Evaluation of Wavelength Requirements for Stratospheric Optical Transport Networks

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***Abstract*—This paper addresses the concept of optical transport network based on high altitude platforms (HAPs) flying in lower stratosphere and equipped with optical communications payload. The stratospheric transport network is formed of optical links between HAPs and optical backhaul uplinks and downlinks between HAPs and ground stations (GSs) hosting gateways to the backbone network. In order to consider limitations of free space optics (FSO) for the dimensioning of stratospheric optical transport network (OTN), we investigate the physical layer aspects for a DWDM based optical interplatform link (IPL). Taking into account the physical constraints imposed by FSO, we estimate the number of wavelengths required for full interconnectivity without wavelength conversions. We are using an analytical approach for bus and full mesh regular topologies, and a numerical approach for circumcircled star, ring and star regular topologies. We also evaluate the performance of a representative network with irregular topology using different routing and wavelength assignment algorithms. We show that the number of wavelengths needed to achieve full interconnectivity strongly depends on the physical topology of the network, and that adaptive routing yields better overall performance of the network compared to fixed and fixed alternate routing. The analysis also shows that resources in realistic network topologies tend to be used very inefficiently, which could be improved by traffic engineering solutions or wavelength conversions.**

***Index Terms*—Optical Transport Network, High Altitude Platform, Free Space Optics, Network Dimensioning, Routing and Wavelength Assignment**

I. INTRODUCTION

The performance of services and applications, such as internet access, interconnection of remote networks, or provision of transmission link for high-resolution Earth observation data, meteorology data or science missions, is conditioned by the capabilities of the available telecommunication networks. For many years, the main bottleneck in such networks has been the wireless access segment, whose performance depends also on the access to the backbone network. The latter is not always readily available even in populated areas, and less so in remote areas. In this respect, high altitude platforms (HAPs) based on long endurance manned or unmanned aircrafts, air stations or balloons, typically flying at altitudes between 17 and 22 km and carrying communications payload, represent a particularly attractive solution, capable of providing both access and transport segments of the network [1, 2]. HAPs can be deployed rapidly and on demand relocated in compliance with changing communication demands to the desired coverage area on the ground. During the operation they can keep quasistationary position, and they can be landed for upgrading and maintenance.

HAPs are expected to be first deployed in a stand-alone configuration, providing users with the access to the backbone network through a ground station (GS). As the demand for coverage and/or system capacity increases, further platforms can be added to the system forming a network of HAPs connected indirectly with backhaul platform to ground links (PGLs) via GSs or directly with interplatform links (IPLs), in the latter case providing an airborne transport network. Distant HAPs can even be interconnected via satellite using platform to satellite links (PSLs) [3, 4]. Depending on the network architecture, the transit traffic can be directed on a backhaul PGL to a ground station (GS), along PSL to a satellite, or on IPL to other HAP. Fig. 1 shows reference system architecture.

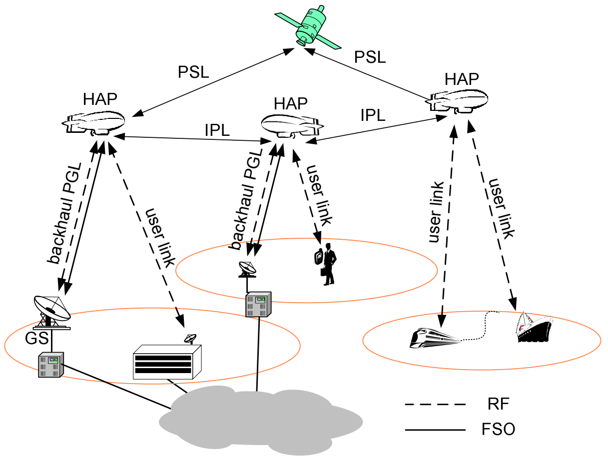

Figure 1. System architecture

Manuscript received April 1, 2009; revised June 20, 2009; accepted June 29, 2009.

