Simulation Modelling Practice and Theory 84 (2018) 69–82

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

A novel hybrid priority discipline for multi-class secondary users in cognitive radio networks

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ARTICLE INFO

Article history:
Received 24 August 2017
Revised 19 January 2018
Accepted 22 January 2018

Keywords:
Cognitive radio
Spectrum handoff
Queueing theory
Priority schemes

ABSTRACT

Recently, service differentiation in cognitive radio networks is an important issue. Delay-sensitive traffic such as VoIP transmission is given a higher priority over delay-insensitive traffic such as data transmission. Modeling such situation using classical preemption or non-preemption priority service disciplines may result in a severe degradation of the QoS for a particular class. To address this problem, we propose a hybrid service discipline at which low priority secondary users are no longer preempted by high priority secondary users when their number of interruptions reaches a certain threshold value. We carefully design this novel service discipline taking into account that the arrival of a primary user always preempts any secondary user ongoing transmission. Analytical formulas are derived for the extended data delivery time, the overall system time and the dropping probability for each class. Based on a set of numerical results presented for a 2-class network, it is shown that adjusting the threshold value according to the performance metric of interest provides a promising performance.

1. Introduction

Cognitive radio (CR) is a form of a wireless communication in which a transceiver can intelligently detect which communication channels are in use by primary users (PUs) or licensed users and which are not, and instantly allows the secondary users (SUs) or the unlicensed users to access the vacant channels while avoiding occupied ones. This optimizes the use of available radio-frequency spectrum. Spectrum handoff mechanisms must be considered so that the SU evacuates the channel once a PU appears in this channel and continues his transmission on an appropriate target channel. There are three basic approaches for spectrum handoff, 1) always stay [1]: the SU stays on the current channel and does not transmit data until the channel becomes free again, and this is the basic mode of IEEE 802.22 wireless regional area network standard [2], 2) pure proactive handoff strategy [3]: the target channels for future handoff are predetermined before the data connection is established based on long term traffic statistics, 3) pure reactive handoff strategy [4]: at each handoff the SU searches for an idle channel using specific spectrum sensing algorithms.

The SU traffic of the CR is generally with different delay requirements and importance. For example, real time applications (such as VoIP service) are considered a delay-sensitive applications, while data transmissions (such as uploading

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https://doi.org/10.1016/j.simpat.2018.01.007
1569-190X/

a large file) may allow some delay during transmissions. Hence, the SUs traffic comprises classes with different priorities. However, the CR has a special feature since the PU always preempts any class of SUs. The interaction between SUs classes is basically either preemption or non-preemption. In the preemption priority (PP) setting, the arrival of a high priority SU immediately preempts the ongoing transmission of a low priority SU. When the interrupted SU accesses the channel again, he starts transmission from the point of interruption (resume model) or repeats the whole transmission again (repeat model). On the other hand, in the non-preemption priority (NPP) setting, an arriving high priority SU can not interrupt the ongoing transmission of a lower priority SU.

Both the PP and NPP service disciplines have been considered in the literature of multi-class SUs CR network [5–8]. In [5], the CR network was modeled using a preemption resume priority (PRP) M/M/2 queueing system. The SUs were classified into two classes. A Markov transition model was investigated to analyze the effect of multiple spectrum handoff using reactive handoff procedure. In [6,7], the CR network was modeled using an M/G/1 queueing system with mixed preemption and non-preemption resume priority service disciplines (PRP/NPRP). The PU always preempts the SUs, but the interaction between SUs is NPRP in order to avoid frequent spectrum handoffs. In [6], after each interruption from the PU, the priority of the secondary user increases within the same class in order to reduce the handoff delay. In [7], an aging mechanism is considered, at which the priority of the low priority SU is increased when he waits more than three frame times in the queue.

Immediate interruption of the low priority SU transmission upon the arrival of a high priority user is not always applicable in CR environment. Hardware and technical limitations prevent SUs sensing the existence of the PU continuously. Instead, such sensing is usually done periodically. The sensing frequency is a design parameter for the CR network that must be matched with the variability of the state of both PU and high priority SUs ([9,10]). In [8], the CR network was modeled using an M/G/1 multi-class queueing system under the T-preemptive priority discipline. SUs periodically (every T time units) sense the ongoing transmission of the PU and the high priority SUs. If the channel is empty during the sensing period (whose length depends on the SU class), the SU transmits data without any interruption for the remaining time of the T period.

Using classical PP or NPP may result in a severe degradation of the QoS for a particular class. To address this problem, a combination of PP and NPP disciplines has been considered in the queueing system literature. The interaction between different classes may be PP or NPP according to a specific condition. There are four basic approaches for such combination [8]. In the first approach, the preemption depends on the elapsed or remaining service time of the user being served [11–17]. In the second approach, the preemption is decided according to the distance (the difference in indices) between the user requesting the service and user being served [18–21]. In the third approach, the preemption depends on the queue length of the higher priority class [22]. In the fourth approach, the preemption is controlled via the number of interruptions of the user being in service [23].

Our work in this paper belongs to the fourth approach [23] but with basic differences motivated by CR setting. In [23], a priority queue with preemptive repeat-different discipline is considered, in which after each interruption a potentially different service distribution may be used when this user gains the server again. When the number of preemptions of the user being served reaches a certain threshold value, three service alternatives are considered:

1. Repetitive service: the preempted user repeats his service with the same service characteristics in a premptible basis.
2. Guaranteed service: the preempted user is guaranteed to finish his service without any preemptions.
3. Promoted service: the preempted user is promoted to the next priority class.

Our strategy in this paper is a modification of the guaranteed service proposed in [23] to be more applicable to the concept of CR. We summarize the differences between our model and the model proposed in [23] in the following points:

1. The PU (the highest class of users) has the right to preempt the service of the SUs at any time which is not considered in [23].
2. A virtual queue is added to the model at which the guaranteed SU waits when interrupted by the PU. This ensures that the guaranteed SU still has higher priority over all other SUs. This virtual queue was not considered in [23].
3. We consider the resume strategy instead of the repeat strategy considered in [23]. Resume strategy is commonly used to model CR network [5–8].

Considering an M/M/1 multi-class queueing system with this novel guaranteed service discipline, we derive closed form expressions for the extended data delivery time, the overall system time and the dropping probability for each class of SUs. It is noteworthy that assuming Poisson arrival processes and exponential service times facilitates the derivations of (1), (3) and (4) in Section 2. However, the formulas presented in Section 3 are valid for any general service time distribution. A numerical study is presented considering a 2-class CR network. It appears that the proposed discipline outperforms the classical PRP and NPRP disciplines considering a balanced performance for both SU classes. Moreover, it is shown that selecting the threshold value depends on the performance measure of interest. Specific values are suggested when the extended data delivery time is more important than the overall system time and vice versa.

The rest of this paper is organized as follows. In Section 2, we present the system model and assumptions. Analysis of the performance metrics is given in Section 3. Numerical results appear in Section 4. Finally, our conclusions and future work are presented in Section 5.