The PU and SU_1 are the two signal presents in the environment, each of these can be active or silent. Hence, on the behalf of these signal there are four cases should be clearly defined as: H_{00}, denotes that the primary transmitter is not transmitting the data and secondary transmitter not detecting the status of PT. Hence, ST gives the false alarm and does not transmit the data. H_{01}, denotes that the primary transmitter is active and secondary transmitter is silent. H_{10} , denotes that the secondary transmitter transmit data. Hence, in this case, the consumed energy is utilized to perform sensing and transmitting of data. H_{11}, denotes the primary transmitter and secondary transmitter both active at a same time due to miss-detection.

For SU_1, the suppression of received signal at Ant_{11}, is the residual self-interference (RSI). The RSI is modeled according to Gaussian distributed [22-24], and the variance is proportional to SU_1's transmit power. Hence, the received signal at Ant_1, presented as:

$$y_1 = \begin{cases} h_1 s_p + w + u_1, & H_{00} \\ w + u_1 & H_{10} \\ h_1 s_p + u_1 & H_{01} \\ u_1 & H_{11} \end{cases} \quad (1)$$

Where, s_p is the PU's signal, $h_1 \sim \mathcal{CN}(0,\ \sigma_1^2)$σ12 denotes the Rayleigh channel gain from the PU to Ant_1, $u_1 \sim \mathcal{CN}(0,\ \sigma_u^2)$, shows the complex-valued Gaussian noise and $w \sim \mathcal{CN}(0,\ \sigma_{11}^2 \sigma_s^2)$, shows the residual self-interference term with σ_s^2 and σ_{11}^2 presents the SU_1's signal power and the level of suppression of SI respectively.

For SUs other than *i=1*, other SU_i ($i \neq 1$), signal from SU_1 is deported as interference. Then we can get y_i as:

$$y_i = \begin{cases} h_i s_p + h_{1i} s_1 + u_i, & H_{00} \\ h_{1i} s_1 + u_i, & H_{10} \\ h_i s_p + u_i, & H_{01} \\ u_i & H_{11} \end{cases} \quad (2)$$

where s_1 Presents the SU_1's signal, $h_i \sim \mathcal{CN}(0,\ \sigma_i^2)$, denotes channel gain from PU to SU_1 and $h_{1i} \sim \mathcal{CN}(0,\ \sigma_{1i}^2)$ presents the channels gain from the PU to SU_i. Here, we consider SUs are use the energy detection technique for SS, in which, the test statistics M_i is used to calculate average power in one time slot.

$$M_i = \frac{1}{N_s} \sum_{n=1}^{N_s} |y_i(n)|^2, \quad (3)$$

In this model, SU uses energy detection to perform sensing of signal, where Ns is the total number of sample taken and M_i is the received signal energy and number of sample $Ns = fs*T$, with fs sampling rate. $y_i(n)$ is the n^{th} sample of the received signal. Local detection threshold would vary accordingly as received signal activity because the all SU varies according to SU_1's activity

Let X = 0/1 presents the state of SU_1 as silent/active. Let us consider ϵ_{iX} denotes decision threshold at SU_i then local false alarm probabilities and probability of miss detection given by:

$$P_{im}^X(\epsilon_{iX}) = P_r(M_i < \epsilon_{iX} | \mathcal{H}_{X1}) \quad (4)$$
$$P_{if}^X(\epsilon_{iX}) = P_r(M_i < \epsilon_{iX} | \mathcal{H}_{X0}) \quad (5)$$

B. Data Reporting and decision-making process at FC

Here, let us consider that the SUs sends their own decision to the FC. By considering that there is no error present in data reporting process. The 'OR' fusion rule is use to make final decision. In 'OR' fusion rule, the FC decides that PU is present, if at least one SU reports, that the PU is present. On the basis of this decision, the miss detection probability and false alarm probability is obtained as

$$P_m^X = \prod_{i=1}^{k} P_{im}^X,$$
$$P_f^X = 1 - \prod_{i=1}^{k} 1 - P_{if}^X, \quad (6)$$

Analysis of CSS in the FD-CRN

This section mainly focuses on sensing performance and throughput in cooperative spectrum sensing (CSS) using LAT protocol.

A. Probabilities of Miss Detection and Probabilities False Alarm

In (3), the y (n) is independent identically distributed (iid) in any certain period of time and Ns are large enough. The probability density function (PDF) of M_i can be approximated by a Gaussian distribution [18]. As presented in [19], the probability density function (PDF) of the test statistics at any SU_i, is according to (1) and (2). Here we consider that the SU_1's and PU's signals is modulated as phase shift keying (PSK) with all the independent channels. σ_P^2 denotes the PU's signal power. The interference term $h_{1i} s_1$ is modeled as random complex gaussian distributed. We can write the PDF of $Mi (i \neq 1)$ and Mi, in similar forms. Statistical properties and their details description are presented in Table I. Here signal to noise ratio (SNR) from the PU to SUi and INR due to SU_1 is denoted as $\gamma_i = \frac{\sigma_i^2 \sigma_P^2}{\sigma_u^2}$ and $\gamma_{1i} = \frac{\sigma_{1i}^2 \sigma_s^2}{\sigma_u^2}$, respectively.

