AVIONIC OPTICAL LINKS FOR HIGH DATA-RATE COMMUNICATIONS

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Abstract

Data services for air-passengers are emerging especially on long-duration flights. With the increasing number of passengers, the amount of data on wide-body aircraft is increasing and thus high speed connection technologies are required. These links with data-rates over 100 Mbps can realistically only be realized using free space optical communications technology. Possibilities, problems and design requirements for avionic free-space optical (AFSO) links are discussed in this paper.

1 Introduction

The work presented in this paper partially relates to the ATENAA project [4], funded by the European Union, aiming to establish broadband wireless optical communication for commercial aviation.

The development of inter-aircraft communications capability through the implementation of an avionic network was introduced since the early eighties by the International Civil Aviation Organization (ICAO). Currently, the avionic network concept is being further developed to a real mobile ad-hoc networked environment (MANET), in which each node may play the role of communication router and network manager at the same time. MANET technology was investigated in the past with the purpose of being deployed in defense applications.

The laser free-space optical (FSO) communications technology has a major potential to outperform radio-frequency (RF) technology in terms of data rate and size, mass, and power consumption of the terminals – criteria that are of great importance for airborne use. The inherent advantage of laser communications is its much smaller transmitted beam-width, which concentrates a larger fraction of the transmit power onto the receiver aperture. Since the optical signal wavelengths are *4* to *6* orders-of-magnitude smaller than RF wavelengths, the intensity of the received signal rises accordingly *8* to *12* orders-of-magnitude. Practically (also regarding other constraints) this results in a sensitivity increase of *40* to *60 dB*. This increased sensitivity can be invested in the reduction of volume and power of the communication terminals as well as the increase of data-rates.

Usually an optical communication terminal consists of two co-aligned transmitting beams: One modulated beam for data-communication and a continuous-wave laser-beam, a so called *beacon* signal used for pointing, acquisition and tracking (PAT). This extra effort is necessary because due to the small signal divergence, the precise pointing and tracking of the optical signal is crucial to exploit the benefits of optical communications. Typically the beacon beam divergence angle would be one or two orders of magnitude larger than the divergence of the data-communication beam. In the receiver, the beacon is detected by a tracking detector e.g. by a wide-field of view camera. The camera measures the alignment of the terminal with the beacon and helps to point the receiver directly to the transmitter. Further, the receive-terminal transmits a beacon signal which is used by the transmitter to point accurately to the receiver terminal. When optical acquisition by beacon signals is completed, the narrow data beam also points accurately enough to the narrow field of view data-receiver so that data communication can start.

Demonstrations of this kind of mobile optical free-space communication have proven that the technology is ready to be used in aeronautical and space environment. Examples are inter-satellite links e.g. the OICETS (LEO) to ARTEMIS (GEO) link (data-rate: *50 Mbps*) [1], or terrestrial links like the FASOLT experiment (*100 Mbps* over *61 km*) [3] or the CAPANINA-STROPEX downlink (*1250 Mbps* over *60 km* out of the stratosphere) [2]. Inter-aircraft links are also being investigated and demonstrators are being built for example in the European project ATENAA [4].

For the communication scenario, we anticipate a mobile ad-hoc network consisting of several A/C en-route. Especially for high traffic regions, (e.g. North Atlantic corridor) many A/C can be connected to each other under line-of-sight conditions. Each A/C can be seen as network node. Some A/C are connected to the terrestrial network via RF satellite-links. In the future, these links can also be realized with optical technology. When direct downlinks to terrestrial nodes are required, these should preferably be realized with microwave frequencies due to the high probability of cloud-blockage of optical downlinks. While optical signals can transverse thin clouds in the upper troposphere (with some Decibel attenuation penalty), the thick water clouds in the lower atmosphere act as opaque obstacles.

FSO applications are less favorable for supporting ATC or ATM, due to the intrinsic limitations of free space optical communication systems, in particular limited availability due to link blockage (e.g. from clouds for altitudes lower than *10 km*) and latencies (between tens of milliseconds to several seconds depending on the link topology) due to link establishment procedures. The main use of FSO systems should be for connections from or into the terrestrial data networks via HAPs and satellites and for interconnection between A/C en-route which cruise above the cloud layer. Foreseen services include internet-download, VPN, IFE, TV/Radio-streaming, voice-phone, some non-time critical ATM data like weather maps or medical communications during emergencies en-route.

In chapter 2, application areas for avionic free-space optical communication are introduced. Since the optical channel is much different from the commonly known RF one, the channel behavior is shortly described in chapter 3. Chapter 4 introduces main technology aspects used for free-space optical communication terminal design. In chapter 5 a basic concept for FSO communication terminals is introduced. Finally chapter 6 discusses several design trade-offs for terminal design.

