

Exploiting Temporal Secondary Access Opportunities in Radar Spectrum

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Abstract

In this paper, we quantify the temporal opportunities for secondary access to radar spectrum. Secondary users are assumed to be WLANs which opportunistically share the radar frequency band under the constraint that the aggregate interference does not harm radar operation. Each WLAN device employs dynamic frequency selection (DFS) as a mechanism to protect the radar from the interference. We also consider an advanced interference protection mechanism, which is termed *temporal DFS*. It exploits the temporal variation of interference power due to the periodic rotation of radar antenna. It is observed that the probability of accessing the radar spectrum is significantly higher when the temporal DFS is used compared to the conventional DFS. As a consequence, more WLANs can utilize the radar spectrum when the temporal DFS mechanism is considered. This shows that having better knowledge of the primary user activity can bring about the increased opportunity of secondary spectrum access to radar band, and thus improve the spectrum utilization.

Keywords

Secondary spectrum access, radar spectrum, aggregate interference, dynamic frequency selection, temporal opportunity.

1. Introduction

The useful radio spectrum is fully allocated to various systems such as TV broadcasting, satellite, radar, and mobile communications. However, it does not necessarily mean that the spectrum is efficiently used. Measurement results indicate that the allocated spectrum is mostly being under-utilized [1-2]. The spectrum utilization can be improved by using a dynamic spectrum access (DSA) mechanism based on hierarchical access strategy, i.e. secondary spectrum access. It allows secondary users to access the spectrum that has already been assigned to

primary users if the secondary users do not cause harmful interference to the primary users.

An interesting example of secondary spectrum access can be found in the 5 GHz frequency band (5150-5350 MHz and 5470-5725 MHz) where the WLAN devices can opportunistically access the spectrum primarily allocated to radars [3]. WLANs using these frequency bands are mandated to protect the radars by implementing an interference protection mechanism called dynamic frequency selection (DFS), which is specified in ETSI standard [4].

In order to assess the benefit of the secondary access, it is important to quantify the opportunities the WLANs can have. The opportunities can be found in spatial and temporal dimension. The spatial opportunity comes from the attenuation of radio signal from the secondary transmitter, whereas the temporal opportunity exploits the activity or mobility of the primary user [5]. The existing DFS mechanism mainly relies on the spatial opportunity. The temporal aspect of secondary access in the radar spectrum has yet not been studied thoroughly. Thus, it is of great interest to examine how much the secondary users will benefit from the temporal opportunity. Typical radar has an antenna with a narrow beam width, which is rotating in a regular manner. This property is expected to create a temporal opportunity to the secondary users. In [6], the authors proposed a beacon signal from the radar that helps WLANs access the spectrum temporally while the main beam of the radar antenna does not face them. However, the benefit of the temporal opportunity has not been investigated yet.

In this paper, we quantify the temporal opportunity of the secondary access under the assumption that the antenna pattern and the rotation of the radar are accurately known to the WLAN devices. We consider an advanced interference protection scheme that utilizes the information of the radar rotation, which we term *temporal DFS*. The performance of the temporal DFS is compared with a benchmark case where WLANs implement the conventional DFS. In the performance evaluation, we consider multiple WLANs that are randomly distributed over a large area. In essence, our aim is to *quantify the benefit of exploiting the temporal aspect of radar in the transmission opportunities of the secondary users*.

The radar must be protected from harmful interference that could be generated by multiple WLANs transmitting simultaneously over a large area. Therefore, it is important to develop an accurate model to describe the aggregate interference coming from the multiple WLANs. In [7], we proposed a mathematical model of the aggregate interference that considers an interference protection scheme resembling the DFS. The model was applied to practical secondary access scenarios in [3,8]. In this study, we further extend our model in [7] to obtain the probability distribution of the aggregate interference under the temporal DFS.

The remainder of the paper is organized as follows: Section 2 details the primary and secondary systems. In Section 3, the concepts of DFS and temporal DFS are explained. Section 4 presents the analytic model for the probability distribution of the aggregate interference. Section 5 shows the numerical results obtained from numerical analysis. Finally, we close with the conclusion in Section 6.

