Energy Harvesting Cognitive Radio with Channel-Aware Sensing Strategy

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***Abstract*—An energy harvesting cognitive radio scenario is considered where a secondary user (SU) with finite battery capacity opportunistically accesses the primary user (PU) channels. The objective is to maximize the throughput of SU under energy neutrality constraint and fading channel conditions in a single-user multi-channel setting. Channel selection criterion based on the probabilistic availability of energy with SU, channel conditions, and primary network's belief state is proposed, which chooses the best subset of channels for sensing, yielding higher throughput. We construct channel-aware optimal and myopic sensing strategies in a Partially Observable Markov Decision Process framework based on the proposed channel selection criterion. The effects of sensing errors and collisions between PU and SU on the throughput of latter are studied. It is shown that there exists a trade-off between the transmission duration and the energy lost in collisions.**

***Index Terms*—Channel-aware sensing, cognitive radio, energy harvesting, POMDP, sensing errors.**

I. Introduction

COGNITIVE radio (CR) with energy harvesting (EH) capability is a way to overcome spectrum scarcity problem while achieving green communications [1]. In CR, when the spectrum access for a secondary user (SU) is opportunistic and restrained by sensing errors, the possibility of transmission, in turn, the throughput of SU is limited. Moreover, the time-varying and random nature of fading channels may significantly reduce the SU throughput. Thus, it is imperative to access the channels with better conditions and low primary user (PU) occupancy, emphasizing that the design of channel sensing strategies should take these factors into account.

The optimal and sub-optimal sensing strategies for CR *ad hoc* networks in an unconstrained energy setting over finite horizon have been developed in [2]. In [3], the proposed sub-optimal policy in [2] is analyzed for EH opportunistic spectrum access (OSA) based CR networks under perfect sensing. A single-user multi-channel setting is considered in [2], [3] in a Partially Observable Markov Decision Process (POMDP) framework. In [4], spectrum sensing policies are studied for energy-constrained CR taking into account the dynamics of the primary network in a POMDP framework. Energy harvesting CR which optimizes its sensing and transmit energies is analyzed in [5] for a single-user single-channel setting in the presence of sensing errors.

The main contributions of this letter are as follows. Firstly, under energy neutrality constraint [6], we propose a channel selection criterion for an energy harvesting CR to maximize the average spectral efficiency of SU. The proposed criterion exploits not only the knowledge of PU occupancy and channel conditions taking sensing errors into account, but also the dependency of the decision of SU to sense and access PU channels on the probabilistic availability of energy with SU. Secondly, based on the proposed channel selection criterion, we develop optimal and myopic policies in a POMDP framework for SU to choose the channel(s) for sensing. Thirdly, we highlight the effect of sensing errors on SU's average spectral efficiency through the trade-off between the transmission duration and the energy lost in collisions between PU and SU.

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II. System Model

Consider a spectrum consisting of N channels each of bandwidth B licensed to a primary network (PN). The occupancy of PN follows a discrete-time Markov process with 2^N states. Both PN and SU are assumed to follow time-slotted synchronous communication [2]. SU is embedded with energy harvesting capability and has finite battery capacity e_{max}. The energy harvesting process is assumed to be stationary and ergodic with mean P_{EH} J/s similar to [7]. The Bernoulli model is used for illustration, which is as follows: In each time slot, SU harvests energy e_h with probability p_h, thus, $P_{EH} = p_h e_h$.

