

Saturation Throughput in a Heterogeneous Multi-channel Cognitive Radio Network

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Abstract—In this paper we consider a cognitive radio network in a heterogeneous multi-channel scenario where channels are different in terms of achievable bit rates. Upon arrival licensed users (PUs) will occupy first the channels with higher achievable rates. As a result, secondary users (SUs) will see a set of channels which are different not only in their physical capacities but also in the activity profile of PUs. Consequently, from the point of view of the effective throughput that SUs can obtain in each channel there exists a trade-off between the rate they can obtain in a certain channel and the amount of time they can use it. We develop a model that allows to solve this trade-off by computing the maximum effective throughput that SUs can achieve in each channel.

I. INTRODUCTION

Cognitive Radio (CR) networks are envisaged as the key technology to realize dynamic spectrum access. Such paradigm shift in wireless communications aims at solving the scarcity of radio spectrum [1]. The problem of spectrum scarcity is the result of, or is exacerbated by, the long-running static spectrum allocation policies, which are based on assigning spectrum bands to license holders on a long-term basis for large geographical regions. While there is an increasing demand of spectrum, those spectrum management policies have lead to an important underutilization (both temporally and spatially) of a big part of the assigned bands: conducted spectrum occupancy measurement studies yield average utilization figures as low as 5.2% [2], and below 20% in big cities such as New York or Chicago [3]. The CR concept proposes to boost spectrum utilization by allowing CR users (secondary users, SU) to access the licensed wireless channel in an opportunistic manner so that interference to licensed users (primary users, PU) is kept to a minimum.

The idea of CR is undoubtedly compelling and its realization will induce a huge advance in wireless communications. However, there are many challenges and open questions that have to be addressed before CR networks become practically realizable [4].

Spectrum management is carried out by cognitive users through a series of tasks that form a *cognitive cycle*. These tasks can also be divided into four major spectrum management functions [4], [5]: spectrum sensing, spectrum de-

cision, spectrum sharing and spectrum mobility. In most of these functions assessment and comparison among different spectrum bands is an inherent part. For instance, in spectrum sensing it must be decided which channels to sense, in which order, and when to stop sensing as good enough opportunities have already been discovered; in spectrum decision the most suitable of the sensed as available channels has to be identified.

Precise and timely measurements of the radio environment are a central element in the operation of CR. However, although absolutely necessary they are not enough by themselves to take the necessary spectrum management decisions. Ultimately measurements will feed the appropriate decision models.

In this paper we consider a heterogeneous multi-channel scenario and build a model for assessing the saturation throughput of SUs in each channel. Channels are different in terms of bandwidth and radio characteristics, e.g. signal-to-noise-plus-interference ratio (SNIR), thus yielding different achievable bit rates. Moreover, since some channels are better than others licensed users (PUs) will tend to occupy better channels first. As a result, SUs will see a set of channels which are different not only in their physical capacities but also in the activity profile of PUs. Indeed, from the perspective of SUs there exists a trade-off between the rate they can obtain in a certain channel and the amount of time they can use it, both in total and without interruptions.

In the proposed model the bit rate of each channel and the traffic parameters of PUs are inputs to the model. From these, we derive the probability distribution for the duration of white spaces in each channel. We consider that SUs employ a packet-based interface that works under a preemptive repeat discipline, i.e., either the whole packet is transmitted without interruption or it will have to be retransmitted from the beginning [6]. Then the derived distributions for white space duration are applied in order to obtain the saturation throughput for SUs, i.e., the throughput when SUs always have backlogged packets, under the preemptive repeat discipline.

Most of the existing research studies rely on some model of the spectrum availability resulting from PUs activity. The ON-OFF model with exponentially distributed ON (busy) and OFF (idle) times is perhaps the most widely adopted model (see [7], [8] and references therein). In [9]–[12] the duration distributions of the busy and idle periods are studied. The results obtained in these works cannot be applied to the

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scenario of interest in this paper since they address either the single channel case or the case of multiple channels but where PUs access them in random order. In [13], [14] large-scale measurement campaigns and subsequent thorough statistical analyses are reported. However, none of these works has specifically addressed the statistical characterization of white spaces duration.

