Evaluation of Frequency Sharing Scheme between Satellite and Terrestrial Links

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Evaluations are carried out in order to verify the feasibility of frequency sharing scheme between satellite and terrestrial links in Satellite/Terrestrial Integrated mobile Communication System (STICS), considering radio-wave interference between those links. The interference level for each interference path is evaluated by using the simple interference model. The capacity of terrestrial and satellite links under co-channel interference is evaluated by using the detailed interference model. Minimum separation distance between satellite terminal and base station is evaluated. From these evaluations, the feasibility of frequency sharing scheme between satellite and terrestrial links is confirmed.

1 Introduction

Research and development activities have been implemented for the Satellite/Terrestrial Integrated Mobile Communication System (STICS) that enables mobile phones to seamlessly switch terrestrial communication links/satellite communication links[1]. In STICS, through taking advantage of a large-antenna multi-beam satellite communication system, the satellite/terrestrial communications links are supposed to share frequency bandwidth. Such frequency sharing is accomplished in the following way: dividing the frequency bandwidth allocated to the system into sub-bands, allocating the sub-bands to the satellite cell, and also allowing the terrestrial links to use the same sub-bands in the circumference of the satellite cell. However, because the satellite antenna has sensitivities to areas outside the satellite cell, interference will occur between satellite links and terrestrial links. Furthermore, even inside the satellite cell, the terminals using the satellite communications links will receive interference from the terminals or base stations located outside the satellite cell. So, it is necessary to evaluate such interference and clarify the conditions for the frequency sharing.

Therefore, National Institute of Information and Communications Technology (NICT), for the purpose of proving the feasibility of STICS's frequency sharing method, conducted evaluations as follows: first, by applying a simple interference model, estimating the interference-levels along each of the interference paths to clarify the interference characteristics of each interference path and confirm the feasibility of the frequency sharing method; second, for the purpose of quantitatively ascertaining the upper-limit number of links that the system can accommodate under the satellite/terrestrial co-channel interference environment, making estimations on the number of simultaneously accommodated links for which the system can establish both its satellite communications link and a terrestrial communications link[2].

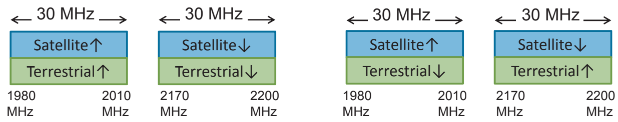
For the estimation of such simultaneously accommodated links, NICT, newly developed a detailed interference model[3] that can simulate the number and transmission power of terminals and ground stations as precisely as possible through accepting as the model parameters actual country-wide traffic distributions, and for the purpose of improving accuracy, applied statistical data that NICT had collected through cellular phone terminal transmission power observations in a variety of situations[4]–[6]. Furthermore, as for base-station-to-satellite terminal interference, which is caused by a different mechanism from that of terrestrial-to-satellite interference, we made estimations on the base-station-to-satellite terminal separation distance that ensures the establishment of a link.

In the following sections, we will introduce, in Section **2**, the generalities of the satellite/terrestrial frequency sharing method and interference; in Section **3**, the interference evaluations of each interference path using the simple interference model; in Section **4**, the estimations of the number of simultaneously accommodated stations under co-channel interference environment; in Section **5**, the evaluations of satellite terminal-to-base-station separation distances, and finally, in Section **6**, the conclusions of this study.

2 Satellite/terrestrial frequency sharing method and interferences: generalities

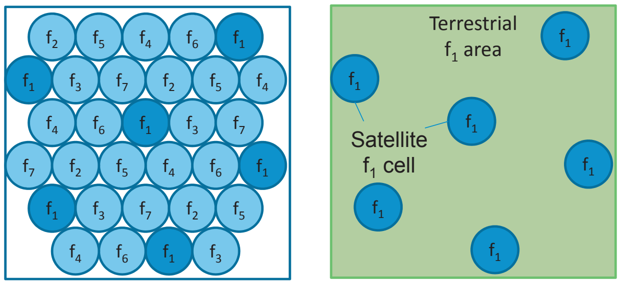
In STICS, it is supposed that the 2 GHz band that is reserved for Mobile Satellite Services—1,980 to 2,010 MHz for up-link, and 2,170 MHz to 2,200 MHz for down-link—is shared by the terrestrial communications links and the satellite communications links. In such a scheme, the two configurations—normal mode and reverse mode as shown in Fig. 1—are employable according to which of the bands that is used for the satellite up- or down-link is open to terrestrial communications links. Frequency sharing is accomplished in the following way: first, as shown in Fig. 2 (a), dividing the allocated band into sub-bands, and allocating them to the satellite cell by the multi-color deployment method to enable frequency reuse—note that Fig. 2 (a) shows the seven sub-band configuration of f_1–f_7—, and then for the terrestrial system, as indicated in Fig. 2 (b), allocating the sub-bands that are already allocated to a certain satellite to the terrestrial communications links when they are used in the areas outside the satellite cell.

As described above, frequency sharing all over the allocated bands is accomplished by dividing the space where the same sub-bands are shared into an area for the satellite communications link and an area for the terrestrial communications links. However, as described in the Section **1**, radiowave interference will occur between the terrestrial system and the satellite system such as shown in Fig. 3; in the figure, SMS, TMS and BTS respectively denote a terminal using a satellite communications link (hereinafter referred to as “satellite terminal”), a terminal using a terrestrial communications link (referred to as “terrestrial terminal”), and a ground base-station (referred to as “base station”). As shown in the figure, each of the four desired links has interference paths—two interfering links, the satellite link and the terrestrial link. In such a situation, a quite different interference mechanism works depending on whether the interference path is satellite-to-terrestrial terminal (satellite propagation path) or satellite terminal-to-base-station (terrestrial propagation path). In the case of the satellite-to-terrestrial terminal path, because the propagation distance is almost equivalent for any terminal, all the terminals in the coverage area cumulatively give interference. On the other hand, in the case of the satellite terminal-to-base-station path, the interference quantity



(a) Normal mode (b) Reverse mode

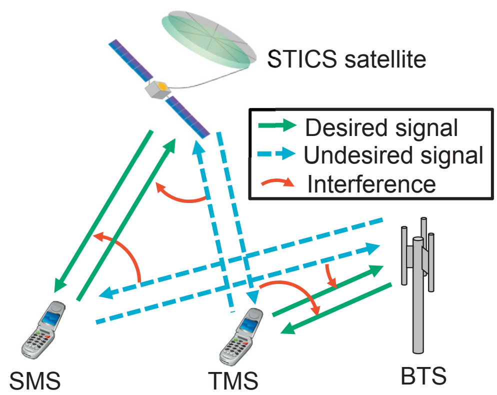
Fig. 1 Satellite/terrestrial frequency sharing method



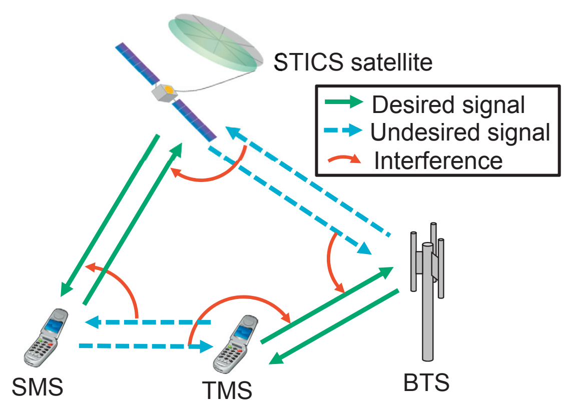
(a) Instance of sub-band allocation to satellite cell

(b) The area where terrestrial communications links are allowed to use the same frequencies with the satellite communications links.

