Performance Measures of Dynamic Spectrum Access Networks

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Abstract— In this paper we give insight into the performance of Dynamic Spectrum Access Networks (DSAN), analyzing Quality of Detection of Primary User (PU) and DSAN blocking probability, when the channel is under the effect of log-normal shadowing. Specifically we propose a distributed power conserving PU detection architecture and investigate the impact of PU detection accuracy on DSAN performance. We measure DSAN blocking probability as a function of the number of PU channels and their utilization. Finally we propose two efficient DSAN channel access schemes called Least-used and Least-used with Channel Hopping which aim at minimizing packet dropping due to the arrival of the PU.

I. INTRODUCTION

In today's wireless world some spectrum bands are highly utilized while many remain moderately or rarely occupied [1]. This observation has lead to the introduction of the Dynamic Spectrum Access (DSA) paradigm where the secondary wireless network is allowed to dynamically choose some parts of licensed radio bands, while causing minimal or no interference to Primary User (PU) occupying those frequencies. DSA is expected to be applied first into networks with an ad hoc need for additional bandwidth, for example, in military and emergency services [2]. Wireless ad hoc networks will also benefit from DSA since they currently work in crowded bands like ISM or UNII.

Dynamic Spectrum Access Network (DSAN) can opportunistically and in an ad hoc manner utilize non-occupied parts of the spectrum where only PUs are allowed [3], in contrast to the case when spectrum can be assigned statically by external spectrum managers [4]. A necessary component of such an opportunistic network is the frequency scanning block responsible for the detection of the PU on a particular frequency channel [5]. Detection of spectrum opportunities, i.e., periods of PU absence, should be very precise while accessing PU channels. Thus appropriate *Quality of Detection* (QoD) has to be incorporated into a DSAN, taking into account the type of detected PU and maximum level of interference caused by DSAN to PU, while accessing PU's frequency band [6], [7].

For the detection of PUs who are constantly occupying the channel, e.g. TV and FM radio broadcast, sporadic observation

would be sufficient. However when a DSAN utilizes channels that are intermittently used by PUs, DSAN has to scan constantly to detect the transitions between channel-busy and channel-free states to optimally use the PU channels. Such behavior is inefficient from the power saving perspective, since continuous scanning can consume excessive amount of power. Furthermore, continuous scanning procedures can introduce additional delay to DSAN, when scanning nodes share their RF front-end between scanning and Tx-Rx module. Finally, the duty cycle of a particular PU, i.e., the average time when the PU is present on the channel, can also impact the performance of DSAN, since the optimal choice of detected as free channels minimize the probability of loosing a DSAN packet due to a PU arrival.

These issues motivated our work for the DSAN performance analysis, presented here, which incorporates QoD and its impact on the network throughput, measured in terms of blocking probability. Specifically we apply cooperative scanning architecture in our DSAN model based on energy detection. We compare two scanning schemes, *Random* and *Synchronized*, that aim at minimizing energy consumption at each DSAN node while striving for complete information about the presence of a PU in each channel. We generalize our network model to the case, when DSAN has access to a set of PU (licensed) and unlicensed channels, where each of the PU channels has different duty cycles. Here we propose two channel access algorithms, *Least-used* and *Least-used with Channel Hopping*, that minimize the probability of dropping a packet due to the arrival of a PU. Finally we analytically show the impact of the PU duty cycle and detection accuracy on the throughput of DSAN.

We note that similar studies on the teletraffic analysis of DSAN have been performed recently, but without looking at the QoD and channel preemption by PUs. In [8] authors assumed for simplicity of analysis that a set of multiple primary channels, available to the DSAN, could be considered as one aggregated band, thus modeled as a $M/G/1$ queue with preemptive priorities. In [9] two types of unlicensed networks are taken into consideration – generic WLAN and Bluetooth, both having access to a limited set of channels. There, queuing was assumed when one type of network occupies particular channel, thus limiting other network's access to this resource. However no preemption and packet dropping was considered

in the Markov model analyzed.

This paper is structured as follows. The system model and initial variables are introduced in Section II. In Section III the proposed cooperative frequency scanning architecture is analyzed. Section IV focuses on various channel access schemes and influence of QoD on the DSAN throughput. Finally Section V concludes the paper, giving directions towards future work.

