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Impulse-Radio Waveforms for MM-Wave Satellite Communications: Potential Benefits and Open Issues

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Outline

- *Introduction;*
- *MmWave satellite communications: opportunities and challenges;*
- *IR waveforms for mmWave Satcoms;*
- *Performance analysis;*
- *Conclusion and future work.*

Introduction

- **MmWave: the new broadband frontier**
  - Since early 2000, EHF spectrum portions beyond Ka-band have been conceived for satellite communications (DAVID, WAVE experiments 1999-2004) *[Cianca11]*;
  - Finally, in July 2013, the *"Aldo Paraboni"* payload has been launched by ESA in order to carry on the first experiment over a Q/V band satellite link (DVB-S2 standard transmission);
  - In the meanwhile, terrestrial communications have considered the use of mmWave (81 GHz frequency) for wireless LOS backhaul of mobile cells (explicitly forecasted in LTE), with some related commercial products *[Ceragon]*;
  - Recent works have successfully tested the use of E-band (71-76 GHz, 81-86 GHz) also for NLOS cellular communications in the framework of future 5G standards *[Rappaport13]*.

- **EHF frequency allocation for satellite communications**

	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

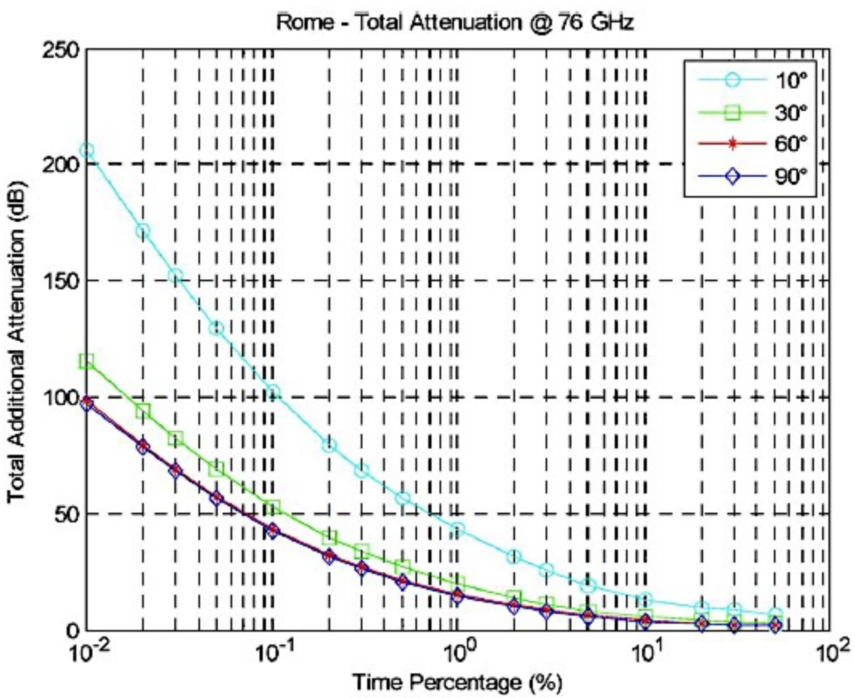
Notice the overlap of W-band frequency allocation with terrestrial E-band slots! Satellite downlink will have to co-exist with terrestrial E-band uplink and terrestrial E-band downlink and backhaul with satellite uplink. Cognitive and opportunistic coexistence strategies will be welcome, in the future!

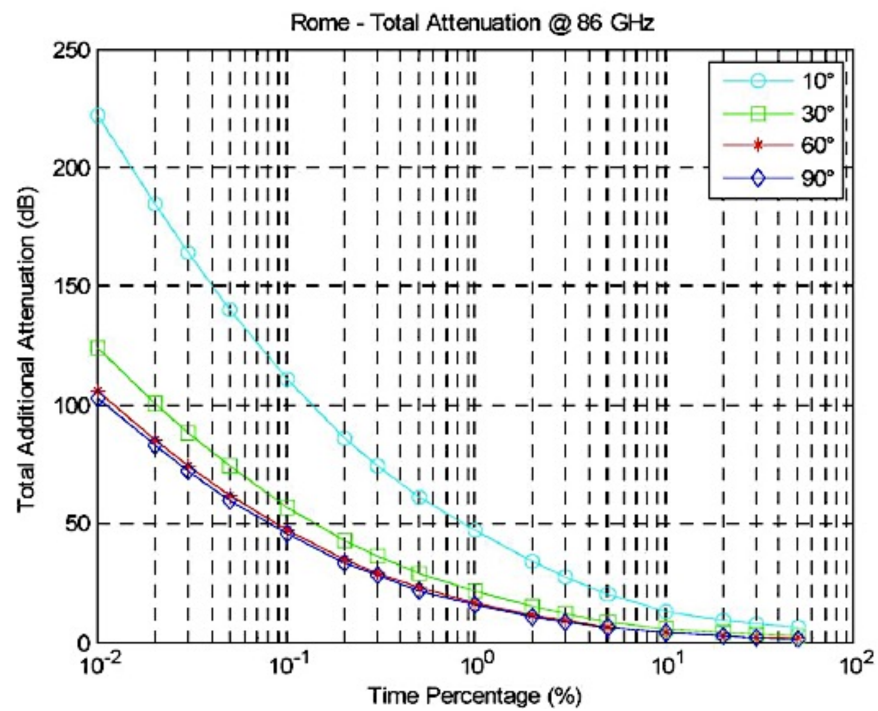
MmWave satellite communications: opportunities and challenges

