Optical Links for Fast and Secure Communications on Ground and in Space

Sergio Mottini
Thales Alenia Space Italia, Str. Antica di Collegno 253, Torino
ITALY

sergio.mottini@thalesaleniaspace.com

Luciana Bonino
Thales Alenia Space Italia, Str. Antica di Collegno 253, Torino
ITALY

luciana.bonino@thalesaleniaspace.com

ABSTRACT

The interest in fast and secure optical communication link has grown in the last years driven by the increasing demand in data throughput for applications spanning from small satellites for global services to large satellites for secure communications, from Earth Observation distributed sensing networks to CubeSat constellations for in-orbit inspections of large satellites; in addition particular interest is also demonstrated by military market. Moreover, besides speed, in modern information society the secure communications are of the utmost importance: confidential and authenticated transfer of data between companies, financial institutions, military operators and public administration is crucial for maintaining the competitiveness of industry and increasingly it is also important for individuals. And optics offer new revolutionary tools to provide security in an unprecedented manner. This paper shows how this objectives are going to be reached.

1.0 INTRODUCTION

The market for optical data link constellations and HTS feeder links is very active and competitive; there is a new diffused tendency to propose the use of mini and micro satellites for the space activities related to optical data link networks. The interest on satellite optical communication link has grown also in the science domain, driven by the increasing demand in data downlink for scientific, planetary exploration and earth observation missions; in addition particular interest is also demonstrated by military and commercial market not only for the high data rates achievable but also for the security levels: low probability of intercept, quantum cryptography.

And all this in a wide variety of possible scenarios: space-space, space-ground, space-aircraft, ground-ground links, suitable to different kind of users with different purposes.

Free space optical communication systems (FSO) answer to specific needs for satellite communication technologies, fitting with the objective of moving towards the Terabit-throughput satellite systems or target constellations in lower Earth orbit, making use of laser-based optical communication terminals.
FSO communications is the technology which offers the possibility of breaking the bottleneck of radio frequency link by using an optical carrier with a frequency 10,000 times higher than in RF. Today optical communication systems using optical fibres already reach even beyond 1 Terabit/s capacity thanks to the dense wavelength division multiplexing (DWDM) technology. FSO demonstrators above 1 Tbps have been realized on ground. The activities described in this paper aim at extending the use of these technologies into space, as already planned (and funded) by most of the NATO Member States and by NASA and the

European Space Agency (e.g. the ARTES programme).

2.0 OPTICAL VS. RF

FSO communications are based on similar concept developed for radio frequency communication systems (RFS), in terms of system architecture and physical parameters that provide the communication behaviour. The main difference between the two systems is that FSO uses light (frequencies of hundreds of Thz) as carrier to transfer information while RFS uses electromagnetic waves with a much longer wavelength (in the MHz and GHz domain). The propagation channel properties in the two cases (optical and RF) lead the application fields and mission scenario of the two communication systems (FSO and RFS).

A remarkable advantage is represented by the fact that optical communications working at optical frequencies permits to use devices with very large modulation and demodulation bandwidth allowing much higher bit rate inaccessible to RF communications.

The expected bit rate for a typical FSO link is in the range between some hundreds Mbps (for deep space communications) to some tens of Gbps depending on distance, laser output power and telescopes (optical antenna) size. These transmission speeds cannot be reached with an equivalent RF transmission systems (i.e. same dimensions, mass and power). To cope with similar bit rate, an RF communications system would need larger antennas for both terminals (in order to reduce beam divergence) and / or greater power in the transmitter (which means, for space applications, larger S/C with larger power systems). Ground antennas are already large, but intensifying power also the side lobes become energetic as well, and the problem of interception (e.g. for military applications) becomes a concern. FSO systems are free from all these problems.

The increase in high-speed data link and data handling capability of satellites and planned satellite clusters has reached a point that calls for the wide implementation of free-space laser communication links. The advantage related to the possibility of dealing with a huge data volume is related to the positive impact on the expanded content of the mission (or the reduction of mission duration) and on the duration of the required on-board processing (also considering that raw data are always more interesting as they may contain hidden significant information). Also the possibility of a faster data uplink has advantages, related to faster upload of observation planes, of planned SW upgrades and of SW bug fixing activity.

Then, also the possibility to use mobile portable Optical Ground Stations (OGS) increases flexibility of this technique, allowing e.g. a laboratory to receive directly data originated by its instrument.

