# SoarNet

Nirwan Ansari, *Fellow, IEEE*, Qiang Fan, *Student Member, IEEE*, Xiang Sun, *Member, IEEE*, Liang Zhang, *Student Member, IEEE*

***Abstract*—In mobile access networks, different types of Internet of Things (IoT) devices (e.g., sensor nodes and smartphones) generate vast traffic demands, thus dramatically increasing the traffic loads of their connected access nodes, especially in the 5G era. Considering the possible traffic congestion of the access nodes, drone base stations (DBSs) can be flexibly deployed to hotspot areas as relays between the access nodes and IoT devices. As the DBSs' batteries are limited while their backhauls towards access nodes directly impact the throughput of IoT devices in downloading their data, how to improve the flight time of DBSs and the backhaul capacity remains critical in drone-assisted access networks. Hence, we propose a Free Space Optics as Backhaul and Energizer for Drone-assisted Networking (SoarNet) architecture, where a free space optics (FSO) link serves as the backhaul link between a DBS and its access node. That is, a laser beam, which carries both data and energy, will be emitted from the access node to the DBS. Therefore, the DBS can simultaneously receive high-speed data streams and energy via the laser beam. The received energy is used to power the DBS to prolong its flight, and received data streams are delivered to IoT devices via existing Radio Frequency (RF) channels. Several research challenges are identified in the context of SoarNet to further improve the network performance.**

***Index Terms*—Drone-Assisted Networking, IoT, FSO.**

## I. Introduction

The rapid growth of mobile traffic is throttling current mobile networks. In order to accommodate this growth in mobile traffic and to avoid what has become known as the last mile problem, mobile networks, in terms of capacity and quality of service (QoS) provisioning, have to be enhanced accordingly. A huge number of small cells (e.g., pico and femto cells) have been deployed in hotspots to offload mobile traffic from access nodes (i.e., macro base stations) onto the wireline network in order to speedup the mobile access network. However, hotspots appear unpredictably and occasionally, thus hampering these small cells from covering these hotspots efficiently. A new hotspot might arise, for example, after an accident owing to an auto accident, when mobile users begin to stress the access point by downloading and watching related news content. To facilitate traffic delivery in these hot spot areas, Drone Base Stations (DBSs) can be flexibly deployed over these areas. Specifically, a DBS hovering over a hotspot area can relay the data traffic between access nodes and users at a higher data rate as compared to the users communicating with access nodes directly [1]. Throughout this article, a user is referred to as an IoT device (e.g., a smartphone, a sensor node, etc.), which communicates with its associated access node.

Although deploying DBSs may accelerate the flash crowd traffic delivery between access nodes and users in hotspot areas, there are two critical challenges in such drone-assisted network. On one hand, as a DBS hovers in the air, the wireless backhaul link between an access node and its users may impact the throughput of downloading data from the access node to the users. However, the capacity of a traditional RF-based wireless backhaul link is limited especially when the distance between the access node and the DBS is long, and thus the backhaul link may become the bottleneck between the access node and users. On the other hand, DBSs are generally powered by their portable batteries that constrain their flight time. The limited battery life cannot enable a DBS to continuously relay the traffic between an access node and a DBS. In this case, how to wirelessly recharge the DBS to extend its flight time becomes a critical issue for the drone-assisted network.

Free space optics (FSO) is a promising wireless technology to provision broadband services via point-to-point links owing to its wide available frequency (over 300 GHz). It is an optical communications technology that employs directional light beam to wirelessly transmit data through atmosphere. The feature of directional communications enables the system to be immune to the impact of multi-path propagation and interference. Note that the performance of FSO is impacted by different factors such as atmospheric attenuation, turbulence, and pointing loss.

To increase the wireless backhaul capacity and prolong the battery life of a DBS, we propose the Free Space Optics as Backhaul and Energizer for Drone-assisted Networking (SoarNet) architecture. SoarNet utilizes the FSO technology to establish the wireless backhaul communications between an access node and its DBS and recharge the DBS simultaneously. That is, a laser beam, which carries both data and energy, will be emitted from the access node to the DBS. On one hand, an FSO link has a much higher capacity than the existing RF backhaul link, and can thus prevent the wireless backhaul from becoming the bottleneck in drone-assisted networks [2]. On the other hand, the laser beam can also be used to recharge the DBSs owing to its high charging efficiency. The major contributions are summarized as follows:

- We propose a new network architecture, referred to as SoarNet, by leveraging drones and FSO to provision mobile, flexible and reliable broadband access.
- We design the SoarNet architecture and describe the specific functions of different components of the architecture. We also analyze how to adjust the data rate of a DBS's backhaul and recharging rate.

