Three-Layered Prioritized Cognitive Radio Networks with Channel Aggregation and Fragmentation Techniques

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***Abstract*—Dynamic spectrum allocation techniques are usually based on the assumption of a homogeneous cognitive radio network. In this work we describe a Continuous time Markov chain model that allows different types of bandwidth requirements and priority traffic. We have improved the lowest priority user's performance using channel aggregation and fragmentation, which are mechanisms envisioned for the LTE-A/4G standard. The evaluation consists on analytical and simulation results that have shown that pure channel aggregation performs similarly to the combined use of aggregation and fragmentation while both outperformed the fixed bandwidth approach.**

***Keywords*—Cognitive Radio; Channel Aggregation, Channel Fragmentation.**

I. INTRODUCTION

In cognitive radio networks (CRNs) the secondary users (SUs) access the spectrum that is temporarily unused by primary users (PUs) in a opportunistic manner [1]. Many papers have considered CRNs composed by a single PU and SU types, with homogeneous characteristics. Thus, different quality of service (QoS) requirements coexisting in the same CRN were neglected. Multiple service class support is a present feature in wireless standards such as LTE-A and IEEE 802.11p for Vehicular Ad Hoc Networks (VANETs) [2]. For instance, bandwidth categorization is already a concern in VANETs, especially because the infotainment traffic that may cause collision with vital types of flows such as the safety applications. In this respect, prioritization is a well-known approach for traffic management and, when deployed for SUs, enables better resource utilization while providing the desired QoS for each kind of opportunistic user. Moreover, channel aggregation (CA) and fragmentation (CF) techniques have been proposed to leverage data rates and provide better spectrum usage in CRNs [3] and LTE networks. CA allows a single SU to assemble multiple contiguous or non-contiguous free channels whereas CF enables multiple SUs to share a single free channel. By using CA and CF the service time of some applications (e.g., file download) can be reduced. Previous works [4-5] have demonstrated that CA and CF may coexist in a single algorithm. However, until now the sharing algorithms rely on equally sharing the free spectrum among the active SUs, independently of the service type each user requires, which may lead to resource wastage in cases where the bandwidth increase does not improve its service time (e.g. live streaming). In [5], the authors proposed the coexistence of different types of SUs with PUs but on separate experiments, i.e., a single homogenous secondary layer in each experiment, which does not represent the secondary heterogeneous scenario. Finally, [6] provides a three-layered CRN model with similar assumptions to this work, however, no dynamic aggregation or fragmentation is considered, i.e., the elastic bandwidth behavior is not studied.

This paper introduces a Markov Chain-based model to evaluate a CRN that comprises different traffic classes and priorities. For this, two types of secondary traffic (in terms of bandwidth) are considered: fixed and elastic. The former encompasses SUs that require a fixed bandwidth amount, i.e., the provided bandwidth does not change throughout the communication process, while the latter allows the elastic behavior for the SUs, i.e., resources can be either assembled or shared, which is enabled by channel aggregation and fragmentation. Also, being aware that prioritization may cause starvation on lower level flows, we evaluate the impact of channel aggregation only for the inferior ranked services, under two different approaches: pure channel aggregation (CA) and combined channel aggregation and fragmentation (CAF). Because the lower priority SU may suffer preemption due to higher priority users (SUs and PUs), we consider that the former may have elastic bandwidth and the latter adopts a fixed approach. The secondary system was analyzed in terms of blocking and forced termination probabilities, throughput and spectral utilization.

The remainder of this paper is organized as follows. Section II presents the system model and the formulated performance metrics. Model validation and numerical results are conducted in Section III and Section IV concludes this paper and provides future directions.

II. COGNITIVE RADIO NETWORK MODEL

A. Assumptions

Unlike previous works, we adopt two SU types coexisting in the same CRN, which are denoted as SU_1 and SU_2 having

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respectively fixed and elastic bandwidth. This model considers three priority levels: PU (highest priority user) followed by the SU_1 (intermediate priority) and SU_2 (lowest priority). In order to access the network, both the resource availability and user priority should be taken into account in the following manner: Because the PUs are not aware of the SU's presence, they can trigger a secondary forced termination (SU_1 or SU_2). For a PU, a channel is said to be available only if another PU is not using it. Thus, in case the CRN is totally occupied by PUs, a new PU or SU request is blocked.

