Power and Contention Control Scheme: As a Good Candidate for Interference Modeling in Cognitive Radio Network

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***Abstract*—Due to the ever growing need for spectrum, the cognitive radio (CR) has been proposed to improve the radio spectrum utilization. In this scenario, the secondary users (SU) are permitted to share spectrum with the licensed primary users (SU) with a strict condition that they do not cause harmful interference to the cognitive network. In this work, we have proposed an interference model for cognitive radio network that utilizes power or contention control interference management schemes. We derived the probability density function (PDF) with the power control scheme, where the power of transmission of the CR transmitter is guided by the power control law and also with contention control scheme that has a fixed transmission power for all CR transmitter controlled by a contention control protocol. This protocol makes a decision on which CR transmitter can transmit at any point in time. In this work, we have shown that power and contention control schemes are good candidates for interference modeling in cognitive radio system. The impact of the unknown location of the primary receiver on the resulting interference generated by the CR transmitters was investigated and the results shows that the challenges of the hidden primary receivers lead to higher CR-primary interference in respect to higher mean and variance. Finally, the presented results show power control and the contention control scheme are good candidates in reducing the interference generated by the cognitive radio network.**

Keyword—Aggregate interference; cognitive radio; interference management; interference modeling

I. Introduction

In wireless communication, the availability of spectrum has become scarce due to the rapid growth of wireless communication devices. However, the measurement of spectrum shows that spectrum resources are underutilized in terms of time and space [1]. Due to the growing desire for frequency bandwidth, the conventional method for spectrum assignment becomes unsuitable for the course. In other to make use of the underutilized spectrum resource, the cognitive radio (CR) technology was proposed [2-5] because it allows communication between unlicensed users which is also known as secondary user (SU) and the licensed users otherwise known as the primary users (PU) without causing any harmful interference. A CR user can exist side by side with the licensed PU on the basis of non-interference which is also known as the Interweave CR network or the interference – tolerant basis also known as the overlay CR networks [6-8].

On a non-interference basis, the assigned spectrums to the licensed PU are exploited by the SU for transmission without compromising the PU network [9]. In the interference tolerant basis, the CR user splits spectrum allocated to the licensed spectrum with a condition that the CR user would not cause interference which would be harmful to the PU network. If the interference that emanates from CR network to the PU network becomes assertive and vicious, it would become necessary for the CR network to avoid it. Therefore with these features, modelling and analyzing the interference created by the CR networks it becomes necessary to show the degeneration of the primary network and how the CR network can be employed. The interference modeling of CR network in literature is classified into three main groups which include; spatial, frequency-domain and accumulated interference [10-12]. In the spatial distribution of white spaces white is dependent on the conduct of the primary transmitter such as the geographical position and transmit power. The area fraction of white spaces are studied in detailed in [13-15] it was found out in the study that their enormous amount of white spaces in existence. However, it becomes paramount for the CR to apply robust technologies which suits the power and contention control schemes.

The frequency-domain are modeled using a two-dimensional poison point process, details on the frequency domain are emphasized in [16-17]. Another category of the interference modeling is the accumulated interference, the CR user have to give a guarantee that they would not cause harmful interference to the PU. However, if there is no assurance on the interference, it becomes a challenge to persuade the PU to give access to the CR users to utilize its spectrum. However giving assurance on the intensity of the interference the PU can endure is a challenging task in wireless communication [18-20]. Although, a CR user satisfies the constraint Set could still cause excessive interference to the PU when the CR transmits concurrently with another CR which satisfies the CR sensing constraints.

In this work, we studied power and contention control interference management scheme as a good candidate for interference modeling in cognitive radio. We compared results obtained the two management schemes in situations where there is a perfect knowledge of the location of the primary receiver and an unknown location of primary receiver. We proposed a power and contention control interference management mechanism as a successful method in reducing the CR-Primary interference. The rest of this paper is organized as follows; Section II. Related work. Section III. System Model. Section IV. Interference modeling. Section V. Results and discussion and Section VI. Conclusion

II. Related Work

Although there are significant number of researches has been done in interference modeling but only a few work cited in literature with interference modeling employing all interference management schemes. In [21], a host of heterogeneous CR transmitters around the primary receiver was obtained. This host of SU must give guaranteed services to surrounding PUs. The outage probability was used to evaluate the interference caused by the CR network. This was obtained for the underlay and overlay spectrum sharing scenarios [20]. The interference channel was assumed to be a pathloss only channel in [22-23]. The interference channel is assumed to be a pathloss only channel. However, this work was extended by Menon *et. al* [22] this was done by introducing the shadowing and fading. In all the reviewed work in literature, the CR transmitter is assumed to perform its transmission at fixed power without considering power control scheme. However, it is assumed All CR users in the network communicate simultaneously. In this paper we extended the interference modelling by using the power and contention control interference management mechanism. We derived the probability density function (PDF) numerically. In this paper we model the total interference for the CR transmitters in power and contention control interference management scheme. We considered two scenario of the location of the primary receiver. The first scenario we considered when the primary receiver is known and the second scenario when the primary receiver is unknown.