2 Application areas and scenarios for aeronautical optical links

Feasible scenarios for optical communication are inter-A/C links which are used to build up an ad-hoc network in high traffic areas, e.g. North-Atlantic corridor. FSO is preferable for A/C en-route. Optical connection of A/C on the ground or while climbing is less reliable due to high cloud blockage probability for the optical link. Furthermore, high data rate communication services are normally only necessary during the en-route flight phase. High-speed connections to the space-backbone communications network via HAPs or satellites are also supposable.

As studies from aircraft manufactures show, data rates above *100 Mbps* are desired in the future. Passenger services like infotainment, video-streaming, e-mail or internet are desired. Also things like remote maintenance or cabin health services are conceivable.

Typical link distances can be read out of Fig. 2. For A/C and HAP connection maximum distances are in the range of *400 km*. For long links it is important to ensure that the lowest point of the link will not be too close to the ground. In general, link blockage probability due to clouds increases with lower altitudes. Without considering unfrequent weather situations like thunder storms, thick clouds typically occur below *6 km* altitude.

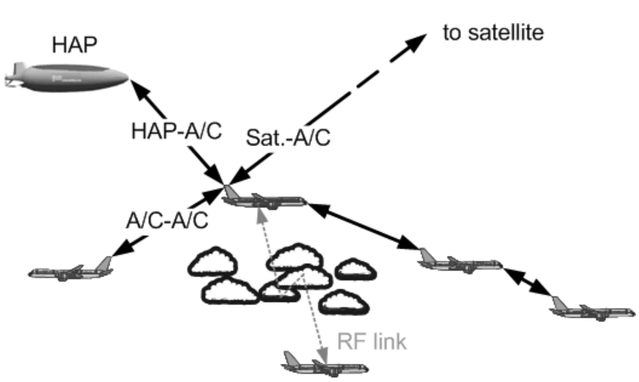

Fig. 1 Application scenarios for aeronautical optical links

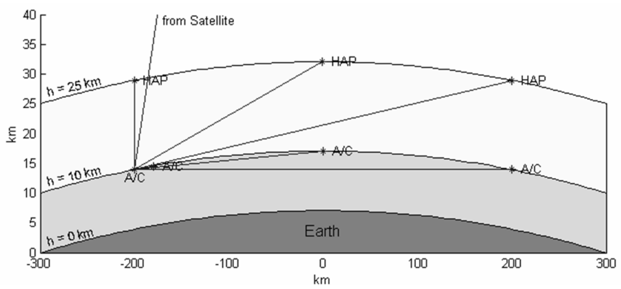

Fig. 2 FSO link distances for links between A/C, HAP and satellites

3 Description of atmospheric optical transmission channel behaviour

The atmospheric index of refraction behaves turbulently in most cases (IRT). Atmospheric disturbances on electromagnetic waves in the optical domain, such as intensity fluctuations and wave front distortions, reduce signal quality significantly. Theoretical investigations and channel measurements clearly show that atmospheric optical communication is often interrupted by strong and very slow fading (slow compared with the data rate). Thus, the atmospheric optical channel can be said to be a very slow fading channel [5], [6]. Characterising the optical fading channel with terms from the microwave channel behaviour description, the optical channel is also non frequency selective. Furthermore, the channel has a very long memory. This is because the channel state is constant during the transmission of a very large number of data bits.

4 Discussion of applicable technology

In this chapter basic parameters specifying a mobile free-space optical terminal (MFSOT) setup are discussed. The design of MFSOTs is mainly driven by the following parameters: *modulation scheme*, *receive aperture size and beam divergence angle, system wavelengths, PAT-concept, distances, IRT over link path, reliability and robustness* as well as *requirements from the network* the terminal has to serve.

4.1 Selection of the modulation and transmission scheme

In general, the selection is between coherent and incoherent modulation schemes. Incoherent direct detection (DD) receivers just detect the optical received power. Hence they are suitable for intensity modulation (IM). Practical direct detection receivers operating in the on-off keying (OOK) mode do not reach the theoretical sensitivity limit. Pulse-position modulation (PPM) has received considerable attention as the modulation of choice for direct-detection optical communication over unguided optical channels. There is a key aspect of this modulation that is critical for the development of modulation schemes for free-space communications. Q-switched lasers are usually employed for generating high energy short pulses. The current technology does not support a Q-switched laser that can be toggled between the "on" and "off" states at a high rate. Therefore high data-rates are not possible.

Coherent schemes rely on the coherence of light. A superposition of a reference signal from a synchronous local oscillator allows for detection of Phase Shift Keying (PSK). Coherent detection scheme systems are in general more complex than direct detection scheme systems, since the synchronization of frequency, phase and polarization is required. However, the sensitivity increases significantly, especially when considering high levels of background-light. Operational coherent receivers operate much closer to their theoretical limit than direct detection receivers. A BPSK homodyne system developed by DLR reached a sensitivity of *16 photons per bit* (without error correction coding) at a bit error rate of 10^{-9} [7] in 1994.

