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Trends in Modulation/Demodulation and Coding Techniques for Mobile Satellite Communications Systems

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SUMMARY With the rapid advance in satellite communications technologies, development of mobile satellite communications systems has been carried out in various countries. In a technical aspect to construct high-capacity and high-reliable mobile satellite communication networks, there are two main barriers to get over, i.e., bandwidth limitation and power limitation. In addition, another barrier associated with mobile motion is fading and shadowing. Digital modulation/demodulation and coding techniques, which are key technologies to get over these barriers, have been developed in fusion of advanced satellite communication techniques and specific techniques having grown in terrestrial mobile communication systems. This paper summarizes the mobile satellite channel characteristics and describes a trend of modulation/demodulation and coding techniques for mobile satellite communications systems.

1. Introduction

With the rapid and remarkable advance in satellite communications technologies, development of mobile satellite communications systems has been carried out in various countries. The mobile satellite communications systems are expected to provide various services such as voice, data, message, facsimile and image transmissions for land vehicles, ships, aircraft and so on. Domestic, regional or worldwide mobile satellite communications systems have been developed with the demands for the mobile satellite communications services, because of the advantages of satellite system such as its wider coverage and flexibility in networking.

For transmission of information, digital systems have become increasingly attractive mainly because of increased demands for data transmission, the flexibility of digital transmission not available with analog transmission, and the cost effectiveness. In a technical aspect to construct digital mobile satellite communication networks, however, there are two main barriers to get over, i.e., bandwidth limitation and power limitation. The mobile satellite system is severely bandwidth-limited because of both the geographical frequency reuse difficulties and narrower bandwidth allocated for the mobile services. Furthermore, the mobile satellite system is power-limited because of the small satellite EIRP, long distance propagation and power penalty of the satellite transponder for solar battery. In addition, another barrier associated with mobile motion is rapid fading and shadowing, which the system designer of satellite communications has never been faced with. Digital modulation/demodulation and coding techniques are key technologies to get over these barriers, and they have been developed in fusion of the advanced satellite communication techniques and specific techniques having grown in terrestrial mobile communication systems. In other words, a great effort has been made to add robustness against fading and shadowing to the conventional techniques for the satellite channel characteristics, bandwidth limitation and power limitation.

Much attention being focused on digital transmission, this paper provides an overall survey of modulation/demodulation and coding techniques for mobile satellite communications systems. After summarizing the mobile satellite channel characteristics, described are the developments and future trends in modulation/demodulation and coding techniques.

2. Mobile Satellite Channel

2.1 Bandwidth- and Power-Limited Channel

It is necessary to increase the frequency spectrum utilization efficiency, since the mobile satellite channel is severely bandwidth-limited both because of narrower bandwidth allocated for the mobile services using L-band or S-band as compared with that for the fixed services using C-band, Ku-band and Ka-band, and because of the difficulties in the geographical frequency reuse.

The mobile satellite system is also power-limited because of the small satellite EIRP, long distance propagation and the power penalty of satellite transponder for solar battery. Moreover, the further problem of power limitation arises from the small mobile vehicle antenna gain.

To satisfy the bandwidth- and power-limitations,

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we will employ the bandwidth efficient modulation techniques with forward error correction (FEC) coding.

2. 2 Nonlinear Channel

The satellite channel is inherently a nonlinear one due to the nonlinearities of the satellite transponder and the power amplifier of the mobile terminal, although the recent developments in solid-state linear power amplifier designs have decreased the effects of nonlinearities.

The investigations concerning digital modulation technique in the mobile satellite channel have been concentrated on constant envelope modulations robust to nonlinearities so far, whereas much attention will be paid to nonconstant envelope modulation in the future.

2. 3 Fading Channel

The mobile satellite channel can be generally characterized by the combination of a direct line-of-sight wave and a multipath diffused wave which exhibits rapid variation in both envelope and phase at a mobile vehicle in motion. Fading in such channels as satellite/land vehicle(1), satellite/ship(2) and satellite/aircraft(3) can be well modeled by the Rician distribution with a parameter K called 'Rician factor' corresponding to the ratio of the coherent (specular) component power (C) to the incoherent (diffused) component power (M). When $K=0$, the channel is the Rayleigh fading channel encountered in land mobile radios. When $K=\infty$, the channel is the well-known additive Gaussian noise (AWGN) channel.