Table 1: Hypothesis Testing

Hypothesis	PU	SU1	Mean E[M_i]	Var[M_i]
H00	Idle	Silent	σ_u^2	$\frac{\sigma_u^4}{N_s}$
H01	Busy	Silent	$(1+\gamma_i)\sigma_u^2$	$\frac{(1+\gamma_i)^2 \sigma_u^4}{N_s}$
H10	Idle	Active	$(1+\gamma_{1i})\sigma_u^2$	$\frac{(1+\gamma_{1i})^2 \sigma_u^4}{N_s}$
H11	Busy	Active	$(1+\gamma_i + \gamma_{1i})\sigma_u^2$	$\frac{(1+\gamma_i+\gamma_{1i})^2}{N_s}$

Using Table I, the local miss detection probabilities and the probability of false alarm at SU_i can be derived from (4) and (5) as:

$$P_{im}^0(\epsilon_{i0}) = 1 - Q\left(\left(\frac{\epsilon_{i0}}{(1+\gamma_i)\sigma_u^2} - 1\right)\sqrt{N_s}\right),$$
$$P_{if}^0(\epsilon_{i0}) = Q\left(\left(\frac{\epsilon_{i0}}{\sigma_u^2} - 1\right)\sqrt{N_s}\right),$$
$$P_{im}^1(\epsilon_{i1}) = 1 - Q\left(\left(\frac{\epsilon_{i1}}{(1+\gamma_i+\gamma_{1i})\sigma_u^2} - 1\right)\sqrt{N_s}\right), \quad (7)$$
$$P_{im}^1(\epsilon_{i1}) = Q\left(\left(\frac{\epsilon_{i1}}{(1+\gamma_{1i})\sigma_u^2} - 1\right)\sqrt{N_s}\right),$$

Where, Q(.) is complementary cumulative distribution function of standard Gaussian function.

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt.$$

The miss detection probability and false alarm probability can be presented as [19, 21], respectively,

$$P_m = \frac{P_m^0}{1+P_m^0-P_m^1}$$
$$P_f = \frac{P_f^1}{1+P_f^0-P_f^1} \quad (8)$$

We can obtain miss detection probability and probability false alarm for the system by substituting the equation (7) to 6), and then to (8). Let us assume the common case, where the maximum miss detection probability of the system is stable. Constraints of P_m^0, P_m^1 and P_{im}^X of are presented in (8), and (6) respectively. For convenience, we fix all the probability of miss detection P_{im}^X to be the same without further optimization.

$$P_{im}^X = (P_m)^{1/k}, \ \forall_m = 1,2,\dots,k, \ X = 0,1 \quad (9)$$

The respective thresholds ϵ_{iX} can be obtained as:

$$\epsilon_{i0} = \left(\frac{Q^{-1}\left(1-P_m^{1/k}\right)}{\sqrt{N_s}}+1\right)(1+\gamma_i)\sigma_u^2$$

$$\epsilon_{i1} = \left(\frac{Q^{-1}\left(1-P_m^{1/k}\right)}{\sqrt{N_s}}+1\right)(1+\gamma_i+\gamma_{1i})\sigma_u^2$$

From the above equation, we can observe the increase in thresholds if RSI included in the system. Then the local false alarm probabilities will be:

$$P_{if}^0(P_m) = Q\left(Q^{-1}\left(1-P_m^{1/k}\right)(1+\gamma_i)+\gamma_i\sqrt{N_s}\right),$$
$$P_{if}^1(P_m) = Q\left(Q^{-1}\left(1-P_m^{1/k}\right)\left(1+\frac{\gamma_i}{1+\gamma_{1_i}}\right)+\frac{\gamma_i\sqrt{N_s}}{1+\gamma_{1i}}\right) \quad (10)$$

Putting (10) to (6) and (8), the false alarm probability of the system can be formulated.

Now we can compare the performance of CSS-LAT protocol and the (non-CSS) performance on the basis of equation obtained from (7) and (8). In CSS, as presented in (9), the local miss detection probabilities P_{im}^X at higher level are permitted at every cooperating SU and the respective local false alarm probabilities drastically reduced. Let us consider, if there are 10 cooperative SUs and miss detection probability of system is set to 0.01. Using (9), P_{im}^X > 63%, which is comparatively large, and P_{if}^X which is reduced at their minimum level. Prosecute, interference among two SUs may be very small level and the result of sensing may be much authentic compared to transmitting SU result. Hence, the performance of CSS is far better than non-CSS CRN.

B. Secondary Throughput

SU_1 starts transmitting the data to the secondary receiver (SR), once white spaces are detected. The secondary throughput can be calculated as:

$$C = (1-P_f)log_2\left(1+\frac{\sigma_s^2\sigma_t^2}{\sigma_u^2}\right) = (1-P_f)log_2(1+\gamma_t)$$
$$= \frac{1-P_f^0}{1-P_f{}^0+P_f^1} \cdot log_2(1+\gamma_t) \quad (11)$$

Where, the Rayleigh channel variance from SU1 to the receiver is denoted as σ_t^2, and the SNR in transmission is denoted as $\gamma_t = \frac{\sigma_s^2\sigma_t^2}{\sigma_u^2}$, P_f^0 and P_f^1 are probability of false alarm.

From the (11), it is clear that two factors are related to transmit power σ_s^2. As the σ_s^2 increases, the interference to noise ratio (INRs), (γi) also increases and P_f^1 increases accordingly. Besides that, the obtainable sum rate $log_2(1+\gamma_t)$ increases. Hence, there is tradeoff between throughput and transmit power is obtained.

Conclusion

Full duplex CRNs can improve the throughput by simultaneous sensing and transmission of data. Due to advancement in self-interference suppression (SIS) technology, FD-CRN evolves as the better promising solution for licensed band exploitation. In this article, we have done extensive comparison of half duplex (HD) and full duplex (FD) communication and also covered the analysis of cooperative spectrum and throughput calculations. After analyzing these parameters, we concluded that the in FD-CRN improves the detection.

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