Fig. 2 Scheme of frequency sharing (7-cell repetitive use for a satellite cell)



(a) Normal mode



(b) Reverse mode

Fig. 3 Satellite/terrestrial interference paths

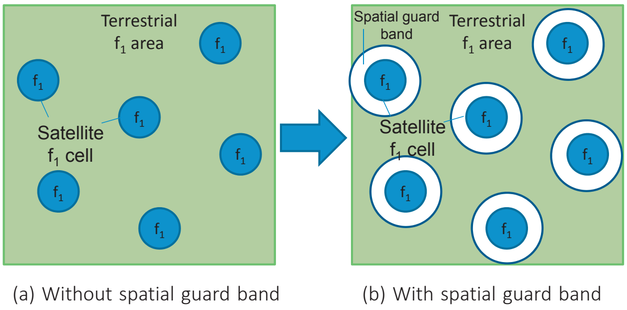


Fig. 4 Conceptual scheme of spatial guard band

heavily depends on the distance from the satellite terminal to the base station. However, because a satellite cell has a very large diameter of around 200 km, the satellite terminals in the vicinity of the cell center give almost negligibly small interference for the base stations outside the cell that are using the same frequency as the frequency used for the satellite terminal link. Therefore, the exceptional case is where the satellite terminals close to the satellite cell edge give interference to the base stations.

In addition, as for STICS, setting up spatial guard bands will be effective as an interference mitigation measure, as shown in Fig. 4. In the spatial guard band method, the area (guard band) is located in the circumference of the satellite cell, in which terrestrial links in the area are prohibited from using the same sub-band as the band used by the satellite cell. However, because the spatial guard band method, although having an advantage of reducing ground-to-satellite interference, limits the communication areas of terrestrial communications links, assessments are required on its effects and drawbacks.

3 Simple model path-by-path interference evaluation

3.1 Purposes

Interference evaluations using a simple model are conducted for the purpose of gaining knowledge on the path-by-path interference characteristics and assessing the feasibility of STICS's frequency sharing method. The model system, consisting of a single satellite and a single terrestrial cell, is assumed to have interference along the four paths shown in Fig. 3 whichever mode, normal or reverse, is taken. Evaluations are conducted on such four paths for each mode.

3.2 Model system configuration and evaluation method

The model system for evaluation has a satellite cell, a terrestrial cell, and more than or equal to one station (terminals or base stations) in each of the cells—the number of stations is determined from the case situation. In such a configuration, the Carrier-to-Interference Ratio (CIR) for each case is estimated. In addition, for the purpose of evaluating the improvement in CIR by a spatial guard band that is setup to encircle the satellite-beam foot-print on the ground, CIRs are estimated for various guard band levels. The other assumed parameters or configurations for the evaluation are described below, and the general specifications of the links are listed in Table 1.

- Communications link: CDMA (5 MHz channel bandwidth) for terrestrial, and FDMA (19.2 kHz channel bandwidth) for satellite
- For simulating the worst-case, the satellite terminal and the terrestrial cell are respectively placed on the satellite cell Edge of Coverage (EOC), and on the spatial guard band edge.
- Transmit power for the case of interference to the satellite communication links: each of the interfering terrestrial terminals is assumed to emit interference of constant power in the range of 1 mW to 250 mW, and a base station emits interference power of 20 W, its capacity limit, for simulating the worst case.
- For evaluating the interference from the satellite communications link to the terrestrial communications link, the level of interference reduction due to the process gain of the terrestrial system's CDMA demodulator is assumed as 25 dB, and the evaluations are conducted for the two cases of the satellite FDMA signals where a single channel is accommodated or channels of its capacity limit are accommodated.
- In the evaluations of the interference to the terrestrial communications link, the received power of the desired signal is determined using the required received power shown in the reference [7], showing the required received power for the W-CDMA up-link/down-link common control channel.

3.3 Evaluation results

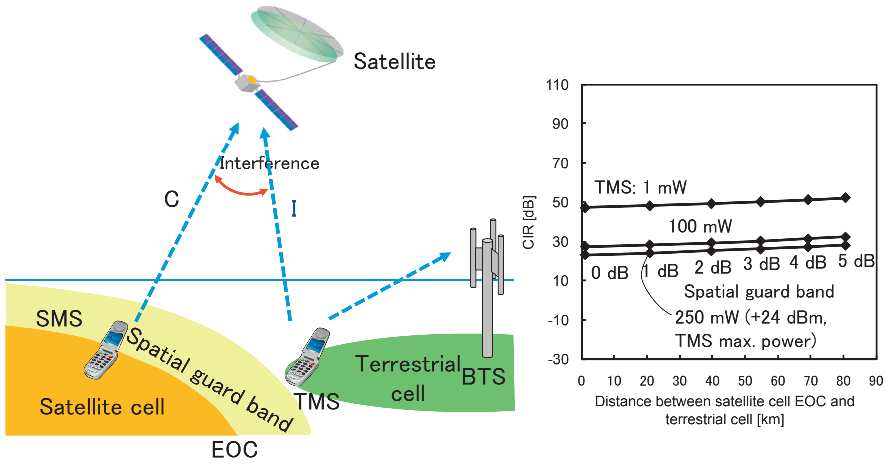
3.3.1 Normal mode

(a) Satellite up-link

Figure 5 shows the paths/evaluations of the interference to the normal mode satellite up-link. The evaluations shown in Fig. 5 (b), where the horizontal axis is for the distance between the satellite beam EOC and the terrestrial

Table 1 Conditions of links

Link	Channel bandwidth [kHz]	TX			Propagation channel			RX		
		TX station	TX power [W]	Antenna gain [dBi]	Propagation distance [km]	Propagation model	Propagation loss [dB]	RX station	Antenna gain [dBi]	Req. RX power [dBm]
Satellite uplink	19.2	SMS	0.2	0	36000	Free-space	190	Satellite	47	
Satellite downlink	19.2	Satellite	0.2	47	36000	Free-space	190	SMS	0	
Terrestrial uplink	5000	TMS	0.001 - 0.25	0	1	COST231-Hata model	140	BTS	17	-116
Terrestrial downlink	5000	BTS	20	17	1	COST231-Hata model	140	TMS	0	-117



(a) (b)

Fig. 5 Interference paths and evaluation: normal mode satellite up-link

cell, depicts the relation of the spatial guard band level to CIR, indicating that CIR depends on the transmitted power per terrestrial terminal. Evaluations also suggest the following not shown in the figure: as the number of the interfering terrestrial communication links grows, the interference level goes up. What has been mentioned so far suggests that the concerned communications link can be shared, but the conditions for sharing are determined by the terminal's transmitted power and the number of simultaneously served terminals.

