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저궤도 이동위성통신에 있어서의 신호열화 해석 및 이의 보상기술

Analysis of the Signal Degradations and Its Compensation Techniques in the LEO Mobile Satellite Communication

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요 약

저궤도 이동위성 통신시스템의 신호열화는 주로 페이딩 및 도플러 시프트에 기인하므로 이로 인한 신호의 열화 해석 및 이의 보상기법이 중요하다. 도플러 시프트 보상기로서 블록 복조기는 시간 변화의 도플러 시프트 보상에는 유용하지만 그 보상 능력이 32 ksymbols /s QAM(또는 QPSK) 신호 전송에 있어서 수 백 Hz 정도밖에 되지 않는다.

따라서 본 논문에서는 먼저 페이딩과 도플러 시프트에 기인하는 QAM 신호열화를 분석한 후, 보상기로서 기존의 파일롯 신호를 이용한 페이딩 보상기의 이용과 새로운 도플러 시프트 보상기를 제안하여 그 성능을 분석하였다. 그 결과 제안된 보상기는 수 kHz 이상의 도플러 시프트를 보상할 수 있으며, 기존의 파일롯 신호를 이용한 페이딩 보상기는 레일리 페이딩 뿐만 아니라 강한 라이시안 페이딩 ($K \leq 10$ dB) 보상회로로서 유용하다는 것을 알 수 있었다. 더욱이 등이득 다이버시티를 이용함으로써 보상기로 완전히 보상할 수 없는 강한 페이딩 및 도플러 시프트하에서도 시스템 성능을 상당히 개선할 수 있었다.

Abstract

In LEO system, the signal degradation is mainly due to fading and Doppler shift, so that the analysis of the signal degradation and compensation techniques are very important. As the Doppler shift compensator, the block demodulator has been known to be useful in compensating for the time-varing Doppler shift, but its compensating ability is about several hundreds Hz in 32 ksymbols /s QAM (QPSK) signal transmission.

Therefore, in this paper, to compensate for severe fading and Doppler shift more than several kHz, we use a conventional pilot symbol-aided fading compensator, and propose the Doppler shift compensator. It is shown that the proposed compensator is able to compensate for Doppler shift more than several kHz. And a pilot symbol-aided fading compensator is shown to be a suitable scheme for severe Rician fading ($K \leq 10$ dB) as well as Rayleigh fading. Also, it is shown that the equal gain combiner improves greatly the QAM performance even if the fading or Doppler shift becomes deeper or larger.

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Ⅰ. Introduction

From the past several decades, space communication services have been offered almost through the geostationary orbit (GEO) except for some special cases. As to the geostationary orbit satellite systems, 24-hours communication services are available using only one satellite and the tracking of the satellite is simply carried out. But, since the propagation delay and loss are serious problems in the GEO system due to its extremely long distance between satellite on the orbit and earth station, GEO system may not be suitable for the applications which require severely short response time and small power transmitter such as the portable terminal[1],[2]. So as to solve above problems and satisfy our desires for personality, the low earth orbit (LEO) mobile satellite communication systems, such as Iridium and Globalstar, etc., have been developed from the beginning of 90's[3]. In LEO system, the signal degradations due to both fading and Doppler shift are serious problems. Therefore, the analysis and evaluation of the signal degradation and its compensation techniques are very important.

In order to analyse the fading phenomena, a lot of channel models have been developed, e. g., Loo's model[4] for shadowing case by trees, Rician model[5] for line-of-sight case, and Rayleigh model[6] for multipath case by buildings. Among these models, the Rician model which can represent the Rayleigh fading as a special case ($K=-\infty$ dB), is commonly regarded as a good description for the LEO mobile satellite links.

The Doppler shift, as well as fading, is one of the main transmission impairments in the LEO mobile satellite system unlike the land mobile system. The LEO system is suffered from the effects of large Doppler shift when the distance between a satellite and an earth station rapidly moves, and the characteristics of Doppler shift was calculated with satellite altitudes in [1],[2]. These results show that the Doppler shift becomes larger as the altitude of satellite becomes lower as in the LEO system.

