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Radiocommunication Sector of ITU

Recommendation ITU-R S.1878

(12/2010)

Multi-carrier based transmission techniques for satellite systems

S Series

Fixed-satellite service

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***Note**: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R S.1878

Multi-carrier based transmission techniques for satellite systems

(Questions ITU-R 46-3/4 and ITU-R 73-2/4)

(2010)

Scope

For the efficient use of frequency resources and high-speed data services, multi-carrier based transmission techniques are considered as promising technologies for providing future radiocommunication services. This Recommendation presents an overview of multi-carrier based transmission techniques over satellite links, briefly giving guidance for the utilization of multi-carrier code division multiple access (MC-CDMA) and carrier interferometry orthogonal frequency division multiplexing (CI-OFDM) schemes for satellite radiocommunication systems.

The ITU Radiocommunication Assembly,

considering

a) that satellites in the fixed-satellite service (FSS) and mobile-satellite service (MSS) are simultaneously used by many earth stations at different locations;

b) that multicarrier-based multiple-access schemes such as orthogonal frequency division multiplexing – frequency division multiple-access (OFDM-FDMA or OFDMA), MC-CDMA and multi-frequency TDMA (MF-TDMA) have been adopted or are being considered to be adopted in many terrestrial and satellite system standards for future implementation;

c) that although OFDM-type systems are largely used in terrestrial networks as a means for providing good spectral and energy efficiency over frequency selective channels, OFDM has high peak to average power ratio (PAPR), which is problematic for the high power amplifier (HPA) in the satellite;

d) that there is a need for a high degree of freedom especially for bursty (i.e. non-continuous and variable rate) and high-rate packet transmissions;

e) that, in order to ensure the efficient use of frequency spectrum and orbits, it may be desirable to determine the optimum multiple-access characteristics;

f) that the transmission characteristics of multiple-access systems, especially multi-carrier-based multiple-access systems, may be of importance in their interaction with one another,

noting

a) that Recommendation ITU-R S.1709 specifies MF-TDMA as an inbound traffic access format for global broadband satellite systems;

b) that Recommendation ITU-R BO.1130 specifies coded OFDM (COFDM) as one of transmission techniques used for satellite digital sound broadcasting services to vehicular, portable and fixed receivers in the frequency range 1 400-2 700 MHz;

c) that Report ITU-R S.2173 provides background material on multi-carrier transmissions over satellite links, including basic operational principles, application scenarios and the performance of multi-carrier-based transmissions over satellite links, analysed through computer simulation, *recommends*

1 that Annex 1 should be used as guidance for planning the utilization of a CI-OFDM scheme for multi-carrier satellite radiocommunication systems;

2 that Annex 2 should be used as guidance for planning the utilization of a MC-CDMA scheme for satellite radiocommunication systems;

3 that the subject techniques may even be used in combination provided that no basic incompatibility exists among them.

Annex 1

CI-OFDM transmission in satellite radiocommunication systems

1 Introduction

This Annex presents a satellite radiocommunication system that makes use of CI-OFDM transmissions and its performance when compared with satellite radiocommunication systems using single-carrier and OFDM transmissions.

2 System model

OFDM is a multi-carrier technology that is used to overcome the frequency selective nature of terrestrial radiocommunications environments. Apart from this advantage, there are several other advantages of OFDM that could be exploited by a satellite radiocommunication system. These advantages are listed in § 5.2 of Report ITU-R S.2173. However, as mentioned in Report ITU-R S.2173, OFDM has high peak to average power ratio (PAPR), which is problematic for the high power amplifier (HPA) in the satellite.

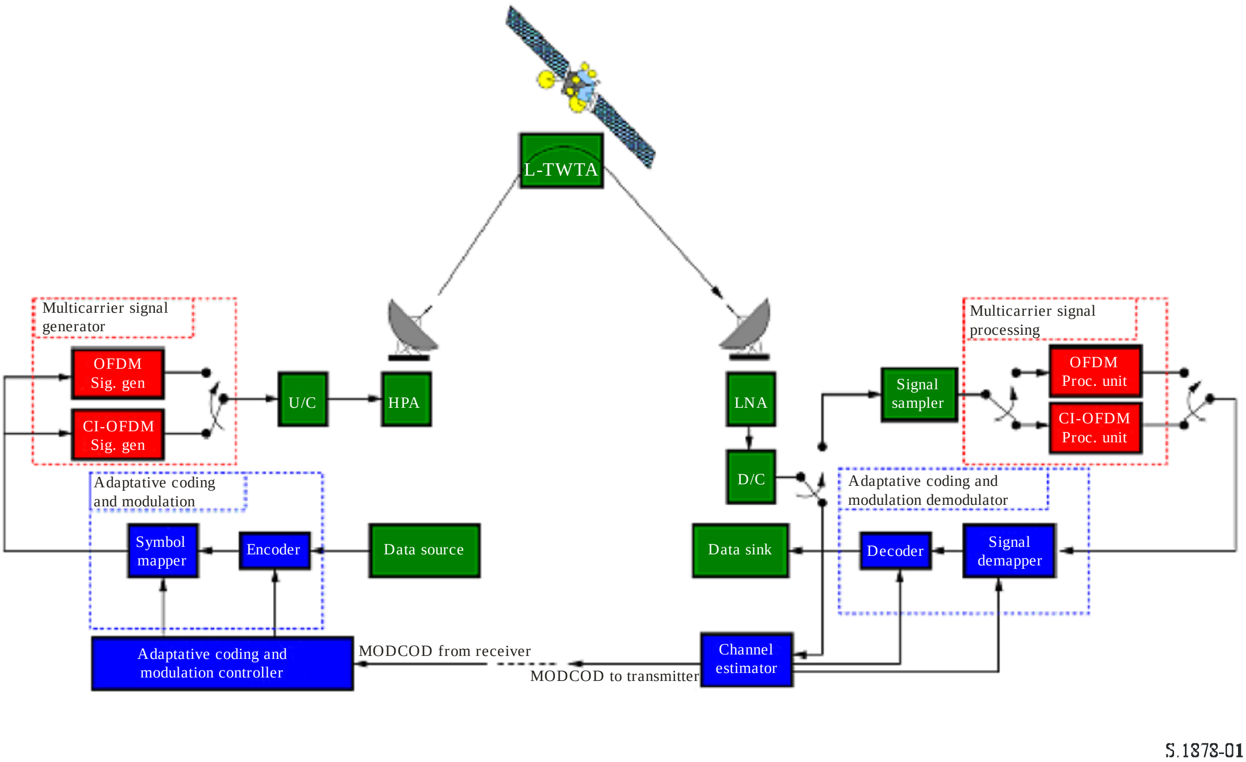
CI-OFDM is a type of sub-carrier scrambling technology that can be implemented for an OFDM system at the cost of an additional fast Fourier transform (FFT) module at the transmitter and receiver end of a radiocommunication system, in order to reduce the PAPR of OFDM signals. The detailed operational principles of CI-OFDM are well described in § 6.3 of Report ITU-R S.2173.

