On Hybrid Access for Cognitive Radio Systems with Time-Varying Connectivity

Jeongho Jeon†, Anthony Ephremides†, Marian Codreanu‡, and Matti Latva-aho‡

†Department of Electrical and Computer Engineering and Institute for Systems Research
University of Maryland, College Park, MD 20742
‡Center for Wireless Communications, University of Oulu, FIN-90014, Oulu, Finland
Email: †{jeongho, etony}@umd.edu, ‡{codreanu, matti.latva-aho}@ee.oulu.fi

***Abstract*—In this work, we consider a hybrid of interweave and underlay modes of operation for cognitive radio systems with random connectivity and bursty packet arrivals. Under the designed hybrid access policy, the secondary communication system is allowed to operate in the interweave mode only when its transmission has no harm on the primary communication. This is when the primary communication system is idle or the interference link from the secondary source to the primary destination is disconnected. The secondary communication system can optionally operate in the underlay mode, although when it is inevitable to interfere with the primary communication. The underlay mode is activated with some probability, called the hybrid rate. We analyze the stability of the hybrid access policy and show that it is not always beneficial when compared against the interweave-only mode. Thus, the condition for which the hybrid access policy can outperform is specified.**

I. Introduction

There have been different communication models proposed for cognitive radio, which are broadly classified into *overlay*, *underlay*, and *interweave* modes [1]. The overlay approach allows concurrent primary and secondary transmissions, but the secondary sources are required to use part of their power to assist primary transmissions and the remainder for its own communication. The enabling premise is that the secondary source knows the primary message non-casually, which makes the implementation of the overlay mode practically challenging. The underlay mode also allows concurrent primary and secondary transmissions, but the primary communication is protected via regulating the power of the secondary source such that the induced amount of interference at the primary destination is kept below the acceptable noise floor. In both the underlay and overlay modes, concurrent primary and secondary user operation is invariably associated with interference at the primary destination, which is not desired. The interweave approach is based on the idea of opportunistic communication exploiting the idleness of the primary user.

In this work, we are interested in a hybrid of interweave and underlay modes of operation for the system consisting of primary and secondary communication systems, each of which has their own destination and bursty traffic demand. The considered system is dynamic in the sense that all the links from sources to destinations have time-varying random *connectivity*. It is assumed that the primary source transmits uninterruptedly whenever the link from itself to the primary destination is connected and its queue is non-empty. The secondary source, on the other hand, transmits opportunistically by observing the primary source's activity and taking into account the connectivity of the links from itself to both primary and secondary destinations[1]. That is, the secondary communication system runs in the interweave mode when it is guaranteed that its operation has no effect on the primary communication. This is when the primary source is idle or the interference link from the secondary source to the primary destination is disconnected, which can be viewed as an example of the spatial resource reuse. In addition to the interweave mode, the secondary communication system can optionally operate in the underlay mode, even when it is unavoidable to interfere with the primary communication. The underlay mode is activated with some probability, which we call a *hybrid rate*.

In [2] and [3], a similar hybrid access policy was proposed as in our work, but the channels with static multipacket reception (MPR) capability was assumed [4]. It was also assumed that the secondary source is always backlogged. In [5], a complete stability analysis was performed for the case when both primary and secondary sources have bursty arrivals. However, the analysis is again based on the static MPR model as in [2]. In [6], it was considered that the secondary source adjusts its hybrid rate according to the channel condition alternating between *good* and *bad* states. However, both primary and secondary sources communicate with a common destination, and only the link between the secondary source and the common destination is assumed time-varying. Moreover, how to adjust the hybrid rate according to the channel state is missing.

Our contributions in this work can be summarized as follows. First, the stability of the hybrid access policy is precisely analyzed for a dynamic system with time-varying connectivity.

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[1] It is assumed that the secondary source knows the connectivity of the link from itself to the primary destination by overhearing the pilot signal broadcasted from the primary destination.

