

# A simplified evaluation of protection distance in areal spectrum sharing

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**Abstract:** This paper focuses on a spectrum sharing cellular system primarily used by noncellular, stand-alone wireless systems. Geographically deployed base stations (BSs) that cover the service area to continuously provide spectrum sharing act as a secondary system, where the sharing condition is provided to the total interference power at the primary system. In this case, how much transmission power from each BS is allowed on the shared spectrum? By applying the propagation model originally used to evaluate cellular systems, this paper numerically and theoretically reveals the relation between the protection distance (PD) and allowable transmission power.

**Keywords:** Spectrum Sharing, Cellular System, Protection Distance

**Classification:** Wireless communication technologies

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## 1. Introduction

To cope with the rapid traffic growth of mobile communication, spectrum sharing has received attention [1]. The idea is basically to reuse the spectrum among different systems while keeping enough distance from each other to attenuate radio waves for both primary and secondary stations or to use the spectrum when it is not used by the primary station. Dynamic methods, such as those using the primary location database referred by the secondary system, have been studied [2-3]. To the best of our knowledge, secondary systems are generally assumed to be unlicensed or private systems, wherein secondary stations are isolated or randomly distributed in some non-restricted areas.

Reference [4] estimated the protection distance (PD) from the primary DTV (digital television) system for unlicensed devices distributed uniformly outside the restriction area in a Poisson point process (PPP). Because of the probable uneven distribution of the secondary stations due to a PPP, the derived formula and results in [4] are hard to apply for the case of geographically fixed secondary stations, such as base stations (BSs) of cellular systems. In addition, estimation accuracy depends on the probability density functions assumed appropriately for aggregated interference power.

The authors are interested in a spectrum sharing cellular system, i.e., a system in which the cellular system is secondary. Here, we focus on the downlink where the BSs outside the PD share the spectrum of the noncellular system. Using a somewhat simple and pragmatic channel model, this paper reveals the relation between the PD and the allowable transmission power for BSs under interference conditions. Following a statement of the system model in section 2, section 3 analyzes aggregated interference power on average and derives a closed-form formula, which leads to an expected allowable transmission power for a given PD. In section 4, computer simulation verifies the derived formula in section 3 and numerically provides the relation between the allowable transmission power and the PD, and also discusses the effect of the density of the cellular system.

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## 2. System Model

As shown in Fig. 1, BSs farther away from the primary station than the PD,  $r_{\min}$ , share the spectrum. Let the transmission power from each BS of the secondary system outside the protection area be  $P_{\min}$ . The BS forms a hexagonal cell and is infinitely located regularly on a ground plane, where the global curvature is not considered for simplicity. In computer simulation, however, BSs are limited within

a well-defined large finite area whose size is  $x_A \times y_A$ . The primary station is set to the middle of the center cell. Here, the PD is defined as a horizontal distance.

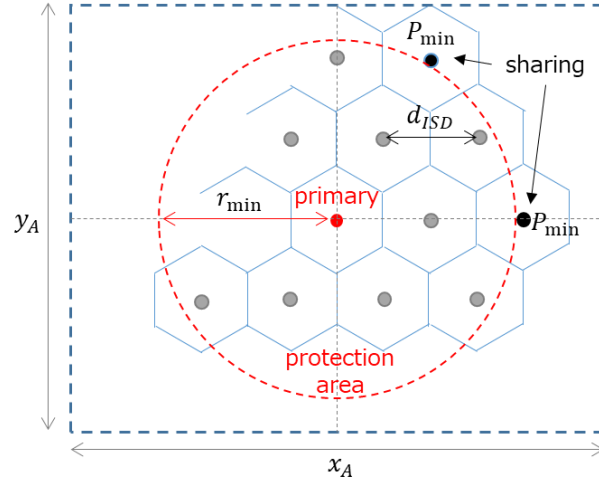


Fig. 1 System model layout

The receiving antenna gain,  $G_{\text{pri}}$ , and the height of the primary antenna,  $h_{\text{pri}}$ , are assumed to be 12 dBi and 10 m, respectively, as determined by referring to a typical value of field pickup unit. That is operated as wireless transmission system for television program contribution, and its operating band is one of a candidate band for the spectrum sharing in Japan [5,6]. The parameters of the secondary BSs, such as the antenna height,  $h_{\text{sec}}$ , are based on the 3GPP urban macro (UMa) model [7]. System parameters are summarized in Table I. As calculating pathloss between the primary and BS, we assume the mixed situation of LOS and NLOS outdoor environments, and apply user terminal (UT) parameters in the UMa model for the primary parameters. Other parameters in Table I are stated in the following section. Here,  $[x]$  represents the decibel expression of the true value of  $x$ .