Figure 1 shows a satellite system employing CI-OFDM transmissions. The data source passes on vector message-words to an encoder, whose rate is set by the adaptive coding and modulation (ACM) controller. The encoded data is then passed on to a symbol mapper, whose output is passed to a multi-carrier signal generator (MSG). The MSG is composed of two blocks for simulation purposes: an OFDM signal generator and a CI-OFDM signal generator. Only one MSG block is used during simulation. Each MSG generates a multi-carrier symbol from a collection of N symbols; where N is the number of subcarriers used for transmission. The output of the MSG is passed on to a HPA. The HPA output is then passed on to an analogue signal up-converter (U/C) that creates an analogue signal from the digital baseband symbols at a desired carrier frequency and sends it through the channel to the satellite. Given a bent-pipe satellite, the received signal is amplified and re-transmitted. A travelling-wave-tube amplifier (TWTA) is often used for satellite transponders and symbol predistortion can be used by the multi-carrier satellite system (MCSS) to linearize the output of the TWTA. Note that many modern satellites are now being manufactured with linearized TWTAs (L-TWTA)s, and that the combination of a symbol precoder with a TWTA is essentially a L-TWTA.

The receiver receives the transmitted analogue signal corrupted by noise and other impairments, and passes it on to either a signal sampler or channel estimator. The received signal is passed on to the channel estimator if pilot signals are transmitted. The channel estimator estimates the instantaneous carrier-to-noise ratio (CNR) through the channel and selects an appropriate modulation and coding combination (MODCOD). The MODCOD selection is then relayed back to ACM controller at the transmitter and used to set the appropriate modulation and coding to be used in demodulating and decoding the received samples. When data is received by the receiver, the signals are passed on to the signal sampler, which creates a set of samples, sampled at the Nyquist rate, for the multi-carrier processing unit (MPU). The MPU is composed of two modules for simulation: an OFDM processing unit and a CI-OFDM processing unit. The receiver uses the MPU module corresponding to the MSG module used by the transmitter. Each MPU produces a set of *N* symbol samples from a multi-carrier symbol sample. The MPU output is then passed on to a symbol demapper. The symbol demapper uses the average received constellations of each modulation and their respective error vector magnitudes to create hard- or soft-estimates for each transmitted bit, which are passed on to the decoder. The decoder outputs a decision on the transmitted data and passes it on to the data sink.

FIGURE 1

Simulation block diagram of MCSS employing CI-OFDM transmissions



3 Performance results of CI-OFDM in a non-linear satellite channel

Simulation results presented in this section are obtained using the system model described in § 2 of this Annex. The DVB-S2 ACM scheme[1] is used by the system model with 100 belief propagation algorithm decoding iterations[2]. The baseband symbols are oversampled by a factor of 4 in order to obtain a proper representation of the modulated signal and 64 subcarriers are used to generate the multi-carrier symbols. The L-TWTA is that described in § 10.3.1 of Report ITU-R S.2173. Channel and noise estimation and feedback from the receiver to transmitter are assumed to be error-free.

The fairest way to evaluate the performance of a PAPR mitigation technique is by measuring the total degradation (TD) in packet error rate (PER) performance between a system with an ideal linear amplifier[3] – henceforth referred to as a linear amplifier – and the system under study[4], taking into account the degradation due to input back-off (IBO). Mathematically this is:

$$TD\text{ (dB)} = CNR_{nonlinear}\text{ (dB)} - CNR_{linear}\text{ (dB)} + IBO \qquad \text{dB} \qquad (1)$$

where CNR_{linear} and $CNR_{nonlinear}$ are the CNRs required to obtain a particular PER for the linear and nonlinear HPA respectively.

Table 1 demonstrates the TD caused by passing a different DVB-S2 modulation through a L-TWTA, obtained at a PER of 10^{-3}. Note that to properly compare the CNR of the linear HPA with the CNR of the system with L-TWTA, the equivalent CNR is:

$$CNR_{eq}\text{ (dB)} = CNR\text{ (dB)} + IBO_{opt} \qquad \text{dB} \qquad (2)$$

This conversion must be done to fairly compare the performance of both systems, operating at their maximal output power. The linear HPA always operates at 0 dB IBO (HPA saturation), whereas the L-TWTA is not necessarily operated at saturation. Simulation results for the SCSS with L-TWTA specify that the optimal IBO[5] (IBO_{opt}) at which to operate the L-TWTA is 0 dB[6]. For constant-envelope modulation such as *M*-ary PSK there is no degradation; however the degradation for 16-APSK is negligible, while there is a noticeable degradation for 32-APSK. Table 1 demonstrates that a single-carrier satellite system (SCSS) can operate using the DVB-S2 with very little loss when compared to the theoretical system with linear amplifier.

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[1] For more information on DVB-S2 consult § 9.2 of Report ITU-R S.2173.

[2] For more information on the belief propagation algorithm, please consult § 7.4.4 of Report ITU-R S.2173.

[3] Note that an ideal linear amplifier has a linear transfer function and no saturation point. This means that the ideal linear amplifier does not introduce noise due to clipping.

[4] The system under study could be a SCSS with nonlinear amplifier or a MCSS with or without PAPR reduction techniques.

[5] For more information on how to determine IBO_{opt}, see § 10.3.2 of Report ITU-R S.2173.

[6] This corroborates the results presented in § 10.3.2 of Report ITU-R S.2173.

TABLE 1

Degradation due to L-TWTA for a satellite system using various combinations of DVB-S2 MODCOD

MODCOD	Spectral Efficiency (bit/s/Hz)	Linear Amp.	L-TWTA	
		CNR_{eq} (dB) @ PER = 10^{-3}	CNR_{eq} (dB) @ PER = 10^{-3}	$TD_{L\text{-}TWTA}$ (dB)
QPSK 1/4	0.49	–2.96	–2.96	0
QPSK 2/5	0.79	–0.64	–0.64	0
QPSK 1/2	0.99	1.13	1.13	0
QPSK 5/6	1.65	5.05	5.05	0
8-PSK 3/5	1.78	5.61	5.61	0
8-PSK 3/4	2.23	7.84	7.84	0
8-PSK 5/6	2.48	9.31	9.31	0
8-PSK 9/10	2.68	10.84	10.84	0
16-APSK 3/4	2.96	10.14	10.21	0.07
16-APSK 4/5	3.16	10.92	11.00	0.08
16-APSK 5/6	3.30	11.53	11.63	0.10
16-APSK 8/9	3.52	12.76	12.88	0.12
16-APSK 9/10	3.56	12.99	13.13	0.14
32-APSK 3/4	3.70	12.80	13.48	0.68
32-APSK 4/5	3.95	13.61	14.45	0.84
32-APSK 5/6	4.12	14.26	15.20	0.94
32-APSK 8/9	4.39	15.50	16.70	1.20
32-APSK 9/10	4.45	15.75	16.98	1.23

Table 2 demonstrates the TD performance loss for a MCSS using CI-OFDM transmissions when compared with a MCSS using OFDM transmissions. The change in TD for the MCSS systems is far more dramatic than when compared to the SCSS systems. This is because of the high PAPR of multi-carrier signals. It can also be observed that the MCSS with CI-OFDM transmissions has between 0.5 and 4.5 dB gain in terms of TD over the MCSS with OFDM transmissions depending on the MODCOD employed.