The problem of obtaining the saturation throughput of SUs as addressed in this paper can be seen as that of computing the average *service completion time* in a queueing system with service interruptions. While the queueing literature on systems with service interruptions is abundant and rather general and complex systems have been analyzed (see for instance the *related work* sections in [15], [16]), to the best of our knowledge none of the existing models covers the specific case that we tackle here.

The rest of the paper is structured as follows. In Section II we detail the system characteristics and a matrix-analytic model is developed and analyzed. Section III presents a series of numerical experiments which illustrate the capabilities of our analysis and provide useful insights into the phenomena arising in the studied scenario. Finally, Section IV concludes the paper.

II. MODEL DESCRIPTION AND ANALYSIS

We consider a set of N frequency bands (channels) and assume channels are numbered according to their radio characteristics, e.g. SNIR, in decreasing quality, i.e., channel 1 is the best and channel N is the worst. These characteristics are homogeneous for all users in the system, both PUs and SUs, and are considered to be static for the time scale of interest.

PUs access the channels following an order of preference, i.e., an idle channel n will be occupied upon arrival of a PU only if all the better channels, $1, \dots, n-1$, are busy.

SUs can transmit at rate R_i on the i -th channel, $R_1 > R_2 > \dots > R_N$ and transmit data units, e.g. packets, in a preemptive non-resume manner (as in [6]).

We assume that PUs arrive according to a Poisson process of rate λ . When a PU arrives it is assigned the idle channel with the lowest index. If all channels are occupied the PU is blocked. The channel holding time is assumed to be exponentially distributed with rate μ . By assuming that the holding time of PUs is the same in all channels we are implicitly considering that PUs generate streaming traffic, i.e., while a higher feasible rate will have an impact on the perceived quality the service duration is kept the same. Due to the lack of space we have only addressed this case here, but the model and analysis can be easily modified to consider PUs generating elastic traffic.

We consider a fixed size of SU's packets $L = D + H$ in bits, where D is the payload size and H the header size.

Let $\mathbf{x} = (x_1, \dots, x_N)$ represent the system where $x_i = 0$ if the i -th channel is idle and $x_i = 1$ if it is busy.

Let $I_0(\mathbf{x}) = \{i | x_i = 0\}$ and $I_1(\mathbf{x}) = \{i | x_i = 1\}$, i.e., $I_0(\mathbf{x})$ (respectively, $I_1(\mathbf{x})$) is the set of indices corresponding to idle (busy) channels.

The transition rate $q_{\mathbf{x},\mathbf{y}}$ from a state \mathbf{x} to a state \mathbf{y} is given as

$$q_{\mathbf{x},\mathbf{y}} = \begin{cases} \mu & \text{if } \mathbf{y} = \mathbf{x} - \mathbf{e}_i \text{ and } i \in I_1(\mathbf{x}), \\ \lambda & \text{if } \mathbf{y} = \mathbf{x} + \mathbf{e}_i \text{ and } i = \min I_0(\mathbf{x}), \\ 0 & \text{otherwise} \end{cases}$$

where \mathbf{e}_i denotes a vector with a 1 on the i -th position and 0's elsewhere.

Let $Q = [q_{\mathbf{x},\mathbf{y}}]$ denote the infinitesimal generator of the system obtained by considering states sorted in lexicographical order, and π the vector of stationary probabilities.

Consider now an arbitrary channel $i = 1, \dots, N$. Let us define

$$\begin{aligned} I(i) &= \{\mathbf{x} | x_i = 0\} && \text{and} \\ B(i) &= \{\mathbf{x} | x_i = 1\} = \{1, \dots, N\} \setminus I(i), \end{aligned}$$

i.e., $I(i)$ (respectively, $B(i)$) is the set of states where channel i is idle (busy).

