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Resource Allocation in Solar-Powered FiWi Networks

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ABSTRACT The ever increasing demand for higher data rates and more flexible deployment has accelerated the need for integrating optical fiber with wireless networks. Fiber-wireless (FiWi) network consists of a fiber back-end network integrated with a wireless front-end. With the growing popularity of the FiWi network, it is essential to look into energy conservation mechanisms as well. One such energy conservation mechanism is to employ a renewable source of energy, such as solar energy. In this article, we have analysed an integrated FiWi network composed of a 10-Gigabit-capable passive optical network (XG-PON) with a WiFi front end. It is assumed that solar panels are installed at the optical network units (ONUs). Depending on the availability of solar power as well as the load generated due to data traffic at ONU, the requirement of resources to power the ONU varies. Consequently, we propose a) Battery allocation (BA) algorithm and b) Photovoltaic (PV) panel allocation (PA) algorithm, for both off-grid as well as on-grid scenarios. To analyse the cost-effectiveness of the proposed algorithms, battery lifetime has also been calculated. Through the obtained results, it has been demonstrated that for locations with good solar profile, there can be a significant reduction in the number of batteries as well as PV panels required to operate a FiWi network.

INDEX TERMS FiWi, lead-acid battery, outage probability, PV panel, solar power.

I. INTRODUCTION

Increasing demand for ubiquitous coverage with seamless connectivity has created many new opportunities for the development of an access network. Fiber-Wireless (FiWi) network has recently attracted considerable attention to alleviate some of the issues of the conventional access networks. FiWi network consists of an optical fiber network as a back-end network connected with a wireless network at the front-end. FiWi integrates the salient features of wireless networks, such as high mobility, universality, elasticity, and cost-effectiveness, with high bandwidth of the optical fiber networks. For instance, by integrating next-generation access network technologies such as a 10-Gigabit-capable passive optical network (XG-PON) and WiFi-based network, cost-effective and energy-efficient services can be delivered to the users. XG-PON is a point-to-multipoint access network technology with an upstream data rate of 2.48 Gbps and a downstream data rate of 10 Gbps [1]. XG-PON consists of an optical line terminal (OLT) at the central office (CO) connected to optical network units (ONUs) using an optical distribution network (ODN). In [2], the authors suggested that there are two popular ways in which FiWi networks are conventionally deployed: i) Radio-over-fiber (RoF): where radio frequencies (RFs) are carried over optical fiber links, ii) Radio and fiber (R&F): where optical and wireless networks are controlled separately. A considerable literature focusing on the integrated FiWi architecture is available. For instance, integration of next-generation PON (NG-PON) with WLAN [3], PON with wireless mesh network (WMN) [4], [5], ethernet passive optical network (E-PON), and worldwide interoperability for microwave access (WiMAX) [6] have been extensively studied in the literature. Further, some of the recent works have also explored the problems related to minimized routing, bandwidth allocation, energy conservation in the context of FiWi networks. The routing algorithms for FiWi network such as delay aware routing algorithm (DARA), delay-differentiated routing

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algorithm (DDRA), capacity and delay aware routing (CaDAR) are discussed in [2]. In [3], the authors proposed an optimized FiWi routing algorithm (OFRA) for an integrated FiWi architecture based on NG-PON and WLAN. The OFRA provides an advantage in terms of throughput over traditional wireless hop and delay aware routing. The authors in [4] presented the trends of ONU placement for a PON and WMN based FiWi network. Further, they also discussed the ONU sleeping strategies for energy conservation of the network. In [6], the authors presented the state of the art for the optical fiber-to-the-home (FTTH) and the WMN access network. The authors also presented the various architectures for integrated EPON-WiMAX based FiWi networks. In [7], an integrated approach for an orthogonal frequency division multiplexing (OFDM)-PON based optical-wireless communication (OWC) system is presented. The authors considered an M-ary pulse amplitude modulation (M-PAM) scheme to evaluate the bit-error-rate (BER) for both indoor and outdoor communication systems using an adaptive envelope modulation technique. In [8], the authors integrated the XG-PON network with IEEE 802.11n network. Based on the deficit dynamic bandwidth allocation (DBA) scheme, the authors evaluated the performance of integrated architecture. The authors showed that for a fully loaded network, the use of deficit DBA resulted in an improvement in the throughput, delay, and fairness index of the FiWi network. In [9], the authors surveyed the recent trends in integrated FiWi network architecture. The key problems, such as reliability, scalability, energy-saving, and QoS provisioning are addressed. Further, it also discusses the emerging trends and research areas for FiWi networks such as the internet of things (IoT), NG-PONs, smart grid, next-generation wireless technologies, software-defined network (SDN).

