International Journal of Electronics Communication and Computer Engineering
Volume 4, Issue 1, ISSN (Online): 2249–071X, ISSN (Print): 2278–4209

# Development of a Mathematical Framework for Comparison of Underlay and Overlay Systems

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*Abstract* – **Overlay and underlayare two main spectrum access strategies in cognitive radio.In this work, wehave driven closed form expressions for the primary service outage probabilitiesof both techniques. We have also formulated and solved optimization problems with the objective of maximizing the secondary service's capacity with constraints on primary service's outage probability and secondary service power budget. A mathematical frame work for comparing the performance of the two systems has been developed. The performances of the two systems havebeen compared against different levels of primary service interference, activity, and secondary service power budget levels, and the strengths of each system has been clarified.**

*Keywords* – **Capacity, Cognitive Radio, Outage Probability, Overlay, Spectrum Sharing, Underlay.**

## I. Introduction

The dramatic increase in wireless applications has sparked fears that we may be running out of usable spectrum. One potential solution to spectrum shortage is cognitive radio [1, 2]. The main idea of cognitive radio is to open up the spectrum to a set of secondary users. Primary users are licensed to use the spectrum. Secondary users can utilize the spectrum, if their interference on the primary users signal keptlimited. There are two main strategies under which a secondary user can access the spectrum: overlay and underlay [3]. In both strategies the secondary service has to maximize its capacity while dealing with restriction onprimary service's Quality of Service (QoS) degradation. A widely used measure for primary service QoS is primary service outage probability. If the Signal to Interference plus Noise Ratio (SINR) at the primary receiver falls below a threshold $(Q)$,necessary for primary service operation, the primary is considered to be in outage.In order to preserve the primary service's QoS, primary service outage probability is limited to a defined level $(\xi)$.

Regarding overlay spectrum sharing in [4] the fundamental tradeoffs between sensing parameters and secondary capacity has been investigated. An optimization problem has been defined to maximize the throughput of the secondary service. Although, the solution of the proposed optimization problem allegedly maximizes the secondary service capacity, the effects of fading in wireless channels has nit been not takeninto accountin wireless channels. They have also replaced the primary service outage probability constraint with miss detection probability. These two assumptions significantly hamper the accessible capacity of the secondary service. To maximize ergodic capacity of the secondary service, dynamic programming with miss detection constraints has been considered in [5]. The authors have tailored their approach to a specific spectrum sensing technique, which narrows the use of the results obtained.

A new parameter has been taken into consideration in [6]. The authors have assumed a minimum SINR for the secondary user. Outage occurs if the value drops below this threshold. Then they have embarked on minimize secondary users outage probability while keeping the primary users QoS in check. The results obtained are for a general channel distribution. The assumption has been made that the secondary service has prior knowledge of the channel between the secondary transmitter and primary receiver. For the Channel Side Information (CSI) to be useful, itshould be obtained and distributed within the coherent time of the channel. This time limitationand the overhead traffic generated, makes the implementation of such a system unpractical. Regarding to underlay systems, in [7] instead of primary service outage probability, peak average interference at the primary receiver has been limited to preserve the primary service's QoS. The authors have also assumed that the CSI between the secondary user and primary service is available. In [8,9] optimization problem has been introduces with the objective of minimizing the secondary service's outage probability while limiting the primary service's outage probability.

A comparison between overlay and underlay system has been made in [10, 11]. The authors of [10] have replaced the primary service outage probability with miss detection error and the performances of the two systems have only been compared against the primary service activity. In [11] only the impact of the primary service outage probability is taken into account.

In this work, we present a simple and useful approach to drive exact primary service outage probability. We formulate an optimization problem for secondary service power allocation with constraints on primary service outage probability and secondary service power budget. We validate our work with simulation and numerical results. The main contribution of our work is to propose a mathematical frame work to compare underlay and overlay systems in different scenarios. The results obtained in this work indicate the advantages and disadvantages of each system.

## II. System Model

We have considered a single primary receiver-transmitter pair and a single secondary receiver-transmitter pair, both using the same spectrum band. In this scenario there are four different channel gains:

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Volume 4, Issue 1, ISSN (Online): 2249–071X, ISSN (Print): 2278–4209

1- primary user's transmitter to secondary user's receiver, $g_{ps}$
2- primary user's receiver to secondary user's transmitter, $g_{sp}$
3- primary user's transmitter to primary user's receiver, $g_{pp}$
4- secondary user's transmitter to secondary user's receiver, $g_{ss}$

The above-mentioned cases are shown in Fig.1.

