

An Empirical Study on Free Space Optical Backhaul

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Abstract—Free Space Optical (FSO) communication technology allows to improve connectivity and bandwidth in urban scenarios through wireless fiber-like point-to-point links. These links, however, are subject to strict line-of-sight (LoS) requirements, and their capacity (throughput) is sensitive to and strongly depends on various atmospheric phenomena. These constraints limit their range. This work examines the topological characteristics of the (supplementary) connectivity graph that can be obtained by implementing FSO on existing cell sites (*i.e.*, without new additional cell sites), taking into account existing topographic obstructions and FSO technical constraints and features (*e.g.*, link reconfiguration). In particular, the paper examines the distribution of distance in FSO LoS-compliant links between existing cell sites. The study relies on public data and FSO link and obstruction empirical models. Results are presented for Paris and three other French urban regions (Lyon, Bordeaux, Toulouse), but the described methodology (based on open-source code) can be applied to other territories as well. Preliminary obtained results indicate that utilization of existing cell sites and deployment of FSO technologies in urban areas lead to highly connected FSO meshes resilient to individual link failures and localized physical obstacles, and thus have the potential to substantially complement existing communication capacities, as well as to improve robustness of existing communication infrastructures.

Index Terms—Free Space Optical Communication (FSO), mobile networks, backhaul, line-of-sight (LoS), mesh networks

I. INTRODUCTION

The development of novel generations of mobile networks, including 5G and 6G, continuously improves network throughput and latency. These networks are designed to enable a vast variety of applications, ranging from classical telephony to highly intensive and low-latency constrained applications such as online gaming, telemedicine, industrial automation or virtual and augmented reality.

Backhaul networks bridge radio access networks (RAN) and operators' core networks. The increase in traffic and the popularization of traffic-intensive applications thus entail a substantial growth in backhaul capacity demands, which are expected to almost triple between 2023 and 2029 [1], and encourages backhaul technologies upgrade and evolution.

Many communication technologies have been used in backhaul networks. Legacy backhaul networks, such as copper and radio frequency (RF) microwave networks, are being gradually replaced by other technologies due, in part, to their capacity limitations [2], [3]. Among the alternatives, optical fiber is able to handle terabits per second, and is not subject to

electromagnetic interference. The share of fiber in backhaul networks is consequently growing, and is expected to match that of microwave by 2030 [3]. However, due to its wired nature, deploying fiber requires highly-constrained logistics to dig trenches and lay cables, as well as securing permits for these deployments, leading to high deployment costs and capital expenditure [2]. The high cell density required by 5G and 6G networks exacerbates these deployment costs [4].

Free Space Optics (FSO) stands as a competitive candidate in this context. FSO offers fiber-like terabits per second throughput and ultra-low latency over many kilometers without the trenching/leasing costs typically associated with optical fiber, nor the spectrum licensing fees associated with radio frequency alternatives [5]–[7].

Since FSO uses light beams for wireless point-to-point communication through air, its major limitations stem from the necessity of a line-of-sight (LoS) and its sensitivity to atmospheric conditions. This is why researchers have considered relaying traffic at several intermediate hops to mitigate the problem by splitting long paths into shorter ones that withstand adverse conditions better [8], [9]. This architecture can establish robust network connectivity during meteorological conditions, given a sufficient amount of relays. Most existing works proposing an FSO deployment for urban mobile backhaul have considered totally new, optimized sets of transceiver locations [10]–[12], ignoring practical deployment constraints. Others approach FSO network creation as an optimization problem based on more realistic data, with node locations selected randomly on building roofs [13] or with the goal of maximizing LoS probability to others [14]. As they require new hardware deployment, such approaches entail a substantial deployment cost.

A. Contribution

This paper examines the characteristics of the FSO topology achievable through reusing existing mobile (4G/5G) cell sites. To the best of our knowledge, this is the first study of FSO link availability on existing cellular infrastructures (*i.e.*, without considering new sites in the infrastructure).

The contribution of the paper consists of:

- A systematic methodology to extract and analyze LoS-compliant links for FSO deployment purposes, from publicly available data sources for mobile antenna locations and sub-meter precision LiDAR data for obstacles.

- A study of FSO-enabled topology and connectivity achievable through existing cell sites in the Paris metropolitan area and three other French metropolitan areas (Lyon, Bordeaux and Toulouse), based on this methodology.
- Data and software (web app) developed to perform the presented analysis, publicly available online¹.

