Analysis and Design of a Point-to-Point Radio-Link at W Band for Future Satellite Telecommunication Experiments

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Abstract—In the last years EHF (Extremely High Frequency / 30-300 GHz) band is acquiring more and more interest in different fields, such as telecommunications, radar applications and Earth observation, due to advantageous characteristics. Actually, the higher operating frequency with respect to traditional ranges (Ka and lower) allows the achievement of some advantages: no crowding in frequency and hence reduced interference, large bandwidth availability, reduced antenna and electronic components size, and more security in point-to-point links due to smaller beamwidth. Moreover, the increase of frequencies allows the realization of, with respect to lower bands, high resolution applications, as radar images and Earth Observation sensors.[1 2]

However, although W band is an attractive range, it is yet an experimental frontier since no telecommunication mission has been carried out and the technology development at this frequency is still poor, costly and relatively not ready. However, some specific applications, such as radar and radio-astronomy, and just for some frequencies (typically around 94-96 GHz), make an exception.

Considering this context, a very significant and preliminary step to useful W band exploitation for terrestrial and satellite telecommunications is represented by the analysis and the validation of a terrestrial link operating at these frequencies with the capability of carrying out transmission/reception experiments.
In this frame, the University of Rome, "Tor Vergata" in collaboration with the company Rheinmetall Italy is carrying out an experiment based on the establishment of a W band point-to-point terrestrial link over a distance of some kilometers between the University of Rome "Tor Vergata" (Rome) and Villa Mondragone (Frascati, near Rome). The work aims at showing an overview of the preliminary design of the experimental W band terrestrial air link. It will be very useful mainly for two reasons: firstly, in order to provide a test-bed for evaluating atmospheric effects (fading and scintillation, along with amplitude, phase, and polarization distortion) that could compromise the performance of satellite-to-ground communications systems operating at these frequencies; and secondly to verify performance of W band critical technology. The last part of the work investigates the possibility of using, in addition to the traditional approach, Impulse Radio Ultra Wide-Band (IR-UWB) technology for realizing very high bit-rate point-to-point Line Of Sight (LOS) last mile links beyond 60 GHz.

This paper will firstly provide a preliminary orographic and propagation analysis of the terrestrial link. Then, a detailed insight into link architecture and transmitter/receiver schemes will be reported taking into account constraints related to the characteristic of the available HardWare (H/W) in Rheinmetall Italy. Finally, an accurate link budget for dimensioning the system in terms of maximum link capability will be reported.

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1. INTRODUCTION

Since 1998 the University of Rome "Tor Vergata" has been deeply involved in studying and verifying use and potentialities of high frequency in satellite telecommunications, specifically focusing on the lower EHF

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band, ranging from 75 GHz to 110 GHz, already known as W band.
In the last years an increasing interest for such a range has been demonstrated in some fields due to its advantageous intrinsic characteristics such as higher bandwidth availability, minimum oxygen attenuation around 95 GHz, reduced interference and smaller dimensions of antennas. On the other hand, the influence of the atmosphere on signal propagation at these frequencies is considerable and it has to be carefully taken into account in systems dimensioning. Actually, the transmitted signal is more affected as frequency increases (above 10 GHz) by atmosphere (absorption) and by weather conditions (rain, clouds, fog, snow, etc.).
So far, W band has found its main application in radar and radio-astronomy systems. Actually, this frequency range, specifically 94-96 GHz, is currently employed both for terrestrial and space radar applications.
In this framework, a preliminary useful step toward the W band exploitation in satellite telecommunications is represented by the analysis and the validation of a terrestrial link operating at those frequencies with the capability of carrying out transmission/reception experiments. Such experiment could give important feedback from the technology point of view and also for the channel characterization.
Concerning the link establishing, many technological issues have to be faced. The work shows an overview of the preliminary design of such a telecommunication link between the University of Rome "Tor Vergata," at Dept. of Electronic Engineering, and Villa Mondragone. This project, called PERLA-W (acronym standing for Propagation Experiment for a Radio-Link Analysis at W band), mainly aims at carrying out measurements on the channel to understand its behaviour at these frequencies. In this scenario, the propagation channel evaluation and technology validation of a terrestrial air link operating at W band can be envisaged as a first step of strategic worth toward a future phase of development of a telecommunication satellite PayLoad (P/L) at these frequencies. Currently, a terrestrial air link at W band can be considered representative of a more challenging satellite-to-ground link. Specifically, a terrestrial link reproduces many of the dynamic atmospheric conditions experienced by a satellite link, allowing the evaluation of the way atmosphere affects signal propagation and the identification and testing of possible countermeasures, such as ACM (Adaptive and Coding Modulation). Consequently, tests conducted on this terrestrial link would allow the quantification of how to improve the communications performance of the system. This would constitute an expertise acquired on the field to be potentially extended to future satellite links establishment.
Moreover, in addition to W band channel impairments estimation, the validation of technology represents an additional common item to space link. Actually, besides the components and devices space qualification, the reliability of W band technology, being a "technological frontier," needs to be proved on the field, especially for long duration missions (as for channel statistics evaluation). A terrestrial link would provide an easy way of testing different equipment (Low Noise Amplifiers/LNAs, Solid State Power Amplifiers/SSPAs, Local Oscillators/LOs, etc.) through a continuous monitoring to derive worth information on their behavior (including also possible commercial components to be used in future satellites).
Further advantages of a terrestrial link are identified by the following points:

