# Capacity Analysis of Centralized Cognitive Radio Networks for Best-effort Traffics

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*Received June 20, 2013; revised August 20, 2013; accepted September 9, 2013; published September 30, 2013*

## Abstract

A centralized cognitive radio (CR) network is proposed and its system capacity is studied. The CR network is designed with power control and multi-user scheduling schemes to support best-effort traffics under peak interference power constraints. We provide an analytical framework to quantify its system capacity, taking into account various key factors such as interference constraints, density of primary users, cell radius, the number of CR users, and propagations effects. Furthermore, closed-form formulas are derived for its capacities when only path loss is considered in the channel model. Semi-analytical expressions for the capacities are also given when more realistic channel models that include path loss, shadowing, and small-scale fading are used. The accuracy of the proposed analytical framework is validated by Monte Carlo simulations. Illustrated with a practical example, the provided analytical framework is shown to be useful for the strategic planning of centralized CR networks.

***Keywords:*** Cognitive radio network, interference constraint, capacity, best-fffort traffic

Submitted to KSII Transactions on Internet and Information Systems. This paper was presented in part at the IEEE International Conference on Communications, Circuits and Systems, Xiamen, China, May 2008. The authors acknowledge the support from the Natural Science Foundation of China (NSFC) (Grant No. 61201195), Natural Science Foundation of Fujian (2012J01292), and Research Fund for the Doctoral Program of Higher Education of China (20110121120019).

**http://dx.doi.org/10.3837/tiis.2013.09.005**

## 1. Introduction

The current rigid and static spectrum licensing policy has resulted in very inefficient utilization of the radio spectrum [1][2], which is a precious natural resource shared by various wireless services. Cognitive radio (CR) [3]-[5] has been proposed as a new spectrum management paradigm to improve the spectrum utilization by allowing new wireless systems, operating as secondary networks, to access the licensed spectrum of primary networks (i.e., incumbents) without harming their services. It is envisioned that by collectively sensing the radio environment and adaptively adjusting its radio parameters, a CR network can effectively protect primary services while achieving its own communication goals.

CR networks can be broadly categorized into two types: interweave CR and overlay CR systems. The former exploits the existence of spectrum holes [4], which refer to the frequency segments that are unused or partly utilized at a given location and/or a given time. An interweave CR network dynamically discovers the spectrum holes via sensing and adaptively tunes its radio transceivers to the most suitable "free" channels to communicate. Essentially, it manages interference by seeking to operate in the orthogonal space of primary signals. Overlay CR networks, on the other hand, take a more fundamental view in coexistence by recognizing interference as a receiver-side phenomenon. It exploits the fact that primary receivers can usually tolerate certain amount of interference, especially when strong primary signals are available. Therefore, secondary transmissions can be permitted in the same channel of primary users as long as the actual interference perceived at the primary receivers is controlled to fulfill certain protective constraints. Despite facing greater technical and regulatory challenges, overlay CR networks can achieve better spectrum utilization since they promise the "true" coexistence, i.e., secondary networks can overlap with primary networks in the same time, frequency, and space. In this paper, we restrict our study to the overlay CR networks.

Interference constraints are required in overlay CR networks to protect primary receivers from harmful interference. There are three types of interference constraints. 1) The average interference power constraint (e.g., [6]-[8]) puts limits on the average power of the interfering signal. It is appropriate when the quality-of-service (QoS) of the primary network is determined by the average signal-to-noise-and-interference ratio (SINR), e.g., delay-insensitive communication services. 2) The interference outage constraint (e.g., [9]) limits the probability that the interference signal power exceeds a certain threshold. This constraint is more appropriate when the QoS of the primary system depends on the instantaneous SINR, e.g., delay sensitive communication services. The above two constraints may not require a real-time primary receiver feedback. 3) The peak interference power constraint (e.g., [6][7]) bounds the peak power of the interference perceived by primary receivers. It can be used to impose a strict protection on mission-critical primary services such as radiolocation or military/government communications. To implement this constraint in practice, certain feedback mechanisms are required to inform CR transmitters periodically about the instantaneous interference power at the primary receivers. For instance, primary receivers can either report the measured interference levels via a dedicated common control channel [10] or transmit pilot/beacon signals [11], which can be sensed by CR transmitters to estimate the channel gain.

Capacity studies are important to understand the fundamental limits and long-term potential of overlay CR networks. CR capacity studies can be roughly classified into link and system level approaches. Typically, the link level study is information-theoretic oriented and concerns the maximum error-free transmission rate of a single transmit-receive pair. The capacity of Gaussian CR channels were studied in [6] and [12]-[15]. Extensions of the above results to fading channels and multiple-input multiple-output (MIMO) channels under different received-interference constraints were presented in [7], [16]-[19] and [20][21], respectively. The issue of imperfect channel knowledge was recently studied in [22].

Unlike link level studies, system level capacity study is network-engineering oriented and focuses on the performance of large scale networks where multiple users share the given resources. It extends the link level capacity results to the multi-user regime by considering various system level factors such as multiple access, user distribution/density, and realistic propagation effects. The purpose is to predict the system performance and provide guidelines to the strategic planning of large-scale networks. At the system level, CR networks can be either ad-hoc networks or centralized networks. For ad-hoc networks, the commonly used capacity metrics are the transport capacity [23] and transmission capacity [24]. The capacity of ad-hoc CR networks were investigated in [25]-[29]. For centralized CR networks, the most popular capacity measure is sum/aggregate capacity at a centralized base station (BS) or access point [30].