Note that this work focuses purely on link and path availability for FSO backhaul mesh networks at a topological level, rather than dimensioning a fully operational architecture that accounts for transceiver specifications, hardware costs and precise capacity requirements. Topics like network pruning, traffic simulations, or routing mechanics are beyond the scope of this paper.

B. Outline

The remainder of this paper is organized as follows. Section II presents related work. Section III introduces our methodology, including the data source selection, and ray tracing algorithms. We present the main results of our approach in Section IV before closing with our conclusion in Section V.

II. RELATED WORK

a) FSO performances: Theoretically, FSO can achieve very high throughput and ultra-low latency on very long distances, but is also very sensitive to channel challenges including obstacles and atmospheric conditions. Many works have investigated the performance conditions of FSO depending on transmission range and atmospheric conditions, building both theoretical models and simulations [15], [16]. Other works have focused on real-world experimental evaluation of this performance in various atmospheric conditions, reporting worst case ranges of below 1000 m [17], 140 m to 500 m [18] or 250 m [19], depending on the intended application.

Rather than modeling or measuring FSO performance as done by these works, we take this performance as a constraint and approach the problem from the other side: we find which performance is achievable with urban FSO backhaul mesh networks when the mounting locations are not optimized for this purpose.

b) Wireless Mobile Backhaul: Because of their flexibility and lower costs, many works have investigated the usage of wireless technologies (*e.g.*, microwave, mmWave, THz and FSO) for mobile backhaul. A first line of work focuses on optimized deployment of FSO to maximize performance. Early works have considered totally synthetic transceiver locations [10]–[12], focusing on theoretical study and ignoring practical deployment constraints. Others approach network creation as an optimization problem based on more realistic data, with node locations selected randomly on building roofs [13] or with the goal of maximizing LoS probability to others [14]. As they would require totally new hardware deployment, such approaches would lead to a high deployment cost. More recently, other works have proposed to use real



Fig. 1. Building models of varying level of detail [24].

coordinates of street furniture nodes, *e.g.*, light poles [20] for mmWave transceivers, or cell towers for continent-wide low-latency mmWave networks [21].

Compared to all these works, our work aims to study urban deployment of FSO transceivers on already existing mobile antennas whose locations are not optimized for FSO communication. For realistic results, we use official data sources for both cell sites and obstructions, as compared to synthetic, probabilistic or simplified models. Our approach of using a 0.25 m²-resolution DSM provides level of detail (LoD) 3 results, whereas building models as used in [13], [22], [23] only offer LoD 1 for buildings (see Fig. 1) and lack other obstructions, such as trees, entirely. This generates realistic results, custom-tailored to the deployment environment.

III. METHODOLOGY

This paper studies the outcome of deploying FSO communication links as mobile backhaul by exploiting existing antennas as FSO transceivers. Data sources are introduced in Section III-A. Graph generation is described in Section III-B. Network/graph properties under consideration are detailed in Section III-C.

A. Data Sources

The analysis of realistic (LoS-constrained) FSO deployment depends primarily on a database of mobile antenna locations and an obstruction model, *i.e.*, a 3D mapping of buildings and other obstacles in the region of interest.

1) Cell Tower Database: Most existing cell antenna location databases are private because this information is considered proprietary, a national security risk or is not collected officially. Some initiatives are building global, crowd-sourced cellular coverage databases, but these fail to reliably capture the real locations of cell sites [25], [26].

As a case study, our analysis exploits a filtered version of the official (and publicly available) “Database of radio installations exceeding 5 W” of the French National Frequencies Agency (ANFR) [27]. This is a country-wide database of cell sites that includes exact coordinates and mounting heights of 193 931 emitter supports. These supports are structures on which several antennas by different operators can be mounted. 74.5 % of these supports are buildings, 23.5 % towers and masts, and 2.0 % of different nature. Although the antennas may be mounted on many locations on large supports (*i.e.*, large buildings and wide broadcasting towers), this database provides enough information for network topology analysis.

However, the coordinates given in the database do not always correspond to the exact location of the antenna support.

¹See <https://cellfso.web.app/>

We quantify this error based on manual checks against Google Maps 3D imagery of a subset of 360 randomly chosen site locations, and observe higher vertical accuracy compared to the horizontal one, with a median horizontal shift of 6.73 m. Monte Carlo sensitivity simulations using this spatial error distribution on short links (<300 m) result in a 0.8 % to 2.3 % reduction of total unobstructed links.

