A Hybrid Cognitive Radio System: A Combination of Underlay and Overlay Approaches

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***Abstract*—This paper proposes a hybrid cognitive radio (CR) system where underlay and overlay CR approaches are combined. Occasional switches from an overlay CR mode to an underlay CR mode enable to maximize the average throughput of a secondary (unlicensed) network and stable transmission of a secondary user. By controlling switching from an overlay CR mode to an underlay CR mode in a probabilistic sense, the throughput of a secondary user is maximized while the target departure rate of a primary (licensed) user is retained. Since a primary user in a hybrid approach is likely to suffer from additional interference, optimal transmit power of a secondary user in an overlay mode is derived for given switching rate. Our analysis and numerical results show that the proposed hybrid CR system takes benefits in maximizing throughput and maintaining stability of a queue.**

I. Introduction

In order to alleviate inefficient spectrum utilization, cognitive radio (CR) techniques have been proposed. CR techniques are in general classified into *underlay* CR [1]–[5] and *overlay* CR [6]–[10] according to the ways of utilizing the primary users' spectrum.

In underlay CR systems, secondary users (SU) are admitted to access spectrum bands originally allocated to primary users (PU) only if interference caused by the secondary users is regulated below a predetermined level, i.e., *interference temperature* [1]. Reliable communications of primary users are guaranteed only if the perceived interference from secondary transmitter does not exceed a predetermined interference temperature. Because secondary users in underlay CR systems can always access the licensed spectrum by regulating transmit power not to cause excessive interference to primary users, underlay CR is considered a more aggressive spectrum access technique compared to overlay CR where secondary users opportunistically access primary users' spectrum only when it is not occupied. In overlay CR, interference caused by secondary users to primary users depends on sensing performance of secondary users. Overlay CR systems are considered more practical than underlay CR systems since overlay CR does not require instantaneous knowledge of interference channel contrary to underlay CR.

There have been many studies of cognitive radio networks applying queuing theory [11]- [13]. *Stable* throughput of a cognitive interference channel where a secondary transmitter is equipped with infinite queues was analyzed in [11] by determining transmit power of a secondary transmitter to guarantee primary user's QoS (Quality of Service). In [12], a protocol design was investigated in a cognitive cooperative system with many secondary users unlike a single secondary user case in [11]. The cognitive radio system based on queueing process was also applied to the packet-based vertical handover between different radio interfaces in [13].

In this paper, we propose a hybrid CR system to guarantee the stability of secondary user's transmitter queue and obtain the maximum throughput of a secondary network with underlay access. In our proposed hybrid CR system, the underlay approach is incorporated in the frame of an overlay CR system – the CR system is normally working in an overlay mode and thus a secondary transmitter opportunistically access the licensed spectrum when a primary user is idle. However, when a secondary user makes its throughput to maximize and maintains secondary user's queue to be stable, the CR system operates in an underlay mode and a secondary transmitter is allowed to send their packets to its destination even though the primary user is also transmitting.

Switching to an underlay mode is beneficial to secondary users but they cause performance degradation of primary users. So the transmit power of a secondary transmitter in an overlay mode is required to be lower than that in a stand-alone (non-hybrid) overlay CR system to compensate for the performance loss of primary users by adopting an underlay mode. In our hybrid CR system, switching to an underlay mode is probabilistically controlled to maximize the departure rate of a secondary transmitter while satisfying QoS requirement for a primary transmitter and stability of secondary user's transmit queue. Through mathematical and numerical analysis, we derive the optimal switching rate, namely *hybrid rate* (ϵ), and corresponding transmit power of a secondary user in an overlay mode. We also identify the range of the hybrid rate to guarantee the stability of secondary user's transmit queue.