The characteristics of laser communication beam in FSO implies the following considerations:

- The relative small beam aperture and the high gain of the transmitter and receiver antenna (implemented with telescope) in the optical domain mean narrower beam width with respect to RF systems, making difficult the possibility of intercepting the data stream. As counterpart, it requires an accurate tracking acquisition and pointing system, one order of magnitude more accurate compared to the RF Systems
- FSO, which is highly directional, is a typical point to point communication; broadcast requires an additional optical communication networks (e.g. satellites constellation)
- In general, power budget is proportional to the system communication carrier frequency squared, so being FSO frequency carrier much higher with respect to RF system case, less transmitter power and larger link distances can be attained while maintaining the same performance

From above considerations, it is clear that an optical communications network provides, besides the increased data throughput, additional competitive advantages compared to conventional RF systems:

Huge modulation bandwidth – In any communication system, the amount of data transported is directly related to the bandwidth of the modulated carrier. The allowable data bandwidth can be up to 20 % of the carrier frequency. Using an optical carrier whose frequency ranges from 10^{12} – 10^{16} Hz could thus permit up to 2000 THz data bandwidth. Optical communication therefore guarantees an increased information capacity compared to radio frequency based communication systems. This is simply because on the electromagnetic spectrum, the optical carrier frequency, which includes infrared, visible and ultra violet frequencies, is far greater than the radio frequency. The usable frequency bandwidth in RF range is comparatively lower by a factor of 10^5.

Narrow beam divergence – The beam divergence is proportional to λ/D, where λ is the carrier wavelength and D the aperture diameter. Thus, the beam spread offered by the optical carrier is narrower than that of RF carrier. The optical radiation is known for its extremely narrow beam, a typical laser beam has a diffraction limited divergence of between 0.01 – 0.1 mrad . This leads to increase in the intensity of signal at the receiver for a given transmitted power or a larger link distance. This implies that the transmitted power is only concentrated within a very narrow area, thus providing an FSO link with adequate spatial isolation from its potential interferers. The tight spatial confinement also allows for the laser beams to operate nearly independently, providing virtually unlimited degrees of frequency reuse in many environments and makes data interception by unintended users difficult. Conversely, the narrowness of the beam implies a tighter alignment requirement.

Operating on non-regulated frequencies – Optical frequencies are not regulated and due to their highly focused beam (see also security aspect) are less prone for interference. This avoids the need of frequency fillings for a communication constellation, thus clearly reducing legal and administrative risks. In addition, the lacks of regulations give the system operator a much higher freedom to utilize and deploy the system in line with customer needs. If e.g. demand in a certain geographical region increases, this demand can be easily satisfied with increased bandwidth, while in conventional RF either new frequency slots have to be requested or the market might not even be servable as no frequencies are available. Thus the freedom to deploy the system and the freedom to scale and adjust the communication capacity to needs and not to regulatory constrains provide a great benefit. In addition an optical satellite network does not interfere with existing satellite or terrestrial infrastructure reducing development and operational complexity.

More bits per Watt/Kilo – The high data rates achievable with optical frequencies can also be translated in a much more fundamental advantage of the technology that has quite a significant impact . Optical frequencies allow transmitting more bits per required Watt/Weight. an optical terminal would use less on-board resources and such would enable a smaller and less complex design, e.g. a satellite could reduce the size of solar panels and batteries, with lower costs and the possibility of either deploying more satellites or enabling a more cost efficient satellite system. Also launch costs would benefit of smaller weight. Or in case of providing similar on-board resources as for an conventional RF System, it is possible to significantly increase the data throughput, thus providing a more capable system for similar satellite and launch costs. a smaller wavelength of optical carrier permits the FSO designer to come up with a system that has smaller antenna than RF system to achieve the same gain (as antenna gain scales inversely proportional to the square of operating wavelength). Moreover the narrower beacon provides higher power density making sufficient a smaller antenna to collect the same power.

Inherit security – An optical link is a point-to-point connection that has an inherent security due to the highly focused nature of the communication beam. E.g. in case of a LEO-to-Ground communication the footprint diameter on the ground of the laser signal is about 100 m, which makes it almost impossible to intercept the signal without the receiving entity to notice. The same is true to inter-satellite communication thus making it impossible to intercept and spoof an optical communication link. Therefore this built-in security could further reduce the cost as on-satellite encryption systems might not be necessary to protect the signal and given the increased interest in secure communication, might provide an inherent competitive advantage of an All optical satellite system. Furthermore, an optical communication link from satellite opens the path to a quantum key distribution system, thus allowing such an all optical satellite system to provide a highly secure communication system, that is difficult to intercept and provides the highly secure data keys for further encryption on the ground.

3.0 SECURE OPTICAL COMMUNICATIONS

National security agencies and military infrastructures and alliances, such as NATO, has to deal with many factors, in current worldwide sensible panorama, in order to ensure security and confidentiality of exchanged information and of all communication links carrying classified data.

Communication Security (ComSec) has the objective of defending and protecting information from unauthorized interception, use or modification of communications networks in a global sense, from voice to images, to data.

The heart of communication security is the CIA triad (Confidentiality, Integrity, Availability) (Figure 1)

Figure 1: The CIA security triad

The CIA triad is a highly diffused model for security policy development which provides a benchmark of parameter, with the inclusion also of identity authentication, which we have to protect against those that can attack our communication system.

Confidentiality ensures that the information is not disclosed to unauthorized individuals or entities. Usually, confidentiality can be saved by suitable cryptographic techniques. In this case we don't avoid the signals and related messages could be captured by a malicious actor, but we only want the meaning of the messages (semantic) could not be decoded.

