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Performance Analysis on the Coexistence of Multiple Cognitive Radio Networks

Lijun Qian[1,*], Oluwaseyi Omotere[1], Riku Jäntti[2]

[1]Department of Electrical and Computer Engineering, Prairie View A&M University, Texas A&M University System, Prairie View, Texas 77446, USA
[2]Department of Communications and Networking, Aalto University, P.O. Box 13000, 00076 Aalto, Finland

Abstract

The demand for wireless services is growing on a daily basis while spectral resources to support this growth are static. Therefore, there is need for the adoption of a new spectrum sharing paradigm. Cognitive Radio (CR) is a revolutionary technology aiming to increase spectrum utilization through dynamic spectrum access, as well as mitigating interference among multiple coexisting wireless networks. In many practical scenarios, multiple CR networks may coexist in the same geographical area, and they may interfere with each other and also have to yield to the primary user (PU). In this study, we investigate how much throughput a node in a CR network can achieve in the presence of another CR network and a PU. The results of this study illustrate how the transmission probability and sensing performance affect the achievable throughput of a node in coexisting CR networks. In addition, these results may serve as guidance for the deployment of multiple CR networks.

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1. Introduction

The growth of wireless services in recent years is astronomical, this has lead to growing demand on the scarce spectrum resources. Cognitive radio is a key in minimizing the spectral congestion through its adaptability, where the radio parameters (such as frequency, power, modulation, bandwidth) can be changed depending on the radio environment, users situation, network condition, geolocation etc.

The regulation of wireless networks is done by government agencies through which spectrum is allocated to a particular application, this kind of static allocation of spectrum results in congestion in some parts of the spectrum and non use in some others, therefore, spectra utilization is very low over most of the bands. Cognitive radios are seen as a way to mitigate this low spectra usage. These radios sense the medium and dynamically adapt their waveforms to comply with the compliance policies fixed by the regulatory authorities and opportunistically access portions of the spectrum that are not used by the primary systems. A good example of this scenario is in the unlicensed bands such as the Industrial Scientific and Medical (ISM) band in 2.4 GHz where the Federal Communications Commission (FCC) [1] rules if complied with by any technology is allowed to operate, there are multiple wireless technologies that are operating in these bands such as IEEE 802.11 Wireless Local Area Networks (WLAN), cordless phones and Bluetooth Wireless Personal Area Networks (WPAN). While unlicensed bands have opened up avenues for the advent of new technologies, their full potential is not realizable because of the presence of interference from other technologies operating in those bands. These unlicensed bands are overcrowded, while some licensed bands, such as the TV bands are not fully utilized. This results in poor spectrum utilization.

Multiple CR networks may coexist in the same geographical area, the cognitive capability of CR networks allows them to sense their communication environment and adapt the parameters of their communication scheme to maximize throughput, while minimizing the interference to the PU. One example is in disaster relief effort, where different organizations such as police, fire fighters, and emergency medical services are all deployed in the disaster area at the same time. All of these participating organizations use CRs to sweep a wide range of spectrum looking for suitable spectrum for communication. Another example is in battlefield communications, where multiple wireless networks may coexist. These networks may belong to different military branches or organizations such as the army and the air force. With the advancement of CR

*Corresponding author. Email: liqian@pvamu.edu

technology, it is expected that many of the network elements will have cognitive capability enabled by a software defined radio platform, such as the Joint Tactical Radio System (JTRS) program being a prime example.

In this study will consider two type of secondary access namely (1) Equal Secondary Access (2) Prioritized Secondary Access, their possible transmission scenarios, and their corresponding performance bound with the interference analysis over both Gaussian and Nakagami-m fading channels are considered. This bound determines whether it is feasible to deploy multiple CR networks in the same region with the required quality-of-service, say, the minimum throughput. We analyze the performance of a CR network in detail by considering the effects of various CR network parameters such as transmission probability and performance of spectrum sensing (false alarm and miss rate probabilities). The Complementary Cumulative Distribution Function (CCDF) and Moment Generating Function (MGF) of multiple interferers over Gaussian and Nakagami-m fading channels in a multiple coexisting CR networks are presented and the upper bound for the probability of false alarm, which is required to achieve a certain throughput is deduced.

2. Related Work

There are rich literatures on the coexistence of heterogeneous wireless networks in the ISM bands, such as the coexistence of WiFi (802.11) and Zigbee (802.15.4) radios [2]-[7]. IEEE 802.11 b/g networks may interfere with IEEE 802.15.4 sensor networks and thereby introduce significant coexistence problems for low-power sensor nodes [2] and [3]. In [4], a coexistence model of IEEE 802.15.4 and IEEE 802.11b/g, which exposes the interactive behavior between these two standards and therefore accurately explains their coexistence performance was proposed. The model focused on power and timing, and the concept of coexistence range was introduced. The authors of [5] used a multi-agent system based approach to achieve information sharing and decision distribution among multiple 802.11 networks deployed within small geographic vicinity. A multi-agent constraint optimization problem was formulated to solve the distributed resource management in multiple 802.11 networks. An experimental study was performed in [6], where the results raise important coexistence issues for 802.15.4 and 802.11 by showing that 802.15.4 significantly impacts 802.11 performance in many cases. The more recent study [7] proposed a novel MAC, Cooperative Busy Tone (CBT), that enables the reliable coexistence between WiFi and Zigbee. CBT allows a separate ZigBee node to schedule a busy tone concurrently with the desired transmission, thereby improving the visibility of ZigBee devices to WiFi. In addition, a frequency flip scheme that prevents the mutual interference between cooperative ZigBee nodes, and a busy tone scheduler that minimizes the interference to WiFi are also designed in CBT. However, these works focus on the coexistence of heterogeneous wireless networks in the ISM bands. Furthermore, the analysis were mainly on the different PHY/MAC structures and standards of WiFi (802.11) and Zigbee (802.15.4) radios, rather than the coexistence of multiple homogeneous cognitive radio networks with PU network.

Although intensive research has been carried out on CR technology and single CR networks, only a few studies address the coexistence of multiple CR networks [8]-[11]. In [8], customer admission and eviction control was investigated using game theory for two co-located wireless service providers that temporarily lease a licensed spectrum band from the licensees and opportunistically utilize it during the absence of the legacy users. The goal is to provide WiFi-like Internet access in the spectrum whitespaces with better service quality than that of WiFi in the ISM band. The minimum blocking probabilities and maximum spectrum utilizations of three co-located systems with different bandwidth requirements were derived for one-channel band scenario in [9]. A channel packing scheme was then proposed for the multiple-channel band scenario to decrease the blocking probability and reduce the overall failure probability of the cognitive radio systems. A priority queue model was proposed for cognitive radio networks in [10], where the PU has preemptive priority while the cognitive users are further divided into different priority levels. A scheduling model was built based on the hybrid priority dynamic policy. In [11], three state sensing model was proposed to detect the PU active and idle states as well as the secondary user (SU) activities in multiple CR networks. It is shown that the scheduler provided much needed gain during congestions. However, none of the existing works discuss the fundamental per-node throughput of a cognitive radio user when multiple homogeneous cognitive radio networks coexist with PUs. Furthermore, we provide insights on the dominant factors of the per-link throughput and these were validated in the results.

The authors in [12] discussed the fundamental per-node throughput of a CR user when multiple CR networks coexist under simultaneous access with the PU but did not considered the performance under prioritized access and over Nakagami-m fading channels.

