Efficient Fronthaul and Backhaul Connectivity for IoT Traffic in Rural Areas

Elias Yaacoub and Mohamed-Slim Alouini

ABSTRACT

In this article, internet of things (IoT) connectivity in rural areas is investigated. Both fronthaul and backhaul considerations are studied. First, intelligent radio resource management (RRM) and network planning techniques are discussed for IoT access/fronthaul networks. The proposed RRM scheduling approach was shown to lead to good performance in scheduling IoT devices. Then, several backhauling techniques for providing connectivity to rural areas are investigated and their cost efficiency is analyzed. Techniques based on free space optics with solar powered devices are found to be a suitable backhaul solution.

INTRODUCTION

The internet of things (IoT), with its billions of devices sensing every aspect of our daily lives, is considered as the backbone of smart cities [1]. There are a lot of applications where IoT is at the heart of smart cities, e.g., smart grid, intelligent transportation systems, environment protection, water resources monitoring and management, and smart healthcare, among others [2].

All these systems rely on accurate and ubiquitous connectivity, thus necessitating the deployment of efficient communication networks. From the fiber infrastructure to 5G and beyond wireless access, communication networks need to support the load of increased IoT machine-to-machine (M2M) communications, under the umbrella of massive machine type communications (mMTC) in the 5G standards, in addition to the tremendous bandwidth demand in traditional communications (data, video, etc.), falling under the scenario of enhanced mobile broadband (eMBB) in the 5G standards. Consequently, they must satisfy the stringent requirements of certain M2M applications (smart grid, m-Health), while maintaining the quality of service (QoS) and quality of experience (QoE) of network subscribers. Furthermore, it is to be noted that this enhanced network operation should take into account energy efficiency and the power consumption of the communication networks. Therefore, several techniques come into play to reach this target: software defined networking and smart network slicing, coupled with green networking techniques, inter-operator collaborations, and the use of cellular base stations powered by renewable energy.

It can be argued that the above technological advances, although necessary for a smart city, can enable smart living in general (e.g., smart villages, smart suburbs). However, to ensure their successful implementation in rural areas outside cities, not only efficient IoT deployments should take place, but also the deployment of an adequate backhaul network relaying the rural IoT traffic to the network core is essential.

Therefore, this article addresses the problem of IoT deployments in rural areas. First, we present a radio resource management approach (RRM) that can adapt to various IoT traffic densities. Although this approach is applicable to both urban and rural areas, it is particularly suited to IoT deployments in areas with limited spectrum resources. Then, we address the problem of providing backhaul connectivity for the rural IoT traffic. Indeed, the main challenge is in ensuring fast, reliable connectivity in rural areas supporting the needed IoT traffic to enable a smart living environment. Hence, we discuss several technological solutions for rural backhaul, and analyze their cost efficiency taking into account capital expenditures (CAPEX) and long-term operational expenditures (OPEX).

FROM SMART CITIES TO SMART LIVING

Smart city advocates aim to manage the problem of having half the world population already living in cities and another couple billion being on their way. As stated in [3], “the world is becoming far more urbanized, and mega cities with populations greater than 10 to 20 million people are emerging, there is a greater need for large-scale operations and management for cities to effectively serve their inhabitants.”

However, with the expected technological advances, especially the ones based on IoT, we can have smart villages, smart towns, smart suburbs, etc. In fact, with the advances in communication technologies, remote work by employees can be afforded by many jobs. Moreover, better healthcare and good quality education can be achieved without necessarily moving to a big city, leading to enhanced quality of life in a rural environment with reduced pollution and no overpopulation.

Imagine you live in a “smart home” in a quiet, clean village, with solar panels generating energy to (at least partially) meet the consumption demands; you work from home, where you are connected to your colleagues through a high bandwidth communications network, whether they are also working from home or at the company’s headquarters; you kids enjoy distance learning through technology and virtual reality (VR) methods; you can enjoy fresh organic food due to smart agriculture; you can rely on a high speed rail network whenever you (occasionally) need to go to the city; quality healthcare is available at a local health center, with even complicated surgeries being possible with the help of robotics, augmented reality (AR), VR, and ultra-reliability low latency communications (URLLC) in 5G networks. Would you need to live in a crowded, polluted city just to benefit from the same advantages?