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doi:10.4304/jcm.4.8.588-596

The transit traffic will be high-capacity aggregated traffic requiring adequate transport technologies. The technology used for the different transport links has to be carefully chosen taking into account the propagation channel, link capacity, payload weight and power consumption restrictions [5]. Free space optics (FSO) offers several advantages compared to traditional radio technology such as high capacity, low terminal power consumption and terminal weight, good transmission channel quality due to the low atmospheric density, no interference problems and tap proofness due to very low beam divergence. Furthermore, utilization of FSO for IPLs, PSLs and possibly also for backhaul PGLs also enables seamless integration of HAP based networks with next generation of satellite systems and terrestrial fiber networks [6], yielding all-optical integrated backhaul network.

In this paper, we investigate the concept of optical transport network based on HAPs, focusing on the wavelength requirements taking into account the physical constraints imposed by FSO. Section II introduces the concept of HAP-based optical transport network. Section III focuses on physical-layer limitations for the implementation and dimensioning of optical IPLs, while Section IV deals with network dimensioning developing analytical approach for analysis of regular network topologies. Section V extends the investigation of wavelength requirements to synthetic regular network topologies and to a realistic irregular network topology using simulation approach with different routing and wavelength assignment (RWA) algorithms. Section VI draws conclusions and summarizes the paper.

II. HAP-BASED OPTICAL TRANSPORT NETWORK

A. *Operating Environment Implications*

Due to the small coverage area of HAPs compared to satellites, and due to the nature of data traffic, the traffic generated in a HAP network is expected to be predominantly long distance [5]. Connections will mostly extend beyond the single HAP footprint, requiring a terrestrial or airborne transport network and a transition to other networks via appropriate gateways. This puts demanding requirements to IPLs and PGLs, making the FSO particularly attractive for their implementation due to the high data rates optical technology is able to deliver. IPLs are less problematic than PGLs due to the fact that they are deployed above the line of clouds, in the low air density stratosphere, where attenuation is smaller than in the troposphere. The main constraint put on optical IPLs is that they are situated above the tropopause, a boundary region between the troposphere and the stratosphere, essentially limiting the maximum distance between the HAPs.

The described relations are illustrated in Fig. 2, where c and h stand for the cloud ceiling altitude and HAP altitude, respectively. The maximum IPL length for mid latitudes (Europe) can be estimated by a simple calculation as given in (1) [5], where R represents the mean Earth radius. Assuming the cloud ceiling $c = 13$ km and Earth radius $R = 6372.1$ km, maximum IPL length reaches $d_{max} = 452$ km for HAP altitude $h = 17$ km and $d_{max} = 783$ km for $h = 25$ km. In reality, maximum IPL length may be shorter due to the atmospheric turbulence conditions, described in Section III.

$$d_{\max} = 2\sqrt{(R+h)^2 - (R+c)^2} \qquad (1)$$

For PGLs, on the other hand, the limiting factor is the weather conditioned optical visibility between the HAP and the GS. Thus, the geographical sites for establishing reliable optical PGLs should be selected according to the probability of cloud coverage. The link reliability of optical PGLs can be increased by:

- Using backup radio links between HAPs and GSs, guaranteeing basic connectivity at reduced data rate.
- Using the site diversity concept and rerouting, with the condition that respective GSs are separated by such a distance as to ensure uncorrelated cloud cover statistics (as shown in [7] the distance between pairs of sites for relatively low cloud correlation coefficient should typically exceed 200-300 km). The availability of the PGL in a network in dependency of the separation distance has been already studied in [3] and [8].

These measures already result in high link availability. FSO transmission through clouds and fog, which is possible for applications with shorter link distance (e.g. ground to ground links between buildings), is not taken into account here since the resulting attenuation is always beyond system abilities in the medium and worst case.

In clear sky conditions, however, several research groups already proved the feasibility of high-speed optical links from atmosphere to the ground. CAPANINA project established an optical 1.25 Gbit/s downlink from the stratosphere over a maximum link distance of 64 km [8] and the Applied Physics Laboratory at the John Hopkins University demonstrated an air-to-ground 80 Gbit/s optical link between a tethered aerostat and a GS [9].