Figure 2 demonstrates this behaviour by plotting TD with respect to the spectral efficiency (in bits per second per hertz (bit/s/Hz)) of the DVB-S2 ACM scheme. Note that the results are presented in terms of CNR_{eq} – as calculated in (2) – for each MCSS system. Also note that the curves are plotted using the maximum spectral efficiency generated by all MODCODs at each CNR_{eq} for a particular system. That is, if MODCOD *x* has higher spectral efficiency than MODCOD *y*, and MODCOD *x* has lower CNR_{eq} than MODCOD *y*, then MODCOD *y* is omitted from Fig. 2. MODCODs not included in Fig. 2 are underlined in Tables 1 and 2. It can be observed that the curve representing the MCSS using OFDM transmission has a much steeper ascent than the MCSS using CI-OFDM transmissions. In fact, up to a spectral efficiency of 3.6 bit/s/Hz, the MCSS with CI-OFDM transmissions has a TD less than 3 dB. This means that the MCSS with CI-OFDM transmissions could be employed for spectral efficiencies of up to 3.6 bit/s/Hz, at no more than double the required transmission power.

TABLE 2

Comparison of TD performance for MCSS with OFDM and CI-OFDM transmissions using various combinations of DVB-S2 MODCOD

MODCOD	Spectral Efficiency (bit/s/Hz)	OFDM			CI-OFDM		
		CNReq (dB) @PER = 10^{-3}	IBOopt (dB)	TD (dB)	CNReq (dB) @PER = 10^{-3}	IBOopt (dB)	TD (dB)
QPSK 1/4	0.49	–2.29	0	0.67	–2.78	0	0.18
QPSK 2/5	0.79	0.16	0	0.80	–0.44	0	0.20
QPSK 1/2	0.99	1.73	0	0.60	1.23	0	0.10
QPSK 5/6	1.65	6.78	0	1.73	5.43	0	0.38
8-PSK 3/5	1.78	8.12	0	2.51	6.01	0	0.40
8-PSK 3/4	2.23	11.17	0	3.33	8.29	0	0.45
8-PSK 5/6	2.48	13.93	1	4.62	9.95	0	0.64
8-PSK 9/10	2.68	16.69	3	5.85	11.72	0	0.88
16-APSK 3/4	2.96	15.41	2	5.27	11.53	0	1.39
16-APSK 4/5	3.16	16.79	3	5.87	12.59	0	1.67
16-APSK 5/6	3.30	18.08	3	6.55	13.56	0	2.03
16-APSK 8/9	3.51	20.04	5	7.28	15.42	1	2.66
16-APSK 9/10	3.56	20.76	5	7.77	15.81	1	2.82
32-APSK 3/4	3.70	20.40	5	7.60	16.26	2	3.46
32-APSK 4/5	3.95	22.05	6	8.13	17.47	2	3.55
32-APSK 5/6	4.12	23.16	6	8.9	18.55	2	4.29
32-APSK 8/9	4.39	25.43	8	9.93	21.81	2	6.31
32-APSK 9/10	4.45	25.81	8	10.06	22.75	2	7.00

Figure 3 gives the energy efficiency of the SCSS with linear HPA, SCSS with L-TWTA, MCSS with OFDM transmissions and MCSS with CI-OFDM transmissions, by plotting the spectral efficiency of these systems – at a PER of 10^{-3} – versus CNR_{eq} using Tables 1 and 2. Each step in a curve represents the use of a new MODCOD with higher spectral efficiency. Note that as was explained with Fig. 2, only the MODCODs giving a maximum spectral efficiency are used to plot Fig. 3. The results in Fig. 3 reflect those of Fig. 2, with the SCSSs having better energy efficiency than the MCSSs, especially for MODCODs having higher spectral efficiency. In particular, MCSSs using MODCODs with 32-APSK modulation have very poor energy efficiency when compared with the SCSS with L-TWTA. However, it is clear that the CI-OFDM greatly improves the energy efficiency of the MCSS when compared with the MCSS using OFDM transmissions. The spectral efficiency that can be obtained for a MCSS using OFDM transmissions, while limiting the increase in the transmission power to 3 dB or less, is 2.05 bit/s/Hz. This is roughly 1.55 bit/s/Hz lower than it is for the MCSS using CI-OFDM transmissions.