Because the latter are susceptible to wavefront distortions - which are induced by atmospheric index-of-refraction turbulence - coherent modulation formats can only be used in atmospheric scenarios and avionic application scenarios when special non common of the shelf (COTS) and very complex receiver technologies are employed. As PPM is only advantageous in low data rate applications, OOK is primarily chosen as modulation scheme for atmospheric FSO links.

When adopting terrestrial fiber communications for FSO, one would transmit the binary data as a continuous uninterrupted stream of bits (synchronous transmission). Slow fading in an FSO atmospheric channel reduces the performance of a synchronous transmission scheme, mainly because of losses of synchronisation during data transmission. During a fade, a great quantity of data is lost and cannot be recovered by a forward error correction (FEC) implemented in the physical-layer transmission [6]. Obviously, in that case, the communication scheme will not work because the FEC-decoder and the interleaving devices can not work without a continuously locked synchronisation.

Instead of having a synchronous transmission, an asynchronous - packet-oriented - datagram transmission can be chosen. Each packet has its own clock-synchronization preamble and thus synchronisation is independent of preceding fades. If the synchronisation gets lost, e.g. in a deep fade with very low received power, the synchronisation will be locked again upon receiving the start of the next packet. As for asynchronous transmission a continuously locked synchronisation is not necessary because due to recurring synchronisation process fading can not totally lead to a loss of system-synchronisation as it could happen in a synchronous system.

4.2 Selection of the communication wavelength

The atmospheric attenuation under clear-sky weather conditions is due to scattering and absorption by air molecules and aerosol particles. Water vapour causes strong and broad absorption bands in the optical spectrum. Based on the spectral distribution of these bands, so called atmospheric optical transmission windows can be defined. Typical near-infrared laser wavelengths like as *808 nm* (Si), *1064 nm* (Nd-YAG) or *1550 nm* (InGaAs) are applicable whereas *950 nm* or *1300 nm* are not applicable for atmospheric systems. The attenuation within a window is smaller for longer wavelengths due to the decreasing Rayleigh-scattering (see Fig. 3)

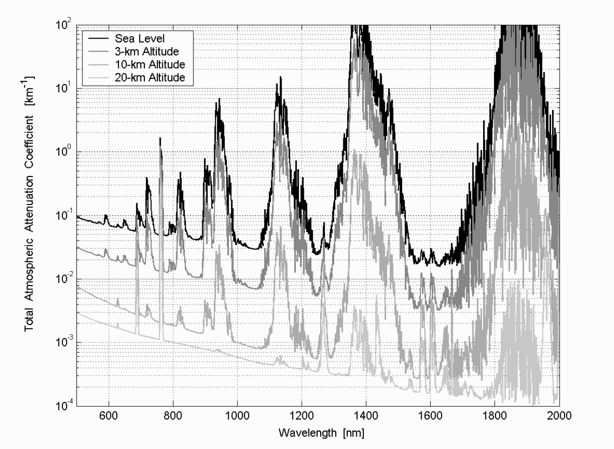

Fig. 3 Altitude dependant coefficient of clear-sky atmospheric attenuation vs. optical and near-infrared wavelengths. Four different altitudes are considered: sea level (uppermost curve), *3 km*, *10 km*, *20 km* (lowest curve) Attenuation values are averaged over *1 nm* [9]

The maximum allowed optical transmit power depends on the desired laser classification. A laser system class that is safe to use under any operating conditions is considered in this paper. This avoids the application of restrictions and safety mechanisms in the MFSO system.

As set out in [8], the class of a laser product is assigned according to the operating wavelength, the duration of exposure, the spatial characteristics of the output beam and output power. Without entering into detailed calculations, in the following we provide the maximum permissible exposure (MPE) values for cornea exposure given as maximum allowed transmit power. The unintentional exposure time is assumed to be longer than *10 seconds*. It is obvious that allowed transmit power increases significantly with wavelength.

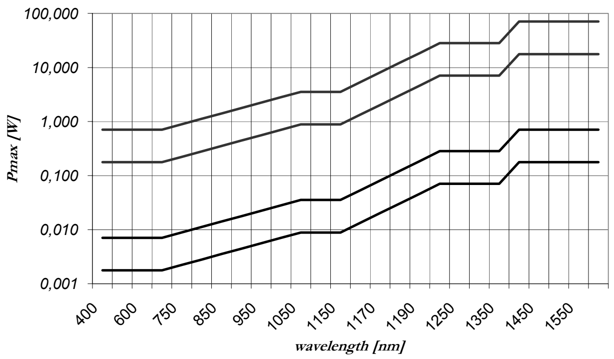

Fig. 4 Maximum terminal transmit power P_{max} *[W]* for cornea exposure vs. wavelength [nm] for the FWHM-divergence angles *50* (lowest curve), *100*, *500* and *1000 µrad* (uppermost curve) and a distance to the transmitter of *300* m (minimum in-flight A/C distance due to air-traffic regulations)

Background-light either from the sun or scattered light from clouds or sunlit earth surface (see Fig. 5) degrade the performance of a direct detection receiver. Since the sun spectrum decreases with increasing wavelength, longer wavelengths e.g. *1550 nm* are favorable. OOK suffers from background-light noise, but its impact is reduced with increasing data rate because of the improving relation between signal- and background-light [14].

