Efficiency of a Cognitive Radio Link with Opportunistic Interference Mitigation

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***Abstract*—To increase spectrum utilization, cognitive radio allows concurrent secondary and primary transmissions as long as interference to primary users is constrained under a threshold. This research proposes an enhanced opportunistic interference mitigation scheme utilizing both successfully and unsuccessfully decoded primary packets to improve data rate of secondary transmission. Moreover, we propose an analytical model to investigate characteristic changes of the spectrum usage affected by the coexisting secondary transmission in terms of overall spectral efficiency. The interference mitigation scheme can be applied to realistic two-tier femtocell networks to enable robust communication against cross-tier interference thereby obtaining a substantial spectrum reuse gain.**

***Index Terms*—Automatic Repeat-reQuest (ARQ), cognitive radio, concurrent transmission, interference mitigation.**

I. Introduction

RECENTLY, cognitive radio (CR) technology has received great attention due to its tremendous promise for improving spectrum utilization in wireless systems. With advanced sensing and signal-processing capabilities, CR could intelligently adopt side information of coexisting users to interweave, underlay, or overlay its signal with those of existing users [1]. In these cases, the CR is often referred as a secondary user (SU), which cannot cause harmful interference to the existing users, known as primary users (PUs).

Most prior research [2], [3] addresses on interweave paradigm, where secondary transmitter (ST) opportunistically exploits the temporary frequency voids to completely avoid interference to primary receiver (PR). To improve spectrum reuse, ST in underlay paradigm exploits channel side information (CSI) to concurrently transmit with primary transmitter (PT) subject to an interference threshold constraint at PR [4], [5]. However, the heavy interference from primary transmission limits the data rate of secondary transmission. As ST performs encoding technique such as dirty-paper coding [6], [7] using PTs' codebook and messages, interference is cancelled and additional throughput is obtained.

In the popular retransmission-based primary wireless network, SU could exploit Automatic Repeat-reQuest (ARQ) message to reduce interference to PU [8] or tolerate extra interference [9]. A protocol in [9] cancels interference at secondary receiver (SR) by leveraging opportunity that arises during primary retransmission. Specifically, SR listens and successfully decodes primary packet in the initial transmission so that during the retransmissions it can eliminate the interference caused by PT. Thus, the throughput of underlaid secondary transmission during primary retransmission is improved; however, the incurred interference increases the probability of decoding failure of primary packets at PR [10], [11]. As a result, primary retransmissions are triggered more often and the idle period becomes shorter, which degrades the efficiency for interweave access. Thus, the impact of coexisting secondary transmission on characteristic changes of spectrum usage shall be considered when analyzing performance of interference mitigation.

The contributions of this letter are as follows.

(1) **Enhanced interference mitigation.** We enhance the capability of existing interference cancellation scheme in [9] by enabling SR to exploit primary packets in the initial transmissions, which are overheard but can not be successfully decoded, to mitigate interference during the primary retransmission.

(2) **Spectral efficiency.** To capture the characteristic changes of spectrum usage when SU coexists, this letter considers overall spectral efficiency as the performance metric, which includes both spectrum usage ratio and outage capacity (i.e., the maximum information rate with an outage constraint).

(3) **Model for analyzing access strategies.** We apply a mixed access strategy in schemes with and without interference mitigation, where ST always transmits during the idle periods and makes transmission during the busy periods with access probability p. Given the status of primary link, ST could decide to apply interference mitigation or not and choose p with the objective of maximizing the overall spectral efficiency according to the analytical model.

(4) **Applications on two-tier femto networks.** We demonstrate that the enhanced interference mitigation can be applied in the existing retransmission-based femtocell network to achieve high reuse gain.

II. System Model

As shown in Fig. 1, we consider a typical interference channel/network model where multiple network entity pairs (i.e., PT-PR and ST-SR) communicate concurrently in the presence of mutual interference. We respectively denote $d_{X,Y}$ and $h_{X,Y}$ as the distance and the amplitude of fading channel coefficient between entities X and Y. The power gains of the fading channels are all assumed to be exponentially distributed with unit mean. We assume that SR can overhear (but not necessary successfully decode) the messages sent by PT and

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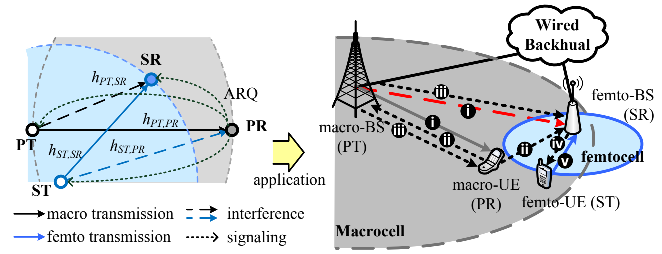

Fig. 1. Network model and application on two-tier femto networks. Direct links, interfering links, and ARQ feedbacks are represented by solid, dashed, and doted arrows, respectively.