2. Primary and Secondary Systems

A. Primary system

We consider a ground-based meteorological radar operating in 5600-5650 MHz band as the primary system. Technical specifications of the radar can be found in [9]. Notably, it is equipped with an antenna that scans through 360° in a regular manner and has a sharp beam width of about 2° .

The protection of radar is usually expressed in terms of the interference to noise ratio (INR). We consider the minimum tolerable INR of -9dB . Let us define the maximum aggregate interference power that the radar can tolerate as A_{thr} . The INR of -9dB corresponds to $A_{thr} = -109\text{dBm}$ with the radar parameters shown in Table 1. Additional margins can be considered such as apportionment margin [8] (the portion of interference that the secondary users account for) and fast fading margin.

Let I_a denote the aggregate interference that the radar receives from multiple active WLANs. If I_a is greater than A_{thr} , the radar will experience a degradation in performance. Therefore, a regulatory constraint β is defined as the maximum permitted probability of interference such that

$$\Pr[I_a > A_{thr}] \leq \beta. \quad (1)$$

The value of β is crucial for the performance of the radar. Reasonable range of β for the meteorological radar has not been discussed in the literature. In this work, we adopt the value applied to the air traffic control radar, which is extremely conservative ($\beta = 0.001\%$).

B. Secondary system

We consider WLAN access points and end user devices for indoor broadband access as the secondary users. We assume that N active secondary users are uniformly distributed in a large circular area with the radius R , where the radar is located at the center.

We assume the secondary users can accurately estimate the mid-term propagation loss to the radar, i.e. distance-dependent path loss and shadow fading. This is a reasonable assumption because the radar emits strong pulses and gathers reflected signals using the same antenna, i.e. the radar transmitter and receiver are collocated and they employ the same frequency. The secondary users are also assumed to have the same transmission power P_{tx} . Some of the secondary users may be prevented from transmitting in order to satisfy the constraint (1). Detailed interference control schemes will be described in the next section.

3. Interference Protection Mechanisms

A. Dynamic frequency selection

DFS refers to an interference avoidance mechanism described in the ETSI standard [4]. The DFS is based on the detection of radar signals by individual WLAN network. The WLAN avoids the use of a channel identified as being

occupied by the radar. In the current DFS scheme, the detection threshold to identify the presence of the radar is fixed to a certain value (either -62dBm or -64dBm depending on the transmission power of the WLAN). In this work, however, we assume the detection threshold can be adjusted with different secondary user densities to ensure the protection of the radar and at the same time to maximize the opportunity of the secondary users.

Let us consider an arbitrary secondary user j whose location is (r_j, θ_j) in polar coordinate. We define ξ_j as the interference power that the radar would receive from the user j if it were to transmit. Also, let $\widehat{\xi_j}$ be the estimate of ξ_j which is measured by the user j . The transmission decision of the user j is based on the individual interference threshold I_{thr} that applies to every secondary user in the system. The user j decides to transmit if the estimated interference does not exceed the threshold. As a result of the decision, the actual interference from the user j to the radar is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \widehat{\xi_j} \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

In (2), ξ_j can be expressed as

$$\xi_j = P_{tx} L_{oth} G_{rad}(\theta_j) G_{wlan} L(r_j) X_j, \quad (3)$$

where $G_{rad}(\theta_j)$ and G_{wlan} denote the antenna gain of radar and WLAN, respectively, X_j is a random variable modeling shadow fading effect, and $L(r_j)$ is the distance-dependent path loss defined as

$$L(r_j) = C r_j^{-\alpha} \quad (4)$$

with C and α denoting the path loss constant and exponent, respectively. Other gains and losses such as bandwidth mismatch and wall penetration loss are accounted for by L_{oth} .

Note that the value of ξ_j varies over time due to the rotation of the radar antenna. We employ a simplified antenna pattern model for radar as shown below:

$$G_{rad}(\theta_j) = \begin{cases} G_{rad}^{\max}, & \text{if } 0 < \theta_j \leq \theta_{MB}, \\ G_{rad}^{\min}, & \text{otherwise,} \end{cases} \quad (5)$$

where $G_{rad}^{\max}$ represents the antenna gain when the user j faces the main beam, and $G_{rad}^{\min}$ stands for the other case. The beam width of the radar is denoted by θ_{MB} . This means that ξ_j has two values in a given location depending on time. The difference between $G_{rad}^{\max}$ and $G_{rad}^{\min}$ is usually higher than 30dB. Let $\xi_j^{\max}$ be the value of ξ_j when the WLAN j faces the radar main beam.