2) *Obstruction Model*: An obstruction model provides 3D representations of buildings and other obstacles in the region of interest. Previous studies have exploited either statistical models, *e.g.*, the Manhattan Grid Model, or building footprints. While these models are easy to build and exploit, they are generally inaccurate as they model each building as a cuboid, irrespective of its real shape, leading to a low Level of Detail, see Fig. 1. Furthermore, other obstructions, such as vegetation or bridges, are not captured. On the other hand, empirical models offer increased accuracy in LoS-finding process [14]. Available commercial options, however, use closed proprietary formats and are expensive.

This study relies on an open-source, official and empirical database provided by the French National Institute of Geographic and Forest Information (IGN) [28]. It provides a Digital Surface Model (DSM), which is a map raster where each pixel encodes the height of the first and highest LiDAR return, capturing the surface elevation of the covered area. Conceptually, this equals LoD 3. LiDAR is generally well-suited for FSO LoS checks as they commonly share the same near-infrared band [29]. The DSM covers almost the entirety of metropolitan France. The underlying LiDAR impulse data by IGN has an average of 10 impulses/cm² with vertical accuracy of ~ 10 cm and horizontal accuracy of ~ 50 cm [28]. The DSM output is generally delivered at a grid space of 50 cm, lowering resolution by a factor of 2.5. Modeling only the surface, it also crops information about the shape of objects underneath the surface, leading to any gaps through which a LoS could pass, for example through the Eiffel Tower or underneath bridges, not being modeled. As the DSM captures obstructions as they appear at the time of LiDAR data collection, obstructions emerging afterward, such as seasonal tree foliage or new construction, are not modeled. It is 8.7 TB in size, which is around three orders of magnitude less than the LiDAR point cloud. DSMs can be derived directly from LiDAR data, which is available in many countries [30].

B. Graph Generation

Each mobile antenna support is considered a node in the network; candidate links are computed based on geographical proximity, before selecting them on the criteria of the existence of a non-obstructed LoS.

Computing collisions of a line with the obstruction model requires calculating which pixels of the DSM raster the line crosses and checking if the surface at any of those pixels is higher than the line. We implement the algorithm described in [31], which iterates over each pixel of the DSM raster crossed by a given line.

Algorithm 1 Line of Sight Validation via DSM Intersection

Require: DSM, $x_0, y_0, z_0, x_1, y_1, z_1$

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1:  $\ell := \text{distance}(x_0, y_0, x_1, y_1)$ 
2: for  $x, y$  in  $\text{intersected\_pixels}(x_0, y_0, x_1, y_1)$  do
3:    $d := \text{distance}(x_0, y_0, x, y)$ 
4:    $t := \frac{d}{\ell}$ 
5:    $z := t \cdot z_0 + (1 - t) \cdot z_1 - \text{curvature\_drop}(R_{\text{eff}}, d, \ell)$ 
6:   if  $\text{DSM}[x, y] > z$  then
7:     return true
8:   end if
9: end for
10: return false

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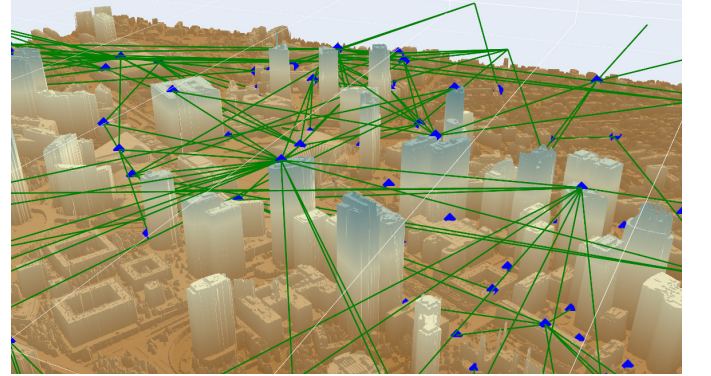


Fig. 2. Graph generation: clear line-of-sight links for an urban FSO network with nodes located at current mobile antennas locations.

During the transmission of an optical signal, its distance to the surface of the earth will be reduced due to the earth's curvature and atmospheric refraction. This reduction in distance is referred to as *curvature drop*. For its computation, an *effective earth radius* is defined as $R_{\text{eff}} = 1.13 \cdot R$ to account for atmospheric refraction [32]. In this equation, R denotes the radius of the earth. Combining pixel traversal with curvature drop yields Algorithm 1, which computes the intersection of a line with a DSM.