A. RELATED WORK

With the growing popularity of the FiWi network, many key issues have also come into existence. One such issue is to optimize the energy efficiency of such networks. According to ITU-T G.987.3 [10], there are two modes proposed to reduce ONU power consumption for Gigabit-PON (GPON), namely, cyclic sleep and doze modes. In [11], the authors discussed the energy conservation scheme based on medium access control (MAC) protocol for NG-PON. They observed that in terms of energy efficiency, cost-effectiveness, and delay, cyclic sleep mode is more apt than the other modes of operation. An energy conservation mechanism for flexible time wave division multiplexing (TWDM)-PON is proposed in [12]. Specifically, the authors considered flexibility as a key parameter and divided the network into two categories: a) Fully-flexible architecture (using power switches) and b) Partially flexible architectures (using wavelength selective switches). In addition to the above, [12] also proposed a flexibility analyis for a cascaded configuration of wavelength selective switches and arrayed waveguide grating (AWG). Using the cascaded configuration, authors were able to achieve energy conservation up to 60%. In [13], the authors extended the cyclic sleep mode of ONU to watchful sleep mode. In watchful sleep mode, the sleeping mode of ONUs is divided into two subparts: T_{hold} and T_{sleep}, as a consequence, the sleeping mode of ONU does not affect the QoS. However, the authors only considered PON architecture for analyses. The authors in [5] proposed an approach to integrate the ONU sleep mechanism with radio-offs. Thus, the authors were able to achieve energy conservation at the wireless as well as the optical end. However, the integrated approach is complex to implement as it involves wireless rerouting also along with energy saving scheme at the wireless and optical end. An energy conservation mechanism for FiWi network involving energy conservation at ONU, OLT, and WiFi stations is proposed in [14]. The proposed algorithm proposed in [14] provides 70% energy-saving for the scenarios where the upstream traffic load is 60%.

The advantages of renewable sources of energy, such as hydroelectric, geothermal, solar, wind, etc. do not only help in reducing the carbon footprint, but also promote sustainable development. As per the insights shared in [15], only 13% of the total energy served globally was supplied by renewable sources of energy. Further, out of the total renewable energy, only 32% of the energy is served using solar power. However, due to ease of availability, solar power has a higher potential to serve as an alternative to non-renewable sources of energy. There is a growing impetus to provide broadband coverage to both urban and rural environments, this may lead to a significant increase in energy consumption. The problem will be further compounded due to the limited availability of grid power supply and power outages, especially in the rural areas. Therefore, it is necessary to take renewable sources of energy into account, especially when the grid power supply is not available. A hybrid power supply based base station sleeping strategy in the IoT environment is proposed in [16]. Specifically, the authors proposed an algorithm where the base stations (BSs) cooperatively adjust their sleeping/non-sleeping state based on the actual traffic load and solar energy state. In [17], a scenario is considered wherein a backup supply or grid supply is always available to the BS. Hence, the BS can utilize the grid power supply whenever there is an outage of solar power. In addition, the trade-off between delay and energy consumption of the solar and grid-powered cellular network is also investigated. In [18], the authors presented an off-grid solar-powered BS. In this case, two problems were primarily addressed, i.e., power outage and QoS in terms of network load. As evident from above, the use of solar power has been well studied for cellular networks, especially where the BSs are equipped with solar panels. However, to the best of our knowledge, the use of solar power to power the FiWi network has not been investigated yet.

