AN ANALYTICAL PERFORMANCE FOR MULTI-ANTENNA COGNITIVE RADIO NETWORK (CRN) SYSTEMS

G. SUSMITHA
PG Scholar, Dept.of ECE, CVS College of Engineering,
Tirupathi, A.P.
susmitha.g16@gmail.com

DR. V. THRIMURTHULU
Professor, Dept.of ECE,
C R Engineering College,
Tirupathi, A.P.
vtmurthy.v@gmail.com

K. JAGADISH KUMAR
Asst.Professor, Dept.of ECE, C R Engineering College,
Tirupathi, A.P.
jagadish.kasula@gmail.com

ABSTRACT

In this paper, an analytical performance study for multi-antenna Cognitive Radio (CR) systems is presented. The two most popular CR approaches, namely, the interweave and underlay system designs, are considered and based on the derived analytical framework, a throughput-based comparison of these two system designs is presented. The system parameters are selected such that a quality of service (QoS) constraint on primary communication is satisfied. Closed form expressions for the outage probability at the Primary User (PU), as well as expressions for the ergodic rate of the Secondary User (SU) are derived, for both system designs. The derived expressions are functions of key design parameters, such as the sensing time and the detection threshold in the case of interweave CR, and the maximum allowable interference power received by the PU, in the case of underlay CR. Based on the derived expressions, for interweave CR, the sensing parameters, i.e., sensing time and energy detection threshold, are optimized such as to maximize the secondary system rate. By comparing the throughput performance for both system designs, the existence of specific regimes (in terms of primary activity, number of transmit and receive antennas as well as the outage probability of the PU), where one CR approach outperforms the other, is highlighted.

Index Terms*—Cognitive radio, interweave, underlay, performance analysis, ergodic rate.*

INTRODUCTION

The massive spread of current wireless services and wireless communication evolution has given rise to a great need for bandwidth with the aim of offering various services with high data rates. As a consequence, the accessible radio spectrum is becoming critically scarce, as mentioned by the Federal Communications Commission (FCC) [1]. To overcome this obstacle, the notion of Cognitive Radio Networks (CRNs), introduced by Mitola [2], has emerged as a novel, promising technology, aiming to tackle the problem of spectrum scarcity and thus, to enhance spectral efficiency via optimizing the use of the-currently underutilized- radio spectrum [3], [4]. Up to the present, two popular CR design approaches have emerged: (i) Underlay CRNs, where a primary service provider allows the reuse of its spectral resources by an unlicensed secondary system, provided that a specified, maximum tolerated interference level generated by the secondary transmitter will not be violated and (ii) Interweave CRNs, in which the secondary network (either the transmitter or the receiver) senses the frequency spectrum and decides to transmit whenever the spectrum is not occupied by primary Transmissions.

Quite surprisingly and to the best of our knowledge, little effort has been made to compare such designs, based on a meaningful, fair, and even less so in an analytical manner.

Indeed, the philosophies behind each CRN approach seem incompatible at first glance. The underlay approach seems to be typically reserved for applications with only loose QoS guarantees at the legacy (primary) network. On the other hand, the interweave design is expected to offer a near-zero disturbance at the PU, hence seems to offer hard QoS guarantees. Upon closer inspection, it is clear that the QoS achieved at the PU under the interweave approach, strongly depends on the sensing capability at the secondary side.

Sensing imperfections due to a number of factors such as channel fading, shadowing, or noise give rise to miss-detection events, which, in turn, lead to outage events at the PU due to unintentional, harmful interference towards it (5). Arguably, a strictly conservative spectrum sensing design would ensure that near zero interference is generated at the PU. However, this strategy would inevitably lead to a wasteful spending of secondary communication resources, as it is practically difficult for the secondary system to sense and communicate at the same time.