N. Ansari, Q. Fan, L. Zhang are with Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ, 07102 USA (Email: {nirwan.ansari, qf4, lz284}@njit.edu). X. Sun is with Department of Electrical and Computer Engineering, University of New Mexico, Email: (sunxiang@unm.edu). This work was supported in part by National Science Foundation under grant no. CNS-1814748.

- We present the problem of placing DBSs in SoarNet to improve the data rate of users while guaranteeing the DBS's required recharging rate.
- We also analyze how to adjust the access node association and user association to balance the traffic load while satisfying the recharging requirement.

## II. State of the Art

### A. Wireless backhaul technologies

Backhaul can be wired and wireless, but wireless backhaul is preferred to connect drones and the access node. Different types of wireless backhauls provision various data rates. The drone backhaul solution could leverage microwave spectrum between 6 GHz and 60 GHz bands, the millimeter wave (mmWave) spectrum in 60 GHz and 70-80 GHz bands, TV white spaces, and satellite technologies. These solutions are implemented according to the propagation environment as well as a number of system parameters such as locations and deployment density of small cells, desired backhaul capacity, interference conditions, cost, coverage, hardware requirements, and spectrum availability.

Galkin *et al.* [3] proposed to employ existing LTE networks to provide backhauls for drones and analyzed the backhaul performance (i.e., data rate). Meanwhile, mmWave is attractive for high-capacity short-range links, and its spectrum is spacious and can potentially minimize interference with highly directive narrow beamwidth antennas [4]. Nevertheless, mmWave is greatly affected by atmospheric attenuation (e.g., oxygen, dry air, water molecules, etc.). A large amount of TV spectrum, referred to as TV white space, has become vacant and can be exploited for backhaul provisioning in a cognitive (unlicensed) manner [5]. TV white space often provides better propagation characteristics as compared to traditional low-frequency cellular bands. Nonetheless, the utilization of TV white space is strictly limited by the transmit power and locations of primary TV transmitters. The main benefit of satellite-based backhauling is its higher coverage and support for high mobility scenarios (e.g., airplanes, ships and automotive vehicles). However, satellite backhaul suffers from long time delay and jitter due to the long distance communication between a remote satellite modem and a DBS.

FSO has recently gained attention as it relies on license-free point to point narrow beams. It is an optical technology that utilizes laser beams to send high bandwidth information data [6], though non-lasing sources such as light-emitting diodes or IR-emitting diodes may be adopted. Alzenad *et. al.* [7] proposed a vertical backhaul/fronthaul framework based on the FSO-based backhaul link and their simulation results showed that the data rate of the FSO-based vertical backhaul/fronthaul framework is higher than the baseline. Siddique *et. al.* [8] provided an overview of different backhaul technologies. FSO is indeed a promising solution for the backhaul/fronthaul of the future wireless networks. FSO based backhaul, which provisions higher capacity, higher coverage, and lower cost, can be appropriately integrated into the DBS to gain flexibility and mobility.

### B. Recharging a DBS

That a drone needs to refuel more frequently than any other vehicle is the most challenging issue, and commercial drones can usually fly 15-30 minutes based on the current battery technology.

In recent years, wireless power transfer technology has been increasingly required for many purposes, especially in applications of wireless charging systems for drones. Recharging is important to provide additional energy to the DBS's battery. Alsharoa *et al.* [9] proposed to equip a DBS with a solar panel to harvest energy, but the amount of harvested energy is very limited. Gmez-Tornero *et. al.* [10] designed a wireless power transfer system to power a light drone by the RF link; however, given the transmission power of 70kW, the harvested power of the drone at 25 m distance is only 21.3 W (i.e., remarkably low efficiency). Mostafa *et. al.* [11] proposed a charging system for drones by leveraging capacitive power transfer technology, which requires the landing of drones and thus cannot guarantee service continuity.

Being able to recharge the DBS wirelessly can help alleviate the imposition of grounding the drone for charging, and improve the utilization efficiency of the DBS. AT&T Foundry [12] proposed "10 Bold Projections on The Future of Drones", and "Drones will never have to land" is one of the projections. DBS-assisted networking empowered with high power charging and high-speed communications is desirable, but has never been addressed yet. Thus, we propose SoarNet to fill this gap.