Due to its theoretical importance, the capacity of overlay CR networks has been extensively investigated in the literature. One branch of literature, e.g., [31]-[33], focus on optimal power and bandwidth allocation to maximize the system capacity. These studies, however, use the averaged sum capacity (i.e., Ergodic capacity) as an optimization objective and do not aim to characterize the exact distribution of the random capacity. Moreover, these works typically use highly idealized i.i.d. Rayleigh fading channels and do not take into account the spatial distribution of multiple primary users and channel path loss. Another branch of literature focus on the system capacity directly. These studies can be classified according to different types of interference constraints, including average interference power constraints [8][34][35], interference outage constraints [36]-[39], and peak interference power constraints [40]-[43]. Among those works that considered peak interference power constraints, [40]-[42] are link-level analysis that do not consider multiple CR users and their spatial distributions. Although a system-level capacity analysis was initially presented in [43], the study focused on the average system capacity and failed to give a closed-form formula to characterize the exact distribution of the random system capacity.

In this paper, we focus on the system level capacity of a centralized CR network. To our best knowledge, this is the first work that attempts to derive the exact capacity distribution in the case of multiple primary users and peak interference power constraints. The particular challenge of capacity analysis in this scenario is twofold: (1) In overlay CR network, the capacity of a CR user not only depends on the channel from the CR user to CR BS, but also the channel from the CR to the most susceptible primary receiver (due to peak interference constraint and power control). (2) For system level analysis, two sources of randomness should be jointly considered in the channel: one is small-scale channel fading, the other is the random location of primary and CR users. As mentioned in the above literature overview, consider fading alone for link level analysis of a CR network is already a challenging task [40]-[42], combining both source of randomness to yield a tractable result is even more challenging and remains a research gap. Specifically, our contributions are summarized as follows.

- First, we propose a centralized CR network that uses power control to support best-effort traffic under peak interference power constraints. We provide a framework to characterize the random capacity of the proposed CR network. Our framework is not only more general than that in [43], but also gives a closed-form cumulative distribution function (CDF) of the capacity for non-fading channels. In addition, the effectiveness of using multi-user scheduling for capacity enhancement is studied.

- Second, for the above CR network we proposed, we provide a theoretical framework to facilitate systematic investigation on the impacts of channel fading, primary user density, and CR cell size on the system capacity. The accuracy of the theoretical framework is validated by Monte Carlo simulations. We further use an example to demonstrate the useful application of our theoretical framework for the strategic planning of centralized CR networks. Important guidelines for deploying the proposed networks in a practical band are provided.

The remainder of this paper is organized as follows. The coexistence scenario and channel models are described in Section 2. Section 3 studies the system capacities of the CR network designed to support best-effort traffic in non-fading channels and fading channels, respectively. Numerical results, simulation results, and discussions are presented in Section 4. Finally, conclusions are drawn in Section 5.

## 2. Coexistence Scenario and Channel Models

The coexistence scenario we considered is shown in **Fig. 1** where primary users (illustrated as disk antennas) and CR users (illustrated as mobile phones) coexist on a plane. The primary users are randomly distributed on the plane and their locations follow a Poisson point process [44] with a density parameter $\lambda_p$, which denotes the average number of primary users per unit area. We consider a centralized circular CR cell with a BS located at the center and *N* CR users uniformly distributed within the cell. The cell radius is denoted as *R*. In this paper, we consider the uplink capacity analysis of the CR cell, while the same approach can be extended for downlink analysis.

We assume that multiple CR users transmit in orthogonal channels to avoid mutual interferences. This assumption implies that only one CR user within the cell is generating interference to the primary network in a particular channel at any time. We will subsequently focus on the capacity of a single channel, which may represent a physical channel in various systems applying different channalization and multiple access schemes. Correspondingly, the interference constraints in this paper are specified for a single channel. We note that interference constraints on a single channel can be easily translated from the total interference constraint on the system. Moreover, the total system capacity can be easily calculated given the capacity of a single channel and the number of parallel orthogonal channels.

The channels from the CR transmitters to the primary receivers are referred to as interference channels. The instantaneous channel power gains from the *j*th ($1 \le j \le N$) CR user to the *i*th ($1 \le i \le \infty$) primary receiver is denoted as $h_{i,j}^I$. On the other hand, the channels from the CR transmitters to the center BS are referred to as access channels. The instantaneous channel power gain from the *j*th CR user to the BS is denoted as $h_j^A$. All radio channels under consideration are narrowband channels (or single carriers of a multi-carrier system) and are assumed to be stationary and ergodic.

In previous works such as [8][15][36], only the path loss effect is considered in the channel, ignoring other effects of shadowing and fading. Although such an assumption is not very realistic, it is convenient since they often lead to elegant analytical results which can reveal important insights without over-complicating the problem. With only the path loss we have

$$h_{i,j}^{I} = K_I / \left(d_{i,j}^{I}\right)^{\alpha} \quad (1)$$

$$h_{j}^{A} = K_A / \left(d_{j}^{A}\right)^{\alpha} \quad (2)$$

where $K_I$ and $K_A$ are constants related to path loss and antenna gains in the interference and access channels, respectively, $d_{i,j}^{I}$ is the distance between the $i$th primary receiver and the $j$th CR transmitter, $d_{j}^{A}$ is the distance between the $j$th CR transmitter and the BS, and $\alpha$ is the path loss exponent typically ranging from 2 to 5 [45].