The wavelengths within the atmospheric optical window around *1550 nm* are preferable for atmospheric optical free space communications i.e. there is low atmospheric absorption and scattering in the optical window (*1500 -1750 nm*) and low levels of background-light (important for IM/DD-Rx). Furthermore, commercial of the shelf (COTS) technology and well developed components are available from terrestrial fiber communication at this wavelength range. Additionally, eye-safety restrictions allow high emission power levels for wavelengths longer than *1300 nm*.

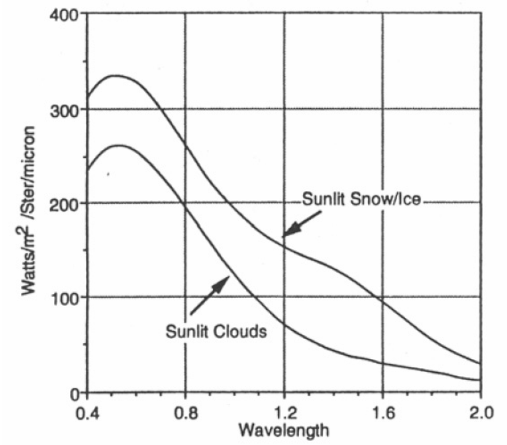

Fig. 5 Radiance of sunlit clouds and sunlit snow and ice [10]

4.3 Network requirements

An optical communication terminal must fit into the network structure. Therefore each terminal is expected to be able to talk with each other terminal to achieve arbitrary connectivity. Therefore the communication and beacon wavelength must be cooperative and coordinated. Generally there is the problem that receiving and transmitting at the same wavelength can blind the own receiver due to reflections and scattering on surfaces (lenses, mirrors, etc.) or stray light from dust particle in the air. This renders working at only one common wavelength nearly impossible. But when using different wavelengths, the Tx-wavelength of terminal *A* must match the Rx-wavelength of terminal *B* and the same for the return channel. This means that both terminals are not built identically but rather symmetrically. So two different types of terminals will exist in the network where only compatible pairs will be able to communicate with each other. This halves the chance that any two terminals can communicate, or in other words, no arbitrary connectivity between any two terminals is possible.

4.4 Full/half-duplex system approach for arbitrary connectivity

To set up a conventional full-duplex system four wavelengths are required in order to avoid blinding of the receiver by the own transmitter. Beacon and data-signal wavelengths for transmit and receive paths are separated by means of chromatic separation. The four wavelengths in such a system are:

- Data signal transmit wavelength
- Data signal receive wavelength
- Beacon / tracking transmit wavelength
- Beacon / tracking receive wavelength

If modulated beacons are used, only one beacon wavelength is required. In this case, beacons on both sides are switched on one after the other. This requires a coordination process between the terminals which controls the beacon modulation.

Using fixed wavelengths, arbitrary connectivity of terminals can not be achieved. Therefore switchable or tuneable transmit and receive wavelengths are preferable (see upper part of Fig. 6 as an example). Using two laser transmit assemblies (TXA) with different wavelengths (e.g. *1550 nm* and *1560 nm*) separated only by a few nanometres in the *1550 nm* band the same broadband-fiber-amplifier (FA) can be used for both TXAs. Only one TXA is used at one time depending on the current network-wavelength configuration. On the receiver side, a chromatic beam splitter (CBS) and a fiber switch (FS) can be used to select the receive wavelength. The transmit wavelength will be blocked by the switch in order to avoid blinding of the currently used receiver. Both transmitter and receiver can be implemented using standard fiber components.

Another way to achieve arbitrary connectivity is to fix the communication wavelength to a global value and use a half duplex system. Now the two partners must be coordinated not to send at the same time so no data to be received is lost due to receiver blinding. Now, when also choosing a beacon-less approach, only one system wavelength exists. Optical tracking is interrupted at one side during the send phase. To avoid tracking loss during the signal breaks, very fast half-duplex alteration is necessary, which also reduces the overall time lag of the connection.