Fortunately, in the mobile satellite channel, since there is a 'steady' coherent component in the received signal, the extraction of the coherent component from the received signal perturbed by fading is very effective. For example, by applying fading reduction method that makes efficient use of a characteristic of circularly polarized signal reflected by the sea surface(4), we can eliminate the reflected signal and can receive only the direct signal without the fading. In the land mobile channel with the Rayleigh distributed envelope, on the other hand, since there is no coherent component in the received signal, we usually use the diversity and/or equalization techniques for combating fading.

The additional serious source of performance degradation associated with mobile vehicle motion is the Doppler frequency shift. Since the fading with rapid frequency shifts makes the problem of carrier recovery much difficult, various techniques for coherent detection have been investigated. Differential detection is also considered to be a simple and attractive method for recovering data from a fading signal, even though the static performance is inferior to that of coherent system.

Other barriers associated with mobile motion are blocking and shadowing. The former is often caused by ship superstructures in satellite/ship communication system and the latter by trees and buildings in satellite/land vehicle communication system. Since these effects interrupt communication especially at low elevation angle, it is important to develop rapid reacquisition technique after interruption.

3. Coding and Modulation Techniques

3. 1 Coding and Modulation for Bandwidth- and Power-Limited Channel

As bandwidth efficiency and power efficiency are contrary to each other in the design of modulation technique, it is difficult to increase both efficiencies. In other words, although multi-level modulation techniques such as M-ary phase shift keying (MPSK) and quadrature amplitude modulation (QAM) are preferable from the viewpoint of bandwidth efficiency, they require much more high Eb/N0 (signal energy per-bit to noise power density ratio). Therefore, to satisfy the bandwidth limitation and the power limitation simultaneously, we will use the FEC coding with such bandwidth efficient modulation techniques (see Fig. 1).

In bandwidth efficient modulation techniques, MPSK and QAM have the advantage of achieving bandwidth efficiency easily compared with continuous phase modulation (CPM) techniques. Furthermore, MPSK is preferable to QAM because of the nonlinear characteristic of the channel.

It is important to design FEC codes with high coding gain and low redundancy. The two alternatives for FEC codes are block code and convolutional code.

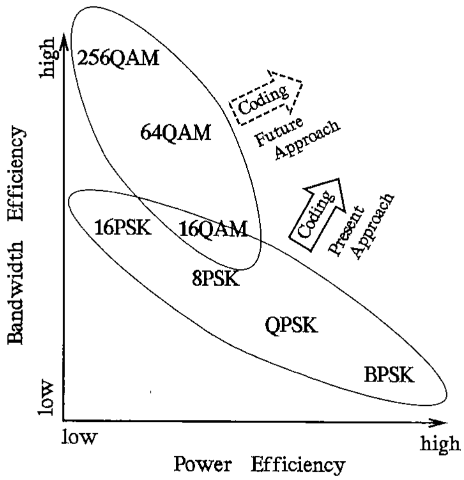


Fig. 1 Relation between power efficiency and bandwidth efficiency in signal design.

Both are attractive, and recently it is expected that convolutional code will predominate in mobile satellite communications systems because of their easy implementation and high decoding availability combined with the Viterbi algorithm (VA).

3. 1. 1 Convolutional Coding with PSK Modulation

Usually, coding and modulation have been separately treated in an overall system design. From the viewpoint of maximizing the minimum Hamming distance for FEC coding and maximizing the distance between signal points for modulation, the convolutional codes with QPSK or OQPSK modulation have been investigated for many years[5],[6]. Much attention has been also paid to punctured convolutional codes for the higher code rate[6].

3. 1. 2 Trellis Coded Modulation

Ungerboeck[7], in his definitive paper on trellis coded modulation (TCM), showed the possibility to achieve significant coding gain without bandwidth expansion compared with uncoded 2^{k-1} signal constellation set, by doubling the signal constellation set from 2^{k-1} to 2^k with optimally designed trellis codes to maximize Euclidean distance.