FIGURE 2

Total degradation of SCSS and MCSS versus spectral efficiency

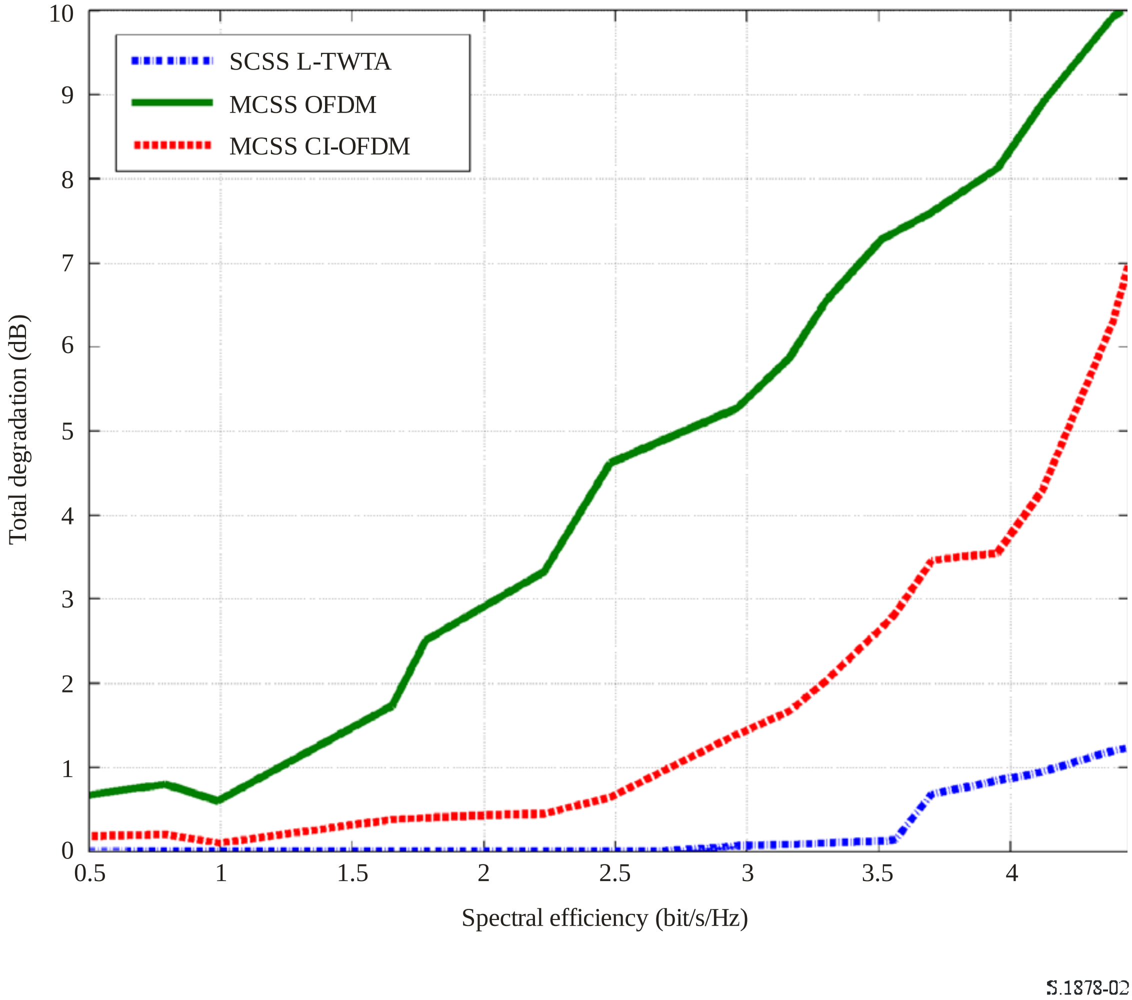
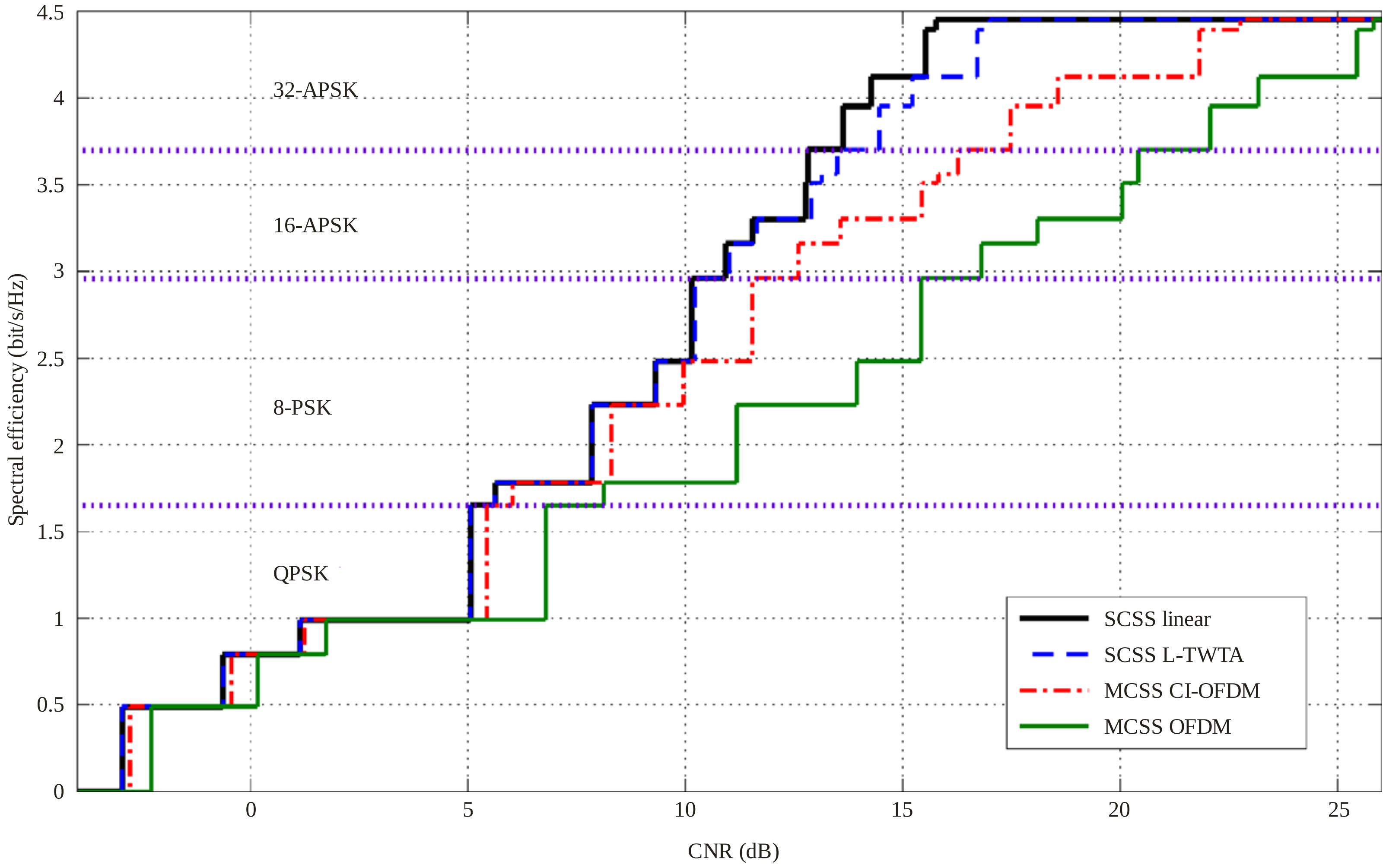


FIGURE 3

Energy efficiency of SCSS and MCSS for various combinations of DVB-S2 MODCOD



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4 Summary

This Annex demonstrates that it is possible to use CI-OFDM transmissions for satellite radiocommunication systems and obtain spectral efficiencies up to 3.6 bit/s/Hz, while limiting the increase in required transmission power to 3 dB or less. Unmodified OFDM transmissions have high PAPRs and, as a result, can only be used for MCSSs to obtain spectral efficiencies of up to about 2.05 bit/s/Hz, while limiting the increase in the required transmission power to 3 dB or less[7]. This demonstrates that CI-OFDM allows a MCSS to operate at a spectral efficiency that is roughly 1.55 bit/s/Hz greater than a MCSS with OFDM transmissions.

Annex 2

MC-CDMA in satellite radiocommunication systems

1 Introduction

Annex 2 presents a satellite radiocommunication system with MC-CDMA transmissions and its corresponding performance, evaluated using computer simulations.

2 System model

Figure 4 is a synchronous multibeam geostationary satellite system providing IP-based satellite packet services using an adaptive MC-CDMA scheme. Services for mobile and fixed users are linked to a terrestrial IP core network through a fixed earth station (FES) and satellite. The FES performs adaptive resource allocation on the downlink and is a gateway to link the user services to the terrestrial network. When the satellite has an on-board processing capability, it can perform the adaptive resource allocation.

In the synchronous multibeam system, all the downlink signals from a satellite are synchronized in the time and frequency domains. The downlink radio frame consists of multiple frequency/time slots divided in an FDM/TDM fashion. In each time/frequency slot, the radio resource is subdivided by orthogonal spreading codes in a CDM fashion. A radio resource unit (RRU) is defined by a specific spreading code in a specific frequency/time slot. All beams share the orthogonal RRUs for packet transmission. Due to the synchronized transmission, every RRU is orthogonal to one another. A unique pilot symbol sequence for each beam is transmitted in a predefined portion of the frame. The pilot sequence is spread by a beam-specific pilot code.

In a slot, the traffic signal is spread by the orthogonal spreading codes, but it is not scrambled by a beam-specific pilot code. Therefore, due to the synchronized transmission on all of the beams, the transmission signals from different beams are orthogonal to each other if the beams use different spreading codes in the same slot. Due to the orthogonality between RRUs, the interbeam interference is minimized, which improves the system capacity.

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[7] It should be noted that these results are specific to multi-carrier systems with 64-subcarriers.

