Cost Effective Hybrid FSO-Wireless Architecture for Broadband Access Network

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***Abstract*—Free space optics (FSO) is known to be a viable alternative to optical fiber in fiber-wireless (FiWi) architecture. FSO has benefits such as high bandwidth, cost-efficiency, ease of deployment, flexibility, and an unlicensed spectrum. In this paper, we propose a novel hybrid FSO-wireless (FoWi) architecture that integrates wireless-fidelity (Wi-Fi) enabled front-end with FSO based back-end for an active optical network (AON) to provide seamless connection to the last-mile users. In addition, we analyze signal-to-noise ratio (SNR) distribution, average data rate, deployment cost, and fairness of the proposed hybrid architecture. The proposed architecture is compared with conventional FiWi architecture in the presence of weak, moderate, and high atmospheric turbulence. The simulation results demonstrate that the proposed hybrid FoWi architecture achieves a significantly lower deployment cost as compared to conventional FiWi architecture albeit with some trade-off in the performance specifically for weak atmospheric turbulence. In addition, this paper provides fairness analysis of the proposed architecture vis-a-vis conventional FiWi architecture.**

***Index Terms*—Free Space Optics (FSO), Fiber-Wireless (FiWi), FSO-Wireless (FoWi), Atmospheric turbulence, Wireless fidelity (Wi-Fi), data rate, Fairness, Deployment cost.**

I. Introduction

With the exponential increase in data traffic, network service providers are facing numerous challenges such as demand for large network capacity, low latency, high data rate, and low deployment cost. Fiber-wireless (FiWi) architecture has been shown to be a promising solution to alleviate some of the above challenges. In the conventional FiWi architecture, next-generation access network technologies such as next-generation passive optical network (NG-PON), 10-Gigabit-capable PON (XG-PON), etc. are integrated with wireless-fidelity (Wi-Fi) based front-end networks such as IEEE 802.11n/ac/ax or worldwide interoperability for microwave access (WiMAX) [1]. XG-PON is a promising technology that provides a data rate of 2.48 Gbps and 10 Gbps in the upstream and downstream direction, respectively [2]. Regarding architectural view, in XG-PON architecture, an optical line terminal (OLT) is placed at the central location and is connected to a passive splitter through a feeder fiber. Further, this passive splitter is connected to the optical network units (ONUs) using distribution fibers [1]. Each ONU is generally colocated with an access point (AP) that provides the required quality of services (QoS) to the users via wireless links. In FiWi front-end architecture, each AP is employed with Wi-Fi standard. It is worthwhile to note that large-scale deployment of optical fibers in conventional FiWi architecture may not be appropriate for challenging deployment scenarios such as in difficult terrains, remote locations, or in the center of the city where the deployment of additional fiber is prohibited because of limited flexibility and high installation cost. One possible solution to alleviate the aforementioned problems is to introduce the free space optics (FSO) link in active optical network (AON) architecture. The FSO is an attractive solution as it offers greater flexibility and easier redeployment. The FSO has numerous benefits such as provides unlicensed spectrum, high bandwidth, immune to electromagnetic interference, high-speed communication, and quick deployment to the end-users [3]. Therefore, the integration of FSO based back-end and Wi-Fi based front-end in XG-PON architecture can exploit advantages of both FSO and Wi-Fi technology to provide flexibility and a high data rate. However, the FSO links have a limited communication range since they suffer from atmospheric turbulence, atmospheric attenuation, and pointing error [4].

