Interference Mitigation Technique for the Sharing between IMT-Advanced and Fixed Satellite Service

Jae-Woo Lim, Han-Shin Jo, Hyun-Goo Yoon, and Jong-Gwan Yook

Abstract: **In this paper, we propose an efficient and robust interference mitigation technique based on a nullsteering multi-user multiple-input multiple-output (MU-MIMO) spatial division multiple access (SDMA) scheme for frequency sharing between IMT-advanced and fixed satellite service (FSS) in the 3400–4200 and 4500–4800 MHz bands. In the proposed scheme, the pre-existing precoding matrix for SDMA unitary precoded (UPC) MIMO proposed by the authors is modified to construct nulls in the spatial spectrum corresponding to the direction angles of the victim FSS earth station (ES). Furthermore, a numerical formula to calculate the power of the interference signal received at the FSS ES when IMT-Advanced base stations (BS) are operated with the interference mitigation technique is presented. This formula can be derived in closed form and is simply implemented with the help of simulation, resulting in significantly reduced time to obtain the solution. Finally, the frequency sharing results are analyzed in the co-channel and adjacent channel with respect to minimum separation distance and direction of FSS earth station (DOE). Simulation results indicate that the proposed mitigation scheme is highly efficient in terms of reducing the separation distance as well as robust against DOE estimation errors.**

Index Terms: **Fixed Satellite Service (FSS), frequency sharing, IMT-Advanced, interference mitigation technique, null steering.**

I. INTRODUCTION

The radio-frequency spectrum is a limited natural resource essential to global, regional, and domestic communication infrastructures. In order to update frequency allocation decisions and other conditions of use of the radio spectrum at the global level, the World Radiocommunication Conference (WRC) is held every two to four years. WRC-07 agenda item 1.4 considers frequency-related matters for the future development of international mobile telecommunication 2000 (IMT-2000) and systems beyond IMT-2000, taking into account the results of International Telecommunication Union for Radiocommunication (ITU-R) studies in accordance with Revolution 228 (Rev.WRC-03). Thus, ITU-R has become involved with the spectrum allocation for next generation mobile communication services in preparation for WRC-07.

During preparatory work performed within ITU-R working party (WP) 8F, the frequency bands of 3400–4200 MHz and 4400–4990 MHz have been identified as candidate bands for the future development of IMT-Advanced systems [1]. These bands are already being used for fixed-satellite services (FSS) in many countries around the world. Therefore, the spectrum allocation should be preceded by sharing studies between FSS and IMT-Advanced systems. In [1], the sharing results of using a minimum coupling loss (MCL) link budget show that, the required separation distance should be greater than 40 km to avoid mutually harmful interference between two systems operating in the same frequency bands. Similar results are also given in [2]–[4]. From a practical point of view, however, the 40 km separation distance is too great. Therefore, an interference mitigation technique is needed to share IMT-Advanced systems with FSS systems.

Multiple-input multiple-output (MIMO) technology and orthogonal frequency-division multiplexing (OFDM) are currently considered the most promising access schemes to support IMT-Advanced systems. OFDM is a multicarrier modulaton technique that offers excellent performance in combating multipath fading as well as superb efficiency in terms of use of available bandwidth [5]. The antennas array in MIMO systems can be used in various ways for improving system performance: Spatial diversity for anti-fading, beamforming, spatial multiplexing of multiple data transmissions to a user, and spatial multiplexing of multiple data transmissions to multiple users. Spatial multiplexing for multi users is known as spatial division multiple access (SDMA) or multi-user MIMO (MU-MIMO). For Gaussian broadcast multiuser MIMO channels, it was recently proven in [6] that dirty paper coding (DPC) [7] can achieve the sum capacity, the maximum aggregation of all users' data rates. Although DPC can achieve the sum capacity, deploying DPC in real-time systems is impractical because of the complicated encoding and decoding schemes and excess uplink feedback load for the channel knowledge of all users at the transmitter. Therefore, an efficient and practical precoding technique for downlink broadcast MIMO channels has been proposed [8]. SDMA unitary precoded (UPC) MIMO described in [8] adjusts a precoding matrix based on limited feedback information on the preferred basis set and the corresponding CQIs. According to the number of mobile receivers and their channel conditions, a precoding matrix and a subset of receivers to serve can be adjusted with limited feedback. SDMA UPC MIMO scheme with a smaller transmit antenna spacing can considerably enhance the transmission rate with lower and minimal additional feedback rate.