II. SYSTEM MODEL

The DSAN cooperatively detects the absence of PUs in the set $\mathbb{M}$ of M radio channels, by means of energy detection [10]. We call this process *frequency scanning*. We neglect other signal detection techniques, i.e., those based on the feature detection, or where interaction between DSAN and the PU is allowed, i.e., by means of spectrum etiquette.

The DSAN consists of a set $\mathbb{N}$ of N nodes, each having the capability of sensing PU channels. Specifically let us assume that we have a sufficient number of nodes in the DSAN, such that each channel $m \in \mathbb{M}$ is scanned by a set of g_m groups $\mathbb{G}_m = \{\mathbb{G}_{m,1}, \ldots, \mathbb{G}_{m,g_m}\}$ of nodes, where $\mathbb{G}_{m,i} \subset \mathbb{N}$, $|\mathbb{G}_{m,i}| = k_m$, and $\mathbb{G}_{m,i} \cap \mathbb{G}_{m,j} = \emptyset$. Each group $\mathbb{G}_{m,i}$ scans channel m for t_{int} observation time, after which a period of no scanning, t_{is}, occurs. We assume that PU do not change state in t_{int}, i.e., PU was either absent or present during whole t_{int}. We also assume that DSAN can distinguish whether channel m was used by PU or DSAN itself, so the nodes that do not take part in the scanning can communicate on channel m during t_{int}. During the inter scanning time t_{is} nodes contact the *Detection Entity* (DE), through a dedicated, non-PU *control channel*, to share their knowledge about the scanned frequency bands. DE can be treated as a dedicated DSAN node responsible for collection and analysis of scanning data obtained by scanning nodes. Interval t_{is} is also used to exchange data on selected PU channels between DSAN nodes. We denote $t_c = t_{is} + t_{int}$ as one *scanning cycle* performed by $\mathbb{G}_{m,i}$.

DSAN nodes can incorporate two simple cooperative scanning schemes, that aim at observing PUs of each channel $m \in \mathbb{M}$ as long as possible, without excessive power consumption at each DSAN node [11]. In *Scheduled* scanning, the group $\mathbb{G}_{m,i}$ starts its scanning cycle immediately after the group $\mathbb{G}_{m,i-1}$, and after scanning cycle of group $\mathbb{G}_{m,g_m}$ group $\mathbb{G}_{m,1}$ starts. While in *Random* scanning, each group switches between scanning cycles randomly, such that time until group $\mathbb{G}_{m,i}$ takes part in the scanning process again, and its scanning duration, are exponentially distributed with parameters $\lambda_{s,m,i}$ and $\mu_{s,m,i}$, respectively. In both schemes assignment of particular groups and their members during each scanning cycle can be performed either by DE or the nodes itself. We note that both schemes require synchronization of all scanning DSAN nodes.

In our network model the mean energy value observed during t_{int} from each of k_m nodes in one scanning group is sent to the DE. Then DE then makes a decision about the presence of the PU, based upon the set of energy values obtained from other nodes in scanning group, by comparing the sum of energy values with a given threshold, and respond back to the DSAN, through control channel, about PU channels' availability. This is in contrast to the case when DE itself would make a decision based on its own measurement. For simplicity of analysis we neglect propagation delays, transmission errors and multi access issues, which are discussed more detail in [12].

Since nodes are moving, each time they have a different instantaneous SNR, denoted as η, and for saving power, after each t_{int}, a different set of k_m nodes are chosen to scan channel m in $\mathbb{G}_{m,i}$. The DSAN nodes are distributed over a region $\mathfrak{R}$, such that they are placed within the operational area of each PU. The PU signal detected by each DSAN node is attenuated and suffers from log-normal shadow fading with a mean value of 0 dB and standard deviation σ_η dB. Thus the PDF of the SNR of the detected signal from PU m is given by

$$f_m(\eta, r_{n,m}) = \frac{10/\ln 10}{\sqrt{2\pi}\sigma_\eta \eta} \exp\left(-\frac{(10\log_{10}\eta - \mu_\eta(r_{n,m}))^2}{2\sigma_\eta^2}\right), \tag{1}$$

where σ_η, is the signal variance in dB due to the shadowing and $\mu_\eta(r_{n,m}) = P_{t,m} - 10\delta \log_{10}(r_{n,m}/r_{0,m})$ is the expected pathloss in dB observed by node n, at a distance $r_{n,m}$ from the PU m. Here $r_{0,m}$ is the reference range in the far field of the PU antenna, where the transmitted power $P_{t,m}$ is attenuated over distance with the path loss exponent δ.