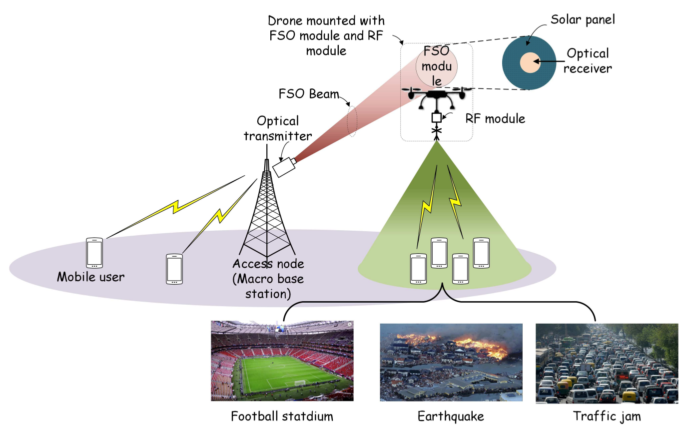


Fig. 1. The SoarNet architecture.

## III. The SoarNet Architecture

We propose SoarNet by leveraging FSO to transfer data streams and energy simultaneously to mitigate the drawbacks of utilizing DBSs including the limited backhaul capacity and flight time. As shown in Fig. 1, FSO is applied to enable communications between a DBS and an access node. Specifically, the FSO transmitter of the access node sends an optical beam to the FSO receiver mounted on the drone, which comprises an optical receiver and a solar panel. The data streams carried by the optical beam are received by the optical receiver, converted into RF signals and relayed to the users accordingly. Meanwhile, the solar panel is to receive the energy carried by the FSO beam, and thus can be used to recharge the DBS.

In addition, FSO is conducted over the unlicensed spectrum, and thus applying FSO as a backhauling technology will not increase the operational cost of the mobile network providers. Moreover, the spectrum used by FSO is not overlapped with the spectrum of the mobile access network, and thus more radio spectrum can be used by access links (i.e., the links between the access node and users, and the DBS and users). On the other hand, owing to the directional transmission, the optical beam has a higher efficiency in charging drones as compared to the traditional wireless charging technologies (such as RF and solar energy harvesting). Note that each DBS is also equipped with an FSO transmitter to relay the data streams generated by users to the access node.

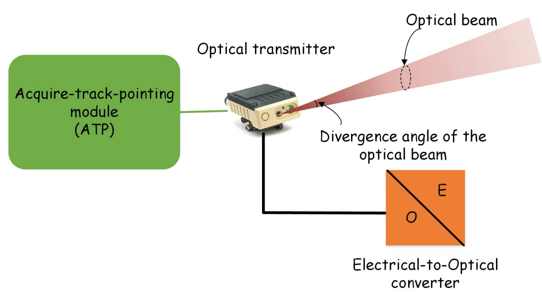


Fig. 2. FSO transmitter at an access node.

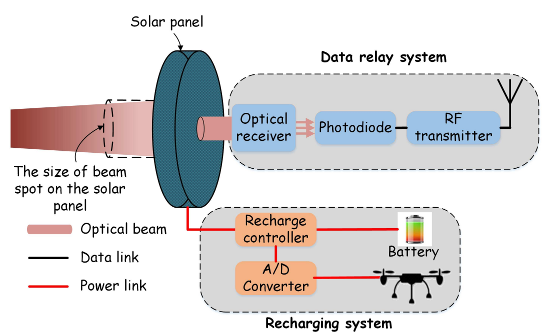


Fig. 3. FSO receiver at a DBS when using the same optical beam for transmitting energy and data streams.

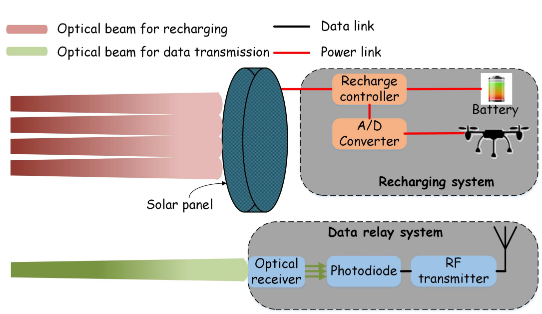


Fig. 4. FSO receiver at a DBS when using different optical beams for transmitting energy and data streams.

