# Impact of Channel Switching in Energy Constrained Cognitive Radio Networks

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***Abstract*—In this letter, we investigate the energy efficiency of multichannel spectrum access in cognitive radio networks. We consider two channel access schemes. In one case, a secondary user (SU) is assigned multiple channels and the channels are switched whenever a primary user (PU) returns. In the other, the SU operates on a single channel without switching to other channels. We develop an analytic framework on achievable channel utilization and energy consumption performance of the SU. From the results, we examine the trade-off between SU channel utilization and energy consumption, and identify the PU traffic conditions where one scheme outperforms the other.**

***Index Terms*—Cognitive radio networks, dynamic spectrum access, single channel access, multichannel access, energy efficiency**

## I. Introduction

We consider a dynamic spectrum access (DSA) scenario with multiple primary user (PU) channels. A secondary user (SU) could be exclusively allocated one channel or multiple channels for its operation in a cognitive radio network. In multichannel DSA (MC-DSA) (e.g., [1]), an SU is allowed to access multiple channels in a controlled way. At a time an SU senses a chosen channel and transmits data over it, if it is idle. Otherwise the SU switches to another channel and repeats the process. In an alternative approach, called single channel DSA (SC-DSA) (e.g., in [2]), an SU is assigned a fixed channel. The SU remains in the channel even if it is currently unavailable, and utilizes whenever the channel is available.

SU consumption is important in energy constrained cognitive radio networks [3], [4]. In MC-DSA, compared to sensing or transmission, an SU consumes considerable amount of energy in channel switching, causing decreased energy efficiency. On the other hand, in SC-DSA, the energy consumption due to channel switching is eliminated, however at the cost of less transmission opportunity for the SUs, which also may lead to a poor energy efficiency. Although there are apparent energy versus utilization trade-offs associated with MC-DSA and SC-DSA, to our best knowledge there has been no study reported in the literature that objectively quantifies these trade-offs.

In this work we study the SUs' channel utilization and energy efficiency in MC-DSA and SC-DSA schemes. Using discrete time Markov chain (DTMC) models, we analyze the performance and obtain the threshold condition on PU activity dynamics when SC-DSA scheme is beneficial over MC-DSA. Numerical results are generated for the case when the PU's idle and busy periods are exponentially distributed, while simulation results are presented for cellular and ISM bands.

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## II. System Model and Performance Analysis

We consider $N$ PU channels with independent and identically distributed (i.i.d.) traffic. The performances of the two schemes are evaluated in terms of SU channel *utilization* and *energy efficiency*. SU *utilization* is the successful SU transmission per unit time. *Energy efficiency* is measured as the successful SU transmissions per unit energy consumption. SU transmits over the channel only when it meets an acceptable PU collision ratio threshold. *PU collision ratio* is the ratio of PU transmissions interfered to the total PU transmissions.

Channel model and performance analysis are presented next.

### A. Channel and node models

The PU channels are characterized using 'ON-OFF' model. For intuitive understanding on system performance through closed form analysis, 'ON' and 'OFF' period lengths are assumed exponentially distributed with the respective means $\mu$ and $\lambda$. SU senses the channel for time $T$ to meet the channel sensing performance requirements. Channel sensing imperfection as a function of sensing duration is not accounted. Channel usage is considered time slotted, with slot duration $T$ units (same as the sensing duration). $S_k^i$ denotes the state of channel $i$ in slot $k$, with states $\{0 \text{ (idle)}, 1 \text{ (busy)}\}$. All channels are of equal bandwidth. The SUs are assumed to have in-built sensing capability. The SU transmitter-receiver pair is located in a small geographical region and experience the same channel conditions. An SU incurs a delay of $n_s$ slots and consumes $\Phi_{sw}$ energy per channel switching.

We analyze the maximum achievable channel utilization and energy efficiency by the SUs in a given PU scenario.