III. System Model

In this work we have considered a system where the location of the primary receiver is unknown to the CR network. From the figure 1, it is shown that the CR transmitters are distributed around the outer circle. Let R represent the radius of the inner circle and L represent the radius of the outer circle. From figure 1, we have assumed that θ is the angle of intersection between d and d_{pr}.The distance between from the primary transmitters to CR transmitter is denoted by d. While d_{pr} represents the distance between primary transmitters pairs. Therefore the distance between CR-transmitter to the primary receiver d_{cp} is denoted as;

$$d_{cp}(d,\theta) = [d^2 + d_{pr} - 2rd_{pr}\cos(\theta)]^{\frac{1}{2}}, d \in [R,L]; \theta[0,2\pi] \quad (1)$$

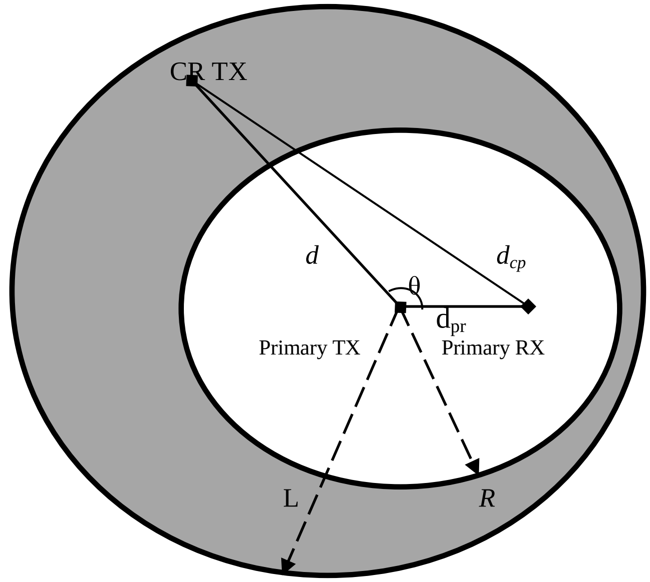

Fig. 1. System model for CR network coexisting with primary network

The CR transmitter is assumed to be distributed following the Poisson point process. Let d be distributed as shown in equation (2); [24].

$$f_d(d) = \begin{cases} 2_x/(L^2 - R^2), & R \le x \le L \\ 0, & otherwise \end{cases} \quad (2)$$

A. Power Control Scheme

The power of transmission of the CR transmitter is guided by the power control law proposed in [10]. The power control law is represented as;

$$P_{pcr}(r_{ccn}) = \begin{cases} \left(\frac{r_{ccn}}{r_{pcr}}\right)^{\delta} P_{max,} & 0 < r_{ccn}, \le r_{pcr} \\ P_{max,} & 0 < r_{ccn} > r_{pcr} \end{cases} \quad (3)$$

Let r_{ccn} stands for nearest distance from the n^{th} active CR transmitter to its closest transmitter [20]. The power control exponent is denoted with δ while P_{max} represents the maximum transmitting power for CR transmitter. The power control range is represented by r_{pcr} this regulates the minimum r_{ccn} which gives rise to the maximum transmits power of CR transmitter. The PDF of r_{ccn} is represented as;

$$f_{cc}(r_{ccn}) = 2\pi\lambda r_{ccn} e^{-\lambda\pi r_{rccn}^2} \quad (4)$$

In this work we have assumed that the value of δ and γ which stands for power control exponent and pathloss exponent respectively to be equal, with the boundaries of the power control range the interference is equal to the constant P_{max}or r_{pcr} This is due to the fact that when the power control range is exceeded, the resulting interference is becomes smaller than the constant. Meaning that at any CR transmitter, the interference which emanates from the closest surrounding CR transmitter becomes restricted and independent of the closest neighbor's distance within the neighborhood of the power control range.

B. Contention Control Scheme

In contrast to the previously introduced power control scheme, the contention control scheme has fixed transmission power p at every CR transmitter. However, the CR transmission is controlled by a contention protocol to make a decision on which transmitter can transmit at any point in time [23]. The multiple access protocol in the IEEE 802.11 networks is assumed in this work which is the carrier sense multiple access with collision avoidance (CSMA/CA). All the CR transmitters perform sensing in the medium before transmission, if the CR transmitter identifies a transmission from any CR transmitters around its contention region, it delays its transmission else it starts its transmission. Due to the contention control all CR transmitters are spaced from one and other with a contention distance d_{min} across two CR transmitters. The distribution of all the transmitting CR transmitters can be modelled in a Matern Hard-core (MH) point process [30]. However, approximation for MH point process usually disregards the dependence amongst the CR transmitters and treats an MH point's process as a result of independent thinning process. Therefore all CR transmitters follow the original Poisson point process, with intensity λ however the n^{th} CR transmitter has a probability q_{mh} to transmit at a power level p. The characteristics function of accumulated interference of contention control is given as;

$$\varphi_I(\omega) = exp\left(\lambda\pi q_{mh}\int_H f_h(h)T(\omega ph)dh\right) \tag{5}$$

The PDF of the interference is derived from (5) and (12), however, this is further reduced in similar way like (12) with the following equation;

$$k = q_{mh}\int_H f_h(h)\sqrt{ph}\,dh \tag{6}$$

The detailed derivation of (5) is given in Appendix A.