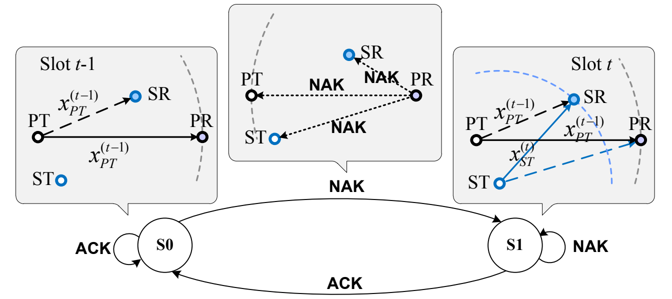

Fig. 2. Procedure to achieve concurrent secondary transmission during primary retransmission period.

both ST and SR can overhear the ARQ feedback sent by PR. Also, we assume that ST knows the channel statistics of the primary link and the link between itself and PR, and SR knows CSI between itself and PT. SU could adopt recent innovations such as CRN tomography [12] to actively probe signals of PU and estimate CSI between itself and PU without heavy overheads.

The primary traffic comprises series of packets with Poisson arrival rate λ and fixed service time D (named a slot), which is defined as the quotient between the primary message length and the primary information rate R_{PS}. The channel coherence time is also assumed to be D, i.e., the channel gain changes independently from slot to slot. Perfect synchronization between PUs and SUs is assumed and ST is supposed to be backlogged. The success reception of a primary transmission at PR depends on if the channel can support the information rate R_{PS}. To guarantee the transmission quality, there is an outage constraint at PR with maximum outage probability (approximating the decoding error probability) ϵ_{PS}. Once decoding errors occur, stop-and-wait (SAW) ARQ is adopted. We assume no constraint on the number of retransmissions, that is, packet is kept retransmitting until it is successfully received at PR. On the other hand, no ARQ for secondary transmission is assumed due to the opportunistic nature.

A. Interference Mitigation Scheme

Fig. 2 illustrates the process of interference mitigation including two states $S_0 = \{$PT transmits a new packet; ST keeps silence; SR overhears primary signal$\}$ and $S_1 = \{$PT retransmits the old packet; ST transmits a new packet; SR mitigates interference$\}$. The process starts from state S_0 where SR probes the primary packet while ST stays silence. When packet decoding error occurs, PR feedbacks a NAK message, which is overheard by both ST and SR. In the next slot, the process transients to state S_1 where PT retransmits the previous packet while ST sends its own data simultaneously. SR adopts the packet overheard at state S_0 to achieve interference mitigation. If the overheard primary packet could be successfully decoded, interference could be perfectly subtracted [9]. If not, SR combines signals received in states S_0 and S_1 in a maximizing SINR fashion [13] to retrieve capacity gains.

B. Access Strategies

Typically, the usage of primary spectrum consists of interlacing idle period and busy period, and the busy period can be utilized for either primary initial transmission or retransmission. To fully exploit available spectrum, traditional mixed access strategy always transmits during the idle periods and makes transmission during the busy periods with a probability p subject to an outage constraint. Fig. 3 illustrates cases of $p = 1$ and $p = 0$. With interference mitigation, a novel mixed access strategy is applied, where ST still transmits during the idle periods but only makes transmission during primary retransmissions. SR overhears the primary initial transmission for interference cancellation. As shown in Fig. 3, ST decides to access all retransmission slots following the initial transmission as a whole with probability p. To analyze the spectrum behavior when SU coexists, the performance metric considered is the overall spectral efficiency, which is defined as the product of spectrum usage ratio and corresponding outage capacity.

III. Efficiency for Mixed Strategy with Interference Mitigation

A. Spectrum Usage

To obtain prior information for interference mitigation, SUs stay silent and sense during primary initial transmission, and the corresponding outage probability ϵ'_{PS} at PR is

$$\epsilon'_{PS} = \mathbb{P}\left(\frac{P_{PT}|h_{PT,PR}|^2/d^{\alpha}_{PT,PR}}{N_0} \le 2^{R_{PS}} - 1\right) < \epsilon_{PS}, \quad (1)$$

where α is the path loss exponent, N_0 is the background noise power, and P_{PT} is the transmission power of a PT. Please note that P_{PT} remains fixed along the retransmission. During retransmission slots, ST transmits packet concurrently while the outage constraint ϵ_{PS} at PR shall be satisfied