The SU_1 has similar perception to the PU, regarding users with equal or lower priority. However, it is aware of the PU's presence and it does not cause primary interruptions (SU_1 has lower priority than the PU). Therefore, a SU_1 request is accepted by the CRN only if there are enough available channels, i.e., not used by PU or used by SU_2. In the second case, the SU_2 has its communication terminated abruptly. Finally, the lowest priority user (SU_2) perceives the PUs and SU_1s and does not interrupt their communication. Thus, a CRN only accepts a new SU_2 request if there are enough available channels, i.e., not used by PUs or SU_1s.

We consider *N* channels being shared by all users, with each PU and SU_1 requiring a single channel unit. The bandwidth allocated to the SU_2 is defined in the interval $[B_m, B_M]$, where B_m, B_M are the minimum and maximum amount of bandwidth (number of channels), with $B_m \geq 1$. The SU_2 channel occupation will be given according to three scenarios: In the first (homogeneous case), the SU_2 will require only one channel unit for its communication (similar to the PU and SU_1), but in the second and third scenarios, the SU_2 will be able to aggregate multiple channels, where the number of aggregated channels will be integer (by adopting CA) and real (by adopting CA and CF, i.e., CAF), respectively.

B. System Model

A continuous time Markov chain (CTMC) was adopted to model the CRN, assuming that the user arrivals are Poisson processes with rates λ_{PU}, λ_{SU_1} and λ_{SU_2} for the PU, SU_1 and SU_2, respectively while the service times are exponentially distributed with service rates μ_{PU}, μ_{SU_1} and μ_{SU_2}. The service rate for the SU_2 may vary according to the number of aggregated channels, that is, if m channels are assembled for a single user, then its new service rate is tuned to $m * \mu_{SU_2}$.

We have selected the Equal Sharing Algorithm (ESA) [3] for only part of the secondary network, i.e., the SU_2s. These will utilize the maximum allowed number of channels if there are enough available, otherwise, the ESA will evenly distribute a determined amount of bandwidth for each of active SU_2. This strategy also guarantees that each active SU_2 has a bandwidth of at least B_m, and if there are no vacant channels, another SU_2 arrival will be blocked. After any user (PU, SU_1 or SU_2) completes a transmission and vacates its channel(s), the CRN equally balances the SU_2s bandwidth according to the available resources.

In this model, each state is represented as a tuple (i, j, k), where i, j, k are the numbers of active PUs, SU_1s and SU_2s in the system. The feasible state space for all scenarios is generated according to (1). Note that in the first scenario, each SU2 adopts one channel to perform its communication, i.e. $B_m = B_M = 1$. Thus, its service rate and bandwidth do not change during the communication.

$$S = \left\{ (i,j,k) \mid 0 \leq i \leq N, 0 \leq j \leq N, 0 \leq k \leq \left\lfloor \frac{N}{B_m} \right\rfloor, (i + j + k * B_m) \leq N \right\} \quad (1)$$

For the second scenario, which allows integer aggregation (denoted as CA), the SU_2 bandwidth and service rate are defined by (2) and (3), respectively.

$$B_{SU_2,CA}(i,j,k) = \begin{cases} \min\left\{ B_M, \max\left\{ B_m, \left\lfloor \frac{N-i-j}{k} \right\rfloor \right\} \right\}, \ \textit{if} \ 0 \leq i+j \leq \lfloor N - B_m \rfloor, 1 \leq k \leq \left\lfloor \frac{N}{B_m} \right\rfloor \\ 0, \ \textit{otherwise} \end{cases} \quad (2)$$

$$\mu_{SU_2,CA}(i,j,k) = B_{SU_2,CA} * \mu_{SU_2} \quad (3)$$

For the third scenario, which admits channel aggregation and fragmentation, the bandwidth and service rate of the SU_2 are defined by (4) and (5), respectively.