IV. Interference Modeling

In this section, we have modeled the aggregate interference from all CR transmitters by implementing the two interference management schemes which were introduced in section II. We employed the method used in [27] which was later developed by *Hong et. al* in [27], to derive the PDF. This was modeled considering a scenario where the Primary receiver location is unknown to the CR network.

A. Power Control Scheme in when primary receiver location is unknown

From the system model, we have adopted the characteristics based function used in [25-26] and obtained the characteristics function $\varphi_I(\omega)$ of the total interference I at the primary receiver from all cooperating CR transmitters.

$$\varphi_I(\omega) = exp\left(\lambda\pi\int_H f_h(h)\int_p f_p(p)\mathrm{T}(\omega ph)dp\,dh\right) \tag{7}$$

Where $f_p(.)$The PDF of the transmit power of $P_{pcr}(r_{ccn})$ of a CR transmitter shown in (3), the we can rewrite the equation as follows;

$$T(\omega ph) = R^2\left(1 - e^{i\omega g(R)ph}\right) + i\omega ph\int_0^{g(R)}[g^{-1}(t)]^2\, e^{i\omega tph}dt \tag{8}$$

From equation (8), $g^{-1}(.)$ symbolized the inverse function of the $g(.)$in the pathloss function in (9)

$$g(r_n) = r_n^{-\gamma} \tag{9}$$

In (5), p is a function of r_{ccn} as expressed in (3). Therefore, the assumption of $T(\omega ph)$ in respect to p is equal to the prediction of $T\left(\omega P_{pcr}(r_{ccn})h\right)$ over r_{ccn}. However, using the PDF which was given in (4) then we can rewrite equation (5) as;

$$\varphi_I(\omega) = \exp\left(\lambda\pi\int_H f_h(h)\int_{r_{ccn}} f_{ccn}(r)T(\omega P_{pcr}(r_{ccn})h)\right)drdh \tag{10}$$

However, (10) can still be rewritten as shown in (11), a detailed derivation of (10) is given in appendix B.

$$\varphi_I(\omega) = exp\Bigg\{\lambda\pi\int_H f_h(h)\int_0^{r_{pcr}} f_{ccn}(r)\Bigg[R^2\left(1{-}e^{\frac{i\omega r^{\delta}P_{maxg(R)h}}{r_{pcr}\delta}}\right) + \frac{i\omega r^{\delta}P_{max}h}{r_{pcr}\delta}\int_0^{g(R)} t^{\frac{-2}{\gamma}}\, e^{\frac{1\omega tr^{\delta}P_{maxg(R)h}}{r_{pcr}\delta}}\, dt\Bigg]drdh + \lambda\pi\int_H f_h(h)\int_{r_{pcr}}^{\infty} f_{ccn}(r)\Big[R^2\left(1 - e^{i\omega g(R)P_{max}h}\right) + i\omega P_{max}h\int_0^{g(R)} t^{-\frac{2}{\gamma}}\, e^{i\omega tP_{max}h}\, dt\Big]drdh\Bigg\} \tag{11}$$

The PDF of the interference is obtained by calculating the inverse Fourier transform on (12);

$$f_I(y) = \frac{\pi}{2\pi}\int_{-\infty}^{+\infty}\varphi_I(\omega)e^{-2\pi i\omega y}\, d\omega \tag{12}$$

The equations (11) and (12), acts as generic statements for the characteristics function and PDF respectively of the interference when implementing the power control scheme. We choose to make use of the value of the pathloss exponent and the power control exponent γ and δ respectively to be equal capping it at value 4. This is because the power control is designed that the interference caused by the n^{th} active transmitter within a power control range is equal to a constant. When the constant is above the power control range the interference becomes smaller. The radius of the interference region R was set as 0. Then the PDF $f_I(y)$ can further be reduced following the steps used by Sousa et. al. in [26] and obtained the following equation.

$$f_I(y) = \frac{\pi}{2}\, K\lambda y^{-3/2}\, exp\left(\frac{-\pi^3\lambda^2k^2}{4y}\right) \tag{13}$$

Let K be the following;

$$K = \sqrt{P_{max}}\int_H f_h(h)\sqrt{h}\, dh\left[\int_0^{r_{pcr}} 2\pi\lambda_e^{-\lambda\pi r^2}\left(\frac{r}{r_{pcr}}\right)^{\frac{\delta}{2}}dr + e^{-\lambda\pi {r_{pcr}}^2}\right] \tag{14}$$