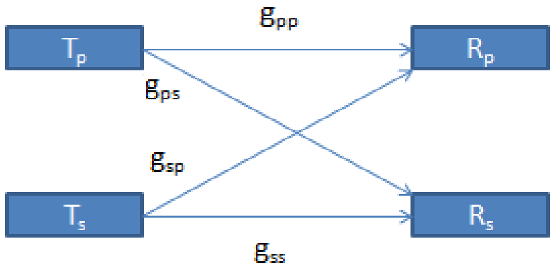


Fig.1. System model

All channels are considered to undergo Rayleigh block fading and have Additive White Gaussian Noise (AWGN). Noise at each receiver is independent and has zero mean and variance $N_0$. Rayleigh fading for the signals means that the channel power gains have an exponential distribution with mean $\mu$, and the probability distribution function (pdf) of the channel gain will be:

$$f_P(p) = \frac{1}{\mu} e^{-(p/\mu)} U(p). \quad (1)$$

Thus the signals received at the primary and secondary receivers are:

$$Y_s = (\sqrt{g_{ss}})S_s + (\sqrt{g_{ps}})S_p + N_p, \quad (2)$$

$$Y_p = (\sqrt{g_{sp}})S_s + (\sqrt{g_{pp}})S_p + N_s. \quad (3)$$

Where $Y_s$ ($Y_p$) is the signal at the secondary (primary) user's receiver, $S_s$ ($S_p$) is the transmitted signal by the secondary (primary) user and $N_s$ ($N_p$) is the AWGN at the secondary (primary) user's receiver. This system model has also been successfully used in other works relating cognitive radio [6, 10].

## III. Overlay System

In overlay spectrum sharing the secondary service measures the spectrum band, if the spectrum is detected as idle, the secondary initiates transmission.Under the assumption of perfect spectrum sensing the secondary service will have access to the spectrum when the primary service is not using it and will not be transmitting while the primary service is utilizing the spectrum. This means there will not be any collisions between the two services, and the secondary service will notaffect the primary service.This approach increases spectrum efficiency significantly. However, in practice sensing methods are not perfect [12]. Sensing errors make the performance of overlay systems to be dependent on spectrum sensing. Performance of a spectrum sensing technique is measured with two metrics:

1) *Probability of false alarm*: detecting the primary user is using the spectrum, while the spectrum is idle. A false alarm will result in a lost spectrum access opportunity and thus lowers spectrum efficiency. Here after we refer to false alarm probability as$\varepsilon$.
2) *Probability of miss detection*: detecting that the spectrum is unutilized, while the primary user is using the spectrum. Miss detection will lead to both secondary and primary users transmitting at the same time. This situation is referred to as a collision. The signal from one service will act as interference for another. This may degrade their SINR and eventually their QoS. Primary service QoS is of particular importance, because the cardinal rule of cognitive radio is to minimize interference on the licensed user. Here after we refer to miss detection probability as $\delta$.

Spectrum sensing in a nutshell is a detection problem, thus probability of miss detection and false alarm are interrelated. This relation is displayed in a Receiver Operating Characteristic (ROC) curve which is a fundamental characteristic of one spectrum sensing technique [12]. This relation has a profound effect on spectrum utilization efficiency. Lowering the probability of miss detection will result in higher probabilities of false alarm. As a result, this will lead to lower spectrum efficiency. Lowering probability of false alarm will lead to better spectrum efficiency but, it will also increase the probability of miss detection and degrade primary service's QoS.

### *A. Primary service outage probability*

For a primary service outage to occurthe secondary service must be in a miss detection situation and the secondary service transmission power and the channel gain between the respective transmitter and receiver should be high enough to take the primary services SINR below the threshold $Q$. In mathematical terms we can write:

$$P_{out} = P(SINR < Q|P_m). \quad (4)$$

Where$P_m$ denotes being in a state of miss detection. Assuming that miss detection probability is$\delta$and it is statistically independent of the channel gains, primary outage probability could be expressed as:

$$P_{out} = P(\frac{g_{pp}S_p}{g_{sp}S_s} < Q).\delta\,, \quad (5)$$

We have assumed a high SNR regime, thus the effects of noise are neglected and SINR is replaced with Signal to Interference Ratio (SIR). with the made assumptions, primary service outage probability could be expressed as:

$$\delta.P\left(g_{pp} < Q\frac{S_s}{S_p}g_{sp}\middle|g_{sp}, S_s\right). \quad (6)$$

