QoS-Aware Reliable Architecture for Broadband Fiber-Wireless Access Networks

Priyanka Singh, Akshita Gupta, Vivek Ashok Bohara, and Anand Srivastava

In the era of continuous traffic demands, failure of fiber-wireless (FiWi) access network components, such as optical network unit (ONU), access point (AP), or fiber links, compromises the user connectivity and leads to enormous traffic loss. In this work, we propose a novel strategy for FiWi network planning to ensure reliability and survivability of the network. Moreover, our proposed FiWi planning strategy satisfies the required quality of service (QoS) to the users even in the case of failures. It has been shown that by deploying the proposed network framework, user services like received signal strength, throughput, delay, etc., are not significantly affected even when there is a failure. The position of backup ONU-AP is optimized in the FiWi network using a stochastic optimization algorithm. Furthermore, we compare different scenarios wherein backup ONU-AP is equipped with varying antenna configurations, such as omnidirectional antenna, sector antenna, and point-to-point (P2P) link to provide the required services to the users. Simulation results show that the P2P solution offers better services compared to sector or omnidirectional antenna configurations. Moreover, results demonstrate that the proposed survivable FiWi network can be successfully deployed without compromising the QoS requirement of the users. In addition, the paper also provide reliability of the proposed survivable FiWi network.

***Index Terms*—Backup ONU-AP, Fiber-Wireless (FiWi) system, IEEE 802.11ac, Omnidirectional antenna, P2P link, Quality of service, Reliability, Sector antenna, Stochastic optimization, Survivability, XG-PON.**

I. INTRODUCTION

THE explosive growth in the demand for bandwidth-intensive applications has accelerated the integration of fiber and wireless networks to provide massive amount of bandwidth, great flexibility, and ubiquitous access to the users [1]. Fiber network ensures enormous bandwidth to the network. In contrast, the wireless access network provides flexible connectivity to the users. Prior research activities on the above area concentrated on seamless integration of fiber network such as Ethernet passive optical network (EPON), Gigabit passive optical network (GPON), 10-Gigabit-passive optical network (XG-PON) with various standards of networks such as wireless local area network (WLAN), worldwide interoperability for microwave access (WiMAX), and 4G long-term evolution (LTE) network [2], [3]. XG-PON is a potential candidate to integrate with WLAN-based wireless access network because it provides a high data rate of 10 Gbps in the downstream and 2.5 Gbps in the upstream [4].

In XG-PON, the optical line terminal (OLT) is positioned at the central office (CO), providing the required bandwidth to the network. The splitter connected to the OLT splits the bandwidth among the optical network units (ONUs). The OLT is connected to the splitter through a feeder fiber, and the splitter is connected to the ONUs through distribution fibers. Each ONU is generally collocated with an access point (AP) that provides the required service to the users. In the wireless fronthaul network, AP can enable multiple WiFi standards such as IEEE 802.11n/ac/ax. Thus, in the fiber-wireless (FiWi) network, the ONUs are connected to the wireless APs, which serves the users via wireless links.

Due to the high number of ONUs installed and huge amount of traffic carried in the FiWi network, any failures lead to significant traffic loss. Therefore, network survivability is one of the critical issues in planning the FiWi network and needs to be addressed more efficiently.

The authors are with Wirocomm Research Group, Department of Electronics & Communication Engineering, Indraprastha Institute of Information Technology Delhi (IIITD), New Delhi, 110020, India (e-mail: {priyankas, akshitag, vivek.b, anand}@iiitd.ac.in).

A. Related Works

Survivability is a vital issue observed in planning and deployment of the FiWi network. Any failure in the FiWi network directly affects the quality of service (QoS) requirements of the users. Therefore, survivability is an essential issue for network planning from the perspective of both the service providers as well as the users. In [5-6], the authors employed the existing ONUs as a backup and deployed a redundant fiber link to provide a survivable network.

In [1], the authors presented an integer linear programming (ILP) model to provide maximum user coverage by optimizing the location of the ONUs, splitter, and wireless routers in the network. The method proposed in [1] ensures survivability, connectivity, delay, and capacity constraints to provide maximum user coverage. The interrupted traffic from the affected ONU is routed to backup ONU through wireless routing. Authors in [5] presented survivable time and wavelength division multiplexed (TWDM) PON architectures by combining the detection and the protection switching against failures. The paper presented three survivable architecture with different degrees of protection: a) protection against feeder fiber failure, b) protection against both feeder fiber and OLT failure, and c) protection from the full network failure.

In [6], the authors analysed the performance of two level cloud and mobile-edge computing (MEC) enabled integrated FiWi network. In addition, the authors proposed an algorithm for unified resource management scheme to effectively manage cloud, MEC and human-to-human traffic such as, conventional data, voice, and video traffic for the multi-hop scenario. The authors in [7] developed ILP model and a bucket effect-based heuristic algorithm for backup resource allocation to protect

MEC services in FiWi network. In [8], the authors proposed a lossless fault-tolerance mechanism combining the parallel routing and network coding against any failures. In [9], the authors formulated a survivable virtual network embedding (SVNE) problem in the FiWi network as an ILP problem to minimize the resource cost while allocating resources for Internet of things (IoT) virtual nodes. The authors in [10] presented detailed comparison of various optimization algorithms such as teaching–learning-based optimization (TLBO), whale optimization algorithm, and genetic algorithm (GA) for deploying energy efficient and survivable FiWi network. In the context of survivability and reliability, the failure of the network components is a significant cause of connection loss in the network. Consequently, one of the vision of the 5G network, is to achieve a network reliability close to 100% [11]. In order to make the FiWi network 100% reliable, the network component failure in the network must be reduced. International Telecommunication Union-Telecommunication (ITU-T) G.983.1 [12] has already standardized some protection schemes against fiber and component failures such as type A, B, C, and D. In type A protection scheme, feeder fiber protection is employed, complete OLT and feeder fiber protection is employed in type B, and complete duplication of the PON is done in type C. In contrast, in type D, duplication of feeder fiber and individual distribution fiber is employed [6]. The different kinds of network failure are discussed below:

1) Fiber failure

Fiber cut is one of the major causes for the failure of the optical network. There can be two kinds of fiber failures in the FiWi network: feeder fiber failure (between OLT and splitter) and distribution fiber failure (splitter and ONU-AP). In the case of feeder fiber failure, the connectivity of the complete network will be lost. Therefore, in such cases, a strong backup support is needed for the network. Conventionally this has been addressed by placing a backup fiber cable between the OLT and the splitter [6]. Duplication of fibers can enhance the reliability of the FiWi network. However, at the same time, it will also increase the overall installation cost of the network.

2) Component failure

The various network components such as ONU and AP failure in the network can also adversely affect the network's connectivity. In the FiWi network, failure of ONUs and APs can happen due to their malfunctioning. As a consequence, the interrupted traffic needs to be rerouted to working ONU and AP so that the FiWi network's survivability is ensured.

It is evident from above, most of prior work related to survivability of the FiWi network and tolerance against failures was achieved either by deploying backup fiber or by selecting backup ONU from the set of existing ONUs in the network. Deploying redundant backup fibers increases the cost in the network planning, and choosing backup ONU from the set of active ONUs has a limited residual capacity to carry the interrupted traffic of the disconnected users. Therefore, the previous work achieved limited success in improving the survivability of the FiWi network.

In this work, we intend to alleviate the above drawbacks by addressing the survivability against three types of failure scenarios: distribution fiber cut, ONU failure, and AP failure.