Integrity aims at assuring the accuracy and completeness of data from sender to receiver; it is usually referred as the capability of saving the signal/message from corruption, or at least, of detecting the happened corruption it may concern either the physical signal or the message. Its importance in the navigation field, for instance, is paramount (e.g.: think to GALILEO navigation system and its Integrity Monitoring network or to EGNOS and to the several Agency studies about this topic). To detect if a message has been altered, either intentionally or unintentionally, many techniques have been developed, from the error-detecting codes used to compensate for noisy channels up to the digital signatures. They differ for goals and usage scenario: Hash usage is the base technique.

Availability is the system capability of allowing easiness in data accessibility, also in terms of continuity and/or rapidity.

Finally, **Identification** and verification of a claim of identity (**Authentication**), for system/service access purposes, is very important for any type of SecCom network.

Thales Alenia Space Italia (TAS-I) has been recently awarded (2012-2014) from ESA for a study to investigate the application of secure optical communication to next generation of navigation systems (GNSS), which are envisaged to be driven on the one hand by increased navigation performances (in terms of accuracy, integrity, continuity, availability), and on the other hand by dual-use operation entailing increased robustness / resilience / security.

The GNSS navigation systems belong to the domain of Radio-Navigation which, in turn, bases its theoretical basis in statistical theory of communications. Some of the NavCom application domains where security aspects play a relevant role are:

- Air Traffic Management (e.g.: UAS);
- Intelligence, Surveillance & Reconnaissance (ISR) via Remote Sensing;
- Location Based Telemedicine Services;
- Maritime Traffic Management;
- Financial Transactions Control;
- Wireless Networks Access Control;
- Etc.

And the list, well known in literature, of possible threats for NavCom systems is:

- Physical tampering, of the associated circuits, of the sensors control software, or even replacement with malicious sensors under the attacker control;
- Physical Interference, which can interrupts, obstructs or otherwise degrades or limits the effective performance of the architecture of global communication.
- Physical Jamming and scrambling , i.e. the deliberate radiation or reflection of electromagnetic energy to damage the link;
- Data Link Interception, Monitor and Eavesdropping, which is an effective violation of the privacy;
- Communication
- Data link Protocol Violation, with the attempt to generate continuous collisions
- Network Spoofing, to generates radio signals that mimic a useful signal and spread it on the same frequency to deceive network operations.
- Network Meaconing, i.e. system which intercept the signals and retransmits them on the same frequency to confuse network operations.
- Network Traffic Analysis, to identify a number of sensors with special roles or activities;
- Network nodes camouflage, in which opponents can insert their node or compromise nodes to hide in the sensor network.
- Transport Flooding, consisting in sending many connection requests to a sensitive node which

allocates all the requested resources until is saturation and is consequent inoperability.

Optical communications addresses the ComSec problem at two levels: transmission security but also cryptography. Besides the 'confidentiality' provided by the narrow beam width and the accurate beam pointing, optical communications provides another revolutionary tool to address the problem of secure communications, i.e. the question of data cryptography. Today a breakthrough in mathematics or computer science could make current electronic data transfer encryption methods (such as SSL or RSA) instantaneously vulnerable. This is because the security of classical cryptography in use today relies on the (currently unproven) computational difficulty of certain mathematical functions. Hence, classical cryptography does not guarantee absolute and unconditional security, and any future quantum computer would enable solving exactly the mathematical functions in use today to encrypt data in polynomial time. Modern quantum cryptography, often also called quantum key distribution (QKD), looks essential in order to avoid that any quantum computer would be able to capture the plain text from the encrypted message within a very short time frame compared to its classical counterpart.

Quantum Mechanics is one of the most revolutionary and successful physical theory of the last century we have and its predictions have been up to now verified with very high precision in experiments that no classical theory can otherwise explain.

In recent years research into the very foundations of Quantum Physics has also led to a new field: quantum information technology, which carries the potential to revolutionize the way we communicate and process information. This conceptual revolution is based on the idea that information is not independent of the physical laws used to store and processes it. Therefore, in this new approach, the information is treated as a quantum concept. While the elementary quantity of classical information is the bit, which can take on one of two well defined states (0 or 1), in Quantum Information Theory the basic system in which information is encoded is the qubit, which is a coherent superposition of quantum states $|0>$ and $|1>$. Important consequences of this new approach are the impossibility to make a perfect copy of a qubit (no-cloning theorem), and the possibility to share correlations stronger than any classical correlation between distinct parties (quantum entanglement). These new features can be exploited in new information processing protocols with enhanced performance and capabilities. Among these new protocols, the most successful ones are: Quantum Key Distribution, the topic of this discussion, and quantum teleportation, related to the fascinating (and bothering) concept of Quantum Entanglement, according to which two entangled particles (for example two electrons or two photons) are described by means of a global wave-function which reveals itself as a "spooky action at a distance".

The general cryptographic scheme for secure communication is called symmetric key cryptography, since the cryptographic key used at the transmitter to encrypt the message, according to a specific algorithm or function (cipher), is the same at the receiver. The security of a system is not determined by the secrecy of its algorithm, but only by the secrecy and length of the cryptographic key. The problem of security is shifted then to another issue: the distribution of random keys in a secure way.

