The Coexistence of OFDM-Based Systems Beyond 3G with Fixed Service Microwave Systems

Han-Shin Jo, Hyun-Goo Yoon, Jaewoo Lim, Woo-Ghee Chung, Jong-Gwan Yook, and Han-Kyu Park

Abstract: **In this paper, we study the coexistence of orthogonal frequency division multiplexing (OFDM)-based systems beyond 3G (B3G) and point-to-point (P-P) fixed service (FS) microwave systems. The advanced general analytical model derived via a power spectral density (PSD) analysis proposed in this paper has two advantages in comparison with the conventional minimum coupling loss (MCL) method. First, the interfering signal power that appears in the band of a victim system can be easily assessed without a spectrum emission mask. Second, when transmit power is not allocated to some subcarriers overlapping the band of the victim system in order to mitigate B3G OFDM-based systems interference with other systems, the general analytical model can successfully assess the interference from the B3G systems into FS systems, whereas the MCL method incorporating the spectrum emission mask cannot be applied in the presence of the same interference condition. The proposed model can be derived in a closed form and is simply implemented with the help of simulation, and thus the solution can be obtained in significantly reduced time. Through application of the proposed model, coexistence results are analyzed in a co-channel and adjacent channel with respect to guard band and minimum separation distance.**

Index Terms: **Beyond 3G (B3G) orthogonal frequency division multiplexing (OFDM)-based system, coexistence, guard band, minimum coupling loss (MCL) method, minimum separation distance, point-to-point (P-P) fixed services (FS) systems, power spectral density (PSD).**

I. INTRODUCTION

The framework and overall objectives of the systems beyond international mobile telecommunication (IMT)-2000 are defined by the international telecommunication union (ITU) [1]. Those overall objectives include the target bit rates: Approximately 100 Mbps and 1 Gbps with high mobility and low mobility, respectively. The simple assumption of achieving bit rates of 100 Mbps for most users means that the bandwidth will typically need to be 100 MHz [2]. Taking into account sufficient mobility and an acceptable trade-off between cost and full area coverage, it is suggested that the suitable frequency range for beyond 3G (B3G) services is below 6 GHz.

Both 3400–4200 MHz and 4400–5000 MHz overlapping with the potential candidate bands for B3G systems are currently allocated to point-to-point (P-P) fixed service (FS) microwave systems. Therefore, the impact of the interference of B3G on P-P FS systems needs to be studied. Moreover, orthogonal frequency division multiplexing (OFDM) is currently considered the most promising modulation scheme to support B3G future wireless multimedia communications systems, owing to its excellent performance in combating multipath fading and superb efficiency in terms of use of available bandwidth [3].

There are three basic schemes dedicated to analysis of the interference potential between systems that have been addressed in previous work [4], namely, the minimum coupling loss (MCL) method, the enhanced minimum coupling loss (E-MCL), and the Monte Carlo method. First, the MCL method utilizing analytical approximations is simple to use and can be constructed in less time than the other models. However, it is conservative and gives spectrally more pessimistic results than are obtained by the other methods. Moreover, this method can be only adopted as a special case of the "static" interference situations.

A coexistence analysis based on the MCL approach of universal mobile telecommunications system (UMTS) with P-P FS systems was reported in [5] and [6]. In [5], UMTS interference on the FS systems is analyzed and discussed. The coexistence study [6] applied a spectrum emission mask, an essential parameter for adjacent frequency sharing analysis, to evaluate the attenuation of the interference signal power in the band of the victim system. However, that method can not be utilized in assessing interference caused by B3G systems for which there is no spectrum emission mask. Furthermore, even if there is a spectrum emission mask, the MCL method can not be applied to evaluate the B3G interference with other systems when the transmit power is not allocated to some subcarriers overlapping the band of the victim system in order to mitigate the B3G interference to other systems. The main contribution of this paper is the development of a general analytical model that overcomes the limitations of the MCL scheme for evaluating interference in B3G OFDM-based systems.

The remainder of this paper is organized as follows. In Section II, a interference model suitable for OFDM systems is formulated and a wave propagation model is described in detail. Section III is devoted to describing the system parameters and interference scenarios. The coexistence results are executed in a co-channel and adjacent channel in Section IV. Finally, the conclusions are presented in Section V.

