Overview of PHY-Layer Design Challenges and Viable Solutions in W-Band Broadband Satellite Communications

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Abstract. The exploitation of Extremely High Frequency (EHF) bands for broadband satellite communications really represents a challenging frontier for aerospace R&D. In few time, ALPHASAT mission (through the Technology Demonstration Payload 5) should test Q/V band (40-50GHz) digital satellite transmission. Moreover, a lot of effort is spent to study the feasibility of broadband links in W-band (70-110GHz). This paper is devoted at showing the most relevant challenges to be faced in the effective PHY-layer design of W-band satellite connections. Some practical solutions will be analyzed together with a look to future solutions in phase of testing. From the proposed analysis, it is clear that effects of nonlinear distortions and phase noise should be adequately counteracted by considering spectrally-efficient solutions. In such a perspective, it seems that efficient coded modulations employed together with appropriate pulse shaping can be regarded as effective PHY-layer solutions for future high-frequency and high-data rate connections.

Keywords: Satellite communications, EHF communications, gigabit connectivity, Modulation, Pulse shaping, Channel coding.

1 Introduction

The future exploitation of higher frequency bands for broadband aerospace communications will provide new opportunities, but also generate critical challenges to be adequately considered. It is known by literature [1] that the rush towards higher and higher frequencies will characterize future R&D on satellite communications. The objective is to reach "gigabit connectivity" by aerospace links in order to make such a radio segment a potential "backbone on the air" for global wireless connectivity [2]. Such objective is not realistically achievable by exploiting currently saturated bandwidth (Ku and Ka bands).

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Some proposals for the exploitation of Q/V-bands (31-60 GHz) and W-band (75-110 GHz) in satellite communications are being recently issued [3]. W-band seems to provide a very favorable “attenuation window” related to Oxygen absorption [4]. In addition, W-band is still scarcely used for data transmission (only analog radar applications are supported in those frequencies [3]) and, therefore, interference level is very low. For these reasons, despite the increasing attenuation due to rain, water vapor and clouds, W-band is regarded as a good candidate for supporting future broadband services in the millimeter wave domain.

The exploitation of Q/V band is in advanced phase. In fact, the satellite mission ALPHASAT, whose launch is forecast in 2011, will embark a Q/V band payload in order to perform two experiments [5]: a propagation experiment targeted at evaluating 2nd order statistics of atmospheric attenuation and a communication experiment devoted at testing Propagation Impairment Mitigation Technique (PIMT) and Adaptive Coding and Modulation (AMC). On the other hand, the experimentation of W-band for data transmission is currently in a very early stage. In recent years, Italian Space Agency (ASI) issued two “startup experiments” proposed by Ruggieri et. al.: DAVID-DCE (Digital Audio-Video Interactive Distribution – Data Collection Experiment) [3] [6] and WAVE (W-band Analysis and evaluation) [7] [8].

Preliminary on-going experimentations evidenced the actual possibility of exploiting W-band for broadband connections at very high data rates. Nevertheless, some areas of uncertainty and risk can hinder the efficient exploitation of these large and almost interference-free bandwidth portions. These are related to: a) non-idealities of communication payloads (phase-noise, linear and nonlinear distortions, timing uncertainties etc.) [9] and b) lack of knowledge of signal propagation modalities in W-band. PHY-layer design should carefully take into account all these problems in order to provide the desired quality of service. The analysis of requirements of an efficient W-band satellite PHY-layer should start from the known issues that can be listed as follows [9]:

1) heavy pathloss due to high carrier frequency;
2) presence of nonlinear distortions due to the necessity of using High Power Amplifiers (HPAs) and Travelling Wave Tube Amplifiers (TWTAs) at the maximum level of power efficiency (W-band power resources are quite scarce and should be intensively exploited);
3) presence of time and frequency uncertainties (symbol unbalance, phase noise) that become more and more relevant as the data rate increases;
4) finite system passband and nonideal bandpass characterization of the satellite system (presence of linear distortion);
5) spectrum management issues, related to the presence of other transmitters exploiting adjacent bandwidth portions (in practical satellite applications, bandwidth resources are always limited and spectrum is always shared by a variety of users).

In this paper, all these critical issues about broadband W-band PHY-layer design will be considered, together with an overview of some feasible solutions in terms of modulation format, channel coding and advanced pulse shaping. The introduction to W-band PHY-layer design will be presented in Section 2. Coded modulation solutions based on Manchester-coded BPSK and trellis-coded QAM will be analyzed in the presence of nonlinear distortions and phase-noise (Section 3). Innovative strategies of PHY-layer design based on UWB pulse-shaping techniques (namely: Prolate Spheroidal Wave Functions (PSWF)) will be considered in the perspective of gaining robustness against channel distortion without sacrificing spectral efficiency (Section 4). A look to advanced solutions considering together turbo-coded modulation techniques and adaptive pulse shaping will be mentioned (Section 5). Paper conclusions will be drawn in Section 6.