What is normally called quantum cryptography can help to solve the problem just mentioned of the distribution of a random key in a secure manner. Quantum cryptography cannot be used to communicate information in a secure way but it can indeed be used by two users to share a cryptographic key between each other in a secure way. That is why we normally call quantum cryptography with the name of quantum key distribution.

A quantum key distribution system needs two communication channels:

1. The Quantum Channel, for the transmission of the quantum bits.

2. The Classical Public Channel, for the communication of classical messages between the transmitter

and the receiver.

The most famous QKD protocol, called BB84 from the name of the inventors (Bennet and Brassard) which proposed it in 1984, uses two orthogonal polarization bases, for example the horizontal-vertical and the right-left circular ones. The transmitter (Alice) sends single qubits to the receiver (Bob), randomly chosen between the four possible states. Bob performs a measurement on the qubits on one of the two bases, again chosen at random: in the cases when Alice and Bob choose the same basis they get perfectly correlated results, in the other cases they will just get random independent values.

After the qubit exchange phase, Bob publicly announces on a public classical channel which basis he had chosen for each qubit. Alice then reveals for each case if the chosen basis was the correct one: this way the uncorrelated bits can be discarded.

According to Heisenberg's uncertainty principle, any measurement performed on a wrong basis (different from the one in which information has been encoded) perturbs the qubit state. Therefore Alice and Bob, comparing a subset of their exchange outcomes, can detect the presence of an eavesdropper in the channel by an increase of the bit error rate beyond a fixed threshold.

The photons participating to the link, among other properties, have an intrinsic spin. This property appears at large scale as the polarization of light, and it spans a bi-dimensional space. The active exploitation of this larger states space of a single quanta is the essence of the advancement introduced by the optical quantum communication. On Alice side, the generation of a train of controlled suitable quantum states may be realized by one or more laser source and components like polarizers and modulators. On Bob side, the measurement of the states is accomplished once the temporal synchronization as well as the spatial and spectral filtering of the incoming beam is established.

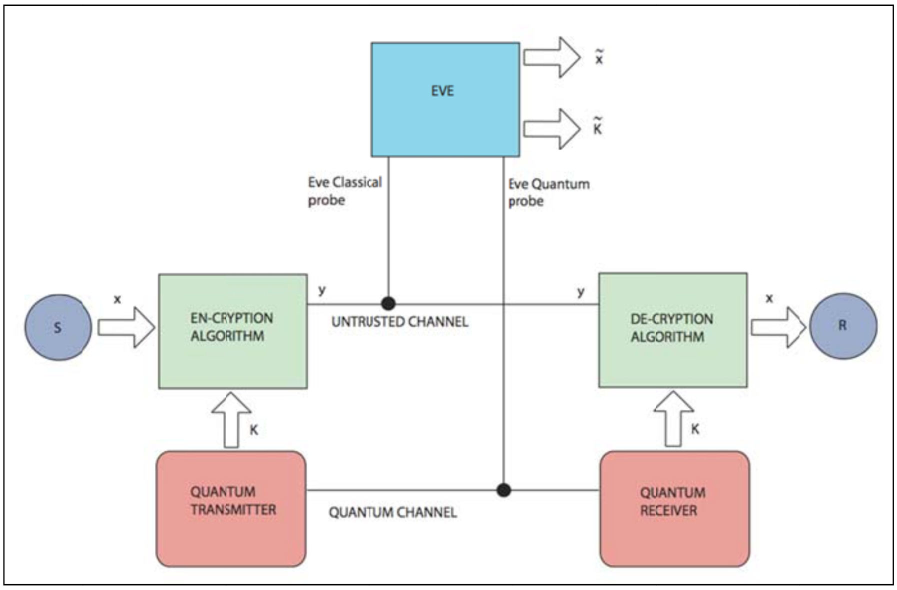

Figure 2: Block Scheme of QKD system

Quantum Key Distribution is the first application of quantum information theory which is getting out of the physics laboratories to reach the industrial and commercial worlds. QKD is the only way to assure it by distributing keys for encryption making use of Quantum Mechanics and the laws of Nature: because of the no-cloning theorem that states that it is not possible to perform a perfect copy of a quantum state, the presence of an eavesdropper is detected through the perturbation of the state that is traveling in the quantum channel. Hence it has the intrinsic capability of saving messages integrity, not in terms of corruption avoidance, but detecting corruption with high degree of reliability

The mathematical unconditional security of QKD has been demonstrated in many papers for several protocol and under different attacks [2][3]. It is remarkable that the fact that a measurement of a quantum system alters in some way the system was considered a problem in the applications of quantum information whereas it has been demonstrated very powerful and QKD is indeed the first "real" application that exploit quantum mechanics.

