Waveform Design Solutions for EHF Broadband Satellite Communications

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Abstract

The problematic RF environment experienced by broadband satellite communications at EHF frequency bands, in particular Q/W bands, call for the use of novel waveforms. This paper presents a detailed comparison of several waveforms in presence of nonlinear distortions and typical values of phase noise introduced at Q/W band. Two main types of waveforms have been compared: Constant Envelope multicarrier waveforms (CE-OFDM and CE-SCFDMA) and single carrier impulse-based waveforms (TH-UWB, DS-UWB and PSWF-based PSM). This comparison will allow to draw some practical guidelines for the waveforms design of EHF broadband satellite communications.

I. INTRODUCTION

Satellites for broadband communications in Ka-band with throughput capabilities around 100 Gbit/s have been recently launched. Examples include KA-SAT, Echostar 17, Viasat-1, Astra 2E and Hylas-2. However, they are still not able to cope with the user broadband demands that are predicted to considerably increase in the next years [1]. Consequently, next-generation High Throughput Satellites (HTSs) will push for the increase of the system capacity and optimization of system resources. The visionary target of "terabit satellite capacity" is considered in [1]. Terabit capacity can be approached in Ka-band by means of intensive frequency reuse through multi-beam satellite systems. However, the use of additional spectrum is essential to boost system capacity to the limit of 1 Tbit/s and such bandwidth resources can be found only in the Extremely High Frequency (EHF) domain.

In Table 1 the slices of available EHF spectrum beyond Ka-band frequencies are listed.

Table 1: EHF frequencies allocation for satellite communication services.

	Uplink	**Downlink**
Q/V-band	42.5-43.5 GHz 47.2-50.2 GHz 50.4-51.4 GHz	37.5-42.5 GHz
W-band	81-86 GHz	71-76 GHz

The use of higher bands for the feeder links, like Q/V bands or W-band, would allow a maximization of both the terminal and the gateway spectrum, with a consequential increase of system capacity and minimization of the number of gateways and related costs.

In this framework, the ALPHASAT satellite launched on July 25, 2013 together with its "Aldo Paraboni"[1] payload is an important step towards HTSs allowing to carry out, for the first time, a

[1] *In memory of Prof. Aldo Paraboni (1940-2011), pioneer of EHF exploitation for satellite communications.*

communication experiment over a Q/V band satellite link using the second generation of the DVB-S2 standard [2]. DVB-S2 presents some new and innovative elements with respect to the older version of DVB-S: introduction of Low Density Parity Check (LDPC) codes and the possibility of using Adaptive Coding and Modulation (ACM) techniques. Nevertheless, the communication technology did not experience a radical change: we are still talking about traditional single carrier modulated signals, with Nyquist shaping and time-domain equalization.

As outlined in [3] the challenges posed by multi-gigabit communications at frequency bands beyond Ka-band call for the use of novel waveforms and in some cases rethinking the traditional baseband and RF design of the air interface. The EHF satellite links are characterized by significant power losses due to large path loss, atmospheric attenuations, and rain fading. Therefore, the link budget is usually constrained at these frequencies. For this reason, the available power resources should be efficiently exploited, taking into account the presence of significant link impairments, nonlinear distortions and phase noise. The tradeoffs to be tackled are not trivial. The designed radio interface should be robust against link impairments, provide high spectral efficiency and – considering the very high data rates involved by broadband applications – characterized by low-complexity in the waveform generation and detection process.

Besides conventional single-carrier modulation formats, like raised-cosine-filtered QPSK, QAM, Minimum Shift Keying (MSK) and Gaussian Minimum Shift Keying (GMSK), other state-of-the-art techniques that have recently gained some attention for satellite communications are multicarrier modulations, namely: Orthogonal Frequency Division Multiplexing (OFDM) and Single-Carrier Frequency Division Multiple Access (SC-FDMA). Multicarrier modulations have been originally conceived for terrestrial communications, in particular, for highly frequency selective channels. The motivation for their applicability to satellite broadband links is not straightforward and stems mainly from the need of an effective integration of terrestrial and satellite broadband systems [4].

Nevertheless, for the applicability to a “dirty RF” environment, such as the EHF channel, the modification to Constant Envelope (CE) multicarrier waveforms, which are natively more robust to nonlinear distortions, should be considered. Other typologies of waveforms that have been proposed for satellite communication and, in particular, for EHF satellite communications are impulse-based ultra-wideband (UWB) [5], [6].