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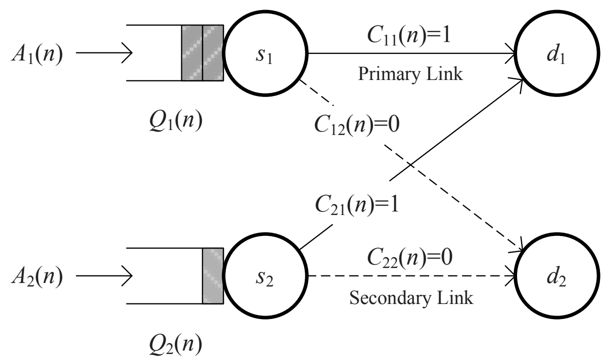

Fig. 1. The cognitive radio system model with time-varying connectivity (the solid and dotted lines denote that a link is connected and disconnected, respectively.)

Secondly, we observe that the hybrid access policy is not always beneficial when compared against the interweave-only mode and, consequently, the condition for which the hybrid access policy can outperform is obtained.

The rest of the paper is organized as follows. In Section II, we explain the channel model and describe the hybrid access policy. In Section III, we revisit the notion of stability and present our main result on the stability of the hybrid access policy. A geometric interpretation of the main result is given in Section IV. Finally, we draw some conclusions in Section V.

II. System Model

We consider a system consisting of two source-destination pairs, the primary pair (s_1, d_1) and the secondary pair (s_2, d_2), as shown in Fig. 1. Each source s_i, $i \in \{1, 2\}$, has an infinite size queue for storing the arriving packets of fixed length. Time is slotted and the slot duration is equal to a packet transmission time. It is assumed that the acknowledgments on the success of transmissions are sent back from the destinations to the corresponding sources instantaneously and error-free. Let $Q_i(n)$ denote the number of packets buffered at s_i at the beginning of the n-th slot, which evolves according to

$$Q_i(n+1) = \max[Q_i(n) - \mu_i(n), 0] + A_i(n)$$

where the stochastic processes $\{A_i(n)\}_{n=0}^{\infty}$ and $\{\mu_i(n)\}_{n=0}^{\infty}$ are sequences of random variables representing the number of arrivals and services at s_i during time slot n, respectively. The arrival process $\{A_i(n)\}_{n=0}^{\infty}$ at each source is modeled as an independent and identically distributed (i.i.d.) Bernoulli process with $E[A_i(n)] = \lambda_i$, and the processes at different nodes are assumed to be independent of each other. The service process $\{\mu_i(n)\}_{n=0}^{\infty}$ depends jointly on the transmission protocol and the underlying channel model, which governs the success of the transmissions.

At time slot n, the link between s_i and d_j, $\forall i, j \in \{1, 2\}$, may be either *connected* or *disconnected* due to such as the shadowing effect [7]; that is denoted by the binary variable $C_{ij}(n)$, which is equal to 1 and 0, respectively. The fact that an interference link such as those from s_1 to d_2 and from s_2 to d_1 is disconnected implies that a transmission over a designated link such as those from s_1 to d_1 and from s_2 to d_2 is not affected by the interference signal. The connectivity process $\{C_{ij}(n)\}_{n=0}^{\infty}$ is i.i.d. with $\Pr[C_{ij}(n) = 1] = c_{ij}$. In complying with widely accepted requirements on cognitive radio systems, that is, the primary communication system is oblivious of the existence of any additional systems, it is assumed that the primary source s_1 knows only the connectivity of its own link, i.e., $C_{11}(n)$, based on the pilot signal sent from d_1. On the other hand, the secondary source s_2 is assumed to know the connectivity of not only its own link, i.e., $C_{22}(n)$, but also the interference link from itself to the primary destination, i.e, $C_{21}(n)$, by overhearing the the pilot signal sent from d_1. To focus on the effect of channel dynamics, it is assumed that the sensing at the secondary source on the activity of the primary system is accurate and error-free.

