FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks

Mohamed Alzenad, Muhammad Z. Shakir, Halim Yanikomeroglu, and Mohamed-Slim Alouini

Motivated by the mounting interest in the unmanned flying platforms of various types, including UAVs, drones, balloons, and HAPs/MAPs/LAPs, which the authors refer to as networked flying platforms (NFPs), for providing communications services, and by the recent advances in free space optics (FSO), the authors investigate the feasibility of a novel vertical backhaul/fronthaul framework where the NFPs transport the backhaul/fronthaul traffic between the access and core networks via point-to-point FSO links.

ABSTRACT

The presence of a super high rate, but also cost-efficient, easy-to-deploy, and scalable, backhaul/fronthaul framework, is essential in the upcoming 5G wireless networks and beyond. Motivated by the mounting interest in unmanned flying platforms of various types, including UAVs, drones, balloons, and HAPs/MAPs/LAPs, which we refer to as networked flying platforms (NFPs), for providing communications services, and by the recent advances in free space optics (FSO), this article investigates the feasibility of a novel vertical backhaul/fronthaul framework where the NFPs transport the backhaul/fronthaul traffic between the access and core networks via point-to-point FSO links. The performance of the proposed innovative approach is investigated under different weather conditions and a broad range of system parameters. Simulation results demonstrate that the FSO-based vertical backhaul/fronthaul framework can offer data rates higher than the baseline alternatives, and thus can be considered a promising solution to the emerging backhaul/fronthaul requirements of the 5G+ wireless networks, particularly in the presence of ultra-dense heterogeneous small cells. This article also presents the challenges that accompany such a novel framework and provides some key ideas toward overcoming these challenges.

INTRODUCTION

It is widely acknowledged that one of the key architectural enablers toward the extremely high data rate coverage in wireless networks is the dense deployment of small cells. Although the small cell concept has been envisioned and studied for many years within the 4G LTE framework, the concept has never found widespread application mainly due to the difficulty and cost of backhauling/fronthauling a high number of small cell base stations (SBSs). At the time of this writing, the 5G standardization process has already started. The 5G networks are expected to be deployed starting in approximately 2020; the small cell concept is still perceived as a key 5G enabler. However, the efficient backhauling/fronthauling of the SBSs remains a significant challenge.

This article aims at exploring a novel radio access network (RAN) architecture to realize a dense small cell deployment, in which SBSs are connected to the core network through a vertical backhaul/fronthaul. The key technologies within this novel framework are the free-space optics (FSO) and networked flying platforms (NFPs). In this article, we adopt the generic term NFPs to encompass the floating and moving aspects of the unmanned flying platforms of various types including unmanned aerial vehicles (UAVs), drones, balloons, and high-altitude/medium-altitude/low-altitude platforms (HAPs/MAPs/LAPs). It is worth noting that although the explored RAN architecture may have a higher cost in comparison to other competing existing solutions according to the pricing estimate at the time of this writing, the sharp reduction expected in the cost of FSO as well as in the operation of NFPs may make the studied novel approach a viable solution in the next 10 years. At that time, 5G networks will likely be fully operational, and the standardization of the evolved 5G and even perhaps 6G networks will have started. For these reasons, in this article we are using the generic term 5G+ to denote the 5G and beyond-5G wireless networks of the future.

OVERVIEW OF BACKHAULING/FRONTHAULING

Two fundamentally different backhauling/fronthauling possibilities exist, namely, wired and wireless backhaul/fronthaul networks. Wired backhaul/fronthaul solutions include copper and fiber. Fiber is always the best option. However, installing fiber for SBSs may not be an acceptable solution due to the high cost in many environments [1].

A more cost-effective alternative is wireless backhaul/fronthaul, where SBSs traffic is carried over microwave links or FSO links. The microwave backhaul relies on particular frequency bands in the range 6–60 GHz. However, these frequency bands are becoming congested in a number of countries [2]. Moreover, line-of-sight (LOS) FSO has recently gained attention as it relies on license-free point-to-point (PtP) narrow beams.

Current backhauling/fronthauling solutions are based on delivering the traffic of SBSs to an aggregation point (central hub). The optimal hub placement problem has been shown to be NP-complete. Furthermore, the LoS hub placement may turn out to be simply infeasible since some SBSs may be deployed in hard to reach areas where LOS propagation is impossible [3]. In such scenarios, RF non-LOS point-to-multipoint (NLOS PtM) solutions that rely on licensed sub-6 GHz spectrum or microwave frequencies could be used at the expense of severe interference,

Digital Object Identifier: 10.1109/MCOM.2017.1600735

Mohamed Alzenad and Halim Yanikomeroglu are with Carleton University; Mohamed Alzenad is also with Sirte University; Muhammad Z. Shakir is with the University of the West of Scotland; Mohamed-Slim Alouini is with King Abdullah University of Science and Technology.

