TRELLIS-CODED DPSK WITH MULTIPLE-SYMBOL VITERBI DECODING OVER MOBILE SATELLITE CHANNEL AT K AND L BANDS

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SUMMARY

Mobile satellite communication systems at K_a/K band (30/20 GHz) are attractive because of their large bandwidth availability and potentiality to support smaller earth-stations and satellite antennas compared with L-band (1·6/1·5 GHz) systems. In this paper, multiple-symbol Viterbi decoding and dual-space equal-gain diversity reception for trellis-coded differential M-ary phase-shift-keying (DPSK) modulation are investigated as two mitigation techniques for severe channel impairments expected from a land mobile satellite communication channel at K band and, for comparison purposes, at L band. The multiple-symbol Viterbi decoder (MSVD) is a modified Viterbi decoder with inputs from multiple differential detectors. The channel is modelled as Rayleigh distributed multipath fading with a lognormally distributed line-of-sight (LOS) component due to shadowing. Four trellis-coded modulation (TCM) schemes are studied. The dependency of the system performance improvement on the decoder structure, the TCM scheme, and the system RF frequency band is presented.

KEY WORDS: trellis-coded modulation; multiple-symbol Viterbi decoder; diversity reception; mobile satellite communications

1. INTRODUCTION

Personal communications systems have undergone tremendous development in the last few years. Mobile satellite communications, as a part of the personal communications, will provide services to vast regions where communications by purely terrestrial systems are difficult or impossible due to geographical location.[1] The L-band (1·6/1·5 GHz) frequency bands allocated to mobile satellite communications are insufficient to provide various services to the potential users. Extremely high-frequency (EHF) satellite communications provide a promising solution with advantages of its frequency band availability, and its potentiality to support smaller earth-stations and satellite antennas. Several experimental satellites and systems operating at K_a/K band (30/20 GHz) are in advanced stages of development.[2] However, K_a/K-band satellite communications also pose significant challenges to the system design due to severe impairments of the communication channel, such as increased path losses, hydrometeor attenuation, shadowing and multipath fading, etc. Communication systems at K_a/K band have to mitigate these impairments, which becomes even more challenging when the design of low margin systems is required. Although serious hydrometeor attenuation is one of the primary concerns in the K_a/K band system design, in this paper we concentrate on mitigating other channel impairments due to the mobility of earth stations, i.e. multipath fading and shadowing.

The channel impairments can be alleviated by properly designing the transmission system. As to the modulation schemes, M-ary phase-shift-keying (PSK) with differential detection is a good choice, because of its reduced hardware complexity, low cost, high spectral efficiency (when band-limited), high tolerance to fading, and fast synchronization. For example, the North American IS-54 digital cellular system employs $\pi/4$-shifted differential QPSK as the modulation scheme.[3,4] On channel coding, trellis-coded modulation (TCM)[5] can improve the reliability of a digital transmission link without increasing the transmitted power or the required bandwidth. TCM has been applied to systems operating in shadowed land mobile satellite (LMS) communication channels. McLane *et al.*[6] and Lee and McLane[7] have studied trellis-coded PSK and differential M-ary PSK (DPSK) for fast fading mobile satellite channels. Their research work has emphasized TCM with a conventional Viterbi decoder for mobile satellite communications at L band.

In this paper, a multiple-symbol Viterbi decoder (MSVD)[8] and dual-space equal-gain diversity reception for trellis-coded DPSK modulation are investigated as two impairment mitigation techniques for

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an LMS communication channel at K_a/K band and, for comparison purposes, at L band. Since the channel statistics at L band are available only for the down-link between the satellite and the mobile terminals, the 20 GHz and 1·5 GHz down-link propagation channels are considered. The channel is modelled as Rayleigh distributed multipath fading with lognormally distributed LOS component due to shadowing.[9–12] The primary application considered here is digital voice transmission, for which the system performance targets a BER of 10^{-3} or better. This paper is organized as follows. Section 2 describes the mobile satellite communication system model. Section 3 discusses the characteristics of the LMS channel at K and L Bands. Section 4 presents the BER performance improvements achieved by using TCM with an MSVD over that with a conventional Viterbi decoder (VD), and with diversity reception over that with non-diversity reception. The performance evaluation is based on computer simulations. It is shown that both MSVD and diversity reception are effective approaches, especially at K band, to improve the BER transmission performance. The conclusions of this work are given in Section 5.

2. SYSTEM MODEL DESCRIPTION

A functional block diagram of a personal satellite communication system model at baseband is shown in Figure 1. It consists of a transmitter, a shadowed LMS channel and a receiver. The major components of the transmitter are a data source, a trellis encoder and a DPSK modulator. The data source generates an independently and identically distributed (i.i.d.) binary sequence at a rate of 2400 b/s, which is converted into a sequence of independent k-bit information source-words: $\mathbf{x}_i^k = \{x_i^0, x_i^1, \ldots, x_i^{k-1}\}$. The output of the rate k/n trellis encoder is a sequence of coded n-bit code-words: $\mathbf{y}_i^n = \{y_i^0, y_i^1, \ldots, y_i^{n-1}\}$, where $y_i^j \in \{0,1\}$. The DPSK modulator consists of a phase mapper, a differential encoder and a quadrature modulator. Each n-bit codeword is differentially mapped into a carrier phase $\theta(t)$ by the phase mapper and the differential encoder

$$\theta(i) = \theta(i-1) + \frac{2\pi}{M}\sum_{j=0}^{n-1}(2^j y_i^j) \qquad (1)$$

where $M = 2^n$. Since the in-phase and quadrature baseband signals of the quadrature modulator over $t \in [iT, iT+T]$ are $d_i(t) = A\cos[\theta(i)]$ and $d_q(t) = A\sin[\theta(t)]$, the transmitted RF signal (in complex form) is

$$s_i(t) = A\exp\{j[\omega_c t + \theta(i)]\} \qquad (2)$$

where A is the signal amplitude and ω_c is the RF carrier angular frequency.