2 PHY-Layer Design for W-Band Satellite Communications: Critical Aspects

2.1 Radio Interface Design Issues

W-band satellite communications is a novel and very interesting field of research that shall be deeply investigated in order to design the proper radio interface.

W-band satellite communication shows some interesting characteristics that can be very attractive, both for commercial and dual-use applications, such as good interference protection, through the use of very narrow spot beams.

Antennas operating in this band have a higher directivity than antennas (of the same size) operating at lower frequencies, so the interference between adjacent satellite position is reduced; moreover this high directivity makes it possible the use of high-gain spot beam satellite antennas, increasing down-link power flux density and saving satellite power (one of the most important resource of the platform); moreover high frequency reuse can be realized, exploiting the bandwidth resource in a very efficient way.

Another important improvement provided by EHF is the reduction of all RF hardware equipment. This makes the use of W-band particularly attractive with respect to realization of portable terminals and smaller satellite payloads, for example in the context of space exploration, where mass and size are one of the most important mission driver. On the other hand, W-band telecommunications technologies are currently under development; some equipment has been already used for satellite Earth observation applications (i.e.: cloud profiling) and terrestrial radar applications and need to be slightly changed to be used for TLC applications but other critical components shall be completely developed. In this frame, one of the most critical issues is the power generation: therefore, very low HPA back-off level shall be used.

The most relevant sources of signal degradation in a W-band geostationary satellite link are amplifiers, oscillators and frequency Doppler. HPA are hardware components explicitly required in order to guarantee suitable transmission power, taking into account the very high pathloss typical of EHF GEO satellite transmissions. HPAs exhibit two relevant distortions that can severely affect the received signal: nonlinear distortion due to the saturating characteristic of the amplifier and linear bandpass distortion due to non-ideal bandpass characterization of RF amplifier circuitry. The nonlinear saturation of AM/AM characteristic may involve a noticeable alteration of the envelope of the RF modulated signal [10]. On the other hand, nonlinear AM/PM characteristic introduces a phase drift that fluctuates in dependence of the signal amplitude excursions [10].

Linear bandpass distortion consists of a frequency-selective alteration of the RF modulated signal amplitude, due to the "bell-shaped" bandpass characteristics of HPAs, together with a phase distortion mainly due to the frequency-selective group delay of front-end filters [11]. The degradation of the transmitted signal due to linear and nonlinear distortions causes Inter-Symbol-Interference and relevant phase jitters at the receiver side. Moreover, spectral re-growth involved by nonlinear effects [11] will cause adjacent channel interference and violation of spectral mask requirements, as shown in [12].

With a commonly-accepted degree of approximation (see e.g. [9]), we can say that nonlinear distortion of the satellite modem chain is imposed by HPAs, linear amplitude distortion is mostly imposed by amplifiers (HPAs and LNAs, Low Noise Amplifier) and, finally, the linear group delay distortion is mainly imposed by front-end filters.

EHF satellite links are affected also by relevant frequency uncertainties. High-frequency oscillators present both in the up-conversion and in the down-conversion stages are not ideal and they can exhibit high levels of phase noise. Consequently, we have a frequency instability that may impact on the performance of the carrier recovery loop in terms of longer acquisition time, frequency mistracking, and may yield to a residual phase jitter able to significantly lower final BER performance.

2.2 Atmospheric Attenuation and Rain Fading

As previously introduced, one of the main drawbacks of W-band satellite links is the large atmospheric fade experienced when rainfall occurs along the path, in addition to the gaseous atmospheric absorption by oxygen and water vapor; this attenuation shall be carefully taken into account in W-band link testing simulation, in particular rain fading time-series shall be synthesized.

In literature there are different methodologies used for rain attenuation time-series synthesis for EHF satellite links [13]; the most important are: spectral model, synthetic storm techniques, two-sample model, second-order Markov chain and N-states Markov chain models. These models are used for link operating in Ka and Q/V bands, being obtained from empirical measurements performed during scientific satellite missions [14]. Most of these models cannot be effectively used for W band rain attenuation time-series synthesis because they need data from empirical measurements as input; as a matter of fact, no attenuation record database is available for W band satellite link. In this framework, the N-state Markov chain model could be considered as one of the best choices in order to achieve some results. This model does not require empirical measurements; the only inputs are the link characteristics (including rain attenuation cumulative distribution function), the geographical meteorological data of the ground station and the fade slope characteristics. The N-states Markov chain model [15] is divided into two sub-models. The first one is referred to as macroscopic model and provides a time series consisting of two possible states: "rain" and "no rain". The second part of the model is the so-called microscopic model. Its task is to fill the boxes of "rain" states obtained from the macroscopic model. The microscopic model provides the short-term dynamic behavior of rain attenuation (using the information provided by the fade slope distribution). In order to generate complete long-term time-series the two time-series obtained from the previous parts have to be combined. The transition probabilities of the N-states Markov chain model are based on ITU-R Recommendation [16]. An example of W-band synthesized rain attenuation series (related to 1 day observation) has been shown in [29].

