Impact of Transmit Power Control and Receiver Association on Interweave Network Interference

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***Abstract*—Erroneous beacon detection by interweave secondary nodes generates interference on the primary system. This paper analyzes how the aggregate interference behaves when secondary nodes use transmit power control and receiver association schemes. For this purpose, secondary transmitter nodes and receiver nodes are assumed to be distributed over a circular region and over the entire 2-D plane respectively. Two independent Poisson point processes model these distributions. We propose a receiver association scheme where each secondary transmitter attempts to connect to the closest available receiver. If it is not available, the transmitter attempts to connect with the next closest. This process continues until the M-th closest receivers are scanned. If no receiver is available, the transmitter remains silent. Moreover, a per-user transmit power control scheme is considered in which the transmit power is based on the distance between the transmitter and the associated receiver subject to a cut-off power level. All links are assumed to undergo path-loss and Rayleigh fading. The exact moment generating function (MGF) of the aggregate interference, the outage probability of the primary system, and the average probability of concurrent transmission are derived. Validated by simulations, our results show how the aggregate interference is affected by secondary power thresholds, receiver densities, and availability of the secondary receiver.**

I. Introduction

In interweave cognitive radio (CR) networks, the secondary transmitting nodes sense the frequency spectrum and access unoccupied slots opportunistically [1] by detecting an out-of band beacon signal [2], [3]. However, when the beacon is misdetected due to fading and path-loss [4], resulting secondary transmissions will cause interference to the primary receiver. This interference hinders the CR deployment, and must be kept below a manageable level.

Secondary receiver association schemes (receiver selection by the transmitter) and power control schemes are important in communication networks to conserve energy and to provide enhanced availability to the secondary network. Receiver association schemes can be based on the transmitter-receiver distance or the signal to noise ratio (SNR) of the transmitter-receiver channel [5]. Transmit power control schemes are classified as fixed power, distance based, and measurement based methods [6]. Such schemes are widely used in modern mobile communication networks [7]. To characterize the primary network interference accurately, such power control and receiver association techniques need to be considered for secondary nodes.

Characterizing the interference from secondary nodes is important in assessing the primary network performance. Moreover this interference characterization helps to identify optimum system parameters which provide the best availability to the secondary nodes while contributing the least interference to the primary system under different channel conditions. To this end, this paper proposes a secondary node power control and a receiver association scheme for interweave networks, and analyzes the aggregate interference and primary receiver performance under those schemes while considering spatial distributions of secondary nodes and channel factors.

A. Prior Research

The effect of power control and receiver association methods for CR networks has been widely studied. Reference [8] proposes a new approach for smart cognitive medium access control in order to adaptively control transmission parameters. An iterative power control algorithm which is robust against channel uncertainty is proposed in [9], while an adaptive power control scheme and an analytical model for the distribution of interference to the primary user is developed in [10]. Furthermore, [11] develops interference statistics of a Poisson field of interferers with random puncturing and approximates the cumulants of the interference.

Spectrum sensing with the aid of a beacon and the implications of beacon misdetection have also received attention. Reference [12] develops a statistical model for the aggregate interference under different sensing protocols. The capacity-outage probability due to beacon misdetection is analyzed in [13] under a deterministic number of secondary nodes. Moreover, [4] analyzes the effects of beacon misdetection in hybrid underlay-interweave networks while [14] investigates the primary system interference under different secondary co-operation schemes.

B. Motivation and contribution

Although previous research [4], [11], [13], [15] consider spectrum sensing, transmit power control schemes and receiver association schemes have not been analyzed. However, due to the practical importance of these schemes for mobile, ad-hoc, and sensor networks, the aggregate interference from a finite random field of interweave secondary nodes employing power and contention control will be analyzed in this paper. The following assumptions are made regarding the system: 1) Secondary nodes detect a beacon signal (pilot channel) emitted from the primary receiver for spectrum sensing. Misdetection of the beacon is caused by path-loss and Rayleigh fading. 2) The secondary transmitter and receiver nodes are spatially distributed as two independent homogeneous Poisson point

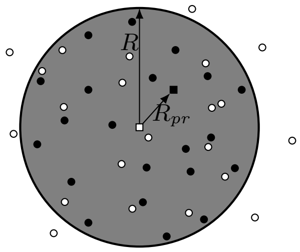

Fig. 1: Sytem model. The secondary transmitter nodes (black dots) are located within the shaded area while the secondary receiver nodes (white dots) are located in the entire 2-dimensional plane. R represents the radius of the circular area encompassing the transmitter nodes while R_{pr} denotes the primary transmitter (black square) to primary receiver (white square) distance.