II. The Proposed Hybrid CR System

A. System Configuration

Fig. 1 depicts our system configuration with two communication links – primary and secondary links. We assume *packet-by-packet* transmission as in [13] so that packets are accessed in a time-slotted manner and one packet is transmitted in each time slot. Not only a primary user but also a secondary user

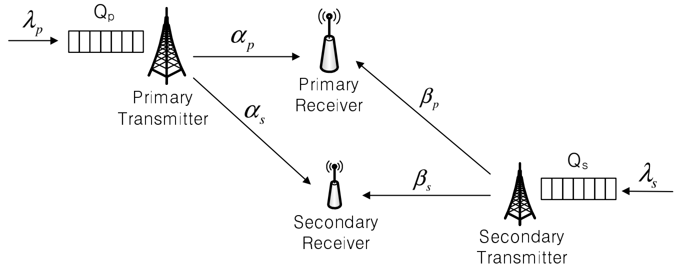

Fig. 1. System model

are equipped with infinite-length queues to store the incoming packets. When the secondary user's queue is empty, the secondary network's transmitter transmits dummy packets. So, the secondary user always looks like transmitting its own packets. The incoming packet traffics at all transmitters are modeled by independent and identically distributed (i.i.d.) Bernoulli processes with average arrival rate λ and average departure rate μ. The average arrival rate denotes the probability which packets are incoming into a queue during one time slot and the average departure rate represents the probability of successful transmission from a queue to its destination in an unit time slot. Note that the departure rate depends on interference and channel conditions of a transmitter-to-receiver link.

The channel gains from the primary transmitter to the primary receiver and from the secondary transmitter to the secondary receiver are denoted by α_p and β_s, respectively. β_p and α_s are the interference channel gains from the secondary transmitter to the primary receiver and from the primary transmitter to the secondary receiver, respectively. All the channels suffer from Rayleigh fading so that channel gains are assumed to be i.i.d. exponential random variables with unit mean. The additive noise is supposed to be a white Gaussian random variable with zero mean and unit variance. The secondary transmitter is assumed to know the channel statistics of α_p, α_s and β_s and the instantaneous channel state information of β_p to adjust the interference perceived at the primary user in an underlay mode. We assume that the instantaneous channel information of β_p is attained by a periodic sensing of a pilot beacon from the primary receiver in a block fading channel with the help of channel reciprocity [15].

In an overlay mode, system performance depends on sensing errors which are typically captured by a missed detection probability p_m and a false alarm probability p_f. The missed detection probability denotes the probability that the secondary user considers the primary user's spectrum is empty although it is occupied. The false alarm probability means the probability that the secondary user declares the existence of the primary user even though the primary user is idle.

Since the primary user needs to be protected from interference by secondary user's sensing errors and accessing of a secondary user in an underlay mode, we set a constraint that the departure rate of primary transmitter's queue should be greater than a target value μ_{th} such that

$$\mu_p \geq \mu_{th}. \tag{1}$$

B. The Proposed Hybrid CR System

Maintaining the stability of secondary user's queue is difficult process in conventional overlay CR systems because transmission of a secondary user is allowed only in the absence of a primary user. It is necessary for the secondary user to access the primary user's spectrum in some times despite the presence of a primary user for maintaining the stability and maximizing the departure rate of a secondary user. This reasoning naturally motivates a hybrid CR system combining overlay and underlay approaches. However, a primary user suffers from additional interference from a secondary user by adopting an underlay mode. So, to compensate for the loss of a primary user by adopting an underlay mode, the transmit power of a secondary user in an overlay mode should be reduced compared to that in (non-hybrid) conventional overlay CR system. Switches to an underlay mode should also be controlled to protect a primary user and to reduce burden of estimating the instantaneous interference channel, β_p, in an underlay mode.

In our hybrid CR system, switching to an underlay mode is probabilistically controlled. The switching rate, ϵ, is termed by *hybrid rate* and determined to maximize the departure rate of a secondary transmitter while satisfying QoS requirement for a primary transmitter and stability of secondary user's transmit queue. Note that $\epsilon = 0$ and $\epsilon = 1$ correspond (non-hybrid) stand-alone overlay and underlay CR systems, respectively.