3 PHY-Layer Solutions Based on Coded Modulations

3.1 Manchester-Coded Split-Phase BPSK Modulation

The choice of using a Split-Phase Manchester-Coded BPSK modulation was considered both in DAVID-DCE experiment and in WAVE mission. The reason of such a choice is to have the availability of a tone carrier in the spectrum in order to make easier carrier recovery in the presence of relevant frequency uncertainties (i.e. high Doppler shift and phase noise). Moreover SP-BPSK with Manchester coding presents a constant envelope that is good to counteract nonlinear distortions due to HPA. The mathematical expression for the transmitted signal is given as follows:

$$s_k(t) = \sqrt{2P}\sum_{k=0}^{+\infty}\exp\left(j\omega_c t + b_k\phi_m\right) \quad \frac{kT_b}{2} \le t < \frac{(k+1)T_b}{2} \tag{1}$$

where ω_c is the RF radian frequency, $b_k \in \{-1,1\}$ is the binary Manchester symbol level of half-bit time duration, $\phi_m = 60°$ is the modulation index, and P is the carrier power. Fig. 1 shows the amplitude spectrum of the transmitted signal. The pattern of the signal spectrum points out the presence of a residual carrier in the hole spacing two sidelobes [17].

The presence of the residual carrier is very useful in terms of the carrier recovery. A simple second-order Phase-Locked-Loop (PLL) circuit [18] can be employed for carrier recovery; provided that the bit-rate is much larger than the Doppler shift (otherwise the loop filter cannot isolate the carrier row [19]). Results shown in [9] about carrier recovery in the presence of high Doppler and high phase noise for a simulated W-band data link at 100 Mb/s of channel data rate fully confirms the claim that carrier recovery really becomes simple, robust and effective.

SP-BPSK modulation with Manchester coding may present some advantages that have been previously mentioned. However, its employment in broadband W-band satellite applications is not really convenient. In fact, this modulation is spectrally inefficient (spectral efficiency less than 0.5 bit/sec/Hz) and power demanding (3dB of power waste due to the presence of the residual carrier in the spectrum). Moreover, being baseband Manchester-coded binary signal continuously transient, the demodulation and synchronization process can suffer a lot from symbol duration unbalance [9]. The total performance degradation encountered at the demodulator side is about 4.25 dB with respect to the ideal case [9] that is surely relevant.

The channel bit-error-rate achieved by simulations is reported in Fig. 2 (see the complete simulation settings in [9]). Considering the channel data rate of 100 Mb/s, the E_b/N_0 value of 15dB corresponds to the "clear-sky" working point of the satellite link budget fixed at a C/N_0 equal to 95 dBHz [9]. At this working point, a BER value of $8 \cdot 10^{-4}$ is measured in the absence of symbol unbalance that is acceptable in the perspective of the use of a Reed-Solomon channel coding RS(255,223) upon the recommendation of the Consultative Committee for Space Data System (CCSDS) [20]. However, in the presence of a 52% of symbol unbalance (ideal value: 50%), the BER increases up to $3 \cdot 10^{-3}$ that is above the waterfall zone of the error curve of the RS(255,223) coding and quite close to the error-floor zone.

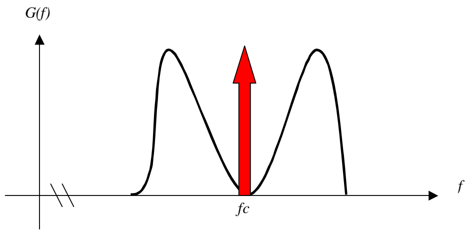

Fig. 1. Amplitude spectrum of the Manchester-coded Split-Phase BPSK signal

To sum up, SP-BPSK solution with Manchester coding can be considered a valuable arrangement to be pretty sure to succeed to transmit "something in the sky" without caring too much about the bandwidth and power expense. It may be proposed as a "backup" solution for preliminary testing operations.