Ungerboeck could improve the error-event probability (EEP) by a signal mapping technique called "set partitioning (SP)", while most earlier works on TCM concentrated upon minimizing the EEP. Du et al.[8] and Umeda et al.[9] could succeed in improving the post-decoding information-bit error rate (IBER) by the Gray-code (GC) mapping and Maximum Hamming Distance (MHD) mapping, respectively. Divsalar et al.[10] further improved the performance of TCM by combining asymmetric MPSK signal constellations with the SP mapping. Figure 2 shows the examples of the SP mapping (a), the GC mapping (b), the MHD mapping (c) and the asymmetric signal constellation (d) for 8PSK, respectively.

Although such TCM techniques were originally developed for the telephone channel, some new approaches which integrate coding and modulation have been widely investigated in the satellite channel mostly for TCM techniques concerned with constant envelope modulation such as QPSK, 8PSK[11] and 16PSK[12] because of the nonlinear characteristics of the channel. Furthermore, the recent developments in solid-state linear power amplifier design imply the multi-level modulation technique such as 16QAM[13], 64QAM, and 256QAM[14] in future digital mobile satellite communications systems with high speed information rate. However, it should be noted that the modulation technique with higher bandwidth efficiency requires more precise phase recovery at the receiver.

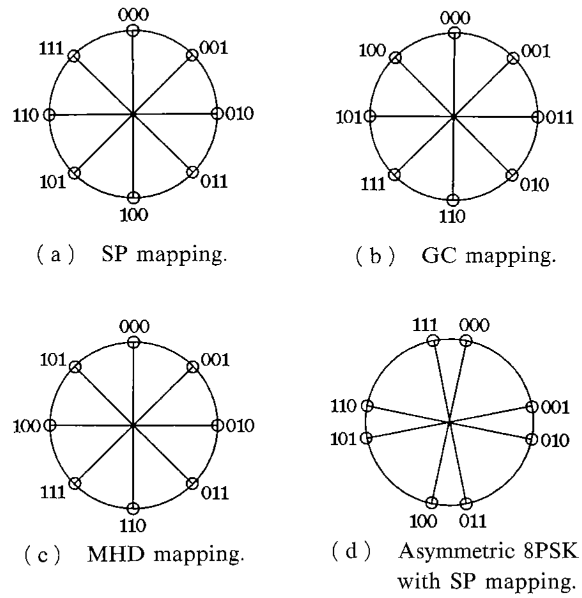


Fig. 2 8PSK signal constellations and mappings.

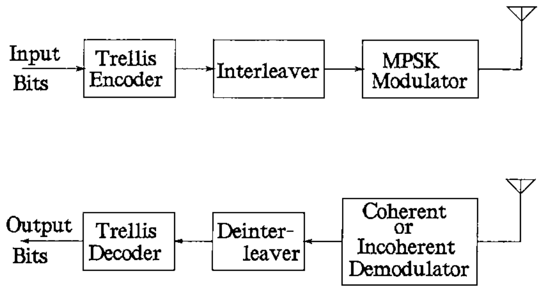


Fig. 3 System block diagram for evaluation of error rate performance.

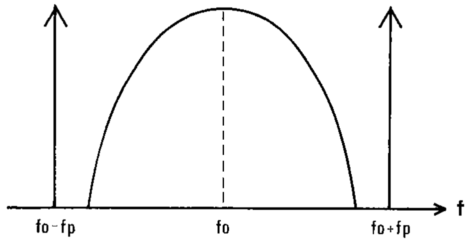
3. 2 Coding and Modulation for Fading Channel

3. 2. 1 Coding for Fading Channel

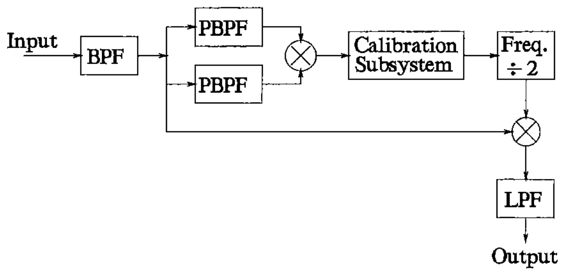
As the mobile satellite channel exhibits bursty error characteristics because of fading and shadowing, coding should be carried out with interleaving for obtaining the time diversity breaking up the burst errors. Figure 3 illustrates a typical example of the system block diagram[11],[15]. The depth of interleaving is chosen in relation to the maximum fade duration, and is constraint on the order of the decoder buffer size and total allowable delay.