$$\mathbb{P}\left(\frac{P_{PT}|h_{PT,PR}|^2/d^{\alpha}_{PT,PR}}{N_0 + \overline{P}_{ST}|h_{ST,PR}|^2/d^{\alpha}_{ST,PR}} \le 2^{R_{PS}} - 1\right) = \epsilon_{PS}, \quad (2)$$

where $\overline{P}_{ST}$ is the maximum permissible transmission power of an ST. From (2), we have

$$\begin{aligned} 1 - \epsilon_{PS} &\overset{(a)}{=} \mathbb{E}_{|h_{ST,PR}|^2}\Big[\exp\Big(-(2^{R_{PS}} - 1) \\ &\quad \cdot \left(\frac{(N_0 + \overline{P}_{ST}|h_{ST,PR}|^2/d^{\alpha}_{ST,PR})}{P_{PT}/d^{\alpha}_{PT,PR}}\right)\Big]\\ &\overset{(b)}{=} \exp\left(-\frac{(2^{R_{PS}} - 1)N_0}{P_{PT}/d^{\alpha}_{PT,PR}}\right) \end{aligned}$$

$$\Bigg/ \left(1 + \frac{(2^{R_{PS}} - 1)\overline{P}_{ST}/d_{ST,PR}^{\alpha}}{P_{PT}/d_{PT,PR}^{\alpha}}\right), \quad (3)$$

where (a) and (b) respectively follow by $\mathbb{P}(|h_{PT,PR}|^2 > x) = e^{-x}$ and $\mathbb{E}[e^{-s|h_{ST,PR}|^2}] = \frac{1}{1+s}$. Thus, $\overline{P}_{ST} = \left(\frac{P_{PT}/d_{PT,PR}^{\alpha}}{(2^{R_{PS}}-1)/d_{ST,PR}^{\alpha}}\right)\left(\frac{\exp\left(-\frac{(2^{R_{PS}}-1)N_0}{P_{PT}/d_{PT,PR}^{\alpha}}\right)}{1-\epsilon_{PS}} - 1\right)$. Given the outage probability ϵ'_{PS}, the constraint ϵ_{PS}, the ARQ scheme, and the access probability p, the primary traffic pattern can be modeled as an M/G/1 queue with arrival rate λ and mean service time $\mathbb{E}[S_p]$. $\mathbb{E}[S_p]$ is calculated as

$$\begin{aligned}\mathbb{E}[S_p] &= p\mathbb{E}[S_p|\text{ST accesses}] \\ &\quad + (1-p)\mathbb{E}[S_p|\text{ST does not access}] \\ &= D\left(\frac{p(1-\epsilon_{PS}+\epsilon'_{PS})}{1-\epsilon_{PS}} + \frac{1-p}{1-\epsilon'_{PS}}\right). \end{aligned} \quad (4)$$

The means of the busy and idle periods of primary traffic under SU access probability p are respectively [14] $\mathbb{E}[T_p^{\text{Busy}}] = \frac{\mathbb{E}[S_p]}{1-\lambda\mathbb{E}[S_p]}$ and $\mathbb{E}[T_p^{\text{Idle}}] = \frac{1}{\lambda}$.

B. Efficiency during Idle Period

During the idle period, interweave paradigm is applied and stand-alone secondary transmission exists. With an outage constraint ϵ_{SS} at SR, the outage capacity $\mathbb{C}_{SR}^{\text{Idle}}$ satisfies

$$\mathbb{P}\left(\frac{|h_{ST,SR}|^2 P_{ST}/d_{ST,SR}^{\alpha}}{N_0} \le 2^{\mathbb{C}_{SR}^{\text{Idle}}} - 1\right) = \epsilon_{SS}, \quad (5)$$

where P_{ST} is the transmission power of an ST during the idle period. It is further derived as $\mathbb{C}_{SR}^{\text{Idle}} = \log\left(1 - \frac{\ln(1-\epsilon_{SS})P_{ST}/d_{ST,SR}^{\alpha}}{N_0}\right)$. By multiplying it with the spectrum usage ratio $\frac{\mathbb{E}[T_p^{\text{Idle}}]}{\mathbb{E}[T_p^{\text{Busy}}]+\mathbb{E}[T_p^{\text{Idle}}]}$, the efficiency during idle period under access probability p is $\eta_p^{\text{Idle}} = \frac{\mathbb{E}[T_p^{\text{Idle}}]}{\mathbb{E}[T_p^{\text{Busy}}]+\mathbb{E}[T_p^{\text{Idle}}]}\mathbb{C}_{SR}^{\text{Idle}}$.