- **Opportunities**
  - Enormous bandwidth availability, as compared with existing bands (Ku and Ka bands);
  - Reduced interference level (EHF are not largely used);
  - Thanks to very short wavelength, antennas with high gain and reduced size can be used;
  - The EHF beam is very narrow: high-capacity multi-beam satellite systems with aggressive frequency reuse are enabled (*terabit satellites [Gay09]*).

MmWave satellite communications: opportunities and challenges

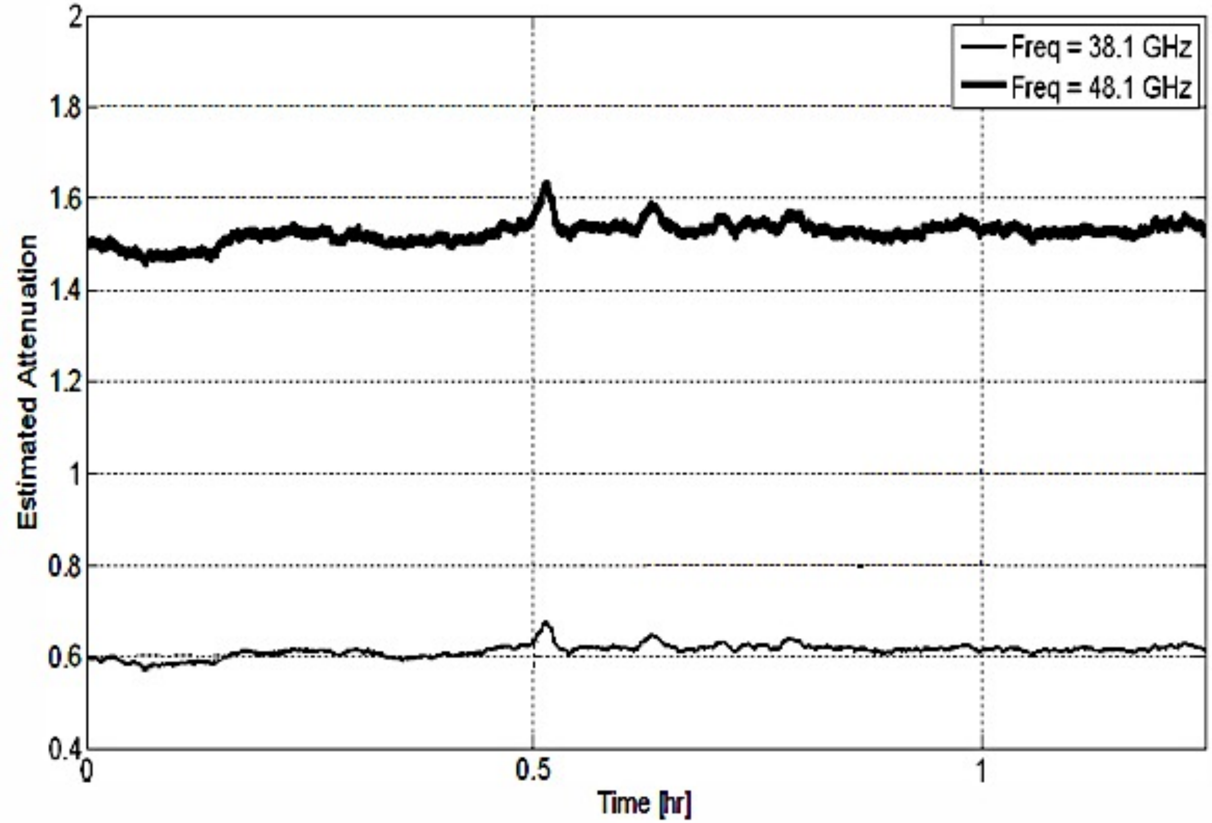
- **Challenges: atmospheric propagation impairments (1)**
  - Estimated (CDF) atmospheric attenuation in dB (rain, cloud attenuation, oxygen absorption, scintillations) *[Cianca11]*:



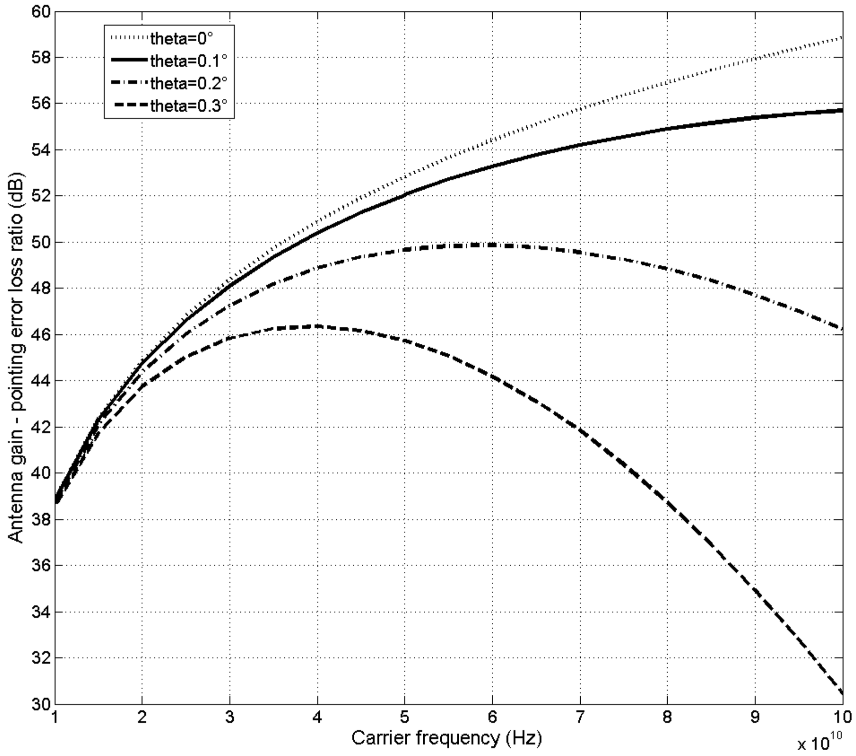


MmWave satellite communications: opportunities and challenges

- **Challenges: atmospheric propagation impairments (2)**
  - Radiometric estimation of the atmospheric attenuation in *"clear-sky"* conditions, obtained form ALPHASAT in-orbit data [Rossi16]:



- **Challenges: de-pointing losses**
  - Very accurate antenna pointing is required in EHF satellite transmission: very little de-pointing may dramatically impact on link performance *[Cianca11]*:

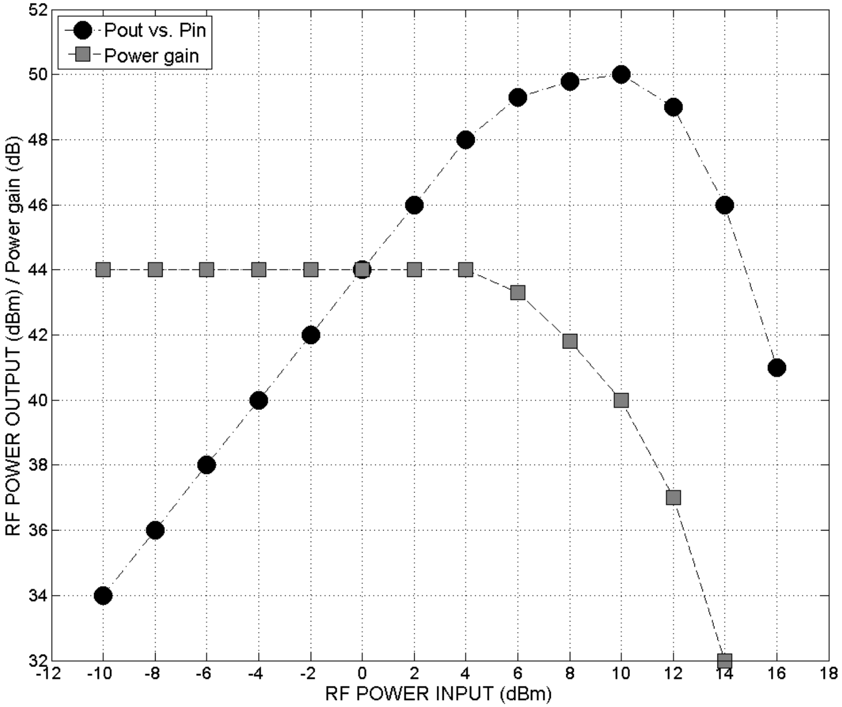


$$L_{pe} \approx 12\left(\frac{\theta \cdot D \cdot f_c}{65c}\right)^2 (dB)$$

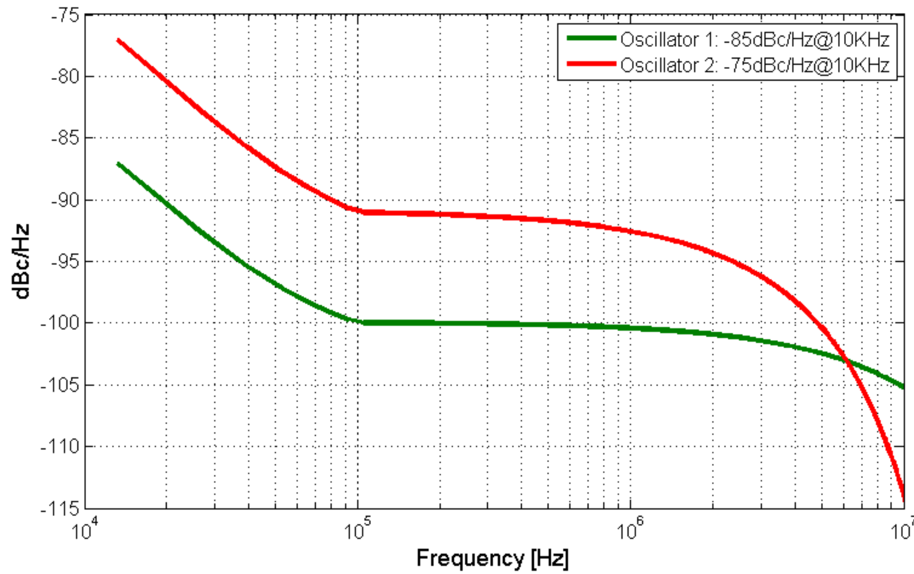
Pointing error loss (dB) – *D* is the antenna diameter (in meters) and *theta* the pointing misalignment (in degrees)

MmWave satellite communications: opportunities and challenges

- **Challenges: non ideal behavior of RF hardware**
  - EHF is a "dirty RF" environment, because RF hardware is very far from ideal (and linear) behaviors:



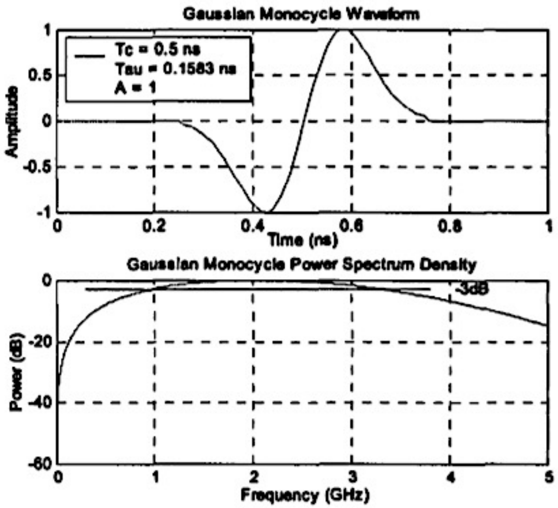
94 GHz Klystron amplifier (CPI – CAN): Pin-Pout / gain characteristic (OBO=5dB)



Phase noise: one-sided PSD of oscillators used in DVB-S2 applications

MmWave satellite communications: opportunities and challenges

- **Summary of requirements of mmWave satcoms**
  - Link budget is severely constrained by long-range pathloss, depointing losses, atmospheric attenuations, rain fading and scintillations (in terrestrial communications multipath fading is dominant);
  - For this reason, amplifiers should be operated at the maximum efficiency, very close to saturation (power back-offs are not welcome; in short-range terrestrial communications they can be tolerated);
  - Transmission should be robust against nonlinear distortion and phase noise rather than spectrally-efficient (spectral efficiency in crowded terrestrial spectrum is a must);
  - Simple, robust and cost-effective receiver architectures with reduced time-frequency synchronization issues are generally preferred in orbit;
  - The waveform should be designed to occupy large spectrum portions without prohibitive hardware complexity and/or sampling rate.