3. 2. 2 Tone Calibration Technique

The basic concept of tone calibration techniques (TCT)[16],[17] is to transmit a pilot tone along with the data signal in order to calibrate the fading channel continuously. If the fading impairments on the pilot tone and the data signal are the same, then the extract-



(a) DPTCT spectrum.



(b) DPTCT receiver block diagram.

Fig. 4 DPTCT system.

ed pilot tone at the receiver can be used as a coherent reference to remove the fading amplitude variations and the fading phase fluctuations. Therefore, the TCT systems are robust to fading. Although the TCT system yields good error rate performance, the spectral arrangement by insertion of a pilot tone is inefficient in bandwidth use. Figure 4(a) illustrates the spectrum of dual-pilot tone calibration technique (DPTCT[18]) system proposed by Simon.

When the Viterbi algorithm is applied for decoding trellis codes at the receiver, the channel state information (CSI) estimated from the recovered pilot tone can be effectively used, since the metric depends on the accuracy of CSI.

3. 2. 3 Signal Format for Blocking and Shadowing

In the future INMARSAT standard-M system which will provide digital voice and facsimile services for land vehicles and ships, since the signal format is composed of some short subframes and each subframe has a continuous wave (CW) and unique word (UW) preamble, the modem can reacquire very fast for short interruptions by blocking and shadowing[19].

4. Decoding and Demodulation Techniques

Figure 5 shows the relations between the mobile satellite channel characteristics and the detection techniques. The detection techniques are divided into four groups, i.e., decoding, coherent detection, differential detection and diversity. All the techniques are aimed to combat fading with rapid envelope and phase variations, while decoding, demodulation using stored digital signal processing, and diversity can compensate for the power limitation.

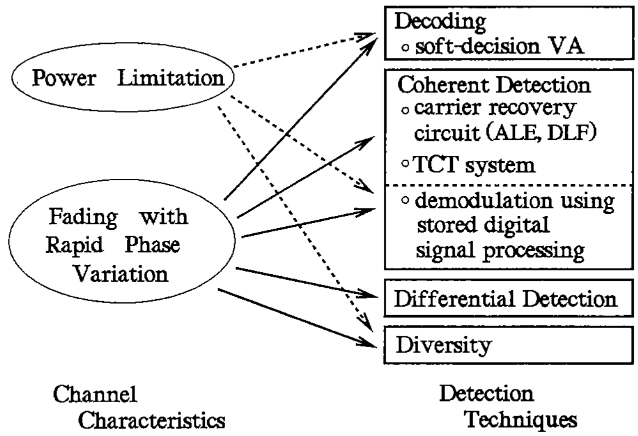


Fig. 5 Channel characteristics and detection techniques.

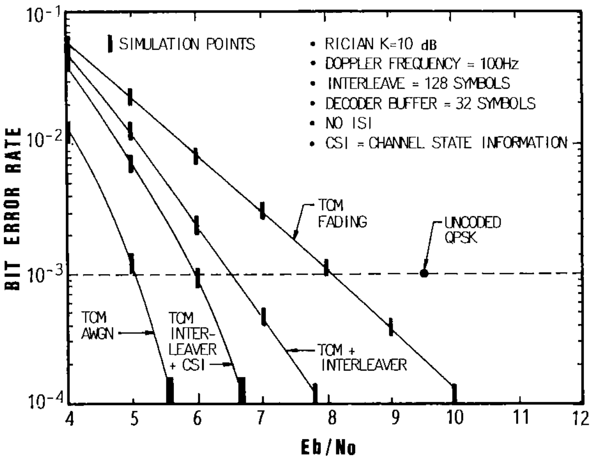


Fig. 6 Bit error rate performance of TCM-8PSK.