We model SU in OSA paradigm, in which the PU channels are accessed opportunistically with sufficient protection to PU by satisfying the target probability of detection P_D and the probability of false alarm P_F. For a given channel gain $\sqrt{h}$ between PU and SU, to satisfy the target P_D and P_F when PU signal and noise are zero mean circularly symmetric complex Gaussian (CSCG), the minimum number of samples required for sensing using energy detection is [8]

$$L_{s,\min} = \left\lceil (1/36)\left(p + \sqrt{p^2+4}\right)^2 \right\rceil, \tag{1}$$

where $p = ((1+\gamma|h|)^{-1/3}Q^{-1}(P_F) - Q^{-1}(P_D))/(1-(1+\gamma|h|)^{-1/3})$, γ denotes the received signal-to-noise ratio of PU signal at SU and $Q(x) = (1/\sqrt{2\pi})\int_x^\infty \exp(-u^2/2)du$. Then the minimum sensing time is

$$T_{s,\min} = L_{s,\min}/f_s, \tag{2}$$

where f_s is the sampling frequency. The energy required for sensing is the product of number of samples L_s and the energy required for sensing each sample $e_{s,\text{sample}}$, which is given by

$$e_s = L_s \times e_{s,\text{sample}}. \tag{3}$$

Once the PU channel is found idle, SU may transmit over the channel. We consider frequency-flat, block Rayleigh fading channel of bandwidth B and coherence time T_c between secondary pair. The SU transmitter sends pilot of duration T_{est} to the SU receiver and gets the perfect channel state information (CSI) through an error-free and dedicated feedback channel. The received signal v at the SU receiver in a time slot is $v = \sqrt{g}u + n$ where g is the channel power gain, u is SU's transmitted signal and n is CSCG noise with power spectral density $N_0/2$. We consider the case that SU always has data to transmit in order to determine the maximum achievable throughput. The receiver acknowledges the transmitter by an error-free ACK (ACK = 1 for successful transmission) on a dedicated feedback channel at the end of the slot [5]. The ACK is assumed of very short duration compared to slot duration T. An unsuccessful transmission occurs only when SU's transmission collides with PU's transmission.

The EH secondary transmitter adapts the transmit power and rate according to the channel power gain g and the available energy e. SU adopts a M-QAM constellation set $M \in \{M_1, \dots, M_K\}$ for some K, where $M_k = 2^{2(k-1)}$, $k = 1, \dots, K$ and M_1 corresponds to no transmission. The channel power gain levels are divided into K regions denoted by $\mathcal{G}_k$ and each region is mapped to a constellation size M_k [7]. Then the throughput is $\log_2 M_k$. The transmit power P_{tr} for given M_k and g at time slot t is [7]

$$P_{tr}(g, M_k) = \frac{-\ln(P_b/c_1)}{c_2}(2^{c_3 \log_2 M_k} - c_4)\frac{N_0 B}{g}, \quad (4)$$

where P_b is the bit error rate, $c_1 = 2$, $c_2 = 1.5$, $c_3 = 1$, $c_4 = 1$. The energies required for transmission e_{tr} and for circuit operation e_{ckt} are given by

$$e_{tr} = P_{tr}T_{tr} \text{ and } e_{ckt} = (P_{ckt} + \kappa P_{tr})T_{tr}, \quad (5)$$

where $1/(1+\kappa)$ is the power drain efficiency of power amplifier [9], T_{tr} is the transmission duration in a time slot, P_{ckt} is the power required for circuit operation and κP_{tr} denotes the power consumed by the power amplifier.

III. Problem Formulation

We assume that SU has partial knowledge about PN as SU may not be able to sense all the channels in PN due to hardware and energy constraints. Also, sensing errors add uncertainty about PN. The PN occupancy is partially observable, whereas the residual energy and channel power gain are fully observable. Note that g is estimated, i.e., fully known only if $e \geq e_{est}$, where e_{est} is the energy required for estimation.