Define also

$$\begin{aligned} Q_{00}^{(i)} &= [q_{\mathbf{x},\mathbf{y}}]_{\mathbf{x},\mathbf{y} \in I(i)} && \text{and} \\ Q_{10}^{(i)} &= [q_{\mathbf{x},\mathbf{y}}]_{\mathbf{x} \in B(i), \mathbf{y} \in I(i)}. \end{aligned}$$

The matrix $Q_{00}^{(i)}$ contains the transition rates among states in $I(i)$ and it is obtained by removing from Q the rows and columns that correspond to states in $B(i)$. The matrix $Q_{10}^{(i)}$ contains the transition rates from states in $B(i)$ to states in $I(i)$, and it is obtained by removing from Q the rows that correspond to states in $I(i)$ and the columns that correspond to states in $B(i)$. Likewise, let $\pi_0^{(i)}$ ($\pi_1^{(i)}$) be a row vector with the stationary probabilities for states in $I(i)$ ($B(i)$), which are obtained by taking the appropriate entries from π .

We are interested in the duration of the busy period $B_p^{(i)}$ and of the idle period $I_p^{(i)}$ (for an arbitrary channel i). The busy period clearly corresponds to the PU holding time of channel i , which follows an exponential distribution of rate μ for all i . The idle period corresponds to the sojourn time in the set of states $I(i)$. Thus, the duration of the idle period can be represented by the *phase-type* distribution $PH(\alpha(i), T(i))$ [17], where $T(i) = Q_{00}^{(i)}$ and the probability vector $\alpha(i)$, which contains the probabilities of initiating the sojourn at each of the states in $I(i)$, is given by

$$\alpha(i) = \frac{1}{\pi_1^{(i)} Q_{10}^{(i)} \mathbf{1}} \pi_1^{(i)} Q_{10}^{(i)},$$

where $\mathbf{1}$ is a column vector of 1's.

The saturation throughput for SUs can be calculated as follows. The probability that at least k packets can be transmitted during an idle period on channel i is given as

$$p_k^{(i)} = P\left(I_p^{(i)} \geq k \cdot \frac{L}{R_i}\right) = 1 - F_{I_p^{(i)}}\left(\frac{kL}{R_i}\right) = \alpha(i) e^{\frac{kL}{R_i} T(i)} \mathbf{1},$$

where $F_{I_p^{(i)}}(\cdot)$ is the cumulative distribution function of the idle period duration on channel i .

Let $N_s^{(i)}$ be the number of SU packets that are successfully transmitted during an idle period on channel i , then

$$\begin{aligned} \mathbb{E}[N_s^{(i)}] &= \sum_{k=1}^{\infty} p_k^{(i)} = \sum_{k=1}^{\infty} \alpha(i) e^{\frac{kL}{R_i} T(i)} \mathbf{1} \\ &= \alpha(i) \left(e^{-\frac{L}{R_i} T(i)} - \mathbf{I} \right)^{-1} \mathbf{1}, \end{aligned} \quad (1)$$

where \mathbf{I} is the identity matrix.

The saturation throughput $\gamma_s^{(i)}$ for SUs on channel i can be now computed as the average number of (payload) bits that can be transmitted during an idle period over the average duration of the sequence of an idle plus a busy period. This leads to

$$\gamma_s^{(i)} = \frac{D \cdot \mathbb{E}[N_s^{(i)}]}{\mathbb{E}[I_p^{(i)}] + \mathbb{E}[B_p^{(i)}]} = \frac{\alpha(i) \left(e^{-\frac{L}{R_i} T(i)} - \mathbf{I} \right)^{-1} \mathbf{1}}{-\alpha(i) T(i)^{-1} \mathbf{1} + 1/\mu} D. \quad (2)$$

