Impact of Collaborative Spectrum Sensing and Nakagami-*m* Fading on the Transmission Capacity of Cognitive Radio Networks

Mohammed Abdel-Hafez[1], Khaled Shuaib[2], and Omkalthoum Hamad[3]
[1] Department of Electrical Engineering, College of Engineering, UAE University, Al-Ain, United Arab Emirates.
[2] College of Information Technology, UAE University, Al-Ain, United Arab Emirates.
[3] Petroleum Institute, Abu-Dhabi, United Arab Emirates.
Email: mhafez@uaeu.ac.ae; k.shuaib@uaeu.ac.ae; o.hamed@pi.ae

Abstract —Spectrum sharing has become a promising approach to meet the rapid development of cognitive radio technologies and improving the spectrum utilization and mitigate the spectrum starvation problems. This paper discusses the achievable transmission capacity of secondary users in a cognitive radio network employing collaborative spectrum sensing and undergoes Nakagami-m fading channel. Efficient and spectrum detection of licensed user is crucial to a successful deployment of cognitive radio. However, spectrum detection in mobile fading channels is challenging and it affects the detection performance. The proposed system model consists of a primary or licensed network, secondary users' network and infrastructure collaborative spectrum sensor, each with independent and none identical propagation channel model that follow Nakagami-m fading statistics. We develop a new mathematical framework and derive new expressions for the transmission capacity of secondary users with all channels undergoing Nakagami-m fading with non-integer fading parameters. Among numerus combining methods, we consider the impact of soft and hard decision combining of the spectrum detector on the transmission capacity. Moreover, we derived exact and alternative expressions of the transmission capacity for integer-fading parameter cases. The pertinent numerical results are generated to evaluate our analytical solution for the transmission capacity under various scenarios such as primary network traffic, channel fading parameters and collaborative sensing methods.

Index Terms—Spectrum sensing, opportunistic access, cognitive radio networks, collaborative sensing, Nakagami-m fading channel, transmission capacity and spectrum utilization.

I. INTRODUCTION

Spectrum scarcity is one of the serious challenges facing rapid development of wireless communication services and demand on wireless spectrum. However, works have shown that this starvation is artificially imposed on wireless systems fixed spectrum allocation policies adopted in today's networks which suffer from a hidden underutilization problem [1]. This has gained the attention of the research community and regulatory bodies during the last two decades to adopt a new dynamic spectrum access methods aiming at enhancing the spectrum resource utilization. Cognitive Radio (CR) or opportunistic spectrum access techniques has been proposed as the enabling technology to effectively manage spectrum resources and efficiently make use of limited spectrum bands. In cognitive radio unlicensed secondary users (SUs) are allowed to dynamically access the licensed spectrum allocated to primary users (PUs) on opportunistic basis. The objective is to reutilize the spectrum holes by secondary users with minimum interference to primary users. This is achievable by making a reliable decision about the presence or absence or the PU. Therefore, Spectrum Sensing (SS) constitutes the key element of cognitive radio networks. The performance of various temporal spectrum-sensing strategies is well investigated in the literature. Among many, collaborative sensing has already attached research community to improve the sensing accuracy and efficiency using multiple spectrum detectors [3]-[6]. The sensing strategies that collaboratively deploy a spectrum occupancy detection system are evaluated regarding the probability of detection and false alarm performance measures using the Receiver Operating Characteristic (ROC).

The ROC curves are one of the approaches to evaluate the performance of spectrum detection systems. However, ROC does not provide the spectral utilization gain when secondary users use cognitive radio. Recently, researchers used capacity calculations to quantify the resulting increment in utilization. The authors in [7] addressed the optimization of sensing duration that maximize the achievable throughput of secondary users in an Additive White Gaussian Noise (AWGN) channel. This was done by mathematically formulating the sensing throughput trade-off problem in conjunction with an energy detection scheme. This has resulted in forming an optimal sensing time, which yields the highest throughput for secondary users. In [8], the authors investigated the capacity of primary users when they undergo fading subject to constraints on the received power when perfect channel information is available to both transmitter and receiver.

The work of previous studies were extended in [9] to account for imperfect channel-side information and its impact on the channel capacity of secondary users.

Manuscript received May 25, 2019; revised November 8, 2019.
Corresponding author email: mhafez@uaeu.ac.ae.
doi:10.12720/jcm.14.12.1155-1167

However, all previous studies were restricted to either AWGN channels or special cases of the fading channels. In [10], the authors investigated the capacity of cognitive radio in a Rayleigh fading channel from the interference temperature perception with absence of any spectrum coordination between the primary and the secondary networks. The capacity is achived using water-filling power allocation strategy with a constrain on average and peak secondary to primary user interference ratio. The work is also extended to include path loss that reflects the geometric relations between network size and link pairs. Most of transmission capacity studies in the literature are from the primary receiver perspective. The systems models considered are with power constraints to protect the primary user from high interference. The author in [7] studied the capacity of secondary users in non-fading channels. Moreover, the work in [11] presented the secondary users' network capacity in Rayleigh fading channels and non-collaborative sensing. Recently, secondary user's transmission capacity in Nakagmi-m fading channel using non-collaborative sensing was presented in [12]. None of the previous research considered the collaborative spectrum sensing effect on the capacity of secondary users in cognitive radio networks.

In none cognitive radio networks the capacity is solely defined for the primary user only. The transmission capacity in cognitive radio networks is calculated for secondary users sharing the frequency spectrum with primary users, in addition to the primary users' capacity. Thus, in a cognitive radio networks, the transmission capacity has different prospective, it is calculated at the primary receiver while considering some constraints on its interference or power level as defined by [10].

Motivated by prior research we focus on how the transmission capacity is calculated from secondary receiver prospective to evaluate the performance of collaborative spectrum sensing scheme and the improvement on spectrum utilization. The proposed systems model considers of three key networks namely, primary, secondary and spectrum-sensing networks, each is undergoing an independent and none-identical Nakagami-m fading. To improve the transmission capacity of secondary users due to cognitive radio, a collaborative spectrum sensing approach is proposed in which spectrum sensor sends signal information to the band manager who make inferring decisions about spectrum occupancy by primary users. In this paper, our attention is focused on deriving a new mathematical framework and expressions for the transmission capacity of secondary users in cognitive radio using collaborative spectrum sensing employing hard-decision combing and two of the soft-decision combining techniques, namely Square Law Combining (SLC) and Maximum Selection Combining (MSC). The effect of primary user traffic and spectrum occupancy, channel fading parameters of the primary and secondary networks and spectrum sensors network, probability of false alarm, primary signal power and the number of collaborative spectrum sensors are considered in the analytical analysis and numerical results.

The rest of this paper is organized as follows. In Section 2 we describe the system and channel models. Sections 3 presents an analytical summary on the performance collaborative spectrum sensing in Gaussian and Nakagami-m fading channels. Sections 4 and 5 present the mathematical analysis of transmission capacity for secondary users in AWGN and Nakagami-m fading channels; respectively. In section 6 we present numerical results to evaluate our analytical solution. Finally, concluding remarks are given in Section 7.

II. System and Channel Model

One of the most popular disciple in cognitive radio is the interweave discipline where the spectral coexistence approach is allowed with objective of enabling secondary devices to occupy the vacant spectrum rooms that has been left vacant by primary users. The neighborhood is observed to predict the state of each portion of the frequency spectrum, portions of spectrum that are considered as being under-utilized if the primary user activity remains ideal that allows the secondary users to access the vacant frequency bands. With the help of infrastructure spectrum sensors and frequency spectrum manager, the coexistence of both primary and secondary traffics within the same network in an opportunistic transmission mode made possible. Our proposed system model consists of a primary network, secondary network, and spectrum sensors and manager as shown in Fig. 1. In this model, the channel of primary users, secondary users and spectrum sensors are assumed independents and non-identical Nakagami-m fading channel [15].

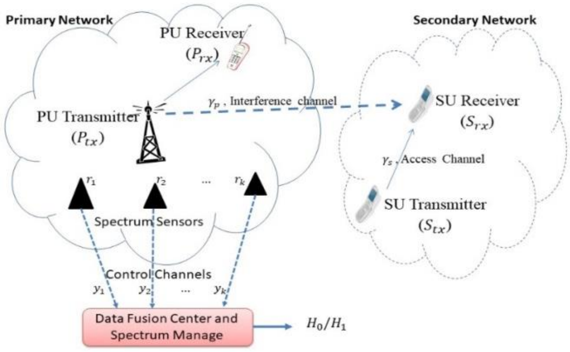

Fig. 1. System and channel model.

