# Throughput and Delay Analysis for Real-Time Applications in Ad-Hoc Cognitive Networks

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*Abstract*—We consider a simple ad-hoc cognitive scenario with two data up-links, one licensed to uses the spectral resource (primary) and the other unlicensed (secondary or cognitive). It is assumed that the cognitive link accesses the channel only when the channel is sensed idle. An ON-OFF channel model is used for the primary link, where traffic statistical characteristics are taken into account. A closed-form expression for the signal-to-noise-plus interference (SINR) statistics of the cognitive nodes is derived that can be used for estimating the network performance. Moreover, a M/G/1 queueing model is exploited for deriving a simple expression for the average packet delay. Finally, a MAC strategy based on a channel-and-queue aware scheduling is introduced.

*Index Terms*—Cognitive networks, Dynamic resource allocation, scheduling, Delay

## I. INTRODUCTION

Based on evidence that a fixed (licensed) spectrum allocation can result in a highly inefficient resource utilization [1], cognitive radio prescribes the coexistence of licensed (primary) and unlicensed (secondary or cognitive) radio nodes on the same bandwidth. While the first group is allowed to access the spectrum at any time, the second seeks opportunities for transmission by exploiting the idle periods of primary nodes [2]. The main requirement is that the activity of secondary nodes should be transparent to the primary users, so as not to interfere with the licensed use of the spectrum. Cognitive radio, a term first coined by Mitola [3], is a highly flexible alternative to the classic mode of operation. By sensing and adapting to its environment, a cognitive radio is able to avoid interference and fill voids in the wireless spectrum, thus increasing spectral efficiency. Although the gains to be made by the combination of cognitive radios and primary spectrum licensing seem intuitive, the fundamental theoretical limits of the gains to be made by this coupling have only recently been explored [4]. In [5] and [6], the capacity limits of cognitive networks are studied at the physical layer. Resource allocation algorithms based on Markov chain channel models, where the primary link might be either busy or idle, have been proposed [7], while in contributions such as [8], game theory is used to dynamically obtain spectrum sharing rules.

In essence, cognitive radio relies on access to knowledge of the primary users' activity by the secondary users. However, obtaining sufficiently accurate information on the radio environment (e.g., on the primary activity) at the cognitive nodes

is one of the key problems in the implementation of cognitive networks [9].

In this paper, we consider an ad-hoc scenario both for the primary and the secondary networks, where pairs of cognitive nodes are entitled to communicate by a novel proposed distributed scheduler only when primaries are not using the channel. We revise the well-known ON-OFF channel model, taking into account both the traffic model and the physical channel characteristics. In particular, we use a Pareto distribution [10] for modeling the burstiness of stochastically heavy-tailed primary traffic (e.g., Internet traffic) in order to test the ability of the resource allocation algorithm to fulfill the secondary users' real-time constraints. Statistical properties, in terms of probability density function (pdf) and cumulative density function (cdf), are derived in closed form for the system considered. Moreover, an M/G/1 queuing model with vacation is used for modeling the delay characteristics of the cognitive network. Finally, a utility-function-based scheduling is introduced, particularly tailored to the ad-hoc network setting (i.e., fitted into a distributed CSMA framework).

The paper is organized by covering in Section II a model of the cognitive network, in particular regarding the ON-OFF channel model, while the statistical properties of SINR and delay are derived in Section III. The decentralized scheduling algorithm is introduced in Section IV, and numerical results are presented in Section V.

## II. SYSTEM MODEL

We consider a set of $M$ cognitive nodes (CN) that are organized in an ad-hoc network. The CNs are entitled to opportunistically exploit the same resources of a primary network. In the paper, we assume that CNs are allowed to communicate only if the primary nodes are not transmitting. Channel sensing is considered to be error free. We suppose the primary network is formed by $N$ primary users. The single frequency band can be accessed only by one primary user at each time slot.