Hence, while the technological progress has made the existence of smart cities with huge populations possible, that same
progress also made it possible for people to enjoy quality living in their rural areas. This “smart everywhere” concept, coupled with smart governance, can lead to a more balanced population density between cities and rural areas, while allowing all citizens to enjoy quality living. However, while the deployment of IoT devices can take place in both rural and urban areas, the “smart everywhere” scenario depends on high speed connectivity between the IoT devices and the core network. This can be performed in a profitable manner in cities and densely populated areas. However, the challenge is in providing high-speed backhaul connectivity to rural areas [4].

In addition, when discussing connectivity in rural areas, there must be a differentiation between:

- Remote areas in developed countries, where transportation networks (e.g., rail) and electricity are provided, and
- Poor areas in developing countries, where the basic services are hardly provided to the population.

**Rural Backhaul in Developed Countries**

Generally, these rural areas are accessible by transportation networks, e.g., railroad networks. Furthermore, power is provided through the electricity grid. The challenges in providing connectivity to these areas lie in the difficulty of obtaining a good return on investment (ROI) for mobile operators. A possible solution is that fiber optic cables can be deployed along the railroad track, thus benefiting from the existing transportation infrastructure. Base station (BS) towers can be erected near the train stops corresponding to population agglomerations in nearby villages/towns. In addition, microwave links can be used for backhaul connectivity by reusing the existing towers used for deploying GSM-R BSs to maintain connectivity for operating the train system. Fiber can also be deployed at lower costs by using micro-trenching on the border of roadways [5]. Access technologies can then be implemented as needed, whether traditional methods, or novel ones, e.g., millimeter wave (mmWave) multi-hop multi-point wireless distribution networks.

Thus, in these areas, Access/Fronthaul connectivity can be provided within each town/village using the appropriate technology, then the access BSs can be connected to the backbone network through the microwave or fiber systems deployed along the transportation routes.

**Rural Backhaul in Developing Countries**

This scenario corresponds to poor areas in developing countries where the challenge is to reduce the digital divide with developed countries. Hence, connectivity needs to be provided to secure basic services, such as healthcare, education, basic web access, etc. In these areas, transportation roads are under-developed or even non-existent, and the villages are almost isolated from the deployment cities within their country, e.g., see [6]. Power generation could rely on local generators, or on a small local grid.

Hence, providing backhaul connectivity to these rural areas cannot benefit from existing infrastructure, and often has to be done from scratch. Furthermore, the poverty of the people living there, even regardless of the population density, does not promise sufficient revenues to justify the backhaul deployment costs of a mobile operator. State subsidies can be provided to support the deployment, which nevertheless should be as cost efficient as possible.

Therefore, analyzing the costs of providing backhaul solutions for this kind of rural area is one of the two main objectives of this article. In the next section, we discuss the first main objective of providing a fronthaul/access approach for IoT devices that can be adapted dynamically to population density. Then, in the following section, we tackle the second main objective by investigating in more detail rural backhaul costs and suitable solutions.

**An RRM Approach for IoT Access/Fronthaul**

In this section, we present a smart RRM approach, coupled with an intelligent network planning approach, that allows IoT devices to access the network and transmit their data. The proposed approach allows the accommodation of varying densities of IoT devices and thus can be used in urban and rural areas. Although the proposed RRM approach is analyzed in a simulation environment based on LTE-Advanced-Pro Narrowband-IoT (NB-IoT) and on scheduling using proportional fair in time and frequency (PFFT) as proposed in [2], it can be easily extended to other technologies by replacing LTE resource blocks (RBs) with the resources that can be allocated in a given technology.

**RRM Algorithm**

This section presents the RRM algorithm for IoT traffic. In LTE, each transmission time interval (TTI) has a duration of 1 ms. In addition, orthogonal frequency division multiple access (OFDMA) is used. In each TTI, the smallest allocated resource is a group of 12 OFDMA subcarriers, forming an LTE resource block (RB). We assume that each IoT device has to achieve an average target data rate $R_T$ during a certain time interval, corresponding to a number of $N_{TTI}$ TTI.