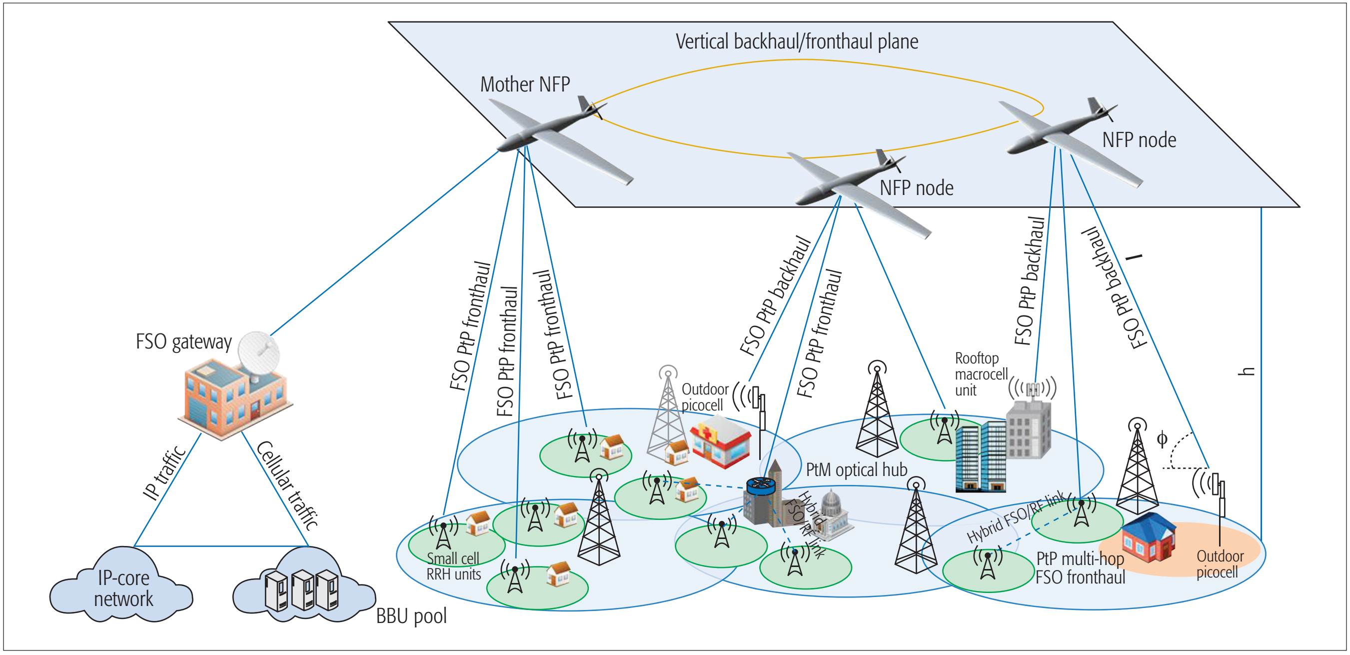

Figure 1. Graphical illustration of vertical fronthaul/backhaul framework for 5G+ wireless networks.

congestion and higher cost [2]. Therefore, a novel paradigm shift of backhaul/fronthaul network design for 5G networks and beyond is needed.

NFPs have recently gained great attention in the communications sector [4]. They can, for instance, deliver cellular and Internet services to remote regions where infrastructure is not available and expensive to deploy. Recently, Facebook's project Internet.org has been launched to provide Internet coverage via stratosphere communications.[1] Another example is the recently envisioned drone-BS concept [5].

OVERVIEW OF NETWORKED-FLYING PLATFORMS

Different terms are used for unmanned aircraft in the literature and in practice. The term unmanned aerial vehicle (UAV) often refers to the flying platform including its payload, while the term unmanned aerial system (UAS) refers to the flying platform and the ground station that controls the aerial platform [6]. The terms low altitude platform (LAP), medium altitude platform (MAP), and high altitude platform (HAP) are mainly used for quasi-stationary objects such as unmanned airships or balloons. In this article, we consider NFPs that can carry heavy payloads (FSO transceivers), float in the air at a quasi-stationary position with the ability to move horizontally and vertically, and offer wireless links to backhaul/fronthaul SBSs. The ability to move is necessary because the NFPs may need to float most of the time and may only move based on weather conditions, coverage requirements, and even due to some real-time traffic changes/abnormalities in the network.

A NFP can either fly autonomously or non-autonomously. In non-autonomous operation, the NFP is controlled remotely by a human operator on the ground. In autonomous operation, the NFP can perform the task without the need for direct human control. The NFPs can either operate in single NFP mode or in a swarm of NFPs. In single NFP operation, the mission is performed by a single NFP with no cooperation with other NFPs, if they exist. An NFP swarm operation allows multiple interconnected NFPs to cooperate and perform the mission autonomously with one of the NFPs acting as the lead.

PROPOSED SYSTEM

Consider a multi-tier HetNet where ultra-dense small cells are overlaid with macro cells within some geographical area. We assume that our system is complementary to the terrestrial backhaul/fronthaul network, and needs to be deployed in many challenging environments, for example, due to a failure in the terrestrial transport network or a temporary demand for backhaul/fronthaul during a social event such as a sporting event. Moreover, our system is capable of offering backhaul/fronthaul to the SBSs that are located in hard to reach areas where fiber or microwave links may not be readily available and expensive to deploy. Examples of these locations could be in rural/remote areas or urban areas below surrounding buildings where SBSs are expected to be deployed closer to street level and mounted on street furniture such as walls and lamp posts.

Figure 1 shows a graphical illustration of the proposed system referred to as a vertical backhaul/fronthaul framework for 5G+ wireless networks. The proposed system comprises several connected NFPs, which we refer to as the NFP nodes. The flying altitude *h* could range from a few hundred meters to several kilometers (typically 20 km), depending on coverage area, weather conditions and the NFP's serving capability.[2] The NFPs are assumed to fly autonomously in a swarm of NFPs. The swarm is controlled by a NFP called a mother NFP, which also connects the swarm of NFPs to the core network on the ground. The NFP to mother NFP and mother NFP to core network connectivity are based on FSO links. The connectivity between SBSs or aggregation points and the NFPs is also

---

[1] Visit http://info.internet.org for further information about the project.

