On Challenges of Frequency Sharing Scheme and its Effectiveness

Tadashi MINOWA and Amane MIURA

This paper presents the satellite-terrestrial user coexisting schemes (frequency separation scheme, frequency sharing scheme) as a key technology of Satellite and Terrestrial Integrated mobile Communication System (STICS). The frequency sharing scheme, which is expected to realize high spectrum efficiency, is introduced with its principle, the interference problem, and the interference suppression/mitigation technologies. Then, theoretical analyses and computational simulations to compare the spectrum efficiencies between frequency separation and sharing schemes are carried out to show the effectiveness of the frequency sharing scheme.

1 Introduction

In recent years in Europe and North America, with the increase in demand for mobile broadband, organizations such as the Federal Communications Commission and the European Commission have granted radio station licenses to Satellite/Terrestrial Integrated Mobile Communication Systems that use Ancillary Terrestrial Components (ATC) with the aim of supplementing Mobile Satellite Services (MSS) (hereafter referred to as “MSS/ATC”; in Europe, called “MSS/CGC” (CGC stands for “Complementary Ground Components”)) (Table 1). A major feature of these systems is satellite systems and terrestrial systems sharing the same frequency band.

MSS/ATC began in the United States with the release of the Report and Order in 2003 by the FCC regarding MSS licenses that provide ATC to their satellite system. The FCC issued ATC authorization to MSV in the L-band and to Globalstar in the Big LEO band. At the same time, ICO and TerreStar have submitted their applications for ATC authorization and are actively planning to develop ATC. However, at this point, none of these companies provide ATC service[1].

Also in Japan, as is mentioned in Chapter **1** of this Special Issue, possibilities are being explored for the Satellite/Terrestrial Integrated mobile Communication

Table 1 The world’s providers planning to provide ATC services

Service provider	Orbit	Coverage area	Freq. band	OBP	ISL	Licensed by
LightSquared（formerly SkyTerra, MSV）	GEO	North and Central America	L	Yes	Yes	FCC
Globalstar	LEO	North and South America, Europe, Australia, North Africa and parts of Asia	L	No	No	FCC
Inmarsat	GEO	Global except polar regions	S	No	No	EC
ICO	GEO	North America	S	No	No	FCC
Eutelsat	GEO	Europe, Middle East, Africa, India, most part of Asia, and North and South America	S	Yes	No	EC
Terrestar	GEO	Continental U.S., Canada, Puerto Rico, U.S. Virgin Island, Hawaii and Alaska	S	Yes	No	FCC

※OBP (Onboard processing), ISL (Inter-satellite link)

System (STICS), which allows for same-frequency band sharing with a terrestrial mobile phone system (hereafter “terrestrial system”) and a mobile satellite communication system (hereafter “satellite system”)[2].

After explaining the concept of STICS, this paper will propose frequency-sharing and frequency-separation methods for use in allowing coexistence of users of terrestrial and satellite systems. Then, in addition to this, the paper will discuss the basic principles of the frequency-sharing method, from which high frequency utilization efficiency can be expected, its challenges, namely interference problems, and measures to avoid or reduce interference. Following, the effectiveness of the frequency-sharing method will be shown by conducting a comparative evaluation involving a theoretical analysis and a computerized simulation of the frequency utilization efficiency and spatial guard bands for the frequency-sharing and frequency-separation methods.

2 Satellite/Terrestrial Integrated mobile Communication System (STICS)

Within a Line of Sight (LOS) environment, the satellite system is superior to the terrestrial system in its resilience against disasters, its ability to cover large areas, and its multicasting capabilities. Although it is effective in terms of helping to solve the digital divide issue and providing support during disaster relief, the system cannot be used in a non-LOS environment such as urban areas and indoors.

On the other hand, the terrestrial system is increasing in communication speed and population coverage rate and becoming more globalized, but there is a higher risk of communication failure in the case of large-scale natural disasters such as earthquakes and typhoons. In addition, as it cannot be used for communication with aircraft and ships, true universal communication cannot easily be achieved through the terrestrial system alone. For this reason, it is highly desirable that STICS is realized, allowing the terrestrial system and the satellite system to complement each other’s weaknesses while capitalizing on each other’s strengths.

STICS combines satellite and terrestrial system communication networks so that communication services can be provided by the same provider using the same frequency band. In STICS, the satellite and terrestrial systems connect with each other on the Public Switched Telephone Network (PSTN) via the core network. The system allows for dual-mode user devices that automatically switch between the terrestrial and the satellite system (Fig. 1).

In order to downsize and minimize power usage for user devices running on STICS, the satellite station will be equipped with a large-scale 30 m-class diameter antenna. Further, the satellite station will be equipped with a high-performance onboard processor in order to achieve high frequency utilization efficiency by creating 100 beam-class multibeams with a digital beam former (DBF), and also to achieve high line utilization efficiency and high channel capacity by means of demultiplexing/multiplexing frequency signals (channelizing).