In this paper, we shall focus our attention on practical solutions for waveform design in future EHF multi-gigabit satellite communications. The analysis of the most significant impairments characterizing EHF satellite links, presented in section II, will drive the waveform design. In particular, we shall consider the following transmission techniques:

- Single-carrier impulse-based UWB transmission techniques, namely Time-Hopping UWB (TH-UWB), Direct Sequence UWB (DS-UWB) and binary Pulse-Shaped Modulation (PSM) using Prolate Spheroidal Wave Functions (PSWF) of order 1 [6] (section III);
- Constant-envelope (CE) multicarrier waveforms, namely CE-OFDM [7] and CE-SC-FDMA [8] (section IV).

Section V will show the performance comparison among the different proposed waveform solutions by discussing some selected simulation results. After that, some practical guidelines for waveform design in EHF satellite links will be proposed. Finally, paper conclusion will be drawn in section VI.

II. EHF SATELLITE LINK IMPAIRMENTS

One of the main characteristics of satellite communications is the need to transmit signals at high power so that the signal received on the ground has enough power for a correct reception. Furthermore, the space and the power onboard the satellite is limited and these resources should be used very efficiently. As demonstrated in [1], the EHF satellite transmission is clearly in the power-limited capacity region. Shannon capacity of the order of 600 Gb/s can be theoretically reached in Q/V band with 200 spots, frequency reuse factor equal to 4 and spectral efficiency of 1.2 bit/s/Hz [1]. Such a low spectral efficiency indicates that the available signal-to-noise ratio (SNR) is substantially reduced by atmospheric attenuations, scintillations and rain fading [3]. Very significant power attenuations at frequencies beyond 30 GHz are also yielded by antenna de-pointing losses, as shown in [3]. For instance, at 80 GHz, a pointing error of 0.3° involves a power loss of 18 dB.

Moreover, to increase the amount of available power resources, the most important role is played by the RF power amplifier. Despite recent advances in microwave solid-state power amplifiers, tube amplifiers such as Traveling-Wave Tubes (TWTs) and klystrons still provide the best combination of power output, power efficiency and bandwidth. The biggest issue of high-power tube amplifiers is related to nonlinear behavior of the power gain. The maximum power gain – of the order of 50-60 dB – is reached at the saturation point of the amplitude-to-amplitude (AM/AM) characteristic. Moreover, a noisy time-varying phase drift is produced by the amplitude-to-phase (AM/PM) conversion typical of TWTs and klystrons. Nonlinear amplification automatically involves nonlinear distortion that might significantly alter both the amplitude and the phase of the modulated waveform. Nonlinear amplification is usually accounted by the Output Back-Off (OBO), which is the difference (in dB) between the output saturation power and the output average power of the amplifier.

Phase noise is an unwanted phase modulation of an RF signal and can be viewed as spurious sidebands on a wanted carrier. Higher-frequency oscillators generally have higher phase noise associated with them, but nonlinear amplifiers may also increase the phase noise of a processed signal. Phase noise is able at compromising the efficiency of carrier synchronization in coherent demodulation systems by introducing significant phase jitters. On the other hand, in OFDM systems, phase noise can produce inter-carrier interference with a consequential error-floor [9]. Some works about W-band satellite communications evidenced in clear manner the detrimental impact of phase noise on the detection of single-carrier trellis-coded [10] and turbo-coded [11] modulated signals. Both [10] and [11] concluded that phase noise should be conveniently limited in order to obtain acceptable performance.

The analysis of EHF link impairments shown in this section may suggest to PHY-layer designers the following basic hints:

- Power resources are very scarce and (therefore) precious in EHF bands and cannot be wasted. This implies that modulation formats highly resilient against nonlinear distortion should be considered in order to exploit the power amplifiers at their maximal efficiency.
- The robustness against thermal noise and phase noise is a primary requirement. It has higher priority than mere spectral efficiency (higher order modulations can be considered only if they cope with robustness requirements).

The basic Nyquist-shaped pulse waveforms, like root-raised cosine, do not match up well with such requirements, because they are vulnerable to nonlinear distortions. Unfiltered binary or quaternary modulations using rectangular pulse shaping (BPSK, QPSK), characterized by constant amplitude, are not acceptable for broadband transmission applications due to their high sidelobe power levels, not complying with the standard recommendation about spectrum usage. Frequency modulation schemes like Minimum Shift Keying (MSK) and Gaussian Minimum Shift Keying (GMSK) are resilient against nonlinear distortion and characterized by negligible sidelobe power level but, as shown in [6], are vulnerable to phase noise. We think that the efficient exploitation of EHF bandwidth portion will require a step-ahead in waveform design with respect to conventional state-of-the-art solutions. This will be dealt in the rest of the paper.