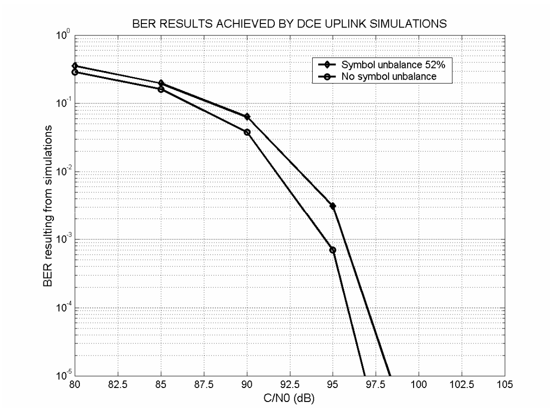

Fig. 2. BER performances achieved by SP-BPSK Manchester-coded modulation: simulation results of DAVID-DCE data collection uplink (channel data-rate 100 Mb/s)

3.2 Trellis-Coded Modulation (TCM)

The use of TCM for gigabit/sec connections over LEO satellite networks working in W-band has been explored by Sacchi and Grigorova in [21]. The basic idea underlying Trellis-Coded-Modulation consists of transmitting *m* bits/waveform in each signaling interval of duration *T*, using a modulator with a set of *M* waveforms. In general $M = 2^{m+1}$. The redundancy in the number of available waveforms is exploited through a proper choice, made on the basis of the past transmitted signals through the memory of the channel encoder: i.e.: a convolutional encoder represented by its trellis diagram [22]. The decoding process is performed by means of a Viterbi-based soft maximum-likelihood decoding algorithm acting on the unquantized demodulator outputs. TCM transmitters can gain efficiency with respect to the corresponding waveform uncoded modulation (from 3 to 6dB as stated by Ungerboeck in [22]), without sacrificing data or requiring more bandwidth. In our specific application context, we considered the use of M-QAM modulation with TCM. A mixed phase-amplitude modulation instead of a phase-shift-keying modulation might not seem best-suited solution for an uplink satellite application. In fact, according to [11], a power back-off has been introduced depending on the AM/AM and AM/PM amplifier saturating characteristics. But, as contrast, constant-envelope PSK modulations are very vulnerable to the effects of phase distortions (involved by amplifiers and filters), phase noise, and exhibit relevant performance degradation in the presence of additive Gaussian noise with respect to M-ary QAM modulations. In [18], the SNR degradation involved by the use of an M-PSK instead of the corresponding M-QAM has been measured in 1.65dB for an 8-QAM, 4.20dB for a 16-QAM and 9.95dB for a 64-QAM. This performance gain inherent to the use of M-QAM instead of M-PSK is only partially eroded by the backoff and, in such a way, the coding gain can be fully exploited. The waveforms used for carrying the modulated TCM symbols are the usual rectangular Non-Return-to-Zero (NRZ). Therefore, the absence of linear filtering and, consequently, the availability of infinite bandwidth have been supposed. The TWTA memoryless non-linear model proposed by Saleh in [10] and parameterized in terms of Clip Level (CL) has been considered by authors of [21].

The following state-of-the-art TCM modulation schemes have been experimented, fixing a data bit-rate of 1Gb/s:

- 8-state systematic encoder at rate 2/3 jointly with 8-QAM modulation. Given a 1Gb/s of pure data rate, we shall obtain a symbol rate of 500Mbaud/sec and an occupied RF bandwidth (referred to the sinc main lobe) of about 500MHz (theoretical spectral efficiency η=2b/s/Hz);
- 8-state systematic encoder at rate 3/4, jointly with a 16-QAM modulation. Given a 1Gb/s of pure data rate, we shall obtain a symbol rate of 333Mbaud/sec and an occupied RF bandwidth (referred to the sinc main lobe) of about 333MHz (theoretical spectral efficiency η=3b/s/Hz);
- 8-state systematic encoder at rate 5/6, jointly with a 64-QAM modulation. Given a 1Gb/s of pure data rate, we shall obtain a symbol rate of 200Mbaud/sec and an occupied RF bandwidth (referred to the sinc main lobe) of about 200MHz (spectral efficiency η=5b/s/Hz).

In order to appreciate the effects of phase-noise on TCM performances, the state-of-the art carrier recovery loop of [23] has been adopted by authors of [21] in their simulations. The loop of [23] is based on the improvement of the well-know Rustako and Greenstein's carrier recovery circuit presented in [24].

Simulation results about TCM modulation for W-band satellite connections are shown in Fig.3. A saturating nonlinear distortion (CL=5dB) has been considered, with a power back-off equal to 3dB. BER results are shown vs. phase-noise standard deviation for all the above-mentioned TCM configurations. In such a way, we have a comparative overview of different TCM configurations, each one requiring a different amount of bandwidth. It is worth noting that all TCM configurations fall inside the "low-quality" band when the phase noise standard deviation is higher than 12°. Phase-noise standard deviation of the order of 10° is quite common to be encountered in W-band connection with non-ideal high-frequency oscillators. The problem is related to the coherent detection using a carrier recovery loop. It is known by literature [25] that a generic carrier recovery loop, in the presence of phase noise, converges to the expected frequency with a residual phase jitter φ_{jitt} that is expressed as follows:

$$\varphi_{jitt} = \sqrt{2 \int_{B_L}^{R_S/2} S_\phi(f) df} \tag{2}$$

where B_L is the carrier loop bandwidth [18], R_s is the symbol rate, and $S_\phi(f)$ is the one-sided PSD, converted from dBc/Hz to rad^2/Hz. It is clear that the sharp reduction in the PSD obtained at the lowest frequency offset values is of paramount importance to reduce the residual phase jitter.