At time slot n, the primary source s_1 transmits with probability 1 at some fixed power if $Q_1(n) \neq 0$ and $C_{11}(n) = 1$. Otherwise, it remains silent. The secondary source s_2, on the other hand, makes decision on its transmission based on the activity of s_1 and the connectivity of both its own link and the interference link from itself to d_1. The interweave mode is enabled only when the transmission by s_2 has no effect on the primary communication. That is, if either s_1 does not transmit at time slot n (i.e., either due to $Q_1(n) = 0$ or $C_{11}(n) = 0$) or s_1 does transmit but the interference link from s_2 to d_1 is disconnected, i.e., $C_{21}(n) = 0$, s_2 transmits with probability 1 at some fixed power if $Q_2(n) \neq 0$ and $C_{22}(n) = 1$. The underlay mode is optionally enabled, although when it is inevitable to cause interference to the primary communication, but at lower power than the interweave mode. That is, even when s_1 transmits at time slot n and the interference link is connected, i.e., $C_{21}(n) = 1$, s_2 transmits with probability p_h, which is called hybrid rate, if $Q_2(n) \neq 0$ and $C_{22}(n) = 1$. This can be viewed as a stationary randomized policy for triggering the underlay mode of operation.

The success of transmissions jointly depend on the actions made by both sources and the underlying connectivity of the links. Also note that a transmission over a connected link can fail even without interference due to fast fading and/or background noise. The followings are the probabilities of success at given set of actions and configuration of channel connectivity, which also take into account the effect of random failure.

- $q_{1|\{1\}}$: the probability of success of a transmission by s_1 when s_2 does not transmit or it does transmit but $C_{21}(n) = 0$.
- $q_{1|\{1,2\}}$: the probability of success of a transmission by s_1 when both s_1 and s_2 transmit and $C_{21}(n) = 1$, i.e., s_2 operates in the underlay mode.
- $q^i_{2|\{2\}}$: the probability of success of a transmission by s_2 when it operates in the interweave mode and either s_1 does not transmit or it does transmit but $C_{12}(n) = 0$.
- $q^i_{2|\{1,2\}}$: the probability of success of a transmission by s_2 when it operates in the interweave mode, s_1 transmits and $C_{12}(n) = 1$.

$$\mathbf{\Lambda}_1 = \left\{ \boldsymbol{\lambda} : \lambda_1 \leq c_{11} \left(q_{1|\{1\}} - \Delta_1 c_{21} c_{22} p_h \right), \lambda_2 \leq c_{22} \left(q^i_{2|\{2\}} - \frac{\Psi(p_h)\lambda_1}{q_{1|\{1\}} - \Delta_1 c_{21} c_{22} p_h} \right) \right\} \tag{1}$$

$$\mathbf{\Lambda}_2 = \left\{ \boldsymbol{\lambda} : \lambda_1 \leq c_{11} \left(q_{1|\{1\}} - \frac{\Delta_1 c_{21} p_h \lambda_2}{q^i_{2|\{2\}} - c_{11}\Psi(p_h)} \right), \lambda_2 \leq c_{22} \left(q^i_{2|\{2\}} - c_{11}\Psi(p_h) \right) \right\} \tag{2}$$

- $q^u_{2|\{2\}}$: the probability of success of a transmission by s_2 when it operates in the underlay mode and $C_{12}(n) = 0$.
- $q^u_{2|\{1,2\}}$: the probability of success of a transmission by s_2 when it operates in the underlay mode and $C_{12}(n) = 1$.

In the above probabilities, although not mentioned specifically, if s_i transmits, the corresponding designated channel is connected, i.e., $C_{ii}(n) = 1$. Once transmit power levels and other physical characteristics such as the distance, propagation loss exponent, statistics of fading are known, those probabilities can be readily computed. The details on the computation are omitted here due to space limitation and can be found in [8].

III. Stability Analysis

A. Stability Criteria

We adopted the notion of stability used in [9] where the stability of a queue is equivalent to the existence of a proper limiting distribution. That is, a queue is said to be *stable* if

$$\lim_{n\to\infty} \Pr[Q_i(n) < x] = F(x) \quad \text{and} \quad \lim_{x\to\infty} F(x) = 1.$$