Motivated by the above, in this article, we propose a resource allocation scheme to power ONU in a solar-powered FiWi network. There are three kinds of power supplies available to power the ONU, namely, solar, grid, and batteries. We consider two scenarios for analyses: a) off-grid scenario-where grid power supply is not available and b) on-grid scenario-where grid power supply is available for a limited number of hours in a day. For the off-grid scenario, the ONU can only be powered using solar panels and batteries. Moreover, the PV panels are also used to charge the batteries so that battery can power the ONU in non-solar hours. Consequently, we propose off-grid battery allocation (OFF-BA) and PV panel allocation (OFF-PA) algorithms to minimize the number of batteries and PV panels required by the ONU for the off-grid scenario. Further, for the locations where impediment grid power supply is available, the ONU relies upon the battery power and solar power. In order to cater to this, we also propose on-grid BA (ON-BA) and PA (ON-PA) algorithms. We consider three types of geographical locations based on the average solar power profile for a typical meteorological year (TMY). Further, we consider three kinds of average throughput requirements of the users. Based on the average throughput requirement, the power consumption of ONU varies. The hourly data for power consumption of the ONU and the solar profile of the location is utilized to allocate the resources to the ONU.

B. CONTRIBUTIONS

In this article, the resource allocation in terms of the number of batteries and PV panels required at ONU is presented. The major contributions of our work are summarized as follows:

- We propose an off-grid battery allocation (OFF-BA) algorithm to minimize the number of batteries required to power the ONU for the scenarios where grid power supply is not available.
- Moreover, for a given number of batteries, we propose an off-grid PV panel allocation (OFF-PA) algorithm to minimize the number of PV panels required by the ONU.
- Similar to the off-grid scenario, we propose on-grid BA and PA algorithms, ON-BA and ON-PA, respectively, for the scenarios where grid power supply is partially available.
- Further, we extend our work for different values of tolerable power outage limits at the ONU and calculate the minimum number of batteries required for different outage probabilities.

The rest of the paper is organized as follows. In Section II, the system model and the parameters considered for the proposed FiWi network are presented. In Section III, the problem formulation and its proposed solutions are discussed. The performance evaluation results are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

Fig. 1 shows the system architecture for the considered FiWi network. The XG-PON is connected to a WiFi module. The XG-PON consists of an OLT at the central office connected to ONUs using an optical distribution network (ODN) and passive optical splitter. The XG-PON uses time-division multiple access (TDMA) for upstream traffic flow, and for downstream traffic flow, time-division multiplexing (TDM) is used [1]. In the considered FiWi architecture, each ONU is connected to a WiFi access point (AP) using a point-to-point ethernet link. User equipments (UEs) are connected to AP via wireless links. Each UE in the considered network generates exponential traffic, which will be discussed later in detail in Section II A. The traffic request arrival rate at ONU is the same as the traffic request arrival rate of AP because ONU and AP are connected using point-to-point links. Based on the traffic requests, the power consumption of the ONU is calculated as given in Section II B.

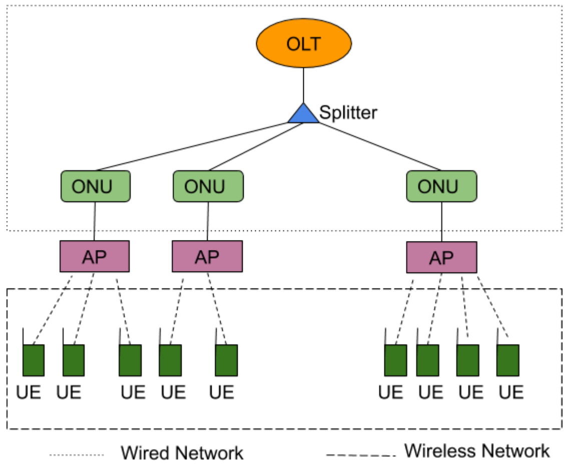


FIGURE 1. FiWi network architecture.