### B. Analysis of switching based DSA (MC-DSA)

In MC-DSA (cf. Fig. 1), upon entering to a channel, if the SU senses it to be idle, it transmits in next $l$ consecutive slots. $l$ is chosen so as to meet the PU collision ratio threshold $\eta$. After the transmission, SU senses the channel again in the next slot and decides to transmit in next $l$ slots (if it is sensed idle) or switch to the next channel (if it is sensed busy).

We represent the ON/OFF channel states in terms of DTMC. The state transition probability can be computed as:

$$Pr\{OFF \rightarrow ON\} \triangleq \mathbf{P}(0,1) = \int_0^T \frac{1}{\lambda} e^{-x/\lambda}\, dx = 1 - e^{-T/\lambda}.$$

The other transition probabilities can be similarly obtained. The channel state transition matrix $\mathbf{P}$ is obtained as:

$$\mathbf{P} = \begin{bmatrix} e^{-T/\lambda} & 1-e^{-T/\lambda} \\ 1-e^{-T/\mu} & e^{-T/\mu} \end{bmatrix}. \quad (1)$$

For a given PU collision ratio threshold $\eta$, PU can tolerate $\eta\mu$ fraction of average ON period due to SU collision. Accordingly, SU transmission length $l$ ($l \ll \mu/T$) is obtained as $\mathbb{E}[\text{SU transmission collision}|\text{transmission collided}] \leq \frac{\eta\mu}{T}$,

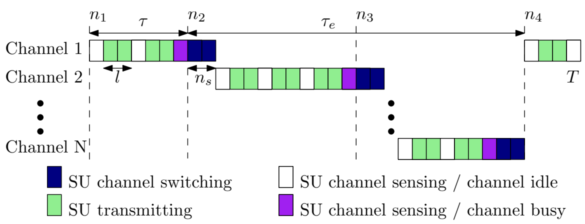


Fig. 1: Illustration of switched multichannel access (MC-DSA).

$$\text{i.e.,} \quad \sum_{k=1}^{l} \frac{(l-k+1)e^{-\frac{T(k-1)}{\lambda}}(1-e^{-\frac{T}{\lambda}})}{1-e^{-\frac{T(l+1)}{\lambda}}} \leq \frac{\eta\mu}{T}, \quad \text{or,}$$

$$l \leq \frac{r+e^{-\frac{T}{\lambda}}}{1-e^{-\frac{T}{\lambda}}} + \frac{\lambda}{T}\mathbf{W}\left(\frac{e^{-\frac{T}{\lambda}}T(1+r)}{\lambda(e^{-\frac{T}{\lambda}}-1)}e^{-\frac{T\left(e^{-T/\lambda}+r\right)}{\lambda\left(1-e^{-T/\lambda}\right)}}\right). \quad (2)$$

$\mathbf{W}(\cdot)$ is the Lambert-W function and $r = \eta\mu(1-e^{-T/\lambda})/T$. Optimal transmission length is taken as $\max(l \in \mathbb{I}^+)$.

The DTMC model provides closed-form expressions of the performance metrics, as will be seen next. However, the number of states in the Markov chain for $N = 2$ is 8, and it increases exponentially with $N$. Hence, for larger values of $N$, we introduce an iterative scheme in Section II-B2.

*1) For $N = 2$:* Channel switching behavior in 2-channel MC-DSA can be represented by an 8-state DTMC (Fig. 2). The states in a slot are denoted as the combination of channel-1 state, channel-2 state, and the channel occupancy by SU. For example, in state 'A' both channels are idle and the SU is tuned to channel 1. In states 'A', 'B', 'E', and 'G', SU transmits for $l$ slots, while in the other states SU switches to another channel.

The DTMC transitions are from state 'A' to states 'A', 'B', 'C', and 'D', as the SU remains on the same channel. Similarly, from state 'C' transitions are to state 'E', 'F', 'G', and 'H', as in this case the SU switches from channel 1 to 2.