In Nakagami-m fading channel, the probability density function (pdf) of the received signal-to-noise ratio (SNR) is described by the gamma distribution given as,

$$f_\gamma(\gamma) = \frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}}\right)^m \gamma^{m-1} \exp\left(\frac{-m}{\bar{\gamma}}\gamma\right) \tag{1}$$

where $\bar{\gamma}$ is the average SNR in the fading channel and m is the Nakagami-m fading parameter (with the constraint that $m \geq \frac{1}{2}$) which describes the fading degree of propagation filed due to scattering and multipath interference.

Spectrum sensors considered in this paper are energy detectors proposed by [3]. It is a common method of spectrum sensing because of its implementation and computational simplicity that does not need any prior knowledge of the primary user's signal characteristics. The detector output of is a test statistics for two hypotheses H_0 and H_1, where H_0 and H_1 are the two hypotheses of the primary user's signal absence and presence, with corresponding probabilities $P(H_0)$ and $P(H_1)$, respectively. Due to uncertain nature of the spectrum sensing process, there is always sensing error modeled by two probabilities, namely, false alarm, P_f, and misdetection, P_m,that were described in the literature. To enhance the spectrum sensing process, collaborative sensing methods were enormously described in the literature, [6]. Among many, soft decision combining, square law and maximum selection combining, and hard decision combining are considered. All spectrum sensors information are collected at the spectrum and data fusion center employing various combining methods. The band manager will then decide about the occupancy status of a certain frequency band based on the information reported by the sensors.

The primary user traffic behavior is assumed to follow a two-state continuous-time Markov chain (CTMC) with the birth and death rates of λ_{off} and λ_{on}, respectively. Note that this is the most common model used to model primary user behavior [20] where the state ON/OFF implies the presence/absence of primary user. The stationary probabilities of the chain at each state are as follows [21]:

$$P(H_0) = \frac{\lambda_{on}}{\lambda_{off} + \lambda_{on}} \tag{2}$$

$$P(H_1) = \frac{\lambda_{off}}{\lambda_{off} + \lambda_{on}} \tag{3}$$

The traffic behavior of primary network is assumed to be quasi static and the transition probability that the chain changes state during the transmission phase is negligible. Therefore, to simplify our traffic model, we may ignore the interference due to primary user re-occupancies since the primary user can return to the spectrum at the beginning of the transmission phase only. On the other hand, the secondary user will use the frequency manager decisions about the occupancy information of the frequency band to access a certain frequency channel. The secondary user is allowed to access the channel if the spectrum manager grants an access permission.

Based on the proposed model, one can identify three different channels:

1. Sensing Channel: The channel between the PU transmitter and the spectrum sensor (SS), denoted by PU-SS channel with a particular signal to noise ratio γ and fading parameter m.
2. Interference Channel: The channel between the PU transmitter and the SU receiver is denoted by PU-SU channel, with signal-to-noise ratio γ_p and the fading parameter m_p.
3. Accessing Channel: The channel between the SU transmitter and the SU receiver is denoted by SU-SU channel and with signal-to-noise ratio γ_s and fading parameter m_s.

When the PU utilizes a specific frequency band, the spectrum sensor will sense the primary channel occupancy and report it to the band manager. Based on the spectrum manager decision the SU transmitter is granted permission to use a specific channel to communicate with the SU receiver via the SU-SU accessing channel. If a PU is misdetected then it will interfere with the SU signal at the secondary receiver via the PU-SU interference channel. In this paper, the transmission capacity of the opportunistic spectrum access by SUs is evaluated and the impact of the three channels' parameters are considered.

III. Collaborative Spectrum Sensing in Nakagami Fading

To improve the spectrum detection in fading channels, collaborative sensing is employed. There are different possible topologies for the way k sensors can collaborate to sense the desired spectrum. The most common topologies are the parallel distribution of the sensors with and without fusion center or spectrum manager, [6]. In this paper, we use distributed sensors with data fusion to collaboratively detect the PU spectrum activities. The fusion center will combine information gathered from k sensors to finalize the decision. Different combining techniques have been enormously suggested in literature such as soft and hard decision combining techniques. Hard decision combing and two of the soft combining techniques, namely Square Law Combining technique (SLC) and Maximum Selection Combining technique (MSC), are addressed in this paper.

A. Non-Collaborative Spectrum Sensing

The probability of detection and probability of false alarm of none-collaborative spectrum sensing, i.e. $k = 1$, in AWGN and Nakagami fading channels are summarized in this section. According to [3] the probability of detection, P_d, and probability of false alarm, P_f, in AWGN channel can be expressed by,

$$P_{d,AWGN} = Q_N\left(\sqrt{\frac{2\gamma}{\sigma^2}}, \sqrt{\frac{\lambda}{\sigma^2}}\right) \tag{4}$$

and

$$P_{f,AWGN} = \frac{\Gamma\left(N, \frac{\lambda}{2\sigma^2}\right)}{\Gamma(N)} \triangleq G_N(\lambda) \tag{5}$$

where γ is the SNR and σ^2 is the variance of the channel. Without loss of generality and for simplicity, $\sigma^2 = 1$ is assumed across this paper, $\Gamma(.,.)$ is the incomplete gamma function [14], N is the half number of samples, and $Q_N\,(.,.)$ is the Generalized Marcum Q function [14].

Since, under H_0, no primary user signal exists, P_f is not affected by channel fading, hence the probability of false alarm in Nakagami fading channel is $P_{f,Nak} = P_{f,AWGN}$. On the other hand, probability of detection over Nakagami-m fading channel, $P_{d,Nak}$, can be found by averaging (4) over (1) as,

$$P_{d,Nak} = \frac{1}{\Gamma(m)} \int_0^{\infty} Q_N\left(\sqrt{(2\gamma)}, \sqrt{\lambda}\right) \left(\frac{m}{\bar{\gamma}}\right)^m . \gamma^{m-1} \exp\left(\frac{-m}{\bar{\gamma}}\gamma\right) d\gamma \tag{6}$$

After some manipulations and using [16] and the integral definition for the Marcum Q-function [17], and with reference to [6], the probability of misdetection, defined by $P_{m,Nak} = 1 - P_{d,Nak}$, in Nakagami channel can be expressed as,

$$P_{m,Nak} = \frac{2^{-N+1}}{\Gamma(N)} \left(\frac{m}{\bar{\gamma}+m}\right)^m \int_0^{\sqrt{\lambda}} \alpha^{2N-1}\, e^{-\frac{\alpha^2}{2}} . \varphi\left(m, N; \frac{\alpha^2\bar{\gamma}}{2(\bar{\gamma}+m)}\right) d\alpha \tag{7}$$

where $\varphi(.,.,)$ is the degenerate hyper-geometric function ${}_1F_1(\,;\,;\,)$ defined in [14].

B. Soft-Decision Combining

With reference to [6] and under the assumption of identical and independent distributed (iid) k sensors, the P_f, P_d, and P_m under AWGN and Nakagami-m fading channels using two combining methods, SLC and MSC, are defined by,

$$P_{d,SLC\_AWGN} = Q_{kN}\left(\sqrt{2k\gamma}, \sqrt{\lambda}\right) \tag{8}$$

$$P_{f,SLC\_Nak} = P_{f,SLC\_AWGN} = \frac{\Gamma(kN, \lambda/2)}{\Gamma(kN)} \triangleq G_{kN}(\lambda) \tag{9}$$

$$P_{d,SLC\_Nak} = \frac{1}{\Gamma(km)} \int_0^{\infty} Q_{kN}\left(\sqrt{2k\gamma}, \sqrt{\lambda}\right) . \left(\frac{m}{\bar{\gamma}}\right)^{km} \gamma^{km-1} \exp\left(\frac{-m}{\bar{\gamma}}\gamma\right) d\gamma \tag{10}$$

$$P_{f,MSC\_Nak} = P_{f,MSC\_AWGN} = 1 - \left(1 - \frac{\Gamma\left(N, \frac{\lambda}{2}\right)}{\Gamma(N)}\right)^k \tag{11}$$

$$P_{d,MSC,AWGN} = 1 - \left(1 - Q_N\left(\sqrt{2\gamma}, \sqrt{\lambda}\right)\right)^k \tag{12}$$

$$P_{d,MSC\_Nak} = 1 - \left(P_{m,Nak}\right)^k \tag{13}$$

and the probability of misdetection, in general, is defined by $P_m = 1 - P_d$. Marcum Q-function defined by [17] is used where,

$$Q_N(x, b) = \int_b^{\infty} \frac{\alpha^N}{x^{N-1}}\, e^{-\left(\frac{x^2+\alpha^2}{2}\right)} I_{N-1}(\alpha x)\, d\alpha \tag{14}$$

C. Hard-Decision Combining

Although soft combining techniques perform well enough, it requires complete signal information to be sent to the fusion or spectrum manager. Sending the signal information includes the burden on network performance and introduces unnecessary complexity. Moreover, processing vast signal information would be more complicated and time consuming for the band manager to handle. To reduce the communication overhead, collaborative hard decision technique can be used.