A. System Components

The PN occupancy during time slot t is given by $\mathbf{s} = [s_1, s_2, \dots, s_N]$ where $s_i \in \{0 \text{ (occupied)}, 1 \text{ (idle)}\}$. The state of the secondary network $\mathcal{S}$ is characterized by PN occupancy $\mathbf{s}$, energy available in the battery e and the channel power gain g between the secondary pair. It can be defined as

$$\mathcal{S} \triangleq \{(\mathbf{s}, e, g) : \mathbf{s} \in \{0,1\}^N, e \in [0, e_{\max}], g \in [0, \infty)\}. \quad (6)$$

Let Λ_0, Λ_1 and Λ_2 be the sets of estimated channels, channels to sense and channels to access, respectively. At the beginning of a slot, SU can either remain idle or perform the following sequence of operations: (i) Estimate upto $|\Lambda_0|$ ($|\Lambda_0| \leq N$) channels; (ii) Sense upto $|\Lambda_1|$ ($|\Lambda_1| \leq |\Lambda_0|$) estimated channels; (iii) Access upto $|\Lambda_2|$ ($|\Lambda_2| \leq |\Lambda_1|$) sensed channels. Let $a \in \{0 \text{ (idle)}, 1, \dots, N\}$, $\hat{a} \in \{0 \text{ (idle)}, 1, \dots, N\}$, $d_{\hat{a}} \in \{0 \text{ (no access)}, 1 \text{ (access)}\}$ denote the indices of estimated channels, channels available for sensing and access decision, respectively. SU observes the channel either as occupied (0) or idle (1) after sensing. The probability of the sensing observation o, given the channel $\hat{a}$ is sensed with errors is

$$P(o_{\hat{a}} = 0) = P_D \mathrm{I}_{s_{\hat{a}}=0} + P_F \mathrm{I}_{s_{\hat{a}}=1} \quad \text{if } \hat{a} \neq 0, \quad (7)$$

$$P(o_{\hat{a}} = 1) = (1-P_D)\mathrm{I}_{s_{\hat{a}}=0} + (1-P_F)\mathrm{I}_{s_{\hat{a}}=1} \text{ if } \hat{a} \neq 0, \quad (8)$$

where I_x denotes the indicator function which takes value 1 if x is true, otherwise 0; $s_{\hat{a}}$ is the state of the channel $\hat{a}$.

The probability that PN occupancy transits to state $\mathbf{s}'$ at the beginning of time slot $t+1$ from $\mathbf{s}$ at time slot t is denoted by $P_{\mathbf{s}',\mathbf{s}}$. The energy available e' at the start of time slot $t+1$, is dependent on the energy available e, energy consumed e_c and energy harvested e_h at slot t. Then

$$P(e' \mid e) = \begin{cases} p_h & e' = \min(e - e_c + e_h, e_{\max}), \\ 1 - p_h & e' = e - e_c, \end{cases} \quad (9)$$

with

$$e_c = \begin{cases} e_{est} + e_s + e_{ckt} + e_{tr} & \text{if } \hat{a} \neq 0, \, o_{\hat{a}} = 1, \\ e_{est} + e_s & \text{if } \hat{a} \neq 0, \, o_{\hat{a}} = 0, \\ e_{est} & \text{if } \hat{a} = 0, \\ e_i & \text{if } a = 0, \end{cases} \quad (10)$$

where e_{est}, e_s, e_{ckt} and e_{tr} are given by (13), (3) and (5), respectively. e_i is the energy consumed when SU is idle and it is considered to be negligible. We assume that the channel power gain g' at time slot $t+1$ is independent of the channel power gain at previous time slots, i.e., g' can be traced to any of the K fading regions [7].

SU maintains a belief vector $\mathbf{b} = [b(1), b(2), \dots, b(2^N)]$ about PN, where $b(i)$ is the conditional probability that the network state is i given all the past decisions and observations.

B. Channel Selection Criterion

We propose a channel selection criterion as a function of belief about PN occupancy and the energy-constrained spectral efficiency η. Given e and P_b, for a channel with power gain g, $\eta = \log_2 M_k$ if $g \in \mathcal{G}_k$ and $e_s + e_{ckt} + e_{tr} \leq e - e_{est}$; η is zero when $g \in \mathcal{G}_1$ or/and $\mathrm{I}_{e \geq e_c} = 0$.