The reference scenario referred in TAS-I study is summarised in the next figure:

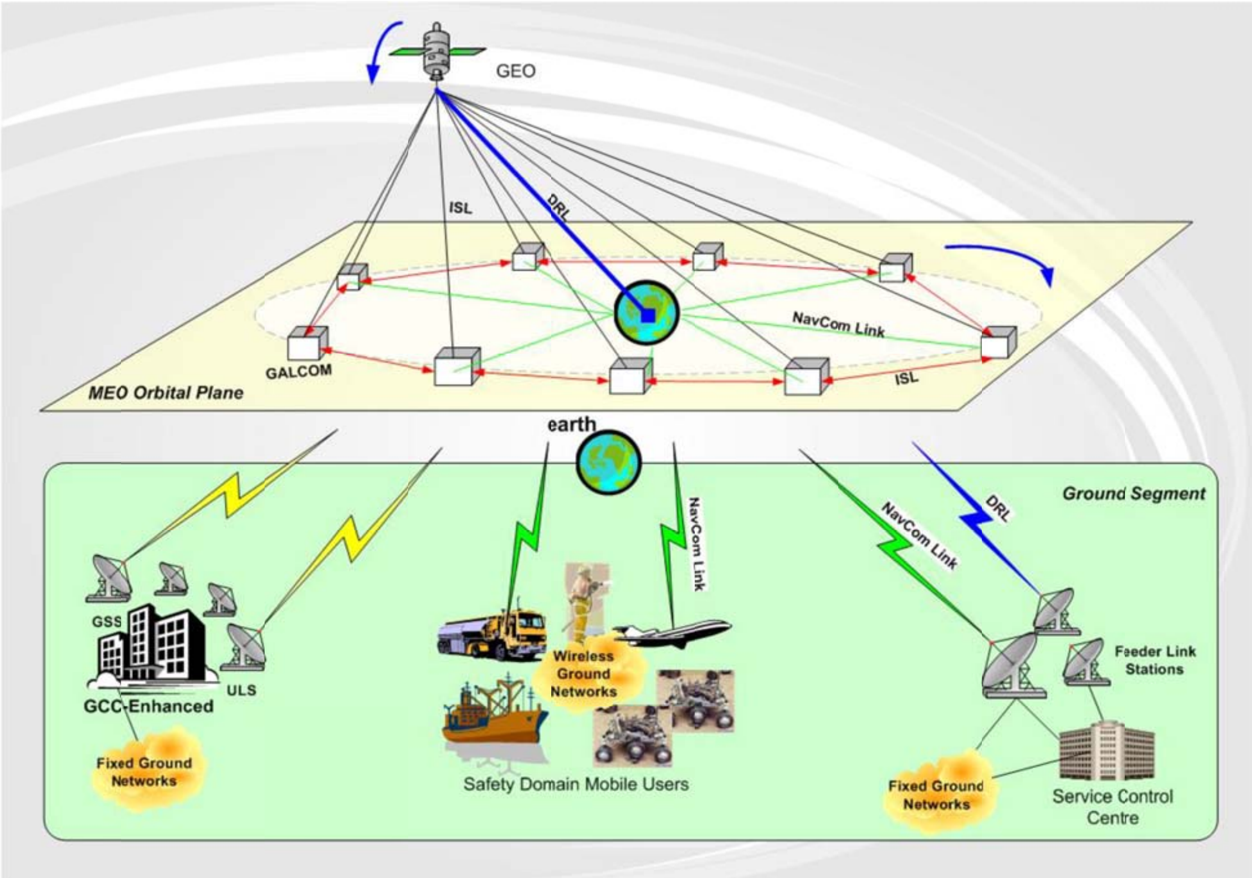

Figure 3: Reference scenarios for ComSec models study [1]

With reference to the Figure 3, the following links can be identified, each subjected to specific threats (as defined above) and consequently to specific protection levels:

- MEO-MEO inter-satellite link (ISL)
- Data Relay Link (DRL) between MEO satellites and GEO satellite
- DRL between GEO and Ground Station(s) (wide band comms);
- NavCom Links between MEO satellite(s) and User Segment (i.e.: Terrestrial, Maritime and Aeronautical users) for navigation signals reception and communication messages exchanging (mainly Low bandwidth);
- Control links between Ground Control Segment and MEO satellites.

- Ground-Ground link

Each link will use a classical optical communication link for narrow-beam secured data transmission, possibly enhanced by cryptographic means; and a quantum optical link for secure transmission of navigation data, GNSS management telemetry and telecommand via cryptographic secrecy, unconditionally secure integrity protection and authentication with quantum distributed keys

Ground-Ground link can be performed in two ways.

a) If there is the direct visibility between two Ground-Segments (they are not so distant that Earth curvature can influence the feasibility of the link) the signal can be sent by one Ground-Segment and received by the second Ground-Segment.

If there are not the conditions of visibility for a direct Ground-Ground link, this can be performed using GNSS satellites; the signal is transmitted from the first Ground-Station to one GNSS satellite passing above, which approaches to the Second-Ground station for sending the signal down (Figure 4). In this case the satellites act a Trusted node between the two ground station. If needed, Ground-Ground link can involve more satellites and intra-satellites links can be perform, as shown in Figure 5.

