Cognitive System with VoIP Secondary Users over VoIP Primary Users

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Abstract—**This paper investigates the call-level traffic capacity for cognitive secondary VoIP users in a system with primary VoIP users. The system is modeled as a serving system with preemptive priority of primary calls over secondary calls. An analytical approach is developed to evaluate the VoIP service capacity and the quality of service provisioning for the secondary users, namely the call blocking and dropping probabilities. Methods for call dropping probability regulation are proposed. A novel analytical approach for approximate evaluation of the effect of limitation is developed and validated by simulation experiments.**

Keywords-call blocking probability; call dropping probability; cognitive radio; VoIP

I. INTRODUCTION

The combination of scarce radio spectrum and increasing demands due to newly emerging wireless services is a reason to search for a more efficient spectrum use. There are many different approaches, such as hierarchical structures with micro- and femto-cells, multi-hop connections, new multiple access methods, adaptive modulation and coding, etc. Not very long ago, a new non-traditional paradigm, namely Dynamic Spectrum Access (DSA), was proposed [1]–[4]. The main idea of hierarchical spectrum overlay as a method of DSA is that some sectors of licensed spectrum which are not currently being used by incumbent (primary) users might be temporarily and opportunistically used by other (secondary) users. If a primary user (PU) returns to activity, a secondary user (SU) has to leave the occupied spectrum. Cognitive radio (CR) is the key enabling technology for DSA. Among the essential CR functions are *spectrum sensing* and *admission control* dependent on available spectrum. The variable character of the spectrum available to SUs makes the service of multimedia traffic difficult due to its stringent packet delay requirements. This is particularly true for dialog traffic such as VoIP.

Because of the connection-oriented packet switching technique for the service of VoIP traffic and the preemptive priority of PU calls over SU calls, two important probabilities exist: call blocking probability and call dropping probability of a SU call. Since SUs must not affect the service of PUs, an ongoing SU call might be interrupted and prematurely terminated (dropped) due to the arrival of a new PU call. Furthermore, the available capacity to SUs is restricted not only by the overall system capacity but also by the number of ongoing PU calls.

The rest of the paper is organized as follows. Section II presents related work. The system model, the analytical approach, and methods for call dropping probability regulation are discussed in Sections III – V, followed by numerical results in Section VI. Finally, Section VII concludes the paper.

II. RELATED WORK

Although the application of CR for VoIP seems promising, there are only few papers about VoIP over CR published recently. The authors of [5] and its extension [6] use the well-known Markov Modulated Poisson Process (MMPP) [7] for characterization of SU VoIP traffic in a way similar to that in [8]. The PU traffic is modeled as generated by on-off sources and for each primary channel an individual Markov channel model (as in [9]) is applied. As a result, a combined complicated model is derived which is numerically clumsy. The non-explicit assumption that the same amount of bandwidth is utilized for PU and SU calls is not used for a more straightforward approach.

In [10] and its extension [11], the authors also claim to be the first to consider the voice-service capacity analysis for CR. These papers propose two cognitive MAC protocols for a single channel system shared in a slotted manner by PUs and SUs. The PU traffic influence is accounted by the probability that a channel time-slot is occupied by a PU packet transmission. The process of arrival and service of PU and SU packets is modeled by a discrete-time Markov chain.

A third approach to voice capacity evaluation of CR networks is presented in [12]. The transmission media is time-slotted and multi-channel. The main difference to the works mentioned above is the more general and system-oriented approach. The authors apply the definitions of *effective bandwidth* [13], [14] to determine the constant amount of radio resources required to provide the QoS guarantee and *effective capacity* [15] to determine the constant source rate that a channel can support.

In the literature, there are some papers devoted to CR call-level capacity and the corresponding study of SU call blocking and dropping probabilities. References [16] and [17] investigate the special case when the PU call bandwidth is exactly N times greater than the SU call bandwidth. A continuous time Markov chain is applied to obtain the call blocking and dropping probabilities. In [18], a case in which a PU needs the same bandwidth as a SU in order to be served is examined. The PU and SU traffic flows are assumed to

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have different arrival and service rates. The analytical evaluation of the call dropping probability is presumed to be difficult, so statistical simulation is applied.