At a time slot t, the reward $R_{\hat{a}}$ on a channel $\hat{a}$ is defined as the spectral efficiency $\eta_{\hat{a}}$ for that channel $\hat{a}$ and is given by

$$R_{\hat{a}}(t) = \begin{cases} s_{\hat{a}} \times \eta_{\hat{a}}(t) & \text{if } \hat{a} \neq 0, \text{ACK} = 1, \\ 0 & \text{if } \hat{a} = 0 \text{ or ACK} \neq 1. \end{cases} \quad (11)$$

The channel will be sensed if and only if η on that particular channel is non-zero. The optimal and myopic policies to choose the channel(s) for sensing are as follows:

1) Optimal Policy: The value function for a finite horizon T_F including the partially and fully observable system components can be formulated as

$$V^*_{t=T_F}(\mathbf{b}, e, g) = \max_{\hat{a}} \sum_{\mathbf{s}' \in \mathbf{S}} b(\mathbf{s}') \sum_{\mathbf{s} \in \mathbf{S}} P_{\mathbf{s}',\mathbf{s}} \sum_{z=0}^{1} P(o = z \mid \mathbf{s}, \hat{a})$$
$$\times \left(z R_{\hat{a}}(t) + \sum_{e'} \sum_{\mathcal{G}_1}^{\mathcal{G}_K} P(e' \mid a, \hat{a}, o_{\hat{a}}, e) P(g') V^*_{t-1}(\mathbf{b}', e', g') \right), \quad (12)$$

with $|\mathbf{S}| = 2^{|\Lambda_0|}$, V^*_{t-1} is the maximum expected reward that can be accrued over $t-1$ remaining slots and the updated belief b' obtained using Bayes' rule is as follows:

$$
b'(\mathbf{s}) = \begin{cases} \sum_{\mathbf{s}'} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}}, & \hat{a} = 0 \text{ or } a = 0, \\ \frac{\sum_{\mathbf{s}'} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}} I_{s_{\hat{a}}=1}}{\sum_{\mathbf{s}' \in \mathbf{S}} \sum_{\mathbf{s}'' \in \mathbf{S}} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}''} I_{s''_{\hat{a}}=1}}, & \hat{a} \neq 0, o_{\hat{a}} = 1, \mathrm{ACK} = 1, \\ \frac{\sum_{\mathbf{s}'} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}} I_{s_{\hat{a}}=0}}{\sum_{\mathbf{s}' \in \mathbf{S}} \sum_{\mathbf{s}'' \in \mathbf{S}} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}''} I_{s''_{\hat{a}}=0}}, & \hat{a} \neq 0, o_{\hat{a}} = 1, \mathrm{ACK} \neq 1, \\ \frac{\sum_{\mathbf{s}'} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}} I_{s_{\hat{a}}=1} P(o_{\hat{a}}=0 | s_{\hat{a}})}{W}, & \hat{a} \neq 0, o_{\hat{a}} = 0, \end{cases}
$$

where $W = \sum_{\mathbf{s}' \in \mathbf{S}} \sum_{\mathbf{s}'' \in \mathbf{S}} b(\mathbf{s}') P_{\mathbf{s}',\mathbf{s}''} (\mathrm{I}_{s''_{\hat{a}}=1} P(o_{\hat{a}} = 0 \mid s''_{\hat{a}}) + \mathrm{I}_{s''_{\hat{a}}=0} P(o_{\hat{a}} = 0 \mid s''_{\hat{a}}))$. The optimal policy chooses the channel for sensing that maximizes the expected reward, in turn, the throughput over T_F slots. In the presence of sensing errors, to obtain the optimal access policy, the collision probability P_{col} between PU and SU should be equal to $1 - P_D$ [10]. Then, the access decision is same as that of sensing observation and it is represented as $d_{\hat{a}} = \mathrm{I}_{\{o_{\hat{a}}=1\}}$. Finding the optimal policy for a POMDP is computationally prohibitive as the complexity grows exponentially with N and is $\mathcal{O}(N^{T_F})$ [2], [11]. Hence, we consider a myopic policy with reduced state space whose complexity increases linearly with N, i.e., the complexity is $\mathcal{O}(N)$ [2]. The detailed analysis about the complexity of the optimal policy can be found in [11].