Figure 2 illustrates the graph generation, combining mobile antenna locations with the obstruction model.

C. Network Analysis

We analyze size, density, link length, clearance rate and path length of the network described in Section III-B. We also analyze existence of connected components and their statistics and degree of *urbanization*. To account for different levels of resilience to atmospheric conditions, we perform this analysis for different values of the maximum allowed distance between connected nodes, while taking *whole*, *single-operator* or *2-operator coordination* perspectives. Finally, we analyze the level of resilience offered by the network, *i.e.*, its *k-connectivity* and likelihood that an obstacle blocks all the neighbors of a node.

TABLE I
COMPARISON OF KEY STATISTICS ACROSS EVALUATED REGIONS

Statistic	Paris	Bordeaux	Lyon	Toulouse
Region population	9.9M	1.1M	2.0M	1.2M
Cell sites (U/S/R %)*	8,031 (93/7/0)	783 (71/29/0)	1,698 (72/28/0)	1,011 (74/26/0)
Area km ² (U/S/R %)*	2500 (54/15/31)	2500 (8/13/79)	2500 (10/18/72)	2500 (10/17/73)
Urban cell site density	5.6/km²	2.8/km ²	4.9/km ²	3.0/km ²
Candidate links	9.5M	0.2M	0.8M	0.3M

* Distribution of Urban / Suburban / Rural classifications.

IV. EVALUATION

This section examines the characteristics of the FSO topology achievable through reusing existing mobile (4G/5G) cell sites. Section IV-A describes the analysis setup and key parameters. Using the methodology defined in Section III, we describe the network properties starting with general statistics (Section IV-B), followed by an analysis of connected components (Section IV-C), link failure resilience (Section IV-D) and network path lengths (Section IV-E).

A. Setup

Candidate links. The candidate links are the edges of the complete graph on the cell sites. Previous works on FSO performance reported that link ranges that can be sustained with carrier-grade availability are limited to 150 m to 1000 m (see Section II). Here, we consider links of up to $L_{max} = 10$ km. This allows us to provide insight in the network connectivity beyond the worst-case scenario, as well as for future supported link ranges. All links are assumed to be bidirectional.

Regions. We analyze the Paris metropolitan area as well as three other French metropolitan areas (Lyon, Bordeaux and Toulouse). These regions are selected because they contain a large city at the center, and suburban and rural areas, and are thus comparable. Due to the large size of the DSMs, we focus on $50 \text{ km} \times 50 \text{ km}$ regions, plus a margin of L_{max} for nodes positioned at the edge, to not skew their connectivity metrics. The surface data for each resulting $70 \text{ km} \times 70 \text{ km}$ region is 78.4 GB in size. The analysis, however, only considers nodes within the active $50 \text{ km} \times 50 \text{ km}$ region. Table I summarizes key metrics of these metropolitan areas including population, area, cell sites and number of candidate links.

Unless otherwise stated, the results refer to the Paris region.

B. General Statistics

We first compute the number of candidate and LoS links in each region. Figure 3 shows the distribution of these links with respect to their lengths, in Paris region. On average, 11.8% of all candidate links are unobstructed and therefore suitable for FSO links. In other regions, we observe 31.1%, 16.5% and 31.9% unobstructed links for Bordeaux, Lyon and Toulouse metropolitan areas, respectively. This difference can be explained by the difference in cell site density, city layout (dense vs. spread-out), type and height of buildings

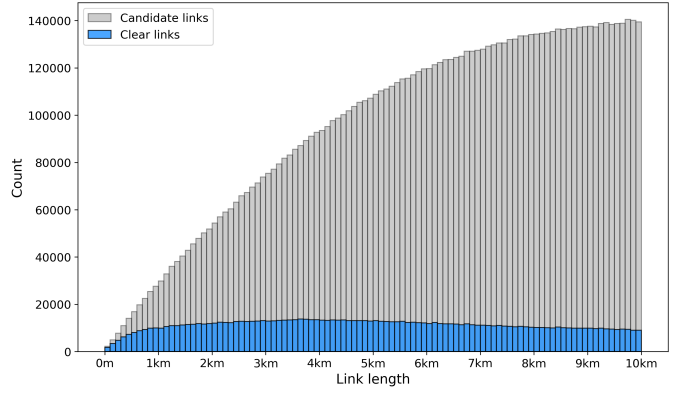


Fig. 3. Distribution of candidate links and clear links of up to 10 km in the Paris region. 11.8% of candidate links are LoS ones.