B. DFS without temporal opportunity exploitation

If the secondary user does not have a precise knowledge about the rotation of the radar, it will have to make a conservative decision that it will always face the radar beam when it transmits, i.e. $\hat{\xi}_j$ equals to $\xi_j^{\max}$. Therefore, the conventional DFS mechanism can be described as

$$I_j = \begin{cases} \xi_j, & \text{if } \xi_j^{\max} \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

Figure 1 shows a graphical representation of the conventional DFS scheme. A large exclusion region is observed regardless of the current radar antenna direction.

C. DFS exploiting temporal opportunity

Let us consider an ideal case that the secondary users are aware of the antenna gain and rotation pattern of the radar. This can be feasible if the radar helps the secondary users by transmitting beacon signal [6], or if the secondary users are fed information about the radar by a central database. With the assumption, the secondary users can make refined decision based on the instantaneous interference rather than the worst case. Therefore, I_j under the temporal DFS is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \xi_j \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

Figure 2 illustrates how the number of active WLANs is increased by using the temporal DFS scheme. The beam width of 30° was employed in the figure to clearly visualize the impact of the radar antenna. It is observed that the temporal DFS dramatically increases the size of area where WLANs can transmit, and thus provides higher opportunity to the secondary users. Note that we assume that the secondary users have the perfect knowledge of temporal radar characteristics. Thus, this result can be viewed as the maximum achievable gain of the temporal DFS.

4. Probability Distribution of Aggregate Interference

In order to quantify the benefit of the temporal DFS, it is essential to accurately describe the characteristics of aggregate interference under the conventional and temporal DFS schemes. The probability distribution of I_a under the conventional DFS has already been derived in our previous work [3]. Thus, we will focus on obtaining the probability density function (pdf) of I_a with the temporal DFS based on the method proposed in [7].

As discussed in the previous section, the interference that the radar receives from a secondary user differs significantly depending on whether it faces the main beam or not. Thus, two regions of different interference characteristics should be considered in calculating I_a . Aggregate interference coming from the heterogeneous regions can be addressed by applying the concept of hot zone, which was proposed in [10]. With this concept, several annulus sectors of different characteristics (e.g. traffic load and propagation) can be overlaid in a background circle to account for the various types of areas such as cities, towns, and suburbs. Here, we divide the whole area into the two non-overlapping zones: one facing main beam (zone 1) and the rest (zone 2). Then, the total N secondary users can be classified into N_1 users in zone 1 and N_2 users in zone 2. Note that the number of N_1 is proportional to the size of radar beam width θ_{MB} .

Let us consider the user j in the zone 1 first. According to [7], the pdf of ξ_j can be expressed as follows by using Gaussian error function:

$$f_{\xi_j}(z) = \Omega z^{\frac{-2}{\alpha}-1} \left[1 + \operatorname{erf} \left(\frac{\ln(z/Q) - 2\sigma_{X_j}^2 / \alpha}{\sqrt{2\sigma_{X_j}^2}} \right) \right], \quad (8)$$

where $\sigma_{X_j} = \sigma_{X_j}^{dB} \ln(10)/10$, and $\sigma_{X_j}^{dB}$ denotes the standard deviation of the shadow fading in dB scale. The parameters Ω and Q are defined as

$$\Omega = \frac{1}{R^2 \alpha} \left(\frac{1}{G_{rad}^{\max} G_{wlan} L_{oth} P_{tx} C} \right)^{\frac{-2}{\alpha}} \exp \left[2\sigma_{X_j}^2 / \alpha^2 \right], \quad (9)$$

$$Q = G_{rad}^{\max} G_{wlan} L_{oth} P_{tx} L(R). \quad (10)$$

When I_{thr} is applied to the user j , it is prohibited from transmission if ξ_j exceeds I_{thr} as depicted in (7). This means that a portion of secondary users have zero transmission power. That portion of users is given as $1 - F_{\xi_j}(I_{thr})$ where $F_{\xi_j}(\cdot)$ denotes the cumulative distribution function (CDF) of ξ_j . Thus, the pdf of I_j is as follows:

$$f_{I_j}(z) = \begin{cases} 1 - F_{\xi_j}(I_{thr}), & \text{if } z = 0, \\ f_{\xi_j}(z), & \text{if } 0 < z \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

To obtain the pdf of I_j for the secondary user in zone 2, $G_{rad}^{\max}$ should be replaced by $G_{rad}^{\min}$ in (9) and (10).