II. MODEL FOR STUDY OF COEXISTENCE

A. Interference

An assessment of frequency sharing is based on the concept of permissible interference power at the antenna terminals of

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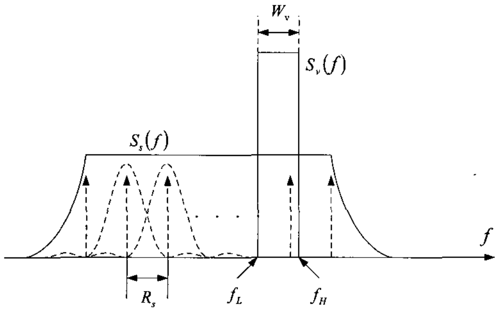

Fig. 1. PSD of OFDM-based systems B3G overlapping PSD of P-P FS systems.

a victim system. Hence, the attenuation required to limit the level of interference between an interfering system to the permissible interference power for $p\%$ of the time is represented by the "minimum required loss." This is the loss that needs to be equaled or exceeded by the predicted path loss for all but $p\%$ of the time [7], [8]. When p is a small percentage of the time, in a range of 0.001% to 1.0%, the interference is referred to as "short term," while it is referred to as "long term" for $p \geq 20\%$.

The minimum required loss in dB is described by

$$L_{\min} = P_t + G_t + G_r + L_r - I_{\max} \tag{1}$$

where P_t is the transmit power of interferer (dBW) in the reference bandwidth and $I_{\max}$ is the maximum permissible interference power (dBW) in the reference bandwidth to be exceeded for no more than $p\%$ of the time at the terminals of the antenna of receiving P-P FS systems. The antenna gains are to be G_t and G_r for the interfering transmitter and the victim receiver in dBi, respectively. Both antenna gains are towards the physical horizon on a given azimuth. L_r is the interfering signal power loss, which accounts for the fraction of interfering signal power that appears in the band of the victim system with dB scale.

The interfering signal power loss L_r for the interfering system with OFDM is derived through a power spectral density (PSD) analysis of the OFDM signals. Assuming an OFDM system having N subcarriers and a rectangular pulse, the PSD of the OFDM signal is represented as

$$S_s(f) = \sum_{i=0}^{N-1} \frac{P_s}{R_s} \mathrm{sinc}^2\left(\frac{f}{R_s} - i\right) \tag{2}$$

where P_s is the power of a single OFDM subcarrier, and R_s is the subcarrier spacing. Here, the PSD of the FS system is rectangular.

$$S_v(f) = \frac{P_v}{W_v} \mathrm{rect}\left(\frac{f}{W_v}\right) \tag{3}$$

where P_v and W_v are the transmit power and bandwidth of P-P FS systems, respectively. Fig. 1 shows that the PSD of B3G OFDM-based systems overlaps the PSD of P-P FS systems.

Interfering signal power attenuation by bandwidth overlapping ratio can be expressed as

$$L_r = 10\log_{10}\left(\frac{\int_{f_c-W_v/2}^{f_c+W_v/2} S_s(f)\,df}{P_t}\right) \tag{4}$$

where f_c is the center frequency of the victim receiver. Applying the definition of (2) and $\mathrm{sinc}x = \sin\pi x/\pi x$, the numerator of (4) can be formulated as

$$\begin{aligned}\int_{f_c-W_v/2}^{f_c+W_v/2} S_s(f)\,df &= \int_{f_c-W_v/2}^{f_c+W_v/2} \sum_{i=0}^{N-1} \frac{P_s}{R_s} \mathrm{sinc}^2\left(\frac{f}{R_s} - i\right) df \\ &= \sum_{i=0}^{N-1} \frac{P_s}{R_s} \int_{f_c-W_v/2}^{f_c+W_v/2} \frac{\sin^2\left[\pi\left(\frac{f}{R_s} - i\right)\right]}{\left[\pi\left(\frac{f}{R_s} - i\right)\right]^2} df.\end{aligned} \tag{5}$$

In (5), let $h = \pi(f/R_s - i)$, $R_+ = f_c/R_s + W_v/2R_s$, and $R_- = f_c/R_s - W_v/2R_s$.