Further derivation of (14) is given in Appendix C

Considering the system model which is depicted in figure 1, and the proposed power control scheme which has been proposed in the earlier section of this work, we can then derive the total interference as:-

$$\varphi_I(\omega) = \lim_{i\to\infty} exp\Bigg\{\lambda\int_H f_h(h)\int_0^{r_{pcr}} f_{ccn}(x)\int_0^{2\pi}\int_R^L e^{i\omega\left(\frac{r}{r_{pcr}}\right)^{\delta}P_{max}(x)g(d_{cp}(d,\theta))^h} d - d\, dr\, d\theta\, dx\, dh + \lambda\int_H f_h(h)\int_{r_{pcr}}^{\infty} f_{ccn}(x)\int_0^{2\pi}\int_R^L e^{i\omega P_{max}(x)g(d_{cp}(d,\theta))^h}d - d\, dr\, d\theta\, dx\, dh\Bigg\}. \tag{15}$$

Detailed derivations of (15) see Appendix D

Interference modelling is known to be computationally complex. It is a known fact that the closed form expression cannot be used for characteristics based functions or Inverse Fourier transforms. However, it is advantageous to model the interference with less complexity. To solve the issue of the complexity of interference modeling, it would be desirable to make an estimation of the PDF of the interference. Therefore in this work we would fit the total interference under the power control and contention control scheme to be log-normal distribution. In [20], it was shown that the sum of interference from evenly distributed interferers in a circular area is asymptotically log-normal. This implies that the total interference why implementing both the power and contention control scheme can be estimated as a log-normal distribution. Also the summation of the randomly weighted log-normal distribution variable can be modeled as a normal log-normal distribution which gives assurance that the total interference is log-normally distributed even when the shadow fading effect is considered in (2) [22]. We have used the cumulant-matching method to approximate the mean and variance of the log-normal distribution function. The randomly distributed variable x was approximated using the first two order cumulant in [10]. The PDF of the log-normal variable x is shown in equation (16)

$$P_n(x) = \frac{1}{\sqrt{2\pi\sigma x}} exp\left\{\left(\frac{-\ln(x)-\mu)^2}{2\sigma^2}\right)\right\} \tag{16}$$

The mean μ and variance σ^2 can be calculated by using its first two cumulant K_1 and K_2 as expressed below [32].

$$\mu = \ln\frac{k_1}{\sqrt{\frac{k_2}{k_1^2}+1}} \tag{17}$$

$$\sigma^2 = \ln\left(\frac{k_2}{k_1^2}+1\right) \tag{18}$$

Taking the interference distribution into consideration, the n^{th}cumulant k_n of the total interference I, can then be derived from its characteristics function $\varphi_I(\omega)$ using the following equation.

$$k_n = \frac{1}{i^n}\left[\frac{\partial^n \ln\varphi_I(\omega)}{\partial\omega^n}\right]_{\omega=0} \tag{19}$$

Using equation (19) and the characteristics function in (11) the cumulant for the total interference when the power control scheme is implemented can then be obtained as:

$$k_n = \frac{2\lambda\pi P_{max}^n e^{n\mu+\frac{n^2\sigma^2}{2}}}{(n\Upsilon-2)R^{n\Upsilon-2}}\left[\frac{n\delta(n\delta-2)\ldots2}{{r_{pcr}}^{n\delta}(2\pi\lambda)^{\frac{n\delta}{2}}}\left(1-e^{-\lambda\pi_{rpcr^2}}\right)-\sum_{i=1}^{\frac{n\delta}{2}-1}\frac{n\delta(n\delta-2)\ldots.(n\delta-2i+2)}{(2\pi\lambda {r_{pcr}}^2)^i}{r_{pcr}}^{n\delta-2i}e^{-\lambda\pi {r_{pcr}}^2}\right] \tag{20}$$

This approximation method is applicable to both the pathloss only and shadow fading channel.

When the log-normal approximation is applied to equation (15), we can then derive the k^{th} cumulant of the interference as follows;

$$k_n = \lim_{i\to\infty}\lambda\left\{\int_H f_h(h)\int_0^{r_{pcr}} f_{ccn}(x)\int_0^{2\pi}\int_R^L \frac{d^\delta P_{max}(x)g(d_{cp}(d,\theta)h)^n}{{r_{pcr}}^{n\delta}}\,ddr\,d\theta\,dx\,dh + \int_H f_h(h)\int_{r_{pcr}}^{\infty} f_{ccn}(x)\int_0^{2\pi}\int_R^L [P_{max}(x)g(\,d_{cp}(d,\theta)h]^n ddr\,d\theta\,dx\,dh\right\} \tag{21}$$

In the subsequent section in this paper, we show experimental results which show the effect of unknown primary receiver location on interference in comparison with a known primary receiver location. The experiment also shows that the challenges of the hidden primary user location also increase the interference in respect to higher mean and variance. It is also seen that the log-normal estimation satisfies both the derived CDF and Monte Carlo's simulations. However, we can also see the effect of some CR implementation parameters on the total interference under the power control scheme.