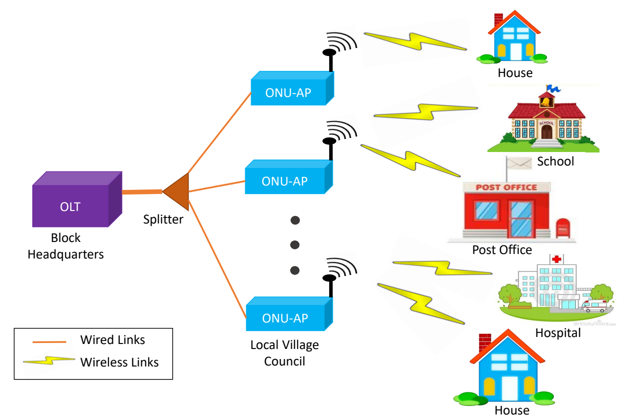


Fig. 1. FiWi system architecture

In line with previous literature, it is assumed that ONUs and APs are collocated and collectively called ONU-AP [13]. The failure scenarios considered above have conventionally led to an immense traffic loss and affect the QoS of the users. In order to alleviate the loss due to failures, the paper proposes the use of additional FiWi element, i.e., backup ONU-AP. Backup ONU-AP is placed within a cluster of active ONU-APs to provide the required services and reliability to the disconnected users in case of failures. Moreover, it may be noted that proposed placement of backup ONU-AP may not be compared to the conventional literature on the placement of the BS in the cellular network.[1]

Specifically, in the case of distribution fiber cut, ONU and AP failure, interrupted traffic is re-routed to OLT through backup ONU-AP via wireless path. Furthermore, the performance of the wireless access network also depends upon the position of backup ONU-AP. Hence, it is essential to find the optimal position of backup ONU-AP within the cluster of active ONU-APs. Therefore, a stochastic optimization algorithm is proposed to determine the optimal position for backup ONU-AP by minimizing the average distance between all the users and backup ONU-AP. The distinct behavior of backup ONU-AP is also analysed with different antenna configurations such as omnidirectional, sector antenna and parabolic grid antenna for establishing point-to-point (P2P) link between backup ONU-AP and active ONU-APs.

B. Contributions

Motivated by the prior research work related to survivable and reliable FiWi network where the researchers address the survivability issue for FiWi network either by deploying redundant fibers or components. In this paper, our approach is to exploit wireless path routing for the interrupted traffic to

[1] In case of BS placement, the main focus was on increasing BS capacity, increasing downlink coverage performance, and minimizing BS installation cost. However, in this work, our approach is very different from conventional BS placement approach, the placement of backup ONU-AP is restricted within the cluster of three ONU-APs. The positions of users are assumed to be within the cell radius of ONU-AP. Therefore, the position of the users is not the key factor determining the position of backup ONU-AP unlike BS placement [14], [15].

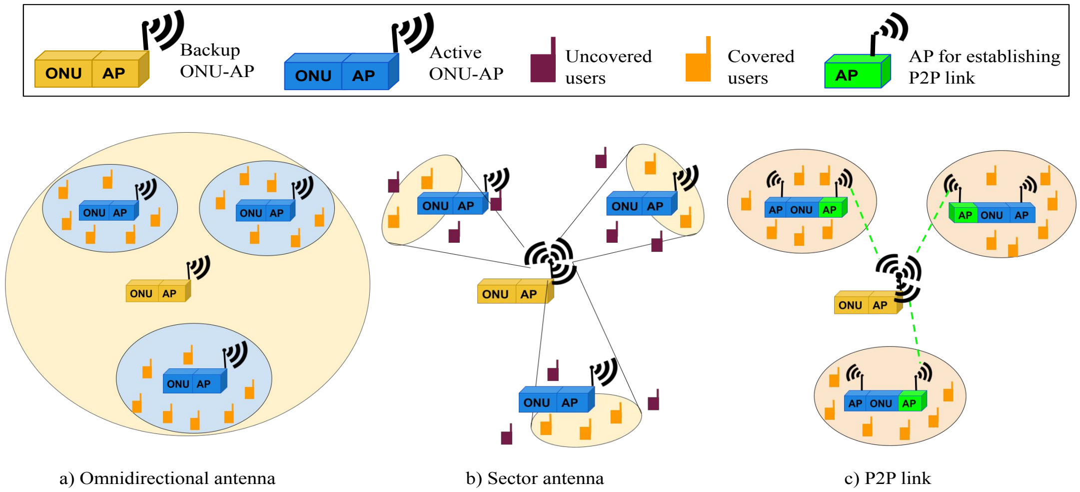


Fig. 2. Clustered architecture of active ONU-APs, where backup ONU-AP is equipped with a) Omnidirectional antenna, b) Sector antenna, and c) Parabolic grid antenna for P2P link.

OLT via backup ONU-AP without deploying redundant fibers. Furthermore, the access network's performance also depends upon the position of backup ONU-AP. However, in the prior research works, the optimal position of backup ONU-AP has not been investigated. In this work, we optimize the position of backup ONU-AP using stochastic optimization algorithm. Moreover, the performance of the proposed FiWi network has been analysed by incorporating backup ONU-AP with three different antenna configurations, namely omnidirectional antenna, sector antenna, and parabolic grid antenna for establishing P2P link between backup ONU-AP and active ONU-AP. Furthermore, we provide detailed QoS and reliability analysis of our proposed survivable FiWi network which demonstrates that our proposed framework satisfies the QoS requirement of the users in case of failures. Moreover, as a benchmark for comparison, we have also compared failure scenario of the proposed survivable backup ONU-AP placement architecture with no-failure scenario in terms of QoS parameters.

The major contributions of this paper are summarized as:

1) We ensure survivability and reliability of the FiWi network by optimizing the position of backup ONU-AP using a stochastic optimization algorithm. Specifically, in case of distribution fiber cut, ONU and AP failure, interrupted traffic is re-routed to OLT through backup ONU-AP via wireless path.
2) We compare the proposed survivable FiWi network's performance in terms of QoS parameters such as received signal strength indicator (RSSI), average throughput, packet loss rate (PLR), end-to-end delay, when backup ONU-AP is equipped with omnidirectional antenna or sector antenna or parabolic grid antennas for P2P link configurations.
3) Furthermore, we analyse the reliability of the proposed survivable FiWi network and evaluate using probabilistic modelling. We evaluate reliability of proposed FiWi network by estimating probability of user connectivity to the backbone network even in the case of distribution fiber cut and failures of components.

In addition to above, the proposed solution is cost effective as it doesn't require duplication of fibers. Further, for the fiber failure, we will focus on the distribution fiber failures scenario, as it is assumed that protection fiber is available for the feeder fiber [16].

The remaining paper is organized as follows: Section II describes the system model of the FiWi architecture. In Section III, the problem formulation is presented. Section IV discusses the proposed methodology and the proposed algorithm for placement of backup ONU-AP. Section V presents a detailed comparative analysis of the performance evaluation for three different antenna configurations: omnidirectional antenna, sector antenna, and parabolic grid antenna for P2P link configuration. In Section VI, the performance of the proposed methodology is evaluated via simulation results. Finally, Section VII concludes the paper.

