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A full Secondary User model for Cognitive Radio in a GSM-900 scenario

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***Abstract*— In this paper, we propose a Petri Net based model able to characterize the QoS of a Secondary User network in a cognitive radio environment operating in the GSM900 band. The proposed model is quite flexible as that it can consider several Primary User network loads, several Secondary User types of services (that involve semantic transparency or time transparency) and it's able to take into account mistakes of sensing spectrum algorithm used by Secondary Users. Specifically, we derive the response time distribution of Secondary User from which it is possible to obtain an estimation of both the maximum throughput and jitter. The proposed cognitive radio scenario considers a Secondary User synchronized access to the channel with the GSM frame structure.**

***Index Terms*—Cognitive radio, Non Markovian Stochastic Petri Net, GSM, QoS**

I. INTRODUCTION

Industrial, scientific and medical (ISM) radio bands have often been overcrowded due to several wireless technologies working in the same bands. Measurement results in the uplink channel of the 850 MHz GSM band show that currently the duty cycle is less than 10% over a 24 hours period measurement time [1], [2]. The goals of achieving an occupancy reduction of overcrowded unlicensed ISM bands and an increase in utilization of the licensed bands can be obtained using Cognitive Radio (CR). The migration to more recent technologies (3G/4G) has decreased occupancy level of band reserved to 2G technology, making it desirable to CR applications.

GSM uses a combination of Time-Division and Frequency-Division Multiple Access (TDMA/FDMA). Each 200kHz channel is divided into eigth timeslots. Moreover GSM uses slow freqeuncy hopping, power control and discontinuous transmission and reception to increase quality and to reduce battery consumption. A CR Secondary User (SU) can access unused channels at certain times (e.g. at night) or unused timeslots due to low traffic conditions or to discontinuous transmission. Although locations of base stations are usually fixed, movements of mobile equipments make difficult to CR devices to avoid interference with Primary Users (PU) [3].

In this work, we take into account synchronized SUs which are able to recognize the GSM time slot boundaries in order to reduce interference with PUs. In order to characterize the SUs QoS, we implement a Petri net based model capable to derive SU performances.

The rest of the paper is organized as follows: Section II describes the CR environment we referred to and introduces a brief state of the art of modeling technique used in CR research activity; we describe the Petri net models we developed to study SU QoS in the reference scenario in Section III. In Section IV some numerical results derived by the introduced model are shown. Finally, Section V summarizes the paper.

II. COGNITIVE ENVIRONMENT

GSM operates in different bands around the world. Specifically the 900 MHz band is used in Europe. The 25 MHz bandwidth is divided in 124 200 kHz sub-bandwidths. In a specific area (cell), more than one sub-band can be assigned according to the expected load. Each of these carrier frequencies is then divided in time, using a TDMA scheme. In Downlink, timeslot 0 (TS0) is always used to transmit control channels while TS1 to TS7 are usually used to transmit the Transportation Channels (TCHs) both in Downlink and in Uplink. The problem of frequency-selective fading and the problem of co-channel interference could be optionally addressed using slow frequency hopping.

Our cognitive environment proposal is composed by several SUs disseminated in the coverage area of a cell. One of the possible topology can consider a star or mesh network in which the SU sink node is allocated in the GSM base transceiver station (BTS). Using this kind of topology the SU nodes can sense environmental variables and opportunistically transmit them. The GSM operator, allocating the sink node in the BTS, can offer a free or a charge service who not interfere with the primary GSM service. Privates can exploit this service installing SU nodes in the cell coverage area which operate according to the cognitive access rules.