If a weaker condition holds, namely,

$$\lim_{x\to\infty} \liminf_{n\to\infty} \Pr[Q_i(n) < x] = 1$$

the queue is said to be *substable* or bounded in probability. Otherwise, the queue is *unstable*. If $Q_i(n)$ is an aperiodic and irreducible Markov chain defined on a countable space, which is the case considered in this paper, substability is equivalent to the stability and both can be understood as the recurrence of the chain. Both the positive and null recurrence imply stability because a limiting distribution exists for both cases, although the latter may be degenerate. Loynes' theorem, as it relates to stability, plays a central role in our approach [10]. It states that if the arrival and service processes of a queue are strictly jointly stationary and the average arrival rate is less than the average service rate, the queue is stable. If the average arrival rate is greater than the average service rate, the queue is unstable and the value of $Q_i(n)$ approaches infinity almost surely. If they are equal, the queue can be either stable or substable but in our case the distinction is irrelevant, as mentioned earlier. Finally, the stability region of the system is defined as the pair of arrival rates $\boldsymbol{\lambda} = (\lambda_1, \lambda_2)$ for which the queues at both s_1 and s_2 are stable.

B. Stability Result

In this section, we find the stability region of the considered hybrid access policy for the system with time-varying connectivity. This enables us to judge the stability of the system at any given input rate vector. As noted earlier, however, the queues in the system are interacting, which makes the analysis challenging. Let $\Delta_1 = q_{1|\{1\}} - q_{1|\{1,2\}}$, which is the difference in the success probabilities of s_1 when it transmits alone and when s_2 transmits along with s_1 in the underlay mode. Similarly, let $\Delta^i_2 = q^i_{2|\{2\}} - q^i_{2|\{1,2\}}$ and $\Delta^u_2 = q^u_{2|\{2\}} - q^u_{2|\{1,2\}}$. Further define

$$\Psi(p_h) \triangleq q^i_{2|\{2\}} c_{21} + \Delta^i_2 c_{12} \bar{c}_{21} - c_{21} p_h (q^u_{2|\{2\}} - \Delta^u_2 c_{12}) \tag{3}$$

where $\bar{c} = 1 - c$ and this notation is used throughout the paper. Also note that $\Psi(p_h)$ is a decreasing function of p_h and strictly positive for any feasible value of p_h.

Theorem 3.1: The system is stable under the hybrid access policy with hybrid rate p_h if and only if $\boldsymbol{\lambda} \in \bigcup_{i\in\{1,2\}} \mathbf{\Lambda}_i$ where the subregions $\mathbf{\Lambda}_i$ are given in (1) and (2).

Proof: Under the hybrid access protocol described in Section II, the average service rates of the queues at the sources can be expressed as

$$\begin{aligned} \mu_1 = q_{1|\{1\}} c_{11} \{ &\Pr[Q_2 = 0] \\ &+ \Pr[Q_2 \neq 0](\bar{c}_{22} + \bar{c}_{21} c_{22} + c_{21} c_{22} \bar{p}_h)\} \\ &+ q_{1|\{1,2\}} c_{11} c_{21} c_{22} p_h \Pr[Q_2 \neq 0] \end{aligned}$$

and

$$\begin{aligned} \mu_2 = q^i_{2|\{2\}} c_{22} \{ &\Pr[Q_1 = 0] + \Pr[Q_1 \neq 0] \left(\bar{c}_{11} + c_{11} \bar{c}_{12} \bar{c}_{21} \right) \} \\ &+ \Pr[Q_1 \neq 0] \Big\{ q^i_{2|\{1,2\}} c_{11} c_{12} \bar{c}_{21} c_{22} \\ &+ q^u_{2|\{2\}} c_{11} \bar{c}_{12} c_{21} c_{22} p_h + q^u_{2|\{1,2\}} c_{11} c_{12} c_{21} c_{22} p_h \Big\} \end{aligned}$$

By substituting $\Pr[Q_1 = 0] = 1 - \Pr[Q_1 \neq 0]$ into the above equations and rearranging the terms, they are further simplified to

$$\mu_1 = q_{1|\{1\}} c_{11} - \Delta_1 c_{11} c_{21} c_{22} p_h \Pr[Q_2 \neq 0] \tag{4}$$

and

$$\mu_2 = q^i_{2|\{2\}} c_{22} - c_{11} c_{22} \Psi(p_h) \Pr[Q_1 \neq 0] \tag{5}$$

where $\Psi(p_h)$ was defined in Eq. (3).