Besides the throughput, a useful metric could also be the probability that the transmission of a SU packet is interrupted. Let ν_i be the interruption probability for SU transmissions on channel i , then

$$\nu_i = \frac{1}{1 + \mathbb{E}[N_s^{(i)}]},$$

since during an idle time there are $N_s^{(i)}$ successful transmissions and exactly one interrupted transmission. For the same reason, the number of transmissions per time unit on channel i is

$$\frac{\mathbb{E}[N_s^{(i)}] + 1}{\mathbb{E}[B_p^{(i)}] + \mathbb{E}[I_p^{(i)}]}.$$

The overall interruption probability ν for SU transmissions on any of the N channels results from weighting the probabilities ν_i by the fractions of transmissions per time unit on each of the channels, i.e.

$$\begin{aligned} \nu &= \frac{1}{\sum_{i=1}^N \frac{\mathbb{E}[N_s^{(i)}] + 1}{\mathbb{E}[B_p^{(i)}] + \mathbb{E}[I_p^{(i)}]}} \sum_{j=1}^N \frac{\mathbb{E}[N_s^{(j)}] + 1}{\mathbb{E}[B_p^{(j)}] + \mathbb{E}[I_p^{(j)}]} \nu_j \\ &= \frac{1}{\gamma_s/D + \sum_{i=1}^N \frac{1}{\mathbb{E}[B_p^{(i)}] + \mathbb{E}[I_p^{(i)}]}} \sum_{j=1}^N \frac{1}{\mathbb{E}[B_p^{(j)}] + \mathbb{E}[I_p^{(j)}]}. \end{aligned}$$

Introducing the harmonic mean β of the mean cycle lengths on the channels, i.e. of the mean times between subsequent PU allocations on the channels, we find

$$\nu = \frac{N}{\beta \gamma_s / D + N}, \quad \text{with} \quad \frac{N}{\beta} = \sum_{i=1}^N \frac{1}{\mathbb{E}[B_p^{(i)}] + \mathbb{E}[I_p^{(i)}]}.$$

Finally, from a QoS perspective, it is interesting to know how long it takes for a SU packet to be effectively transmitted. Let us assume that if a packet's transmission on a certain channel is interrupted by a PU, it will be retransmitted on the same channel. We define the *transmission delay* d_i of a packet on channel i as the time period between the start of this packet's first transmission and the end of its final (successful) transmission. The average delay on channel i is given by $\mathbb{E}[d_i] = D/\gamma_s^{(i)}$, while the delay of an arbitrary SU packet has mean value $\mathbb{E}[d] = ND/\gamma_s$.

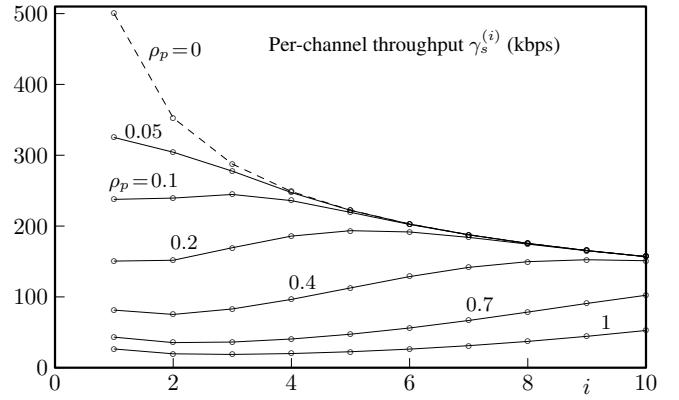


Fig. 1. Throughput $\gamma_s^{(i)}$ in kbps of the $N = 10$ channels for $1/\mu = 10$ ms and various values of the PU load $\rho_p = 0, 0.05, 0.1, 0.2, 0.4, 0.7, 1$. The channel bandwidths R_i obey a Zipf law such that $R_1 = 1$ Mbps and $R = 5$ Mbps. The SU packets have length $L = 1000$ bit with a header length of $H = 500$ bit.