The LMS channel corrupts the signal waveform transmitted through it by introducing an amplitude fluctuation (multiplicative gain) $r(t)$ and a carrier phase jitter $\varphi(t)$. The received RF signal is also degraded by an additive white Gaussian noise (AWGN) $n(t)$ component with a one-sided spectral density N_0. As a result, the received RF signal over $t \in [iT, iT+T]$ can be expressed as

$$\begin{aligned} x_r(t) &= r(t)\exp[j\varphi(t)]s_i(t) + n(t) \\ &= Ar(t)\exp\{j[\omega_c t + \theta(i) + \varphi(t)]\} + n(t) \end{aligned} \qquad (3)$$

Let $n_i(t)$ and $n_q(t)$ represent independent lowpass zero mean Gaussian random processes with variance $\sigma^2 = N_0 B_r$ (where B_r is the equivalent IF noise bandwidth of the receiver). Then the noise $n(t)$ can be represented in its narrowband form

$$n(t) = n_i(t)\cos(\omega_c t) - n_q(t)\sin(\omega_c t) \qquad (4)$$

The corresponding received baseband signals of the in-phase and quadrature channels are

$$\begin{aligned} R_i(t) &= d_i(t)r(t)\cos[\varphi(t)] - d_q(t)r(t)\sin[\varphi(t)] + n_i(t) \\ R_q(t) &= d_q(t)r(t)\cos[\varphi(t)] + d_i(t)r(t)\sin[\varphi(t)] - n_q(t) \end{aligned} \qquad (5)$$

With equal-gain diversity combining of signals from two independent LMS fading channels, the in-phase and quadrature received signals at baseband are

$$\begin{aligned} R_i(t) &= d_i(t)[r_1(t)\cos\varphi_1(t) + r_2(t)\cos\varphi_2(t)] \\ &\quad - d_q(t)[r_1(t)\sin\varphi_1(t) + r_2(t)\sin\varphi_2(t)] \\ &\quad + n_{i1}(t) + n_{i2}(t) \\ R_q(t) &= d_q(t)[r_1(t)\cos\varphi_1(t) + r_2(t)\cos\varphi_2(t)] \\ &\quad + d_i(t)[r_1(t)\sin\varphi_1(t) + r_2(t)\sin\varphi_2(t)] \\ &\quad - n_{q1}(t) - n_{q2}(t) \end{aligned} \qquad (6)$$

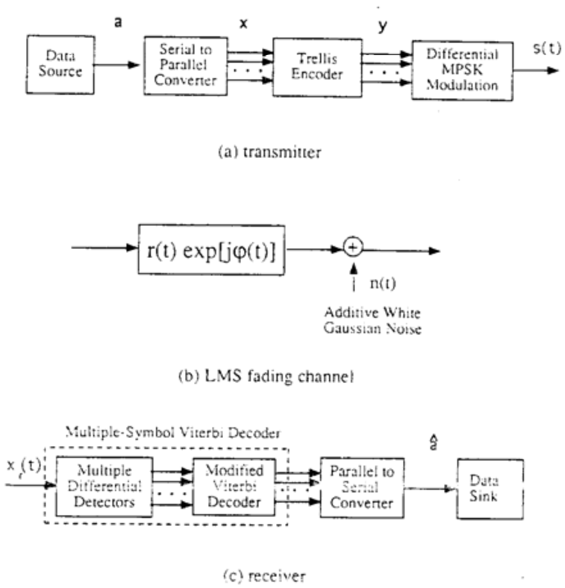

Figure 1. Block diagram of trellis-coded differential MPSK in a shadowed LMS channel

where $r_1(t)$ and $r_2(t)$ are the envelope fluctuations, and $\varphi_1(t)$ and $\varphi_2(t)$ are the phase distortions of the two independently fading channels, respectively.

The received baseband signals are then demodulated and decoded by an MSVD, which consists of multiple differential detectors[13] and a modified Viterbi decoder, as shown in Figure 2 (where $j+1$ is the number of symbols used in each detection). This modified Viterbi decoder exploits the redundancy introduced by the differential encoder, which results from the joint use of several differential detectors. The performance improvement with the decoder is obtained by increasing the number of states in the trellis (by using multiple differential detection) at the decoder.

3. THE LMS FADING CHANNEL

It is well known that an LMS channel can be modelled as Rayleigh fading with its local mean, the LOS component, following a lognormal statistical distribution. It has been shown that the lognormal distribution for the local mean fits experimental data for microwave mobile communications from 100 MHz to 11·2 GHz[10] and for land mobile satellite communications at 870 MHz and 1·5 GHz.[9,11] Here, we assume that the channel model is also valid for a mobile satellite communication channel at 20 GHz. It is expected that the down-link signal at K band will have more attenuation compared with that at L band, owing to much more significant shadowing attenuation from vegetated areas. Because the experimental channel data for mobile applications at K_a/K band is very limited and is not readily available to most researchers, an attempt has been made to study the channel characteristics based on experimental data available at L band[9,11] and the use of a frequency scaling technique proposed in References 12 and 14. The frequency scaling technique is developed based on static propagation measurements through deciduous trees, and it is only used to scale the ensemble average of shadowing attenuation. It should be pointed out that such an estimate model is based on particular channel conditions and that further modifications may be necessary when experimental data at K band

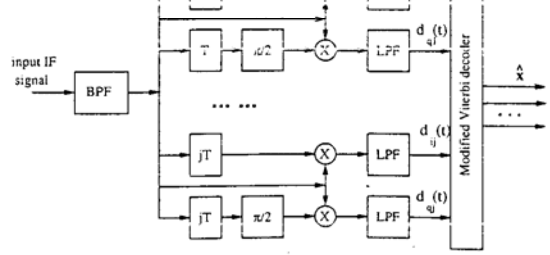

Figure 2. Block diagram of multiple-symbol Viterbi decoder (MSVD)

becomes available. The probability density function (p.d.f.) of the received signal amplitude fluctuation $r(t)$ due to fading is[9]

$$p(r) = \frac{r}{b_0\sqrt{(2\pi d_0)}} \int_0^\infty \frac{1}{z} \exp\left[-\frac{(\ln z-\mu)^2}{2d_0} - \frac{r^2+z^2}{2b_0}\right] I_0\left(\frac{rz}{b_0}\right) dz \tag{7}$$

where b_0 is the power of the multipath signal component, μ and $\sqrt{d_0}$ are the mean value and standard deviation, respectively, of the normally distributed random process $\ln[z(t)]$, $z(t)$ is the shadowed LOS component, and $I_0(\cdot)$ is the zero-order modified Bessel function. The channel parameters at L and K bands are obtained and listed in Table I.[12] Other channel parameters used to carry out computer simulations are discussed below and in Section 4.