C. Efficiency during Busy Period

The successive interlacing durations of burst initial primary packet transmissions and burst retransmissions of a failed primary packet in a busy period are respectively denoted as D_p^I and D_p^R under SU access probability p. Note that secondary transmissions and primary retransmissions may coexist in D_p^R, while only primary transmissions happen in D_p^I. Fig. 3 shows an example with several interlacing D_p^I and D_p^R. The average length of D_p^R is

$$\begin{aligned}\mathbb{E}[D_p^R] &= p\mathbb{E}[D_p^R|\text{ST accesses}] \\ &\quad + (1-p)\mathbb{E}[D_p^R|\text{ST does not access}] \\ &= D\left(\frac{p}{1-\epsilon_{PS}} + \frac{1-p}{1-\epsilon'_{PS}}\right). \end{aligned} \quad (6)$$

The average length of D_p^I, $\mathbb{E}[D_p^I]$, is $D(1+(1-\epsilon'_{PS})+(1-\epsilon'_{PS})^2+\dots) = \frac{D}{\epsilon'_{PS}}$. From renewal reward theorem [14], the long run proportion of concurrent transmission within a busy period is $\frac{Dp/(1-\epsilon_{PS})}{\mathbb{E}[D_p^R]+\mathbb{E}[D_p^I]}$. We explore the outage capacity of underlaid secondary transmission during primary retransmission with interference mitigation in the following. As shown in Fig. 2, during initial transmission of a primary packet $x_{PT}^{(t-1)}$ at slot $t-1$, SR also overhears signal $y_{PT,SR}^{(t-1)}$ transmitted by PT intended to PR, i.e.,

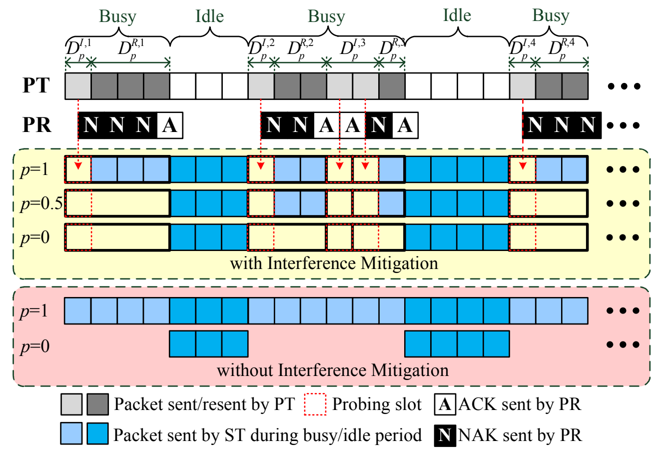

Fig. 3. Access strategies of ST: In traditional one without interference mitigation, p is the access probability of an ST during each primary transmission. On the other hand, in proposed one with interference mitigation, no concurrent transmission happens in PT's initial transmission slot so that SR can overhear the initial primary packet to further perform interference mitigation during successive retransmission slots. ST decides to access all retransmission slots following the initial transmission as a whole with probability p.

$$y_{PT,SR}^{(t-1)} = (h_{PT,SR}^{(t-1)}/d_{PT,SR}^{\alpha/2})x_{PT}^{(t-1)} + n^{(t-1)}. \quad (7)$$

$y_{PT,SR}^{(t-1)}$ can be successfully decoded when no outage occurs at SR with probability $1 - \mathbb{P}_{out}^{PT,SR}$, where

$$\begin{aligned}\mathbb{P}_{out}^{PT,SR} &= \mathbb{P}\left(\frac{|h_{PT,SR}|^2 P_{PT}/d_{PT,SR}^{\alpha}}{N_0} \le 2^{R_{PS}} - 1\right) \\ &= 1 - \exp\left(-\frac{(2^{R_{PS}}-1)N_0}{P_{PT}/d_{PT,SR}^{\alpha}}\right). \end{aligned} \quad (8)$$

Assume that $x_{PT}^{(t-1)}$ cannot be decoded at PR and retransmission occurs at slot t. Under access probability p, ST transmits packet $x_{ST}^{(t)}$, and SR at slot t receives signal as

$$\begin{aligned}y_{SR}^{(t)} &= y_{PT,SR}^{(t)} + y_{ST,SR}^{(t)} + n^{(t)} = (h_{PT,SR}^{(t)}/d_{PT,SR}^{\alpha/2})x_{PT}^{(t-1)} \\ &\quad + (h_{ST,SR}^{(t)}/d_{ST,SR}^{\alpha/2})x_{ST}^{(t)} + n^{(t)}, \end{aligned} \quad (9)$$