B. Contention Control Scheme in when primary receiver location is unknown

In modeling interference in the contention control scheme, can derive the n^{th} cumulant following the same process which was used in (21) and utilizing the characteristics function in (5) then the cumulant k_n of the total interference becomes;

$$k_n = \frac{\lambda\pi q_{mh}}{i^n}\int_H f_h(h)\left[-R^2(ipg(R)h)^n + n(iph)^n\int_0^{g(R)} t^{n-1-\frac{2}{\gamma}}dt\right]dh = \lambda\pi q_{mh}\left(\frac{n}{n-\frac{2}{\gamma}}g^{n-\frac{2}{\gamma}}(R) - R^2 g^n(R)\right)p^n\int_H f_h(h)h^n dh = \frac{2p^n\left(1-e^{-\lambda\pi d_{min}^2}\right)e^{n\mu+\frac{\sigma^2}{2}}}{(n\gamma-2)d_{min}^2 R^{n\gamma-2}} \tag{22}$$

Considering the system which is represented in figure 1, and the proposed contention control earlier in this work, then the characteristics function of the entire interference can then be denoted as;

$$\varphi_I(\omega) = \lim_{i\to\infty} exp\{q_{mh}\lambda\pi D_L(E(e^{i\omega pg(V)h}) - 1)\}$$
$$= \lim_{i\to\infty} exp\left\{q_{mh}\lambda\pi D_L\left(\int_H f_h(h)\int_0^{2\pi}\frac{1}{2\pi}\int_R^L exp[iwpg(d_{cp}(d,\theta)h]\frac{2d}{DL}dd\,d\theta\,dh - 1\right)\right\}$$
$$= \lim_{l\to\infty} exp\left\{q_{mh}\lambda\int_H f_h(h)\int_0^{2\pi}\int_0^{2\pi}\int_R^L [pg\left(d_{cp}(d,\theta)\right)h]^n\, r - dr\, d\theta\, dh\right\} \quad (23)$$

When we implement the log-normal estimation as used in the power control scheme, we can then derive the k^{th} cumulant of the interference as follows;

$$k_n = \lim_{i\to\infty}\lambda\left\{\int_H f_h(h)\int_0^{r_{pcr}} f_{ccn}(x)\int_0^{2\pi}\int_R^L \frac{(d^\delta P_{max}(x)g\left(d_{cp}(d,\theta)\right)h)^n}{r_{pcr}{}^{n\delta}}\, rdr\, d\theta\, dxdh\right.$$
$$\left. + \int_H f_h(h)\int_{r_{pcr}}^{\infty} f_{ccn}(x)\int_0^{2\pi}[P_{max}(x)g(d_{cp}\,(d,\theta))h]^n\, rdr\, d\theta\, dx\, dh\right\} \quad (24)$$

V. Results and Discussions

In this section we have shown experimental results of the total interference power from all CR transmitters utilizing the power control and contention control schemes. In this work, we have investigated how the unknown location of the primary receiver affects the interference in both the power control and contention schemes. Also from this work it has be proven that the proposed schemes is an efficient way of increasing CR-primary interference. Furthermore we have also investigated the effects of shadow fading on the aggregate interference on a CR networks which implements both interference management schemes.

In figure 2, we have shown the effect of unknown location of the primary user location affects interference. The figure shows the log-normal approximation compatibility with the derived CDF and Monte Carlo's simulation. The parameters used are defined as follows; R is the radius of the interference region, the density of the stationary Poisson point process is denoted as λ**.** The pathloss exponent is represented as γ, the power control range is denoted as r_{pcr}, the power control exponent is represented as δ the maximum power and distance between transmitters are represented by P_{max} and d_p respectively.

The following values for the parameters where used under the control scheme in figure 2; R= 200m, λ=3 user/10^4m^2, γ=4, r_{pcr}=20m, δ=4, P_{max}=1W, d_p=0.5R.

In figure 2, we have analyzed the impact of the unknown location of the primary user on the resulting interference where we assumed a pathloss only channel. It has been shown from the figure that the hidden primary user problem increases the interference in terms of mean and variance when compared to the scenario when there is perfect knowledge of the location of the primary user. Also the shows that the log- normal approximation is appropriate for both derived CDF and Monte Carlo's Simulation.

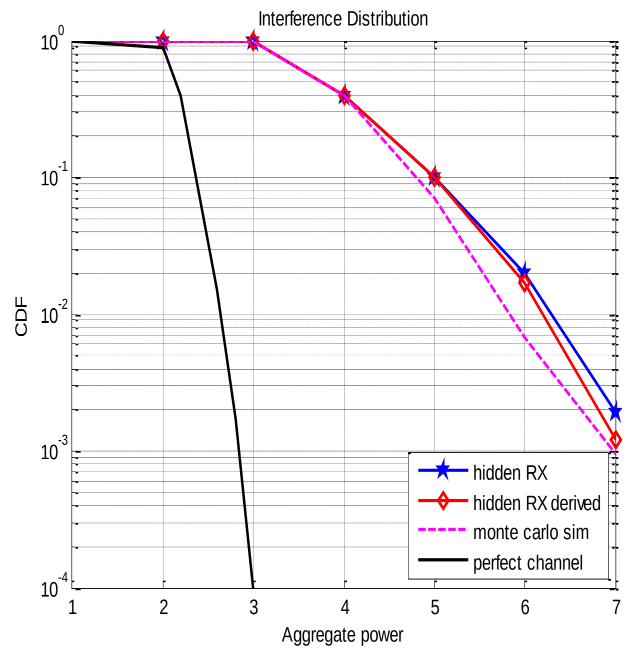

Fig. 2. Log normal approximation for interference distribution with hidden primary user location under Power control

In figure 3, we have shown the experimental results of the effect of the unknown location of the primary receiver under the contention control scheme. We setup the system just like the power control scheme with addition of the minimum contention distance between two CR transmitters d_{min}. We assumed a pathloss only channel, in regards to the presented results in figure 3; we can see that the uncertainty of the location of the primary user increases interference in terms of mean and variance [33]. Also the log – normal approximation for the interference is prone to inaccuracy [34] as the interferences increases when compared to the power control scheme in figure 2.