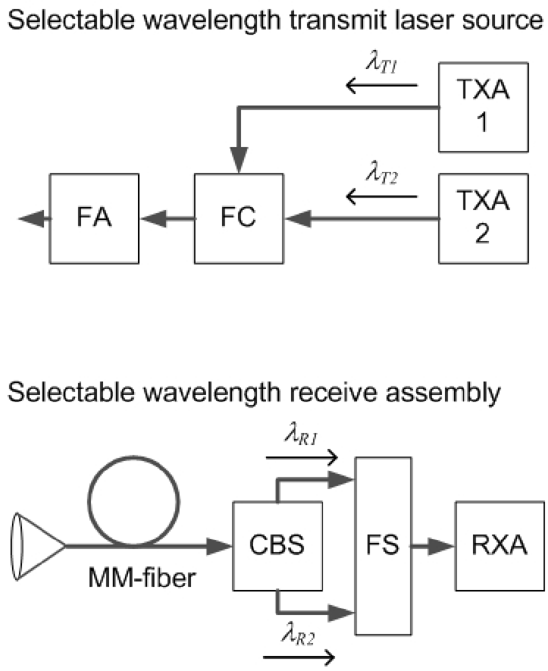

Fig. 6 Full-duplex system approach with arbitrary connectivity using selectable transmit and receive wavelengths paths (FA: fiber-amplifier, FC: fiber-combiner, TXA: transmit assembly, CBS: chromatic beam splitter, FS: fiber-switch, RXA: receive assembly)

4.5 Pointing Acquisition and Tracking (PAT)

Coarse acquisition and pointing can be implemented by knowing the own orientation, the own position and the position of the partner. This position-data and further information (wavelengths, data-rates,…) can be exchanged e.g. by an RF-signalling link system, like ADS-B (*90* miles radius coverage range) or Galileo-messaging (global coverage) [11]. Position of a terminal can be measured using a GPS or Galileo based AHRS.

In order to avoid a scanning process to find each other, the AHRS-coarse pointing should be accurate enough so that the beacon consistently illuminates the partner terminal and thus can immediately be observed by the wide field of view sensor. For tracking, normally active pixel arrays (APA) with a large number of pixels (e.g.

cameras) are used in order to reach a large field of view, high angular resolution and low background-light sensitivity at the same time. The update rate of CCD cameras is in the range of *60 frames per second*. This is slow but in most cases acceptable. These silicon semiconductor cameras only work effectively for wavelengths shorter than *1100 nm*. The preferable wavelength for communication has been figured out to be in the *1550 nm* band. Cost effective, fast and sophisticated InGaAs-Cameras for *1550 nm* are currently not available on the market. Four-quadrant-detectors can be used instead of cameras at *1550 nm*. They have the advantage of higher update-rates (*~100 kHz*) but they have problems with non equal distributed background-light as one will observe when the partner is near to the horizon. This is because quadrant detectors only measure the received power on a quadrant instead of detecting a spot by centre-of-gravity calculation as a camera does. Therefore a trade-off has to be made and maybe a beacon based system having an *800 nm* beacon with a camera as tracking receiver and a *1550 nm* communication wavelength is preferable.

In order to reduce the number of wavelengths needed in a system, a beaconless system is favourable. Two or more wavelengths require a system with more components and a more complex achromatic optic. A disadvantage of a beacon-less system is that received power has to be split for use on beacon tracking-receiver (APA) and data-receiver (RXA). Further in most cases a scan for acquisition is needed because transmit-power can not be made high enough to allow large beam divergence angles and high enough received power for data communications. At *1550 nm* power is limited to about *1 W* because of laser-safety regulations and technology limits.

The time to settle a link is defined as the time required to establish a new connection. This time period starts when the datalink connection is interrupted from previous connection and ends when the new datalink connection is established. For a connection oriented service, the time to settle can be seen as a worst case of latency because data has to be buffered during the whole procedure. The time to settle can be in the order of milliseconds up to several seconds. Depending on the time to settle, a connection loss during link hand-over can be seen as a long signal fade. When this hand-over-fade is in the same order as a fade produced by turbulent atmosphere (*1 ... 100 ms*) an error correction coding scheme can be implemented to mitigate this fading-loss. Therefore packet-layer coding schemes are preferable in order to achieve long codewords or interleaver-depth in the same order as fade duration, even when using high data rates.

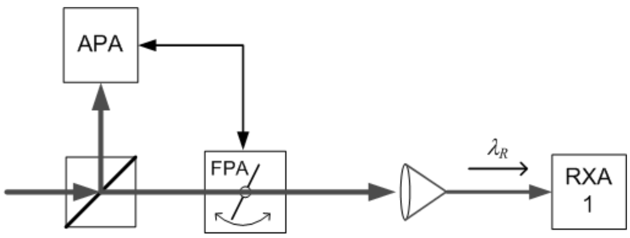

Fig. 7 Beaconless receiver concept: The Rx-coms.-signal is split. One part is used on the tracking receiver (APA) to detect the beam alignment and to control the fine pointing assembly (FPA). The other part is focused on the data receive assembly (RXA).

4.6 Reliability and robustness

Generally the number of components should be reduced to get a simple and robust system. COTS technology should be used as much as possible. Numerous communication products are available from the terrestrial *1550 nm*-fiber-technology which should be reused for MFSOT design in order to minimise effort for developing and qualifying new components.