As compensation techniques for above mentioned, fading and Doppler shift, a pilot symbol-aided scheme[7] and a block demodulator[8],[9] have been well known respectively. The former scheme is a very effective as a fading compensation technique in QAM(Quadrature Amplitude Modulation), especially in the Rayleigh fading environments, and also may be useful in the severe Rician fading channel (in this paper, we regard the Rician fading of $K\leq 10$ dB as the severe Rician fading).

The block demodulator, on the other hand, is useful particularly in compensating for the time-varying Doppler shift, but its compensating ability depends on the phase relation between modulated symbols. For example, the ability is up to the maximum 4 kHz in 32 ksymbols/s QAM(or QPSK) signal transmission at high E_b/N_0 (energy per bit to the noise spectral density ratio), but in practice about several hundreds Hz at the operating E_b/N_0. In the LEO system, however, the magnitude of Doppler shift may be more than several kHz so that a scheme must be proposed to compensate for the large Doppler shift like this value. A proposed scheme is carried out as follows; the unmodulated symbols are inserted in midamble, sampled with a rate of 8 samples/symbol. Then the phase shift between samples are estimated, and compensated coarsely at the early stage of the conventional block demodulator.

In this paper, firstly, the performance of QAM(or QPSK) system with the pilot-aided fading and Doppler shift compensator have been analysed for the LEO mobile satellite system modeled as a fading channel shifted with the Doppler frequency. Secondly, the system performance of QAM signal have been shown with as 2-branch equal gain(EG) diversity combiner[10] used to improve the undesirable degradation due to the deep fading and the large Doppler shift.

This paper is composed as follows. The QAM system model equipped with the fading and the Doppler shift compensator for the LEO mobile satellite system is presented in Section 2. In Section 3, the degradations due to fading and Doppler shift are analyzed. In Section 4, the proposed Doppler shift compensation circuit is illustrated. Section 5 shows the improvement effects on the system performance of QAM(or QPSK) signal by using the proposed circuit in both only Doppler shift with no fading and fading with Doppler shift environments. In Section 6, moreover, the improvements by the EG diversity combiner are discussed. Some conclusions are presented in Section 7.

Ⅱ. The configuration of QAM Transmitter and Receiver

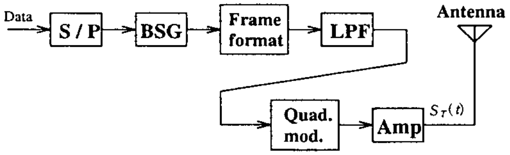


Fig. 1. Transmitter.

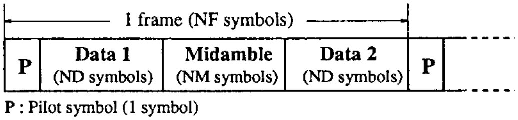


Fig. 2. Frame format.

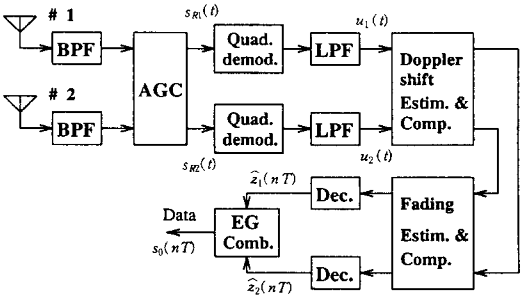


Fig. 3. Receiver.

Fig. 1 and Fig. 3 show the configurations of QAM transmitter and receiver for the LEO mobile satellite communication system. In the transmitter, the serial data is first converted to the parallel data, then a complex baseband signal is generated at the baseband generator (BSG).

These data are written into the compression buffer in the frame formatter to construct the TDMA burst as shown in Fig. 2. Unmodulated symbols are inserted in the midamble to compensate for the Doppler shift, and simultaneously pilot symbols are used for compensating for the fading. After the burst signal is band-limited by the low-pass filter (LPF), a carrier is modulated, amplified and transmitted.