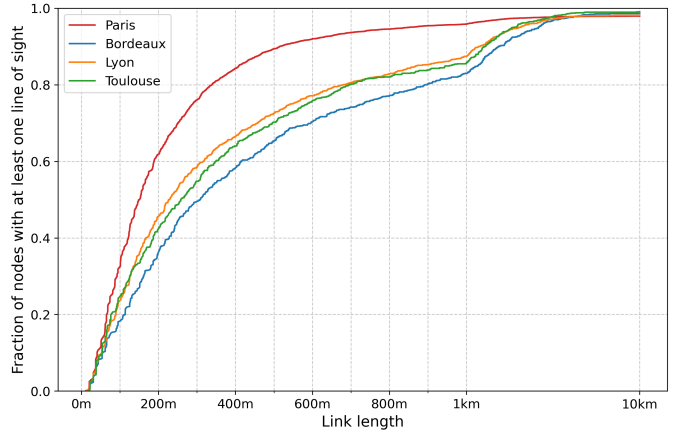


Fig. 4. Fraction of nodes of all operators that have at least one LoS to another node over varying maximum link lengths up to $L_{max} = 10$ km.

(skyscrapers vs. single-family homes), and the topography of the city (flat vs. peaks/valleys).

Figure 4 shows the percentage of cell sites connected to at least one neighbor with respect to the maximum allowed link length, for all regions. This figure shows that, in Paris, 95.5% of cell sites are connected by these LoS links if we consider links of length up to $L_{max} = 10$ km. In other regions, these percentages are 98.6%, 98.1% and 99.0% for Bordeaux, Lyon and Toulouse areas, respectively.

The data also show that LoS links are not distributed equally with respect to their lengths. We focus on short links, which exhibit higher robustness to atmospheric conditions, as link quality degrades with increasing link length. We find that less than 2.1% of clear links are <500 m. This is because the larger number of candidate links at greater distances causes these links to dominate. We observe from Fig. 4 that, in a topology with link lengths of <400 m, up to 84.3% of mobile cell sites in the Paris region are connected by at least one LoS. Another observation is that links of >1000 m yield diminishing returns in newly connected nodes around Paris.

Overall, these results show that placing FSO transceivers at current mobile antenna locations would result in a network

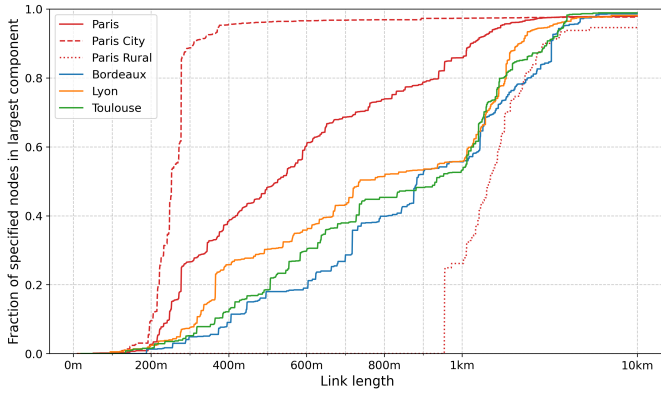


Fig. 5. Fraction of nodes of all operators included in the largest connected component of at least 10 nodes.

connecting a high percentage of all nodes, even if we consider only very short links.

C. Connectedness

We analyze the mesh network emerging from the individual LoS links by computing statistics from the largest connected component that is formed. Figure 5 shows the fraction of nodes included in the largest connected component of at least 10 nodes, for all the regions. For Paris, we further separate data for cells in the main city and in surrounding rural areas. This figure shows that the networks converge to a single large connected component when we consider links of up to L_{max} . We individually consider nodes owned by the four major companies operating cell sites across France, Bouygues Telecom, Free Mobile, SFR and Orange, which jointly are present on 86.0%-88.4% of cell sites across all regions. Each of their networks form a single connected component that spans the city of Paris much earlier at around 500 m. By combining the cell sites of any two operators, the component consistently already shows up at <410 m. A similar connected component emerges already at 315 m when all four operators pool their topologies.