Notations: $\mathbb{E}$ is used to denote the expectation of the random variable. R^+ represents set of positive real numbers. 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 illustrates the FiWi system architecture in which XG-PON is integrated with IEEE 802.11ac based wireless access network. Conventionally, in XG-PON, OLT is located at central office and serves N number of ONU-APs which are connected to OLT through a 1:N optical splitter. Here, N can be 2, 4, 8, 16, 32, etc. We have assumed the proposed survivable FiWi architecture consists of splitter of 1:16 split ratio [3]. Further, 16 ONU-APs are divided into four clusters of four ONU-APs. In each cluster, three ONU-APs act as active ONU-APs and one ONU-AP will acts as backup ONU-AP which provides connectivity to the users of other three active ONU-APs in the case of a failure. The users distributed according to the Poisson point process with a density of λ users/km^2 in the coverage region of active ONU-APs. We assume the coverage region of active ONU-AP as the circular cell[2] of radius of 1000 m [1]. Whenever failure occurs, backup ONU-AP provides the required services to the users through wireless path. Since we have assumed XG-PON based back-end network, there in no bandwidth limitation from the network up to ONU-level and each backup ONU-AP has sufficient bandwidth to guarantee the QoS to users in case of failures. As shown in Fig. 2, each backup ONU-AP can be equipped with omnidirectional antenna or sector antenna or parabolic grid antenna for establishing a wireless path between backup ONU-AP and active ONU-APs. In Fig. 2(a), backup ONU-AP is equipped with omnidirectional antenna to provide services to the users through point to multipoint (P2MP) wireless links. Similarly, in Fig. 2(b), backup ONU-AP is equipped with three sector antennas in which the main lobe of radiation pattern of each sector antenna is directed towards the users of active ONU-AP to provide services via P2MP links. In Fig. 2(b), the coverage region of the each sector antenna is assumed to be an elliptical in shape. The P2P link is established between backup ONU-AP and active ONU-APs using parabolic grid antennas at both the ends. Further, the users in the failed ONU gets connectivity via AP as shown in Fig. 2(c). Due to the different clustered architectures, backup ONU-AP position also needs to be optimized according to the user's location, the position of active ONU-APs, and the number of users connected to active ONU-APs. In this work, the position of backup ONU-AP is optimized by minimizing the average distance between backup ONU-AP and the users.

III. Problem Formulation

In case of failures, disconnected users must remain connected to the backhaul network via backup ONU-AP to prevent significant traffic loss. The performance of the proposed survivable FiWi network is critically determined by the placement of backup ONU-AP. Hence, it is essential to optimize the position of backup ONU-AP in such a way so that it will provide coverage to the users of active ONU-APs in case of failure. The proposed placement algorithm optimizes the position of backup ONU-AP such that the average distance between backup ONU-AP and the users in the cluster is minimized using stochastic gradient method. Specifically, the stochastic optimization problem is formulated as minimization of the average distance between backup ONU-AP and the users in the cluster by optimizing the position of backup ONU-AP and radius of backup ONU-AP in (1)

$$(P1): \min_{R_{BONU}, P_{BONU}} \quad \mathbb{E}_{P_u}[D_{BONU,u}], \tag{1}$$

$$\text{s.t.} \quad R_{BONU} \in R^+, \tag{2}$$

$$P_{BONU} \in \mathcal{A}, \tag{3}$$

where, $\mathcal{A}$ is the area of the cluster of active ONU-APs, the position of backup ONU-AP is P_{BONU}, radius of the circular cell of backup ONU-AP is R_{BONU}, the positions of the users is P_u, and $D_{BONU,u}$ is average distance between backup ONU-AP and u^{th} user. In practice, due to the mobility of the users, P_u varies from time to time within radius of the circular cell of active ONU-APs. Therefore, we are interested in the long-term average of the distance between backup ONU-AP and all the users $\mathbb{E}_{P_u}[D_{BONU,u}]$, which depends on the positions, P_{BONU} and radius of backup ONU-AP, R_{BONU}.

[2]Specifically, circular cell means that radiation pattern of circularly polarized omnidirectional antenna is circular in shape and provides 360^o full coverage [17]

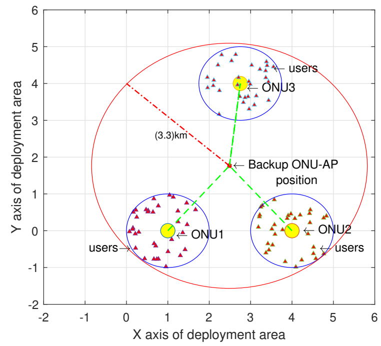


Fig. 3. Optimal position for backup ONU-AP in case of uniform distribution of users

IV. Proposed Methodology

To solve the Problem ($P1$), one way is to calculate $\mathbb{E}_{P_u}[D_{BONU,u}]$ and turn it into a deterministic optimization problem. However, there is one more efficient way to solve this problem using a stochastic optimization techniques [18].

This stochastic optimization problem can be solved through the stochastic gradient method, in which decision variables iteratively update along a stochastic gradient. It is a more efficient and less complex approach to solve this type of stochastic optimization problem [19], [20]. Using stochastic gradient method, we aim to give backup ONU-AP optimized position as shown in Algorithm 1.

Let the total number of users in the network be U. The set of the users u= $\{1, 2, ..., U\}$, $P_u = (X_u, Y_u)$ denotes the position of the u^{th} user, where, X_u and Y_u are the X and Y coordinates of the position of u^{th} user. $P_{BONU} = (X_{BONU}, Y_{BONU})$ denotes the position of backup ONU-AP, where, X_{BONU} and Y_{BONU} are the X and Y coordinates of backup ONU-AP. In order to find optimal position of backup ONU-AP that solves problem P1, position and radius of backup ONU-AP needs to be updated iteratively as

$$[P^{(n+1)}_{\mathrm{BONU}}, R^{(n+1)}_{BONU}] = ([P^n_{\mathrm{BONU}}, R^n_{BONU}] - \mu^n \Delta^n_{U_o}) \tag{4}$$

where n = 0, 1,... is iteration index, $\mu^n > 0$ is step size, P^n_{BONU} and R^n_{BONU} is initial position and radius of backup ONU-AP, respectively. For updating the position of backup ONU-AP, we need to calculate stochastic gradient of the numbers of users outside the radius of backup ONU-AP, U_o with respect to position P_{BONU} and radius R_{BONU} of backup ONU-AP respectively. The derivation of calculating stochastic gradient of U_o with respect to P_{BONU} and R_{BONU} is given

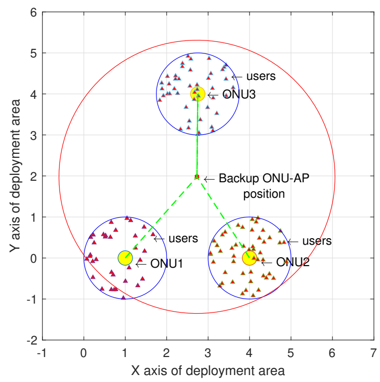


Fig. 4. Optimal position for backup ONU-AP in case of non-uniform distribution of users

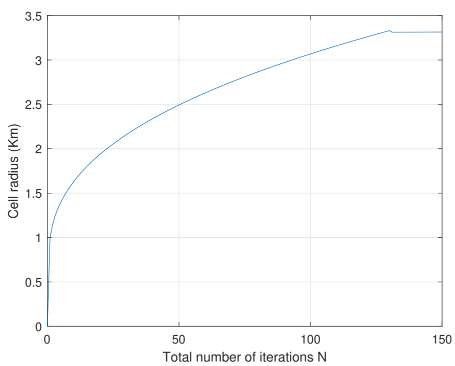


Fig. 5. Cell radius of backup ONU-AP versus number of iterations, N

in Appendix. However, we use sigmoid function to make U_o differentiable [21]. U_o can be calculated as

$$U_o = \sum_{u=1}^{U} S(D_{\mathrm{BONU,u}} - R_{B_{ONU}}), \tag{5}$$

where, $S(.)$ is the sigmoid function defined as

$$S(D_{\mathrm{BONU,u}} - R_{B_{ONU}}) = \frac{1}{1 + e^{-\beta(D_{\mathrm{BONU,u}} - R_{B_{ONU}})}}, \tag{6}$$

where, $\beta > 0$ is the steepness factor that controls the accuracy of sigmoid function. The average distance between backup ONU-AP and u^{th} user ($D_{B_{ONU},u}$) is given by

$$D_{B_{ONU},u} = ||P_{B_{ONU}} - P_u||. \tag{7}$$

Now, to enhance the convergence rate of the proposed algorithm, we need to set the learning rate μ^n of the algorithm [19], [20]. The learning rate is normalized by the norm of stochastic gradient for the number of users outside the radius of backup ONU-AP,

$$\mu^n = \frac{L}{||\Delta^n_{Uo}||}, \tag{8}$$

where, $L = \frac{a}{n^b}$ and we set positive constants, $a = 0.15$ and $b = 0.6$ for our simulations. To analyse the performance of the proposed placement algorithm, we first consider the uniform distribution of users wherein equal number of users

