Cross-Layer Analysis and Performance Evaluation of Cognitive Radio Networks

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Abstract—**This paper investigates the traffic capacity and the quality of service provisioning in cognitive radio networks used as secondary networks for dynamic spectrum access in accordance with the hierarchical spectrum overlay approach. An analytical model for cross-layer performance analysis of secondary cognitive radio networks is developed. New performance measures for the interference experienced by the primary and the secondary users are proposed. A novel approach for evaluation of the call dropping probability of the secondary users is suggested.**

Keywords-cognitive radio; cross-layer analysis; dynamic spectrum access; quality of service; traffic capacity

I. INTRODUCTION

Cognitive radio (CR) is the key enabling technology for dynamic spectrum access (DSA) [1]. DSA is a new paradigm for spectrum regulation which is expected to solve the problem with the inefficient spectrum use caused by the current static command-and-control approach for spectrum regulation (see [2] and the references therein). Radio spectrum is a scarce and precious resource and the spectrum demands grow increasingly due to newly emerging wireless services and applications. Therefore, efficient spectrum utilization becomes a matter of great importance.

Hierarchical spectrum overlay is an approach for DSA where secondary (unlicensed or cognitive) users (SUs) are allowed to use opportunistically and on a non-interference basis spectrum resources which have been assigned to primary (licensed or incumbent) users (PUs) but are not currently being used (by any PU). The SUs transmit on momentarily unoccupied spectrum segments without causing harmful interference to the PUs. Because of the dynamic nature of the spectrum available to the SUs, the capacity evaluation and the quality of service (QoS) provisioning for the SUs is a challenging and demanding task.

There are many publications on CR used for DSA in the literature. Issues related to spectrum sensing are investigated in [3]-[9]. Spectrum handover is studied in [10]-[13]. QoS-related issues in CR networks (CRNs) are investigated in [14]-[19]. The capacity of CRNs is considered in [20]-[22].

Due to the nature of CR, cross-layer analysis has to be applied for a comprehensive and exhaustive performance evaluation. There are numerous publications related to cross-layer issues in CRNs (see [23]-[30]). An overview of the general methodology for cross-layer design and some cross-layer optimization schemes and algorithms are presented in [23]. Unified cognitive cross-layer architecture for the next-generation IP-based mobile tactical networks is proposed in [24]. The resource allocation problem in a multiuser orthogonal frequency division multiplexing (OFDM) based CR system concerning the QoS provisioning for both real-time and non-real-time applications is investigated in [26]. Although the papers mentioned above provide important results, they do not present a thorough CRN performance evaluation encompassing jointly the capacity, the QoS provisioning, and some specific CR mechanisms, such as spectrum sensing and spectrum handover.

In this paper, a general and comprehensive cross-layer analytical model for thorough performance evaluation of CRNs is developed. It jointly considers the CR throughput and capacity, the CR QoS provisioning, namely the SU call dropping probability and the maximum tolerable transmission delay in the CRN, and the spectrum sensing and spectrum handover mechanisms. To the best knowledge of the author, the present paper is the first in the literature to propose and apply such a model.

The rest of the paper is organized as follows. The novel cross-layer model is presented in Section II, followed by numerical results in Section III. Section IV concludes this paper.

II. THE ANALYTICAL CROSS-LAYER MODEL

In the model, each SU is assumed to use one and the same transceiver for spectrum sensing and for transmission or reception. Spectrum sensing is performed periodically in compliance with predetermined quiet periods (QPs) during which all SUs stop transmitting to sense PU channels.

In general, physical layer spectrum sensing for PU transmitter detection can be based on energy detection, matched filter detection, and cyclostationary feature detection [3], [4]. The latter two approaches outperform the energy-based detection but require some prior knowledge about the PU signals which may not always be readily available. In order to preserve the generality and the wide applicability of the proposed model, energy-based spectrum sensing is considered and assumed to be applied.