A. Related Works

In recent years, due to advancements in the FSO technology, it is foreseen as an viable alternative to optical fibers since it requires low installation cost and can be deployed at places where laying and trenching of fibers is more cumbersome [3]. In [5], the authors proposed time and wavelength division multiplexing (TWDM) PON architecture by integrating both PON and FSO links for ensuring survivability against failures of fibers. The authors also evaluated the bit error ratio (BER) of the proposed framework. In [6], the authors analyzed the performance of FSO-based optical code-division multiple-access (OCDMA) PON architecture where FSO link is considered between OLT and passive splitter. In [7], the integration and transmission of optical baseband, FSO, millimeter-wave traffic in PON architecture using on–off keying (OOK) signal are investigated. In [8], the authors analyzed the performance of a bidirectional time division multiplexing (TDM) FSO based PON. Specifically, for ensuring survivability, the authors utilized a unique self protection mechanism in the proposed network. The authors in [9], demonstrated the effect of different weather parameters such as temperature, humidity, and wind speed on fiber-FSO-fiber links. A hybrid system based on TWDM PON along with FSO has been proposed [10], and its network performance is analyzed in terms of BER. In [11], the authors analyzed the performance of wavelength-division-multiplexing (WDM) PON where fiber and FSO links are integrated in PON architecture with modulation and detection based on modified OOK signal. The authors in [12] presented cost analysis of proposed architecture in which PON and FSO based fronthaul architecture are integrated. They also installed FSO links in place of distribution fiber in the proposed PON architecture.

B. Contribution

In this work, we propose and evaluate the performance of a novel hybrid FSO-wireless (FoWi) architecture in which FSO based back-end network in AON architecture is integrated with a Wi-Fi-based front-end network. Further, FSO links are assumed to replace both feeder and distribution fiber in the back-end of AON architecture. The proposed hybrid FoWi architecture's performance is investigated taking into account the effect of atmospheric turbulence, specifically, weak, moderate, and strong turbulence. Further, we compare the performance of our proposed hybrid FoWi architecture with conventional FiWi architecture in terms of average data rate, fairness, and deployment cost.

To the best of the author's knowledge, the proposed work is the first of its kind to investigate the end-to-end performance of the hybrid FoWi architecture in AON, composed of the FSO based back-end network and Wi-Fi-based front-end network.

The major contributions of this work are summarized below:

1) We investigate the performance of the hybrid FoWi system based AON architecture under the effect of weak, moderate and high atmospheric turbulence by evaluating the received signal-to-noise ratio (SNR) and average data rate.
2) We compare the performance of the proposed hybrid FoWi architecture and traditional FiWi architecture in terms of average data rate and fairness.
3) In addition, we analyze the capital expenditure (CAPEX) cost for the proposed hybrid FoWi architecture and compare it with the conventional FiWi network.

The rest of the paper is organized as follows: The system model of the hybrid FoWi architecture is explained in Section II. In Section III, the channel modeling is presented. Section IV describes the evaluation of the proposed architecture via simulation results. Finally, the conclusion of the work is discussed in Section V.

Notations: Gaussian distribution is denoted by $\mathcal{N}(\mu, \sigma^2)$, where μ is the mean and σ^2 represents the variance.

II. System Model

Fig. 1 depicts the conventional FiWi network composed of optical fiber-based XG-PON back-end network and WiFi-based front-end network. In the FiWi network, the optical line terminal (OLT) is situated at the central location, which is further connected to a passive optical splitter using feeder fiber. A passive optical splitter is connected to the number