Algorithm 1 Proposed algorithm for finding optimal position for backup ONU-AP

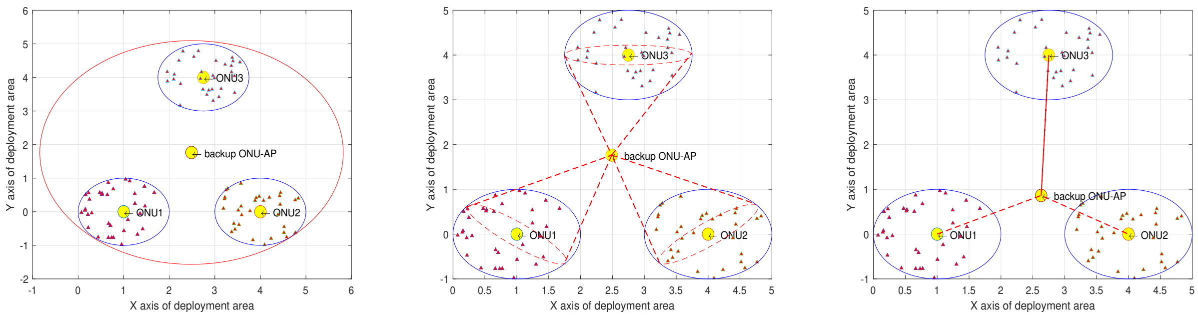
Input:
Given set of users in circular cell of active ONU-APs in a cluster, initial location of backup ONU-AP is the centroid of the three active ONU-APs and radius of circular cell of backup ONU-AP is 1000 m [1]

for n=1, ..., maximum iteration N **do**
  $\Delta^n_{Uo} = (\sum_{u=1}^{U} S'(D_{\mathrm{BONU,u}} - R_{\mathrm{BONU}})\frac{\partial D_{\mathrm{BONU,u}}}{\partial P_{\mathrm{BONU}}}, -\sum_{u=1}^{U} S'(D_{\mathrm{BONU,u}} - R_{\mathrm{BONU}}))$
  Calculate learning rate, μ^n using (8)
  Update the position and radius of backup ONU-AP

$$P^{(n+1)}_{\mathrm{BONU}}, R^{(n+1)}_{B_{ONU}} = (P^n_{\mathrm{BONU}}, R^n_{B_{ONU}} - \mu^n \times \Delta^n_{Uo})$$

  if $D_{B_{ONU},u} \leq R^{n+1}_{B_{ONU}}$ **then**
    $P^{final}_{\mathrm{BONU}} = P^{(n+1)}_{\mathrm{BONU}}$
  end if
end for
return $P^{final}_{\mathrm{BONU}}$

are distributed inside active ONU-APs. In Fig. 3, using proposed algorithm, position of backup ONU-AP is optimized such that average distance between backup ONU-AP and users is minimized. Moreover, it can be observed from Fig. 3 that circular cell of backup ONU-AP touches the circumference of the circular cell of active ONU-APs, when the considered backup ONU-AP is equipped with omnidirectional antenna with antenna height of 30 m. On the contrary, Fig. 4 shows the optimal placement of backup ONU-AP for the case where users are non-uniformly distributed in the cluster, which primarily signifies that the number of users inside each active ONU-AP are not equal. It can be observed that the number of users inside active ONU-AP3 is more than that of active ONU-AP1 and ONU-AP2. Therefore, in such a case, our proposed placement algorithm provides the location for backup ONU-AP which is nearer to the position of active ONU-AP with has higher user density. It may be noted that even with variations in the number of users in the proposed algorithm, there is only a slight difference in backup ONU-AP's positions. Fig. 5 illustrates convergence performance of the proposed algorithm. It can be observed that the cell radius of backup ONU-AP increases with the increase in the number of iterations until the proposed placement algorithm reaches convergence at N $\geq$ 140. It is worthwhile to mention that in stochastic optimization algorithm, at each iteration the cost function is updated recursively by moving a distance step size in the direction opposite to the gradient [22]. The size of the step we take on each iteration to reach the local minimum is determined by the learning rate. For the proposed algorithm, we have used a variable step size, $\mu^n = \frac{a}{n^b||\Delta^n_{Uo}||}$. Hence, the overall time complexity of the proposed algorithm is $O(1/n)$, where n is number of iterations.



(a)   (b)   (c)

Fig. 6. Placement of backup ONU-AP for different antenna configurations a) Omnidirectional Antenna, b) Sector Antenna, and c) P2P link.

V. Performance Analysis

There can be different kinds of antenna configurations used at backup ONU-AP. This paper considers three typical antenna configurations: omnidirectional antenna, sector antenna, and parabolic grid antenna (P2P link). It can be observed in Fig. 6 that backup ONU-AP position can be optimized depending on the above antenna configurations. For instance, in Fig. 6(a), position of backup ONU-AP is optimized when it is equipped with omnidirectional antenna to provide services to the disconnected users via point to multipoint (P2MP) links in the case of failures. Similarly, Fig. 6(b) shows that optimal position of backup ONU-AP in which backup ONU-AP is equipped with sector antenna. Users get connectivity from backup ONU-AP via P2MP wireless links in case of failures. Fig. 6(c) presents the optimal position for backup ONU-AP, when it is equipped with P2P link. For P2P link, the position is optimized with respect to positions of three active ONU-APs as it is assumed that the users are not directly connected to backup ONU-AP; they get connectivity from active ONU-APs via P2MP wireless links. In case of P2P link, the co-channel interference is alleviated as only one P2P link from backup ONU-AP is activated which is directed towards disconnected users in case of failures unlike the case of omnidirectional antenna. The antenna configurations are discussed in detail in the following subsections.

A. *Omnidirectional Antenna*

In this case we consider that backup ONU-AP is equipped with omnidirectional antenna. In any case of failures such as distribution fiber cut, ONU and AP failure, disconnected users will remain connected to the backbone network through backup ONU-AP via P2MP links. To evaluate the coverage obtained through an omnidirectional antenna, we use the simplified two ray ground reflection model [23] as it is predominately used model while considering both direct and reflect wave for predicting signal at the receiver end. By utilizing the above model, we can analytically find the radius of circular cell of backup ONU-AP in terms of critical distance,

$$d_c = \frac{4h_t h_r}{\lambda} \tag{9}$$

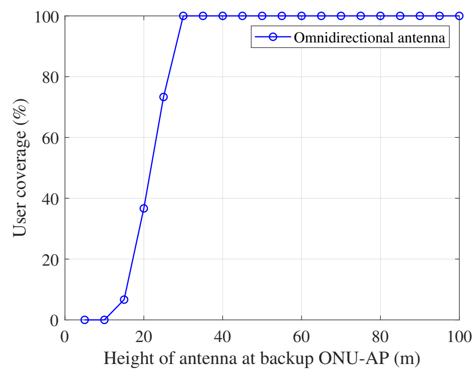


Fig. 7. User coverage (%) with respect to height of antenna at backup ONU-AP equipped with omnidirectional antenna

where, h_r is the height of antenna at user equipment, h_t is the height of omnidirectional antenna at backup ONU-AP, and λ is the wavelength. For analysis, we have considered $h_r = 1.5$ m, $\lambda^3 = 0.0547$ m and h_t varies from 0 m to 100 m.

