

Performance improvement of OFDMA cellular system using code division multiplexing in satellite/terrestrial integrated mobile communication system

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Abstract—A satellite/terrestrial integrated mobile communication system (STICS) is a hybrid mobile communication system using a terrestrial and a satellite cellular systems. If both systems use the same frequency band, the satellite downlink exerts interference to the terrestrial mobile phones. In this paper, we clarify the deterioration of a bit error rate and a throughput performance of the downlink terrestrial cellular system utilizing a multiple-input multiple-output orthogonal frequency division multiple access (MIMO-OFDMA) in STICS by computer simulations. In addition, we propose the application of MIMO-OFDMA-code division multiplexing (CDM) in which the frequency-domain code spreading is applied for MIMO-OFDMA to improve the performance in STICS. Also, it is demonstrated that the sufficient carrier to interference ratio (CIR) of the mobile phone to the satellite signal is about 6 dB.

Keywords— satellite/terrestrial integrated mobile communication system; MIMO-OFDMA, code division multiplexing; interference.

I. INTRODUCTION

A satellite/terrestrial integrated mobile communication system (STICS) is the system that a mobile phone can connect to a base station of terrestrial cellular system and a satellite station. STICS enables a wide-area coverage of the mobile phone not only in the ground but also in the sea. Furthermore, since STICS is quite effective as the communication method in an emergency, it has attracted much attention recently. In National Institute of Information and Communications Technology (NICT), many studies of STICS have been conducted [2-4]. However, since STICS is a wireless communication system, its frequency band is limited and the effective use of the frequency is required. In general, to achieve a hybrid of the terrestrial and the satellite cellular systems, one of two schemes is adopted: frequency division of the terrestrial system and the satellite system, or frequency multiplexing for them. In both cases, there exist different problems to be solved. In the frequency division scheme, the efficient frequency resource allocation for ground and satellite is needed, while in the multiplexing scheme, easing the interference between the terrestrial and the satellite cellular systems is needed.

In the conventional frequency division schemes, the fixed channel assignment (FCA) [5] and the dynamic channel assignment (DCA) [6,7] have been proposed. In those schemes, the satellite and the terrestrial cellular systems share the frequency band fixedly or dynamically. However, each allocated bandwidth is decreased because the frequency band is orthogonally divided. On the other hand, in the multiplexed scheme of both cellular systems, the frequency efficiency is greatly improved compared to the sharing scheme but naturally the interference among them occurs. NICT has conducted the evaluation of this interference [4] and the required carrier to noise ratio (CIR) for this hybrid system has been derived in several scenarios. In this paper we focus on the multiplexing-STICS.

In the current terrestrial cellular system such as 3.9 generation (3.9G) or 4G, an orthogonal frequency division multiple access (OFDMA) is used and also a multiple-input multiple-output (MIMO) technique is being adopted as a mandatory requirement of standardization [8,9]. OFDMA is regarded as a standard multiple access scheme in the terrestrial cellular system beyond 4G. However, the performances of the terrestrial OFDMA under the satellite interference in multiplexing-STICS are not studied yet.

Therefore, in this paper, we clarify the deterioration of a bit error rate (BER) and a throughput performance of the downlink terrestrial cellular system utilizing MIMO-OFDMA due to the satellite interference in multiplexing-STICS by computer simulations. In addition, we propose the application of MIMO-OFDMA-code division multiplexing (CDM) taking into account the proportional fairness (PF) in which the frequency-domain code spreading is applied for MIMO-OFDMA to improve the performance [10] in STICS. Also, it is demonstrated that the sufficient CIR of the mobile phone to the satellite signal is about 6 dB.

In the following, the terrestrial MIMO-OFDMA-CDM in multiplexing-STICS is described in Section 2 and the numerical results are shown in Section 3. The conclusions are drawn in Section 4.

II. MIMO-OFDMA-CDM SYSTEM

A. Cell model

In this paper, we consider the downlink performance of

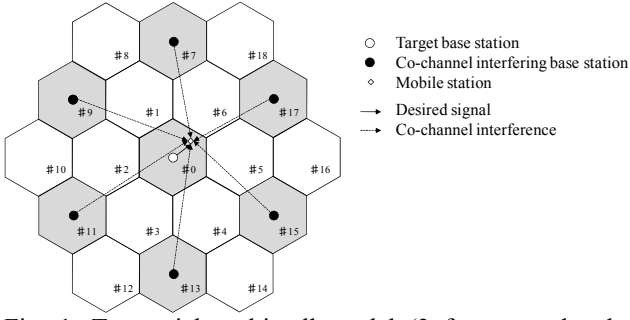


Fig. 1. Terrestrial multi-cell model (3 frequency bands with reuse factor of 3).