### A. Cognitive Network System Model

We consider an ad-hoc cognitive network that exploits the same time-frequency resources as a primary network. For simplicity, the $M$ secondary nodes are arranged according to a uniform distribution in a two-dimensional space with density $\lambda$, as in Fig.1. We label $T$ and $R$ a transmitting and a receiving cognitive node (CN), respectively.
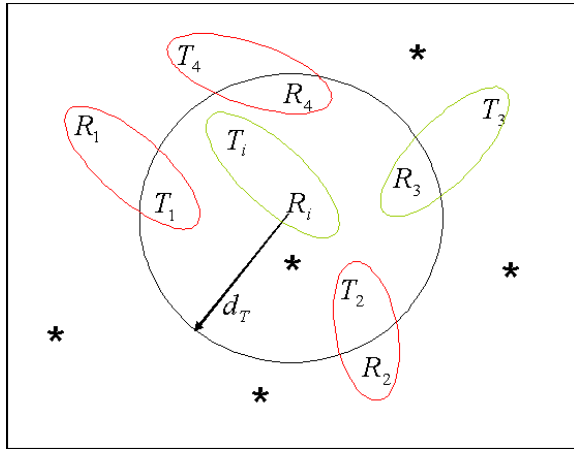
Fig. 1. Model of the secondary cognitive system. Scheduled pairs are in green, not scheduled pairs are in red while not paired CNs are marked by '*'.

The secondary network data frames are organized in time slots of duration $T_S$ seconds as they are for the licensed network. For simplicity of analysis, we suppose that each node is able to synchronize to the primary frames' timing. At each time slot (or on a larger time scale), a routing algorithm tries to find end-to-end routes for the packets by identifying CN source/destination pairs $\{T_i, R_i\}$, and a scheduler selects a subset of the pairs that are thus entitled to communicate in the time slot (see Fig.1). Routing decisions are taken on the basis of the topology of the network, traffic and other application layer issues that are out of the scope of the paper. For simplicity, we assume also that the scheduled transmitting CNs have a uniform distribution in the two dimensional space with density $\lambda_T$, with $\lambda_T < \lambda$.

*B. Primary Traffic Model*

An ON-OFF model is commonly used to capture the burstiness and dependency structure of traffic streams. It is well known that Internet traffic appears similar in different time scales, which is called self-similarity [10]. Statistical analysis shows that the ON periods of self-similar traffic exhibit long-tailed characteristics, which are described by a Pareto distribution as follows:

$$P(X_{ON} > s) = \left(\frac{s_{min}}{s}\right)^{\alpha}, \quad s > s_{min} > 0; \alpha > 0, \quad (1)$$

where $s_{min}$ is the smallest possible value of the random variable $X_{ON}$, which represents the number of consecutive time slots, each of duration $T_S$ seconds, in which the primary channel is ON. The OFF period length $X_{OFF}$ is modeled by an exponentially distributed variable with mean $s_{off}$ [11]. The primary channel is considered to be ON or OFF during a time slot if a primary user is transmitting or not, respectively. The average probabilities of finding the channel busy or idle for a CN are $P_{ON}$ and $P_{OFF} = 1 - P_{ON}$, respectively.

III. COGNITIVE NETWORK PERFORMANCE ANALYSIS

Consider an arbitrary CN $R_i$ and the corresponding paired node $T_i$. We define $M_{T,i}$ as the average number of transmitting

cognitive nodes scheduled in a time slot in a range $d_T$ about $R_i$, and we assume that CNs out of the range $d_T$ do not interfere with node $i$.

Suppose that the CNs are allowed a low transmitting power (compared to that of the primary system) and that $\rho_S^2(m,i)$ is the average power received at the node $R_i$ from the $m$-th scheduled secondary. For simplicity, we normalize the average power received by $R_i$ from the paired node $T_i$ to unity (i.e., $\rho_S^2(i,i) = 1$). The assumption on the CNs transmitted power seems reasonable for an ad-hoc network setting where each node relays packets to the most favorable neighbors, and the fact that the secondary network must operate without being detected by primary users.

During an OFF period (i.e., no primaries transmitting), the received equivalent low-pass signal for the node $R_i$ (scheduled pair $\{T_i, R_i\}$) is

$$r_{i,OFF}(t) = \sum_{m=1}^{M_{T,i}} \rho_S(m,i)h_{m,i}(t)x_m(t) + n_i(t) \quad (2)$$

where $h_{m,i}$ is the complex Gaussian channel gain between the $m$-th CN transmitter $T_m$ and the node $R_i$, $n_i$ is the filtered AWGN of power $\sigma^2$ in the signal bandwidth and $x_m(t)$ is the data transmitted by the $m$-th transmitter, where we assume $E[|x_m(t)|^2] = 1$. The signal-to-interference-plus-noise ratio (SINR) can be written as

$$\gamma_{i,OFF} = \frac{|h_{i,i}|^2}{\sum_{m \neq i} \rho_S^2(m,i)|h_{m,i}|^2 + \sigma^2} \quad (3)$$

