Spatial Multiplexing in Optical Feeder Links for High Throughput Satellites

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***Abstract*—Optical feeder links are an attractive alternative to the RF feeder links in satellite communications (SatCom). In this paper, we present initial results from an optical feeder link study. We discuss the architecture of a geostationary earth orbit (GEO) satellite system based on optical feeder links. To mitigate the effects of cloud coverage, which is the main availability-limiting factor, Optical Ground Station (OGS) diversity is employed. Moreover, a spatial multiplexing scheme is considered. Assuming an ON-OFF channel model, the number of required OGSs to ensure availability and throughput requirements is analyzed.**

I. INTRODUCTION

The main challenge of the broadband SatCom systems is the limited spectrum of about 2 GHz available in current Ka-band. A potential solution for resolving the issue could be moving the feeder link from the Ka-band to the Q/V-band ($40/50$ GHz) and W-band ($70/80$ GHz) where larger bandwidth, up to 5 GHz, is available [1]–[4]. Another revolutionary solution could be to move the feeder link from RF to optical frequencies. This solution has the following potential advantages with respect to RF links [5]: (a) Optical band has 100 to 1000 times more spectral bandwidth than all of RF bands, (b) Optical bands have no frequency regulation constraints due to the highly directive antennas, (c) With the feeder link moved to the optical band, the spectrum released from the RF feeder link can be allocated to the user links, which will be kept in the RF band and require relatively lower data rates and low cost user terminals. Thus, the cost of the optical feeder link in the long term can be potentially negligible compared to the revenue generating RF user links, (d) The light beam can be very narrow, making optical links hard to intercept, thus improving security.

However, there are also some key challenges associated to the use of optical feeder links: (a) The main propagation impairment in optical frequency band is the cloud coverage, which further motivates the investigation of OGS diversity techniques; (b) Currently, there is no technology mature enough for down-converting the optical signal to RF signal transparently, which further imposes stringent requirements on the payload type (transparent vs. regenerative).

Indeed, optical communication through the Earth atmosphere is nearly impossible in the presence of most types of clouds. The blockage of ground stations by cloud coverage is the key factor limiting availability. Clouds are composed of liquid water and/or ice crystals: depending on the physical thickness, they can produce atmospheric fades easily exceeding 10 dB. Therefore, an optical communication system has to utilize a network of multiple OGSs that are geographically dispersed, at least as far apart as the meteorological correlation length of large cloud cover structures, such that there is a high probability of a cloud-free line of sight (CFLOS) from a ground station at any given point in time. This technique, called gateway diversity, provides for the transmission/ reception from multiple stations to tide over the unavailability of some states due to cloud cover or geometric visibility limitations. Adding more de-correlated ground stations as widely separated as possible will always be beneficial. Apart from cloud blockage, another propagation impairment is the refractive index turbulence which affects the CFLOS optical link. This effect is typically factored into the link budget.

The purpose of this work is to study an Optical Ground Stations Network (OGSN) with N active OGSs and P idle (redundant) OGSs, where the N active OGSs are used for multiplexing and each of them is responsible for a portion of the total throughput, whereas the P idle OGSs are used for diversity in order to guarantee the required high availability. The $N + P$ scheme has been studied for RF bands in [1] and [6]–[8]. It should be noted that in RF, N active gateways are used because the bandwidth available at each feeder link is insufficient to satisfy the capacity on the forward link. But in optical band, each OGS can feed very large throughput and additional OGSs are needed to achieve required availability against cloud coverage. However, feeding the whole system by a single active OGS might not be a good idea since it will require very big and expensive OGSs. Besides, it is known that due to cloud blockage, tens of OGSs are mandated. So the idea of using N multiplexing OGSs is to have smaller OGSs. To the authors' best knowledge, this is the first time that the $N + P$ multiplexing scheme is studied for optical feeder links, and this represents the main contribution of this paper to the state-of-the-art literature. In this scheme, when one of the active OGSs is in outage, switching occurs and traffic of the impacted OGS is routed to one of the idle OGS amenable for CFLOS communication. We introduce this scheme for the optical feeder link and assuming a simple ON-OFF channel model [9], we study the number of the required OGSs for different availability and throughput requirements.