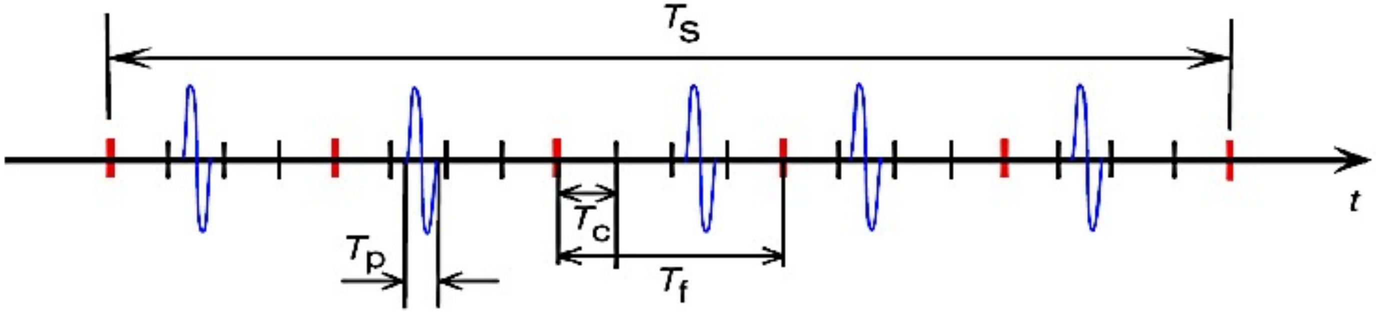


IMPULSE RADIO (IR) WAVEFORMS MAY REPRESENT EFFECTIVE SOLUTIONS!

IR waveforms for mmWave satcoms

- **IR for satcoms: Time-Hopping Impulse-Radio (TH-IR)**
  - It is probably the cheapest and easiest IR solution for broadband communications;
  - It is based on the pulse-position modulation (PPM), using Gaussian monocycle pulses:

$$s(t)=\sum_{k=1}^{K}\sum_{j=-\infty}^{+\infty}A_{d[j/N_s]}^{k}\,p\left(t-jT_f-c_j^{(k)}T_c-\delta_{[j/N_s]}^{(k)}\right)$$



$A_{d[j/N_s]}^{k}$ Binary symbol of k-th user

$c_j^{(k)}$ Time-Hopping pseudo-random sequence of the user k

$\delta^{(k)}$ Time-shift introduced by the PPM

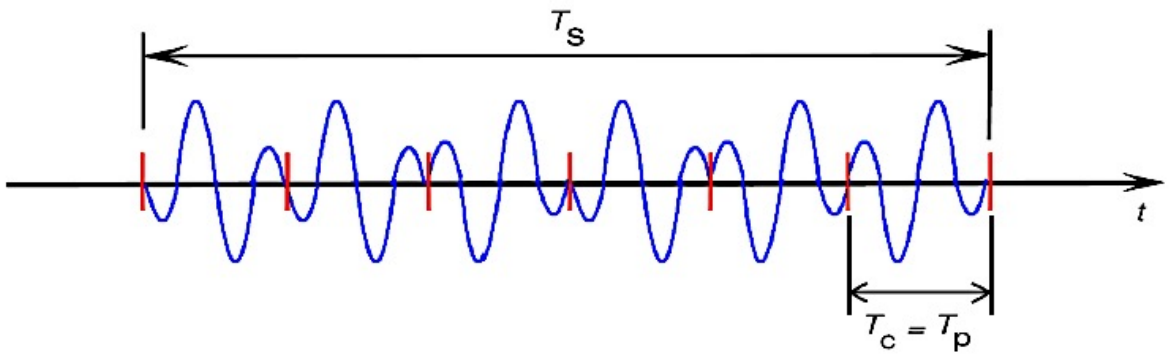
T_f Frame duration (a frame is divided into N_{TH} slots of duration T_c each)

$$p(t)=\frac{At}{\sigma^2}e^{-\frac{t^2}{2\sigma^2}}$$ pulse waveform

IR waveforms for mmWave satcoms

- **IR for satcoms: Direct Sequence-UWB (DS-UWB)**
  - DS-UWB is based on Direct-Sequence Spread Spectrum transmission principle;
  - It is secure and robust against jamming and multipath fading.

$$s(t)=\sum_{k=1}^{K}\sum_{j=-\infty}^{+\infty}\sum_{l=0}^{N_s-1}c_l^k d_j^k p\left(t-lT_c-jT_s\right)$$



d_j^k Binary symbol of user *k*

c_l^k *l*-th chip of pseudo-noise binary sequence of user *k*

$$p(t)=\frac{At}{\sigma^2}e^{-\frac{t^2}{2\sigma^2}}$$ pulse waveform

- **IR for satcoms: Pulse-Shaped Modulation (PSM) with PSWF**
  - Prolate Spheroidal Wave Functions (PSWF) *[Slepian61]* are characterized by the optimal energy concentration in the time and frequency domain;
  - They can exploit pulse-shaped modulation (PSM) *[Usuda04]*;
  - 2-level and 4-level PSM use order 1 and order 2 PSWF characterized by very low PAPR (1dB). 4-level PSM with PSWFs has been considered for W-band satcoms [Sacchi11]:

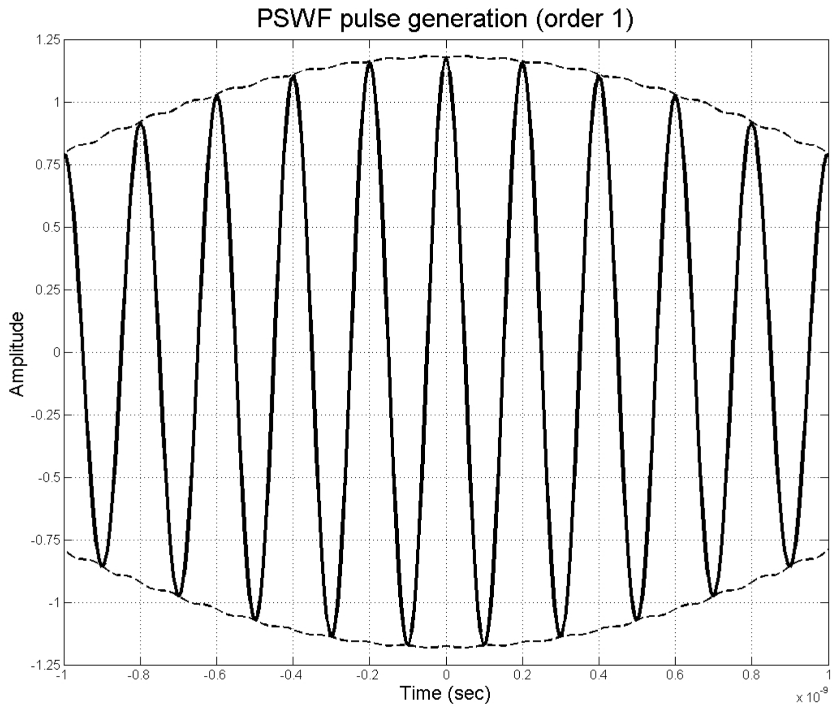
$$s(t) = A\sum_{j=-\infty}^{+\infty}\sum_{n=1}^{N} a_{jn}\psi_n(t - jT_s)$$

A signal amplitude

$\psi_n(t)$ order-n PSWF (*n*=1,2,3, ...)

(read the paper for some notes about PSWF generation)