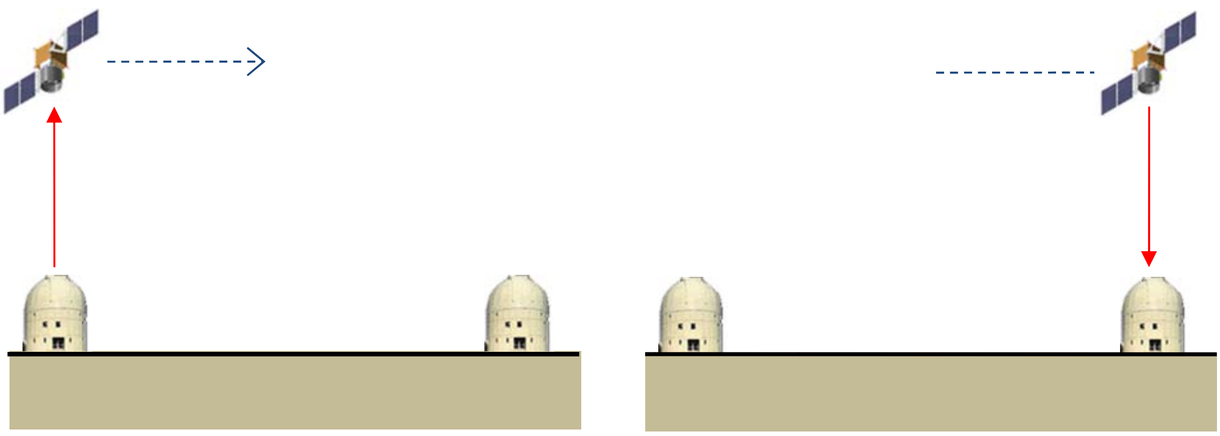

Figure 4 : Ground-Ground link performed using one GNSS satellite: the signal is transmitted from the first Ground-Station to a GNSS satellite passing above, which approaches to the Second-Ground station for sending the signal down.

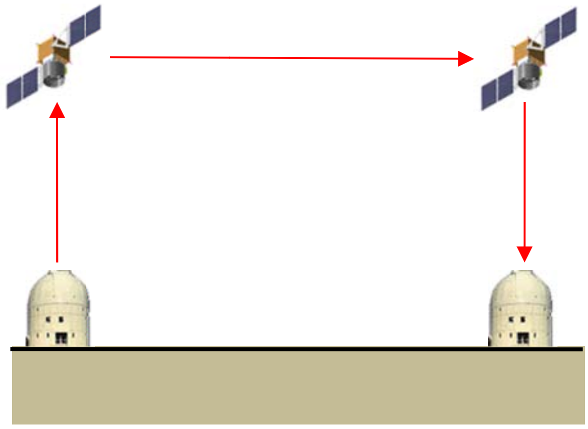

Figure 5 : Ground-Ground link performed using more GNSS satellites: the signal is transmitted from the first Ground-Station to a GNSS satellite, which transmits the signal to a second GNSS satellite, which approaches to the Second-Ground station for sending the signal down.

4.0 OBSTACLES AND MITIGATION STRATEGIES

The major obstacle for FSO communications is related to the large impact of atmospheric effects on the propagation of visible and IR wavelengths: atmospheric turbulence, background radiation, absorption and scattering by air molecules and absorption and scattering by solid or liquid suspended particles present in the atmosphere (aerosols such as dust, haze, mist and fog).

As it propagates through the turbulent atmosphere an optical wave encounters index of refraction fluctuations that cause phase perturbations of the wave, thus impairing link performance. After propagation, these phase perturbations turn into phase and amplitude perturbations due to diffraction, thus impairing link performance. Because of the complexity associated with phase or frequency modulation, current free-space optical communication systems typically use intensity modulation with direct detection (IM/DD).

In the near field, as it is the case in the receiver aperture plane for downlink, intensity patterns arise. Their spatial structure and typical size depend on the turbulence strength and on the propagation distance. These spatial structures cause temporal fluctuations of the collected optical power also known as **scintillation**.

In the far field, as it is the case for downlink in the focal plane of the receiver or for uplink in the spacecraft plane, the interference pattern is no longer an Airy pattern. For downlink, this loss of spatial coherence may cause strong coupling losses when the optical power is injected into a single mode fibre, thus resulting into channel impairments. For uplink, the diffraction pattern undergoes random global displacements (**beam wander**) and is spread into multiple speckles (**beam spreading**) in a proportion related to turbulence strength, both causing strong fluctuations of the collected optical power.

For downlink, scintillation influence is mitigated thanks to aperture averaging. As long as the data rate is reasonable (up to several Gb/s), the use of several hundred µm detectors enables to collect the quasi-totality of the focal plane intensity and the use of a single fine pointing mirror and of a position sensor (a quadrant detector for instance) might be sufficient to stabilize the focal plane intensity distribution on the detector collecting area. For higher data rates, the use of few micrometers detectors or single mode fibered components (as optical amplifiers) is requested. In this case, adaptive optics is considered to restore the spatial coherence of the wave and reach the diffraction limit. For this reason adaptive optics (AO) has become a key technology for space to ground optical links. Several systems are now in operation, either in the US[4] for LCRD (direct detection with pulse position modulation), in Japan as technology demonstrator

[5] (direct detection) in Europe for LEO experimental links [6] (direct detection) or GEO and LEO to ground optical feasibility demonstration [7] (coherent detection).