In mobile environments, the orthogonality between different spreading codes in the same frequency/time slot may not be maintained due to multipath (frequency-selective) fading. Under heavy load conditions, the number of RRUs available in a beam can be restricted because all beams share RRUs. In order to avoid this resource limitation, the RRUs can be reused if the distance between users is sufficiently large so that the interbeam interference does not become significant as would be problematic. The code limitation problem can be solved by using a MODCOD with a high spectral efficiency, such as 16-QAM. The use of high-order modulation schemes can reduce the number of RRUs required for packet transmission.

For the adaptive packet transmission, every user measures the channel state using beam pilots and periodically reports the measured result to the FES through the reverse link. The user report includes the received power and carrier-to-interference ratio on the primary beam and adjacent beam pilots. The primary beam of a user is the beam currently providing packet services to that user. Based on the reported link conditions, the resource management center in the FES performs packet scheduling, selects the best resources for each packet transmission and assigns the transmit power and MODCODs.

Forward link IP-based information signals are asymmetric in bandwidth requirement with respect to the reverse link. Combining bursty and high-rate packet transmissions using MC-CDMA makes transmitters more efficient in terms of spectral efficiency.

MC-CDMA combines the techniques of CDMA and OFDM in a way that offers the advantages of both. The MC-CDMA satellite system offers a high degree of freedom through its multi-carrier transmission scheme, and thus can provide more efficient adaptive transmissions.

FIGURE 4

An example of a multibeam satellite system

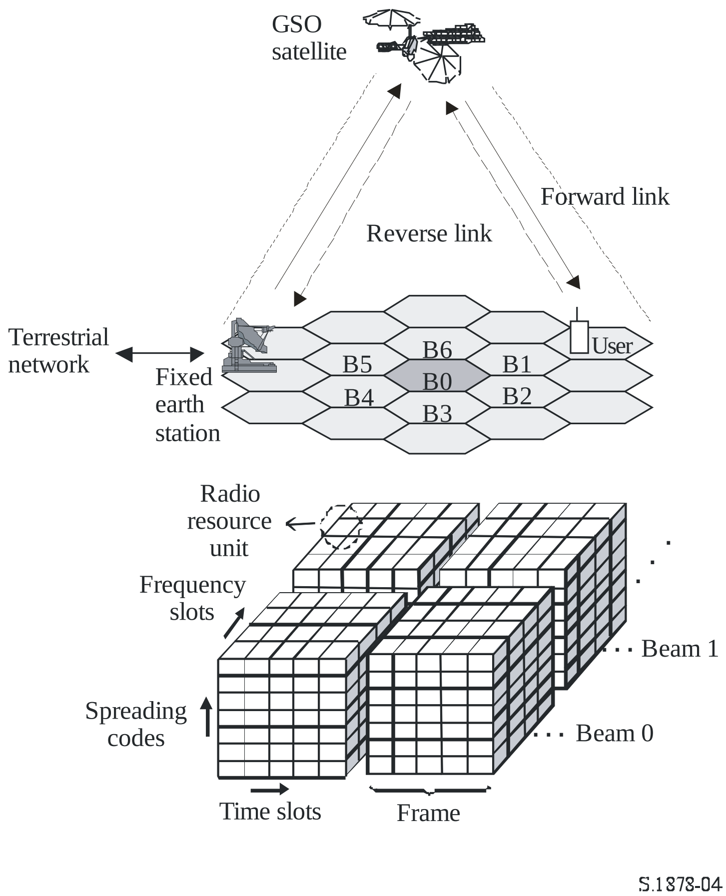

FIGURE 5

Block diagram of the adaptive MC-CDMA satellite system

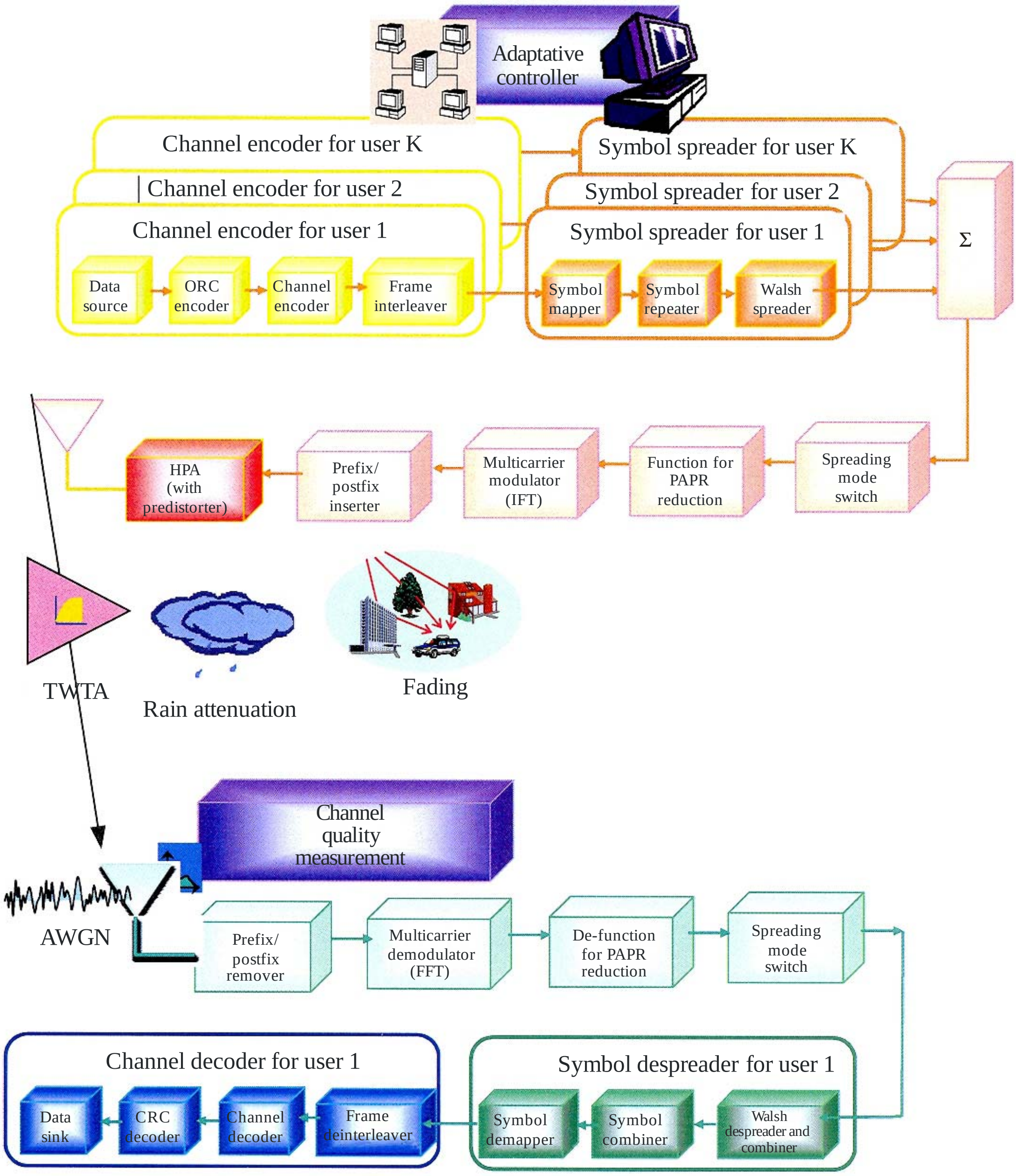

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Figure 5 shows the block diagram for the transmitter and receiver of an adaptive MC-CDMA satellite system. Adaptive MC-CDMA systems can be used as a countermeasure for atmospheric fading. The adaptive transmitter – as shown in Fig. 5 – changes the coding, modulation, and spreading schemes by a control command determined according to the satellite channel conditions. The channel encoder in the adaptive transmitter changes its encoding parameters using the aforementioned control command. The symbol spreader for each user consists of a symbol mapper, a symbol repeater, a Walsh spreader, and also changes its parameters using the control command. The chip interleaver in the transmitter is for dual mode MC-CDMA schemes, which are especially useful for changing the utilized spreading scheme according to the channel and traffic conditions. Adaptive MC-CDMA systems can also utilize techniques for reducing the PAPR. Additionally, a predistorter is used to linearize the HPA. A number of PAPR reduction techniques and predistortion schemes are discussed in § 6.2 of Report ITU-R S.2173.