$$B_{SU_2,CAF}(i,j,k) = \begin{cases} \min\left\{ B_M, \max\left\{ B_m, \frac{N-i-j}{k} \right\} \right\}, \ \textit{if} \ 0 \leq i+j \leq \lfloor N - B_m \rfloor, 1 \leq k \leq \left\lfloor \frac{N}{B_m} \right\rfloor \\ 0, \ \textit{otherwise} \end{cases} \quad (4)$$

$$\mu_{SU_2,CAF}(i,j,k) = B_{SU_2,CAF} * \mu_{SU_2} \quad (5)$$

The transition from a valid state (i, j, k) to another (i', j', k') is represented by $\gamma_{(i,j,k)}^{(i',j',k')}$ and classified as normal (6), dropping (7) and blocking (8) transitions. The following formulation is applicable to the three scenarios, where B_{SU_2} and μ'_{SU_2} must be replaced by the respective terms defined for each scenario. The normal transitions denote the user arrival and departure when no dropping occurs.

$$Normal: \begin{cases} \gamma_{(i,j,k)}^{(i,j,k-1)} = k * \mu'_{SU_2}(i,j,k); \\ \gamma_{(i,j,k)}^{(i,j-1,k)} = j * \mu_{SU_1}(i,j,k); \\ \gamma_{(i,j,k)}^{(i,-1,j,k)} = i * \mu_{PU}(i,j,k) \\ \gamma_{(i,j,k)}^{(i,j,k+1)} = \lambda_{SU_2} \\ \gamma_{(i,j,k)}^{(i,j+1,k)} = \lambda_{SU_1} \\ \gamma_{(i,j,k)}^{(i+1,j,k)} = \lambda_{PU} \end{cases} \quad (5)$$

A SU dropping case may happen in three situations, as shown in (6): First, when the system is full and there is at least one SU_1 and no SU_2 in the CRN, a PU arrival causes a SU_1 dropping. Second, the SU_1 arrival triggers a SU_2 dropping when there are no enough available resources for the SU_1 communication and there is at least one SU_2 in the CRN. Finally, the PU arrival leads to a SU_2 dropping, when the CRN is full and there is at least one SU_2 accessing the resources.

When there are no available resources to meet a new SU request, the new SU is blocked. There are two cases that can trigger a SU blocking, one for each SU type, as denoted in (7).

$$Dropping:\begin{cases}\gamma_{(i,j,k)}^{(i+1,j-1,k)}=\lambda_{PU},\ if\ \ (i+j+1>N)\ and\ k=0;\\ \gamma_{(i,j,k)}^{(i,j+1,k-1)}=\lambda_{SU_1},if\ \ (i+j+1+k*B_m>N);\\ \gamma_{(i,j,k)}^{(i+1,j,k-1)}=\lambda_{PU},\\ if\ \ (i+j+1+k*B_m>N)\ and\ k>0;\end{cases}\tag{6}$$

$$Blocking:\begin{cases}\gamma_{(i,j,k)}^{(i+1,j-1,k)}=\lambda_{SU_1},\ if\ \ (i+j+1+k*B_m>N);\\ \gamma_{(i,j,k)}^{(i,j+1,k-1)}=\lambda_{SU_2},if\ \ (i+j+(k+1)*B_m)>N);\end{cases}\tag{7}$$

An example state transition diagram for a two channels (*N=2*) CRN with bandwidths set to $B_{PU}=1$, $B_{SU1}=1$ and $B_{SU2}=1$, i.e., ($B_m=B_M=1$) is depicted in Fig. 1. In this system only the normal and dropping transitions were drawn because the blocking conditions are used solely for the acceptance check.