2) Myopic Policy: In myopic policy [2], neglecting the impact of current action on future slots, the sensing strategy aims to maximize the expected reward only on the current slot. For this case, the expected reward for the channel $\hat{a}$ is $(\pi_{\hat{a}}(t)\beta_{\hat{a}} + (1 - \pi_{\hat{a}}(t))\alpha_{\hat{a}}) \times \eta_{\hat{a}}(t)$ where $\pi_{\hat{a}}(t)$ is the belief that the channel $\hat{a}$ is idle at time slot t, $\beta_{\hat{a}}$ is the probability that the channel $\hat{a}$ remains in state 1 (unoccupied) and $\alpha_{\hat{a}}$ is the probability that the channel transits from state 0 (occupied) to state 1. The belief that PU is idle at the beginning of slot $t+1$ before state transition is given by Bayes' rule as

$$
\pi_{\hat{a}}(t+1) = \begin{cases} 1, & \hat{a}(t) \neq 0, o_{\hat{a}(t)} = 1, \mathrm{ACK} = 1, \\ 0, & \hat{a}(t) \neq 0, o_{\hat{a}(t)} = 1, \mathrm{ACK} \neq 1, \\ \frac{X P_F}{X P_F + Y P_D}, & \hat{a}(t) \neq 0, o_{\hat{a}(t)} = 0, \\ X, & \hat{a}(t) = 0, \end{cases}
$$

where $X = \pi_{\hat{a}}(t)\beta_{\hat{a}} + (1 - \pi_{\hat{a}}(t))\alpha_{\hat{a}}$ and $Y = \pi_{\hat{a}}(t)(1 - \beta_{\hat{a}}) + (1 - \pi_{\hat{a}}(t))(1 - \alpha_{\hat{a}})$. The access decision is same as that of the optimal policy. Based on the expected reward, the best channel among $|\Lambda_1|$ channels is sensed first and if found busy, only then the next best channel is sensed.

IV. Simulation Results and Discussion

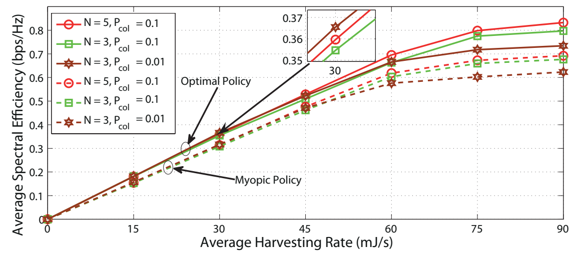
The simulation parameters are assumed without loss of generality (see Table I). The power required for estimation P_{est} is 20% of the power $\overline{P}$ required to transmit average constellation size for an average channel power gain. Then, the energy required to estimate a channel is

$$
e_{est} = P_{est} T_{est}, \tag{13}
$$

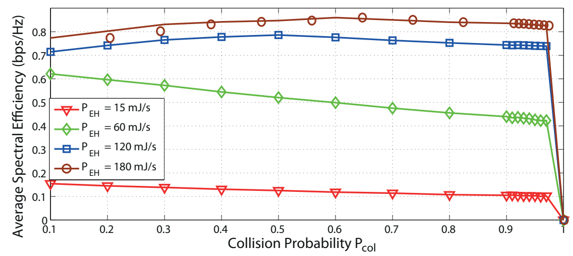
where $T_{est} = 14 T_{sym}$ as 14 pilot symbols are sent for estimation per slot per channel and $B = 1/T_{sym}$. SU may sense multiple channels, but may use the best available channel for its transmission due to energy constraint, i.e., $|\Lambda_2| = 1$. We take $P_{col} = 1 - P_D$, $T_F = 5$ and $e_{\max} = 10 e_h$. The number of iterations for Monte Carlo simulation is 10^5.