The transmitted signal of QAM(or QPSK) is given by

$$\begin{aligned} s_T(t) &= Re[z_0(t)\exp(j2\pi f_c t)] \\ z_0(t) &= z_{0I}(t) + jz_{0Q}(t) \end{aligned} \tag{1}$$

where

$Re[A]$; real part of A

f_c ; carrier frequency

$z_0(t)$; transmitted baseband signal bandlimited by the transmitter filter

The received signal degraded by fading and Doppler shift in LEO system is amplified by an automatic gain controller (AGC), and then given by

$$\begin{aligned} s_{Ri}(t) = Re[&c_i(t)z_0(t)\exp\{j2\pi(f_c-f_D)t\} \\ &+ n_i(t)\exp\{j2\pi ft\}]\ (i=1,2) \end{aligned} \tag{2}$$

where

$s_{Ri}(t)$; The received signal of branch 1 ($i=1$) or branch 2($i=2$)

$c_i(t)$; fading distribution

f_D; Doppler shift frequency

$n_i(t)$; additive white Gaussian noise

The received baseband signal expressed as (2) is obtained by the quadrature detection, and by the band-limited by LPF.

$$u_i(t) = c_i(t)z_i(t)e^{j2\pi f_D t} + n_i(t)\ (i=1,2) \tag{3}$$

where $z_i(t)$ is the transmitted baseband by the transmitter and receiver filters.

After the Doppler shift compensation and the fading estimation, both branch signals are diversity combined using the estimated fading variation in each branch. Therefore, the resultant signal at the output of the equal gain combiner is

$$s_0(nT) = \sum_{i=1}^{2} g_i[\hat{z}_i(nT)]\ (i=1,2) \tag{4}$$

where hat $\hat{z}(nT)$ is the detection value of $z_i(t)$ at $t=nT$, $n=0, 1, 2, \cdots$, and g_i is the branch gain.

Ⅲ. The Degradations due to Fading and Doppler shift

In this section, to analyse the signal degradation due to both fading and Doppler shift in LEO channel, the error performance of 32 ksymbols/s QAM(or QPSK) system without fading and Doppler shift compensators has been simulated, and the results are shown in Fig. 4.

From this figure, we know that in the case of BER $= 10^{-3}$, fading frequency $= 80$ Hz, and Doppler shift $= 0$ Hz, the simulation results degrade by about 5 dB compared to the theoritical results, but if the Doppler shift is only up to 100 Hz, BER performance can be no more improved by increasing E_b/N_0, therefore, the Doppler shift as well as fading must be taken into a great consideration in LEO system design.

However, the normalized amplitude of Doppler shift with a satellite altitude had been caculated theoretically in [1], [2], and the

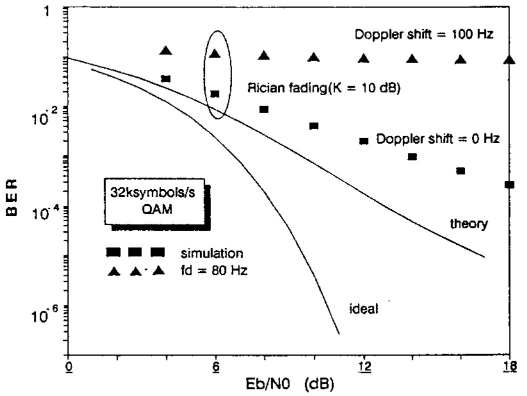


Fig. 4. Degradations due to fading and Doppler shift.

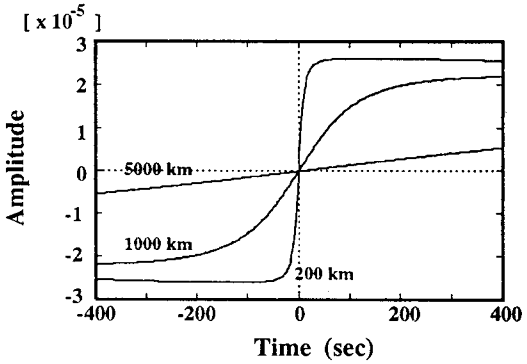


Fig. 5. Examples of normalized Doppler shift with the altitude of satellite versus time.

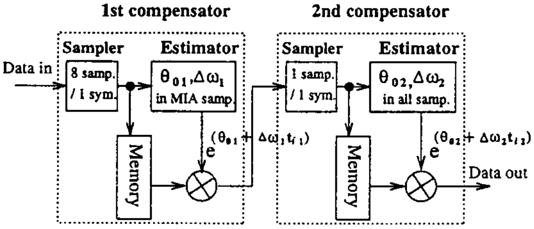
results are shown in Fig. 5. As you are known from this figure, in real LEO mobile satellite communication systems, since the distance between a satellite and earth station time-varies with high speed, the signals suffer from the effects of the time varing large Doppler shift. And the Doppler shift becomes larger as the altitude of satellite becomes lower as in the LEO system.