III. Optimal Hybrid Rate and Transmit Power in a Hybrid CR System

This section derives the optimal hybrid rate and corresponding transmit power of the secondary user in an overlay mode by analyzing throughputs of the primary and the secondary networks. Unless outage occurs in a transmitter-receiver link, a packet is successfully delivered and hence average departure rate is given in terms of outage probability by

$$\mu = 1 - P_{out}. \tag{2}$$

Furthermore, the average departure rate is directly translated into average throughput so that we consider average departure rate instead of average throughput.

A. Average Departure Rate of a Primary User

The average departure rate of a primary user should be guaranteed in CR systems. So we first derive the average departure rate of a primary user in a hybrid CR system to find the optimal hybrid rate and transmit power of a secondary user in an overlay mode.

When the hybrid CR system is working in an underlay mode, the transmit power setting of a secondary user is the same as that in a (non-hybrid) stand-alone underlay CR system because the perceived interference at a primary user should be instantaneously maintained below a pre-determined interference level, i.e., interference temperature, in either cases. So the transmit power of a secondary user in an underlay mode is adjusted by

$$P_s^{underlay} = \begin{cases} P_{s,max}, & \beta_p \leq \frac{Q}{P_{s,max}} \\ \frac{Q}{\beta_p}, & \beta_p > \frac{Q}{P_{s,max}}, \end{cases} \tag{3}$$

where Q is the interference temperature and $P_{s,max}$ denotes the maximum transmit power of a secondary transmitter. Note that the power is instantaneously adapted to the interference channel gain β_p not to exceed the given interference temperature Q.

On the other hand, the transmit power of a secondary user in an overlay mode is determined to secure the target departure rate of a primary user and depends on the hybrid rate and the target departure rate of a primary user.

Taking into account both underlay and overlay modes, the average departure rate of a primary user, μ_p in a hybrid CR system is given by

$$\begin{aligned}\mu_p = &(1-p_m)[\epsilon(1-P_{out}^{underlay}) + (1-\epsilon)(1-P_{out}^{overlay})] \\ &+ p_m(1-P_{out}^{overlay,inf})\end{aligned} \tag{4}$$

where $P_{out}^{underlay}$ denotes the outage probability of a primary link when both primary and secondary users transmit in an underlay mode and is given by

$$\begin{aligned}P_{out}^{underlay} &= \Pr\left[\log_2\left(1 + \frac{\alpha_p P_p}{1+\beta_p P_s^{underlay}}\right) < R_p\right] \\ &= 1 - \exp\left(-\frac{Q}{P_{s,max}} - \frac{Q+1}{P_p}\left(2^{R_p}-1\right)\right) \\ &- \frac{\left(\exp\left(Q\left(\frac{1}{P_{s,max}} + \frac{2^{R_p}-1}{P_p}\right)\right)-1\right)}{P_p + P_{s,max}\left(2^{R_p}-1\right)} \\ &\times P_p \exp\left(-\frac{Q}{P_{s,max}} - \frac{1+Q}{P_p}\left(2^{R_p}-1\right)\right)\end{aligned} \tag{5}$$

where P_p and R_p are the peak transmit power and the required data rate of a primary link, respectively. $P_{out}^{overlay}$ denotes the outage probability of a primary link when a primary user does not experience any interference from a secondary user owing to correct detection at the secondary user in an overlay mode and is given by

$$\begin{aligned}P_{out}^{overlay} &= \Pr\left[\log_2\left(1+\alpha_p P_p\right) < R_p\right] \\ &= 1 - \exp\left(-\frac{2^{R_p}-1}{P_p}\right).\end{aligned} \tag{6}$$