The remainder of this paper is organised as follows. In section II, the overall architecture of a SatCom system with

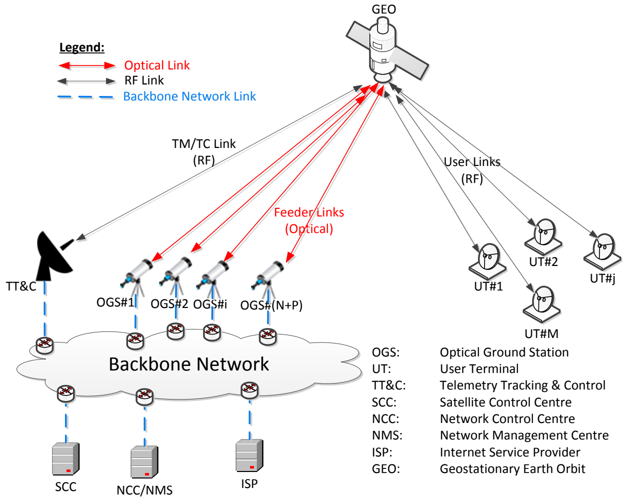

Fig. 1. GEO satellite system architecture based on the optical feeder links

optical Ground-GEO feeder link is introduced. Section II also describes the optical channel model assumed. In section III, availability and mean throughput of the $N+P$ system are discussed and useful numerical results are provided. Concluding remarks and future work plan are provided in Section IV.

II. SYSTEM SCENARIO DESCRIPTION

A. *System Architecture*

Fig. 1 depicts the overall satellite system architecture for the scenario under consideration where optical feeder links to the GEO satellite are employed. Emphasis is put on High Throughput Satellite (HTS) communication systems which offer high-speed broadcast services and/or broadband interactive services.

The satellite access network is composed by the following elements:

- Space Segment: This is composed of one or more satellites in geostationary orbit. The GEO satellite connects the OGSs to the User Terminals (UTs), thanks to a set of feeder and user links.
- Ground Segment: It includes:
  - A main Network Control Centre (NCC), responsible to control and synchronize the overall network.
  - A main Network Management System (NMS) which handles the management of the resources in the network.
  - A Satellite Control Centre (SCC) which is responsible for monitoring and controlling the space segment.
  - A Telemetry Tracking and Control (TT&C) station to transmit and receive telecommand/ telemetry (TM/TC) data to/from the satellite through an RF link.
  - A network of OGSs which are responsible for transmitting and receiving data, control and management of traffic to/from the UTs. Spatial multiplexing is assumed; in particular, a system with N active OGSs and P redundant OGSs is assumed. All $N+P$ OGSs are connected to the Network Control Center (NCC).
- User Segment: It is composed of a set of UTs operating in a RF frequency band (e.g., Ku-band, Ka-band, etc). UTs can be either one-way DTH or two-way terminals.

The access network is complemented by the backbone network, which is responsible of interconnecting the SCC, NCC/NMS, OGSs, TT& C and the Internet Service Providers (ISPs), in order to provide a way to exchange data and manage and control the traffic. The main NCC/NMS is connected in a star topology with the OGSs, whereas the TT&C station is controlled only by the SCC.

B. *Optical Channel Model*

As underlined above, cloud coverage is the central factor limiting availability and the key performance driver in optical communication systems. To this end, OGS diversity is employed such that there is a high probability of a CFLOS to an OGS at any given point in time.

In this paper, to facilitate an analytical study, we first assume that the OGSs experience independent cloud coverage. This requires the OGSN forming the OGS diversity configuration to utilize multiple OGSs that are geographically separated at the least, by the meteorological correlation length of large cloud cover structures. Then for a case study, we consider SES's Teleport network and study the effects of cloud coverage by simulation.