[2] The probability of LoS connection between a ground point and a NFP increases as the NFP altitude increases. Therefore, the NFP should fly at an altitude high enough to guarantee a LoS connection.

	Foggy conditions				
	Dense	Thick	Moderate	Light	Very light
Visibility (m)	50	200	500	770	1900
Wavelength (nm)	Attenuation dB/km				
650	327.61	80.19	31.43	20.16	7.92
850	309.21	73.16	27.75	17.46	6.52
1330	280.77	62.77	22.54	13.73	4.71
1550	271.66	59.57	20.99	12.65	4.22

Table 1. Fog attenuation for different wavelengths and foggy conditions.

based on PtP FSO beams. Each SBS with a clear LOS link with a NFP delivers/receives its uplink/downlink traffic to/from the intended NFP via an FSO link.[3] On the other hand, SBSs with no LOS with a NFP can be served by a nearby SBS which has a clear LOS with a NFP. As a further option, instead of connecting every single SBS to a NFP, traffic is backhauled/fronthauled from SBSs to a NFP in a distributed manner. The traffic of the SBSs is relayed to a specified SBS where an aggregation hub is located, and a LOS with a NFP is available. This distributed solution has been shown to have a higher energy efficiency than a centralized solution where the SBSs traffic is delivered to a macro-BS [7]. Similarly, SBSs served by NFPs are equipped with tracking systems to automatically point the beam to the desired NFP.

Link Budget Analysis of Vertical Backhaul/Fronthaul Framework

The FSO signal is vulnerable to atmospheric attenuation (absorption, scattering and turbulence) and other losses such as geometrical, pointing and optical losses.

Absorption Loss: Absorption occurs when the photons of the FSO beams collide with gaseous molecules. Absorption depends on the type of gas molecules and their concentration as well as on the transmission frequency. The wavelength selectivity of absorption allows specific frequencies to pass through it, which results in transmission windows in which the absorption loss is negligible [8].

Scattering Loss: Scattering occurs when the FSO beam collides with the particles in the atmosphere which is the layer of gases that surround the Earth. Scattering can be classified into three categories: Rayleigh scattering, Mie scattering, and non-selective scattering. Rayleigh scattering occurs when the wavelength of the FSO beam is large compared to the size of the particles such as air molecules. Mie scattering occurs for particles that are of similar size to the wavelength of the FSO beam such as aerosol particles, fog and haze. Non-selective scattering occurs when the radius of the particles, such as raindrops, is much larger than the wavelength of the FSO beam. Among the three scattering mechanisms, the FSO beam is mostly attenuated by Mie scattering. The Kruse model describes the attenuation due to Mie scattering as [9]:

$$L_{sca} = 4.34\beta_{sca} d = 4.34\left(\frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-\delta}\right)d, \qquad (1)$$

where L_{sca} denotes the attenuation in dB, β_{sca} stands for the scattering coefficient in km^{-1} and d represents the distance along which the scattering phenomena occurs in km. Variable V denotes the visibility range in km, λ stands for the transmission wavelength in nm, $\delta = 0.585\ V^{(1/3)}$ for $V < 6$ km, $\delta = 1.3$ for $6 < V < 50$ km, and $\delta = 1.6$ for $V > 50$ km.

•Fog Attenuation: The FSO beam is highly affected by fog as it causes Mie scattering. Equation 1 can be used to predict the fog attenuation (L_{fog}) and $d = \Delta d_{fog}/\sin(\phi)$, where Δd_{fog} is the fog layer thickness. Table 1 shows the relationship between different foggy conditions, visibility, wavelength and attenuation per km for selected operating wavelengths.

•Rain Attenuation: Rainfall causes non-selective scattering. The rain attenuation, L_{rain} (measured in dB) is given by $L_{rain} = 1.076\ R_{rain}^{0.67} d_{rain}$, where R_{rain} denotes the rainfall rate in mm/hour and d_{rain} denotes the distance along which the rain affects the FSO beam in km, given by $d_{rain} = \Delta d_{rain}/\sin(\phi)$, where Δd_{rain} is the rain layer thickness and ϕ is the elevation angle [10].

•Cloud Attenuation: Clouds can be characterized by their height, number density (N_d), liquid water contents (LWC), water droplet size and horizontal distribution extent. Different empirical approaches have been proposed to model cloud attenuation (L_{cloud}). In this article, we adopt the approach developed in [11]. That approach is based on estimating cloud visibility range by dividing the atmosphere into layers. Then, for each layer, the visibility range is estimated from their N_d and LWC, where visibility range is given by $V = 1.002$ (LWC) $N_d^{-0.6473}$. Then, Eq. 1 is used to predict the cloud attenuation.

Turbulence Loss: The refractive index structure parameter $C_n^2(h)$ is an altitude-dependent measure of turbulence strength. Based on measurements, various models are available to predict the parameter $C_n^2(h)$ such as the Hufnagel-Valley (H-V) model [12]. According to the H-V model, the parameter $C_n^2(h)$ for the vertical link in the proposed system is given by

$$C_n^2(h) = 0.00594\left(\frac{v}{27}\right)^2\left(10^{-5}h\right)^{10}\exp\left(\frac{-h}{1000}\right) + 2.7\times10^{-16}\exp\left(\frac{-h}{1500}\right) + A\exp\left(\frac{-h}{100}\right), \qquad (2)$$

where v denotes the rms wind speed in m/s, h is the altitude in meters and typical value for constant A is 1.7×10^{-14} m$^{-2/3}$. The attenuation caused by scintillation, L_{sci} (in dB) is then given by

$$L_{sci} = 2\sqrt{23.17\left(\frac{2\pi}{\lambda}10^9\right)^{\frac{7}{6}} C_n^2(h)\, l^{\frac{11}{6}}},$$

where l is the path length in meters [10].