B. *OTN Technology Implications*

FSO links can be used to establish an optical transport network interconnecting HAPs in the stratosphere as well as HAPs and ground stations in various network topologies. In order to make use of terrestrial fiber-optical components with proven reliability e.g. laser diodes, fiber amplifiers, detectors and receiver electronics, a HAP based transport network can use direct detection with on/off-keying. The simplest concept for an IPL system is OEO conversion at the receiver. The received signal is directly focused on the avalanche photodiode detector (APD). Besides the disadvantage of the additional delay through the electrical conversion, the advantage is that the signal is re-amplified, reshaped and retimed (3R).

As with terrestrial optical infrastructure, Wavelength Division Multiplexing (WDM) can be used also in HAP network to increase the link capacity [3]. WDM is an OTN technology that works similarly to a circuit switched network by assigning a different wavelength for each connection. When more bandwidth is required, the terminal equipment (e.g. multiplexers, demultiplexers, add/drop multiplexers, optical cross connects, etc) has to be upgraded. In case of closely spaced wavelengths in the 1550 nm window, characterized by the smallest attenuation and the possibility to use the Erbium-doped fiber amplifier (EDFA), WDM is referred to as dense WDM (DWDM).

If the two communicating nodes can be connected via a dedicated wavelength, without any conversion to electronic domain, we refer to single-hop connectivity. On the other hand, we talk about multiple-hop connectivity in the case where traffic from multiple nodes is sent on the same wavelength employing optical TDM over WDM or optic-electro-optic conversion and routing in the electronic domain.

A single-hop WDM network can be routed in a static fashion, in which case the connections are pre-established and manually set up for a long time. These types of networks are neither easily reconfigurable nor scalable, and thus ill-suited for a dynamic HAP based network. In case of using dynamic routing the WDM network is able to set up and release connections in response to traffic conditions. Such network makes much better use of physical resources and suits the dynamic nature of a HAP based network.

III. PHYSICAL LAYER ASPECTS FOR OPTICAL IPLS

A. *Atmospheric Attenuation*

FSO for IPLs in the stratosphere, the main application discussed in this paper, is affected by molecular and aerosol absorption, Rayleigh and Mie-scattering. The aerosol effects are not treated as absorption and scattering separately, but are combined to a single absorption coefficient. For highly directional optical communication the impacts of scattering and absorption are nearly the same: the decrease of received intensity. Therefore it is possible to consider these effects with a single damping coefficient.

The power that can be transmitted over an atmospheric distance z is calculated using the altitude-dependent attenuation coefficient α of Beer's law for transmission of radiation in an absorbing medium according to (2).

$$I_{trans}(z) = I_0 \cdot e^{-\alpha \cdot z} \tag{2}$$

The attenuation coefficient α ($\alpha > 0$) is measured in km^{-1}. In Fig. 3, the total atmospheric attenuation coefficient for near infrared wavelength can be seen. This calculation is based on models using the data after Air Force Geophysics Laboratory (AFGL) mid-latitude summer [10]. Besides the absorption maxima, which are mainly caused by water absorption lines, the decrease of background attenuation with the 4th power of the wavelength can be seen due to Rayleigh-scattering.

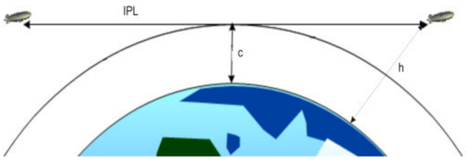


Figure 2. Determining maximum distance between HAPs

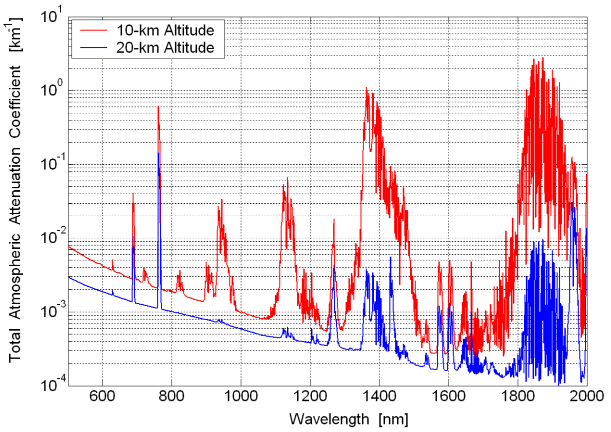


Figure 3. Atmospheric clear air attenuation between 500 µm and 200 µm for two different HAP altitudes