Spectrum sensing may be cooperative or non-cooperative [4], [5]. In general, the former outperforms the latter. Cooperative spectrum sensing has already been exhaustively investigated (see [4], [5], [7] and [8]) and its advantages over non-cooperative spectrum sensing will not be discussed herein. Since under certain conditions (e.g., if only one SU operates on a given frequency band) cooperative spectrum sensing may not be possible, non-cooperative spectrum

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sensing is assumed in order to develop a general and widely applicable framework for cross-layer analysis.

Energy-based spectrum sensing is assumed to be performed with the optimal sensing threshold, i.e. the probability for misdetection is equal to the probability for false alarm:

$$1 - p_d = p_f = p_e, \tag{1}$$

where p_d is the probability for detection, p_f is the probability for false alarm, and p_e is the probability for detection error.

Under these conditions, the probability for detection error can be expressed in terms of the Q-function [3]:

$$p_e = \mathrm{Q}\left(\sqrt{N_B}\,\frac{SNR}{1+\sqrt{(\alpha-1)SNR^2+SNR+1}}\right), \tag{2}$$

where SNR is signal-to-noise ratio (SNR) of the PU signal, α is an intrinsic PU signal parameter that relates to its randomness ($1 \le \alpha \le 2$; $\alpha=1$ for constant amplitude signals, e.g. BPSK, QPSK, and $\alpha=2$ for complex Gaussian signals), and N_B is the buffer size expressed as a number of samples.

According to the Nyquist-Shannon sampling theorem, we have:

$$N_B = 2BW\tau, \tag{3}$$

where τ is the spectrum sensing duration for one PU channel and BW is the bandwidth of a PU channel.

Substituting (3) into (2), τ can be obtained for given p_e, SNR, BW, and α.

Let us denote with T_{ss} the total duration of the spectrum sensing procedure for a SU during one QP and with r the number of observed (sensed) PU channels. Then, we have:

$$T_{ss} = \sum_{i=1}^{r} \tau_i, \tag{4}$$

where τ_i is the duration of the spectrum sensing for the i^{th} observed PU channel.

It should be noted that if the number of PU channels n in the system is relatively large, it is unreasonable for a SU to sense all the PU channels. Therefore, it can be assumed that the following relation holds true:

$$r << n. \tag{5}$$

Let us denote with T_p the duration of the spectrum sensing period. For simplicity, T_{ss} is assumed to be equal to the duration of the QPs. Consequently, the nominal SU transmission time t within one spectrum sensing period is:

$$t = T_p - T_{ss}. \tag{6}$$

It should be noted that due to misdetections, false detections, and the PU activity, the mean effective SU transmission time T_{eff} within one spectrum sensing period is actually less than the nominal transmission time t.

Let us denote with T_{int} the mean interference duration within one spectrum sensing period due to simultaneous PU and SU transmissions on the same PU channel. The cognitive medium access control (MAC) protocol of the CRN is assumed to provide perfect spectrum sharing among SUs, so that no interference occurs due to overlapping SU transmissions.

The proposed approach for evaluation of T_{int} and T_{eff} is similar to that in [4] but unlike the method used in [4] where a single-channel primary system is considered, the derivation of T_{int} and T_{eff} presented in this paper is generalized in order to be applicable to a multichannel primary system.

The PU call arrival and service processes are modeled by Poisson random processes with rates λ_p and μ_p, respectively. Hence, the offered PU traffic is:

$$A_p = \frac{\lambda_p}{\mu_p}, \tag{7}$$

and the PU call blocking probability B_p can be evaluated according to the Erlang loss formula:

$$B_p = E_n(A_p) = \frac{\frac{A_p^n}{n!}}{\sum_{i=0}^{n}\frac{A_p^i}{i!}}. \tag{8}$$

The carried PU traffic per one PU channel, i.e. the mean PU channel utilization, is:

$$\eta = \frac{A_p\left(1-B_p\right)}{n}. \tag{9}$$

The mean number of available (unoccupied by PU transmissions) channels to the CRN is:

$$a = floor\left[n - A_p\left(1-B_p\right)\right], \tag{10}$$

where *floor* is a function that rounds its argument to the nearest integer towards minus infinity. It should be noted that when $n > 1$ (a multichannel primary network is considered) and the PU network is not overloaded with PU traffic, the relation $a > 0$ always holds true; otherwise, if the PU network is overloaded or congested by PU calls, the use of CR for DSA is obviously unreasonable.