III. THE TELETRAFFIC SYSTEM

The offered traffic is modeled by two arrival Poisson random processes – one for the PUs with rate λ_p and another for the SUs with rate λ_s. Therefore, the PU (SU) call inter-arrival time follows a negative exponential distribution with mean $1/\lambda_p$ ($1/\lambda_s$). The call duration also follows a negative exponential distribution with mean $1/\mu$ for both traffic flows.

We denote with C (bps) the overall system capacity and with c (bps) the necessary average rate for a VoIP PU or SU call to be served. The system is considered to have $n = C/c$ channels. PU calls have preemptive priority over SU calls. If a new SU call finds all of the n channels busy, it is blocked. If a new PU call finds all channels busy but there are some channels occupied by SU calls, one SU call will be interrupted and dismissed (dropped). Blocked and dropped calls are lost. Perfect spectrum sensing and spectrum handover procedures are assumed in order to implement the serving discipline described.

The teletraffic system described can be depicted by means of a 2-D continuous-time Markov chain (Fig. 1). Each state (i, j) is presented by two variables: i is the number of PU calls and j is the number of SU calls. The probability that the system is in state (i, j) is $P_{i,j}$. From the call admission algorithm, it follows that a PU call is blocked in state $(n, 0)$. SU call blocking appears in all states where $i+j=n$ (the outermost diagonal states in Fig. 1). In these states without state $(n, 0)$, one SU call is dropped when a PU call arrives.

It is clear that the PU call flow is served as if the SU call flow did not exist. Hence, the probability $P_{n,0}$ that the system is in state $(n,0)$ is easily obtained by the Erlang loss formula:

$$P_{n,0} = \frac{\frac{A_p^n}{n!}}{\sum_{i=0}^{n} \frac{A_p^i}{i!}} = B_p = E_n\left(A_p\right), \tag{1}$$

where A_p is the offered PU traffic:

$$A_p = \lambda_p / \mu. \tag{2}$$

Similarly, $A_s = \lambda_s / \mu$ is the offered SU traffic. The notation B_p refers to the PU call blocking probability and $E_n(A)$ stands for the Erlang loss formula.

The SU call blocking probability is:

$$B_s = \sum_{i+j=n} P_{i,j}. \tag{3}$$

The probability for SU call dropping is:

$$B_d = \sum_{i+j=n} P_{i,j} - P_{n,0}. \tag{4}$$

IV. THE ANALYTICAL MODEL

The state probabilities $P_{i,j}$ necessary to calculate the SU losses by means of (3) and (4) might be obtained using the global balance equations, which can be derived by inspecting the different states of the Markov chain (Fig. 1).

For the states in the first row of Fig. 1, we have:

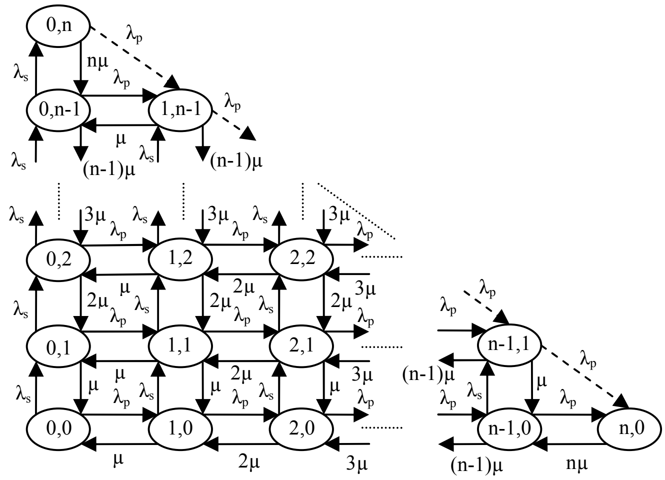

Figure 1. A state-transition diagram used for performance analysis of the teletraffic system.