4.7 Beam divergence angle and receive aperture

Since transmit power and receiver sensitivity is limited by technology, long distance links can only be implemented using small divergence angles and larger Rx-apertures. Large apertures are not feasible in avionic systems because of a great impact on aircraft structure. Smaller divergence angles require a more accurate PAT-system. Link-budget calculation is used to figure out possible system performances. The following table is generated with a link-budget tool [12] taking into account: free-space loss, atmospheric attenuation, receive telescope aperture, turbulence induced fading loss, receiver sensitivity, beam splitting for PAT and data receiver, miss-pointing, tracking errors, and further losses. With pessimistic values, the maximum distances as stated in the following table can be achieved. The link-budget also depends on the data rate (here fixed to *500 Mbps*). A communication receiver needs more power for higher rates. Therefore, when using lower data-rates higher distances can be achieved.

		Rx Aperture Diameter		
		5 cm	***10 cm***	***20 cm***
Tx-Power [mW_{mean}]	***250***	A/C-A/C ***209***	A/C-A/C ***266***	A/C-A/C ***331***
	1000	A/C-A/C ***263***	A/C-A/C ***318***	A/C-A/C ***381***
	250	A/C-HAP ***311***	A/C-HAP ***438***	A/C-HAP ***576***
	1000	A/C-HAP ***436***	A/C-HAP ***567***	A/C-HAP ***706***

Maximum Link Distance [*km*] (from link-budget calculations [12]). For *100 µrad* (FWHM) beam divergence angle of Tx-beam; data-rate: *500 Mbps;* A/C at FL290: about *10 km* altitude, HAP at: *25 km.* For HAP-links a lower index of refraction turbulence is assumed (atmospheric IRT turbulence parameter C_n^2 [13]; A/C-HAP: $C_n^2=0.5\cdot10^{-17}$ $m^{-2/3}$, A/C-A/C: $C_n^2=3\cdot10^{-17}$ $m^{-2/3}$)

It can be seen that maximum distances can not be significantly increased by enlarging the Rx-aperture. This is justified by the intense increase of fading loss produced by IRT. Further, A/C-HAP connections are possible over much larger distances because of decreasing turbulence with altitude. Maximum operational A/C-A/C distances are in the range of *400 km* in order to avoid cloud blockage by links passing through lower altitudes. A/C-HAP distances are not significantly larger. Therefore *10 cm* aperture and *250 mW* transmit power will be enough for most cases of A/C and HAP connections. This transmit power can be easily provided at the *1550 nm* band by COTS EDFAs whereas a *1000 mW* EDFA will be a non-COTS component. Distances can be increased using channel coding which can overcome IRT-fading. However, coding is not regarded in the link-budget calculations as it is out of the scope of this paper.

5 A simple basic terminal concept

In this section a basic terminal concept for a simplex beacon-based optical communication system is introduced. The system overview diagram is given in Fig. 8. The components of such a system are:

- Terminal Antenna (telescope) with coarse pointing assembly (CPA), e.g. a periscope system (see Fig. 9)
- Fine pointing assembly (FPA) for fine beam steering and vibration mitigation, e.g. a piezoelectric mirror system
- Tracking-sensor, here called active pixel array (APA), e.g. a CCD-camera or a four-quadrant-detector
- PAT-Control Assembly (PCA) for generation of coarse and fine pointing control signals
- Data transmit assembly (TXA) which is normally a semiconductor intensity modulated laser diode
- Tx-data signal fiber-amplifier (FA), e.g. erbium-doped fiber amplifier (EDFA)
- High power continuous wave beacon laser diode (BLD)
- Data receive assembly (RXA); includes opto/electrical conversion and electrical signal conditioning

The DLR-built optical terminal FELT (Free-space Experimental Laser Terminal) which was developed in the frame of the CAPANINA project used the design principles described above and shown in the upper part of Fig. 9. Its functionality has been proven in a *1250 Mbps* downlink from a stratospheric balloon. The terminal has a beacon receive aperture of *25 mm* diameter and a *1550 nm* TXA combined with a *100 mW* output power FA. Two redundant *980 nm* BLD of *250 mW* output power each are used. The weight of the whole experimental system is *17.5 kg* and power consumption is about *70 W*. Weight and power consumption can significantly be reduced when designing for a commercial product. The CPA periscope system including its protective cap (dome which is shown in Fig. 9) has a diameter of *200 mm*.