The term $P_{out}^{overlay,inf}$ represents the outage probability of a primary link with interference from a secondary user due to missed detection in an overlay mode and is given by

$$\begin{aligned}P_{out}^{overlay,inf} &= \Pr\left[\log_2\left(1 + \frac{\alpha_p P_p}{1+\beta_p P_s^{overlay}}\right) < R_p\right] \\ &= 1 - \frac{\exp\left(-\frac{2^{R_p}-1}{P_p}\right)}{1 + \frac{2^{R_p}-1}{P_p} P_s^{overlay}}\end{aligned} \tag{7}$$

where $P_s^{overlay}$ is the transmit power of a secondary transmitter in an overlay mode and will be determined according to the hybrid rate and the target average departure rate of a primary user.

B. Average Departure Rate of a Secondary User

Average departure rate of a secondary user is determined by departure rates achieved in underlay and overlay modes. For a given hybrid rate ϵ, the departure rate of a secondary user is given by

$$\mu_s = \mu_s^{overlay} + (1-\rho)\cdot\epsilon\cdot\mu_s^{underlay} \tag{8}$$

where ρ reflects a penalty term caused by periodically monitoring the interference channel β_p in an underlay mode. $\mu_s^{overlay}$ and $\mu_s^{underlay}$ are departure rates of the secondary user in overlay and underlay modes and given, respectively, by

$$\begin{aligned}\mu_s^{overlay} = &\Pr\left[Q_p(t)=0\right](1-p_f)\left(1-P_{out}^{S,overlay}\right) \\ &+ \Pr\left[Q_p(t)\neq 0\right]\cdot p_m \cdot\left(1-P_{out}^{S,overlay,Inf}\right)\end{aligned} \tag{9}$$

$$\begin{aligned}\mu_s^{underlay} = &\Pr\left[Q_p(t)=0\right]\cdot p_f\cdot\left(1-P_{out}^{S,underlay}\right) \\ &+ \Pr\left[Q_p(t)\neq 0\right](1-p_m)\left(1-P_{out}^{S,underlay,Inf}\right)\end{aligned} \tag{10}$$

where $\Pr\left[Q_p(t)=0\right]$ is the probability that the queue of a primary transmitter is empty and given by $\Pr\left[Q_p(t)=0\right] = 1-\lambda_p/\mu_p$ from Little's theorem. $P_{out}^{S,overlay}$ represents the outage probability of a secondary link in an overlay mode when there is no interference from primary users owing to correct detection:

$$\begin{aligned}P_{out}^{S,overlay} &= \Pr\left[\log_2\left(1+\beta_s P_s^{overlay}\right) < R_s\right] \\ &= 1 - \exp\left(-\frac{2^{R_s}-1}{P_s^{overlay}}\right).\end{aligned} \tag{11}$$

$P_{out}^{S,overlay,Inf}$ denotes the outage probability of a secondary link when a secondary user suffers from interference from primary users in an overlay mode due to missed detection:

$$\begin{aligned}P_{out}^{S,overlay,Inf} &= \Pr\left[\log_2\left(1+\frac{\beta_s P_s^{overlay}}{1+\alpha_s P_p}\right) < R_s\right] \\ &= 1 - \frac{\exp\left(-\frac{2^{R_s}-1}{P_s^{overlay}}\right)}{1+\frac{2^{R_s}-1}{P_s^{overlay}}P_p}.\end{aligned} \tag{12}$$

$P_{out}^{S,underlay}$ denotes the outage probability of a secondary link in an underlay mode when a secondary user switches to an underlay mode by a false alarm. So there is no interference from primary users even though it is working in an underlay mode as given by

$$\begin{aligned}&P_{out}^{S,underlay} \\ &= \Pr\left[\log_2\left(1+\beta_s P_s^{underlay}\right) < R_s\right] \\ &= \left(1-\exp\left(-\frac{Q}{P_{s,max}}\right)\right)\left(1-\exp\left(-\frac{2^{R_s}-1}{P_{s,max}}\right)\right) \\ &+ \exp\left(-\frac{Q}{P_{s,max}}\right) - \frac{\exp\left(-\frac{Q}{P_{s,max}}\left(1+\frac{2^{R_s}-1}{Q}\right)\right)}{1+\frac{2^{R_s}-1}{Q}}.\end{aligned} \tag{13}$$

