0 ($\alpha_0 > 0$). We call this mobility model the heterogeneous speed-restricted mobility model (HSRM), where α_0 and h together determine the mobility heterogeneity. Then we will propose a joint routing and scheduling scheme which has fully utilized the spatial heterogeneity of the secondary users, so that both the primary packets and secondary packets could reach the destination in a step-wise fashion. Our main contributions are summarized as follow:

- We propose and study the heterogeneous speed-restricted mobility model for secondary users in CRN. Compared with the hierarchical mobility model in [14], which requires the secondary users to move within regularly partitioned different layer cells in the network area, the HSRM is more general and representative since: (1) the centers of the moving area for the secondary users in HSRM are randomly distributed in the network; (2) the parameter α_0 is a random positive value in HSRM. And the hierarchical mobility model in [14] is a specified case of HSRM when $\alpha_0 = 1+\epsilon^{'}$, where $\epsilon^{'} < \epsilon$. Due to the generality of HSRM, it can be applied to not only CRN, but also other wireless networks such as the wireless sensor networks [15] [16].
- Under HSRM, if we increase the heterogeneity of the secondary users (which means to increase the value of h and α_0), we find the primary network can achieve the near-optimal capacity and delay scaling when $h = \Theta(\log n)$ and $\alpha_0 \geq 1+\epsilon$. Specifically, under the proposed scheme, the primary network can achieve the per-node throughput $\lambda_p = \Theta(\frac{1}{\log n})$, with an average delay of $D_p = \Theta(\log^4 n)$.
- Under HSRM, the secondary network can also achieve the near optimal capacity scaling if we increase the heterogeneity of SUs until $h = \Theta(\log n)$ and $\alpha_0 \geq 1+\epsilon$. Specifically, the secondary network can achieve the per-node throughput of $\lambda_s = \Theta(\frac{1}{\log^3 n})$, with an average delay scaling of $D_{s,j} = O(\log^4 n)$, if $j \geq h^*$; and $D_{s,j} = O(n^{(1+\epsilon-\frac{j\alpha_0}{h})}\log^3 n)$, if $j < h^*$. Here j denotes the type of destination secondary user and h^* is the critical relay type, both of which will be defined later.

The rest of the paper is organized as follows. In Section II, the system model is defined. In section III, we propose the routing and scheduling scheme. In Section IV and V, the capacity and delay scalings for primary and secondary networks are derived respectively. In Section VI, the result is discussed. Finally, we conclude our paper in Section VII.

II. System Model

A. Network Topology

We study a static primary network and a mobile secondary network coexisting in the unit square area. The primary network consists of n randomly and evenly distributed static primary users, which are randomly grouped into source-destination (S-D) pairs one by one.

Moreover, there are $m = (h+1)n^{1+\epsilon}$ randomly distributed mobile secondary users with $h = O(\log n)$ and $\epsilon > 0$, which move under the heterogeneous speed-restricted mobility model defined later. All the secondary users are also randomly grouped into S-D pairs one by one.

The unit square area is divided into non-overlapping small square cells, each covers an area of $\frac{2\log N}{N}$ with side length $r = \sqrt{\frac{2\log N}{N}}$, here $N = n^{1+\epsilon}$. Every node can only communicate with another node inside the same cell, so the transmission range in our scheme is set to be one cell for both the primary network and secondary network.

B. Transmission Model

In this work, we only consider path loss of wireless channel and ignore the influence of shadowing or small scale fading for simplicity. Thus, the normalized channel power gain $g(d)$ is given as

$$g(d) = d^{-\gamma}, \tag{1}$$

where d denotes the distance between a transmitter and its receiver, $\gamma > 2$ represents the path-loss exponent.

We adopt the Gaussian channel model to regulate the transmission rate, which is a continuous function of the Signal to Interference plus Noise Ratio (SINR). Specifically, the data rate from a primary transmitter P_i to its receiver $P_{D(i)}$ is determined by:

$$R(P_i, P_{D(i)}) = \log(1 + \frac{P_p g(\|P_i - P_{D(i)}\|)}{N_0 + I_p + I_{sp}}), \tag{2}$$

Here, P_p is the transmission power for the primary nodes, and N_0 is the ambient noise power. $\|\cdot\|$ denotes the distance for two nodes in the unit area. Moreover, I_p is the sum interference from all the other concurrent primary transmitters to the receiver $P_{D(i)}$, I_{sp} is the sum interference from all the current secondary transmitters to $P_{D(i)}$. Suppose there are N_p and N_s simultaneous primary and secondary transmitters, then I_p is determined by:

$$I_p = P_p \sum_{k=1,k\neq i}^{N_p} g(\|P_k - P_{D(i)}\|), \tag{3}$$

Further if we set P_s to be the transmission power for the secondary nodes, and S_k ($1 \leq k \leq N_s$) to be the secondary transmitters. Then I_{sp} is determined by:

$$I_{sp} = P_s \sum_{k=1}^{N_s} g(\|S_k - P_{D(i)}\|). \tag{4}$$

Similarly, the data rate from the secondary transmitter S_i to its receiver $S_{D(i)}$ is defined as:

$$R(S_i, S_{D(i)}) = \log(1 + \frac{P_s g(\|S_i - S_{D(i)}\|)}{N_0 + I_s + I_{ps}}), \quad (5)$$

Here I_s is the sum interference from all the other simultaneous secondary transmitters, and I_{ps} represents the total interference from the concurrent primary transmitters.

C. Mobility Model

The secondary users would move under the heterogeneous speed-restricted mobility model (HSRM). Similar to the local speed-restricted mobility model (LSRM) in [9], the secondary users are uniformly and randomly distributed at the beginning. All the SUs would move within their own circular area centered at their initial positions, according to the i.i.d. mobility model. The radius R of these circles denotes the restricted speed of the secondary users, and the node positions would be totally reshuffled within their own moving area from one time slot to another.