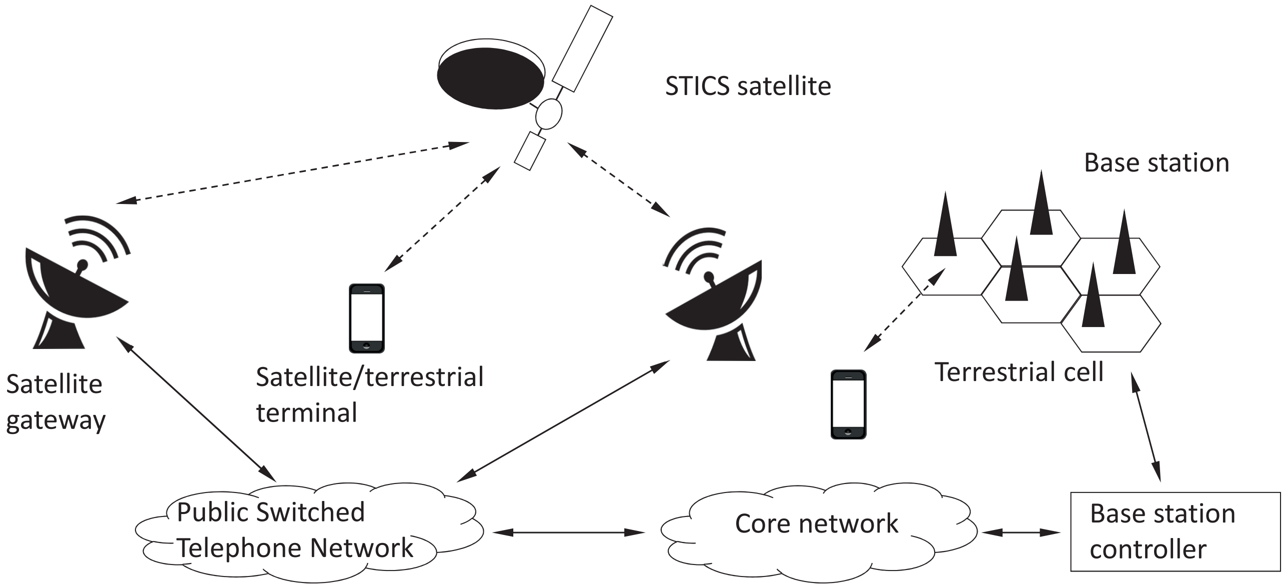

Fig. 1 Satellite/Terrestrial Integrated mobile Communication System (STICS)

Table 2 Conditions on link budget calculation for voice communication ([2] copyright©2008 IEICE)

Item	Content
Required Eb/N0	6.7 dB@BER of 10^{-3}
Forward error correction(FEC)	None
Implementation loss	None
Remarks	Additional coding gain of 5-6 dB is made possible by FEC

Table 3 An example of link budget for voice communication by portable terminal. (Gro.), (Sat.), and (Por.) describe a ground station, satellite, and portable terminal, respectively ([2] copyright©2008 IEICE)

		forward		return	
Item	unit	Gro. → Sat.	Sat.→ Por.	Por. → Sat.	Sat. → Gro.
Transmitter					
Transmission freq.	GHz	14.0	2.0	2.0	12.0
Transmission power	W	0.001	0.2	0.2	0.001
Tx antenna aperture	m	5.0	30.0	-	2.0
Tx antenna gain	dBi	54.7	47.0	0.0	45.4
EIRP	dBm	53.7	69.0	22.0	44.4
Propagation					
Loss in free space	dB	206.5	189.6	189.6	205.2
Rain attenuation	dB	3.0	0.0	0.0	3.0
Fading loss	dB	0.0	3.0	3.0	0.0
Receiver					
Rx antenna aperture	m	2.0	-	30.0	5.0
Rx antenna gain	dBi	46.7	0.0	47.0	53.4
Reception noise figure	dB	3.0	1.5	1.5	3.0
G/T	dB/K	19.1	-23.8	20.9	27.3
C/N0	dB-Hz	60.9	50.2	47.9	61.1
Demodulation					
Reception C/N0	dB-Hz		49.9		47.7
Data rate	kbit/s		9.6		9.6
Required C/N0	dB-Hx		46.5		46.5
Circuit margin	dB		3.4		1.1

STICS will introduce cells for the satellite system (hereafter “satellite cells”) in the same way as it does for the terrestrial system (hereafter “terrestrial cells”). This makes frequency reuse possible, and means that same-frequency channels can be reused from sufficiently removed locations.

The cell sizes for terrestrial cells are as follows: picocells (radius of several dozen meters) for indoor areas; microcells (radius of several hundred meters) for urban areas; and, macrocells (radius of several kilometers) for suburban areas. On the other hand, although the satellite cell radius depends on the latitude, it will be in the range of a few hundred kilometers.

In terms of technology, there is no great difference between STICS in Japan and MSS/ATC in North America (or MSS/CGC in Europe). However, in Europe and North America the main objective of these systems is to complement the satellite system with the terrestrial system primarily in urban areas where obstacles such as buildings can lead to poor signal coverage, whereas in Japan the objective is to complement the terrestrial system with the satellite system when the terrestrial system cannot be used in disaster situations or in remote locations.