If shadowing and fading are further taken into account, (1) and (2) should be modified as

$$h_{i,j}^{I} = K_I \xi_{i,j}^{I} \eta_{i,j}^{I} / \left(d_{i,j}^{I}\right)^{\alpha} \quad (3)$$

$$h_{j}^{A} = K_A \xi_{j}^{A} \eta_{j}^{A} / \left(d_{j}^{A}\right)^{\alpha} \quad (4)$$

where $\xi_{i,j}^{I}$ and $\eta_{i,j}^{I}$ are random variables which model the effects of the shadowing and mutlipath fading in the interference channels, respectively. Similarly, $\xi_{j}^{A}$ and $\eta_{j}^{A}$ represent random shadowing and fading factors in the access channels, respectively. We assume that the shadowing factors $\left\{\xi_{i,j}^{I}\right\}$ and $\left\{\xi_{j}^{A}\right\}$ are mutually independent, each following a log-normal distribution with zero mean and a standard deviation $\sigma_{\xi}$ ranging from 5 to 12 dB [45, pp. 99] with 8 dB being a typical value for macrocellular applications. We further assume that the fading factors $\left\{\eta_{i,j}^{I}\right\}$ and $\left\{\eta_{j}^{A}\right\}$ are also mutually independent and follow identical distributions $f_{\eta}(x)$. When Nakagami fading channels are assumed, the power gain $f_{\eta}(x)$ (squared-envelope) is given by a Gamma distribution [45, pp. 54]

$$f_{\eta}(x) = \frac{m^m x^{m-1}}{\Gamma(m)} \exp(-mx), \quad m \geq \frac{1}{2} \quad (5)$$

where $m$ is the Nakagami shape factor and $\Gamma(\cdot)$ denotes the gamma function.

Let $\kappa_{i,j}^{I} = \xi_{i,j}^{I} \eta_{i,j}^{I}$ and $\kappa_{i,j}^{A} = \xi_{i,j}^{A} \eta_{i,j}^{A}$ denote the composite shadowing and fading factor of the interference channel and access channel, respectively. It follows that all $\kappa_{i,j}^{I}$ and $\kappa_{i,j}^{A}$ follow the same Gamma-log-normal distribution [45, pp. 102] whose probability density function (PDF) is denoted as $f_{\kappa}(x)$. Such a Gamma-log-normal distribution can be approximated by a log-normal distribution as [45, pp. 102]

$$f_{\kappa}(x) \approx \frac{1}{K_{\varepsilon}\sqrt{2\pi}\sigma x} \exp\left\{-\frac{\left(10\log_{10} x - \mu\right)^2}{2\sigma^2}\right\}. \quad (6)$$

In (6), the mean $\mu$ and variance $\sigma^2$ are given by [45]

$$\mu = K_{\varepsilon}^{-1}\left[\psi(m) - \ln(m)\right] \quad (7)$$

$$\sigma^2 = K_{\varepsilon}^{-2}\zeta(2,m) + \sigma_{\xi}^{2} \quad (8)$$

respectively, where $K_\varepsilon = \ln(10)/10$ is a constant. In (7), $\psi(\cdot)$ is the Euler psi function given by [45] $\psi(m) = -K_{Eu} + \sum_{k=1}^{m-1}(1/k)\,(m = 1,2,...)$, where $K_{Eu} \approx 0.5772$ is Euler's constant. In (8), $\zeta(\cdot,\cdot)$ is Riemann's zeta function given by [45] $\zeta(2,m) = \sum_{k=0}^{\infty}\frac{1}{(m+k)^2}\,(m = 1,2,...)$. When $m = 1$ (i.e., Rayleigh fading) the approximation in (6) is valid for $\sigma_\xi > 6$ dB, and for $m > 2$ the approximation is valid for all ranges of $\sigma_\xi$ of interest [45].

Two assumptions are made for our subsequent analysis. First, we assume that a CR user have perfect knowledge of local channels between itself and various primary users. Moreover, the CR BS have perfect knowledge of all channels between itself and various CR users. This is a typical assumption for researches in this area (e.g., [8][31][32][36]), where initial results are developed for the ideal case and later work attempts to relax these assumptions. Second, we assume that the maximum transmit powers for CR devices are very high. Therefore the transmit powers of CR users are always limited by the interference constraints rather than CR device capabilities. This assumption allows us to isolate the impact of primary networks on the CR system capacities. The above two ideal assumptions enable us to derive upper bounds for CR system capacities that are solely limited by the primary network. This dependence on the primary network is what distinguishes CR networks from conventional networks and is the focus of our study. The capacity upper bounds can be used as the first guideline for planning CR networks, e.g., for estimating its range, finding potential applications, and choosing operating frequencies (coexisting primary systems), before substantial efforts are invested to develop a full system. A practical example on CR network planning will be given in Section 4.

## 3. A CR Network for Best-Effort Traffic

In this section, we propose and analyze a CR network where CR users try to communicate with a center CR BS with best-efforts, i.e., with the maximum allowable transmit power under peak interference power constraints. The *j*th CR user, once scheduled to transmit, should control its transmission power $P_j$ so that the interference power perceived at primary receivers $I_i = P_j h_{i,j}^I$ fulfill certain constraints. We consider a peak interference power constraint given by $I_i \le I_{peak}$, where $I_{peak}$ is the maximum interference power that a primary receiver can tolerate. If we further denote

$$h_j^{I_{\max}} = \max_i \left(h_{i,j}^I\right) \tag{9}$$

as the largest interference channel gain associated with the *j*th CR transmitter, it follows that the maximum allowable transmit power of the *j*th CR user is given by

$$P_j^{\max} = I_{peak} / h_j^{I_{\max}}. \tag{10}$$

As explained in Section 2, we assume that a CR user can always transmit with power $P_j^{\max}$. The received signal power at the BS from the *j*th CR user (once scheduled to transmit) is then given by

$$Y_j = P_j^{\max} h_j^A = I_{peak} h_j^A / h_j^{I_{\max}}. \tag{11}$$

In best-effort services, short-term fairness among users is not critical. Therefore, the BS can use opportunistic scheduling [46][47] to improve the system throughput by exploiting the multi-user diversity. Popular scheduling algorithms include round-robin scheduling, maximum-throughput scheduling, and proportional fairness scheduling. The round-robin scheduler allocates time slot to CR users in a circular order without using multi-user diversity. It provides max-min fairness but has relatively low throughput. On the other hand, the maximum-throughput scheduler assigns time slot to the CR user with the highest instantaneous channel capacity. It achieves the highest throughput but is known to be very unfair (e.g., can result in scheduling starvation). Proportional schedulers are designed to provide certain tradeoffs between fairness and throughput. In what follows, we will only discuss the capacities of CR systems with round-robin and maximum throughput schedulers. These capacity results can serve as the lower and upper bounds of the system capacity when using more practical proportional fairness schedulers.