In HSRM, the moving area of mobile SUs is set to be $n^{-\alpha}$, where α is a random variable which follows the discrete uniform distribution with $h+1$ possible different values. Specifically, $\alpha = 0, \frac{\alpha_0}{h}, \frac{2\alpha_0}{h}, ..., \frac{(h-1)\alpha_0}{h}, \alpha_0$, with equal probability $p = \frac{1}{h+1}$. Here α_0 is a random positive value and $h = O(\log_2 n)$. Throughout the paper, we call the SUs with moving area $A_i = n^{-\frac{i\alpha_0}{h}}$ the i-th type SU, where $0 \le i \le h$. Since all the m secondary users are evenly divided into $h+1$ different types, thus each type consists of $N = n^{1+\epsilon}$ mobile secondary users.

From the definition of HSRM, larger α_0 leads to larger difference between the moving area of different type SUs, and larger h corresponds to larger number of types. Therefore, α_0 and h together determine the mobility heterogeneity of SUs. In the following text, we call α_0 *heterogeneity range factor* and h *heterogeneity diversity factor*.

Moreover, we denote the k-th secondary users of type i as $S_{i,k}$ and its corresponding initial position as $X_{i,k}$, where $0 \le i \le h$ and $1 \le k \le N$. Under the HSRM, $\|S_{i,k} - X_{i,k}\| \le R_i$, where $R_i = \sqrt{\frac{A_i}{\pi}} = \Theta(n^{-\frac{i\alpha_0}{2h}})$.

D. Capacity and Delay

The per-node throughput capacity of a S-D pair is defined as the data rate (in bits/time-slot) that each source node can transmit to its destination. For the primary network, we denote its per-node throughput capacity by λ_p, while that of the secondary network is denoted by λ_s.

The delay of S-D pair is defined as the average number of time-slots passed before the packet reaches its destination, after it leaves the source node. For the primary network, we use D_p to denote its average delay. For the secondary network, we use $D_{s,k}$ to denote the delay for secondary S-D pairs with a kth-type destination.

Finally, we list some notations in Table I.

TABLE I: Definition of Symbols and Notations

Symbol	Definition
α_0	Heterogeneity range factor
h	Heterogeneity diversity factor
N	Number of SUs in each type
h^*	Critical relay type
r	The side length of one cell
A_i	The moving area of i-th type SU
R_i	The speed or radius of i-th type SU
$\mathcal{P}_i$	The ith primary user
$\mathcal{S}_{i,k}$	The k-th secondary user of type i
$\mathcal{X}_{i,k}$	The initial position of k-th secondary user of type i
Pr	Probability of an event
λ_p	Per-node throughput of the primary network
λ_s	Per-node throughput of the secondary network
D_p	Delay of primary S-D pairs
$D_{s,k}$	Delay for secondary S-D pairs with a kth-type destination

III. Routing and Scheduling Scheme

In this section, we describe the routing and scheduling scheme in our CRN, which can utilize the heterogeneity of mobile secondary users.

A. Primary Network Routing Scheme

In our scheme, the secondary users could act as the relay for the primary packets, so there is cooperation among primary users and secondary users. Moreover, since the number of each type secondary users is larger than primary users in order sense, thus a randomly selected relay node for the primary packet is a secondary user with high probability. Therefore, we assume all the primary packets would be relayed by secondary users and do not consider the multi-hop transmission in the PU network for simplicity.

Because 0-type SU moves within the whole network area and other type SUs move regionally in the network, our relay algorithm would utilize this mobility heterogeneity to make the packets approach their destination progressively. Specifically, the primary packet would be relayed by a chain of different type secondary users, among which the primary destination node is within the moving area of the relay nodes. This relay procedure starts from a 0 type SU and will continue until the packet is relayed to a particular type SU which is close enough to the primary destination node.

Since the secondary users with larger type would correspond to a smaller area, thus the mobility cannot be exploited if the moving area of certain type SUs is small enough. Consequently, we need to find the maximum type of secondary users that can be exploited to relay the primary packets, which leads to the following definition:

Definition 1: (Critical Relay Type) The critical relay type h^* is denoted by:

$$h^* = \max \{i | R_i \ge 2\sqrt{2}r\}, \quad (6)$$

where $i = 0, 1, ..., h$.

From the above definition, we can derive the value of critical relay type will follow:

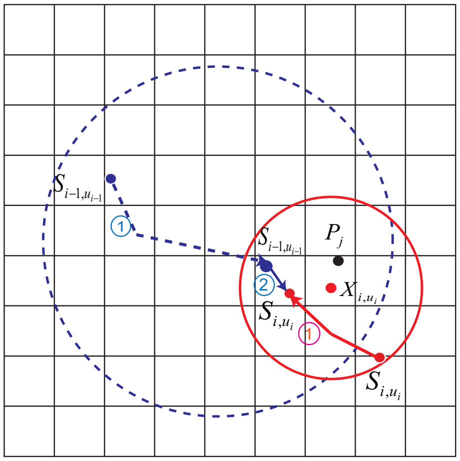

Fig. 1: Relay step from $S_{i-1,u_{i-1}}$ to S_{i,u_i} for a primary packet

$$h^* = \begin{cases} h, & \text{if } \alpha_0 < 1+\epsilon, \\ \lfloor h(\frac{1+\epsilon}{\alpha_0} - \frac{\log\log n + \log 16\pi(1+\epsilon)}{\alpha_0 \log n})\rfloor, & \text{if } \alpha_0 \geq 1+\epsilon. \end{cases}$$

Here, $\lfloor x \rfloor = \max\{n \in \mathbb{Z} | n \leq x\}$. And it can be seen that $h^* = \Theta(h)$.

By introducing the critical relay type, the primary relay algorithm would utilize the relay nodes from type 0 to type h^*, thus the number of relay steps will be $h^* + 2$ and the primary relay algorithm is shown in Algorithm 1.

Algorithm 1 Relay Algorithm for Primary Packet B_p

Input: The primary source node P_i and destiantion node P_j
Output: The h^*+1 intermediate secondary relay nodes

P_i relay B_p to a 0 type SU S_{0,u_0}, when S_{0,u_0} moves to the same cell as P_i.
for k=0 to (h^*-1) **do**
  S_{k,u_k} moves within its moving area until it meets $S_{k+1,u_{k+1}}$ in the same cell, whose initial position satisfies $\|X_{k+1,u_{k+1}} - P_j\| < R_{k+1} - \sqrt{2}r$ and $\|X_{k+1,u_{k+1}} - X_{k,u_k}\| < R_k$.
  S_{k,u_k} relay B_p to $S_{k+1,u_{k+1}}$.
end for
$S_{h^*,u_{h^*}}$ moves within its moving area until it arrives at the same cell as P_j.
$S_{h^*,u_{h^*}}$ relay B_p to P_j.