Table I. System Parameters

Shared frequency [GHz]	$f = 2.3$
Primary station	
Antenna Gain [dBi]	$[G_{\text{pri}}] = 12$
Antenna Height [m]	$h_{\text{pri}} = 10$
Noise Power [dBm]	$[N] = -90$
Secondary stations	
Antenna Gain [dBi]	$[G_{\text{sec}}] = 9.3$
Antenna Height [m]	$h_{\text{sec}} = 25$
Inter-Site Distance (ISD) [m]	$d_{\text{ISD}} = 500$
Pathloss	For horizontal distance, $r$ ,
$A$	$A = \begin{cases} A_{\text{LOS1}} = 3334.3, & r < d_{\text{BP}} \text{ in LOS} \\ A_{\text{LOS2}} = 4.4155 \times 10^{-4}, & r \geq d_{\text{BP}} \text{ in LOS} \\ A_{\text{NLOS}} = 36.940, & \text{in NLOS} \end{cases}$
$\alpha$	$d_{\text{BP}} = \frac{4(h_{\text{pri}} - h_{\text{Epri}})(h_{\text{sec}} - h_{\text{Esec}})}{\lambda} = 6624[\text{m}]$ $\alpha = \begin{cases} \alpha_{\text{LOS1}} = 2.2, & r < d_{\text{BP}} \text{ in LOS} \\ \alpha_{\text{LOS2}} = 4.0, & r \geq d_{\text{BP}} \text{ in LOS} \\ \alpha_{\text{NLOS}} = 3.908 & \text{in NLOS} \end{cases}$
$\sigma$ [dB], $\beta$	$\sigma = \begin{cases} \sigma_{\text{LOS}} = 4 & \text{in LOS} \\ \sigma_{\text{NLOS}} = 6 & \text{in NLOS} \end{cases}$ $\therefore \beta = \begin{cases} \beta_{\text{LOS}} = 1.528 & \text{in LOS} \\ \beta_{\text{NLOS}} = 2.597 & \text{in NLOS} \end{cases}$

LOS probability	$g(r) = \frac{18}{r} + \exp\left(-\frac{r}{63}\right)\left(1 - \frac{18}{r}\right)$	(1)
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### 3. Approximate analysis of aggregated interference power

#### 3.1 General formula for a simple path loss model

The transmission power of the BSs,  $P_{\min}$ , is required to meet an interference condition where the total interference power  $I$  at the primary station is less than or equal to  $K$  times the noise power  $N$ , i.e.,  $I/N \leq K$ . An element of the interference power  $I_0$  from a BS outside the protection area is calculated as follows.

$$[I_0] = [P_{\min}] + [G_{\text{sec}}] + [G_{\text{pri}}] - [L] \quad (2)$$

$L$  is the path loss between a secondary BS and the primary station and is expressed as  $L(d) = A\xi d^\alpha$ , where  $\xi$  is shadow loss, which obeys a log-normal distribution with a standard deviation of  $\sigma$  dB and is independent of the distance  $d$ .  $d$  is the 3-dimensional distance between two stations, although it is approximated as horizontal distance  $r$  if the height difference between two antennas is too small for  $r$ , i.e.,  $d \cong r$ .  $A$  is a constant. These parameters are listed in Table I and vary depending on the environment, LOS or NLOS. For the LOS condition, there are two parameters separated inside and outside the breakpoint (BP).

BSs are uniformly distributed with a density of approximately  $\rho$  since they are located regularly, and  $\rho$  is equal to the inverse of the hexagonal cell area.

$$\rho = \frac{2}{\sqrt{3}d_{\text{ISD}}^2} \quad (3)$$

If all BSs outside protection area share the spectrum, the total interference power  $\bar{I}$  at the primary station can be approximately expressed as follows, where  $p(\xi)$  is the probability density function of the shadowing loss.

$$\begin{aligned} \bar{I} &\cong \int \int_{r_{\min}}^{\infty} \frac{P_{\min} G_{\text{pri}} G_{\text{sec}}}{L(d)} 2\pi r \rho dr p(\xi) d\xi \\ &= \frac{2\pi\rho P_{\min} G_{\text{pri}} G_{\text{sec}}}{A} \int_{r_{\min}}^{\infty} r^{1-\alpha} dr \int \frac{p(\xi)}{\xi} d\xi \\ &= \frac{2\pi\rho P_{\min} G_{\text{pri}} G_{\text{sec}}}{(\alpha - 2)A} \beta r_{\min}^{2-\alpha} \end{aligned} \quad (4)$$

$$\beta = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\infty} 10^{\frac{-\chi}{10}} e^{-\frac{\chi^2}{2\sigma^2}} d\chi = \exp\left(\frac{(\sigma \ln 10)^2}{200}\right) \quad (5)$$

Here, the convergence condition for Eq. (4) is  $\alpha > 2$ , which is satisfied by the UMa model. Eq. (1) gives the LOS probability  $g(r)$  as a function of horizontal distance  $r$ , which can be applied when UT antenna height is 10 m and  $r > 18$  m.