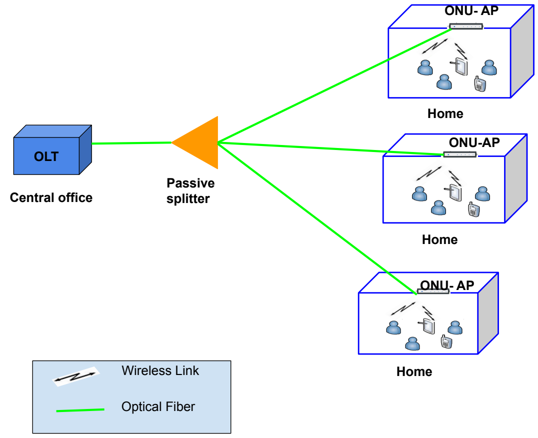

Fig. 1. Conventional FiWi architecture

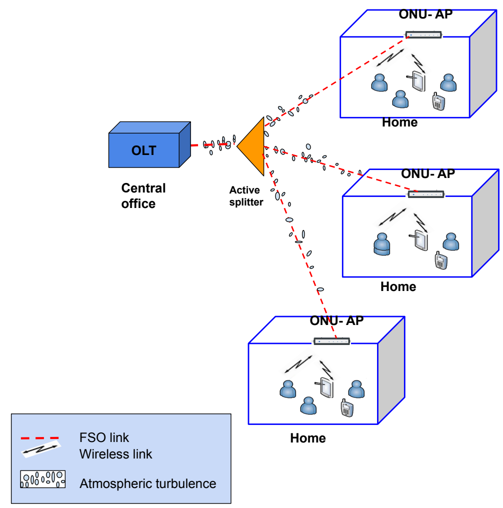

Fig. 2. Proposed hybrid FSO-wireless (FoWi) architecture

of optical network units (ONUs) through distribution fiber. These ONUs are colocated and connected with WiFi access points (APs). XG-PON utilizes time-division multiple access (TDMA) and TDM for upstream and downstream traffic flow, respectively. For indoor communication, we have considered a room in which one WiFi AP is assumed to provide seamless connectivity to uniformly distributed users. As mentioned before, in addition to conventional FiWi architecture, we consider the proposed hybrid FoWi architecture as shown in Fig. 2. In this architecture, we assume that FSO based XG-PON back-end network is connected with IEEE 802.11n based front-end wireless access network. In the proposed hybrid architecture, we assumed that optical line terminal (OLT) consists of a 1550 nm laser diode (LD) to generate an optical signal and launched to 10 GHz Mach-Zehnder modulator (MZM). The optical signal travels over the FSO link and reaches the active splitter.

From the active splitter, the signal reaches to ONUs through the optical distribution network (ODN). In ODN, we consider that FSO links are deployed from the active splitter to ONUs to reach the user's premises where ONUs are placed. At the ONUs, PIN photodiode (PD) is employed for the conversion of the optical signal into an electrical signal. Further, these ONUs are connected/colocated with Wi-Fi APs. For indoor communication, one WiFi AP is assumed to provide seamless wireless connectivity to the users present inside the room. Further, we have assumed that N mobile users are distributed uniformly in the coverage area of Wi-Fi AP.

III. CHANNEL MODELLING

In the proposed hybrid FoWi architecture, FSO links are modeled according to Gamma-Gamma distribution in the presence of atmospheric turbulence, whereas the Wi-Fi channels are modeled according to the path loss model for indoor communication that is defined in [13].

A. FSO channel model

An FSO channel can be modeled as fading channel under the influence of atmospheric turbulence where atmospheric turbulence is considered to be as random process with Gamma-Gamma distribution and its probability distribution function (pdf) is expressed as [13]

$$G_H(h) = \frac{2(\alpha_f\beta_f)^{\frac{\alpha_f+\beta_f}{2}}}{\Gamma(\alpha_f)\Gamma(\beta_f)} l^{\frac{\alpha_f+\beta_f}{2}-1} K_{\alpha_f-\beta_f}(2\sqrt{\alpha_f\beta_f l}), \quad (1)$$

where $\Gamma(.)$ and $K_x(.)$ is the Gamma function and modified Bessel function of the second kind of order x-th, respectively, l denotes optical irradiance, α_f and β_f are the scintillation parameters of FSO link f and their pdfs are given as [13]

$$\begin{aligned} \alpha_f &= \left\{\exp\left[\frac{0.49\sigma_R^2}{(1+0.56\sigma_R^{12/5})^{7/6}}\right]-1\right\}^{-1}, \\ \beta_f &= \left\{\exp\left[\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{12/5})^{5/6}}\right]-1\right\}^{-1}, \end{aligned} \quad (2)$$

where σ_R^2 is the Rytov variance in plane wave propagation, and is given by

$$\sigma_R^2 = 0.5C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6}, \quad (3)$$

where λ is the wavelength of the FSO channel, L is the length of the FSO link, and C_n^2 is the refractive index structure that characterizes the strength of atmospheric turbulence. The simulation parameters for FSO and fiber channel are presented in Table I.