Let $I_{a,1}$ and $I_{a,2}$ be the aggregate interference from the zone 1 and zone 2, respectively ($I_a = I_{a,1} + I_{a,2}$). We employ a cumulant-based approach to approximate the pdf of I_a . Note that the cumulants have a property that the m^{th} cumulant of the sum of independent RVs is equal to the sum of the individual m^{th} cumulants. Also, the first and second cumulants of a RV correspond to the

mean and variance. Let $k_{I_{a,1}}(m)$ and $k_{I_{a,2}}(m)$ denote the m^{th} cumulant of $I_{a,1}$ and $I_{a,2}$, respectively. Then,

$$k_{I_a}(m) = k_{I_{a,1}}(m) + k_{I_{a,2}}(m) = \sum_{j=1}^{N_1} k_{I_{j,1}}(m) + \sum_{j=1}^{N_2} k_{I_{j,2}}(m). \quad (12)$$

From the cumulants of I_a , the pdf of I_a can be approximated as a known distribution by employing the method of moments. We use a log-normal distribution to approximate the pdf of I_a as proposed in [7]:

$$f_{I_a}(z) = \frac{1}{z\sqrt{2\pi\sigma_{I_a}^2}} \exp\left(-\frac{(\ln(z) - \mu_{I_a})^2}{2\sigma_{I_a}^2}\right). \quad (13)$$

The parameters μ_{I_a} and $\sigma_{I_a}^2$ of the pdf can be obtained from the first and second cumulant computations as

$$k_{I_a}(1) = \mathbf{E}[I_a] = \exp[\mu_{I_a} + \sigma_{I_a}^2 / 2], \quad (14)$$

$$k_{I_a}(2) = \mathbf{Var}[I_a] = (\exp[\sigma_{I_a}^2] - 1) \exp[2\mu_{I_a} + \sigma_{I_a}^2]. \quad (15)$$

5. Numerical Results

The parameter values used for numerical experiments are summarized in Table 1. The path loss model used in this study is the C1-suburban WINNER model which is proposed for 5GHz band by WINNER project [11].

In Figure 3, the CDF of I_a obtained by (13) is compared with the CDF by Monte Carlo simulation. The proposed log-normal approximation shows a good agreement with the simulation result. The analytic CDF matches with the simulation particularly in the tail region. Since the protection of the radar requires extremely low interference violation probability, the accuracy in the tail region is significantly important.

As more secondary users want to access the radar spectrum, i.e. as the density of the WLANs increases, the stricter I_{thr} should be applied to the secondary users in order to keep the same level of aggregate interference. This results in reduced chances of accessing the spectrum for the secondary users close to the radar. Figure 4 presents the probability of transmission for a secondary user at a distance of 10 km from the radar. The density of the secondary users per km^2 varies from 1 to 100. When the conventional DFS scheme is applied, the probability of transmission decreases sharply as the density of the secondary users grows. This is also the case for the users facing the radar main beam under the temporal DFS scheme. However, the secondary users who do not face the radar beam enjoy the transmission probability of almost one.

Note that the radar has an antenna with narrow beam width. Thus, the secondary users face the radar main beam only in a small fraction of time. Figure 5 illustrates the portion of secondary users that can have access to the radar spectrum within a circle of 20 km from the radar. Under the conventional DFS scheme, more than half of the secondary users cannot use the spectrum when the density is higher than 40 users per km^2 . On the contrary, most of the secondary users can utilize the radar spectrum when the temporal DFS is applied even when the density reaches 100 users per km^2 . Only those who face radar main beam are temporarily prevented from transmitting.