$$\begin{aligned}&(i = 0)\\ &\left(\lambda_p + \lambda_s\right) P_{0,0} = \mu(P_{1,0} + P_{0,1}),\end{aligned} \tag{5}$$

$$\begin{aligned}&(0 < i < n)\\ &\left(\lambda_p + \lambda_s + i\mu\right) P_{i,0} = \lambda_p P_{i-1,0} + \left(i+1\right)\mu P_{i+1,0} + \mu P_{i,1},\end{aligned} \tag{6}$$

$$\begin{aligned}&(i = n)\\ &n\mu P_{n.0} = \lambda_p (P_{n-1,0} + P_{n-1,1}).\end{aligned} \tag{7}$$

For the states in the most left column, we obtain:

$$\begin{aligned}&(0 < j < n)\\ &\left(\lambda_p + \lambda_s + j\mu\right) P_{0,j} = \lambda_s P_{0,j-1} + \mu P_{1,j} + (j+1)\mu P_{0,j+1},\end{aligned} \tag{8}$$

$$\begin{aligned}&(j = n)\\ &\left(\lambda_p + n\mu\right) P_{0,n} = \lambda_s P_{0,n-1}.\end{aligned} \tag{9}$$

For the states on the hypotenuse, we have:

$$\begin{aligned}&(i > 0; j > 0; i + j = n)\\ &\left(\lambda_p + n\mu\right) P_{i,j} = \lambda_p (P_{i-1,j} + P_{i-1,j+1}) + \lambda_s P_{i,j-1}.\end{aligned} \tag{10}$$

For the rest states on Fig. 1, we have:

$$\begin{aligned}&(i > 0; j > 0; i + j < n)\\ &\left(\lambda_p + \lambda_s + (i+j)\mu\right) P_{i,j} = \lambda_p P_{i-1,j} + \lambda_s P_{i,j-1} +\\ &+\left(i+1\right)\mu P_{i+1,j} + (j+1)\mu P_{i,j+1}.\end{aligned} \tag{11}$$

Equations (5) – (11) contain (n+1)(n+2)/2 unknown variables. For our purposes, it is not necessary to calculate each separate state probability. Let us apply the notation:

$$P_{i,c} = \sum_{j=0}^{n-i} P_{i,j}, \tag{12}$$

where $P_{i,c}$ is the sum of the state probabilities of column i of our diagram. Summarizing (5), (8) and (9) for all values of j from 1 to n and after cancelation of equal terms, we obtain:

$$\lambda_p P_{0,c} = \mu P_{1,c}. \tag{13}$$

Applying the offered traffic (2), we have:

$$A_p P_{0,c} = P_{1,c}. \tag{14}$$

Summarizing (6), (10) and (11) for a given value of i and for all values of j from 1 to n - i, and after cancelation of equal terms, we obtain:

$$(0 < i < n)$$
$$\left(\lambda_p + i\mu\right) P_{i,c} = \lambda_p P_{i-1,c} + (i+1)\mu P_{i+1,c} \tag{15}$$

or

$$\left(A_p + i\right) P_{i,c} = A_p P_{i-1,c} + (i+1) P_{i+1,c}. \tag{16}$$

Simply applying notation (12) to (7), it becomes:

$$n\mu P_{n,c} = \lambda_p P_{n-1,c} \tag{17}$$

or

$$nP_{n,c} = A_p P_{n-1,c}. \tag{18}$$

Equations (14), (16) and (18) differ from the well-known Erlang distribution state equilibrium equations for the PU traffic only by the notation used and consequently could be considered as a proof of (1).

Let us apply the notations: $q = i + j$ and

$$P_q = \sum\nolimits_{i+j=q} P_{i,j}. \tag{19}$$

After substituting $i = q - j$ in (5) – (11) and summarizing for all values of j from 0 to q, we have:

$$(q = 0)$$
$$\left(A_p + A_s\right) P_0 = P_1, \tag{20}$$

$$(0 < q < n)$$
$$(A_p + A_s + q) P_q = \left(q+1\right) P_{q+1} + (A_p + A_s) P_{q-1}, \tag{21}$$

$$(q = n)$$
$$nP_n = (A_p + A_s) P_{n-1}. \tag{22}$$

These are Erlang distribution equilibrium equations for the total traffic flow $A_p + A_s$. The solution is the Erlang loss formula, which gives the SU call blocking probability:

$$P_{q=n} = \frac{\dfrac{\left(A_p + A_s\right)^n}{n!}}{\sum_{i=0}^{n} \dfrac{\left(A_p + A_s\right)^i}{i!}} = B_s = E_n\left(A_p + A_s\right). \tag{23}$$