### A. *FSO transmitter at access node*

In order to provision FSO-enabled wireless backhaul communications, an access node is equipped with an FSO transmitter to emit an optical beam, which carries high volume data streams, to a DBS. As shown in Fig. 2, the FSO transmitter comprises Electrical-to-Optical (E2O) converter, optical transmitter, and the acquire-track-pointing (ATP) module. The E2O converter is used to convert the electrical signal from the mobile network into the optical signal. The optical transmitter is used to transmit the optical signal by emitting an optical beam to the DBS. Note that the transmission power and the divergence angle of the optical beam can be adjusted by the optical transmitter [13]. The ATP module is used to reduce pointing losses at the DBS side, i.e., the ATP can automatically adjust the direction of the optical beam based on the 3-D location of the DBS in order to guarantee reception of the optical beam by the DBS.

On the other hand, the optical beam, which carries high volume data streams, can also be used to recharge the DBS, i.e., the optical beam carries not only the data streams but also energy. The FSO transmitter can schedule the data transmission and the energy transmission by adjusting the transmission power and the divergence angle to alter the data rate and the charging rate, respectively.

Alternatively, the access node can use different separate optical beams to conduct data transmission and energy transmission, respectively. In this way, although the access node may need to equip multiple optical transmitters to emit multiple optical beams (which may increase the capital cost of mobile providers), the access node does not have to transmit high power optical beam (safer from the safety perspective). Specifically, as shown in Fig. 3, one optical beam is emitted from the access node to transmit data streams to the DBS; on the other hand, as shown in Fig. 4, a number of low power optical beams are also emitted from the access node to transmit energy to the DBS.

### B. *FSO receiver at DBS*

The FSO receiver system at a DBS is used to receive the data steams and energy, which are carried by the optical beam sent from the access node. As shown in Fig. 3, the FSO receiver system comprises two subsystems, i.e., the data relay system and the recharging system. The recharging system consists of a solar panel, a recharge controller, an A/D converter, and a portable battery. The solar panel absorbs most part of the received optical beam and converts them into electrical power, the charge controller regulates the electrical power from the solar panel, and the electrical power is converted between AC and DC by the inverter. The converted electrical power is then used to power various power consuming modules (e.g., the motor and the RF module) at the DBS. The data relay system consists of an optical receiver, a photodiode, and an RF transmitter. A tiny hole is located at the center of the solar panel such that a small part of the received optical beam can go through the solar panel and reach the optical receiver. The photodiode is used to convert the optical signal into the electrical signal, which is then converted into the RF signal by the RF transmitter and transmitted to users accordingly.

Note that if the method of transmitting energy and data streams by using different optical beams is applied, the data relay system and the recharging system are two independent subsystems on the DBS, as shown in Fig. 4.

### C. Adjusting the recharging rate of the DBS

The recharging rate of the DBS determines the amount of energy that can be harvested from the optical beam by the solar panel at the DBS. The total amount of energy harvested from the optical beam is determined by the total amount of energy received at the solar panel, which depends on many factors. First, as the transmission power of the optical transmitter (denoted as $P_t$) varies from $p_{min}$ to $p_{max}$, the received power at the DBS also changes correspondingly. Second, owing to atmosphere attenuation (the atmospheric attenuation factor $\gamma$[1]), an optical beam is attenuated as it passes through the atmosphere [2]. As the distance between the access node and the DBS (denoted as $L$) increases, the atmosphere attenuation of the optical beam becomes more severe, and thus the received power degrades correspondingly. Therefore, the distance between the access node and the DBS plays a significant impact on the received power at the solar panel. Third, the optical beam is directional and the size of the beam spot at the solar panel is determined by the divergence angle $\theta$ of the optical beam if $L$ is given [2]. Specifically, an optical beam is a Gaussian beam, i.e., as shown in Fig. 5, the center of the beam spot incurs the highest light intensity (in terms of power per area) and the light intensity of the area decreases as the distance between the area and the center of the beam increases, following a typical Gaussian shape. Since the spot size at the receiver is determined by the divergence angle of the FSO transmitter, the Gaussian distribution is impacted by the divergence angle of the FSO transmitter. Thus, we can adjust the divergence angle of the FSO transmitter to change the Gaussian distribution of light intensity fallen on the receiver, and thus change the received power of the optical receiver and the solar panel. Thus, as shown in Fig. 5, if $L$ is fixed, the optical beam with a smaller divergence angle produces a smaller size beam spot at the solar panel, i.e., higher light intensity at the center of the beam spot. In this case, the optical receiver receives higher received power through the hole at the center, but the solar panel receives lower received power. Therefore, the received power of both the solar panel and optical receiver may be significantly impacted by the divergence angle of the beam. Note that if the method of using different optical beams for transmitting energy and data streams is applied, the divergence angle may not significantly affect the total amount of power harvested from the optical beams once all the optical beams are received by the solar panel.