where $y_{PT,SR}^{(t)}$ is the received signal from PT intended to PR at slot t and $y_{ST,SR}^{(t)}$ denotes received signal from ST at slot t. From (9) we observe that obtaining $x_{ST}^{(t)}$ from $y_{SR}^{(t)}$ at SR depends on the prior information $y_{PT,SR}^{(t-1)}$ from PT at slot $t-1$. If SR successfully decodes the signal $y_{PT,SR}^{(t-1)}$, $x_{PT}^{(t-1)}$ can be obtained after re-encoding. It is then scaled by $h_{PT,SR}^{(t)}/d_{PT,SR}^{\alpha/2}$ and subtracted from signal $y_{SR}^{(t)}$, and we have

$$\hat{y}_{SR}^{(t)} = (h_{ST,SR}^{(t)}/d_{ST,SR}^{\alpha/2})x_{ST}^{(t)} + n^{(t)}. \quad (10)$$

The outage capacity during concurrent transmission with successfully decoded primary signal is

$$\mathbb{C}_{SR,s}^{\text{Busy}} = \log\left(1 - \frac{\ln(1-\epsilon_{SS})\overline{P}_{ST}/d_{ST,SR}^{\alpha}}{N_0}\right). \quad (11)$$

Different from the existing protocol [9], we further consider that if SR is not able to decode the signal $y_{PT,SR}^{(t-1)}$ from PT at slot $t-1$. We scale it with an optimal proportionality (denoted as β) and then subtract it from $y_{SR}^{(t)}$, such that the SINR of the dedicated signal at SR is maximized [13]. It results in

$$\hat{y}_{SR}^{(t)} = y_{SR}^{(t)} - \beta y_{PT,SR}^{(t-1)} = \frac{h_{ST,SR}^{(t)}}{d_{ST,SR}^{\alpha/2}} x_{ST}^{(t)} + \frac{h_{PT,SR}^{(t)} - \beta h_{PT,SR}^{(t-1)}}{d_{PT,SR}^{\alpha/2}} x_{PT}^{(t-1)} + (n^{(t)} - \beta n^{(t-1)}),$$

where $\beta = \frac{h_{PT,SR}^{(t)} |h_{PT,SR}^{(t-1)}|^2 P_{PT}/d_{PT,SR}^{\alpha}}{h_{PT,SR}^{(t-1)}(|h_{PT,SR}^{(t-1)}|^2 P_{PT}/d_{PT,SR}^{\alpha} + N_0)}$. The outage capacity satisfies

$$\mathbb{P}\left(\frac{|h_{ST,SR}^{(t)}|^2 \overline{P}_{ST}/d_{ST,SR}^{\alpha}}{N_0 + \frac{|h_{PT,SR}^{(t)}|^2 P_{PT} N_0 / d_{PT,SR}^{\alpha}}{|h_{PT,SR}^{(t-1)}|^2 P_{PT}/d_{PT,SR}^{\alpha} + N_0}} \le 2^{\mathbb{C}_{SR,f}^{\text{Busy}}} - 1 \right) = \epsilon_{SS}. \quad (12)$$

Let $F(\cdot)$ denote the c.d.f. of the above SINR, we obtain $\mathbb{C}_{SR,f}^{\text{Busy}} = \log\left(1 + F^{-1}(\epsilon_{SS})\right)$.

The efficiency for SU during busy period under access probability p equals to the product of the spectrum usage ratio of primary retransmission duration and the corresponding outage capacity, that is,

$$\eta_p^{\text{Busy}} = \frac{\mathbb{E}[T_p^{\text{Busy}}]}{\mathbb{E}[T_p^{\text{Busy}}] + \mathbb{E}[T_p^{\text{Idle}}]} \frac{Dp(1-\epsilon_{PS})}{\mathbb{E}[D_p^R] + \mathbb{E}[D_p^I]} \cdot [(1 - \mathbb{P}_{out}^{PT,SR}) \mathbb{C}_{SR,s}^{\text{Busy}} + \mathbb{P}_{out}^{PT,SR} \mathbb{C}_{SR,f}^{\text{Busy}}]. \quad (13)$$

And the overall efficiency under SU access probability p is $\eta_p = \eta_p^{\text{Idle}} + \eta_p^{\text{Busy}}$.

D. Optimal SU Access Probability

With interference mitigation, maximizing the overall efficiency with respect to the access probability under the interference constraint on PR can be formulated as the following optimization problem

$$\text{maximize } \eta_p, \qquad \text{subject to } 0 \le p \le 1.$$

The optimal SU access probability p^* with the maximum overall efficiency η_p^* can be found by differentiating the objective function with respect to p, and setting the result as zero. It results in a polynomial of degree 5 and can be solved numerically.