We assume that the DSAN knows the duty cycle of the PUs in $\mathbb{M}$, such that the period of PU absence and presence on the observed channel are exponentially distributed with parameters $\lambda_{p,m}$ and $\mu_{p,m}$, respectively[1]. This knowledge can be gained, prior to DSAN deployment, from external spectrum regulators, who measure occupancy of PU channels, or by DSAN itself estimating the channel occupancy parameters after each scanning cycle. We also assume that traffic from all the DSAN nodes can be aggregated into one stream, and DSAN packets are generated such that inter-arrival time and packet lengths are exponentially distributed with parameters λ_D and μ_D, respectively.

III. COOPERATIVE DETECTION OF PUs

A. Obtaining Optimal Number of Scanning Nodes

We assume detection of signals in the presence of AWGN with known parameters [14]. Moreover for generality of our analysis we assume that the signal from the PU is deterministic and unknown. Let us assume first that DE itself is detecting the presence of PU. Without taking into account log-normal shadow fading, for a given decision threshold ν_m for channel m, the probability of false alarm, when PU is absent, can be computed as [10]

$$P_{f,m} = F(u/2, \nu_m/2), \tag{2}$$

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[1]The observation of different channel occupancy has been discussed in [13], supported by the measurements of PUs' activity.

where $u = \lfloor 2t_{int}W \rfloor$, W is the bandwidth of channel m, and $F(.,.)$ is the regularized incomplete lower gamma function. The probability of detection can be computed as

$$P_{d,m} = Q_{u/2}(\sqrt{\eta}, \sqrt{\nu_m}), \qquad (3)$$

where $\eta = 2\frac{E_s}{N_0}$, E_s is the signal energy, N_0 is the one sided noise PSD, and $Q_x(.,.)$ is the regularized Marcum Q function.

For simplicity we assume that the scanning nodes are uniformly distributed within a region $\mathfrak{R}$, ranging from r_1 to r_2 meters, thus the PDF of the distance distribution from the PU m, is $p_m(r) = \frac{1}{r_2 - r_1}$. In our model, during each scanning cycle different set of k_m nodes in scanning group $\mathbb{G}_{m,i}$ are chosen. Thus we can have a different representative SNR from each node, depending on its position. Therefore

$$
\begin{aligned}
E[\mu_\eta(r_{n,m})] &= P_{t,m} - 10\delta \int_{r_1}^{r_2} \frac{\log_{10}\left(\frac{r_{n,m}}{r_{0,m}}\right)}{r_2 - r_1} dr_{n,m} \\
&= P_{t,m} - 10\delta \left(\frac{\ln\left(r_2^{r_d} r_{0,m}^{-r_d} - r_d\right)}{r_d \ln(10)}\right), \quad (4)
\end{aligned}
$$

where $r_d = r_2 - r_1$. We assume that DSAN is farther away from PU such that σ_η does not change appreciably, and therefore we can write (1) independent of position of nodes leading to $f_m(\eta, r_{n,m})$ with $\mu_\eta(r_{n,m})$ given by (4) (which we denote later as $f_m(\eta)$).