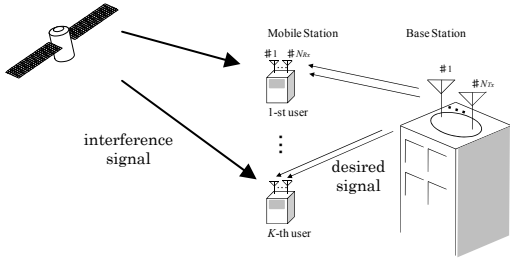


Fig. 2. Downlink model of multiplexing-STICS.

users accommodated in the terrestrial cellular systems in STICS. Fig. 1 shows the terrestrial multi-cell model. We assume that the allocated frequency band for terrestrial system is divided into three, and assume a hexagonal 19-cell model with the same frequency-band reuse over 3 cells. Thus, the co-channel interference is received from 6 secondary adjacent cells. It is also assumed that K users are randomly distributed in #0 cell. The multiplexing-STICS is applied where the satellite uses the same and all of the frequency band of the terrestrial cellular system (i. e., three frequency bands in Fig. 1). In this system, we evaluate the terrestrial downlink user performances of the BER and the throughput with the satellite interference in STICS as shown in Fig. 2.

B. Conventional MIMO-OFDMA scheme

The terrestrial downlink multiple access scheme adopted in 3.9G cellular system is MIMO-OFDMA [8,9]. As shown in Fig. 1, the channel matrix of user k between the N_{Tx} -transmit antennas of the base station and N_{Rx} -receive antennas of the user is defined in the following where the number of subcarriers in OFDMA is N_c . It is assumed that the transmission channel is frequency-selective consisting of discrete L delay paths and its impulse response between tx -th transmit antenna and rx -th receive antenna of k -th user from j -th base station is given by $h_{j-k,rx,tx}(\tau)$ as follows:

$$h_{j-k,rx,tx}(\tau) = \sum_{l=0}^{L-1} h'_{j-k,l,rx,tx} \delta(\tau - \tau_l) \quad (1)$$

where $h'_{j-k,l,rx,tx}$ and τ_l are the complex channel coefficient and the delay time of l -th path, respectively. This channel coefficient is normalized as $E[\sum_{l=0}^{L-1} |h'_{j-k,l,rx,tx}|^2] = 1$ and if the propagation loss and shadowing is taken into account, $h_{j-k,l,rx,tx}$ is given by

$$h_{j-k,l,rx,tx} = \sqrt{d_{j-k}^{-\alpha} 10^{-\beta_{j-k}/10}} h'_{j-k,l,rx,tx} \quad (2)$$

where d_{j-k} is the k -th user distance from the j -th base station, α is the propagation loss exponent, and β_{j-k} is the shadowing deviation. The shadowing component obeys the lognormal distribution as follows:

$$f_L(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\beta x} \exp\left\{-\frac{(\log x - \mu)^2}{2\beta^2}\right\}, & x > 0 \\ 0, & x \leq 0 \end{cases} \quad (3)$$

where μ is the mean value of lognormal distribution and x is the instantaneous shadowing amplitude. Then, the channel gain in the frequency domain is obtained by

$$H_{j-k,n,rx,tx} = \sum_{l=0}^{L-1} h_{j-k,l,rx,tx} \exp\left(-j2\pi \frac{\tau_l}{N_c}\right) \quad (4)$$

where n is the subcarrier index. The channel matrix of user k and subcarrier n in MIMO transmission is given by

$$\mathbf{H}_{j-k,n} = \begin{bmatrix} H_{j-k,n,1,1} & H_{j-k,n,1,2} & \cdots & H_{j-k,n,1,N_{Rx}} \\ H_{j-k,n,2,1} & H_{j-k,n,2,2} & \cdots & H_{j-k,n,2,N_{Rx}} \\ \vdots & \vdots & \ddots & \vdots \\ H_{j-k,n,N_{Tx},1} & H_{j-k,n,N_{Tx},2} & \cdots & H_{j-k,n,N_{Tx},N_{Rx}} \end{bmatrix} \quad (5)$$