A high-level summary of the RRM algorithm can then be presented as follows:

1. For each TTI (going from 1 to $N_{TTI}$)
2. Consider the set of available RBs for IoT traffic
3. Consider the set of active IoT devices in the current period
4. For each RB
5. Find the device that, when allocated, that RB can achieve the highest proportional increase in its data rate, compared to its data rate before being allocated that RB
6. Allocate the RB to that device
7. Remove the RB from the set of available RBs
8. If the device can meet its target rate on time with its allocated RB(s)
9. Remove the device from the set of available IoT devices (i.e., those requesting resources)
10. Else
11. Keep the device in the set of available IoT devices
12. End
13. End
14. End

The above algorithm goes through the available RBs in the Loop at Line 4, and then, for each RB, finds the device to which this RB should be allocated. Once the RBs start being allocated and devices start being served, the number of times the algorithm goes through the loop at Line 4 and through the devices at Line 5 gets reduced. Consequently, the algorithm has a linear complexity in the number of RBs $N_{RB}$ and the number of devices $N_{DI}$, thus having a complexity of order $O(N_{RB} \cdot N_{DI})$.

**Simulation Results**

This section presents the simulation results using the RRM algorithm of the previous section. We consider a cell of 500m radius. The simulation parameters concerning transmit power and the channel model are used as in [2]. Fig. 1 shows the outage rate versus the number of simultaneously active IoT devices, for different numbers of available RBs and different target rates $R_T$. Fig. 1 shows that when $R_T$ decreases, the number of IoT devices that can be simultaneously served, for a given outage rate, increases significantly. Furthermore, it shows the expected result that as the number of RBs dedicated for IoT traffic increases, the number of served IoT devices also increases significantly.

To get more insights on how to use these results for dimensioning 5G networks to handle IoT traffic, a closer look at the results of Fig. 1 shows that 2000 IoT devices can be served simultaneously with an outage rate below 0.5 percent if 50 RBs are available, for a target rate $R_T = 20$ kbps. Also, around 300 IoT devices can be served simultaneously with an outage rate below 0.2 percent if 25 RBs are available, for a target rate $R_T$
TABLE I: IoT network planning example for $R_T = 60$kbps, and each device transmitting for 500ms every 120s.

| Number of Relays ($N_{RS}$) | Number of Devices served per Relay ($N_{D,RS}$) |
|-----------------------------|---------------------------------|
| $N_{RS} = 500$              | $N_{D,RS} = 240$               |
| $N_{RS} = 50$               | $N_{D,RS} = 2400$              |
| $N_{RS} = 100$              | $N_{D,RS} = 1200$              |
| $N_{RS} = 250$              | $N_{D,RS} = 480$               |

Figure 1. Outage results using the proposed RRM algorithm. $R_T = 60$kbps.

PLANNING IoT ACCESS NETWORKS

This section presents insights on planning the IoT access network using the results of Fig. 1. For example, as stated in [2] and the references therein for real-time smart meter readings, data transmission by a smart meter occurs every $T_{period} = 120s$, where the meter performs a transaction by accessing the channel for a duration of $N_{TTI} = 500ms$, to transmit the meter’s data at a rate of $R_T = 60$kbps. Thus, for every $N_{TTI} = 500ms$, the number of simultaneously active meters can be derived from Fig. 1, for a given $R_T$ and a given tolerable outage threshold $Th$ (e.g., 0.2%). However, since each meter has to access the channel for 500ms during 120s, then the actual number of served meters can be multiplied by 240 (= 120s/0.5s) since they can be scheduled to access the channel in different batches. Consequently, relay stations (RSs)/aggregators can be deployed to serve a group of IoT devices using $N_{RR,RS}$ RBs on the link between aggregator and devices, with the aggregators transmitting continuously the traffic to a BS using $N_{RR,BS}$ RBs dedicated to the RS-BS link. With this scenario, each device accesses the channel for $N_{TTI}$ ms during $T_{period}$ whereas the RS is continuously transmitting the aggregated traffic. An example is shown in Table 1.