Therefore, in this paper, we proposed an interference mitigation technique, which is based on SDMA UPC MIMO presented in [8], for frequency sharing between IMT-Advanced and FSS in the 3400–4200 and 4500–4800 MHz bands. In the proposed technique, the precoding matrix suggested in [8] is modified such that a signal transmit transmitted from an IMT-Advanced base station (BS) to users is nulled to a FSS earth station (ES).

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The modification process is composed of 3 steps: (1) Computation of null points of original precoding vectors, (2) steering null into the direction of the FSS ES, (3) selection of modified precoding vectors.

The remainder of this paper is organized as follows. In Section II, we describe the proposed interference mitigation algorithm and assumptions in our approach. In Section III, an interference model suitable for the IMT-Advanced system with the interference mitigation technique is formulated and a wave propagation model is described in detail. Section IV is devoted to describing the system parameters, interference scenarios, and sharing results in a co-channel and adjacent channel. Finally, the conclusions are presented Section V.

II. PROPOSED INTERFERENCE MITIGATION ALGORITHM

The basic concept of the algorithm is to form nulls in the spatial spectrum that correspond to the direction angles of the victim FSS ES. In this paper, for convenience the term DOE denotes the direction angles of the victim FSS ES. First, the IMT-Advance BS has to obtain DOE information in order to perform nullsteering. DOE information can be obtained by adopting a popular spatial spectrum estimation direction finding method or from the database including information about the direction from the interfering IMT-Advanced BS to the victim FSS ES. In this paper, it is assumed that the IMT-Advanced BS is already aware of DOE information.

The main steps of the algorithm are outlined as follows:

ALGORITHM

- *Step 1* : Compute the null points θ_0 generated by n_T precoding vectors $\mathbf{e}_{g,m} (m = 0, 1, \cdots, n_T - 1)$.
- *Step 2* : Calculate the n_T precoding vectors $\mathbf{w}_{g,m}$ $(m = 0, 1, \cdots, n_T - 1)$ depending on DOE $\hat{\theta}$ and the null points θ_0 computed in Step 1.
- *Step 3* : Select the $n_T - 1$ precoding vectors, $\mathbf{w}_{g,n} (n = 0, 1, \cdots, n_T - 2)$, forming nulls at DOE $\hat{\theta}$ from n_T precoding vectors $\mathbf{w}_{g,m}$.

We use a set of unitary precoding matrices, $U = \{\mathbf{E}_0, \cdots, \mathbf{E}_{G-1}\}$, where $\mathbf{E}_g = [\mathbf{e}_{g,0}, \cdots, \mathbf{e}_{g,n_T-1}]$ is the gth precoding matrix. $\mathbf{e}_{g,m}$ is the mth precoding vector in the matrix $\mathbf{E}_g$ and is given by [8]

$$\mathbf{e}_{g,m} = \frac{1}{\sqrt{n_T}} \begin{bmatrix} 1 & e^{j\frac{2\pi}{n_T}\left(\frac{g}{G}+m\right)} & \ldots & e^{j\frac{2\pi}{n_T}(n_T-1)\left(\frac{g}{G}+m\right)} \end{bmatrix}^T. \tag{1}$$

If a plane wave impinges up the array at an angle θ with respect to the array normal, the array propagation vector for an uniformly spaced linear array is defined by

$$\mathbf{v} = \begin{bmatrix} 1 & e^{j2\pi\frac{d}{\lambda}\sin\theta} & \ldots & e^{j2\pi(n_T-1)\frac{d}{\lambda}\sin\theta} \end{bmatrix}^T \tag{2}$$

where λ is a wavelength and an antenna spacing between transmit antennas of $d = 0.5\lambda$ is considered. The array factor can be expressed in terms of the vector inner product

$$F_m(\theta) = \mathbf{e}_{g,m}^T \mathbf{v} = \frac{1}{\sqrt{n_T}} \sum_{k=0}^{n_T-1} e^{j2\pi k\left\{\frac{1}{n_T}\left(\frac{g}{G}+m\right)+\frac{d}{\lambda}\sin\theta\right\}}. \tag{3}$$

Then, θ_0 satisfying $F_m(\theta) = 0$ can be obtained, and these values mean the null points generated by the precoding matrices.