The previous figures suggest that the opportunity for a secondary user varies depending on time. This effect is illustrated in Figure 6 which shows the probability of transmission in the temporal domain. Let us consider a WLAN who is 10 km away from the radar under the density of 60 users per km^2 . This figure demonstrates that the secondary user has higher chance to transmit most of the time by using the temporal DFS. Note that we assume it takes 30 seconds for the radar to complete a rotation (RPM of 2). During one minute, the secondary user can transmit 99.45% of the time with the probability of almost 1 when the temporal DFS is employed. Although the transmission can be interrupted once every 30 seconds, its impact would be negligible in most of mobile data services as long as the interruption pattern is known. The probability of transmission is fixed to 19% all the time for the conventional DFS case.

6. Conclusion

We quantified the number of WLANs that can access the radar spectrum as secondary users. Particularly, we examined how much opportunity the secondary users can obtain if they exploit the temporal variation of interference due to the regular rotation of radar antenna. The number of active secondary users is calculated under the condition that the aggregate interference to the radar does not exceed the interference threshold, guaranteeing no harmful interference to the primary user. The transmission of each WLAN is regulated by an interference protection mechanism, temporal DFS, which takes into account the radar antenna pattern and rotation. We compared the performance of the temporal DFS with the conventional DFS in terms of the probability of transmission in a certain distance to the radar with various densities of secondary users.

It is shown that by using the temporal DFS as the interference control mechanism WLANs can increase the probability of accessing the radar spectrum significantly compared with the conventional DFS mechanism. Therefore, the radar spectrum is better utilized and the radar is protected from harmful interference. In this work, we assumed that the WLANs can accurately estimate the temporal variation of propagation loss. The study of miss detection, false alarm, and inaccurate estimation of temporal radar characteristics remain as the direction for future research.

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Table 1: Summary of parameter values for numerical analysis

Parameters	Values
Primary user (meteorological radar)	
Center frequency [MHz]	5600
Antenna height [meter]	30
Transmission power [dBm]	84
Bandwidth [MHz]	4
Antenna gain (main beam), $G_{rad}^{\max}$ [dBi]	40
Antenna gain (side lobe), $G_{rad}^{\min}$ [dBi]	0
Antenna beam width, θ_{MB}	2
Rotation per minute (RPM)	2
INR threshold [dBm]	-9
Aggregate interference threshold, A_{thr} [dBm]	-109
Apportionment margin [dB]	6
Fast fading margin [dB]	10.6
Probability of maximum interference, β	0.00001
Secondary user (WLAN)	
Antenna height [meter]	1.5
Transmission power, P_{tx} [dBm]	20
Bandwidth [MHz]	20
Antenna gain, G_{wlan} [dBi]	0
Common parameters	
Radius of evaluation area, R [km]	150
Shadow fading standard deviation, $\sigma_{x_j}^{dB}$ [dB]	8
Wall penetration loss [dB]	10