The following values for the parameters where used under the contention control scheme in figure 2; R= 100m, λ=3 user/10^4m^2, γ=4, d_{min}=20m, δ=4, P_{max}=1W, d_p=0.5R.

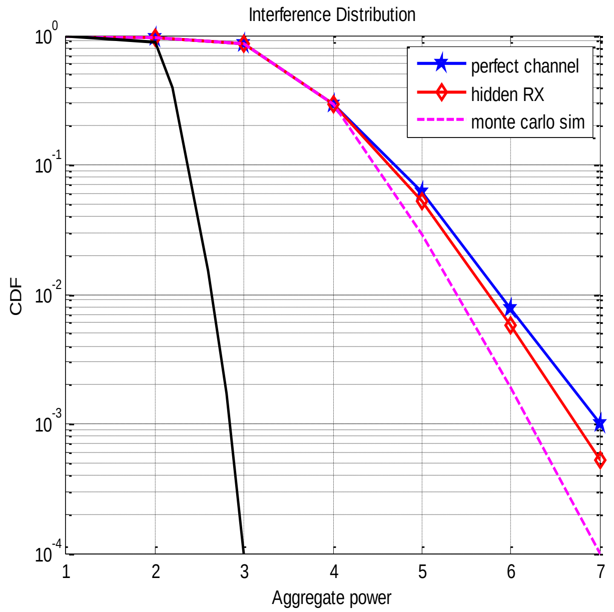

Fig. 3. Log normal approximation for interference distribution with hidden primary user location under Contention control

In this section, we have also investigated the impacts which the shadow fading has on the aggregate interference for CR network. The investigation was done considering various values of the Nakagami shape factor *m* under both schemes. The setup is the same as the initial setup as previously used with the additional standard variance σ_Ω=4dB.

The following values for the parameters where used under the Power control scheme; R= 100m, λ=3 user/10^4m^2, γ=4, r_{pcr}=20m, δ=4, P_{max}=1W, σ_Ω=4dB.

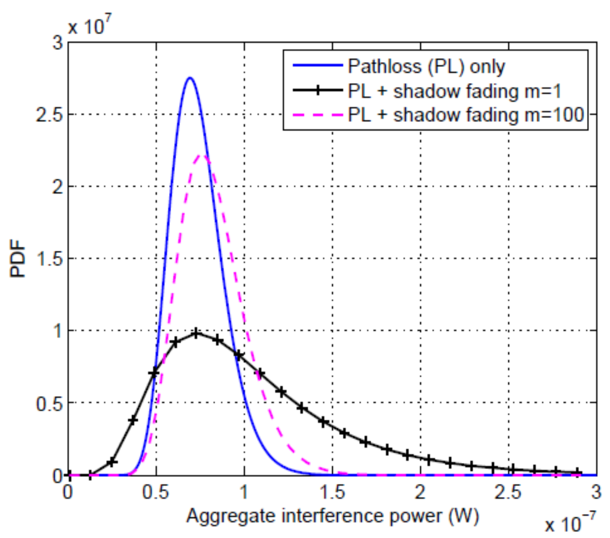

Fig. 4. The effect of shadow fading on the total interference power CR network under power control scheme

From figure 4, it can be seen that when the Nakagam-*m*=1, the interference channel becomes a Rayleigh channel which is influenced by the log-normal shadowing, however, when *m*=100, the instability or variations of the channel are greatly decreased. It is observed from figure 4, that the interference distribution possesses higher variance and heavier tails when shadow fading in integrated into the power control scheme.

The figure 5 shows the impact of shadow fading on the interference distribution under the contention control scheme. The setup is exactly like the power control with the exception of the power control range (r_{pcr}) which is replaced withd_{min}.

The following values for the parameters where used under the Power control scheme; R= 100m, λ=3 user/10^4m^2, γ=4, d_{min}=20m, δ=4, p=1W, σ_Ω=4dB

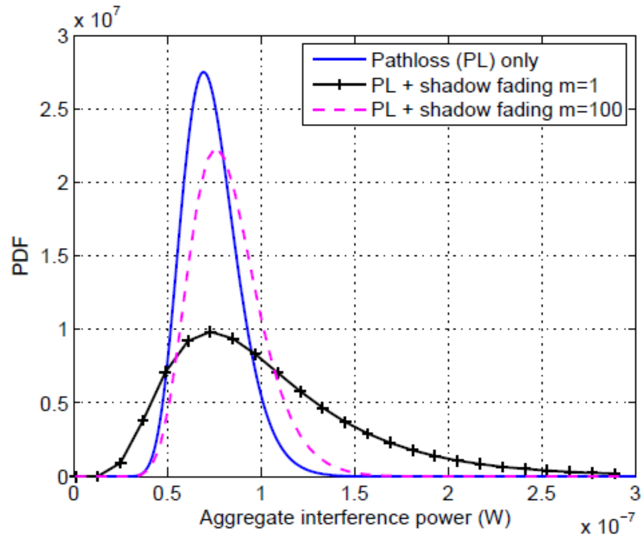

Fig. 5. The effect of shadow fading on the total interference power CR network under Contention control scheme

The incorporated shadow fading in the contention control scheme has similar effect with that of the power control. Hence it produces similar result.