Second-order statistics are used to describe the time-dependent fading channel characteristics, which include level-crossing rate (LCR) and average fading duration (AFD). It is expected that the K-band channel will fade at a much faster rate than the L-band channel, owing to its higher RF frequency. In the computer simulations to be discussed, a vehicle speed of 43·2 km/h is taken as an example, corresponding to a maximum Doppler frequency shift (which determines the multipath fading bandwidth) of 60 Hz at L band and 800 Hz at K band. The bandwidth of the shadowing process is taken as one twentieth (1/20) of the multipath fading bandwidth, which is 3 Hz at L band and 40 Hz at K band. Since the shadowing random process has a much slower fading rate than multipath process, for a dual-space diversity reception, it is necessary to separate the two receiver antennas by approximately ten wavelengths (i.e. 15 cm for the K-band signal), in order to obtain two independnetly faded received signals (including both multipath and shadowing components). It has been shown[12] that the maximum values of the LCR normalized to the maximum Doppler shift for both L-band and K-band fading channels are very close to 1·0, which means that the LCRs increase almost linearly with an increase of the vehicle speed and/or an increase of the RF frequency. Hence, the product of the maximum Doppler frequency shift f_D and the transmitted signal symbol duration T_s determines the

Table I. The LMS channel model parameters

Channel	RF(GHz)	b_0	μ	$\sqrt{d_0}$
Light shadowing	1·5	0·158	0·115	0·115
	20·0	0·158	0·2415	0·2415
Average shadowing	1·5	0·126	−0·115	0·161
	20·0	0·126	−0·2415	0·3381
Heavy shadowing	1·5	0·0631	−3·91	0·806
	20·0	0·0631	−8·211	1·6926

degree of signal fading. With a data transmission rate of 2400 b/s, the value of $f_D T_s$ is 1/40 and 1/3 for a rate 1/2 TCM scheme, and 1/20 and 2/3 for a rate 2/3 TCM scheme at L and K bands, respectively.

Zhuang *et al.*[12] have shown that a dual-space diversity reception (with equal-gain combining of two independent fading channels) not only combats deep channel amplitude fades, but also reduces the normalized AFD to less than 10 per cent of that with single channel reception, i.e. the deep fading duration is dramatically reduced and, therefore, we can expect that the LMS system performance will be significantly improved when TCM with Viterbi decoding is used. Furthermore, the diversity reception mitigates more channel fading at K band than at L band, especially in the cases of light shadowing and average shadowing. In the following, the computer simulations are performed to study the system transmission performance over the LMS channel with average shadowing at L and K bands.

4. PERFORMANCE ANALYSIS

Four TCM schemes are investigated: (a) four-state trellis-coded differential QPSK, (b)(i) four-state trellis-coded differential 8PSK with parallel transitions, (b)(ii) four-state trellis-coded differential 8PSK with distinct transitions, and (b)(iii) eight-state trellis-coded differential 8PSK. The details of the trellis encoder structures, bit-to-symbol mapping rules, PSK constellations and trellis diagrams for each scheme are given in Reference 6.

As discussed in Section 3, both amplitude fluctuation and carrier phase jitter resulting from the channel fading degrade the system transmission performance. Owing to the much faster fading rate of the LMS channel at K-band, the variation of the carrier phase jitter over the two consecutive symbols due to the fading channel cannot be removed simply by differential detection. Consequently the system would fail to provide satisfactory performance at K-band if no further techniques are used to remove the phase jitter variations of the received RF signal. One possible approach to reduce the effects of the carrier phase jitter on the BER performance of DPSK is to increase the data transmission rate, i.e. to reduce the $f_D T_s$ value. However, the increase of the data rate is limited by the transmitter power, path loss and other channel impairments, and the required BER performance. Another possible way is to use a pilot signal to obtain variations of the carrier phase disturbance over a few consecutive symbols.[15] In the following, we assume that variations of the carrier phase jitter of the received signal in the radio frequency band are removed in the intermediate frequency band and that only the amplitude fading impairs the transmission performance. The performances with both single channel reception (L = 1) and dual-space equal-gain diver-

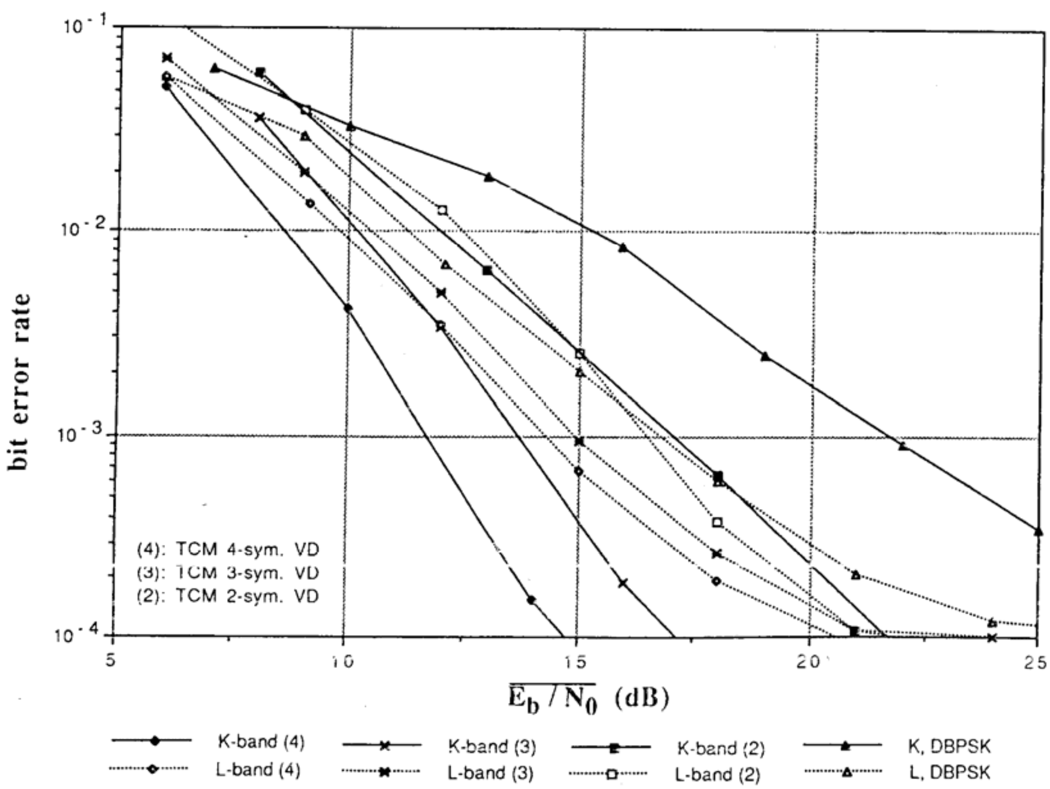

Figure 3. Performance of four-state trellis-coded differential QPSK system with single channel reception