However, our objective is to form nulls at DOE $\hat{\theta}$. Therefore, it is necessary to perform the step of nullsteering for the case of $\hat{\theta} \neq \theta_0$. Let $\hat{\theta} = \theta_0 + \alpha$. Then, in order to form nulls at $\hat{\theta}$, the array factors $F_m(\theta)$ for the precoding vectors $\mathbf{e}_{g,m}$ have to be shifted to α, that is,

$$F_m(\theta - \alpha) = \frac{1}{\sqrt{n_T}} \sum_{k=0}^{n_T-1} e^{j2\pi k\left\{\frac{1}{n_T}\left(\frac{g}{G}+m\right)+\frac{d}{\lambda}\sin(\theta-\alpha)\right\}}. \tag{4}$$

Using the addition formula of trigonometric functions, $\sin(A - B) = \sin A \cos B - \cos A \sin B$, (4) can be induced as

$$\begin{aligned} F_m(\theta - \alpha) = \frac{1}{\sqrt{n_T}} \sum_{k=0}^{n_T-1} \Bigg[& e^{j2\pi k\left\{\frac{1}{n_T}\left(\frac{g}{G}+m\right)+\frac{d}{\lambda}\sin\theta\right\}} \\ & \times e^{-j2\pi k\frac{d}{\lambda}\cos\theta\sin\alpha} \left(e^{j2\pi k\frac{d}{\lambda}\sin\theta}\right)^{\cos\alpha-1} \Bigg]. \end{aligned} \tag{5}$$

For $\theta = \hat{\theta}$, (5) can be rewritten as

$$\begin{aligned} F_m(\hat{\theta} - \alpha) = & \frac{1}{\sqrt{n_T}} \sum_{k=0}^{n_T-1} \Bigg[e^{j2\pi k\left\{\frac{1}{n_T}\left(\frac{g}{G}+m\right)+\frac{d}{\lambda}\sin\hat{\theta}\right\}} \\ & \times e^{-j2\pi k\frac{d}{\lambda}\cos\hat{\theta}\sin\alpha} \left(e^{j2\pi k\frac{d}{\lambda}\sin\hat{\theta}}\right)^{\cos\alpha-1} \Bigg] \\ = & F_m(\theta_0) \\ = & 0. \end{aligned} \tag{6}$$

Employing (3), (6) can be represented as

$$F_m(\hat{\theta} - \alpha) = (\mathbf{e}_{g,m} \odot \mathbf{s})^T \mathbf{v} \tag{7}$$

where $\odot$ denotes the Hadamard (pointwise) product and

$$\begin{aligned} \mathbf{s} = \Bigg[& 1 \quad e^{-j2\pi\frac{d}{\lambda}\cos\hat{\theta}\sin\alpha} \left(e^{j2\pi\frac{d}{\lambda}\sin\hat{\theta}}\right)^{\cos\alpha-1} \cdots \\ & e^{-j\frac{2\pi(n_T-1)d\cos\hat{\theta}\sin\alpha}{\lambda}} \left(e^{j\frac{2\pi(n_T-1)d\sin\hat{\theta}}{\lambda}}\right)^{\cos\alpha-1} \Bigg]^T. \end{aligned} \tag{8}$$

Therefore, the adapted precoding vectors, which are denoted by $\mathbf{w}_{g,m}$, for forming nulls at $\hat{\theta}$ can be calculated as

$$\mathbf{w}_{g,m} = \mathbf{e}_{g,m} \odot \mathbf{s}. \tag{9}$$

Because the beams produced by n_T precoding vectors $\mathbf{w}_{g,m}$ are mutually orthogonal, only one of n_T beams does not construct null at DOE $\hat{\theta}$. Therefore, the $n_T - 1$ precoding vectors $\mathbf{w}_{g,n} (n = 0, 1, \cdots, n_T - 2)$, which form null at $\hat{\theta}$, are selected from $\mathbf{w}_{g,m} (m = 0, 1, \cdots, n_T - 1)$. In conclusion, $n_T - 1$ precoding vectors $\mathbf{w}_{g,n}$ are used for data transmission of IMT-Advanced service.

From the beam patterns formed by the precoding vectors $\mathbf{e}_{g,m}$ illustrated in Fig. 1, where $G = 2$, $g = 1$, and $n_T = 4$, it is found that the null points θ_0 are ±14.5° and ±48.6°. Fig. 2 shows mutually orthogonal overlapped beams produced by the

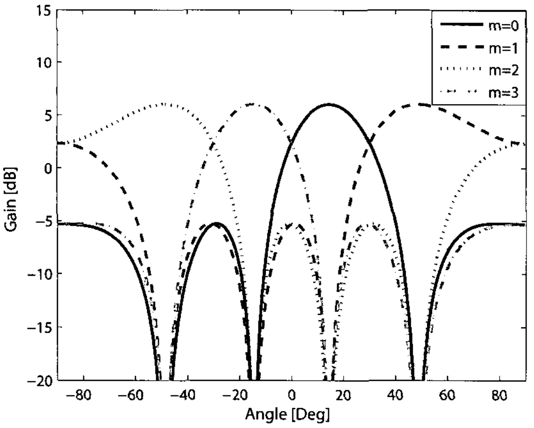


Fig. 1. Four mutually orthogonal overlapped beams produced by the precoding vectors $\mathbf{e}_{1,m}$ $(m = 0, 1, 2, 3)$.