Therefore, a low outage probability at the PU, induced by a high accuracy sensing goes at the cost of data rate for the SU. An interesting question lies in whether a similar trade-off can be explored for the underlay scenario and ultimately compared with that obtained in the interweave case. Our answer is positive. In the underlay case, a low outage probability at the PU is maintained through a suitable power control policy at the secondary transmitter, augmented with a possible beam forming (BF) solution, when the latter is equipped with several antennas.

More generally, a specific precoding and power allocation policy will lead to a specific point in the so-called outage (at PU) versus average rate (at SU) region. The above observations motivate us to compare the throughput performance of the interweave and underlay CRN approaches on an equal footing. More concretely, our aim is to compare the two CRN approaches with respect to the achievable SU ergodic rate, subject to a common outage probability at the PU. Marking the difference with prior CRN work, where the main quality indicator at the PU is expressed in terms of the event that the interference power, received by the PU, does not exceed a predefined threshold, we use a definition of outage with a greater relevance to the actual PU quality-of-experience. Here, an outage event is declared when the rate at the PU falls below a given threshold, whether due to interference or a fading event in its own channel.

The intuition is that a PU with a higher quality channel is likely to tolerate more interference, which ought to benefit the data rate of the secondary system. In this context, some interesting prior work is noteworthy. In [6], the throughput potential of different CR techniques has been investigated from an information theoretical point of view. Nevertheless, no expressions describing the achievable ergodic rate of the SU or the outage probability of the primary system are given considering a fading environment. Also, although expressions for the instantaneous rate of the SU are given, the assumption of perfect spectrum sensing is adopted, which is rather unrealistic within the CRN context.

Furthermore, novel spectrum sharing models are proposed, either mixed ones or variants of the interweave model, though no explicit performance comparison of the two mentioned CRN approaches is presented. Additionally, works such focus on the derivation of either approximations or closed form expressions for the ergodic rate of SU as well as for the outage probability of the primary system. Yet, no performance comparison between interweave and underlay CRN approaches is illustrated in these works. Finally, it is worth noticing that in [18] a performance-based comparison was conducted with respect to Single-Input-Single-Output (SISO) CRNs, which differs from the work in this paper.

I. CONTRIBUTION

In this paper, both the interweave and underlay CRN approaches are investigated with respect to a multiple antenna CRN and compared with reference to the ergodic rate of the SU for a target outage probability of the PU, as well as for various primary communication activity profiles and transmit antenna numbers. More concretely, our contributions are the following:

- Closed form expressions for the outage probability of primary communication, regarding both Multiple-Input- Single-Output (MISO) interweave and underlay CRN approaches, are derived.
- Expressions for the ergodic rate of the SU are derived with respect to both MISO CRN approaches.
- Motivated by the fact that current terminals are equipped with K = 2 antennas, the case of Multiple-Input-Multiple- Output (MIMO) CRNs with receive antenna selection is investigated later on. Expressions describing the PU outage probability and the average rate of the SU are derived, both for an interweave and for an underlay CRN.
- Rate-optimal values of each CR system's generic design parameters are found, corresponding to a common outage probability at the PU.
- The optimal SU ergodic throughput levels of the two CRN approaches are finally compared, under a target outage level of the PU, for various system scenarios. It is shown that the performance comparison results are driven by a set of key system parameters, such as the number of transmit and receive antennas, the activity profile of the primary system

as well as the targeted outage probability at the PU.

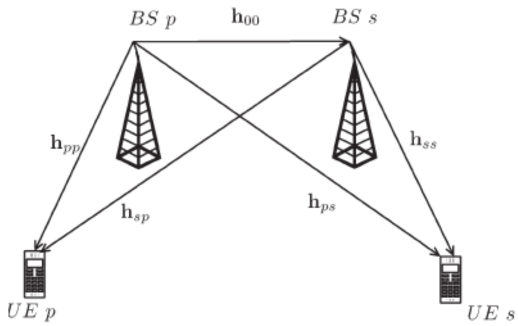

Fig. 1. MISO CRN-System topology.