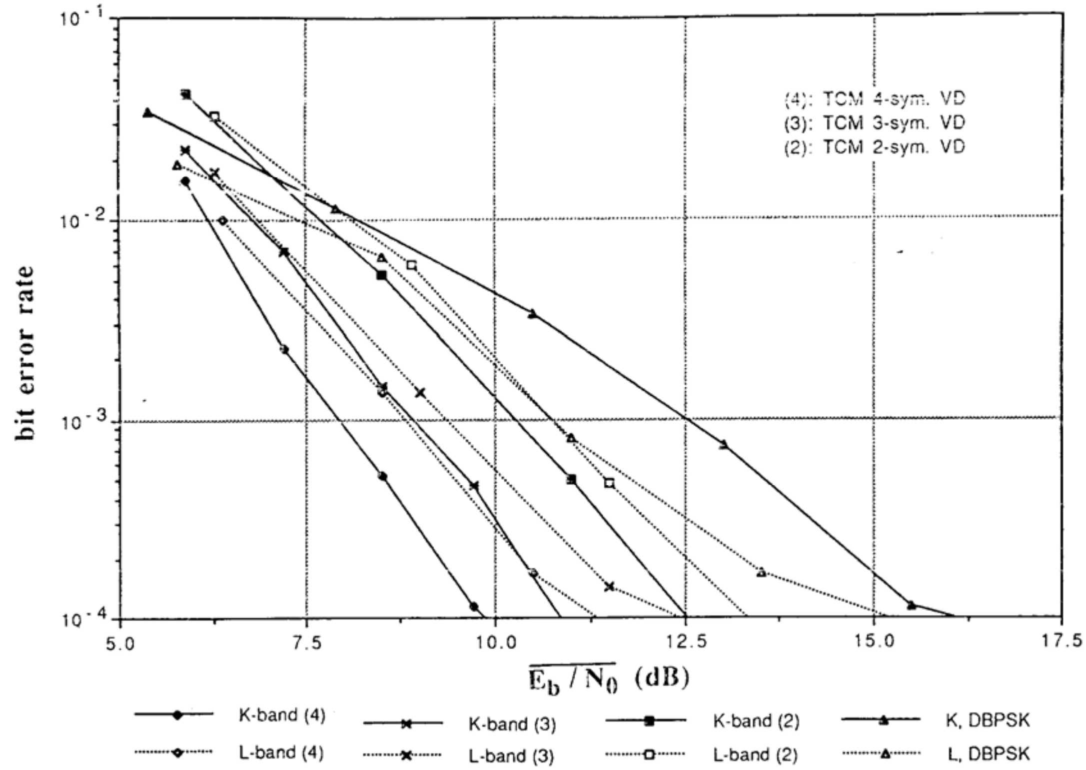

Figure 4. Performance of four-state trellis-coded differential QPSK system with dual-space equal gain diversity reception

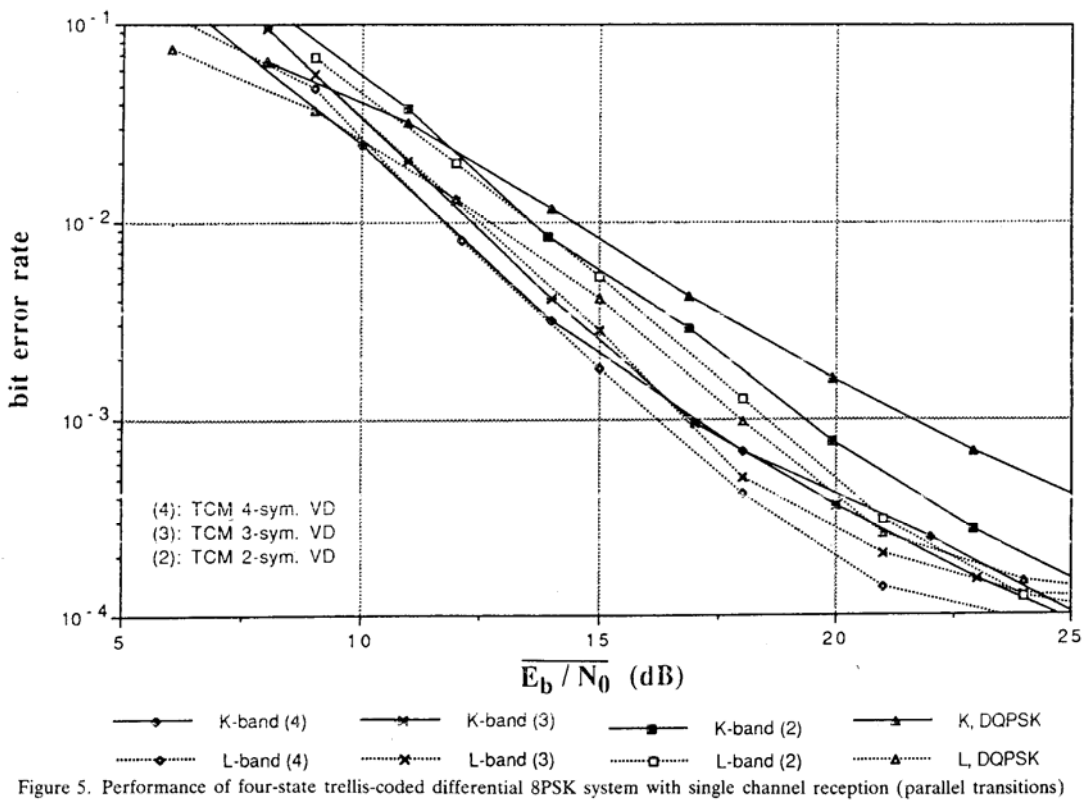

Figure 5. Performance of four-state trellis-coded differential 8PSK system with single channel reception (parallel transitions)