Using hard decision combing technique the spectrum sensor sends only one-bit information as an individual decision. It sends 0 if the locally detected signal energy is less than the threshold to decide on H_0. Otherwise, it sends 1 to decide on H_1. Then the band manager finalizes the decision using votes according to the "$n\ out\ of\ k$" rule, where n is the required number of voters necessary to decide on the existence of the primary signal. It decides H_1 if n or more vote to H_1, otherwise, it will decide on H_0. The average probabilities of detection and false alarm for the $n\ out\ of\ k$ rule are related to their single user probabilities through binomial distribution. The AND and the OR decision rules are considered as special cases from the general $n\ out\ of\ k$ rule. By using AND rule, the band manager will decide on H_1 if all the sensors agree on deciding on the primary user existence. On the other hand, by the OR rule, the band manager will decide on H_1 when at least one sensor has decided locally on the primary user existence, [18]. The corresponding probabilities of false alarm and detection hard decision combining are, respectively, given by:

$$P_{f_{Nak,HD}} = \sum_{i=n}^{k} \binom{k}{i} P_f^{\,i} \left(1 - P_f\right)^{k-i} \tag{15}$$

and

$$P_{d_{Nak,HD}} = \sum_{i=n}^{k} \binom{k}{i} P_{d,nak}^{\,i} \left(1 - P_{d,nak}\right)^{k-i} \tag{16}$$

where P_f and $P_{d,Nak}$ are the individual probabilities of false alarm and detection as defined by (5) and (6) with $k = 1$, respectively.

IV. Ergodic Capacity of Secondary users in AWGN Channel

In this section we consider the case of an AWGN channel where the secondary user's network operates at the primary user's licensed band under two scenarios:

- Detection of an idle primary user: In this case, the capacity at the secondary link is denoted as C_0, which is the capacity of the secondary network when it operates in the absence of primary users, [13],

$$C_0 = log_2(1+\gamma_s) \quad (17)$$

where $\gamma_s = \frac{P_s}{N_0}$ is the signal-to-noise ratio of the channel between the secondary transmitter and the secondary receiver (Su_Su), P_s is the signal power of the secondary user, and N_o is the noise power at the secondary receiver.

- Misdetection of an active primary user: The secondary user will use the channel with capacity of C_1, the capacity of the secondary network when it operates in the presence of the primary user that acts as an addition interference, [12],

$$C_1 = log_2\left(1+\frac{\gamma_s}{1+\gamma_p}\right) \quad (18)$$

where $\gamma_p = \frac{P_p}{N_0}$ is the signal-to-noise ratio of the channel between the primary transmitter and the secondary receiver (PU-SU), and P_p is the primary user's signal power which represents the interference power.

Using the estimated values for primary user traffic, $P(H_1)$ and $P(H_0)$ defined by (2) and (3), the average capacity for the secondary user channel is written as,

$$C = C_0(1-P_f)\,P(H_0) + \mathrm{C}_1 P_m\, P(H_1) \quad (19)$$

where C_0 and C_1 are given by (17) and (18), $P_m = 1 - P_d$ represent the capacities when both PU_SU and PU_SU channels are AWGN channels, $P_m = 1 - P_d$ where P_f and P_d are given by (4,5,8,9,11,12) for different combining techniques, soft decision MSC and SLC, and Hard decision combining. Capacity in a fading environment is presented in Section 6 where fading is considered for both sensing and accessing channels.

V. Ergodic Capacity of Secondary Users in Fading Channel

In case of a fading channel, the capacity is found by averaging the capacity in AWGN over the fading channel statistics. A Nakagami-*m* fading model is assumed for the PU-SU and PU-SU channels. The average capacity given by (17) is averaged over the *pdf* of γ_s as,

$$C_0 = \int_0^\infty log_2(1+\gamma_s) f_{\gamma_s}(\gamma_s)\, d\gamma_s \quad (20)$$

where, $f_{\gamma_s}(\gamma_s)$ is the pdf of the SNR, γ_s, of the SU-SU channel described by Gamma distribution, described by (1). Thus, the average capacity in the Nakagami channel can be written as,

$$C_0 = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\int_0^\infty log_2(1+\gamma_s) \\ .\,{\gamma_s}^{m_s-1}\exp\left(-\frac{m_s}{\bar{\gamma}_s}\gamma_s\right)\, d\gamma_s \quad (21)$$

Similarly,

$$C_1 = \int_0^\infty log_2(1+\gamma_I) f_{\gamma_I}(\gamma_I)\, d\gamma_I \quad (22)$$

where $\gamma_I = \frac{\gamma_s}{1+\gamma_p}$ is the signal-to-interference plus noise ratio (SINR) in the PU-SU channel, γ_s and γ_p are signal-to-noise ratio of SU-SU and PU-SU links, respectively. It is known that γ_s and γ_p have a gamma distribution with distinct fading parameters m_s and m_p, respectively. Here γ_I am a new random variable where its pdf, $f_{\gamma_I}(\gamma_I)$, can be found by using [17] as follows,

$$f_{\gamma_I}(\gamma_I) = \int_0^\infty y f(y\gamma_I, y)\, dy \quad (23)$$

where $y = 1+\gamma_p$, $f_y(y) = f_{\gamma_p}(y-1)$ and $\gamma_s = \gamma_I y$.

Under the assumption that γ_s and γ_p are independent, (23) can then be written as,

$$f_{\gamma_I}(\gamma_I) = \int_0^\infty y f(y\gamma_I) f(y) dy \quad (24)$$

since

$$f_{\gamma_s}(y\gamma_I) \\ = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}(y\gamma_I)^{m_s-1}\exp\left(\frac{m_s}{\bar{\gamma}_s}\,y\gamma_I\right) \quad (25)$$

where $\bar{\gamma}_s$ is the average of the secondary user SNR, γ_s, and

$$f_y(y) = \frac{1}{\Gamma(m_p)}\left(\frac{m_p}{\bar{\gamma}_p}\right)^{m_p}(y-1)^{m_p-1} \\ .\exp\left(\frac{m_p}{\bar{\gamma}_p+1}\,(y-1)\right) \quad (26)$$

where $\bar{\gamma}_p$ is the average of the primary user SNR, γ_p, (24) can be written as

$$f_{\gamma_I}(\gamma_I) \\ = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\frac{1}{\Gamma(m_p)}\left(\frac{m_p}{\bar{\gamma}_p}\right)^{m_p}{\gamma_I}^{m_s-1}\int_1^\infty y^{m_s}\,(y \\ -1)^{m_p-1}\exp\left(-\left(\frac{m_p}{\bar{\gamma}_p}(y-1)+\frac{m_s}{\bar{\gamma}_s}\gamma_I y\right)\right)dy \quad (27)$$

Using [16], one can reduce (27) to

$$f_{\gamma_I}(\gamma_I) \\ = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\left(\frac{m_p}{\bar{\gamma}_p}\right)^{m_p}{\gamma_I}^{m_s-1}\exp\left(\frac{m_p}{\bar{\gamma}_p}\right)\left(\frac{m_p}{\bar{\gamma}_p} \\ +\frac{m_s}{\bar{\gamma}_s}\gamma_I\right)^{-\frac{(m_p+m_s+1)}{2}}.\exp\left(-\left(\frac{m_p}{\bar{\gamma}_p}+\frac{m_s}{\bar{\gamma}_s}\gamma_I\right)\right) \\ .\,W_{\frac{m_s-m_p+1}{2},\frac{-m_p-m_s}{2}}\left(\frac{m_p}{\bar{\gamma}_p}+\frac{m_s}{\bar{\gamma}_s}\gamma_I\right) \quad (28)$$

where $W_{\mu,\nu}(.)$ is the Whittaker function, [16]. Substituting in (23) by (28) yields C_1.

A. *Case 1: $m_p = 1$ and m_s is Any Real Number*

With $m_p = 1$ and m_s is any real number, (26) is reduced to,

$$f_{\gamma_I}(\gamma_I) = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\left(\frac{1}{\bar{\gamma}_p}\right){\gamma_I}^{m_s-1}$$
$$\int_1^\infty y^{m_s}\exp\left(-\left(\frac{1}{\bar{\gamma}_p}(y-1) + \frac{m_s}{\bar{\gamma}_s}\gamma_I y\right)\right)dy \quad (29)$$

using [16], (29) can be written as,

$$f_{\gamma_I}(\gamma_I) = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\left(\frac{1}{\bar{\gamma}_p}\right){\gamma_I}^{m_s-1}exp\left(\frac{1}{\bar{\gamma}_p}\right).\left(\frac{1}{\bar{\gamma}_p} + \frac{m_s}{\bar{\gamma}_s}\gamma_I\right)^{-(m_s+1)}\Gamma\left(m_s+1, \frac{1}{\bar{\gamma}_p} + \frac{m_s}{\bar{\gamma}_s}\gamma_I\right) \quad (30)$$

Substituting in (22) by (30) yields C_1.