It can be seen from Eq. (4) and Eq. (5) that the service rate of one depends on the other and, thus, the individual rates cannot be computed separately without knowing the stationary distribution of the joint queue length process. We bypass this difficulty by using the stochastic dominance technique, which decouples the interaction between queues via the construction of hypothetical systems [11]. The hypothetical system operates as follows: i) the packet arrivals at each source occur at *exactly* the same instants as in the original system, ii) the Bernoulli trial with success probability p_h that determines the activation of the underlay mode at the secondary source has *exactly* the same outcomes in both systems, iii) however, one of the sources in the system continues to transmit dummy packets even when its queue is empty.

Consider first a hypothetical system which is identical to the original system except that the secondary source s_2 transmits dummy packets when it decides to transmit but its queue is empty. Since s_2 transmits regardless of the emptiness of its queue, it is equivalent to setting $\Pr[Q_2 \neq 0] = 1$. Hence, from Eq. (4), the average service rate of s_1 in this hypothetical system becomes

$$\mu_1^\star = c_{11}(q_{1|\{1\}} - \Delta_1 c_{21} c_{22} p_h)$$

By Loynes' Theorem, the queue at s_1 is stable if $\lambda_1 \le \mu_1^\star$, and the content size follows a discrete-time $M/M/1$ model. For a stable rate $\lambda_1 (\le \mu_1^\star)$, the probability that the queue at s_1 is non-empty is given by

$$\Pr[Q_1 \neq 0] = \frac{\lambda_1}{\mu_1^\star} = \frac{\lambda_1}{c_{11}(q_{1|\{1\}} - \Delta_1 c_{21} c_{22} p_h)} \qquad (6)$$

and, by substituting Eq. (6) into Eq. (5), we obtain

$$\mu_2^\star = c_{22}\left(q^i_{2|\{2\}} - \frac{\Psi(p_h)\lambda_1}{q_{1|\{1\}} - \Delta_1 c_{22} c_{21} p_h}\right)$$

and the queue at s_2 is stable if $\lambda_2 \le \mu_2^\star$. For a given hybrid rate p_h, input rate pairs (λ_1, λ_2) that can be stably admitted into the system are those componentwise less than $(\mu_1^\star, \mu_2^\star)$. The stability region of this dominant system is denoted by $\mathbf{\Lambda}_1$ in Theorem 3.1.

It is obvious that sample-pathwise the queue sizes in this dominant system will never be smaller than their counterparts in the original system, provided the queues start with identical initial conditions. Thus, the stability condition obtained for the dominant system is a sufficient condition for the stability of the original system. It turns out, however, that it is indeed sufficient and necessary for the range of values of λ_1 that is less than $\mu_1^\star$[2]. The reason is this: if for some λ_2, the queue at s_2 is unstable in the hypothetical system, then $Q_2(n)$ approaches infinity almost surely. Note that as long as the queue does not empty, the behavior of the hypothetical system and the original system are identical since dummy packets will never have to be used. A sample-path that goes to infinity without visiting the empty state, which is a feasible one for a queue that is unstable, will be identical for both the hypothetical and the original systems. Therefore, the instability of the hypothetical system implies the instability of the original system. This is the so-called *indistinguishability* argument [11].

Construct next a parallel dominant system in which the primary source s_1 transmits dummy packets, instead of the secondary source s_2, when its queue is empty. Then, the average service rate of s_2 in Eq. (5) becomes

$$\mu_2^* = c_{22}(q^i_{2|\{2\}} - c_{11}\Psi(p_h)) \qquad (7)$$

[2]This is sufficient for the stability of the queue at s_1. Thus, in the following, we are only concerned about the stability of the queue at s_2.

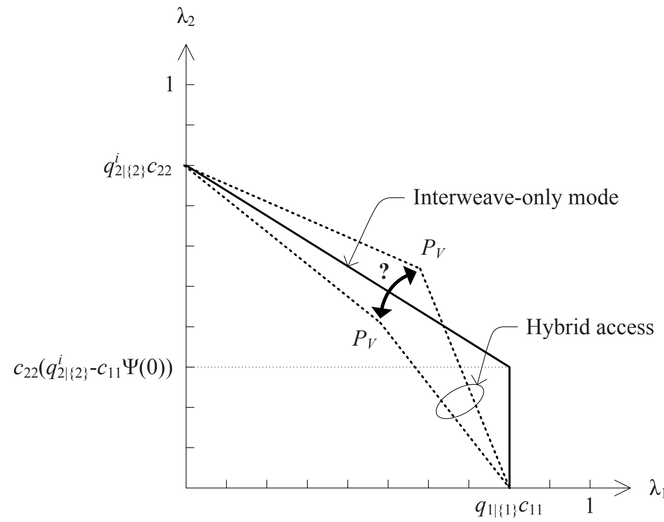

Fig. 2. Illustration of the stability region: Interweave-only mode vs. hybrid access