Furthermore when exploiting a CR network under the power control scheme, its resulting interference can be regulated by altering the parameters which include P_{max} , r_{pcr} , λ and R. Figure 6 shows the effect of different CR implementation on the aggregate interference in a CR network, it has been shown that the interference can be reduced by either reducing the maximum transmission power P_{max} and or CR density λ or increasing power control range r_{pcr} and or the interference radius. However, it has been shown that modifying the IR radius is a good method to manage the interference.

This is due to the fact that the interference has high sensitivity to the IR radius than any other parameter as shown in figure 6. The previous setup for the power control scheme was retained with the exception of manipulating the parameter P_{max} , r_{pcr} , λ and R.

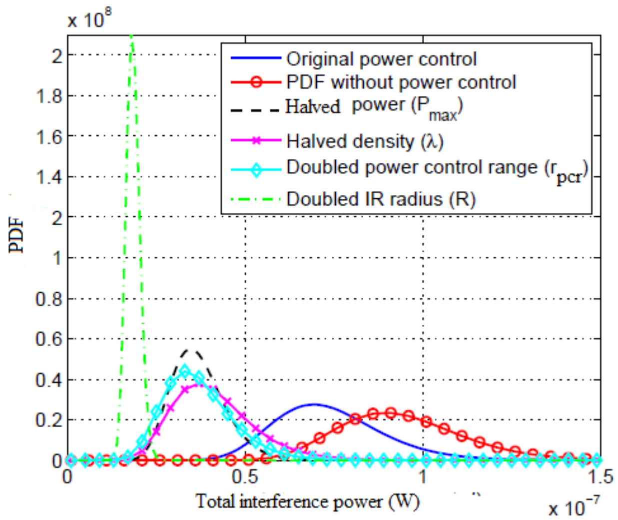

Fig. 6. Effect of different CR implementation on the total interference for CR network under power control

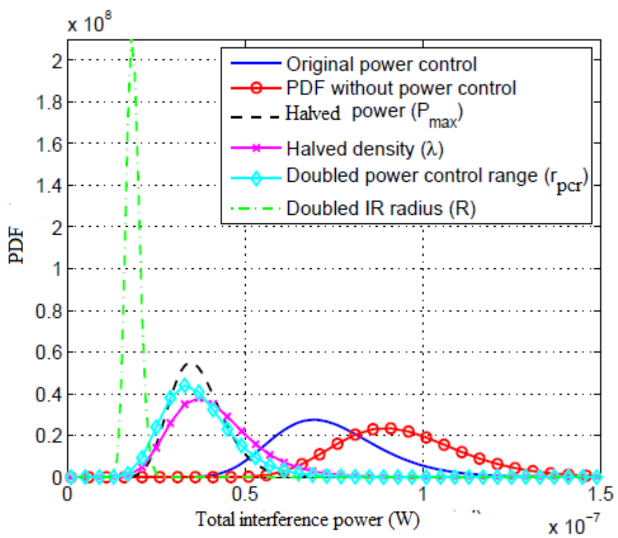

Fig. 7. Effect of different CR implementation on the total interference for CR network under Contention control

Figure 7 shows the impact which the different CR implementation has on the total interference for CR networks under the contention control scheme. It can be seen from figure 7, that the resulting interference has reduced mean just like that in the power control scheme, however the interference is reduced by decreasing p, λ and/ or increasing R or d_{min}. When comparing figure 6 and 7, it can be seen that increasing the interference radius is a good method in reducing the interference for both power and contention control scheme. Although, the power control scheme has higher sensitivity to the interference radius than the contention scheme. It also shows that when the transmission power or the CR transmitter density is reduced, the effect on the interference is the same in both schemes.

VI. Conclusion

In this work, we have investigated the interference at the primary receiver generated by the CR transmitters using power and contention control schemes. The power and contention control scheme have been estimated analytically, the interference distribution for the power and contention control have been estimated by log-normal distribution utilizing the cumulant based method. Both schemes have been proven to be good candidates in reducing interference at the primary receiver which is generated by the CR transmitters. The impacts of the unknown location of the primary receiver on the CR-primary interference was also investigated and it was found out that the unknown location of the primary receiver leads to higher CR-primary interference. Finally, it has been shown numerically that the impacts of the different CR implementation parameters on the resulting total interference under the power and contention control scheme.