4. 1 Soft-Decision Viterbi Decoding

Since the trellis coding with the Viterbi decoding algorithm is simple to implement and is effective because of its essential maximum-likelihood decoding scheme, it appears to be one of the most cost-effective forward error control techniques.

To evaluate the error rate performance of TCM in the mobile satellite channel, it is usually assumed that the reference signal used for coherent demodulation is perfectly phase synchronized to the transmitted signal. Figure 6 shows the error rate performance of TCM-8PSK in Ref. (11). In Ref. (20), it is theoretically proved that the error rate performance of TCM in fading channels depended on not Euclidean distance but effective code length (ECL) assuming that the depth of interleaving is infinite. As for a practical application of TCM, the error rate performance of TCM-8PSK in the Rician fading channel is analyzed by computer simulation in Ref. (21) (see Fig. 7).

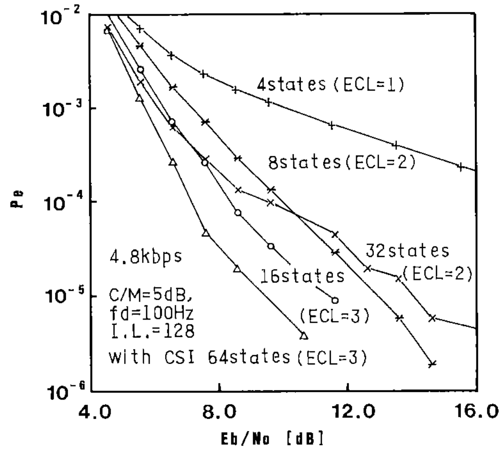
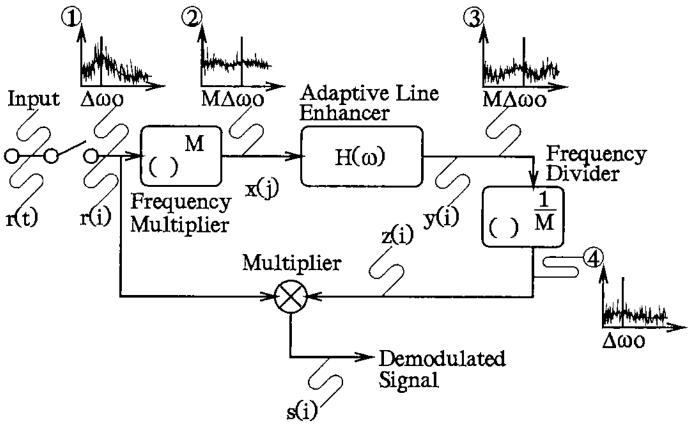
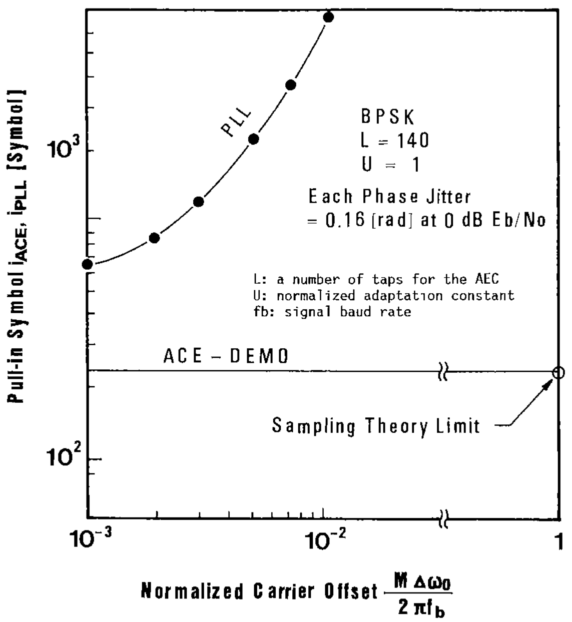


Fig. 7 Bit error rate performance of TCM-8PSK.



(a) Block diagram.



(b) Pull-in range comparison between PLL and ACE-DEMO.