From Algorithm 1, the primary packet could reach the primary destination in a step wise fashion after each relay step. The relay step from $S_{i-1,u_{i-1}}$ to S_{i,u_i} is shown in Figure 1 ($1 \leq i \leq h^*$). In step 1 of Figure 1, $S_{i-1,u_{i-1}}$ moves until it meets an eligible i-th type SU S_{i,u_i} in the same cell; in step 2, the primary packet is relayed from $S_{i-1,u_{i-1}}$ to S_{i,u_i}. The blue dotted circle and red solid circle denotes the moving area of $S_{i-1,u_{i-1}}$ and S_{i,u_i} respectively.

After we have derived the primary network relay algorithm, a critical step is to ensure the feasibility of each relay step, which means the number of eligible relay SUs should be larger than 1 with high probability. Before proving the feasibility of the relay algorithm, we first present the following two lemmas.

Lemma 1: Denote $C_r(x)$ as the circle with radius r, which is centered at point x. If two circles $C_{r_1}(x_1)$ and $C_{r_2}(x_2)$ satisfies:

$$r_1 \geq r_2, \|x1 - x2\| < r_1,$$

then the overlap area of the two circles, denoted as $C_{r_1}(x_1) \cap C_{r_2}(x_2)$, satisfies:

$$\frac{\pi}{3} r_2^2 < C_{r_1}(x_1) \cap C_{r_2}(x_2) \leq \pi r_2^2. \tag{7}$$

Lemma 1 can be proved using the basic geometry knowledge and thus we do not provide a specific proof here.

Lemma 2: If z number of nodes are randomly and uniformly distributed in the unit square, then we can ensure at least $\frac{z\pi R^2}{2\log(1/R)+\pi R^2}$ nodes are placed in a circle with radius R with high probability.

We refer readers to Theorem 4.1 in [9] for a detailed proof of Lemma 2.

Based on Lemma 1 and Lemma 2, we have the following lemma which guarantees the feasibility of the relay algorithm.

Lemma 3: With a random positive heterogeneity range factor α_0 and $h = O(\log_2 n)$, the number of eligible relay SUs in each step of Algorithm 1 is larger than 1 with high probability.

Proof: From Algorithm 1, we know the initial positions for the eligible $(k+1)$-th type relay SUs should reside in the area of $C_{R_k}(X_{k,u_k}) \cap C_{R_{k+1}-\sqrt{2}r}(P_j)$. Combining the results of Lemma 1 and Lemma 2, it can be guaranteed that the number of eligible relay SUs of each type is larger than 1 with high probability. ■

B. Secondary Network Routing Scheme

Similar to the primary network routing scheme, the secondary network would also utilize the cooperation among different types of SUs to make the secondary packets approach the destination progressively.

Pick a random secondary source node S_{i,k_i}, whose corresponding destination node is S_{j,k_j}, and the packet from S_{i,k_i} to S_{j,k_j} is denoted by $B_{s,j}$. The number of relay steps for $B_{s,j}$ will depend on the value of j and h^*. Specifically, when $j > h^*$, $B_{s,j}$ will be relayed from a 0-type relay SU down to a h^*-type relay SU. On the other hand, when $j \leq h^*$, $B_{s,j}$ will only be relayed from a 0-type SU down to a j-th type SU.

Thus, if we denote $h' = \min(j, h^*)$, the relay process of $B_{s,j}$ will take up $h' + 2$ steps. Due to the mobility of secondary transmitters and receiver, the secondary relay algorithm is different from the primary network, as shown in Algorithm 2. From Lemma 3, we can also guarantee the feasibility of the secondary relay algorithm.

C. Primary Scheduling Scheme

After we have defined the routing scheme, we will build up the scheduling scheme for the primary and secondary network. In our scheme, the primary network and secondary network share the same time frame structure. In order to ensure equal

Algorithm 2 Relay Algorithm for Secondary Packet $B_{s,j}$

Input: The source node S_{i,k_i} and destination node S_{j,k_j}
Output: The $h^{'}+1$ intermediate secondary relay nodes

S_{i,k_i} moves within its moving area until it meets a 0-type SU S_{0,u_0} in the same cell.
S_{i,k_i} relay $B_{s,j}$ to S_{0,u_0}.
for k=0 to $(h^{'}-1)$ **do**
  S_{k,u_k} moves within its moving area until it meets $S_{k+1,u_{k+1}}$ in the same cell, whose initial position satisfies $\|X_{k+1,u_{k+1}}-X_{j,k_j}\|<R_{k+1}-\sqrt{2}r$ and $\|X_{k+1,u_{k+1}}-X_{k,u_k}\|<R_k$.
  S_{k,u_k} relay $B_{s,j}$ to $S_{k+1,u_{k+1}}$.
end for
$S_{h^{'},u_{h^{'}}}$ moves within its moving area until it encounters S_{j,k_j} in the same cell.
$S_{h^{'},u_{h^{'}}}$ relay $B_{s,j}$ to S_{j,k_j}.

opportunity for all the cells to be activated and also limit the interference among concurrent transmissions, a 25-TDMA scheme is adopted which is similar to the scheme in [11]. Specifically, all the cells are divided into 25 subsets according to a 5×5 pattern. Each time slot is divided into 25 sub-slots, and the cells of different subsets would be activated during one sub-slot with a round-robin fashion.

From the primary relay algorithm, all the primary packets would be relayed by SUs. Thus the scheduling scheme for the primary network only needs to select the primary transmitter in each time slot, which is described as follow:

Primary Scheduling Scheme: During the active period of each cell, randomly select a source PU P_i in this cell (if there is any). Let P_i relay a primary packet B_p to a random 0-type SU S_{0,u_0}, if there exists 0-type SU in this cell.

D. Secondary Scheduling Scheme

The secondary network shares the same time frame structure with the primary network, and a 25-TDMA scheme is also adopted by the secondary network.