(b) Satellite down-link

Figure 6 shows the paths/evaluations of the interference to the normal mode satellite down-link. The evaluations shown in Fig. 6 (b) indicate that there will be a great improvement in CIR by setting up spatial guard bands. This comes from the fact that the propagation loss between the interfering base-station and the satellite terminal (calculated by using COST231-Hata Model) is heavily dependent on the separation distance. It is concluded that, because the CIR of the concerned link is expected to be improved by properly setting up spatial guard bands, the sharing of the concerned link is feasible.

(c) Terrestrial up-link

Figure 7 shows the paths/evaluations of the interference to the normal mode terrestrial up-link. The evaluations shown in Fig. 7 (b) indicate that the CIR is dependent on the number of satellite terminals and the spatial guard band setting. In the situation where all the channels are occupied (the number of satellite terminals N, N = MAX shown in the figure), the CIR varies from -14 dB (spatial guard band: 0 dB) to 30 dB (spatial guard band: 1 dB). Such a result comes from the fact that, because the interference comes along terrestrial propagation paths, the propagation losses largely vary depending on the separation distance. It is concluded that, because CIR is expected to be improved by properly setting up spatial guard bands, the sharing of the concerned link is feasible.

(d) Terrestrial down-link

Figure 8 shows the paths/evaluations of the interference to the normal mode terrestrial down-link. The evaluations shown in Fig. 8 (b) indicate that the CIR is dependent on the number of satellite terminals. While the CIR is close

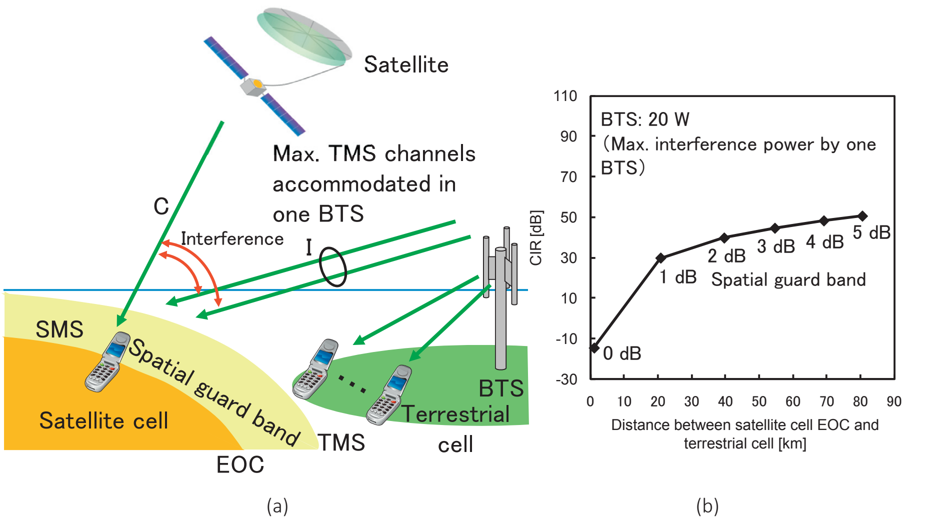


Fig. 6 Interference paths and evaluations: normal mode satellite down-link

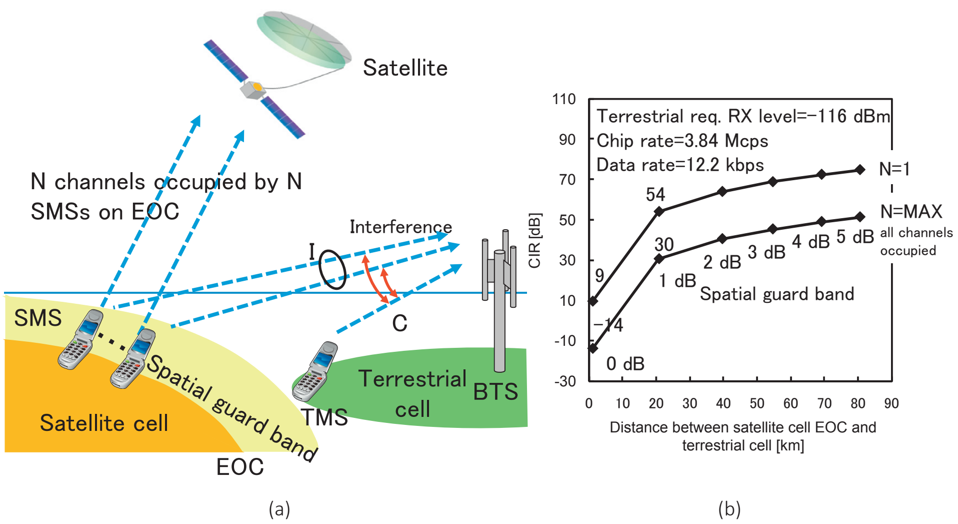


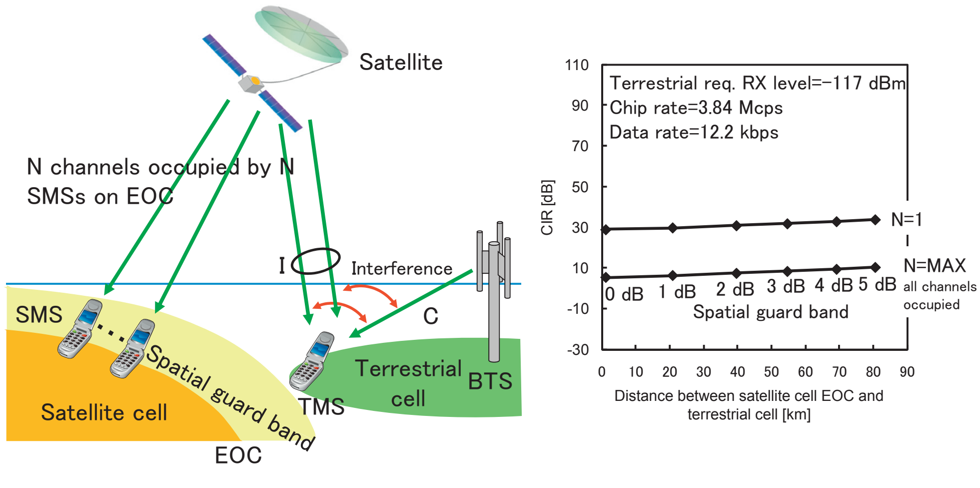
Fig. 7 Interference paths and evaluations: normal mode terrestrial up-link

to 30 dB when the number of terminals is one (N = 1, in Fig. 8 (b)), and the CIR is as small as 5-10 dB when all the channels are occupied (N = MAX, in Fig. 8 (b)). Such an "N = MAX" case will occur, for example, in a disaster situation where satellite communication traffic congestion occurs in a specific satellite beam. In such a situation, raising the spatial guard band level taken for the purpose of improving CIR is not expected to work well, different from the CIR improvement that would be accomplished against terrestrial interference. In addition, a higher spatial guard band level will lead to loss in the terrestrial terminal service area. Therefore, it is concluded that countermeasures are required because the concerned link has a drawback of a risk of traffic congestion on its satellite link.