Assume that a perfect maximum-throughput scheduler is used to estimate and compare the instantaneous SINR of $M\left(M \le N\right)$ CR users and allocate each time slot to the user with the highest SINR. The signal power received at the BS is then given by

$$Y = \max_{j}\left(Y_j\right) \ \left(1 \le j \le M\right). \tag{12}$$

When $M = 1$, the above scheduler reduces to a round-robin scheduler since random user locations are considered. It follows that the instantaneous uplink capacity perceived at the BS, normalized over the bandwidth, is given by

$$C = \log_2\left(1 + Y/\Omega_0\right) \tag{13}$$

where $\Omega_0$ denotes the total interference and noise power received at the BS. Clearly, the uplink capacity $C$ is a random variable, whose distribution will be analyzed subsequently.

### 3.1 Capacity for Non-fading Channels

In this subsection we only consider the effect of path loss. Substituting (1) and (9) to (10), we have

$$P_j^{\max} = \frac{I_{peak}}{K_I}\left(d_j^{I_{\min}}\right)^{\alpha} \tag{14}$$

where $d_j^{I_{\min}} = \min\left(d_{i,j}^{I}\right)$ is the distance between the $j$th CR transmitter to the nearest primary receiver. According to the properties of Poisson point processes [44], $\left(d_j^{I_{\min}}\right)^2$ follows an exponential distribution given by [44]

$$f_{\left(d_j^{I_{\min}}\right)^2}\left(x\right) = \lambda_p \pi \exp\left(-\lambda_p \pi x\right). \tag{15}$$

From (14) and (15), the CDF of $P_j^{\max}$ can then be derived using the transformation of random variables [48] with the following expression

$$F_{P_j^{\max}}\left(x\right) = 1 - \exp\left(-\lambda_p \pi \left(x K_I / I_{peak}\right)^{2/\alpha}\right). \tag{16}$$

Substituting (1) and (2) into (9) and (11), we have

$$Y_j = I_{peak} \frac{K_A}{K_I} \left( \frac{d_j^{I_{\min}}}{d_j^A} \right)^{\alpha} . \tag{17}$$

Since the CR users are uniformly distributed in the cell, $\left(d_j^A\right)^2$ follows a uniform distribution ranging from 0 to $R^2$. Using the transformation of random variables, it is easy to show that the CDF of $Y_j$ is given by

$$F_{Y_j}(x) = 1 - \frac{1 - \exp\left( \lambda_p \pi R^2 \left( \frac{K_I x}{K_A I_{peak}} \right)^{2/\alpha} \right)}{\lambda_p \pi R^2 \left( \frac{K_I x}{K_A I_{peak}} \right)^{2/\alpha}} . \tag{18}$$

We assume that the received powers $Y_j$ from different CR users are mutually independent and follow the same CDF given by (18). With opportunistic scheduling, the received signal power Y given in (12) has a CDF given by $F_Y(x) = \left[ F_{Y_j}(x) \right]^M$. It follows that the CDF of the uplink capacity *C* can be obtained as

$$F_C(x) = \left\{ 1 - \frac{1 - \exp\left( \lambda_p \pi R^2 \left[ \frac{\Omega_0}{I_{peak}} \frac{K_I}{K_A} \left(2^x - 1\right) \right]^{2/\alpha} \right)}{\lambda_p \pi R^2 \left[ \frac{\Omega_0}{I_{peak}} \frac{K_I}{K_A} \left(2^x - 1\right) \right]^{2/\alpha}} \right\}^M . \tag{19}$$

### 3.2 Capacity for Fading Channels

In this subsection we consider a composite channel model which takes into account fading effects along with the path loss. Due to random channel fading, the peak transmit power of a CR user is no longer limited by the nearest primary receiver, but the primary receiver that has the greatest composite channel gains. As a result, a rather different analytical approach from Section 3. A is needed to calculate the system capacity. The channel approximation in (6) will subsequently be used to give a unified framework for the treatment of shadowing and small-scale fading. For convenience, we rewrite (11) in the dB form

$$\left(Y_j\right)_{dB} = \left(P_j^{\max}\right)_{dB} + \left(h_j^A\right)_{dB} \tag{20}$$

where $\left(Y_j\right)_{dB} = 10\log_{10} Y_j$, $\left(P_j^{\max}\right)_{dB} = 10\log_{10} P_j^{\max}$, and $\left(h_j^A\right)_{dB} = 10\log_{10} h_j^A$. In (20), $\left(P_j^{\max}\right)_{dB}$ is a random variable whose PDF can be derived from that of $P_j^{\max}$ as follows

$$f_{\left(P_j^{\max}\right)_{dB}}(x) = K_\varepsilon 10^{x/10} f_{P_j^{\max}}\left(10^{x/10}\right) \tag{21}$$

where $K_\varepsilon = \ln(10)/10$ and $f_{\left(P_j^{\max}\right)_{dB}}(x)$ is the PDF of $P_j^{\max}$. Substituting (3) into (9) and (10), the CDF of $P_j^{\max}$ can be derived as (see Appendix)

$$F_{P_j^{\max}} = 1 - \exp\left[ -\lambda_p \pi \Lambda \left( x K_I / I_{peak} \right)^{2/\alpha} \right] \tag{22}$$

where $\Lambda$ is a constant given by

$$\Lambda = \exp\left( \frac{2\left( K_\varepsilon \mu \alpha + K_\varepsilon^2 \sigma^2 \right)}{\alpha^2} \right) \tag{23}$$

where $\alpha$ is the path loss exponent and other parameters are defined in (7)-(8). Comparing (22) with (16), we can see that the transmit power CDFs under non-fading and fading channel models only differ by a factor $\Lambda$. In **Table 1**, we show the values of $\Lambda$ under typical shadowing and fading scenarios. Taking the derivative of the transmit power CDF in (22), the corresponding PDF $f_{P_j^{\max}}(x)$ can be easily obtained as

$$f_{P_j^{\max}}(x) = \frac{2}{\alpha} \lambda_p \pi \Lambda \left( \frac{K_I}{I_{peak}} \right)^{\frac{2}{\alpha}} x^{\frac{2}{\alpha}-1} \exp\left[ -\lambda_p \pi \Lambda \left( x \frac{K_I}{I_{peak}} \right)^{\frac{2}{\alpha}} \right]. \tag{24}$$