B. Case 2: m_s is Integer-valued, and m_p is Real-valued

In this paper, a special case where m_s is an integer value and m_p is real value is considered. In this case (27) can be written as,

$$f_{\gamma_I}(\gamma_I) = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\frac{1}{\Gamma(m_p)}\left(\frac{m_p}{\bar{\gamma}_p+1}\right)^{m_p}{\gamma_I}^{m_s-1}\exp$$
$$.\int_0^\infty (y+1)^{m_s}(y)^{m_p-1}\exp\left(-\left(\frac{m_p}{\bar{\gamma}_p} + \frac{m_s}{\bar{\gamma}_s}\gamma_I\right)y\right)dy \quad (31)$$

Under the assumption of having an integer-valued of m_s and using the well-known binomial series expansion and applying [16] for evaluating the integration, (31) can be reduced to,

$$f_{\gamma_I}(\gamma_I) = \frac{1}{\Gamma(m_s)}\left(\frac{m_s}{\bar{\gamma}_s}\right)^{m_s}\frac{1}{\Gamma(m_p)}\left(\frac{m_p}{\bar{\gamma}_p+1}\right)^{m_p}$$
$$.{\gamma_I}^{m_s-1}\exp\left(\frac{-m_s}{\bar{\gamma}_s}\bar{\gamma}_I\right)$$
$$.\sum_{i=0}^{m_s}\binom{m_s}{i}\left(\frac{m_p}{\bar{\gamma}_p} + \frac{m_s}{\bar{\gamma}_s}\gamma_I\right)^{-(m_p+i)}\Gamma(m_p+i) \quad (32)$$

where C_1 can be evaluated by substituting (32) in (23).

Numerical evaluation of C_0 and C_1 in a fading channel can be easily done using numerical methods. Some numerical examples are explored in the next section for different parameters that affect the average capacity for the particular case of having integer m_s values. Using the estimated values of $P(H_1)$ and $P(H_0)$ and the average capacity for the secondary network can be calculated using (19). The probabilities of misdetection and false alarms in Nakagami-m fading channel using different combining techniques are provide by equations (6, 7, 9, 10, 11and 12).

VI. Numerical Results

In this section, we generate numerical evaluation results for the transmission capacity of secondary users in the cognitive radio network. The results present the evaluation of transmission capacity of secondary users with respect to different parameters for spectrum sensing network, primary and secondary channels' parameters, $(\bar{\gamma}, m)$, $(\bar{\gamma}_p, m_p)$, and $(\bar{\gamma}_s, m_s)$, respectively. Note that the average signal-to noise ratio of the spectrum sensing, primary and secondary channels, SNR, SNR_p, and SNR_s , represent $\bar{\gamma}$, $\bar{\gamma}_p$, and $\bar{\gamma}_s$, respectively.

A. Impact of Channel Parameters

In this section, the impact of secondary user's channel parameters are studied under various spectrum detection assumptions. The average received SNR from the primary user through spectrum sensing channel is set to $\bar{\gamma} = 10dB$ and its fading parameter assumed to be $m = 1.8$. Under non-collaborative spectrum sensing, $k = 1$, the probability of false alarm is taken to be $P_f = 0.01$. Moreover, it is assumed that the average channel occupancy by the primary user is 60% of the time, i.e. $P(H_1) = 0.6$.

1) Transmission capacity versus primary and secondary users' SNR ($\bar{\gamma}_p, \bar{\gamma}_s$) in AWGN channel

Fig. 2 shows the capacity of the secondary user for $\bar{\gamma}_p = [-20 \ -10 \ 0 \ 10 \ 20]dB$ when both the PU-SU and the SU-SU channels are AWGN channels. This Figure proves the effectiveness of the opportunistic spectrum access in enhancing the utilization of wireless networks. The capacity can be increased by around 5 Bits/Sec per unit bandwidth. It can be noticed that the capacity increases as the secondary user's SNR_s , $\bar{\gamma}_s$, increases. It is also important to see how the capacity decreases for high primary user's $SNR_p, \bar{\gamma}_p$. It is evident that $\bar{\gamma}_s$ has the most effect on the capacity compared to $\bar{\gamma}_p$. The reason behind this is that most of the capacity is gained from utilizing the channel when the primary user is idle. The variation in the secondary user capacity for different values of $\bar{\gamma}_p$ is due to accessing the channel when the primary user is available but not detected by the sensor. Such minimal variation means that the probability of misdetecting the primary signal is small, and the primary user is well protected.

2) Transmission Capacity versus Primary and Secondary Users' SNR ($\bar{\gamma}_p, \bar{\gamma}_s$) in Fading Channels

The capacity of the secondary user for $\bar{\gamma}_p = [-20\ -10\ 0\ 10\ 20]\ dB$ is depicted in Fig. 3. Both PU-SU and SU-SU channels are Nakagami fading channels with $m_p = 1.5$ and $m_s = 2$, respectively. It can be noticed that the capacity increases as in the case of having an AWGN channel, but the values are much less due to fading.

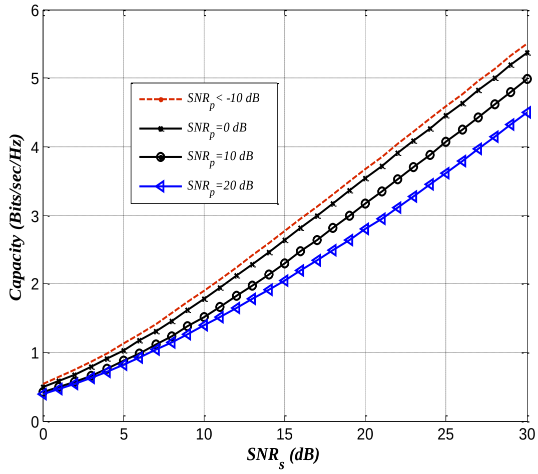

Fig. 2. Effect of $\bar{\gamma}_p$ and $\bar{\gamma}_s$ on secondary user's channel capacity in AWGN channel.

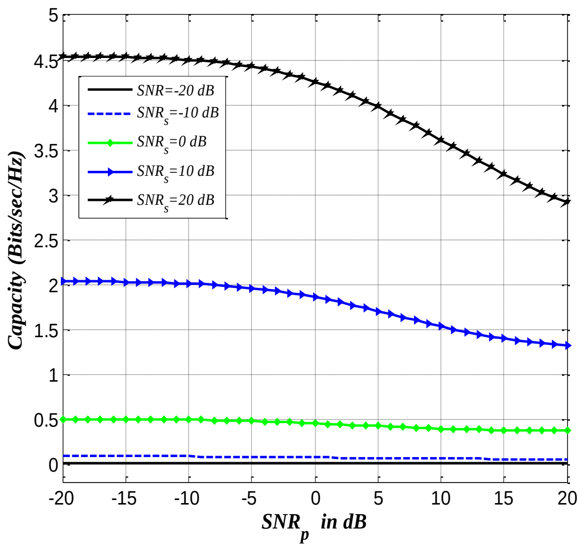

Fig. 3. Capacity versus $\bar{\gamma}_s$ for various values of $\bar{\gamma}_p$ in Nakagami fading channel with $m_s = 2$ and $m_p = 1.5$.

The capacity with respect to $\bar{\gamma}_p$, for different values of $\bar{\gamma}_s$, is presented in Fig. 4. It is clear that the capacity is profoundly affected by the secondary SNR_s. It clearly shows that $\bar{\gamma}_s$ has a significant effect when compared to $\bar{\gamma}_p$ on the capacity. The impact of $\bar{\gamma}_p$ is apparent for the high value of $\bar{\gamma}_s$. It is also clear that the gained capacity is negligible when $\bar{\gamma}_s < 0$ dB. Therefore, a secondary user with the right channel conditions is a plus for the opportunistic spectrum access system.