We have also assumed independent Rayleigh fading channels, thus the primary service's outage probability can be calculated by:

$$P_{out} = \delta.\int_0^\infty\int_0^\infty (1 - e^{\frac{-Q(S_s g_{sp})}{S_p\mu}})\frac{e^{\frac{-g_{sp}}{\mu}}}{\mu} f(S_s) d_{g_{sp}} df(S_s). \quad (7)$$

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Where $f(S_s)$ denotes the pdf of secondary service power distribution.Using $\int_0^\infty \frac{S_s}{\mu} e^{-x(s+\frac{1}{\mu})} dx = \frac{S_s}{s\mu+1}$. The outage probability is evaluated by:

$$P_{out} = \delta . \int_0^\infty \frac{\frac{QS_s}{S_p}}{\frac{QS_s}{S_p}+1} f(S_s) df(S_s). \quad (8)$$

## B. Secondary service capacity

The probability of detecting a white space correctly is 1 − [10]. Under this situation the capacity of the secondary user is:

$$C_s = E_{g_{ss}} \left[\log\left(1+\frac{g_{ss}S_s}{N_0}\right)\right]. \quad (9)$$

In (9) the logarithm function is in the base of two. In a miss detection situationa close estimation of the secondary user's capacity could be calculated by assuming the primary user's transmissions as interference. The interference caused by the primary user in a miss detection situation is:

$$I = E_{g_{ps}}\left[g_{ps}S_p\right]. \quad (10)$$

In (10) $S_p$ is the primary user's transmission power. Thus the capacity of the secondary user in miss detection would be:

$$C_s = E_{g_{ss}} \left[\log\left(1+\frac{g_{ss}S_s}{N_0+I}\right)\right]. \quad (11)$$

In (11) the primary users signal is considered to have a Gaussian distribution. If this assumption does not hold, then (11) acts as a lower bound for the secondary service capacity. The overall capacity of the secondary user is the (10) times the probability of correct spectrum detectionplus (11) times the probability of miss detection. The overall capacity could be written as:

$$C_s = E_{g_{ss}} \left[P_b(\delta)\log\left(1+\frac{g_{ss}S_s}{N_0+I}\right) + P_i\,(1-\ )\log\left(1+\frac{g_{ss}S_s}{N_0}\right)\right]$$
$$= E_{g_{ss}} \left[\log\left(1+\frac{g_{ss}S_s}{N_0+I}\right)^{\delta P_b} + \log\left(1+\frac{g_{ss}S_s}{N_0}\right)^{(1-\mathcal{E})P_i}\right]. \quad (12)$$

In (12) $P_b$ and $P_i$ are the probability of the channel being in use and left idle by the primary service respectively. To simplify the equations we consider a lower bound on (12) by using Jensen's inequality [13] and replacing interference $I$by its overall statistical value, $P_b\delta I$ . Thus the secondary service capacity is expressed as:

$$Cs \geq E_{g_{ss}}[\log(1+\frac{g_{ss}S_s}{N_0+P_b\delta I})^{(1-\varepsilon)Pi} + \log(1+\frac{g_{ss}S_s}{N_0+P_b\delta I})^{\delta Pb}]$$
$$= E_{g_{ss}}[\log(1+\left(1+\frac{g_{ss}S_s}{N_0+P_b\delta I}\right))^{(1-\varepsilon)Pi+\delta Pb}]$$
$$=((1-\varepsilon)P_i+\delta P_b)\ E_{g_{ss}}\left[\log\left(1+\frac{g_{ss}S_s}{N_0+P_b\delta I}\right)\right]. \quad (13)$$

In (13), $(1-\varepsilon)P_i+\delta P_b$represents the average time that the secondary service transmits on the channel. If we consider the ROC to be:

$$1-\delta = ROC(\varepsilon). \quad (14)$$

Using the notation $(1-\varepsilon)P_i+\delta P_b$we can write:

$$P_{ac} = \left(1-ROC^{-1}(1-\delta)\right)P_i + \delta P_b. \quad (15)$$

## C. Secondary service capacity optimization

We would like to achieve maximum secondary service capacity while maintaining the primary service's QoS. We could summarize this as the following optimization problem.