In survivable FiWi network, it is essential to achieve maximum user coverage even in the case of failures. In this context, user coverage is defined as the number of users present inside the cell radius of backup ONU-AP or active ONU-AP. Fig. 7 shows the user coverage with respect to the height of the omnidirectional antenna at backup ONU-AP. It can be observed that there is steep increase in user coverage with the increase in antenna height. Further, it can be observed that no user is covered with 10 m of antenna height. However, user coverage gradually increases with an increase in antenna height. Further, for antenna height ≥ 30 m, 100% user coverage is achieved.

According to (9), if the antenna height is 15 m, we can achieve a critical distance of 1.6 km for a circular cell's radius. In addition, if we further increase the antenna's height to 30 m, this critical distance increases up to 3.29 km. Therefore, it is noted that by increasing antenna height, we can improve the critical distance that finally improves the user coverage.

[3]corresponding to IEEE 802.11ac frequency of 5.48 GHz [24]

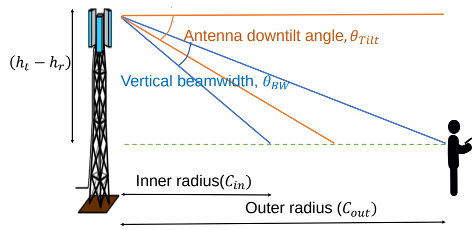


Fig. 8. Illustration inner and outer radius of ellipsoid region of backup ONU-AP, when it is equipped with sector antennas

B. Sector Antenna

In the case of sector antenna, backup ONU-AP is equipped with the one sector antenna for each active ONU-AP. Sector based APs have focused radiation patterns in a particular direction in the form of the beam with specific azimuth and elevation half-power beam-width [25]. For the coverage analysis, we assume that the radiation pattern of each sector antenna at backup ONU-AP consists of the main lobe with horizontal and vertical beamwidth of 120^o and $\theta_{BW} = 6.5^o$, respectively. According to [26], the tilt angle, θ_{tilt} can be calculated as $\theta_{tilt} = \tan^{-1}\left(\frac{\mathrm{h_t - h_r}}{D}\right)$, where, D is distance between backup ONU-AP and the farthest user of active ONU-AP.

Fig. 8 depicts the inner radius (C_{in}) and outer radius (C_{out}) of the ellipsoid region of backup ONU-AP equipped with sector antenna as shown in Fig. 6(b). The C_{in} and C_{out} can be written as

$$C_{in} = \frac{h_t - h_r}{\tan(\theta_{tilt} + 0.5.\theta_{BW})}, \tag{10}$$

$$C_{out} = \frac{h_t - h_r}{\tan(\theta_{tilt} - 0.5.\theta_{BW})}. \tag{11}$$

For each sector, antenna radiates only in one direction therefore, the path loss for one sector can be calculated as

$$P_r^{sec} = P_d^{sec} \times A_{eff}, \tag{12}$$

where, P_r^{sec} is the received power, P_d^{sec} is transmitted power density for a particular sector and A_{eff} is effective area of antenna. Using [27], (12) can be rewritten as

$$P_r^{sec} = \frac{P_t G_t}{\int_0^{\frac{2\pi}{3}} \int_0^{\pi} d^2 \sin\theta d\theta d\phi} \times \frac{G_r \lambda^2}{4\pi}, \tag{13}$$

where, d is the distance between backup ONU-AP and the users of active ONU-AP, P_t is transmit power from backup ONU-AP, G_t, and G_r are gains of antenna at backup ONU-AP and users, respectively. (13) can be rewritten as

$$P_r^{sec} = \frac{P_t G_t}{(4/3)\pi d^2} \times \frac{G_r \lambda^2}{4\pi}. \tag{14}$$

Using (14), the path loss, PL_{sec} for the sector antenna can be expressed as

$$PL_{sec} = 10\eta \log\left(\frac{4\pi d}{\lambda}\right) - 10\log(3), \tag{15}$$

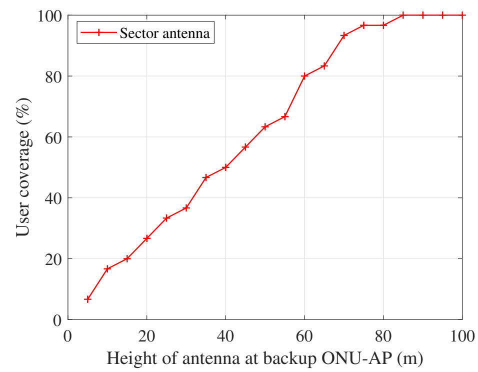


Fig. 9. User coverage (%) with respect to height of antenna at backup ONU-AP (in case of sector antenna)

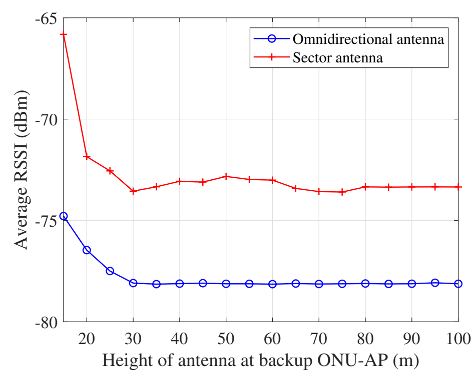


Fig. 10. Average RSSI (dBm) with respect to height of antenna at backup ONU-AP (m).

where, $\eta = 2$ denotes the path loss exponent as given in [24].

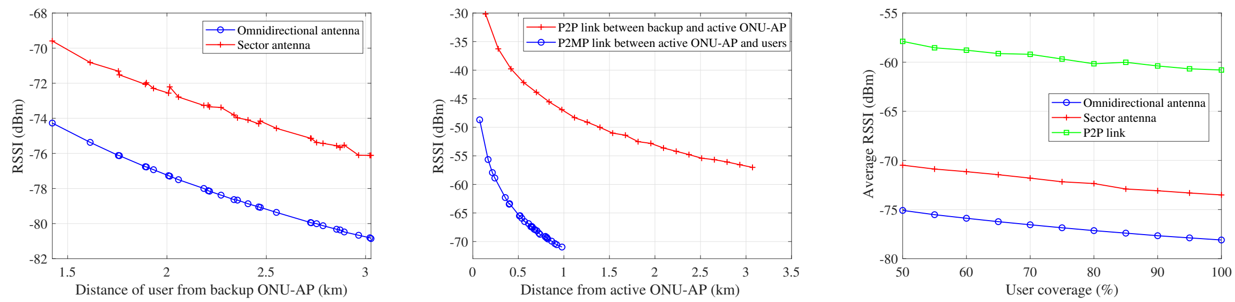
Fig. 9 shows the user coverage with respect to sector antenna height at backup ONU-AP. It is observed that as antenna height increases, the user coverage also increases. It is seen that only 20% user coverage is achieved with 15 m of antenna height, when this height is further increased to 30 m, user coverage is also increased to 36.6%. If antenna's height is further increased up to 80 m, 100% user coverage is possible.

C. P2P Link

In the proposed survivable FiWi network, P2P link is considered between backup ONU-AP and active ONU-AP. It is also assumed that, active ONU-AP consists of two APs, where one AP is equipped with parabolic antenna used for establishing a P2P link between backup ONU-AP and active ONU-AP, and another AP is used for providing connectivity to the users via P2MP wireless links. In this type of scenario, parabolic grid antennas are used to make a P2P link between backup ONU-AP and active ONU-AP. Whenever failure occurs in FiWi network, the disconnected users are reconnected to the backbone network through the P2P link.