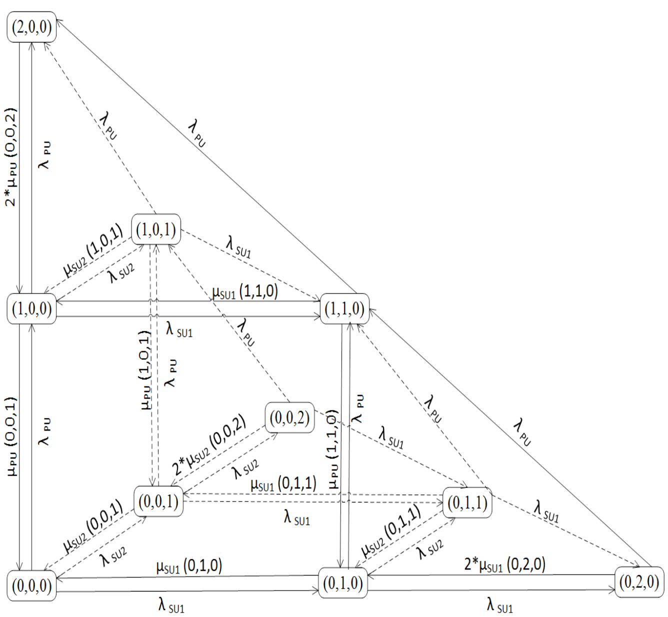

Fig. 1. *State transition diagram for N = 2,* $B_{PU}=B_{SU1}=B_{SU2}=1$.

In order to obtain the steady-state probabilities, a linear system composed of flow balance equations (8) and normalization condition (9) should be solved. For each state (i,j,k), a flow balance equation is defined so the following rule: $\sum flow\ in=\sum flow\ out$ together with the normalization condition (9) are applied. In addition, we adopt the function $I(i,j,k)=\begin{cases}1,\ if\,(i,j,k)\in S\\ 0,\ otherwise\end{cases}$ that indicates if a given state is feasible. The solution for the linear system is the steady state probability vector, which is used in the formulation of important metrics that are adopted in the performance analysis of the secondary communication.

$$\begin{gathered}\sum_{i'=0}^{N}\sum_{j'=0}^{N}\sum_{k'=0}^{\left\lfloor\frac{N}{B_m}\right\rfloor}\pi(i,j,k)*\gamma_{(i,j,k)}^{(i',j',k')}*I(i,j,k)*I(i',j',k')=\\ \sum_{i'=0}^{N}\sum_{j'=0}^{N}\sum_{k'=0}^{\left\lfloor\frac{N}{B_m}\right\rfloor}\pi(i',j',k')*\gamma_{(i',j',k')}^{(i,j,k)}*I(i,j,k)*I(i',j',k')\\ where\ (i,j,k)\neq(i',j',k')\end{gathered}\tag{8}$$

$$\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{\left\lfloor\frac{N}{B_m}\right\rfloor}\pi(i,j,k)*I(i,j,k)=1\tag{9}$$

C. SU Blocking Probability

A SU is blocked when it tries to access the CRN but there are no available resources. In this respect, the blocking probability symbolizes the percentage of secondary requests that are not accepted by the CRN, being a useful quality of service (QoS) indicator. A SU_1 arrival is blocked when the CRN is full $(i+j+k)=N$ and there is no SU_2 being served ($k=0$). On the other hand, a SU_2 arrival is rejected when all channels are occupied $(i+j+k)=N$, independently of which type of user is active. The SU_1 and SU_2 blocking probabilities are given by (10) and (11), respectively.

$$BP_{SU_1}=\sum_{i=0}^{N}\sum_{j=N-i}^{N}(i,j,k)*I(i,j,k)\tag{10}$$

$$BP_{SU_2}=\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=\left\lceil\frac{N-i-j}{B_m}\right\rceil}^{\left\lfloor\frac{N}{B_m}\right\rfloor}(i,j,k)*I(i,j,k)\tag{11}$$

D. SU Dropping Probability

Once the SUs are admitted, their communication may be abruptly interrupted by the higher priority user arrivals, causing degradation in the secondary communication. For the SU_1, this shall occur if the there are no available resources when a PU arrives and there is no SU_2 currently being served. The SU_1 dropping probability is given by (12).