[1]The atmospheric attenuation factor varies based on different weather condition, e.g., fog, snow, rain, and sunshine.

### D. Adjusting the date rate of the FSO-based backhaul link

The data rate (i.e., bps) of the FSO-based backhaul link is also mainly determined by the power received by the optical receiver, denoted as $P_r^{data}$. Similarly, $P_r^{data}$ is also impacted by $P_t$, $\gamma$, $L$, and $\theta$ [14]. Hence, given the distance between an access node and a DBS, we can adjust the transmission power of the optical transmitter and the divergence angle of the beam to adjust the data rate of the FSO-based backhaul link, thus satisfying the QoS requirements of users.

## IV. DBS PLACEMENT IN SOARNET

The FSO-based backhaul link (i.e., the link between the access node and the DBS) and the mobile access link (i.e., the link between the DBS and the users) are used to deliver traffic of users associated to the DBS. The location of the DBS may affect the throughput of both links [15].

**Throughput of the mobile access link.** The traffic demand exhibits spatial dynamics, and thus the DBS would hover over the area with higher traffic demand. Meanwhile, as the users at the edge of an access node's coverage experience more severe pathloss towards the access node, it is desirable to place DBS over the areas with higher user densities at the edge of the access node's coverage. In addition, the altitude of the DBS also affects the throughput of the mobile access link. Specifically, the DBS with lower altitude reduces the distance between the DBS and the users, thus potentially reducing the path loss from the DBS to the users; on the other hand, since the wireless access channel between the DBS and the users is modeled by a probabilistic LoS channel, the DBS with lower altitude increases the probability of the Non-Line-of-Sight (NLoS) to the users, thus potentially increasing the path loss from the DBS to the users. Hence, it is important to select the optimal altitude of the DBS to improve the throughput of the mobile access link.

**Throughput of the FSO-based backhaul link.** The FSO link can be established only when the transmitter and the receiver are in the LoS. Thus, the DBS placement should guarantee that the access node and the DBS are in the LoS. In addition, the data rate of the FSO-based backhaul link is a function of the distance between the DBS and the access node, i.e., the DBS placed close to the access node would increase the throughput of the backhaul link, and vice versa. Moreover, in order to guarantee the user safety, the altitude of the DBS should always be higher than that of the access node such that the optical beam from the access node would be pointed to the air when the alignment between the optical transmitter (at the access node side) and the optical receiver (at the DBS side) fails. Thus, the throughput of the FSO-based backhaul link and the mobile access link should be jointly considered in placing the DBS.

In addition, the location of a DBS also affects the recharging rate of the DBS, i.e., a short distance between the DBS and the access node incurs a higher recharging rate of the DBS. Hence, the requirement of a DBS's recharging rate should be guaranteed in placing the DBS. Denote $J$ as the set of DBSs and $j \in J$ as the index of a DBS. Denote $r_j^b$ as the backhaul capacity of DBS $j$, $r_{ij}$ as the data rate of user $i$

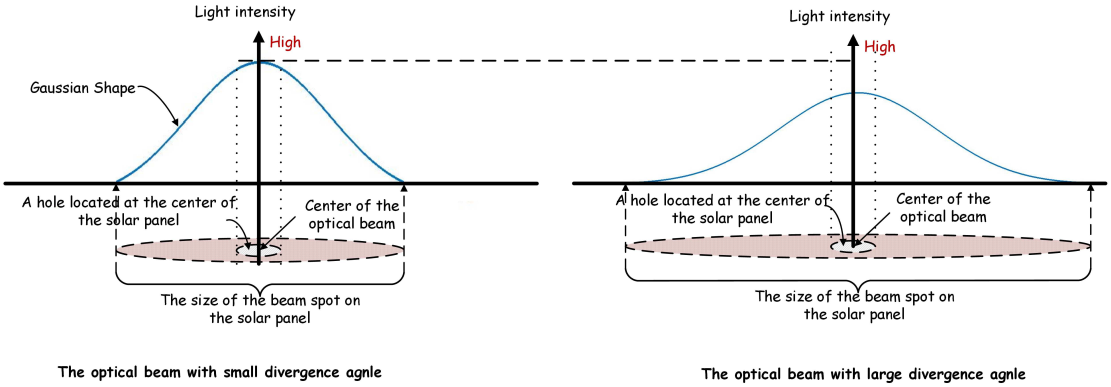


Fig. 5. The power received at the solar panel by varying the divergence angle of the optical beam.

