Relay Assisted Spectrum Sensing in Presence of IQ Imbalance in Multi-Channel System

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Abstract The increasing demand of wireless technology leads to a need for dynamic spectrum access that is positively accomplished by cognitive radio (CR) technology. For its acceptable efficiency it needs a robust detection scheme which detect the spectrum holes. This paper investigates a cooperative spectrum sensing method for a relay-based cognitive radio network. In general relay is a low cost device and is more prone to hardware impairment such as In-phase and Quadrature-phase Imbalance (IQI), which can considerably limit the capabilities of sensing spectrum holes. This work studies the energy detection (ED) based spectrum sensing in multi-channel receiver scenarios that are affected by IQI. The detection and false alarm probabilities considering Gaussian primary user signal models are derived. Our results are simulation based and verified with theoretical findings.

Keywords Cognitive radio · IQI · Energy detection

1 Introduction

The radio spectrum in wireless communications is an expensive and restricted resource. Licensed users termed as primary users (PU) are found to rarely use all the allocated frequency bands at all times. This results in the existence of spectrum holes (frequency bands) that are not occupied by PUs at a given time and location [1]. The presence of spectrum holes has inspired CR technology where unlicensed users termed as secondary users (SUs) can detect

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PU activities and access the spectrum if there are no PU activities. Accurate sensing of PU activities is, therefore, essential to avoid interference with PUs. Traditional methods can be employed to perform spectrum sensing, namely matched filter, energy detection, and cyclostationary feature detection, where the most common approach is the energy detection [2].

Relay-based cooperative wireless communication systems have drawn significant attention to improve the accuracy of spectrum sensing [3]. Relays are low-cost RF devices and are prone to hardware impairments such as non-linear power amplifier, phase noise, IQI, and dc offset [4,5] that cause system performance degradation. In particular, IQI refers to the mismatch of amplitude and phase between the in-phase and quadrature-phase branches of a transceiver. This results in imperfect image rejection, which results in significant degradation of performance. Out of several categories of relaying techniques, amplifying-and-forward (AF) relaying and decoding-and-forward relaying are the most popular [6]. Our research is based on AF relaying, as it deploys low-complexity relays that amplify the received signal and do not adopt any decoding technique.

Reference [5], evaluates the effects of IQI in single and multichannel energy detectors based spectrum sensing under direct-conversion receiver scenarios. A complex Gaussian PU signal model is considered where the single-channel receiver scenario is shown to be reasonably resilient to IQI while the wideband multi-channel receiver is sensitive to IQI-induced image channel crosstalk. In [12], the received signal of a singleinput-multiple-output (SIMO) cognitive radio with IQI in the transmitter is modeled. The authors have formulated the spectrum sensing problem as a composite hypothesis testing problem.

Reference [7] analyzes the channel state information-assisted dual-hop AF relay system in the presence of IQI. Under both cooperative and non-cooperative spectrum sensing scenarios, the effects of IQI in single and multichannel energy detectors operating in full-duplex mode is studied in [8]. Reference [9] considers transceiver hardware imperfections and investigates an improved energy detector (IED) statistics using $\alpha - \mu$ distribution over additive white Gaussian noise (AWGN) and Nakagami-m fading channel. Reference [10] suggests a cooperative spectrum sensing scheme based on selective-relay without the dedicated channel. Authors in [11] consider cooperative spectrum sensing with best relay selection where relays transmit over orthogonal Rayleigh fading channels.

To the best of the authors' knowledge, the detrimental effect of IQI on relay based spectrum sensing techniques using the energy detector in cooperative wireless communication systems have not been well studied in literature. Motivated by this, and the recent developments in relay based spectrum sensing techniques, we study the impact of the RF impairments on the AF relays spectrum sensing capabilities. In particular, the contribution of this paper can be summarised as follows:

- Signal models explaining the effects of IQI are presented for multi-channel energy detectors.

Fig. 1 Relay assisted spectrum sensing under IQI.

- The effect of IQI in the transmitter (Tx) and receiver (Rx) of relay that assists the SU in spectrum sensing is analysed while PU and SU are assumed to be perfect.
- An analytical framework to evaluate the false alarm and the detection probabilities of multi-channel EDs that are affected by IQI.
- The test statistics for energy detection is derived and is compared with a derived threshold to determine if the the channel is idle.

2 System Model

This work presents a signal model for the received signal at SU where, for purposes of this study, both additive noise and PU signal are considered to be circularly symmetric complex white Gaussian processes.