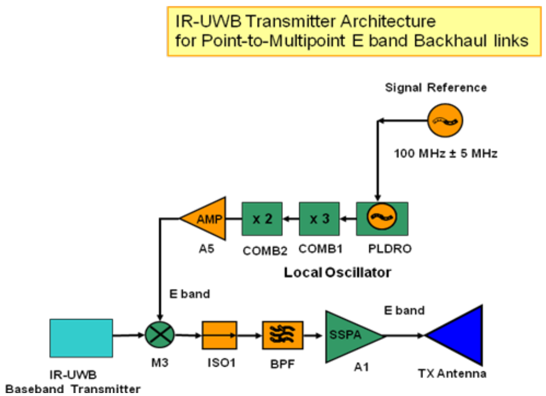
$a_{jn} \in \{-1,1\}$ PSM coefficient

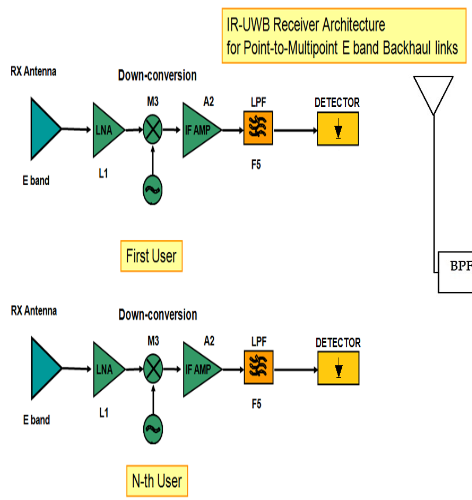


IR waveforms for mmWave satcoms

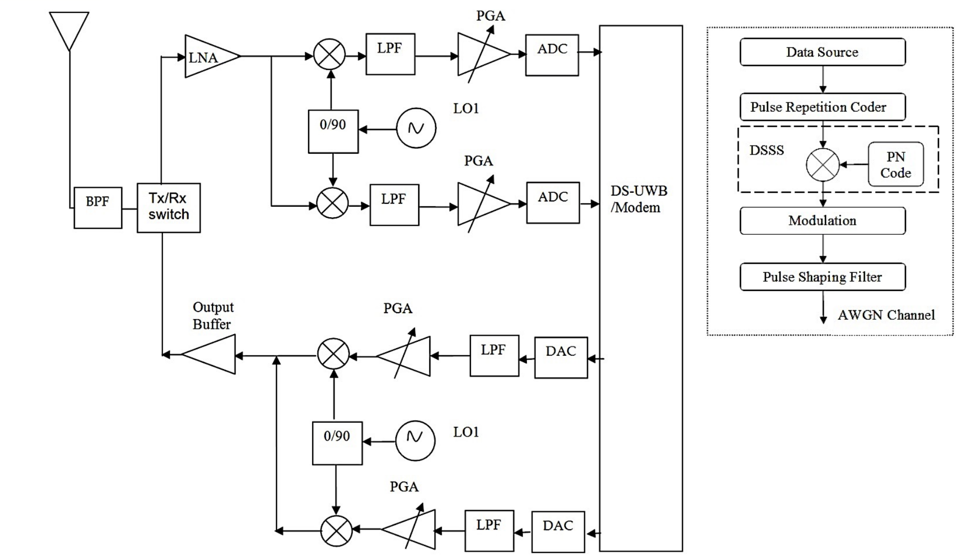
- **Transmitter and receiver schemes**

TH-IR

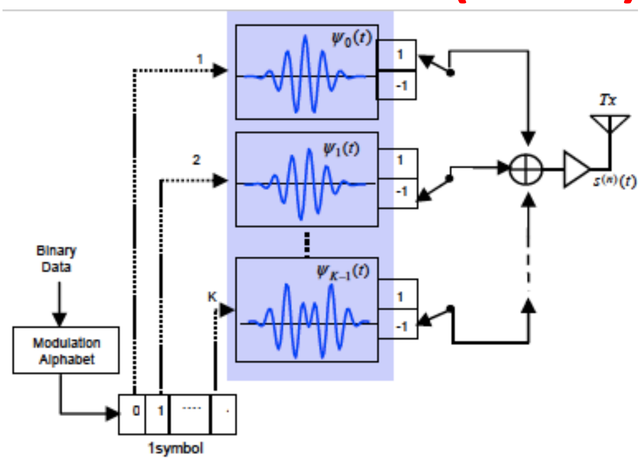


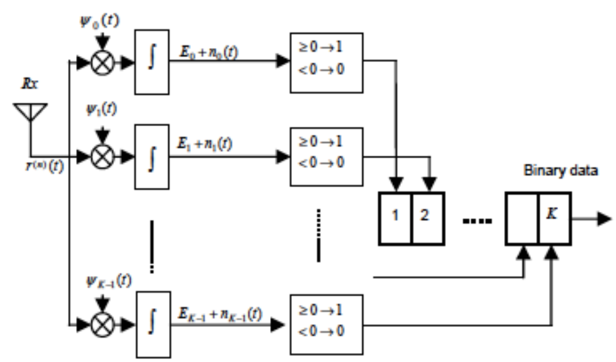


DS-UWB



8-level PSM (PSWF)