Then, (5) can be rewritten as

$$\int_{f_c-W_v/2}^{f_c+W_v/2} S_s(f)\,df = \sum_{i=0}^{N-1} \frac{P_s}{\pi} \int_{R_- - i}^{R_+ - i} \frac{\sin^2 h}{h^2}. \tag{6}$$

Using the powers of trigonometric functions, $\sin^2 x = (1 - \cos 2x)/2$, (6) can be induced as

$$\int_{f_c-W_v/2}^{f_c+W_v/2} S_s(f)\,df = \sum_{i=0}^{N-1} \frac{P_s}{2\pi} \int_{R_- - i}^{R_+ - i} \frac{1 - \cos 2h}{h^2} dh. \tag{7}$$

The integral in (7) can be evaluated using [9]

$$\int_a^b \frac{\cos 2x}{x^2} = \frac{\cos 2a}{a} - \frac{\cos 2b}{b} - 2\int_a^b \frac{\sin 2x}{x} dx. \tag{8}$$

Using the equality of $\int_a^b \frac{\sin 2x}{x}\,dx = \sum_{k=1}^{\infty} \frac{(-1)^{k-1}}{(2k-1)(2k-1)!} \times \left[(2b)^{2k-1} - (2a)^{2k-1}\right]$ in [9], (8) can be rewritten as

$$\int_a^b \frac{\cos 2x}{x^2} = x - 2\left[\sum_{k=1}^{\infty} \frac{(-1)^{k-1}\left[(2b)^{2k-1} - (2a)^{2k-1}\right]}{(2k-1)(2k-1)!}\right]. \tag{9}$$

Employing (9), (7) can be represented as (10). Hence, using the result (10), the interfering signal power attenuation can be written as (11).

$$\begin{aligned}\int_{f_c-W_v/2}^{f_c+W_v/2} S_s(f)\,df = \sum_{i=0}^{N-1} \frac{P_s}{2\pi}&\left[\frac{1}{\pi(R_- - i)} - \frac{1}{\pi(R_+ - i)} - \frac{\cos 2\pi(R_- - i)}{\pi(R_- - i)} + \frac{\cos 2\pi(R_+ - i)}{\pi(R_+ - i)}\right. \\ &\left. + 2\sum_{k=1}^{\infty} \frac{(-1)^{k-1}\left[(2\pi(R_+ - i))^{2k-1} - (2\pi(R_- - i))^{2k-1}\right]}{(2k-1)(2k-1)!}\right].\end{aligned} \tag{10}$$

$$L_r = 10\log_{10}\left[\sum_{i=0}^{N-1}\frac{P_s}{2\pi P_t}\left[\frac{1}{\pi(R_- - i)} - \frac{1}{\pi(R_+ - i)} - \frac{\cos 2\pi(R_- - i)}{\pi(R_- - i)} + \frac{\cos 2\pi(R_+ - i)}{\pi(R_+ - i)} + 2\sum_{k=1}^{\infty}\frac{(-1)^{k-1}\left[(2\pi(R_+ - i))^{2k-1} - (2\pi(R_- - i))^{2k-1}\right]}{(2k-1)(2k-1)!}\right]\right]. \quad (11)$$

Table 1. Nominal clutter heights and distances.

Category	Clutter height h_a	Nominal distance d_k
Dense urban	25	0.02
Suburban	9	0.025
Rural	4	0.1

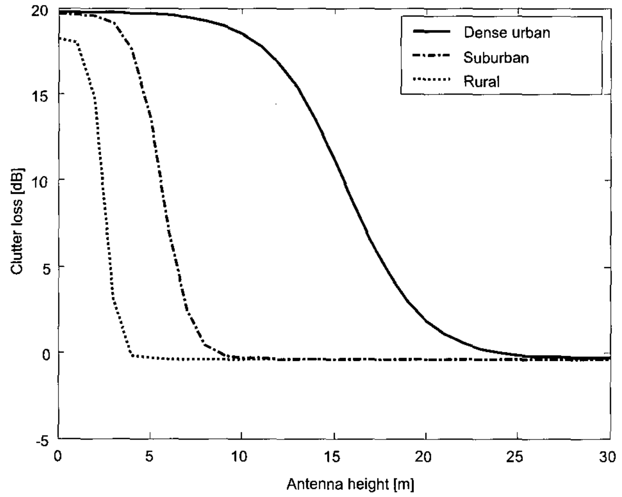

Fig. 2. Clutter loss for dense urban, suburban, and rural areas.