Problem.1

$$\max C_s = P_{ac}E_{g_{ss}}\left[\log\left(1+\frac{g_{ss}S_s}{N_0+P_b\delta I}\right)\right], \quad (16.a)$$
$$s.t.\ P_{ac}E_{g_{ss}}[S_s] \leq \overline{Ss}, \quad (16.b)$$
$$P_b\delta P(\frac{g_{pp}S_p}{g_{sp}S_s} < Q) \leq \xi, \quad (13.c)$$
$$S_s \geq 0. \quad (16.d)$$

In Problem.1 the objective is to maximize the secondary user's capacity. The constraint function represented in (16.b) is a constraint on secondary power to exclude solutions that exceed the power limits of the secondary service. The constraint in (16.c) confines the primary user's outage probability to a maximum in order to protect its QoS. The secondary service can only force a primary service outage when the primary service is on (or the channel is busy), which is the reasonthe obtained outage probability is multiplied by $P_b$ (16.c). Constraint (16.d) is to prevent solutions with negative secondary transmission power and only play a mathematical role.

Problem.1 is solved by using the Lagrange multipliers method:

$$L(S_s,\lambda_1,\lambda_2) = \int_0^\infty \log\left(1+\frac{g_{ss}S_s}{N_0+P_b\delta I}\right)\left(\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}\right)dg_{ss}$$
$$-\lambda_1\left(\int_0^\infty S_s\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} - \frac{\overline{S}_s}{P_{ac}}\right)$$
$$-\lambda_2\left(\int_0^\infty \frac{\frac{QS_s}{S_p}}{\frac{QS_s}{S_p}+1}\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} - \frac{\xi}{P_b\delta}\right) \quad (17)$$

As the channels were assumed to undergo Rayleigh fading, in (17) we have considered, $\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}$ as the channel power pdf.Putting the partial derivates of $L$ with respect to $S_s$, $\lambda_1$and $\lambda_2$equal to zero the optimal secondary service power allocation is:

$$S_s = \begin{cases} \frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b\delta I}{g_{ss}}, & g_{ss} > \vartheta \\ 0, & Otherwise \end{cases} \quad (18)$$

Where$\vartheta = (N_0+P_b\delta I)(\lambda_1^*+\lambda_2^*)$and $\lambda_1^*$,$\lambda_2^*$are calculated from:

$$\begin{cases} \int_\vartheta^\infty \left(\frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b\delta I}{g_{ss}}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} = \frac{\overline{S}_s}{P_{ac}} \\ \int_\vartheta^\infty \left(\frac{\frac{Q}{S_p}\left(\frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b\delta I}{g_{ss}}\right)}{\frac{Q}{S_p}\left(\frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b\delta I}{g_{ss}}\right)+1}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} = \frac{\xi}{P_b\delta} \end{cases}. \quad (19)$$

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The maximum achievable capacity will be:

$$C_s = P_{ac}\int_{\vartheta}^{\infty} \log\left(\frac{g_{ss}}{(N_0 + P_b\delta I)(\lambda_1^* + \lambda_2^*)}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} \qquad (20)$$

## IV. Underlay System

In underlay systems, the secondary service transmits continuously and concurrently with the primary service. The secondary service preserves the primaries QoS by limiting itstransmission power.

### A. Primary service outage probability

The outage probability of underlay systems arethe same as that for overlay systems. However as underlay systems don't use spectrum sensing, the secondary service will be transmitting at all times. Thus the excretion will be:

$$P_{out} = \int_{0}^{\infty} \frac{\frac{QS_s}{S_p}}{\frac{QS_s}{S_p} + 1} f(S_s)df(S_s). \qquad (21)$$

### B. Secondary service capacity

The capacity of underlay systems is easily calculated by adding primary service's interference to noise. The Primary service interference is defined in (9), we only need to take into account the average time that the primary service is causing this interference by multiplying (9) with, $P_b$, the probability of the channel being in use by the primary service. Thus the secondary service capacity is:

$$C_s = E_{g_{ss}}\left[\log\left(1 + \frac{g_{ss}S_s}{N_0 + P_b I}\right)\right]. \qquad (22)$$