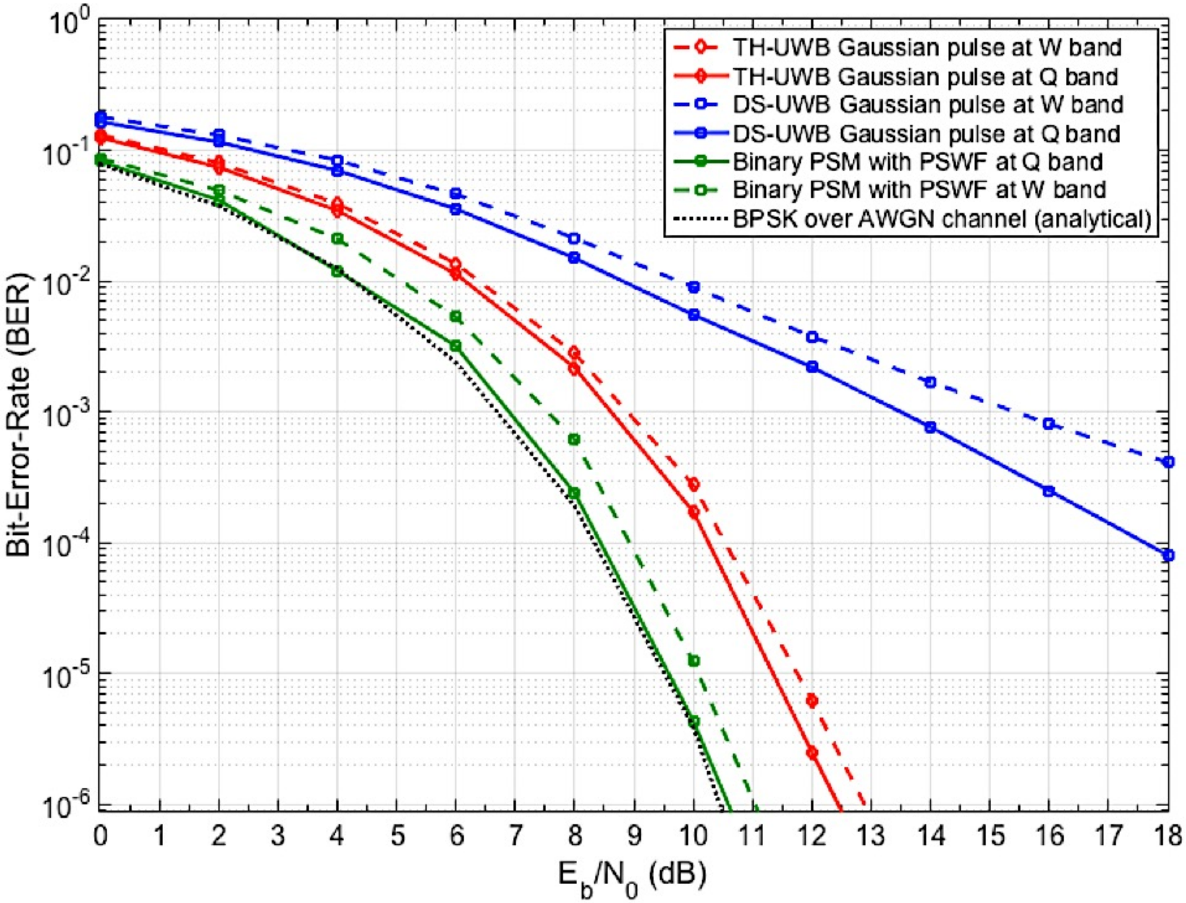


Performance analysis

- **Simulation parameters and setup**
  - Simulations in MATLAB and SIMULINK environment have been performed in order to evaluate the performance of different IR technique in multi-gigabit Q-band (40 GHz) and W-band (83 GHz) satellite transmission;
  - Assessed waveforms: TH-IR (Gaussian monocycle pulse), DS-UWB (Gaussian monocycle pulse) and 2-level PSM with 1st-order PSWF;
  - Spectral efficiency 1b/s/Hz (for all), occupied bandwidth: 5GHz (without channelization);

Parameter	Q band	W band
Carrier frequency	40 GHz	83 GHz
Spectral Efficiency	1 bit/s/Hz	1 bit/s/Hz
HPA OBO	5 dB	5 dB
Phase Noise PSD (1 MHz)	-140 dBc/Hz	-100 dBc/Hz
Phase Noise PSD (10 MHz)	-160 dBc/Hz	-120 dBc/Hz

- **Link performance (Bit-Error-Rate)**
  - Simulation results in terms of BER are shown below:



Performance analysis

- **Discussion of results and practical considerations**
  - 2-level PSM with PSWFs offer the best performance as expected: its very low PAPR allows to effectively face nonlinear distortion. A slight performance degradation is involved by phase-noise (in 4-level PSM is not so slight [Sacchi11];
  - TH-IR satisfactorily performs in the presence of nonlinear amplification and is fairly degraded by phase-noise;
  - DS-UWB is strongly degraded by nonlinear distortion (the detector is matched to the pseudo-noise waveform that is altered by nonlinear amplification) and by phase-noise;
  - The generation of PSWF at very high data rates requires very high sampling rates, not afforded by current state-of-the-art signal processing devices;
  - TH-IR is a good "suboptimal" solution, characterized by the best tradeoff between efficient generation of very short pulses and robustness against mmWave satellite link impairments.

Conclusion and future work

- Impulse radio techniques (used in terrestrial UWB) represent good and viable solutions for robust transmission in mmWave satellite communications;
- The reached spectral efficiency is low, but IR waveforms can easily occupy large spectrum portions with controlled power spectrum level;
- Prolate Spheroidal Wave Functions (PSWFs) with PSM modulation seems to perform better than other IR waveforms, but their generation is still beyond the capabilities of state-of-the-art devices;
- TH-IR is an efficient solution characterized by affordable complexity and easy waveform generation;
- Future work may be related to the direct mmWave waveform generation by means of band-pass filtering of extremely "short" pulses (psec. duration);
- This arrangement would allow to avoid the effects of phase noise, injected by high frequency oscillators and mixers. Some preliminary works are already available in the literature (e.g. [Kraemer07] and [Nakasa08]).

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- For further information, please contact us:

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