Let us now consider the PDF of the access channel gain. Using the transformation of random variables, the PDF of $\left( h_j^A \right)$ can be derived from (4) as

$$f_{h_j^A}(x) = \frac{2\left( K_A \right)^{2/\alpha}}{\alpha R^2} \Lambda x^{-1-2/\alpha} erf\left[ g(x) \right] \tag{25}$$

where $\Lambda$ is given by (23), $erf(\cdot)$ is the Gaussian error function, and $g(x)$ is given by

$$g(x) = \frac{\ln(x) + \alpha \ln(R) - \ln(K_A) - \mu / K_\varepsilon - \frac{2}{\alpha}(K_\varepsilon \sigma)^2}{K_\varepsilon \sigma}. \tag{26}$$

The PDF of $\left( h_j^A \right)_{dB}$ in (20) is then given by

$$f_{\left(h_j^A\right)_{dB}}(x) = K_\varepsilon 10^{x/10} f_{h_j^A}\left( 10^{x/10} \right). \tag{27}$$

Since $\left( P_j^{\max} \right)_{dB}$ and $\left( h_j^A \right)_{dB}$ in (20) are mutually independent, the PDF of their sum $\left( Y_j \right)_{dB}$ is the convolution of their individual PDFs, namely,

$$f_{\left(Y_j\right)_{dB}}(x) = f_{\left(P_j^{\max}\right)_{dB}}(x) * f_{\left(h_j^A\right)_{dB}}(x) \tag{28}$$

where "$*$" denotes convolution. The CDF $F_{\left(Y_j\right)_{dB}}(x)$ of $\left( Y_j \right)_{dB}$ can be obtained by taking the numerical integration of the PDF $f_{\left(Y_j\right)_{dB}}(x)$, i.e.,

$$F_{\left(Y_j\right)_{dB}}(x) = \int_{-\infty}^{x} f_{\left(h_j^A\right)_{dB}}(y) dy. \tag{29}$$

When opportunistic scheduling is considered, it follows that the CDF of $(Y)_{dB} = 10\log_{10} Y$ is given by

$$F_{(Y)_{dB}}(x) = \left[ F_{\left(Y_j\right)_{dB}}(x) \right]^M \tag{30}$$

Finally, the CDF of the capacity can be evaluated as

$$F_C(x) = F_{(Y)_{dB}}\left[10\log_{10}\left(\Omega_0\left(2^x - 1\right)\right)\right]. \quad (31)$$

## 4. Numerical Results and Discussions

In this section, we present the capacities of the proposed CR network that supports best-effort traffic in realistic scenarios. As a practical application, we consider a fixed microwave communication (FMC) system as the primary network. FMC systems (e.g., fixed WiMax) are characterized by highly directive transmissions that, intuitively, present opportunities for other systems to share their spectrum. Non-hierarchical spectrum sharing with FMC systems has been considered in e.g., [49][50], for non-cognitive systems. Here we will consider (hierarchical) spectrum sharing in the new context of CR networks. It is interesting to note that interweave CR networks may not be able to operate in these bands because highly directive primary transmissions are difficult to be detected reliably. The overlay CR then becomes the only feasible CR system to exploit spectrum opportunities in these bands.

We assume an omnidirectional antenna at the CR BS and directional antenna at the primary receivers. Based on the practical parameters discussed in [49] we assume that $K_A / K_I = 10$, $I_{peak} / \Omega_0 = 1$, $I_{out} / \Omega_0 = 1$, the path loss exponent $\alpha = 4$, and the shadowing standard deviation $\sigma_\xi = 8$ dB. Three different channel configurations, i.e., the path loss-only model, the path loss-shadowing model, and the path loss-shadowing-fading models will be used for comparison purpose to reveal the impacts of shadowing and fading on the capacity.

The random capacity reflecting the best-effort transmission of the target user are computed from (19) and (31). We focus on understanding the impacts of three key parameters on the distribution of *C*: the density of primary users $\lambda_p$¸ the cell radius *R*, and the number of opportunistically scheduled CR users *M*. The default values of these key parameters are taken as¸ $\lambda_p = 100$ user/km$^2$, $R = 100$ m, and $M = 4$.

**Fig. 2** shows $F_C(x)$ with $\lambda_p$ ranging from 1 to 1000 users/km$^2$, under both fading and non-fading channels. It is observed that when $\lambda_p$ increases, the capacity reduces and its variance increases. This is expected since a higher density of primary receivers will impose tighter limits on the emission powers of the CR transmitters. Capacity results obtained from corresponding Monte Carlo simulations are also presented in **Fig. 2**, where good matches are observed to serve as the proof to the accuracy of our derived theoretical frameworks. It is worth noting that theoretical frameworks have advantages over Monte Carlo simulations in having wider dynamic ranges and less computing time, as well as giving in-depth insights into the relationship between different system parameters and the capacity. For clarity purpose, only the theoretical/numerical results will be shown subsequently in **Figs 3-5**.