Taking into account the negative exponential distributions of the inter-arrival time and the service time of PU calls, η, a, t, and the possibilities for misdetection and false detection, T_{int} and T_{eff} can be derived as follows:

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$$T_{int} = \eta(1-p_d)\left[te^{-\mu_p t} + \eta t\left(1-e^{-\mu_p t}\right)\right] + \\ +(1-\eta)(1-p_f)\frac{\left(1-e^{-\lambda_p t}\right)}{a}\eta t, \quad (11)$$

where the first addend in (11) refers to the case in which a SU misdetects an occupied PU channel, starts transmitting on that channel and the PU call does not end until the next spectrum sensing period or ends before the next spectrum sensing period; the second addend in (11) refers to the case in which a SU starts transmitting on an available channel and later a new PU call arrives and occupies that channel;

and

$$T_{eff} = (1-\eta)(1-p_f)\begin{bmatrix} te^{-\lambda_p t} + \left(1-e^{-\lambda_p t}\right)\left(1-\frac{1}{a}\right)t + \\ +\frac{\left(1-e^{-\lambda_p t}\right)}{a}(1-\eta)t \end{bmatrix} + \\ +\eta(1-p_d)\left(1-e^{-\mu_p t}\right)(1-\eta)t, \quad (12)$$

where the first addend in (12) refers to the case in which a SU starts transmitting on an available channel and no PU calls arrive until the next spectrum sensing period or a new PU call arrives before the next spectrum sensing period but occupies another available channel or occupies the same channel; the second addend in (12) refers to the case in which a SU misdetects an occupied PU channel, starts transmitting on that channel and the PU call ends before the next spectrum sensing period.

In (11) and (12), ηt is assumed to be the mean interference duration when a SU starts transmitting on an available channel and a new PU call occupies that channel before the beginning of the next QP or when a SU misdetects and starts transmitting on an occupied channel and the ongoing PU call ends before the next QP.

Now the CRN throughput and capacity can easily be derived. The normalized mean effective transmission time ρ of a SU is:

$$\rho = \frac{T_{eff}}{T_p}. \quad (13)$$

The CR is assumed to use non-contiguous OFDM (NC-OFDM) waveform. NC-OFDM allows the CR to deactivate (null) the subcarriers overlapping with any PU transmission and thus to adjust the spectrum of its signal to fit into the available frequency gaps [17]. Furthermore, CR with NC-OFDM can be deployed in any primary network irrespective of its channelization scheme and even if fixed channelization is not supported, which facilitates the wide applicability of the model developed in this paper. It has already been assumed that perfect spectrum sharing is provided by the cognitive MAC protocol. Based on the above-mentioned assumptions, the mean throughput of the CRN C (bit/s) can be obtained:

$$C = n\varepsilon BW\rho, \quad (14)$$

where ε is the mean spectral efficiency (bit/s/Hz) of the SUs.

The CRN can be considered as a serving system with m channels:

$$m = floor\left[\frac{C}{c}\right], \quad (15)$$

where c (bit/s) is the necessary mean rate for a SU call to be served.

The traffic capacity of the CRN can be determined according to the Erlang loss formula:

$$B_s = E_m(A_s) = \frac{\frac{A_s^m}{m!}}{\sum_{i=0}^{m}\frac{A_s^i}{i!}}, \quad (16)$$

where A_s is the offered SU traffic and B_s is the SU call blocking probability.

In order to evaluate the interference experienced by the PUs and to guarantee that the CRN will not degrade the performance of the primary network, the following constraints have to be satisfied:

$$t \le T_{int}^{max}, \quad (17)$$

and

$$\gamma = \frac{T_{int}}{T_p} \le \gamma_{max}, \quad (18)$$

where T_{int}^{max} is the maximum tolerable interference duration in the PU network and γ_{max} is the maximum tolerable normalized mean interference duration. In (18), γ is introduced as a new precise performance measure for the interference experienced by the PUs.