Using this matrix, the receive vector $\mathbf{R}_{k,n} = (R_{k,n,1}, \dots, R_{k,n,N_{Rx}})^T$ of user k is given by

$$\mathbf{R}_{k,n} = \sqrt{P_{t,0-k,n}} \mathbf{H}_{0-k,n} \mathbf{s}_{0-k,n} + \mathbf{N}_{0-k,n} + \sum_{j,j \neq 0} \sqrt{P_{t,j-k,n}} \mathbf{H}_{j-k,n} \mathbf{s}_{j-k,n} + \mathbf{I}_{S,k,n} \quad (6)$$

where $P_{t,k,n}$ is the transmit power, $N_{iBS}(=6)$ is the number of co-channel interfering base stations, $\mathbf{s}_{j-k,n} = (s_{j-k,n,1}, \dots, s_{j-k,n,N_{Tx}})^T$ is the transmit vector, $\mathbf{N}_{k,n} = (N_{k,n,1}, \dots, N_{k,n,N_{Rx}})^T$ is the frequency-domain noise components obtained by

$$N_{k,n,rx} = \frac{1}{\sqrt{N_c}} \sum_{t=0}^{N_c-1} n_{k,t,rx} \exp\left(-j2\pi \frac{t}{N_c}\right) \quad (7)$$

and $\mathbf{I}_{S,k,n} = (I_{S,k,n,1}, \dots, I_{S,k,n,N_{Rx}})^T$ is the interference from the satellite which is assumed as identical for any k, n , and rx . The third term of right hand side in (6) is the interference component from second adjacent cells. Then, channel capacity is obtained by

$$C_{k,n} = \sum_{i=1}^{\text{RANK}(\mathbf{H}_{k,n})} \log(1 + \gamma_{k,n,i}) \quad (8)$$

where $\lambda_{j-k,n,i}$ is i -th eigenvalue of the MIMO channel matrix at k -th user's n -th subcarrier from j -th base station of (5), and $\text{RANK}(\mathbf{H}_{k,n})$ is the rank of channel matrix. It is assumed that the channel matrices of all users are perfectly known to the base station by feedback information. Using this channel information, the base station selects one user k for each subcarrier n , and transmits the data for user k of $\mathbf{s}_{j-k,n} = (s_{j-k,n,1}, \dots, s_{j-k,n,N_{Tx}})^T$. In MIMO-OFDMA, exploiting the fact that the channel matrix of subcarrier n is independent on every user k , the user having a good channel, i. e., a large summation of eigenvalues, is selected as the user whose data are to be transmitted on subcarrier n . This enlarges the total capacity of the cell and this

improvement effect by the adaptive selection of (n,k) -pairs is called multiuser diversity. As the subcarrier allocation, i. e., the determination scheme of (n,k) -pairs, the maximum capacity (MAX) algorithm and the proportional fairness (PF) algorithm have been proposed [11]. In the MAX scheme, each subcarrier is allocated to the user having the largest channel coefficient. This can maximize a system capacity but the fairness among users is not guaranteed. On the other hand, the PF scheme allocates subcarriers with considering users' fairness. PF scheme cannot keep the maximum capacity but can keep the fairness among users, and many schemes based on PF have been considered. PF scheme can improve the throughput of cell-edge users, which is important in recent cellular systems. In general, the system capacity and the fairness are in the trade-off relationship on subcarrier allocation schemes. To conduct the PF allocation algorithm, usually the summation of capacities of the subcarrier already allocated to user k given by

$$C_k = \sum_{n \in \Omega_k} \sum_{i=1}^{RANK(H_{k,n})} \log_2(1 + \gamma_{k,n,i}) \quad (9)$$

is calculated where Ω_k is a set of subcarriers allocated to user k . Then, the next subcarrier is allocated to the user having the smallest C_k . By this algorithm, the fairness of the subcarrier allocation for all users is greatly improved compared with MAX scheme although the total capacity becomes smaller than MAX scheme.