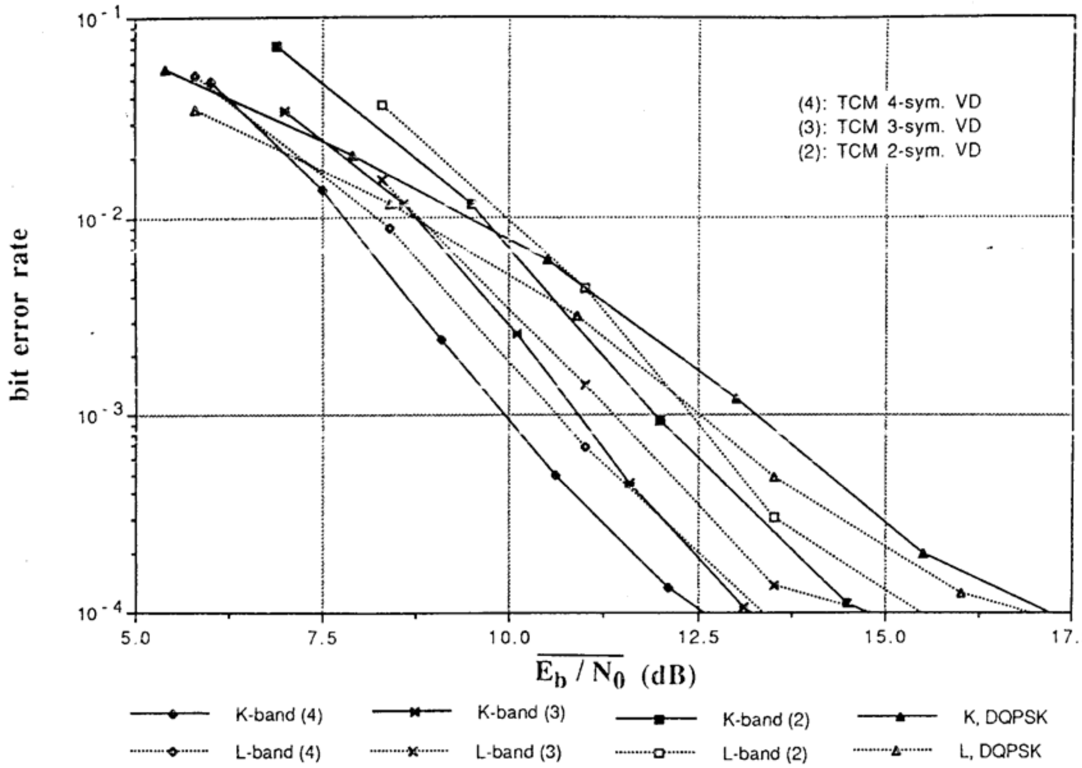

Figure 6. Performance of four-state trellis-coded differential 8PSK system with dual-space equal gain diversity reception (parallel transitions)

sity reception ($L = 2$) are studied. For comparison purposes, the performance of the corresponding uncoded DPSK system with a Viterbi decoder is also presented. A computer simulation model based on Figure 1 has been developed to study the system performance. The decoding depths of the Viterbi decoders are set to at least $6(m+1)$ in order to balance the decoder complexity and performance, where $(m+1)$ is the constraint length of the trellis codes. The performance of the simulation model in an AWGN channel has been verified with the previously published results.[8] The LMS channel is simulated by using the 'sum of sine waves' method.[10,12] The received signal power is normalized to that of line-of-sight (LOS) signal without shadowing. A Monte Carlo simulation technique is used, and the number of information bits transmitted through the system for each average ratio of energy per received information bit to one-sided noise density $\overline{E_b/N_0}$ is chosen in such a way that the simulated BER performance results are within a 90 per cent confidence interval of [0·5BER, 2·0BER]. For each TCM scheme, simulations are performed with four-symbol, three-symbol and two-symbol (i.e. conventional) Viterbi decoders, respectively. Usually, an interleaving technique can be used to combat slow fading.[6] However, interleaving also introduces a digital speech processing delay in addition to the signal propagation delay and the decoding delay. For the applications of the delay-sensitive voice transmission, interleaving is not considered here because of the additional process delay. As mentioned earlier, all the performance comparisons to be discussed are referred to a BER of 10^{-3}.

(a) Four-state trellis-coded differential QPSK system (TCM4)

In the TCM scheme, for each information bit x_i, the encoder produces two coded bits $\{y_i^0, y_i^1\}$, which are mapped differentially into a QPSK signal. The symbol duration T_s is the same as the bit duration T_b. When a conventional Viterbi decoder (with two-symbol differential detection) is used, the decoder requires only four states; however, a three-symbol Viterbi decoder requires eight states and a four-symbol Viterbi decoder requires 16 states. The BER performance with single channel reception is shown in Figure 3. The uncoded modulation counterpart of the TCM scheme is BPSK, which has the same data transmission rate as the TCM. Compared with uncoded BPSK, the TCM system with a conventional VD has an $\overline{E_b/N_0}$ gain of 4·6 dB at K band and 0·4 dB at L band, the gain increases as the BER decreases; the performance improvement by three-symbol and four-symbol VDs (over a two-symbol VD) is 3·3 dB and 7·1 dB at K band, 1·6 dB and 2·1 dB at L band, respectively. The MSVDs