III. NUMERICAL EXAMPLES AND DISCUSSION

To demonstrate the feasibility of our analysis, we now consider some specific scenarios for a system of $N = 10$ channels. Since the ordering of the channels $i = 1, \dots, 10$ results from a ranking from best to worst, it is reasonable to assume a Zipf law for their bandwidths R_i , i.e.

$$R_i = \frac{R_1}{i^\theta}, \quad \text{and} \quad R = \sum_{i=1}^N R_i, \quad (3)$$

for some shape parameter $\theta > 0$ and with R_1 the bandwidth of the best channel. We choose $R_1 = 1$ Mbps and $\theta = 0.5034$, such that the total available bandwidth of all channels together is $R = 5$ Mbps. The average PU holding time on all channels is equal to $1/\mu = 10$ ms. The offered load of PU traffic to the system is defined as

$$\rho_p = \frac{\lambda}{N\mu}.$$

In Fig. 1 we look at the influence of the PU load ρ_p on the saturation throughput. The packet length is chosen to be $L = 1000$ bit, half of which is header information $H = 500$ bit. The upper dashed curve shows the saturation throughput of the channels if the transmission of SU packets over the channels is not impaired by PU traffic, i.e. if $\lambda = 0$. Since the payload consists of half a packet, this curve corresponds to $R_i/2$, as given in (3). The figure clearly demonstrates that for a small PU load ρ_p , only the lower channels are affected, as one expects. For a higher PU load, the upper channels carry a significant part of the PU traffic as well, which results in a decreasing SU throughput in those channels.

In Fig. 2 the SU throughput of each channel is shown for some values of the SU packet length L , in case $\rho_p = 0.2$. One observes that with increasing packet length, the bulk of the throughput shifts more and more towards the upper channels. Since the lower channels carry most of the PU traffic, the ‘gaps’ between the PU transmissions are small there and larger

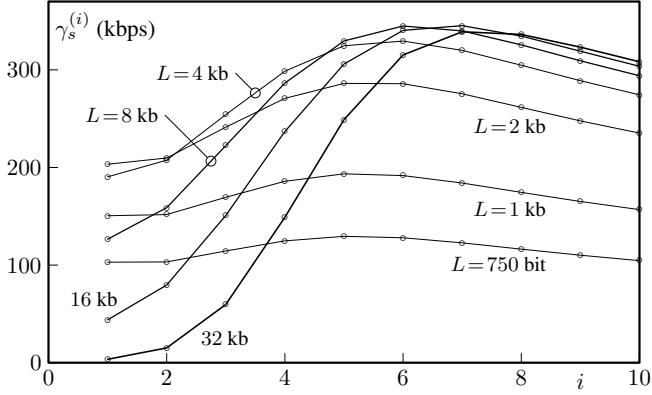


Fig. 2. Throughput $\gamma_s^{(i)}$ in kbps of the $N = 10$ channels for $1/\mu = 10$ ms, $\rho_p = 0.2$ and various values of the SU packet length $L = 0.75, 1, 2, 4, 8, 16, 32$ kb, with a header of $H = 500$ bit.

SU packets will no longer fit in. For $L = 32$ kb there are almost no gaps on channel 1 that are large enough to contain a complete SU packet, which results in a throughput $\gamma_s^{(1)}$ that is almost zero.

The crucial influence of the SU packet length is further demonstrated in Fig. 3. The total throughput $\gamma_s = \sum_{i=1}^N \gamma_s^{(i)}$ on all channels together is shown as a function of the packet length L , still assuming a header of 500 bit for each packet. Regardless of the amount of carried PU traffic, the throughput of SU data first increases with L , reaches an optimal point and then decreases again to zero. This can be explained as follows. If small SU packets are used, they will consist mostly of header information and have little payload. Therefore, although a lot of packets may be transmitted over the channels, the useful throughput is small. On the other hand, if the packet length L is large, the packets will no longer fit in the gaps between the PU transmissions, resulting in frequent interruption and subsequent retransmission of SU packets. This is especially the case on the lower channels with best quality (as was demonstrated in Fig. 2) because more PU traffic will be allocated there, resulting in smaller gaps. Consequently, we can conclude that there will always be an *optimal* value of the packet length L^* that maximises the overall throughput γ_s and which depends on the PU load of the system.