Satellite system line design is implemented as part of the study for the STICS system[2]. Evaluation of the frequency-sharing method (interference evaluation) (Term A) and antenna system design, etc. (Term B), as outlined in Chapter **2** of this Special Issue onwards, are conducted with reference to the line design for voice communication for mobile devices. Thus, the following is outlined for reference. In the line design, the satellite employs an antenna with a 30 m aperture and antenna gain of 47 dBi at beam edge. Prerequisites and line design for double hop connections for small-sized mobile devices using voice communication in the bit range of 9.6 kbps are indicated in Tables 2 and 3. From Table 3 it is evident that the system can run for voice communications even if the satellite receiving device has a small antenna of around 0 dBi if the satellite itself is equipped with a large-sized 30 m-class antenna.

3 Satellite/terrestrial integration methods

As a method through which terrestrial and satellite system users can co-exist, mobile satellite communication systems using the S band (2 GHz band) are under consideration. Through STICS, one can envisage both frequency-separation and frequency-sharing methods, as shown in Fig. 2.

Under the frequency-separation method, the respective frequency bands used by the satellite and the terrestrial system are separated, meaning that there is no interference generated between those systems. The satellite system uses one frequency band while the remainder is used by the terrestrial system.

Under the frequency-sharing method, both the satellite and the terrestrial system make use of the same frequency band. Under either method, the assigned frequency band is divided up and, by reusing the same frequencies, an improvement in frequency utilization efficiency can be expected.

Again, as shown in Fig. 2, in the case of either the frequency-separation or the frequency-sharing method, it can be envisaged that they will have a normal mode and a reverse mode. In normal mode, satellite uplink and terrestrial uplink are assigned the same band, as are satellite downlink and terrestrial downlink. On the other hand, in reverse mode, satellite uplink and terrestrial downlink are assigned the same band, as are satellite downlink and terrestrial uplink.

When the frequency-separation and frequency-sharing methods are compared with one another, generally speaking it is the sharing method, rather than that of separation, that allows the satellite system and the terrestrial system to share the entire band. Due to this, the sharing method has the merits of allowing high frequency utilization efficiency and of expanding the bandwidth per satellite system beam. On the other hand, when seeking to realize a shared-frequency system, one is faced with the issue of anti-interference strategies to allow the satellite system and the terrestrial system to share the same frequency.

4 The frequency-sharing method

The frequency-sharing method is important in maximizing capacity, that is, the number of users that the satellite system and the terrestrial system can accommodate under STICS. In this section, we will discuss the principles of the STICS shared-frequency method, the related issue of the problem of interference, and possible workarounds. Figure 3 shows the frequency allocation patterns for satellite cells and terrestrial cells under the frequency-sharing

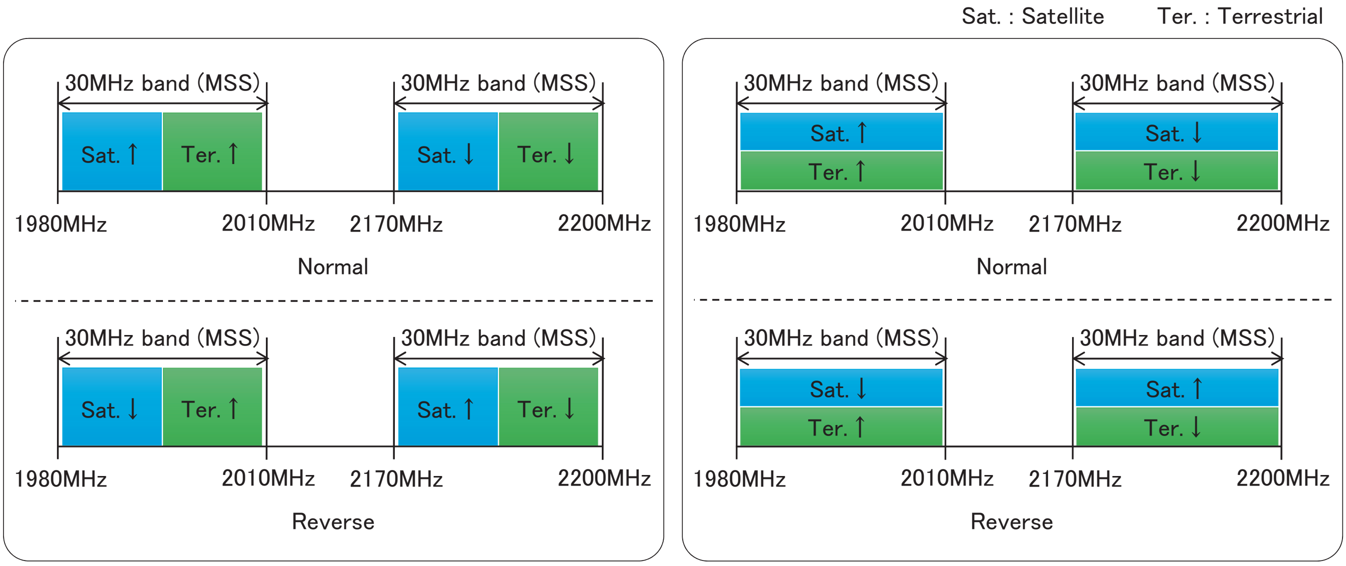

Fig. 2 Frequency separation scheme(left), and frequency sharing scheme(right)

method. The Figure shows an example of 7-cell frequency reuse allocation; f_1 through f_7 are assigned as differing frequencies.