Now to obtain the desired probability of detection of the PU on channel m by the DE, based on scanning result from k_m DSAN nodes, in the presence of log-normal shadowing we first need to find $f_m(\eta_\Sigma)$ – PDF of instantaneous SNR $\eta_\Sigma = \sum_{i=1}^{k_m} \eta_i$ detected by each of the k_m nodes – which the DE combines to detect the presence of the PU. Since there is no closed form expression for the PDF of the sum of log-normally distributed variables, one of the methods is to approximate such PDF as another log-normal distribution and find its parameters by means of numerical integration [15]. Further we need to integrate $\eta = \eta_\Sigma$ in (3) upon $f_m(\eta_\Sigma)$, i.e.,

$$P_{d,m} = \int_0^\infty Q_{k_m u/2}(\sqrt{\eta_\Sigma}, \sqrt{\nu_m}) f_m(\eta_\Sigma) d\eta_\Sigma, \qquad (5)$$

yielding the probability of detection of the PU by k_m DSAN nodes. To the best of authors' knowledge there is no known closed form expression for $P_{d,m,\Sigma}$ when the fading distribution of η_Σ is log-normal. Thus one has to evaluate (5) numerically[2]. Probability of false alarm if k_m nodes are scanning is computed using (2) as

$$P_{f,m} = F(k_m u/2, \nu_m/2). \qquad (6)$$

Before computing an optimal number k_m, let us first derive the probability of channel m being in busy state. Solving the two state Markov chain

$$\mathbf{Q}_m = \begin{bmatrix} -\lambda_{p,m} & \lambda_{p,m} \\ \mu_{p,m} & -\mu_{p,m} \end{bmatrix},$$

[2]In the case of Rayleigh fading $P_{d,m}$ is given by [10, Eq. 16].

for $\mathbf{P}(t) = e^{\mathbf{Q}_m t}$ for arbitrarily large t we get the steady state probability of channel m being in the busy state as, $\Pr[B_m = 1] = \frac{\lambda_{p,m}}{\lambda_{p,m} + \mu_{p,m}}$.

Thus to find the number of scanning nodes resulting in the required QoD $\triangleq 1 - P_{e,m}$, where

$$P_{e,m} = \Pr[B_m = 1](1 - P_{d,m}) + \Pr[B_m = 0]P_{f,m}, \quad (7)$$

denotes probability of detection error, for a given $P_{d,m}$ (because DSAN has to minimize interference introduce to PU while hypothetical channel access), ν_m, and u. Finally to obtain required number of scanning nodes we only need to solve (6) over k_m for $P_{f,m}$ evaluated from (7), possibly with the help of numerical integration.

B. Scheduling of PU Observations within DSAN

We need to compare the observation intervals of both introduced scanning schemes: Scheduled and Random. For simplicity we assume that t_{int} is the total channel observation time in one scanning cycle of one scanning group.

In the Scheduled scheme the normalized channel observation for one node in set $\mathbb{G}_m$ during scanning interval of length t_c equals to

$$C_s = \frac{1 - t_{is}/t_c}{g_m}.$$

We now need to find C_r, the expected channel observation time of one node in scanning group utilizing Random scheme. With the assumption of an exponential on-off behavior of the Random scheme we can construct a sampled time continuous Markov chain that allows us to compute the steady state probabilities $\Pr[B_{\mathbb{G}_{m,i}} = 1]$, i.e., group $\mathbb{G}_{m,i}$ is scanning channel m. The infinitesimal generator matrix $\mathbf{Q}_{S,g_m}$ for the Random scanning scheme of channel m with g_m sets of scanning nodes is defined in compact form as

$$\mathbf{Q}_{S,g_m} = (\mathbf{Q}_{s,g_m} - \mathbf{\Lambda}_{s,g_m}) t_c,$$

where

$$\mathbf{\Lambda}_{s,g_m} = diag\left(\sum_{i=1}^{2^{g_m}} Q_{s,g_m}[1,i], \ldots, \sum_{i=1}^{2^{g_m}} Q_{s,g_m}[g_m,i]\right),$$

$$\mathbf{Q}_{s,i} = \begin{bmatrix} \mathbf{Q}_{s,i-1} & \mathbf{D}_i(\lambda_{s,i}) \\ \mathbf{D}_i(\mu_{s,i}) & \mathbf{Q}_{s,i-1} \end{bmatrix},$$

$$\mathbf{Q}_{s,1} = \begin{bmatrix} 0 & \lambda_{s,1} \\ \mu_{s,1} & 0 \end{bmatrix},$$

and $\mathbf{D}_i(x) = diag(x, \ldots, x)$, where $\mathbf{D}_i$ is an $i \times i$ matrix. Solving $\mathbf{P}(t) = e^{\mathbf{Q}_{S,g_m} t}$ will yield a steady state probability vector,

$$\mathbf{B}_{\mathbb{G}_m} = \left[\frac{\lambda_{s,m,1}}{\lambda_{s,m,1} + \mu_{s,m,1}}, \ldots, \frac{\lambda_{s,m,g_m}}{\lambda_{s,m,g_m} + \mu_{s,m,g_m}}\right].$$