B. Wave Propagation Model

The result of the interference calculation is the minimum required loss. Having chosen an appropriate path loss model, this can subsequently be converted into a physical separation. In order to ensure satisfactory coexistence of the involved P-P FS systems and B3G systems, it is important to ensure that the interference potential between these systems can be predicted with reasonable accuracy. This is accomplished using prediction procedures and models that are acceptable to all parties concerned and have demonstrated accuracy and reliability. The standard model agreed upon in the ITU and CEPT for a terrestrial interference assessment at microwave frequencies is clearly denoted in ITU-R Recommendation P.452-8 [10]. Therefore, this propagation model, which includes the attenuation due to LOS propagation as well as additional attenuation due to clutter in various environments, is used for the frequency sharing study for P-P FS systems and B3G systems.

$$L(d) = 32.5 + 20\log_{10} f + 20\log_{10} d + A_h \quad (12)$$

where f is the carrier frequency in MHz and d is the transmission distance in kilometers. In (12), A_h represents the clutter loss following

$$A_h = 10.25e^{-d_k}\left[1 - \tanh\left[6\left(\frac{h}{h_a} - 0.625\right)\right]\right] - 0.33 \quad (13)$$

where d_k is the distance (km) from the nominal clutter point to the antenna, h is the antenna height (m) above local ground level, and $h_a$is the nominal clutter height (m) above local ground level. In [10], clutter losses are evaluated for different categories: Dense urban, urban, suburban, rural, and trees, etc. Since the geographical area where B3G services will be operated is divided into three categories, dense urban, suburban, and rural [2], these categories are considered. The clutter loss decreases with the antenna height increase up to the clutter height, as shown in Table 1 and Fig. 2.

Table 2. Typical P-P FS system parameters.

Parameter	Value
Center frequency of operation (MHz)	3500
Receiver bandwidth (MHz)	40
Modulation	64-QAM
Receiver thermal noise (dBW)	−127.5
Rx input level for 1×10^{-3} BER (dBW)	−106
Antenna type	Dish (diameter: 2 m)
Maximum antenna gain (dBi)	42.5
Feeder loss (minimum) (dB)	3.5
Maximum permissible long-term interference power (20% of time, $I/N = -13$ dB) (dBW/40 MHz)	−140.5

III. SHARING SCENARIO

A. System Parameters for Frequency Sharing

ITU-R defined the sharing parameters between the terrestrial fixed service and other services [8]. With reference to the ITU-R recommendation, P-P FS system parameters under consideration of sharing between the FS and other services are shown in Table 2. The system occupies a bandwidth of 40 MHz assigned with a center frequency of 3500 MHz. The dish-shaped directional antenna, having a diameter of 2 meters and a maximum antenna gain of 42.5 dBi, is deployed. Fig. 3 illustrates antenna patterns modeled mathematically for use in interference assessment in cases where the ratio between the antenna diameter and the wavelength is less than or equal to 100 ($D/\lambda \leq 100$) in [11]. The permissible long-term interference power is considered to be -140.5 dBW/40 MHz, which is calculated based