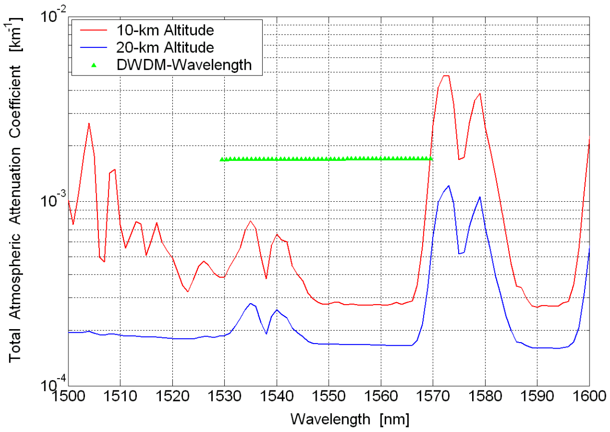


Figure 4. Atmospheric attenuation between 1550 µm and 1600 µm with indicated wavelengths of a 51 channel DWDM system

Fig. 4 is the same plot as Fig. 3 but with a frequency range between 1500 and 1600 nm. The small triangles denote the wavelengths of a 51 channel DWDM system according to the standard ITU C frequency grid DWDM applications with 100 GHz channel spacing between 191 THz (1569.59 nm) and 196 THz (1529.55 nm) [11]. Even if the worst case clear-air absorption coefficient α of 5×10^{-5} for a 110 km link at an altitude of 10 km is considered, the total atmospheric attenuation is only 2.4 dB. Since fog- and cloud attenuation does not appear in IPLs when the HAP is placed at adequate altitude (see Fig 6 and 7) the attenuation is not a problem for long IPLs and can be easily taken into account in the system link budget.

In this paper we also assume the possibility of a system with twice as many channels as depicted in Fig. 4, i.e. 102 channels assuming 50 GHz channel spacing in the 1550 nm window.

B. *Transmission Power for a DWDM-IPL System*

According to theory, a mean of 10 incoming photons per bit are sufficient for an uncoded Bit-Error-Rate (BER) of 10^{-9}. However, in practical systems using standard APD-detectors, the receiver sensitivity is usually not

TABLE I.
PARAMETERS OF IPL SYSTEM

Receiver aperture diameter	10 cm
Receiver field of view	100 µrad
Transmission distance	517 km
Optical transmitter losses	3%
Residual pointing error	20 µrad

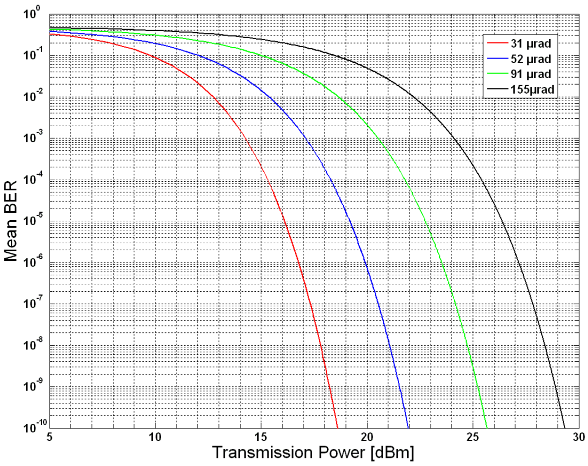


Figure 5. Dependency of BER on transmission power for a single channel and different transmitter divergence angles

better than several hundred of photons per bit. This is due to thermal receiver noise and other degrading electronic effects. The use of optical pre-amplifiers at the receiver enables higher sensitivity compared to APD receivers [12]. The results of an example link budget calculations with system parameters displayed in Table I are shown in Fig. 5.

The calculations have been performed with methods after [13], using an off-the-shelf 2.5 Gbit/s APD receiver. Atmospheric turbulence effects have been considered using numerical split-step simulation methods after [14]. The output of the simulations are time vectors of the received power with the used aperture size of 10 cm. Moderate blue sky background light, which is already relatively small at 1550 nm compared to smaller wavelength, has been taken into account. Further details on the link budget calculation are reported in [13].