TABLE I
PARAMETERS FOR FSO CHANNEL AND FIBER LINK

Parameters	Values
FSO link length, L	2 km
Feeder fiber length	2 km
Distribution fiber length	2 km
Optical wavelength, λ [12]	1550 nm
FSO transmit power, P_t^{FSO}	17.78 dBm
Receiver aperture diameter	0.1 m
Refractive index structure, C_n^2 (Weak turbulence) [11]	1×10^{-17} m$^{-2/3}$
Refractive index structure, C_n^2 (Moderate turbulence) [11]	1×10^{-15} m$^{-2/3}$
Refractive index structure, C_n^2 (High turbulence) [11]	1×10^{-13} m$^{-2/3}$
Attenuation coefficient of optical fiber [12]	0.2 dB/km
PD responsivity	0.8 AW^{-1}

B. Wi-Fi channel model

In this subsection of the paper, we describe the path loss model used for modeling the Wi-Fi channel in the indoor scenario, and it is expressed as [14]

$$PL(d) = \begin{cases} PL_{\text{FS}}(d) + \zeta_\sigma, & d \le d_{\text{BP}} \\ PL_{\text{FS}}(d) + 35\log_{10}\left(\frac{d}{d_{\text{BP}}}\right) + \zeta_\sigma, & d > d_{\text{BP}}, \end{cases} \quad (4)$$

where d corresponds to the distance between Wi-Fi AP and u^{th} user, d_{BP} denotes breakpoint distance, $\zeta_\sigma \sim \mathcal{N}(0,\sigma^2)$ represents for the Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2. The path loss in free space, PL_{FS} is given as

$$PL_{\text{FS}}(d) = 20\log_{10}(d) + 20\log_{10}(f_c) - 147.5, \quad (5)$$

where f_c denotes carrier frequency. Further, we also consider multipath propagation in wireless access channel, and is expressed as

$$G_{\text{Wi-Fi}} = \sqrt{\frac{K}{K+1}}e^{j\phi} + \sqrt{\frac{1}{K+1}}\zeta_1, \quad (6)$$

where $\zeta_1 \sim \mathcal{N}(0,1)$ denotes for the AWGN with zero mean and unit variance. Arrival/departure angle of the Line-of-Sight (LOS) signal is denoted by ϕ. We have also assumed that before the breakpoint, Rician factor K is equal to one and after the breakpoint, K is equal to zero. The channel gain between u^{th} user and AP is represented as $H^u_{\text{Wi-Fi}}$, and it is calculated as [15]

$$H^u_{\text{Wi-Fi}} = |G_{\text{Wi-Fi}}|^2\, 10^{-\frac{PL(d)}{10}}. \quad (7)$$

Therefore, SNR of a u^{th} user is given as

$$\text{SNR}^u_{\text{Wi-Fi}} = \frac{H^u_{\text{Wi-Fi}}P_{\text{t}}^{\text{Wi-Fi}}}{\mathcal{N}.\mathcal{BW}}, \quad (8)$$

where $P_{\text{t}}^{\text{Wi-Fi}}$ indicates transmit power of Wi-Fi AP, $\mathcal{N}$ denotes power spectral density (PSD) of noise in Wi-Fi channel, and $\mathcal{BW}$ represents the bandwidth of AP.