We define the *preservation region* so as to limit the interference from the SUs to PUs. To be specific, the preservation region is a square area that contains 9 cells, with the current active primary transmitter at the center cell. Only the secondary users outside any current preservation region can transmit or relay packets.

Since the secondary users are required to relay not only secondary packets, but also primary packets, thus we propose a scheduling scheme which would guarantee transmission opportunity for both the primary packets and secondary packets.

Specifically, the secondary scheduling scheme would consist of $2h^*+3$ phases and each phase consumes one time slot. Note during each phase, if the SUs are inside the current preservation region, they can only buffer the packets, or receive the primary packets. Otherwise, the secondary network would operate under the following phases:

For $k=1,2,...,h^*$,

Phase k: During the active period of each cell, all pairs of nodes $(S_{k-1,u_{k-1}},S_{k,u_k})$ residing in this cell are eligible for transmission in this phase, if $S_{k-1,u_{k-1}}$ contains a primary packet B_p to relay and S_{k,u_k} can act as the k-th type relay SU for this B_p. One of such node pairs would be randomly selected to transmit if the eligible transmission node pairs is non-empty in this cell.

Phase (h^*+1)**:** During the active period of each cell, all pairs of nodes $(S_{h^*,u_{h^*}},P_j)$ residing in this cell are eligible for transmission in this phase, if $S_{h^*,u_{h^*}}$ contains a primary packet B_p destined to P_j. One of such node pairs would be randomly selected to transmit if the eligible transmission node pairs is non-empty in this cell.

Phase (h^*+2)**:** During the active period of each cell, randomly select a source SU S_{i,k_i} in this cell (if there is any). Let S_{i,k_i} relay a secondary packet $B_{s,j}$ to a random 0-type SU S_{0,u_0}, if there exists any 0-type SU in this cell.

For $k=1,2,...h^*$,

Phase (h^*+2+k)**:** During the active period of each cell, two types of SU pairs residing in this cell are eligible for transmission in this phase: (1) node pair $(S_{k-1,u_{k-1}},S_{k-1,j_{k-1}})$ which satisfies: $S_{k-1,u_{k-1}}$ contains a secondary packet $B_{s,k-1}$ destined to $S_{k-1,j_{k-1}}$; or (2) node pair $(S_{k-1,u_{k-1}},S_{k,u_k})$ which satisfies: $S_{k-1,j_{k-1}}$ contains a secondary packet $B_{s,k'}$ $(k\leq k^{'}\leq h^*)$ to relay and S_{k,u_k} can act as the k-th type relay SU for $B_{s,k'}$. One of such node pairs would be randomly selected to transmit if the eligible transmission node pairs is non-empty in this cell.

Phase $(2h^*+3)$**:** During the active period of each cell, all pairs of nodes $(S_{h^*,u_{h^*}},S_{j,k_j})$ $(h^*\leq j\leq h)$ residing in this cell are eligible for transmission in this phase, if $S_{h^*,u_{h^*}}$ contains a secondary packet $B_{s,j}$ destined to S_{j,k_j}. One of such node pairs would be randomly selected to transmit if the eligible transmission node pairs is non-empty in this cell.

IV. Capacity and Delay Scalings for the Primary Network

In this section, we first evaluate the capacity scaling of the primary network, and then study the delay performance for the primary network.

A. Capacity Performance

We first give the following lemmas:

***Lemma 4** (Ji et al. [17]):* Assume x nodes are placed into y equal-sized areas randomly, evenly and independently. Let $Z(x,y)$ be the random variable that counts the maximum number of nodes in any area. Then with high probability,

$$Z(x,y) = \begin{cases} \Theta(\frac{x}{y}), & \text{if } x\gg y\log y, \\ \Theta(\log y), & \text{if } x=cy\log y \text{ for some constant } c, \\ \Theta(\frac{\log y}{\log\frac{y\log y}{x}}), & \text{if } \frac{y}{\text{polylog}(y)}\leq x\ll y\log y, \\ \Theta(\frac{\log y}{\log\frac{y}{x}}), & \text{if } x<\frac{y}{\log y}. \end{cases}$$

Based on Lemma 4, we can easily derive the following two lemmas:

***Lemma** 5:* At any moment, there are at most $\Theta(1)$ PUs in any cell with high probability.

***Lemma** 6:* At any moment, for $0 \leq i \leq h$, the number of i-th type secondary users in each cell is at most $\Theta(\log n)$ with high probability.

Lemma 5 and Lemma 6 can be proved since the number of primary users is n and each type secondary users is N, thus we do not provide the specific proof here. Next, we have the following lemma:

***Lemma** 7:* During the routing process of primary packets, the primary transmitters and secondary relay nodes can support a constant data rate in each cell.

Proof: Since we have adopted the 25-TDMA scheme and the preservation region, so the interference from the other concurrent primary or secondary transmitters to the intended receiver in each relay step could be bounded by a constant. Therefore, from Equation (2) and Equation (5), the primary transmitters and secondary relay nodes can support a constant data rate.

■

According to the primary scheduling scheme and the results of Lemma 5 and Lemma 7, we can derive the following theorem that counts the per-node throughput of the primary network.

***Theorem** 1:* Under the proposed primary relay algorithm, the primary network can achieve the following average per-node throughput with high probability:

$$\lambda_p = \Theta\left(\frac{1}{h}\right). \tag{8}$$

Proof: During the routing process of the primary packet, since every primary transmitter and secondary relay nodes could support a constant data rate, thus we assume any node could transmit or relay at a rate of R bits per time-slot. We divide the whole routing process into three parts: input, relay and output.

In the input process, the primary packet is relayed from the primary transmitter to a 0 type relay SU. Since there are at most $\Theta(1)$ within each cell, thus the per-node time-average input rate of PUs should be $\Theta(1)$ with high probability. Since there are $\Theta(n)$ S-D pairs, thus the aggregated input rate of all PUs should be $\Theta(n)$.