Adaptive Optics consists in a real time compensation of the wavefront phase perturbations with a deformable mirror. The residual wavefront is measured thanks to a wavefront sensor. The real-time computer (RTC) converts the wavefront measurement into actuators commands to minimize the wavefront error. Thanks to this real-time correction, coupling losses can be drastically reduced. As the most important part of the turbulence contribution consists in the tip/tilt modes, the deformable mirror is usually cascaded with a fine pointing mirror sharing a common wavefront sensor.

For uplink, the displacement of the spacecraft during the flight of the light between the emitter and the spacecraft must be compensated when pointing toward the spacecraft, resulting into a point-ahead angle (PAA). For the closest objects (HAP, LEO or MeO) the PAA is of several dozen µrad (around 50 µrad for typical LEO links). As it is greater than the typical decorrelation angle of atmospheric turbulence (also called anisoplanatism angle, AA), the pre-compensation of the uplink beam by AO from the measurement of the perturbations of the downlink beam is partially effective only. For being effective, the measurement must be performed in the direction of the PAA. In astronomy, this issue is solved using an artificial reference source created with a high power laser in the 90 km high sodium layer of the atmosphere, at the expense of significant costs and complexity. For uplink with GEO, pre-compensation using the wavefront measurement and correcting devices of the downlink is now considered with interest (mono-static configuration), as the PAA and AA are of the same order of magnitude. Various cases have been numerically studied considering the joint influence of PAA and of a tip/tilt compensation [8]. The consequences of a higher order pre-compensation depend on the turbulence strength, of the turbulence distribution along the line of sight, and of the considered diameter for uplink.

Another way to mitigate the effects of atmospheric turbulences is to take advantage of the reciprocity principle for bidirectional communication links[9]. The idea is to use the channel availability information given by the instantaneous level of the received signal to shape the emitted signal, either using a threshold or adapting the throughput to the actual budget link. Since the round-trip flight time of light is not taken into account, the a-priori more suitable situation is the uplink with GEO.

In the last years, the use of OAM (Orbital Angular Momentum) states of a light beam has proved to be an efficient way to add multiplexing capabilities to the transmission channel. These states are characterized by helicoïdal phases that can be generated by electrically driven SLM (Spatial Light Modulator), and are mutually orthogonal. The OAM being a property of a single photon, its use is also suitable to low flux transmission (scenario 2). The effect of atmospheric turbulences is, besides possible fading of individual signals, to induce cross-talk between neighbouring (sub) channels, thus deteriorating the link performance. Mitigation techniques using suitable coding to correct random errors, wavefront corrections (AO) to compensate for the crosstalk interferences [10], or both have been proposed. To our knowledge no implementation of this multiplexing approach has yet been reported for space communications.

Similar to other atmospheric factors cloud attention is based on extinction (**absorption** and **scattering** processes). Normally, clouds produce easily atmospheric attenuations exceeding 15 dB up to hundreds of dB per km, which could block the optical signal completely. They also introduce temporal dispersion, causing pulse spreading, which limits the bandwidth and makes the effect of clouds even more severe than fog. All this leads to fact that the mitigation of cloud attenuation is very problematic. Although it is possible to be used PPM modulation from very high order and LDPC with very low code rate the probability for reliable communication is very low.

The problem can be mitigate by analysing OGS site selection and site diversity. Moreover a PAT system with short acquisition time and fast target switch and the use of inertial tracking can improve the link quality.

5.0 SPACE DEMONSTRATORS AND TAS ACTIVITIES

While RF communications are consolidated systems, the FSO systems are a relatively new application, although several experimental demonstrators have been successfully carried out in the last twenty years. USA has been a precursor with the development of this technology since decades, and now results are becoming evident with LADEE (Lunar Atmosphere and Dust Environment Explorer) mission, which carried a Laser Link Communication Demonstrator (LLCD) that, using pulse-position modulation (PPM) at 1550 nm, successfully transmitted up to 622 Mbps of data back to Earth. And now plans to demonstrate data relay from LEO through GEO and then down to Ground, with the support of a network of Optical Ground Stations [11].

But also Europe and ESA are reaching important targets, like the implementation of the European Data Relay System (EDRS) for data relay services for the Sentinel 1a, 1b and Sentinel 2a, 2b Earth observation satellites. Related technology is under development by major industries in Germany, France and Switzerland.

In recent years, Thales Alenia Space Italia has led important studies in this context and performed a number of specific activities related to the development of FSO communication prototypes, but also different related subsystems.

In 2008 TAS-I successfully tested a pair of communication terminal prototypes for feasibility demonstration of optical communication system with the goal of a stratospheric flight mission in the next future. An optical link at 2.5 Gbps has been established between two fixed locations on ground, in direct visibility and at an horizontal distance representative of the corresponding stratospheric mission path in atmosphere.

In 2014 TAS-I upgraded the existing terminals by integrating in the same architecture a quantum secure channel with the objective of investigating the potential of optical-quantum links for the next generation navigation systems. The achievable performances of the proposed design has been experimentally assessed verified and validated by means of a successful test campaign performed with an open-field demonstrator, which integrated multiple functionalities (i.e., free space quantum key distribution and full-duplex bidirectional high speed communications link) in a challenging environment (link through atmosphere).