Ⅳ. The Proposed Doppler Shift Compensator

The block demodulator[8],[9] has been well known as a Doppler shift compensator. It is a very useful scheme for compensating the time-varing Doppler shift. But it has such a drawback that its compensating ability is practically limited to less than several hundreds Hz for 32 ksymbols/s QAM signal transmission because of using the phase shift between the modulated symbols.

In the LEO system, however, the magnitude of Doppler shift may be more than several kHz so that a scheme must be proposed to compensate for the large Doppler shift like this. In order to compensate more than several kHz, therefore, we insert the first compensator, which is able to compensate for the Doppler shift coarsely by using 8 samples per one symbol in midamble, followed by the second compensator on the conventional block demodulator, as shown in Fig. 6.

The principle of phase estimation and compensation in the first and the second schemes is based on the block demodulation technique [9]. However there are two different points between both schemes; the one is that 8 samples per symbol are used in the first scheme while 1 sample per symbol is used in the second scheme. The other is that the samples only in



θ_{02}, θ_{01} : initial phase t_{i1}, t_{i2}: sampling time

$\Delta\omega_1$, $\Delta\omega_2$: frequency offset between samples

Fig. 6. A proposed Doppler shift compensator.

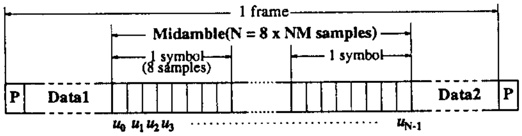


Fig. 7. Samples used in the first scheme.

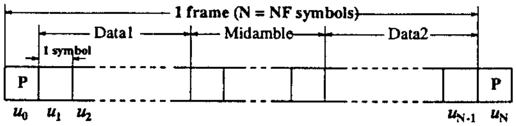


Fig. 8. Samples used in the second shceme.

the midamble are used in the first scheme (shown in Fig. 7), while all samples in a frame are used in the second scheme (shown in Fig. 8).

The accumulative phase rotation from t_0 to t_n of sampling time can be obtained by accumulating the phase transition $\theta_D(t_i, t_{i-1})$ between adjacent samples to the initial phase θ_0, that is

$$A_n = \theta_0 + \sum_{i=1}^{n} \theta_D(t_i, t_{i-1}) \quad (5)$$

Eq. 5 is changed as follows by using the complex expression of the phase estimation sample U_i shown in Fig. 7 and Fig. 8.

$$A_n = \arg(U_0) + \sum_{i=1}^{n} \arg\left\{\frac{U_i}{U_{i-1}}\right\} \quad (6)$$

Fig. 9 shows the accmulative phase rotation, A_n under the noise and Doppler shift disturbance.

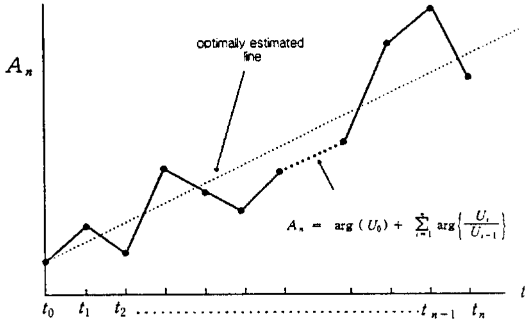


Fig. 9. Accmulative phase rotation under the noise and Doppler shift disturbance.

If the minimum squared error of sample points shown in Fig. 9 is obtained, the dashed line $\theta(t_i) = \Delta\omega t_i + \theta_0$ can be estimated as the following equation[9].

$$\begin{bmatrix} \theta_0 \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} 1 & \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{n} t_i^0 A_n \\ \sum_{n=1}^{n} t_i A_n \end{bmatrix} \quad (7)$$

Once the initial phase transition θ_0 and the Doppler shift $\Delta\omega$ are calculated using eqs. 6 and 7, all samples can be compensated by multiplying $e^{-j(\theta_0 + \Delta\omega t_i)}$.