III. Impulse-based UWB Waveforms

In impulse-based UWB waveforms, the information bits are encoded in various characteristics of the transmitted pulse, such as the pulse presence, position and shape. UWB is mostly applied to short-range wireless applications as a consequence of the limitations to the radiated power required for unlicensed use of the spectrum. Nevertheless, the definition of UWB signals given by the FCC on the 1998, is concerned only with the bandwidth and not with the power emission. The FCC defines UWB as a signal with either a fractional bandwidth of 20% of the center frequency or 500 MHz. Therefore, UWB communications technologies can also be used in licensed systems at the condition that a large bandwidth is available for a single signal and this condition could be fulfilled at Q/V/W bands. Their use in the satellite context is undoubtedly an innovative approach. This type of waveforms could bring some substantial advantages in the direction of relaxing HW requirements and reducing systems costs [12], with the disadvantage of a reduced spectral efficiency.

Several works have demonstrated that IR-UWB at EHF, namely at 60 GHz band, can provide transceiver simplicity, i.e. no need of stable sources, oscillators or mixers [13]. Moreover, as reported in [14] in case of impulse-based communications, it is possible to avoid the use of oscillator and mixers; the idea consists in generating extremely narrow pulses (picoseconds), which have a bandwidth of 100 GHz and then filter them with a bandpass filter centered at 78 GHz. The involved hardware technology is quite complex and far from being space-qualified. Nevertheless, this result encourages in looking for novel RF architectures for pulsed-based communications. Finally, UWB-waveforms have been proposed in all the contexts where power efficiency and robustness to channel non-idealities is preferred to high spectral efficiency (wireless sensor networks, WBAN). In general, a modulation in which the information is encoded in the pulse position such as the Pulse Position Modulation (PPM) is expected to be more robust to nonlinear distortions introduced by the HPA with respect to modulation format where the information is encoded in the polarity of the pulse. This higher robustness could be used to relax the requirements on the HPA.

Different motivations that have led to propose the use of other innovative UWB pulse shaping, such as Prolate Spheroidal Wave Functions (PSWF) waveforms. PSWFs were discovered by Slepian and Pollack in 1961, but their use in practical communication systems has been proposed quite recently.

These waveforms, based on the solution of specific differential equations, are characterized by optimal energy concentration in time and frequency domain. In particular, PSWF of order 1 and order 2 can provide RF modulated signals characterized by a near-optimal compromise between spectral compactness (sidelobe power level 31.5 dB below the main lobe [6]) and envelope compactness (their Peak-to-Average-Power-Ratio (PAPR) is 1 dB [6]). Therefore, the effect of nonlinear distortions can be drastically reduced, while maintaining a spectral efficiency rather similar to bandwidth-limited raised cosine waveforms. In Section V, a detailed comparison of PSWFs with other classical IR-UWB waveforms is shown.

IV. CONSTANT-ENVELOPE MULTICARRIER MODULATION SCHEMES

OFDM and its multi-user extension (OFDMA) found a lot of applications in recent standards for terrestrial wireless networking (IEEE 802.11n, WiMAX, LTE) for three main reasons: a) it offers a lower complexity solutions than current single carrier systems to the problem of performance degradation over frequency selective channels; b) it potentially offers good spectral efficiency; c) it efficiently supports variable data rates and provides high flexibility in radio resource management.

On the other hand, the application of this transmission technique has been considered for many years unfit for satellite communications. An OFDM signal is characterized by high amplitude fluctuations that produce large PAPRs. Moreover, high-frequency satellite channels are usually not frequency selective and, hence, the main motivation to use OFDM does no longer hold. Several studies can be found on its use in both mobile and fixed satellite communication systems transmitting in the lower bands of the satellite spectrum (L, S and C bands), where multipath propagation still involves frequency selectivity. Moreover, OFDM has been adopted by the standard for Digital Video Broadcasting Satellite services to Handhelds (DVB-SH) [14], which is the same signal format defined in DVB-H for terrestrial systems. The main reason for adopting OFDM in this context stems from the fact that satellite and terrestrial transmitters form a Single Frequency Network (SFN). Moreover, the use of the same technique for the satellite component would reduce the complexity of the terminal. Less straightforward is the motivation to use OFDM in satellite fixed broadband systems. In this context, some studies have proved that SC-FDMA is less sensitive than OFDM to nonlinear distortions thanks to the reduced PAPR. However, PAPR of SC-FDMA may be still significant, in particular if Localized-FDMA subcarrier allocation is done. Therefore, OBO is still required to make SC-FDMA safely working on satellite links.