We consider a binary (ON-OFF) model for the optical feeder link channel. In this model, the channel will be in OFF mode (unavailable) in case of cloud blockage whereas the channel will be in ON mode (available) in case of cloud-free LOS. We denote the cloud blockage probability by p_c and clear sky probability by $1-p_c$.

III. SYSTEM AVAILABILITY ANALYSIS

In this section, we study the availability and thoughput performance of the proposed $N+P$ scheme. The purpose is to find the minimum value of P that satisfies given availability and throughput requirements. In this respect, two performance metrics are used: the Maximum Throughput Availability and the Mean Throughput. These metrics are detailed next.

A. *Maximum Throughput Availability (MTA)*

We denote the maximum possible throughput of the system by T_{max} and assume that the throughput of each of the N multiplexing active OGSs is T_{max}/N. We define that the system is available when the maximum throughput (T_{max}) is achieved. This means that the system is considered available in MTA sense when at least N OGSs encounter an ON channel. Based on this definition, we can find the maximum throughput availability of the $N+P$ scheme as follows

$$\begin{aligned} P_A^{T_{max}} &= \Pr\{n_{av} \geq N\} \\ &= \sum_{i=N}^{N+P} \binom{N+P}{i} (1-p_c)^i {p_c}^{N+P-i} \qquad (1) \end{aligned}$$

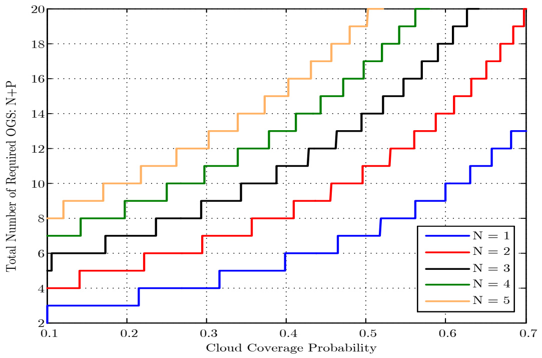

Fig. 2. Total number of OGSs required for the maximum throughput availability of 99%

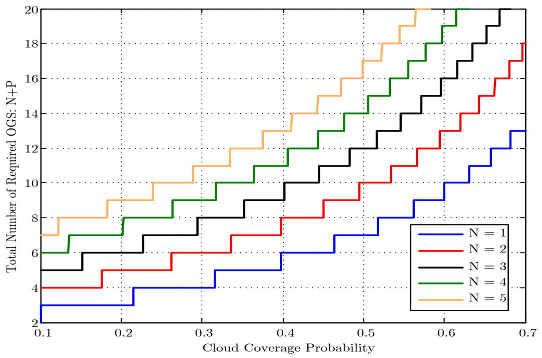

Fig. 3. Total number of OGSs required for the mean throughput of 0.99 T_{max}

where n_{av} is the number of available OGSs. Using the numerical evaluation, considering different number of the active OGSs, N, we find the minimum number of idle OGSs, P, that provide availability of $P_A^{T_{max}} \geq 99\%$.

In Fig. 2, we can see the total number of required OGSs for different values of N and for different probabilities of cloud coverage. As an illustration, for a cloud coverage probability of 0.5 we need $P = 6$ redundant OGSs when $N = 1$ to ensure the 99.9% availability. But when $N = 2$, we need $P = 9$ redundant OGSs. A important point here is that when $N = 2$, maximum throughput of each OGS should be $T_{max}/2$. This results in the use of smaller, low power and more cost efficient OGSs (e.g., see [10]) and it highlights one of the advantages of having multiple active OGSs (multiplexing). On the contrary, when there is a single active OGS (no multiplexing), $N = 1$, each of the redundant OGSs should be able to provide the throughput of T_{max} which forces deployment of larger and costly OGSs.