Ⅴ. The System Performance

5-1 The performance under Doppler shift without fading

In this section, it is assumed that there is no pilot symbol-aided fading compensator in Fig. 3 to analyse the performance of the proposed Doppler shift compensator under Doppler shift without fading. The BER performance of the proposed compensator in QAM(or QPSK) signal transmission are simulated, and the results are shown in Fig. 10 compared with those of the first and the second schemes for ND = 30 and NM = 39 symbols, where, ND and NM are the number of symbols in data block and midamble (see Fig. 2), respectively. The roll off factor of receiving filter (α_r) is assumed to be a brickwall filter to exclude the effect of the bandwidth of receiving filter.

From Fig. 10, it is shown that the conventional block demodulator can compensate for the Doppler shift only less than 300 Hz while the first and the proposed compensator more than several kHz. Furthermore, the proposed compensator, in which the block demodulator is added to the first scheme, has the best performance. For example, in the case of E_b/N_0 = 9 dB, for obtaining BER less than 2.0×10^{-4}, the proposed scheme can compensate for the Doppler shift up to about 12 kHz, but the first scheme less than 4 kHz, and the second scheme on the block demodulator, only less than 300 Hz.

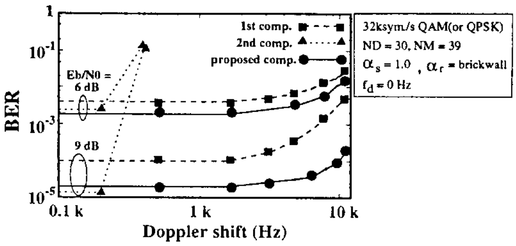


Fig. 10. Comparisons of the performance of the proposed compensator and those of the 1st compensator and the 2nd compensator versus the Doppler shift.

However, in the case of E_b/N_0 = 9 dB and the Doppler shift ≤ 200 Hz, the conventional block demodulation scheme shows the best performance because the phase shift between symbols can be estimated exactely by using all symbols in one frame.

Figs. 11 and 12 show the effects of the roll off factor of receiving filter for transmitting filter fixed at α_s = 1.0, and the effects of the number of symbols in data block (see Fig. 2), respectively.

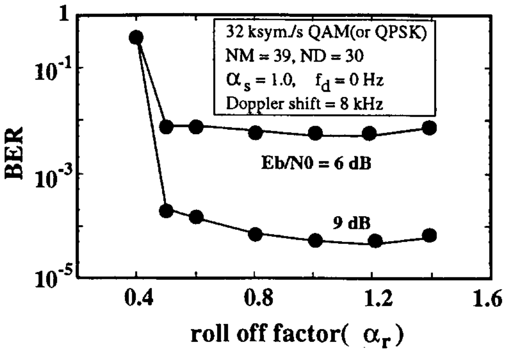


Fig. 11. The effects of the roll off factor of receiving filter, at Doppler shift = 8 kHz.

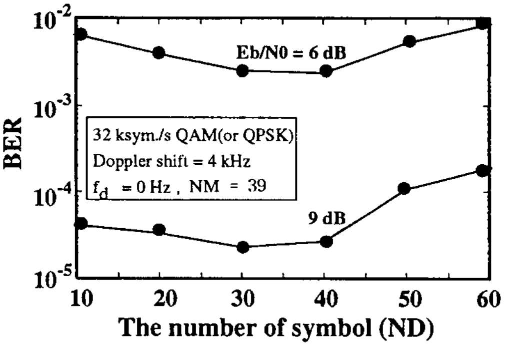


Fig. 12. The effects of the number of symbols in data block, at Doppler shift = 4 kHz.

In Fig. 11, if the roll off factor is more than 0.5, the BER performances are almost same, although the best preformance may obtain at around α_r = 1.0. Therefore, we set α_s = 1.0 and α_r = 1.0 in all following simulations.

As mentioned in [2], the performance of the block demodulation scheme is affected by the number of samples used in estimating the phase shift. If the number of samples is too much or too less, the performance degrades as shown in Fig. 12. From the results, the performance becomes best for ND = 30 and NM = 39 as used in all simulations.