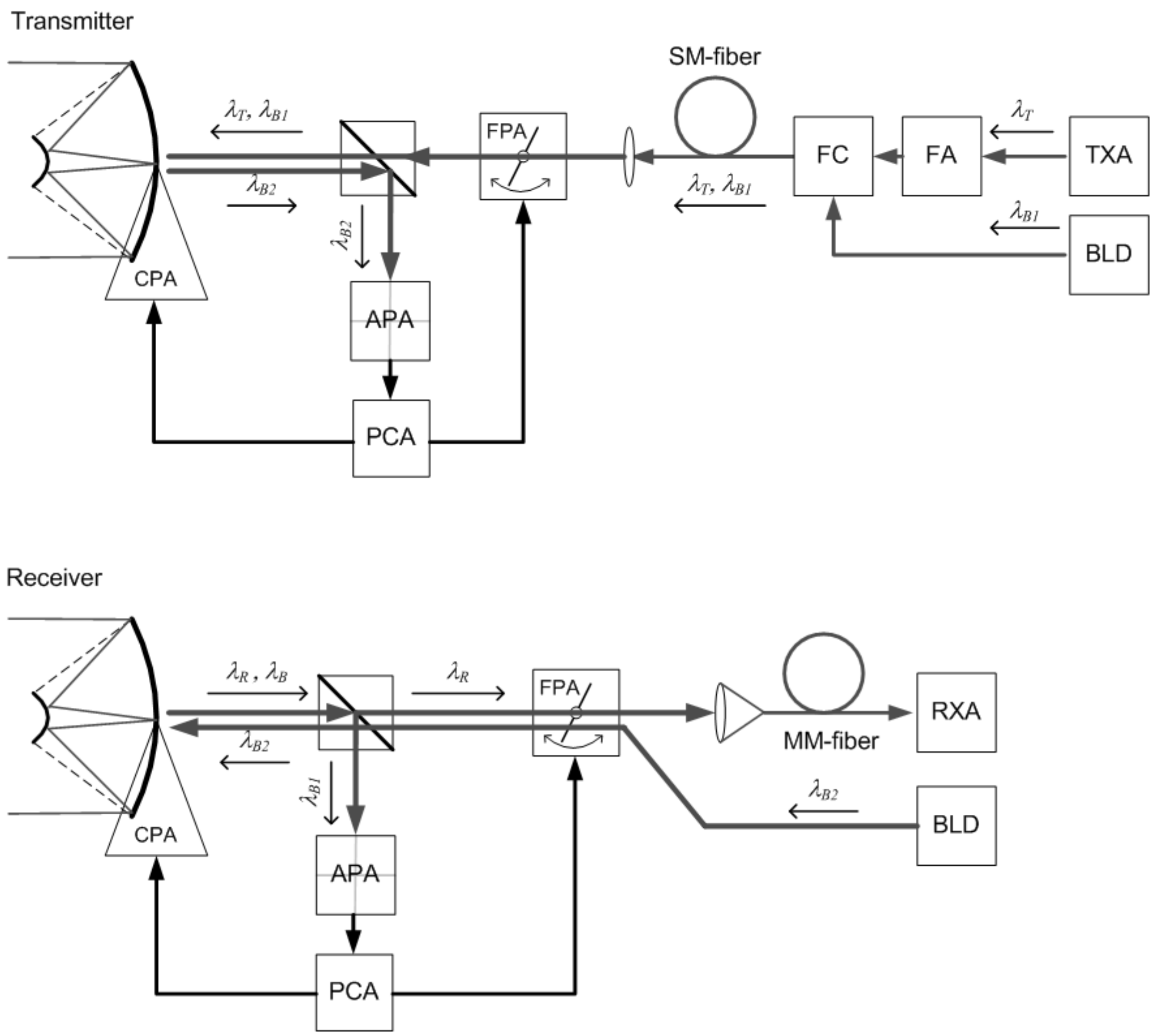

Fig. 8 Basic terminal concept for a simplex link; PAT based on beacon approach: The beacon-wavelength is separated in the receiver from the data-wavelength using a chromatic beam splitter.

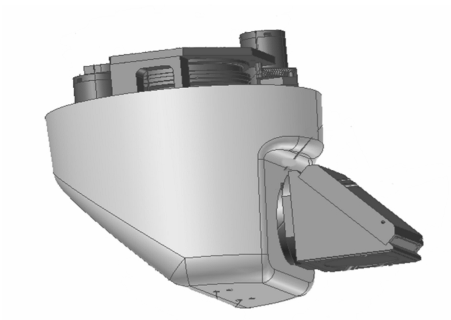

Fig. 9 DLR-design of an optical terminal antenna with CPA. This system was proven for a *1250 Mbps* downlink from a slowly moving stratospheric balloon-platform, but can be adapted for avionic applications. The pointing accuracy of this system is about *0.2 mrad*.

6 Discussion of terminal design concepts

This chapter is dedicated to the identification and analysis of the relationships between the PAT and communication subsystem characteristics, with the aim to provide guidelines to identify the more appropriate technical solutions. A trade-off between several concepts e.g. beacon vs. beacon-less or full/half-duplex system has to be made.