VI. Result Analysis

This section presents the performance evaluation of the proposed survivable FiWi network. The analysis presented is



(a) (b) (c)

Fig. 11. RSSI of the users with respect to distance, when backup ONU-AP is connected to active ONU-AP via (a) omnidirectional antenna and sector antenna, (b) P2P link, and (c) Average RSSI (dBm) with respect to user coverage (%)

for the farthest ONU-AP failure in a cluster of three active ONU-APs as shown in Fig. 6. For fair comparison, we assume the effective isotropic radiated power (EIRP) of 36 dBm [28] for all the three cases of the antenna configurations. The antenna gain of the omnidirectional and sector antenna is considered to be 14 dBi, while that for the parabolic grid antenna is considered to be 24 dBi [29] for the analysis. For simulations, we have considered a fully loaded network with 20 users inside the coverage area of an active ONU-AP and each user generates a 10 Mbps traffic [30]. The comparative analysis for three antenna configurations are discussed in detail below.

A. RSSI Analysis

This subsection analyses the RSSI of users connected to the failed ONU-AP. In all the three cases of antenna configuration, we considered the log-normal shadowing model for predicting the received signal strength from backup ONU-AP and can be given in [31] as

$$P_r = P_o - 10\eta \log\left(\frac{d_u}{d_o}\right) + W_\sigma, \tag{16}$$

where, P_o is received signal strength from backup ONU-AP at reference distance d_o = 20 m [23], $W_\sigma \sim \mathcal{N}(0, 8)$ [2] and d_u is Euclidean distance between the user and backup ONU-AP.

Fig. 10 indicate that the average RSSI of users from backup ONU-AP is higher in the case of sector antenna compared to the omnidirectional antenna for the same antenna height at backup ONU-AP. Furthermore, for an antenna height of 30 m, we can observe an apparent gain of average RSSI is 4.68 dBm for the sector antenna configuration. This is because with the antenna height of 30 m, backup ONU-AP with sector antenna can only cover 36.6% of the users inside its ellipsoid region. In contrast, omnidirectional antenna can cover 100% of the users but with poor received signal strength. It may also be noted that in the case of sector antenna, as the height of antenna further increases from 30 m to 100 m, the average RSSI of users becomes constant. As we increase the antenna's height, user coverage increases; however, the position of backup ONU-AP is also changed with respect to a change in the user coverage. Since in this case, the optimal position of backup ONU-AP depends on the number of users inside the sector antenna's ellipsoid region.

Fig. 11(a) shows the variation in received RSSI of the users of failed active ONU-AP from backup ONU-AP with respect to the distance between backup ONU-AP and users. It can be seen that as the distance between user and backup ONU-AP decreases, the received RSSI increases. Moreover, there is a significant improvement in RSSI in the case of sector antenna compared to the omnidirectional antenna configuration.

Fig. 11(b) shows the variation of RSSI received by the user with respect to the distance from failed active ONU-AP and user in case of P2P link. First, the signal is received by active ONU-AP from backup ONU-AP with RSSI of -57.02 dBm, where RSSI varies with respect to distance between backup ONU-AP and active ONU-AP. Then, the signal received by active ONU-AP is further transmitted to the users connected to active ONU-AP via P2MP links. It can be seen that using parabolic grid antennas at both backup ONU-AP and farthest active ONU-AP, the far-away user of active ONU-AP can receive signal strength of -70.96 dBm, when antenna height at backup ONU-AP is 30 m.

Fig. 11(c) shows the comparison of the average RSSI received by the each user connected to farthest active ONU-AP when backup ONU-AP is equipped with omnidirectional antenna, sector antenna, and P2P link. It is also observed that by increasing the user coverage in case of omnidirectional antenna, sector antenna and P2P link, received average RSSI by the users gradually decreases. From this result, it is observed that the P2P link performs better than sector and omnidirectional antenna even with 100% user coverage.

TABLE I
RSSI ANALYSIS

Antenna configuration at backup ONU-AP	Height of antenna at backup ONU-AP(m)	User coverage (%)	Average RSSI (dBm)
Omnidirectional	30	100	-78.09
Sector	80	100	-73.25
P2P link	30	100	-61.19

Table I gives more insight into the RSSI analysis for the three antenna configurations. It is clear that sector antenna performs better in terms of an average RSSI than omnidirectional antenna. However, we need to increase the antenna's

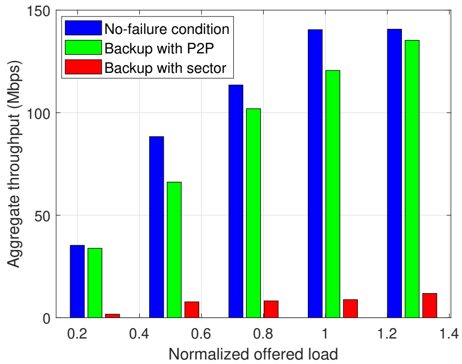


Fig. 12. Aggregate throughput with respect to normalized offered load

height at backup ONU-AP in the case of sector antenna from 30 m to 80 m for obtaining 100% user coverage. In contrast, the P2P link provides an average RSSI of -61.19 dBm along with 100% user coverage. This observation validates that the P2P link performs much better than omnidirectional and sector antenna configurations.

B. QoS Analysis

In this section, the QoS for the proposed three antenna configurations at backup ONU-AP is evaluated and compared with the no-failure scenario (i.e., when there is no-failure of active ONUs and backup ONU-AP is not required). The network simulator-3 (NS-3) modules for enhanced distributed channel access (EDCA) based 802.11ac WiFi network and XG-PON [32] are used to simulate the FiWi network system [33]. The wireless part consist of a 4×4 antenna configuration. The uplink traffic from each user consists of three traffic types: voice, video, and best-effort (BE). OLT is deployed with deficit dynamic bandwidth allocation (DBA) algorithm to provide bandwidth access to voice, video, and BE traffics based on their priority [3].

TABLE II
UPLINK TRAFFIC PARAMETERS

Traffic type	Packet Size	Bit rate	Traffic Model
BE	1472 Bytes	9 Mbps	PPBP, H=0.5
Video	795 Bytes	2 Mbps	PPBP, H=0.9
Voice	160 Bytes	350 Kbps	ON-OFF model, ON duration: $e^{0.35}$s & OFF duration: $e^{0.65}$s

The incoming traffic distribution from each user is summarized in Table II. The Pareto Poisson Burst Process (PPBP) [34] is used to simulate the real-time video and BE traffic with different burst parameters, H [3]. From Table III it is evident that with the increase in channel bandwidth the tolerable load capacity of the network improves. For instance, for video traffic at 20 MHz, the network is able to handle 60% of the load without violating the ITU-T tolerable PLR limit of 1%, while for 80 MHz, the network can tolerate 100% load without contravening ITU-T standard limits. Thus, for analysis we consider a channel bandwidth of 80 MHz.