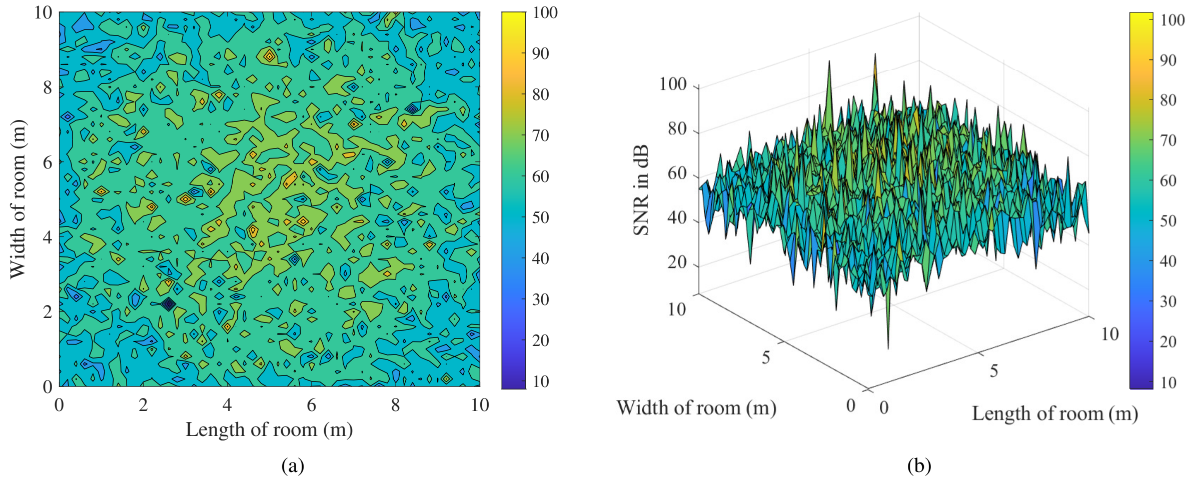

Fig. 3. SNR distribution profile in the room scenario

TABLE II
WI-FI CHANNEL PARAMETERS [15]

Parameters	Values
Room size (L x W x H)	10 m x 10 m x 3 m
User height above floor level	0.85 m
Standard deviation of fading, σ (before d_{BP})	3 dB
Standard deviation of fading, σ (after d_{BP})	5 dB
Breakpoint distance, d_{BP}	5 m
Carrier frequency, f_c	2.4 GHz
Transmit Power of Wi-Fi AP , P_t^{Wi-Fi}	20 dBm
Bandwidth of Wi-Fi AP, $\mathcal{BW}$	20 MHz
Power spectral density of noise, $\mathcal{N}$	-174 dBm/Hz

The simulation parameters for the Wi-Fi channel are stated in Table II. Data rate achieved by u^{th} user from Wi-Fi AP can be calculated as [15]

$$D_u = \tau_u \eta_u \cdot \mathcal{BW} \tag{9}$$

where τ_u corresponds to the proportion of the transmission time that Wi-Fi AP spends on u^{th} user, η_u indicates spectral efficiency achieved by u^{th} user from Wi-Fi AP. Given the SNR of the users, the modulation and coding scheme (MCS) is used to determine its spectral efficiency. The relationship between SNR, MCS, and spectral efficiency is summarized and given in Table III of [15].

IV. SIMULATION RESULTS AND DISCUSSIONS

To investigate the end-to-end performance of the proposed hybrid FoWi architecture, we have used the commercially available simulation software tool VPI Transmission Maker [16]. It is a powerful simulator to design and analyze the optical network and its components. However, it cannot analyze the optical signal propagating outside the optical fiber. Therefore, we have utilized the co-simulation capability of VPI with MATLAB for analyzing the signal in free space. It is assumed that at OLT, an optical source operating at 1550 nm wavelength is utilized to generate 10 Gbps OOK data. Further, this data is encoded by MZM and transmitted over the FSO link of 2 km length received by the active splitter. Furthermore, this optical signal reaches to the 16 ONUs through ODN, which consists of the FSO links of length 2 km, thereafter each ONU converts the optical signal into an electrical signal through PD. As already mentioned these ONUs are colocated with Wi-Fi AP. A room size of $10\text{m} \times 10\text{m} \times 3\text{m}$ is considered in the analysis. The users are distributed uniformly in the entire room.

A. Performance Comparison

Figs. 3(a) and 3(b) show the spatial distribution of SNR within the room area where Wi-Fi AP is placed at the center of the ceiling. Random fluctuations due to non-LOS components can be observed in received SNR for the entire room. Fig. 3(a) portrays the contour plot of the received SNR versus the length and width of the room. As shown, the yellow area in the center of the room represents high SNR values, while the blue area at the corners of the room depicts low SNR values, and the green area shows areas where SNR values lie between 55 dB to 65 dB. From Fig. 3(b), it can be seen that SNR drops to less than 20 dB at the room corners and above 70 dB directly underneath of Wi-Fi AP. The average SNR across the room is around 60 dB. Fig. 4 depicts the average data rate of users with respect to the rise in the number of users (N). As shown, the average data rate in downlink decreases with respect to the increase in the number of users. It is evident that the proposed hybrid FoWi architecture performs the same as conventional FiWi architecture under the impact of weak turbulence. However, it can be observed that as the strength of atmospheric turbulence increases from weak to strong, the system throughput of the proposed hybrid FoWi architecture degrades. Thus, the performance of hybrid FoWi