$P_{out}^{S,underlay,Inf}$ represents the outage probability of a secondary link in an underlay mode when there exists a primary user in the spectrum and is given by

$$
\begin{aligned}
&P_{out}^{S,underlay,Inf} \\
&= \Pr\left[\log_2\left(1+\frac{\beta_s P_s^{underlay}}{1+\alpha_s P_p}\right) < R_s\right] \\
&= \left(1-\exp\left(-\frac{Q}{P_{s,max}}\right)\right)\left(1-\frac{\exp\left(-\frac{2^{R_s}-1}{P_{s,max}}\right)}{1+\frac{P_p}{P_{s,max}}\left(2^{R_s}-1\right)}\right) \\
&+\exp\left(-\frac{Q}{P_{s,max}}\right)-\frac{\exp\left(\frac{1}{P_p}+\frac{Q}{P_p(2^{R_s}-1)}\right)Q}{P_p\left(2^{R_s}-1\right)} \\
&\times E_1\left(\frac{\left(Q+2^{R_s}-1\right)\left(P_{s,max}+P_p\left(2^{R_s}-1\right)\right)}{P_pP_{s,max}\left(2^{R_s}-1\right)}\right) \qquad (14)
\end{aligned}
$$

where $E_1(\cdot)$ denotes an exponential integral function.

C. Optimal Hybrid Rate and Transmit Power

The optimal values of the hybrid rate and transmit power of a secondary user in an overlay mode are obtained from the following optimization problem:

$$
\begin{aligned}
\max_{\epsilon,P_s^{overlay}} \; & [\mu_s^{overlay}+(1-\rho)\cdot\epsilon\cdot\mu_s^{underlay}] \qquad (15)\\
\text{s.t.} \quad & \mu_p \geq \mu_{th}, \\
& P_s^{overlay} \leq P_{s,max}
\end{aligned}
$$

To guarantee primary user's QoS in terms of average departure rate ($\mu_p \geq \mu_{th}$), the maximum allowable transmit power of a secondary transmitter in an overlay mode is determined for given hybrid rate ϵ, when μ_p is equal to μ_{th}, by

$$
\begin{aligned}
P_s^{overlay}(\epsilon) = &\left[\frac{p_m \exp\left(-\frac{2^{R_p}-1}{P_p}\right)}{\mu_{th}-(1-p_m)\left(K\epsilon+\exp\left(-\frac{2^{R_p}-1}{P_p}\right)\right)}-1\right] \\
&\times\left(\frac{P_p}{2^{R_p}-1}\right) \qquad (16)
\end{aligned}
$$

where K $(= P_{out}^{overlay} - P_{out}^{underlay})$ is a constant given by

$$
\begin{aligned}
K = &\frac{\left(\exp\left(Q\left(\frac{1}{P_{s,max}}+\frac{2^{R_p}-1}{P_p}\right)\right)-1\right)}{P_p+P_{s,max}\left(2^{R_p}-1\right)} \\
&\times P_p\exp\left(-\frac{Q}{P_{s,max}}-\frac{1+Q}{P_p}\left(2^{R_p}-1\right)\right) \\
&+\exp\left(-\frac{Q}{P_{s,max}}-\frac{Q+1}{P_p}\left(2^{R_p}-1\right)\right) \\
&-\exp\left(-\frac{2^{R_p}-1}{P_p}\right). \qquad (17)
\end{aligned}
$$

Note that K is typically negative because $P_{out}^{overlay}$ is in general smaller than $P_{out}^{underlay}$.