covered by DBS $j$, and $\eta_{ij}$ as the user association indicator to reflect whether user $i$ is associated with DBS $j$. Meanwhile, $\{x_j, y_j, h_j\}$ are 3-D co-ordinates of the $j$th DBS where $h_j$ is the altitude; $P_j^c$ is the recharging rate of DBS $j$; $P^{req}$ is the recharging rate requirement of each DBS. As both the access and backhaul links are jointly considered, the throughput of DBS $j$ can be modeled as $R_j = \min(r_j^b, \sum_i r_{ij}\eta_{ij})$. Therefore, the objective function of the DBS placement is to maximize the throughput of delivering traffic from the access node to the users via DBSs, and can be formulated as follows:

$$\max_{x_j, y_j, h_j} \sum_j R_j \tag{1}$$

$$s.t.: \quad P_j^c(P_t, \gamma, L, \theta) \geqslant P^{req}, \forall j \in J, \tag{2}$$

$$h_{\min} \leqslant h_j \leqslant h_{\max}, \forall j \in J. \tag{3}$$

Here, Eq. (2) imposes the recharging rate requirement of each DBS; Eq. (3) imposes the DBS to be within a certain range.

To improve the throughput of more users in the access link, DBSs should be placed at the locations that are far away from an access node and has high user densities. Meanwhile, to improve the throughput and recharging rate of the FSO based backhaul, it is desirable to place the DBSs close to the access node. In this case, we have to make a tradeoff between these two issues in order to maximize the effective throughput between users and access nodes via DBSs.

## V. Dynamic Access Node Association and User Association

Note that a DBS associated to an access node implies that the FSO-based wirless backhaul link is established between the DBS and the access node, and thus the DBS would download traffic from the access node. Associating the DBS with the nearest access node normally provides the highest wireless backhaul data rate and energy charging rate for given transmission power of the optical transmitter. However, the nearest access node may be heavy-loaded, i.e., too much traffic has been buffered in the access node. For instance, as shown in Fig. 6, the nearest access node with respect to the DBS is AN-A, which is heavy-loaded, and thus the average delay of transmitting traffic from AN-A is long. Thus, associating the DBS to a light-loaded access node may balance the traffic load among different access nodes and reduce the average delay of delivering traffic to users in the network. For instance, as shown in Fig. 6, associating the DBS to AN-B, which has the LoS connection to the DBS and is light-loaded, may be a better solution to minimize the average delay of delivering traffic to users in the network.

Associating the DBS to the light-loaded access node may not be enough to balance the traffic load among access nodes. Dynamically adjusting the coverage area of the DBS may further balance the traffic load. For instance, as shown in Fig. 6, the DBS is currently associated with AN-B to balance the traffic load between the two access nodes. In order to further balance the traffic load, the coverage area of the DBS is increased to cover more users such that the traffic load of AN-A is offloaded to AN-B, and thus the average delay of delivering traffic to users may be reduced accordingly.

In summary, to reduce the average delay in delivering traffic to users, we need to jointly optimize the access node association and user association of the DBS. Specifically, given the 3D locations and the required recharging rate of DBSs, each DBS should select the access node with lower traffic load among the ones that can satisfy its recharging requirement. Afterwards, we need to further adjust the coverage size of each DBS to further balance the traffic load among access nodes so as to minimize the delivery latency of data streams.

Note that the access node association and the user association problem may be coupled with the 3D DBS placement problem, i.e., the DBS associating with a different access node may change the optimal 3D location of the DBS and the optimal user association accordingly. Thus, it is promising to jointly optimize the 3D location of the DBS, the access node association, and the user association to minimize the average delay of users.