Fig. 13 shows the performance of the proposed scheme in QAM(or QPSK) signal transmission compared to those of the first and the second compensators under the condition of the Doppler shift at the satellite altitude = 200 km and f_c = 2 GHz as shown in Fig. 5. Although the block demodulator shows the good performance in compensating for the Doppler shift due to the LEO satellite system whose altitude is 1,000 km for f_c = 2 GHz[8], it can no longer compensate for Doppler shift as the satellite altitude becomes lower to 200 km. Therefore, when the satellite orbit is low or the carrier frequency is large (as the amplitude of Doppler shift is normalized by the carrier frequency as shown in Fig. 5), the conventional block demodulator will not be able to operate as a Doppler shift compensator at all. On the other hand, the proposed scheme would provide the theoretical BER characteristics in $E_b/N_0 \geq 6$ dB, even if the satellite altitude becomes lower or the carrier frequency becomes higher to some degrees. However, the BER performance of the proposed scheme is degraded in the region of $E_b/N_0 \leq 4$ dB.

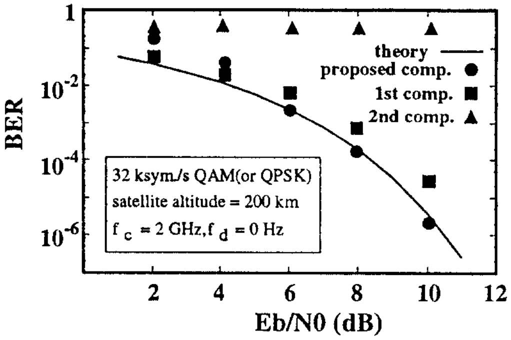


Fig. 13. Comparisons of the performance of the proposed scheme and those of the 1st and the 2nd compensator E_b/N_0, at the satellite altitude = 200 km, and f_c = 2 GHz.

5-2 The performance under fading with Doppler shift

Since the LEO satellite system can be affected easily by fading as well as Doppler shift, a scheme would be needed to compensate for fading. A pilot symbol-aided scheme[7] is well known in QAM system as a fading compensator, especially in Rayleigh fading environments. The advantage of this technique is that it neither requires complex signal processing nor increases the peak factor of the modulated signal. Since the pilot symbol-aided scheme may be considered to be an useful compensator for severe Rician fading ($K \leq 10$ dB, where, K is Rician parameter), it is introduced as a fading compensator in this paper.

In this section, firstly, only fading with no Doppler shift is assumed in order to analyse the system performance with the pilot symbol-aided scheme. Under this assumption, the BER performance of QAM signal are simulated and the results are shown in Figs. 14 and 15.

Fig. 14 shows a comparison of the simulation results and theoretical results of QAM system in fading environment versus the Rician parameter, K at the fading frequency $f_d = 80$ Hz. From Fig. 14, it is shown that as K increases, the simulation results are degraded from the theoretical value. For example, at $K = \infty$ dB (noise only), the simulated result is degraded at by about 2 dB compared to the theoretical value as mentioned in [7].

Fig. 15 shows a comparison of the BER performance of QAM system with and without a pilot symbol-aided scheme, where we can see the pilot-aided scheme is very useful to compensate for the severe Rician fading for $K \leq 10$ dB.

Next, the BER performance of QAM signal versus the Doppler shift are simulated in fading channel with Doppler shift, and the results are shown in Fig. 16. From this figure, we conclude that in Rayleigh fading ($K = -\infty$ dB), the BER is not so sensitive to the Doppler shift, while it is sensitive to the Doppler shift in Rician fading (ex., $K = 10$ dB). For example, in Rayleigh fading, at $E_b/N_0 = 30$ dB, the BER performance are almost same for the Doppler shift $\leq$ 10 kHz, while in Rician fading the performance for $E_b/N_0 = 14$ dB is degraded from 6×10^{-5} at Doppler shift = 100 Hz to 5×10^{-4} at the Doppler shift = 10 kHz.