If $|h_{m,i}|$ is Rayleigh distributed, we can rewrite (3) as

$$x = \frac{z}{y + \sigma^2}, \quad (4)$$

where the random variable $z$ is distributed as a $\chi_2^2$ (or, equivalently, an exponential) distribution, and $y$ is the weighted sum of $M_{T,i} - 1$ $\chi_2^2$ each with weight $\rho_S^2(m,i)$:

$$y = \sum_{m=1,m\neq i}^{M_{T,i}-1} \rho_S^2(m,i)|h_{m,i}|^2. \quad (5)$$

From [12], the probability density function (pdf) of a weighted sum of independent chi-square random variables with 2 degrees of freedom can be written as

$$f_Y(y) = \sum_{m=1,m\neq i}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)}e^{-y/\rho_S^2(m,i)}, \quad (6)$$

where $a_m = \prod_{j=1,j\neq m}^{M_{T,i}-1} \frac{\rho_S^2(m,i)}{\rho_S^2(m,i)-\rho_S^2(j,i)}$.

The SINR pdf can be expressed as

$$f_X(x) = \int_0^\infty f_{X|Y}(x|y)f_Y(y)dy, \quad (7)$$

where

$$f_{X|Y}(x|y) = (\sigma^2 + y)e^{-(\sigma^2+y)x}. \quad (8)$$

We can now rewrite the SINR pdf as

$$f_X(x) = \int_0^\infty (\sigma^2 + y)e^{-(\sigma^2+y)x} \sum_{m=1}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)} e^{-y/\rho_S^2(m,i)} dy$$

$$= \sum_{m=1}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)} e^{-\rho^2 x} \left[ \int_0^\infty \sigma^2 e^{-y(x+1/\rho_S^2(m,i))} dy + \int_0^\infty y e^{-y(x+1/\rho_S^2(m,i))} dy \right]$$

$$= \sum_{m=1}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)} e^{-\sigma^2 x} \left[ \frac{\sigma^2(x+1/\rho_S^2(m,i))+1}{(x+1/\rho_S^2(m,i))^2} \right], \quad (9)$$

where we used the identity [13]

$$\int_0^\infty e^{-y(x+a)} y^i dy = \frac{i!}{(x+a)^{i+1}}. \quad (10)$$

We can also calculate the CDF as

$$F_X(x) = \int_0^x \sum_{m=1}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)} e^{-\sigma^2 z} \left[ \frac{\sigma^2(z+1/\rho_S^2(m,i))+1}{(z+1/\rho_S^2(m,i))^2} \right] dz$$

$$= \sum_{m=1}^{M_{T,i}-1} \frac{a_m}{\rho_S^2(m,i)} \left[ \rho_S^2(m,i) - \frac{e^{-\sigma^2 x}}{(1/\rho_S^2(m,i)+x)} \right], \quad (11)$$

where we used the derivative

$$\frac{d}{dz} \frac{e^{-\sigma^2 z}}{(1/\rho_S^2(m,i)+z)} = -e^{-\sigma^2 z} \frac{\sigma^2(z+1/\rho_S^2(m,i))+1}{(z+1/\rho_S^2(m,i))^2} \quad (12)$$

It is straightforward to compute the outage probability for node $R_i$ (and thus for the $i$-th pair) as

$$P_{o,OFF}(i) = F_X(\gamma_T), \quad (13)$$

where $\gamma_T$ is the minimum SINR threshold for a CN node to be able to decode the intended received data.

*Queuing Analysis:* A cognitive node's buffer can be modeled as a M/G/1 queue with vacation [14], in which we have a service time and vacation time during which the node is able to transmit or remains idle, respectively [15]. In [16], vacation time and service time are referred to as irrelevant and relevant epochs, respectively. An epoch includes one or several time slots that are used for the transmission of the packets from an active CN to its destination. Note that other active nodes might be transmitting during the epoch as well. From the viewpoint of a particular cognitive node, say node $i$, two kinds of epochs can be distinguished, according to whether or not node $i$ is active in this epoch. If CN $i$ sends a packet during the slot of an epoch, this epoch is a relevant epoch to node $i$ . Otherwise, this epoch is an irrelevant epoch to node $i$.