In our approach, each SU should be able to synchronize itself with the GSM frame structure. In such a way every SU can detect the boundaries of each single time slots. At the beginning of a time slot, each SU, having some IUs to transmit, executes the sensing spectrum algorithm to verify whether the current slot is busy due to a transmission of a PU. If the channel is vacant, the SU can transmit a portion of the IU until the end of the current time slot. Of course, the SU sensing can induce three different kinds of errors: 1) the SU detects an occupied time slot by a primary user as free and begin its transmission; 2) the SU detects a free time slot as occupied; 3) more than one SU in the same coverage area detect a free

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time slot and access the channel at the same time. The first error is the worst because SUs can destroy PUs information. Therefore, it's important to reduce it to the minimum. Anyway, when this error occurs the SU's IU will be destroyed too. Here, we assume the SU application protocol is able to detect such a situation and retransmits collided IUs. The second one implies a non efficient use by SUs of the band left free by PUs. In order to obtain a good forecast of SUs network QoS metrics, it's necessary to consider at least the first two errors in the model (the last one is specific of SUs network and for comparison purpose it can be considered null). In this context, one of the most important metric to evaluate is the response time because expected maximum throughput SU may achieve and maximum jitter can be obtained from its knowledge, and, accordingly, important information related to the use of SUs network to support real time services can be derived. Thus, response time provides a relevant information to evaluate QoS of the CR networks when SUs transmit over a typical GSM cellular channel.

The GSM spectrum availability was analyzed in different works, e.g. [4] in Aivero, Portugal, [5] analyzes the spectrum availability in seven different European locations and [6] performs a similar work in India. Another well investigated issue in the context of CR is the identification of the GSM signal [7], [8], [9]. Service time distribution required to transmit a packet in a cognitive radio scenario operating in the GSM band has been obtained in [10], [9]. In these latter works, SUs do not operate synchronized with the PUs and the model in [10] was simplified to obtain results in [9]: it takes into account only SU traffic-saturated condition and a geometric distribution of SUs data packet length. Moreover, all these models take into account only perfect spectrum sensing.

Usually the PU behavior and GSM primary network are modeled by means of continuous Markov chain [11], [12], [13], [14]. Instead, in this work, we analyze the use of GSM channels by narrow band devices acting as SUs in different ways: 1) we consider a synchronized access to the channel in order to reduce the collision probability with PUs; 2) we propose a non markovian stochastic Petri nets (NMSPNs) based model of GSM PUs traffic which takes into account both the base transmission station (BTS) load condition and the slotted periodical TDMA multiplexing; (3) both not saturated traffic condition of SUs with a generic traffic behavior and not perfect spectrum sensing by specifying the PU's detection and false alarm probabilies are considered; (4) characterization of GSM channels in terms of busy and idle time is obtained by considering a specified distribution of call arrivals and durations. Thus, we are able to derive response time distribution of SU transmission, that is a usually difficult metrics to evaluate.

III. MODELING USER INTERACTIONS

In this Section, we introduce a stochastic Petri net model [15] with the aim to study interactions between PUs and SUs in the GSM based cognitive environment. We chose Petri nets as modeling tool because of their ease of representing synchronizations and parallelism in even complex systems.

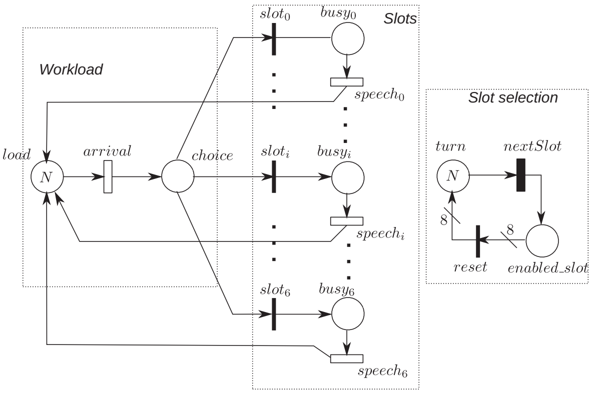

Fig. 1. The `PU model`: primary users NMSPN model

We make use of some Petri net extensions introduced over the time for improving model expressiveness; in particular, we use NMSPNs with the use of enabling functions. Due to lack of space, we do not introduce NMSPN definition and enabling functions, and we refer the interested readers to [16].

Our model is organized into two interacting NMSPNs as depicted in Fig. 1 and Fig. 2. They respectively represent a GSM base station used by PU phone calls on circuit switched network and SUs trying to opportunistically acces the GSM resources. We exploited the independence of PUs with respect to the SU in developing the two models: in fact, when a PU wants to make a call, the resources in the base station are reserved for establishing a connection if any slot is free, independently by the will of the SUs; instead, a SU can use a time slot only if no PU is already using it for a call.

