Cognitive Networks Achieve Throughput Scaling of a Homogeneous Network

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***Abstract*— We study two distinct, but overlapping, networks which operate at the same time, space and frequency. The first network consists of n randomly distributed *primary* users, which form either an ad hoc network, or an infrastructure-supported ad hoc network in which l additional base stations support the primary users. The second network consists of m randomly distributed *secondary* or *cognitive* users. The primary users have priority access to the spectrum and do not change their communication protocol in the presence of secondary users. The secondary users, however, need to adjust their protocol based on knowledge about the locations of the primary users so as not to harm the primary network's scaling law. Base on percolation theory, we show that surprisingly, when the secondary network is denser than the primary network, *both* networks can *simultaneously* achieve the same throughput scaling law as a stand-alone ad hoc network.**

I. Introduction

In their pioneering work [1], Gupta and Kumar posed and studied the limits of communication in ad hoc wireless networks. Assuming n nodes are uniformly distributed in a plane and grouped into source-destination (S-D) pairs at random, they showed that one can achieve a sum throughput of $S(n) = \Theta(\sqrt{n/\log n})$. The nearest multihop transmission in which nodes transmit to one of the nodes in their neighboring cells was used to prove this throughput scaling, requiring full connectivity with at least one node per cell. A trade-off between throughput and delay of fully-connected networks was studied in [2]. In [3], it was proved that partial connectivity is enough to achieve $S(n) = \Theta\left(\sqrt{n}\right)$ using percolation theory. Recently, a hierarchical cooperation scheme was proposed in [4] and was shown to achieve better throughput scaling than the multihop transmission in low attenuation regime, achieving a scaling very close to their new upper bound.

Recently *hybrid networks* have been studied in which the nodes' communication is aided by additional infrastructures such as base stations (BSs). These are generally assumed to have high bandwidth connections to each other. The connectivity of hybrid networks has been analyzed in [5] and the throughput scaling of hybrid networks has been studied in [6], [7] . In order for the hyrbid network's throughput scaling to outperform that of a strictly ad hoc network, it was determined that the number of infrastructures should be greater than a certain threshold [6], [7]. In this case, hybrid networks operate in a manner similar to cellular systems.

The existing literatures have focused on the throughput scaling of a *single* network. However, the necessity of extending and expanding results to capture *multiple* overlapping networks is becoming apparent. Recent measurements have shown that despite increasing demands for bandwidth, much of the currently licensed spectrum remains unused a surprisingly large portion of the time [8]. In the US, this has led the Federal Communications Commission (FCC) to consider easing the regulations towards *secondary spectrum sharing* through their *Secondary Markets Initiative* [9]. The essence of secondary spectrum sharing involves having *primary* license holders allow secondary license holders to access their spectrum. Different types of spectrum sharing exist but most agree that the primary user has a higher priority to access the spectrum, while the secondary users *opportunistically* use it. These secondary users often require greater sensing abilities and more flexible and diverse communication abilities compared to legacy primary users. Secondary users are often assumed to be *cognitive radios*, or wireless devices which are able to transmit and receive according to a variety of protocols and are also able to sense and adapt to their environment [10]. These features allow them to behave in a more "intelligent" manner than current wireless devices.

In this paper, we study *cognitive networks*, which consist of secondary, or cognitive, users who wish to transmit over the spectrum licensed to the primary users. The single user case in which a single primary and a single cognitive S-D pairs share the spectrum has been considered in the literatures, see for example [11]–[14] and the references therein. Recently, a single-hop cognitive network was considered in [15], where multiple secondary S-D pairs transmit in the presence of a single primary S-D pair. It was shown that a linear throughput scaling law of the single-hop secondary network is obtained when its operation is constrained to guarantee a particular outage constraint for the primary S-D pair.