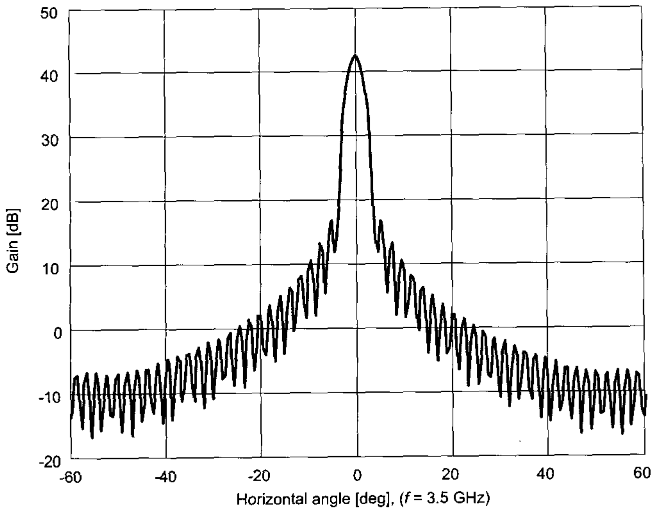

Fig. 3. P-P FS system antenna of 2 m diameter at 3.5 GHz ($D/\lambda = 23.3$, peak gain = 42.5 dBi).

Table 3. B3G system parameters.

Parameter	Value
Center frequency of operation (MHz)	3500
Multiplexing/multiple access	OFDM/OFDMA
Duplex	TDD
Subcarrier frequency spacing (KHz)	10.24
Channel bandwidth (MHz)	80
Total number of subcarriers	8192
Transmit power (dBW)	13
Maximum antenna gain (dBi)	14.5

on $I/N = -13$ dB. It is also presumed that P-P FS systems employ space diversity, which gives an interfering signal level 3 dB gains. Therefore, an interference criterion of $I/N = -13$ dB is applied in place of $I/N = -10$ dB for 20% of the time [8]. The long-term interference criterion allows the error performance objective for a digital system to be met. This criterion will be generally represented for a low level of interference.

The P-P FS system is currently well defined and no restrictions and limitations for the B3G system exist. Therefore, we assume a cellular OFDM/OFDMA system with a bandwidth of 80 MHz. The parameters of the B3G base station (BS) system are presented in Table 3. The BS antenna pattern used for each sector is plotted in Fig. 4 and is specified by [12]

$$G_{BS}(\theta) = G_{\max} + A_{BS}(\theta) \tag{14}$$

where

$$A_{BS}(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3\mathrm{dB}}}\right)^2, A_m\right], -180 \le \theta \le 180 \tag{15}$$

where $G_{\max} = 14.5$ dBi is the maximum antenna gain, $\theta_{3\mathrm{dB}} = 70°$ is the 3 dB bandwidth, and $A_m = 20$ dB is the maximum attenuation.

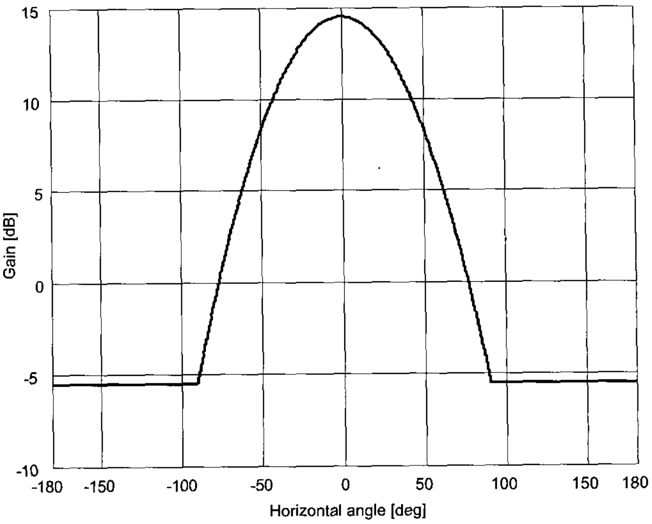

Fig. 4. B3G system antenna pattern for 3-sector cells.

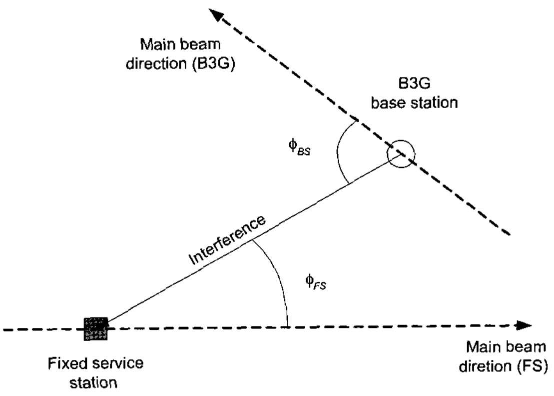

Fig. 5. B3G interference scenario in spatial view.