A. PU model

The model in Fig. 1 is used to derive the probabilities at steady state to find a free slot in the base station assuming a given traffic load generated by GSM users. These probabilities are then used in the NMSPN of Fig. 2 to model PU active connections in the system. In this way we implement the dependency of SU with respect to PUs.

The GSM base station model is characterized by three blocks. The `Workload` block models generation of PU calls; it is made by the places $load$ and $choice$, and the transition $arrival$: tokens in place $load$ enable the timed transition $arrival$ to fire. In this work, we assume the PU calls arrive according to a Poisson process thus the timed transition is an exponential transition with parameter λ_a, being λ_a the parameter of the arrival process. The number of tokens N in the place $load$ represents the available free slots, thus when the place is empty the system is full and no new call can start. Since in real systems (here we are considering a BTS operating in a single 200kHz band), eight slots are available and one of them is used for channel control and synchronization, only seven calls can be simultaneously managed by a station, thus we set $N = 7$. When a new call request arrives (when $arrival$ fires) a token is put in place $choice$ and all the immediate transitions $slot_i$, with $i = 0, \ldots, 6$, corresponding to free slots, are enabled. The state of slot i is modeled through places $busy_i$ in block `Slots`. A token in place $busy_i$ means the slot i is busy, otherwise it is not used by any user, thus an inhibitor arc from place $busy_i$ to transition $slot_i$ ensure to disable a transition corresponding to busy slots. One of the enabled $busy_i$ transitions is randomly selected to fire; we set all their weights to 1.0 in such a way the random selection follows a uniform distribution. When a token is in the place $busy_i$ the slot is busy and it remains in such a state during all the call; we used the timed transition $speech_i$ to model the call duration. Let us assume its mean time is $\frac{1}{\lambda_s}$; since the GSM system sends data coding a $(N+1)$ time slot length portion of call, we set the expected firing time of $busy_i$ to $\frac{1}{(N+1)\lambda_s}$. The firing of $speech_i$, meaning the call is over, consumes the token from its input place $busy_i$ and put a new token in the place $load$ making the corresponding slot free.

The last block of the model, `Slot selection`, is used to represent activation of slots; the number of tokens in the place $enabled\_slot$ models the slot actually active, i.e. i tokens in the place means slot i is the active slot. Instead the place $turn$ is used to count the turns inside a round of N slot activations. The mechanism is implemented as follows. When the round starts there are 0 and N tokens in the places $turn$ and $enabled\_slot$ respectively; the transition $nextSlot$ is enabled till tokens are in its input place $turn$. Transition $nextSlot$ is a timed deterministic transition whose firing time is set to the slot length τ_s; since $turn$ is its only input place, it will fire N times at regular intervals moving a token from $turn$ to $enabled\_slot$. When all the N slots are moved the immediate transition, $reset$ becomes enabled thanks to its input arc whose multiplicity is set to N and all the tokens are immediately moved into $turn$ resetting the round. We used the `Slot selection` sub-model to enable the activities in the slots at the correct time period. In fact the transitions $slot_i$ and $speech_i$ can fire only when the slot i is active thus, in order to be correctly enabled, we added an enabling function to each of them as reported in TABLE I, where we used the usual notation $\#P$ to denote the number of tokens in place P[1].

Model	**Transition**	**Enabling function**
`PU model`	$slot_i$ $speech_i$	$\#enabled\_slot == i$ $\#enabled\_slot == i$
`SU model`	$primary$ $secondary$	$\#sending == 0$ $\#sending > 0$

TABLE I
ENABLING FUNCTIONS USED IN THE NMSPN MODELS

We used the model in Fig. 1 to evaluate the probability each single slot is free at stable state. Let P_s^i, with $0 \leq i \leq 6$ be the probability the i-th slot is free; it is evaluated by the model as

$$P_s^i = P\left\{\#busy_i == 0\right\},\ 0 \leq i \leq 6 \tag{1}$$

Due to the symmetries and the uniform random choice of a free slot, these latter probabilities are all equal thus it is enough to evaluate only one of them; we denote its value with P_s, e.g. we set $P_s = P_s^0$.