A. THROUGHPUT AND TRAFFIC MODEL

The throughput requirement for each WiFi client is assumed to generate a traffic request flow, which is dependent on the time of the day. The traffic requests from multiple clients get added up at the AP. The sum of these traffic requests from multiple clients at AP is considered to follow an exponential probability distribution function (pdf), which is dependent on the time of the hour 't' as given in [20]. The pdf for throughput ($f(x)$) is described as follows:

$$f(x) = \lambda \exp(-\lambda x), \tag{1}$$

where, λ is the rate parameter of the traffic which is modelled as a Gaussian mixture model (GMM) given as follows:

$$\lambda = \sum_{j=1}^{m} \alpha_j \exp\left(-\left(\frac{t-\beta_j}{\gamma_j}\right)^2\right), \tag{2}$$

where, α_j is the amplitude, β_j is the centroid location and γ_j relates to the peak width, t is the hour of the day, and $m = 7$ [20].

At different locations, the throughput requirement varies according to the population density, type of population, geographical area (urban or rural), etc. In this work, we have analyzed the system for three average throughput requirement per AP viz., a) 20 Mbps, b) 40 Mbps, and c) 60 Mbps. The average data requirement of typical Indian rural clusters are shown in Fig. 2 [19].

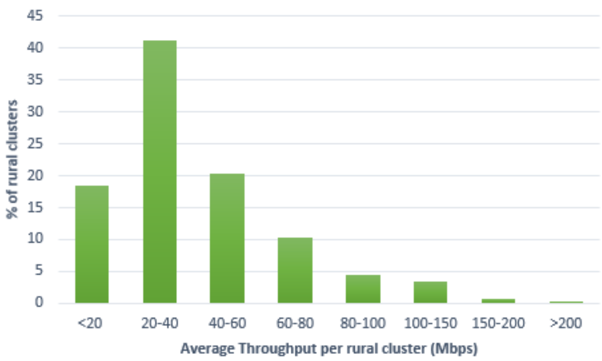


FIGURE 2. Throughput requirement per rural cluster [19].

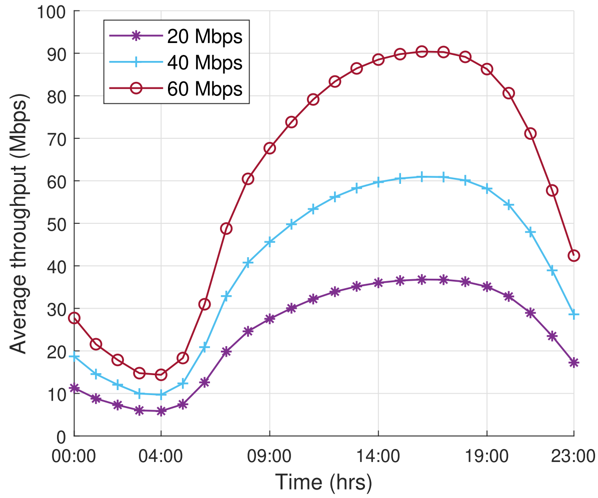


FIGURE 3. Different categories of average throughput required.

B. POWER CONSUMPTION OF ONU

The power management mechanisms for XG-PON and XGS-PON include the exploitation of various power management states of ONU such as active held, active free, asleep, listen, doze aware, sleep aware [1], [21]. Some of the power consumption mechanisms, as mentioned in [1], are cyclic sleep, doze mode, and watchful sleep modes. There exists a considerable body of literature on the expression for power conservation of ONU based on these modes. In [22], the authors analysed the power consumed by the ONUs considering two stages of operation i.e., cyclic sleep mode and doze mode. The authors consider the traffic arrival requests to be a poisson point process (PPP) with an upstream traffic arrival rate of λ_u and a downstream traffic arrival rate of λ_d. Considering both (cyclic sleep and doze) mode of operation to be active, the authors derive an analytical expression for the power consumption of the ONU described as follows:

$$P_{ONU} = \delta_1 \cdot P_{ah} + \delta_2 \cdot P_{af} + \delta_3 \cdot P_{da} + \delta_4 \cdot P_{ls} + \delta_5 \cdot P_{da} + \delta_6 \cdot P_{sa} + \delta_7 \cdot P_{as} + \delta_8 + P_{sa}, \quad (3)$$

where, P_{ah}, P_{af}, P_{da}, P_{ls}, P_{sa}, P_{as} are the power consumption of ONU in ActiveHeld, ActiveFree, DozeAware, Listen, SleepAware and Asleep modes, respectively. Further, δ_1, δ_2, δ_3, δ_4, δ_5, δ_6, δ_7 and δ_8 are the stationary probabilities for ActiveHeld, ActiveFree, DozeAware, Listen, SleepAware and Asleep modes, respectively. The stationary probabilities are related to upstream and downstream traffic request rate (λ_u and λ_d) as mentioned in [22], and the sum of stationary probabilities is

$$\delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8 = 1. \quad (4)$$

In this article, we consider a power consumption model of ONU as given by [22]. Since our work focus on the upstream traffic flow, therefore the traffic arrival request rate for the downstream traffic is considered to be very low (0.05 request per 125μs), and the upstream traffic request rate is based upon the sum of the average throughput requirement for the users associated with the ONU. We consider a burst size for the upstream traffic is considered to be 450 Bytes. Thus, traffic request rate are calculated by utilizing the average throughput at an hour t, $T(t)$ is calculated as

$$\lambda_u(t) = \frac{T(t)}{450 \times 8} \times 125\mu sec. \quad (5)$$

C. SOLAR POWER PROFILE

The solar profile is obtained using the solar irradiance data provided by National Renewable Energy Laboratory (NREL) [23]. In order to get the hourly solar profile, we feed the solar irradiance value in the system advisory module (SAM) tool. For analysis, the considered PV panel consists of an DC to AC inverter of size 0.01 W, with a DC to AC ratio of 1.2. The efficiency of the inverter is taken to be 96%. The tilt of the PV panel is considered to be 33° and the azimuth angle is 180°. We use a yearly average of this hourly solar power profile for analyses.

D. BATTERY

Commercially available batteries can be broadly categorized as lithium-ion battery and lead-acid battery. Lead-acid batteries are cost-effective and highly reliable with an added advantage of energy efficiency with minimal effect on battery lifetime even with the partial state of charge [24]. Therefore, for analysis, we consider lead-acid batteries for powering the ONU. Some of the terminologies related to the battery are mentioned below:

- Battery capacity (C_B): It is defined as the maximum storage capacity of the battery, after which it cannot be charged.
- Depth-of-discharge (DoD): It is defined as the maximum discharge limit of the battery.
- If N batteries are installed and are connected in series, then the total power generated by the batteries is $N \times C_B$.

III. PROBLEM FORMULATION

As discussed earlier, we consider three average throughput requirement of the users per day, i.e., a) T1: 20 Mbps, b) T2: 40 Mbps and c) T3: 60 Mbps. Fig. 3 shows the different per day throughput requirements of the users. The throughput

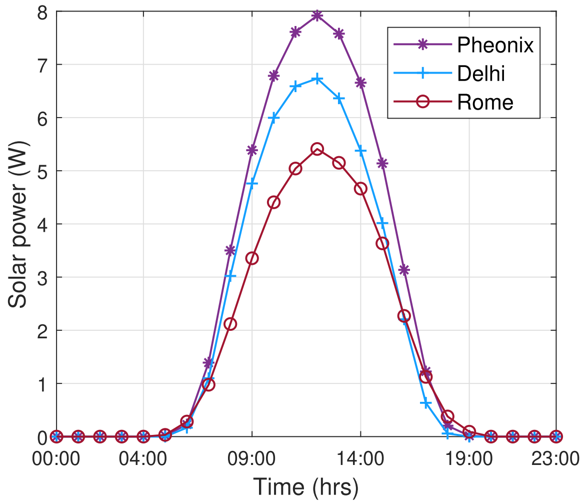


FIGURE 4. Solar power at different locations.