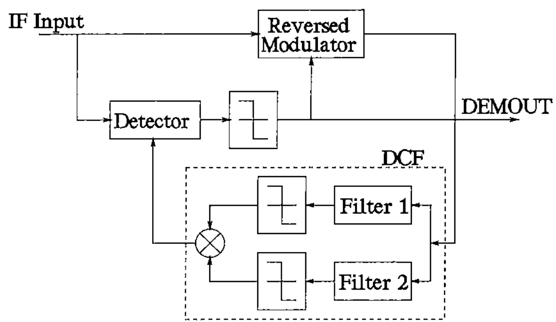
Fig. 8 ACE-DEMO.

4. 2 Coherent Detection Techniques

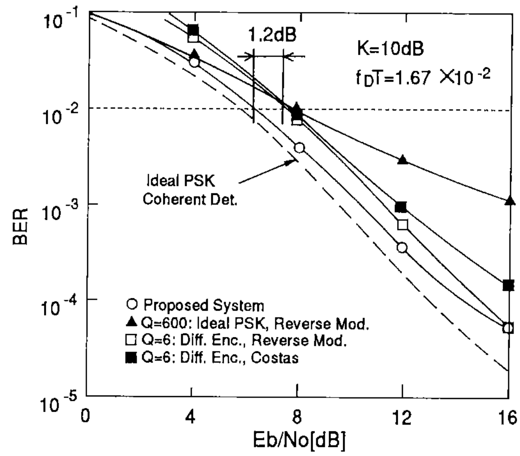
To evaluate the error rate performance of various coded modulation techniques in the mobile satellite channel, it is mostly assumed that the reference signal used for the coherent demodulation is perfectly phase synchronized to the transmitted signal. In a practical system, however, a noisy reference loss leads to the degradation of the coherent system performance. Therefore, various techniques for the coherent and differential detections have been widely investigated.

4. 2. 1 Carrier Recovery Using Adaptive Line Enhancer (ALE)

An adaptive line enhancer (ALE) is an adaptive noise canceler which operates as a self-tuning filter to enhance the line spectrum in the additive white Gaussian noise (AWGN). The demodulator using the ALE as an adaptive carrier estimator (ACE-DEMO)[(22)], which has been developed as an INMARSAT standard-C modem, makes pull-in time significantly shorter and has a wide pull-in range. Figures 8(a) and (b) show the ACE-DEMO block diagram and a



(a) Block diagram.



(b) Bit error rate performance.

Fig. 9 DCF reverse modulation type carrier recovery circuit.

pull-in range comparison between PLL and ACE-DEMO, respectively.

4.2.2 Carrier Recovery Using Dual Carrier Filters (DCF)

A reverse modulation type carrier recovery circuit with dual carrier filters (DCF)[23] can make accurate carrier recovery possible in various Rician fading channels. This carrier recovery circuit has a narrow-band filter to decrease the cycle slip rate and a wide-band filter to improve the tracking performance for carrier frequency shift. The reference carrier is constructed by two vector outputs from the filters. Figures 9(a) and (b) show the block diagram of the carrier recovery circuit and the error rate performance in the Rician fading channel, respectively.

4.2.3 Demodulation Techniques Using Stored Digital Signal Processing (Block Demodulation or Calculative Demodulation)

Demodulation technique using stored digital signal processing, often called block demodulation[24] or calculative demodulation[25], has been developed for a low rate burst mode PSK signal. In the demodulator, the received signal is detected quasi-coherently with a fixed reference carrier and then sampled. After the samples are stored in memory, they are demodulated by a digital signal processing by the time when the next burst signal is received. In this demodulation technique, there are two basic techniques for the carrier estimation:

(1) Using the method of least mean squares in the time domain[24].

(2) Using the discrete Fourier transform (DFT) in the frequency domain[25].

Figure 10(a) illustrates the schematic diagram of the demodulator using FFT for carrier recovery[25]. In this method, the power spectrum of the received signal is searched to find its center frequency by the first estimator, then its precise frequency and phase are estimated by the second estimator. This demodulator can operate at relatively low C/N in the presence of a large frequency offset as shown in Fig. 10(b) without preamble.