- it allows the acquirement of measurements in a continuous way without suffering from satellite movements (in case of Low Earth Orbits/LEOs);
- it allows the management of the power without severe constraints (as for satellite transmitters);
- no antenna tracking is required (as for LEO satellites);
- it introduces more flexibility in carrying out telecommunications experiments due to the ground-based transmitter and receiver (ease of access).

Moreover, a more affordable feasibility is envisaged from the technical point of view and in terms of costs. In fact, a ground-based link also allows a more accessible and less expensive testing facility than a satellite-to-ground system. On the other hand, the link distance and the signal path are different with respect to space links. However, a preliminary understanding of the channel conditions and the selection of the approach to be pursued for future satellite links could be achieved. At the present state of the art, such an experiment would be the first terrestrial characterization of a W band link for telecommunication experiments. Moreover, it will be an important preliminary test of the technology.
The proposed experiment aims at manifold objectives:

- to demonstrate the theoretical and experimental feasibility of a W band terrestrial link over a significant distance ($\cong$ 7.4 km);
- to carry out transmission/reception experiments of un-modulated and modulated signals (employing different modulation schemes and evaluating the BER);
- to evaluate attenuation phenomena for different observation times and weather conditions;
- to test W band technology (with special attention to commercial equipment and devices).

The feasibility of the proposed link will be evaluated through a theoretical approach followed by an experimental phase. From a technological point of view, the feasibility of the link shows some criticalities. At first, the microwave technology at W band is currently poor and few developed at applications level, due to the lack of a significant market providing the necessary funding. Therefore, its use is currently limited to the research in radio-astronomy and cosmology, where signals at such frequencies and higher are passively collected to study interstellar and cosmic sources. Consequently, the technology is just available through ad-hoc (and so, costly) developments and at particular frequencies, depending on the research topic (for instance, some specific emission lines by interstellar molecules). Another item to be considered is the precise pointing requested to align Transmitter (Tx) and Receiver (Rx) antenna over a path of 7.4 kilometers and the related logistic problems related to maintain fixed antennas for 3-6 months.

2. OROGRAPHIC AND PROPAGATION ANALYSIS

The state of art on terrestrial links up to now developed at EHF shows that just 2-3 experiments were carried out, but their results are not available in literature and especially no publications were found about their conclusions [1], [2], [3]. Therefore, although some experiments were carried out in the past, nowadays no experimental telecommunication link is performed at EHF band and especially at W frequency. This section is devoted to provide an orographic analysis of the W band terrestrial link between Tor Vergata University, at Electronic Department, and Villa Mondragone, Frascati. In order to investigate the clearance of the first Fresnel's ellipsoid, some information about the environment involved in the propagation has to be well-known. First of all, the heights (meters from the sea level) of places located under the straight line between Tx and Rx antennas have to be provided. There are several methods of obtaining elevation information of a given point on the Earth, due to the high number of missions funded by some world's space agencies [4]. SRT (Shuttle Radar Topography) Digital Elevation Model (DEM) has been used in order to derive detailed information about the orographic profile of places along the point-to-point radio-link between Electronic Department of University of Rome "Tor Vergata" and Villa Mondragone.

Moreover, at frequency above about 2 GHz, diffraction fading represents one of the biggest challenges in the design of a Line Of Sight (LOS) radio-links.

This effect has in the past been alleviated by installing antennas that are sufficiently high, so that the most severe ray bending would not place the receiver in the diffraction region when the effective Earth radius is reduced below its normal value. Diffraction theory indicates that the direct path between the transmitter and the receiver sides needs a clearance above ground of at least 60% of the radius of the first Fresnel zone to achieve free-space propagation conditions [5].

Recently, with more information on this mechanism and the statistics of that is required to make statistical predictions, some administrations are installing antennas at heights that will produce some small known outage. In the absence of a general procedure that would allow a predictable amount of diffraction loss for various small percentages of time and therefore a statistical path clearance criterion, the following procedure is advised for temperate and tropical climates.

On the basis of procedures reported in [5], the analysis of the first Fresnel ellipsoid has been carried out, taking into account the Earth bending over the path and the tropospheric bending. The result is reported in Figure 1. Figure 2 and Figure 3 show a detail of Tor Vergata and Villa Mondragone sites respectively. They confirm that the link is not affected by diffraction phenomena being the first Fresnel ellipsoid not intersected, confirming the preliminary analysis carried out through Global Mapper [6]. Therefore, a line-of-sight link (the straight line connecting Tx/Rx) does not cross the red line, which represents the estimated height for which the Fresnel ellipsoid is crossed. Moreover, we have demonstrated through Fresnel analysis that no strict requirements on antenna positioning have to be satisfied.