According to the adaptive operation of the transmitter, the receiver in Fig. 5 also changes its decoding, demodulating, and de-spreading schemes using the control command in synchronization with the command utilized by the transmitter. Multi-carrier demodulation is accomplished by a simple FFT, and all other operations performed by the receiver are applied in reverse-order with respect to those operations performed by the transmitter.

Choice of modulation and coding schemes is subject to system implementation. A detailed discussion on channel coding schemes and link adaptation achieved by using ACM are discussed in §§ 7 and 8 of Report ITU-R S.2173, respectively. Simulation results concerning these topics are also given in § 10 of Report ITU-R S.2173.

3 Performance of MC-CDMA satellite system

The system parameters in Table 4 are used to investigate the signal distortions appearing in the symbol constellations due to the nonlinear transfer function of the TWTA in the MC-CDMA satellite system. For simulation purposes, the transfer function of the TWTA is that described in § 10.3.1 of Report ITU-R S.2173. Figure 6 shows signal distortions for various numbers of users and OBO values. It is assumed that the MC-CDMA system uses 128 subcarriers and a Walsh-Hadamard (WH) code of length 16. There are up to 16 active users in the system, and the 128 subcarriers are evenly allocated to each active user. In Fig. 6, the small red circles in the constellation represent the signal without distortion; the outer blue dots represent the signal when number of current users, $K = 16$; the green dots represent the signal when $K = 8$, and the inner black dots represent the signal when $K = 1$. The nonlinear distortion produced by the TWTA increases as the number of users increases. It is also evident that the signal distortion increases as the OBO value of TWTA decreases. This signal distortion degrades the BER performance of the system.

TABLE 4

Parameters for MC-CDMA satellite system

Signal constellation	QPSK, 16-QAM
Spreading sequence	Walsh-Hadamard
Processing gain	16
Number of symbol per frame (M)	4, 8, 16
Number of active user (K)	1-16
Number of subcarrier (N)	64, 128, 256
Scrambling code	Random code

FIGURE 6

Signal constellation distorted by the TWTA

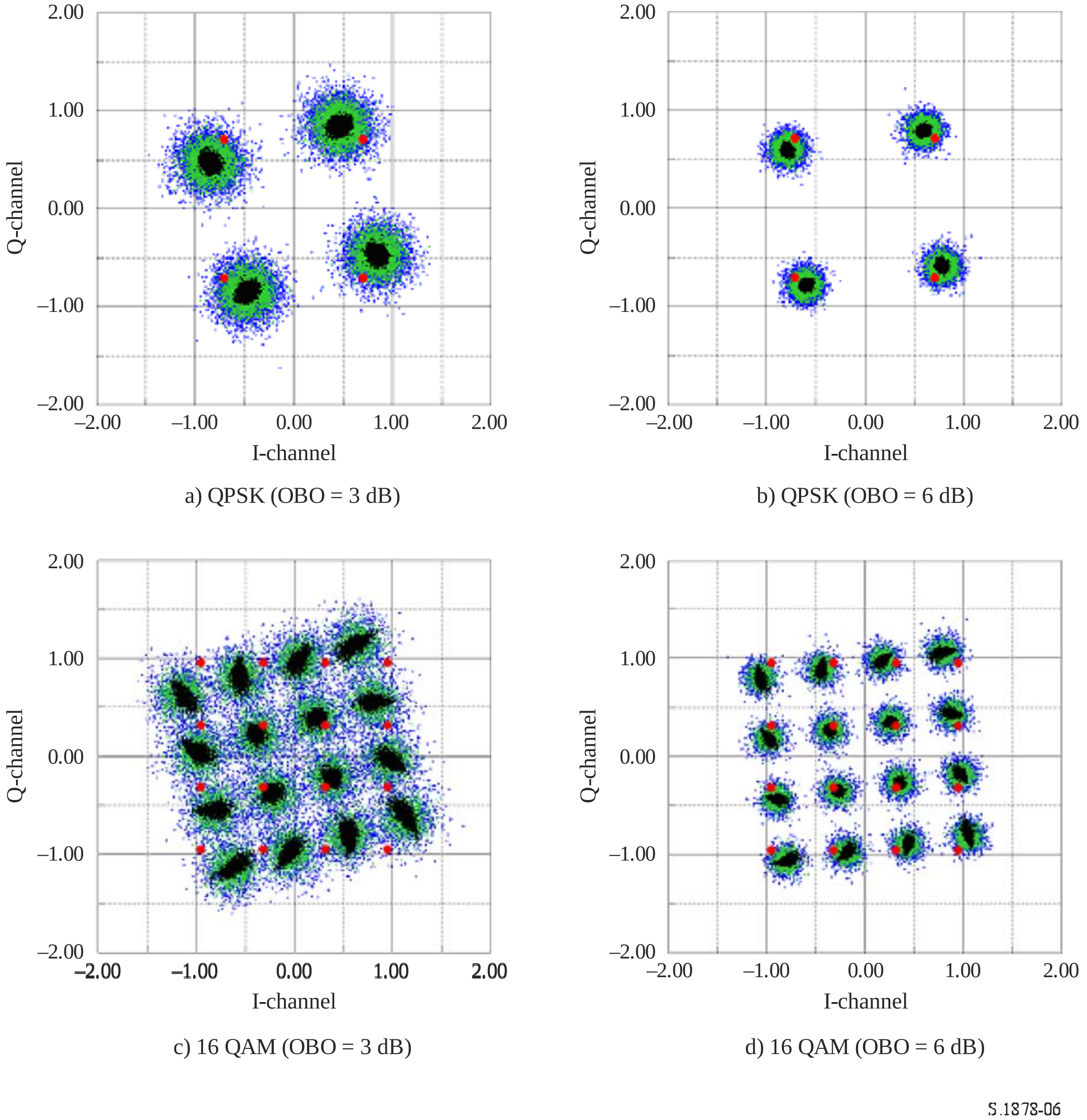
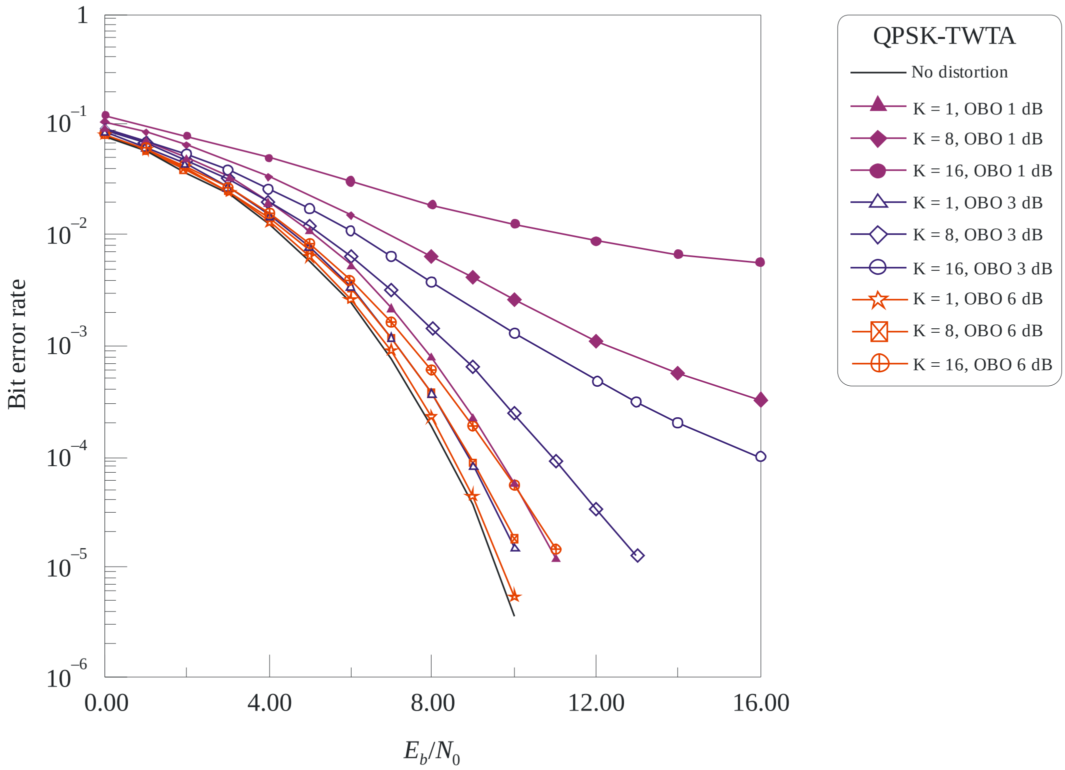