#### 3.2 Aggregated formula for the urban macro model

Assuming a sufficiently large,  $r$ ,  $g(r)$  is approximated as follows.

$$g(r) \cong \frac{18}{r} \quad (6)$$

Following the same method used to derive Eq. (4), the total interference power on average is expressed by Eq. (7) with three integral components: LOS both inside and outside the BP and NLOS components. Note that  $d'_{\text{BP}}$  is defined as  $d'_{\text{BP}} = \max(r_{\min}, d_{\text{BP}})$ . In the case of  $d'_{\text{BP}} = r_{\min}$ , the integral component for the LOS inside the BP vanishes because the PD is larger than the BP; therefore, the average

interference power effectively consists of two integral components.

$$\begin{aligned}
 \bar{I} &= 2\pi\rho P_{\min} G_{\text{pri}} G_{\text{sec}} \left\{ \beta_{\text{LOS}} \left( \int_{r_{\min}}^{d'_{\text{BP}}} g(r) \frac{r^{1-\alpha_{\text{LOS1}}}}{A_{\text{LOS1}}} dr \right. \right. \\
 &\quad \left. \left. + \int_{d'_{\text{BP}}}^{\infty} g(r) \frac{r^{1-\alpha_{\text{LOS2}}}}{A_{\text{LOS2}}} dr \right) \right. \\
 &\quad \left. + \frac{\beta_{\text{NLOS}}}{A_{\text{NLOS}}} \int_{r_{\min}}^{\infty} (1-g(r)) r^{1-\alpha_{\text{NLOS}}} dr \right\} \\
 &= 2\pi\rho P_{\min} G_{\text{pri}} G_{\text{sec}} \left\{ \frac{18\delta_{\text{LOS1}}}{\alpha_{\text{LOS1}} - 1} (r_{\min}^{1-\alpha_{\text{LOS1}}} - d'_{\text{BP}}{}^{1-\alpha_{\text{LOS1}}}) \right. \\
 &\quad \left. + \frac{18\delta_{\text{LOS2}}}{\alpha_{\text{LOS2}} - 1} d'_{\text{BP}}{}^{1-\alpha_{\text{LOS2}}} \right. \\
 &\quad \left. + \delta_{\text{NLOS}} \left( \frac{r_{\min}^{2-\alpha_{\text{NLOS}}}}{\alpha_{\text{NLOS}} - 2} - 18 \frac{r_{\min}^{1-\alpha_{\text{NLOS}}}}{\alpha_{\text{NLOS}} - 1} \right) \right\} \\
 &= 2\pi\rho P_{\min} (a_1 r_{\min}^{1-\alpha_{\text{LOS1}}} + a_2 r_{\min}^{2-\alpha_{\text{NLOS}}} - a_3 r_{\min}^{1-\alpha_{\text{NLOS}}} - \delta_0)
 \end{aligned} \tag{7}$$

Here,

$$\begin{aligned}
 \delta_{\text{LOS1}} &= \beta_{\text{LOS}}/A_{\text{LOS1}}, \quad \delta_{\text{LOS2}} = \beta_{\text{LOS}}/A_{\text{LOS2}}, \quad \delta_{\text{NLOS}} = \beta_{\text{NLOS}}/A_{\text{NLOS}} \\
 a_1 &= \frac{18\delta_{\text{LOS1}}}{\alpha_{\text{LOS1}} - 1}, \quad a_2 = \frac{\delta_{\text{NLOS}}}{\alpha_{\text{NLOS}} - 2}, \quad a_3 = \frac{18\delta_{\text{NLOS}}}{\alpha_{\text{NLOS}} - 1}
 \end{aligned} \tag{8}$$

and

$$\begin{aligned}
 \delta_0 &= \frac{18\delta_{\text{LOS1}}}{\alpha_{\text{LOS1}} - 1} d'_{\text{BP}}{}^{1-\alpha_{\text{LOS1}}} - \frac{18\delta_{\text{LOS2}}}{\alpha_{\text{LOS2}} - 1} d'_{\text{BP}}{}^{1-\alpha_{\text{LOS2}}} \\
 &= a_1 d'_{\text{BP}}{}^{1-\alpha_{\text{LOS1}}} - 6\delta_{\text{LOS2}} d'_{\text{BP}}{}^{1-\alpha_{\text{LOS2}}}
 \end{aligned} \tag{9}$$

Applying the parameters in Table I to the above, the coefficients are given by the numerical values below.

$$a_1 = 6.875 \times 10^{-3}, \quad a_2 = 0.03685, \quad a_3 = 0.4352.$$

The expected transmission power  $\bar{P}_{\min}$  from a BS satisfying the condition of  $\bar{I}/N < K$  is given by Eq. (10).