processes (PPPs) [16] as explained in the next section. 3) We propose a receiver association scheme as follows: Each transmitter attempts to connect with the nearest available receiver. If it is not available, the transmitter attempts to connect with the next closest. This process continues until the M-th closest receiver nodes are scanned. If no receiver node is available, the transmitter node remains silent. Each secondary receiver node is characterized by a probability β_r of being available. We assume that the receiver nodes will be of a similar type, and thus β_r is constant for all secondary receiver nodes. 4) The secondary transmit power control scheme will be based on the secondary transmitter node-receiver node distance subject to a cut-off power level. The cut-off power level is highly critical for smaller battery powered devices.

Utilizing these assumptions, we will derive the exact moment generating function (MGF) of the aggregate interference, the outage probability of the primary receiver, and the average probability of concurrent primary-secondary transmission. The MGF completely defines the probability distribution while enabling moments to be found. Thus, further statistics of the aggregate interference can be found as necessary. The primary outage and the probability of concurrent transmission are important performance measures in assessing the viability of an interweave CR design.

Notations: $\Gamma(x,a) = \int_a^\infty t^{x-1}e^{-t}dt$ and $\Gamma(x) = \Gamma(x,0)$ [17]. $\Pr[A]$ is the probability of event A, $f_X(\cdot)$ is the probability density function (PDF), $F_X(\cdot)$ is the cumulative distribution function (CDF), $M_X(\cdot)$ is the MGF, and $E_X[\cdot]$ denotes the expectation over random variable X. The PPP is defined in [16, p. 11]

II. System model

This section describes the spatial and signal models.

A. Spatial model

We want to characterize the interference from secondary transmitter nodes located within a distance of R from the primary receiver (Fig. 1) as the interference from nodes further away is negligible due to path loss. However, there is no loss of generality because an infinite field of transmitter nodes which can be obtained when $R \to \infty$. The secondary receiver nodes do not directly cause interference to the primary receiver. As we will see in the next subsection, the power control and receiver association schemes are based on the distance between the secondary transmitter-receiver nodes. Therefore, we will model the secondary receiver nodes to be distributed in the entire 2-dimensional plane. Moreover, the primary transmitter is located a distance R_{pr} from the primary receiver.

The locations and numbers of secondary transmitter and receiver nodes are random. Therefore, stochastic geometry is more appropriate to model the spatial distributions of these nodes. We model the locations of secondary transmitter and receiver nodes via two independent homogeneous PPPs with intensities (densities) λ_t and λ_r. The PPP has been highly adapted in modeling the spatial distribution of wireless nodes in general, and CR networks in particular [12], [18].

Under the homogeneous PPP model, the probability of having n nodes ($P(n)$) within an area of A is given by [16],

$$P(n) = \frac{(\lambda_j A)^n}{n!}e^{-\lambda_j A}, \quad n = 0, 1, 2 \dots, \tag{1}$$

where $j = \{r, t\}$. Without the loss of generality, we assume that all the secondary transmitters attempt to transmit all the time. If a transmitter node has a probability of transmitting β_t, by using the Coloring theorem [16] the potential interfers can be represented by a PPP with intensity $\beta_t\lambda_t$.

B. Channel model

All signals namely primary, secondary, and beacon undergo Rayleigh fading and path-loss. Rayleigh fading yields a channel power gain $|h|^2$ that has an exponential distribution. The PDF of $|h|^2$ becomes $f_{|h|^2}(x) = e^{-x}, 0 < x < \infty$. We will use the simplified path-loss model of [19] where the power level drops exponentially. If P_0 is the observed power at a distance of r_0 from the transmitter, the power at a distance r from the transmitter (P_r) is given as $P_r = Pr^{-\alpha}$, where α is the path-loss exponent and $P = P_0 r_0^\alpha$.

C. Spectrum sensing, receiver association and power control model

Each secondary transmitter node independently senses an out-of-band beacon signal transmitted by the primary receiver. The beacon indicates when primary signals are occupying the spectrum. If the beacon signal is not present or if it is detected incorrectly (detecting that the beacon is not present when there actually is one), a transmission attempt will be initiated.