$$DP_{SU1}=\frac{\sum_{i=0}^{N}\sum_{j=N-i}^{N}\sum_{k=0}^{0}\lambda_{PU}\pi(i,j,k)*I(i,j,k)}{(1-BP_{SU_1})*\lambda_{SU_1}}\tag{12}$$

Furthermore, because the SU_2 is the lowest priority user, its communication can be interrupted by PUs and SU_1s arrivals, when the system is full. Thus, the SU_2 dropping probability is given by the ratio between the total rate of dropped SU2s and the rate of admitted SU2s (15), where D_1 (13) and D_2 (14) are the dropping rates due to PU and SU_1 arrivals, respectively.

$$D_1=\sum_{i=0}^{N}\sum_{j=N-i}^{N}\sum_{k=0}^{\left\lfloor\frac{N}{B_m}\right\rfloor}\lambda_{PU}*\pi(i,j,k)*I(i,j,k)*I(i+1,j,k-1)\tag{13}$$

$$D_2 = \sum_{i=0}^{N} \sum_{j=N-i}^{N} \sum_{k=0}^{\left\lfloor \frac{N}{B_m} \right\rfloor} \lambda_{SU_1} * \pi(i,j,k) * I(i,j,k) * I(i,j+1,k-1) \quad (14)$$

$$DP_{SU_2} = \frac{D_1 + D_2}{(1 - BP_{SU_2}) * \lambda_{SU_2}} \quad (15)$$

E. Spectral Utilization

An important metric regarding CRNs is the spectral utilization achieved by the use of opportunistic access and defined as the ratio between the average number of channels occupied by each SU type and the total number of available channels (N). Thus, the spectral utilization for the SU_1 and SU_2 is given by (16) and (17), respectively.

$$S_{SU1} = \frac{\sum_{i=0}^{N} \sum_{j=N-i}^{N} \sum_{k=0}^{\frac{N}{B_m}} j * \pi(i,j,k) * I(i,j,k)}{N} \quad (16)$$

$$S_{SU2} = \frac{\sum_{i=0}^{N} \sum_{j=N-i}^{N} \sum_{k=0}^{\frac{N}{B_m}} k * B_{SU_2}(i,j,k) * \pi(i,j,k) * I(i,j,k)}{N} \quad (17)$$

F. SU Throughput

Finally, we have defined the throughput as the number of completed services per time unit, hence, the SU_1 and SU_2 throughput are given by (18) and (19).

$$T_{SU1} = \sum_{i=0}^{N} \sum_{j=N-i}^{N} \sum_{k=0}^{\frac{N}{B_m}} \mu_{SU_1} * j * \pi(i,j,k) * I(i,j,k) \quad (18)$$

$$T_{SU2} = \sum_{i=0}^{N} \sum_{j=N-i}^{N} \sum_{k=0}^{\frac{N}{B_m}} \mu'_{SU_2}(i,j,k) * k * \pi(i,j,k) * I(i,j,k) \quad (19)$$

III. Numerical Results

The analytical and simulation results were obtained considering the following parameters: N=12, $\lambda_{SU_1} = 4.6$, $\lambda_{SU_2} = 4.6$, $\mu_{PU} = 1$ $\mu_{SU_1} = 1$, $\mu_{SU_2} = 1$. The arrival rate(λ_{PU}) was tuned (from 1 to 5) in order to analyze the secondary system's performance under different PU loads. For the simulation model, we provide a mean from one hundred instances (executions) with simulation time set to 10^4 time units. The assessment of statistical significance was performed and our results present a 95% confidence level, but no bars were drawn due to the small difference between upper and lower bounds.

In order to evaluate the effects of channel aggregation and fragmentation mechanisms, we have defined three CRN configurations: The first consists of all users (PU, SU_1 and SU_2) adopting a single channel as bandwidth, i.e., the homogeneous scenario, without CA and CF. In the second, the SU_2 may aggregate multiple channels (an integer number) by using channel aggregation (CA), while the other users (PU and SU_1) will request only one channel. The last configuration is similar to the second, but it enables the channel aggregation and fragmentation (CAF) by the SU_2, instead of CA. The CRN performance was analyzed in terms of blocking and dropping probabilities, spectral utilization and throughput, which were defined in Section II.