Geometrical Loss (Box 1): As light travels through the atmosphere, light energy spreads out over a larger area. This in turn reduces the power collected by the receiver. The geometrical loss in dB is given by

---

[3] Such FSO transceiver for flying platforms is already available, for example, MLT-20 from Vialight. Visit http://www.vialight.de/ for further information.

$$L_{geo} = 10\log\left(\frac{\pi r^2}{\pi(\theta l/2)^2}\right),$$

where r is the radius of the receiver's aperture in m, l is the length of the communication link in km, and θ is the divergence angle of the transmitter in mrad.

Pointing and Optical Losses: The FSO link is a point-to-point link. Moving NFPs at high altitudes and under extreme turbulence conditions may cause higher pointing losses (L_{poi}) that could result in a link failure or a significant reduction in the received signal power.[4] On the other hand, optical loss (L_{opt}) is due to the imperfect optical elements used at the FSO transceiver, which reduces the optical efficiency of the FSO transmitter (η_t) and receiver (η_r). The optical losses in dB is given by $L_{opt} = 10\log(\eta_t\eta_r)$.

PERFORMANCE EVALUATION OF THE PROPOSED VERTICAL LINK

In this section, we first present the experimental results of the system under different weather conditions. Then we discuss some of the economics associated with the underlying system.

DATA RATE AND LINK MARGIN

The achievable data rate R of a FSO link is given by [14]

$$R = \frac{P_t\eta_t\eta_r 10^{\frac{-L_{poi}}{10}} 10^{\frac{-L_{atm}}{10}} A_R}{A_B E_p N_b}[b/s], \tag{3}$$

where P_t denotes the transmit power, η_t and η_r stand for the optical efficiencies of the transmitter and receiver, respectively, L_{poi} is the pointing loss measured in dB, L_{atm} denotes the atmospheric attenuation due to rain, fog, cloud or turbulence measured in dB over the path length and given by $L_{atm} = L_{rain} + L_{fog} + L_{cloud} + L_{sci}$. Moreover, $E_p = h_p c/\lambda$ denotes the photon energy while h_p denotes Planck's constant, c denotes the speed of light and l stands for the transmission wavelength. Finally, N_b represents the receiver sensitivity in number of photons/b. Table 2 summarizes the simulation parameters used in this article.

Figure 2 shows the data rate and available link margin versus NFP altitude for different weather conditions. As shown in Fig. 2a, the data rate decreases as the altitude increases due to the increase in geometrical loss. It can also be seen that the vertical FSO link is mostly affected by the clouds because they cause Mie scattering. Although fog also causes Mie scattering, fog may not be a key issue for the vertical FSO links as it is for terrestrial FSO links because the vertical FSO beam is vulnerable to fog for a relatively much shorter distance (fog layer thickness) while terrestrial FSO links are vulnerable to fog along the communication link. As seen in Fig. 2b, 23 dB and 11.5 dB are available at an altitude of 5 km and 20 km, respectively, for a clear sky. Under cloudy, rainy and foggy conditions, the FSO link fails because the received power is less than the sensitivity of the receiver, for example, the available link margin is –42 dB for cloudy and foggy conditions at 20 km.

Geometrical loss: The geometrical loss in dB is given by $L_{geo} = 10\log(A_R/A_B)$, where A_R and A_B denote the area of the FSO receiver and beam, respectively. Assuming the receiver has a circular mirror with a radius r, then, $A_R = \pi r^2$. The area of the beam at the receiver is a circular disc with some diameter d_B that depends on the length of the communication link l and the divergence angle of the transmitter θ, and it is given by $d_B = \theta l$. The radius of the beam at the receiver is given by $r_B = d_B/2 = \theta l/2$. The area of the beam at the receiver is then $A_B = \pi r_B^2$. The geometrical loss is then given by

$$L_{geo} = 10\log\left(\frac{\pi r^2}{\pi(\theta l/2)^2}\right).$$

Box 1.

Doppler Effect: The relative motion between the NFPs and the SBSs may result in Doppler effect. Some examples of the techniques, which have been proposed for space FSO, are Optical Phase-Lock Loop (OPLL), the Optical Injection Locking (OIL) technique, a combination of the OPLL technique and the OIL technique, and Optical Frequency Locked Loop (OPLL) [8].

Box 2.

Parameter	Value
Transmit power (P_t)	200 mWatt
Pointing losses (L_{poi})	2 dB
Optical losses (L_{opt})	2 dB
Divergence angle (θ)	1 mrad
Elevation angle (ϕ)	45°
Receiver radius (r)	0.04 m
Transmission wavelength (λ)	1550 nm
NFP height (h)	1 km–20 km
Wind speed (v)	21 m/s
Receiver sensitivity (N_b)	100 photons/b
BER	$< 10^{-9}$
Fog visibility (V)	50 m
Fog layer thickness (Δd_{fog})	50 m
Cloud attenuation (L_{cloud})	As proposed in [11]
Rain rate (R_{rain})	50 mm/hr
Rain layer thickness (Δd_{rain})	1000 m
Planck's constant (h_p)	6.626×10^{-34} J-s
Speed of light (c)	3×10^{-8} m/s

Table 2. Summary of simulation parameters.