Once this happens, it has to associate itself with a secondary receiver node. However, each receiver is only available with a probability of β_r. This availability factor is independent of other receiver nodes. The transmitter node would initially attempt to connect to the nearest receiver node. If this fails, it would attempt to connect to the next nearest receiver. This process would continue until the M-th closest receiver node is scanned. If no available receiver is found, the transmitter node remains silent. The M nearest nodes can be found in practical scenarios through pilot channel sensing (calculating the distance based on the average received power of pilot signals from the secondary receiver nodes) or through a central controller.

If an association is made, the transmission should be made while ensuring a constant received power (P_c) when averaged over small scale fading. P_c will be the receiver sensitivity of plus the required fade margin. In mobile systems employing Code Division Multiple Access systems, this is especially used to avoid the near-far problem [7]. Using the path loss model explained in the previous section, the transmit power needed would thus become $P_c r^\alpha$. However, if this value exceeds the maximum possible transmit power of a (P_s), the transmission is aborted.

III. Interference Analysis

This section derives the MGF of the aggregate interference. The aggregate interference (I) is written as $I = \sum_{i=1}^{N} I_i$, where I_i is the interference from the i-th secondary transmitter node, and N is the number of transmitter nodes within the area defined according to (1). The MGF of the aggregate interference I is defined as $M_I(s) = E[e^{-sI}]$. $M_I(s)$ given N transmitter nodes when different I_i are independent and identically distributed is given by $M_{I/N}(s) = (M_{I_i}(s))^N$ where M_{I_i} is the MGF of the interference from the i-th transmitter node. After averaging with respect to (1), $M_I(s)$ becomes

$$M_I(s) = e^{\lambda_t \pi R^2 (M_{I_i}(s)-1)}. \tag{2}$$

We now have to obtain $M_{I_i}(s)$ in order to evaluate $M_I(s)$ in (2). Using the channel, power control and association models defined above, I_i can be written as

$$I_i = B_i P_i |h_i|^2 r_i^{-\alpha}, \tag{3}$$

where B_i is the actual transmission factor of the i-th transmitter node when primary transmissions occur, P_i is the transmit power level of the i-th transmitter node, while r_i and $|h_i|^2$ are the distance and channel power gain from the i-th transmitter node to the primary receiver. Because a homogeneous PPP is considered, the transmitter nodes are uniformly distributed in space. Therefore, r_i is distributed as

$$f_R(r_i) = \begin{cases} 2\frac{r_i}{R^2} & , 0 < r_i < R \\ 0 & , \text{otherwise} \end{cases}. \tag{4}$$

A. Probability of concurrent transmission

B_i is a Bernoulli random variable with a success probability (probability of concurrent transmission of a secondary transmitter node with the primary system) of b_i. This concurrent transmission probability depends on the beacon misdetection probability q_i, receiver availability parameter β_r, the number of nearest receivers a transmitter node is allowed to conduct transmission to (M), and the probability that the required transmit power level of a transmitter node associated with the k-th nearest receiver is within the maximum possible transmit power P_s (denoted as p_k). In a nutshell, for a transmitter node to conduct a transmission concurrently with the primary system, the beacon has to be misdetected, at least one of the M nearest receivers should be available, and the required transmit power should be lower than P_s. The concurrent transmission probability is thus written as

$$b_i = q_i \beta_r \sum_{k=1}^{M} (1-\beta_r)^{k-1} p_k. \tag{5}$$

Let P_b be the beacon transmit power, $|h_{b,i}|^2$ be the beacon channel power gain from the primary receiver to the i-th transmitter node, and P_{T_b} be the required power threshold for a transmitter node to correctly detect a beacon. The beacon misdetection probability q_i is thus written as

$$q_i = \Pr[P_b |h_{b,i}|^2 r_i^{-\alpha} < P_{T_b}] = 1 - e^{-\frac{P_{T_b} r_i^\alpha}{P_b}}. \tag{6}$$

If a transmission is required to the k-th nearest receiver, the required power of the transmitter node would be $P_c r_k^\alpha$, where r_k is the distance from a given transmitter node to its k-th nearest receiver node. Therefore, p_k becomes $p_k = \Pr[P_c r_k^\alpha < P_s]$. In order to evaluate this, we need the distribution of r_k. The secondary transmitter and receiver nodes form independent PPPs and thus their locations are independent of each other. Thus, r_k is identical to the distance from any given location in space to the k-th nearest node with the distribution [16]

$$f_{r_k}(x) = \frac{2(\pi\lambda_r)^k}{(k-1)!} x^{2k-1} e^{-\pi\lambda_r x^2}, 0 < x < \infty. \tag{7}$$