In order to evaluate the interference experienced by the SUs, another new performance measure δ is proposed which is implicitly relevant to the CR QoS provisioning:

$$\delta = \frac{T_{int}}{T_{eff} + T_{int}}. \quad (19)$$

Next, the SU QoS provisioning is analyzed. A novel approach for evaluation of the SU call dropping probability which incorporates the maximum tolerable transmission delay in the CRN is proposed. It is particularly applicable to the system model considered in this paper.

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It can be assumed without loss of generality that SU call dropping occurs only if SU connection failure occurs. SU connection failure occurs when a SU is unable to transmit during several consecutive spectrum sensing periods and the maximum tolerable transmission delay D in the CRN is exceeded. It should be noted that D is a QoS-dependent parameter and may vary according to the type of application.

Let us denote with q the minimum number of consecutive spectrum sensing periods for which SU connection failure occurs if a SU does not have a successful transmission during all of these periods. Therefore, we have:

$$q = floor\left[\frac{D}{T_p}\right] + 1. \tag{20}$$

A SU is unable to transmit during a spectrum sensing period either due to misdetection and continuous interference during the nominal transmission time t, or due to detections of PU transmissions or false alarms on all of the observed channels. No transmission opportunities are missed due to unsuccessful spectrum handovers since the cognitive MAC protocol is assumed to provide perfect spectrum handover procedure. Consequently, taking into account the above considerations and (5), the SU connection failure probability p_{cf} is obtained:

$$p_{cf} = \sum_{i=0}^{q} \binom{q}{i} \left[\eta\left(1-p_d\right)e^{-\mu_p t}\right]^{i} \left[\eta p_d + \left(1-\eta\right)p_f\right]^{r(q-i)}. \tag{21}$$

III. NUMERICAL RESULTS

In this section, some numerical results (Fig. 1 – Fig. 6) obtained using the analytical model described above are presented and analyzed. For simplicity, but without loss of generality, it has been assumed that the SNR of the PU signals is equal on all of the n PU channels and that the duration of the QPs is equal to the duration of the spectrum sensing procedure T_{ss}.

Fig. 1 - Fig. 3 show the SU transmission efficiency ρ, the interference experienced by the PUs γ and by the SUs δ, and the SU call dropping probability, i.e. the SU connection failure probability p_{cf}, as a function of the spectrum sensing period T_p for different number of observed channels r. When T_p increases, ρ, γ, δ, and p_{cf} also increase. As r increases, ρ, and p_{cf} decrease but the change in γ and δ is negligible. Moreover, when $T_p >> \tau$ and r is relatively small (as it has already been assumed in (5)), a change in r slightly affects ρ. Therefore, in this case, T_p has a dominant effect on both the CR throughput and on the interference, whereas r has a dominant effect only on the SU call dropping probability and affects the CR throughput to a significantly lesser extent in comparison with T_p.

New performance measures γ and δ for evaluation of the interference experienced by the PUs and by the SUs have been proposed. In order to guarantee that the CRN operates on a non-interference basis both (17) and (18) have to be satisfied. When ρ is high and δ is relatively low, the CR operates efficiently under low interference. If δ is relatively high, the CR operates in a high interference environment either because of improper configuration of the spectrum sensing mechanism or because of unfavorable conditions for DSA, e.g. very high PU traffic load.

Fig. 1 and Fig. 3 also show that if r increases, ρ and p_{cf} both decrease, and vice versa. Consequently, by increasing r, it is possible to achieve more reliable communications in the CRN at the price of reduced throughput and capacity.

Fig. 4 illustrates that the SU call dropping probability, i.e. the SU connection failure probability p_{cf}, decreases if the maximum tolerable transmission delay D in the CRN increases. As r increases, p_{cf} also decreases. Since D depends on the QoS requirements of the provided service, it can be concluded that the CR is particularly suitable for delivering of non-real-time delay-tolerant services.