Some interesting measurements about residual phase jitter concerning the application of Trellis-Coded-Modulation (TCM) have been reported in Table 1. In the first column of the table values are shown of $L(f_m)$ (measured in dBcarrier/Hz) accounting the phase-noise level at the output of an oscillator, in the second column the corresponding values of the phase-noise standard deviation are listed. Note that, as expected, the residual jitter increases as the modulated signal bandwidth increases. Values reported in Tab.1 clearly motivate results shown in Fig.3.

4 PHY-Layer Solutions Based on Adaptive and Spectrally Efficient Pulse Shaping

In Section 3.2, the ideal hypothesis of unlimited bandwidth availability has been assumed and, consequently, the use of rectangular pulse as digital waveform has been considered by authors. Such a solution is advantageous in terms of resilience against nonlinear distortions. In fact, phase modulations (PSK) using such kind of waveforms are characterized by constant envelope and, for this reason, they are irrespective of envelope clipping. But, as contrast, rectangular pulses are unlimited in bandwidth with high-power sidelobes. The resulting modulated signal would span its bandwidth on a very large frequency range with relevant power level measured outside the main spectral lobe. Considering that satellite channels are closely located, adjacent channel interference (ACI) would become a major issue that might severely limit the spectral efficiency and, definitely, the achievable capacity. Another drawback of rectangular pulses is related to their sensitivity to linear bandpass filtering. In order to avoid waveform corruption and subsequent ISI (Inter Symbol Interference), a very large system passband is required, say, e.g.: 5-10 times the baud-rate [26][27].

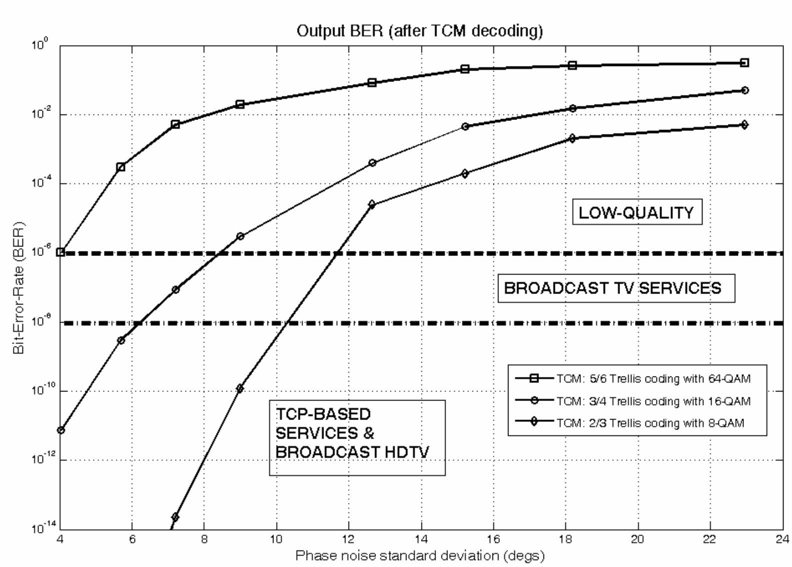

Fig. 3. Data BER provided at the output of the different TCM decoders, versus phase-noise standard deviation, for *CL*=5dB and C/N_0=106.75dBHz

Table 1. Residual phase jitter (deg.) in a 1Gb/s W-band LEO connection using TCM

$L(f_m)$	$\varphi_{jtt}(8-QAM)$	$\psi_\phi(16-QAM)$	$\psi_\phi(64-QAM)$
-70dBc/Hz	19.85	16.21°	12.81
-75dBc/Hz	11.16	9.11°	7.21
-80dBc/Hz	6.27	5.12°	4.05
-85dBc/Hz	3.52	2.88°	2.27