3. System Model

A model for the coexistence of multiple CR networks with a PU is illustrated in Figure 1 and Figure 2. These two figures show both the physical and logical representation of these networks under equal and prioritize access scheme. The two CR networks (CRN_1 and CRN_2) in Figure 1a and Figure 2a have equal access to spectrum, so they sense for spectrum availability in their surroundings ensuring interference to PU is avoided. Figure 1b and Figure 2b show Cognitive Gateway Network (CGN) and CR network (CRN) with different priority to access the spectrum whenever it is available, both CGN and CRN are in the same spatial domain and are using the same frequency opportunistically without causing interference to PU. Thus, both CGN and CRN need to perform spectrum sensing of the PU, and CRN need to perform additional spectrum sensing of the CGN because CRN has lower priority on spectrum. The main problem is that the CR networks under equal access will interfere with each other in such situations, in addition to yielding to the PUs, while under prioritize access, interference is avoided to the two CR networks since they both have different priority to spectrum utilization because the lower priority CRN will yield to the PU and CGN. We specifically study the impact of the interfering CR network on the performance of a given CR network under equal access and prioritize access.

3.1. Common Assumptions

We will focus on the case where two CR networks are uncoordinated and deployed in the same geographical area at the same time in addition to a PU. Each CR network performs its own spectrum sensing and the corresponding probabilities of detection and false alarm are taken into account. However, they do not coordinate their sensing nor share the sensing results. For example, although the organizations are collaborating on the disaster relief mission, each organization has its own CR network and these CR networks are not coordinated since the spectrum situation in the disaster area is not known a priori and each organization has its own administrative constraints such as security requirements.

Since CSMA/CA is a well-established Media Access Control (MAC) protocol and has been adopted by many practical wireless networks, we presume that the CR networks use CSMA/CA as the basis of their MAC protocol. It is also assumed that CR nodes can detect others' transmissions by using CSMA/CA, where the RTS/CTS message exchange is carried out before data transmission. The secondary CR networks are homogeneous in the sense that the nodes in the CR networks have similar capabilities and behaviors, such as the transmission power.

We assumed CR networks are located in an urban area. Since the CR nodes are typically less powerful than the primary nodes, they have smaller transmission ranges and are located closer to each other, we model the channel between CR nodes with Rayleigh fading. Noise is Additive White Gaussian Noise (AWGN). For the interference from CR nodes, we considered Gaussian and Nakagami-m distribution. A Gaussian distribution is mainly encountered when values of the quantity considered result from the additive effect of numerous random causes, each of them of relatively slight importance. In propagation, most of the physical quantities involved (power, voltage, fading time, etc.) are essentially positive quantities and cannot therefore be represented directly by a Gaussian distribution. On the other hand this distribution is used to represent the fluctuations of a quantity around its mean value (scintillation) and to represent the logarithm of a quantity. Nakagami-m is more flexible and it can model fading conditions from worst to moderate. The reason behind taking this distribution is its good fit to empirical fading data. Due to free parameter it provides more flexibility.

We focus on CR ad hoc networks instead of CR networks with infrastructure support such as the IEEE 802.22 systems [13]. There is a universal detector for PU signals in each CR network while each CR node uses CSMA/CA protocol by exploiting this detection result.

3.2. Equal Access Assumptions

The presence of the PU is defined using the following hypotheses. For equal access Hypothesis, H_0 denotes the case in which the PU is not present and H_1 stands for the case in which the PU is present.

3.3. Prioritized Access Assumptions

For the prioritized access, Hypothesis H_0^{PU} denotes the case in which the PU is idle and H_1^{PU} stands for the case in which the PU is active and because one of the CR networks has higher priority to access the spectrum, we denote this CR network has Cognitive Gateway Network (CGN) and its node as Cognitive Gateway (CG) and the lower priority CR network is denoted as CRN and its node as CR, therefore CR in CRN must sense for CG before transmitting data. H_0^{CG} denotes the case where CG is idle and H_1^{CG} stand for the case where CG is active. We assume a simplified frame structure with a sensing period τ and data period $T - \tau$ such that T is one frame duration. CRN may need a sensing period τ_2 longer than that of CGN (τ_1) to perform sensing of active CGs.

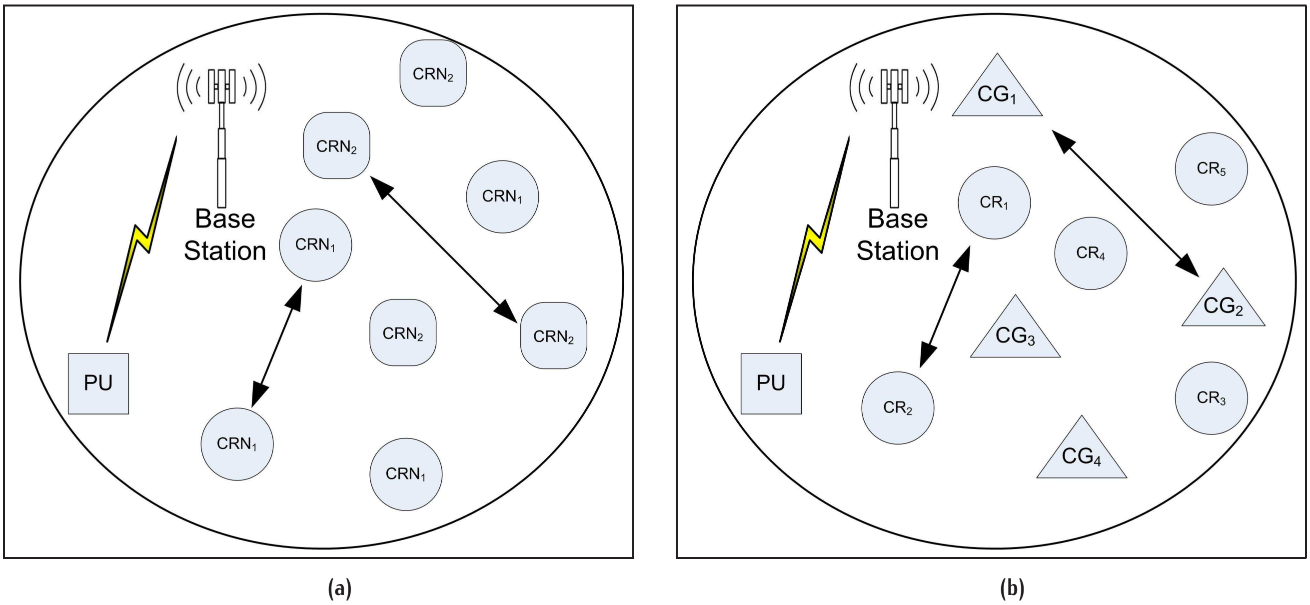


Figure 1. Physical network scenario, where two coexisting CR networks are within the range of a PU. (a) Equal Access (CRN1 and CRN2). (b) Prioritize Access (CGN and CRN).