Since each group is scanning independently each PU channel we can use the inclusion-exclusion formula for evaluating probability $\Pr\left[\bigcup_{i=1}^{g_m} B_{\mathbb{G}_{m,i}} = 1\right] = \Pr[\Sigma]$ that at least one
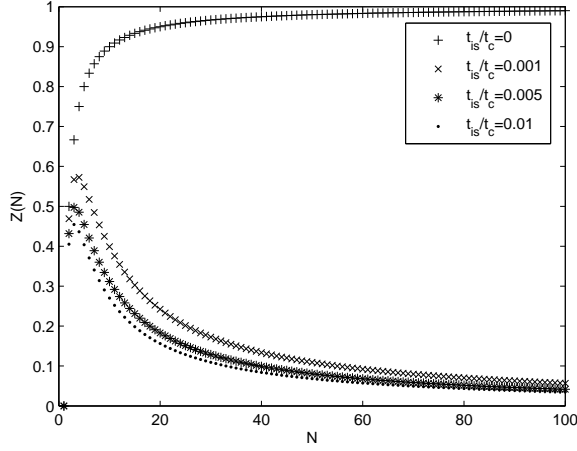
Fig. 1. Plot of $Z(g_m)$ for $t_{is}/t_c = \{0, 0.001, 0.005, 0.01\}$.

of the g_m groups of DSAN nodes was observing the channel m as

$$\Pr[\Sigma] = 1 - \prod_{i=1}^{g_m} \Pr[B_{\mathbb{G}_{m,i}} = 0]. \qquad (8)$$

Since each set $\mathbb{G}_{m,i}$ should consume the same amount of power during scanning, i.e., $\lambda_{s,m,i} = \lambda_{s,m}$, $\mu_{s,m,i} = \mu_{s,m}$ which yields $\Pr[B_{\mathbb{G}_{m,1}} = 1] = \ldots = \Pr[B_{\mathbb{G}_{m,g_m}} = 1] \triangleq \Pr[B_{\mathbb{G}_m} = 1]$ we can express (8) as

$$\Pr[\Sigma] = \sum_{i=1}^{g_m} (-1)^{i-1} \binom{g_m}{i} \Pr[B_{\mathbb{G}_m} = 1]^i$$
$$= 1 - \Pr[B_{\mathbb{G}_m} = 0]^{g_m}. \qquad (9)$$

Therefore solving (9) for $\Pr[\Sigma] = 1 - t_{is}/t_c$, i.e., such that one scanning group with Random scanning scheme would scan the channel m for the same fraction of time as with Scheduled scheme, over $C_r = \Pr[B_{\mathbb{G}_m} = 1]$ yields

$$C_r = 1 - \sqrt[g_m]{t_{is}/t_c}.$$

Finally defining function $Z(g_m) = C_r - C_s$ we can compare two proposed channel observation algorithms. We see that difference between the Random and the Scheduled schemes, expressed in terms of normalized average observation time, converges to zero for large g_m, with $t_{is} > 0$. The function $Z(g_m)$ has one extreme point at

$$g_{m_{ext}} = \left\lceil \frac{\ln(t_{is}/t_c)}{\ln(t_{is}/t_c - 1) - \ln(\ln(t_{is}/t_c))} \right\rceil.$$

Therefore each DSAN node is observing on an average the same fraction of time given by C_s and C_r for large g_m. Moreover the larger t_{is} the faster both algorithms converge. Plot of $Z(g_m)$ for different t_{is} is given in Fig. 1.

IV. PERFORMANCE EVALUATION OF DSAN

Having performance measures of DSANs' scanning system, we need to connect them with the DSAN throughput measures. In this paper we focus specifically on interference level introduced to PU by DSAN and DSANs' blocking probability.