The dependency of mean BER on transmitter power is plotted for 4 different transmitter divergence angles, i.e. 31 µrad, 52 µrad, 91 µrad and 155 µrad. It can be seen that in case of the lowest beam divergence of 31 µrad a transmission power of 18.2 dBm per channel is sufficient for a BER of 10^{-9}.

The small beam divergence assumes a well designed tracking system with a residual pointing error of well below the beam divergence. For optical satellite terminals such and even higher pointing precisions have been already demonstrated several times (Silex System, DLR-LCT System etc.). The mechanical vibration spectrum and base motion disturbance of a LEO satellite is of course not so severe. But for optical links on turbo-prop aircrafts with worst case disturbance compared to HAPs, a mean residual pointing error of 266 µrad, even without fine pointing assembly has already been demonstrated [15].

C. Atmospheric Turbulence

Atmospheric turbulence effects have been already taken into account in the link budget calculations. Here, a closer look on these effects will be taken and some open issues will be discussed.

The inhomogeneities within the index of refraction of the air along the transmission path lead to both, time dependent wave-front distortion and scintillation.

Especially the wave-front distortion is an important effect which has to be taken into account when it comes to the system aspect of channel separation. Channel separation before focusing to the detector is just possible up to a certain number of channels. For multi-channel systems, the number of necessary channels as well as the channel spacing exceeds the possibilities of discrete optical free-space filter benches in several points: complexity, insertion loss, susceptibility of misalignment etc. Integrated fibre optics components would solve the task of wavelength separation but the received signal has to be coupled into a mono-mode fiber for that. The possible architecture of such a unidirectional DWDM-FSO system is given in [3] which will be assumed for the following further considerations.

If the wave-front distortion is too large, the mono-mode fiber coupling at the receiver would require wave-front correction in order to maximize the Strehl ratio in the focus and thus increase mono-mode fiber coupling efficiency. If the effect of wave-front distortion would be negligible, tip/tilt tracking performed by the Fine Pointing Assembly (FPA) would be sufficient for high fiber coupling gain.

Wave-front distortion is evaluated by the coherence diameter r_0 which is given by integrating the atmospheric structure parameter C_n^2 over the path ([16] Sect. 12.4.1):

$$r_0 = 2.1\times\left[1.45k^2\int_0^L C_n^2\left(h(z)\right)dz\right]^{-3/5} \tag{3}$$

C_n^2 gives the degree of turbulent energy along the transmission path z, λ is the wavelength and $k = 2\pi/\lambda$.

Fig. 6 shows the dependency of the Fried parameter on IPL link distance and HAP altitude. The assumed atmospheric C_n^2 turbulence profile is modeled with profiles described in [4]. The cloud ceiling that prevents 100 % availability (dark grey area) starts from an altitude of 13 km downwards.

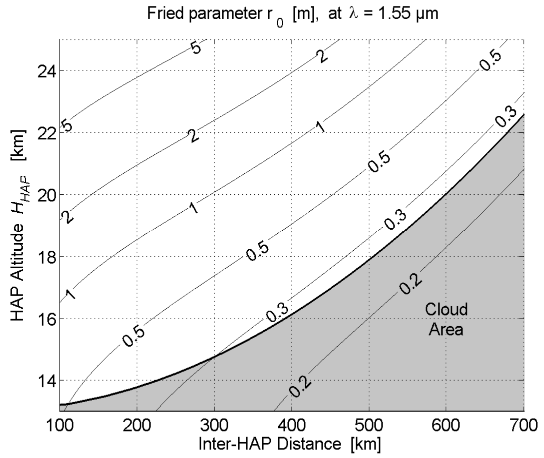


Figure 6. Scintillation for an inter platform link in dependence on link distance and HAP altitude.

It can be seen that the Fried parameter is always larger than the receive aperture. Outside the region of higher cloud blocking probability, the Fried parameter is at least 3 times larger than the aperture. Therefore the high technical effort of wave-front correction is not necessary for coupling the received light into the mono mode fiber at the receiver. Thus, for IPL terminals channel separation of DWDM wavelength can be done with integrated fiber optics components due to the fiber coupled received signal. The Doppler Effect does not have to be taken into account here due to the low HAP velocities.