Figure 3 shows the data rate and link margin for cloudy and foggy conditions (worst scenario) versus the NFP altitude for different divergence angles. As seen in Fig. 3a, the data rate can be improved by reducing the divergence angle. It can also be seen in Fig. 3b that reducing the divergence angle results in increasing the available link margin at the receiver, for example, at an altitude of 20 km, a link margin of 12 dB is available at the receiver with a divergence angle of 1 μrad compared to –2.6 dB (link failure) with a divergence angle of 10 μrad.

---

[4] Recently, some emerging FSO systems are designed with tracking systems using electro-optic or acousto-optic devices that especially applicable to the fast moving platforms for compensating the pointing losses [13].

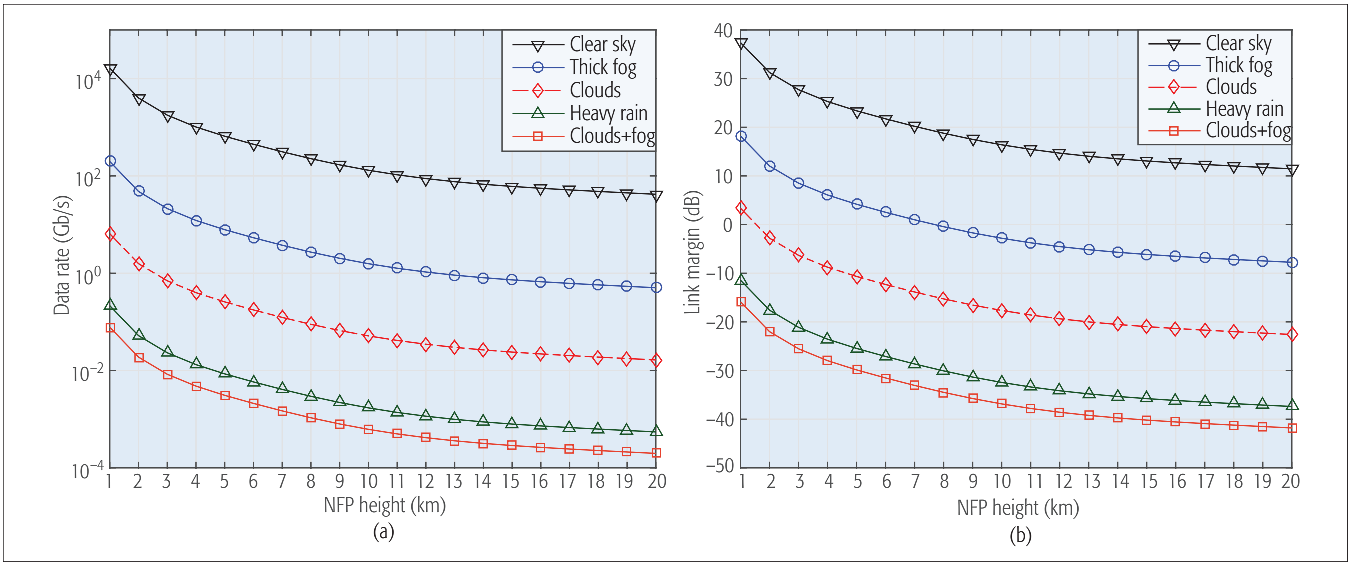

Figure 2. Comparative performance summary of vertical FSO link for different weather conditions vs range of NFPs' altitude: (a) data rate, and (b) link margin.

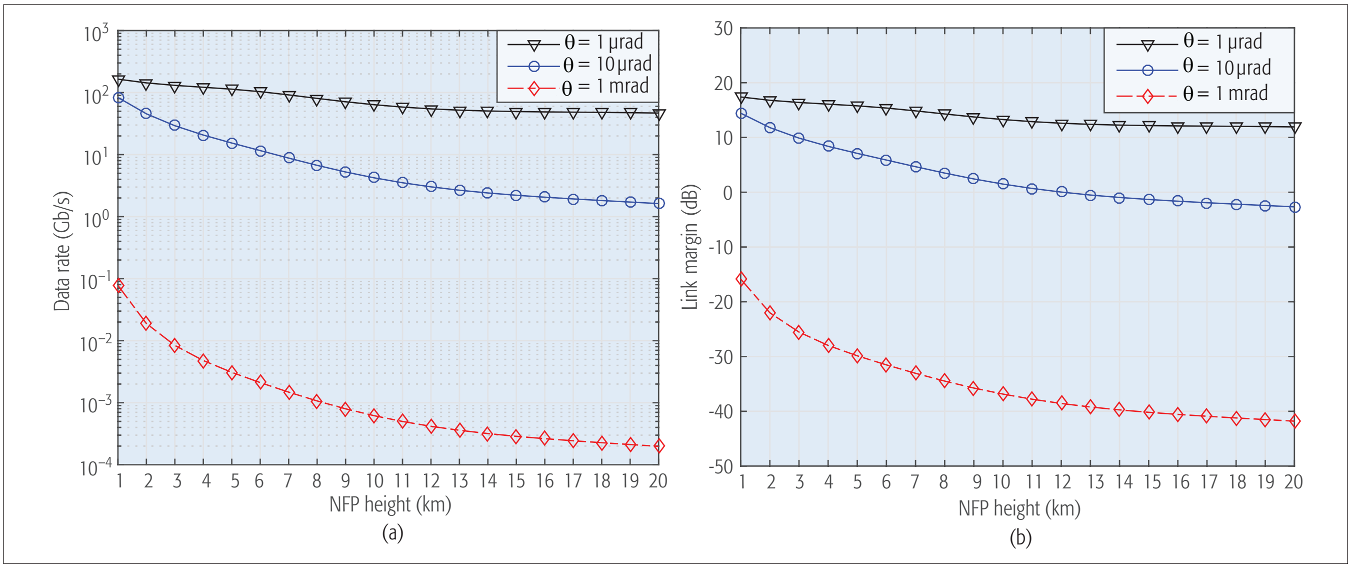

Figure 3. Comparative performance summary of vertical FSO link for different divergence angles vs range of NFPs' altitude: (a) data rate, and (b) link margin.