A. Level of Interference to Primary Users

Assuming that both the Random and the Scheduled schemes perform equally, i.e, they do not observe channel m only for t_{is} during each scanning cycle, and nodes that do not scan channel m can communicate on it, the average interference to PU on channel m is equal to

$$I_m = \big(\Pr[B_{p,m} = 0](1 - e^{-\lambda_{p,m}t_{is}})(1 - P_{f,m})$$
$$+ \Pr[B_{p,m} = 1](1 - e^{-\mu_{p,m}t_{is}})(1 - P_{d,m})\big) t_{is},$$

where $I_{m,\max} \geq I_m$, and $I_{m,\max}$ is the maximum level of interference that PU m can accept. Parameter $I_{m,\max}$ just like $P_{e,m}$, can be given by Radio Regulator before DSAN is deployed.

B. Channel Access Schemes

DSAN accessing M channels will experience two types of blocking. *Type I blocking* occurs when all channels are busy occupied either by a PU, DSAN, or both. *Type II blocking* is due to the arrival of a PU when DSAN was using the channel. For simplicity of analysis we assume that DSAN has no queue, where arriving blocked packets could be stored.

For the case of one PU channel to which DSAN has access to, the infinitesimal generation matrix is defined as

$$\mathbf{Q}_{P,m} = \mathbf{Q}_{p,m} - \mathbf{\Lambda}_{p,m},$$

where

$$\mathbf{\Lambda}_{p,m} = diag\left(\sum_{i=1}^{4} \mathbf{Q}_{p,m}[1,i], \ldots, \sum_{i=1}^{4} \mathbf{Q}_{p,m}[4,i]\right),$$

$$\mathbf{Q}_{p,m} = \begin{bmatrix} 0 & \lambda_D & 0 & \lambda_{p,m} \\ \mu_D & 0 & \lambda_{p,m} & 0 \\ \mu_{p,m} & 0 & 0 & \mu_D \\ \mu_{p,m} & 0 & 0 & 0 \end{bmatrix}.$$

In the above Markov chain state 1 means *channel free*, state 2 *channel occupied by DSAN*, state 3 *channel occupied by PU* and state 4 *arrival of PU while channel was serving DSAN*. Again solving $\mathbf{P}(t) = e^{\mathbf{Q}_{P,m}t}$ we get steady state probability vector $\mathbf{B}_{b,m}$. Type I blocking in this case is equal to

$$\Pr[B_{b,m}^{(1)} = 1] = 1 - \mathbf{B}_{b,m}(1)$$
$$= 1 - \frac{\mu_{p,m}(\lambda_{p,m} + \mu_D)}{\lambda_{p,m}(D + \lambda_{p,m} + \mu_{p,m}) + \mu_{p,m}D},$$

where $D = \lambda_D + \mu_D$, and type II blocking is equal to

$$\Pr[B_{b,m}^{(2)} = 1] = \mathbf{B}_{P,1}(1)\frac{\lambda_{p,m}}{\mu_D + \lambda_{p,m}}. \qquad (10)$$

In (10) term $\frac{\lambda_{p,m}}{\mu_D + \lambda_{p,m}}$ represents the fraction of secondary packets that were dropped due to the interference caused by the arrival of PU on the channel m. $\mathbf{B}_{P,1}(1)$ is the fraction of DSAN traffic that was admitted to the PU channel. Thus the total blocking probability is equal to $\Pr[B_{b,m} = 1] = \Pr[B_{b,m}^{(1)} = 1] + \Pr[B_{b,m}^{(2)} = 1]$.

We note that similar procedure of constructing $\mathbf{Q}_{P,m}$ matrix for M PU channels, based on specifying all possible states of
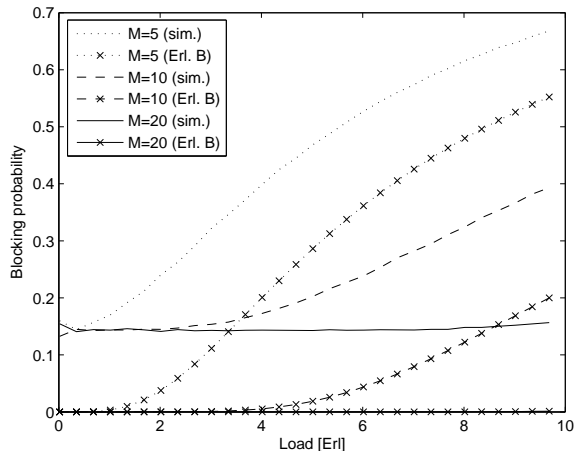
Fig. 2. Simulation of blocking probability for M={5,10,20} where DSAN was using RND algorithm. Each channel is utilized with by PUs equally with parameters $\lambda_{p,M} = 1$ and $\mu_{p,M} = 3$. Plots of blocking probability with Erlang B formula for the respective number of channels are shown for comparison.