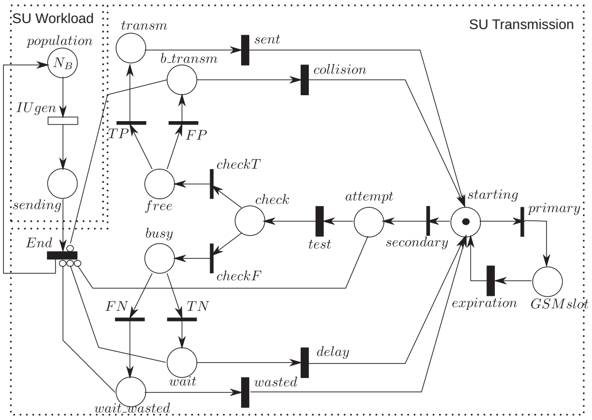

Fig. 2. The `SU model`: secondary user performance model

B. SU model

The model in Fig. 2 has been designed with the aim of evaluating the performance of a secondary user using the GSM band as described in Section II. It is constituted by two main blocks respectively representing the workload generated by the SU (`SU Workload`) and the SU data transmission when a GSM slot is found free (`SU Transmission`). The `SU Workload` block is characterized by two places: *population* and *sending*. The former is used to represent the maximum number of informational unit (IU) managed by the system, the latter taking into account the number of IUs produced by the SU and waiting to be transmitted. To this aims, until tokens are in place $population$ a new IU could be generated and accepted by the system; we limited the number of requests to the buffer size N_B even if the application would need to send data; if this is the case the request is lost. It is worth noting that a specific workload profile is modelled by appropriately setting the `SU Workload` block; it is enough to design a, also complex, block where the place *sending* stores tokens representing IUs to send.

In this work, we considered a *monitoring* workload (Fig. 2) representing a scenario where SU collects data coming from a huge wireless sensor network (WSN) whose sensor nodes are all equal and generate data independently with a given constant mean rate λ_m. Until there is space to store new frames the place $population$ is not empty, the transition $IUgen$ is enabled and it will fires adding a new token in the place $sending$. The monitoring workload profile is characterized by a Poisson arrival process, and we set the firing time of transition $IUgen$ to an exponentially distributed random variable (r.v.) with parameter $N_w \cdot \lambda_m$, where N_w is the number of nodes in WSN. In our approach, the model could be extended to represent other workload profiles can be considered and any `SU Workload` block can be used with the only requirements to have the places $population$ and $sending$, with the meaning introduced

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[1] An enabling function is a logical condition on a transition that must be true for the transition to be enabled together with the enabling conditions due to its input places.

above, that are connected to the `SU Transmission` block as in Fig. 2.

The `SU Transmission` block is designed to model transmission of IUs. Our idea is based on the transition End; it is a deterministic transition whose delay is computed considering the size N_B of an IU and the GSM transmission bit rate λ_G. If all the GSM slot were available, the delay needed to sent an IU will be $\tau_{IU} = \dfrac{N_B}{\lambda_G}$, but in the cognitive environment some slots are useless because used by PUs, and free slots are partially used by SU to run the detection algorithm for checking slot status, as described in Sec.II. When the place sending has tokens the transition End is enabled; during the enabling period the time advances and the transition will fire after τ_{IU} time instants. Sometimes the transition is disabled because either the checking algorithm found the slot busy (token in places $wait$ and $wait\_wasted$) or it found the slot erroneously free and the SU transmission collided with the PU transmission (token in place b_transm - we assumed the SU application is able to detect collisions). During the disable time intervals, the passed amount of time has to be remembered and the time progress has to start from this latter value. To this aim, we set the *preemptive resume* memory policy (*prs*) of NMSPNs [16] to the *End* transition that is coherent with the SU behavior, otherwise the firing delay would not reflect the real SU activity. Also, we used three inhibitor arcs to suspend the enabling of End in the relevant states said above.