A class of FFT-based modulation schemes that are robust to nonlinear distortions and that is worth considering for transmission at Q/V/W bands, is the class of Constant Envelope (CE) multicarrier modulations, namely CE-OFDM [7] and CE-SC-FDMA [8]. The main idea of CE multicarrier systems is to add a nonlinear phase modulation to a real-valued multicarrier signal. The block diagram of the CE-SC-FDMA modulator/demodulator is shown in Fig. 1.

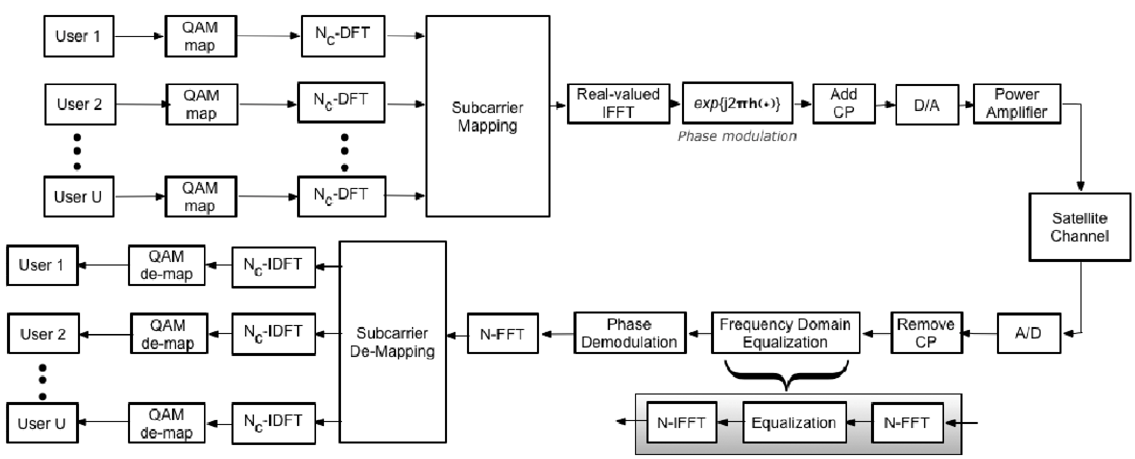

Fig. 1: CE-SC-FDMA modulation/demodulation scheme.

The PAPR of the CE-modulated signal is constrained to 0 dB. The price to be paid is an increase of the signal bandwidth due to the real-valued I-FFT operation [7] [8]. The spectral efficiency *S* of CE-OFDM and CE-SC-FDMA transmission using a M-QAM constellation ($M=2^k$, k even) equals to:

$S = \log_2\left(\sqrt{M}\right)/\max\left(2\pi h, 1\right)$ b/s/Hz. The tradeoff performance/spectral efficiency is accounted in CE multicarrier modulations by two parameters: M and $2\pi h$, as shown in [7]. Theoretically, fixing M, it is possible to decrease the symbol-error-probability simply by increasing $2\pi h$. Practically, this is not always true because of the threshold effect typical of nonlinear modulations. Anyway, as pointed out in [7] and [8], such tradeoff is very interesting and may deserve a formal analysis.

Both [7] and in [8] confirmed the very good performance yielded by CE-OFDM and CE-SC-FDMA in the presence of nonlinear amplification and frequency-selective multipath fading, which is a typical situation related to low-frequency mobile satellite communications. We think that CE multicarrier modulations may represent an interesting alternative solution for EHF broadband satellite communications, because they would allow benefiting of the favorable features of multicarrier modulations, while avoiding the detrimental effects of nonlinear distortions and power backoffs. A significant open issue is related to the effect of phase noise on such kind of waveforms that have not yet been appreciated. It is demonstrated in [7] that a constant phase offset has no impact on the CE receiver performance. On the other hand, phase noise becomes additive noise after the arctangent detector performing phase demodulation. The arctangent detector is followed by a phase unwrapper aimed at minimizing the effects of ambiguities due to phase jumps crossing the π boundaries [7]. The introduction of significant amounts of phase noise would increase phase ambiguities and the phase unwrapper might make mistakes. An error-floor would result from such mistakes. In the next section, we shall verify the occurrence of this potential drawback by means of selected simulations.