**Fig. 3** shows the impact of the CR cell radius *R* on the capacity. Since the transmit powers of the CR users are limited by the primary networks, the cell radius *R* should be properly chosen in practice so that the BS is within a reasonable range to communicate. **Fig. 4** aims to show the benefits of opportunistic scheduling which exploits multi-user diversity. It is observed that with an increasing number of the scheduled users, the capacity increases and the variance reduces. Finally in **Fig. 5**, we show the capacity CDFs with different types of channel models. The results reveal that shadowing has small impacts on the capacity distribution, while the impact of small scale fading is even less significant. The reason that shadowing and fading have only small impacts on the capacity result is because the negative impact of shadowed/faded access channels on the capacity is statistically compensated by the positive impact of shadowed/faded interference channels on the capacity.

In summary, we obtain the following four guidelines in deploying CR networks in the FMC band to support best-effort traffic. First, the CR network capacity is a random variable with a large variance. Adaptive modulation and coding (AMC) techniques are therefore desirable to exploit this random capacity effectively. Second, opportunistic scheduling is effective to improve and stabilize the cell capacity at the cost of reduced fairness among users. Third, deployment of micro-cell CR networks ($R \approx 200\,\text{m}$) seems promising to achieve an averaged cell capacity of 2 bits/Hz/s with a reasonable number of scheduled users (e.g., $M = 4$). Fourth, shadowing and fading have marginal impacts on the capacity distribution. The CR network performance is therefore expected to be robust to different propagation environments.

## 5. Conclusions

A centralized CR network has been proposed to support best-effort traffic under peak interference power constraints and its system capacity has been analyzed, taking into account all major system parameters. For the CR network supporting best-effort traffic, we have found that its capacity is susceptible to the primary user density and radius of the CR cell, but rather insensitive to channel shadowing and fading. Opportunistic scheduling among multiple CR users has been found beneficial in increasing and stabilizing the cell capacity. Consistent numerical and simulation results have shown promising capacity potential for deploying the CR network we proposed in the FMC bands. Important deployment guidelines have been discussed. We expect that the flexible analytical frameworks provided in this paper can be adopted for the strategic planning of a wide range of centralized CR networks.

## Appendix: Derivation of (22)

The problem is to find the CDF of $P_j^{\max}$ defined in (10) where $h_j^{I_{\max}}$ and $h_{i,j}^{I}$ are given by (9) and (3), respectively. We will first work on the CDF $F_{h_j^{I_{\max}}}(x)$ of $h_j^{I_{\max}}$. Assume that a transmitting CR user only interferes with primary receivers within a distance of $l$. Namely, the disk centered at the transmitting CR user with a radius of $l$ is considered as the effective interfering area. Given the primary receiver density $\lambda_p$, the probability that there are $k$ primary receivers within the interfering disk area $\pi l^2$ is given by

$$f_k(k) = \frac{\exp\left(-\lambda_p \pi l^2\right)\left(\lambda_p \pi l^2\right)^k}{k!} \left(k = 0, 1, \ldots, \infty\right). \tag{32}$$

Let $f_{h_j^{I_{\max}}}(x)$ denote the PDF of $h_j^{I_{\max}}$. Using the conditional probability we have

$$f_{h_j^{I_{\max}}}(x) = \sum_{k=0}^{\infty} f_k(k) f_{h_j^{I_{\max}}}(x \mid k) \tag{33}$$

where $f_{h_j^{I\max}}\left(x\,|\,k\right)$ is the PDF of $h_j^{I\max}$ conditioned on *k*. According to the property of Poisson point process, given that there are *k* primary users in the interfering disk, the location of these *k* primary users will follow independent and identical uniform distributions. Namely, $\left(d_{i,j}^I\right)^2$ in (3) have identical uniform distributions within $\left[0, l^2\right]$. Since the composite shadowing and fading factor $\xi_{i,j}^I \eta_{i,j}^I$ are also independent and identically distributed, it follows that the distribution of $h_{i,j}^I$ are independent and identical. We use $f_{h_{i,j}^I}\left(x\right)$ and $F_{h_{i,j}^I}\left(x\right)$ to denote the PDF and CDF of $h_{i,j}^I$, respectively. The CDF of $h_j^{I\max}$ conditioned on *k* is then given by

$$F_{h_j^{I\max}}\left(x\right) = \left[F_{h_{i,j}^I}\left(x\right)\right]^k. \tag{34}$$

The derivative of (34) gives the conditional PDF of $h_j^{I\max}$

$$f_{h_j^{I\max}}\left(x\,|\,k\right) = k\left[F_{h_{i,j}^I}\left(x\right)\right]^{k-1} f_{h_{i,j}^I}\left(x\right). \tag{35}$$

Substitute (35) into (33) and summing the exponential series we get

$$f_{h_j^{I\max}}\left(x\right) = \lambda_p \pi l^2 f_{h_{i,j}^I}\left(x\right)\exp\left(-\lambda_p \pi l^2\left(1 - F_{h_{i,j}^I}\left(x\right)\right)\right). \tag{36}$$

Taking the indefinite integral of (36) will give the CDF of $h_j^{I\max}$ as

$$F_{h_j^{I\max}}\left(x\right) = \exp\left(-\lambda_p \pi l^2\left(1 - F_{h_{i,j}^I}\left(x\right)\right)\right). \tag{37}$$

Now we wish to obtain $F_{h_{i,j}^I}\left(x\right)$ in (37). It turns out that the deviations can be simplified if we involve another distribution function $F_{\left(h_{i,j}^I\right)^{-1}}\left(x^{-1}\right)$: the CDF of $\left(h_{i,j}^I\right)^{-1}$. These two CDFs are related by

$$F_{h_{i,j}^I}\left(x\right) = 1 - F_{\left(h_{i,j}^I\right)^{-1}}\left(x^{-1}\right). \tag{38}$$