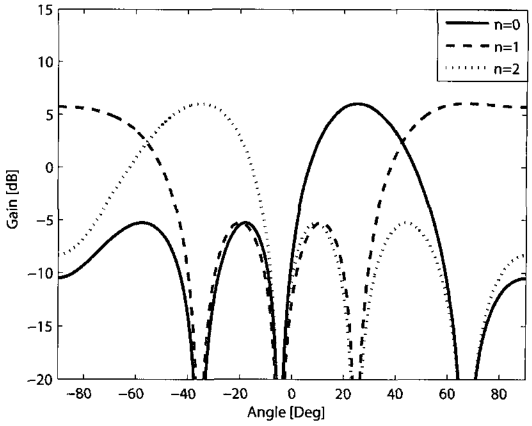


Fig. 3. Three mutually orthogonal overlapped beams produced by the precoding vectors $\mathbf{w}_{1,n}$ $(n = 0, 1, 2)$.

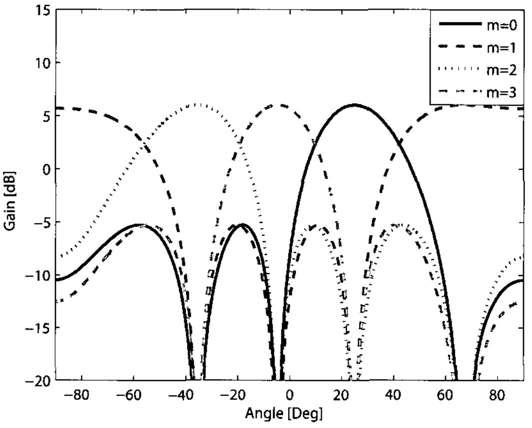


Fig. 2. Four mutually orthogonal overlapped beams produced by the precoding vectors $\mathbf{w}_{1,m}$ $(m = 0, 1, 2, 3)$.

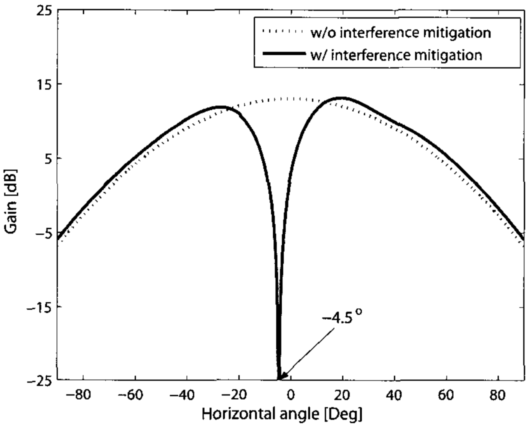


Fig. 4. IMT-Advanced BS radiation patterns.

precoding vectors $\mathbf{w}_{g,m}$ for $\hat{\theta} = -4.5^\circ$ and $\alpha = 10^\circ$. It is clear that $\mathbf{w}_{g,m}$ builds up nulls at $\hat{\theta} = -4.5^\circ$, which is consistent with DOE. Fig. 3 indicates that the proposed interference mitigation techniques adopt only three beams selected from the four beams. Finally, Fig. 4 depicts the IMT-Advanced BS radiation pattern regardless of whether the proposed algorithm applied. The results confirm that, with the help of the proposed method, very little IMT-Advanced BS power is radiated to the FSS ES.

III. INTERFERENCE ASSESSMENT

A. Interference Model

An assessment of frequency sharing is based on the concept of permissible interference power at the antenna terminals of a victim system. Hence, the attenuation required to limit the level of interference from 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 [9], [10]. 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"; it is referred to as "long term" for $p \geq 20\%$.