Fig. 5 shows the CR traffic capacity A_s as a function of the signal-to-noise ratio SNR of the PU signals. As SNR increases, the time required for spectrum sensing decreases. Therefore, the nominal transmission time t, and thus A_s, both increase. However, in order to satisfy the interference constraints (17) and (18), it may be necessary to reduce t by decreasing T_p. Due to the strong dependence of A_s on SNR, PU channels with higher SNR should be preferred for spectrum sensing.

Fig. 6 shows the CR traffic capacity A_s as a function of the offered PU traffic A_p. As A_p increases, spectrum sensing has to be performed more frequently in order to satisfy the interference constraints imposed by the primary network, which means that T_p, and thus ρ and A_s, both decrease. The interplay of PU traffic and SU traffic should always be carefully considered. The deployment of CRNs for DSA is reasonable only if the primary network is sufficiently underutilized.

The presented numerical results in this section lead to the general conclusion that many cross-layer interdependencies, such as those analyzed herein, should be considered in order to achieve optimal CRN performance.

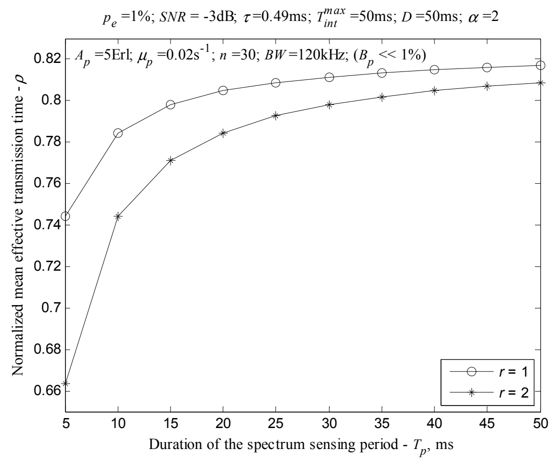

Figure 1. Transmission efficiency versus the spectrum sensing period for different number of observed channels.

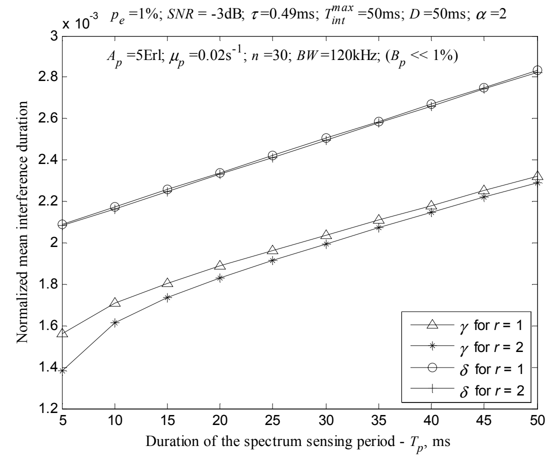

Figure 2. Interference experienced by the PUs (γ) and by the SUs (δ) versus the spectrum sensing period for different number of observed channels.

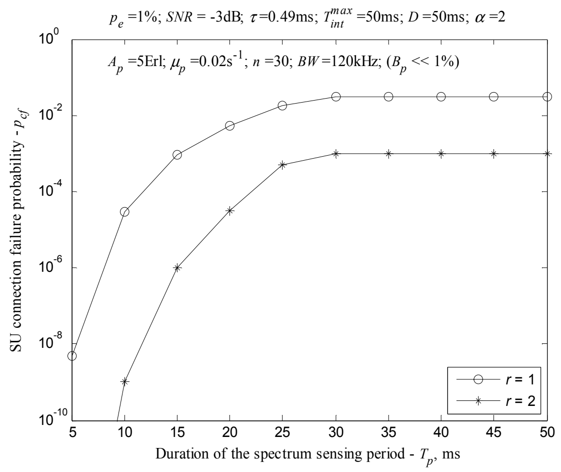

Figure 3. SU call dropping probability versus the spectrum sensing period for different number of observed channels.