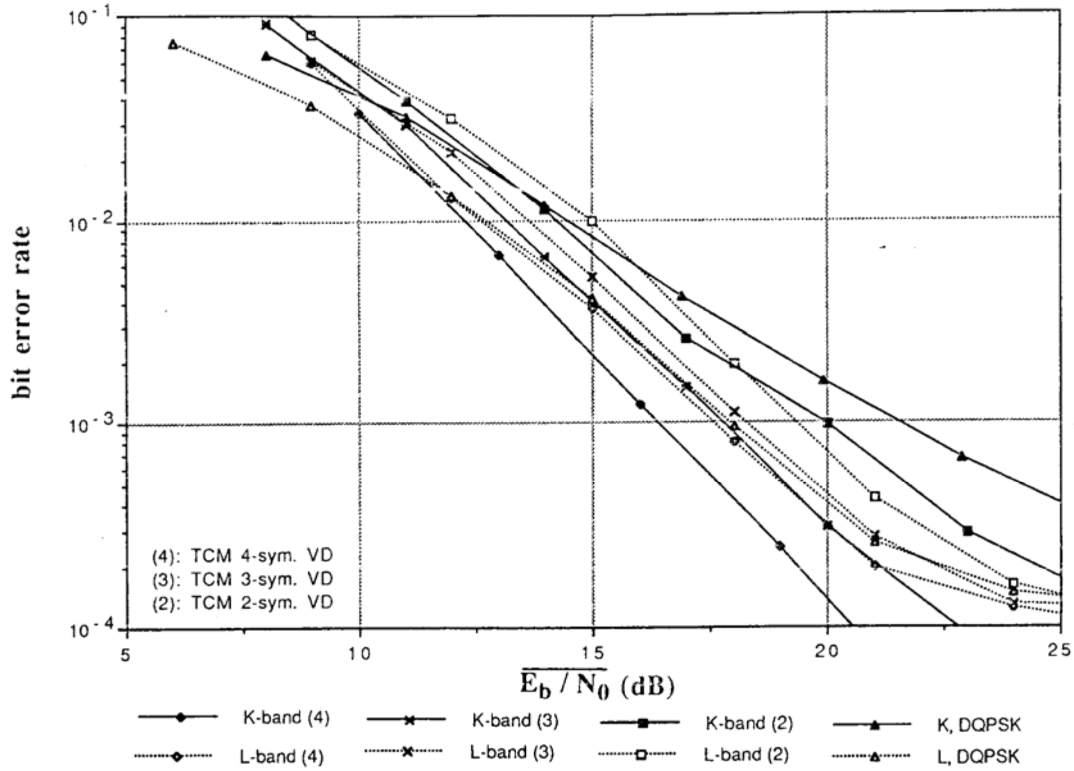

Figure 7. Performance of four-state trellis-coded differential 8PSK system with single channel reception (distinct transitions)

have much more improvement at K band than at L band, because the LMS channel fades at a much faster rate at K band so that the correlation of the channel fading over the symbols in each multiple differential detection is greatly reduced. With the channel fading less correlated (in time), the AFD of deep fades is reduced, so that statistically not all the symbol samples used in each multiple differential detection experience deep fading at the same time. Therefore, MSVD is more effective in combating the channel fading at K band than at L band. Figure 4 illustrates the corresponding performance in the case of $L = 2$. Compared with the case of $L = 1$, the diversity reception provides gains of 9·0 dB (at K band) and 6·2 dB (at L band) for the uncoded BPSK systems. The diversity reception improvements for the TCM system with two-symbol, three-symbol and four-symbol VDs, respectively, are 6·8 dB, 4·9 dB, 3·9 dB (at K band) and 5·8 dB, 6·5 dB, 5·7 dB (at L band). The performance improvement provided by the MSVDs for both $L = 1$ and $L = 2$ can be clearly observed (especially for the K-band system).

(b)(i) Four-state trellis-coded differential 8PSK system with parallel transitions (TCM4P)

In the TCM scheme, each two-bit information word $\{x_i^0, x_i^1\}$ is coded into a three-bit word $\{y_i^0, y_i^1, y_i^2\}$ which is then mapped into a differential 8PSK signal. In this case, $T_s = 2T_b$. The uncoded counterpart of a rate 2/3 trellis-coded differential 8PSK is differential QPSK, because both coded and uncoded schemes have the same data transmission rate. Figures 5 and 6 give the simulation results for $L = 1$ and $L = 2$, respectively. With single channel reception (Figure 5), at K band, TCM with two-symbol VD gains 2·2 dB over uncoded differential QPSK system, and both three-symbol and four-symbol VDs outperform the two-symbol VD by 2·5 dB. For the L-band system, the TCM with two-symbol VD loses 0·5 dB compared with the uncoded differential QPSK system. The reason that the TCM scheme with a Viterbi decoder using only a single differential detector does not outperform uncoded QPSK at L band can be explained as follows. With the slow fading rate ($f_d T_s = 1/20$), the fading channel has strong memory; it is possible that almost all the received symbols used in a final decision on decoding a two-bit information word experience deep channel fade(s) at the same time (taking into account that the decoding depth of the decoder is 18 in this case). Consequently, a decoding error is likely to occur when deep fading is experienced. It is an inherent property of the Viterbi algorithm that if an error is made in selecting an information word at any instant, several information words in succession may be detected incorrectly before the correct path is reached. In summary, the strong channel memory of deep fading combined with error propa-

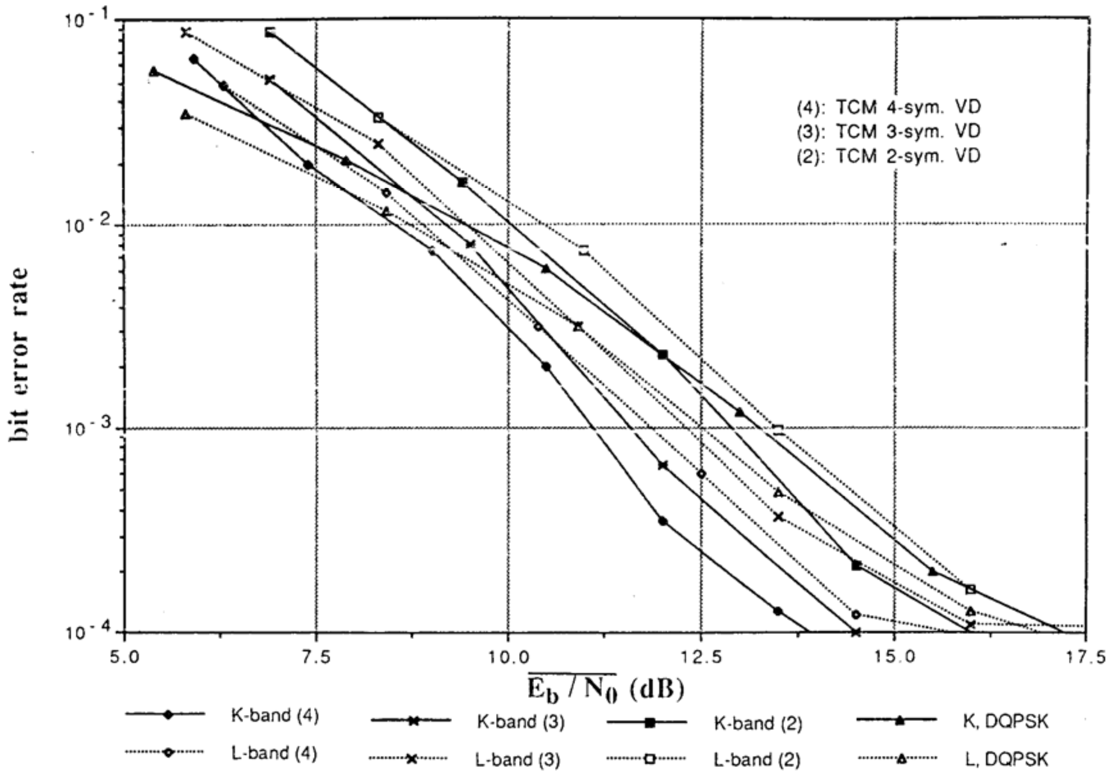

Figure 8. Performance of four-state trellis-coded differential 8PSK system with dual space equal gain diversity reception (distinct transitions)

gation due to the Viterbi algorithm results in a performance degradation. However, the four-symbol and three-symbol VDs have $\overline{E_b/N_0}$ gains of 1·1 dB and 1·6 dB over uncoded QPSK, respectively. The performance improvement by the MSVDs in the case of diversity reception is obvious from Figure 6. At K band, the TCM system gains 1·3 dB over uncoded differential 8PSK system, and the gain is increased by 2·0 dB and 1·1 dB with the four-symbol and three-symbol VDs, respectively. The improvement at L band is 1·7 dB and 1·0 dB by the four-symbol and three-symbol Viterbi decoders, respectively. The diversity reception has approximately 5·7 to 8·3 dB improvement over the single channel reception.