3.3.2 Reverse mode

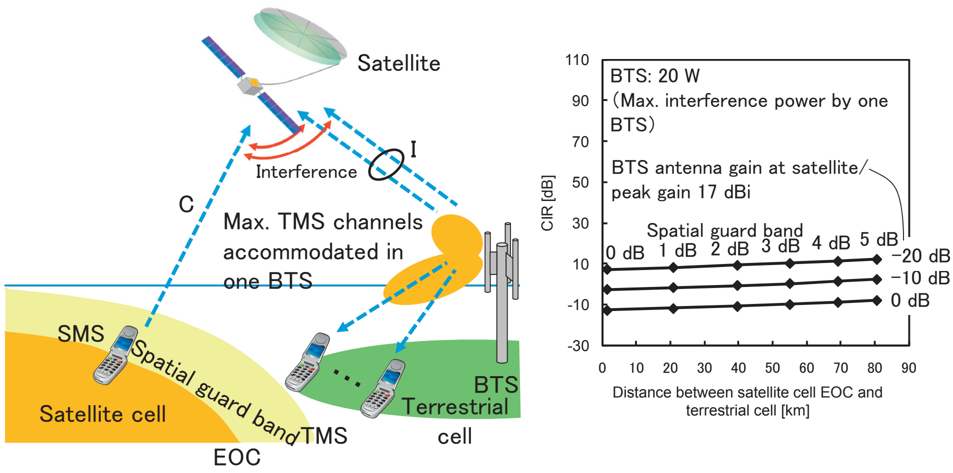
(a) Satellite up-link

Figure 9 shows the paths/evaluations of the interference to the reverse mode satellite up-link. The evaluations shown in Fig. 9 (b) indicate that the CIR is dependent on the satellite direction gain of the base-station antenna. The CIR is no worse than -13 dB in the situation where the antenna gain reaches its peak in the satellite direction (Satellite direction gain = peak gain, shown in the figure), and no worse than 7 dB in the situation where the satellite direction gain is 20 dB below the peak gain (Satellite direction gain = -20 dB of peak gain). Those evaluations, because they are conducted under the assumption that the base station is emitting power of 20 W—the typical maximum power emitted by a base station—, will presumably lead to



(a) (b)

Fig. 8 Interference paths/evaluations: normal mode terrestrial down-link



(a) (b)

Fig. 9 Interference paths/evaluations: reverse mode satellite up-link

an overestimation of the per-station interference power; so, the interference powers in actual situations will be smaller than the evaluated interference power. However, because the evaluated value for CIR is the value per base station, as the number of the involved base stations grows, the total interference level will become larger. Therefore, it is concluded that the sharing of the concerned link may cause problems and countermeasures are needed.

(b) Satellite down-link

Figure 10 shows the paths/evaluations of the interference to the reverse mode satellite down-link. The evaluations shown in Fig. 10 (b) indicate that the CIR is greatly improved by raising the guard band level. This comes from the fact that, because the interference in this case comes along terrestrial propagation paths, the propagation losses are heavily dependent on the distance along the propagation path of interference. Therefore, it is concluded that the sharing of the concerned link is feasible.

(c) Terrestrial up-link

Figure 11 shows the paths/evaluations of the interference to the reverse mode terrestrial up-link. The evaluations shown in Fig. 11 (b) indicate that the CIR in this case is dependent on the satellite direction gain of the base-station antenna and the number of satellite terminals. In a situation where the number of satellite terminals is maximum (N = MAX, in the figure), the CIR is no worse than – 11 dB, and in a situation where the satellite direction gain is 20 dB below the peak gain (Satellite direction gain = -20 dB of peak gain, in the figure), the CIR is 9 dB or greater; such a case of “N = MAX” will occur, for example, in a disaster situation where traffic congestion occurs in a specific satellite beam.

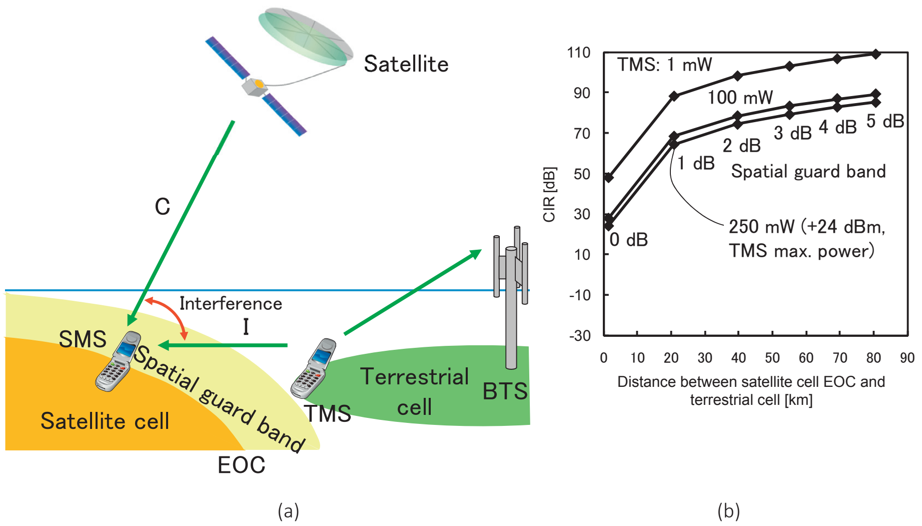


Fig. 10 nterference paths/evaluations: reverse mode satellite down-link

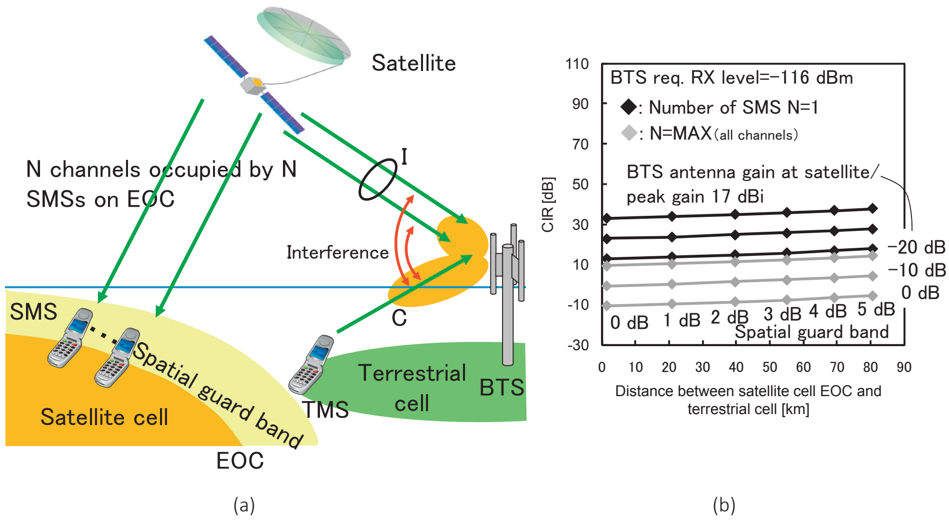


Fig. 11 Interference paths/evaluations: reverse mode terrestrial up-link

Therefore, it is concluded that the sharing of the concerned link is feasible on condition that the proper combination of the following measures is taken: controlling the number of permissible satellite terminals and the satellite direction gain of the base-station antennas; and setting up spatial guard bands. At the same time, it is also confirmed that the concerned link has a problem related to frequency sharing when traffic congestion occurs on the satellite communications link.