Our system model which is shown in Fig.1 is based on two time slots: T_1 and T_2 . In the T_1 slot, the relay and the SU receive the signal from the PU. In the T_2 slot, The SU receives an amplified signal from the relay. Finally, the SU combines both the data and detects the PU using an energy detector. In the T_1 slot, the signal received by the SU and the relay is respectively given by

$$y_{s1}(n) = \theta x_k(n) + w_k(n) \quad (1)$$

$$y_r(n) = K_1 \{\theta x_k(n) + w_k(n)\} + K_2 \{\zeta x_{-k}^*(n) + w_{-k}^*(n)\} \quad (2)$$

where $n = 1, 2, \dots, \frac{N}{2}$, $x_k(n) \sim CN(0, \sigma_x^2(k))$ is the PU signal, $x_{-k}(n) \sim CN(0, \sigma_x^2(-k))$ is the image PU signal, $w_k(n) = w_{-k}(n) \sim CN(0, \sigma_w^2(k))$ is the received noise. N is the number of samples. We assume $x_k(n)$, $x_{-k}(n)$ and $w_k(n)$ are circularly symmetric complex white Gaussian (CSCWG) processes. K_1 and K_2 are the IQI coefficients of the receiver and are given as $K_1 = \frac{1+\rho_R e^{-j\phi_R}}{2}$ and $K_2 = \frac{1-\rho_R e^{-j\phi_R}}{2}$ where ϕ_R (radians) and ρ_R represent the phase and amplitude imbalances of the receiver. The notation $(.)^*$ denote conjugation operation. Here $\theta \in \{0, 1\}$ and $\zeta \in \{0, 1\}$ describes the presence

and absence of primary and image signal respectively. In slot T_2 the received signal at SU through relay from PU is given as

$$y_{s_2}(n) = \theta x_k(n) + \beta \left\{ G_1 y_r \left(n - \frac{N}{2} \right) + G_2^* y_r^* \left(n - \frac{N}{2} \right) \right\} + w_k(n) \quad (3)$$

where $n = \frac{N}{2}, \dots, N$. G_1 and G_2 are the IQI coefficients of the transmitter of the relay which are given as $G_1 = \frac{1+\rho_T e^{-j\phi_T}}{2}$ and $G_2 = \frac{1-\rho_T e^{-j\phi_T}}{2}$ where ρ_T and ϕ_T (radians) denote the amplitude and phase imbalances of the transmitter. β is the amplification factor of relay which is given as

$$\beta = \sqrt{\frac{P}{\{|G_1|^2 + |G_2|^2\} \{ |K_1|^2 + (\sigma_x^2(k) + \sigma_w^2) + |K_2|^2 + (\sigma_x^2(-k) + \sigma_w^2) \}}} \quad (4)$$

where P is the power constraint of relay. Thus the total received signal at SU in slot T_2 is expressed as given below.

$$\begin{aligned} y_s(n) = & \theta \left\{ x_k(n) + \beta G_1 K_1 x_k \left(n - \frac{N}{2} \right) \right\} + \left\{ \beta G_1 K_1 w_k \left(n - \frac{N}{2} \right) + w_k(n) \right\} + \\ & \beta \left\{ \theta G_2^* K_1^* x_k^* \left(n - \frac{N}{2} \right) + \zeta G_1 K_2 x_{-k}^* \left(n - \frac{N}{2} \right) + \zeta G_2^* K_2^* x_{-k} \left(n - \frac{N}{2} \right) \right\} \\ & + \beta \left\{ G_1 K_2 w_{-k}^* \left(n - \frac{N}{2} \right) + G_2^* \left(K_1^* w_k^* \left(n - \frac{N}{2} \right) + K_2^* w_{-k} \left(n - \frac{N}{2} \right) \right) \right\} \end{aligned} \quad (5)$$

where $n = \frac{N}{2}, \dots, N$. First term in (5) represents the useful primary signal, second term represents noise, third term represents interference from image primary signal and the fourth term represents noise from image primary signal.