$$\begin{aligned}
 \bar{P}_{\min} &= \frac{\bar{I}}{2\pi\rho G_{\text{pri}} G_{\text{sec}} (a_1 r_{\min}^{-1.2} + a_2 r_{\min}^{-1.908} - a_3 r_{\min}^{-2.908} - \delta_0)} \\
 &< \frac{\bar{I}}{KN} \\
 &< \frac{\bar{I}}{2\pi\rho G_{\text{pri}} G_{\text{sec}} (a_1 r_{\min}^{-1.2} + a_2 r_{\min}^{-1.908} - a_3 r_{\min}^{-2.908} - \delta_0)}
 \end{aligned} \tag{10}$$

Eq. (10) shows that the expected transmission power approximately increases in proportion to the  $(\alpha_{\text{NLOS}} - 2)$ -th power of  $r_{\min}$  when  $r_{\min}$  is large enough.

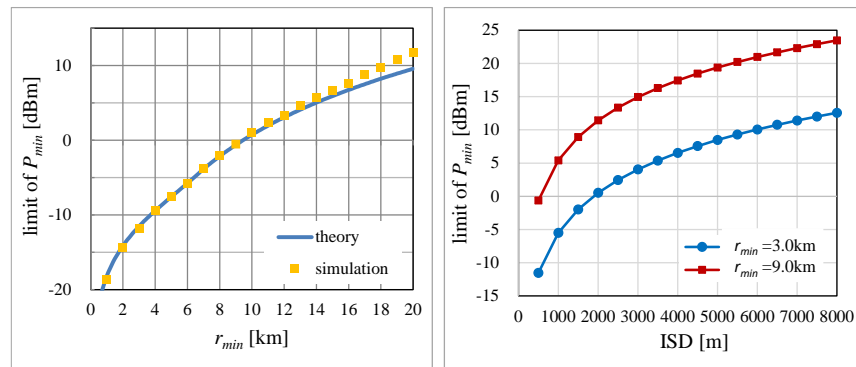
#### 4. Evaluation of the protection distance

This section sets the PD to plural concrete values and calculates total channel gains between the primary and the sharing BSs through computer simulations with the parameters shown in Table I. Unlike the previous analysis, BSs are discrete and located within a 50 km×50 km finite area. Simulations include a stochastic process for the shadowing loss and LOS/NLOS situation; therefore, they were repeated 10000 times for each parameter. Here an allowable interference coefficient  $K = 0.1$  as an example.

Figure 2(a) compares the results from Eq. (10) and the computer simulations to confirm the validity of the theoretical analysis in section 3. It can be seen that they agree well. In detail, the simulation results obtained for the limit of  $P_{\min}$  are slightly higher than those obtained with Eq. (10) at larger  $r_{\min}$  values because the

computer simulation limits the evaluation area; therefore, it estimates the total interference power to be lower than that of the theoretical equation. Considering the limit of  $P_{\min}$  itself, more than 9 km is required for the PD to allow a transmission power of 0 dBm. It is noteworthy that the interference in the formulation and simulation are expressed by average, and rigorous determination of the allowable transmission power might require to take margin corresponding to the deviation of the stochastic elements such as the shadowing.

Derived closed form Eq. (10) also gives relationships between allowable transmission power  $P_{\min}$  and density  $\rho$  of the BS under a fixed PD and  $K$ . Fig. 2(b) shows them under PD=3km, 9km, respectively. These plots can be options to deploy and to operate BSs. For example,  $P_{\min}$  can be increased by reducing  $\rho$  that corresponds to increase ISD as shown by (3). In addition, if "density" is defined by simultaneous operating BS, it makes more flexible options by dividing time and spectrum into some group of slots and/or sub-bands, and by reusing each resource by BSs grouped with keeping a certain  $\rho$ .



(a) Comparison with simulation

(b) Relationships with ISD

Fig. 2 Allowable transmission power at a certain PD meeting  $\bar{I}/N \leq K = 0.1$ 

## 5 Conclusion

We analytically and numerally evaluated areal spectrum sharing using the UMa model for cellular systems. This propagation model gives a stochastic process not only to the shadowing loss but also to the LOS/NLOS status. This paper first derives an approximate formula for the total interference power on average, leading to the expected transmission power meeting the interference condition in an average sense. We also show that the computer simulation agrees numerically with the approximated formula. According to this result, for example, a 0 dBm transmission power requires a 9 km PD, on average in the case the density of BS corresponding to ISD=500m. In addition, the derived closed form expression indicates the transmission power restriction can be eased by reducing the density of operating BSs. Its relationship could give some insights to deploy and/or operate BS more flexibly with various options.

## Acknowledgments

This research is supported by the Ministry of Internal Affairs and Communications in Japan (JPJ000254).