B. B3G Interference Scenario

FS systems have a "fixed" nature and are often deployed in dense urban, suburban, and rural outdoor areas. As such, they are affected by B3G BS according to their position. We focused primarily on the interference modes where the interfering signal emitted from one BS impacts one FS station. Furthermore, the interfering signals are attenuated by the path loss as well as antenna discrimination dependent on the off axis angles ϕ_{BS} and ϕ_{FS} in Fig. 5. Fig. 6 depicts sharing scenarios categorized by co-channel band sharing and adjacent channel compatibility.

IV. COEXISTENCE ANALYSIS

A. Co-Channel Band Sharing

The minimum separation distance is analyzed for both cluster loss which is determined by antenna height at the B3G BS system and antenna discrimination loss, which results from the antenna direction of the B3G BS system and P-P FS system. Figs. 7–9 depict the same required minimum separation distance versus antenna height of the B3G BS system in dense urban, suburban, and rural areas, respectively. In the three plots, it is clearly observed that the increment of minimum required dis-

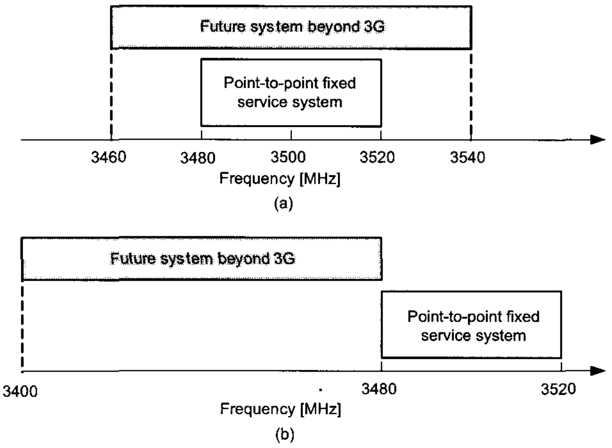

Fig. 6. B3G interference scenario in frequency view: (a) Co-channel band sharing case, (b) adjacent channel sharing case.

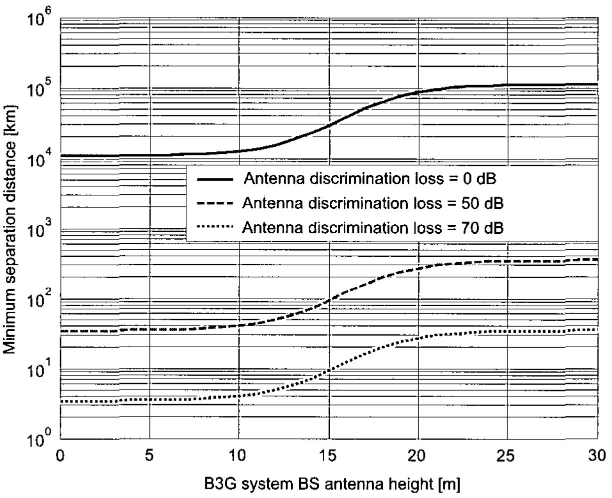

Fig. 7. Minimum separation distance in dense urban area.

tance corresponds to the increase in the antenna height at the BS, and the minimum required distance no longer increases when the antenna height is higher than the clutter height. This result is expected because the clutter loss increases as the clutter height increases, and the clutter loss values present a constant value when the antenna height is higher than the clutter height.

In Fig. 10, we show the minimum separation distance yielded by the off axis angle. It is clearly seen that for $\phi_{FS} = 0^\circ$and $\phi_{BS} = 0^\circ$, the antenna discrimination loss is 0 dB, whereas for $|\phi_{FS}| \geq 50^\circ$and $|\phi_{BS}| \geq 90^\circ$, the loss is 70 dB. The results of the minimum separation distance are summarized in Table 4. The minimum separation distance is 10^5 km when both clutter loss and antenna discrimination loss equals 0 dB. This value is too large to be practically realizable, whereas it is degrades up to 3.5 km for both 20 dB clutter loss and 70 dB antenna discrimination loss. The results indicate that co-channel band sharing of B3G systems with P-P FS systems is feasible if the off axis angles ϕ_{BS} and ϕ_{FS} are properly adjusted.