(*b*)(*ii*) *Four-state trellis-coded differential* 8*PSK system with distinct transitions* (*TCM*4*D*)

The performance of the TCM scheme over the LMS channel with average shadowing is shown in Figures 7 and 8. Without diversity reception, the improvement by the TCM scheme over the uncoded system at K band is 5·1 dB, 4·0 dB and 1·5 dB by four-symbol, three-symbol, and two-symbol VDs, respectively. At L band, the much stronger correlation (compared with K band) among the channel fades and error propagation due to the Viterbi decoding algorithm make the TCM with a two-symbol VD lose 1·4 dB by comparison with the uncoded system. The improvement of multiple-symbol VDs over the conventional VD is approximately 1·0 to 1·4 dB. The diversity reception gains approximately 8·2 dB for the uncoded system and 5·3 to 6·9 dB for the coded system at K band, and 5·5 dB for the uncoded scheme and 5·9 to 6·1 dB for the coded system at L band.

(*b*)(*iii*) *Eight-state trellis-coded differential* 8*PSK system* (*TCM*8)

Figures 9 and 10 illustrate the BER transmission performance of the TCM scheme. The TCM system gains 6·7 dB, 5·1 dB, 2·8 dB with single channel reception, and 3·4 dB, 2·6 dB, 0·9 dB in the case of diversity with the four-symbol, three-symbol and two-symbol VDs, respectively compared to the uncoded system at K band. The corresponding improvements at L band are 2·0 dB, 1·3 dB, 0·0 dB without diversity, and 1·8 dB, 1·2 dB, 0·0 dB with diversity. The improvement due to the diversity reception is 8·2 dB (at K band) and 5·5 dB (at L band) for the uncoded system, 4·9 to 6·3 dB (at K band) and 5·3 to 5·5 dB (at L band) for the TCM systems.

The performance improvement by the TCM systems over the corresponding uncoded systems (without diversity) is summarized in Table II. It is

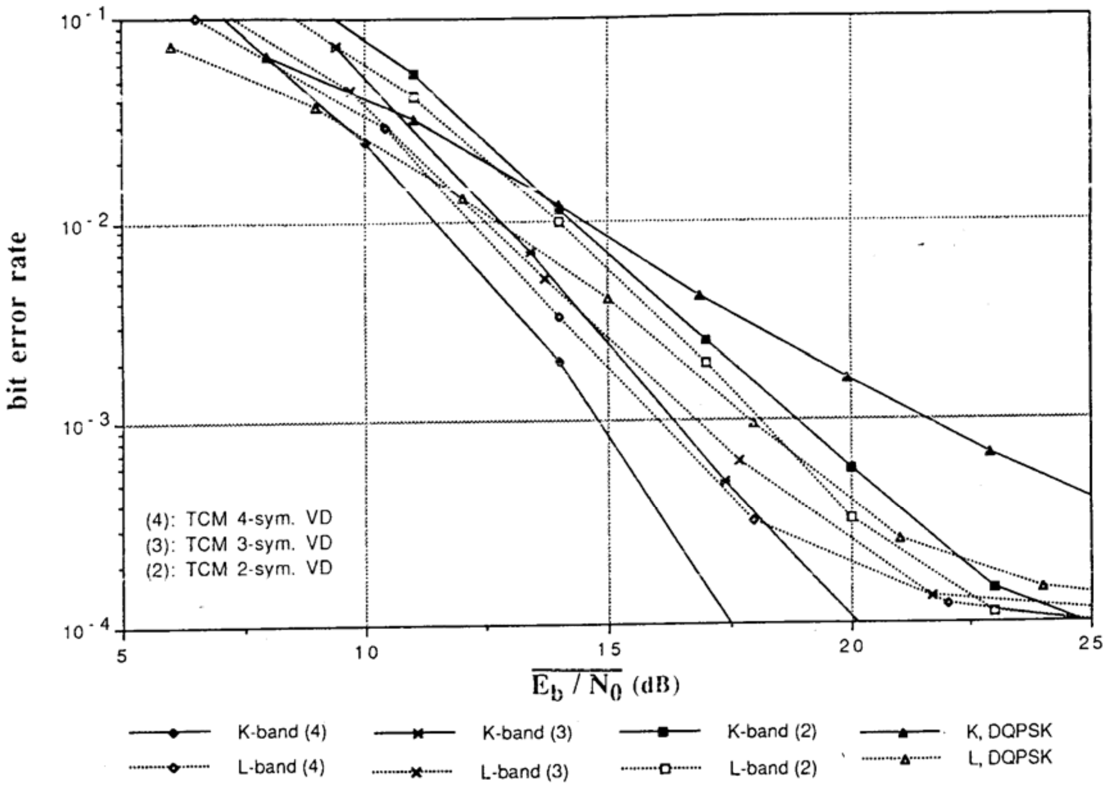

Figure 9. Performance of eight-state trellis-coded differential 8PSK system with single channel reception