3) Impact of Primary Channel Fading Parameter, m_p

The capacity of the secondary network with respect to the secondary SNR_s is presented in Fig. 5; $\bar{\gamma}_s = [-20\ \ 20]dB$ and $\bar{\gamma}_p = 10\ dB$. The graph shows the capacity for different values of the channel fading parameter m_p when the secondary user channel is a Nakagami with $m_s = 2$. This graph shows that the effect of m_p is almost negligible. Fig. 5 shows a zoom in for part of the graph. This graph shows that the capacity decreases slightly as the fading severity of the PU-SU channel decreases, i.e. m_p increases. This is because the interference from the primary user when it goes under severe fading is less and doesn't degrade the capacity of the secondary user, and vice versa. On the other hand, the effect is marginal because most of the capacity comes from the channel access when the primary user is idle. Therefore, the primary signal doesn't affect the capacity gain significantly. It can be seen that the achieved capacity for fading parameter $m_p = 0.5$ is the highest with a small difference compared with the other values of fading parameters.

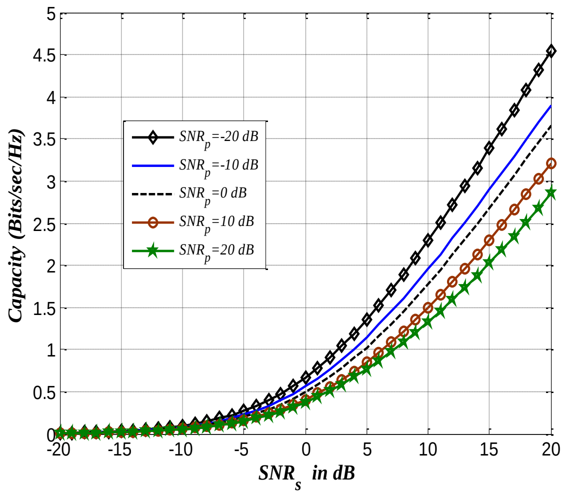

Fig. 4. Capacity versus $\bar{\gamma}_p$ and for various values of $\bar{\gamma}_s$, in Nakagami fading channel.

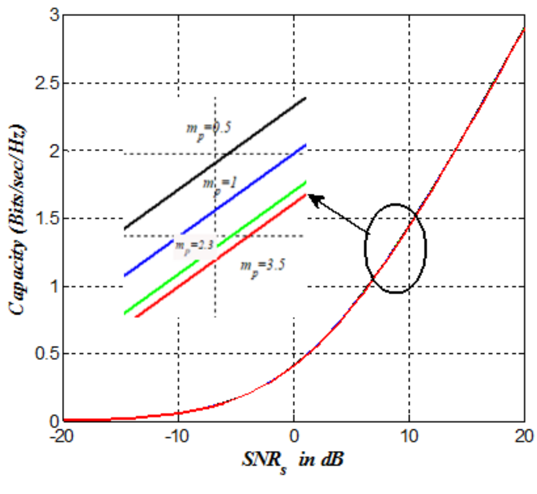

Fig. 5. Capacity versus $\bar{\gamma}_s$ for different values of $m_p = [0.5\ 1\ 2.3\ 3.5]$.

4) Impact of Secondary User Fading Parameters, m_s

Fig. 6 shows the capacity of the secondary users under Nakagami fading with different parameters m_s and $R_s = \bar{\gamma}_s = [0\ -20]dB$, $\bar{\gamma}_p = 0dB$, and $m_p = 1.2$. It is evident that the network capacity increases when the SU-SU channel fading parameter increases or the channel fading severity decreases.

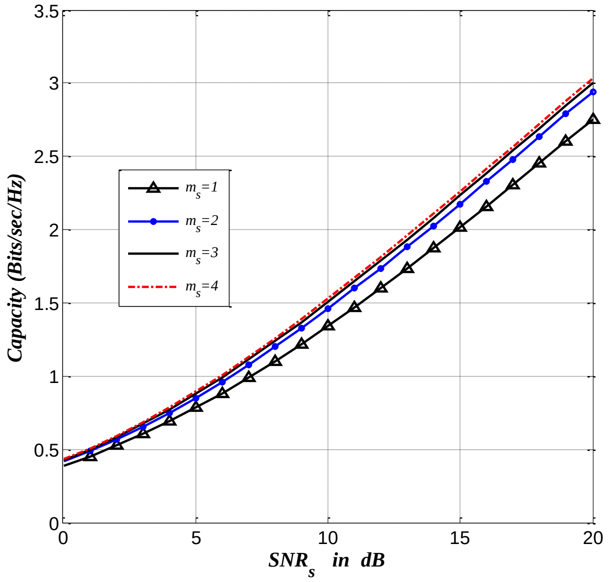

Fig. 6. Capacity versus $\bar{\gamma}_s$ for various values of m_s where $m_p = 1.2$.

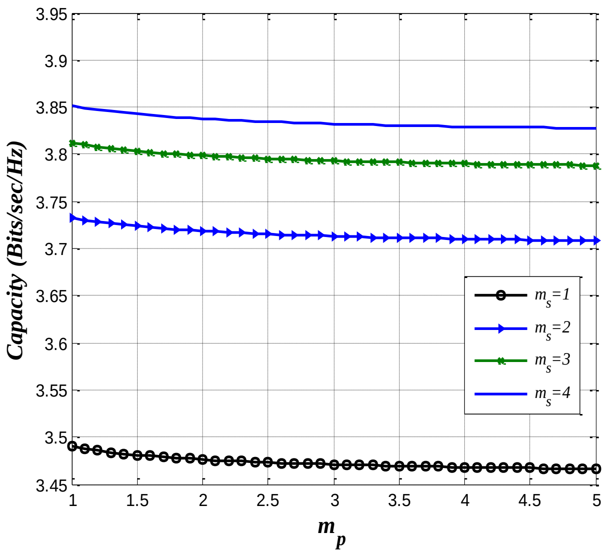

Fig. 7. Capacity versus m_p for different values of m_s.

Another look at the effect of fading severity is presented in Fig. 7. The capacity of the secondary network under Nakagami-m fading with parameters $m_s = [1\ 2\ 3\ 4]$ and $\bar{\gamma}_s = 10$ dB and $\bar{\gamma}_p = 0$ dB. Moreover, the PU-SU channel is a Nakagami channel with fading parameter in the range $m_p = [1,\ 5]$. This supports the results investigated previously that show the proportional relationship between the channel capacity and the fading parameter m_s, and the inverse proportionality between the channel capacity and the fading parameter m_p. It also shows that m_s has little effect on the capacity and m_p has an even a lesser effect. In general, the secondary user channel condition is more critical than the primary channel condition. The secondary user's capacity decreases if it goes under severe fading or low $\bar{\gamma}_s$. This is not because of the opportunistic system but because the secondary user is not qualified enough to use the channel. The scenario of having more than one secondary user increases the probability of having an excellent secondary user candidate to access the channel.

B. Impact of Collaborative Spectrum-Sensing

The impact of collaborative spectrum detection parameters is studied under valid assumptions on the secondary user's channel. The secondary transmitter is supposed to be close to the secondary receiver with an acceptable average SNR_s of $\bar{\gamma}_s = 15dB$. The primary user's signal will interfere with the secondary receiver and have and average received SNR_p of $\bar{\gamma}_p = -10\ dB$. Our previous results, Figs. 2 and 3, showed that the average SNR_p of the primary user has a marginal effect on the system capacity. The secondary users' channels is considered either AWGN or Nakagami channel.

1) Effect of PU traffic and probability of false alarms on system capacity in AWGN channel

The transmission capacity in AWGN channel versus PU traffic model, probability of false alarm with single energy detector is illustrated Fig. 8. It is clear to observe how the capacity drops dramatically as the SNR of the primary user increases. For small values of sensing channel SNR ($\bar{\gamma} < -5\ dB$), the capacity saturates at a maximum value. Under low $\bar{\gamma}$, the secondary user will assume free accessible channel. On the other hand, when $\bar{\gamma}$ is above a certain threshold (>15 dB), the capacity of the secondary network will saturate at the minimum value, which depends on the availability of the primary user.

When the primary user is using the channel all the time, $P(H_0) = 0$ or $P(H_1) = 1$, the transmission capacity of the secondary user drops to zero. Therefore, we can see that the minimum capacity allocated to the secondary user depends on the actual usage of the channel by the primary user. The capacity curve is high when the channel is free most of the time regardless of the primary channel conditions. On the other hand, the capacity is small when the channel is busy most of the time.

Another look at this graph conveys the primary user protection level. The secondary user is using the channel only when the received primary signal is either zero or very low. Such protection level can be determined by the system controller using the detection threshold λ or the value of desired probability of false alarm (λ is a function of the probability of false alarm).

The capacity with respect to sensing channel SNR, $\bar{\gamma}$, for different probability of false alarm values $P_f = [.001\ .01\ .05\ .1\ \ .2]$ is shown in Fig. 9. It can be noticed that as the probability of false alarm increases, the maximum achievable capacity decreases because when there is a high probability of false alarm the chance of using the un-occupied spectrum is missed, and as a result decreases the utilization. Therefore, the probability of a false alarm should be set small enough to maximize the channel utilization. For the rest of this section, the probability of the false alarm is set to 0.01.