3 False Alarm and Detection Probabilities

This section presents the expressions to evaluate the false alarm and detection probabilities of hardware constrained EDs. The SU individually evaluates the energy of the received signals at T_1 and T_2 . If we assume the number of samples collected in each time slot is $\frac{N}{2}$, then the energy test statistic can be given as

$$Z = \underbrace{\sum_{n=1}^{\frac{N}{2}} |y_{s_1}(n)|^2}_{Z_{T_1}} + \underbrace{\sum_{n=\frac{N}{2}+1}^N |y_s(n)|^2}_{Z_{T_2}}. \quad (6)$$

The mean and variance of Z can be represented as $\mu_\Theta = E\{Z_{T_1}\} + E\{Z_{T_2}\}$ and $\sigma_\Theta^2 = Var\{Z_{T_1}\} + Var\{Z_{T_2}\} + 2Cov\{Z_{T_1}, Z_{T_2}\}$ where $E\{\cdot\}$ represents expected value, $Var\{\cdot\}$ represents the variance of random variable and $Cov\{\cdot, \cdot\}$ represents the covariance of two random variables and are as given below.

$$\begin{aligned} E\{Z_{T_1}\} &= \frac{N}{2}(\theta\sigma_x^2(k) + \sigma_w^2) \\ E\{Z_{T_2}\} &= \frac{N}{2}[\theta\sigma_x^2(k) + \sigma_w^2 + \beta^2(|G_1|^2 + |G_2|^2) \times \\ &\quad \{|K_1|^2(\theta\sigma_x^2(k) + \sigma_w^2) + |K_1|^2(\zeta\sigma_x^2(-k) + \sigma_w^2)\}] \\ Var\{Z_{T_1}\} &= \frac{E\{Z_{T_1}\}^2}{N/2}, \quad Var\{Z_{T_2}\} = \frac{E\{Z_{T_2}\}^2}{N/2} \\ Cov\{Z_{T_1}, Z_{T_2}\} &= \frac{N}{2}\beta^2\sigma_x^4(k) \end{aligned} \quad (7)$$

To determine the state of the channel (busy or idle), Z is compared to the threshold γ . If $Z > \gamma$, the channel is busy. Otherwise, it is idle.

Proposition. The cumulative distribution function (CDF) of energy test statistics conditional to $\Theta = \{\theta, \zeta\}$ when relay suffers from Tx and Rx IQI for sufficient large number of samples (Ns) can be well approximated by Gaussian distribution with CDF

$$F_G(\gamma|\Theta) = 1 - Q\left(\frac{\gamma - \mu_\Theta}{\sqrt{\sigma_\Theta^2}}\right), \quad (8)$$

where μ_Θ and σ_Θ^2 represent the mean and variance of energy test statistic respectively and are expressed as given below.

$$\begin{aligned} \mu_\Theta &= \frac{N}{2}[2\theta\sigma_x^2(k) + 2\sigma_w^2 + \beta^2(|G_1|^2 + |G_2|^2) \times \\ &\quad \{|K_1|^2(\theta\sigma_x^2(k) + \sigma_w^2) + |K_1|^2(\zeta\sigma_x^2(-k) + \sigma_w^2)\}] \\ \sigma_\Theta^2 &= \frac{N}{2}[\theta\sigma_x^2(k) + \sigma_w^2]^2 + \frac{N}{2}[\theta\sigma_x^2(k) + \beta^2(|G_1|^2 + |G_2|^2) \times \\ &\quad \{|K_1|^2(\theta\sigma_x^2(k) + \sigma_w^2) + |K_1|^2(\zeta\sigma_x^2(-k) + \sigma_w^2)\} + \sigma_w^2]^2 \\ &\quad + N\beta^2\sigma_x^4(k) \end{aligned} \quad (9)$$

The false alarm (P_{fa}) and detection probability (P_d) conditioned on $\Theta = \{\theta, \zeta\}$ is given by

$$P_{fa|\underbrace{\{\theta=0, \zeta\}}_{\Theta_0}} = Q\left(\frac{\gamma - \mu_{\Theta_0}}{\sqrt{\sigma_{\Theta_0}^2}}\right) \quad (11)$$

$$P_{d|\underbrace{\{\theta=1, \zeta\}}_{\Theta_1}} = Q\left(\frac{\gamma - \mu_{\Theta_1}}{\sqrt{\sigma_{\Theta_1}^2}}\right) \quad (12)$$

We can calculate the energy threshold using (11) for a target false alarm probability p_{fa}^{target} as

$$\gamma^{target} = \sqrt{\sigma_{\Theta_0}^2} Q^{-1} \left(P_{fa}^{target} \right) + \mu_{\Theta_0} \quad (13)$$