IV. Efficiency for Mixed Strategy without Interference Mitigation

In traditional access strategy, ST transmits packets concurrently during all primary transmission slots independently with probability p. The mean service time and the mean of busy period respectively become

$$\mathbb{E}[\tilde{S}_p] = \frac{D}{1 - (p\epsilon_{PS} + (1-p)\epsilon'_{PS})}; \quad \mathbb{E}[\tilde{T}_p^{\text{Busy}}] = \frac{\mathbb{E}[\tilde{S}_p]}{1 - \lambda \mathbb{E}[\tilde{S}_p]}. \quad (14)$$

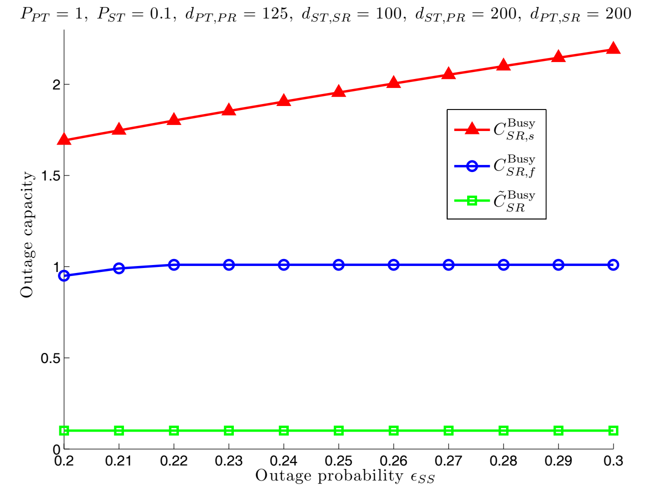

Fig. 4. Impacts of ϵ_{SS} on outage capacities, $\mathbb{C}_{SR,s}^{\text{Busy}}$, $\mathbb{C}_{SR,f}^{\text{Busy}}$, and $\tilde{\mathbb{C}}_{SR}^{\text{Busy}}$. The system parameters are set as $d_{PT,PR} = 125$, $d_{ST,SR} = 100$, $d_{ST,PR} = d_{PT,SR} = 200$, $P_{PT} = 1$, $P_{ST} = 0.1$, $\alpha = 4$, $\epsilon_{PS} = \epsilon_{SS} = 0.2$, $R_{PS} = \log 6$, $N_0 = 10^{-10}$, $\lambda = 1/70$, $D = 50$.

Given access probability p, the efficiency during idle period $\tilde{\eta}_p^{\text{Idle}}$ is $\frac{\mathbb{E}[T_p^{\text{Idle}}]}{\mathbb{E}[\tilde{T}_p^{\text{Busy}}] + \mathbb{E}[T_p^{\text{Idle}}]} \mathbb{C}_{SR}^{\text{Idle}}$, and the long run proportion of concurrent transmission within a busy period is p.

Without the help of interference mitigation, interference to SR can not be subtracted, and the signal received at SR is $y_{SR}^{(t)} = y_{PT,SR}^{(t)} + y_{ST,SR}^{(t)} + n^{(t)}$. The outage capacity $\tilde{\mathbb{C}}_{SR}^{\text{Busy}}$ satisfies

$$\mathbb{P}\left(\frac{|h_{ST,SR}^{(t)}|^2 \overline{P}_{ST}/d_{ST,SR}^{\alpha}}{N_0 + |h_{PT,SR}^{(t)}|^2 P_{PT}/d_{PT,SR}^{\alpha}} \le 2^{\tilde{\mathbb{C}}_{SR}^{\text{Busy}}} - 1 \right) = \epsilon_{SS}. \quad (15)$$

After simplifications, we obtain

$$\exp\left(-\frac{(2^{\tilde{\mathbb{C}}_{SR}^{\text{Busy}}} - 1) N_0}{\overline{P}_{ST}/d_{ST,SR}^{\alpha}} \right) \Big/ \left(1 + \frac{(2^{\tilde{\mathbb{C}}_{SR}^{\text{Busy}}} - 1) P_{PT}/d_{PT,SR}^{\alpha}}{\overline{P}_{ST}/d_{ST,SR}^{\alpha}} \right) = 1 - \epsilon_{SS}, \quad (16)$$

from which $\tilde{\mathbb{C}}_{SR}^{\text{Busy}}$ is found. Then the efficiency during busy period under access probability p is

$$\tilde{\eta}_p^{\text{Busy}} = \frac{\mathbb{E}[\tilde{T}_p^{\text{Busy}}]}{\mathbb{E}[\tilde{T}_p^{\text{Busy}}] + \mathbb{E}[T_p^{\text{Idle}}]} p \tilde{\mathbb{C}}_{SR}^{\text{Busy}}. \quad (17)$$

And the overall efficiency under SU access probability p is $\tilde{\eta}_p = \tilde{\eta}_p^{\text{Idle}} + \tilde{\eta}_p^{\text{Busy}}$.