In order to avoid satellite/terrestrial co-channel interference, the terrestrial system must reuse frequencies other than those being used by the satellite system. For example, as shown in Fig. 3, inside satellite cell f_1, terrestrial cells use f_2–f_7 only—not f_1—and reuse those frequencies.

Further, in order to reduce interference between the systems, as shown in Fig. 3, there is a spatial guard band set up around the outside of satellite cell f_1. This guard band is used in order to reduce the co-channel interference that is introduced by the sidelobe of the satellite spot beam that generates the satellite cell. Due to the spatial guard band, for example as shown in Fig. 3, it is possible to reduce co-channel interference from terrestrial cell f_1, which is being used inside the satellite cell f_2–f_7 region.

Interference arising between the satellite system and the terrestrial system under STICS is divided into two types: interference within the respective systems themselves, and interference occurring between the two. The first type of interference, i.e., inter-system, is the same as that produced by the technologies used in traditional satellite and terrestrial systems. Thus, below we will discuss the latter, i.e., intra-system interference, which is important in the STICS system.

Shown in Fig. 4 are the satellite/terrestrial intra-interference routes in normal and reverse modes under the frequency-sharing method. Interference routes exist for each of the four separate lines of the desired signal, but it is thought that the main source of problematic interference is the uplink signal on the same frequency as that being sent from multiple terrestrial system user devices and base stations and received by the satellite in a LOS environment[3]. In the case of normal mode, even though the transmit power of each individual terrestrial system user device is small, the amount of interference becomes huge because of an extremely high number of terrestrial system user devices. On the other hand, in reverse mode, transmit power per base station, which is the source of interference, is larger than that of terrestrial system user devices, but base stations are fewer in number. Considering this, it is important to ascertain, by way of fine-tuned interference evaluations, whether normal mode or reverse mode is more suitable.

As a strategy for avoiding or reducing the intra-system interference between the terrestrial system and the satellite system generated through the frequency-sharing method, a spatial guard band, as mentioned above, has been suggested. The sidelobe level of the satellite antenna beam is reduced by way of a flexible beamforming function via DBF, and this makes it possible to minimize interference between different individual satellite cells and between satellite and terrestrial cells that are using the same frequency. Further, DBF makes it possible to suppress intentional jamming or accidental interference by creating nulls in the satellite antenna beam.