From Table 1, the scenario with 500 relays each serving 240 devices corresponds to a sparse deployment, e.g., smart meter deployment in a small rural village. However, the scenario with 50 relays each serving 2400 devices corresponds to a much denser deployment, e.g., in an urban neighborhood. Other examples can be less demanding, e.g., sensor measurements for air pollution monitoring can be received every five minutes, or even 15 minutes (instead of two minutes as in Table 1), and can be satisfied with $R_T = 20$kbps [2]. This would lead to higher numbers of RSs and devices than shown in Table 1.

These results are in agreement with those found in the relevant literature. For example, in [7], around 50k-70k devices can be served with their NB-IoT approach in an outdoor scenario. In this article, the number reaches 120k devices in the scenario of Table 1. In [8], “service denial” is investigated, and it increases significantly at high load. In this article, an outage rate below 0.2% was reached with 25 RBs, for a target rate $R_T = 60$kbps.

Nevertheless, it should be noted that the proposed algorithm is a low-complexity simple algorithm. Several more advanced algorithms were investigated in the literature, e.g., [9], and the references therein, and might achieve better performance. However, the objective in this article is to show that even a low-complexity algorithm, when combined with intelligent network planning, can support a large number of IoT devices and scale well in rural areas, as shown in the results of Fig. 1 and Table 1. Consequently, the challenge is in providing backhaul connectivity from the access BSs in rural areas to the core network. This will be the topic of the next section.

OVERVIEW OF RURAL BACKHAUL SOLUTIONS

This section describes several solutions for providing backhaul connectivity to rural areas. These solutions are assessed in terms of their capital expenditure (CAPEX) and operational expenditure (OPEX) costs. The studied technologies include fiber, microwave, satellite, mmWave, and free space optics (FSO). The publication in the literature that is most relevant to this work is [10], where the authors analyze and compare the costs of fiber optics, microwave links, and terrestrial and vertical FSO. The main difference with this article is that in [10], the authors investigate a fronthaul/backhaul scenario comprising a dense deployment of BSs, where a 5x5 Km$^2$ area is covered by 100 macro BSs and 1000 small cell BSs. Clearly, such a scenario is significantly different than the pure backhaul scenario investigated in this article, where the main objective is to transport the traffic through remote rural areas over hundreds of kilometers. This is similar to the area considered in [6], where one needs to drive for 12 hours through the rural area before reaching the nearest urban town.

Consequently, we consider a distance of 100 Km for our cost analysis. We assess the costs of laying fiber optic cables, erecting microwave, mmWave, or terrestrial FSO towers, leasing bandwidth from satellites, or using high altitude platforms (HAPS) for “vertical” FSO and/or mmWave. The cost parameters are obtained from [10-12], and are shown in Table 2 along with a summary of the properties of the various technologies.

Fiber Optics: Fiber optic deployment typically ensures the highest bandwidth. It is based on laying fiber optic cables. Due to the large distance to be traversed in the case of sparse rural areas, this solution might face obstacles due to the geographic nature of the terrain. Nevertheless, it might still be feasible in certain scenarios, e.g., in large plains or desert areas, depending on costs. These costs can vary widely between dense urban areas (where they could reach 30 USD/meter [11]) and sparse rural areas (where they could reach 300 USD/meter [11]).

Microwave Links: Microwave links are based on placing radio frequency (RF) equipment on towers. The backhaul transmissions using microwave links are performed over licensed frequencies. mmWave communications can also be used for backhaul using unlicensed frequencies, but their current equipment costs are higher than microwave. The towers carrying the equipment need to be built in order to transmit the signal over long distances in sparsely populated rural areas, and thus their cost, approximated at 50,000 USD/tower [10] and sparse rural areas (where they could reach 300 USD/meter [11]).
rural area, rather than costs per capita. In our analysis, different tower separation distances are investigated: 3, 5, and 10 Km. This corresponds to various deployment conditions based on geographic and weather constraints in the area of interest.