Denoting $\mathbf{P_k} = \mathbf{P}^k$ as the $k$-step channel state transition probability matrix, transition probability $Pr[A \to B]$ is:

$$\begin{aligned} Pr[\text{A} \to \text{B}] =& Pr[S_i^1 = 0|S_{i-l-1}^1 = 0]Pr[S_i^2 = 1|S_{i-l-1}^2 = 0] \\ =& \mathbf{P_{(l+1)}}(1,1)\mathbf{P_{(l+1)}}(1,2). \end{aligned}$$

Transition from state 'C' to 'F' involves channel switching, which takes $n_s$ slots and has the probability:

$$\begin{aligned} Pr[\text{C} \to \text{F}] =& Pr[S_i^1 = 0|S_{i-n_s-1}^1 = 1]Pr[S_i^2 = 1|S_{i-n_s-1}^2 = 0] \\ =& \mathbf{P_{(n_s+1)}}(2,1)\mathbf{P_{(n_s+1)}}(1,2). \end{aligned}$$

The other transition probabilities are similarly derived. The complete state transition probability matrix is denoted by $\mathbf{Q}$. Switching happens when the system enters states 'C', 'D', 'F', and 'H'. Hence the rate of switching is obtained as:

$$R_{sw} = \sum_{i \in \mathcal{X}} \sum_{j \in \mathcal{Y}} \pi_i \mathbf{Q}(i,j).$$

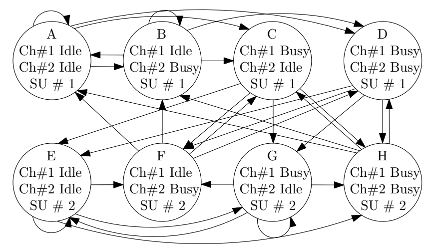


Fig. 2: DTMC representation of two channel MC-DSA.

$\mathcal{X} = \{A, B, \cdots, H\}$ and $\mathcal{Y} = \{C, D, F, H\}$. The limiting state probabilities, $\pi_i$, $i \in \mathcal{X}$, are obtained by: $\underline{\pi} = \underline{\pi} \cdot \mathbf{Q}$.

Per slot energy consumption for sensing, transmission, idling, and switching the channel are denoted as $\Phi_{se}$, $\Phi_t$, $\Phi_i$, and $\Phi_{sw}$, respectively. The utilization and energy efficiency of SU in MC-DSA scheme is given in (3) and (4), respectively.

*2) For general $N$:* Let the SU switches to channel 1 at some slot $n_1$ (cf. Fig. 1). Also, let the probability of channel 1 being in OFF state at time $n_1$ be $p_0(n_1) = Pr[S_{n_1}^1 = 0]$. SU senses the channel for a slot and transmits over it, if it is found idle. If the channel is found busy, SU switches to the next channel.

Starting from the instant when the SU switches to channel 1, we compute the distribution of time the SU remains in channel 1 before switching to the next. Denote the random variable $\tau$ as the amount of time SU remains in channel 1 before switching. The probability mass function (pmf) of $\tau$, $G_\tau$ is given as:

$$G_\tau = \begin{cases} 1-p_0(n_1) & \tau = 1 \\ p_0(n_1)(\mathbf{P_{(l+1)}}(1,1))^{k-1}\mathbf{P_{(l+1)}}(1,2) & \tau = (l+1)k+1 \\ 0 & \text{otherwise.} \end{cases}$$

SU switches from channel 1 at time $n_2$ and reenters to 1 at time $n_4$ (Fig. 1). During this time SU operates sequentially on channels 2 to $N$. $\tau_e = n_4 - n_2$ is the time elapsed between two successive entries to channel 1 by the SU. The pmf of $\tau_e$, $H_{\tau_e}$ is given as $H_{\tau_e} = G^{\star(N-1)}(\tau_e - Nn_s)$. Here $G^{\star(N-1)}$ is $N-1$ times convolution of $G$. The probability of channel 1 being in OFF state at time $n_4$ can be obtained as:

$$p_0(n_4) = \sum_{i=Nn_s+1}^{\infty} H_{\tau_e=i}\ \mathbf{P_i}(2,1). \quad (5)$$