There is also a more straightforward approach for the derivation of B_s. Our serving system state-transition diagram (Fig. 1) differs from an ordinary multi-dimensional state-transition diagram (with no preemptive priority) in the additional transitions designated with dashed arrows. For an ordinary multi-dimensional loss system [19] is valid the recursion:

$$(0 < q \le n)$$
$$P_q = \frac{1}{q}(A_p + A_s) P_{q-1}, \tag{24}$$

which also leads to the Erlang loss formula (23). Both relations are valid for our serving system because:

a) the additional transitions are only between states forming one macro-state $i + j = n$.

b) due to the memory-less property of the Poisson process, the displacement of a SU call by a PU call with the same mean service time of $1/\mu$ will not affect the expected time the system spends in the macro-state $i + j = n$.

Therefore, the SU call dropping probability B_d is:

$$B_d = E_n\left(A_p + A_s\right) - E_n\left(A_p\right). \tag{25}$$

Note that recursion (24) (called also Kaufman algorithm [20] for fast calculation of multi-dimensional Erlang loss formula) can be derived in our case from (20) – (22).

V. Call Dropping Probability Regulation

The users are much more sensitive to interruption of an ongoing call than to rejection of a new call. Therefore, traffic losses due to SU call dropping has to be much lower than losses due to SU call blocking. A comparison between (23) and (25) shows that there is not a big difference between B_s and B_d. The call admission control (CAC) mechanism can be used to regulate the relation between these two probabilities.

A similar problem with handover call dropping occurs in wireless cellular networks. The most widely used method for reduction of handover call dropping probability is the so-called *channel* (*trunk*) *reservation* [21], [22]. Other techniques, commonly called *class limitation* or *threshold policy* [19], [23], have been used for QoS regulation in wireline integrated multiservice systems. For the system considered in our paper, we propose the application of analogous methods.

LIMITATION. The maximum number of admitted SU calls by the CAC should be limited to a certain threshold value $l < n$. Consequently, a new SU call will be admitted only if the number j of occupied channels by SU calls satisfies the following relation:

$$0 \le j < l < n. \tag{26}$$

RESERVATION. The admission of a new SU call is possible only if:

$$0 \le i + j < n - r, \tag{27}$$

where r is the number of reserved channels.

There is a close bond between n and A_p for a given B_p (1). Most often B_p is in the range of 0.5% – 2% for VoIP over wireless access networks. Considering the VoIP PU network as a given fact, our aim is to evaluate the VoIP capacity available to the CR network. The main constraint for the allowable SU traffic A_s is not B_s but B_d. The possibilities for reducing B_d are: decreasing A_s; applying limitation (26) or reservation (27), which also reduce A_s but to a lesser extent. Limitation is investigated in our paper.

Let us denote by $P_{r,j}$ the sum of the state probabilities of row j of our state-transition diagram (Fig. 1):

$$P_{r,j} = \sum\nolimits_{i=0}^{n-j} P_{i,j}, \tag{28}$$

Considering the truncated state space of the diagram due to applying limitation, we have:

$$B_s = P_{r,l} - P_{n-l,l} + \sum\nolimits_{i+j=n} P_{i,j}, \quad (29)$$

$$B_d = \sum\nolimits_{i+j=n} P_{i,j} - P_{n,0}. \quad (30)$$

Since the direct application of (28) – (30) is clumsy from numerical point of view, we propose a new approach for the evaluation of B_s and B_d that gives *approximate* results but has a relatively low computational complexity. Moreover, we validate this approach by simulation experiments.