During the relay process, the primary packet is relayed from the $(i-1)$-th type relay SU to an i-th type SU, for $1 \leq i \leq h^*$. Since the transmission range is set to be r^2 and each relay SU can support a constant data rate in each cell, thus the whole network can support a maximum aggregated relay rate of $\Theta(\frac{N}{2\log N})$, which is larger than the aggregated input rate. This indicates the relay process could forward an aggregated $\Theta(n)$ bits per time-slot. Since each relay process consumes $\frac{1}{2h^*+3}$ fraction of the secondary scheduling cycle, thus the primary network can achieve per-node time-average relay rate of $\Theta(\frac{1}{h^*})$.

Finally, during the output process, the primary packet is transmitted to the destination primary user. The output process is similar to the input process, and $\Theta(n)$ bits can be forwarded to the primary destination nodes during the output process. Since each output process consumes $\frac{1}{2h^*+3}$ fraction of the secondary scheduling cycle, thus the output process can achieve the per-node time-average output rate of $\Theta(\frac{1}{h^*})$.

Consequently, the primary network can achieve the per-node throughput of $\lambda_p = \min(\Theta\left(\frac{1}{h^*}\right), \Theta(1)) = \Theta(\frac{1}{h})$.

■

B. Delay Performance

In order to derive the delay performance of the primary network, we will first give the following lemmas.

***Lemma** 8:* For random positive value l and N such that $0 < l < 1$ and $N \geq \Theta(1)$, the following equation holds with high probability:

$$1 - (1-l)^N = \min(\Theta(1), \Theta(Nl)). \tag{9}$$

Proof: We consider the following three conditions depending on the value of l and N:

(1) $l = \Theta(1)$. In this case, $1 - (1-l)^N = \Theta(1)$ holds.

(2) $l = o(1)$ and $Nl \geq \Theta(1)$. Since l can be arbitrarily small when n is large enough, thus $1 - \exp(-Nl) < 1 - (1-l)^N < 1 - \exp(-2Nl)$. Because $Nl \geq \Theta(1)$, so $1 - (1-l)^N = \Theta(1)$.

(3) $l = o(1)$ and $Nl = o(1)$. In this case,since $x - \frac{x^2}{2} < 1 - \exp(-x) < x$ always holds when $x > 0$. Thus, $Nl - \frac{(Nl)^2}{2} < 1 - (1-l)^N < Nl$ will be satisfied. Thus, $1-(1-l)^N = \Theta(Nl)$.

■

By using the results of Lemma 8 and Lemma 6, we can have the following lemma that counts the delay for the primary network.

***Theorem** 2:* Under the proposed primary relay algorithm, the primary network can achieve the following average delay with high probability:

$$D_p = \Theta(hn^{(1+\epsilon-h^*\frac{\alpha_0}{h})} + h^2 n^{\frac{\alpha_0}{h}} \log^2 n). \tag{10}$$

Proof: Consider the routing process for a primary packet B_p, which is sent from P_i to P_j. Similar to Section VI-C [8], we would evaluate the average number of time slots for B_p to be successfully relayed in each process. During the routing process, we ignore the possible contention for transmission among different packets in each node. The routing process is also divided into input, relay and output process.

(a) First we analyze the input process, in which primary source node P_i will transmit to an eligible 0 type SU. A successful relay from P_i to the eligible 0 type relay node will happen when the two conditions hold: (1) an eligible 0 type relay node S_{0,u_0} is found in the same cell as P_i; (2) among all the eligible transmission pairs in this cell, P_i is the transmitter of the selected pair and an eligible 0 type relay SU is the selected receiver. Denote the two conditions as a_0 and b_0.

For an arbitrary 0 type SU S_{0,u_0}, the probability that S_{0,u_0} moves to the cell, denoted by p_s^0, should be $p_s^0 = r^2$. If we consider all the 0 type SUs together and use the result of Lemma 8, we have $\Pr(a_0) = 1 - (1-p_s^0)^N = \Theta(1)$.

In addition, since there are at most $\Theta(1)$ primary users and $\Theta(\log n)$ 0 type SUs in any cell, thus $\Pr(b_0|a_0) = \Theta(\frac{1}{\log n})$. So the probability for successful relay is $p_0 = \Pr(a_0)\Pr(b_0|a_0) = \Theta(\frac{1}{\log n})$. Thus, the delay for the input process is $D_0 = \Theta(1/p_0) = \Theta(\log n)$.

(b) Next we consider the relay and output process. For $1 \le i \le h^* + 1$, suppose B_p is currently held by $S_{i-1,u_{i-1}}$, then a successful relay of B_p during the relay and output process will happen when the following three conditions happen: (1) the current slot is assigned to Phase i of the secondary scheduling scheme ; (2) an eligible i-th type relay node, or the destination node resides in the same cell as $S_{i-1,u_{i-1}}$ in the current time slot; (3) For $1 \le i \le h^*$, among all the eligible transmission pairs in this cell, $S_{i-1,u_{i-1}}$ is the transmitter of the selected pair and an eligible i-th type relay SU is the selected receiver. While for $i = h^* + 1$, $(S_{h^*,u_{h^*}}, P_j)$ is the selected transmission pair. We denote the three conditions as t_i, a_i and b_i respectively.

Since a complete scheduling cycle of the secondary network consists of $2h^* + 3$ phases, thus $\Pr(t_i) = \frac{1}{2h^*+3} = \Theta(\frac{1}{h})$.

Then we will calculate $\Pr(a_i)$ for relay process, i.e., $1 \le i \le h^*$. If we denote $\mathcal{T}_i$ as the set of i-th type SUs that can relay B_p from $S_{i-1,u_{i-1}}$, and Q as the set of cells inside the moving range of the SUs in $\mathcal{T}_i$, i.e., the cells inside $C_{R_{i-1}}(X_{i-1,u_{i-1}}) \cap C_{2R_i-\sqrt{2}r}(P_j)$. Thus,

$$\Pr(a_i) = \sum_Q \Pr(S_{i-1,u_{i-1}} \in Q)(1 - \prod_{S_{i,k}\in\mathcal{T}_i}(1 - \Pr(S_{i,k} \in Q)))$$