Let us consider the case in which the CN nodes are entitled to transmit only if primaries are not using the channel. Thus, an epoch is relevant to CN $i$ if, during an OFF state of the channel, node $i$ is scheduled for transmitting at the beginning of the OFF period. On the other hand, the epoch is irrelevant if the channel is in the ON state or if node $i$ is not scheduled. Let us assume that each cognitive node's buffer is fed with a Poisson source having rate $\lambda_P$ packets/slot. We choose to model the real-time traffic for the CNs with a

Poisson distribution in order to be able to derive closed-form expressions for the average packets delay. The average system delay for a packet can be expressed as [17]

$$D_i = \frac{\lambda_P \overline{E^2}_R}{2(1 - \lambda_P \overline{E}_R)} + \frac{\overline{E^2}_I}{2\overline{E}_I} \quad (14)$$

where $\overline{E}_R$ and $\overline{E^2}_R$ are first and second moments of the duration (in slots) of a relevant epoch $E_R$, and $\overline{E}_I$ and $\overline{E^2}_I$ are the first and second moment of the duration (in slots) of an irrelevant epoch $E_I$. The term $\lambda_P \overline{E}_R$ is commonly referred to as network load [14], and it has to be $\lambda_P \overline{E}_R < 1$ for the queues stability. As described in Sect. II-B, the OFF period length $X_{OFF}$ is modeled according to an exponential distribution of parameter $s_{off}$. Thus, if we assume that the CN $i$ is scheduled with probability $\lambda_T/\lambda$ and it is able to communicate with probability $1 - P_{o,OFF}$, the duration of the relevant epoch $E_R$ is that of the OFF period length $X_{OFF}$, weighted by the probability $(1 - P_{o,OFF})\lambda_T/\lambda$. The relevant epochs statistical moments are given by

$$\overline{E}_R = s_{off}(1 - P_{o,OFF})\frac{\lambda_T}{\lambda} \quad (15)$$

$$\overline{E^2}_R = 2(s_{off})^2 [(1 - P_{o,OFF})\frac{\lambda_T}{\lambda}]. \quad (16)$$

From basic statistics, $E[X_{OFF}] = s_{off}$ and $E[X_{OFF}^2] = 2s_{off}^2$ for an exponential distribution. Accordingly, the irrelevant epochs statistical moments are given by

$$\overline{E}_I = E[X_{ON}] + s_{off}[1 - (1 - P_{o,OFF})\frac{\lambda_T}{\lambda}] \quad (17)$$

$$\overline{E^2}_I = E[X_{ON}^2] + 2(s_{off})^2[1 - (1 - P_{o,OFF})\frac{\lambda_T}{\lambda}], \quad (18)$$

where $E[X_{ON}]$ and $E[X_{ON}^2]$ are the first and the second moment of the Pareto distributed ON periods. The other terms in (17) and (18) account for the moments of the OFF periods weighted by the probability that CN $i$ is not able to transmit during an OFF period which is $1 - (1 - P_{o,OFF})\frac{\lambda_T}{\lambda}$. The epoch is irrelevant for node $i$ if the primaries are transmitting (i.e., ON periods) or if node $i$ is not transmitting during an OFF period. Substituting the Pareto distribution first and second moments $E[X_{ON}] = \frac{\alpha s_{min}}{\alpha-1}$ and $E[X_{ON}^2] = \frac{\alpha s_{min}^2}{\alpha-2}$ , we can rewrite (17) and (18) as

$$\overline{E}_I = \frac{\alpha s_{min}}{\alpha - 1} + s_{off}[1 - (1 - P_{o,OFF})\frac{\lambda_T}{\lambda}] \quad (19)$$

$$\overline{E^2}_I = \frac{\alpha s_{min}^2}{\alpha - 2} + 2(s_{off})^2[1 - (1 - P_{o,OFF})\frac{\lambda_T}{\lambda}], \quad (20)$$

from which we can compute the average packet delay.