B. Mean Throughput

In the previous subsection, we considered that the $N + P$ multiplexing system is available only when at least N OGSs (maximum throughput, T_{max}) are available. However, in practice, even with less than N active OGSs, there is still some portion of T_{max} available. For example when $N = 3$, each of the OGSs can provide $T_{max}/3$ throughput. When the number of the available OGSs is more than 3 ($n_{av} \geq 3$), the throughput of the system will be T_{max}. But when $n_{av} = 2$, for example, the throughput of the system will be $2 \times T_{max}/3$. This is another advantage of having multiple active OGS (multiplexing). Taking this partial availability of the throughput into account, we define the mean throughput as follow

$$T_{mean} = \Pr\{n_{av} \geq N\} \times T_{max} + \sum_{k=1}^{N-1} \Pr\{n_{av} = k\} \times \frac{kT_{max}}{N}. \quad (2)$$

Considering the binary ON-OFF channel model, we can find the T_{mean} as

$$T_{mean} = \sum_{i=N}^{N+P} \binom{N+P}{i} (1-p_c)^i {p_c}^{N+P-i} \times T_{max} + \sum_{k=1}^{N-1} \binom{N+P}{i} (1-p_c)^k {p_c}^{N+P-k} \times \frac{kT_{max}}{N}. \quad (3)$$

Now, we can consider T_{mean} as another criterion for finding the required number of OGSs. Instead of designing the system for the required maximum throughput availability, we can design it so that it ensures a certain amount of mean throughput. We can show this requirement by $T_{mean} \geq rT_{max}$ where $0 < r \leq 1$. By numerical analysis, the required number of OGSs is found for $r = 0.99$ as depicted in Fig. 3. As expected, we can see that the number of OGSs for satisfying the mean throughput requirement is less than the number of OGSs required for the maximum throughput availability requirement.

C. Case Study: SES Global Access Network (SGAN)

In this section, an illustrative case study is considered with correlated OGSs and unequal cloud blockage probabilities. In particular, the SES Teleport network is considered towards an illustrative example and the spatial multiplexing performance is studied for hypothetical OGSs co-located with SES teleports. SES operates and manages the SES Global Access Network (SGAN), which consists of several owned and partner teleports, a comprehensive fibre-based terrestrial network and numerous points of presences (POP) [11]. Based on secure Multi-Protocol Label Switching (MPLS) technology, SES extensive fibre-based network is designed to transport content from virtually any city in the world to one of the several SES-owned teleports or numerous partner teleports via the numerous SES POPs (see Fig.(4)). SES network is secure, redundant and reliable. For this case study, 20 teleports (OGS locations) were selected which are located in Europe, Africa and Asia. The approximate average cloud coverage probabilities of the teleports are found using a map in [12].

In general, cloud coverage of the OGSs are correlated and the correlation coefficient can be modelled by $r = \exp(-d/d_0)$ [13] where d is the distance between two OGSs and d_0 is the cloud correlation distance ($\sim$ 300 km). Based on this model, if the distances between OGSs are large enough