For the above reasons, the use of band-limited pulse shaping may be envisaged for broadband satellite applications. A well-known band-limited pulse is the raised cosine (RSC) [26]. RSC is commonly employed in satellite communications in combination with QAM (Quadrature Amplitude Modulation) (or QPSK, Quadrature Phase-Shift Keying) modulation, implementing the so-called RSC-filtered QAM (or QPSK) [26]. RSC is intrinsically ISI-free (it fulfills Nyquist's conditions) and can be generated by means of digital FIR (Finite Impulse Response) filters. Moreover, it is much less sensitive to filtering than rectangular pulse. The main disadvantages of RSC are: a) unlimited pulse duration in time that may involve inter-pulse interference (IPI), in particular when the transmission rate is very high and b) very relevant envelope fluctuations of the RF (Radio Frequency) modulated signal resulting in high values of the Peak-to-Average-Power-Ratio (PAPR). As RF power amplifiers usually employed in W-band satellite connections (like Traveling Wave Tube Amplifiers – TWTA) efficiently work in nonlinear saturation zone, the transmitted signal can be severely affected by waveform corruption and ISI. As noted in [27], no ISI-free point can be observed in the eye-pattern diagram of the received RSC signal in the presence of nonlinear distortions. Therefore, the use of raised cosine in satellite communications, advisable from the spectral efficiency viewpoint, requires appropriate countermeasures against nonlinear distortions.

The usual solution considered in satellite communications is to sacrifice power efficiency in order to avoid nonlinear distortion effects. This is realized by fixing the working point of the amplifier at the border of the linear zone of the AM/AM characteristic, backing off the transmitted power [11]. In such a way, nonlinear distortions would be removed at the price of a substantial reduction of the power efficiency due to the involved Output Back-Off (OBO).

The necessity of sidelobe power reduction and constant envelope of the RF signal makes Gaussian Minimum Shift Keying (GMSK) modulation a feasible and theoretically favorable solution to W-band PHY-layer design. GMSK is a modulation technique widely employed in terrestrial telephony, in particular in the GSM standard. More recently, GMSK also found some interesting applications in satellite communications [28]. GMSK is derived by Minimum Shift Keying (MSK) signal that is a form of Offset-QPSK signaling with sinusoidal pulse shaping [26]. MSK is characterized by constant envelope (being a frequency modulation) and sidelobes considerably lower than QPSK, but at the expense of a significantly larger main lobe [26]. For GMSK, unmodulated data (rectangular-shaped pulses) are processed by a LPF filter, having Gaussian-shaped frequency response, before the data are frequency-modulated onto the carrier [26]. This filter greatly reduces the spectral sidelobes with respect to MSK signals. The introduction of the Gaussian filter involves a decrease of efficiency due to the increase of ISI. Literature points out that a good compromise for relatively low sidelobes and tolerable ISI is given by a bandwidth of the Gaussian LPF that equals 0.3 times the bit-rate [26]. GMSK may represent a good PHY-later solution for satellite communications thanks to some unquestionable advantages in terms of ACI reduction and resilience against nonlinear distortions. The main problem of GMSK is related to the reduced spectral efficiency with respect to QPSK and RSC-filtered QAM/QPSK. In fact, the main lobe of GMSK is about 1.5 times larger than the main lobe of usual (not filtered) QPSK and 2 times larger (and even more) than that of RSC-filtered QPSK [26]. This fact should be adequately taken into account when dealing with finite and non-ideal bandpass characteristics of satellite systems.

A very innovative solution in the satellite communications panorama has been proposed in [29] Prolate Spheroidal Wave Functions (PSWF) were firstly studied by D. Slepian and H. Pollack (Bell Labs) in 1961 [30]. The fundamental concept standing at the basis of PSWF is to concentrate the energy of the pulse in limited regions, both in time and frequency domains. PSWFs are characterized by some interesting properties, i.e.:

- Pulse waveforms of different orders are mutually orthogonal;
- Pulse width and pulse bandwidth can be simultaneously controlled to match with arbitrary spectral masks (adaptive pulse shaping);
- Pulse width and bandwidth are the same for all orders;

- by definition, PSWFs exhibit an optimized tradeoff between concentration of the energy in a finite time window and in a finite bandwidth: this means that the resulting modulated signal is characterized by “almost finite” pulse duration and, at the same time, “almost limited” bandwidth.

PSWF found interesting applications in UWB applications thanks to spectral compactness and full shaping programmability (they can be employed in cognitive radio systems).For our aims, it is very interesting to note that PSWFs of order 1 and order 2 are characterized by surprising envelope compactness, as shown in Fig.4. This observation suggested us to use order 1 and order 2 PSWFs as in-phase and in-quadrature component of a 4-level modulation that should present “almost constant” envelope. To this aim, the 4-ary Pulse Shape Modulation (PSM) scheme proposed in [31] is employed (4-ary mapping is reported in Tab.2). In Tab.3, the value of Peak to Average Power Ratio (PAPR) is shown for 4-ary PSM and RSC-filtered QAM with different roll-off.