Using (7), p_k is found as

$$p_k = 1 - \frac{\Gamma\left(k, \pi\lambda_r \left(\frac{P_s}{P_c}\right)^{\frac{2}{\alpha}}\right)}{(k-1)!}. \tag{8}$$

Thus, using the expansion of e^{-x} for q_i, the average probability that a secondary transmitter node would transmit concurrently with the primary system $E[b_i]$ is

$$E[b_i] = \left(-\sum_{w=1}^{\infty} \frac{2R^{\alpha w}(-P_{T_b})^w}{P_b^w w!(2+\alpha w)}\right) \left(\sum_{k=1}^{M} \beta_r (1-\beta_r)^{k-1} p_k\right). \tag{9}$$

B. Finding $M_{I_i}(s)$

Coming back to our original objective of finding $M_{I_i}(s) = E[e^{-sB_i P_i |h_i|^2 r_i^{-\alpha}}]$, after averaging with respect to B_i and $|h_i|^2$ and substituting for P_i, we can write

$$M_{I_i}(s) = E\left[1 - q_i\beta_r \sum_{k=1}^{M} (1-\beta_r)^{k-1} p_k + \sum_{k=1}^{M} \frac{q_i \beta_r (1-\beta_r)^{k-1} p_k}{1 + sP_c r_k^\alpha r_i^{-\alpha}}\right]. \tag{10}$$

Using the expansion for e^{-x} in q_i, $M_{I_i}(s)$ becomes

$$M_{I_i}(s) = E\left[1 + \sum_{l=1}^{\infty} \frac{(-P_{T_b} r_i^\alpha)^l}{P_b^l l!} \beta_r \sum_{k=1}^{M} (1-\beta_r)^{k-1} p_k\right] + \mathcal{W}, \tag{11}$$

where $\mathcal{W} = E\left[\sum_{k=1}^{M} \frac{q_i\beta_r(1-\beta_r)^{k-1}p_k}{1+sP_c r_k^{\alpha} r_i^{-\alpha}}\right]$. $\mathcal{W}$ can be further expanded and averaged with respect to the distributions of r_i (4) and r_k (7) as

$$\mathcal{W} = -\sum_{v=1}^{\infty}\sum_{k=1}^{M}\sum_{t=0}^{\infty} \frac{(-P_{T_b})^v}{P_b^v v!}\beta_r(1-\beta_r)^{k-1}(-sP_c)^t \times\left(\frac{2}{R^2}\int_0^R r_i^{\alpha v-\alpha t+1}dr_i\right)\left(\frac{2(\pi\lambda_r)^k}{(k-1)!p_k}\int_0^{(\frac{P_s}{P_c})^{\frac{1}{\alpha}}} p_k r_k^{\alpha t+2k-1}e^{-\pi\lambda_r r_k^2}dr_k\right). \tag{12}$$

Finally, after performing the averaging of $\mathcal{W}$ and (11), the final expression for $M_{I_i}(s)$ is obtained as (13). We will see in Section V that the infinite summations of (13) converge in a finite number of terms (under 10) for practical parameter values.

IV. Outage Performance Analysis

This section will derive the outage performance of the primary receiver.

The received power (P_R) at the primary receiver can be written as $P_R = P_p|h_p|^2R_{pr}^{-\alpha}$, where P_p is the transmit power level of the primary transmitter, and $|h_p|^2$ is the exponential channel power gain between the primary transmitter and receiver pair. The signal to interference and noise ratio (SINR) of the primary receiver (γ) is defined as

$$\gamma = \frac{P_R}{I+\sigma_n^2}, \tag{14}$$

where σ_n^2 is the noise variance. The CDF of the SINR is written as $F_\gamma(x) = \Pr[\gamma \le x]$. After mathematical manipulation and averaging, the final equation for the CDF is obtained as [4]

$$F_\gamma(x) = 1 - e^{\left(-\frac{x\sigma_n^2}{P_pR_{pr}^{-\alpha}}\right)} M_I\left(\frac{x}{P_pR_{pr}^{-\alpha}}\right). \tag{15}$$

The outage is obtained by substituting the required SINR threshold of the primary receiver (γ_{th}) in place of x in (15).