II. COGNITIVE RADIO NETWORKS

A cognitive radio (CR) is an intelligent radio that can be programmed and configured dynamically. Its transceiver is designed to use the best wireless channels in its vicinity. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location. This process is a form of dynamic spectrum management.

In response to the operator's commands, the cognitive engine is capable of configuring radio-system parameters. These parameters include "waveform, protocol, operating frequency, and networking". This functions as an autonomous unit in the communications environment, exchanging information about the environment with the networks it accesses and other cognitive radios (CRs). A CR "monitors its own performance continuously", in addition to "reading the radio's outputs"; it then uses this information to "determine the RF environment, channel conditions, link performance, etc.", and adjusts the "radio's settings to deliver the required quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints".

Some "smart radio" proposals combine wireless mesh network—dynamically changing the path messages take between two given nodes using cooperative diversity; cognitive radio—dynamically changing the frequency band used by messages between two consecutive nodes on the path; and software-defined radio—dynamically changing the protocol used by message between two consecutive nodes.

III. PERFORMANCE ANALYSIS OF THE INTERWEAVE APPROACH

A. General Model

We consider first the interweave approach, as it is shown in Fig. 2, where each Medium Access Control (MAC) frame is assumed to have a duration of T time units, including a subframe dedicated to spectrum sensing, which lasts for $\tau<T$ time units. The rest of the frame is dedicated to data transmission.

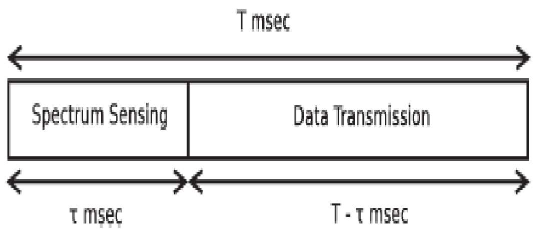

Fig. 2. MAC frame structure.

Moreover, during each sensing phase, BS s receives N = τ fs samples, where fs is the sampling frequency of the received signal. It is also assumed that during sensing, BS s is kept silent and all instantaneous channels remain constant within a MAC frame. It should be noted that the spectrum sensing process takes place at the secondary transmitter as opposed to e.g., at the receiving terminal side, thereby bypassing the need for a dedicated sensing feedback channel. Energy detection is applied as it is a popular and easily applicable spectrum sensing scheme1 [21]. At the n-th, n = 1,2, . . . ,N time instant, the binary hypothesis test for spectrum sensing is expressed as

$$y_s[n] = \begin{cases} z(n) & \text{if } \mathcal{H}_0 \\ h_{00} w_p S_p[n] + z[n], & \text{if } \mathcal{H}_1, \end{cases} \quad (1)$$

where additive noise z[n] is a CSCG, independent, identically distributed (i.i.d.) process with z[n] ∼ CN(0,N0) and the information symbol sp[n] is selected from a CSCG codebook, i.e., sp[n] ∼ CN(0,1) and is independent of z[n]. Vector wp ∈ CM×1 is the applied BF vector at BS p. We assume that when the primary system is in transmission mode, Maximal Ratio Transmission (MRT) BF with full power is applied at BS p (and this will hold in what follows in the paper), since the goal of the primary transmitter is to maximize the rate of the PU. Similarly, when the secondary system decides to transmit, also full power MRT BF is applied at BS s. Hence, we obtain the following expressions for the unit-norm beam formers (BFs):

$$w_p = \sqrt{P_p}\frac{h_{pp}^H}{\|h_{pp}\|} = \sqrt{P_p}\tilde{h}_{pp}^H \quad (2)$$

and

$$w_s^{int} = \sqrt{P_s}\frac{h_{pp}^H}{\|h_{ss}\|} = \sqrt{P_s}\tilde{h}_{ss}^H \quad (3)$$

Respectively. Pp and Ps stand for the maximum available instantaneous power levels at BS p and BS s, respectively. As it can be easily derived, signal s[n] = h00wpsp[n], for a fixed channel h00, will have a variance of σ2s = E{|s[n]|2} =Pp|h00˜hHpp|2.