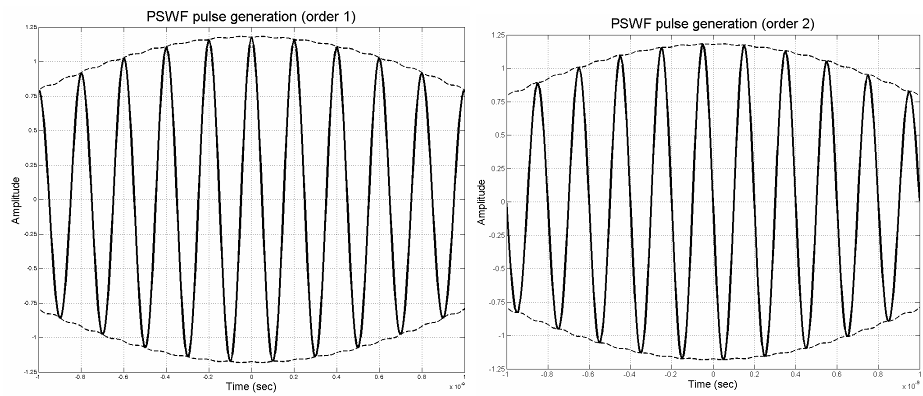

Fig. 4. PSWF pulse shaping: order 1 PSWF (left side), order 2 PSWF (right side)

Table 2. 4-level PSM mapping

Symbol	1st order PSWF (pulse 1)	2nd order PSWF (pulse 2)
00	-pulse 1	-pulse 2
01	-pulse1	pulse 2
11	pulse 1	pulse 2
10	pulse 1	-pulse 2

Numerical values reported in Tab.3 evidenced the potential advantages taken by PSWF in terms of envelope compactness. The PAPR value yielded by the 4-level PSM signal is very close to the ideality, whereas RSC-filtered QAM, as already noted by literature, exhibits high PAPRs. Fig.5 shows the power spectra of different pulse-shaped modulations used in the framework of W-band satellite connections at 1Gb/s of channel data rates. It is clear that the sidelobe power of conventional QAM using rectangular pulses is not acceptable in terms of adjacent channel interference. RSC-filtered QAM is bandlimited and, therefore, it is optimal from the viewpoint of sidelobe power reduction. However, the use of RSC-filtered QAM in satellite communications is viable only by backing off transmitted power. Sidelobe power of 4-ary PSM modulation is comparable with that one of GMSK. The main advantage taken by 4-ary PSM with respect to GMSK is related to the reduced width of the main spectral lobe.

Table 3. Peak-to-Average-Power-Ratio (PAPR) for different pulse shaping

PULSE SHAPING	PAPR VALUE
RSC-filtered QAM (roll-off 0.5)	3.22 dB
RSC-filtered QAM (roll-off 0.35)	3.80 dB
4-ary PSM	1.04 dB
GMSK, QAM	0dB

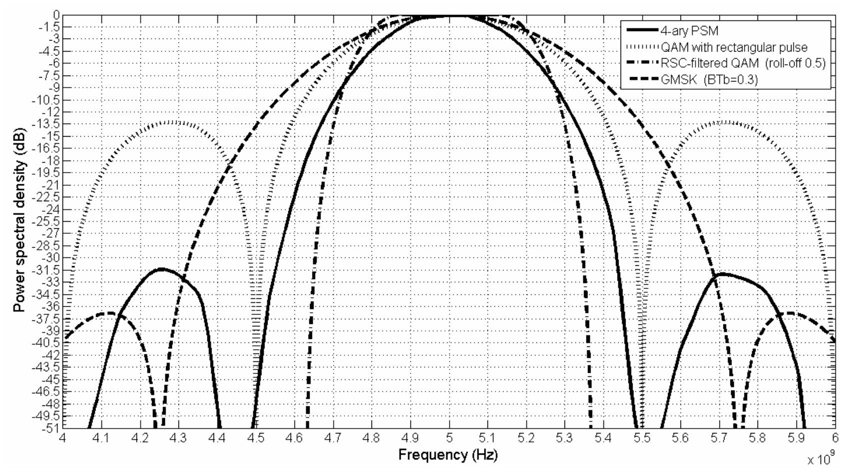

Fig. 5. Power spectral density of different pulse-shaped modulation used for W-band satellite links working in the framework of gigabit connectivity

Other results have been shown in Fig.6, where curves BER vs. per-bit signal-to-noise ratio have been shown for different pulse-shaped modulated signals employed to transmit data at a channel data-rate of 1Gb/s over a geostationary forward W-band satellite link. In this figure, the presence of nonlinear amplifier and linear passband distortions has been taken into account, without considering the presence of phase-noise at this stage. One can note that 4-ary PSM and GMSK outperform RSC-filtered QAM, this last one transmitted with a power back-off. This improvement is motivated by the fact that 4-ary PSM and GMSK can be transmitted at the saturation point of the non-linear amplifier, without any power back-off. In this comparison, 4-ary PSM is the winner because BER performances are rather close to those ones of GMSK, but the spectral efficiency of 4-ary PSM is better than GMSK one (see Fig.4).