The image PU existence parameter ζ at image channel is deterministic if $\zeta = 1$ or 0 . We assume that ζ is Bernoulli distributed with success parameter c . Thus the false alarm and detection probability can be given as

$$\begin{aligned} P_{fa}^{iq} &= cP_{fa|\{\theta=0, \zeta=1\}} + (1-c)P_{fa|\{\theta=0, \zeta=0\}} \\ P_d^{iq} &= cP_{d|\{\theta=1, \zeta=1\}} + (1-c)P_{d|\{\theta=1, \zeta=0\}} \end{aligned} \quad (14)$$

4 Simulation results

For simulation we consider $\rho = \rho_R = \rho_T = 0.95$, $\phi = \phi_R = \phi_T = 6^0$, $P = 1$, $N_s = 8 \times 10^4$ and $p_{fa}^{target} = 0.1$. Simulations are averaged over 10^4 iteration throughout.

Fig. 2 Detection probability vs Threshold at different values of c and INR.

In Fig.2 and 3, the detection probability and the false alarm probability are shown for different threshold values, respectively. It is noticed that detection probability is an increasing function of interference-to-noise ratio (INR). Such an increase is due to the presence of a strong image signal. This change however comes at the expense of increased probability of false alarm. When INR is 20 dB and $c = 0.8$, detection probability increases by almost 25 percent and also increases the false alarm probability beyond P_{fa}^{target} . For instance, if the target false alarm probability is 0.1, then in the ideal case, the energy threshold should be set at 4.05 dB. When considering a non-ideal CR device with INR= 20 dB,

Fig. 3 False alarm probability vs Threshold at different values of c and INR.

Fig. 4 False alarm probability vs INR at different values of c .

this should be set at 4.33 dB, which does not seem to be a substantial increase. As illustrated in Fig.2, The detection probability is 1 for both of the mentioned threshold values because the detection probability starts to decrease from 1 at a threshold value of 4.6 dB.

The relation between false alarm probability with INR is further validated by the simulation result shown in Fig. 4. $P_{fa|\{\theta=0, \zeta=0\}} \approx P_{fa}^{target}$ and $P_{fa|\{\theta=0, \zeta=1\}}$ approaches 1 as INR approaches infinity [5]. Therefore, there exist a constant false alarm probability floor which is equivalent to $P_{fa}^{floor} = c + (1 - c)P_{fa}^{target}$ and the false alarm probability saturates after a high value of INR (Fig. 4).

Fig. 5 Detection probability vs primary signal power for different values of c .

Fig. 6 Detection probability vs primary signal power for $c=0.8$ and $INR=10$ dB.

Fig 5 shows the impact of primary signal strength on detection probability. This simulation is conducted for different values of success parameter c . The detection probability reaches value 1 when the primary signal power is greater than -10 dB. Within the legend, the corresponding false alarm probabilities are stated for different success parameters. It is observed that the image signal strength increases as c increases and the probability of detection increases as well. In Fig.6, the interference parameters are set to $INR = 10$ dB and $c = 0.8$. Similar to Fig.5, the detection probability reaches value 1 when the primary signal power is greater than -10 dB.

In Fig. 7, the detection probability for the direct path and the relay-based model is compared for various values of IQI parameters. The interference pa-

Fig. 7 Detection probability vs primary signal power for $c=0.8$ and $INR=10dB$.

Fig. 8 Detection probability vs primary signal power at $INR = 10dB$, $\rho = 0.97$ and $\phi = 6^\circ$.

rameters are set to $INR = 10$ dB and $c = 0.8$. Here we consider the number of samples received at SU in two different paths is the same. The corresponding false alarm probabilities are stated within the legend for different IQI parameters. It is noticed that the detection probability increases with an increase in both amplitude and phase imbalance levels and is higher for the relay-based model.

In Fig. 8, the detection probability for the direct path and the relay-based model is compared for various values of c . The interference parameters are set to $INR = 10dB$, $\rho = 0.97$ and $\phi = 6^\circ$. Here we consider the number of samples received at SU in two different paths is the same. The corresponding false alarm probabilities are stated within the legend for different values of c .

It is observed that for increasing values of c , detection probability increases and is higher for the relay-based model.

5 Conclusion

In this work, a relay-based spectrum sensing under IQI effects are being studied. The effect of IQI in the transmitter and receiver section of the relay is considered while PU and SU are assumed to be perfect. A wrong choice of the energy threshold is reported when the effect of IQI is neglected. For increasing levels of both phase and amplitude imbalance and value of success parameter c , detection probability increases at the cost of increase in the false alarm probability. However, for a target false alarm probability, a careful selection of the threshold mitigates the mentioned problem.

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