In Fig. 4, we show $\log_{10} \nu$ as a function of the PU packet length L for different values of the PU load. As expected, the interruption probability ν increases with both. Note that transmission interruptions do not depend on the header size of the packets, so no specific value for H has been considered here.

In Fig. 5 we show a doubly logarithmic plot of the transmission delay, in case the header size is 500 bit and the packet length is either 1 kb or 5 kb. Obviously, under light PU traffic conditions $\rho_p \ll 1$, the delay is equal to the transmission time L/R_i because SU transmissions are almost never interrupted. For increasing load ρ_p , more and more retransmissions are required, resulting in an increasing transmission delay on all

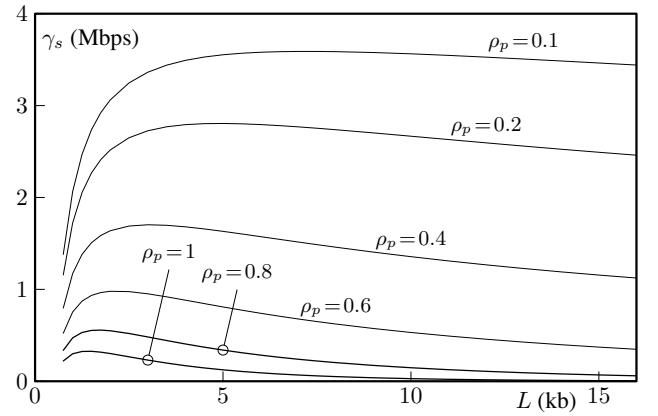


Fig. 3. Total throughput γ_s in Mbps of the system as a function of the SU packet length L , for an average PU holding time $1/\mu = 10$ ms and various values of the PU load $\rho_p = 0.1, 0.2, 0.4, 0.6, 0.8, 1$. SU packets have a header of $H = 500$ bit.

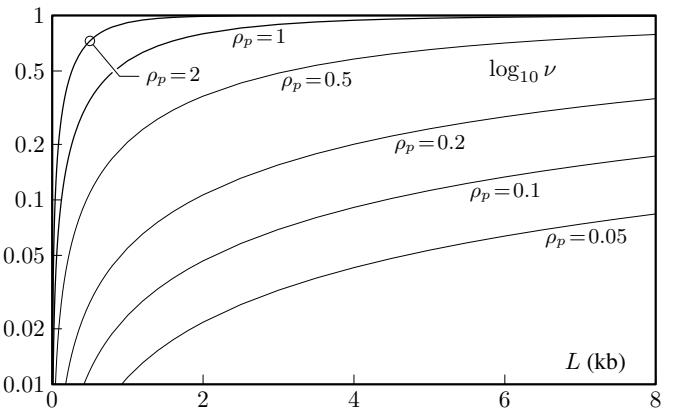


Fig. 4. Logarithmic plot of the overall interruption probability ν of SU transmissions versus the packet length L in kb, for various values of the PU load $\rho_p = 0.05, 0.1, 0.2, 0.5, 1, 2$.

channels. In case of Fig. 5 we see that the curves for the different channels overtake each other in the region $\rho_p < 0.5$. As we already discussed, this is due to the PU traffic gradually occupying the system, starting with the lowest channels. A striking observation however, is that the order of the curves switches *again* for higher values of ρ_p . Although not entirely visible on the figure, in extreme PU overload situations $\rho_p \gg 1$, the mean SU transmission delays on the channels are ordered as $E[d_1] < \dots < E[d_N]$, even though channel i carries more PU traffic than channel $i+1$. Hence we can conclude that for extreme overload, just as for extreme underload, the intrinsic rates R_i determine which channel has the best throughput. In between, which channel has the best throughput is also (and possibly predominantly) influenced by the amount of PU occupation of the channels.