Substituting the derived transmit power of a secondary user in an overlay mode, which is given as a function of the hybrid rate ϵ, the optimization problem is reduced in terms of ϵ to

$$\max_{\epsilon}[\mu_s^{overlay}+(1-\rho)\cdot\epsilon\cdot\mu_s^{underlay}]. \qquad (18)$$

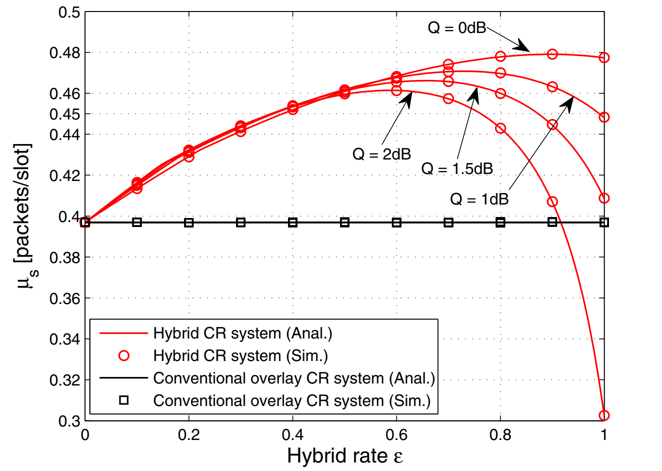

Fig. 2. Throughput of a secondary user μ_s versus hybrid rate ϵ for different values of Q (p_m=0.2, p_f=0.25, R_p=1, R_s=0.5, P_p=10dB, $P_{s,max}$=10dB, μ_{th}=0.8, λ_p=λ_s=0.45, ρ=0.2ϵ)

Even though an explicit expression of the optimal ϵ is not available, an numerical search over $\{0 \leq \epsilon \leq 1\}$ readily gives an optimal solution. Some examples of the optimal values of ϵ are presented in numerical results. The range of the hybrid rate ϵ simultaneously satisfying the required target departure rate of a primary user and stability of a transmit queue of a secondary user can also be identified such as $\mu_s > \lambda_s$.

IV. Numerical results

In this section, numerical results are provided to support our analysis. The missed detection probability, p_m, and the false alarm probability, p_f, are set to be 0.2 and 0.25, respectively. Since AWGN is assumed to have a unit variance, P_p and $P_{s,max}$ represent transmit SNRs at the primary and the secondary transmitters, respectively, and both of them are assumed to be 10dB. The required data rates of primary and secondary users are $R_p = 1$ bps/Hz and $R_s = 0.5$ bps/Hz, respectively. μ_{th} is set to be 0.8 and the penalty ρ by instantaneously monitoring the interference channel in an underlay mode is assumed to be proportional to the hybrid rate ϵ, $\rho = 0.2\epsilon$, because more frequent switchings to an underlay mode result in huger burden. The average arrival rates at primary and secondary transmitters are all assumed to be 0.45 if there is no specification.

Fig. 2 shows average departure rate of a secondary user versus hybrid rate for various interference temperature Q. The departure rate of a secondary user looks concave because an increase of secondary user's departure rate in an underlay mode is dominant when ϵ is small while a decrease of secondary user's departure rate in an overlay mode becomes rather prominent as ϵ and Q increase. The rapidly decreasing transmit power of a secondary user in an overlay mode to guarantee the minimum departure rate of a primary user results in the dominant decrease of secondary user's departure rate as ϵ and Q increase. In this figure, the optimal hybrid rates for