V. Numerical Results

This section provides numerical results of the primary receiver outage and the probability of concurrent transmission ($E[b_i]$). Unless otherwise stated, we will use the parameters $R = 100$, $R_{pr} = 30$, $\gamma_{th} = 1$, $\alpha = 3$, $\lambda_t = 0.001$, $P_p = 0\,\text{dB}$, $\frac{P_{T_b}}{P_b} = 2\times10^{-6}$, and $\sigma_n^2 = 0$. The noise variance σ_n^2 has been set to 0 in order to highlight the effects of system parameters on the interference.

Fig. (2) plots the primary receiver outage with respect to the cut-off transmit power level P_s. There is an exact match between the simulation and the theoretical results. For the infinite sums of (13), a tight convergence occurred before 15 iterations for the network considered. With increasing P_s, all the curves show an initial increase in outage before flattening out. The flattening occurs due to the required transmit power being always lower than P_s. Therefore, any further increase in P_s does not have a significant effect. When the number of nearest receivers a transmitter node attempts to connect (M) increases, the outage increases because transmitter nodes have a higher probability of associating with an available receiver. However, the amount of the increase decreases with respect to M. For low P_s values, M does not affect the outage. This is because transmissions to receiver nodes farther away being impossible due to the low cut-off transmit power level.

The primary receiver outage is plotted vs the availability of a receiver node (β_r) in Fig. (3). When the average received power of a receiver (P_c) is 10^{-8}, the outage initially increases with β_r and subsequently drops. But, when $P_c = 10^{-7}$, the outage shows a gradual increase with β_r. This is because for a higher P_c, the cut-off power P_s prevents transmissions to receivers farther away. Thus, most transmissions are only possible to the nearest receivers, and the probability of these increases with β_r. For the same reason, there is no significant deviation of the curves for $M = 3$ and $M = 10$. This is not the case when P_c is lower. The cut-off power P_s would have a lower effect, and transmission is possible to far away receivers if required. As β_r approaches unity, only transmissions to close-by receiver nodes would be required. As such, the outage increases initially, and subsequently drops. It's interesting to note that when $M = 10$, the outage under $P_c = 10^{-8}$ is greater than when $P_c = 10^{-7}$ for low β_r.

Fig. (4) plots the average concurrent transmission probability ($E[b_i]$) vs M. The possibility of a concurrent transmission reduces with the receiver node density (λ) and the receiver availability (β_r). Under the parameters used, the concurrent transmission probability does not change significantly with M for $\lambda_r = 10^{-4}$. When $\lambda_r = 10^{-3}$, it still only shows a diminishing increase.

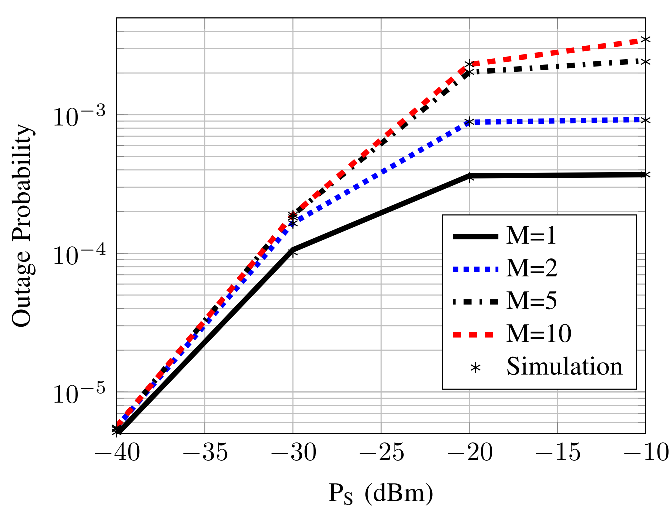

Fig. 2: The primary receiver outage probability vs the cut-off power level P_s for different M. $\beta_r = 0.4$, $\lambda_r = 0.001$, and $P_c = 10^{-7}$ mW.