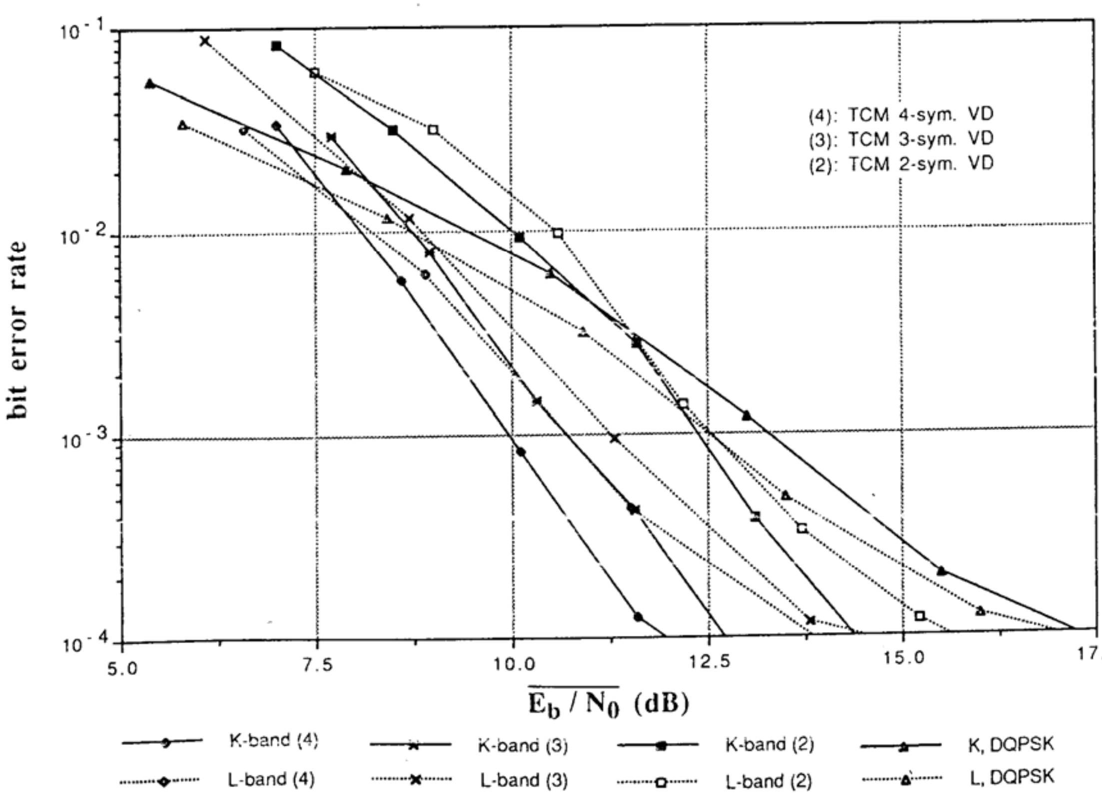

Figure 10. Performance of eight-state trellis-coded differential 8PSK system with dual-space equal gain diversity reception

Table II. Performance improvement of TCM schemes with multiple-symbol Viterbi decoders over uncoded schemes

Decoder	RF (GHz)	QPSK TCM4	8PSK TCM4P	8PSK TCM4D	8PSK TCM8
4-symbol	1·5	2·5 dB	1·6 dB	0·4 dB	2·0 dB
VD	20·0	9·6 dB	4·7 dB	5·1 dB	6·7 dB
3-symbol	1·5	2·0 dB	1·1 dB	0·2 dB	1·3 dB
VD	20·0	7·8 dB	4·7 dB	4·0 dB	5·1 dB
2-symbol	1·5	0·4 dB	−0·5 dB	−1·4 dB	0·0 dB
VD	20·0	4·6 dB	2·2 dB	1·5 dB	2·8 dB

Table III. Performance improvement of diversity reception for TCM schemes with multiple-symbol Viterbi decoders

Decoder	RF (GHz)	QPSK TCM4	8PSK TCM4P	8PSK TCM4D	8PSK TCM8
4-symbol	1·5	5·7 dB	5·7 dB	5·8 dB	5·3 dB
VD	20·0	3·9 dB	6·9 dB	5·3 dB	4·9 dB
3-symbol	1·5	6·5 dB	5·5 dB	5·4 dB	5·4 dB
VD	20·0	4·9 dB	6·0 dB	5·1 dB	5·7 dB
2-symbol	1·5	5·8 dB	6·1 dB	5·9 dB	5·5 dB
VD	20·0	6·8 dB	7·4 dB	6·9 dB	6·3 dB

shown that the four-state trellis-coded differential QPSK has the best performance of BER versus $\overline{E_b/N_0}$ among the four TCM schemes considered, which is obtained at the expense of bandwidth efficiency. It should be pointed out that trellis-coded QPSK is approximately only 50 per cent bandwidth efficient as trellis-coded 8PSK. Among the three trellis-coded differential 8PSK schemes, clearly the eight-state code gives the best performance and the four-state code with distinct transitions gives the worst performance (a similar conclusion has been reached in Reference 6 with a conventional Viterbi decoder at L band). Furthermore, the performance improvement of the TCM schemes with a conventional, three- or four-symbol VD at K band is much more significant than that of the corresponding schemes at L band due to a much faster fading rate at K band. With the increase of the number of symbols used in each detection, the gain of $\overline{E_b/N_0}$ at a BER of 10^{-3} also increases. Table III lists the performance improvement of diversity reception for the TCM systems over single channel reception. The additional improvement is significant in all cases. It is also observed that the uncoded PSK schemes at K band lose approximately 1·5 to 5·0 dB compared with those at L band in the case of $L = 1$, and 0·8 to 1·8 dB in the case of $L = 2$. This results from the much more shadowing attenuation expected at K band than at L band. It is expected that the above analysis is applicable to the case where the mobile terminals move at a speed higher than 43·2 km/h. The analysis is also applicable to other data transmission rates if the value of $f_D T_s$ is relatively large. In the case of small $f_D T_s$ values (such as the case of high data transmission rate), interleaving techniques can be used to enhance the effectiveness of the MSVD in combating the channel impairments.

5. CONCLUSIONS

The transmission performance of four trellis-coded DPSK schemes with multiple-symbol Viterbi decoding in a shadowed land mobile satellite channel at K and L bands has been analysed and compared with their uncoded counterparts. The following conclusions have been reached: (1) In the case of single channel reception (i.e. no diversity), the TCM schemes with multiple-symbol Viterbi decoders can reduce the effect of the channel impairments at K band as much as 9·6 dB depending on the TCM scheme and the number of symbols used in each detection. (2) The gain of the multiple-symbol Viterbi decoder over a conventional Viterbi decoder ranges from 2·0 to 5·0 dB without diversity reception and can be up to 2·5 dB with diversity reception. (3) Diversity reception gains 3·9 to 7·4 dB at K band for the TCM schemes and 5·4 to 9·0 dB for the uncoded schemes. (4) The system performance is improved by the multiple-symbol Viterbi decoders and by diversity reception (with a conventional Viterbi decoder) and the improvements are more significant at K band than at L band. (5) The K-band system suffers more shadowing attenuation than the L-band system.

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