From an initial $p_0$, its steady state value is obtained by iterating (5). The SU utilization and energy efficiency are given as:

$$\mathcal{U}_{\text{MC}} = \frac{l(\pi_A+\pi_B+\pi_E+\pi_G) - \eta\mu(\sum_{i=\{A,B\}}\sum_{j=\{C,D\}}\pi_i\mathbf{Q}(i,j) + \sum_{i=\{E,G\}}\sum_{j=\{F,H\}}\pi_i\mathbf{Q}(i,j))}{(\pi_A+\pi_B+\pi_E+\pi_G)(l+1) + (\pi_C+\pi_D+\pi_F+\pi_H)(n_s+1)} \quad (3)$$

$$\mathcal{E}_{\text{MC}} = \frac{lT(\pi_A+\pi_B+\pi_E+\pi_G) - \eta\mu T(\sum_{i=\{A,B\}}\sum_{j=\{C,D\}}\pi_i\mathbf{Q}(i,j) + \sum_{i=\{E,G\}}\sum_{j=\{F,H\}}\pi_i\mathbf{Q}(i,j))}{l(\pi_A+\pi_B+\pi_E+\pi_G)\Phi_t + (\pi_A+\pi_B+\pi_E+\pi_G)\Phi_{se} + R_{sw}(\Phi_{se}+\Phi_{sw}+n_s\Phi_i)}. \quad (4)$$

$$\mathcal{U}_{\text{MC}} = \frac{lv - p_0\eta\mu/T}{1+(l+1)v+n_s} \tag{6}$$

$$\mathcal{E}_{\text{MC}} = \frac{lvT - p_0\eta\mu}{(1+v)\Phi_{se} + lv\Phi_t + \Phi_{sw} + n_s\Phi_i} \tag{7}$$

where $v = p_0/\mathbf{P}_{(\mathbf{l+1})}(1,2)$ is the expected number of transmission instances by the SU between two channel switchings.

Channel state in the next visit depends on the time elapsed $\tau_e$ between the two successive visits. Probability of finding the channel $S^1_{(n_4=n_2+\tau_e)}$ idle in the next visit is given as:

$$\begin{aligned}\Gamma(\tau_e) &\triangleq Pr[S^1_{(n_2+\tau_e)} = 0 | S^1_{n_2} = 1] = \mathbf{P}_{\tau_\mathbf{e}}(2,1)\\ &= \frac{(1-e^{T/\mu})(1-(e^{T/\mu}+e^{T/\lambda}-1)^{\tau_e})}{(2-e^{T/\mu}-e^{T/\lambda})}.\end{aligned}$$

$\Gamma(\tau_e)$ increases with $\tau_e$ and saturates to the steady state channel idling probability when $\tau_e \to \infty$. Thus, with i.i.d. PU activity over the channels, for a higher utilization and energy efficiency, it is better to revisit the channel after a long interval. Round robin scheme guarantees the maximum elapsed time between the two successive visits to the same channel.

### *C. Single channel DSA (SC-DSA)*

In SC-DSA, an SU continues to sense the channel at each slot until it is found idle. When the channel is idle, SU transmits for $l$-slots and senses the channel again. Number of transmission instances ($k_l$) is distributed as

$$Pr(k_l = k) = (\mathbf{P}_{(\mathbf{l+1})}(1,1))^{(k-1)}\mathbf{P}_{(\mathbf{l+1})}(1,2)$$

with mean $\mathbb{E}[k_l] = 1/\mathbf{P}_{(\mathbf{l+1})}(1,2)$. Similarly, number of times ($k_s$) SU senses the channel busy is distributed as

$$Pr(k_s = k) = (\mathbf{P}(2,2))^{(k-1)}\mathbf{P}(2,1)$$

with mean $\mathbb{E}[k_s] = 1/\mathbf{P}(2,1)$. SU channel utilization and energy efficiency for SC-DSA scheme are given as:

$$\mathcal{U}_{\text{SC}} = \frac{l\ \mathbb{E}[k_l] - \eta\mu/T}{(l+1)\mathbb{E}[k_l] + \mathbb{E}[k_s]} \tag{8}$$

$$\mathcal{E}_{\text{SC}} = \frac{lT\mathbb{E}[k_l] - \eta\mu}{\mathbb{E}[k_l](l\Phi_t + \Phi_{se}) + \mathbb{E}[k_s]\Phi_{se}}. \tag{9}$$