Let us denote with $P_s^i(j)$ the conditional probability that there are j SU calls in the system, provided that the number of ongoing PU calls is i. Taking into account the facts that the PU and SU arrival traffic flows are independent of each other and that the service of PU calls is independent of the service of SU calls, we analyze our state-transition diagram that is truncated on the upper side due to (26) and obtain:

$$\begin{aligned} B_s &= \sum_{i=0}^{n-l-1} P_{i,c} P_s^i(l) + B_d + B_p = \\ &= E_l(A_s) \sum_{i=0}^{n-l-1} P_{i,c} + B_d + B_p, \end{aligned} \quad (31)$$

$$B_d = \sum_{i=n-l}^{n-1} P_{i,c} P_s^i(n-i), \quad (32)$$

where $P_{i,c}$ has already been introduced by (12); $E_l(A)$ stands for the Erlang loss formula; B_p is obtained from (1); $P_s^i(n\text{-}i), \{n\text{-}l \le i < n\}$ will further be derived.

The preemptive priority of PUs over SUs makes our state-transition diagram different from an ordinary multi-dimensional state-transition diagram and a simple and straightforward approach for the evaluation of the state probabilities cannot be used. Due to the unidirectional transitions, the diagram is not reversible and does not have the *product-form* solution property [19]. Therefore, a simple evaluation of $P_s^i(n\text{-}i)$ with either the *convolutional algorithm* for loss systems (which aggregates traffic streams) or with any *state-based algorithms* (which aggregate state space) cannot be applied. Recursion (24) is also inapplicable.

It is obvious that the state equilibrium equations for SU traffic only (the columns of the diagram) would resemble the equations of the Erlang distribution if the unidirectional transitions λ_p were not introduced. They affect the service of both PU and SU calls. On the one hand the unidirectional transition λ_p in state (i, $n\text{-}i$) depicts the admission of a PU call and from this point of view it does not differ from the other transitions λ_p. On the other hand it depicts the dropping of a SU call and from that point of view λ_p could be considered as the departure (service) rate of one SU call. Moreover, the inter-arrival time of PU calls and the service time of SU calls are independent and identically distributed variables. Based on these considerations, the total effective service rate of SU calls in state (i, $n\text{-}i$) is assumed to be $(n\text{-}i)\mu + \lambda_p$.

Solving the state equilibrium equations for the SU traffic by inspecting the states in column i, $P_s^i(n\text{-}i)$ can be obtained in a way very similar to the derivation of the Erlang loss formula. Thus, we obtain the approximation:

$$P_s^i(n-i) = \frac{\dfrac{A_s^{n-i}}{(n-i-1)!(n-i+A_p)}}{\sum_{j=0}^{n-i-1} \dfrac{A_s^j}{j!} + \dfrac{A_s^{n-i}}{(n-i-1)!(n-i+A_p)}}, \quad (33)$$

where $n\text{-}l \le i < n$.

Substituting (33) into (32), B_d can be evaluated. Substituting (32) into (31), B_s can be calculated.

VI. Numerical Results

In this section, we validate by simulation experiments our new analytical approach for approximate evaluation of B_s and B_d when limitation (26) is applied. Next, we present and analyze some numerical results obtained via the analytical model described above.

In our simulation model, we take into account all the essential factors required for the performance evaluation of the described teletraffic system, such as the Poisson PU and SU call arrival flows, the random service time of a call with negative exponential distribution, the preemptive priority of PU calls over SU calls, the application of limitation as a method for SU QoS provisioning, etc. In Table I, a comparison between analytical and simulation results for B_p, B_s and B_d is presented. The analytical results match well with the simulation results in all cases. This verifies and validates the use of approximation (33). Therefore, the proposed computationally efficient and simple novel approach for approximate evaluation of B_s and B_d when limitation is applied gives sufficiently precise results. Now we proceed to investigate the call-level traffic capacity and the QoS provisioning for the SUs based on our analytical model.

We first analyze the effect of the offered PU VoIP traffic A_p on the SU VoIP traffic capacity A_s. As A_p decreases, the utilization of transmission resources by PUs also decreases. Hence, A_s increases when A_p decreases, as shown in Fig. 2. This general relation reveals that the capacity of the CR network is variable and depends on the momentary PU activity. Therefore, CR should be deployed in primary networks whose transmission resources are underutilized.