The minimum required loss $L_{\min}$ in dB is described by

$$L_{\min} = P_{BS} + G_{BS} + G_{FS} + L_r - I_{\max} \tag{10}$$

where P_{BS} is the transmit power of IMT-Advanced base stations (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 antennas of the receiving FSS earth stations. G_{FS} is the FSS earth station antenna gain in the IMT-Advanced BS direction and G_{BS} is the IMT-Advanced BS antenna gain in the FSS earth station direction and can be expressed as

$$G_{BS} = G_{ANT}(\phi) + G_{BF}(\phi). \tag{11}$$

$G_{ANT}(\phi)$, the conventional BS antenna pattern without interference mitigation techniques, is specified by [11]

$$G_{ANT}(\phi) = G_{\max} - \min\left[12\left(\frac{\phi}{\phi_{3\,\mathrm{dB}}}\right)^2, A_m\right] \quad (-180^\circ \leq \phi \leq 180^\circ) \tag{12}$$

where $-180^\circ \le \phi \le 180^\circ$, maximum antenna gain, $G_{\max}$ is 42.5 dBi, 3dB bandwidth, $\theta_{3\mathrm{dB}}$, is 70°, and the maximum attenuation, A_m, is 20 dB. $G_{BF}(\phi)$ is adaptive beamforming patterns generated by the proposed interference mitigation technique and can be expressed as

$$G_{BF}(\phi) = 20\log_{10}\left|\frac{P_{BS}}{n_s}\sum_{\forall m\in\Gamma}\mathbf{w}_{g,m}^{T}\mathbf{v}(\phi)\right| \qquad (13)$$

where Γ denotes the set of the index m of the selected precoding vectors and n_s is the number of elements in a set Γ. 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 [12].

The interfering signal power loss for the interfering system with OFDM is derived through a PSD analysis of the OFDM signals. As indicated in [12], assuming an OFDM system having subcarriers and a rectangular pulse, the interfering signal power loss can be written as (14) where

$$R_+ = \frac{f_c}{R_s} + \frac{W_v}{2R_s}, \qquad (15)$$

$$R_- = \frac{f_c}{R_s} - \frac{W_v}{2R_s}. \qquad (16)$$

B. Interference Criterion

ITU-R Recommendation S.1432 contains the allowable degradations to fixed-satellite service systems below 15 GHz [13]. This recommendation limits the total long-term interference to 27% of the system noise corresponding to the performance requirements in ITU-R Recommendations [14]–[16], as applicable, apportioning 20% to interference from other FSS systems, 6% to interference from other co-primary services, and 1% to all other sources of interference.

Regarding the criteria for the apportionment of the aggregate interference received by an FSS link, the ITU-R recommendation S.1432 specifies:

- A criterion of 6% (corresponding to an I/N ratio of -12.2 dB) for non-FSS systems operating within services having co-primary status
- A criterion of 1% (corresponding to an I/N ratio of -20 dB) for systems operating neither within the fixed-satellite service nor within a service having a co-primary status.

Considering that the bands 3400–4200 MHz and 4500–4800 MHz are identified for IMT-Advanced, mobile service would be upgraded to primary status for all regions and the relevant criteria according to this recommendation would be 12.2 dB. Therefore, $I/N = 12.2$ dB is used in the calculations of this study.

C. Wave Propagation Model

The result of an interference calculation is a minimum required loss, which having chosen and an appropriate path loss model, can then subsequently be converted into a physical separation. In order to ensure satisfactory coexistence of the FSS earth stations and the involved IMT-Advanced BS, it is important to ensure that the interference potential between them can be predicted with reasonable accuracy. To this end, prediction procedures and models that are not only acceptable to all parties concerned but also which have demonstrated accuracy and reliability must be used. The standard model agreed upon in the ITU and CEPT for terrestrial interference assessment at microwave frequencies is clearly denoted in the ITU-R recommendation P.452-12 [17]. Therefore, P.452 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

Table 1. FSS Earth station system parameters.

Parameter	Value
Center frequency of operation	4000 MHz
Receiver bandwidth	72 MHz
Noise temperaturre	100 K
Receiver thermal noise	-130.03 dBW
Antenna type	Parabolic ($D = 3.8$ m)
Maximum antenna gain	41 dBi
Antenna height	5 m
Maximum permissible long-term interference power ($I/N = -12.2$ dB)	-142.23 [dBW/ 72 MHz]

$$L(d) = 32.5 + 20\log_{10}(f) + 20\log_{10}(d) + A_h \qquad (17)$$

where f is the carrier frequency in MHz and d is the transmission distance in km. As given In (17), A_h represents the clutter loss:

$$A_h = 10.25e^{-d_k}\left[1 - \tanh\left[6\left(\frac{h}{h_a} - 0.625\right)\right]\right] - 0.33 \quad (18)$$

where d_k is the distance (km) from a nominal clutter point to the antenna, h is the antenna height (m) above the local ground level, and $h_a$is a nominal clutter height (m) above the local ground level. In [17], clutter losses are evaluated for different categories of dense urban, urban, suburban, rural, forested, etc. A subruban environment has been considered in this paper.