Since $R_i \ge 2\sqrt{2}r$, so that $\Theta(2R_i - \sqrt{2}r) = \Theta(R_i)$. The upper bound of p_a^i can be calculated as follow:

$$\begin{aligned}\Pr(a_i) &\le \sum_Q \Pr(S_{i-1,u_{i-1}} \in Q)\\ &= \Theta(\frac{(2R_i - \sqrt{2}r)^2}{r^2})\Theta(\frac{r^2}{R_{i-1}^2})\\ &= \Theta(n^{-\frac{\alpha_0}{h}})\end{aligned}$$

Next, if we denote K as the set of cells inside $C_{R_{i-1}}(X_{i-1,u_{i-1}}) \cap C_{R_i-\sqrt{2}r}(P_j)$, then $K \in Q$. For any cell $a \in K$, we can guarantee that on average, a is within the moving area of $\Theta(N(R_i - \sqrt{2}r)^2)$ SUs inside $\mathcal{T}_i$. Thus we can calculate the lower bound of $\Pr(a_i)$ as:

$$\begin{aligned}\Pr(a_i) &\ge \sum_K \Pr(S_{i-1,u_{i-1}} \in K)(1 - \prod_{S_{i,k}\in\mathcal{T}_i}(1 - \Pr(S_{i,k} \in K)))\\ &\ge \sum_K \Theta(\frac{r^2}{R_{i-1}^2})\ \min(\Theta(1), \Theta(N(R_i - \sqrt{2}r)^2\frac{r^2}{R_i^2}))\\ &= \Theta(\frac{(R_i - \sqrt{2}r)^2}{r^2})\Theta(\frac{r^2}{R_{i-1}^2})\Theta(1)\\ &= \Theta(n^{-\frac{\alpha_0}{h}})\end{aligned}$$

Therefore, we can conclude $\Pr(a_i) = \Theta(n^{-\frac{\alpha_0}{h}})$, for $1 \le i \le h^*$.

As to the output process, $\Pr(a_{h^*+1}) = r^2 n^{\frac{h^*\alpha_0}{h}}$, since the cell in which P_j resides is totally in the moving area of $S_{h^*,u_{h^*}}$.

Finally, we will calculate the conditional probability $\Pr(b_i|t_i a_i)$. During the relay process, since the number of each type SUs in every cell does not exceed $\Theta(\log n)$, thus under the pessimistic assumption that all the $(i-1)$-th type SUs are holding the primary packet to transmit and all the i-th type SUs are able to receive the packet, then $\Pr(b_i)$ is lower bounded by $\Pr(b_i|t_i a_i) = \Theta(\frac{1}{\log^2 n})$, for $1 \le i \le h^*$. During the output process, since there are $\Theta(\log n)$ number of h^*-type relay SUs and $\Theta(1)$ number of receiving PUs. Thus the probability for $(S_{h^*,u_{h^*}}, P_j)$ to be the selected transmission pair is $\Pr(b_{h^*+1}|t_{h^*+1}a_{h^*+1}) = \Theta(\frac{1}{\log n})\Theta(1) = \Theta(\frac{1}{\log n})$

Consequently, for $1 \le i \le h^* + 1$, the relay or output step will take an average delay of

$$\begin{aligned}D_i &= \Theta(\frac{1}{\Pr(t_i a_i b_i)})\\ &= \Theta(\frac{1}{\Pr(t_i)\Pr(a_i)\Pr(b_i|t_i a_i)})\\ &= \begin{cases}\Theta(hn^{\frac{\alpha_0}{h}}\log^2 n), & \text{for } 1 \le i \le h^*,\\ \Theta(hn^{(1+\epsilon-\frac{h^*\alpha_0}{h})}), & i = h^* + 1.\end{cases}\end{aligned} \tag{11}$$

Combining all the delay for each relay step, we can derive the delay performance for the primary network is:

$$\begin{aligned}D_p &= \Sigma_{i=0}^{h^*+1} D_i\\ &= \Theta(hn^{(1+\epsilon-h^*\frac{\alpha_0}{h})} + h^2 n^{\frac{\alpha_0}{h}}\log^2 n)\end{aligned} \tag{12}$$

■

V. Capacity and Delay Scalings for the Secondary network

The secondary network is different from the primary network because the secondary users should access the spectrum opportunistically, i.e., only when the secondary users are outside the current preservation regions can they transmit or relay the packets. According to our scheme, a portion of secondary users would inevitably jump into the preservation region. But due to the node density of each type secondary users is higher than primary users, as well as the choice of cell size, the portion of SUs that falls into preservation region approaches 0 with high probability. This fact is already observed in many previous works, including [10]. Thus, the introduction of preservation region will not degenerate the transmission opportunity for secondary users with high probability.

A. Capacity Performance

Lemma 9: During the routing process of secondary packets, the secondary transmitters and relay nodes can support a constant data rate in each cell.

The proof of Lemma 9 is similar to that of Lemma 7, thus we do not repeat it here.

Combining the result of Lemma 9 and Lemma 6, we can derive the following theorem:

Theorem 3: Under the proposed secondary relay algorithm, the secondary network can achieve the following per-node throughput with high probability:

$$\lambda_s = \Theta(\frac{1}{h^2 \log n}). \tag{13}$$

Proof: Since the number of each type secondary users does not exceed $\Theta(\log n)$, thus the number of source SUs in the input process does not exceed $\Theta(h\log n)$. And since the input process consumes $\frac{1}{2h^*+3}$ fraction of the secondary scheduling cycle, thus the time-average per-node input rate of SUs is $\Theta(\frac{1}{h^2\log n})$.

During the relay and output process, since at most $\Theta(\log n)$ SUs of each type reside in the cell, thus a time-average relay and output rate of $\Theta(\frac{1}{h\log n})$ is achievable.

Consequently, the secondary network can achieve the per-node throughput of $\lambda_s = \min(\Theta(\frac{1}{h^2\log n}), \Theta(\frac{1}{h\log n})) = \Theta(\frac{1}{h^2\log n})$

■

B. Delay Performance

***Theorem** 4:* Under the proposed secondary relay algorithm, the secondary network can achieve the following average delay with high probability:

$$D_{s,j} = O(h^2\log n + h^2 n^{\frac{\alpha_0}{h}}\log^2 n + h^2 n^{(1+\epsilon-\frac{h'\alpha_0}{h})}\log n), \tag{14}$$

where j denotes the type of the destination node, and $h' = \min(h^*, j)$, which is defined in Algorithm 2.