ECONOMICS OF VERTICAL SYSTEMS

The total cost of ownership consists of the capital expenditures (CAPEX) and the operational expenditures (OPEX) of the backhaul/fronthaul network. While the CAPEX describes the cost of equipment, planning and installation, the OPEX describes the cost of spectrum, maintenance, power and fuel.

Assume a HetNet where 100 macro cells and 1000 small cells are deployed over an urban area of 5 km by 5 km. For RF NLOS PtM, fiber optics and FSO solutions, we assume that the SBSs backhaul/fronthaul traffic is aggregated at an aggregation hub located at the macro-BS. For RF NLOS PtM, the configuration is assumed to be 1:4, that is, the hub communicates with four remote backhaul modules located at the SBSs. The cost of the hub and the remote backhaul module is assumed to be $4000 and $2000, respectively [1].[5] The installation cost for the hub and the remote backhaul module is assumed to be $270 and $140, respectively. We also assume that the RF NLOS PtM solution operates in a 40 MHz licensed spectrum at a cost of $0.007 per MHz per capita. The cost of leasing a pole is assumed to be $1250 per year and the power and maintenance cost is $375 per year. For the optical fiber, the fiber optic cable is $10 per meter and the installation cost is $200 per meter while the power and maintenance cost is $200 per link per year. For the terrestrial FSO, we assume that 50 percent of the SBSs have no LOS to the aggregation hubs, which is the case in urban areas. The cost of the terrestrial FSO equipment is assumed to be $15,000 and the associated planning and installation cost is further assumed to be $5000. The cost of power and maintenance is $8000 per link per year. For the proposed vertical solution, we assume 20 medium altitude long endurance (MALE) NFPs, which can carry heavy payloads for long endurance. The cost of the platform is assumed to be $50,000.[6] We also assume that the operating cost of each platform is $859 per flight-hour [15].

---

[5] The cost assumptions are based on the average prices in North America. However, they are applicable to the countries or regions of similar demographics.

[6] Assumptions on costing of FSO equipment have been deduced from the discussions presented at the Panel US German Aerospace Round Table (UGART) on the next big thing in space, organized during an annual trade show and conference, Space Tech. Expo. Europe, Bremen, Germany, Nov. 2015.

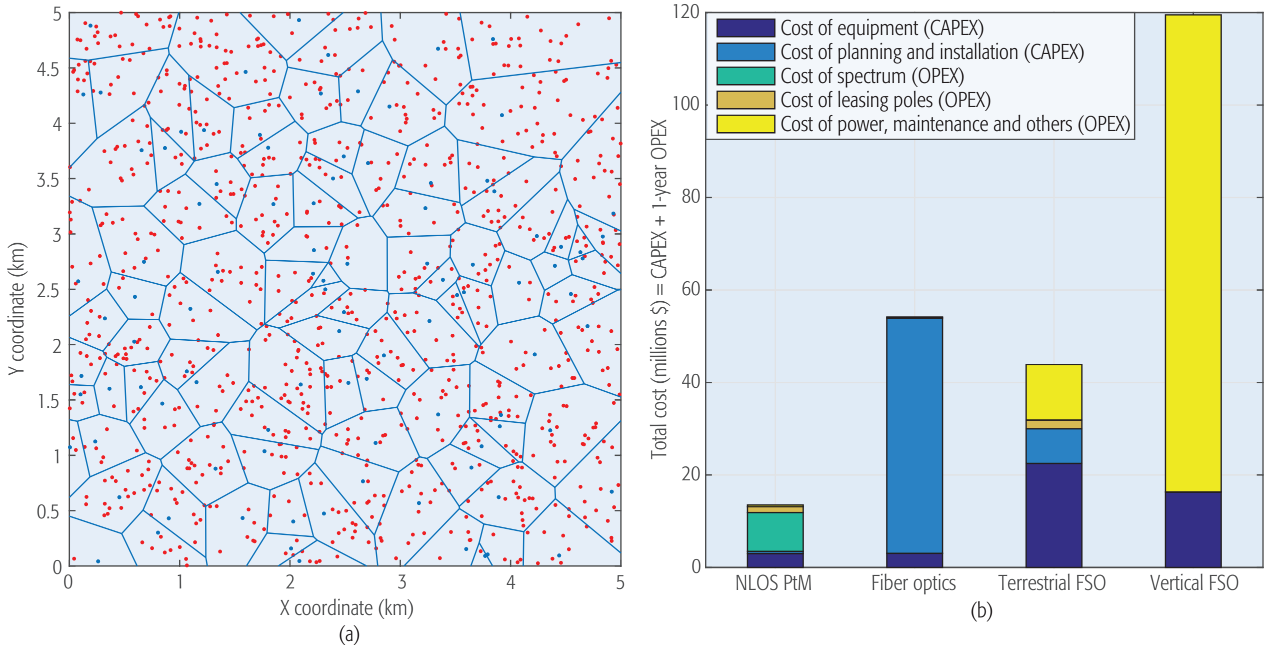

Figure 4. Comparative summary of deployment of several backhaul/fronthaul technologies: (a) a snapshot of the typical Poisson distributed HetNet used to estimate the cost of backhaul/fronthaul links, and (b) associated cost of several backhaul/fronthaul technologies in underlying HetNet.