TABLE I
Simulation Parameters

Notation	Value	Notation	Value
B	200 kHz	P_b	10^{-3}
T_c	1 ms	κ	1.9 [9]
T	1 ms	$e_{s,\text{sample}}$	0.11×10^{-6}J [1]
P_{ckt}	188 mW [9]	Pilot symbols/channel	14
f_s	200 kHz	K	4
γ	0 dB	N_0	2×10^{-10} W/Hz



(a) Comparison of optimal and myopic policies.



(b) Effect of P_{col} and P_{EH} for myopic policy, N = 5.

Fig. 1. Effect of P_{col} and harvesting rate P_{EH} on SU throughput when the channel between the secondary pair is Rayleigh with power gain g and the channel between PU and SU is AWGN $\left(\sqrt{h} = 1\right)$, $P_F = 0.1$, $N = |\Lambda_0|$, $|\Lambda_1|$ = 1. Each channel has transition probabilities $\beta = 0.7$ and $\alpha = 0.5$.

Fig. 1(a) compares the optimal and myopic policies. It can be seen that with increase in N, the throughput (average spectral efficiency) increases as SU has more number of PU channels to consider for sensing increasing the probability of choosing a channel with better gain. In Figs. 1(a) and 1(b), we have shown how the throughput varies with the collision probability P_{col} for different harvesting rates P_{EH}, when the sensing duration is kept to its required minimum given by (2). At lower harvesting rates, the throughput declines monotonically with increase in P_{col}. However, at higher harvesting rates, the trend is not monotonous and dependent on the value of P_{col}. Such behavior can be explained intuitively as follows: As P_{col} increases (in turn, P_D decreases), two opposite behaviors exist that affect the throughput: 1) SU attempts to transmit more number of times. However, increase in P_{col} results in more number of collisions with PU and the number of failed attempts increases. Thus, the energy is wasted in failed attempts and the energy available for transmission decreases, which defines the drop in throughput. 2) The number of samples required for sensing decreases according to (1). This increases the time available for transmission, increasing the throughput.

At low P_{EH} (15, 60 mJ/s, Fig. 1(b)), the effect of energy lost in collisions is more pronounced than the increased transmission duration as the energy loss cannot be compensated

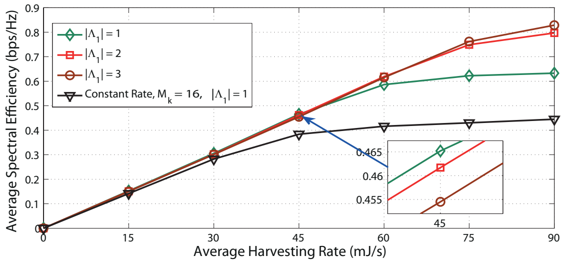


Fig. 2. Effect of number of channels chosen for sensing $|\Lambda_1|$ on throughput for myopic policy with $P_{col} = P_F = 0.1$ when the channel between the secondary pair is Rayleigh with power gain g and the channel between PU and SU is AWGN, $N = |\Lambda_0| = 5$. Transition probabilities for 5 channels are β = [0.8 0.7 0.65 0.6 0.5] and α = [0.3 0.4 0.45 0.5 0.6].