Here, we show that an equal-number allocation of subcarriers for all users is effective in PF scheme. It is achieved by the additional step that the user k is skipped for allocation if the N_c/K subcarriers have already been allocated to user k . This equalizes the number of subcarriers for all users. We compare the throughput performance of terrestrial users without the satellite interference on the parameters of Tab. I. It is assumed that

Tab. I. Simulation conditions of terrestrial cellular system.

Transmitter	Transmission scheme	MIMO-OFDMA downlink
	Num. of antennas	$(N_{Ts}, N_{Rc}) = (2, 2)$
	Resource allocation scheme	Proportional fairness
	Num. of subcarriers	$N_c = 1024$
	Num of users	$K = 16$
	1OFDMsymbol length	$1024T_s$
	Guard interval length	$16T_s$
	Fading	16path 1dB-decayed Quasi static Rayleigh
	Cell model	Hexagonal grid
Channel	Cell layout	19 cell sites without sectorization
	Path loss exponent	$\alpha = 3.5$
	Standard deviation of shadowing loss	$\beta = 7$ (dB)
	Channel code	Non-systematic convolutional code, $R = 1/2$
Receiver	Channel estimation	Ideal
	MIMO detection and equalization	Nulling (SINR based MMSE criteria)

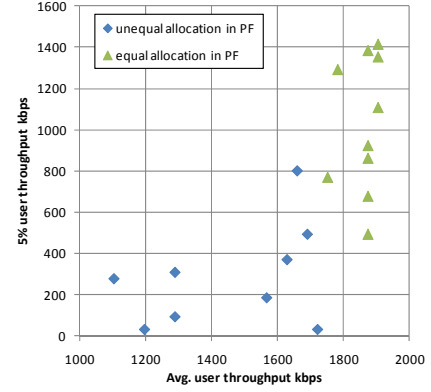


Fig. 3. Throughput performance of lowest 5% user versus average throughput of all users.

$T_s = 1/15k$ sec in the simulation. Fig. 3 shows the throughput performance of the lowest 5% user versus the average throughput in the cell when the subcarriers are equally allocated or not. The number of trial is set to ten. Here, the cell-edge user is defined as the user having the throughput within the lowest 5%. In this figure, the dots in the upper-right area indicate the better and balanced performance because both the cell-edge user and all users have higher throughputs. Then, it was confirmed that the PF scheme with the equal subcarrier allocation had the better performance.

C. PF-based MIMO-OFDMA-CDM scheme for STICS

In the previous subsection it was shown that the same number of subcarriers should be allocated for all users in PF algorithm. In this case, a code spreading with an identical-length code can be applied. MIMO-OFDMA-CDM has been proposed [11] in which the spreading code is multiplied to the subcarriers allocated to user k in the frequency direction, and the frequency diversity is exploited in MIMO-OFDMA system. The authors also have proposed the PF-based allocation scheme for MIMO-OFDMA-CDM in [10].

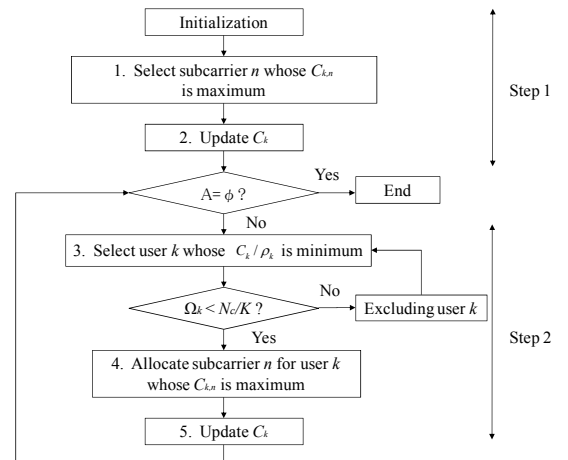


Fig. 4. PF-based subcarrier allocation algorithm for MIMO-OFDMA-CDM.