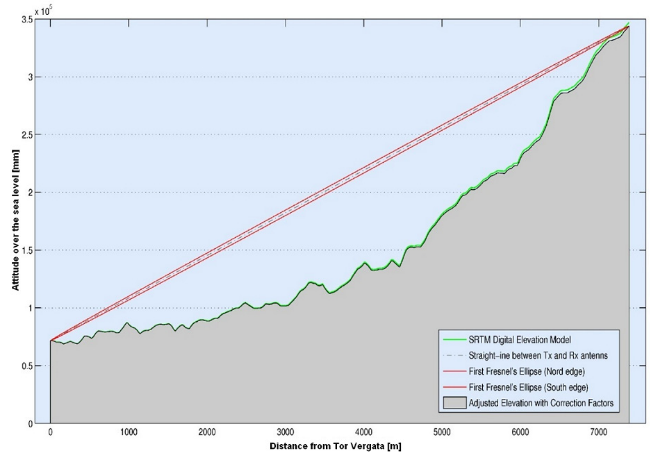

Figure 1 - Orographic profile and straight line between Tor Vergata University and Villa Mondragone

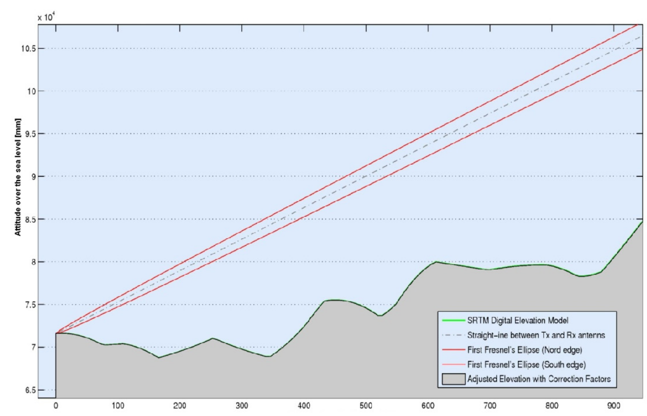

Figure 2 - Orographic profile at Tor Vergata side

The procedure reported in [5] provides a significant contribution in order to calculate the medium behavior through appropriate propagation prediction methods and data. Following it, some considerations have been carried out to investigate the channel behavior at W band, from a theoretical point of view. Several propagation effects have to be considered in the design of line-of-sight systems.

These include:

- free-space attenuation;
- attenuation due to atmospheric gases;
- fading due to atmospheric multi-path or beam spreading (commonly referred to as defocusing) associate with abnormal refractive layers;

- fading due to multi-path arising from surface reflection;
- attenuation due to precipitation;
- attenuation due to solid particles in the atmosphere;
- variation of the angle-of-arrival at the receiver terminal and the angle-of-launch at the transmitter terminal due to refraction;
- reduction in cross-polarization discrimination in multi-path or precipitation conditions;
- signal distortion due frequency selective fading and delay during multi-path propagation.

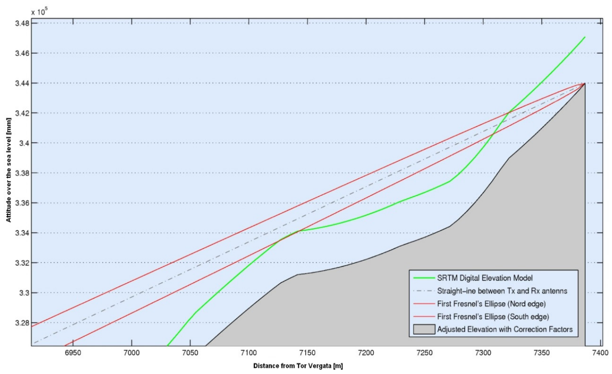

Figure 3 - Orographic profile at Villa Mondragone side

In order to design Tx and Rx architectures we have to know the behavior of the W band channel during the propagation of an electromagnetic radiation. Figure 4 shows the total attenuation due to atmospheric gaseous over the path from Tor Vergata to Villa Mondragone, which should be considered in the link-budget. It is clearly visible how the attenuation at 96 GHz is approximatively 2.7 dB, whereas the ones obtained from (yellow line) Figure 5 is slightly greater (3.058 dB). This behavior can be considered as confirm of the theory at the basis of this phenomenon, which foresees a reduction of the atmospheric absorption with the increase of the height over the sea level.