Figs. 2-5 show the analytical (solid lines) and simulation results (markers), where each curve represents a configuration that may characterize the user type (SU_1 or SU_2), adopted aggregation strategy: fixed bandwidth (FB), channel aggregation (CA) or channel aggregation and fragmentation (CAF). Besides, the minimum (B_m) and maximum (B_M) bandwidth values were set to one and five in order to simulate a LTE-A system [7] and can be identified inside the square brackets as the lower and upper bounds, respectively.

According to Figs. 2-5, the SU_1 achieves the same performance for all scenarios (configurations). This behavior was expected since this user type has higher priority than the SU_2 and, hence, does not suffer with the SU_2 presence, even when the lowest priority user adopts the CA or CF techniques. These facts lead us to highlight the results only for the SU_2s, which, differently from the SU_1, will enable variable results depending on the adopted mechanism (FB, CA or CAF).

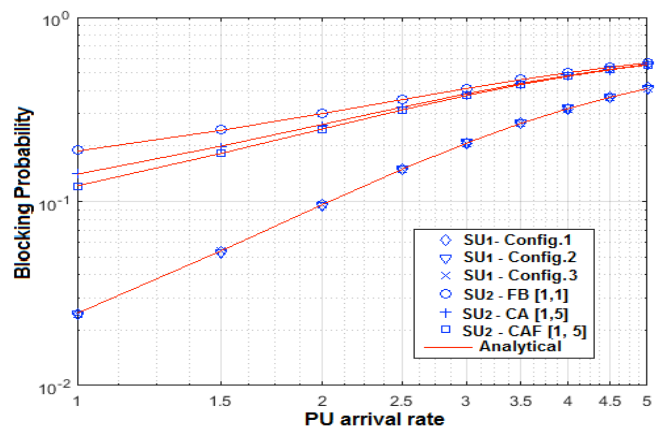

Fig. 2 *Blocking Probabilities for the SU_1 and SU_2 as a function of* λ_{PU}

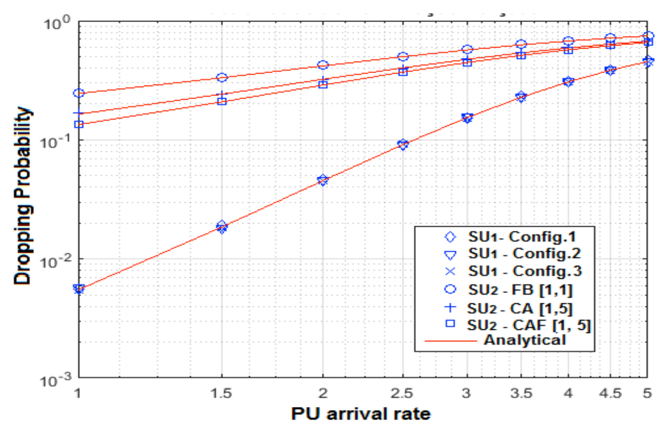

Fig. 3 *Dropping Probabilities for the SU_1 and SU_2 as a function of* λ_{PU}

In [2], the authors explored the difference between the CAF strategy and two fixed channel aggregation techniques namely: maximum and minimum rules. In this work, we provide an equivalent form of their minimum aggregation rule (FB) that adopts the minimum bandwidth value, i.e., one unit channel. However, we have not considered the maximum aggregation rule for our experiments, as it is obvious that an elastic aggregation strategy will outperform any fixed alternative, under the same circumstances. Instead, we have provided a pure aggregation strategy (CA) in order to measure the difference towards CAF and the fixed baseline FB.

The CA strategy seems to be a compromise of the two other techniques such that the system performance should fall in between them, although its lower and upper bandwidth bounds are the same as in CAF ([1, 5]). By analyzing Figs. 3-5, both dynamic aggregation strategies outperform the fixed aggregation approach. Because CA and CAF are able to assemble up to five channels, we would expect a larger difference from FB when the PU load is low ($\lambda_{PU} = 1$) as opposed to a loaded network ($\lambda_{PU} = 4$), where FB, CA and CAF converge, i.e., for a busy network the load pressures the SU_2's bandwidth to the minimum value, which is a single channel unit.