IV. CONCLUSIONS

In this contribution we assess the maximum data throughput for unlicensed users (SUs) in the cognitive radio network

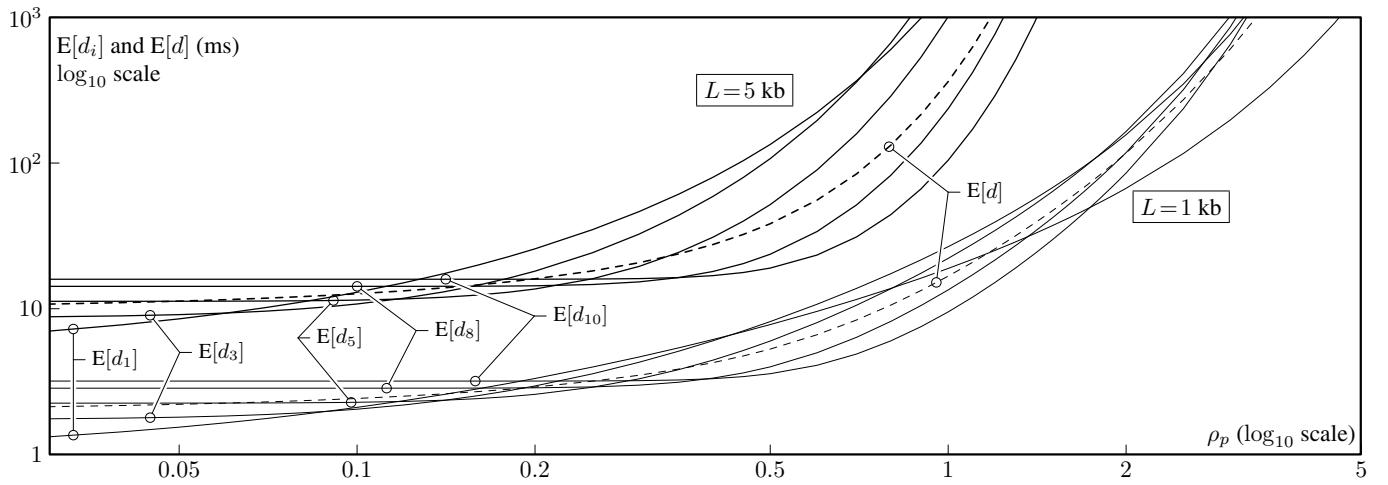


Fig. 5. Log-log plot of the mean transmission delay d_i in ms of SU packets in channel $i=1, 3, 5, 8, 10$ (solid lines), as well as the mean overall transmission delay d (dashed lines) as a function of the PU load ρ_p . The SU packet length is either $L=1\text{ kb}$ or $L=5\text{ kb}$, while the header size is always $H=500$ bit.

paradigm. We use a model with N channels having heterogeneous transmission rates R_i , where incoming requests of licensed users (PUs) are allocated to the highest-rate channel that is unoccupied. SU packets, which are assumed to be of fixed length L , can only use the ‘white spaces’ on a channel between the PU allocations. Any ongoing SU transmission will be forcefully interrupted if a new PU is allocated to the channel, which results in a preemptive repeat discipline for unlicensed packets. The model is tackled analytically, using a Markov chain description of the channels’ occupation. Expressions are obtained for the maximum useful SU throughput as well as related performance criteria such as interruption probability and mean transmission delay.