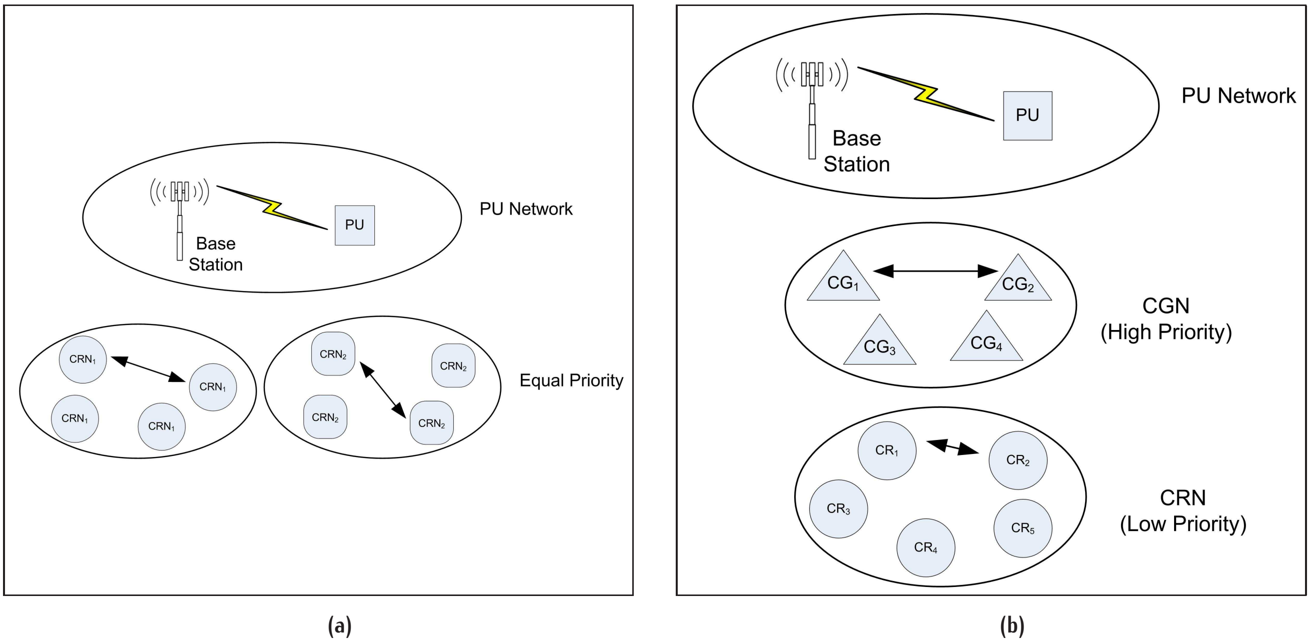


Figure 2. Logical network scenario, where two coexisting CR networks have different priority of spectrum access while yielding to a primary user. (a) Equal Access (CRN1 and CRN2). (b) Prioritize Access (CGN and CRN).

4. Theoretical Model

In this section we first derive the interference model for overlapping CR networks which is then exploited to deduce the per-node probabilistic throughput for such scenario. As discussed in the previous section, we consider both Gaussian and Nakagami-m distribution for the Interferer.

4.1. Probabilistic Throughput Per-node for Gaussian Interference

Both of the CR networks are uniformly random networks where nodes are independently distributed in an area according to a Poisson Point Process (PPP). Node densities of CRN_1 and CRN_2 are denoted by λ_1 and λ_2, respectively. We consider Rayleigh fading, x with $E\{x\} = 1$. The Cartesian coordinates of a node are denoted by X and Y . These random variables are independent of the other nodes' locations and uniformly distributed in $[-L, L]$. By setting the node density $\lambda = N/(4L^2)$, where N is the number of nodes, the probability of finding k nodes in an area A in the plane is given by

$$\Pr\{k \in A\} = \frac{e^{-\lambda A} (\lambda A)^k}{k!}. \tag{1}$$

With these assumption we can calculate the mean μ and variance σ^2 of interference I for a random Poisson network with density λ as follows [14]

$$\mu = \frac{2\lambda p \pi d_0^{(2-\alpha)}}{\alpha - 2} \tag{2}$$

$$\sigma^2 = \frac{2\lambda p \pi d_0^{2(1-\alpha)}}{\alpha - 1}, \tag{3}$$

where p is the transmission probability and d_0 the near field cut-off radius. The near field cut-off radius defines the distance in which other nodes in a network cannot transmit. For a large number of interferers, the interference can be modeled as Gaussian distributed due to the Central Limit Theorem, with parameters μ and σ^2 [15]. We call this as intra-network interference within one CR network.

In our case, the problem is that nodes in the other CR network may decide to transmit as well (depending on the sensing results) and thus, create inter-network interference. We can model inter-network interference similarly as before using Equations (2) and (3). The resulting interference $\mathcal{I}$ is Gaussian distributed $\mathcal{N}(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2)$ which gives

$$\mu = \frac{2\lambda_1 p_1 \pi d_{0,1}^{(2-\alpha)}}{\alpha - 2} + \frac{2\lambda_2 p_2 \pi d_{0,2}^{(2-\alpha)}}{\alpha - 2} \tag{4}$$

$$\sigma^2 = \frac{2\lambda_1 p_1 \pi d_{0,1}^{2(1-\alpha)}}{\alpha - 1} + \frac{2\lambda_2 p_2 \pi d_{0,2}^{2(1-\alpha)}}{\alpha - 1}. \tag{5}$$

Furthermore, the received SINR γ is calculated as follows

$$\gamma = \frac{P x^2 R^{-\alpha}}{\mathcal{I} + \sigma_n^2}, \tag{6}$$

where P is the transmission power, R the distance between a transmitter and a receiver and σ_n^2 is the noise power. Then, we can calculate the probabilistic throughput

$$\begin{aligned} \Pr\{\gamma > \theta\} &= \Pr\left\{\frac{x^2 P R^{-\alpha}}{\mathcal{I} + \sigma_n^2} > \theta\right\} \\ &= \Pr\left\{x^2 > \frac{\theta(\mathcal{I} + \sigma_n^2) R^{\alpha}}{P}\right\}, \end{aligned} \tag{7}$$

where θ is the required SINR for successful reception (threshold). By denoting $w = x^2$ this can be deduced to the following form

$$\begin{aligned} \Pr\{\gamma > \theta\} &= E\left\{F_{c,w}\left(\frac{\theta(\mathcal{I} + \sigma_n^2)}{PR^{-\alpha}}\right)\right\} \\ &= E\left\{\exp\left(\frac{-\theta(\mathcal{I} + \sigma_n^2)}{PR^{-\alpha}}\right)\right\}, \end{aligned} \tag{8}$$

where $F_c(.)$ stands for the Complementary Cumulative Distribution Function (CCDF). Moreover, note that w is an exponential random variable and $F_{c,w}(w) = e^{-w}$. The expectation is taken over the Gaussian distribution which gives [15]

$$\begin{aligned} \Pr\{\gamma > \theta\} &= \exp\left(-\frac{\theta(\mu + \sigma_n^2)}{PR^{-\alpha}}\right) \exp\left(\frac{\theta^2 \sigma^2}{2(PR^{-\alpha})^2}\right) \\ &\times Q\left(\frac{\theta \sigma^2}{PR^{-\alpha}} - \frac{\mu}{\sigma}\right). \end{aligned} \tag{9}$$

4.2. Probabilistic Throughput Per-node for Nakagami-m Interference

Both of the CR networks are uniformly random networks where nodes are independently distributed in an area according to a Poisson Point Process (PPP). Node densities of CRN_1 and CRN_2 and are denoted by λ_1 and λ_2, respectively. We consider Rayleigh fading, x_0 with $E\{x_0\} = 1$. The Cartesian coordinates of a node are denoted by X and Y . These random variables are independent of the other nodes' locations and uniformly distributed in $[-L, L]$. By setting the node density $\lambda = N/(4L^2)$, where N is the number of nodes, the probability of finding k nodes in an area A in the plane is given by

$$\Pr\{k \in A\} = \frac{e^{-\lambda A} (\lambda A)^k}{k!}. \tag{10}$$

Furthermore, the received SINR γ is calculated as follows

$$\gamma = \frac{x_0^2 R^{-\alpha} P_0}{\sum x_i^2 r_i{}^{-\alpha} \mathcal{P}_i + \sigma_n^2} \tag{11}$$

where P_0 is the CR node transmission power, R the distance between a CR network transmitter and a receiver and σ_n^2 is the noise power. P_i is the transmission power of the interfering transmission. We use a deterministic distance-dependent path loss $r^{-\alpha}$ as a channel model, where r is the distance between the interfering transmitter and its victim receiver and α is the path loss exponent. x_i, $i = 1, 2, ..., K$ are independent gamma distributed RVs that represent the squared fading gains of the Nakagami-m fading. The Nakagami-m distribution, parameterized by fading severity parameter m, can model different flat fading environment, it reduces to Rayleigh fading model for $m = 1$ and describes less severe fading condition as m increases. γ is a ratio of mixture of large number of RVs, for which closed-form expression for its Complementary Cumulative Distribution Function (CCDF) is generally difficult to obtain, if not impossible. Therefore, we derived a closed form expression $\mathcal{M}(z) = \mathbb{E}[e^{-yz}]$ for the MGF of $\sum x_i^2 r_i{}^{-\alpha} \mathcal{P}_i$ expressed as

$$\mathcal{M}(z) = \mathbb{E}[e^{-z \sum_{i=1}^{K} x_i^2 r_i{}^{-\alpha} \mathcal{P}_i}] \tag{12}$$