Fig. 3. Simulation of blocking probability for M={5,10,20} where DSAN was using RND algorithm. Channels are utilized non-uniformly by PUs, i.e., $\forall m > 2, \lambda_{p,m} = \lambda_{p,m-1} - \lambda_{p,1}/2, \lambda_{p,1} = 20$ and $\mu_{p,M} = 3$.

interaction between PUs and DSAN can be applied, however due to non-symmetric nature it is hard to provide a closed form expression for blocking probability.

Since detection error is independent of usage (here we treat interference from PU also as blocking) of PU channel we can compute total blocking probability $\Pr[B_{b+e,\mathbb{M}} = 1]$, taking into account detection errors, for the case of M channels, as

$$\Pr[B_{b+e,\mathbb{M}} = 1] = \Pr\left[\bigcup_{i=1}^{M} P_{e,i} = 1 \cup B_{b,\mathbb{M}} = 1\right]. \quad (11)$$

In the above Markov chain analysis we have assumed that from the set of free channels $\mathbb{F} \leq \mathbb{M}$, DSAN chooses a channel randomly. We call this access scheme as *Random* (RND). However we can also think of two other access schemes:

1) Least-used (LU), when DSAN chooses channel m with $\min(\lambda_{p,1}, \ldots, \lambda_{p,F})$; whenever PU arrives on a chosen channel blocking occurs. And

2) Least-used with Channel Hopping (LUCH), when DSAN chooses a channel according to LU scheme finds out that PU has arrived and then tries to choose another channel with the smallest $\lambda_{p,m}$ possible, and continue transmitting rest of the data there. With no more option of channel hopping blocking occurs.

Such channel access, based on the knowledge of duty cycle of PUs, aims at minimizing type II blocking. This observation is confirmed by simulations, provided in the next section.

C. Simulation results

All simulations were performed in C++, and each simulation ran for 100000 seconds. In our program all DSAN packets were offered to a pool of PU channels, each having specified arrival and departure parameters. No radio propagation phenomena were implemented in the simulator.
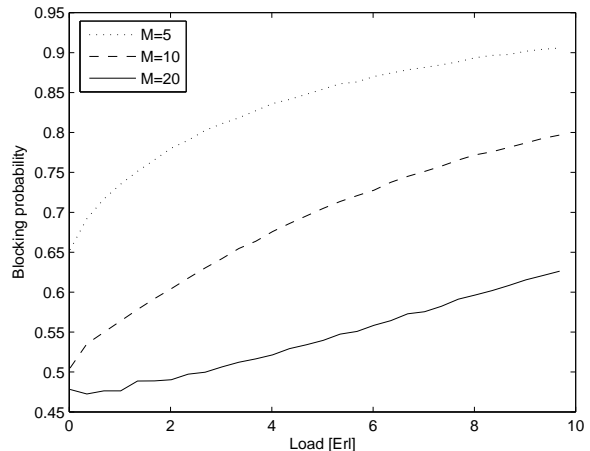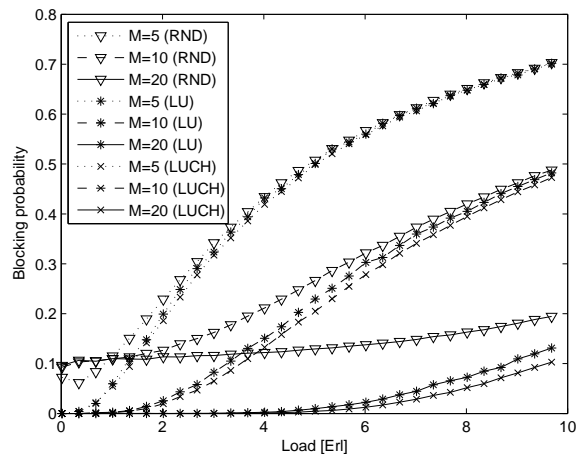