TABLE I. COMPARISON BETWEEN ANALYTICAL AND SIMULATION RESULTS

l=6; n=14; A_s=2 Erl; A_p =5 Erl;			
Analytical Results	B_p=0.0472%	B_s=1.4498%	B_d= 0.3551%
Simulation Results	B_p=0.05%	B_s=1.45%	B_d=0.36%
l=14; n=30; A_s=8 Erl; A_p =11 Erl;			
Analytical Results	B_p= 0.0001%	B_s= 1.7955%	B_d=0.2327%
Simulation Results	B_p=0.00%	B_s=1.80%	B_d=0.23%
n=30; A_s=7 Erl; A_p =15 Erl;			
Analytical Results	B_p=0.0221%	B_s=2.0535%	B_d=2.0314%
Simulation Results	B_p=0.02%	B_s=2.05%	B_d=2.03%

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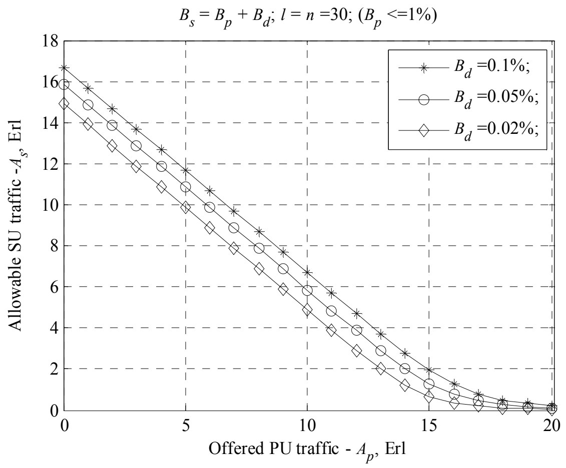

Figure 2. Cognitive VoIP traffic capacity versus the actual PU VoIP traffic load without CAC limitation of SU calls.

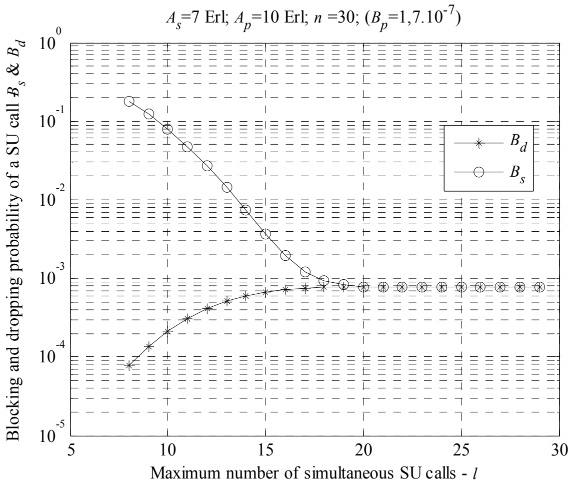

Figure 3. Blocking and dropping probability of a SU call versus the CAC threshold value l for SU calls.

It is clear that a lower B_d, i.e. better SU QoS provisioning, could be achieved by reducing A_s, provided that A_p and the parameters of the serving system are fixed. In this case (Fig. 2), due to the relation $B_s = B_d + B_p$ and the stringent requirements on B_d, B_s is much lower than its maximum allowable value, which means that the QoS provisioning for the SUs is achieved at the price of a significant reduction in A_s. The use of limitation as a method for SU call dropping probability regulation enables us to achieve the SU QoS provisioning without severely reducing A_s.

Fig. 3 shows the effect of applying limitation (26). If the SU CAC threshold l is relatively large (close to n), the performance of the serving system is very similar to its performance without limitation, i.e. the values of B_s and B_d are approximately equal. If l is relatively small and decreases, B_s increases and B_d decreases. It is straightforward that when the admissible number of SU calls in the system is smaller, the probability for SU call dropping is also lower and the probability for SU call blocking is greater. On the one hand the decrease in B_d improves the SU QoS provisioning. On the other hand the allowable increase in B_s improves the CR traffic capacity. Hence, if properly applied, limitation can improve the overall performance of the CR network.