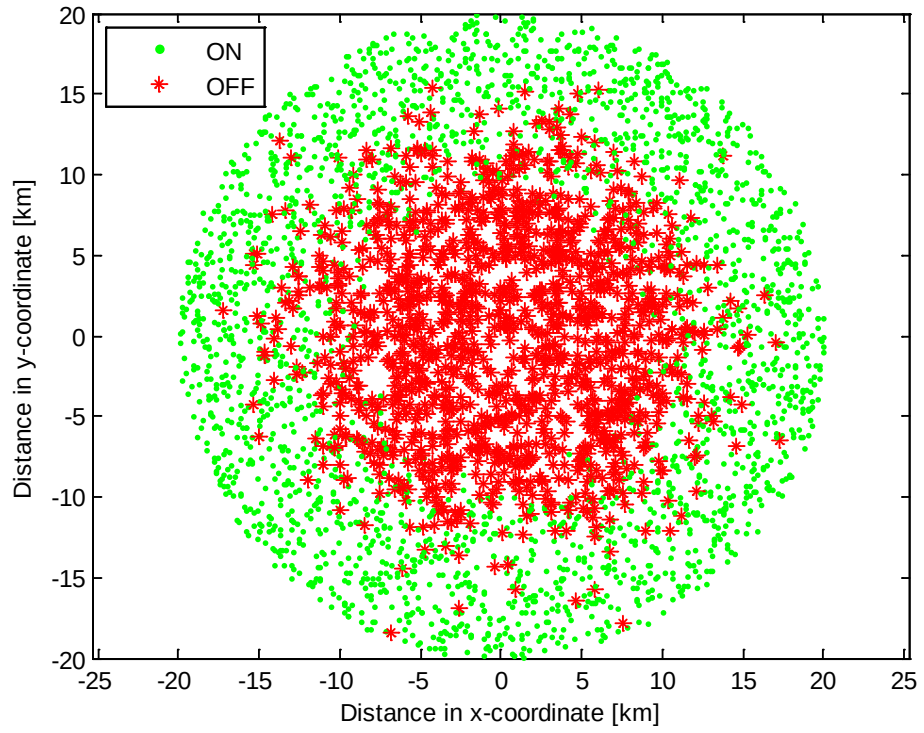


Figure 1: A graphical representation of the exclusion region under the conventional DFS scheme.

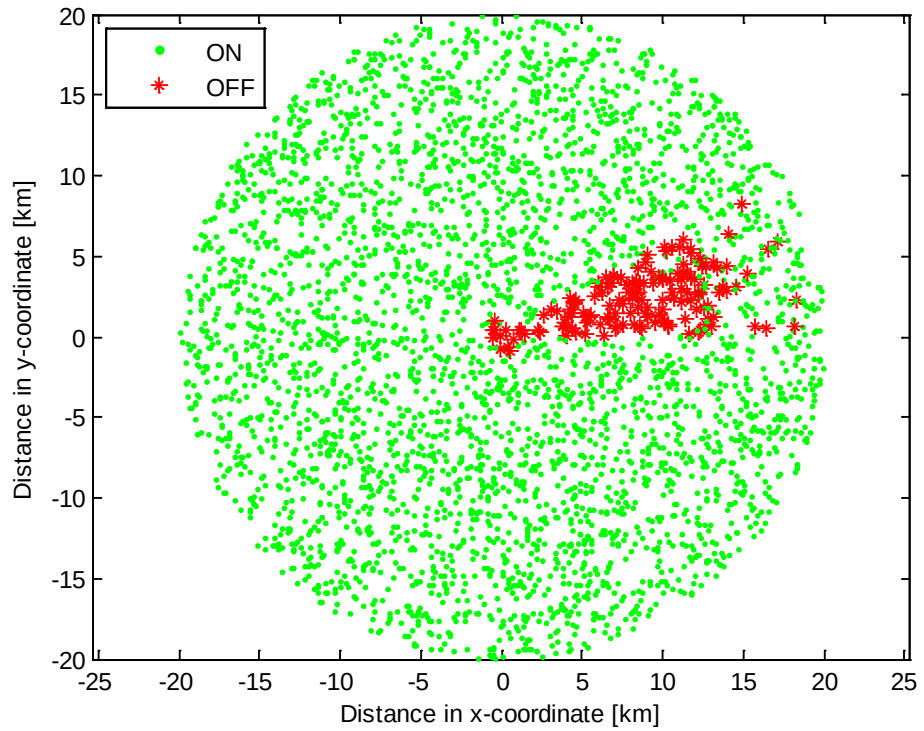


Figure 2: A graphical representation of the exclusion region under the proposed temporal DFS scheme.