Figure 4a shows a snapshot of a typical Poisson distributed HetNet. Figure 4b shows the cost for RF NLOS PtM, optical fiber, terrestrial FSO and FSO-based vertical systems for one year. Figure 4b shows that fiber optics has the highest deployment cost because of the high cost of digging and trenching in urban areas. On the other hand, the RF NLOS solution seems to be the most cost effective solution but it suffers from interference and low data rate due to spectrum sharing between the remote backhaul modules. Terrestrial FSO has a high deployment cost because LOS is not always available in urban areas. Therefore, more FSO equipment is required to reach the SBSs. The vertical system has the highest total cost of ownership at around $120 million, while the NLOS PtM, terrestrial FSO, and optical fiber solutions cost around $14 million, $44 million, and $55 million, respectively.

OPEN CHALLENGES AND FUTURE RESEARCH

Implementation: As previously discussed, the vertical FSO link is greatly affected by weather conditions. One possible approach is to design an adaptive algorithm that adjusts the transmit power and divergence angle according to weather conditions, for example, under rainy conditions, high power and small divergence angle should be used. The future implementation may also optimize the NFP placement, for example, flying below clouds over negligible turbulence regions. Another possibility is to use the Millimeter-wave spectrum (mm-wave) in a combination with FSO. Unlike FSO, mm-waves are not attenuated by fog. However, mm-waves are highly attenuated by water molecules such as rainfall [2]. The system may use FSO during rainy conditions and switches to mm-waves during foggy conditions. The vertical system could also consider a hybrid FSO/RF as a potential alternative solution to overcome the link degradation under bad weather conditions [1].

Cost: The proposed vertical system requires NFPs that can fly with heavy payloads (FSO systems) with long endurance. Such UAVs are mainly designed for military missions. The operating cost of these UAVs is high, for example, the Predator, which is a MALE UAV, costs around a thousand dollars per flight-hour [15]. However, with the increasing interest of UAVs, they are becoming less expensive, which may reduce the cost of the vertical system. Another option is to use unmanned balloons as flying hubs. The balloons are often solar-powered and fly at a quasi-stationary position, which could reduce the operational cost of the proposed system.

Safety and Regulatory: The regulation (safety, environment, and so on) to exploit NFPs for commercial use in cellular networks is still underway. Several Canadian, U.S. and European organizations have been working very closely to harmonize the regulatory approaches for flying platforms in their respective airspaces for commercial use. The regulatory processes include, but are not limited to, issuance of flight operating licenses and air operator certificates to authorize the flying of platforms and ensure that the platform is equipped with the adequate safety equipment and capable of managing the risk associated with NFPs. The current focus of regulatory bodies is largely on the safety aspects of platform flight, particularly if they are to operate beyond LOS and in populated urban areas.

NFP-Small Cell Association: NFPs have a constraint on the payload they can carry. Therefore, each NFP can serve at most a particular number of SBSs. Furthermore, the NFP-backhaul link that forwards the traffic from the NFP node to the mother NFP or vice versa could be strictly constrained by the limited capacity of that link. It is clear that successful integration of the proposed vertical system relies on advanced optimization of sophisticated design parameters such as the optimal number of NFPs required to provide fronthaul/backhaul to the SBSs and their association with the SBSs considering the typical factors, for example, payload, achieving data rate and backhaul data rate between the NFP and ground station.

Security and Privacy: Security and privacy are fundamental requirements for the vertical system. The use of NFPs for future cellular networks could be limited due to following two reasons:

- The security risk that the NFPs could be hijacked/sabotaged may result in disruption or complete failure of the cellular system. Operators or cellular vendors are required to integrate advanced control mechanisms to ensure the security of the NFPs and their operation.
- The privacy and data protection of the cellular network entities could also be at risk. Some regulatory measures could be taken to maintain additional privacy and protection of the cellular entities such as prohibiting the NFPs from flying over critical and unauthorized infrastructure and from carrying payload that could potentially collect personal data and information.

Conclusion

In this article, we investigated a vertical framework to backhaul/fronthaul SBSs via NFPs. The proposed system is envisioned to be deployed as a complementary solution to the terrestrial solutions to offer highly reliable backhaul/fronthaul system. The efficacy of the proposed system has been investigated in terms of link budget and achievable data rate. Simulations have shown that the key challenge is the high path loss under some weather conditions. However, performance can be improved significantly and rates in the order of multi Gb/s can be achieved by reducing the divergence angle. The economics of the system have also shown that the vertical network has a high total cost of ownership compared to terrestrial backhaul/fronthaul networks. It should be noted, however, that this cost is expected to decrease rapidly as the novel technologies enabling the vertical backhaul/fronthaul concept (such as FSO and NFPs) mature.

> The efficacy of the proposed system has been investigated in terms of link budget and achievable data rate. Simulations have shown that the key challenge is the high path loss under some weather conditions. However, the performance can be improved significantly and rates in the order of multi Gb/s can be achieved by reducing the divergence angle.

Acknowledgments

This work was supported in part by the Ministry of Higher Education and Scientific Research (MOHESR), Libya, through the Libyan-North American Scholarship Program, in part by Huawei Technologies Canada, and in part by the Ontario Ministry of Economic Development and Innovations Ontario Research Fund Research Excellence Program.

References

[1] H. Dahrouj *et al.*, "Cost-Effective Hybrid RF/FSO Backhaul Solution for Next Generation Wireless Systems," *IEEE Wireless Commun.*, vol. 22, no. 5, Oct. 2015, pp. 98–104.