From (3) and (6), applying the transformation of random variables we have

$$F_{\left(h_{i,j}^I\right)^{-1}}\left(x\right) = \frac{2}{\alpha K_I l^2}\int_0^x F\left(z\right) z^{\frac{2}{\alpha}-1} dz \tag{39}$$

where

$$F\left(z\right) = \int_0^{(l)^\alpha / z} y^{\frac{2}{\alpha}} f_k\left(\frac{y}{K_I}\right) dy. \tag{40}$$

Substituting (38), (39), and (40) into (37) and taking $l \to \infty$, after some mathematical manipu-lations we get

$$F_{h_j^{I\max}}\left(x\right) = \exp\left(-\lambda_p \pi \Lambda\left(\frac{K_I}{x}\right)^{\frac{2}{\alpha}}\right) \tag{41}$$

where $\Lambda$ is first given by

$$\Lambda = \int_0^{\infty} y^{\frac{2}{\alpha}} f_{\kappa}(y)\,dy \tag{42}$$

and can be further simplified to the form given in (23).

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**Table 1.** Values of given by (23) under different shadowing and fading scenarios ($\alpha = 4$)

| | m = 1 | m = 2 | m = 4 | m = 16 | m = ∞ |
|---|---|---|---|---|---|
| $\sigma_\xi$ = 6 dB | 1.02 | 1.05 | 1.78 | 1.10 | 1.11 |
| $\sigma_\xi$ = 8 dB | 1.20 | 1.23 | 1.26 | 1.29 | 1.30 |
| $\sigma_\xi$ = 10 dB | 1.79 | 1.84 | 1.88 | 1.93 | 1.94 |
| $\sigma_\xi$ = 12 dB | 4.86 | 5.00 | 5.13 | 5.24 | 5.28 |

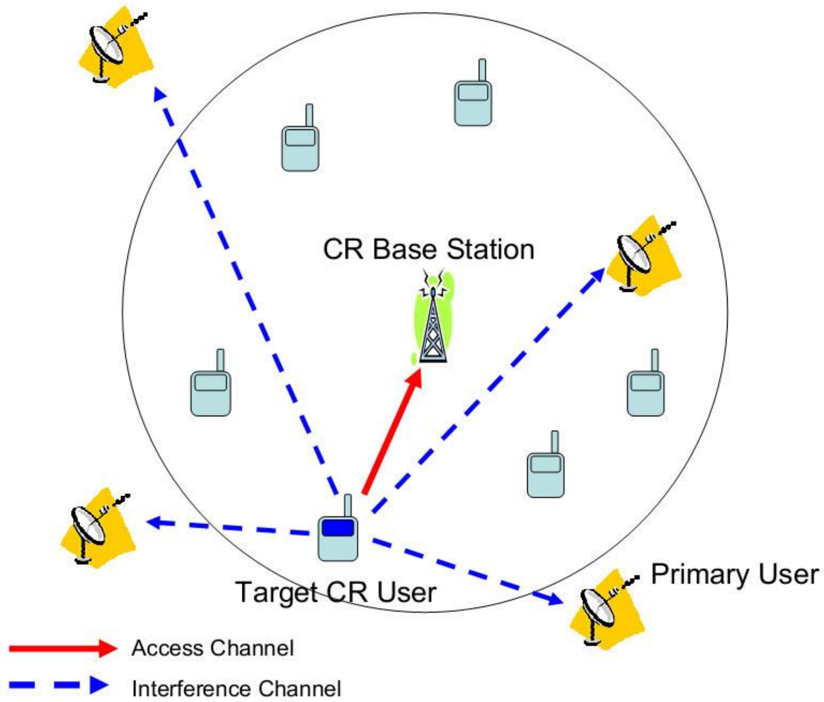


**Fig. 1.** System model of centralized CR networks.

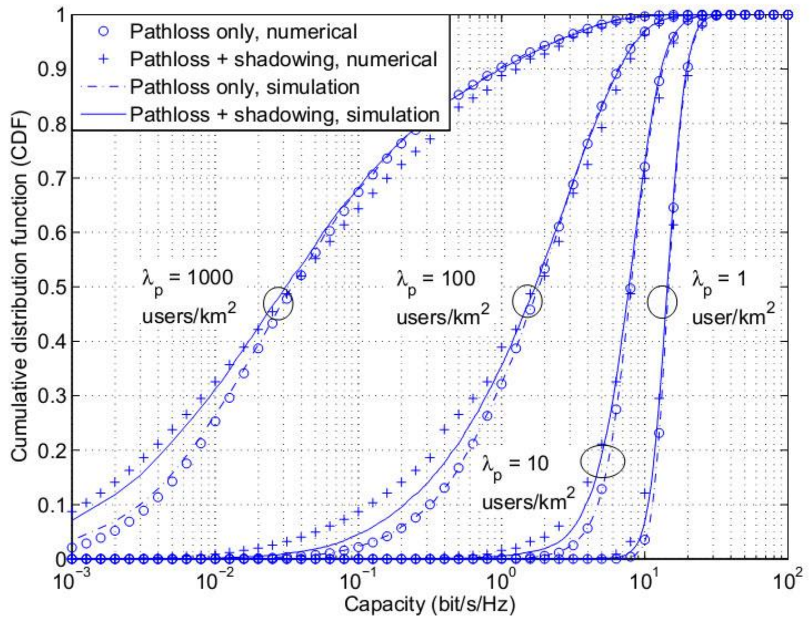


**Fig. 2.** CDFs of the capacity of CR networks supporting best-effort traffic with different values of $\lambda_p$, with and without shadowing ($R = 200$ m, $M = 4$, $\sigma_\xi = 8$ dB, $I_{peak} / \Omega_0 = 1$, and $K_A / K_I = 10$).