V. COMPARISON OF DIFFERENT WAVEFORM SOLUTIONS

With the final objective to provide guidelines for the design of novel waveforms for satellite transmissions at Q/W bands, and according to the literature review shown in previous Sections on the most related studies, in this section the following waveforms are compared:

- *UWB-based techniques:* TH-UWB, DS-UWB, binary antipodal PSM using order 1 PSWF;
- *CE multicarrier modulations:* CE-OFDM and CE-SC-FDMA.

The main simulation parameters are shown in Table 2.

Table 2. Main simulation parameters

Parameter	Q band	W band
Center Frequency	40 GHz	85 GHz
Spectral Efficiency	1 bit/s/Hz	1 bit/s/Hz
HPA Output Power Backoff	5 dB	5 dB
Phase Noise at 1 MHz	-140 dBc/Hz	-100 dBc/Hz
Phase Noise at 10 MHz	-160 dBc/Hz	-120 dBc/Hz

In order to have a coherent comparison, a fixed spectral efficiency of 1bit/s/Hz has been considered for all the modulation formats. In case of impulse-based UWB, some kind of multiplexing is needed to fully exploit the available bandwidth. For this purpose, two different approaches are considered:

- TH-UWB utilizes low-duty-cycle pulses of duration T_p, which are transmitted with a repetition period T_f. The position of the transmitted pulse within each repetition period is determined by a pseudorandom code c_n which selects one of the N_s slots, each having duration of T_m. The pseudorandom code takes integer value between 0 ~ N_s-1. Assuming that each bit has a length of N_{TH} pulses, the bit duration is $T_b=N_{TH}T_f$.
- DS-UWB utilizes a pseudorandom code c_n that takes value {±1} to modulate the amplitude of the DS-UWB pulse train. Each bit has a length of N_{DS} pulses and has duration of $T_b=N_{DS}T_p$.

In the simulations, the transmitted data stream is divided in 8 streams, which are sent in parallel through 8 orthogonal codes of length 8. As far as CE multicarrier modulations are concerned, a 4-QAM constellation has been adopted with angular modulation index of 0.7 rad. According to (4), the resulting spectral efficiency is 1b/s/Hz. The multiplexing is considered also for CE-OFDM and CE-SC-FDMA, in order to exploit all the available subcarriers. In particular, 128 subcarriers have been allocated to 4 streams in block of 32 each.

Fig. 2, Fig 3 and Fig. 4 show the comparison in presence of nonlinear distortion only, phase noise only and with both phase noise and nonlinear distortions, respectively. By comparing Fig. 2, Fig 3 and 4, it is possible to infer which RF channel impairment is dominant for each waveform.

Curves in Fig. 2 confirm that CE waveforms are not very sensitive to the nonlinear distortions. On the other hand, an error-floor arises at W-band for CE waveforms, evidently due to the phase noise (see Fig. 3). As a matter of fact, the severe phase noise introduced at W-band (at Q-band phase noise is much less severe) it is able to produce noticeable phase discontinuities that the phase unwrapping used in the CE modulations are not able to compensate. Moreover, Fig. 2, Fig. 3 and Fig. 4 show that the considered UWB-based waveforms have very different behavior with respect to these two impairments. As expected, TH-UWB, where the information is on the pulse position, is not much sensitive to the nonlinear distortions introduced by the power amplifier (curves in Fig. 3). Nevertheless, from Fig. 3 TH-UWB appears to be sensitive to the phase noise as the higher phase noise introduced at W-band noticeably degrades the performance with respect to the performance at Q-band. As a matter of fact, phase noise in the time-domain can be seen as fluctuations in the times of zero-crossings of the waveform (time jitters). Even if the phase noise is not so strong to change the polarity of the pulse (in case of bi-phase modulation, as the one considered for DS-UWB), it seems to be able to cause a relevant time-jitter, which has an impact on modulation where the information is encoded in the pulse position. On the other hand, for DS-UWB, nonlinear distortions have a dominant effect. In fact, DS-UWB, which uses a bi-phase modulation is not much sensitive to the phase noise but it is shown to be the most sensitive to the high nonlinear distortions introduced at such high frequency bands, which might cause inversion of the pulse polarity.

The more robust solution with respect to both nonlinear distortions and phase noise is the binary antipodal PSM using order 1 PSWF pulse. Nevertheless, it is worth mentioning that the generation of PSWFs is still unaffordable by state-of-the-art signal processing architectures, at least at the high baud-rate considered in our simulations. Indeed, as shown in [6], 64 samples/pulse are required at minimum in order to maintain the optimal properties of these waveforms. This would result in a sampling rate of 320 GHz, clearly unreachable by state-of-the-art devices.