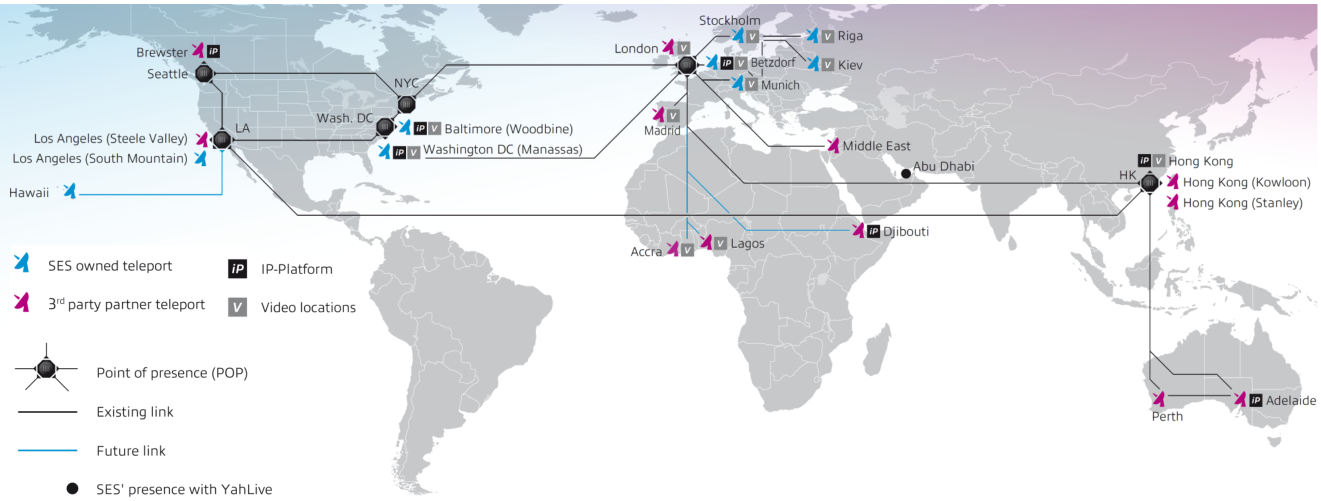

Fig. 4. SES Global Access Network (SGAN)

($\sim$ 1000 km) it can be assumed that OGSs will experience independent cloud coverage. In the selected OGSs from the SES hypothetical study case network, there are both independent and correlated OGSs. For OGS selection, the priority is given to the OGSs with the lowest cloud coverage probability. The average cloud coverage probability of the OGSs is 0.57. The lowest and the highest cloud coverage probabilities among the OGSs are 0.29 and 0.7 respectively.

Having the cloud coverage of the OGSs and the correlation between them, we generated the ON-OFF channel realizations using the method considered in [9]. Then for ensuring target performance introduced earlier, the required number of OGSs was found.

Table I summarizes the results for both independent and SES hypothetical study case network. It shows the number of required idle OGSs, P, for availability requirements and different number of active OGSs, N. It can be seen that for no-multiplexing case ($N = 1$) in SES's network, $N + P = 6$ OGSs are required to achieve $r = 0.99$. For spatial multiplexing case of $N = 2$, $N + P = 8$ OGSs are needed to assure $r = 0.99$. Note that in the former case all 6 OGSs must be able to provide throughput of $T_{\max}$ while in the later case 8 OGSs should provide throughput of $T_{\max}/2$.

It is worth mentioning that in SES's network, there are some OGSs with low cloud blockage probabilities ($p_c \sim 0.30$) that result in less number of required OGSs compared to the independent case with $p_c = 0.57$.

Apart from cloud coverage considerations, there are different aspects that should be taken into account for OGSN planning and site optimization: (a) backbone network connectivity, (b) constraints imposed by aviation and laser safety, (c) political and administrative concerns, (d) cost considerations, (e) availability of existing ground station infrastructure.

TABLE I
NUMBER OF REQUIRED REDUNDANT OGSS (P) FOR INDEPENDENT CASE $p_c = 0.57$ AND SGAN HYPOTHETICAL STUDY CASE

	Indep. Case $p_c = 0.57$		SGAN Case	
	MTA = 99%	$r = 0.99$	MTA = 99%	$r = 0.99$
$N = 1$	8	8	5	5
$N = 2$	11	10	8	6
$N = 3$	13	11	13	9

IV. CONCLUSIONS

In this paper, the design of Ground-to-GEO optical feeder links was studied and initial results were provided on the performance of spatial multiplexing for an OGSN forming an OGS diversity configuration. A system scenario, which is relevant for both high-speed broadcast and broadband interactive services, was described and a simplified binary ON-OFF channel model was utilized to model the effects of cloud coverage on the optical links. Employing two performance metrics – Maximum Throughput availability and Mean Throughput availability – numerical results were provided in order to analyze the number of OGSs required to ensure given availability and throughput requirements. In particular, it was shown that the proposed $N + P$ spatial multiplexing scheme can result in the use of smaller and more cost efficient OGSs, comparing to the case of no multiplexing (diversity only) which forces the use of larger and costly OGSs.

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