For a fixed sensing time, τ, along with a fixed energy detection threshold, ε, by applying the central limit theorem, the probability of false alarm, Pf a, as well as the corresponding probability of detection, Pd, can be derived, with reference to a specific MAC frame, by applying [22, Proposition 1, Proposition 2]. The above probabilities can then be written as

$$\mathcal{P}_{fa} = \mathbb{Q}\left(\sqrt{N}\left(\frac{\epsilon}{N_0}-1\right)\right), \mathcal{P}_d = \mathbb{Q}\left(\frac{\varepsilon-\mu_1}{\sigma_1}\right) \quad (4)$$

Where $\mu_1 = \sigma_s^2 + N_0 = P_p\left|h_{00}\tilde{h}_{pp}^H\right|^2 + N_0$

and

$$\sigma_1^2 = \frac{N_0^2}{N}\left(\frac{P_p\left|h_{00}\tilde{h}_{pp}^H\right|^2}{N_0} = +1\right)^2$$

The average detection probability with reference to random variable (RV) $\beta_{00} = \left|h_{00}\tilde{h}_{pp}^H\right|^2$ is given as

$$\mathcal{P}_d^{avg} = \int_0^\infty \mathcal{P}_d(\beta_{00}) f_{\beta_{00}}(\beta_{00}) d\beta_{00}$$

(5)

Although we need an expression for P avgd as a function of τ and ε so as to maximize the rate of the SU over these two parameters, doing this proves to be difficult due to the lack of a closed form expression of (5). Instead, we now resort to a bounding argument to solve this problem approximately. Note that the accuracy of this bounding strategy is justified by our simulations in Section VII. To obtain a bound on (5), we use the fact that the detection probability in (4), although neither strictly concave nor convex as a function of β00, is concave in the region of interest for β00 (the region corresponding to high detection probability). Therefore, by applying Jensen's inequality, the following bound can be derived

$$\mathcal{P}_{d,B} = Q\left(\sqrt{N}\left(\frac{\varepsilon}{P_p\sigma_{00}^2 + N_0} - 1\right)\right) \qquad (6)$$

Regarding the average false alarm probability, it remains the same under any fading channel, for given τ and ε, since Pf a is considered for the case where only noise is present, thus

$$\mathcal{P}_{f_a}^{avg} = \mathcal{P}_{f_a} \qquad (7)$$

B. Outage Probability of Primary Communication

Although the interference power at the PU is used as a quality indicator in much of the CRN literature, we point out that when it comes to primary data rate, it is the Signal-to-Interference plus Noise Ratio (SINR) at the PU which rather governs performance. To reflect this, we assume an outage at the PU when, given that the primary network is active, the SINR of the PU is below a predefined threshold, γ0. This can occur in two cases: 1) when BSs fails to sense primary activity (missed detection), potentially resulting to a PU SINR that is less than γ0 or when the secondary system has correctly detected the presence of a primary signal and remains silent for the rest of the MAC frame. Yet, the desired signal received at the PU is in deep fade, so that the SINR falls below the threshold γ0.In the proposition that follows, a closed form expression of PU outage probability is given. Proposition 1: The outage probability of primary communication for a MISO interweave CRN is given by the following expression

$$\mathcal{P}_{out}^{int} = (1 - \mathcal{P}_d)\mathcal{P}_1 + \mathcal{P}_d\mathcal{P}_2$$

(8)

Where probabilities $\mathcal{P}_1$ and $\mathcal{P}_2$ are the following

$$\mathcal{P}_1 = 1 - \frac{e^{-\gamma_0 N_0 B\left(\frac{1}{\lambda_{X_1}} - \tilde{\mu}\right)}}{\lambda_{X_2}\lambda_{X_1}^M}\sum_{k=0}^{M-1}\frac{\lambda_{X_1}^{M-k}}{k!\tilde{\mu}^{k+1}}\Gamma(k + 1, \gamma_0 N_0 B\tilde{\mu})$$