[2] U. Siddique *et al.*, "Wireless Backhauling of 5G Small Cells: Challenges and Solution Approaches," *IEEE Wireless Commun.*, vol. 22, no. 5, Oct. 2015, pp. 22–31.

[3] E. Karamad *et al.*, "Optimizing Placements of Backhaul Hubs and Orientations of Antennas in Small Cell Networks," *Proc. IEEE ICC Wksps.*, London, England, Jul. 2015, pp. 68–73.

[4] M. Marcus, "Spectrum Policy Challenges of UAV/Drones [Spectrum Policy and Regulatory Issues]," *IEEE Wireless Commun.*, vol. 21, no. 5, Oct. 2014, pp. 8–9.

[5] I. Bor-Yaliniz and H. Yanikomeroglu, "The New Frontier in RAN Heterogeneity: Multi-Tier Drone-Cells," *IEEE Commun. Mag.*, vol. 54, no. 11, 2016, pp. 48–55.

[6] R. Austin, *Unmanned Aircraft Systems: UAVs Design, Development and Deployment*, John Wiley and Sons, Chichester, England, 2010.

[7] X. Ge *et al.*, "5G Wireless Backhaul Networks: Challenges and Research Advances," *IEEE Network*, vol. 28, no. 6, pp. 6–11, Nov. 2014.

[8] H. Kaushal and G. Kaddoum, "Optical Communication in Space: Challenges and Mitigation Techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, First Quarter 2017, pp. 57–96.

[9] M. Grabner and V. Kvicera, "Fog Attenuation Dependence on Atmospheric Visibility at Two Wavelengths for FSO Link Planning," *Proc. IEEE Antennas and Propag. Conf. (LAPC'2010)*, Loughborough, England, Nov. 2010, pp. 193–96.

[10] S. S. Muhammad, P. Kohldorfer, and E. Leitgeb, "Channel Modeling for Terrestrial Free Space Optical Links," *Proc. IEEE 7th Int'l. Conf. Transparent Optical Networks*, vol. 1, Barcelona, Spain, July 2005, pp. 407–10.

[11] M. Awan *et al.*, "Cloud Attenuations for Free-Space Optical Links," *Proc. IEEE Wksps. Satellite and Space Commun. (IWSSC'2009)*, Siena-Tuscany, Italy, Sept. 2009, pp. 274–78.

[12] B. Epple, "Impact of Ground Profile on Scintillation Index for High-Altitude Optical Wireless Links," *Proc. IEEE Conf. Global Commun. Wksps. (GC Wkshps'2010)*, Miami, FL, USA, Dec. 2010, pp. 1057–61.

[13] S. V. Kartalopoulos, *Free Space Optical Networks for Ultra-Broad Band Services*, John Wiley and Sons, New Jersey, USA, Aug. 2011.

[14] A. K. Majumdar, "Free-Space Laser Communication Performance in the Atmospheric Channel," *Springer J. Optical and Fiber Commun. Reports*, vol. 2, no. 4, Oct. 2005, pp. 345–96.

[15] D. M. D'Agostino *et al.*, "Observations on the Costs and Benefits of an Increased Department of Defense Role in Helping to Secure the Southwest Land Border," *DTIC Document*, Washington D.C, US, Tech. Rep. GAO-12-657T, Apr. 17, 2012.

Biographies

Mohamed Alzenad (mohamed.alzenad@sce.carleton.ca) is a Ph.D. candidate in the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada. He received his B.Sc. degree (with honours) in 2000 from the University of Sirte, Sirte, Libya, and the M.Sc. degree (with Distinction) from Leeds University, Leeds, England in 2007. He joined Carleton University in 2013, where he is currently working under the supervision of Prof. Halim Yanikomeroglu.

Muhammad Zeeshan Shakir (Muhammad.Shakir@uws.ac.uk) is an assistant professor in the School of Engineering and Computing at the University of the West Scotland (UWS), UK. His main research interests lie in the design and development of heterogeneous wireless networks for urban and rural coverage via unconventional aerial and regular architectures including 5G technologies. He has a track record of more than 75 technical journal and conference publications including many in the world's most reputable journals in the areas of wireless communications. He has also contributed to 10 books, including an authored book entitled *Green Heterogeneous Wireless Networks* published by Wiley John & Sons and endorsed by IEEE Press. He has been/is giving tutorials on emerging wireless communication systems at IEEE flagship conferences. He is serving as a Chair of the IEEE ComSoc emerging technical committee on backhaul/fronthaul communications and networking. He is a Senior Member of IEEE and an active member of IEEE ComSoc.

Halim Yanikomeroglu (halim@sce.carleton.ca) is a full professor in the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada. His research interests cover many aspects of 5G/5G+ wireless networks, including layers 1-3, and the architecture. His collaborative research with industry has resulted in about 30 patents (granted and applied). He is a Fellow of the IEEE, a Distinguished Lecturer for the IEEE Communications Society, and a Distinguished Speaker for the IEEE Vehicular Technology Society.

Mohamed-Slim Alouini (slim.alouini@kaust.edu.sa) received the Ph.D. degree in electrical engineering from the California Institute of Technology (Caltech), Pasadena, CA, USA, in 1998. He served as a faculty member at the University of Minnesota, Minneapolis, MN, USA, then at Texas A&M University at Qatar, Education City, Doha, Qatar, before joining King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia as a professor of electrical engineering in 2009. At KAUST, Prof. Alouini leads the Communication Theory Lab and his current research interests include the modeling, design, and performance analysis of wireless communication systems.