and the queue at s_2 is stable if $\lambda_2 \le \mu_2^*$. For a stable rate $\lambda_2 (\le \mu_2^*)$, the probability that the queue at s_2 is non-empty is given by

$$\Pr[Q_2 \neq 0] = \frac{\lambda_2}{c_{22}(q^i_{2|\{2\}} - c_{11}\Psi(p_h))}$$

and by substituting the above probability into Eq. (4), we obtain the average service rate of s_1 as

$$\mu_1^* = c_{11}\left(q_{1|\{1\}} - \frac{\Delta_1 c_{21} p_h \lambda_2}{q^i_{2|\{2\}} - c_{11}\Psi(p_h)}\right) \qquad (8)$$

and the queue at s_1 is stable if $\lambda_1 \le \mu_1^*$. The indistinguishability argument applies here as well. The stability region of this dominant system, which is denoted by $\mathbf{\Lambda}_2$ in Theorem 3.1, is comprised of input rate pairs (λ_1, λ_2) that are componentwise less than (μ_1^*, μ_2^*). ■

IV. Interpretation

This section attempts to answer some of those important yet unaddressed questions on hybrid access for cognitive radio systems. We first illustrate in Fig. 2 the stability region of the system described in Theorem 3.1 for different values of hybrid rate p_h. The vertex of the region, denoted by P_V, in the figure is the point where the boundaries of the subregions $\mathbf{\Lambda}_1$ and $\mathbf{\Lambda}_2$ meet with each other and is given by

$$P_V = \Big(c_{11}(q_{1|\{1\}} - \Delta_1 c_{21} c_{22} p_h), c_{22}(q^i_{2|\{2\}} - c_{11}\Psi(p_h))\Big) \qquad (9)$$

and we denote by $P_{V,x}$ and $P_{V,y}$ the values of x and y coordinates of P_V. The stability region of the interweave-only mode, which is also depicted in the figure, can be found by setting $p_h = 0$ in Theorem 3.1. Let us define

$$\Upsilon \triangleq q_{1|\{1\}}(q^u_{2|\{2\}} - \Delta^u_2 c_{12}) - \Delta_1 c_{22}(q^i_{2|\{2\}} c_{21} + \Delta^i_2 c_{12} \bar{c}_{21})$$

The following corollary answers the question on the necessity of the hybrid access policy. In other words, does the hybrid access policy indeed perform better than the interweave-only mode?

Corollary 4.1: If $\Upsilon \leq 0$, the stability region of the hybrid access policy becomes a proper subset of that of the interweave-only mode for any $p_h \in (0, 1]$. If $\Upsilon > 0$, one is not a subset of the other.

Proof: The upper boundary of the stability region of the interweave-only mode in Fig. 2 is given by

$$\bar{\lambda}_2 = c_{22}\left(q^i_{2|\{2\}} - \frac{\Psi(0)\lambda_1}{q_{1|\{1\}}}\right)$$

for $\lambda_1 \leq c_{11}q_{1|\{1\}}$, which is obtained by substituting $p_h = 0$ into the description of $\mathbf{\Lambda}_1$ in Theorem 3.1. For the proof, it suffices to show that if $\Upsilon \leq 0$, the value of $P_{V,y}$ is less than or equal to the value of $\bar{\lambda}_2$ evaluated at $\lambda_1 = P_{V,x}$. The fact that $\Upsilon \leq 0$ is written as

$$q_{1|\{1\}}(q^u_{2|\{2\}} - \Delta^u_2 c_{12}) \leq \Delta_1 c_{22}\left(q^i_{2|\{2\}}c_{21} + \Delta^i_2 c_{12}\bar{c}_{21}\right)$$