For every other metric CA and CAF behave similar whereas FB is clearly distant especially for blocking and dropping probabilities. For instance, in Figs. 2-3, FB achieves about 15% and 25% of blocking and dropping probabilities respectively, when the CRN presents low PU load ($\lambda_{PU} = 1$). In the same circumstances, the CA [1, 5] provides a reduction of more than 50% in the both metrics and the CAF mechanism achieves the best performance, reducing these values by up to 75% when compared to the FB case. With regard to the spectral utilization and throughput, the SU_2 strategy variation will cause a smaller impact as these are highly dependent on the arrival and service processes and parameter values, and rely less on the bandwidth choice. The results followed our expectations for the afore-mentioned aggregation strategies. We knew beforehand that CAF would outperform CA and FB. However, there is a concern regarding the feasibility of CAF in real experimentation because fragmentation may cause excessive spectral granularity [8].

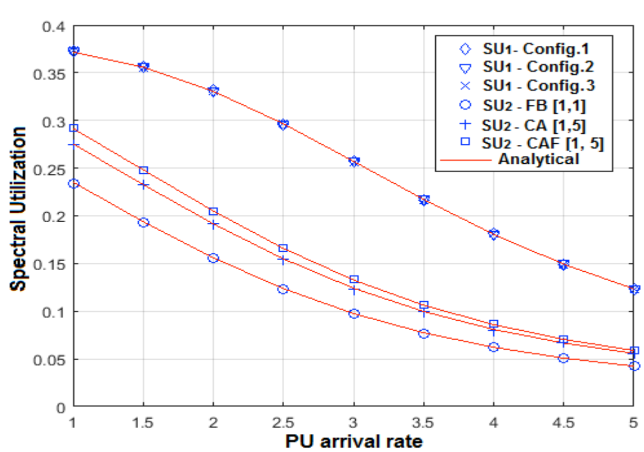

Fig. 4 *Spectral Utilization for the SU_1 and SU_2 as a function of* λ_{PU}

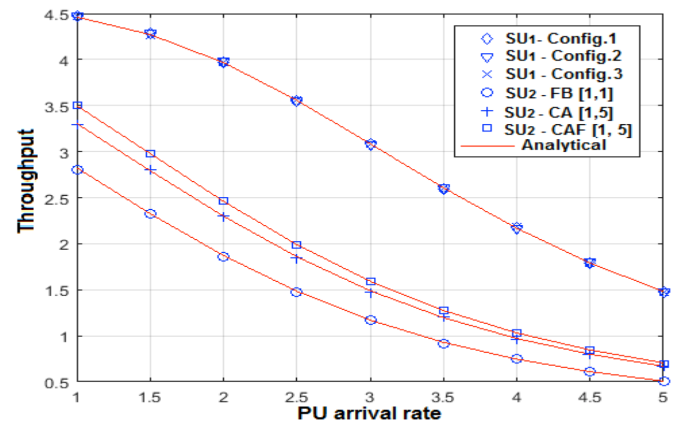

Fig. 5 *Throughput for the SU_1 and SU_2 as a function of* λ_{PU}

IV. CONCLUSION

It is expected that applications with different requirements coexist in the same CRN, where the prioritization is a well-known action for traffic management and for providing the desired QoS to the applications. In this respect, we have modeled a three-layered prioritized CRN, considering four performance metrics for the secondary network: blocking and dropping probabilities, spectral utilization and throughput, comparing different mechanisms for channel allocation. The results have shown that the simultaneous use of channel aggregation and fragmentation (CAF) outperformed the fixed bandwidth approach but presented similar behavior to pure channel aggregation (CA), with the latter being more feasible for real-life implementation, which may be our future line of research as proper hardware platforms for software defined radio development might enable similar scenarios.

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