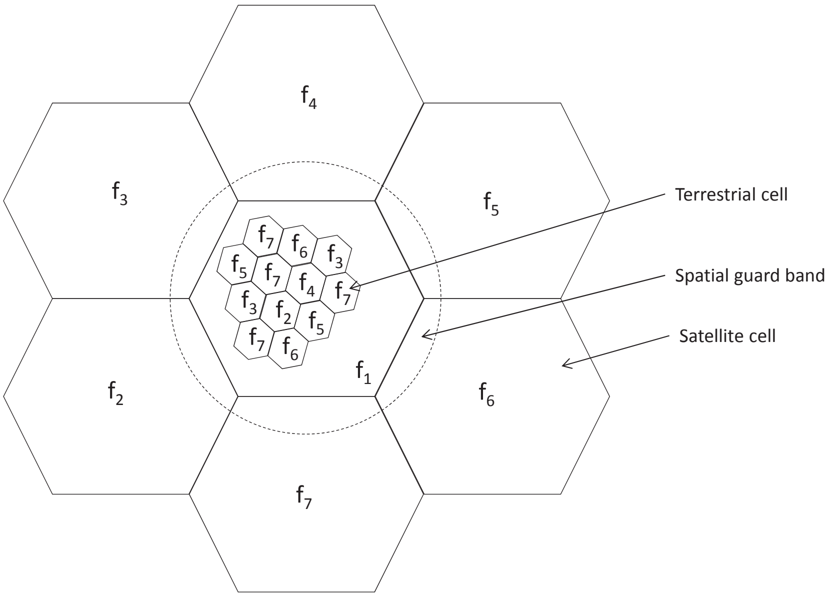

Fig. 3 Frequency reuse pattern in frequency sharing scheme

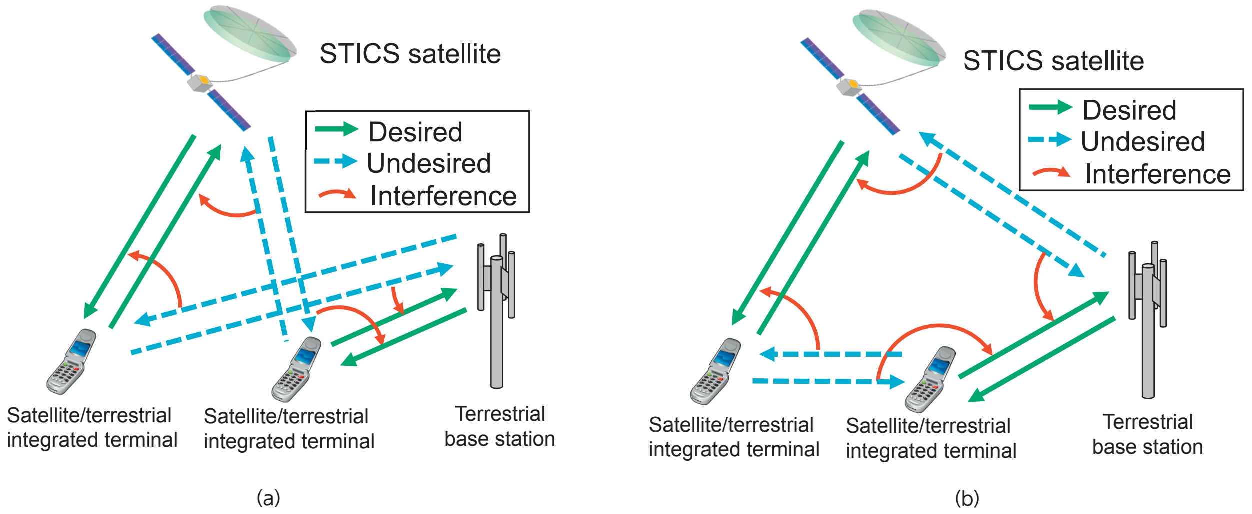

Fig. 4 Interfering routes in frequency sharing scheme: (a)normal mode, (b)reverse mode

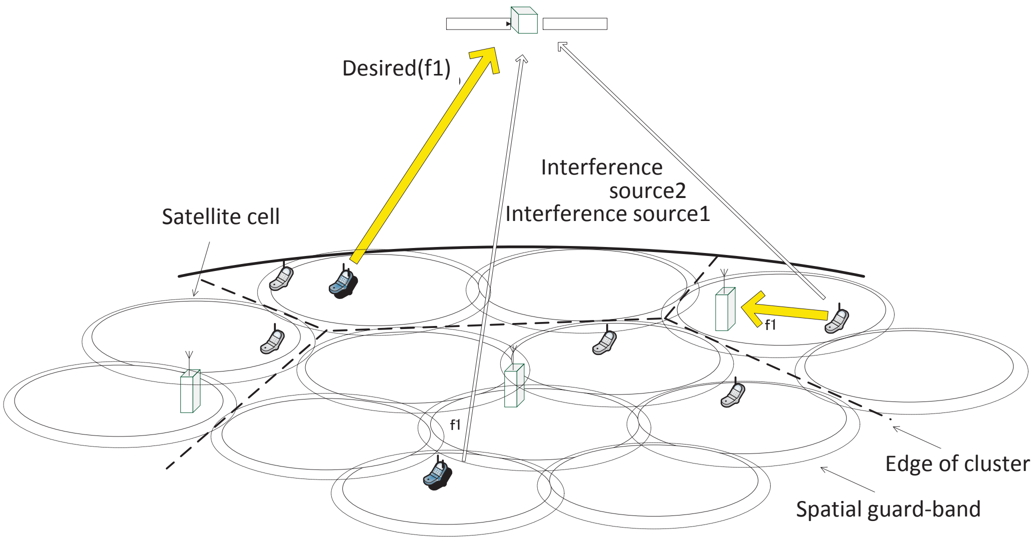

Fig. 5 Image of frequency interference caused by satellite uplink in frequency sharing scheme

5 Evaluation of the effectiveness of the frequency-sharing method

In this section, with the intention of illustrating the effectiveness of the STICS frequency-sharing method, we will compare, by way of theoretical analysis, frequency utilization efficiency between the frequency-separation method and the frequency-sharing method. Further, based on the concept of the STICS system model, we will compare frequency usage efficiency in a simulation of radio frequency interference. An example of radio frequency interference under the frequency-sharing method is shown in Fig. 5 (which illustrates the case of a satellite uplink as the desired signal). As shown in the Figure, all the terrestrial uplinks that surround the satellite cell at the same frequency introduce interference to the desired signal of the satellite uplink. In the simulation, consideration is given to the effect on frequency utilization efficiency with respect to the spatial guard band mentioned in Section **4** and the suppression of satellite antenna sidelobe, as STICS interference-avoiding or reducing strategies. Similar considerations in regard to MSS/CGC can be seen, for example, in Reference [4].

5.1 Theoretical analysis

In order to verify the effect of the STICS system, we will compare, through theoretical analysis, the traditional method of frequency-separation with that of frequency-sharing.

Figure 6 shows a conceptual diagram of the theoretical analysis. The analysis will compare differences between the terrestrial system and the satellite system in regard to frequency bandwidth, but will not treat the issue of intra-line interference. Under the frequency-separation method (at top of Figure), IMT-2000 MSS band (30 MHz) is split into a satellite and a terrestrial band. The satellite band is composed of multi-beams and thereby performing frequency reuse (the Figure shows an example of 7-cell frequency reuse). In contrast, under the frequency-sharing method (at bottom of Figure), the entire IMT-2000 MSS band is shared between the satellite band and the terrestrial band.

Shown in Table 4 are the results of the theoretical analysis of frequency utilization efficiency in the case of 7-cell frequency reuse for the satellite system. As can be seen, frequency utilization efficiency for the satellite band is doubled and for the terrestrial band it is improved by 1.7 times. The frequency utilization efficiency for the terrestrial band, can be improved to a level closer to 2 times by fragmenting the frequency reuse factor.