Figure 5 also shows that when adding rural areas, long links are necessary to reach a high cell sites coverage in the largest connected component. In Paris region, links of up to 1 km leads to 85.8% of nodes included in the largest connected component. In other regions, these percentages are 55.7%, 55.8% and 53.2%, for Bordeaux, Lyon and Toulouse regions, respectively.

However, a thorough observation also shows that inside the concave hull of the largest connected component, some nodes remain disconnected. Uniformly across all regions and maximum link lengths, this fraction stays below 5% of the nodes inside the hull. The lowest disconnection ratio, obtained at L_{max} , is 2.1%. These results imply that providing essential connectivity for a mobile backhaul backbone for the city of Paris already works nearly as well at 300 m as it does with longer <10 km links. Longer links are necessary to expand

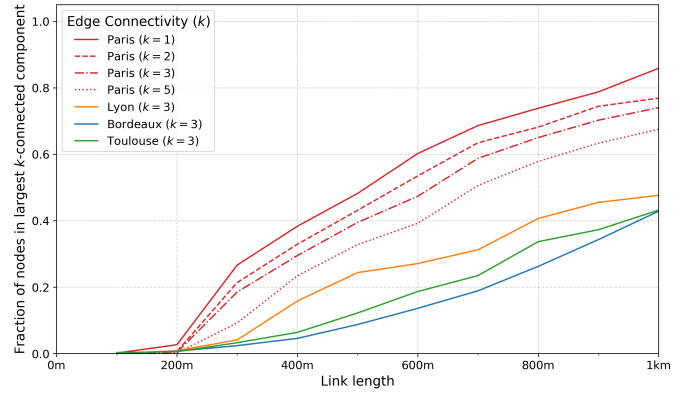


Fig. 6. Fraction of nodes of all operators included in the largest k -connected component for various k across all regions up to 1 km.

the component, but barely to connect further nodes within an already covered area.

D. Resilience

For stronger connectivity guarantees, we analyze how many link failures a connected component can tolerate. For this purpose, we compute statistics of the largest k -edge-connected component, which guarantees that any two nodes are connected by k link-disjoint paths. Figure 6 shows the percentage of cell sites in the largest k -connected component for various maximum link lengths and disjoint paths k . This figure reveals that obtained networks are very connected, still covering a high percentage of cell sites even with the k -connectivity constraints. For Paris city, links of up to only 360 m are needed to have a 2-connected component covering the whole city. In the less dense cell networks of Bordeaux, Lyon and Toulouse, the core cities are covered by one 2-connected component at around 640 m, 375 m and 516 m, respectively.

While k -connected components are protected from individual random link failures, obstacle-induced link failures interrupting the LoS are spatially correlated. This includes vegetation growth close to the node, new buildings, and people or birds crossing. Depending on the size and distance of the obstacle and the angular diversity of links connecting nodes, a single obstacle can block part or all links of a node at once. We look at individual nodes inside the largest 2-connected component of the <360 m topology in Paris. For each of these nodes, we randomly place a rectangular obstacle near the node so that it covers an angle α and compute its probability of blocking all backhaul links of the node. Figure 7 shows the obtained results, averaged over all the nodes. Placing a 90° obstacle randomly around the node isolates it in 0.7% of cases, and 4% of cases when 180° are covered. For a worst-case analysis, we calculate the minimum angle α that a single rectangular obstacle needs to cover in order to block all LoS, isolating the node. 94% of nodes survive any obstacle that covers up to 90°, and 75% are resilient to blockages of 180°. However, angular diversity does not protect against macro-

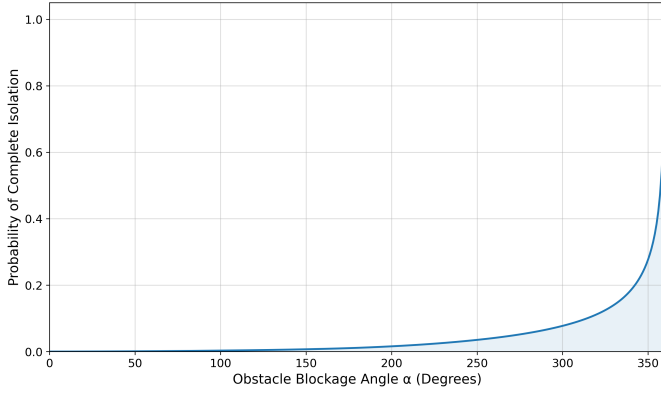


Fig. 7. Average probability that an obstacle of angular size α , placed uniformly at random, isolates a node.

weather events like dense fog, which engulf the node entirely and attenuate all links across 360° simultaneously.