The remaining part of the NMSPN selects the state of the current slot. When the system starts one token is in the place $starting$ and one of the two transitions $primary$ and $secondary$ will fire according to the values of their associated enabling functions (TABLE I): if the place $sending$ is empty $primary$ will fire enabling the timed transition $GSMslot$, a deterministic transition whose delay is equal to the slot time (τ_l); when the time slot expires the process is repeated again. At the opposite $secondary$ transition will fire and the token moves to the $attempt$ place, meaning the slot status checking algorithm started (the transition $test$ is enabled). The detection algorithm will use a fraction f_a, with $0 < f_a < 1$ of time slot to run, thus we set $test$ as a deterministic transition with parameter $f_a \cdot \tau_l$. The firing of $test$ moves the token in the place $check$ enabling both the immediate transitions $checkT$ and $checkF$; their firing probabilities are set to P_S ($checkT$), the probability the slot is free and computed with the PU model, and $1 - P_S$ ($checkF$). When $checkT$ fires the token moves to the $free$ place enabling both the immediate transitions TP and FP; they will fire with probability P_{TP} and $P_{FP} = 1 - P_{TP}$. P_{TP} (P_{FP}) is the probability the checking algorithm evaluate to a true positive (false positive) result. When TP fires the token is put in the $transm$ place, i.e. the state where the SU correctly detected a free slot, otherwise it will be in the b_transm, i.e. an error state because it has been detected a busy slot when free. The NMSPN will remain in the reached state until the corresponding enabled transition doesn't fire; both $sent$ and $collision$ are deterministic transitions whose firing time is set to the remaining slot time, i.e. $(1 - f_a)\tau_l$.

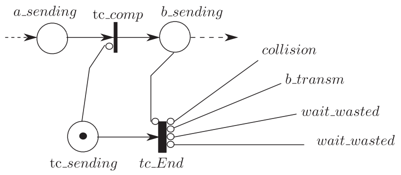


Fig. 3. Modification to the performance model implementing the tagged costumer technique

The remaining part of the model (transitions $checkF$, FN, TN, $delay$ and $wasted$ and places $wait$ and $wait\_wasted$) behaves similarly but representing the behavior when the slot is busy.

1) SU Performance Measures: Despite more measures could be derived from the proposed SU model, we focus on two of them in this work: queue length distribution (and loss probability), and response time distribution. Since the number of IU stored in the buffer (considering the UI under transmission also) is given by the number of tokens in the place $sending$ the system queue length is computed by evaluating

$$P_q(i) = P\{i\ IUs\ are\ in\ the\ system\} = P\{\#sending == i\} \qquad (2)$$

at stable state. Loss probability is equivalent to the probability the system cannot accept any new incoming IU because its buffer is full, thus it is given by $P_l = P_q(N_B)$.

Let us consider the time from the arrival of an IU into the system to the instant it is completely delivered and denote it as τ_r. Of course τ_r is a r.v. and its cumulative distribution function is defined as $F_r(t) = P\{\tau_r <= t\}$. Computation of $F_r(t)$ requires a little modification of the model in order to implement the so called *tagged costumer* method [17] by which a *tagged IU* is choosen and it is observed from its arrival to its delivery. Fig. 3 shows the NMSPN used to this purpose. The performance model is modified by splitting the place $sending$ into two places so as to allow us to distinguish between the tokens already present in the queue ($b\_sending$) and those arrived after the insertion of the tagged IU ($a\_sending$). The tagged IU is modelled by the place $tc\_sending$; one token in the place means the tagged IU is waiting to be delivered. During the time it is waiting new arrived IUs (tokens in $a\_sending$) will not be served thanks to the hinibitor arc from $tc\_sending$ to tc_comp; this latter will be able to fire only when the tagged IU leaves the system. Transition tc_end is set identically to the transition End modeling the delay to transmit the tagged IU also considering the available portion of slots.