3. Link Architecture and Capability

On the basis of the previous analysis, the link architecture has been defined. This architecture, reported in Figure 6 and Figure 7, is the result of a trade-off between the experimental need of a telecommunication link and the availability of components and devices by RHI or by COTS (Commercial Off The Shelf). Moreover, an important driver considered is the need to maintain costs as low as possible (being the experiment led by the University). Therefore, we decided to approach the test-bed design and development through two drivers:

- trade-off between the scientific objectives and the technological feasibility, based on maximizing reuse of components and devices already developed or purchased, exploiting the long theoretical and experimental expertise and background provided by RHI;

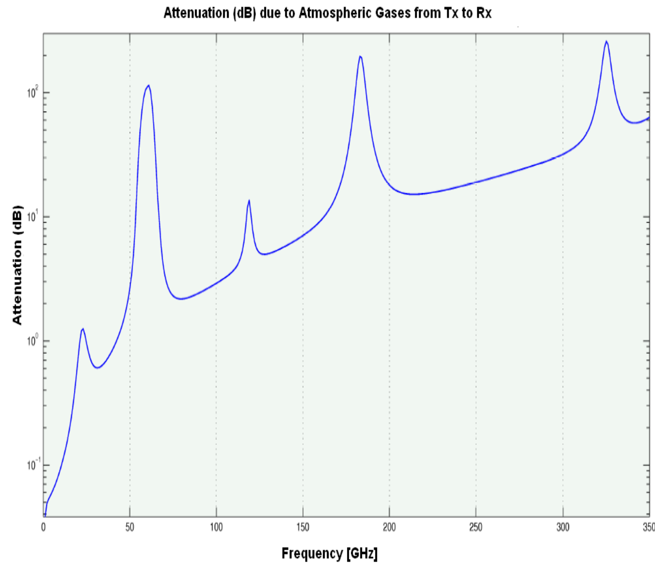

Figure 4 - Total attenuation due to atmospheric gases along the path from Tor Vergata to Villa Mondragone

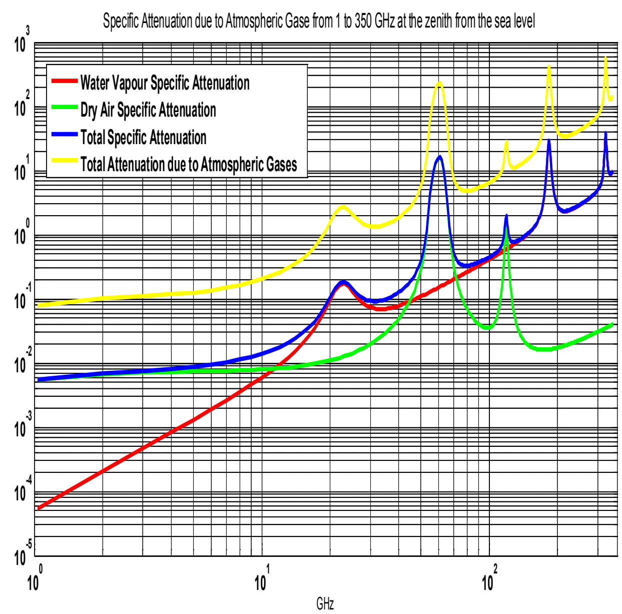

Figure 5 - Specific attenuation due to atmospheric gases from 1 to 350 GHz at the zenith from the sea level with a density of 7.5 g/m³

- minimizing the purchase of new components and at the same time to assign priority to European companies.

3.1 PERLA-W Tx and Rx Architectures

The PERLA-W Tx Architecture is based on the DDS logic (Direct Digital Synthesis) which allows for generating signals through the so-called Software Defined Radio (SDR), simplifying in this way the signal generation. Moreover, it presents a good flexibility allowing the generation of both un-modulated and modulated signals with