### C. Secondary service capacity Optimization

Once more we can define an optimization problem with the objective of maximizing secondary service throughput, under the constraint of primary service outage probability. This optimization problem is presented in the following.
Problem.2:

$$max\ C_s = E_{g_{ss}}\left[\log\left(1 + \frac{g_{ss}S_s}{N_0 + P_b I}\right)\right], \qquad (23.a)$$

$$s.t.\ E_{g_{ss}}[S_s] \le \overline{Ss}, \qquad (23.b)$$

$$P_b P\left(\frac{g_{pp}S_p}{g_{sp}S_s} < Q\right) \le \xi, \qquad (23.c)$$

$$S_s \ge 0. \qquad (23.d)$$

In general, the objective and the constraints are the same asin Problem.1. The same procedure explained in section 3.C is taken to obtain optimal secondary service power allocation. Optimal power allocation scheme is presented in (18). However,$\lambda_1^*$and $\lambda_2^*$ are calculated from:

$$\begin{cases} \int_{\theta}^{\infty}\left(\frac{1}{\lambda_1^* + \lambda_2^*} - \frac{N_0 + P_b I}{g_{ss}}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} = \overline{S_s} \\ \int_{\theta}^{\infty}\left(\frac{\frac{Q}{S_p}\left(\frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b I}{g_{ss}}\right)}{\frac{Q}{S_p}\left(\frac{1}{\lambda_1^*+\lambda_2^*} - \frac{N_0+P_b I}{g_{ss}}\right) + 1}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss} = \frac{\xi}{P_b} \end{cases} . \qquad (24)$$

Where $\theta = (N_0 + I)(\lambda_1^* + \lambda_2^*)$. Thus the maximum achievable capacity would be:

$$C_s = \int_{\theta}^{\infty} \log\left(\frac{g_{ss}}{(N_0 + P_b I)(\lambda_1^* + \lambda_2^*)}\right)\frac{e^{\frac{-g_{ss}}{\mu}}}{\mu}dg_{ss}. \qquad (25)$$

## V. Simulation and Numerical Results

In this section we evaluate the performances of overlay and underlay systems. The main parameter for the secondary service performance is the secondary service capacity. We have considered Monte-Carlo method with enough irritations to cover all possible outcomes and provide us with accurate statistical expectations. In overlay scenario an energy detection spectrum sensing according to the model presented in [14] has been used.Simulation parameters are summarized in Table.1.

Table.1: The Parameters used for simulations

| Parameter | Presentation | Value |
|---|---|---|
| **Primary user SNR** | $SNR_p$ | 3dB |
| **Secondary user SNR** | $SNR_s$ | 3dB |
| **Probability of busy channel** | $P_b$ | 20% |
| **Mean channel gain** | $\mu$ | 0dB |
| **Primary User outage threshold** | $Q$ | 0dB |
| **Primary user outage probability** | $\xi$ | 0.2 |
| **Miss detection probability** | $\delta$ | 0.02 |
| **False alarm probability** | | 0.3 |

The maximum achievable capacity of both systems versus probability of the channel being used by the primary service is shown in Fig.1. At near zero channel occupation probability, sensing error (false alarm) will prevent the overlay system to access all the spectrum holes. Thus the underlay system performs better. As $P_b$increases,spectrum sensing allows the overlay system to allocate most of its transmission power to instances where there is no primary service interference and thus achieve a higher capacitythan underlay systems. As channel occupation levels increase even further spectrum sensing limits the amount of time overlay systems have access to the spectrum and thus limit their capacity. A close comparison of (23.a) and (16.a) reveal the same performance expectation.

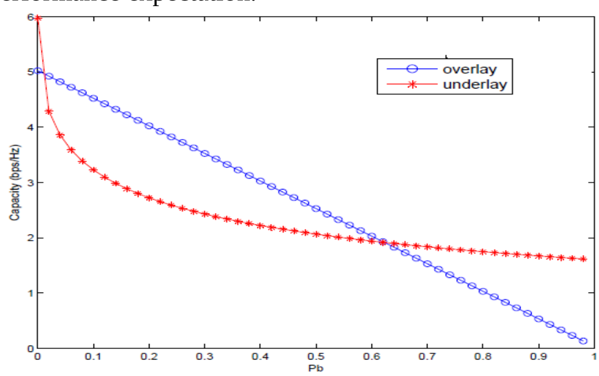


Fig.1 Maximum achievable capacity of overlay and underlay systems vs. channel occupation probability

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Fig.2 shows the maximum achievable capacity of overlay and underlay systems versus imposed primary interference. At low interference levels, the limiting factor is the access time to the spectrum. Underlay systems with no spectrum sensing to hold them back fair better in low interference environments. As interference levels increase, the positive effects of utilizing spectrum sensing overcome its negative effects. In overlay systems the average interference is lowered by a factor of $\delta$. A review of (20) and (25) indicates the same performance.