The intensity fluctuations lead to signal fades and surges and have to be taken into account for the system design. One parameter to quantify the intensity fluctuation is the Rytov index σ_R^2 calculated according to [17] pp. 299 Eq. (155).

Fig. 7 shows the dependency of the Rytov index on the link distance and HAP altitude. For a Rytov index of $\sigma_R^2 > 0.3$ coding and error correction would lead to a significant increase of system performance.

IV. Analytic Network Dimensioning

The number of dedicated channels to support a connection between two points is limited by technological and transmission channel constraints. The larger and the more irregular the network topology, the harder to calculate the number of different wavelengths needed to serve all connection requests.

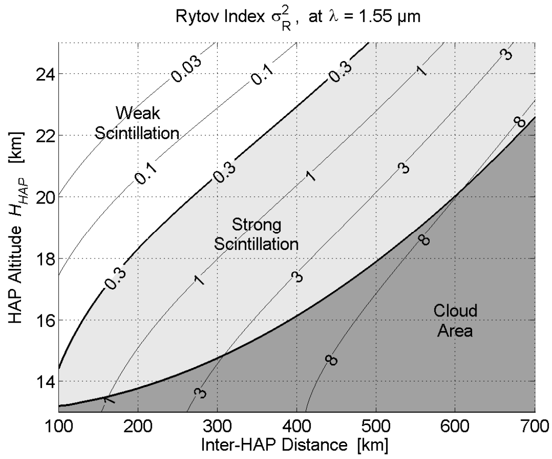


Figure 7. Scintillation for an inter platform link in dependence on link distance and HAP altitude.

For regular network topologies the minimum number of required wavelengths per optical link in order to connect each pair of source destination nodes can be determined analytically. Two such topologies have been identified as extremes, as far as resource usage is regarded, the full mesh and the bus [18]. Fig. 8 depicts their structure, where the number of HAPs and GSs per HAP are arbitrary.

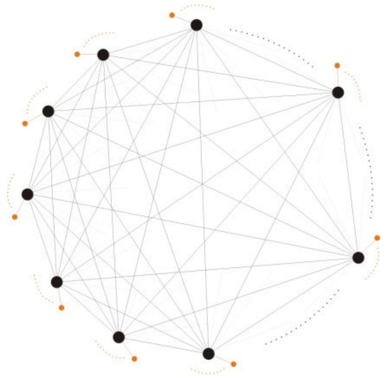
In order to show that OTN dimensioning strongly depends on the physical topology of the network, we first determine the wavelength requirements for single-hop connectivity between each pair of HAPs and each pair of HAP and GS in full mesh and bus topologies. The highest number of wavelengths (n_λ) required to fully interconnect all source-destination nodes in a network is required by the bus topology and is given by (4) where N is the number of HAPs and k is the number of GSs connected to each HAP [19].

$$n_{\lambda,BUS} = \max\{Nk, (2k+1)\lfloor N/2 \rfloor \lceil N/2 \rceil\} \quad ; \quad N > 1 \quad (4)$$

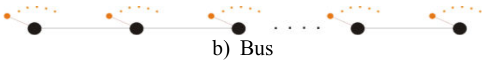
The smallest number of wavelengths to achieve all optical HAP-HAP and HAP-GS interconnection is required by the full mesh topology and can be calculated by (5) [19]. The wavelength requirements for other regular or irregular topologies can be found between these bounds.

$$n_{\lambda,FULLMESH} = \max\{Nk, 2k+1\} \; ; \quad N > 1 \quad (5)$$

Taking into account these equations a network of 7 HAPs with one GS per HAP requires for full interconnection of all nodes 7 different wavelengths in the case of full mesh topology and 36 different wavelengths in the case of bus topology. However, in the case of full mesh topology, the higher number of wavelengths is required on PGLs, which are more critical in terms of link reliability, whereas in the case of bus topology the highest number of wavelengths is required on IPLs.



a) Full mesh



b) Bus

Figure 8. Regular network topologies

TABLE II.
WAVELENGTH REQUIREMENTS FOR REGULAR TOPOLOGIES WITH 7 HAPS AND 7 GSS

Topology	Required wavelengths (n_λ)	Critical links
Full mesh	7	all UL/DL
Bus	36	central IPLs
Ring	18	all IPLs
Circ. star	9	edge IPLs
Star	18	all IPLs