The meaningfulness of average delay depends on the application. For example, for two-way interactive videoconferencing or certain video streaming applications, average delay over the whole video is not a meaningful measure of quality, because packets which do not arrive by their display deadline are useless (will not be displayed) and the video will continue playing without them. Packets which miss this hard deadline by a tiny amount or by an enormous amount are equally useless for display, but the amount of the miss can have

a large and unequal impact on average delay. On the other hand, there are a number of video (and other) applications for which average delay is meaningful. In a military context, there are applications of video, such as for surveillance or bomb damage assessment, which are not fully real-time (although they may be close to real-time) and do not always have a hard display deadline. A small number of missing packets might be concealable, but when too many packets are late, the video will not keep playing; there will be annoying freeze artifacts until the missing packets are received and the video is able to resume playing. Average delay also is meaningful for video applications where a user is directing a robot or a person in real-life, or a virtual avatar in a virtual world, to manipulate an object or navigate through a scene. Examples include a robot directed to investigate a suspicious object, a paramedic directed to monitor or intervene with a patient, or a virtual person moving through an on-line game world. In all cases, the next control commands cannot be sent until an adequate video display showing the scene resulting from past commands arrives, and average delay would be one measure of the user's satisfaction with the system. In next section, we use a finite-length sliding window for estimating the average delay in order to be able to use it as a user's satisfaction index in the scheduling algorithm.

## IV. A DECENTRALIZED COGNITIVE MAC PROTOCOL

In the previous sections, we have not mentioned any particular scheduling algorithm. We just assumed that, on average, $M_{T,i} - 1$ interfering CNs are scheduled in the vicinity of CN receiver $i$.

The scheduler's task consists of choosing which of the CNs of the cognitive ad-hoc network are entitled for transmission at each time slot (or on a longer time basis). We introduce a scheduler whose decision is taken on the basis of both physical (e.g., SINR level) and queuing issues in order to take into account both the channel variability and the real-time constraints. Moreover, the scheduling task is performed in a distributed fashion because of the ad-hoc setting of the cognitive network. The scheduling algorithm falls into the general framework of CSMA/CA algorithms [18][19].

### A. Utility Functions

Utility functions play a key role in resource management and QoS differentiation. Different applications have different utility function curves and/or different parameters. For instance, the utility functions of best-effort applications are with respect to throughput, whereas those of delay-sensitive applications are with respect to delay. There are usually two approaches to obtaining utility functions. For a specific type of application, the utility function may be obtained by sophisticated subjective surveys. Another method is to design utility functions based on the habits of the traffic and appropriate fairness in the network. Therefore, a utility function for an application characterizes its corresponding QoS requirements. The incoming rate of a delay-sensitive stream is usually determined by its source. Assume that user $i$ is associated with an average waiting time $D_i$ and that the corresponding

utility is $U_i(D_i)$. Obviously, with a long average delay, the user has a low level of satisfaction (utility). It is reasonable to assume that $U_i(D_i)$ is decreasing as $D_i$ increases. Averaging over the entire stream length might not be useful in real-time applications. Thus, a finite-length sliding window is used in order to compute the utility function. The long-term optimization objective with respect to average waiting times leads to an instantaneous optimization objective, which is given in [11][20] by

$$max\{\Phi(i)\} = max\{\frac{|U_i^{'}(D_i)|}{\overline{c_i}}c_i\}, \qquad (21)$$

where $\Phi(i)$ is the scheduling function, $U_i^{'}(D_i)$ is the derivative of the utility function, and $\overline{c_i}$ and $c_i$ are the long-term and the instantaneous throughputs for user $i$, respectively. At each stage in the contention window, the CN that satisfies the optimization in (21) begins to transmit. In particular, from [11], we use

$$U_i(D_i) = -\frac{D_i^{\gamma}}{\gamma}, \gamma \geq 1, \qquad (22)$$

where $\gamma$ can be used to provide different degrees of delay fairness for users.

### B. The Slot Structure

The beginning of each slot is dedicated for channel sensing. If the channel is identified as idle, the CN transmitter transmits data. At the end of the slot, the receiver acknowledges a successful data transmission. The basic slot structure is illustrated in Figure 2.
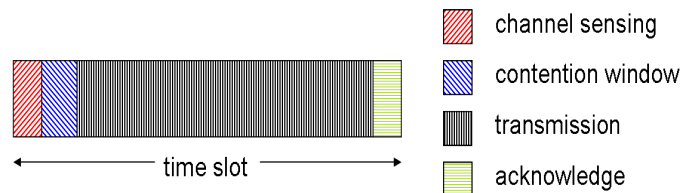


Fig. 2. Slot structure.