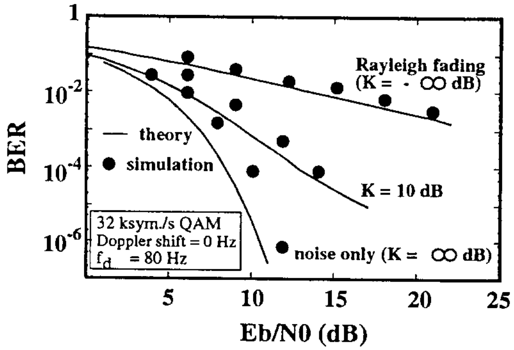


Fig. 14. The BER performance of QAM signal with a pilot symbol-aided scheme in fading without Doppler shift versus E_b/N_0.

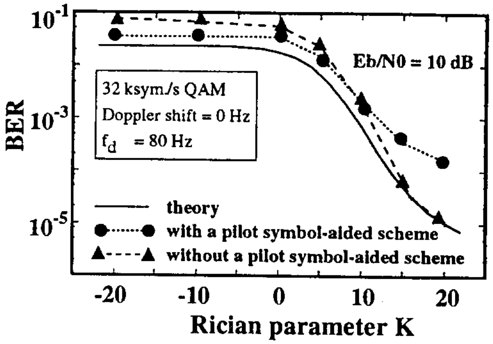


Fig. 15. Comparison of the BER performance of QAM system with and without a pilot symbol-aided scheme versus K.

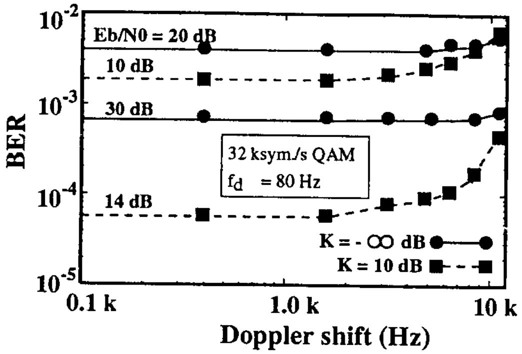


Fig. 16. The BER performance of QAM signal in fading channel with Doppler shift.

Ⅵ. The Performance with EG diversity

Diversity combining, such as space diversity, is a well known method that can be used to combat the effects of fading in wireless systems. Among diversity techniques, an equal gain (EG) diversity is of considerable interest for some reasons. It appears to offer performance which is comparable to that of the optimum maximal ratio (MR) combiner with much greater simplicity than the MR combiner, making it hardware feasible and cost viable[10]. In equal gain combining, the outputs of the different branches are inphased, equally weighted, and then summed up to give the resultant output.

The BER performance of coherent phase shift keying (CPSK) and noncoherent frequency shift keying (NCFSK) with EG combiner diversity in Rician fading environments are introduced theoretically in [10]. Using this technique, the BER performance of QAM system with EG combiner can be obtained easily.

The results are written by,

$$P_e = \frac{2}{T} \sum_{\substack{n=1 \\ odd}}^{\infty} A_n B_n \cos(\tau_n - a_n) \tag{8}$$

where,

$$A_n = \sqrt{\Phi_{I_i}^2 + \Phi_{R_i}^2}, \tag{9}$$

$$B_n = \sqrt{\frac{1}{(nw)^2}\left[1-\exp\left(\frac{-n^2w^2}{4b^2}\right)\right]^2 + \frac{1}{\pi b^2}\left[{}_1F_1\left(1;\frac{3}{2};\frac{-n^2w^2}{4b^2}\right)\right]^2}, \tag{10}$$

$$\tau_n = \sum_{i=1}^{L} \tan^{-1}\left(\frac{\Phi_{I_i}}{\Phi_{R_i}}\right), \tag{11}$$

$$a_n = \tan^{-1}\left\{\frac{\sqrt{\pi}\, b\left[1-\exp\left(\frac{-n^2w^2}{4b^2}\right)\right]}{nw\ {}_1F_1\left(1\,;\frac{3}{2}\,;\frac{-n^2w^2}{4b^2}\right)}\right\}, \tag{12}$$

$$b = \sqrt{\frac{1}{2L}}, \tag{13}$$

and,

$$\Phi_{I_i} = \frac{nwe^{-K}}{\sqrt{(1+K)/\frac{E_b}{N_0}}} \sum_{j=0}^{\infty} \frac{\Gamma(j+\frac{3}{2})}{(j\,!)^2} K^j \times {}_1F_1\left(j+\frac{3}{2};\frac{3}{2};\frac{-n^2w^2\frac{E_b}{N_0}}{4(1+K)}\right), \tag{14}$$

$$\Phi_{R_i} = e^{-K} \sum_{j=0}^{\infty} \frac{K}{j\,!} \times {}_1F_1\left(j+1\,;\frac{1}{2};\frac{-n^2w^2\frac{E_b}{N_0}}{4(1+K)}\right), \tag{15}$$

where T is 200~500[11] and L is the number of branch.