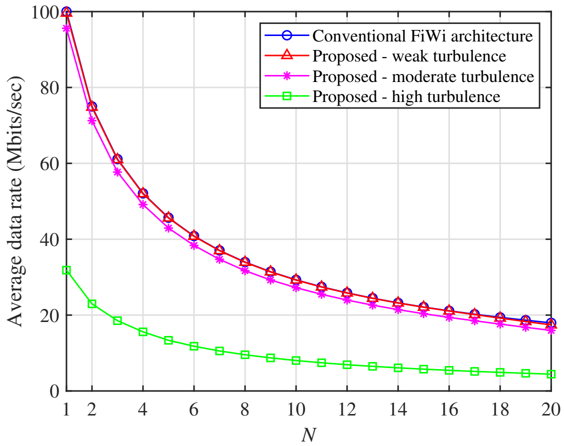

Fig. 4. Average data rate versus the number of users

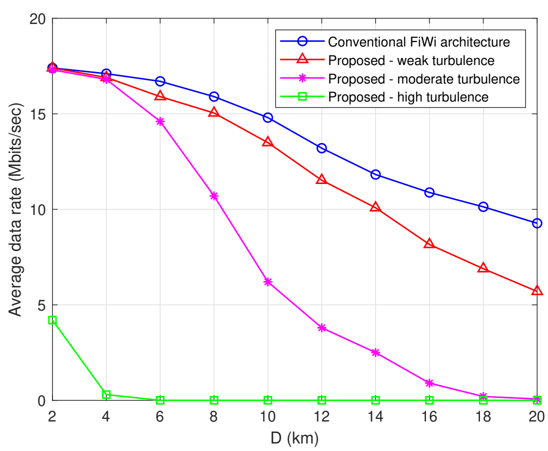

Fig. 5. Average data rate versus distance between OLT and splitter (km)

architecture deteriorates with an increase in the strength of atmospheric turbulence. This problem can be alleviated by choosing an appropriate optical amplifier to nullify the effect of atmospheric turbulence.

Fig. 5 compares the performance of the proposed hybrid FoWi architecture with the conventional FiWi architecture in terms of average data rate. Fig. 5 shows the average data rate achieved by the users as the function of the distance between OLT and splitter, D under the impact of weak, moderate, strong turbulence. As the distance between OLT and splitter increases, the average data rate decreases for both conventional FiWi and proposed hybrid FoWi architecture. It is clearly observed that when the distance between OLT and active splitter is less than 4 km, both FiWi and the proposed FoWi architecture perform the same with the average data rate of 17 Mbps under the impact of weak and moderate atmospheric turbulence. However, the impact of strong atmospheric turbulence is very high on the average data rate for less than 4 km. Furthermore, for greater than 4 km, conventional FiWi architecture performs better than the

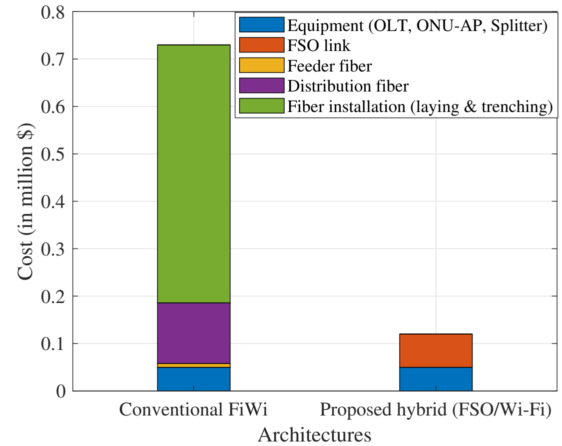

Fig. 6. Deployment cost comparison between conventional FiWi and the proposed hybrid FoWi architecture

proposed hybrid architecture. Therefore, the proposed hybrid FoWi architecture seems to be a reasonable alternative for short range communication in weak and moderate atmospheric turbulence when laying and trenching of fiber is difficult and expensive. Fig. 6 compares the total deployment cost

TABLE III
COST VALUES OF NETWORK COMPONENTS [12], [17]