Generally, when using a combined transmitter (BLD and/or TXA) and receiver (APA and/or RXA) optical path, a blinding of the receiver can occur if chromatic beam splitting and filtering is not sufficient employed and if transmitter and receiver are operating exactly at the same wavelength. This blinding can be avoided using different optical paths, e.g. using different telescopes for transmit and receive beam. The disadvantage for that approach is that this will make the overall system more complicated especially because transmit and receive telescopes have to be very accurately aligned and stable.

Having a separate telescope, flexure or temperature drifts can cause problems with stable co-alignment. For alignment reasons, it is better to use only one optical path (one telescope) for beacon and data wavelength. A beneficial way to align the Tx beacon and data-laser-source beam is to bring them both in one optical fiber using a fiber-combiner (COTS fiber cross coupler). The end of the fiber can be placed in the focal plane of the Tx-telescope. Even if the fiber-end has moved e.g. due to temperature drifts, sustained co-alignment of the beacon and data-laser-beam is assured. Furthermore, mass and space decreases using only one telescope.

For a half-duplex beaconless system which transmits on one single wavelength, no blinding problem will occur if half-duplex time division multiplex is well synchronized.

Arbitrary connectivity is only possible using *selectable* transmitter and receiver wavelengths. Therefore four different wavelengths will be needed for a beacon-based full-duplex concept and only two for a beaconless concept. With a half-duplex beaconless communication system, arbitrary connectivity is always possible. In a beacon-based half-duplex approach, one will additionally need selectable wavelengths. Having one fixed beacon wavelength, on/off-modulation can help to avoid blinding of the own APA and to distinguish between the own and the partner beacon.

For continuous optical tracking a continuous beacon signal is required. Using a beaconless system with asynchronous datagram transmission, a continuous signal can not be ensured because the transmit source will only emit light if data is transmitted. Therefore dummy-data is necessary, especially during the link acquisition phase where the channel is not stable and no user data will be transmitted. For dummy-data a “*101010…*” idle-sequence is preferable because this idle-sequence can be used for synchronisation too. Also for beaconless half-duplex, the tracking-beacon-signal breaks during receive-timeslots, but the impact depends on slot-length which should be minimised.

Different divergence angles for tracking-beacon-signal and data-beam is only possible if using separate beam expanders or separate telescopes for data and beacon signal in a beacon-based concept. In a beaconless approach data-beam is identical with the tracking beacon signal, therefore because of the very narrow beam needed for high speed communication in order to achieve a high enough receive power, a scanning algorithm is required for acquisition.

7 Conclusion

In this paper future aeronautical application areas of high speed optical communication terminals have been introduced. Aspects which influence the terminal design have been discussed. Decisions on the link-design depend on the application scenario. Nevertheless it has been pointed out that OOK modulation at *1550 nm* is preferable for avionic free-space optical (AFSO) communication. Terminals which are used for satellite- or HAP-up/downlink are simple to design as one can work with fixed wavelength in these asymmetric scenarios.
Simplex and half-duplex transmission schemes can easily be implemented for symmetric links but bear some drawbacks concerning throughput and PAT-performance which again reduces communication performance. More complex designs allowing arbitrary connectivity would be needed for a real MANET allowing the connection of all potential avionic communication partners.

Acknowledgment

DLR wishes to thank all ATENAA partners, and in particular Selex Communications, for its valuable contribution.

Acronyms

A/C	Aircraft(s)
ADS-B	Automatic Dependent Surveillance Broadcast
AFSO	Avionic free-space optics
AHRS	Attitude height reference system
APA	Active pixel array
ATC	Air traffic control
ATM	Air traffic management
BER	Bit error rate
BLD	Beacon laser diode
BPSK	Binary phase shift keying
CBS	Chromatic beam splitter
CCD	Charge coupled device
COTS	Commercial of the shelf
CPA	Coarse pointing assembly
DLR	German Aerospace Center
EDFA	Erbium-doped FA
FA	Optical fiber amplifier
FEC	Forward error correction
FELT	Free-space Exp. Laser Terminal
FPA	Fine pointing assembly
FWHM	Full width half maximum angle
Galileo	Europ. satellite navigation system
GEO	Geostationary orbit satellite
GPS	Global positioning system
HAP	High altitude platform
ICAO	International Civil Aviation
IFE	In flight entertainment
IM/DD	Intensity Modul. / Direct Detect.
InGaAs	Indium Gallium Arsenide semic.
IRT	Index-of-refraction turbulence
LEO	Low earth orbit satellite
Mbps	Mega bits per second
MANET	Mobile Ad-Hoc Network
MFSOT	Mobile free space optical terminal
MPE	Maximum permissible exposure
Nd-YAG	Neodymium YAG-Laser
nm	Nanometer
OOK	On/off keying modulation
PAT	Pointing acquisition tracking
PCA	PAT control unit
PPM	Pulse position modulation
PSK	Phase shift keying
Rx	Receiver
RXA	Receive assembly
Si	Silicon semiconductor
Tx	Transmitter
TXA	Transmit assembly
VPN	Virtual private network
FL290	Flight level *29000 feet*

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