V. Numerical Results

Fig. 4 delineates the outage capacity at SR during busy periods in the schemes with interference mitigation using successfully (resp. unsuccessfully) decoded primary signal, and without interference mitigation. The system parameters are set as $d_{PT,PR} = 125$, $d_{ST,SR} = 100$, $d_{ST,PR} = d_{PT,SR} = 200$, $P_{PT} = 1$, $P_{ST} = 0.1$, $\alpha = 4$, $\epsilon_{PS} = \epsilon_{SS} = 0.2$, $R_{PS} = \log 6$, $N_0 = 10^{-10}$, $\lambda = 1/70$, $D = 50$. The quality of prior information obtained dominates the performance of interference mitigation, which results in the intuitive phenomenon that $\mathbb{C}_{SR,s}^{\text{Busy}} > \mathbb{C}_{SR,f}^{\text{Busy}} \gg \tilde{\mathbb{C}}_{SR}^{\text{Busy}}$.

Fig. 5 investigates the impacts of p on efficiency in cases with and without interference mitigation and the cancellation scheme of [9] (denoted by $\breve{\eta}$) in high-interference regime.

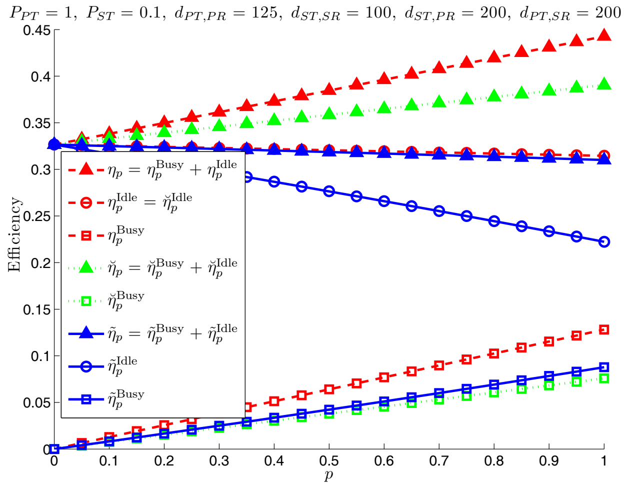

Fig. 5. Impacts of p on efficiencies, η_p, η_p^{Idle}, η_p^{Busy}, $\tilde{\eta}_p$, $\tilde{\eta}_p^{\text{Idle}}$, $\tilde{\eta}_p^{\text{Busy}}$, $\breve{\eta}_p$, $\breve{\eta}_p^{\text{Idle}}$, and $\breve{\eta}_p^{\text{Busy}}$ in high-interference regime. The system parameters are set as $d_{PT,PR}=125$, $d_{ST,SR}=100$, $d_{ST,PR}=d_{PT,SR}=200$, $P_{PT}=1$, $P_{ST}=0.1$, $\alpha=4$, $\epsilon_{PS}=\epsilon_{SS}=0.2$, $R_{PS}=\log 6$, $N_0=10^{-10}$, $\lambda=1/70$, and $D=50$. A larger access probability p incurs smaller fraction of idle period and thus η_p^{Idle} and $\tilde{\eta}_p^{\text{Idle}}$ becomes smaller. Interference mitigation outperforms the case of interference cancellation in [9] and the case without interference mitigation.

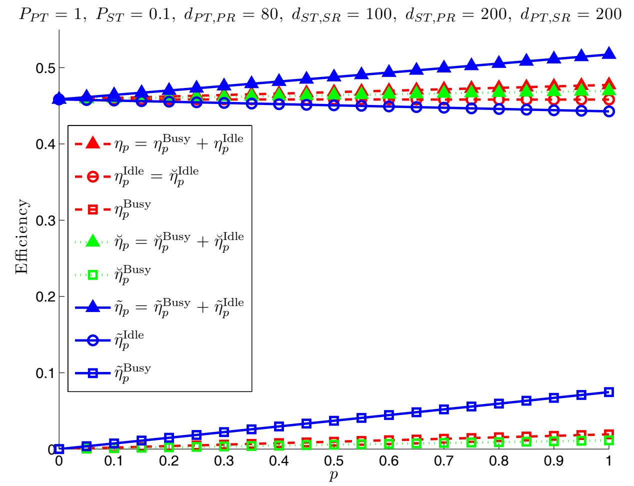

Fig. 6. Impacts of p on efficiencies, η_p, η_p^{Idle}, η_p^{Busy}, $\tilde{\eta}_p$, $\tilde{\eta}_p^{\text{Idle}}$, $\tilde{\eta}_p^{\text{Busy}}$, $\breve{\eta}_p$, $\breve{\eta}_p^{\text{Idle}}$, and $\breve{\eta}_p^{\text{Busy}}$ in low-interference regime. The system parameters are the same as Fig. 5 except $d_{PT,PR}=80$. In this case, primary retransmission seldom happens and it is wasteful to overhear instead of transmitting during primary initial transmissions. ST should switch to the scheme without interference mitigation for maximum performance.