(d) Terrestrial down-link

Figure 12 shows the paths/evaluations of the interference to the reverse mode terrestrial down-link. The evaluations shown in Fig. 12 (b) indicate that the CIR is greatly improved by setting up spatial guard bands. This comes from the fact that the interference, because it comes along the terrestrial propagation paths, suffers heavy propagation losses. It is concluded that the sharing of the concerned link is feasible on condition that spatial guard bands are properly set up.

3.4 Conclusions

We conducted interference evaluations for each of the possible communication links in STICS by using a model of a single satellite/single terrestrial cell, confirmed the feasibility of the sharing of each of the links, and at the same time identified the problems to be solved as shown below. As for the normal mode, while satellite up-link sharing is feasible, the condition for sharing is dependent on both the power emitted on the terrestrial links by the terminals and the number of simultaneously-served terminals.

The terrestrial down-link, while the CIR was confirmed

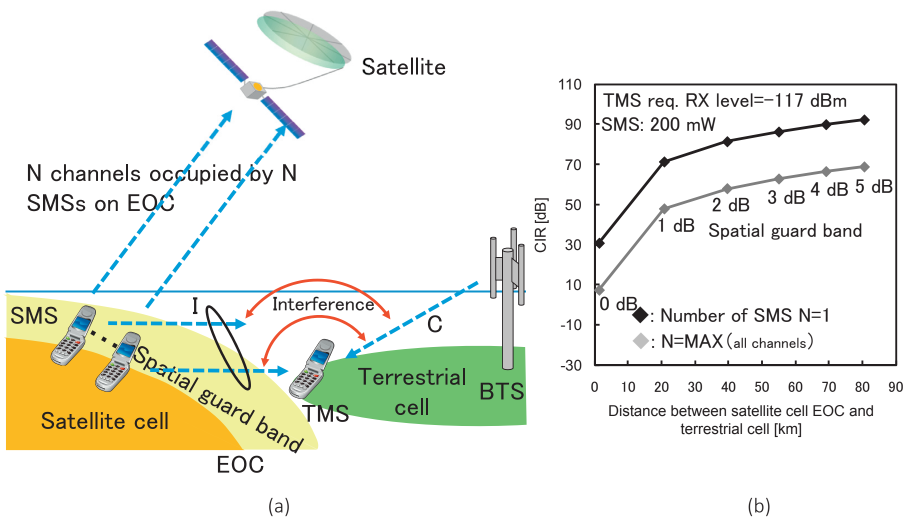


Fig. 12 Interference paths/evaluations: reverse mode terrestrial down-link

as relatively small compared to those of other links, is confirmed to have a problem related to frequency sharing when satellite-communication traffic congestion occurs particularly in a disaster situation.

On the other hand, as for the reverse mode, the following was confirmed: satellite up-link sharing is not feasible because the link is exposed to large interference power emitted from a base station, and the terrestrial up-link has a problem related to frequency sharing when satellite-communication-traffic congestion occurs on a specific satellite beam in such a situation as a disaster.

Interference paths of all the aforementioned cases are satellite-to-ground propagation paths; interfered stations suffer cumulatively large interference from all the interfering sources because any interfering source in the satellite cover area is almost the same distance from the satellite. On the other hand, sharing of the links that receive interference through ground-propagation paths was confirmed as feasible, because spatial guard bands largely contribute to the improvement of CIR.

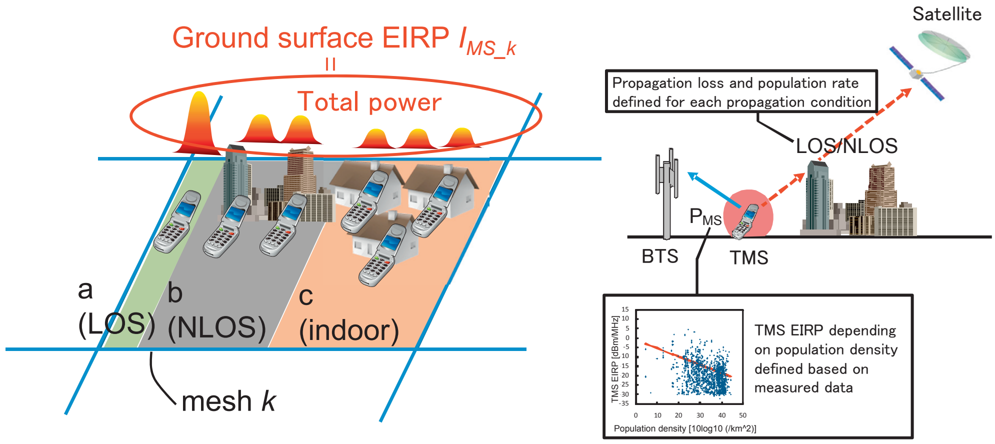
4 Detailed interference model applied evaluation of the number of simultaneously accommodated stations in co-channel interference environment

4.1 Purposes

In this subsection, we will describe the evaluation of the number of simultaneously accommodated stations in a STICS system, considering the co-channel interference resulting from terrestrial/satellite frequency sharing, and then the evaluation of the system feasibility of STICS. We conducted these evaluations on the normal mode, because we had reached the conclusion that normal mode satellite links have advantages for a frequency sharing method from the results of the studies described in the previous subsection and also our real observations of the power emitted from mobile phones/base stations by the experimental campaign using an aircraft that suggest that base stations are giving relatively high-level interference to satellite up-links.

In addition, the evaluations described in Section **3** suggest that the interference between ground systems and satellite systems will be caused by quite different mechanisms according to whether the interference path is bridging the satellite and a terrestrial terminal—taking the satellite propagation path—or bridging a satellite terminal and a base-station—taking the ground propagation path. In the case of terrestrial terminal-to-satellite interference, because no such significant differences exist between the satellite-to-terminal distances, all the terminals in the satellite coverage-area cumulatively give interference to the satellite. On the other hand, in the case of base-station-to-satellite terminal, the interference level takes quite different values according to the distance of the terminal to the base station, and because of the large satellite cell diameter of around 200 km, interference to the base station is significant only in an extraordinary situation where the interfering terminals are located close to the satellite cell edge. In addition, spatial guard bands greatly contribute to the improvement of CIR.