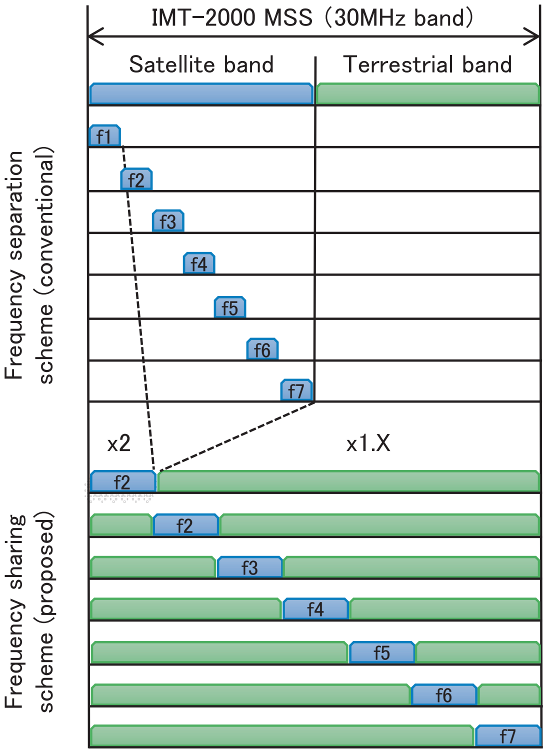

Fig. 6 Conceptual diagram: Frequency sharing scheme and Frequency separation scheme

From the above analysis results, it was found that the frequency-sharing method could produce a satellite system band twice the width of that of the frequency-separation method and that, by fragmenting the frequency reuse factor, the terrestrial system band could be increased to almost twice its original bandwidth.

5.2 Simulation analysis

A simulation of the frequency-sharing method was conducted to determine the maximum number of lines and to compare the results with the frequency-separation method.

5.2.1 Analytical model

This study analyzes how far the number of terrestrial system lines can be increased without having an effect on the satellite system.

The conditions of the study are as follows:

- Targeted lines: satellite uplink lines under the frequency-sharing method in normal mode
- Base station location: with reference to the 3G system, the cell radius is 2.5 km and the base stations will be uniformly distributed
- Traffic distribution: uniform
- Satellite line: equidistributional 7-cell frequency reuse pattern using frequency division multiple access (FDMA), channel bandwidth of 19.2 kHz, and a maximum of 223 lines/4.3 MHz
- Terrestrial line: CDMA and channel bandwidth of 5 MHz
- Maximum number of lines per base station: with

Table 4 Theoretical analysis of spectrum efficiency

Satellite/terrestrial bandwidth range	Frequency sharing scheme（STICS）	Frequency separation scheme（conventional method）	Improvement of spectrum efficiency
Satellite bandwidth range	30/7=4.28 MHz（per/1 color）	30/2/7=2.14 MHz（per/1 color）	4.28/2.14=2 times
Terrestrial bandwidth range	30*6/7=25.7 MHz	30/2=15 MHz	25.7/15=1.7 times

reference to the 3G system, set to 20 lines/frequency

- Satellite receiving device: transmit power of 200 mW and antenna gain of 0 dBi
- Terrestrial terminal: using the project's measurement results for W-CDMA mobile device transmit power as a reference, transmit power was set to 1 mW and antenna gain to 0 dBi

Figure 7 shows the evaluation model employed for the simulation analysis. As seen in the figure, there are 25 satellite beams. In terms of satellite lines, the desired signal is the central line using a frequency f_7 beam, and taking into account interference from other satellite lines, 6 f_7-beams surrounding the central f_7 will also be considered. Terrestrial system lines sharing f_7 frequency will, in the 25 beam area, be positioned in areas other than where there are f_7 beams or where there are spatial guard bands in the vicinity of f_7 beams.

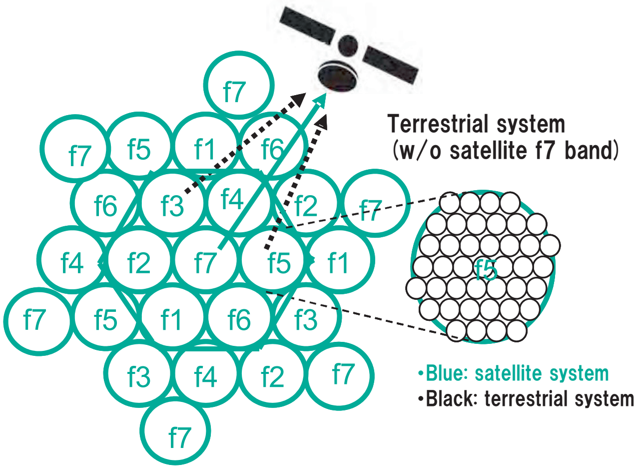

Fig. 7 Evaluation model of spectrum efficiency

The satellite antenna patterns used for the study are indicated in Figs. 8 and 9. Two studies were conducted, one with a sidelobe level of -20 dB and the other with a sidelobe level of -30 dB.

5.2.2 Analysis results

The analysis results for the comparison of possible numbers of lines between the spatial guard bands and the terrestrial system are shown in Figs. 10 and 11.

When there is no limitation to the maximum number of lines for the terrestrial system base station, interference from the terrestrial system can be reduced by widening the spatial guard band. By doing this, the number of terrestrial system lines increases linearly. However, in reality, there is a limit to the maximum number of lines for a base station, so at some point the number of lines will plateau and decrease.