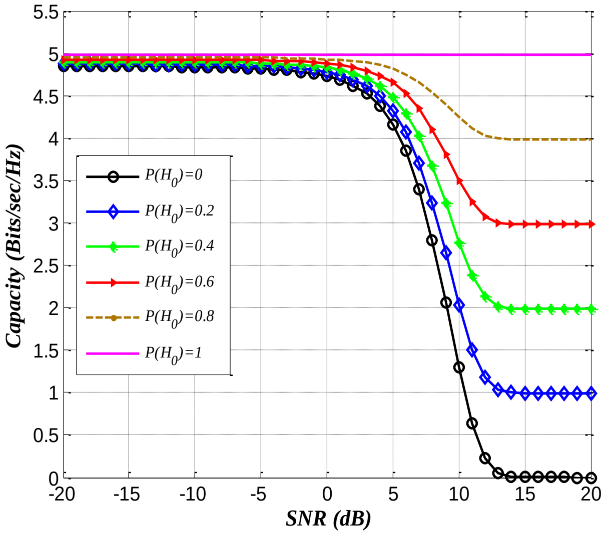

Fig. 8. Capacity versus spectrum sensing channel $SNR\ (dB)$, $\bar{\gamma}$, for different percentages of primary user traffic usage rate $P(H_0)$, and $K = 1$.

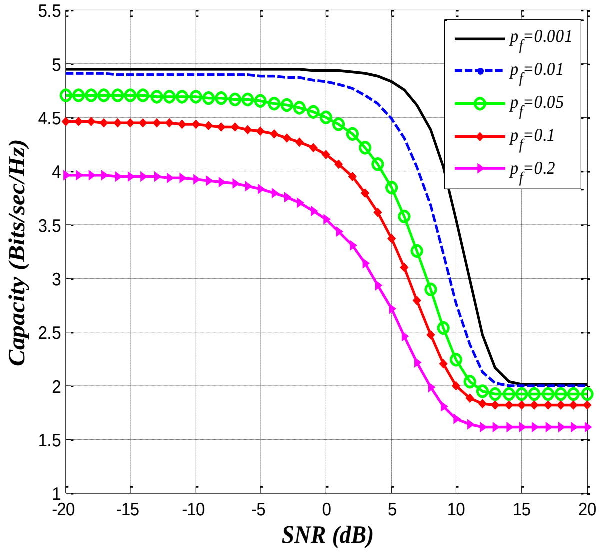

Fig. 9. Capacity versus spectrum sensing channel $SNR, \bar{\gamma}$, for the probability of false alarm and $K = 1$.

From Figs. 8 and 9, the capacity saturates at the maximum value when $SNR < 0\ dB$ and the probability of misdetection reaches its maximum, $P_m = 1$. This is the drawback of the energy detection system which cannot perform well for low SNR.

2) Effect of soft collaborative sensing on transmission capacity in AWGN cannel

Here we consider the impact of two of the soft-decision collaborative spectrum sensing, namely the SLC and MRC, on transmission capacity of secondary users in AWGN channel. The transmission capacity versus number of collaborative spectrum sensing employing SLC and MRC at different values of $P(H_0)$ are generated in Fig. 10 and Fig. 11, respectively. We assume $N = 5$ samples, $SNR = 5dB$, $SNR_s = 15dB$, $SNR_p = -10dB$ and $P_f = 0.01$.

Examining Figs. 10 and 11 one may conclude the following: the number of collaborative spectrum sensors would decrease the probability of false alarms and include the detection accuracy of primary user power. This results into less fortune to use the spectrum holes by secondary users and consequently reduces its transmission capacity. However, the number of spectrum sensors K of MRC has less effect on transmission capacity compared to SLC method. Moreover, the effect of primary user's channel vacancy rate, $P(H_0)$, is illustrated using SLC and MRC in AWGN channel. The same conclusion about the effect of $P(H_0)$ can be drawn from Fig. 8 for SLC and MRC. It is obvious that the effect of $P(H_0)$ is less for MRC compared to SLC method.

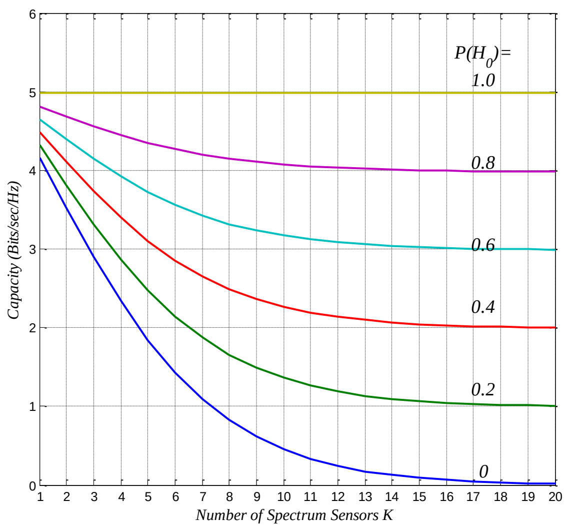

Fig. 10. Capacity versus number of spectrum sensors K in AWGN using SLC for different percentages of primary user traffic rate, $P(H_0)$.

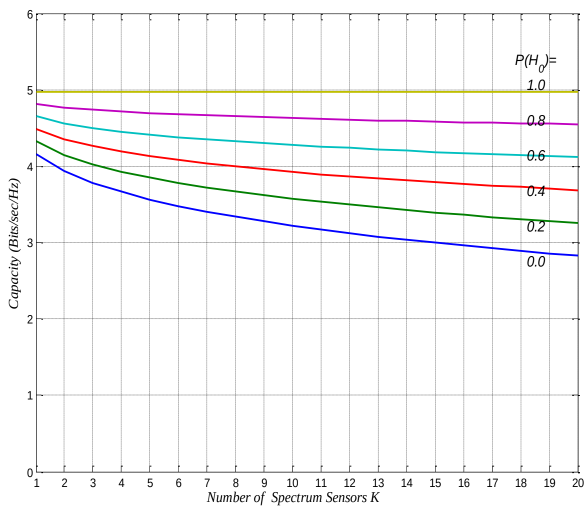

Fig. 11. Capacity versus number of spectrum sensors k in AWGN using MRC for different percentages of primary user traffic rate, $P(H_0)$.

Fig. 12 and Fig. 13, respectively, depict the transmission capacity with respect to the number of spectrum sensors k employing SLC and MRC collaborative sensing methods at different probability of false alarm values $P_f = [.001\ .01\ .05\ .1\ .2]$. We assume that $N = 5$ samples, $P(H_0) = 0.4$, $SNR = 5dB$, $SNR_s = 15dB$, $SNR_p = -10dB$. It can be noticed that as the number of collaborative spectrum sensors and probability of false alarm increase, the maximum achievable capacity decreases because when there is a high probability of false alarm the chance of using the un-occupied spectrum is missed that result into transmission capacity drop. Moreover, increasing the number of spectrum sensors, K, would increase the probability of detections and decreases the achievable transmission capacity of secondary users that results into less interference to primary users.

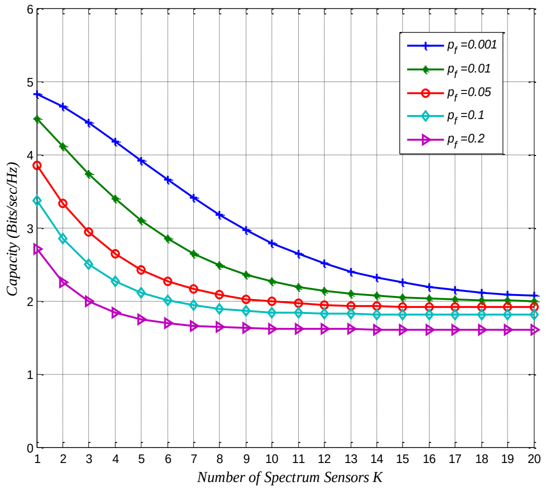

Fig. 12. Capacity versus number of spectrum sensors k in AWGN using SLC for different values of probability of false alarms p_f.