(9a)

$$\mathcal{P}_2 = \frac{\gamma\left(M, \frac{\gamma_0 N_0 B}{\lambda_{X_1}}\right)}{\Gamma(M)} \quad (9b)$$

With $\lambda_{X_1} = P_p \sigma_{pp}^2, \lambda_{X_2} = \gamma_0 P_s \sigma_{sp}^2$

and $\tilde{\mu} = \frac{1}{\lambda_{X_1}} + \frac{1}{\lambda_{X_2}}$

C. Ergodic Rate of Secondary Communication

By applying the upper bound for the average detection probability, Pd,B, the ergodic rate of the SU will have a lower bound, that is given by

$$\mathbb{E}\{R_s^{int}\} \geq \frac{(T-\tau)}{T}\Bigg((\mathcal{P}(\mathcal{H}_0)(1-\mathcal{P}_{fa})B\mathbb{E})\left\{\underbrace{\log_2\left(1+\frac{\mathcal{P}_s\|h_{ss}\|^2}{N_0 B}\right)}\right\} + (\mathcal{P}(\mathcal{H}_1)(1-\mathcal{P}_{d,B})B\mathbb{E})\left\{\underbrace{\log_2\left(1+\frac{P_s\|h_{ss}\|^2}{N_0 B+P_p|h_{ps}\tilde{h}_{pp}^H|^2}\right)}\right\}\Bigg) \quad (10)$$

$$\mathbb{E}\{\mathcal{A}_1\} = \frac{1}{\ln(2)}\sum_{j=0}^{M-1}\frac{1}{(M-j-1)!}\left(\frac{(-1)^{M-j-s}}{\left(\frac{\lambda_{Y_1}}{N_0 B}\right)^{M-j-1}} e^{\frac{N_0 B}{\lambda_{y_1}}} \times E_1\left(\frac{N_0 B}{\lambda_{Y_1}}\right)\right) + \left(\frac{N_0 B}{\lambda_{Y_1}}\right) \quad (11)$$

a closed form expression for the outage probability of the PU, as well as an expression for the ergodic rate of the SU will be derived considering a MISO underlay CRN. Both cases of MRT as well as Zero-Forcing (ZF) BF at the secondary transmitter will be examined.

V. PERFORMANCE ANALYSIS OF THE UNDERLAY APPROACH

A. Power and BF Policies

In the underlay approach, the secondary transmitter is in principle always active. It maintains the prescribed PU outage probability level by suitably adjusting its transmitting power and BF vector. To do so, note that the secondary transmitter requires some knowledge about interference channel hsp, which is otherwise not needed in the interweave scenario. This information is assumed to be obtained via feedback in Frequency Division Duplex (FDD), or reciprocity in Time Division Duplex (TDD) scenarios.

Our Channel State Information at the Transmitter (CSIT) model, nevertheless, leaves the direct primary channel, hpp, unknown at the secondary transmitter; hence the power policy is designed to depend only on the interference channel gain and on the statistics of channel hpp. In such conditions, the secondary transmit power is adapted to meet an average outage constraint at the PU. When it comes to BF, we will focus on the MRT strategy, as in the interweave case. At the end of this section, we also compare with a ZF strategy, for reference. However, this would require full interference channel knowledge.

B. Power Policy at the Secondary Link under MRT BF

To meet an average outage level at the PU, the secondary transmitter adapts its power, Pund s,MRT to meet a certain interference level, I. The optimal interference level is not known a priori but it can be optimized on the basis of the instantaneous interference gain and the statistics of channel hpp. The maximum instantaneous power level is taken to be equal to the one considered in the interweave approach to conduct a fair comparison from a power consumption perspective.