When $p=0$, ST only exploits the spectrum holes, and $\eta_p^{\text{Idle}}=\tilde{\eta}_p^{\text{Idle}}$ indicates the efficiency of pure interweave paradigm. As p becomes larger, ST has more chance to transmit during periods of primary (re)transmissions and thus the interference to PR becomes heavier. As a result, primary retransmissions are triggered more often and fraction of idle period becomes less. Thus, η_p^{Idle} and $\tilde{\eta}_p^{\text{Idle}}$ are monotonic decreasing functions of p. The reason that $\tilde{\eta}_p^{\text{Idle}}$ drops faster than η_p^{Idle} is that secondary transmission coexisted with primary initial transmission in case without interference mitigation makes fraction of idle period even smaller.

We also observe that η_p^{Busy}, $\tilde{\eta}_p^{\text{Busy}}$, and $\breve{\eta}_p^{\text{Busy}}$ are monotonic increasing functions of p. By additionally exploiting unsuccessfully decoded signal, our interference mitigation scheme outperforms that in [9] and that without any interference mitigation. Since in high-interference regime, $\mathbb{C}_{SR}^{\text{Idle}}$ is much larger than $\tilde{\mathbb{C}}_{SR}^{\text{Busy}}$, as p increases, the degradation from decreasing fraction of idle period dominates $\tilde{\eta}_p$. Thus pure interweave paradigm (i.e., $p=0$) is suggested in the case of no interference mitigation. In the case of applying interference mitigation, as p increases, the improvement by η_p^{Busy} is much larger than that degraded by η_p^{Idle}, and the maximum of η_p is occurred about $p=1$.

Fig. 6 shows that as $d_{PT,PR}$ decreases, the primary link is experiencing good channel conditions, and ST can transmit simultaneously without causing harmful interference. As indicated by Fig. 6, we should switch back to the scheme without interference mitigation to utilize all busy periods instead of only the periods of retransmissions, which seldom occurs when the primary channel is good. Given the status of primary link, overall spectral efficiency with optimal access probability in schemes with and without interference mitigation can be computed, and SU simply chooses the scheme with better performance.

VI. Application

The proposed interference mitigation scheme can be applied into retransmission-based wireless networks to improve spectrum efficiency. As shown in Fig. 1, we demonstrate a feasible application in two-tier femtocell networks where coverage for indoor users is provided via femtocell base stations (femto-BSs) to complement the poor signal from macro-BS. In this case, macro-BS and macro-UE respectively act as PT and PR while femto-UE and cognitive femto-BS respectively play the roles of ST and SR. Different from previous SAW ARQ assumption, the (re)transmissions of primary and secondary packets here are scheduled by macro-BS and femto-BS, respectively. In particular, BS allocates available spectrum resource to requested UEs and notifies them the scheduled results for packet (re)reception or (re)transmission. During primary initial transmission, both macro-UE and femto-BS receive the packets (see (i)). With the aid of CR, femto-BS could actively acquire NAK feedback from macro-UE (see (ii)) and rescheduling results from macro-BS (see (iii)), and then locate the retransmission periods of a primary packet for concurrent transmission. Then femto-BS notifies femto-MS when to perform uploading (see (iv)). During the retransmission slot of the primary packet, femto-UE uploads packet to femto-BS (see (v)). At this moment, femto-BS could utilize the prior information to mitigate the interference from macro-BS.

VII. Conclusion

Cognitive radio enables coexisting secondary and primary transmissions only if interference from the secondary transmitter to the primary receiver is constrained. This work enhances the existing interference mitigation by exploiting extra unsuccessfully decoded primary packet in the initial transmission to improve the data rate of the secondary transmission that coexists with primary retransmission. By considering overall spectral efficiency as performance metric, an optimal secondary user access probability is derived, which is further utilized to decide whether or not we should overhear primary initial transmission to perform interference mitigation depending on the primary channel statistics. The scheme can be applied to realistic two-tier femtocell networks to improve spectrum reuse gain.

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