As a result of the analysis, it was found that there exists a spatial guard band that allows the number of lines to reach the maximum. Table 5 shows the spatial guard band level and the number of lines for the terrestrial system. Both of these vary depending on the antenna sidelobe level; and, because interference to the satellite system from the terrestrial level is lessened in relation to a lower sidelobe level, it was found that the spatial guard band level becomes smaller and the number of lines increased for the terrestrial system.

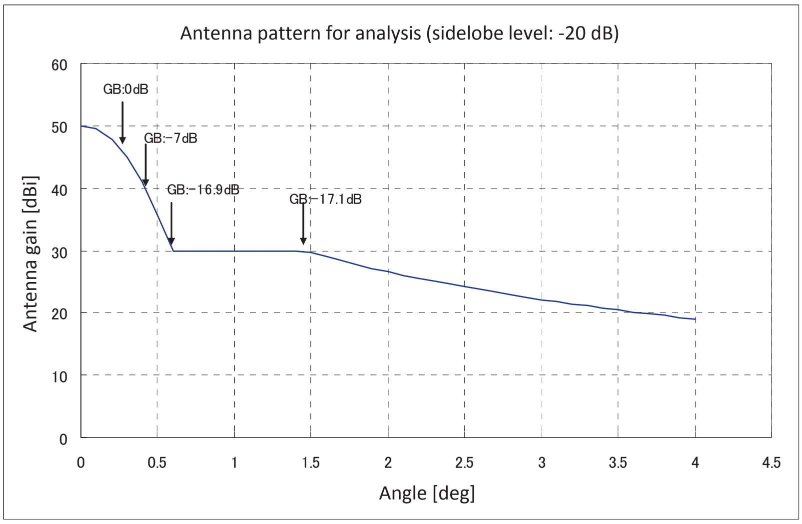

Fig. 8 Antenna pattern used for analysis (sidelobe level: -20 dB)

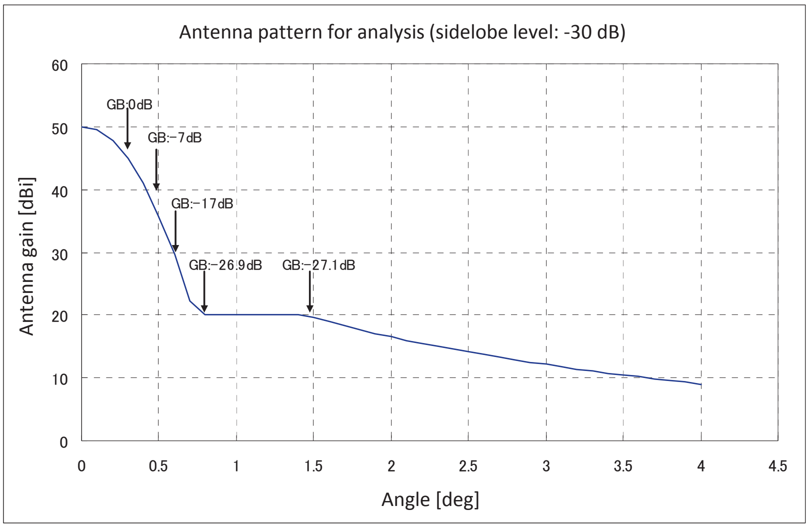

Fig. 9 Antenna pattern used for analysis (sidelobe level: -30 dB)

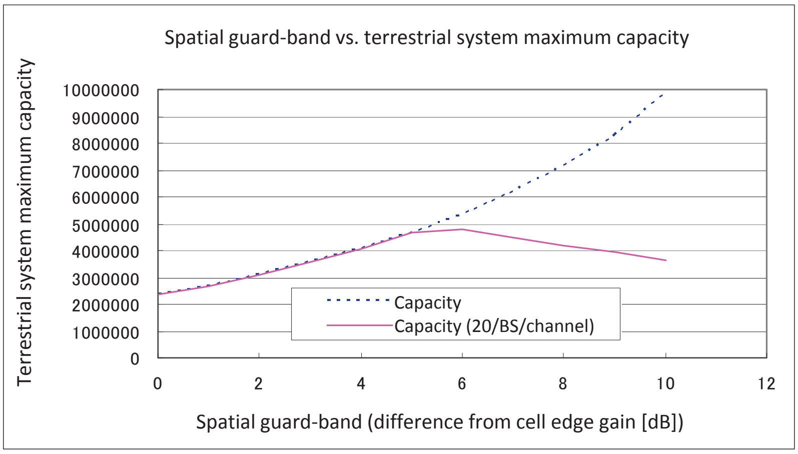

Fig. 10 Analytical result on maximum capacity of a terrestrial system against spatial guard bands (sidelobe level: -20 dB)