IV. SHARING ANALYSIS

A. System Parameters

The characteristics of typical systems as defined in the FSS ITU-R are needed for use in frequency sharing analyses [18]. With reference to the ITU-R Recommendation, FSS earth station parameters under consideration of sharing between the FSS and other services are shown in Table 1. The system occupies a bandwidth of 72 MHz assigned with a center frequency of 4000 MHz. A dish-shaped directional antenna, having a diameter of 3.8 m and a maximum antenna gain of 41 dBi, is deployed. Antenna patterns are 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 ($D/\lambda \le 100$) in [19]. The permissible long-term interference power is considered to be -142.23 dBW/72 MHz, and is calculated based on $I/N = -12.2$ dB.

$$L_r = 10\log_{10}\left[\sum_{i=0}^{N-1}\frac{P_s}{2\pi P_t}\left[\frac{1}{\pi(R_- - i)} - \frac{1}{\pi(R_+ - i)} - \frac{\cos 2\pi(R_- - i)}{\pi(R_- - i)} + \frac{\cos 2\pi(R_+ - i)}{\pi(R_+ - i)} + 2\sum_{k=1}^{\infty}\frac{(-1)^{k-1}\left[(2\pi(R_+ - i))^{2k-1} - (2\pi(R_- - i))^{2k-1}\right]}{(2k-1)(2k-1)!}\right]\right] \tag{14}$$

Table 2. IMT-Advanced base station parameters.

Parameter	Value
Center frequency of operation	4000 MHz
Multiple access	OFDMA/SDMA
Subcarrier freq. spacing	12.2 kHz
Channel bandwidth	50 MHz
Total number of subcarriers	4096
Transmit power	13 dBW
Maximum antenna gain	12 dBi
Feeder loss	4 dB
Tilting Angle	2°
Antenna height	30 m

We assume 3-sector cellular IMT-Advanced systems with a bandwidth of 50 MHz in suburban macrocell environments. Moreover, it is assumed that IMT-Advanced systems are able to support the proposed interference mitigation technique. IMT-Advanced BS parameters are presented in Table 2. The transmit power is 13 dBW and the maximum antenna gain including 4 dB feeder loss is 16 dBi. An antenna tilting angle is 2°, and an antenna height is 15 m.

B. Sharing Scenario

FSS have a "fixed" nature and are often deployed in dense urban, suburban, and rural outdoor areas. As such, they are affected by the IMT-Advanced BS according to their position. We focus 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 both the direction of earth station (DOE) ϕ_{ES} and the direction of earth station (DOB) ϕ_{BS} in Fig. 5. In this study, it is assumed that $\phi_{BS} = 14.5°$ and $\phi_{ES} = 45°$. Fig. 6 depicts sharing scenarios categorized by co-channel band sharing and adjacent channel compatibility.

C. Co-Channel Sharing Results

In this chapter, we demonstrate the superiority of the proposed interference mitigation scheme by calculating the interference powers. The interference power at the victim FSS ES according to increased separation distance between the FSS ES and IMT-Advanced BS is depicted in Fig. 7. Fig. 7(a) shows that when the separation distance between the FSS ES and IMT-Advanced BS is greater than 44 km, the interference power is reached at the maximum permissible interference power $I_{\max}$ when the interference mitigation scheme is not employed. In Fig. 7(b), using the proposed scheme, considerably smaller windows are required to find the interference power that meets $I_{\max}$. It is observed that, using the proposed scheme, the interference power is smaller than the maximum permissible interference power when the distance is more than 35 m, as shown in Fig. 7(b). This constitutes a remarkable distance reduction relative to the case without the proposed mitigation scheme. Note that the proposed scheme in Fig. 7 considers only the case in which DOE is correctly estimated.