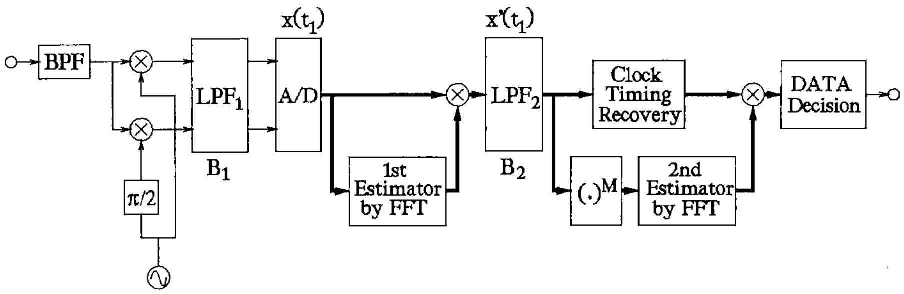
4.2.4 Detection of TCT System

Figure 4(b) illustrates the receiver block diagram of the DPTCT system mentioned in Sect. 3.2.2. In this figure, two pilot bandpass filters (PBPFs) are used for pilot extraction, followed by a calibration subsystem. The purpose of the calibration subsystem is to create a waveform with an amplitude inversely proportional to that of the received pilot without affecting the phase in order to make coherent detection possible.

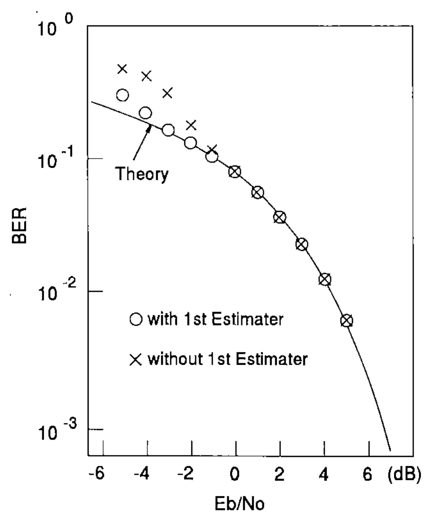
4.3 Differential Detection Techniques

Since the carrier phase for the previous transmitted data symbol is used as a demodulation reference in the differential detection, it can eliminate the need for the carrier recovery. Although the differential detection is a simple and robust technique, it suffers from much more signal to noise power ratio penalty compared with the coherent detection.

To compensate this penalty, a multiple-symbol differential detection of MPSK was proposed in Ref. (26). This technique is based on the idea of making a joint decision over several symbols simultaneously by allowing the longer observation interval than the conventional two symbol intervals. Since the abrupt phase shift by the Doppler effect causes severe degradation to



(a) Block diagram.



(b) Bit error rate performance.

Fig. 10 Calculative demodulation method.

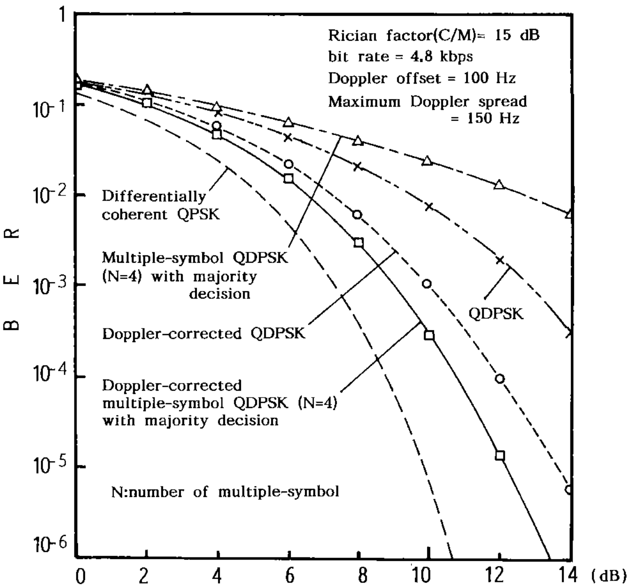
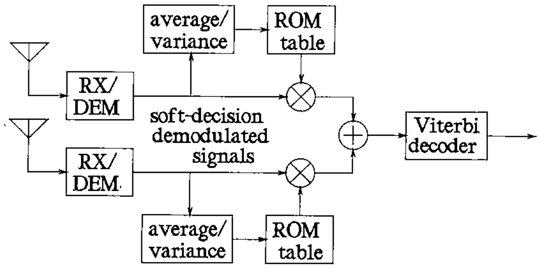
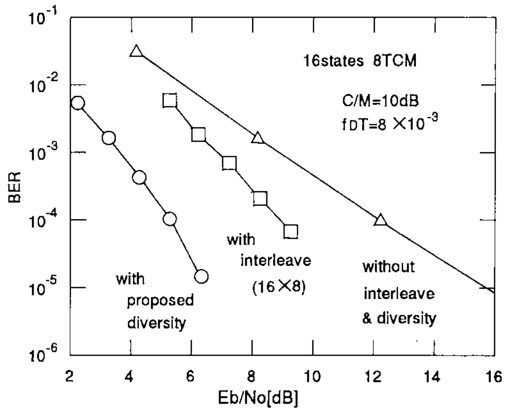