Channel sensing by the SU in each slot during PU busy period contributes towards high energy consumption. SUs energy efficiency can be optimized by suitably adjusting the SU channel inter-sensing interval (SU will sense the channel every $m$ slots in channel busy period). With $m$ slot inter-sensing interval, the number of times SU senses the busy channel to find it available is modified to

$$Pr(k_s = k) = (\mathbf{P_m}(2,2))^{(k-1)}\mathbf{P_m}(2,1).$$

with mean $\mathbb{E}[k_s] = 1/\mathbf{P_m}(2,1)$. SU utilization and energy efficiency are given as:

$$\mathcal{U}^{(m)}_{\text{SC}} = \frac{l\ \mathbb{E}[k_l] - \eta\mu/T}{(l+1)\mathbb{E}[k_l] + m\mathbb{E}[k_s]} \tag{10}$$

$$\mathcal{E}^{(m)}_{\text{SC}} = \frac{lT\mathbb{E}[k_l] - \eta\mu}{\mathbb{E}[k_l](l\Phi_t + \Phi_{se}) + \mathbb{E}[k_s](\Phi_{se} + (m-1)\Phi_i)}. \tag{11}$$

The optimal $m$ that maximizes $\mathcal{E}^{(m)}_{\text{SC}}$ is obtained by setting $d\mathcal{E}^{(m)}_{\text{SC}}/dm = 0$. Denoting $\kappa \triangleq 1 - e^{-T/\lambda} - e^{-T/\mu}$, we have:

$$\kappa^m(\Phi_i - (\Phi_{se} + (m-1)\Phi_i)\ln(\kappa)) - \Phi_i = 0.$$

Solving, we obtain,

$$\begin{aligned}m^{opt} &= \Bigg\lfloor \frac{1}{\ln(\kappa)}\mathbf{W}\left(-e^{\frac{(\Phi_{se}-\Phi_i)\ln(\kappa)-\Phi_i}{\Phi_i}}\right)\\ &\qquad - \frac{(\Phi_{se}-\Phi_i)\ln(\kappa)-\Phi_i}{\Phi_i\ln(\kappa)}\Bigg\rfloor. \end{aligned} \tag{12}$$

## III. Results

*1) Verification of analysis:* Each slot is taken 50$\mu$s long. Sensing, idling, and transmission consumptions are respectively 40mW, 16.9mW, and 69.5mW [5]. Channel switching energy is taken to be 20$\mu$J per switch and channel switching time $n_s$ is taken as 4 slots [6]. $\eta$ is taken as 0.1. The average 'OFF' duration of PUs is taken as 5ms. The average PU activity duty cycle is defined as: $\psi = \frac{\mathbb{E}[ON]}{\mathbb{E}[ON]+\mathbb{E}[OFF]}$.

Fig. 3 plots the performance of SC-DSA and MC-DSA with exponentially distributed PU activity parameters. At low values of $\psi$, $\mathcal{E}_{\text{SC}}$ is higher, because PU ON durations being short the channels are available most of the time. So, channel switching in MC-DSA consumes energy without any significant gain in utilization. At moderate values of $\psi$, MC-DSA performs better as the switching of channels offers the SUs more transmission opportunities. At a higher $\psi$, the channel is mostly busy, hence switching happens frequently – leaving the SUs with only small transmission opportunity gain at a higher energy cost of switching, and thus $\mathcal{E}_{\text{MC}}$ is poorer.