Fig. 4 shows the effect of varying l on A_s. There is an optimal value of l which maximizes A_s, provided that A_p and the parameters of the serving system are fixed. If l is relatively small ($l < l_{opt}$) and increases, A_s also increases, as long as B_s and B_d do not exceed their threshold values. If l is relatively large ($l > l_{opt}$ and close to n), the performance of the serving system is very similar to its performance when no limitation is applied, i.e. in order to achieve the SU QoS provisioning, A_s has to be reduced considerably. Therefore, if the optimal value (l_{opt}) of the SU CAC threshold is selected, the traffic capacity of the CR network can be maximized.

Fig. 5 shows the relation between A_s and A_p when limitation is used and $l = l_{opt}$. A comparison between Fig. 2 and Fig. 5 confirms that if limitation is optimally applied, A_s could be significantly increased.

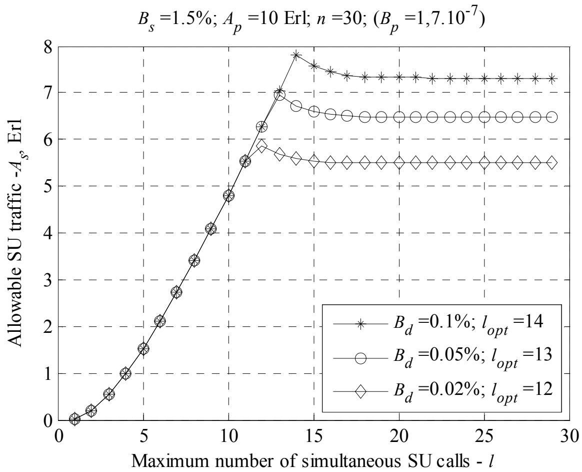

Figure 4. Cognitive VoIP capacity versus the CAC threshold value l for SU calls.

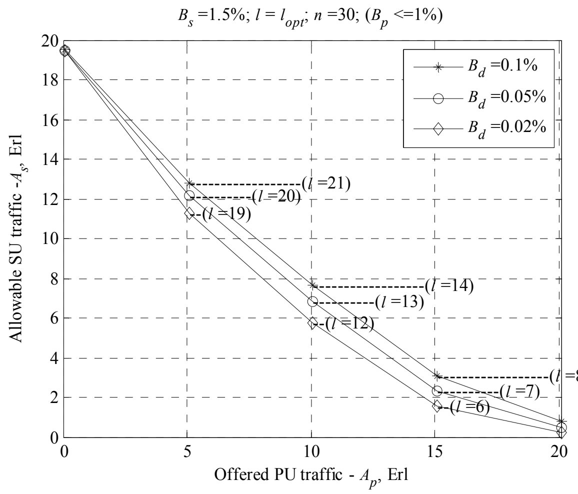

Figure 5. Cognitive VoIP capacity versus the actual PU VoIP traffic load with optimal CAC limitation of SU calls.

VII. CONCLUSION AND FUTURE WORK

In this paper, an analytical model is developed for evaluation of the cognitive SU VoIP traffic capacity and QoS provisioning, namely the SU call blocking and dropping probabilities, in a scenario with VoIP PUs. A method (i.e. limitation) for achieving the required SU QoS provisioning by adjusting the SU call dropping probability is analyzed. A novel computationally efficient and simple analytical approach for approximate evaluation of the effect of applying limitation is developed and validated by simulation experiments. Guidelines for maximizing the CR network capacity by the optimal application of limitation are also proposed.

Since CR utilizes dynamically unoccupied spectrum on an opportunistic basis, the cognitive network capacity is inconstant and depends on the momentary primary traffic load. Our study corroborates that the deployment of a cognitive system is reasonable only if the primary system is underutilized and demonstrates the feasibility of providing VoIP over CR.

The analytical model presented in this paper can be applied to the CR resource management and especially to the call admission control. It can be further elaborated and extended to consider the effects of imperfect spectrum sensing and spectrum handover procedures in order to improve its applicability to more realistic usage scenarios. The model could also be incorporated into a more general cross-layer design framework for the purpose of various system-level analyses.

For future research work, we plan to investigate throughput, QoS, and various cross-layer optimization issues in CR networks used for DSA. Our forthcoming work will be focused on the support of multimedia services over CR networks.

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