E. Path lengths

While enabling robust communication even in bad weather conditions, a fundamental disadvantage of the relaying approach is that it increases the number of hops that have to be traversed to reach any given node. Each hop has to perform switching and optical-electrical-optical conversion, increasing latency and energy consumption. During better weather conditions, however, longer transmission ranges of up to tens of kilometers are possible. Using mirrors or motors, FSO link reconfiguration allows transmitters to dynamically steer the beam at a different receiver, which can be used to replace short links with longer ones. This is comparable to “edge rewiring” in the Watts-Strogatz model, which states that a small percentage of rewired edges that act as shortcuts can drastically reduce hop counts.

We consider the connected component obtained in the Paris region with <300 m links as baseline and randomly replace a varying percentage of these links with unobstructed links longer than 300 m and shorter than 1 km, 2 km, 5 km and 10 km. In each case, we compute the path length (in hop counts) between all possible node pairs and report obtained average hop counts in Fig. 8. We observe that reconfiguring 10 % of <300 m links with <1 km leads the original average path length of 28.4 hops to be reduced by $\sim 44\%$. This would correspond for instance to a transition from worst-case atmospheric conditions (*e.g.*, heavy fog) to less adverse conditions (*e.g.*, light fog). During clear, favorable conditions, with 10 % link reconfigurations up to 5 km, the average hop count shrinks to around 7.5.

V. CONCLUSION

Free Space Optics (FSO) is a suitable, attractive communication technology for improving capacity of metropolitan backhaul networks, in a context dominated by the sustained growth of traffic-intensive applications in the Internet edge, and the consequential increase of transit needs through backhaul links between access (RAN) and core Internet networks.

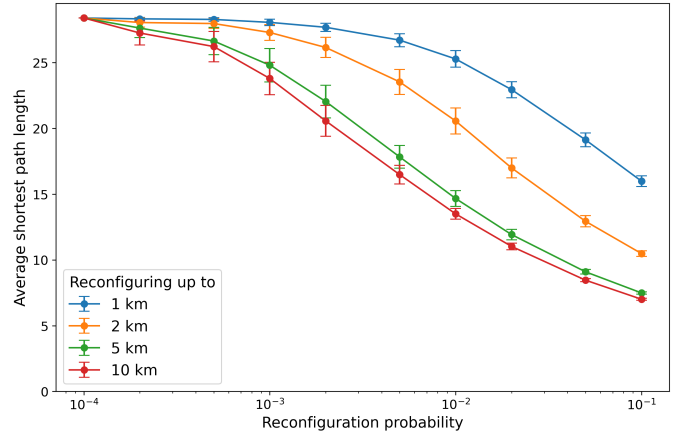


Fig. 8. Average hop counts connecting any pair of nodes in the connected component of links up to 300 m over Paris, with randomly selected links reconfigured to longer distances. Confidence markers show variation across 16 runs.

FSO however depends on unguided Line-of-Sight (LoS) channels that are sensitive to atmospheric attenuation — and this sensitivity substantially increases with link length.

This paper studies the graph characteristics of the FSO topology that would be achievable in practice by reusing existing cell sites in Paris and three other major French metropolitan areas (Lyon, Toulouse, Bordeaux). Selection of LoS-compliant links is based on the official database of cellular sites, from the French National Agency of Frequencies (ANFR), and an open-source digital surface model from the French National Geographic Institute (IGN) based on LiDAR data. The proposed methodology and tools are useful for planning of FSO metropolitan networks, as they can be applied to other geographical areas and their sources are open-source and publicly available through a web-app.

Preliminary graph-based analysis of the obtained results in France suggest that the exploitation of existing cell sites for deploying FSO links in metropolitan areas would lead to a well-connected and robust additional backhaul topology of LoS-compliant links, with sufficient flexibility to efficiently adapt to atmospheric changes by leveraging FSO reconfiguration features. Additional studies in other metropolitan regions are needed to see whether presented observations can be generalized.

The described tools could be extended into a complete backhaul mesh planning tool, with parameters such as link capacity and transceiver cost, to provide reliable estimation of network capacity achievable through plausible FSO LoS-compliant links between existing cell sites.

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