TABLE III
TOLERABLE LOAD ACCORDING TO PLR FOR THE ITU-T STANDARD

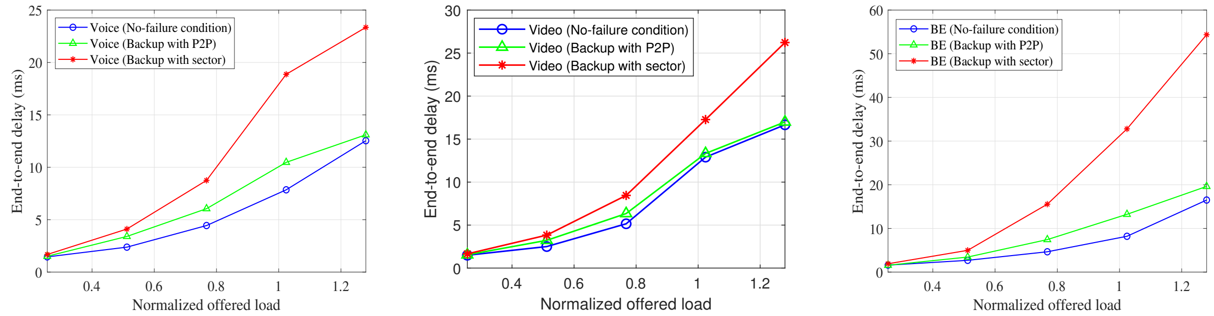
Traffic type	Channel bandwidth		
	80 MHz	40 MHz	20 MHz
Voice	100%	100%	100%
Video	100%	80%	60%

The omnidirectional antenna configuration was simulated using pre-existing omnidirectional antenna module. Moreover, as the RSSI threshold for the receiver is -72 dBm beyond which the packets of the users are not successfully decoded, thus, no packets are being received by the ONU-AP unit in the case of omnidirectional antenna [35].

The sector antenna is simulated using the omnidirectional antenna using a high receiving gain with a limited beam width of 120^o. It was experimentally found that for the antenna gain of less than 63 dB, no packets of the users were received at the receiver. Thus, for analysis, we simulate the sector antenna with receiver antenna gain of 63 dB[4]. Further, we consider a feasible antenna height of 30 m, which gives 30% user coverage, For the P2P case, the parabolic grid antenna configuration is used with the gain of 24 dB from backup ONU-AP to active ONU-AP. Fig. 12 shows the variation of aggregate throughput at the OLT with respect to the normalized offered load of the network for the farthest ONU-AP in a cluster of three ONU-APs. The aggregated throughput of the network increases with the increase in the normalized offered load of the network. This is because as the number of users in the network increases, the aggregate throughput will also increase. Further, it can be observed that if backup ONU-AP is connected with active ONU-AP via a P2P link, the aggregate throughput of backup ONU-AP is close to that of the no-failure condition, unlike the case when backup ONU-AP is equipped with a sector antenna, where the throughput at the OLT decreases significantly.

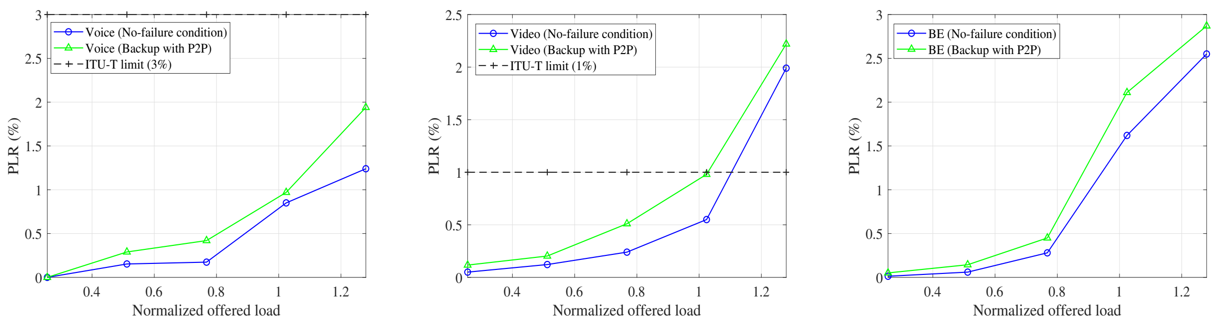
In Fig. 13, the end-to-end delay for the FiWi network from user to the OLT is calculated. The delay is calculated only for the packets received by the OLT from the users. As the normalized offered load increases, the end-to-end delay also increases. It can be observed from Fig. 13 that the end-to-end delay for the P2P link is slightly more compared to the no-failure condition. This is because, for the P2P link, the packet has to travel through an additional link between the parabolic grid antenna as opposed to the no-failure condition. In the case of sector antenna, the users covered by the sector antenna are much lesser as compared to the no-failure condition, hence, the average end-to-end delay of the users increases. The end-to-end delay for voice, video and BE are presented in Figs. 13(a), 13(b), and 13(c), respectively. The end-to-end delay for BE is highest, followed by video followed by voice traffic. This is because of the priorities of the user traffic [3]. As voice is having the highest priority, the end-to-end delay for voice traffic is the lowest, followed by video and BE.

[4]Although, 63 dB is a very high receiving gain which is practically not possible but due to limitation of NS-3, where adjusting the height of the AP is not feasible, a high gain receiving antenna is used to simulate the sector antenna.



(a) (b) (c)

Fig. 13. End-to-end delay with respect to normalized offered load for a) Voice, b) Video, and c) BE traffic.



(a) (b) (c)

Fig. 14. PLR with respect to normalized offered load for a) Voice, b) Video, and c) BE traffic.

Fig. 14 show the comparison of the average PLR for the no-failure and P2P link case. For sector antenna, the covered users were very low and therefore, the packets lost were $> 60\%$ which is very high. From Fig. 14 it can be observed that the PLR for the P2P link is higher than the no-failure condition. Due to this PLR, the aggregate throughput in Fig. 12 also gets affected in a similar manner. Further, it can be seen from Fig. 14(a) that voice traffic is able to follow the ITU-T recommended PLR range for up to 100% of the network traffic load. Also, Fig. 14(b) shows that for the video traffic the tolerable range of ITU-T recommendation is followed for up to 110% and 100% of network load for the no-failure and P2P link case, respectively. Moreover, the PLR for BE is highest as compared to video and voice traffic. This is because the priority for voice traffic is highest, and therefore its PLR is also the lowest. The priority for voice is followed by the video, which is further higher than the BE traffic.

C. Reliability

This subsection evaluates the reliability of the proposed survivable FiWi network with respect to distribution fiber cut, ONU and AP failures. In the FiWi network, the splitter is more reliable than other components as it is a passive component [6]. Reliability is already investigated in some previous literature [2], [6], [16]. In this work, we propose three survivable schemes in which backup ONU-AP can be equipped with either omnidirectional antenna or sector antenna or parabolic grid antenna for reconnecting the disconnected users to the backbone network in case of failures. Further, it is also assumed that backup ONU-AP is connected to OLT through distribution fiber.

Let P_C denote the probability of distribution fiber cut between ONU-AP and the splitter, P_F is the failure probability of components (active ONU, backup ONU and AP). To evaluate the FiWi network's reliability, we have considered ONU and AP's failure probability as 10^{-6} as in [2]. In the first part of the reliability analysis, we consider no backup ONU-AP is deployed in the FiWi network. In this case, the probability of the users connected to the backbone network is given as

$$P^{U}_{con} = (1 - P_C) \times (1 - P^{AO}_{F}) \times (1 - P^{AOAP}_{F}), \qquad (17)$$

where, P^{AO}_{F} and P^{AOAP}_{F} denotes the failure probability of active ONU and AP equipped with active ONU, respectively. Fig. 15(a) depicts that the probability of user connectivity decreases with an increase in distribution fiber cut probability in the FiWi network without any backup ONU-AP.
When backup ONU-AP is deployed in the cluster of active ONU-APs for providing connectivity to the disconnected users in case of distribution fiber cut, ONU, and AP failures, the probability of users connectivity is shown in Fig. 15(b) and computed as follows

$$P^{U}_{con} = (1 - P^{WP}_{F}) \times (1 - (P^{AOAP}_{F} \times P^{AO}_{F} \times P_C)), \qquad (18)$$

where, P^{WP}_{F} is the probability of failure of the wireless protection scheme in which backup ONU-AP is deployed in