We study a more general environment in which a *primary ad hoc network* and a *cognitive ad hoc network* both share the same space, time, and frequency dimensions. Our main assumptions are that (1) the primary network continues to operate as if no secondary network were present, (2) the secondary nodes know the locations of the primary nodes and

(3) the secondary network is denser than the primary network. Under these assumptions, we will illustrate routing protocols for the primary and secondary networks that result in the *same throughput scaling* as if each were a single network.

II. System Model

In this section, we define the underlying network models and then look at the transmission schemes, the resulting achievable rates, and assumptions made about the primary and secondary networks.

A. Network Geometry

We consider a planar area in which a primary network and a secondary network co-exist. Two types of networks are considered as the primary network: an *ad hoc network* and an *infrastructure-supported network*, while the secondary network is always ad hoc. In the ad hoc primary model, primary nodes are distributed according to a Poisson point process (p.p.p.) of density n over a unit square and are randomly grouped into primary S-D pairs. In the infrastructure-supported primary model, primary nodes are still distributed according to a p.p.p. of density n, but these nodes are supported by additional l regularly spaced BSs. The BSs' sole purpose is to relay data for the primary network, they are neither sources nor destinations. We assume that the BSs are connected to each other through wired lines of capacity large enough such that the BS-BS communication is not the limiting factor in the throughput scaling laws. For both cases, secondary nodes are distributed according to a p.p.p. of density m over the same area and are also randomly grouped into secondary S-D pairs.

The densities of primary nodes, secondary nodes, and BSs are related according to $n = m^{\frac{1}{\beta}} = l^{\frac{1}{\gamma}}$, where $\beta > 1$ and $\gamma < 1$. We focus on the case that the density of the secondary nodes is higher than that of the primary nodes. We also assume that the densities of both the primary nodes and secondary nodes are higher than that of the BSs, which is reasonable from a practical point of view. We consider a path loss channel model such that the channel power gain $g(d)$, normalized by a constant, is given by $g(d) = d^{-\alpha}$, where d denotes the distance between a transmitter (Tx) and its receiver (Rx) and $\alpha > 2$ denotes the path-loss exponent.

B. Rates and Throughputs Achieved

Each network operates based on slotted transmissions. We assume the duration of each slot, and the coding scheme employed are such that one can achieve the additive white Gaussian noise (AWGN) channel capacity. For a given signal to interference and noise ratio (SINR), this capacity is given by the well known formula $R = \log(1+\text{SINR})$ bps/Hz assuming the additive interference is also white Gaussian independent with noise and signal. We assume that primary slots and secondary slots have the same duration and are synchronized with each other. We further assume all the primary, secondary, and BS nodes are subject to a transmit power constraint P.

Throughout the paper, the achievable per-node throughput of the primary and secondary networks are defined as follows.

Definition 1: A throughput of $T_p(n)$ per primary node is said to be achievable with high probability[1](w.h.p.) if all primary sources can transmit at a rate of $T_p(n)$ (bps/Hz) to their primary destinations w.h.p. in the presence of the secondary network.

Definition 2: Let $\delta_s(m)$ denote an outage probability of the secondary network, which may vary as a function of m. A throughput of $T_s(m)$ per secondary node is said to be $\delta_s(m)$-achievable w.h.p. if at least $1 - \delta_s(m)$ fraction of secondary sources can transmit at a rate of $T_s(m)$ (bps/Hz) to their secondary destinations w.h.p. in the presence of the primary network.

Let us define $S_p(n)$ as the sum throughput of the primary network, or $T_p(n)$ times the number of primary S-D pairs. Similarly, define $S_s(m)$ as the sum throughput of the secondary network, or $T_s(m)$ times the number of *served* secondary S-D pairs at a rate of $T_s(m)$. We use the notation $T(n)$ and $S(n)$ (without the subscripts) to denote the per-node and sum throughputs of the primary network *in the absence of the secondary network.*

C. Primary and Secondary User Behaviors

Primary networks may be thought of as existing communication systems which operate in licensed bands, having higher priority access to the spectrum than secondary networks. Thus, our first key assumption is that *the primary network does not have to change its protocol due to the secondary network.* The secondary network, which is opportunistic in nature, is responsible for reducing its interference to the primary network to satisfy $S_p(n) = \Theta(S(n))$, while maximizing its own throughput $S_s(m)$. The secondary network may ensure this constraint by adjusting its protocol based on information about the primary network. Thus, our second key assumption is that *the secondary network knows the locations of all primary nodes.* Since the secondary network is denser than the primary network, each secondary node can measure the interference power from its adjacent primary node and send it to a coordinator node. Based on these measured values, the secondary network can establish the locations of the primary node.