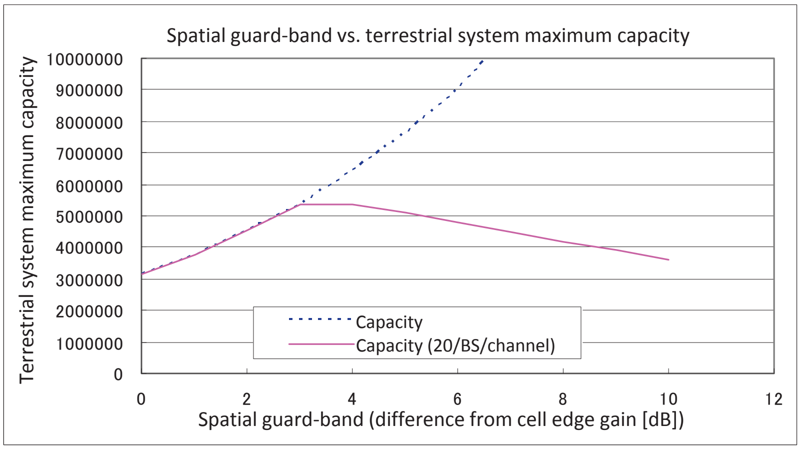

Fig. 11 Analytical result on maximum capacity of a terrestrial system against spatial guard bands (sidelobe level: -30 dB)

Table 5 Analytical results（space guard band and maximum No. of lines)

Sidelobe level	Spatial guard band	Max. No. of lines
-20 dB	6 dB	4,788,909 lines
-30 dB	4 dB	5,386,204 lines

Table 6 Comparison of frequency separation scheme and frequency sharing scheme (sidelobe level：-20 dB)

	Frequency separation scheme	Frequency sharing scheme
No. of satellite lines	Bandwidth/1 beam 15 MHz/7=2.14 MHz Lines/1 beam 2.14 MHz/19.2 kHz=111.5 Total lines 25 beams×111.5 = 2787.5	Bandwidth/1 beam 30 MHz/7=4.3 MHz Lines/1 beam 4.3 MHz/19.2 kHz=223 Total lines 25 beams×223 = 5575
No. of terrestrial lines	No. of stations : 65,628 20 lines/station/1 freq. Freq. range : 3 waves lines 65,628×20×3=3,937,680	Analytical result 4,788,909 lines 1.22 times of Frequency separation scheme

Table 7 Comparison of frequency separation scheme and frequency sharing scheme (sidelobe level：-30 dB)

	Frequency separation scheme	Frequency sharing scheme
No. of satellite lines	Bandwidth/1 beam 15 MHz/7=2.14 MHz Lines/1 beam 2.14 MHz/19.2 kHz=111.5 Total lines 25 beams×111.5 = 2787.5	Bandwidth/1 beam 30 MHz/7=4.3 MHz Lines/1 beam 4.3 MHz/19.2 kHz=223 Total lines 25 beams×223 = 5575
No. of terrestrial lines	No. of stations : 65,628 20 lines/station/1 freq. Freq. range : 3 waves lines 65,628×20×3=3,937,680	Analytical result 5,386,204 lines 1.37 times of Frequency separation scheme

5.2.3 Comparison of frequency-separation and frequency-sharing methods

The results of the comparison of the frequency-separation method and the frequency-sharing method are shown in Tables 6 and 7. Compared with the separation method, the sharing method allows for a doubling in frequency utilization efficiency for the terrestrial system; and, in the case of -20 dB sidelobe level, it is increased by 1.22 times. When the sidelobe level is -30 dB, utilization efficiency increased by 1.37 times. When factoring in interference, it was found that the merits of efficient line utilization under the frequency-sharing method were less than in the theoretical analysis, but that frequency utilization efficiency was still high for both the satellite system and the terrestrial system under this method.

6 Conclusion

In this paper we proposed, as the key to realizing STICS, the two methods of frequency-sharing and frequency-separation, which allow users to co-exist on terrestrial and satellite systems. Further, we discussed the principles of the frequency-sharing method, which can be expected to provide high frequency utilization efficiency, and the important issue of strategies for avoiding or reducing interference. We noted that an issue with frequency-sharing is the interference that is generated between the satellite system and the terrestrial system, and we showed that, as countermeasures against this, the adoption of spatial guard bands and the suppression of satellite antennae sidelobe are important.

In addition, carrying out a computerized simulation alongside the theoretical analysis, we compared the frequency utilization efficiency for the frequency-separation method and the frequency-sharing method. As a result, in the theoretical analysis when not factoring in interference, it was found that, compared to the frequency-separation method, the sharing method allows for a doubling in width of the satellite band. Further, it was found that, by fragmenting the frequency reuse factor, terrestrial bandwidth could be widened by almost 2 times. On the other hand, through the computerized simulation taking into account interference, we found that there exists a spatial guard band where the terrestrial system lines reach their maximum number. It was found that, when considering interference, even though frequency utilization efficiency was lower than theoretical analysis would have suggested, it is still high for both the satellite system and the terrestrial system under the frequency-sharing method.

Through the above results, the effectiveness of the frequency-sharing method for use in STICS was confirmed.

Acknowledgments

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Tadashi MINOWA, Ph.D.

Senior Researcher, Social ICT Laboratory,
Social ICT Research Center
Distributed Algorithms for Wireless Sensor
Network and its Applications to Iot/Big
Data Analysis

Amane MIURA, Ph.D.

Senior Researcher, Space Communication
Systems Laboratory, Wireless Network
Research Institute
Satellite Communications, Antenna