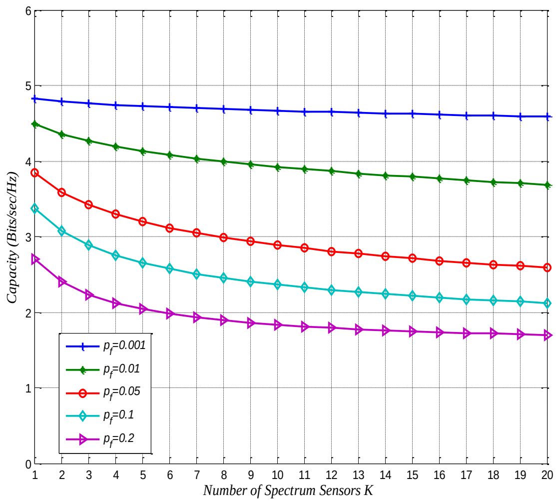

Fig. 13. Capacity versus number of spectrum sensors k in AWGN using MRC for different values of probability of false alarms p_f.

3) *Effect of soft collaborative sensing on transmission capacity in nakagami Channel*

Fig. 14 shows the transmission capacity versus received primary user's SNR at the spectrum sensor for various detection channel fading parameter m. Detection channels explored are Rayleigh and Nakagami-m fading with real fading parameters $m = [0.5\ 1\ 1.8\ 2.3]$ using single spectrum sensor, $k = 1$. It can be observed that the capacity of the secondary user is inversely proportional to the average $SNR = \bar{\gamma}$. For high $\bar{\gamma}$, the secondary user will have limited access to the channel. Such capacity never reaches zero even in the worst case scenario. The effect of fading parameter is evident. The Figure shows that the capacity increases as the fading parameter increases. This is very reasonable as smaller values of m represent severe fading that increases the probability of misdetection. Thus, when the primary signal is misdetected, the transmission capacity for secondary user will increase. This addition will be considered as an improvement only if there is enough protection to the primary user from the secondary user interference. The Figure also shows how the capacity saturates at maximum achievable capacity under assumed fading severities. It shows the capacity when $\bar{\gamma}$ is weak (below $4\ dB$). It is evident that the capacity is high regardless of the fading severity. This is because the probability of misdetection for low $\bar{\gamma}$ is very high due to energy detector unreliability at such SNRs.

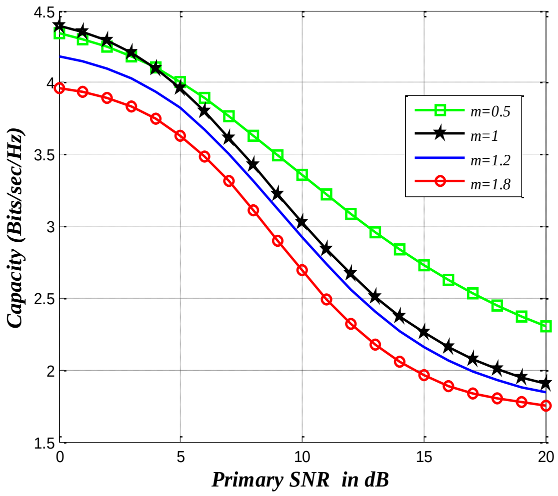

Fig. 14. Capacity versus sensor's SNR (dB) ($\bar{\gamma}$) at different detection channel fading parameter m and $k = 1$.

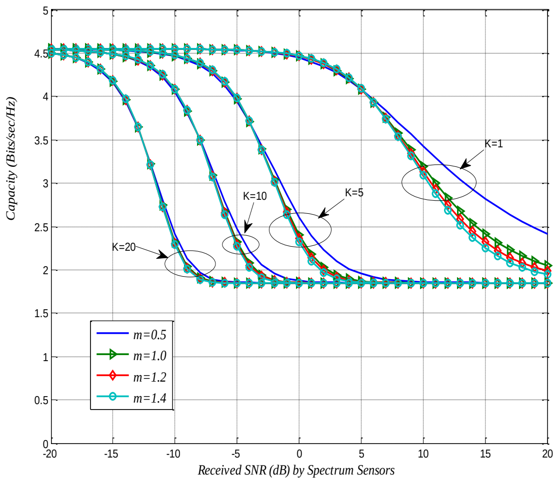

Fig. 15. Capacity versus sensor's SNR for different values of number of spectrum sensors k in Nakagami channel using SLC.

In Fig. 15 and Fig. 16 we illustrate the impact of number of soft collaborative sensors k and sensing channel fading parameter m versus the received average SNR with $m_s = 2, m_p = 1.4, SNR_s = 15dB, SNR_p = -10dB,\ p_f = 0.01,\ N = 5,\quad P(H_0) = 0.4$. The presented results demonstrates the generality and of the presented theoretical results for Nakagami fading channel with real valued fading parameters. The concluding results regarding the effect of number of spectrum sensors and the received SNR agree with previous results.

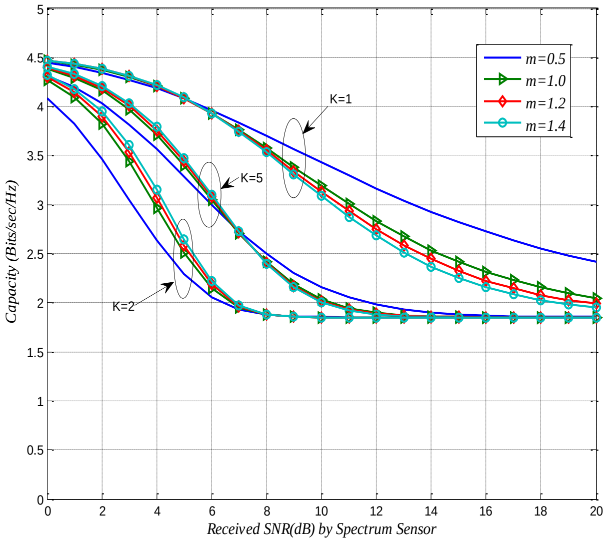

Fig. 16. Capacity versus sensor's SNR for different values of number of spectrum sensors k in Nakagami channel using MRC.

4) *Effect of hard collaborative sensing in AWGN channel*

Fig. 17 shows the capacity of the secondary user network with respect to the primary user's $SNR\ \bar{\gamma}$ measured at the sensor's receiver in AWGN channel. The capacity is measured when the detection is done by four collaborative sensors using the hard decision combining technique presented in [19]. It can be noticed that maximum capacity is achieved at the primary for $\bar{\gamma} < 5\,dB$. But how fast this capacity is reached depends on the decision rule used in this technique. When the decision rule used is the OR rule (which means if any of the sensors detected the primary user, the band manager would decide on primary user availability) it results in the least capacity. However, it will give maximum protection to the primary user from secondary user interference as previously discussed in the detection model analysis. When the decision rule used is the (AND) rule (which means the band manager will decide on primary user availability only if all the sensors detect the primary user signal), the highest capacity is achieved at all examined primary SNRs. Unfortunately, this rule implies the least protection to the primary user from secondary user interference. Thus, it can only be used when there is an interference guard system such as beamforming. Moreover, the capacity will be maximized without affecting the primary user quality of service. The "$n\ out\ of\ k$" rule can be used to make the trade-off between the capacity target and the primary user protection level. The relationship between the probability of detection and the capacity is inversely proportional to each other in limited range.

In Fig. 18, the capacity of the secondary user network is plotted with respect to $\bar{\gamma}$ when the collaborative sensors are increased to 10 sensors using the hard decision combining technique. We can see that the maximum capacity reached is about 3.6 Bits/sec/Unit-bandwidth. The extension of Hard-decision collaborative sensing to Nakagami fading channel is straightforward and will produce the similar results. However, due to paper length limitation this part is not discussed.

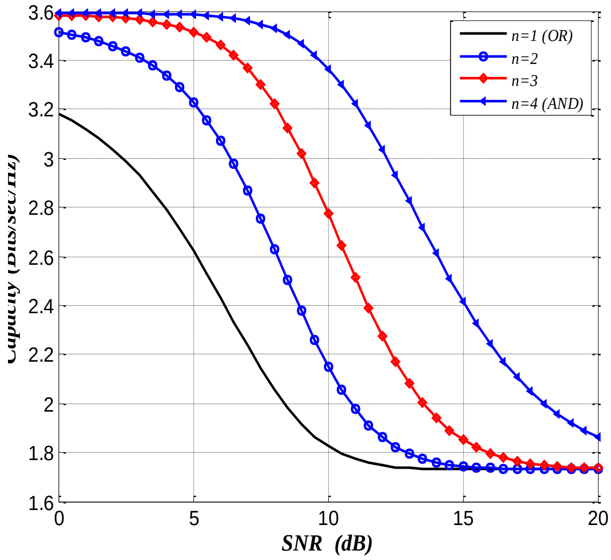

Fig. 17. The Capacity versus sensors SNR, $\bar{\gamma}$, with $k = 4$ collaborative sensors and hard decision combining technique.