Therefore, for the evaluations described in Section **4**, we calculate the maximum number of allowable stations accommodated in the interfering link on condition that the



(a) (b)

Fig. 13 Interference model for satellite terminal: schematic diagram

desired C/N_0 of the interfered link is assured, for the case where the ground-satellite interference occurs along the satellite -to-terrestrial terminal path. With regard to the evaluations of the satellite terminal-to-base-station interference, we will mention this in Section **5**.

4.2 Interference model

In the normal mode configuration, the interference from the terrestrial system to the satellite is caused by terrestrial terminals on the ground. Because a huge number of terminals contribute to the interference, precise estimation of interference level in particular is required, so we developed a model of terrestrial terminal-to-satellite interference; a schematic diagram is shown in Fig. 13. As shown in Fig. 13 (a), in the model, the magnitude of interference is defined by the interference power generated in a unit surface-area—called a ground surface Equivalent Isotropically Radiated Power (EIRP). For the purpose of taking into consideration that the interference power per unit area depends on the terminal's communication environment—LOS, NLOS, or Indoor—, the sum of the powers emitted by the in-service terminals belonging to the propagation-environment classes—denoted by symbols a, b and c in the figure—is used as the interference power per unit area. On the other hand, for estimating the interference power per terminal, as shown in Fig. 13 (b), a variety of parameters are fed into the model—for instance, as the transmitted power per terminal, using the observations of the transmitted-power-to-population-density ratio which were obtained in the ground interference observation experiments, or feeding by-propagation-path propagation losses as parameters. The interference power generated by the satellite terminals in the k-th mesh is defined by the equation (1).

$$I_{MS\_k} = N_k \cdot R_{x_k} \begin{Bmatrix} \left(i_{x_k m} \cdot \Delta i_{x_k a}\right) \cdot r_{x_k a} + \\ \left(i_{x_k m} \cdot \Delta i_{x_k b}\right) \cdot r_{x_k b} + \\ \left(i_{x_k m} \cdot \Delta i_{x_k c}\right) \cdot r_{x_k c} + \cdots \end{Bmatrix} \tag{1}$$

Where,

$i_{x_k a}\cdot\Delta i_{x_k a}$, $i_{x_k b}\cdot\Delta i_{x_k b}$, $i_{x_k c}\cdot\Delta i_{x_k c}$, … are the per-mobile phone transmitted power for each of the population classes/propagation environments in the k-th mesh; it is obtained through making corrections on the $i_{x_k m}$—the per-mobile phone power transmission for each of the population classes which is calculated using the observations obtained in the ground-cruising tests—by $\Delta i_{x_k a}$, $\Delta i_{x_k b}$, $\Delta i_{x_k c}$, …—the deviation in power brought by the difference in propagation environments. $r_{x_k a}$, $r_{x_k b}$, $r_{x_k c}$ ··· is the k-th mesh mobile phone-to-population ratio for each of the population classes/propagation environments. x_k (I, II, III, IV, ···) is a parameter corresponding to service environment such as urban or suburban. a, b, c, ··· is a parameter corresponding to propagation environment such as outdoor-LOS, outdoor-NLOS or Indoor. $i_{x_k m}$ (mobile phone transmission power) is calculated using an approximation equation of the transmission power's relation to population. $i_{x_k m}$ (mobile phone emission power) is obtained by using an approximation formula for mobile phone emission power ratio to population. $\Delta i_{x_k a}$, $\Delta i_{x_k b}$, $\Delta i_{x_k c}$, ··· (transmission power deviation for each propagation environment) is determined by reference to an estimation equation of mobile communication propagation loss or observations. $N_k \cdot R_{x_k}$ is the number of simultaneous in-service calls inside the k-th mesh, and calculated using N_k (population in the k-th mesh) and R_{x_k} (simultaneous in-service rate of mobile phones).

4.3 Evaluation method

Conditions of the satellite link and the terrestrial link are respectively shown in Tables 2 and 3.

As for the terrestrial link, for the purpose of reflecting as precisely as possible the actual traffic distribution in Japan, we, dividing a standard grid cell set by the Geospatial Information Authority of Japan into standard cell 2 (hereinafter referred to as sub-meshes, approximately 10 km by 10 km), allocate to each sub-mesh the number of stations and the summation of their transmission power. The number of base stations is estimated by counting the base stations located in a sub-mesh using the nationwide local government radio station license registration information (as of May 2010), and the summation power is estimated on the assumption that each of the stations is operated with 30-percent of its maximum power. On the other hand, as for terminals, their number is estimated from the daytime population on the assumption that the terminal-in-service rate is 1 percent; for the summation terminal transmission power, the value of the terminal transmission power for each of the population classes which was determined through statistically processing the observations obtained in the W-CDMA cellular phone transmission power measurement[4] by ground-cruising covering the country— according to the observation experiment, a cellular phone transmits 1 mW-power, is largely less than its maximum power of approximately 250 mW.

Figure 14 shows the beam configuration of the satellite link. The satellite link covers the land and Exclusive Economic Zone (EEZ) of Japan using 83 beams, and seven beams are combined into a cluster to allocate sub-bands with a frequency interval of 4.3 MHz. The transmission power per satellite link is assumed as 200 mW. The total transmission power of the satellite system and the maximum number of links that it can accommodate are respectively assumed to be 2 kW and 10,000 links. The satellite links are assumed to work as follows: in a normal situation, terminals are distributed evenly in each of the 83 beams; in a disaster situation, through the activation of STICS's channelizing function for changing the frequency-allocation to each of the satellite beams, such a number of terminals make calls that consume the maximum bandwidth allocatable to a satellite beam (a cluster, 30 MHz).

As for the estimation of the number of maximum accommodated stations, it is evaluated by estimating how many interfering links can exist under the condition that the C/N_0 is kept over a certain level (required C/N_0). Such estimations are conducted for the following interference

Table 2 Link-conditions of terrestrial system

Link parameters	Specifications
Access scheme	CDMA
Uplink frequency (MHz)	1980-2010
Downlink frequency (MHz)	2170-2200
Number of sub-band	6
Sub-band bandwidth (MHz)	5
Information rate (kbps)	9.6
Occupied bandwidth/channel (kHz)	5000
Antenna gain of BS at satellite direction (dBi)	-3
Antenna gain of BS at terrestrial direction(dBi)	17
Transmit power for BS	30% of transmit power of radio station license information for cellular phone base station in Japan
BS required C/N0 (dB-Hz)	47.6
BS antenna noise temperature (K)	200
BS feeder loss (dB)	0
BS noise figure (dB)	1.5
Terminal antenna gain (dBi)	0
Terminal transmit power	Estimated by statistical analysis of measured data of W-CDMA cellular phone transmit power obtained by measurement campaign in Japan (below 1mW)
Terminal required C/N0 (dB-Hz)	47.6
Terminal antenna noise temperature (K)	80
Terminal feeder loss (dB)	0
Terminal noise figure (dB)	1.5