III. Network Protocols

A. Ad Hoc Primary Network

We first consider network protocols when both the primary and secondary networks are ad hoc in nature. The challenge is to prove that the secondary nodes can communicate in a way that allows the primary scaling law to remain $S_p(n) = \Theta(S(n))$.

1) Primary network protocol: We assume that the primary network delivers data using classical multihop routing, in a manner similar to [1] and [2]. The basic multihop protocol is as follows:

- Divide the unit area into square cells of area a.

[1]For simplicity, we use the notation w.h.p. in the paper to mean an event occurs with high probability as $n \to \infty$.

- A 9- time division multiple access (TDMA) scheme is used, in which each cell is activated during one of 9 slots.
- Define the horizontal data path (HDP) and the vertical data path (VDP) of a S-D pair as the horizontal line and the vertical line connecting a source to its destination, respectively. Each source transmits data to its destination by first hopping to the adjacent cells on its HDP and then on its VDP.
- When a cell becomes active, it delivers its traffic. Specifically, a Tx node in the active cell transmits a packet to a node in an adjacent cell (or in the same cell). A simple round-robin scheme is used for all Tx nodes in the same cell.
- At each transmission, a Tx node transmits with power $Pa^{\frac{\alpha}{2}}$.

This protocol requires full connectivity, meaning that each cell should have at least one node. Let a_p denote the area of a primary cell. As proven in [2], this requirement is satisfied w.h.p. if we set $a_p = \frac{2\log n}{n}$. Under the given primary protocol, $S(n) = \Theta(\sqrt{n/\log n})$ is achievable w.h.p. [1].

2) Secondary network protocol: Since the secondary nodes know the primary nodes' locations, an intuitive idea is to have the secondary network operate in a multihop fashion in which they circumvent each primary node in order to reduce the effect of secondary transmissions to each primary node. Around each primary node we define its *preservation region:* a square containing 9 secondary cells, with the primary node at the center cell. The secondary nodes need to avoid these preservation regions in its routing. Our protocol for the secondary network is the same as the basic multihop protocol except that

- The secondary cell size is $a_s = \frac{2\log m}{m}$.
- At each transmission a secondary node transmits its packet *three* times repeatedly (rather than once) using three slots.
- The secondary paths avoid the preservation regions (see Fig. 1). That is, if the HDP or VDP of a secondary S-D pair is blocked by a preservation region, this data path circumvents the preservation region by using its adjacent cells. If a secondary source (or its destination) belongs to preservation regions or its data path is disconnected by preservation regions, the corresponding S-D pair is not served.

As we will show later, the repeated secondary transmissions can guarantee the secondary receivers to have a certain minimum distance from all primary interferers for at least one packet, thus guaranteeing the secondary nodes a non-trivial rate. The main difference between this scheme and previous multhop routing schemes is that the secondary multihop paths must circumvent the preservation regions. By re-routing the secondary nodes' transmission around the primary nodes' preservation regions, we can guarantee the primary nodes a non-trivial rate.

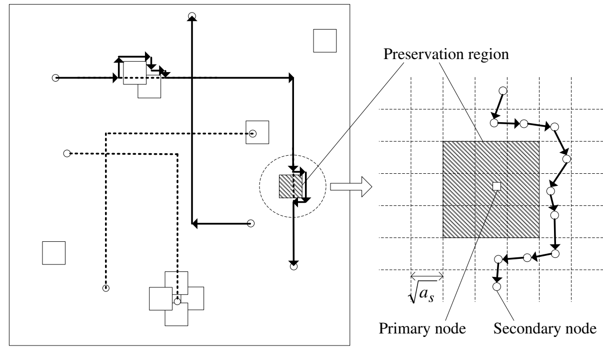

Fig. 1. Secondary data paths for the ad hoc primary model: a secondary S-D pair goes around if it is blocked by a preservation region.