Next, we determine some possible regular HAP based full mesh and bus network topologies considering the physical constraints determined in the previous section (i.e. the number of wavelengths available on an optical link). The optical communication system proposed in the previous section allows 51 different wavelengths per optical link with 100 GHz spacing or 102 wavelengths with 50 GHz spacing. With these constraints, a full mesh network comprising 51 and 102 HAPs could be deployed. The bus topologies that could be deployed with the given constraints and maximize the resource usage are listed in Table II. For 102 wavelengths, a network configuration of 9 HAPs with 2 GS per HAP could be deployed and such a network would use 100 of the 102 available wavelengths. For 51 wavelengths, a configuration of 8 HAPs with 1 GS per configuration that would use 48 of the wavelengths could be deployed. Other configurations are also possible, but they would leave further unused resources.

V. SIMULATION BASED NETWORK DIMENSIONING

For more complex regular and for irregular topologies, network dimensioning becomes a very challenging task, calling for the use of suitable simulation methods. In this section, we analyze three purely synthetic and a representative realistic HAP topology.

We use a simulation tool implementing several RWA algorithms to determine the topology's performance given the limited number of available wavelengths per link. The tool uses Dijkstra's shortest path algorithm to implement three routing algorithms. Fixed routing (FR) simply establishes a connection on the same pre-established path. Fixed alternate routing (FAR) remembers multiple routes between pairs of nodes and each node in the network stores a table with more possible link disjoint routes to each destination. Adaptive routing (AR) establishes a connection upon request according to the current state of the network.

Furthermore, the tool implements two wavelength assignment algorithms. Random assignment algorithm (R) chooses a random wavelength from a set of idle wavelengths on the given path. If there is no wavelength continuity constraint, a random wavelength is chosen among the idle ones on each link along the path. The first fit assignment algorithm (FF) numbers all the wavelengths and assigns the lower numbered before higher numbered. Thus, this algorithm is packing the wavelengths in use toward the lower end of the wavelength space, giving continuous longer paths toward the higher end of the wavelength space a higher probability of being available.

Routing can be performed with full wavelength conversion (FC) capabilities at each HAP or without any conversion in a so called wavelength continuous way. The simulations were performed using incremental traffic, that is, once a lightpath is established it stays on for a long period of time (i.e. resources are not released immediately for idle connections). For the simulation we considered that each HAP can establish a connection to each other HAP and each GS can establish a connection to any HAP.

A. *Synthetic regular topologies*

We analyzed three synthetic topologies, which differ from bus and full mesh topology and do not reflect any realistic structure, i.e. a circumcircled star, a ring and a star topology. Fig. 9 depicts their structure with an arbitrary number of HAPs and GSs.

In order to calculate the required number of wavelengths for full interconnection of all nodes, the AR routing and FF wavelength assignment algorithm were used. Calculation results for the three synthetic topologies as well as for the bus and full mesh topologies are summarized in Table III for the case of 7 HAPs with one GS per HAP.

TABLE III.
DIMENSIONING OF BUS TOPOLOGY

50 GHz DWDM system with 102 wavelengths		
required wavelengths (n_λ)	HAPs (N)	GSs (k)
80	8	2
99	6	5
90	11	1
100	9	2
100 GHz DWDM system with 51 wavelengths		
required wavelengths (n_λ)	HAPs (N)	GSs (k)
36	7	1
42	5	3
45	6	2
48	8	1

a) Circumcircled star b) Ring c) Star

Figure 9. Synthetic topologies

According to Table III, the ring and star topologies require 18 wavelengths, whereas the circumcircled star uses only 9. As expected, the ascertained numbers are higher than 7 required wavelengths in the case of full mesh topology and lower than 36 in the bus topology case. In all three cases, the highest number of wavelengths is required on IPLs.