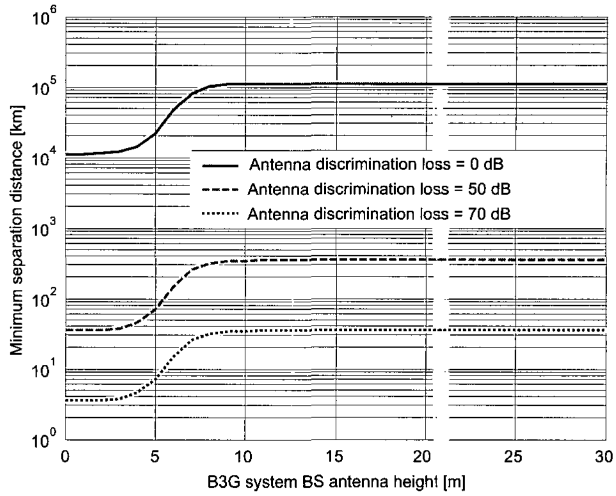

Fig. 8. Minimum separation distance in suburban area.

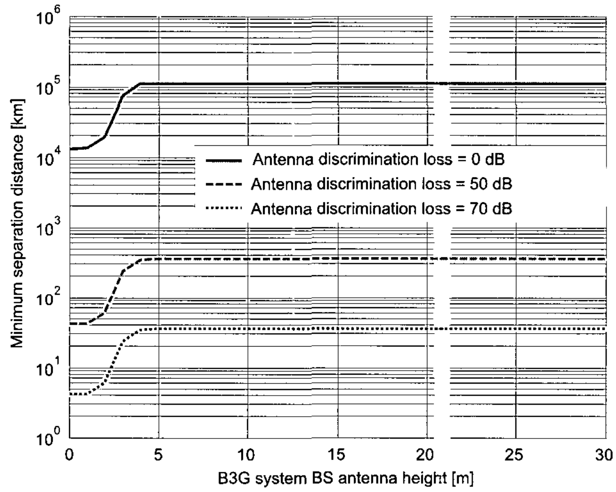

Fig. 9. Minimum separation distance in rural area.

Table 4. Minimum required separation distance for different clutter loss and antenna discrimination attenuation.

Clutter loss (dB)	Antenna discrimination attenuation (dB)	Minimum required separation distance (km)
0	0	N/A
20	0	10^4
0	70	35
20	70	3.5

B. Adjacent Channel Sharing

The guard band variation from -10 MHz to 10 MHz, between B3G systems and P-P FS systems is taken into consideration in analyzing the minimum separation distance. From Fig. 11, together with Table 5, the minimum separation distance is determined to be 408 km for a 10 MHz guard band when both clutter loss and antenna loss are assigned as 0 dB. It is also informed that the -10 MHz guard band can't enable both systems to share

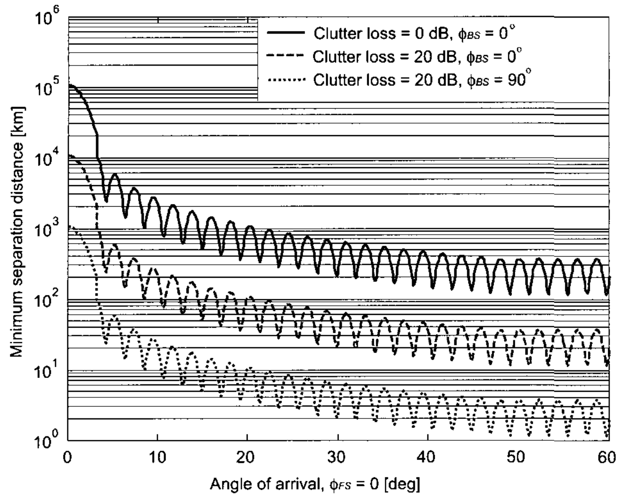

Fig. 10. Minimum separation distance for the off axis angle, ϕ_{FS}, of P-P FS system.