A closed form expression for the outage probability of primary communication, as well as an approximation of the achievable ergodic rate of the SU, will be derived, focusing on the underlay CRN approach, when MRT BF is applied at the secondary transmitter.

IV. OPTIMIZING GENERIC DESIGN PARAMETERS OF THE CRN APPROACHES

In this section, the generic design parameters of each of the two examined CRN approaches will be optimized in the sense of maximizing the ergodic rate of the SU, subject to an outage probability constraint for primary communication, denoted by Po. In what follows, we start with the interweave CRN approach.

Algorithm 1 Optimizing □□and □□for a given Po

1 Initialization (n = 0). Select a □0 ∈ (0,T] and increase
counter by one.

2 For the n-th iteration, compute value □n as follows

$$\tau_n = \tau_{n-1} + \lambda \frac{\partial U(\tau)}{\partial \tau}\Big|_{\tau=\tau_{n-1}}$$

Increase counter n by one and if n > Nmax,1, where Nmax,1 is a maximum number of iterations, stop (given that □n ∈ (0,T]), otherwise go to Step 2.

4 Having found □∗ compute the corresponding

$$\varepsilon^* = m_1\left(\frac{\delta}{\sqrt{\tau^* f_s}} + 1\right)$$

In what follows, the level, I, of interference power received at the PU, corresponding to the same target outage probability, Po, will be derived for the underlay CRN approach when MRT BF is applied at BS s.

Algorithm 2 Determining I∗ for a given Po

1 Initialization (n=0). Select an I0 ≥0 and increase counter by one.

2 For the n-th iteration, compute value In as follows

$$\mathfrak{I}_n = \mathfrak{I}_{n-1} - f(\mathfrak{I}_{n-1})\left(\frac{df(\mathfrak{I})}{d\mathfrak{I}}\Big|_{\mathfrak{I}=\mathfrak{I}_{n-1}}\right)^{-1}$$

3 Increase counter n by one and if n > Nmax,2, where Nmax,2
is a maximum number of iterations, stop, otherwise go to Step 2.

V. EXPERIMENTAL RESULTS

To evaluate the performance of the examined CRN approaches under different conditions, extensive Monte Carlo (MC) simulations have been performed with the aim of confirming the validity of the derived theoretical expressions. More specifically, 5000 MAC frames were simulated.

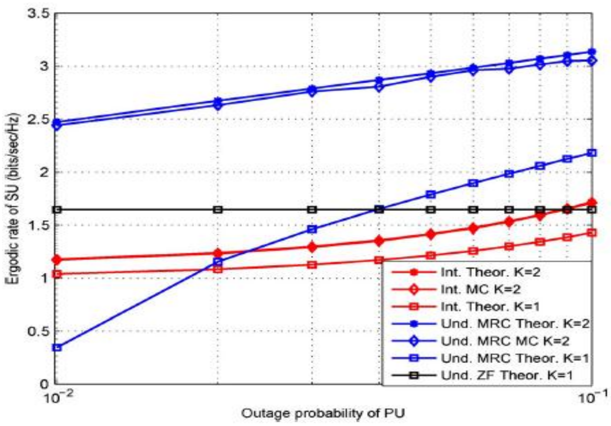

Fig.3. Ergodic SU rate vs. PU outage probability for a MISO and a MIMO CRN, P(H1) = 0.8.

We assume that each BS is equipped with M = 4 antennas and the strengths of the direct links are: σ2 pp = σ2 ss = 10 dB. Moreover, we set B =1 Hz, fs =6MHz and T = 100 ms. For simplicity, we have set the noise variance equal to unity. In addition, the SINR level of the PU, γ0, below which an outage occurs is chosen to be equal to 9 dB.