B. Infrastructure-Supported Primary Network

In this subsection, we consider a different primary network which includes additional regularly-spaced BSs. We assume the primary network uses a classical BS-based data transmission. The challenge is again to prove that the secondary nodes can transmit in such a way that the primary scaling law continues to be $S_p(l) = S(l)$.

1) Primary network protocol: We consider the primary protocol in which a source node transmits a packet to its closest BS and the destination node receives the packet from its closet BS, similar to those in [6] and [7]:

- Divide the unit area into square primary cells of area $a'_p = \frac{1}{l}$, where each primary cell has one BS at its center.
- During the uplink phase, each source node transmits a packet to its closest BS.
- The BS that receives a packet from a source delivers it to the BS closest to the corresponding destination using BS-to-BS links.
- During the downlink phase, each destination node receives its packet from the closest BS.
- A simple round-robin scheme is used for all downlink transmissions and all uplink transmissions in the same primary cell.
- In the downlink phase, a BS transmits with power $Pa'^{\frac{\gamma}{2}}_p$. Similarly, in the uplink phase, a primary node transmits with power $Pa'^{\frac{\gamma}{2}}_p$.

Under the given primary protocol, the sum throughput of $S(l) = \Theta(l)$ is achievable [6]. Note that if $\gamma \geq 1/2$, $S(l) = \Theta(l) > \Theta(\sqrt{n/\log n})$. That is, when $\gamma \geq 1/2$, using BSs helps improve the throughput scaling of the primary network. As was pointed out in [6], to improve throughput scaling, the number of BSs should be high enough. Therefore, this primary protocol is suitable for $\gamma \geq 1/2$, while the result of the ad hoc primary model can be applied for $0 < \gamma < 1/2$.

2) Secondary network protocol: Let us consider the secondary protocol when the primary network is in the downlink phase. The amount of interference from the secondary network to the primary network may be reduced by setting a preservation region around each primary receiving node. However, the repeated transmissions of the same secondary

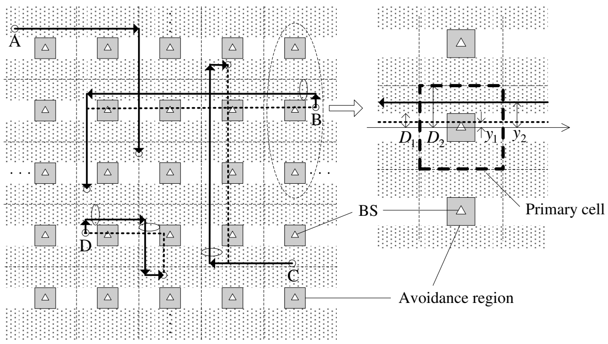

Fig. 2. Secondary data paths for the infrastructure-supported primary model: a horizontal (or vertical) data path is horizontally (or vertically) shifted if it is blocked by an avoidance region.

packet does not guarantee a non-trivial rate for secondary transmissions since all BSs are always active in the worst case for the infrastructure-supported primary model. Similar to the concept of preservation regions, in order to reduce the interference to the secondary nodes, in a certain region around each BS (which are primary Txs) we insist that no secondary users transmit or receive. However, due to the relatively high transmit power of primary transmissions, these regions need a larger area than the previously defined preservation region.

Let us define an *avoidance region* as a square containing M secondary cells, with a BS at the center. We obtain a secondary protocol by replacing the three repeated transmissions of the previous secondary protocol by:

- If a horizontal or vertical data path of each secondary S-D pair is blocked by an avoidance region, this data path is shifted horizontally (or vertically) to the non-blocked region. If a secondary source (or its destination) belongs to an avoidance region, the corresponding S-D pair is not served.