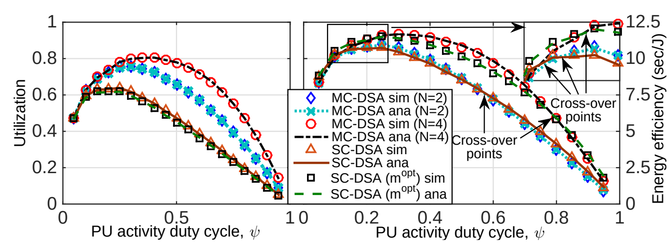



Fig. 3: $\mathcal{U}$ and $\mathcal{E}$ at different PU channel activity with exponentially distributed PU ON and OFF periods. $\Phi_{sw} = 20\mu$J, $n_s = 4$, $\eta = 0.1$, and $\lambda = 5$ms. 'sim': simulation; 'ana': analytical

Increased $N$ allows the SU to have a higher transmission opportunity by switching. Hence $\mathcal{E}_{\text{MC}}$ degradation over $\mathcal{E}_{\text{SC}}$ happens at a higher value of $\psi$. Also, $\mathcal{U}_{\text{MC}}$ is higher at a higher value of $N$, as this offers the SUs more transmission opportunities. In SC-DSA, $m^{opt}$ provides significant increase in $\mathcal{E}^{(m)}_{\text{SC}}$, while providing a comparable $\mathcal{U}^{(m)}_{\text{SC}}$, as the energy consumption is optimized without affecting the utilization.

Effects of channel switching delay $n_s$ on $\mathcal{U}_{\text{MC}}$ and $\mathcal{E}_{\text{MC}}$ are shown in Fig. 4. A high value of $n_s$ has two effects: low channel utilization (more slots used in switching) and low switching energy consumption per slot ($\Phi_{sw}/n_s$). The increase or decrease of $\mathcal{E}_{\text{MC}}$ depends on the factor that dominates with the increase in $n_s$. With lower $N$, transmission opportunity by channel switching is low at low $n_s$. Hence, switching energy consumption dominates, causing increase in $\mathcal{E}_{\text{MC}}$. At larger $n_s$, low SU utilization dominates over $\Phi_{sw}/n_s$ (rate of decrease in $\Phi_{sw}/n_s$ slows down). With large $N$, the transmission opportunity by channel switching is high. Hence, low channel utilization dominates with increasing $n_s$, which decreases $\mathcal{E}_{\text{MC}}$.

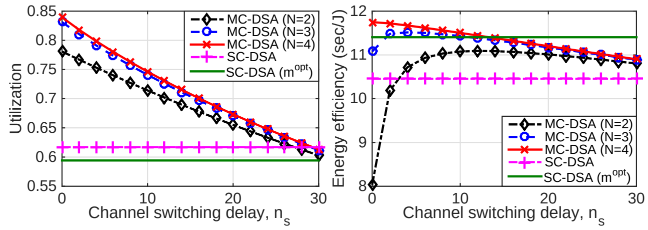
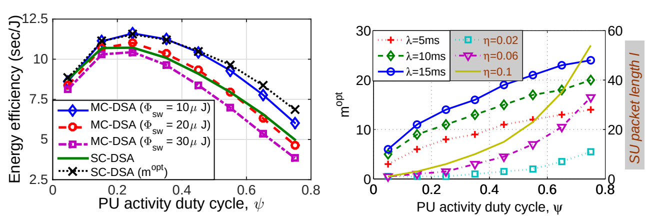



Fig. 4: $\mathcal{U}$ and $\mathcal{E}$ versus $n_s$ for exponentially distributed PU idle and busy periods. $\Phi_{sw} = 20\mu$J, $\lambda = 5$ms, $\eta = 0.1$, and $\psi = 0.3$.

Intuitively, switching consumption $\Phi_{sw}$ plays a vital role in relative $\mathcal{E}$. A higher switching energy lowers the $\mathcal{E}_{\text{MC}}$. For exponentially distributed PU activity parameters with $N = 2$, Fig. 5(a) shows that at a higher value of $\Phi_{sw}$ MC-DSA performs poorer than SC-DSA even at a lower value of $\psi$. Fig. 5(b) shows the optimal value of $m$ and $l$ (in slots) corresponding to variation in $\psi$. It is observed that the $m^{opt}$ increases with $\mu$ (i.e., $\psi$) as a higher SU inter-sensing time would save more energy for large PU ON periods. A higher $\lambda$ reduces the transmission opportunity missed in sensing the channel after longer times. Optimal transmission length increases with $\eta$ and $\mu$, as acceptable PU collisions increases.