Specifically, at the beginning of a time slot, the secondary nodes sense the channel in order to identify if it is idle or occupied by a primary's transmission. If the interference level at a CN node $i$ is less than a certain sensing threshold, the node begins to coordinate with the nearby users at the end of the sensing period. Thus, at the beginning of the contention window, each CN computes its own value of the function $\Phi(i)$, which is a function of the instantaneous SINR level and its own delay constraints. The value computed by each CN is translated into a backoff time during which the CN monitors the channel. The larger is the computed $\Phi(i)$, the shorter is the backoff time, so that the CN with the maximum value is the first to gain access to the channel. If the channel remains idle when its backoff time expires, the CN transmits a

short request-to-send (RTS) message to the receiver, indicating that the channel is available at the transmitter. The receiver, upon receiving the RTS, replies with a clear-to-send (CTS) message if the channel is also available at the receiver. A successful exchange of RTS-CTS completes the identification of a spectrum opportunity. A data packet is then transmitted. A successful data transmission is acknowledged at the end of the slot.

The RTS-CTS exchange has dual functions. Besides facilitating opportunity identification, it also mitigates the hidden and exposed terminal problem. Specifically, a hidden terminal refrains from transmission when it detects a transmission of the CTS, while an exposed terminal attempts to capture the channel if it detects the RTS but not the CTS. Under perfect carrier sensing, wasted spectrum opportunities and collisions among secondary users are avoided.

### C. Cognitive Nodes Coordination

At the beginning of the contention window, each node computes its own scheduling function value that depends on its own queue level and the SINR. The larger is the value computed, the shorter is the waiting time after the channel sensing period. Moreover, the scheduling function is the same for each CN, thus, based on the computed value, the node can start transmission without sharing information about its scheduling function value. Suppose node $i$ starts transmission because it has the largest scheduling function value among its neighbor nodes. All nearby nodes that are able to decode the RTS and/or the CTS sent by the CN pair $i$ are not allowed to try to access the channel in that slot.
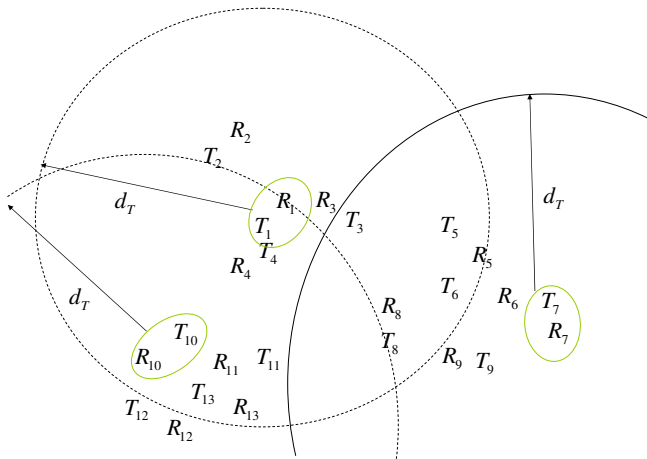


Fig. 3.   Scheduled CNs may interfere with other scheduled CNs.

Meanwhile, further CNs that may not be able to decode the RTS/CTS messages (i.e., received signal under the sensing threshold) can independently compete for channel access with neighboring CNs. At the end of the contention window, each scheduled CN pair will be able to communicate according to the model in (2). Thus, multiple CN pairs can be scheduled si-

multaneously over the entire cognitive network at the expense of an increasing interference level (as in Fig.3).

## V. NUMERICAL ANALYSIS

Simulations are carried out in order to validate our throughput and delay analysis. In particular, we first evaluate our cognitive ad-hoc network performance by considering a cluster of $M_{T,i} = 4$ cognitive pairs communicating only during OFF periods with a scheduling ratio $\frac{\lambda_T}{\lambda} = 1/4$. Then, we compare the throughput of different scheduling algorithms. In particular, we consider a proportional fair (PF) scheduler that takes into account some channel state information (CSI) into the scheduling rule, and we compare its performance with our proposed channel-and-queue (CQ) aware scheduler. In the simulations, we consider a normalized throughput of 1 packet/slot for each scheduled CN and a network load of $\lambda_P \overline{E}_R < 1$.
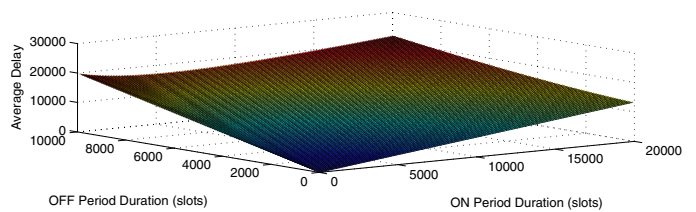