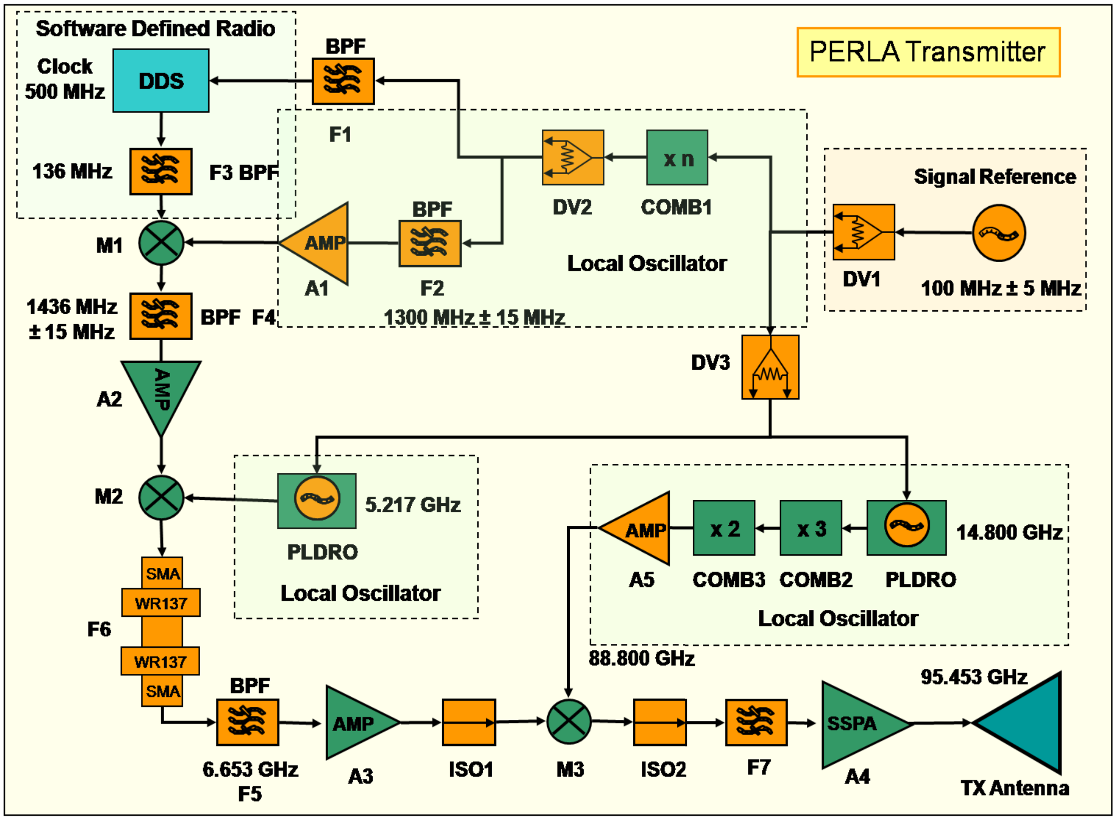

Figure 6 - Perla-W Transmitter architecture

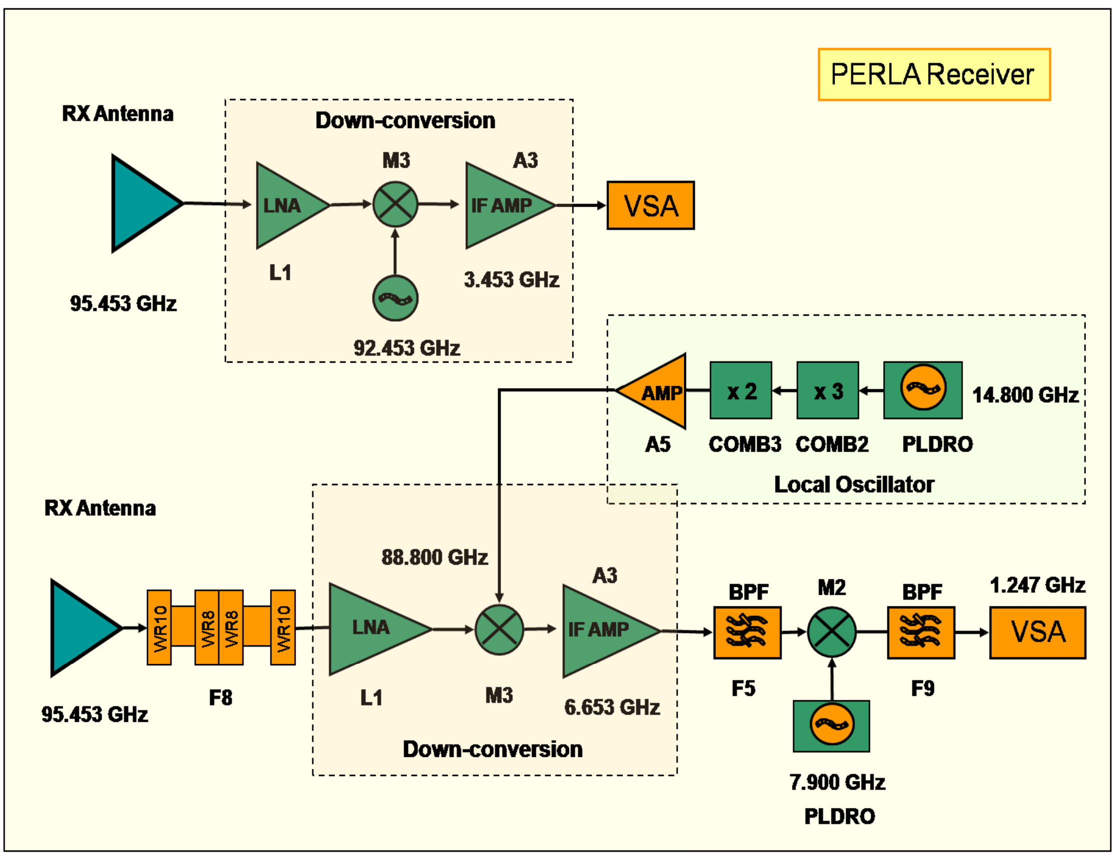

Figure 7 - Perla-W Receiver architecture

a large possibility of choice in terms of modulation types and data rate. This characteristic will be useful during the experimentation of the link on the field. Basically, a reference signal at 100 MHz through following multipliers drives the DDS providing the clock signal at 500 MHz. At the output the DDS, after proper filtering, provides a signal at 136 MHz that is afterwards mixed with another signal at 1300 MHz, generated through a secondary path from the initial signal reference at 100 MHz, creating an output at 1436 MHz signal, the latter one is amplified and then up-converted though mixing with a local oscillator at 5.2 GHz (Locked Dielectric Resonator Oscillator (PLDRO) based). The output signal at 6.65 GHz is then spectrally cleaned from the lower frequencies by using a junction SMA/WR137-WR137/SMA, exploiting the typical cut-off frequency of waveguides. After a new amplification and filtering, the processed signal is again up-converted by mixing it with a local oscillator at 88.8 GHz and generating a 95.5 GHz output. As before, this local oscillator is based on a basic PLDRO at 14.8 GHz and provides the necessary output through two multipliers. Both PLDROs used are driven by the original reference signal at 100 MHz. Finally, an SSPA provides the needed power to be sent to the antenna.