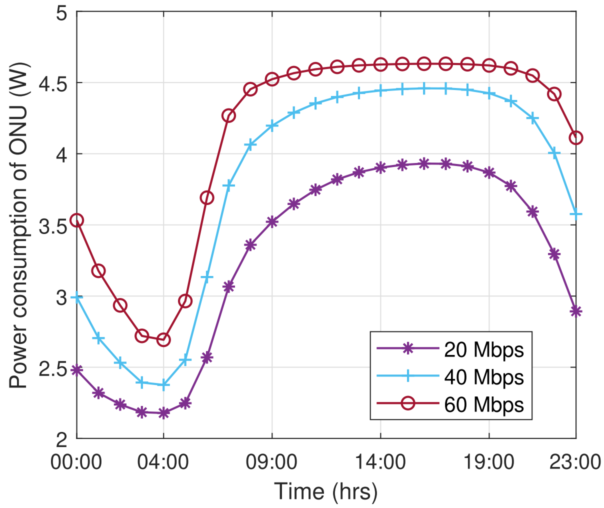


FIGURE 5. Power consumption for different average throughput values.

requirement is modelled as an exponential model. It can be observed from Fig. 3 that at night (2-5 AM), the throughput requirement at the ONU is much lower compared to the morning hours. For the morning hours, as the time increases, the throughput requirement also increases, and the throughput is maximum between 5-8 PM. After 8 PM, as the number of users decreases, the throughput requirement also decreases. For the solar power profile, we consider three different types of solar profiles based on average power harvested during a typical TMY year. We consider two thresholds γ_1 and γ_2, based on these thresholds, the solar profile of a region is divided as a) H1: good ($> \gamma_2$), b) H2: average (between γ_1 and γ_2), and c) H3: bad ($< \gamma_1$). For analysis, we consider $\gamma_1 = 2$ W/hr and $\gamma_2 = 1.8$ W/hr for a PV panel with DC power rating of 12 W. Fig. 4 shows the yearly averaged solar power profile for three locations a) Phoenix (Arizona, U.S.), b) New Delhi (India), and c) Rome (Italy) obtained from the NREL dataset [23]. As seen from Fig. 5, the power consumption of the ONU changes as the average throughput requirement at the ONU changes. Thus, for different average throughput, the resource allocation will also vary. Similarly, we observe a change in solar power profile with the change in location of ONU. Therefore, the combinations of solar power profile and the power consumed by the ONU based on the average throughput requirement at the ONU is used to find the minimum number of batteries and PV panel configuration. In order to consider the randomness in the power supply available by the battery, the initial charge of a single battery is considered randomly between $0.5B_s$ and B_s.

A. SOLUTION METHODOLOGY

In this section, we discuss the proposed solution for obtaining the minimum number of batteries and PV panel required to power the ONU. The proposed OFF-BA algorithm, for calculating the minimum number of batteries required for the off-grid scenario is discussed in Algorithm 1. OFF-PA algorithm, which calculates the minimum number of PV panels required by the ONU for the off-grid scenarios is discussed in Algorithm 2. For the on-grid scenarios, where the grid power supply is only available for the limited hours in a day, the minimum number of batteries required can be calculated using ON-BA, as discussed in Algorithm 3. The minimum number of PV panels required by the ONU for the on-grid scenario is calculated in ON-PA as discussed in Algorithm 4. The notations used in the algorithms are discussed in Table 1.

TABLE 1. Summary of notations.

Notations	Definition
N	Maximum number of batteries
M	Maximum number of PV panels
B_s	Maximum power of a single battery
SP_s	Hourly solar power profile of a single PV panel
$P_{ONU}(t)$	Power consumption profile of ONU at t^{th} hour
$P_{PV}(t)$	Solar power allocated to the ONU at t^{th} hour
$P_{excess}(t)$	Excess solar power available at the PV panel at t^{th} hour
$P_{BAT}(t)$	Power supplied by the battery to the ONU at t^{th} hour
$P_{grid}(t)$	Power supplied by the grid to the ONU at t^{th} hour
$B_{state}(t)$	Power level of the battery at t^{th} hour
β	Depth of discharge factor =30%
γ	Number of hours grid supply is available
t	t^{th} hour of the day
T	Hour of the day for off-grid scenario when we consider the batteries should be entirely charged =4 PM
Λ	Denotes whether solar power harvested is sufficient to power the ONU
P_a	Denotes whether the battery level is beyond DoD