Additional projects are carried on to develop enhanced pointing and tracking systems, able to support optical links from inter-planetary distances (few AUs from Earth).

Today TAS-I is approaching the problem from a new perspective, revising the whole system functional description in order to recognize common functional blocks and identify suitable interfaces to build up a new concept of modular architecture. Thanks to the above described open field test campaigns and complementary studies, TAS-I has established a remarkable background of knowledge and experience of major competitiveness in the European panorama, with the objective of sustaining it throughout this crucial period of renewed interest for this strategic technology.

6.0 CONCLUSIONS

The deployment of space and ground optical communication networks is in the close future. this is also revealed by the increasing number of contracts issued by the worldwide space agencies about a large number of technical and technological aspects of an FSO architecture (PAT techniques, Modulation & Coding, hybrid architectures , Optical Ground Stations and related information networks); telecommunications service providers and newly born venture capital funded start-up are announcing the development of optical communication network services to support high data rate transfer from LEO to Ground, with the objective of sustaining human activities: voice, images, data, navigation, secure communications.

The Inter-agency Operations Advisory Group (IOAG) has also established an Optical Link Study Group

(OLSG with seven international space agency members) to investigate the business case for cross support of spacecraft that may utilize optical communications in the future, also identifying the need to develop a roadmap focused on an efficient standardization process.

Free Space Optical Communication in space is a young market which is going to grow rapidly in the next decades, as it is already observed today in ground applications.

Thales Alenia Space Italia is actively working on the development of Optical Telecommunications Networks (OTN), with the ambitious objective of targeting a larger market combining functionalities and flexibility, matching specific market needs that can arise in the future, disclosing new business strategies while pushing the technological development. The target is an architecture able to address:

- Performance
- Flexibility
- Resilience
- Versatility
- Security
- Power saving
- Efficiency
- Complementarity

The development of a product that targets a dynamical market can also allow to quickly develop different modules to address new stakeholders. It is a flexible product capable to be an optical communications terminal suitable to different environments and different levels of security, but also a scientific instrument that can perform science and transmit its own huge amount of data with the necessary efficiency (see Table 1).

Table 1: Examples of different target markets with specific needs

Product	Target market
Quantum secure optical communications	Military, High security applications
Hybridization FSO-RFS system	Telecom, broadcasting, downlink optimization
HAP (High Altitude Platform) optical terminal	Telecom, broadcasting, downlink optimization
Hybridization FSO-other optical functions (lidar, altimeter, optical observation,…	Exploration (planets, asteroids…)
FSO at different wavelengths	Future technology evolution, research

[1] "Applications of Optical-Quantum Links to GNSS" – Final Report of ESA contract No. 4000104506/11/NL/NA; Ref. n# SD-TN-AI-1517, 29th April 2015.

[2] D. Mayers. Unconditional security in quantum cryptography. Acm Journal, 48:351–406, 2001

[3] H.Inamori, N. Lutkenhaus, and D. Mayers. Uncoditional security of practical quantum key distribution. arXiv e-print archive, 2001

[4] Wilson, K. E. and Roberts Jr, L. C., "Recent developments in adaptive optics for the LCRD optical ground station at table mountain," ICSOS proceedings, May 2014. 5–9, Kobe (Japan).

[5] Yamashita, T. et al., "In-orbit and networked optical ground stations experimental verification advanced testbed (innova): The high-performance and compact ground-tracking system," ICSOS proceedings, May 2014, 5–9, Kobe (Japan).

[6] Petit, C. et al. "Adaptive optics results with sota," in [International Conference on Space Optical Systems], IEEE (2015).

[7] Gregory, M., Troendle, D., Muehlnikel, G., Heine, F., Meyer, R., Lutzer, M., and Czichy, R., "Three years coherent space to ground links: performance results and outlook for the optical ground station equipped with adaptive optics," in [SPIE LASE], 861004–861004, International Society for Optics and Photonics (2013).

[8] S. Basu and D. Voelz, "Tracking in a ground-to-satellite optical link: effects due to lead-ahead and aperture mismatch, including temporal response," Journal of the Optical Society of America, vol. 25, no. 7, pp. 1594-1608, 2008.

[9] Enhanced correlation of received power-signal fluctuations in bidirectional optical links, J. Minet, M. A. Vorontsov, E. Polnau and D. Dolfi, J. Optics 15 2 2013

[10] S. M. Zhao, J. Leach, L. Y. Gong, J. Ding, and B. Y. Zheng, "Aberration corrections for free-space optical communications in atmosphere turbulence using orbital angular momentum states," Opt. Exp., vol. 20, pp. 452–461, 2012

[11] D. M. Cornwell, "NASA's Optical Communications Program for 2015 and beyond", in Free-Space Laser Communication and Atmospheric Propagation XXVII, edited by Hamid Hemmati, Don M. Boroson, Proc. of SPIE Vol. 9354, 93540E