A similar scheme was derived for the receiver, as shown in Figure 7. Basically, after signal receiving at 95.5 GHz, the signal is filtered by using a strategy similar to that one used in the transmitter. A junction WR10/WR8-WR8/WR10 allows the elimination of all the higher frequencies exploiting the cut-off frequency of the waveguide WR8. Afterwards, a LNA amplifies the signal and send it to the mixer where it beats with a local oscillator signal at 88.8 GHz. Then the signal is amplified at IF frequency 6.65 GHz, filtered and again down-converted through a local oscillator at 7.9 GHz (PLDRO based). At last, the received signal can be analyzed by means of a Vector Signal Analyzer (VSA). Considering such schemes, at present the most critical component is represented by the SSPA, while all the other devices can be developed by ourselves or purchased by European companies. Obviously, the theoretical study of the link is just at the beginning, hence further improvements in the Tx/Rx architecture will be introduced. Actually, these schemes and specifically the signal level along the chain need to be compliant with the link budget from which derives the specifications of the SSPA.

4.1 Link Capability

In this section we want to make some transmission hypothesis in order to quantify the power needed at the input of the transmitter antenna, to face toward the attenuation phenomenon and to assure the BER conditions suggested by the quality constraints. On the basis of spectral occupation of the modulated signal, different link budget conditions must be considered; actually, this depends on the modulation approach used and the bandwidth of un-modulated signal. Figure 8 shows the link budget for an uncoded Q-PSK with a data rate of 20 Mbps, considering a commercial SSPA subsystem based on the use of two 150 mW FPA-10-19-21 modules fabricated by Farran [8] and assuming a percentage of time of 99.9% for service availability. It is clear how the SSPA subsystem is one of the most relevant drivers in order to improve the performance link, together with a suitable coding. Moreover, the use of a Horn Antenna with a gain of 25 dBi at receiver side does not allow the achievement of a positive system link margin. Therefore the use of higher gain antennas is needed. However, the realization of a Cassegrain-to-Cassegrain radio link over a distance of more than a few km is a really hard task due to their extremely high values of directivity. Hence, high performance pointing systems are required in order to use Cassegrain reflectors at both Tx side and Rx one: in fact, very small vibrations at the support of the antennas could mean the totality absence of signal at the receiver side.

W band Link Villa Mondragone - Univ. Tor Vergata						
Parameter:	**Value:**	**Units:**	**Comments:**			
Tor Vergata Tx						
Pt (Transmitter Power Output):	0.300	Watts				
In dBW:	-5.23	dBW				
In dBm:	24.77	dBm				
Transmission Line Losses:	0.20	dB				
S/C Connector, Filter or In-Line Switch Losses:	1.50	dB				
Tx Antenna Diameter	0.45	m	**Cassegrain**	45816H1124		
Efficiency	0.60					
Tx Antenna Gain	50.89	dBi				
TxTheta3dB	0.49	degrees				
Depointing	0.14	degree				
Effective Isotropic Radiated Power (EIRP):	43.96	dBW	Effective Isotropic Radiated Power			
Cross polarization Discrimination (XPD)						
In dBm:	73.96	dBm				
Tor Vergata Tx - Villa Mondragone Rx						
Transmission Antenna Pointing Loss:	1.00	dB				
Antenna Polarization Loss:	0.00	dB				
Frequency (Carrier)	9.60E+10	Hz				
Wavelenght	0.00313	m				
Outage Probability (1-δ(t))	0.01000					
Distance	7.4E+03	m				
Free Space Loss:	149.5	dB				
Atmospheric Loss:	2.60	dB	(1-δ(t)) =0.1 %			
Multipath Loss:	33.89	dB	(1-δ(t)) =0.1 %			
Rain Loss:	23.52	dB	(1-δ(t)) =0.1 %			
Isotropic Signal Level at Ground Station:	-166.50	dBW	EIRP/(Final Att.)			
Villa Mondragone Rx						
Receive Antenna Pointing Loss:	2.03	dB				
Rx Antenna Lunghezza	0.45	m				
Efficiency	0.60					
Rx Antenna Gain	50.89	dBi				
RxTheta3dB	0.49	degrees				
Depointing	0.20	degree				
LNA Noise Temperature:	864.51	K				
Transmission Line Temp.:	290	K				
Antenna Sky Temperature:	100	K				
Transmission Line Coefficient (L):	0.90					
Transmission Line Coefficient (L dB):	-0.46					
Ts System Noise Temperature:	943.40	K	Maral-Bousquet			
G/T (Gain to Noise Temperature Ratio):	20.69	dB/K	M=2 for QPSK			
C/No (Carrier-to-Noise Power Density):	80.76	dBHz	-228.6	dBW/K/Hz		
Bn (PLL Noise Bandwidth):	2.00E+07	Hz				
C/N (Carrier-to-Noise Ratio):	7.74	dB				
			M=2 for QPSK			
Rsource (source bit rate):	2.00E+07	bps				
Tb (source bit duration):	0.0000000500	s				
M (number of bits per modulated symbol):	2					
R1 (inner code rate):	1.0000000000					
R2 (outer code rate):	1.0000000000					
Rb (channel bit rate):	2.00E+07	bit/s				
Rs (channel symbol rate):	1.00E+07	symbol/s	uncoded QPSK			
Eb/No:	7.74	dB				
Es/No:	10.76	dB				
Downlink Required Es/No:	10.5	dB	uncoded QPSK			
System Link Margin:	0.26	dB				