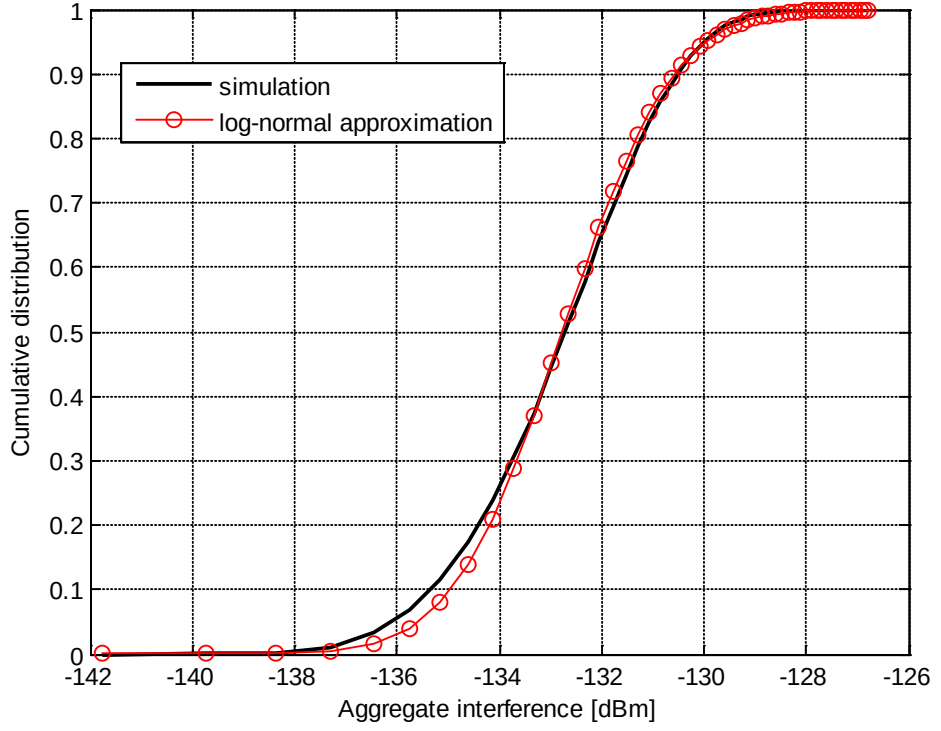


Figure 3: CDF of aggregate interference I_a (secondary user density is 1 per km^2 and $I_{thr} = -135$ dBm).

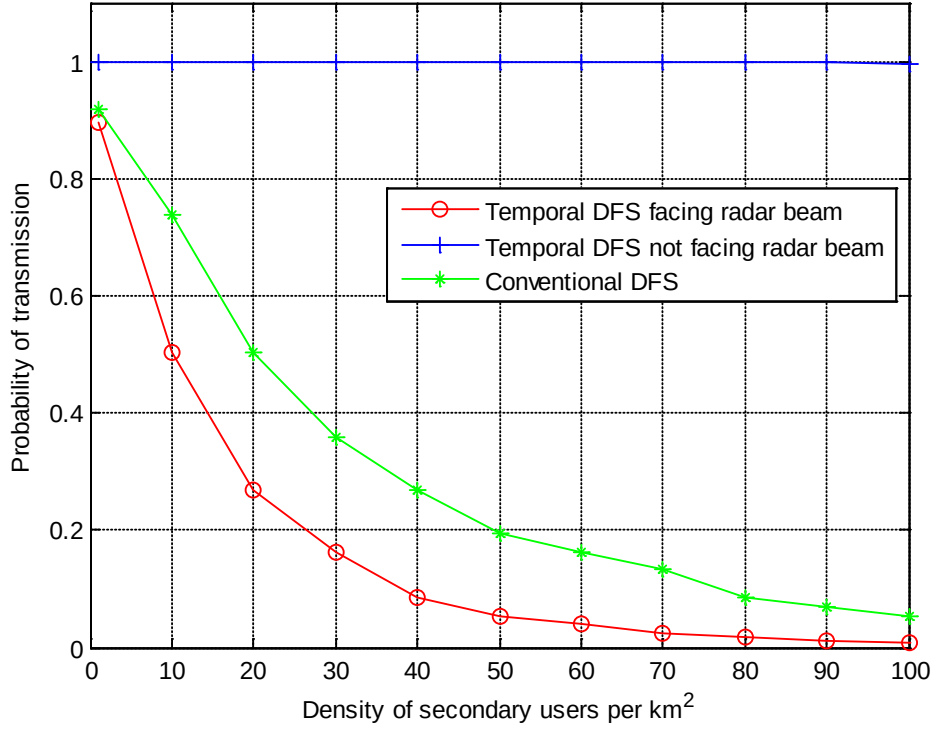


Figure 4: Probability that a secondary user 10 km away from the radar can transmit under conventional DFS and temporal DFS schemes.