Proof: Consider the relay process of the secondary packet $B_{s,j}$, which is sent from S_{i,k_i} to S_{j,k_j}. The relay process of $B_{s,j}$ consumes $h'+2$ steps, for $0\le i\le h'+1$, a successful relay of $B_{s,j}$ will happen if the following three conditions hold simultaneously: (1) the current time slot is assigned to the Phase (h^*+2+i) of the secondary scheduling scheme; (2) an eligible i-th type relay SU, or the destination node is found in the same cell as the secondary users which holds the packet at the current time slot; (3) for $0\le i\le h'$, among all the eligible transmission pairs in the cell, the SU which holds $B_{s,j}$ is the transmitter of the selected pair and an eligible i-th type relay SU is the receiver of the selected pair; while for $i = h'+1$, $(S_{h',u_{h'}}, S_{j,k_j})$ is the selected transmission pair. Denote the three conditions by t_i, a_i and b_i. Using the similar method as the proof in Section IV-B, we can derive that:

$$\Pr(t_i a_i b_i) = \begin{cases} \Theta(\frac{1}{h^2\log n}), & i=0, \\ \Omega(\frac{1}{h\log^2 n} n^{-\frac{\alpha_0}{h}}), & \text{for } 1\le i\le h', \\ \Omega(\frac{1}{h^2\log n} n^{\frac{h'\alpha_0}{h}-(1+\epsilon)}), & i = h'+1. \end{cases}$$

By adding up the reciprocal of $\Pr(t_i a_i b_i)$, we can derive the expression of the delay performance.

■

VI. Discussion

In this section, we will discuss how mobility heterogeneity of the secondary users can affect the capacity and delay scalings of the CRN. Specifically, α_0 measures the range of the mobility heterogeneity and h measures the diversity of mobility heterogeneity. The increase in α_0 and h will lead to the increase of mobility heterogeneity of SUs. Thus we can find which value of α_0 and h will lead to the optimal capacity and delay performance of the primary and secondary network.

A. Optimal Performance of Primary Network

In our scheme, α_0 is a random positive value, and $h = O(\log n)$.

If $h = \Theta(1)$, denote $\alpha_{th} = \frac{1+\epsilon-\frac{2\log\log n}{\log n}}{1+1/h}$, then primary network could achieve the following average delay:

$$D_p = \begin{cases} \Theta(n^{\frac{\alpha_0}{h}}\log^2 n), & \text{if } \alpha_0 \ge \alpha_{th}, \\ \Theta(n^{(1+\epsilon-\alpha_0)}), & \text{if } \alpha_0 < \alpha_{th}. \end{cases} \tag{15}$$

with the per-node throughput $\lambda_p = \Theta(1)$.

In this case, the primary network can achieve the constant per-node throughput, which is theoretically optimal. As for the delay performance, different α_0 leads to different delay. However, from Equation (15), D_p can only achieve sub-optimal condition, since $D_p = \omega(\mathrm{polylog}(n))$. The delay-capacity tradeoff curve when $h=\Theta(1)$ is shown in the blue dotted curve of Figure 2, and note that $\alpha_{th} = \frac{1+\epsilon}{1+1/h}$ with high probability.

If $h = \Theta(\log n)$, denote $\alpha'_{th} = 1+\epsilon-\frac{3\log\log n}{\log n}$. We should note that in this case, $\Theta(n^{\frac{\alpha_0}{h}}) = \Theta(c^{\alpha_0}) = \Theta(1)$, where c is a constant. Thus the primary network could achieve the following average delay:

$$D_p = \begin{cases} \Theta(\log^4 n), & \text{if } \alpha_0 \ge \alpha'_{th}, \\ \Theta(n^{(1+\epsilon-\alpha_0)}\log n), & \text{if } \alpha_0 < \alpha'_{th}. \end{cases} \tag{16}$$

with the per-node throughput $\lambda_p = \Theta(\frac{1}{\log n})$.

In this case, the primary network can achieve the near-optimal capacity performance. And the delay performance can be improved when α_0 increases from 0 to α'_{th}. Specifically, for $\alpha_0 \ge \alpha'_{th}$, the delay performance is near optimal, which is $D_p(\min) = \Theta(\log^4 n)$.

The delay-capacity tradeoff curve when $h = \Theta(\log n)$ is plotted in the red-solid curve in Figure 2. From the perspective of delay-capacity tradeoff, the previous results indicate the increase of heterogeneity of SUs will improve the delay-capacity tradeoff, until the near-optimal tradeoff is obtained.

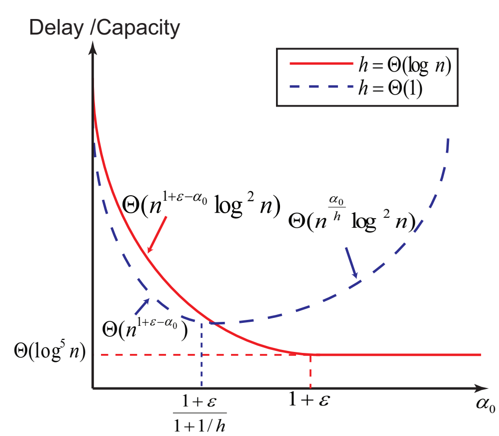

Fig. 2: Relation between Delay/Capacity and the heterogeneity range factor α_0 for primary network

TABLE II: Comparison of optimal scalings of HSRM with other mobility models for SU

Reference	SU Mobility	PU Throughput	PU Delay	SU Throughput	SU Delay	Number of SUs
S. Cui [13]	i.i.d.	$\Theta(1/\log n)$	$\Theta(1)$	$\Theta(1)$	$\Omega(n^2)$	$\Omega(n^2)$
X. Wang [14]	hierarchical	$\Theta(1/\log n)$	$\Theta(\log^2 n)$	$\Theta(1/n^{\delta})$	$\Omega(\log^2 n)$	$O(n^{1+\delta'})$
This paper	HSRM	$\Theta(1/\log n)$	$\Theta(\log^4 n)$	$\Theta(1/\log^3 n)$	$O(\log^4 n)$	$O(n^{1+\delta''})$

B. Optimal Performance of Secondary Network

Using similar method as the previous part, we can show the secondary network can achieve the optimal performance when $h = \Theta(\log n)$ and $\alpha_0 \geq 1 + \epsilon$. Specifically, the secondary network could achieve the following average delay:

$$D_{s,j} = \begin{cases} O(\log^4 n), & \text{if } j \geq h^*, \\ O(n^{(1+\epsilon-\frac{j\alpha_0}{h})} \log^3 n), & \text{if } j < h^*. \end{cases} \tag{17}$$

with per-node throughput of $\lambda_s = \Theta(\frac{1}{\log^3 n})$.