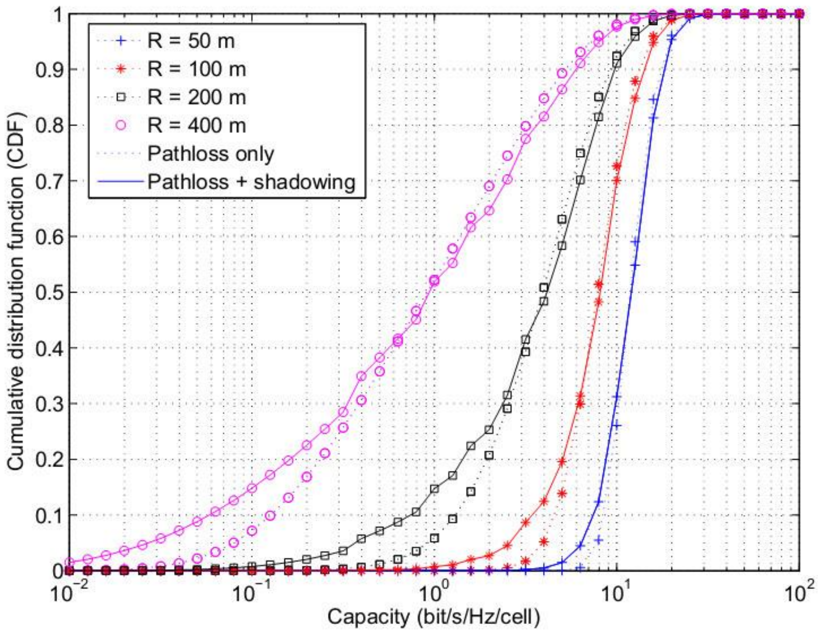


**Fig. 3.** CDFs of the capacity of CR networks supporting best-effort traffic with different values of $R$, with and without shadowing ($\lambda_p = 100$ users/km, $M = 4$, $\sigma_\xi = 8$ dB, $I_{peak} / \Omega_0 = 1$, and $K_A / K_I = 10$).

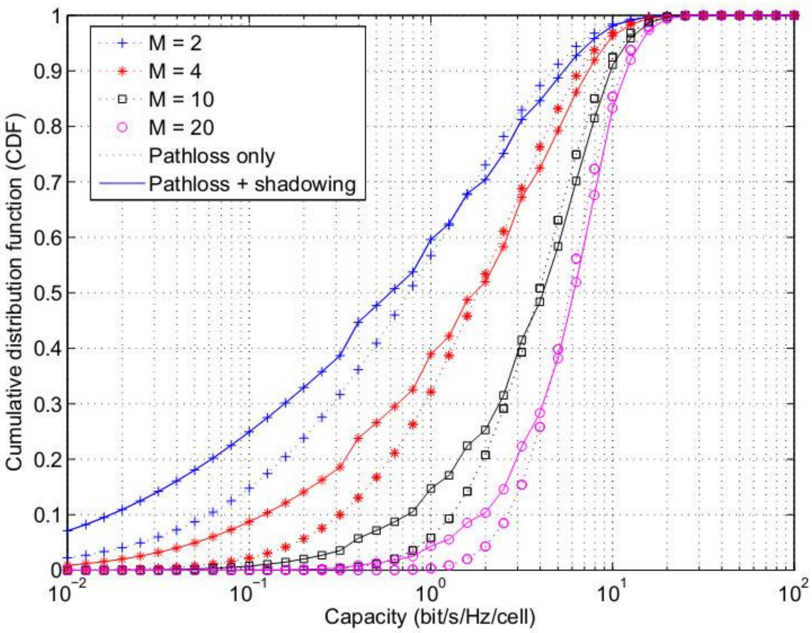


**Fig. 4.** CDFs of the capacity of CR networks supporting best-effort traffic with different values of $M$, with and without shadowing ($\lambda_p = 100$ users/km, $R = 200$ m, $\sigma_\xi = 8$ dB, $I_{peak} / \Omega_0 = 1$, and $K_A / K_I = 10$).

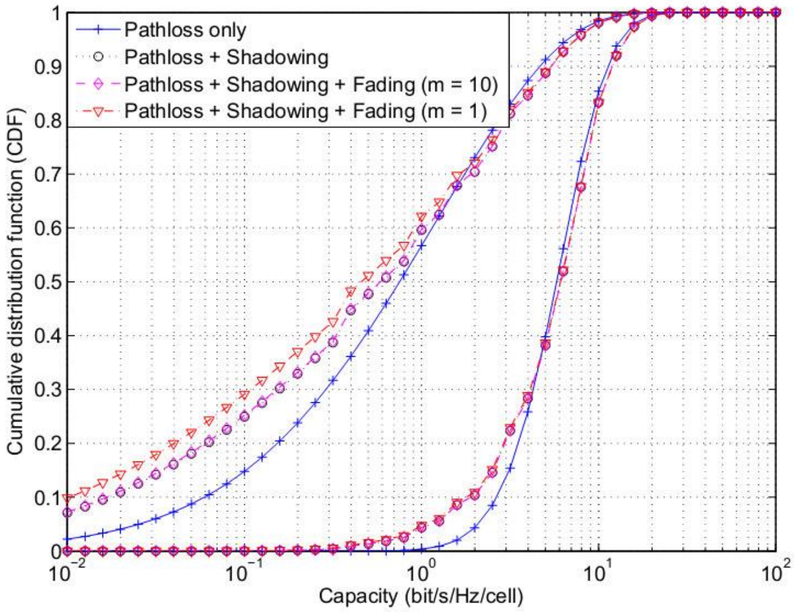


**Fig. 5.** CDFs of the capacity of CR networks supporting best-effort traffic with different values of Nakagami shaping factor *m* ( $\lambda_p = 100$ users/km, $R = 200$ m, $\sigma_\xi = 8$ dB, $I_{peak} / \Omega_0 = 1$, and $K_A / K_I = 10$).

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