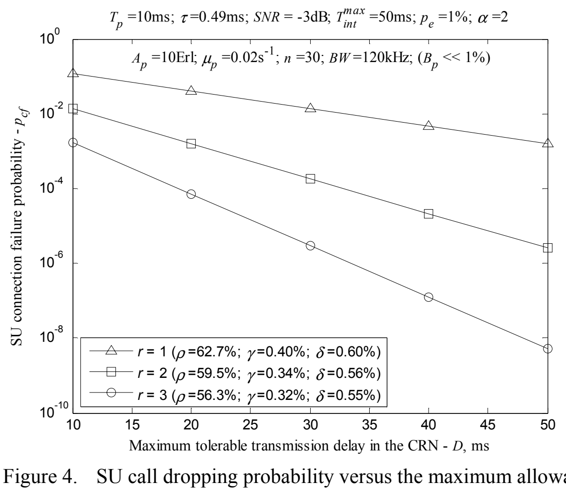

Figure 4. SU call dropping probability versus the maximum allowable transmission delay in the CRN for different number of observed channels.

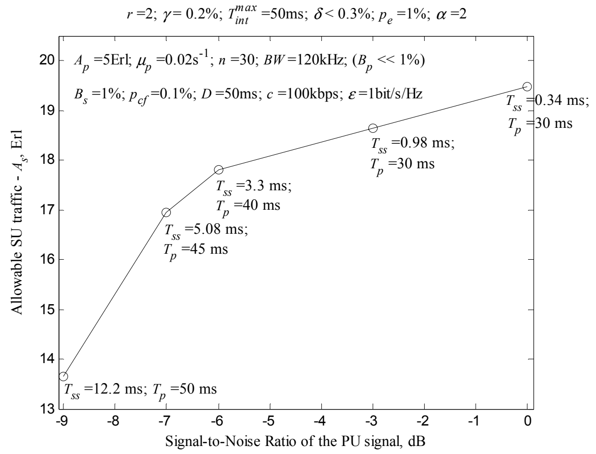

Figure 5. Cognitive traffic capacity for given QoS constraints versus the SNR of the PU signals.

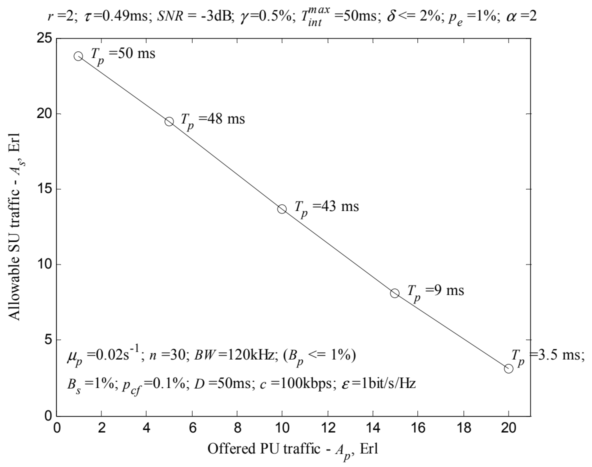

Figure 6. Cognitive traffic capacity for given QoS constraints versus the offered PU traffic.

IV. CONCLUSION AND FUTURE WORK

In this paper, an analytical model for cross-layer analysis and performance evaluation of CRNs is developed. New performance measures, namely γ and δ, for evaluation of the interference experienced by the PUs and by the SUs are suggested. A novel approach for evaluation of the SU call dropping probability is proposed. Various cross-layer interdependencies are investigated and analyzed.

The model is generic and comprehensive, which determines its wide applicability and theoretical significance. It can be applied to both infrastructure and ad hoc CRNs. Moreover, it can be used as a general cross-layer design framework which could be elaborated, modified, or adapted to meet specific design characteristics of a particular CRN.

The analytical model presented in this paper could further be extended to consider cooperative spectrum sensing, imperfect spectrum handover, and imperfect spectrum sharing. The spectrum sensing method could also be modified and matched filter detection or cyclostationary feature detection could be considered.

For future research work, the author plans to extend the cross-layer model developed herein in order to investigate various cross-layer optimization issues and the application of machine learning for enhancing the overall CR performance.

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