Fig. 4 shows the PF-based subcarrier allocation algorithm for MIMO-OFDMA-CDM. In Step 1, the base station chooses the best subcarriers for every user. In Step 2, the subcarrier is allocated iteratively to the user having the smallest capacity amount, which is the fairness-oriented algorithm. In addition the priority parameter ρ_k (larger is prior) for user k can be used. By this algorithm the total cell capacity and the fairness of users can be balanced at a higher region. When CDM is applied, the transmission signal for user k at n -th subcarrier are given by

$$s_{j-k,n,t} = \left(\frac{1}{\sqrt{\Omega_k}} \sum_{p=0}^{\Omega_k-1} w_{N_{Tx}n+tx, N_{Tx}(p+1)+tx} \hat{s}_{j-k,p,t} \right) \exp(j2\pi f_{k,n}t) \quad (10)$$

$$k = 1 \cdots K, \quad \Omega_k = N_{SF} / N_{Tx} = N_c / K$$

where N_{SF} is the spreading factor, $\hat{s}_{j-k,p,t}$ is the information symbol of user k at p -th subcarrier, $f_{k,n}$ is the subcarrier frequency, and $w_{N_{Tx}n+tx, N_{Tx}(p+1)+tx}$ is $[N_{Tx}(p+1)+tx]$ -th element of $[N_{Tx}n+tx]$ -th spreading code. Here, we propose the application of the PF-based MIMO-OFDMA-CDM for the terrestrial downlink transmission in STICS.

In the receiver, a MIMO detection and a channel equalization is processed by multiplication of channel inverse matrix to the receive vector. It is assumed that the interference from the satellite is constant for all user k and subcarrier n , and that the users know the power of the interference by some measurements. Then, the SINR-based minimum mean squared error (MMSE) weight can be calculated. The channel inverse matrix $\mathbf{G}_{k,n}$ is obtained by

$$\mathbf{G}_{k,n} = \mathbf{H}_{0-k,n}^H \left\{ \mathbf{H}_{0-k,n} \mathbf{H}_{0-k,n}^H + N_{Rx} (\sigma_N^2 + \sigma_{I,k}^2 + \sigma_S^2) \mathbf{I}_{N_{Rx}} \right\}^{-1} \quad (11)$$

where $\mathbf{H}_{0-k,n}$ is the channel matrix of (5), H means the Hermite transpose, σ_N^2 is the noise variance, $\sigma_{I,k}^2$ is the power of terrestrial co-channel interference at user k , σ_S^2 is the power of satellite interference, and $\mathbf{I}_{N_{Rx}}$ is the N_{Rx} -th unit matrix. By multiplication of $\mathbf{G}_{k,n}$ to (6) from left hand, the receive symbols are obtained. It is well-known that a SINR-based MMSE criterion is the best linear weight for multi-cell environment, because it considers the fading and co-channel interference. In the receiver, after MMSE-equalization with the weight of (11), the data are decoded.

III. SIMULATION RESULTS

We evaluate the downlink transmission performances of PF-based MIMO-OFDMA-CDM in multiplexing-STICS by computer simulations. In the simulation, other than the condition of Tab. II, the same parameters of Tab. I are used. Tab. II mainly shows the configuration of CDM. The BER and the throughput performance of the users located in #0 cell in Fig. 1 are calculated with the comparison of MIMO-OFDMA as the conventional scheme. Here, the user location is categorized as three areas. In the hexagonal cell of #0 with the radius of R , when the distance between the base station and the user k is defined as r_k , the center area is defined as

Tab. II. Parameters of terrestrial cellular for MIMO-OFDMA-CDM simulation.

Transmitter	Transmission scheme	MIMO-OFDMA-CDM downlink
	Desired rate ratio	$\rho_k = 1$ for all users
	Spreading code	Walsh, $N_{SF}=256$
	Num. of users	$K=8$
Channel	CIR for satellite	-4 to 10 dB

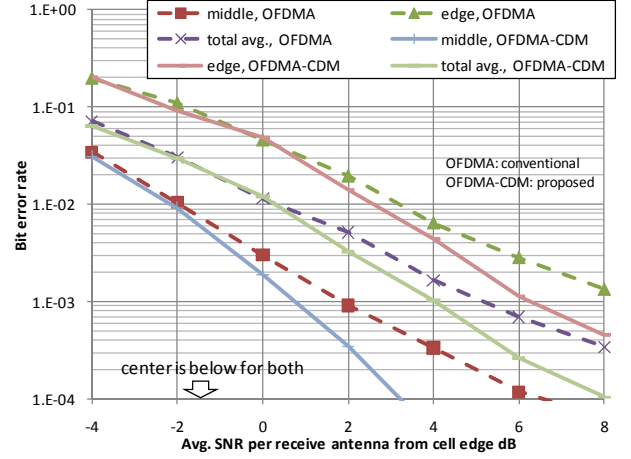


Fig. 5. BER performance of terrestrial cellular user in STICS.