APPENDIX A: Derivation of Equation (5)

Using same steps which were used in [25], we can the express the characteristics function of the total interference as follows;

$$\varphi_I(\omega) = \lim_{i\to\infty} e^{\lambda\pi(L^2-R^2)(Q-1)} \qquad \text{A.1}$$

where

$$Q = E\left(e^{i\omega P g(V) H}\right)$$

$$= \int_H f_h(h) \int_R^L E\left[e^{i\omega P g(r) h}\right] \frac{2r}{L^2-R^2} dr\, dh$$

$$= \int_H f_h(h) \int_R^L \left[(1-q_{mh}) + q_{mh} e^{i\omega p g(r) h}\right] \frac{2r}{L^2-R^2} dr\, dh \qquad \text{A.2}$$

The integral in (A.1) can be rewritten as;

$$\lim_{i\to\infty} \int_H f_h(h) \int_R^L e^{i\omega p g(r) h} \frac{2r}{L^2-R^2}\, dr\, dh =$$

$$1 + \frac{1}{L^2-R^2} \int_H f_h(h) T(\omega p h) dh$$

A.3

with $T(\omega p h)$given then we substitute (A.2) and (A.3) into (A.1) to obtain (5)

APPENDIX B: Derivation of Equation (10)

Substituting (3) and (4) into (11) we then have the following;

$$\varphi_Y(\omega) = exp\Big\{\lambda\pi \int_H f_h(h) \int_{r_{ccn}} f_{ccn}(r) \Big[R^2\big(1 - e^{i\omega g(R) p(r) h}\big) +$$

$$i\omega P_{pcr}(r_{ccn})^h \int_0^{g(R)} (g^{-1}(t))^2 e^{i\omega t p(r) h} dt\Big] dr\, dh\Big\} =$$

$$exp\Big\{\lambda\pi \int_H f_h(h) \int_0^{r_{pcr}} f_{ccn}(r) \Big[R^2 \Big(1 - e^{i\omega (\frac{r}{r_{pcr}})^{\delta} P_{\max g}(R) h}\Big) +$$

$$\frac{i\omega r^{\delta} P_{max} h}{r_{pcr}^{\delta}} \int_0^{g(R)} (g^{-1}(t))^2 e^{i\omega t (\frac{r}{r_{pcr}})^{\delta} P_{max}\, h} dt\Big] dr dh +$$

$$\lambda\pi \int_H f_h(h) \int_{r_{pcr}}^{\infty} f_{ccn}(r) \Big[R^2\big(1 - e^{i\omega g(R) P_{max}\, h}\big) +$$

$$i\omega P_{max} h \int_0^{g(R)} (g^{-1}(t))^2 e^{i\omega t P_{max} h} dt\Big] dr\, dh\Big\} \qquad \text{B.1}$$

The characteristic function in (10) is obtained by using (9) and (B.1)

APPENDIX C: Derivation of (14)

In a situation where the first equality of (C.1) holds according to [15]. Then equation (10) is derived instantly from (C.1).

$$K = \int_H f_h(h) \int_p f_p(p) \sqrt{hp\, dp\, dh} = \int_H f_h(h) \sqrt{h\, dh}$$
$$= \int_p f_p(p) \sqrt{p}\, dp$$
$$= \sqrt{P_{max}} \int_H f_h(h) \sqrt{h}\, dh \, (\int_0^c 2\pi r \lambda e^{-\lambda \pi r^2} (\frac{r}{c})^{\frac{\delta}{2}}\, dr$$
$$+ \int_c^\infty 2\pi \lambda r e^{-\lambda \pi r^2} dr) = \sqrt{P_{max}} \int_H f_h(h) \sqrt{h\, dh}$$
$$\left(\int_0^c 2\pi r \lambda e^{-\lambda \pi r^2} \left(\frac{\delta}{c}\right)^{\frac{\delta}{2}} dr + e^{-\lambda \pi c^2}\right) \qquad \text{C.1}$$

APPENDIX D: Derivation of (15)

$$\varphi_I(\omega) = \lim_{l \to \infty} exp\{\lambda \pi Di(E(e^{i\omega P_{pcr} g(V) h}) - 1)\} =$$
$$\lim_{i \to \infty} exp \begin{Bmatrix} \lambda \pi Di[\int_H f_h(h) \int_0^\infty f_{ccn}(x) \int_0^{2\pi} \frac{1}{2\pi} \int_R^L \exp[i\omega P_{pcr}(x) g(d_{cp} \\ (d,\theta))h] \frac{2r}{Dl}\, dr\, d\theta\, dx\, dh - 1] \end{Bmatrix} =$$
$$\lim_{i \to \infty} exp \begin{Bmatrix} \lambda \int_H f_h(h) \int_0^\infty f_{ccn}(x) \int_0^{2\pi} \exp\left[\omega P_{pcr}(x) g\left(d_{cp}(d,\theta)\right) h\right] \\ r - r dr\, d\theta\, dx\, dh \end{Bmatrix}$$

D.1

where $Dl = l^2 - R^2$ the first equality in (D.1) is derived in similar way as (A.1) and (A.2) then (15) is derived immediately from (D.1)

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