Figure 7 examines the uncoded BER performance of a MC-CDMA satellite system with various numbers of users and OBO values. The simulation results in Fig. 7 show that the nonlinear distortion has a larger impact on the 16-QAM constellation than the QPSK constellation. It is also noticeable that the effect of nonlinear distortion on the BER performance of the MC-CDMA satellite system increases as the number of users increase and the OBO values of TWTA decrease – as is suggested by Fig. 6.

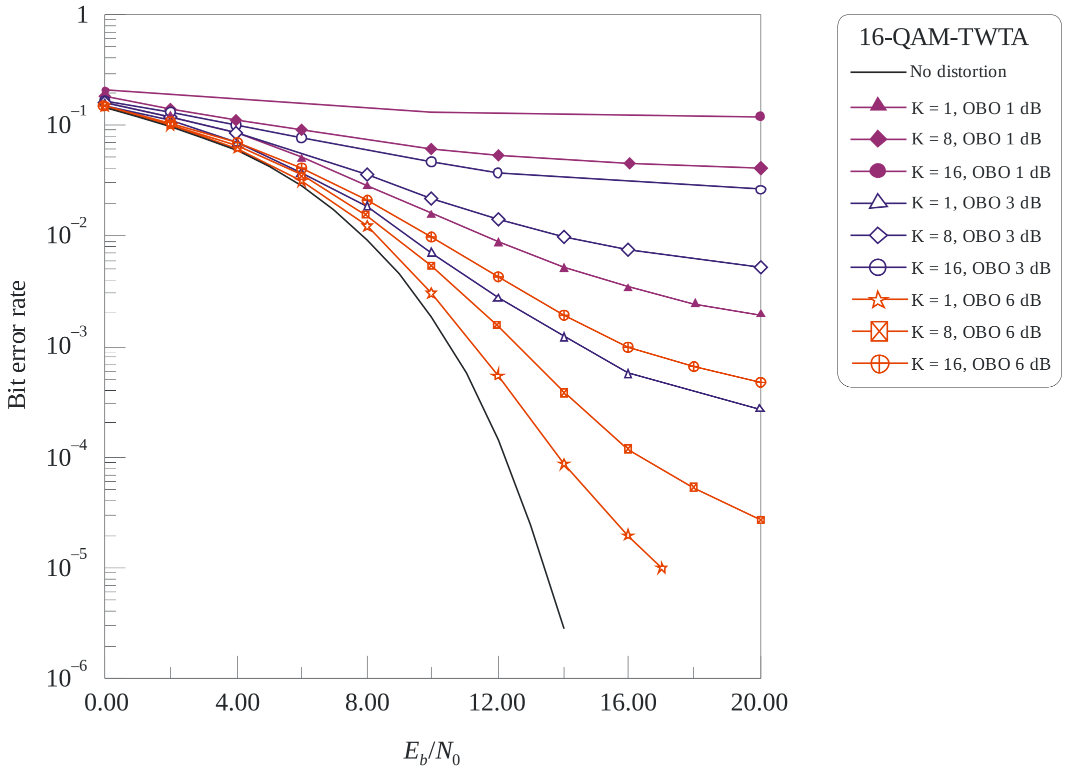
FIGURE 7

BER performance of the MC-CDMA satellite system

a) QPSK



b) 16-QAM



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Using a symbol predistorter can mitigate the performance degradations caused by the nonlinear distortion of the TWTA. Figure 8 shows the uncoded BER performance of the MC-CDMA satellite system when combined with a L-TWTA, which is the combination of a TWTA and an ideal predistorter – henceforth referred to as an ideal L-TWTA. The results presented demonstrate considerable improvement in the BER performance of the MC-CDMA satellite system with ideal predistortion; especially for the case where larger OBO values are observed. The improvement in BER performance is greater with the 16-QAM constellation because 16-QAM experiences greater nonlinear distortion than QPSK. The improvement in performance is the result of phase distortion compensation and the linearizing effect of the predistorter in the regions below HPA saturation. Although simulations results are presented using an ideal predistorter, the high-peak problems of MC-CDMA cannot be fully resolved. This is because the ideal predistorter linearizes signals only in the regions before saturation, and the saturation region is determined by the OBO value. Therefore, it is very important to reduce the PAPR by using an efficient PAPR reduction method. Doing so can reduce the OBO value and results in efficient power usage, as is demonstrated in Annex 1 for CI-OFDM transmissions.

An adaptive MC-CDMA satellite system is investigated when implemented in a mobile satellite channel model for suburban 30/20 GHz band[8]. Various MODCODs with block turbo codes (BTC)[9] are used for adaptive transmission. Detailed performance of BTC MODCODs can be found in § 10.1 of Report ITU-R S.2173. E_s/N_0 is fixed at 20.5 dB which corresponds to the required E_s/N_0 value of 18.5 dB for BTC MODCOD of 64-QAM $(63,56)^2$ (the superscript "*x*" indicates an *x* dimensional BTC) to produce a BER of 10^{-6}, plus an additional 2 dB power margin. Table 5 compares the performance of an adaptive MC-CDMA satellite system with that of a conventional non-adaptive MC-CDMA satellite system. In both simulation systems, an ideal L-TWTA with IBO of 3 dB is used.