VI. Conclusion

This paper investigated the aggregate interference arising due to beacon misdetection in an interweave CR network with secondary transmitter and receiver nodes distributed as

$$M_{I_i}(s) = 1 + \beta_r \left(\sum_{k=1}^{M} (1-\beta_r)^{k-1} \left(1 - \frac{\Gamma\left(k, \pi\lambda_r \left(\frac{P_s}{P_c}\right)^{\frac{2}{\alpha}}\right)}{(k-1)!} \right) \right) \left(\sum_{l=1}^{\infty} \frac{2(-P_{T_b})^l}{P_b^l l!} \frac{R^{\alpha l}}{\alpha l + 2} \right) - \sum_{v=1}^{\infty}\sum_{k=1}^{M}\sum_{t=0}^{\infty} \frac{(-P_{T_b})^v}{P_b^v v!} \beta_r (1-\beta_r)^{k-1} \times (-sP_c)^t \frac{2}{(k-1)!(\pi\lambda_r)^{\frac{\alpha t}{2}}} \left(\frac{R^{\alpha v - \alpha t}}{2+\alpha v - \alpha t}\right) \left(\Gamma\left(k+\frac{\alpha t}{2}\right) - \Gamma\left(k+\frac{\alpha t}{2}, \pi\lambda_r \left(\frac{P_s}{P_c}\right)^{\frac{2}{\alpha}}\right)\right) \qquad (13)$$

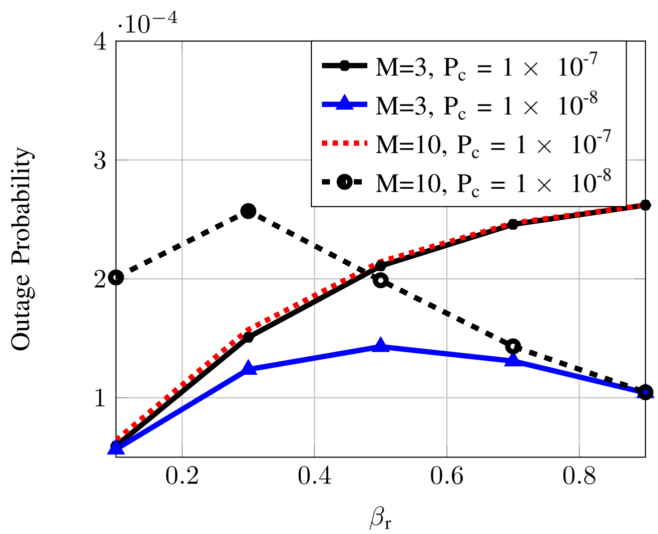

Fig. 3: The primary receiver outage probability vs the availability of a receiver β_r for different M and P_c (mW). $\lambda_r = 0.001$ and $P_s = 10^{-3}$ mW.

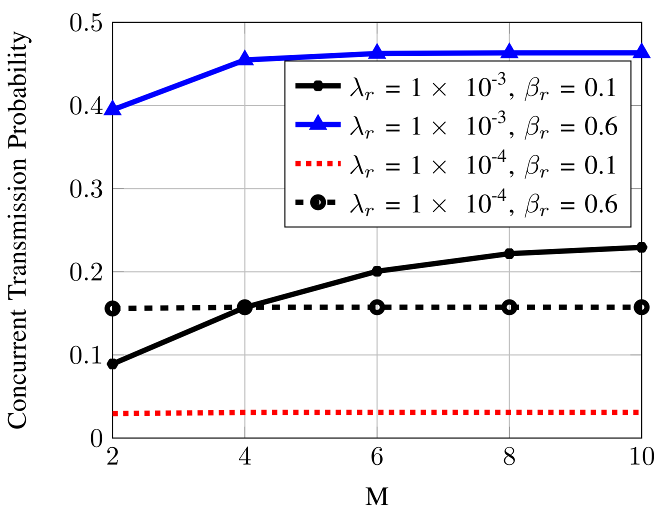

Fig. 4: The concurrent transmission probability vs M for different λ_r and β_r. $P_s = 10^{-2}$ mW and $P_c = 10^{-7}$ mW.

independent PPPs. Each transmitter node connects to the nearest available receiver among the M closest receivers. The secondary node transmit power was based on the transmitter-receiver distance plus a cut-off power. The primary signals, secondary signals and the beacons all experience path-loss and Rayleigh fading. The MGF of the aggregate interference was analyzed along with the outage probability of the primary receiver. It was shown that the secondary receiver availability had a significant effect on the outage probability, and that M was only significant when the cut-off power level (P_s) and the receiver node density are higher, or when the required average received power (P_c) is lower. Moreover, changing M has limited affect on the system performance under low cut-off powers and receiver node densities.

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