The results are demonstrated by means of some specific scenarios. We quantitatively show e.g. that careful choice of the packet length L is extremely important for maximizing the throughput. Additionally, concerning the question which channel achieves the best SU throughput we observed the following. As expected, for very low PU activity this is determined by the intrinsic rates R_i of the channels. If PU activity becomes significant, the SUs may achieve the best throughput on channels with lower rate because the highest-rate channels are the ones preferably used by the PUs. Surprisingly however, for extremely high PU activity on the system, the best SU throughput is again achieved on the channel with the highest intrinsic rate.

REFERENCES

- [1] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey,” *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, 2006.
- [2] S. S. C. (SSC), “Spectrum occupancy measurements,” SSC, 1595 Spring Hill Rd, Suite 110, Vienna, VA 22182, USA, Tech. Rep., 2005. [Online]. Available: <http://www.sharespectrum.com/measurements/>
- [3] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, “Chicago spectrum occupancy measurements & analysis and a long-term studies proposal,” in *TAPAS ’06: Proceedings of the first international workshop on Technology and policy for accessing spectrum*. New York, NY, USA: ACM, 2006, p. 1.
- [4] I. F. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “A survey on spectrum management in cognitive radio networks,” *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, 2008.
- [5] I. Akyildiz, W. Lee, and K. Chowdhury, “CRAHNs: Cognitive radio ad hoc networks,” *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, 2009.
- [6] F. Borgonovo, M. Cesana, and L. Fratta, “Throughput and delay bounds for cognitive transmissions,” in *Advances in Ad Hoc Networking*. Springer, 2008, pp. 179–190.
- [7] B. Canberk, I. F. Akyildiz, and S. Oktug, “Primary user activity modeling using first-difference filter clustering and correlation in cognitive radio networks,” *IEEE/ACM Transactions on Networking*, in press.
- [8] J. Riihijarvi, J. Nasreddine, and P. Mähönen, “Impact of primary user activity patterns on spatial spectrum reuse opportunities,” in *Wireless Conference (EW), 2010 European*, 2010, pp. 962–968.
- [9] S. Geirhofer, L. Tong, and B. Sadler, “Dynamic spectrum access in the time domain: Modeling and exploiting white space,” *IEEE Communications Magazine*, vol. 45, no. 5, pp. 66–72, May 2007.
- [10] P. K. Tang, Y. H. Chew, and L. C. Ong, “On the distribution of opportunity time for the secondary usage of spectrum,” *Vehicular Technology, IEEE Transactions on*, vol. 58, no. 3, pp. 1517–1527, Mar. 2009.
- [11] V. Pla, J.-R. Vidal, J. Martinez-Bauset, and L. Guijarro, “Modeling and characterization of spectrum white spaces for underlay cognitive radio networks,” in *IEEE International Conference on Communications (ICC)*, 2010.
- [12] C. Ghosh, S. Pagadarai, D. Agrawal, and A. Wyglinski, “A framework for statistical wireless spectrum occupancy modeling,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 38–44, Jan. 2010.
- [13] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, “Primary user behavior in cellular networks and implications for dynamic spectrum access,” *IEEE Communications Magazine*, vol. 47, no. 3, pp. 88–95, Mar. 2009.
- [14] M. Wellens and P. Mähönen, “Lessons learned from an extensive spectrum occupancy measurement campaign and a stochastic duty cycle model,” *Mobile Networks and Applications*, vol. 15, pp. 461–474, 2010.
- [15] F. Kamoun, “Performance evaluation of a queuing system with correlated packet-trains and server interruption,” *Telecommunication Systems*, vol. 41, no. 4, pp. 267–277, 2009.
- [16] T. Demoor, D. Fiems, J. Walraevens, and H. Bruneel, “The preemptive repeat hybrid server interruption model,” in *Proceedings of the 17th Analytical and Stochastic Modeling Techniques and Applications (ASMTA’10)*, ser. Lecture Notes in Computer Science. Springer Berlin-Heidelberg, 2010, vol. 6148, pp. 59–71.
- [17] G. Latouche and V. Ramaswami, *Introduction to Matrix Analytic Methods in Stochastic Modeling*. ASA-SIAM, 1999.