Network Component	Unit cost ($)
OLT	24539
Splitter (1:16)	750
ONU	350
Fiber (/km)	4000
Fiber laying and trenching (/km)	16000
FSO link	4103

of conventional FiWi architecture with the proposed hybrid FoWi architecture when split ratio is 1:16. For the CAPEX analysis, we have used Table III which lists the cost values of network components. The total CAPEX of the conventional FiWi architectures is given as [18]:

$$C_{FiWi} = C_{\text{OLT}} + C_{\text{splitter}} + L_{ff}C_{ff} + \sum_{k\epsilon N} L_{df}^{k} C_{df} + NC_{\text{ONU-AP}}, \quad (10)$$

where, C_{OLT} is the total cost of OLT, C_{splitter} is the total cost of splitter, L_{ff} is feeder fiber length, C_{ff} is the cost of feeder fiber, L_{df} is distribution fiber length, C_{df} is the cost of distribution fiber, N is the number of ONU-APs, and C_{ONU-AP} is the cost of ONU-AP. While for proposed hybrid FoWi architecture, (10) can be modified to calculate total CAPEX as

$$C_{FoWi} = C_{\text{OLT}} + C_{\text{splitter}} + C_{FSO1} + C_{FSO2} + NC_{\text{ONU-AP}}, \quad (11)$$

where C_{FSO1}, C_{FSO2} indicates the cost of FSO link between OLT and active splitter and active splitter and ONU-

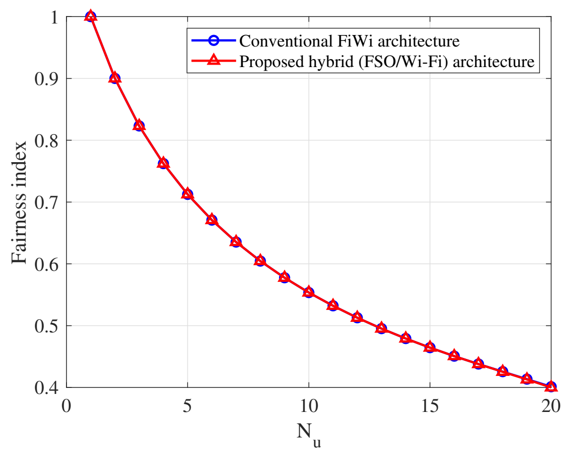

Fig. 7. Fairness index vs the number of users

AP, respectively. For the CAPEX analysis, we have assumed $N = 16$ as a split ratio for both FiWi and proposed hybrid FoWi architecture. It is clearly observed that the primary contribution in the total deployment cost of conventional FiWi architecture is attributed to the cost of fiber as well as digging and trenching of fiber. Therefore, it is worthwhile to note that by deploying the proposed hybrid FoWi architecture, we can save nearly 83% of CAPEX as compared to the conventional FiWi network.

Fig. 7 illustrates the performance of hybrid FoWi architecture in terms of fairness. For the fairness analysis, we adopted Jain's fairness index for measuring fairness among the users and given as [19]

$$J = \frac{\left(\sum_{u=1}^{N_u} D_u\right)^2}{N_u \sum_{u=1}^{N_u} D_u^2}. \tag{12}$$

where D_u denotes the individual data rate achieved by the u^{th} user, N_u indicates the number of users. It may be noted that using the proposed hybrid architecture, we can achieve the same fairness among users as achieved in the conventional FiWi architecture. This is due to the fact that the wireless front-end for both network is the same, and therefore, no significant change in the network's fairness is observed.

V. Conclusions

In this paper, the performance of the proposed hybrid FSO-wireless (FoWi) architecture is analyzed. The proposed architecture is shown to be a reasonable alternative to conventional FiWi architecture for short range communication as well as for the places where installation of optical fiber is not feasible. Further, the performance of the proposed hybrid architecture under the effect of weak, moderate, and high atmospheric turbulence is evaluated. The results demonstrate that the proposed hybrid FoWi architecture is a cost-effective solution when compared with the conventional FiWi architecture. In future, we plan to extend our work to integrate FSO based back-end with other high-end wireless access technologies such as visible light communication (VLC) or 5G millimeter wave communication in AON architecture to compensate for the effect of atmospheric turbulence.

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