**Terrestrial FSO:** Terrestrial FSO is based on deploying towers carrying FSO equipment in order to provide connectivity in the backhaul. Thus, similarly to microwave links, tower costs should be included in the CAPEX. In addition, FSO equipment costs are more expensive. However, no licensing costs are included in the OPEX since FSO uses light transmission. Nevertheless, this makes FSO more sensitive to alignment errors, fog, and other weather conditions [13]. Consequently, the separations between FSO towers that are investigated in this article are based on those of [13] and are relatively shorter than their microwave counterparts: 0.5, 3, and 5 Km.

**Vertical FSO:** In situations where the erection of towers is not practical (or where it faces security issues such as stealing equipment for terrestrial FSO and microwave links), HAPs, such as drones or unmanned aerial vehicles (UAVs), can be used in order to provide backhaul connectivity using FSO. The main advantage of resorting to HAPs is that they are less sensitive to weather conditions. This is due to the fact that they hover at higher altitude; thus, for example, they can fly above fog. Consequently, two HAPs can be separated by a longer distance than two terrestrial FSO towers. Consequently, in our study, we investigate distances of 5, 10, and 20 Km between two flying platforms.

The main drawback is the high CAPEX, as each flying platform costs around 50,000 USD [10]. OPEX is also high, since operational costs are estimated at around 859 USD per flying hour [10]. However, solar powered vertical FSO can significantly alleviate this problem. Maintenance costs for vertical FSO are assumed to be within the same range of that of microwave (approximated by 375 USD/year [10]), but we budget an increase of 33 percent (i.e., around 500 USD/year), in order to take into account the increased complexity of the FSO equipment compared to microwave.

**Solar-Powered Vertical FSO – The Loon Project:** A special case of solar-powered vertical FSO is Google’s Loon project. It allows providing connectivity to rural areas by launching balloons into the stratosphere [14]. We consider this project in our calculations, while using numbers from the feasibility study.

---

**Table 2. Parameter values used in the calculations [10], [11], [12].**

| Parameter                                      | Value      | Type          | Data Rate | Latency | Comments                                                   |
|-----------------------------------------------|------------|---------------|-----------|---------|------------------------------------------------------------|
| Total Backhaul Distance (km)                  | 100        | -             | -         | -       | -                                                          |
| Microwave                                      |            |               |           |         |                                                           |
| Microwave Tower Cost (USD)                    | 50,000     | CAPEX         | ~ 1 Gbps  | Low     | Needs line of sight                                       |
| Microwave Equipment Cost (USD)                | 40,000     | CAPEX         |           |         |                                                           |
| Spectrum License Costs per Year per Link (USD)| 3,000      | OPEX          |           |         |                                                           |
| Microwave Power and Maintenance Cost per Year (USD)| 375 | OPEX          |           |         |                                                           |
| Fiber                                          |            |               |           |         |                                                           |
| Fiber Cable Cost (USD/m)                      | 10         | CAPEX         | ~ 40 Gbps | Very Low| Topology should be suitable for deployment; very high rates achievable with dense wavelength division multiplexing (DWDM) and multimode fiber |
| Fiber Installation Cost (USD/m)               | 30         | CAPEX         |           |         |                                                           |
| Fiber Equipment Cost (USD)                    | 3,500      | CAPEX         |           |         |                                                           |
| Fiber Power and Maintenance Cost per Link per Year (USD)| 200 | OPEX          |           |         |                                                           |
| Terrestrial FSO                                |            |               |           |         |                                                           |
| Terrestrial FSO Tower Cost (USD)               | 50,000     | CAPEX         | ~ 10 Gbps | Low     | Needs line of sight; sensitive to atmospheric turbulence and interference from other light sources (e.g. sunlight) |
| Terrestrial FSO Equipment Cost (USD)           | 20,000     | CAPEX         |           |         |                                                           |
| Terrestrial FSO Link Maintenance Cost per Year (USD)| 8,000 | OPEX          |           |         |                                                           |
| Vertical FSO                                   |            |               |           |         |                                                           |
| Vertical FSO Equipment Cost (USD)              | 50,000.00  | CAPEX         | ~ 10 Gbps | Low     | Needs line of sight; sensitive to atmospheric turbulence and interference from other light sources (e.g. sunlight) |
| Vertical FSO Operation Cost per Hour (USD)     | 859        | OPEX          |           |         |                                                           |
| Vertical FSO Operation Cost per Year (USD)     | 7,524,840  | OPEX          |           |         |                                                           |
| Vertical FSO Solar Powered Operation Cost per Year (USD)| 500 | OPEX          |           |         |                                                           |
| Satellite                                      |            |               |           |         |                                                           |
| VSAT Equipment Cost (USD)                      | 4,000      | CAPEX         | ~ 50-100 Mbps | High | Data rates vary between access/fronthaul and backhaul; Cost of leasing bandwidth is relatively high |
| Satellite Hub + Installation Cost (USD)         | 500,000    | CAPEX         |           |         |                                                           |
| HTS Capacity Cost (USD/Mbps/Month)             | 250        | OPEX          |           |         |                                                           |
| Annual Maintenance Costs (% of CAPEX)          | 15%        | CAPEX         |           |         |                                                           |
performed in [14] as follows:

- The cost per balloon is estimated in [14] at 17,870 USD (CAPEX). In our calculations, this cost is rounded to 18,000 USD.
- Maintenance costs in [14] are estimated at 1,230 USD per balloon per 100 days. In our calculations, these numbers are rounded to 5,000 USD/year.
- In [14], it is indicated that a balloon covers a diameter of 40 Km. In our calculations, we will assume that three balloons are required to cover a 100 Km backhaul distance, thus reducing this range to 33.3 Km. Moreover, to take into account the case where balloons are placed at the edge of the backhaul stretch, we will assume that four balloons are needed.
- CAPEX costs are regenerated every five years, which is estimated in [14] as the service life of a balloon.

**mmWave**: mmWaves are used for short range fronthaul/access in 5G small cells. They can also be used to provide backhaul connectivity, especially when used with massive multiple input multiple output (MIMO) antenna systems. The equipment for mmWave communications can be deployed on towers, similarly to microwave and terrestrial FSO, or carried by HAPs (UAVs, balloons, etc.) similarly to vertical FSO [11]. Since mmWave communications mostly rely on unlicensed frequencies, and they are carried by structures similar to FSO (towers or HAPs) while having comparable transmission ranges, their cost analysis will be similar to that of the FSO solutions. However, an important difference should be noted, as mmWaves are not sensitive to light interference and less sensitive to atmospheric turbulence.

**Satellite**: Satellite backhaul is a good solution to overcome the geographic constraints, and to avoid the deployment delays in the absence of existing infrastructure (e.g., building towers, laying fiber, etc.). The main limitation is the high bandwidth cost, in addition to relatively higher latency compared to other technologies. However, with the increasing deployment of large numbers of high throughput satellites (HTSs), and the current trend of decreasing bandwidth cost that is expected to continue in the coming years [11], satellite backhaul is becoming a competitive solution. Some works in the literature are investigating the deployment of small satellites, CubeSats, for the sole purpose of collecting IoT sensor measurements in remote areas, thus forming an Internet of Space Things (IoST) (e.g., see [11] and the references therein).

**Cost Analysis of Rural Backhaul Solutions**

This section presents the cost analysis results of the technologies listed in the previous section. The various cost parameters are listed in Table 2, and are obtained mainly from [10-12]. Fig. 2(a) shows the CAPEX results. Clearly, Terrestrial FSO with 500m separation between towers (to have acceptable performance in case of fog) is the most expensive due to an increase in the number of towers, whereas the fiber optic scenario follows. Fig. 2(b) shows the 1-year OPEX results. It should be noted that the higher costs incurred in case of non-solar powered Vertical FSO are more than an order of magnitude higher than the costs incurred with other technologies. This is expected due to the high flying costs per hour. Therefore, for better figure clarity and to be able to assess the performance of the other scenarios, we present the one-year OPEX results without non-solar powered Vertical FSO in Fig. 2(b). They are also excluded from Fig. 2(c). Interestingly, solar-powered Vertical FSO appears to be a cost-efficient solution.