Consider the interference generated in an area A around the victim receiver, where K is distributed as a Poisson RV with average $\lambda(L^2 - d_0^2)$. We define d_0 as the near field cut-off radius which defines the distance in which other devices in a network cannot transmit, r_i, $i = 1, 2, ..., K$ are independent and distributed according to the following pdf

$$f(r) = \begin{cases} \frac{2r}{(L^2 - d_0^2)}, & d_0 < r < L \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

x_i, $i = 1, 2, ..., K$ are independent gamma distributed RVs that represent the squared fading gains of the Nakagami-m fading

$$f(x) = \frac{x^{m-1}}{\Gamma(m)} m^m e^{-mx} \tag{14}$$

We seek asymptotic $\mathcal{M}(z)$, therefore, we take the limit of (12) as $L \to \infty$

$$\mathcal{M}(z) = \lim_{L\to\infty} \mathbb{E}[e^{-z \sum_{i=1}^{K} x_i^2 r_i{}^{-\alpha} \mathcal{P}_i}] \tag{15}$$

we conditioned on K in order to compute (15) [16]

$$\begin{aligned} \mathcal{M}(z/K) &= \lim_{L\to\infty} \prod_{i=1}^{K} \mathbb{E}[e^{-z x_i^2 r_i{}^{-\alpha} \mathcal{P}_i}] \\ &= \lim_{L\to\infty} (\mathbb{E}[e^{-z x_1^2 r_1{}^{-\alpha} \mathcal{P}_1}])^K \end{aligned} \tag{16}$$

on averaging out K, we obtain

$$\begin{aligned} \mathcal{M}(z) &= \lim_{L\to\infty} \sum_{\kappa=0}^{\infty} \frac{e^{-\lambda(L^2-d_0^2)} (\lambda(L^2 - d_0^2))^{\kappa}}{\kappa!} \\ &\times (\mathbb{E}[e^{-z x_1^2 r_1{}^{-\alpha} \mathcal{P}_1}])^{\kappa} \end{aligned} \tag{17}$$

Further simplification gives

$$\mathcal{M}(z) = \lim_{L\to\infty} e^{-\lambda(L^2-d_0^2)(1-(\mathbb{E}[e^{-z x_1^2 r_1{}^{-\alpha} \mathcal{P}_1}]))} \tag{18}$$

The exponent of (18) can be evaluated in the limit as $L \to \infty$

$$\lim_{L\to\infty} \lambda(L^2 - d_0^2)(1 - (\mathbb{E}[e^{-z x_1^2 r_1{}^{-\alpha} \mathcal{P}_1}]))$$

$$\begin{aligned} &= \lambda \int_{d_0}^{\infty} [1 - e^{-z x_1^2 r_1{}^{-\alpha} \mathcal{P}_1}] 2 r_1 d r_1 \\ &= \lambda[-d_0^2 + d_0^2 e^{-z x_1^2 \mathcal{P}_1 d_0^{-\alpha}} - (z\mathcal{P}_1)^{\frac{2}{\alpha}} \Gamma(1 - \frac{2}{\alpha}, z x_1^2 \mathcal{P}_1 d_0^{-\alpha})(x_1^{\frac{4}{\alpha}})] \end{aligned} \tag{19}$$

From (19), and using eq.(3.381.9) of [17], viz.

$$\mathbb{E}[x_1^{\frac{2}{\alpha}}] = \int_{d_0}^{\infty} x^{\frac{2}{\alpha}} \frac{x^{m_1-1}}{\Gamma(m_1)} m_1^{m_1} e^{-m_1 x} dx = \frac{\Gamma(m + \frac{2}{\alpha}, m d_0)}{m^{\frac{2}{\alpha}} \Gamma(m)} \tag{20}$$

$$\mathbb{E}[x_1^{\frac{4}{\alpha}}] = \int_{d_0}^{\infty} x^{\frac{4}{\alpha}} \frac{x^{m_1-1}}{\Gamma(m_1)} m_1^{m_1} e^{-m_1 x} dx = \frac{\Gamma(m + \frac{4}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \tag{21}$$

We arrive at the following closed form expression for $\mathcal{M}(z)$

$$\begin{aligned} \mathcal{M}(z) &= \exp -\left\{ \lambda \left(-d_0^2 + d_0^2 e^{-z P_1 d_0^{-\alpha} \left(\frac{\Gamma(m+\frac{2}{\alpha}, m d_0)}{m \Gamma(m)} \right)} \right. \right. \\ &- (z P_1)^{\frac{2}{\alpha}} \Gamma \left(1 - \frac{2}{\alpha}, z P_1 d_0^{-\alpha} \left(\frac{\Gamma(m + \frac{2}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \right) \right) \\ &\times \left. \left. \left(\frac{\Gamma(m + \frac{4}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \right) \right) \right\} \end{aligned} \tag{22}$$

From (11), we can calculate the probabilistic throughput

$$\begin{aligned} \Pr\{\gamma > \theta\} &= \Pr\left\{ \frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i r_i{}^{-\alpha} \mathcal{P}_i + \sigma_n^2} > \theta \right\} \\ &= \Pr\left\{ x_0^2 > \frac{\theta(\sum x_i^2 r_i{}^{-\alpha} \mathcal{P}_i + \sigma_n^2)}{P_0 R^{-\alpha}} \right\} \end{aligned} \tag{23}$$

where θ is the required SINR for successful reception (threshold). By denoting $w = x^2$ and $y = \sum x_i^2 r_i{}^{-\alpha} \mathcal{P}_i$ this can be deduced to the following form

$$\begin{aligned} \Pr\{\gamma > \theta\} &= E\left\{ F_{c,w} \left(\frac{\theta(y + \sigma_n^2)}{P_0 R^{-\alpha}} \right) \right\} \\ &= E\left\{ \exp\left(\frac{-\theta(y + \sigma_n^2)}{P_0 R^{-\alpha}} \right) \right\} \end{aligned} \tag{24}$$

where $F_c(.)$ stands for the CCDF. Moreover, note that w is an exponential random variable and $F_{c,w}(w) = e^{-w}$. The expectation is taken over the Gamma distribution which gives

$$\Pr\{\gamma > \theta\} = \exp\left(\frac{\theta \sigma_n^2}{P_0 R^{-\alpha}} \right) \left(\mathcal{M}_y \left(\frac{\theta}{P_0 R^{-\alpha}} \right) \right) \tag{25}$$

5. Result for Equal Access CR Networks

This section gives the results on probabilistic throughput for coexisting CR networks with equal access. In CR networks, the received interference depends on the sensing results. Furthermore, in case of overlapping CR networks the operations of the other CR networks also affect the performance. Consequently, we have multiple scenarios listed in Table 1 depending on the PU's activities and spectrum sensing results of the CR networks. For instance, if the PU is idle (H_0), and only CRN_2 has a false alarm, then CRN_1 will be able to use that channel for transmission alone. We denote the probability of false alarm and probability of detection as $P_{f,i}$ and $P_{d,i}$ for CRN_i, the probability of this scenario is $(1 - P_{f,1})P_{f,2}P(H_0)$. Other cases are determined using similar reasoning. The probability of miss for CRN_i is defined as $P_{m,i} = 1 - P_{d,i}$.