At W-band, TH-UWB shows performance close to the one of CE waveforms. On the other hand, even if phase noise has a noticeable impact, it does not cause error-floor as it does for the CE waveforms. Furthermore, TH-UWB is practically realizable with current electronic technologies, which is not the case for PSM-PSWF.

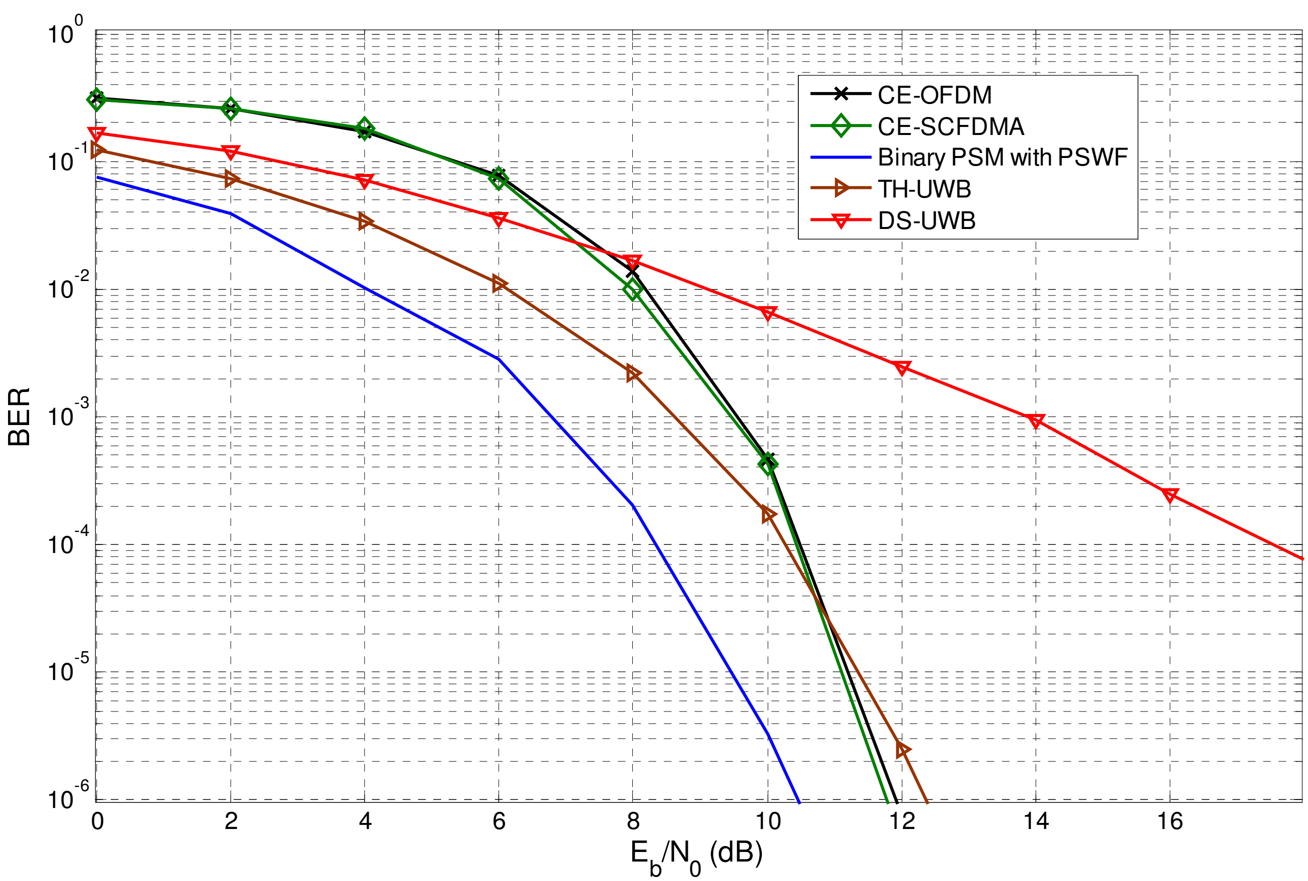

Fig. 2: Performance of UWB and CE transmission schemes in the presence of nonlinear distortions.