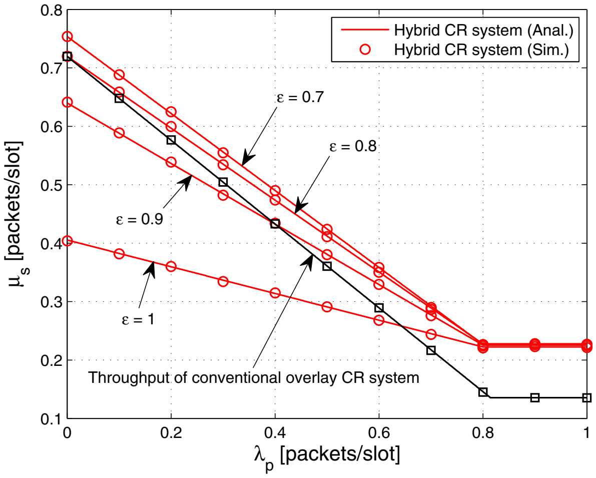

Fig. 3. Throughput of a secondary user μ_s according to arrival rate of a primary user λ_p for different values of ϵ (p_m=0.2, p_f=0.25, R_p=1, R_s=0.5, P_p=10dB, $P_{s,max}$=10dB, Q = 2dB, μ_{th}=0.8, λ_s=0.45, ρ=0.2ϵ)

$Q = 0,\ 1,\ 1.5,\ 2$dB are $0.9,\ 0.73,\ 0.66$,0.59, respectively. The optimal hybrid rate ϵ^* increases as interference temperature decreases. On the other hand, the range of ϵ which retains stability of secondary user's transmit queue is determined by the values that achieve secondary user's departure rate greater than the given arrival rate $\lambda_s = 0.45$. The ranges of hybrid rate guaranteeing stable transmission of secondary network for $Q = 0,\ 1,\ 1.5,\ 2$dB are $\epsilon > 0.39,\ 0.37 < \epsilon < 0.99,\ 0.36 < \epsilon < 0.87,\ 0.36 < \epsilon < 0.76$, respectively. As the interference temperature increases, the range of hybrid rate enabling secondary user's stable transmission becomes small.

Fig. 3 shows throughput of a secondary user μ_s in accordance with arrival rate of a primary user λ_p for the different values of hybrid rate ϵ. If $\epsilon \leq 0.8$, the throughput of a secondary user in a hybrid system is always better than that of a secondary user in the conventional overlay CR system. If $\epsilon \geq 0.8$, throughput of a secondary user in a hybrid CR system is lower than that of a conventional overlay CR system when the arrival rate of a primary user is less than a certain value, i.e., $\lambda_p \leq 0.4$ for $\epsilon = 0.9$ and $\lambda_p \leq 0.65$ for $\epsilon = 1$. For a large ϵ, the transmit power of a secondary user in an overlay mode is set small because interference to a primary user should be reduced to guarantee primary user's target departure rate. As a result, a conventional overlay CR system rather achieves higher throughput as the arrival rate when λ_p is small compared to the overlay mode in a hybrid CR system. It is noted that throughputs of a secondary user in both systems are saturated when $\lambda_p \gtrsim 0.8$. If the λ_p is larger than primary user's target departure rate $\mu_{th} = 0.8$, the probability that primary transmitter's queue is empty becomes zero and thus a secondary transmitter does not have any chance to opportunistically access primary user's spectrum. Throughput of a secondary user in a conventional overlay CR system when $\lambda_p \gtrsim 0.8$ results from missed detection at a secondary user. On the other hand, throughput of a secondary user in a hybrid CR when $\lambda_p \geq 0.8$ comes from an underlay mode and missed detection in an overlay mode.

V. Conclusions

We have proposed and analyzed a hybrid CR system for stable transmission of a secondary network. Our proposed system occasionally switches to an underlay CR mode while it basically operates in an overlay CR mode. The switching from an overlay mode to an underlay mode is probabilistically controlled to maximize throughput of a secondary user while satisfying the target departure rate of a primary user and securing stability of secondary user's transmit queue. We have derived the optimal switching rate, namely hybrid rate, and shown that the proposed hybrid CR system takes advantages in terms of maximized throughput compared to conventional overlay CR systems. We have also identified the range of hybrid rate for stability of secondary transmitter's queue.

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