VII. CONCLUSIONS

The achievable transmission capacity of secondary users' network is investigated to quantify the improvement caused by implementing Cognitive Radio in wireless networks. Closed-form expressions for transmission capacity are derived by finding the channel capacity of the secondary network under Nakagami fading when collaborative spectrum sensing is employed. Effects of sensing and accessing factors on the capacity are studied. We found that the capacity is increased using one of three elements, better secondary accessing channel, less primary interference or desired QoS of the primary user. The effect of using collaborative sensing, soft-decision MSC and SLC and hard decision, techniques ae investigated. With the help of collaborative sensing we manage to enhance the sensing performance significantly but resulted into a drop in transmission capacity of secondary users in favor of primary user QoS. Moreover, collaborative sensing helps in enhancing the spectrum sensing reliability in fading channels but reduces the transmission capacity of secondary user. Under the optimum design of an opportunistic spectrum access system, most of the capacity gain comes from utilizing the channel when the primary user is idle rather than using the channel when the sensors misdetect the primary user. Therefore, the designer should be aware of choosing a good sensing system and then maximize the transmission capacity using the other factors to avoid degrading the service of the primary user.

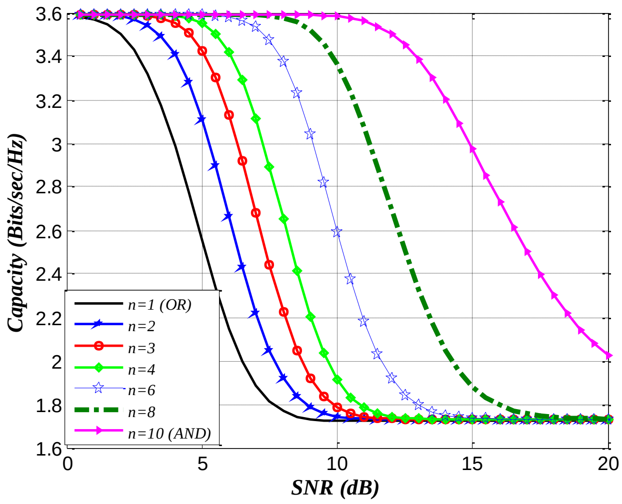

Fig. 18. The capacity versus $\bar{\gamma}$ with $k = 10$ collaborative sensors using hard decision combining technique.

REFERENCES

[1] Federal Communications Commission, Spectrum Policy task force report (ET Docket No. 02-135), November 2002.

[2] J. M. Peha, "Sharing spectrum through spectrum policy reform and cognitive radio," *Proc. IEEE*, vol. 97, no. 4, pp. 708–719, 2009.

[3] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proceedings of the IEEE*, vol. 55, no. 4, April 1967.

[4] A. Ghasemi and E. Sousa, "Opportunistic spectrum access in fading channels through collaborative sensing," *Journal of Communications*, vol. 2, no. 2, March 2007

[5] F. F. Digham and M. Alouni, "On the energy detection of unknown signals over fading channels," *IEEE Transactions on Communications*, vol. 55, no. 1, January 2007.

[6] O. A. Bashir, M. Abdel-Hafez, and K. Shuaib, "Fading severity effects on collaborative sensing for opportunistic spectrum access," *Computer and Electrical Engineering Journal*, vol. 40, no. 2, pp. 577–586, February 2014.

[7] Y. C. Liang, Y. Zeng, E. Peh, and T. Hoang, "Sensing-throughput trade-off for cognitive radio networks," *IEEE Trans on Wireless Communication*, vol. 7, no. 4, pp. 1326-1337, April 2008.

[8] A. A. El-Saleh, M. Ismail, M. A. M. Ali, and A. Alnuaimy, "Capacity optimization for local and cooperative spectrum sensing in cognitive radio networks," *World Academy of Science, Engineering and Technology*, vol. 50, 2009.

[9] J. Sun and H. Zhu, "Channel capacity analysis of spectrum-sharing with imperfect channel sensing," in *Proc. ChinaCom2009-Wireless communications and Networking Symposium*, 2009.

[10] H. Cho and J. G. Andrews, "Capacity analysis of cognitive radio under fading, path loss, and opportunism," July 2008.

[11] M. Abdel-Hafez, O. A. Bashir, and K. Shuaib, "Secondary users capacity in cognitive radio network over rayleigh fading channels," *Journal of Wireless Personal Communications*, Springer, vol. 78, no. 4, pp. 1981-1994, October 2014.

[12] M. Abdel-Hafez, K. Shauib, and O. E. B. Hamed, "Analysis of spectrum utilization of cognitive radio networks in nakagami fading channels," in *Proc. IEEE 82nd Vehicular Technology Conference*, Boston, USA, Sept. 6-9, 2015.

[13] C. Shannon, "A mathematical theory of communication," *Bell System Technology Journal*, pp. 623-656, 1948.

[14] A. M. and I. A. Stegun, *Handbook of Mathematical Functions*, Dover, 1970.

[15] N. Nakagami, "The m-distribution, a general formula for intensity distribution of rapid fading," in *Statistical Methods in Radio Wave Propagation*, W. G. Hoffman, Ed., Oxford, Oxford, England: Pergamon, 1960, pp. 3-36.

[16] I. S. Gryadshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 5th Edition, San Diego: Academic, 1994.

[17] A. H. Nuttal, "Some integral involving the $\mathrm{Q_M}$–function," *Naval Underwater Systems*, 1975.

[18] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, Third Edition, McGraw-Hill, 1991.

[19] O. A. Bashir and M. Abdel-Hafez, "Multi-Level collaborative spectrum sensing in nakagami fading channels," in *Proc. Seventh International Conference on Wireless and Mobile Communications*, Venice, Italy, June 24-29, 2012, pp 284–289.

[20] W. Gabran, C. H. Liu, P. Pawelczak, and D. Cabric, "Primary user traffic estimation for dynamic spectrum access," *IEEE Journal on Selected Areas in Communications*, vol. 31, pp. 544-558, 2013.

[21] S. M. Ross, *Introduction to Probability Models*, Tenth ed., Academic Press, 2009.

Mohammed Abdel-Hafez is an associate professor in the Department of Electrical Engineering (Communications), United Arab Emirates University, UAE. He received his B.Sc, M.Sc, and Ph.D. degrees all in Electrical and Electronic Engineering from Eastern Mediterranean University, Northern Cyprus, and Turkey in 6/1992, 8/1994, and 11/1997, respectively. From 1992 to 1997 he was a Research Engineer at Department of Electrical and Electronic Engineering, EMU, Turkey. During the year 1995, he was an instructor at Jerusalem University, Department of Electrical Engineering. From 1997 to 1999 he was with Palestine Telecommunication Company (PALTEL) as data communication section manager. In August 1999, he joint Centre for Wireless Communications at the University of Oulu as senior research scientist and project manager. He is currently associate professor of Electrical Engineering at United Arab Emirates University in United Arab Emirates. He is a frequent visiting professor at Oulu University, Centre for Wireless Communications, Oulu, Finland. His research of interests includes performance analysis of mobile communication systems, future broadband wireless systems, Smart Grid, cooperative and Cognitive radio networks, 5G and mmwave systems, and UWB systems. Dr. Abdel-Hafez has published more than 75 conference or journal papers in the field of wireless communications and digital signal processing. Dr. Abdel-Hafez is listed in Marquis WhosWho in the word 2006 and Whoswho of Emerging Leaders 2007 and IEEE senior member.

Khaled Shuaib received his PhD in Electrical Engineering from the Graduate School and University Center of the City University of New York, 1999, his ME and BE in Electrical Engineering from the City College of the City University of New York, 1993 and 1991 respectively. Since September 2002, Khaled has been with the College of Information Technology (CIT), at the UAEU where he is currently a Professor and Acting Dean. His research interests are in the area of network design and performance, communication networks, sensor networks, IoT, network security and Smart Grid. Khaled has over 100 refereed publications in journals and conferences and three US patents. Prior to joining the UAEU, Khaled had several years of industrial experience in the US working as a Senior Member of Technical staff at GTE Labs, Waltham, MA (Currently Verizon Technology Center) (1997-1999), and as a Principal Performance Engineer for Lucent Technologies, Westford, MA (1999-2002). His work was focused on the transmission of video over switched networks and on the performance evaluation, design and scalability of major Telecommunication and Internet Service Providers networks.

Omkalthoum El-Bashir Hamed, holds a MSc and a BSc in Electrical Engineering from the UAEU, 2011 and 2003 respectively. Omkalthoum was an Academic Assistant in UAEU from 2003 to 2011. Then she joined the Petroleum Institute as a Lab Engineer, teaching various electrical labs for undergraduate students in Electrical Engineering department. Her research interests include wireless networks and cognitive radio.