It is clear that the performance of the adaptive MC-CDMA satellite system is superior to that of the non-adaptive MC-CDMA system. For example, the adaptive scheme can achieve a spectral efficiency[10] of 1.97 bit/s/Hz, which corresponds to roughly the same spectral efficiency as the 8-PSK $(31,25)^2$ MODCOD, but with far better BER performance for the same E_s/N_0.

TABLE 5

Performance of the adaptive MC-CDMA in a mobile satellite channel

	Adaptive	**8-PSK $(31,25)^2$**	**8-PSK $(15,10)^3$**	**BPSK $(15,10)^3$**
BER	8.91×10^{-6}	1.15×10^{-1}	8.78×10^{-2}	2.09×10^{-2}
PER	3.10×10^{-4}	4.59×10^{-1}	2.81×10^{-1}	8.31×10^{-2}
Spectral efficiency (bit/s/Hz)	1.97	1.95	0.89	0.30

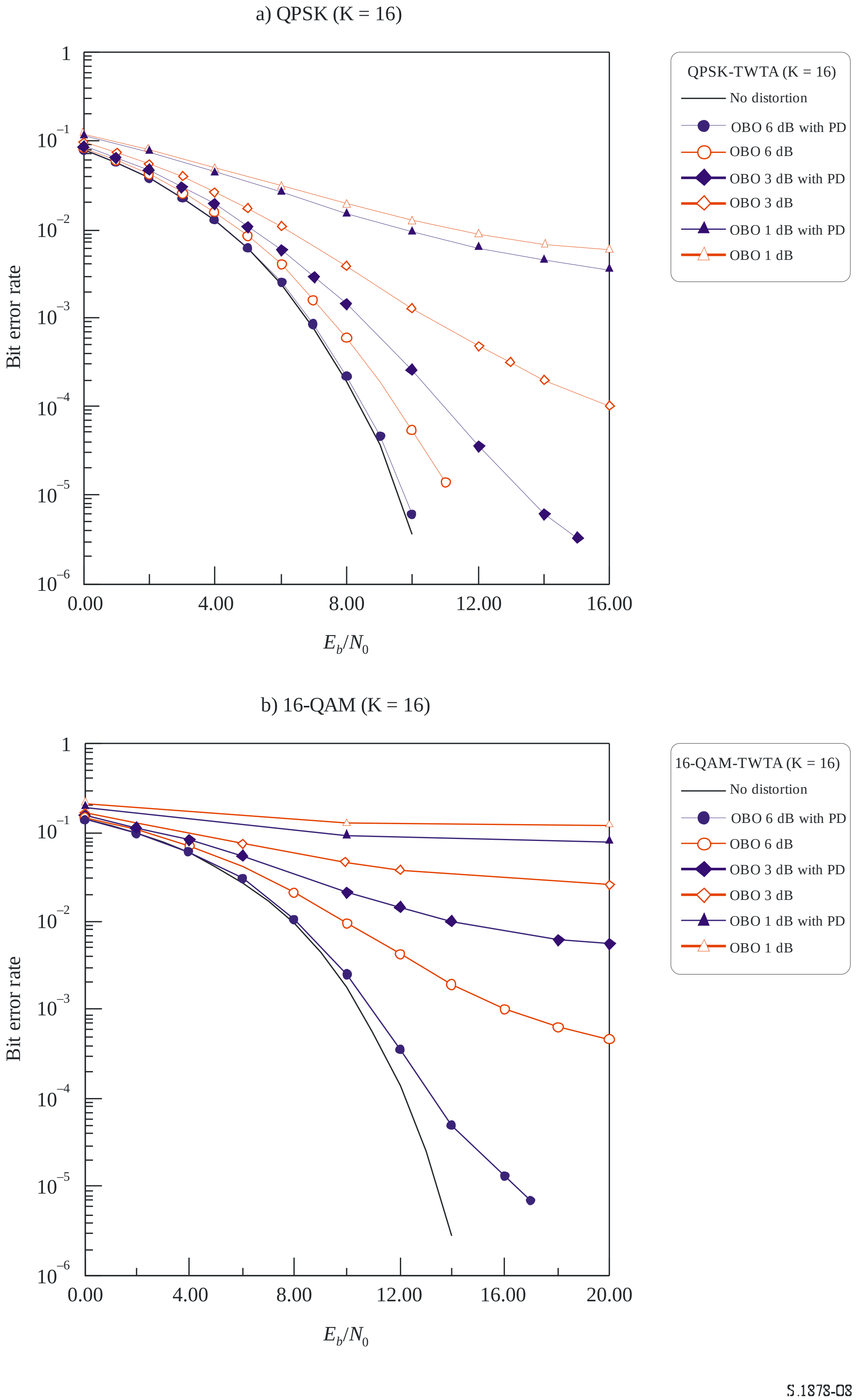
[8] For more information on the mobile satellite channel for suburban 30/20 GHz band, consult reference [Fontán *et al.*, 2001] in § 10.4.3 of Report ITU-R S.2173.

[9] For more information on BTCs, consult § 7.3.3 of Report ITU-R S.2173.

[10] Where the definition of spectral efficiency, in this context, is the average spectral efficiency found by averaging the results from Table 5 over all instantaneous channel realizations generated using the channel model in reference [Fontán *et al.*, 2001] in § 10.4.3 of Report ITU-R S.2173.

FIGURE 8

BER performance of the MC-CDMA with the L-TWTA with an ideal predistorter



4 Summary

Annex 2 demonstrates that adaptive MC-CDMA can offer improved spectral efficiency and BER performance in MSS system. The adaptive MC-CDMA scheme can be utilized to provide IP packet services through a synchronized multibeam satellite system.

List of abbreviations

ACM	Adaptive coding and modulation
APSK	Amplitude and phase shift keying
CI-OFDM	Carrier interferometry orthogonal frequency-division multiplexing
CNR	Carrier-to-noise ratio
COFDM	Coded orthogonal frequency-division multiplexing
FES	Fixed earth station
FFT	Fast Fourier transform
FSS	Fixed-satellite service
HPA	High-power amplifiers
IBO	Input back-off
IFFT	Inverse fast Fourier transform
L-TWTA	Linearized TWTAs
MC-CDMA	Multi-carrier code-division multiple access
MCSS	Multi-carrier satellite system
MF-TDMA	Multifrequency TDMA
MODCOD	Modulation and coding combination
MPU	Multi-carrier processing unit
MSG	Multi-carrier signal generator
MSS	Mobile satellite service
OBO	Output back-off
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiplexing – frequency-division multiple access
PAPR	Peak to average power ratio
PER	Packet error rate
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RF	Radio-frequency
SCSS	Single-carrier satellite system
TD	Total degradation

TWTA	Travelling wave tube amplifier
U/C	Up-converter
UW	Unique word
VSA	Vector signal analyser
VSG	Vector signal generator