Table 1. Possible transmission scenarios

Scenarios	H_0	H_1
Idle	$P_{f,1}P_{f,2}$	$P_{d,1}P_{d,2}$
CRN_1	$(1 - P_{f,1})P_{f,2}$	$P_{m,1}P_{d,2}$
CRN_2	$(1 - P_{f,2})P_{f,1}$	$P_{m,2}P_{d,1}$
CRN_1 & CRN_2	$(1 - P_{f,1})(1 - P_{f,2})$	$P_{m,1}P_{m,2}$

By using the scenarios defined in Table 1 we can derive the following equation for successful packet reception for a node in CRN_1 for both Gaussian and Nakagami-m interference in Equations (26) and (27), respectively.

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,1})P_{f,2}P(H_0)\Pr\left\{\frac{x^2 P_1 R^{-\alpha}}{\mathcal{I}_1 + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}P_{d,2}P(H_1)\Pr\left\{\frac{x^2 P_1 R^{-\alpha}}{\mathcal{I}_1 + \mathcal{I}_{PU} + \sigma_n^2} > \theta\right\} \\
&+ (1 - P_{f,1})(1 - P_{f,2})P(H_0)\Pr\left\{\frac{x^2 P_1 R^{-\alpha}}{\mathcal{I}_1 + \mathcal{I}_2 + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}P_{m,2}P(H_1)\Pr\left\{\frac{x^2 P_1 R^{-\alpha}}{\mathcal{I}_1 + \mathcal{I}_2 + \mathcal{I}_{PU} + \sigma_n^2} > \theta\right\}, \quad (26)
\end{aligned}$$

where $\mathcal{I}_1$, $\mathcal{I}_2$, and $\mathcal{I}_{PU}$ denote the received intra-network, inter-network, and PU's interference, respectively.

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,1})P_{f,2}P(H_0)\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 r_{i1}{}^{-\alpha}\mathcal{P}_{i1} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}P_{d,2}P(H_1)\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 r_{i1}{}^{-\alpha}\mathcal{P}_{i1} + \mathcal{P}_{PU} + \sigma_n^2} > \theta\right\} \\
&+ (1 - P_{f,1})(1 - P_{f,2})P(H_0) \\
&\times \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 r_{i1}{}^{-\alpha}\mathcal{P}_{i1} + \sum x_{i2}^2 r_{i2}{}^{-\alpha}\mathcal{P}_{i2} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}P_{m,2}P(H_1) \\
&\times \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 r_{i1}{}^{-\alpha}\mathcal{P}_{i1} + \sum x_{i2}^2 r_{i2}{}^{-\alpha}\mathcal{P}_{i2} + \mathcal{P}_{PU} + \sigma_n^2} > \theta\right\} \quad (27)
\end{aligned}$$

where $\sum x_{i1}^2 r_{i1}{}^{-\alpha}\mathcal{P}_{i1}$, $\sum x_{i2}^2 r_{i2}{}^{-\alpha}\mathcal{P}_{i2}$ and $\mathcal{P}_{PU}$ denotes the sum of received intra-network, inter-network, and PU's interference respectively.

6. Result for Prioritized Access CR Networks

In this section, we derive the probabilistic throughput for coexisting CR networks with different priority. In a Prioritized access setup, one of the two CR networks has higher priority to access free spectrum and we denote this as Cognitive Gateway Network (CGN) and the one with lower priority we denote as CRN. Consequently, we have multiple transmission scenarios listed in Table 2 for CRN and Table 3 for CGN. In prioritized access, CGN can access the medium first if the channel is sensed as idle. CRN is slightly delayed to find out whether CGN started a transmission or not. After that, CRN can transmit if possible.

Table 2. Possible Transmission Probability for CRN under prioritized access

Scenarios	PU idle (H_0^{PU})	PU active (H_1^{PU})
CGN idle (H_0^{CG})	$(1 - P_{f,2}^{PU})(1 - P_{f,2}^{CG})$	$P_{m,2}^{PU}(1 - P_{f,2}^{CG})$
CGN active (H_1^{CG})	$(1 - P_{f,2}^{PU})P_{m,2}^{CG}$	$P_{m,2}^{PU}P_{m,2}^{CG}$

Table 3. Possible Transmission Probability for CGN under prioritized access

Scenarios	PU idle (H_0^{PU})	PU active (H_1^{PU})
	$(1 - P_{f,2}^{PU})(1 - P_{f,2}^{CG})$	$P_{m,2}^{PU}(1 - P_{f,2}^{CG})$

We denote the miss rate and false alarm probabilities of CGN at CRN by $P_{m,2}^{CG}$ and $P_{f,2}^{CG}$, and those of PU at CRN by $P_{m,2}^{PU}$ and $P_{f,2}^{PU}$, respectively. Similarly, the miss and false alarm probabilities of PU at CGN are denoted by $P_{m,1}^{PU}$ and $P_{f,1}^{PU}$. For successful packet reception of a node in CRN under Gaussian interference, we derived the following equation

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,1}^{PU})(1 - P_{f,2}^{CG})P(H_0^{PU})P(H_0^{CG}) \\
&\times \Pr\left\{\frac{x^2 P_{CRN} R^{-\alpha}}{\mathcal{I}_{CRN} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,2}^{PU}(1 - P_{f,2}^{CG})P(H_1^{PU})P(H_0^{CG}) \\
&\times \Pr\left\{\frac{x^2 P_{CRN} R^{-\alpha}}{\mathcal{I}_{CRN} + \mathcal{I}_{PU} + \sigma_n^2} > \theta\right\} \\
&+ (1 - P_{f,2}^{PU})P_{m,2}^{CG}P(H_0^{PU})P(H_1^{CG}) \\
&\times \Pr\left\{\frac{x^2 P_{CRN} R^{-\alpha}}{\mathcal{I}_{CRN} + \mathcal{I}_{CGN} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,2}^{PU}P_{m,2}^{CG}P(H_1^{PU})P(H_1^{CG}) \\
&\times \Pr\left\{\frac{x^2 P_{CRN} R^{-\alpha}}{\mathcal{I}_{CRN} + \mathcal{I}_{CGN} + \mathcal{I}_{PU} + \sigma_n^2} > \theta\right\}
\end{aligned} \tag{28}$$

for CGN, we have

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,1}^{PU})P(H_0^{PU})\Pr\left\{\frac{x^2 P_{CGN'} R^{-\alpha}}{\mathcal{I}_{CGN} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}^{PU}P(H_1^{PU})\Pr\left\{\frac{x^2 P_{CRN} R^{-\alpha}}{\mathcal{I}_{CGN} + \mathcal{I}_{PU} + \sigma_n^2} > \theta\right\}
\end{aligned} \tag{29}$$