**Cumulative CAPEX + OPEX Results**

Fig. 2(c) shows the cumulative CAPEX + OPEX results after 1, 5, 10, and 15 years, in order to assess the technologies over a longer time visibility. Thus, despite its relatively high initial CAPEX, fiber deployment becomes competitive with microwave and terrestrial FSO in the long run, due to its low maintenance costs of 200 USD OPEX per link per year (as indicated in Table 2). In fact, for the distance considered, no repeaters are needed, which helps reduce the costs, since the distance between repeaters is determined to be in the order of 350-400 Km [15]. Satellite costs seem to be competitive at first, but then increase steadily due to the relatively high bandwidth cost, since we consider 50 Mbps at a cost of 250 USD/Mbps/Month [11]. The most cost efficient results are achieved by solar powered vertical FSO, including the Google Loon project.

**Scaled Cumulative CAPEX + OPEX Results**

Fig. 2 shows the cost results based on some practical assumptions for each technology, although each of these technologies provides a different bandwidth. Fig. 3 shows the same results as Fig. 2, after scaling them by the achievable backhaul capacity. In this case, fiber deployment becomes extremely competitive due to the high data rates that it can achieve, whereas solar powered Vertical FSO maintains its cost efficient performance.

On the other hand, satellite backhaul OPEX costs were too high and were thus removed from Figs 3(b) and 3(c), along...
with non-solar powered vertical FSO, for clarity purposes. Nevertheless, it should be noted that, although satellites can be used to provide backhaul connectivity, satellite backhaul costs are justified when their footprint allows them to provide backhaul connectivity for hundreds of BSs. Since our backhaul calculations are based on a backhaul link of 100 Km constituting an integral part of the backbone network, without considering the availability of nearby access BSs, cost comparisons would not be fair to a satellite backhaul scenario. In Fig. 3, we tried to consider 100 Mbps satellite bandwidth at a reduced average cost of 100 USD/Mbps/month (i.e. reduced cost and more bandwidth compared to Fig. 2), but this did not make the satellite solution much more competitive.

**CONCLUSIONS AND DISCUSSION**

This article investigated connectivity in rural areas to enable the transition from smart cities to smart living everywhere. Intelligent radio resource management and network planning techniques were discussed for IoT access networks. In addition, several backhauling techniques for providing connectivity to rural areas were discussed and their cost efficiency was analyzed. Techniques based on free space optics with solar powered devices were found to be a suitable solution.

Examples of actual IoT deployments in rural areas, along with the challenges faced for backhaul connectivity, are surveyed in [11]. In this article, rather than considering a deployment example, we present a case study demonstrating the impact and benefits of deploying a backhaul network in a rural area. In this case study illustrated in Fig. 4, we analyze the impact of using IoT technology on agriculture in a rural area, and compare the benefits to backhaul costs. For example, we can consider an area of 40,000 m² (square meters). This area is planted with blueberries. Each plant occupies an area of 2.5 m². Using traditional irrigation, each plant requires 4 liters/day to be irrigated. Deploying a sensor network with IoT technology, the sensor measurement data can be collected and transmitted over the Internet, where it can be stored, analyzed, and processed on a cloud server. The sensors can measure different plant related metrics in order to perform precision irrigation by determining more accurately the irrigation needs of the plant and the optimal amount to harvest it. This is expected to lead to approximately 50 to 60 percent savings compared to the traditional irrigation approach, which is equivalent to around 14,000 m³ of water per year. When the above blueberry field is a relatively small portion (200 m x 200 m) of a large agricultural rural area of size 20 km x 20 km for example, that area can contain 10,000 similar fields. Assuming similar savings can be achieved throughout this area, and that the average water consumption per household is 116.8 m³ of water per year, then around 1,200,000 households can be provided with water (whether in nearby villages, or in remote urban areas after channeling the water properly in case the rural area is very sparsely inhabited). At the residential water consumption cost of 1 USD/m³, this will lead to revenues of 140 million USD, significantly exceeding the cost of backhaul deployment technologies shown in Fig. 2(c).