Table 3 Link-conditions of satellite system

Link parameters	Specifications
Access scheme	FDMA
Uplink frequency (MHz)	1980-2010
Downlink frequency (MHz)	2170-2200
Number of sub-band	7
Sub-band bandwidth (MHz)	4.3
Information rate (kbps)	9.6
Occupied bandwidth/channel (kHz)	19.2
Satellite antenna diameter (m)	30
Minimum gain in satellite cell (dBi)	47
Satellite antenna pattern	Rec. ITU-R S.672-4
Satellite antenna sidelobe level (dBi)	30
Satellite total trasmit power (kW)	2
Satellite transmit power/channel (mW)	200
Satellite required C/N0(dB-Hz)	43.8
Satellite antenna noise temperature (K)	300
Satellite feeder loss (dB)	1.1
Satellite noise figure (dB)	1.5
Terminal antenna gain (dBi)	0
Terminal transmit power (mW)	200
Terminal required C/N0 (dB-Hz)	43.8
Terminal antenna noise temperature (K)	80
Terminal feeder loss (dB)	1
Terminal noise figure (dB)	1.5

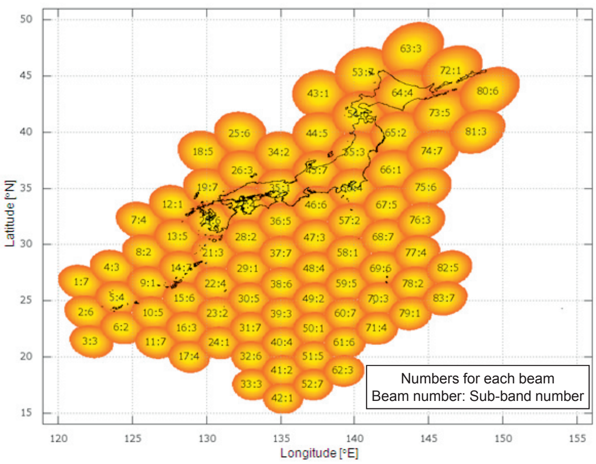


Fig. 14 Satellite beam configuration

situations: only the terrestrial links give interference (neglecting interference by satellite links); only the satellite links give interference (neglecting interference by terrestrial links); and both the satellite and terrestrial links give interference under the condition that the satellite system accommodates links up to its capacity—calculating how many terrestrial interfering links can exist.

For the evaluation described above, a series of calculations are conducted as follows: first, by using a newly developed interference assessment simulator[8], determine the terminal distribution, satellite-beam configuration, link conditions, frequency allocations, and others; and then calculate the levels of received signal and interference for each of the interfered links; next, by using the outputs of the previous operations, estimate the maximum number of accommodated stations according to the procedures described below.

① Applying equation (1), obtain the average interference level per link

$$\bar{I} = \frac{\sum_{m=1}^{M} I_m \bullet B}{M} \tag{2}$$

Where,

M: the number of interfering links sharing frequency with the interfered links

I_m: the interference level from the m-th interfering link

B: the bandwidth-superposition rate of the m-th interfering link and the interfered link

② Obtain, by applying equation (2), the link-coefficient "a" (the maximum number of interfering links such that an interfered link is established under the condition where the required C/N_0 is maintained)

$$C \Big/ (a \bullet \bar{I} + N_0) = \left[C \Big/ N_0 \right]_{req} \tag{3}$$

In addition, for the purpose of confirming the effect of the spatial guard band set up for avoiding satellite-terrestrial interference, iterate the estimations described above by increasing the guard band levels step-by-step as 0, 5, 10 dB and so on.

4.4 Evaluation results

In either of the cases where the desired link is the satellite up-link or the terrestrial down-link, satellite-terrestrial terminal interference will occur. It is confirmed that, in the case where a terrestrial down-link is desired, up to 10,000 links are always established in the satellite communications link interfering with the terrestrial terminals.

Therefore, we will describe below the case where a satellite up-link is desired. There will be two interference situations: a case where all the up-links from the terrestrial terminals outside the satellite cell sharing frequency bands are interfering with the satellite; and another case where the up-links of the satellite terminals belonging to a different satellite beams sharing frequency bands are interfering. Figure 15 shows the estimations of the number of accommodated stations. The satellite communication link is always established up to its capacity limit of 10,000 links. As for the terrestrial links, the evaluations revealed that, in the case of a 0 dB spatial guard band (no guard bands are set up), the number of links is approximately 14 and 13 million links, respectively, before and after the satellite communications link is allocated, and that in the case where a 10 dB spatial guard band is set up, the number of terrestrial links reaches its maximum. On the other hand, under the conditions previously shown, the percentage service area of terrestrial links is 100%, 88% and 31% at the guard band of 0 dB, 5 dB, and 10 dB, respectively. The service area becomes narrower as the spatial guard band level grows.

An instance of the evaluations in a disaster situation is shown in Fig. 16 for the satellite beam condition that all the frequency bands which are allocated in normal situations to the 1-cluster-7-beams out of 83 beams are allocated to one beam. A similar evaluation result to that in a normal situation is obtained as follows: even in a disaster situation, 10,000 satellite communication, its capacity limit, are established. Over 10 million terrestrial links are accommodated, and the number of accommodated terrestrial links

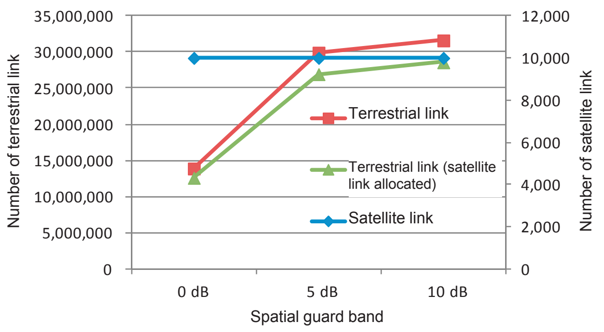


Fig. 15 Number of links simultaneously accommodated when satellite up-link established

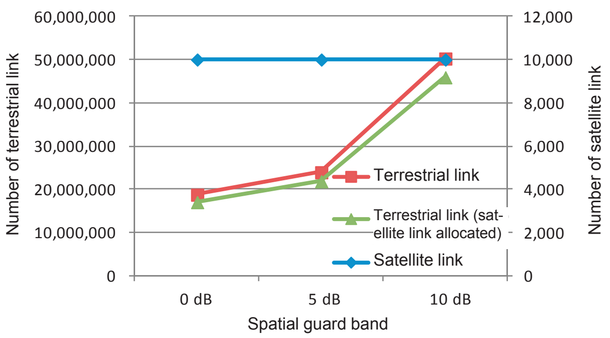


Fig. 16 Number of links simultaneously accommodated when satellite up-link established in disaster situation

reaches its maximum value at the spatial guard band level of 10 dB. On the other hand, the percentage service area of terrestrial links varies with such a similar tendency to that of a normal situation as follows: the service area is 84%, 65%, and 31% at 0, 5, and 10 dB of the guard band level, respectively, under the conditions previously used. Therefore, the service area becomes narrower along with growth of the spatial guard band level.