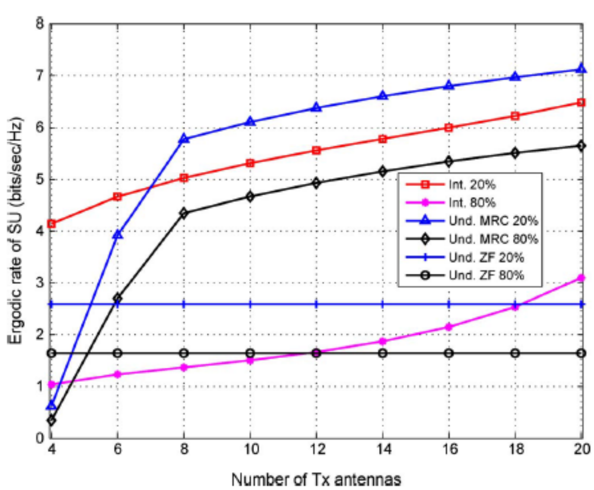

Fig. 4. Ergodic SU rate vs. number of transmit antennas,M, for aMISO CRN. The target PU outage probability is Po = 0.01.

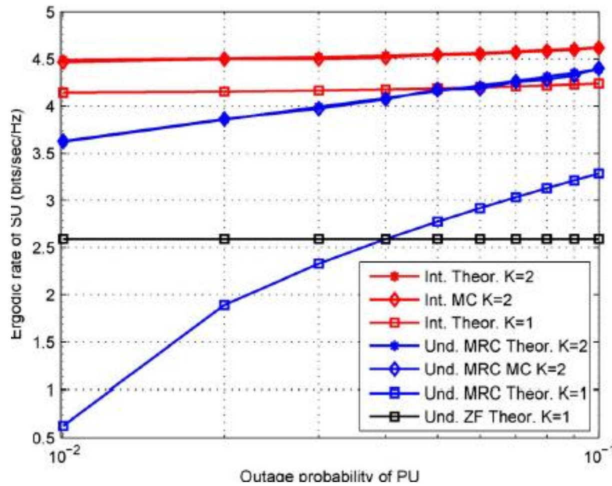

Fig. 6. Ergodic SU rate vs. PU outage probability for a MISO and a MIMO CRN, P(H1) = 0.2.

VI. CONCLUSION

In this paper, the interweave CRN approach was examined and compared with the underlay CRN approach in terms of the ergodic throughput of the SU for a common PU outage level. Expressions for the ergodic rate of the SU as well as for the outage probability of primary communication, were derived for multiple antenna CRNs, representing both approaches. It was shown that the performance comparison results are driven by a set of key system parameters which are: (a) the activity profile of the primary system, (b) the number of transmit and receive antennas and (c) the targeted outage probability at the PU.

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AUTHORS

G.SUSMITHA received her B.Tech

Degree in Electronics and Communication Engineering from kandula lakshummama engineering college for women kadapa(A.P), India, in the year 2013. Currently pursuing her M.Tech degree in DECS Stream at Chadalawada

Venkata subbaiah Engineering College, Tirupati(A.P), India.. Her area of research Includes in An Analytical Performance for Multi-Antenna Cognitive Radio (Cr) Systems.

Dr.V.THRIMURTHULU

M.E., Ph.D., MIETE., MISTE Professor & Head of ECE Dept. He received his Graduation in Electronics & Communication Engineering AMIETE in 1994 from Institute of Electronics & Telecommunication Engineering, New Delhi, Post Graduation in Engineering M.E specialization in Microwaves and Radar Engineering in the year Feb, 2003, from University College of Engineering, Osmania University, Hyderabad., and his Doctorate in philosophy Ph.D from central University, in the year 2012. He has done his research work on Ad-Hoc Networks.

K.JAGADEESH

Asst. professor ECE, He received his

Graduation in Electronics & Communication Engineering in Gates Engineering college Gooty in the year of 2007(A.P). Post Graduation Engineering specialization in Digital electronics and communication system in the year of 2013, from Kottam thulasi reddy Engineering college (A.P), India.