**ACKNOWLEDGMENT**

The authors would like to thank the Editor-In-Chief, the Guest Editor, and the anonymous reviewers for their valuable comments that helped improve the quality and clarity of the article.

**REFERENCES**

[1] S. P. Mohanty, U. Choppali, and E. Kougiouannos, “Everything You Wanted to...
Know about Smart Cities: The Internet of Things is the Backbone,” *IEEE Consumer Electronics Mag.*, vol. 5, no. 3, July 2016, pp. 60–70.

[2] E. Yaacoub and Z. Dawsy, “On Using Relays with Carrier Aggregation for Planning 5G Networks Supporting M2M Traffic,” *Proc. 10th IEEE Int’l Conf. Wireless and Mobile Computing, Networking and Communications (WiMob 2014)*, Larnaca, Cyprus, Oct. 2014.

[3] Deloitte, “National Transformation in the Middle East: A Digital Journey,” 2017.

[4] L. Chiaraviglio et al., “5G in Rural and Low-Income Areas: Are We Ready?” *2016 ITU Kaleidoscope: ICTs for a Sustainable World*, Bangkok, Thailand, Nov. 2016.

[5] V. Diaz, “Backhauling with Fibre,” *Fibre Systems*, no. 6, Winter 2015, pp. 33–34.

[6] K. Ab-Hamid, C. E. Tan, and S. P. Lau, “Self-sustainable Energy Efficient Long Range WiFi Network for Rural Communities,” *IEEE Globecom 2011 Wksp. Rural Communications-Technologies, Applications, Strategies and Policies (RuralCom 2011)*, Houston, TX, USA, Dec. 2011, pp. 1050–55.

[7] M. Lauridsen et al., “Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area,” *Proc. 2016 IEEE 84th Vehic. Tech. Conf. (VTC-Fall)*, Montreal, QC, Canada, Sept. 2016, pp. 1–5.

[8] M. Beshley et al., “End-to-End QoS “Smart Queue” Management Algorithms and Traffic Prioritization Mechanisms for Narrow-Band Internet of Things Services in 4G/5G Networks,” *Sensors (MDPI)*, vol. 20, article no. 2324, 2020, pp. 1–30, doi:10.3390/s20082324.

[9] C. B. Mwakwata et al., “Narrowband Internet of Things (NB-IoT): From Physical (PHY) and Media Access Control (MAC) Layers Perspectives,” *Sensors (MDPI)*, vol. 19, article no. 2613, pp. 1–34, doi:10.3390/s19112613, 2019.

[10] M. Alzenad et al., “FSO-based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks,” *IEEE Commun. Mag.*, vol. 56, no. 1, Jan. 2018, pp. 216–24.

[11] E. Yaacoub and M-S. Alouini, “A Key 6G Challenge and Opportunity—Connecting the Base of the Pyramid: A Survey on Rural Connectivity,” *Proc. IEEE*, vol. 108, no. 4, Apr. 2020, pp. 533–82.

Biographies

Elias Yaacoub [S’08, M’10, SM’14] (eliasy@ieee.org) received the B.E. degree in electrical engineering from the Lebanese University in 2002, the M.E. degree in computer and communications engineering from the American University of Beirut (AUB) in 2005, and the Ph.D. degree in electrical and computer engineering from AUB in 2010. Between 2010 and 2014, he worked as a research scientist/R&D expert at the Qatar Mobility Innovations Center (QMIC). Afterwards, he joined Strategic Decisions Group (SDG) where he worked as a consultant until February 2016. He then joined the Arab Open University (AOU) as an associate professor. Between February 2018 and August 2019, he worked as an independent researcher/consultant, and he was also affiliated with AUB as a part-time faculty member. Since August 2019, he has been an associate professor in the Computer Science and Engineering Department at Qatar University. His research interests include wireless communications, antenna theory, IoT, and physical layer security.

Mohamed-Slim Alouini [S’94, M’98, SM’03, F’09] (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, he leads the Communication Theory Lab (ctl.kaust.edu.sa) and his current research interests include the modeling, design, and performance analysis of wireless communication systems.