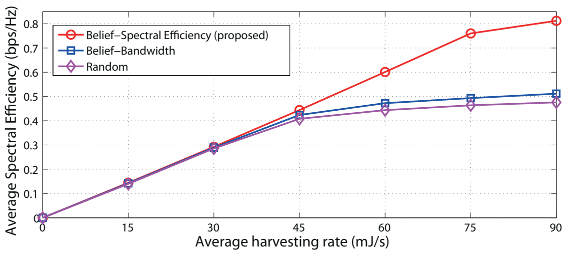


Fig. 3. Comparison of myopic policies with different channel selection criteria. $P_{col} = P_F = 0.1$, $N = |\Lambda_0| = 6$, $|\Lambda_1| = 3$. Each channel has transition probabilities $\beta = 0.7$ and $\alpha = 0.3$.

by the small newly harvested energy. Thus, the throughput reduces with increase in P_{col}. However, at high P_{EH} (120, 180 mJ/s) and small P_{col}, the loss in energy is compensated. Hence, the throughput increases with P_{col} due to increase in the transmission time. But, at high P_{col}, the effect of energy loss is more prominent than the increased transmission time even at high P_{EH} reducing the throughput. Also, a trade-off exists against the variation of P_F. At a given harvesting rate, as P_F increases, the number of minimum samples required reduces increasing the transmission duration, in turn, increasing the throughput. However, simultaneously, SU is more frequently denied access to channel even if the channel is unoccupied, reducing the throughput.

Fig. 2 shows that at lower harvesting rates, the SU throughput when a single channel is sensed is higher than that of when upto 3 channels are sensed; while at higher harvesting rates, the throughput of the latter is higher. This is because at lower harvesting rates, much of the harvested energy and the time in a slot are spent on estimating and sensing multiple channels reducing the energy and the time available for transmission, in turn, reducing the throughput. At higher harvesting rates, enough energy is available to compensate the loss in transmission duration and the expenditure of energy in estimation and sensing giving higher throughput for multiple sensed channels as the probability of finding an available channel to access is higher compared to the case of a single sensed channel. Also, adapting to fading conditions gives better average spectral efficiency than that of the constant rate transmission.

Fig. 3 shows that the proposed channel selection criterion based on belief and energy-constrained spectral efficiency is more suitable for an energy harvesting CR with fading channels compared to existing criteria like belief-bandwidth based channel selection [3] and random channel selection.

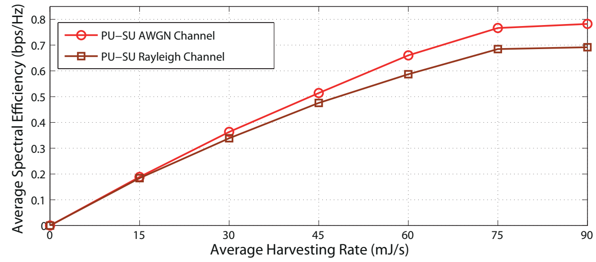


Fig. 4. Comparison of optimal policies for different channel coefficient distributions between PU and SU with $P_{col} = P_F = 0.1$. The channel between the secondary pair is Rayleigh with power gain g, $N = |\Lambda_0| = 4$, $|\Lambda_1| = 1$. Transition probabilities for 4 channels are β = [0.8 0.7 0.65 0.6], α = [0.3 0.4 0.45 0.5].

In belief-bandwidth criterion, the channel selection is purely based on the belief about PU occupancy and bandwidths of channels. However, as the proposed criterion exploits channel conditions and the probabilistic energy availability to make sensing decision, gain in throughput is obtained by choosing channel(s) with better gain(s) and using the energy efficiently.

When the channel between PU and SU is Rayleigh, the minimum sensing duration $T_{s,\min}$ given by (2) and e_s varies in each slot with respect to $\sqrt{h}$ for the given P_D and P_F. In fact, $T_{s,\min}$ may exceed the total time slot duration T for deep fade channel conditions. In that case, no action is taken and the throughput for the corresponding slot is zero. We assume $\mathbb{E}\left[|h|\right] = 1$. As shown in Fig. 4, fading on the sensing channel results in reduction in SU throughput as the throughput remains zero at some slots for Rayleigh channel due to longer sensing duration and more energy is consumed due to deep fade compared to AWGN channel.

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