## VI. Future Research Challenges

Owing to the LoS requirement of the FSO communications, it is critical to maintain the accurate alignment between the transmitter and receivers. As DBSs may not stably hover in the air, the FSO transmitter at the access node need to be equipped with an ATP module to ensure the alignment between the FSO transmitter and FSO receiver. How to design a reliable ATP

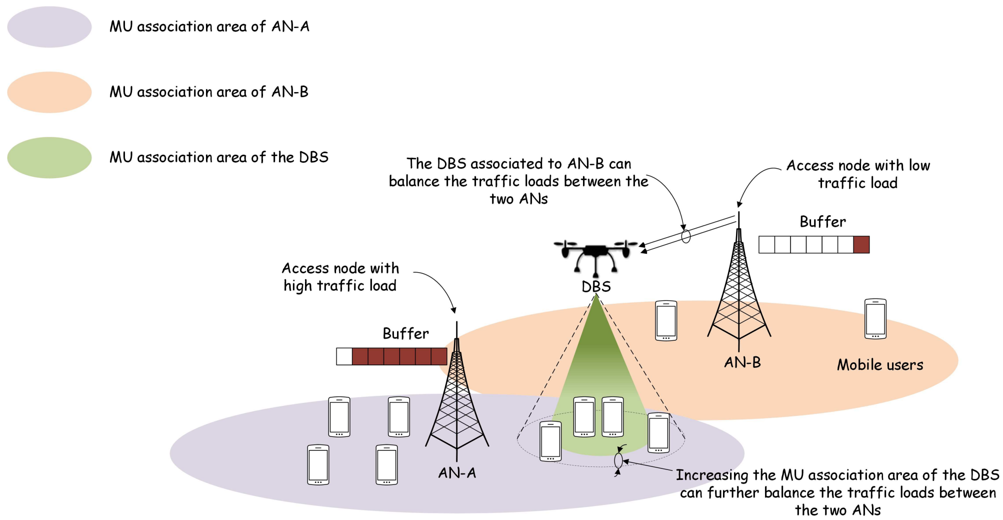


Fig. 6. Dynamic access node association and dynamic user association.

module to accurately track and point to the DBS remains to be a challenging issue.

Furthermore, the trade-off between the network performance (e.g., throughput and latency) and the capital cost has to be carefully taken into account. That is, deploying more DBSs in the network may potentially increase the network throughput, but may also increase the operational cost of the network providers. Hence, it is desirable to determine the suitable number of the DBSs in order to optimize the tradeoff.

## VII. Conclusion

We have proposed and delineated the SoarNet architecture to improve the throughput and flight time of DBSs by utilizing the FSO link to transfer data streams and energy from access nodes to DBSs simultanesouly. We have briefly overviewed the existing wireless backhaul and charging methods for DBSs. We have described how to leverage FSO technologies into the SoarNet architecture, and introduced how the FSO transmitter and FSO receiver can transfer data streams and energy simultaneously. We have also discussed how the DBS placement and user association impact the network performance. Finally, we have elicited the future research challenges in the context of SoarNet, and hope to invigorate the readers to tackle them.

## References

[1] Q. Fan and N. Ansari, "Towards traffic load balancing in drone-assisted communications for IoT," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3633–3640, April 2019.

[2] Q. Fan, M. Taheri, N. Ansari, J. Feng, R. Rojas-Cessa, M. Zhou, and T. Zhang, "Reducing the impact of handovers in ground-to-train free space optical communications," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 2, pp. 1292–1301, Feb 2018.

[3] B. Galkin, J. Kibilda, and L. A. DaSilva, "Backhaul for low-altitude uavs in urban environments," in *2018 IEEE International Conference on Communications (ICC2018)*, Kansas City, MO, May 2018, pp. 1–6.

[4] S. Glisic, *mmWave Networks, in Advanced Wireless Networks: Technology and Business Models*. Wiley Telecom, May 2016.

[5] C. Gerami, N. Mandayam, and L. Greenstein, "Backhauling in TV white spaces," in *2010 IEEE Global Telecommunications Conference (GLOBECOM'2010)*, Miami, FL, Dec 2010, pp. 1–6.

[6] Q. Fan, N. Ansari, J. Feng, R. Rojas-Cessa, M. Zhou, and T. Zhang, "Reducing the number of FSO base stations with dual transceivers for next-generation ground-to-train communications," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 11, pp. 11 143–11 153, Nov 2018.

[7] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks," *CoRR*, vol. abs/1607.01472, Jul. 2016.

[8] U. Siddique, H. Tabassum, E. Hossain, and D. I. Kim, "Wireless backhauling of 5G small cells: challenges and solution approaches," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 22 – 31, Oct. 2015.

[9] A. Alsharoa, H. Ghazzai, A. Kadri, and A. E. Kamal, "Energy management in cellular HetNets assisted by solar powered drone small cells," in *IEEE Wireless Communications and Networking Conference (WCNC'2017)*, San Francisco, CA, Mar. 2017, pp. 1–6.