Under optimal condition, the secondary network also has the potential to achieve the near-optimal delay-capacity tradeoff, when the type of destination SU j satisfies $j \geq h^*$. As for the nodes with $j < h^*$, the delay can be reduced if α_0 increases.

Combining the result of the primary network and secondary network, we can conclude that the increase of mobility heterogeneity for SUs will improve the delay-capacity tradeoff for both primary and secondary network, so that both primary network and part of secondary network can achieve near-optimal capacity and delay scaling laws.

Finally, the optimal capacity and delay scalings of HSR-M is compared with the previous works in Table II, where $\delta, \delta', \delta''$ can choose any arbitrary small positive values. From Table II, a near-constant capacity and delay scalings for the primary netowrk can be achieved in all these works. Compared with [13], the HSRM achieves better delay scaling for secondary network and requires much less secondary users. While compared with [14], HSRM can achieve better capacity scalings for secondary network and is more general and flexible than the hierachical mobility model in [14].

VII. Conclusion

In this paper, we study the impact of mobility heterogeneity on the capacity and delay scaling laws in cognitive radio network. We propose the heterogeneous speed-restricted mobility model for SUs, and put forward the corresponding routing and scheduling scheme which exploits the heterogeneity of SUs. In particular, we show that when the mobility heterogeneity of secondary users increases, the delay-capacity tradeoff for both primary and secondary network can be improved. Under the optimal condition, the primary network and part of the secondary network can achieve near-constant (except for poly-logarithmic factor) capacity and delay scalings. This result indicates the mobility heterogeneity of SUs can be utilized to significantly improve the capacity and delay scalings of the cognitive radio network.

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References

[1] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transaction on Information Theory*, vol. 46, no. 2, pp. 388-404, 2000.

[2] M. Franceschetti, O. Dousse, D. N. C. Tse, and P. Thiran, "Closing the Gap in the Capacity of Wireless Networks via Percolation Theory," *IEEE Transactions on Information Theory*, vol. 53, no. 3, pp. 1009-1018, 2007.

[3] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Transactions on Networking*, vol. 10, pp. 477-486, 2002.

[4] M. J. Neely and E. Modiano, "Capacity and Delay Tradeoffs for Ad-Hoc Mobile Networks," *IEEE Transactions on Information Theory*, vol. 51, no. 6, pp. 1917-1937, 2005.

[5] X. Lin and N. B. Shroff, "The fundamental capacity-delay tradeoff in large mobile wireless networks," *Presented at the Third Annual Mediterranean Ad Hoc Networking Workshop Bodrum, Turkey, 2004*.

[6] G. Sharma, R. Mazumdar, and N. B. Shroff, "Delay and Capacity Trade-offs in Mobile Ad Hoc Networks: A Global Perspective," *IEEE Transactions on Networking*, vol. 15, no. 5, pp. 981-992, October 2007.

[7] L. Ying, S. Yang, R. Srikant, "Optimal Delay-Throughput Trade-Offs in Mobile Ad Hoc Networks," *IEEE Transactions on Information Theory*, vol. 54, no. 9, pp. 4119-4143, 2008.

[8] M. Garetto, and E. Leonardi, "Restricted Mobility Improves Delay-Throughput Trade-offs in Mobile Ad-Hoc Networks," *IEEE Transactions on Information Theory*, vol.56, no.10, pp.5016-5029, October 2010

[9] X. Wang, Y. Bei, Q. Peng, and L. Fu, "Speed improves Delay-Capacity Trade-Off in MotionCast," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 5, pp. 729 - 741, May 2011.

[10] S. Jeon, N. Devroye, M. Vu, S. Chung, and V. Tarokh, "Cognitive Networks Achieve Throughput Scaling of A Homogeneous Network," *submitted to IEEE Transactions on Information Theory*, 2009. Available at http://arxiv.org/abs/0801.0938.

[11] C. Yin, L. Gao, and S. Cui, "Scaling Laws for Overlaid Wireless Networks: A Cognitive Radio Network versus a Primary Network," *IEEE/ACM Transactions on Networking*, vol. 18, no. 4, pp. 1317-1329, August 2010.

[12] W. Huang and X. Wang, "Throughput and Delay Scaling of General Cognitive Networks," *in Proceedings of IEEE INFOCOM, 2011*.

[13] L. Gao, R. Zhang, C. Yin, and S. Cui, "Throughput and Delay Scaling in Supportive Two-tier Networks," *to appear at JSAC, 2011*. Available at http://arxiv.org/abs/0905.3407.

[14] X. Wang, F. Luo, Y. Li, Z. Cao, and X. Gan, "Mobility Reduces the Number of Secondary Users in Cognitive Radio Network," *in Proceedings of IEEE GLOBECOM, 2011*.

[15] Y. Liu, Y. He, M. Li, J. Wang, K. Liu, L. Mo, W. Dong, Z. Yang, M. Xi, J. Zhao, X. Li, "Does Wireless Sensor Network Scale? A Measurement Study on GreenOrbs", *in Proceedings of IEEE INFOCOM, 2011*.

[16] Z. Yang, Y. Liu, X. Li,"Beyond Trilateration: On the Localizability of Wireless Ad-hoc Networks", *IEEE/ACM Transactions on Networking (TON)*, vol. 18, no. 6, pp. 1806-1814, December 2010.

[17] M. Ji, Z. Wang, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, "The Capacity of Ad Hoc Networks with Heterogeneous Traffic Using Cooperation," *in Proceddings of IEEE INFOCOM, 2010*.