Note that the secondary cell size a'_s is the same as a_s. Fig. 2 illustrates examples of shifted secondary data paths due to the avoidance regions (for simplicity, preservation regions are not shown in this figure): A illustrates the case where the HDP and VDP are not blocked, B the case where only the HDP is blocked, C the case where only the VDP is blocked, and D the case where both the HDP and VDP are blocked.

Area of an avoidance region:

If we take a large M, the served secondary nodes can achieve high rates because of a large distance from primary interferers, but the number of served secondary S-D pairs decreases. Heuristically, we wish to increase M up to the limit allowed by the constraint that the number of unserved S-D pairs (due to their lying in avoidance regions) remains a constant fraction of the total S-D pairs. That is, when designing the system, we select a constant $\delta'_1 \in (0, 1-\epsilon)$ for $\epsilon > 0$ and accept that a fraction of $\delta'_1/2$ of the secondary pairs will not be served. The following lemma indicates how to determine the area of each avoidance region, i.e., the parameter M.

Lemma 1: Suppose the infrastructure-supported primary model and $M = \frac{\delta'_1 - \zeta(n)}{4}\frac{a'_p}{a'_s}$, where $\delta'_1 \in (0, 1-\epsilon)$ is a constant and $\zeta(n) > 0$ converges to zero as $n \to \infty$. Then the number of unserved secondary S-D pairs is upper bounded by $\delta'_1 \frac{m}{2}$ w.h.p..

Proof: We refer readers to the full paper [16]. ■

Since the minimum distance of a secondary Rx to all primary Txs or BSs is equal to $\frac{1}{2}\sqrt{Ma'_s} = \Theta\left(\sqrt{a'_p}\right)$, we can guarantee a non-trivial rate for each secondary S-D pair. Moreover, since the fraction of unserved S-D pairs stays *constant* and does not grow with n, the throughput loss due to unserved S-D pairs does not affect the scaling behavior.

Avoidance region re-routing:

Since the area of each avoidance region is much larger than that of each preservation region, secondary cells adjacent to avoidance regions should handle much more traffic than regular cells if we re-route blocked data paths using only these cells. In order to more evenly distribute the re-routed traffic, we shift an entire data path to the non-blocked region based on given mapping rule when it is blocked by an avoidance region. Define $\mathcal{R}_h$ as the region in which extended HDPs are not blocked by avoidance regions shown by the dotted regions in Fig. 2. Let us focus on the case B, where the blocked HDP in $\mathcal{R}_h^c$ is shifted to the new HDP in $\mathcal{R}_h$. Let y_1 and y_2 denote the y-axis of the blocked HDP and of its shifted HDP, respectively. Without loss of generality, it is assumed that y_1 is in $[0, D_1]$, where $D_1 = \frac{1}{2}\sqrt{Ma'_s}$. Then y_2 is given by

$$y_2 = \frac{D_2}{D_1}y_1 + D_1, \tag{1}$$

where $D_2 = \frac{1}{2}\left(\sqrt{a'_p} - \sqrt{Ma'_s}\right)$. Similarly, let $\mathcal{R}_v$ denote the region in which none of VDPs are blocked. We can shift a blocked VDP in $\mathcal{R}_v^c$ to $\mathcal{R}_v$ using the analogous mapping to the horizontal case.

For the uplink phase, we can also define an avoidance region at each Tx (primary node) of the primary network. However, we cannot set M as large as in the downlink case since the density of primary nodes is higher than that of BSs, leading to a smaller throughput than the downlink case. Note that if we operate the secondary network during the uplink and downlink phase separately, then throughput scalings of the secondary network follows the maximum of the uplink and downlink throughputs. Therefore, overall throughput scalings follow those of the downlink phase.

IV. Throughput Analysis and Scaling Laws

In this section, we analyze the per-node and sum throughputs of each network under given protocols and derive the corresponding scaling laws. Because of page limitation, we refer the proof of the main theorems to the paper [16].