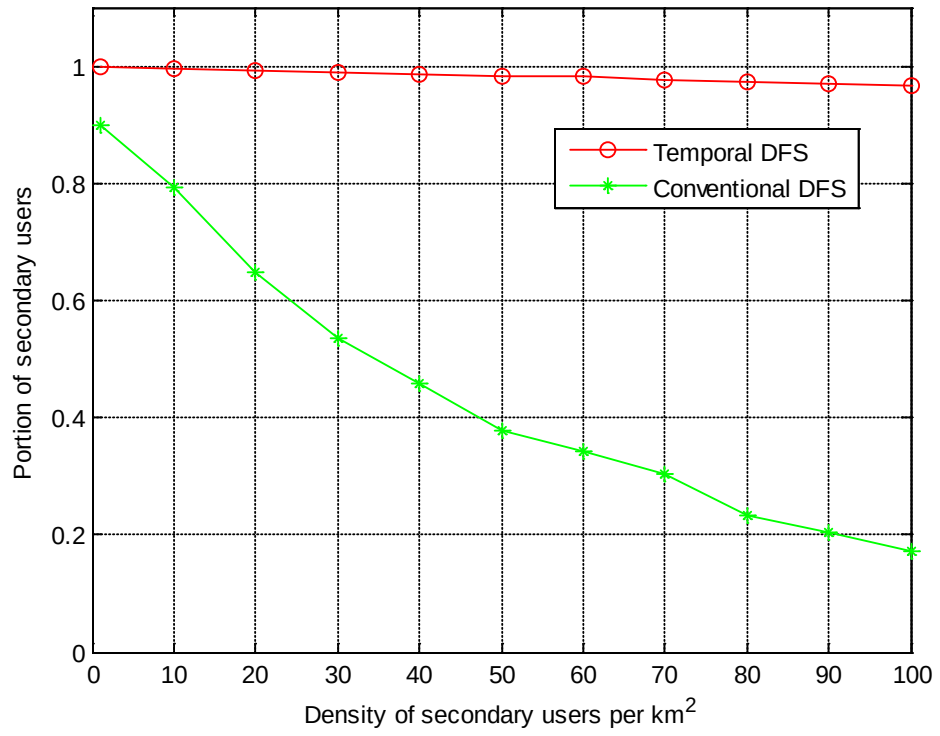


Figure 5: Portion of secondary users who can transmit on the radar spectrum among the users having distance from the radar less than 20 km.

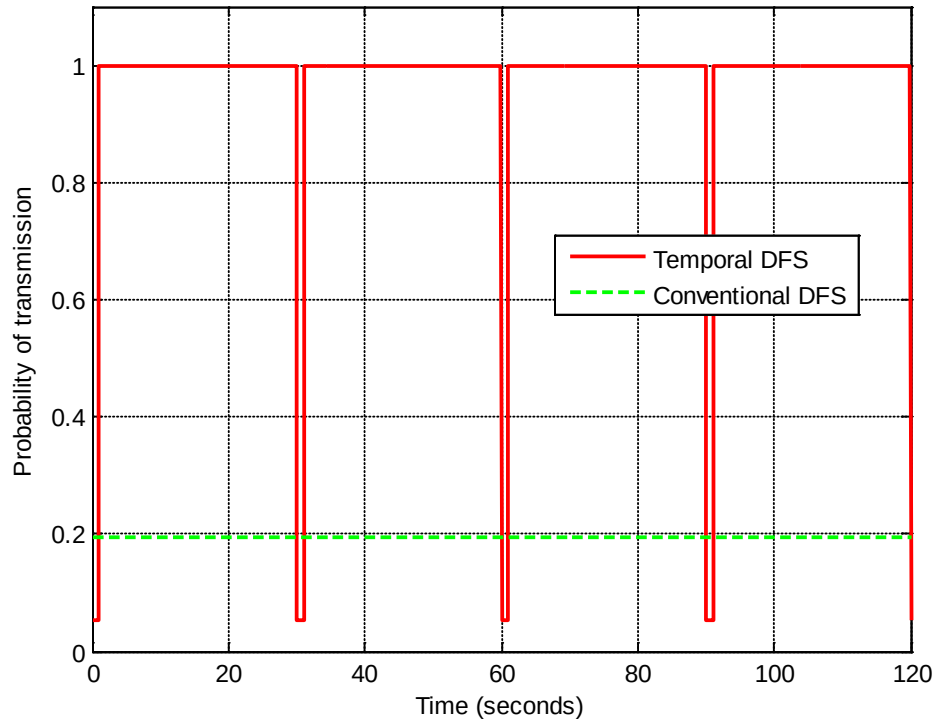


Figure 6: Probability of transmission as a function of time for a secondary user 10 km away from the radar.