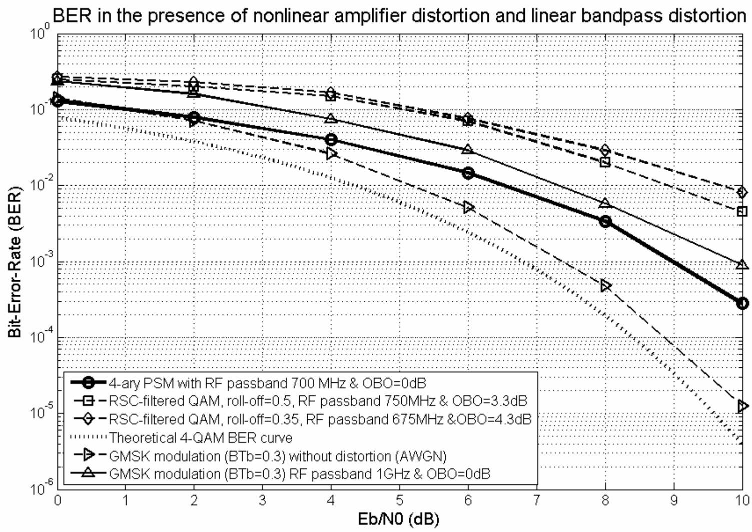

Fig. 6. BER results of different pulse-shaped modulations in the presence of nonlinear amplifier distortion and linear passband distortion

Some simulation results achieved in the presence of phase noise are also available, but not reported here for sake of brevity. Using a state-of-the-art carrier recovery loop already considered for pulse-shaped UWB transmission [33], the effect of phase noise is again relevant and the amount of phase noise at the input of the demodulator should be adequately reduced (maximum acceptable phase-noise standard deviation = 10°).

5 Possible Novel Trends in PHY-Layer Design for W-Band Gigabit Connections

In the previous sections, some open issues about W-band satellite PHY-layer design have been highlighted. The biggest issue to be considered seems related to residual phase jitters involved by phase noise that can affect coherent demodulation. As shown in Fig.3 showing results achieved by TCM, a nasty error floor can be noted for phase noise standard deviation larger than 12°. Similar results have been mentioned (but not shown) in Section 4 dealing with pulse-shaped modulations. Phase noise can be reduced at the source, by using low noise oscillators. Hardware technologies for W-band low noise oscillator consider the use of GaAs MBE material [34] or the so-called Gunn oscillators [35], based on the Gunn diode characterized by a dynamic negative resistance. The cost of this kind of hardware, however decreasing with time, is often not very affordable.

A possible alternative solution should rely in the adoption of differential modulation. It is known that differential modulation is insensitive with respect to phase jitters, as it evaluates the difference between two received samples in order to decide the transmitted symbol. In this framework, it is worth mentioning the work of Howard and Schlegel [36], where a novel approach for turbo-coded differential modulation is shown. The robustness of the proposed coded-modulation scheme is appreciated also in the presence of noticeable phase jitters thanks to a simple channel estimation scheme that can avoid the necessity of channel state information knowledge.

A novel perspective for PHY-layer design can rely on these three hypothetic pillars:

- Coded-modulation to increase robustness without reducing spectral efficiency;
- Differential modulation in order to counteract phase jitters deriving by phase-noise;
- Efficient and adaptive pulse shaping design in order to cope with future spectrum management regulatory issues and to reduce the impact of link distortions (linear and nonlinear).

It should be noted that the proposed analysis doesn't consider any kind of atmospheric effect, which is still to be appreciated. A credible model of W-band channel attenuation, derived by an intensive measurement campaign, will be a key priority issue in the future satellite missions working at these frequencies. Considerations made in this paper might be substantially revised when channel measurements will be available to the scientific community.

6 Conclusion

In this paper an overview of the most challenging aspects related to the PHY-layer design in W-band broadband satellite communications is presented, together with some feasible solutions presented in literature. The most relevant issues that should be considered by PHY-layer designers are related to the presence of frequency uncertainties and phase noise at the input of the coherent demodulators. Another aspect to be carefully considered concerns with the presence of nonlinear distortions in the link due to high-power amplifiers. The introduction of power back-off in order to avoid distortion effects should be carefully analyzed, considering the link budget constraints that in W-band satellite connections are often very tight. The use of spectrally efficient coded modulations should be envisaged, together with the design of adaptive and programmable pulse shaping able at reducing sidelobe power. Possible steps-ahead with respect to state-of-the-art might be related to the use of turbo-coded differential modulations jointly with adaptive pulse shaping. This novelty in terms of PHY-layer design should be effectively tested only when a precise assessment of the W-band satellite channel in terms of reliable statistics will be available. In our opinion, this last one is the most relevant uncertainties that still hinder the effective exploitation of W-band for broadband commercial services.

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