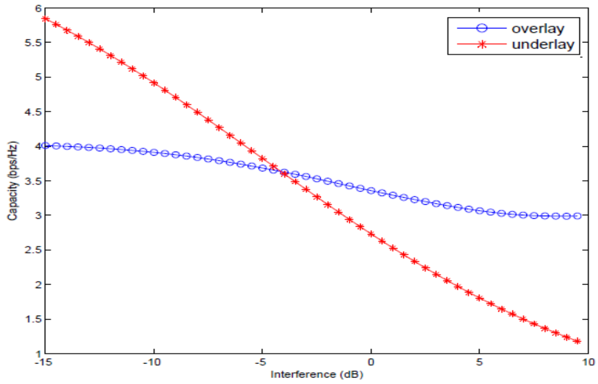


Fig.2. Maximum achievable capacity of overlay and underlay systems vs. imposed primary service interference

The maximum achievable capacity of overlay and underlay systemsversus different secondary service average SINR is show in Fig.3. At low SINR, there is not much difference between the two systems. However, more average access time to the spectrum gives underlay systems a slit advantage. As secondary service SINR increases, spectrum sensing allows overlay systems to allocate their power resource to instances where the primary service is not using the spectrum thus lowering interference. This improves the performance of overlay systems. The effects of power limitation on secondary service capacity are also apparent from (19) and (24) where limitations on power will result in smaller$\lambda_1^* + \lambda_2^*$, which intern will limit capacity.

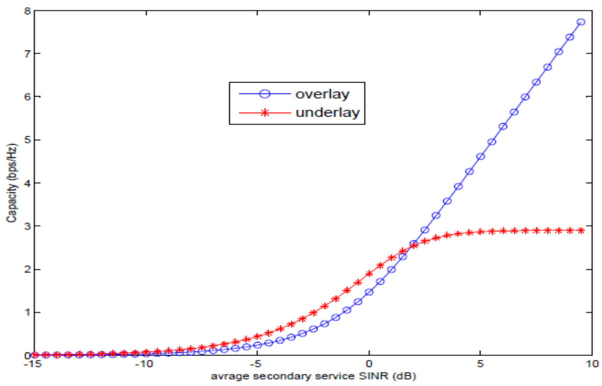


Fig.3. Maximum achievable capacity of overlay and underlay systems vs. secondary service average SINR

The Primary service outage probability is shown in Fig.4, as apparent the theoretical results obtained closely follow simulation results.

## VI. Conclusion

In this work, we have driven upper limits on achievable capacities under overlay and underlay spectrum sharing techniques. We have driven exact primary service outage probabilities. Optimization problems with the objective of maximizing secondary service capacitywith constraints on primary service outage probability were formulated and solved. All the work performed resulted in a mathematical frame work for comparing underlay and overlay systems.
From the numerical results obtained indicate underlay systems have superior performance at low primary activity or interference levels. In both casesspectrum sensing errors limits the access time of overlay systems which has a negative impact on their performance.

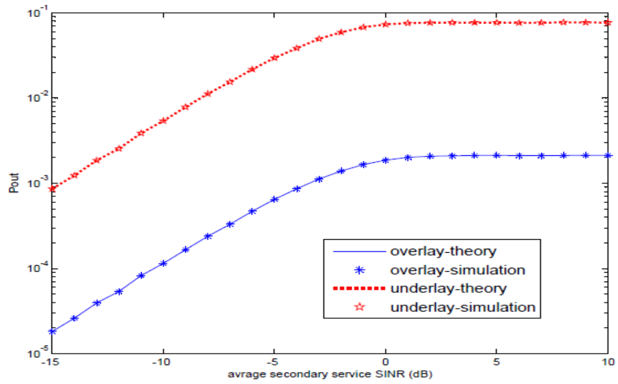


Fig.4. Primary service outage probability vs. secondary service average SINR

However, in highinterference situations spectrum sensing assists to allocate resources to times when the channel is not used by the primary service which not only helps to lower primary service outage probabilities but also lowers interference level at the secondary receiver and provides superior performance for overlay systems.

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