A. Ad Hoc Primary Network

To derive the throughput scalings, we first prove that each primary cell can sustain traffic with a constant rate. Then we derive an upper bound on the number of primary data paths that each cell should carry. We finally obtain $T_p(n)$ as the sustained rate divided by the number of data paths. By obtaining a lower bound on the number of primary S-D pairs, we also derive $S_p(n)$.

For the secondary network, $T_s(m)$ and $S_s(m)$ can be derived in a way similar to the primary case. But, unlike the primary routing, the secondary routing must circumvent the preservation regions, or possibly *cluster(s)* of preservation regions. We use percolation theory to show that this re-routing of the secondary paths around cluster(s) of primary preservation regions does not cause a loss in terms of secondary throughput scaling laws.

Theorem 1: Suppose the ad hoc primary model. The following per-node and sum throughputs are achievable w.h.p. for the primary network: $T_p(n) = \Theta(\sqrt{1/n \log n})$ and $S_p(n) = \Theta(n/\log n)$. The following per-node and sum throughputs are $\delta_s(m)$-achievable w.h.p. for the secondary network: $T_s(m) = \Theta(\sqrt{1/m \log m})$ and $S_s(m) = \Theta(\sqrt{m/\log m})$, where $\delta_s(m)$ converges to zero as $m \to \infty$.

Proof: We refer readers to the full paper [16]. ■

This result is of particular interest as it shows that not only may the primary network operate at the same scaling law as when the secondary network does not exist, but the secondary network may also achieve the exact same scaling law as when the primary network does not exist.

B. Infrastructure-Supported Primary Network

For the infrastructure-supported primary model, the entire HDP (or VDP) is shifted to the non-blocked region if the secondary HDP (or VDP) is blocked by an avoidance region. Although the secondary cells in the non-blocked region may deliver more traffic, we show that this re-routing does not affect the scaling law of $T_s(m)$ and $S_s(m)$.

Theorem 2: Suppose the infrastructure-supported primary model and $\gamma \geq \frac{1}{2}$. The following per-node and sum throughputs are achievable w.h.p. for the primary network: $T_p(l) = \Theta(l^{1-\frac{1}{\gamma}})$ and $S_p(l) = \Theta(l)$. For any $\delta_s > 0$, the following per-node and sum throughputs are $\delta_s(m)$-achievable w.h.p. for the secondary network: $T_s(m) = \Theta(\sqrt{1/m \log m})$ and $S_s(m) = \Theta(\sqrt{m/\log m})$, where $\delta_s(m) \to \delta_s$ as $m \to \infty$.

Proof: We refer readers to the full paper [16]. ■

We show here that the presence of the secondary network does not change the scaling law of the primary network for $\gamma \geq 1/2$ (For $\gamma < 1/2$, results of the previous ad hoc primary model apply). Furthermore, the secondary network can achieve the same scaling law under a multihop routing protocol as when the primary network is absent.

V. Conclusion

In this paper, we studied two co-existing networks with different priorities (a primary and a secondary netwrok) and analyzed their simultaneous throughput scalings. It was shown that each network can achieve the same throughput scaling as when the other network is absent. Furthermore, this may be achieved by adjusting the secondary protocol while keeping that of the primary network unchanged. In essence, the primary network is unaware of the presence of the secondary network. To achieve this result, the secondary nodes need knowledge of the locations of the primary nodes, and the secondary nodes need to be denser than the primary. For $\beta \leq 1$ (the primary is denser than the secondary), on the other hand, it seems more challenging to adjust the secondary protocol while keeping the primary network protocol unchanged since there are many primary nodes around each secondary node. If we allow the primary protocol to adapt to the presence of the secondary network, we can achieve the throughput scaling of two homogenous networks by employing TDMA between the two networks. Our result may be extended to more than two networks, provided each layered network obeys the same three main assumptions as in the two network case.

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