Figure 8 - Link Budget at 96 GHz – Uncoded QPSK-Data Rate 20 Mbps (Max Performance considering a commercial SSPA Subsystem using two 150 mW modules - Output Power = 300 mW (Linear)) -99.9% Link Availability

5. UWB Approach

In the perspective of reaching global and ubiquitous wireless connectivity, the satellite segment will play a key role. The claimed objective is to reach the so-called “gigabit connectivity” in order to make the satellite segment a potential “backbone on the air” for next-generation digital communication services, characterized by high-speed and stringent quality-of-service (QoS) requirements [9]. Such an ambitious objective is not realistically achievable by exploiting currently saturated bandwidth portions (Ku and Ka bands). For this reason, the push towards higher frequencies will characterize future R&D on satellite communications [10]. It is known that the non-ideal behavior of H/W components has a significant impact on global performance of satellite communication systems. Increasing the carrier frequency, these kinds of impairments may also substantially increase their impact. Moreover, path loss and rain fading to which a W band signal is subjected along its propagation path may be very relevant. Therefore, power resources at these frequencies are generally quite scarce and should be intensively exploited.

In order to answer the need of a communication system that is robust to RF non-idealities and very high EHF impairments and at the same time able to deliver multi-gigabit/s data rates, a joint design of the RF and baseband parts could represent an unavoidable path to follow. Moving this direction, we wonder if impulse-radio communications, such as IR-UWB could represent a suitable choice for the satellite physical layer. For this reason, we will try to apply this approach to an advanced version of the W band terrestrial link in order to validate this idea and to achieve useful considerations.

Therefore, the final part of work has at its core the design and BER (Bit Error Rate) performance evaluation of an IR-UWB architecture based on an 85 up-conversion stage of train of Gaussian pulses having duration lower than 1 ns.

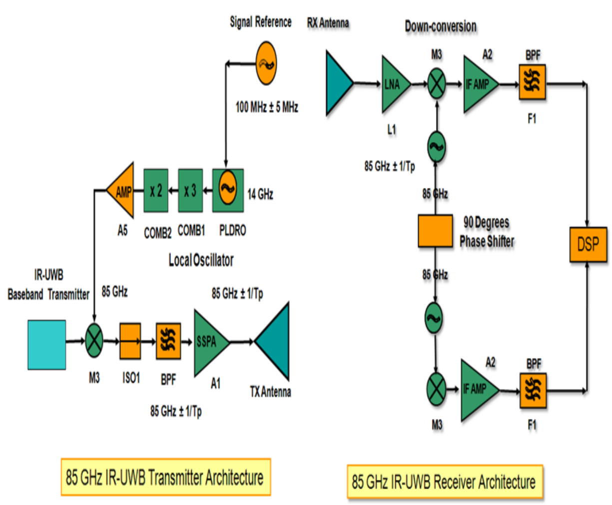

Figure 9 - 85 GHz IR-UWB Transceiver Architecture

In the scheme reported in Figure 9, the UWB baseband transmitter generates very short Gaussian pulses. One transmitted symbol is spread over N_s monocycles to achieve processing gain that may be used to combat noise and RF distortions. To eliminate catastrophic collisions in multiple accessing, an additional time shift, unique to each user, is added to each pulse in the pulse train. Finally, an additional time shift is introduced for each pulse through the PPM technique: when the data symbol is 0, no additional time shift is modulated on the monocycle, but a time shift of δ is added to the pulse waveform when the symbol is 1.