In practice, DOE estimation error can occur. The impact of the DOE estimation error on the performance of the interference mitigation is analyzed in Fig. 8 and is also listed in Table 3. It

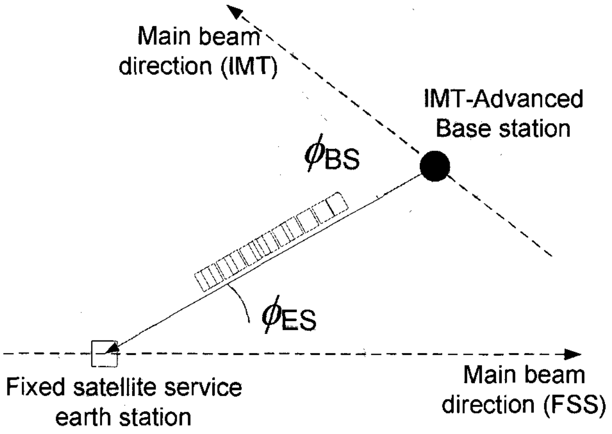


Fig. 5. IMT-Advanced interference scenario in a spatial view.

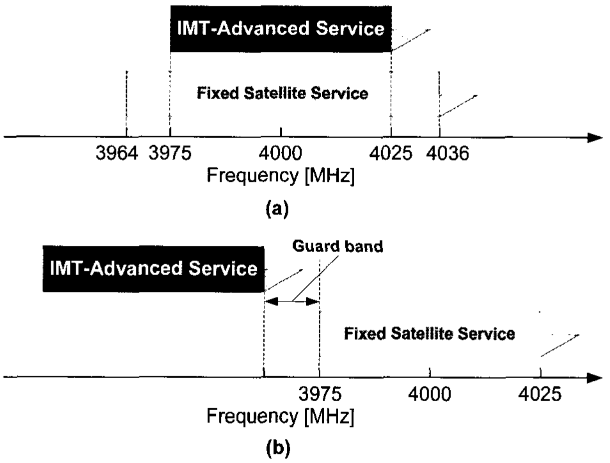
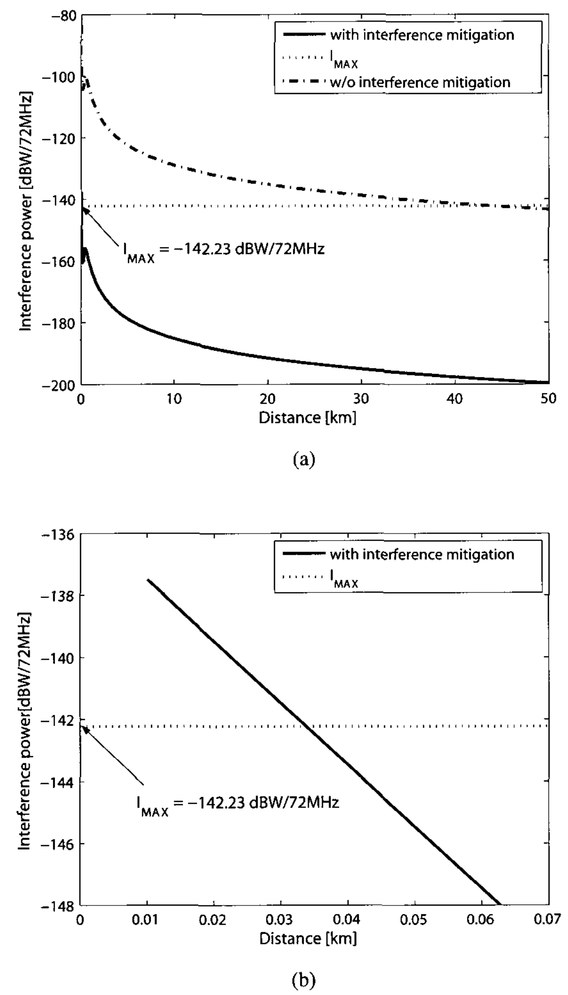


Fig. 6. IMT-Advanced interference scenario in a frequency domain view: (a) A co-channel band sharing case, (b) An adjacent channel sharing case.



(a)

(b)

Fig. 7. (a) Interference power comparison of the proposed interference mitigation algorithm for the co-channel case, (b)The same data as (a), but only the case of with the interference mitigation.

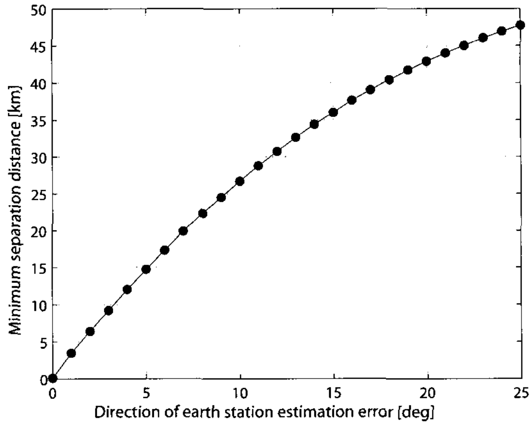


Fig. 8. Minimum separation distance versus for direction of earth station estimation error.