This latter model describes the view of the tagged IU at its arrival in the system. The remaining $N_B - 1$ tokens, i.e. the remaining possible IUs in the system, will be distributed between the places $population$ and $b\_sending$, constrained by $\#population + \#b\_sending = N_B$. All these states, with the associate probabilities, are departure states for the tagged costumer model. The tagged costumer model is solved in transient for each of the possible initial markings to compute

W_l (Erlang)	P_s
0.3	0.957
0.6	0.907
1.0	0.855
1.5	0.763
3.0	0.569

TABLE II
PROBABILITY TO FIND A GSM SLOT FREE.

the response time distribution conditioned on the different configurations by evaluating

$$F_i(t) = P\{\#tc\_sending == 0, t|M_i\}, \ \forall t > 0 \tag{3}$$

where M_i, with $0 \leq i \leq N_B - 1$ is the state where $\#b\_sending = i$. The averall distribution will be

$$F_r(t) = \sum_{i=0}^{N_B-1} P_q(i)F_i(t) \tag{4}$$

IV. NUMERICAL RESULTS

In order to evaluate the proposed model we firstly had to characterize the GSM PUs phone traffic. In [18] a detailed modeling of voice call interarrival and holding time distributions in mobile networks was derived. Although the authors concludes the exponential assumption for these distributions is far from reality, in this work, we assume an exponential distribution in order to simplify our model description but it is very easy to extend it by changing the distribution associated to the $speech_i$ transitions or also substituting them with a more complex sub-network modelling other behaviors. Regarding the exponential assumption of voice call interarrival times, the authors of [19] conclude that restricting evaluation of statistics to peak hours (a good practice in telephone traffic engineering) the call arrival process could be considered an ideal Poisson process. In order to consider different PU traffic loads, in our experiments we set the average call holding time to $180s$ ($\lambda_s = 5.5556\ 10^{-3}\ s^{-1}$) and varied the mean rate of the Poisson process modeling call arrivals from 6 to 60 calls per hour (6, 12, 20, 30 and 60). Taking into account our BTS model operating with one $200kHz$ band and 7 TCHs, we loaded each TCH with 0.043, 0.086, 0.143, 0.214 and 0.419 Erlang; as a consequence the considered system workload Wl was 0.3, 0.6, 1.0, 1.5, 3.0 Erlang. We solved the PU model deriving the probability P_s to find a slot free each time SU wants to use it at these different load conditions. The results are summarized in TABLE II.

We used the WebSPN software tool [20] for numerically solve the NMSPN models. WebSPN provides analytical solution engine also for models with many non exponentially distributed transitions thus we didn't need to resort to simulation for deriving the numerical results from the NMSPN models.

The modeled SUs *monitoring* scenario would depict a very large WSNs ($N_w = 1000$) where each node produces an 8 $kbit$ IU with exponentially distributed times having a mean of 5 hours. Accordingly, we fixed the IU size to 8192 $bits$ while the mean rate of generation has been set to 0.06 IU per second. Thus the averaged SUs global load rate will be equal to 136 $kbps$. Moreover, we assumed the spectrum sensing algorithm needs 25% of a slot time to run, thus setting $f_a = 0.25$ in the `SU model`, and an accuracy such that $P_{TP} = P_{TN} = 0.95$. For lack of space, in this paper we can't show and discuss the impact of non perfect spectrum sensing on the degradation of QoS parameters both for SUs and PUs. Fig. 4 shows results obtained both in term of probability to have n IUs in the queue and in term of cumulative distribution function (CDF) of the response time. Specifically Fig. 4a and Fig. 4d refer to a 5 elements queue size, Fig. 4b and Fig. 4e refer to a 10 elements queue size and Fig. 4c and Fig. 4f refer to a 20 elements queue size. For each queue size condition, as previously specified, we considered 5 different condition of PU load (labeled as $Pwl1 - 5$, with $Pw1$ associated to the lighter load and $Pwl5$ associated to the heavier one).