[10] J. L. Gmez-Tornero, M. Poveda-Garca, R. Guzmn-Quirs, and J. C. Snchez-Arnause, "Design of Ku-band wireless power transfer system to empower light drones," in *IEEE Wireless Power Transfer Conference (WPTC'2016)*, Aveiro, Portugal, May 2016, pp. 1–3.

[11] T. M. Mostafa, A. Muharam, and R. Hattori, "Wireless battery charging system for drones via capacitive power transfer," in *2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer*, Chongqing, China, May 2017, pp. 1–6.

[12] "The future of drones according to the AT&T foundry," AT&T Foundry, Palo Alto, CA, USA, Ericsson, Stockholm, Sweden, and Rocket Space, San Francisco, CA, USA, Tech. Rep., Oct. 2016. [Online]. Available: http://www.rocketspace.com/thefuturistreports/futureofdrones

[13] J. Degnan, G. Jodor, and H. Bourges, "Automated transmitter beam size and divergence control in the SLR2000 system," in *Proc. of the 15th International Laser Ranging Workshop, Canberra, Australia*, Canberra, Australia, Oct. 2006.

[14] A. K. Majumdar, "Free-space laser communication performance in the atmospheric channel," *Springer Journal of Optical and Fiber Communications Reports*, vol. 2, no. 4, pp. 345–396, Oct. 2005.

[15] L. Zhang, Q. Fan, and N. Ansari, "3-D drone-base-station placement with in-band full-duplex communications," *IEEE Communications Letters*, vol. 22, no. 9, pp. 1902–1905, Sep. 2018.

**Nirwan Ansari** (S'78-M'83-SM'94-F'09) is Distinguished Professor of Electrical and Computer Engineering at NJIT. He has (co-)authored 3 books, and more than 600 technical publications, over 280 published in widely cited journals/magazines. He has also been granted more than 40 U.S. patents. His current research focuses on green communications and networking, cloud computing, drone-assisted networking, and various aspects of broadband networks. Some of his recognitions include several excellence in teaching awards, a few best paper awards, the NCE Excellence in Research Award, several ComSoc TC technical recognition awards, the NJ Inventors Hall of Fame Inventor of the Year Award, the Thomas Alva Edison Patent Award,

Purdue University Outstanding Electrical and Computer Engineering Award, and the NCE 100 Medal.

**Qiang Fan** (S'15) received his B.S. degree from Suzhou University of Science and Technology, China, in 2009, his M.S. degree in Electrical Engineering from Yunnan University of Nationalities in 2013. and his Ph.D. degree from Department of Electrical and Computer Engineering, New Jersey Institute of Technology (NJIT) in 2019. His research interests include mobile and cellular networks, mobile cloud computing, machine learning enabled wireless networks, and drone-assisted networking.

**Xiang Sun** (S'13, M'18) is Assistant Professor of Electrical and Computer Engineering at the University of New Mexico. He received the B.E. and M.E. degrees from the Hebei University of Engineering in 2008 and 2011, respectively, and the Ph.D. degree in electrical engineering from the New Jersey Institute of Technology (NJIT) in 2018. He has (co-)authored 26 technical publications, held one U.S. patent, and filed six U.S./PCT non-provisional patent applications. His research interests include mobile edge computing, cloud computing, Internet of Things, wireless networks, big-data-driven networking, and green communications and computing. He has also served as a TPC member of many conferences. He has received several honors and awards, including the 2016 IEEE International Conference on Communications Best Paper Award, the 2017 IEEE Communications Letters Exemplary Reviewers Award, the 2018 NJIT Hashimoto Price, the 2018 Inter Digital Innovation Award on IoT Semantic Mashup, the 2019 NJIT Outstanding Doctorial Dissertation Award, and the 2019 IEICE Communications Society Best Tutorial Paper Award. He is currently an Associate Editor of Digital Communications and Networks.

**Liang Zhang** (S'15) received his M.S. degree from the Department of Information and Communication Engineering, University of Science and Technology of China, in 2014. He is currently pursuing a Ph.D. in ECE at New Jersey Institute of Technology. He received the prize of the National Scholarship of Graduate Students in China in 2013, the Best Paper Award at IEEE ICNC in 2014, and a Travel Grant Award from IEEE GLOBECOM in 2016. His research interests include drone-mounted base-station communications, mobile edge computing, Internet of Things, datacenter networks and optical networks.