Successful packet reception for the case of Nakagami-m for CRN gives

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,2}^{PU})(1 - P_{f,2}^{CG})P(H_0^{PU})P(H_0^{CG}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCR}^2 r_{iCR}^{-\alpha}\mathcal{P}_{iCR} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,2}^{PU}(1 - P_{f,2}^{CG})P(H_1^{PU})P(H_0^{CG}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCR}^2 r_{iCR}^{-\alpha}\mathcal{P}_{iCR} + \mathcal{P}_{PU} + \sigma_n^2} > \theta\right\} \\
&+ (1 - P_{f,2}^{PU})P_{m,2}^{CG}P(H_0^{PU})P(H_1^{CG}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCR}^2 r_{iCR}^{-\alpha}\mathcal{P}_{iCR} + \sum x_{iCG}^2 r_{iCG}^{-\alpha}\mathcal{P}_{iCG} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,2}^{PU}P_{m,2}^{CG}P(H_1^{PU})P(H_1^{CG}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCR}^2 r_{iCR}^{-\alpha}\mathcal{P}_{iCR} + \sum x_{iCG}^2 r_{iCG}^{-\alpha}\mathcal{P}_{iCG} + \mathcal{P}_{PU} + \sigma_n^2} > \theta\right\}
\end{aligned} \tag{30}$$

for CGN, we have

$$\begin{aligned}
\Pr\{\gamma > \theta\} &= (1 - P_{f,1}^{PU})P(H_0^{PU}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCR}^2 r_{iCR}^{-\alpha}\mathcal{P}_{iCR} + \sigma_n^2} > \theta\right\} \\
&+ P_{m,1}^{PU}P(H_1^{PU}) \\
&\times \Pr\left\{\frac{x_0^2 \mathcal{P}_0 R^{-\alpha}}{\sum x_{iCG}^2 r_{iCG}^{-\alpha}\mathcal{P}_{iCG} + \mathcal{P}_{PU} + \sigma_n^2} > \theta\right\}
\end{aligned} \tag{31}$$

The results from Section 5 and Section 6 are summarized in Table 4

Table 4. Summary of Results

	Equal Access	Prioritized Access
Gaussian	(26)	(28) (29)
Nakagami-m	(27)	(30) (31)

7. Performance Bound on Spectrum Sensing of CRN

In this section, the performance bounds on spectrum sensing and transmission probability are derived in order to satisfy certain quality-of-service requirements for coexisting CR networks. By formulating each term of Equation (26), (28) and (29) in the same way as in Equation (8) and solving that we can find an exact value for $\Pr\{\gamma > \theta\}$, similar to Equation (9) for the Gaussian interference. Similarly, formulating each term of Equation (27), (30) and (31) in the same way as in Equation (24) and solving that we can find an exact value for $\Pr\{\gamma > \theta\}$, similar to Equation (25) for the Nakagami-m interference. The main problem is that the performance of CRN_1 will be determined by the operations of CRN_2 and vice versa. By using these formulas we will analyze the throughput of overlapping CR networks to see what are the suitable bounds to guarantee reasonable performance.

We define the per-node throughput J such that the transmitter has a packet to transmit while a receiver is idle, i.e., the receiver does not have a packet to transmit. Moreover, the received SINR has to be larger than the threshold for successful packet reception. This can be mathematically formulated as follows

$$J = p(1-p)\Pr\{\gamma > \theta\}. \tag{32}$$

In practice CR users should achieve reasonable throughput to enable feasibility from the economic perspective. We denote this throughput threshold by

$\hat{J}$. Next, we derive the bound of the probability of false alarm that is required to achieve the desired throughput, $J \geq \hat{J}$. By analyzing Equation (26)-(31) also summarized in Table 4, we have concluded that in practice the second and the fourth term in Equation (26), (27), (28) and (30) and the second term in Equation (29) and (31) have negligible influence on the performance of CR users, since both the miss rate and the probability of the PU being active are small. In addition, it is not practical to design CR networks by assuming that their transmissions would overlap with the transmissions of the PU's.

As an example, let us consider Equation (27), an equal access with Nakagami-m interference, using the following approximation

$$\begin{aligned} &J \geq \hat{J} \Rightarrow \\ &\hat{J} \leq p(1-p)(1-P_{f,1})P_{f,2}P(H_0)\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 {r_{i1}}^{-\alpha}\mathcal{P}_{i1} + \sigma_n^2} > \theta\right\} \\ &+ p(1-p)(1-P_{f,1})(1-P_{f,2})P(H_0) \\ &\times \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 {r_{i1}}^{-\alpha}\mathcal{P}_{i1} + \sum x_{i2}^2 {r_{i2}}^{-\alpha}\mathcal{P}_{i2} + \sigma_n^2} > \theta\right\} \end{aligned} \tag{33}$$

The above inequality shows the maximum achievable throughput for a node in CRN_1 given the PU's activity and the spectrum sensing performance of the two CR networks. Moreover, let us define

$$\xi_1 = P(H_0)\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 {r_{i1}}^{-\alpha}\mathcal{P}_{i1} + \sigma_n^2} > \theta\right\} \tag{34}$$

$$\xi_2 = P(H_0)\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_{i1}^2 {r_{i1}}^{-\alpha}\mathcal{P}_{i1} + \sum x_{i2} {r_{i2}}^{-\alpha}\mathcal{P}_{i2} + \sigma_n^2} > \theta\right\} \tag{35}$$

and assume that both CR networks have the same spectrum sensing performance, i.e., $P_{f,1} = P_{f,2} = P_f$. Then,

$$\hat{J} \leq p(1-p)(1-P_f)[P_f\xi_1 + (1-P_f)\xi_2] \tag{36}$$

It is observed that when the false alarm probability P_f is very small, the achievable throughput approaches $p(1-p)\xi_2$. It can be shown that as long as $\frac{\xi_1}{\xi_2} \leq \frac{2-P_f}{1-P_f}$, the achievable throughput will decrease when P_f increases.

If the spectrum sensing performance of CRN_2 is given a priori, then we can find out the maximum probability of false alarm of CRN_1 for achieving a certain throughput $\hat{J}$.

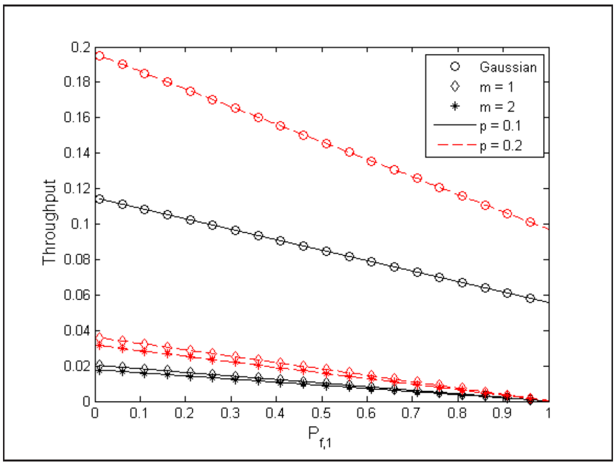


Figure 3. Per-node throughput in two coexisting CR networks with equal access. The throughput is a function of false alarm probability, the effect of Gaussian or Nakagami-m interference and transmission probability (p) on throughput of CRN_1

$$P_{f,1} \leq 1 - \frac{\hat{J}}{(P_{f,2}\xi_1 + (1-P_{f,2})\xi_2)p(1-p)} \tag{37}$$

In other words, Equation (37) defines the upper bound for the probability of false alarm of CRN_1.