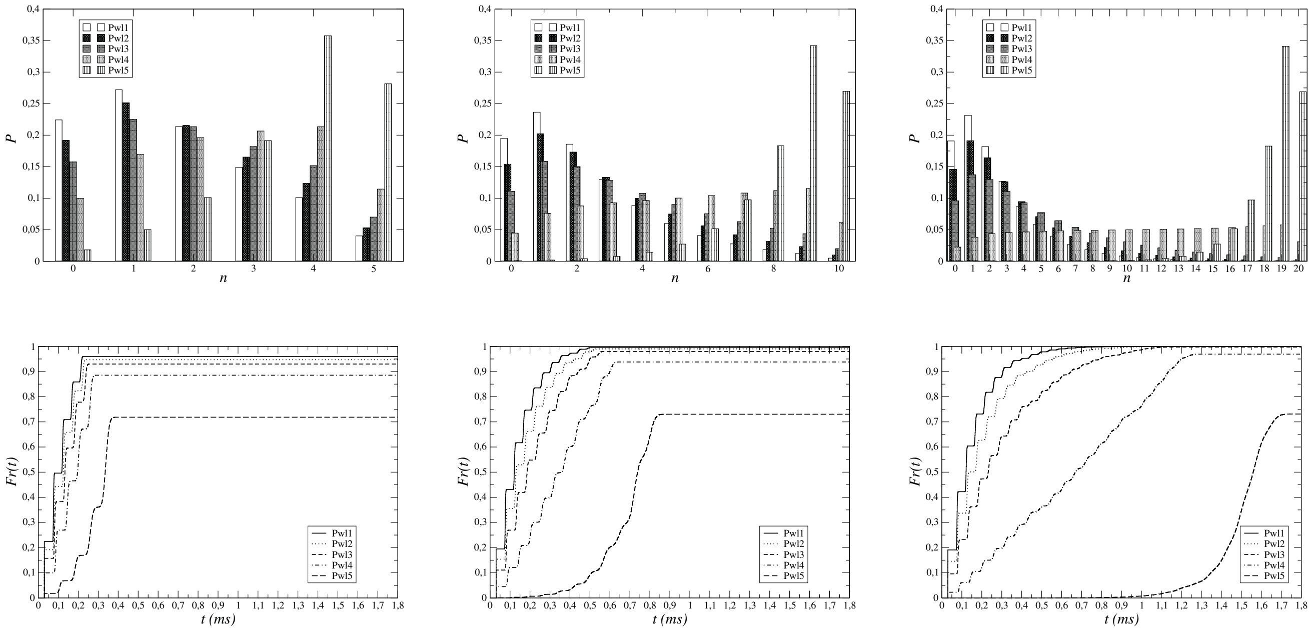
For heavy PU loads ($Pwl4 - 5$), the loss probability of the SUs traffic is not related to the queue size while for light PU loads ($Pwl1-3$) an higher size of the queue is able to mitigate the SU high rate and then to reduce its loss probability.

We point out that the otained CDFs are defective because the size of the queue is finite and a loss is experienced in almost all the cases. In this condition, accordingly to the available rate of the PU network it is not possible to obtain delay higher then a specific constant value. The loss probability P_l is computed taking into account the probability of having a full queue (i.e., $P_s(5)$, $P_s(10)$ and $P_s(20)$ of Fig. 4a, 4b and 4c respectively); we can note that the loss probability corresponds to complement to 1 of the value of each CDF at infinity. Of course, the CDFs give a complete characterization of the response time and it is easy to obtain the mean and the variance of the delay to deliver IUs from them. With this detailed characterization of the response time, it is also possible to evaluate all the maximum "average throughput" (as the inverse of the mean value of the response time), the mean delay (the mean value of the response time) and the maximum jitter (as the difference of the maximum and minimum response time) of the SU traffic and to characterize system QoS accordingly. The proposed model can be considered a good candidate to tune SU network parameters in the specific GSM900 cognitive radio environment in order to obtain a desired QoS.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a new model, based on Non Markovian Stochastic Petri Net, to evaluate QoS performance metrics in a cognitive radio environment operating in the GSM900 band. The proposed model is able to take into account different loads conditions of the licenced band. Moreover the SU model is able to capture the interactions with PUs taking into account possible spectrum sensing mistakes. Results show that the proposed model is able to capture most of the operating characteristics of a SU opportunistically accessing the licensed GSM band.

We will validate, as feature work, the results implementing a SDR block able to perform spectrum sensing synchronized with the frame structure of GSM900. We aim to evaluate the



(d)

(e)

(f)

Fig. 4. Performance results of secondary user

misclassification error in terms of requested sensing time and the portion of time slot used by SUs thus evaluating QoS metrics in a real operating context. Moreover, we will study different PU workloads and SU operating conditions, also considering more realistic event distribuitons, thanks to the high flexibility of the proposed model.

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