$r_k < 0.3R$, and similarly, the middle and edge areas are defined as $0.3R \leq r_k < 0.8R$ and $0.8R \leq r_k \leq R$, respectively. First, the BER performance versus SNR at the cell-edge is calculated where the satellite interference is assumed as CIR=6 dB at the cell-edge user as average. From the results of Fig. 5, we can see that the proposed scheme has better performances than the conventional scheme after around SNR ≥ 0 dB at all user location. At BER of 10^{-3} , the proposed scheme has 3 dB improvement on the average BER because of a frequency diversity effect obtained by the frequency-domain spreading of CDM. Hence, it was shown that the proposed scheme was effective for performance improvement under the interference environment of multiplexing-STICS.

Next, the BER and the throughput versus CIR for the satellite when SNR at the cell-edge user is 4 dB is calculated and the results are shown in Figs. 6 and 7. It is illustrated as well as Fig. 5 that the performances are improved compared to the conventional OFDMA because of the effect of frequency-domain spreading. In Fig. 7, the average throughput of the proposed scheme is saturated at about CIR=6 dB due to the decrease of the satellite interference. Also, it is found that the CDM effect contributes the throughput improvement especially for the cell-edge user at the lower CIR.

Hence, it was clarified that the proposed scheme improved the performance of terrestrial users in the downlink of multiplexing-STICS.

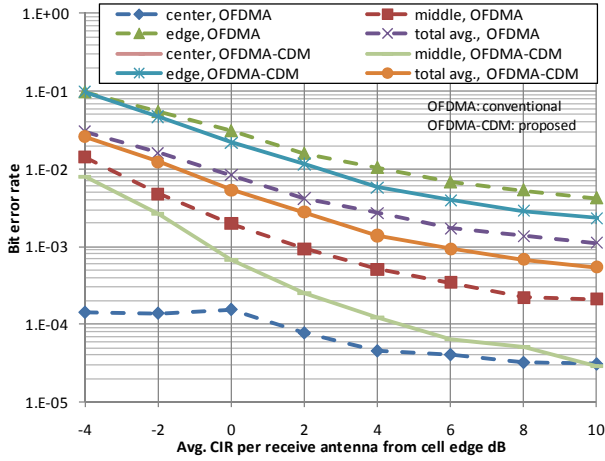


Fig. 6. BER performance versus CIR of terrestrial users for satellite at SNR=4 dB.

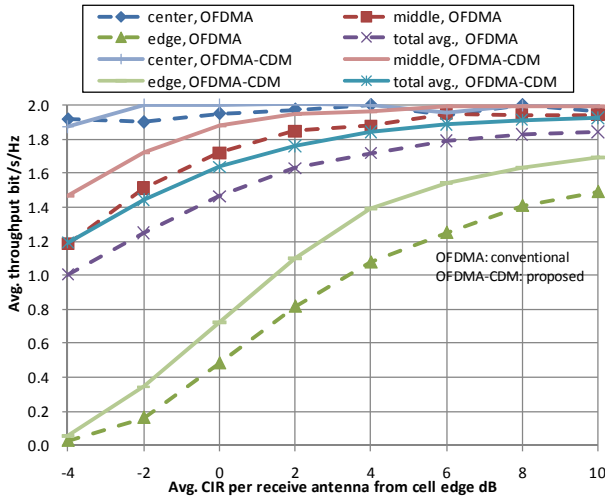


Fig. 7. Throughput performance versus CIR of terrestrial users for satellite at SNR=4 dB.

IV. CONCLUSIONS

In this paper, we demonstrated the interference effect of the satellite in the downlink terrestrial MIMO-OFDMA in the multiplexing-STICS by computer simulations. We also proposed the application of MIMO-OFDMA-CDM in STICS. It was shown by the numerical results of the multi-cell model that the proposed scheme improved the performances by the frequency-domain spreading, and that the sufficient throughput could be obtained in the proposed scheme at CIR=6 dB for the satellite interference.

In the future studies, we will consider raising the frequency-domain spreading effect of CDM by multiplexing a partial frequency band among the terrestrial and the satellite cellular systems in STICS, and the allocation scheme of OFDMA-CDMA for the terrestrial cellular system.

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