Following similar derivation as Equation (37), upper bound for the probability of false alarm can be derived for Equation (26), (28) and (30). For prioritized access we further derived from Equation (29) the upper bound for the probability of false alarm for CGN under Gaussian interference below

$$\begin{aligned} &J \geq \hat{J} \Rightarrow \\ &\hat{J} \leq p(1-p)(1-P_{f,1}^{PU})P(H_0^{PU})\Pr\left\{\frac{x^2 P_{CGN'} R^{-\alpha}}{\mathcal{I}_{CGN} + \sigma_n^2} > \theta\right\} \end{aligned} \tag{38}$$

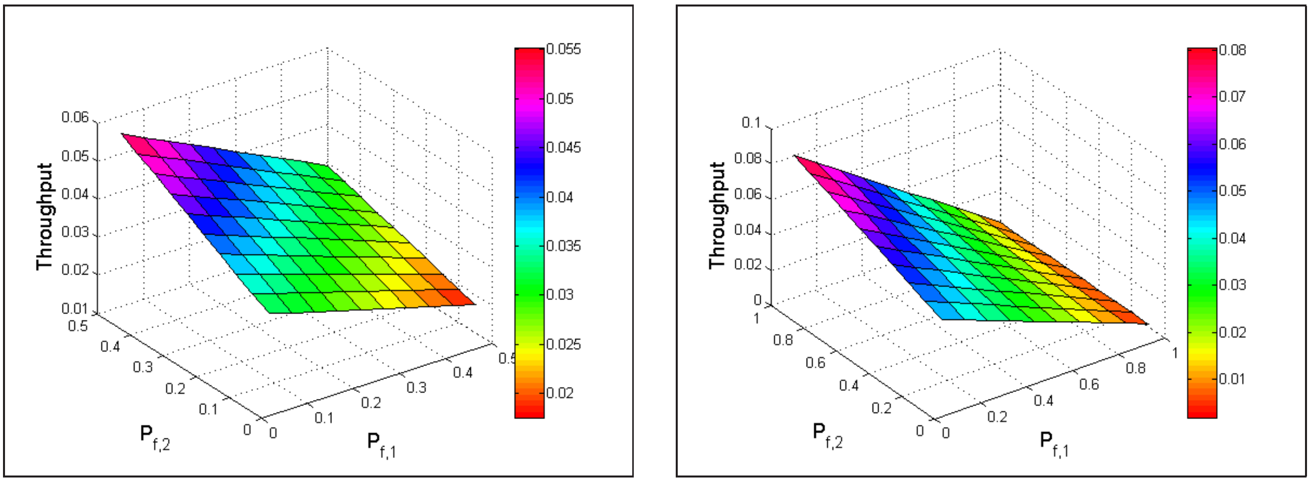
The above inequality is the maximum achievable throughput for a node in CGN, the upper bound for the probability of false alarm of CGN is given by

$$P_{f,1} \leq 1 - \frac{\hat{J}}{P(H_0^{PU})\Pr\left\{\frac{x^2 P_{CGN'} R^{-\alpha}}{\mathcal{I}_{CGN}+\sigma_n^2} > \theta\right\} p(1-p)} \tag{39}$$

Similar derivation is possible from Equation (31) for CGN under Nakagami-m interference.

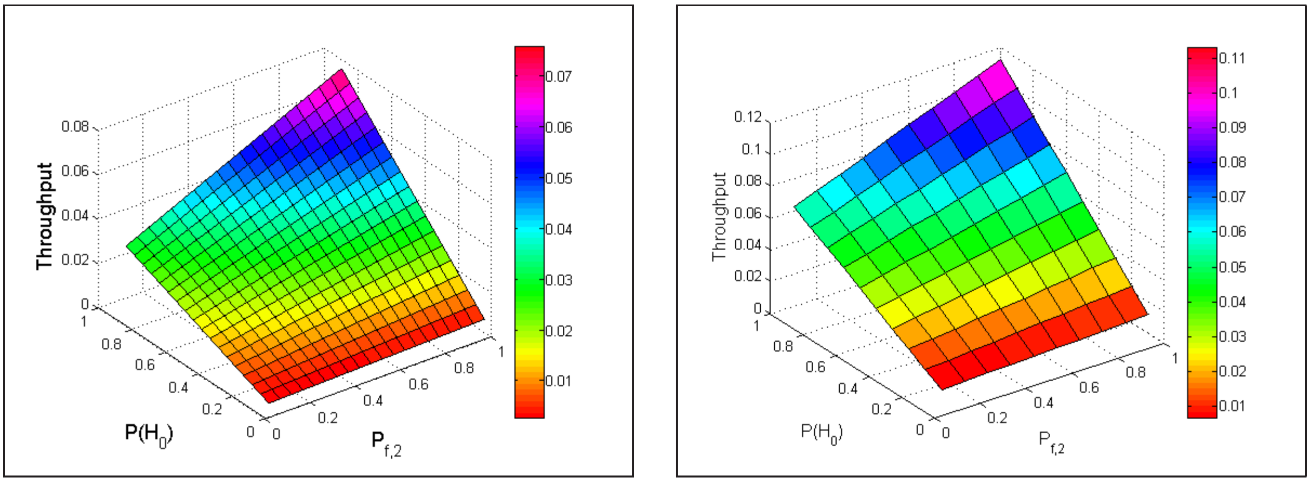
8. Simulation Results

The performance of overlapping CR networks is studied by investigating the effects of different parameters on the throughput of CRN_1. Unless otherwise stated, the following practical values for network parameters



(a) (b)

Figure 4. Effect of false alarm probabilities on the throughput of CRN_1 for coexisting CR networks with equal access (a) Gaussian interference (b) Nakagami-m interference



(a) (b)

Figure 5. Combined effect of primary user's activity and false alarm probability of CRN_2 on the performance of CRN_1 for coexisting CR networks with equal access (a) Gaussian interference (b) Nakagami-m interference

were used: $d_0 = 100m$, $R = 50$, $P = 30dBm$, $P_{PU} = 80dBm$, $\sigma_n = -70dBm$, $\theta = 10dB$, $L = 500m$, $\alpha = 4$, $p_1 = p_2 = 0.5$, and $N_1 = N_2 = 100$. Moreover, the used CR parameters are: $P_{f,1} = P_{f,2} = 0.1$, and $P(H_0) = 0.9$. For each result figure, we varied different parameters to demonstrate their impact.

8.1. Effect of Gaussian and Nakagami-m fading on Performance

We can determine the maximum value for the probability of false alarm that is required to achieve a certain throughput by exploiting Equation (37), this is shown in Figure 3. In Figure 3, we set $d_0 = 3m$, $R = 1m$, $P = 10nW$, $P_{PU} = 10\mu W$, $\sigma_n = 5fW$, and $L = 20m$, it shows the effect of Gaussian, Nakagami parameter m and transmission probability p on the throughput of a node in CRN_1, the figure shows a higher throughput for the Gaussian interference because it does not consider details of the fading conditions as seen in Nakagami-m results, the results further shows that throughput reduces for higher m, but throughput increases as p increases until an optimal p is reached when further increase in p leads to decrease in throughput.

8.2. Effect of Sensing Performance on Throughput Under Equal Access

In this section, the effect of sensing performance on the throughput in case of overlapping CR networks is investigated, this is investigated for coexisting CR networks under equal access. Figure 4 shows the effect of sensing performance on the throughput, the figure captures the fundamental nature of overlapping CR networks. As expected, the sensing performance of both networks has an effect and it seems that both networks have equal and linear influence on the throughput of CRN_1 . These results imply that CR users would like to have as low probability of false alarm as possible to achieve the best performance. Whereas, the false alarm probability of the interfering CR network should be high such that the CR network in question would be able to access and use the spectrum alone as often as possible. The activity of the interfering CR network has a significant impact on the performance in case of overlapping CR networks.

In case of secondary spectrum usage, the activity of the PU determines the amount of transmission opportunities for CR users. Even though there would be large portions of available spectrum in time, high false alarm probabilities of CR users will restrict the achievable throughput. This is shown in Figure 5 where the throughput of CRN_1 is plotted as a function of $P(H_0)$ and $P_{f,2}$. If the PU is active for the most of the time, high probabilities of false alarm have only a minor effect on the throughput. Nevertheless, if the PU is inactive often, the probability of false alarm affects the performance significantly. In any case it is beneficial for CRN_1 to have as high $P(H_0)$ and $P_{f,2}$ as possible for throughput maximization.

8.3. Effect of Sensing Performance on Throughput Under Prioritize Access

In this part of the simulations, the performance of a CR node in a CR network having low priority to spectrum access is examined. Figure 6 and Figure 7 show the effect of sensing performance (false alarm and miss rate probabilities) on throughput in case of overlapping CR networks under prioritize secondary access. These figures capture the fundamental nature of overlapping CR networks. As false alarm probability of CR network increase, the throughput decreases. Miss rate probability has the opposite effect on the throughput. These results imply that CR users would like to have as low probability of false alarm as possible when detecting both PU and CGN, while keeping the required miss rate probability (due to regulations) to achieve the best performance.