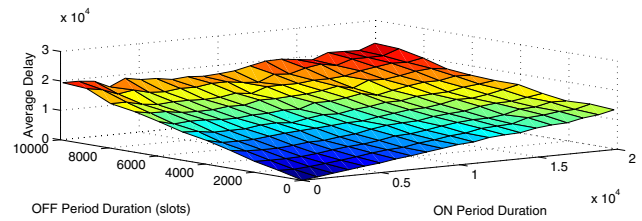Fig. 4.   Average delay for Cognitive Nodes: analytical results.



Fig. 5.   Average delay for Cognitive Nodes: simulation results.

In Fig.4, we compute the average delay using the analytical results in (14), while in Fig.5, we simulate our model of Sect.II and we observe the average delay of a chosen CN. Simulation and analytical results are very close, thus validating the M/G/1 queue with vacation model adopted in our queuing analysis. The average delay increases both for a larger average ON period length and for a larger service time (OFF period length). Thus, for a given probability $P_{ON}$, the delay performance is greatly influenced by the distribution of the ON period length ($s_{min}$ parameter) and the CNs' service policies. In Fig.6, we compare the throughput of CNs having a finite length queue of $Q$ packets. Both a channel-and-queue aware (CQ) scheduler and a proportional fair (PF) scheduler are used. In particular, we consider case (A) in which $Q$ is set equal to the average OFF period length of 500 slots and case (B) in which we have $Q \gg 500$ slots. For low $P_{ON}$ probabilities, the average
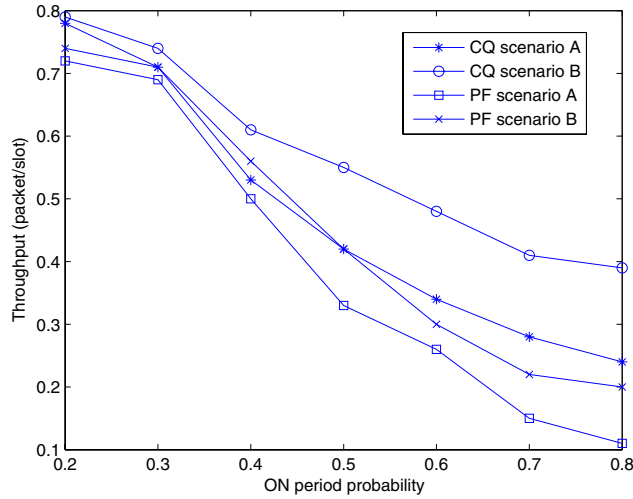
Fig. 6. Average throughput for different queues length and scheduling algorithms.

throughput is similar for the CNs belonging to both cases, and a very small throughput gain is achieved by taking into consideration both channel and queue state for scheduling decisions. In fact, when the queues are rather empty, the PF and the CQ scheduling make similar decisions. However, if the primary network is heavily loaded, the CQ scheduling algorithm outperforms the PF algorithm. A larger queue is needed in order to obtain a significant throughput and the real-time application must allow for a larger delay.

## VI. CONCLUSIONS

In this paper we consider a rather simple model of a cognitive ad-hoc network of $M$ nodes that exploits the same radio resources of a primary network of $N$ nodes. Pairs of cognitive nodes are entitled to communicate by a novel proposed channel-and-queue (CQ) aware distributed scheduler only when primaries are not using the channel. Under this model, we obtained a closed-form expression for the outage probability of the cognitive nodes by deriving the probability and cumulative density functions of the CNs SINR. Moreover, we presented a simple expression for the average packet delay for a general M/G/1 queueing model and an ON-OFF channel model. Primary traffic is modeled by a Pareto distribution that is suitable for Internet-like traffic, while a Poisson process is used for the secondary traffic in order to simplify the queuing analysis. Furthermore, we design a scheduling algorithm based on channel state information (CSI) and utility functions. In particular, each cognitive node is associated with a utility that is a decreasing function of its average packet delay. Finally, we compare the throughput of our proposed scheduler with that of a common proportional fair (PF) algorithm. When delay sensitive traffic is considered, our CQ scheduler is shown to be able to outperform channel-aware only algorithms.

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