5 Separation distance in satellite terminal to base-station interference environment: evaluations

In this section, evaluations will be shown for the case where the interference occurs between satellite terminals and base stations. In such a situation, because interference comes through ground propagation paths, setting a spatial guard band, as shown in the evaluations in Section **3**, is so effective that the CIR is greatly improved. Therefore, for the purpose of making evaluations for the worst-case scenario, we made evaluations on the separation distances that assure frequency sharing (corresponding to the spatial guard band) under more detailed condition setting, by focusing on the situation where the satellite terminal is located close to the satellite cell edge.

(a) Case of satellite down-link desired

In such a situation, a down-link using the same frequency with the satellite link from a base station that is located outside the satellite cell is interfering. For the purpose of studying the worst cases, we, focusing on the situation where a satellite terminal is located on the satellite cell edge, made evaluations on the two cases where a single ground station is involved or more than one station is involved—as for a typical situation, nine stations are located in the neighborhood of the terminal at intervals of 5 km. In addition, we made evaluations on the cases where other satellite links using the same frequency are interfering. For such evaluations, we estimated the minimum separation distance from the terminal to the base station that is using the same frequency on the condition that the satellite link operates with the required C/N_0, and determined the spatial guard band level.

Table 4 lists the evaluation results: in Table 4 (a), the case of a single interfering station; in Table 4 (b), the case of nine interfering stations; in Table 4 (c), the case where an unconcerned satellite link that shares frequency is additionally interfering—assumed to interfere by the power equal to the average same frequency interference power of the 83 beams; for converting the separation distance into a spatial guard band level, the guard band level is defined as the antenna gain difference in the satellite beam gain ground projection pattern of the gain measured at a certain separation distance from the satellite cell edge from the gain measured at the satellite cell edge. Throughout the evaluations, the three propagation path models of the Extended Hata Model—Urban, Suburban, and Open Area—are applied. The table indicates that, as the number of interfering stations grows, the larger separation distance (spatial guard band level) is required for the establishment of satellite down-link. We can find out, as for the evaluation cases, that a separation distance of 30.2 km (corresponding to the spatial guard band level of 1.3 dB) is sufficient for the frequency sharing by a terrestrial system and a satellite system.

(b) Case of terrestrial up-link desired

In this case, the up-links from the satellite terminals existing inside the satellite cell cause interference to the base station outside the satellite cell that shares frequencies with those terminals. We, in this study, for the purpose of analyzing the worst cases, conduct evaluations, by assuming that the interfering satellite terminal is located on the satellite cell edge, on the following three situations: only a single terminal in the cell is in-service; terminals in-service are occupying the full channels up to the allocation limit; and the case where an unconcerned terrestrial links that shares frequencies causes additional interference. Table 5 lists the evaluations. For the case of additional interference from the unconcerned terrestrial links sharing frequencies shown in Table 5 (c), the interfering source is assumed to have a constant interference power (6 dB interference margin). The table indicates that as the number of interfering satellite terminals or the additional interference by terrestrial links grows, the larger separation distance (spatial guard band level) is required for the terrestrial-link establishment. We can find out, as for the evaluation cases,

Table 4 Satellite terminal-to-base station separation distance and spatial guard band level: at the time of satellite down-link establishment

Calculation case	Propagation channel condition		Urban	Suburban	Open area
(a) Single interfering BS (w/o interference from satellite links)	Separation distance between satellite terminal at cell edge and BS	km	3	6.6	23.3
	Spatial guard-band	dB	0.1	0.3	1
(b) Nine interfering BSs (w/o interference from satellite links)	Separation distance between satellite terminal at cell edge and BS	km	3.2	8.3	29.7
	Spatial guard-band	dB	0.1	0.3	1.3
(c) Nine interfering BSs (w/ interference from satellite link: average for 83 beams)	Separation distance between satellite terminal at cell edge and BS	km	3.3	8.6	30.2
	Spatial guard-band	dB	0.1	0.4	1.3

Table 5 Satellite terminal-to-base station separation distance and spatial guard band level: at the time of terrestrial up-link establishment

Calculation case	Propagation channel condition		Urban	Suburban	Open area
(a) Single interfering satellite terminal (w/o interference from terrestrial links)	Separation distance between satellite terminal at cell edge and BS	km	0.7	1.7	6.3
	Spatial guard-band	dB	0	0.1	0.3
(b) 223 interfering satellite terminals (w/o interference from terrestrial links)	Separation distance between satellite terminal at cell edge and BS	km	3.5	7.7	26
	Spatial guard-band	dB	0.1	0.3	1.1
(c) 223 interfering satellite terminals (w/ interference from terrestrial links: interference margin 6 dB)	Separation distance between satellite terminal at cell edge and BS	km	4.5	10.1	30.9
	Spatial guard-band	dB	0.2	0.4	1.4

that a separation distance of 30.9 km (corresponding to the guard band level of 1.4 dB) is sufficient for the frequency sharing by a terrestrial system and a satellite system.

6 Summary

For the purpose of proving the feasibility of STICS's frequency sharing method, we conducted the following evaluations. First, applying a simple interference model that consists of a single satellite cell and a single terrestrial cell, we evaluated interference characteristics on each of the interference paths, and had expectations on the feasibility of the STICS's method. We confirmed through the first-stage evaluations the following as for the normal mode: the sharing of satellite up-link in normal mode is likely feasible; however, the condition for such sharing is dependent on the transmission power of the terminals on the terrestrial link and the number of simultaneously in-service terminals.

There will be a problem related to frequency sharing in situations where large power is transmitted from base stations (for reverse mode satellite down-link) and satellite-communication traffic congestion occurs on a specific satellite beam in such a situation as a disaster (for normal mode terrestrial down-link and reverse mode terrestrial up-link).

Thus, we concluded that, as for a frequency sharing method, the normal mode has advantages over the reverse mode.

Next, we conducted evaluations, for normal mode, on the number of simultaneously accommodated terrestrial and satellite links under the co-channel interference environment. We, applying the newly-developed detailed interference model, reflecting in our evaluations the country-wide actual traffic distribution as precisely as possible on the number of base stations, the number of terminals, and their transmission power, successfully conducted realistic evaluations. We confirmed through such evaluations that, as for the traffic distribution in the normal situation, the satellite system is constantly able to accommodate links up to its capacity limit—10,000 links in the evaluation conditions—, and that a terrestrial system is able to accommodate over 10 million links. On the other hand, as for a disaster situation, we, making evaluations for such a case, confirmed that almost the same number of links as that for the normal situation are accommodated. In addition, we confirmed the following: for either a normal or disaster situation, it is possible to increase the number of terrestrial/satellite links that are simultaneously accommodated by raising the spatial guard band level, however at the cost of loss in the service area of the terrestrial system.

Furthermore, as for the satellite terminal-to-base-station interference environment, we, conducting evaluations for the worst case where a satellite terminal exists on the satellite cell edge, confirmed that the frequency sharing is feasible by taking an appropriate satellite terminal-to-base-station separation distance (corresponding to setting a spatial guard band).

We concluded, through the evaluations so far described, that STICS has the feasibility of frequency sharing in the terrestrial/satellite co-channel interference environment.

7 Acknowledgments

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