Table 3. Minimum required separation distance for the co-channel case.

Simulation environments		Minimum separation distance [km]
With interference mitigation techniques	DOE estimation error: 0°	0.0035
	DOE estimation error: 2°	7
	DOE estimation error: 10°	27
Without interference mitigation techniques		29.8

Table 4. Minimum required separation distance for the adjacent channel case.

Interference mitigation (With:○, Without:×)	DOE estimation error (deg, °)	Minimum separation distance (km)		
		−9 MHz GB	0 MHz GB	9 MHz GB
○	0	< 0.01	< 0.01	< 0.01
○	5	5.56	0.03	0.02
○	10	9.84	0.05	0.03
×	N/A	17	0.3	0.13

is clearly observed that the increased DOE estimation error produces a further minimum distance. Until 22° DOE estimation error, the minimum separation distance with the interference mitigation scheme is shorter than that without the interference mitigation scheme. It should also be observed that at 8° DOE estimation error, the minimum separation distance can be reduced by at least 50% compared with the case of 44 km distance without the interference mitigation scheme. Our results indicate that the proposed mitigation scheme is highly efficient in terms of reducing the separation distance as well as being robust against DOE estimation errors.

D. Adjacent Channel Sharing Results

The guard band (GB) variation from −9 MHz to 9 MHz, between the IMT-Advanced BS and FSS ES, is taken into consideration in analyzing the minimum separation distance in Fig. 9, together with the Table 4. Despite the guard band, the minimum separation distances are less than 10 m without DOE estimation error. On the other hand, the minimum separation distance for 0 MHz guard band is 0.3 km without application of the interference mitigation technique. This result indicates that there is possibility of frequency sharing when a guard band of more than 0 MHz is implemented. Based on 10° DOE estimation error, the guard bands of −9 MHz and 9 MHz show minimum separation distances with 9.84 km and 30 m, respectively. These results indicate that the proposed interference mitigation technique, even for 10° DOE estimation error, guarantees a decrease in the minimum separation distance of more than 50% in comparison with the case where no interference mitigation method is applied.

V. CONCLUSION

We have introduced a novel interference mitigation technique based on a nullsteering MU-MIMO SDMA scheme for frequency sharing between IMT-Advanced and FSS in the 3400–

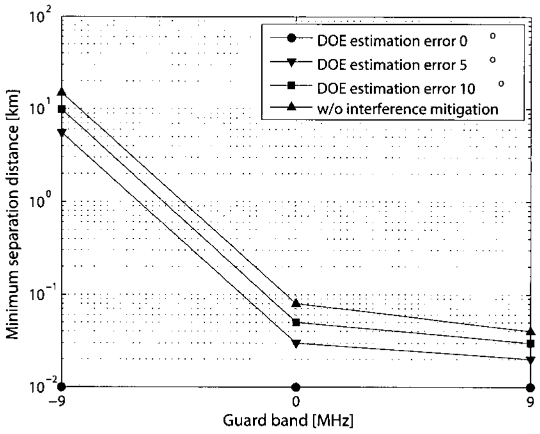


Fig. 9. Minimum separation distance comparison of the proposed interference mitigation algorithm for the adjacent channel case.

4200 and 4500–4800 MHz bands. In the proposed scheme, the pre-existing precoding matrix for SDMA UPC MIMO proposed by the authors has been modified to construct nulls in the spatial spectrum corresponding to the direction angles of the victim FSS ES. Furthermore, a method to evaluate the power of the interference signal received at the FSS ES when the IMT-Advanced BS is operated with the interference mitigation technique has been presented.

The frequency sharing problem is decomposed into two alternating terms, namely co-channel frequency sharing and adjacent channel frequency sharing. First, taking consideration of the co-channel frequency sharing, it can be observed that the interference power is smaller than the maximum permissible interference power when the distance is more than 35 m and the proposed scheme is applied. Moreover, it is observed that, until 22° DOE estimation error, the minimum separation distance with the interference mitigation scheme is shorter than that without application of the interference mitigation scheme. It should also be observed that at 8° DOE estimation error, the minimum separation distance can be reduced by at least 50 % compared with the case of 44 km distance and no interference mitigation scheme. Second, in the case of adjacent channel frequency sharing, despite of guard band, the minimum separation distances are less than 10 m without DOE estimation error. Our results indicate that the proposed mitigation scheme is highly efficient in terms of reducing the separation distance as well as being robust against DOE estimation errors.

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