Fig. 17 shows the BER performance of QAM system with EG combiner versus E_b/N_0 with $L = 1$, 2 in fading channel with Doppler shift. One can see from this figure that the considerable diversity gain can be obtained over the

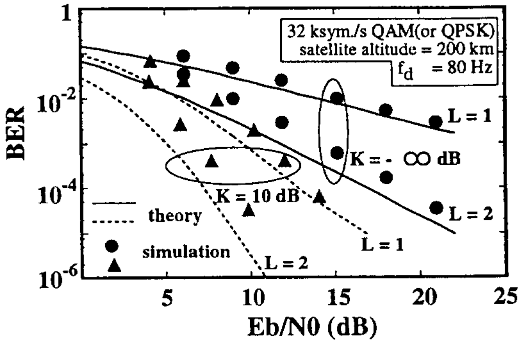


Fig. 17. Improvements of the performance by using EG combiner in fading channel with Doppler shift.

nondiversity case ($L = 1$) even for the Rician fading. For example, for $K = 10$ dB (Rician fading), the gain at BER $= 1 \times 10^{-4}$ is more than 5 dB. In the case of $K = 10$ dB, the performance with $L = 2$ is almost same as that of only noise (see, Fig. 14), but the simulation results are degraded by about 2 dB from theoretical values. This degradation is arised from same reason mentioned in the previous section, Sect. 5.2.

Ⅶ. Conclusions

In this paper, an LEO satellite communication system was modeled as a fading channel with Doppler shift, and a receiving system suitable to compensate for fading and Doppler shift was proposed. The system performance were analysed theoretically and simulated with considering the effect of the equal gain combiner.

It was seen that although the conventional block demodulator is able to combat the Doppler shift only less than several hundreds Hz, the proposed Doppler shift compensator is effective to more than several kHz, and that it is a good compensator enough to combat the Doppler shift due to the extremely low earth orbit mobile satellite system which operates at about 200 km in 32 ksymbols/s QAM(or QPSK) signal transmission. Also, it was found that a pilot symbol-aided fading compensator is suitable for severe Rician fading ($K \leq 10$ dB) as well as Rayleigh fading.

Although, the performance of the receiving system which consists of above two compensators, i.e., the proposed Doppler shift and the conventional fading compensators keep constant up to 10 kHz of Doppler shift in Rayleigh fading, they are degraded as the Doppler shift increases in Rician fading. This means that the receiving system is insensitive to the Doppler shift in Rayleigh fading, while it is sensitive in Rician fading.

It was shown that there is still a considerable improvement over the nondiversity case even for the Rician fading. Therefore, the undesirable signal degradations which can be no longer compensated by about two compensators are able to be improved to great extent using the EG combiner even if the LEO system operates in the severe fading with the large Doppler shift.

However, a drawback of this proposed Doppler shift compensator is data effciency. If a lot of unmodulated symbols are inserted unlike the conventional block demodulator, the data efficiency would be reduced. It is important, therefore, that the number of dummy symbols to be inserted in midamble must be chosen by considering the trade-off between the system performance and the data efficiency.

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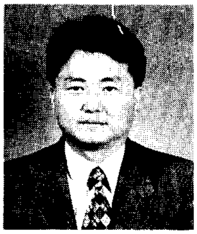
Kang Young Heung



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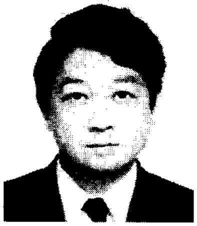

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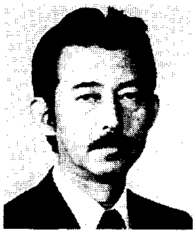

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