Fig. 11 Bit error rate comparison among various differential detectors.



(a) Block diagram.



(b) Bit error rate performance.

Fig. 12 Weighted diversity combining method.

the differential detector in the mobile satellite channel, however, the Doppler-induced phase shift should be corrected.

A Doppler-corrected multiple-symbol differential detection system, which is composed of the Doppler phase shift estimator(27) and the multiple-symbol differential detector, is analyzed in the Rician fading channel(28). It is shown that the system can maintain a simple and robust implementation by applying the majority decision instead of making the observation interval longer. Figure 11 shows a comparison of error rate performances among various differential detection systems.

4.4 Diversity Techniques

The diversity technique is the most powerful method to combat fading and is widely used in various present-day microwave systems. Of various diversity schemes, the space diversity is a most suitable one for mobile satellite communications systems, since without requiring any additional frequency spectrum it can keep the received signal at a higher level even for deep fade. For mobile applications, the post-detection diversity is more attractive, because it needs no complicated phase combiner in RF stage as in the pre-detection diversity.

The post-detection diversity has been widely investigated for MPSK modulation techniques. The error rate performance of equal gain and selection combinings for QDPSK system are analyzed in Ref. (29), and the maximum ratio and equal gain combinings for TCM-8PSK system are treated in Ref. (30). Furthermore, the three diversity combining methods with a soft-decision Viterbi decoding are analyzed in Ref. (31). Figures 12(a) and (b) show the weighted combining method proposed in Ref. (31) and the error rate performance of TCM-8PSK with the proposed diversity method, respectively.

5. Conclusion

This paper has provided a summary of the trend of digital modulation/demodulation and coding techniques for mobile satellite communications systems. In order to construct high-reliable and high-capacity mobile satellite communications systems, there are two main barriers to get over, i.e., bandwidth limitation and power limitation. In designing modulation technique, it is basically difficult to increase both bandwidth efficiency and power efficiency, since they are contrary to each other. Therefore, by using coding technique with it, it is possible to increase both efficiencies reasonably.

In addition to these two barriers, another barrier associated with mobile motion is rapid fading and shadowing. To combat fading and mitigate shadowing, a great effort has been made to add robustness against fading and shadowing to bandwidth and power efficient modulation techniques.

Although much attention is focused on digital transmission, analog transmission has an advantage from the viewpoint of mobile users. For mobile phone use, the transmitter using digital modulator such as PSK always transmits a carrier with or without conversation, while the transmitter using analog modulator such as SSB basically never transmits a carrier without conversation (since ACSSB[32] uses a pilot tone, it always transmits a signal). This is a great property for power saving to mobile users. It will be important to add the power saving function to digital modulation/demodulation techniques.

Some mobile satellite systems seem to have been developed to complement the terrestrial cellular network. If the mobile satellite system is integrated with the terrestrial one and is used as a part of the public network, it would have many advantages for mobile users. But if the mobile satellite system is incompatible with the terrestrial one, it would be much inconvenient. In fact, the modulation format and the frequency band may be different in both systems. Therefore, under such situations, telecommunication system designer should make an effort to develop the modulation/demodulation technique which can maintain compatibility between mobile satellite and terrestrial systems.

Furthermore, to realize a mobile satellite communication system with worldwide coverage, research and development toward efficient utilization of frequency and geostationary obit and the international harmonization will be required.

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