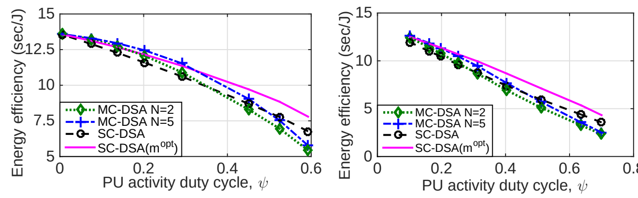

(a) (b)

Fig. 5: (a) $\mathcal{E}$ at different switching energy costs with $\lambda = 50\mu$s, $n_s = 4$, $\eta = 0.1$, and $N = 2$, and (b) $l$ and $m^{opt}$ in SC-DSA for maximized $\mathcal{E}$, with exponentially distributed PU ON-OFF periods.

*2) Performance in practical scenarios:* Through extensive simulations, [7], [8] have identified the optimal PU activity distributions in the cellular and ISM bands. We have performed simulation studies on MC-DSA and SC-DSA in the agile cellular (900MHz) and ISM (2.4GHz) bands.

ON/OFF periods in cellular bands are shown to be respectively generalized Pareto and Gamma distributed [7]. Distribution function (cdf) of generalized Pareto is: $F_{GP}(x) = 1 - \left[1 + \frac{\alpha(x-\delta)}{\beta}\right]^{-1/\alpha}$, where $\alpha = -0.2669$, $\delta = 0.5120$ms, and $\beta = 1.3692$ for $x$ in ms. Cdf of Gamma distribution is: $F_G(x) = \frac{\gamma(\alpha, \frac{x-\delta}{\beta})}{\Gamma(\alpha)}$, where $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function, $\Gamma(\cdot)$ is the complete Gamma function, $\alpha = 0.4805$, $\delta = 0.5120$ms, and $\beta \in [0.1, 700]$ for $x$ in ms.

Similar to the exponential distribution case, we observe from Fig. 6(a) that, though MC-DSA generally has a higher utilization, as the PU channels become busier (i.e., at higher $\psi$), due to higher channel switching rate energy consumption increases, causing $\mathcal{E}_{\text{MC}}$ reduced below $\mathcal{E}_{\text{SC}}$. However, as $N$ increases, the SU gets the opportunity to transmit, and hence the utilization in MC-DSA is more than in SC-DSA.




(a) Cellular band (b) ISM band

Fig. 6: $\mathcal{E}$ at different PU channel activities in cellular and ISM bands with $\Phi_{sw} = 20\mu$J and $n_s = 4$.

Based on the empirical studies on voice traffic over 802.11 networks in 2.4GHz ISM band [8], the authors proposed that the busy period is uniformly distributed due to the fact that the packet transmissions are of fixed size. The idle periods were shown to be close to generalized Pareto distribution. The upper and lower bounds of the uniform distribution of busy periods are respectively 2ms and 100$\mu$s, while the parameters in the generalized Pareto distribution are $\alpha = -0.3$, $\delta = 0$ and $\beta$ is varied from 0.0005 to 0.01 for $x$ expressed in ms. The results on MC-DSA versus SC-DSA over the ISM band in Fig. 6(b) show a similar trend that, SC-DSA is more energy efficient under the extreme PU traffic dynamics.

## IV. Conclusion

Thus, MC-DSA is not always energy-efficient. In fact, it is beneficial only in a small region of PU traffic dynamics. Therefore, the energy constrained devices like cognitive radio sensor nodes operating in a multichannel environment, can be allocated static bands. Besides energy efficiency, this static assignment approach reduces the cost of cognitive radio nodes.

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