Also, the combined effect of primary user's activity ($P(H_0^{PU})$) and false alarm probability of $CRN(P_{f,2}^{PU})$ and $CGN(P_{f,1}^{PU})$ at PU are shown in Figure 8 and Figure 9. In Figure 8, highest CRN throughput is achieved at highest $P(H_0^{PU})$ and lowest $P_{f,2}^{PU}$, while in Figure 9, the highest throughput is achieved at highest $P(H_0^{PU})$ with no visible effect of $P_{f,1}^{PU}$ on throughput.

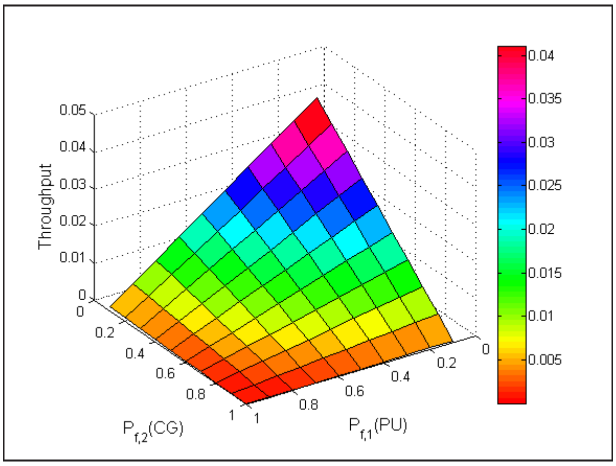


Figure 6. Effect of false alarm probability of CG and PU on the Throughput of CRN

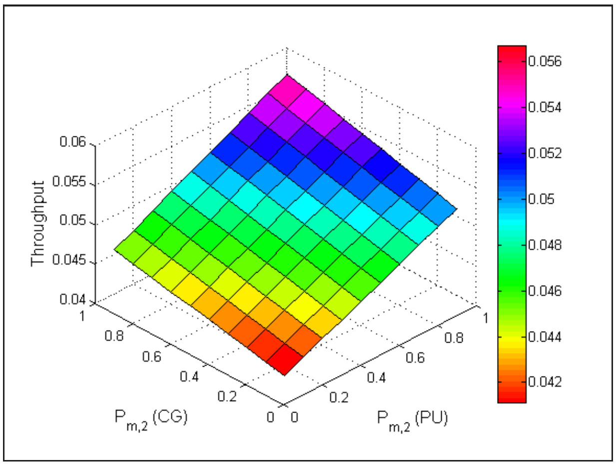


Figure 7. Effect of miss rate probability of CG and PU on the Throughput of CRN

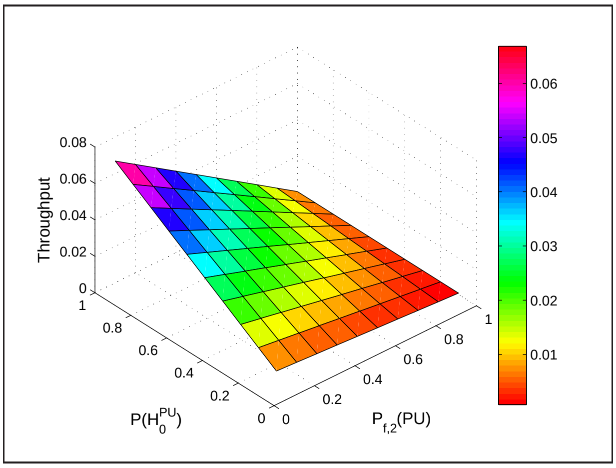


Figure 8. Combined effect of PU's activity and false alarm probability of CRN at PU on the Throughput of CRN

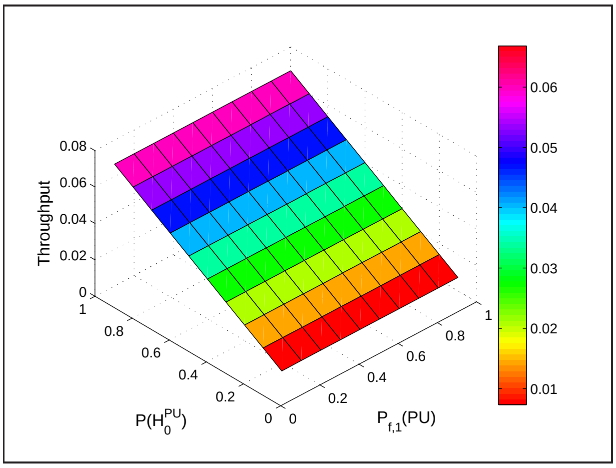


Figure 9. Combined effect of PU's activity and false alarm probability of CGN at PU on the Throughput of CRN

9. Discussions and Open Problems

The coexistence of wireless networks is unavoidable due to the current dilemma of spectrum scarcity. Advances in wireless communications and the introduction of concepts like cognitive radio and cognitive wireless networks, has turned the spectrum sharing among multiple systems from an idea into a possibility.

Our results are fundamental such that they can be applied to other types of wireless ad hoc networks. As an example, this framework finds application in Device-to-Device (D2D) communication [18]. The performance of ad hoc cognitive D2D systems sharing spectrum with cellular users in a macrocell can be investigated, the device throughput for multiple D2D systems in a cellular system can also be derived.

There also exist many challenges in the coexistence of multiple CR networks, these include spectrum availability detection, spectrum sharing, and interference mitigation [19]. Spectrum availability detection ensures identification of channels available for use without causing harmful interference to incumbents, achieved with high sensing performance. In addition, detection of coexisting secondary networks is also important, primarily to enable optimized decisions when selecting operating channels, this with spectrum sharing and interference mitigation ensure improve achievable throughput in CR network.

It will be more interesting to considered multiple CR ad hoc network from the network information theory point-of-view and derive the scaling law for this type of networks. The throughput scaling law for large-scale wireless networks initiated in [20], has been extensively studied [21] - [24]. They studied the random wireless network with 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 achievable per-node throughput in a network was derived. In [25] and [26], the throughput scaling law was considered for a multihop CR network on top of a primary network, they showed that the two network can achieve the same throughput scaling law as a standalone wireless network, with finite outage probability for the secondary users in [25] and zero outage for the secondary users with high probability in [26]. It will be meaningful to compare the per-node throughput using the scaling laws for coexisting multiple CR networks, as this will afford the opportunity to investigate the achievable throughput scaling law promised in [20] for a node in a CR network even when the density is high.

10. Conclusions

In this study, the performance of overlapping CR networks which coexist together with a PU was investigated. We evaluated the performance of CR network over Gaussian and Nakagami-m fading channel by investigating the achievable per-node throughput. Specifically, we consider two cases: (1) equal access case where two CR networks have equal access to the spectrum; and (2) prioritized access case where one cognitive radio network, the cognitive gateway network (CGN), has higher priority to access the spectrum than the other cognitive radio network (CRN). Close form expressions for statistics, the Moment Generating Function (MGF) and Complementary Cumulative Distribution Function (CCDF) of multiple interferers in multiple coexisting CR networks are presented. By using these expressions, we derive the per-node throughput for multiple CR networks. Furthermore, the upper bound for the probability of false alarm during spectrum sensing that is required to achieve a certain throughput is deduced. The results illustrate how the transmission probability and spectrum sensing performance affect the achievable per-node throughput of overlapping CR networks. In addition, these results may serve as guidance for the deployment of multiple CR networks.

11. ACKNOWLEDGMENT

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