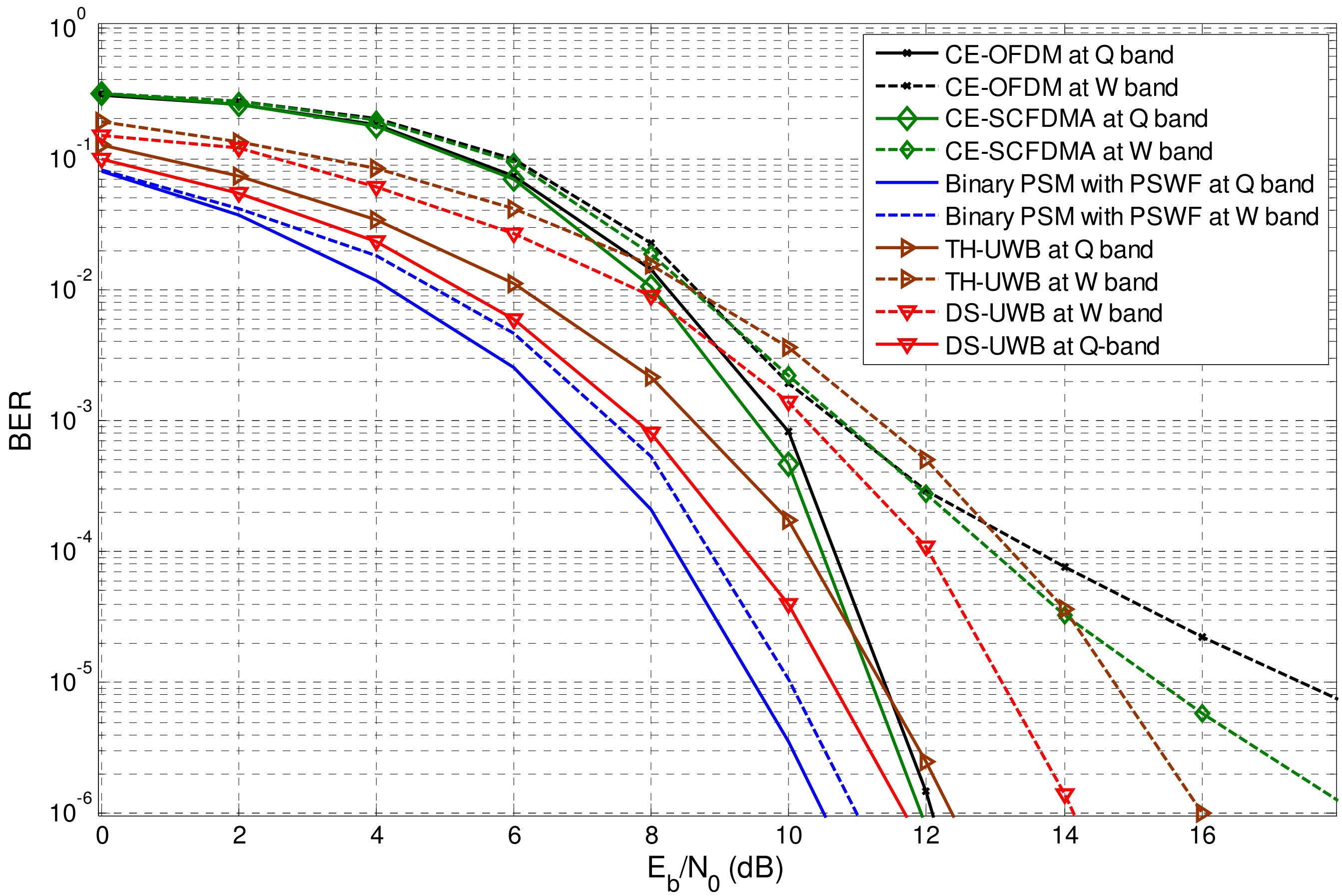

Fig. 3: Performance of UWB and CE transmission schemes in the presence of phase noise.