Therefore, the PPM (Pulse Position Modulation) TH (Time Hopping) IR UWB signal for *k*th user is given by [12]:

$$s^k(t) = \sum_{j=-\infty}^{+\infty} \mathrm{A}^k_{d[j/N_s]}\, p\left(t - j\mathrm{T}_f - c_j^{(k)}T_c - \delta^{(k)}_{[j/N_s]}\right) \qquad (1)$$

where $\mathrm{A}^{(k)}$ is the signal amplitude, $p(t)$ represents the second derivative of Gaussian pulse, with pulse width T_p, T_f is the frame duration (a frame is divided into N_{th} time slots with duration T_c). The pulse shift pattern $c_j^{(k)}$, $0 \le c_j^{(k)} \le N_{th}$ ($N_{th}T_c = T_f$) is the time hopping sequence for the *k*th user and it is pseudorandom with period T_c. $\delta^{(k)}$ is the additional time shift introduced by PPM, as described above. The baseband signal is then up-converted using an 85 GHz oscillator, amplified by the SSPA and then transmitted.

The UWB transceiver shown in Figure 9 uses a direct conversion scheme, thereby eliminating the need of image rejection filter and complicated phase synchronization circuits. In receiver, the received signal is first amplified by an LNA, and then it is down-converted to baseband by two 85 GHz oscillators operating in phase and quadrature. I and Q components are low pass filtered and fed to the DSP (Digital Signal Processing) section. Here they are combined, demodulated and decoded.

Finally, we compare performance of this architecture with the ones of a more traditional continuous wave communications system based on FSK (Frequency Shift Keying) modulation (with same data rate and bandwidth occupation).

Figure 10 shows that BER performance, in presence of RF non-linearities (mainly in terms of phase noise effects, LNA and SSPA distortions [12]), for an IR-UWB transceiver architecture operating at 85 GHz are better than a coherent BFSK scheme working in a similar scenario (14 dB against 17.1 dB for a BER of 10^{-3}), while they are worse considering the ideal case (13 dB against 11 dB corresponding to a BER of 10^{-3}).

6. Conclusions

In this paper, an overview of PERLA-W experiment was provided. The main purpose of the experiment is to carry out a communication link at W band and to test its performance in terms of attenuation and BER of the data transmitted. The main characteristics of the experiment were introduced along with its objectives and technological criticalities. Details were provided about the orographic and propagation analysis along with insight of transmitter and receiver schemes. Finally, an overview of UWB approach was shown as a promising evolution to answer the need of a communication system that is robust to the non-idealities and also able to deliver very high data rates (of the order of multi-gigabit/s).

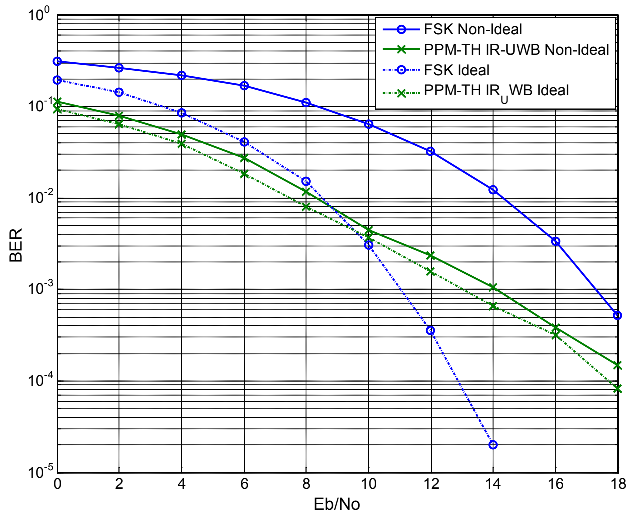

Figure 10 - PPM-TH IR-UWB vs. single carrier FSK BER performance analysis, considering RF non idealities

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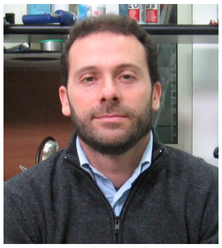
BIOGRAPHY



Marco Lucente *received his University Degree in Physics with specialization of Astrophysics and Space Physics in 2002 from the University of Rome "La Sapienza". He was involved in studying the polarimeter of the BOOMERanG (Balloon Observation of Millimetric Extragalactic Radiation and Geophysics) experiment. He received a MSc Degree cum laude in "Advanced Communication and Navigation Satellite Systems" at the University of Rome "Tor Vergata" in 2004/2005. Since the beginning of 2004, he has been a scientific member of the WAVE (W-band Analysis and VErification) project team.*

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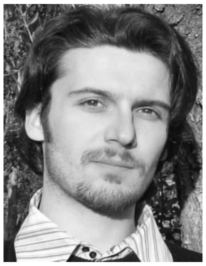

Tommaso Rossi *received his University Degree in Telecommunications in 2002, MSc De gree in "Advanced Communications and Navigation Satellite Systems" in 2004 and PhD in Telecommunications and Microelectronics in 2008 at the University of Rome "Tor Vergata" where he is currently an Assistant Professor (teaching Digital Signal Processing). He is a member of the Italian Space Agency WAVE (W-band Analysis and VErification) Project Technical Team, a feasibility study for W-band telecommunication payloads. He is part of the scientific team that is defining TDP#5 payload embarked on ESA Alphabus satellite. He has been a technical member of the ESA research project on Flowers Constellations. He has been involved in European Space Agency "EDRS" (European Data-Relay Satellite System) project.*
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