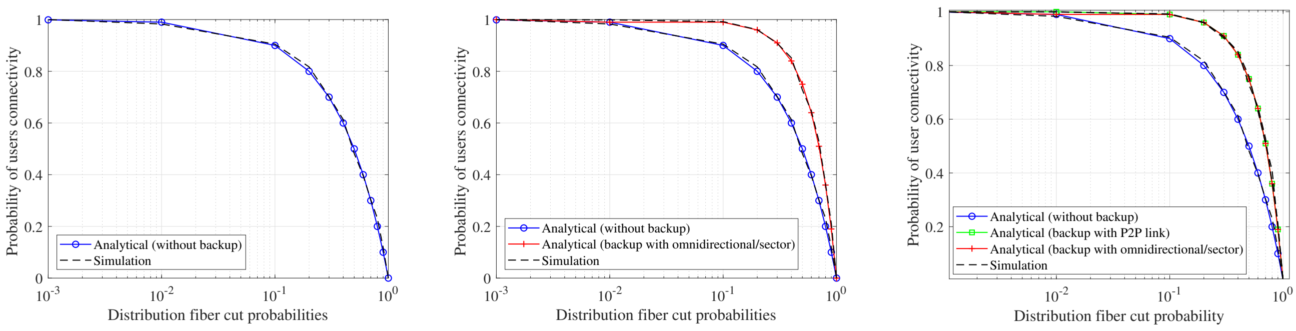


Fig. 15. Probability of users connectivity with respect to distribution fiber cut probabilities a) without backup ONU, b) with backup ONU-AP (equipped with omnidirectional/sector antenna), and c) with backup ONU-AP (P2P link).

the cluster to provide network connectivity to disconnected users via wireless path in case of failures and is given by

$$P_F^{WP} = 1 - [(1 - P_C) \times (1 - P_F^{B_{ONU}}) \times (1 - P_F^{BAP})], \quad (19)$$

where, P_C denotes distribution fiber cut probability, $P_F^{B_{ONU}}$ and P_F^{BAP} denotes failure probability of backup ONU and backup AP, respectively. With the deployment of backup ONU-AP, probability of users connectivity at 0.1 distribution fiber cut probability is enhanced from 0.90 to 0.99 as can be seen from 15(b).

In the proposed survivable FiWi network, when a P2P link is employed between active ONU-AP and backup ONU-AP, then the probability of users connectivity to the backbone network is estimated as follows

$$P_{con}^{U} = (1 - P_F^{WP}) \times (1 - (P_F^{AOAP} \times P_F^{AO} \times P_C)), \quad (20)$$

where, P_F^{WP} is the probability of failure of wireless protection scheme is given by

$$P_F^{WP} = 1 - [(1 - P_C) \times (1 - P_F^{B_{ONU}})(1 - P_F^{BAP})^2]. \quad (21)$$

Fig. 15(c) depicts that in P2P link, with distribution fiber cut probability of 0.1, the probability of users connectivity of 0.92 is achieved. Therefore, the user connectivity probability of the P2P link is improved with respect to the FiWi network having no backup ONU-AP. If we consider that the failure probability of ONU and APs is high as 10^{-1}, then from Fig. 16, it is clearly observed that P2P link is less reliable than backup ONU-AP equipped with either omnidirectional or sector antenna due to the addition of one AP to provide a P2P connectivity of active ONU-AP with backup ONU-AP. As compared to omnidirectional and sector antenna, in case of P2P link, we achieve the probability of user connectivity of 0.91 at distribution fiber cut probability of 0.1.

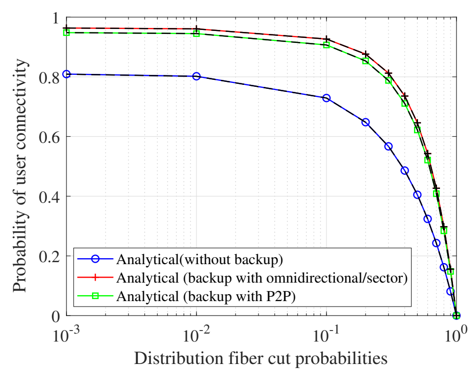


Fig. 16. Probability of users connectivity with respect to distribution fiber cut probabilities (where ONU and AP's failure probability is 10^{-1}) is considered

Conclusion

This paper has proposed a framework to improve the survivability and reliability of the FiWi network while maintaining the QoS requirement of the users. Specifically, we proposed a placement algorithm for backup ONU-AP using stochastic optimization method. This paper compared performance of three different kinds of antenna configurations for backup ONU-AP: omnidirectional antenna, sector antenna, and parabolic grid antenna (P2P link). Furthermore, we analyse the performance of proposed survivable FiWi network in terms various parameters such as RSSI, throughput, PLR, and end-to-end delay. The simulation results show that backup ONU-AP equipped with sector antenna performs better than omnidirectional antenna configuration. However, the QoS requirement of the users is not fulfilled in the case of sector antenna as it provides limited coverage to users of the failed ONU-AP. In order to improve the coverage of the users in the case of sector antenna configuration, the antenna height at backup ONU-AP needs to be increased which sometimes is not practical. Furthermore, it is observed that for the same antenna height, the P2P link performs better than the omnidirectional and sector antenna configuration. Specifically, it has been shown that with the P2P link a survivable FiWi network can be deployed without compromising the QoS requirement of the users, and on par with the performance of the system with no-failure condition. In addition, in order to show the effectiveness of the proposed survivable FiWi network, the reliability analysis using probabilistic modelling is also presented in the paper. It is observed that with the deployment of backup ONU-AP the reliability of the FiWi network increases significantly. In future, we might incorporate other wireless technologies such as such as TWDM PON, free space optics (FSO), visible light communication (VLC), 5G millimeter wave communication in survivable FiWi networks and analyse their performance in terms of required QoS. Another possible research direction would be to investigate the overall impact on the QoS of the users by replacing the fiber with a FSO link.

APPENDIX

For applying stochastic gradient method in Algorithm 1, stochastic gradient of U_o, Δ_{U_o} with respect to $P_{B_{ONU}}$ and $R_{B_{ONU}}$ is computed as

$$\Delta_{U_o} = \sum_{u=1}^{U} S'(D_{\mathrm{B_{ONU}},\mathrm{u}} - R_{B_{ONU}}) \frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial P_{\mathrm{B_{ONU}}}}, \\ - \sum_{u=1}^{U} S'(D_{\mathrm{B_{ONU}},\mathrm{u}} - R_{B_{ONU}}), \tag{22}$$

$$\text{where, } \frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial P_{\mathrm{B_{ONU}}}} = \left(\frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial X_{\mathrm{B_{ONU}}}}, \frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial Y_{\mathrm{B_{ONU}}}} \right), \tag{23}$$

$$\frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial X_{\mathrm{B_{ONU}}}} = \frac{(X_{\mathrm{B_{ONU}}} - X_u)}{\sqrt{(X_{\mathrm{B_{ONU}}} - X_u)^2 + (Y_{\mathrm{B_{ONU}}} - Y_u)^2}}, \tag{24}$$

$$\frac{\partial D_{\mathrm{B_{ONU}},\mathrm{u}}}{\partial Y_{\mathrm{B_{ONU}}}} = \frac{(Y_{\mathrm{B_{ONU}}} - Y_u)}{\sqrt{(X_{\mathrm{B_{ONU}}} - X_u)^2 + (Y_{\mathrm{B_{ONU}}} - Y_u)^2}}. \tag{25}$$

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