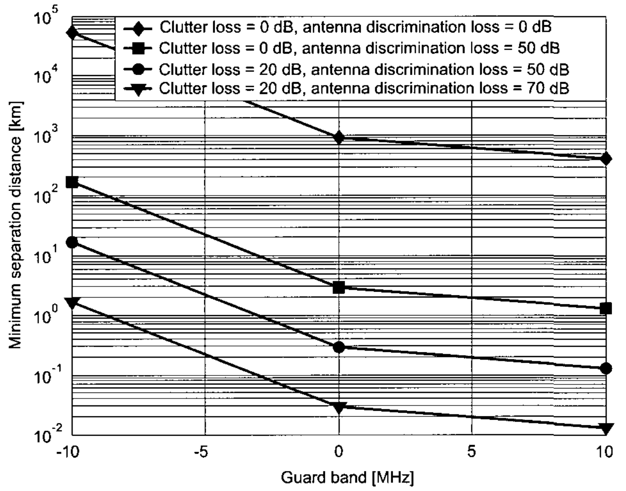

Fig. 11. Minimum separation distance as a function of guard band.

the same frequency bands in the case of 0 dB clutter and antenna discrimination loss. However, when 0 dB clutter loss as well as 50 dB antenna discrimination loss is taken into consideration, the guard bands of 0 MHz and 10 MHz show minimum separation distances of 3 km and 1.3 km, respectively. Therefore, after properly adjusting the off axis angles ϕ_{BS} and ϕ_{FS}, while maintaining 50 dB antenna discrimination loss, the adjacent channel compatibility is realized with the help of the 0 MHz guard band.

V. CONCLUSION

We have introduced a general analytical model as an alternative to MCL method for evaluating the interference of B3G OFDM-based systems on P-P FS systems. A coexistence analysis is thoroughly performed in this paper based on interference models where the interfering signal emitted from a single BS impacts on one FS stations.

The coexistence problem is decomposed into two alternating terms, co-channel frequency sharing and adjacent channel frequency sharing. First, taking into consideration the co-channel frequency sharing, the minimum separation distance is determined to be 10^5 km when both clutter loss and antenna discrimination loss are 0 dB, while it is minimized to 3.5 km for 20 dB clutter loss and 70 dB antenna discrimination loss. The results indicate that co-channel band sharing of B3G systems with P-P FS systems is feasible. Second, in the case of adjacent channel frequency sharing, when 0 dB clutter loss and 50 dB antenna discrimination loss are taken into consideration, the guard bands of 0 MHz and 10 MHz show minimum separation distances of 3 km and 1.3 km, respectively. Therefore, after properly modifying the off axis angles ϕ_{BS} and ϕ_{FS}, while maintaining 50 dB antenna discrimination loss, adjacent channel compatibility is achieved with the help of the 0 MHz guard band.

Table 5. Minimum required separation distance for different clutter losses, antenna discrimination attenuations, and guard bands.

Clutter loss (dB)	Antenna discrimination attenuation (dB)	Minimum required separation distance (km)		
		−10 MHz guard band	0 MHz guard band	10 MHz guard band
0	0	N/A	917	408
0	50	170	3	1.3
20	50	17	0.3	0.13
20	70	1.7	0.03	0.013

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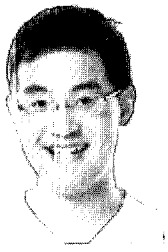

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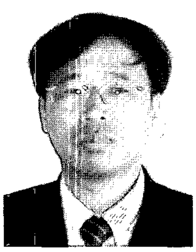

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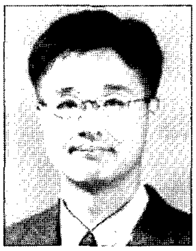

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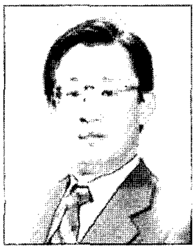

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