Multiplying by a positive number $c_{21}p_h$, $p_h \in (0, 1]$, to both sides, which does not change the inequality, yields

$$q_{1|\{1\}}(\Psi(0) - \Psi(p_h)) \leq \Delta_1 c_{21}c_{22}p_h\Psi(0)$$

By dividing by $q_{1|\{1\}}$, multiplying by $c_{11}c_{22}$ and adding $q^i_{2|\{2\}}c_{22}$ to both sides of the above inequality, which again does not affect the inequality, it follows that

$$\begin{aligned} &c_{22}\left(q^i_{2|\{2\}} - c_{11}\Psi(p_h)\right) \\ &\quad\leq c_{22}\left(q^i_{2|\{2\}} - \frac{c_{11}(q_{1|\{1\}} - \Delta_1 c_{21}c_{22}p_h)\Psi(0)}{q_{1|\{1\}}}\right) \end{aligned}$$

Finally, we observe that the left-hand side of the above inequality is equal to $P_{V,y}$, whereas the right-hand side is the value of $\bar{\lambda}_2$ at $\lambda_1 = P_{V,x}$. This completes the proof. ■

From the above corollary, we see that if $\Upsilon \leq 0$, there is no need for the hybrid mode of operation in terms of the stability region. The following corollary establishes the closure of the stability region over the hybrid rate p_h for the case when $\Upsilon > 0$. Note that when $\Upsilon \leq 0$, the closure is equal to the stability region of the interweave-only mode. Let us define the following points in the two-dimensional Euclidean space to facilitate the description of the next corollary:

$$\begin{aligned} P^1_V &= \left(c_{11}(q_{1|\{1\}} - \Delta_1 c_{21}c_{22}), c_{22}(q^i_{2|\{2\}} - c_{11}\Psi(1))\right) \\ P^0_V &= \left(q_{1|\{1\}}c_{11}, c_{22}(q^i_{2|\{2\}} - c_{11}\Psi(0))\right) \end{aligned}$$

where P^1_V and P^0_V are the points that P_V in Eq. (9) is evaluated at $p_h = 1$ and $p_h = 0$, respectively.

Corollary 4.2: The boundary of the closure of the stability region for the case when $\Upsilon > 0$ is described by three segments: (i) the straight line connecting $(q_{1|\{1\}}c_{11}, 0)$ and P^0_V, (ii) the straight line connecting P^0_V and P^1_V, and (iii) the straight line connecting P^1_V and $(0, q^i_{2|\{2\}}c_{22})$.

Proof: The proof follows from the geometry in Fig. 3, which depicts the stability region of the hybrid access policy by varying p_h from zero (interweave-only mode) to one (full hybrid mode). The fact that $\Psi(p_h)$ is an affine function of p_h gives the straight line from P^0_V to P^1_V. ■

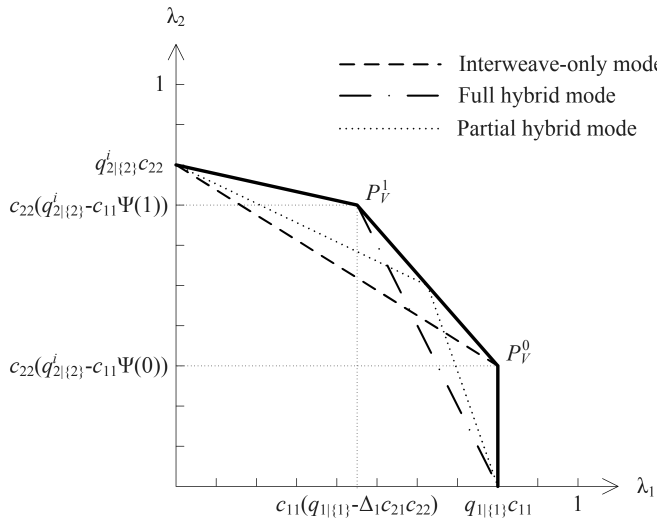

Fig. 3. Closure of the stability region for the case when $\Upsilon > 0$

V. Concluding Remarks

We studied the hybrid access policy for cognitive radio systems with time-varying connectivity and showed that it is not always the case that the hybrid access policy outperforms the interweave-only mode.

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