B. Representative realistic irregular topology

The core topology considered for the pan-European fiber optic network with 16 nodes and 23 links, which has been studied in the COST 266 project [20], is depicted in Fig. 10. We consider that each HAP is optically linked to a ground station and no link failures are taken into account. The longest distance between two nodes of the pan-European core fiber network topology studied in COST 266 is 517 km (Rome-Zagreb). In order to keep the IPL between these HAPs above the graze height, the respective HAPs have to be deployed at approximately 19 km or higher, as it can be calculated using (1).

The average blocking (B), the maximum number of wavelengths used on a link during the simulation (λs) and the number of links on which this maximum occurred (Ls) for each RWA strategy are listed in Tables IV and V for 51 and 102 wavelength DWDM systems, respectively.

The HAP network with 51 wavelengths per link (see Table IV) blocked about 15% of the connection requests using the lowest performance RWA strategy, FR-R, and about 11% using the highest performance RWA strategy, AR-FF-FC. For 102 different wavelengths per link, no blocking occurred (see Table V).

In spite of relatively high blocking in the 51 wavelength DWDM system, the links are not fully or uniformly utilized; the Hamburg-Berlin link, for instance, is highly occupied (over 90% of the link capacity), whereas the Prague-Vienna link is used only at about 60% of its capacity with AR-FF-FC. Adaptive routing distributes the burden over links more homogeneously, unlike FR and FAR that tend to put very high burden on a small number of links and moderate to small burden on most of the other links. The comparison of different routing algorithms (FR, FAR and AR for FF wavelength assignment and full wavelength conversion) in Table IV shows that AR yields smaller blocking with smaller number of burdened links.

Figure 10. Topology of the representative realistic irregular topology

In the DWDM system with 102 wavelengths per link there were no blocked connection requests. However, the results indicate that the network is over-dimensioned in this case, with the AR using only 68 different wavelengths on the most used links, while the FR and FAR used 82 different wavelengths on the most loaded links, so the network should employ some solutions in order to use its resources more efficiently. Traffic engineering solutions, OEO conversions or all optical packet routing might be ways to achieve more efficient service provisioning.

VI. CONCLUSIONS

In this paper we investigated wavelength requirements for full interconnectivity in optical transport networks based on HAPs, taking into account the physical constraints imposed by FSO for DWDM system. Using analytical formulae for the wavelength requirements in regular topologies we determined the closest-match star and bus topologies that fulfill the physical constraints of the FSO. Next, we evaluated the wavelengths requirements using numerical approach for three synthetic regular topologies. Finally, we investigated the wavelength requirements and the performance of different routing and wavelength assignment algorithms in a representative network with irregular topology. We showed that adaptive routing yields better overall performance of the network compared to fixed and fixed

TABLE IV.
SIMULATION RESULTS FOR THE DWDM SYSTEM WITH 51 WAVELENGTHS

Routing	FR				FAR				AR			
Wavelength assignment	R		FF		R		FF		R		FF	
Wavelength conversion	/	FC	/	FC	/	FC	/	FC	/	FC	/	FC
Average blocking	0.156	0.141	0.146	0.141	0.125	0.117	0.120	0.117	0.133	0.115	0.117	0.115
Max. no. λs used	50	51	51	51	51	51	51	51	50	51	51	51
No. links with max. λs	1	5	4	5	1	6	4	6	1	3	3	3

TABLE V.
SIMULATION RESULTS FOR THE DWDM SYSTEM WITH 102 WAVELENGTHS

Routing	FR				FAR				AR			
Wavelength assignment	R		FF		R		FF		R		FF	
Wavelength conversion	/	FC	/	FC	/	FC	/	FC	/	FC	/	FC
Average blocking	0	0	0	0	0	0	0	0	0	0	0	0
Max. no. λs used	81	82	82	82	79	82	82	82	68	68	68	68
No. links with max. λs	1	1	1	1	1	1	1	1	1	1	1	1

alternate routing. The analysis also shows that resources in realistic network topologies tend to be used very inefficiently, which could be improved by traffic engineering solutions or wavelength conversions.

ACKNOWLEDGEMENT

The authors are gratefully acknowledging the contributions of Dr. Nicolas Perlot from the German Aerospace Center (DLR) on atmospheric turbulence (Fig. 6 and Fig. 7).

This work has been partially funded by the European Community through the 6th Framework Programme IST project SatNEx II (FP6-IST-027393).

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