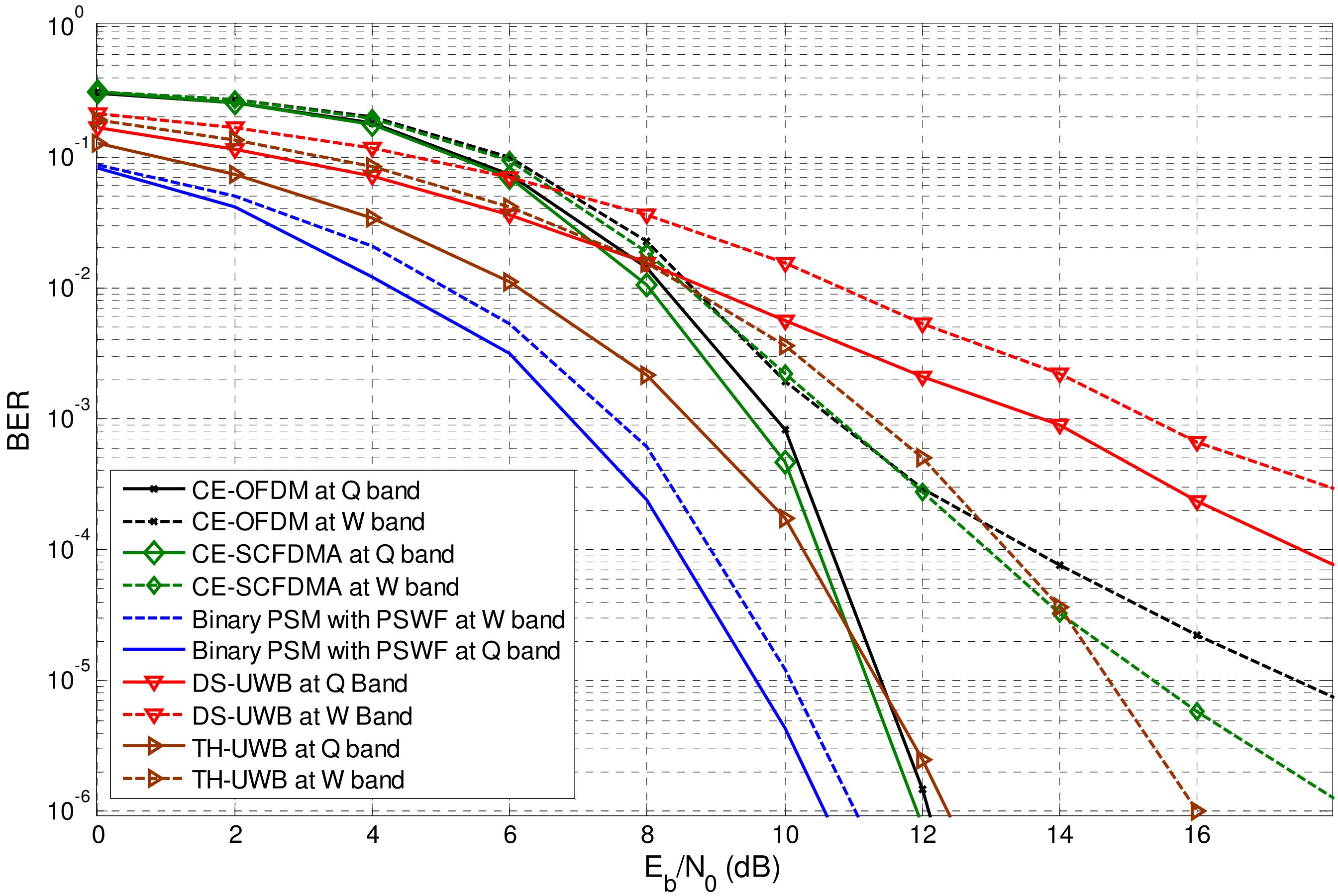

Fig. 4: Performance of UWB and CE transmission schemes at Q-band and W-band in the presence of nonlinear distortions and phase noise.

VI. Conclusion

In this paper, we compared different waveform solutions for future broadband EHF satellite communications. Two main issues should be addressed in such a context: the scarcity of power resources that requires the exploitation of saturating high-power amplifiers at their maximum efficiency and the frequency instability due to phase noise. Some solutions derived by UWB standards, like: TH-UWB, DS-UWB and binary PSM using PSWF have been compared with constant-envelope multicarrier modulations (CE-OFDM and CE-SC-FDMA), whose usage in satellite communications has been very recently proposed. Binary PSM using PSWF theoretically exhibits the best tradeoff between envelope compactness, spectral compactness and robustness against EHF link impairments, but the related waveform generation is complicated, computationally intensive and not affordable by current state-of-the-art signal processing architectures. On the other hand, the generation and the detection of TH-IR signals are very simple and cheap. Such a solution is robust to nonlinear distortion, but it is vulnerable to the effects of phase noise. At the opposite, DS-UWB modulation format is more affected by nonlinear distortions. As far as CE-OFDM and CE-SC-FDMA are concerned, their use may be suggested when the phase noise level is moderate (e.g. in Q band). But, if phase noise increases (e.g. in W band), CE multicarrier techniques may suffer from phase instability. At the present time, TH-UWB looks the best candidate waveform at such high frequency bands, but PSWF-based PSM and CE multicarrier modulations may be considered valuable future alternative, provided that the open issues still impairing them will be solved.

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