Fig. 4. Simulation of blocking probability for M={5,10,20} for different channel access schemes. Channels are utilized non-uniformly by PUs, i.e., for $m = 1, \ldots, M/2, \forall m > 2, \lambda_{p,m} = \lambda_{p,m-1} - \lambda_{p,1}/2, \lambda_{p,1} = 20$ and $\mu_{p,M} = 3$. Rest of the channels are considered unoccupied by PUs.

In case of M primary channels having uniform duty cycle, and DSAN using RND access scheme, blocking probability is plotted in Fig. 2. It is interesting to see that for this set of parameters DSAN, even for the low load of secondary network, experiences significant blocking probability of ≈ 0.15. Simulations for non-uniform traffic, also for RND scheme, is shown in Fig. 3, where, not surprisingly, we have observed much higher blocking probability than in Fig. 2. Results of the simulations for the probability of blocking with different access schemes are depicted in Fig. 4. A simulation scenario was constructed such that it closely mimicked the operation of DSAN, i.e., PU channels with non-uniform utilization and a set of free unlicensed channels. For three different sets of channels we see that LUCH algorithm outperforms two other access schemes. What is interesting to see however, that for
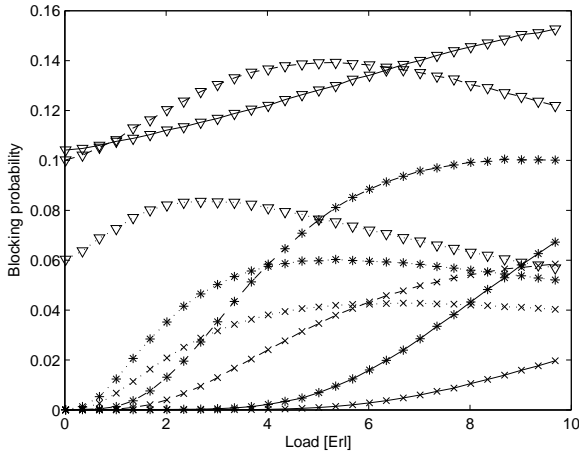
Fig. 5. Simulation of type II blocking probability for M={5,10,20} for different channel access schemes. Channel utilization and naming of the plots is the same as in Fig. 4

the moderate number of channels the difference in blocking probability between LU and LUCH is rather small (less than 0.01). The difference between LU and LUCH is more visible in the case of $M = 20$ channels and it is due to the fact that the secondary packets have more opportunities to switch to different channels. In Fig. 5 plot for type II blocking is shown. For $M = 5$ difference in type II blocking is small for a moderate load from DSAN. But for $M = 20$ this difference is quite significant (around 0.2). However while LUCH is the most efficient compared to other two algorithms the difference in terms of blocking probability between LU and LUCH in many scenarios is negligible. We have to emphasize that LUCH algorithm might on the other hand increases signalling traffic on the control channel since DSAN must schedule the hopping of all the packets.

All simulations were done assuming perfect PU detection. However total blocking probability in the presence of detection errors can be simply found using (11).

V. CONCLUSIONS

In this paper we have proposed a DSAN architecture in which nodes collaboratively sense for free spaces in radio spectrum and try to utilize PU channels such that packet drop for the secondary network due to the arrival of PUs is minimized. We have analyzed the impact of QoD on DSAN performance and have shown that synchronized network detects PUs more efficiently than non-synchronized. We have given preliminary analytical expressions for computing blocking probability for the analyzed DSAN. By simulation we have proven that Least-used with Channel Hopping algorithm minimizes packet loss, in comparison to Random and Least-used algorithms. We believe that our model mimics more closely the behavior of a DSAN than models proposed earlier in [8], [9]. We next focus on the analysis of multiple classes of secondary traffic and their blocking. Moreover the cost of the cooperative detection, i.e., speed of gaining information on PU availability, in DSAN has to be evaluated.

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