B. OFF-GRID SCENARIO

For cases where no grid supply is available, we rely only on the solar power supply and battery power. Thus, we propose an off-grid battery allocation (OFF-BA) algorithm and off-grid PV-panel allocation (OFF-PA) algorithm.

Algorithm 1 The OFF-BA Algorithm

Inputs:
N:Number of batteries.
B_s: Maximum power of a single battery.
P_{ONU}: Hourly power consumption profile of the ONU.
SP_s: Hourly solar power profile for a considered location.
Output:
N_{min}: Minimum number of batteries required by ONU.

for $B_{cap} = B_s$ to $N \times B_s$ **do**
  Initialize: $B_{state}(0) = [0.5B_{cap}\ B_{cap}]$
  for $t = 0$ to 23 **do**
    Function `Outage` $(SP_s, B_{state}(t), B_{cap}, \beta)$
    $P_{PV}(t) = min(P_{ONU}(t), SP_s(t))$
    if $P_{ONU}(t) - P_{PV}(t) > 0$ **then**
      $\Lambda(t) = 1$
      $P_{BAT}(t) = P_{ONU}(t) - P_{PV}(t)$
      $P_{excess}(t) = 0$
    else
      $\Lambda(t) = 0$
      $P_{BAT}(t) = 0$
      $P_{excess}(t) = SP_s(t) - P_{PV}(t)$
    end if
    if $B_{state}(t+1) - P_{BAT}(t) + P_{excess}(t) < \beta B_{cap}$ **then**
      $P_a(t) = 1$
    else
      $P_a(t) = 0$
    end if
    $B_{state}(t+1) =$
    $min(B_{state}(t) - P_{BAT}(t) + P_{excess}(t), B_{cap})$
    End Function
  end for
  if $\sum_{t=0}^{23} P_a(t) = 0$ **then**
    exit
  end if
end for

1) OFF-GRID BATTERY ALLOCATION (OFF-BA) ALGORITHM

The charge in the battery can be used to supply power to the ONU for non-solar hours. To calculate the minimum number of batteries required by the ONU, we propose OFF-BA algorithm, as discussed in Algorithm 1. The OFF-BA algorithm is given hourly solar power (SP_s) and hourly power consumption of the ONU (P_{ONU}) as inputs. For each battery power level $B_{cap} \in [B_s,\ N \times B_s]$ an hourly analysis is performed to compute the minimum number of batteries required by the ONU. For each hour, t, the OFF-BA algorithm checks if the solar power is available at the ONU. If the solar power is available at t^{th} hour, function `Outage()` is called, with arguments (SP_s, $B_{state}(t)$, B_{cap} and β) that calculates the power outage at the t^{th} hour. Within `Outage()`, the amount of solar power allocated to the power the ONU, $P_{PV}(t)$ is calculated as

$$P_{PV}(t) = min(P_{ONU}(t), SP_s(t)), \tag{6}$$

where, $SP_s(t)$ is the solar power profile at t^{th} hour, and $P_{ONU}(t)$ is the power consumption profile of the ONU at t^{th} hour. If the power requirement of the ONU is not fulfilled by the solar power, then the power is supplied by the battery which is given as $P_{BAT}(t) = P_{ONU}(t) - P_{PV}(t)$. The solar sufficiency index ($\Lambda(t)$) is given by

$$\Lambda(t) = \begin{cases} 1, & P_{ONU}(t) - P_{PV}(t) > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

After supplying the power to the ONU, the excess solar power available at the PV panel is $P_{excess}(t) = SP_s(t) - P_{PV}(t)$. The excess solar power is then utilized to calculate the power outage, $P_a(t)$. In case the battery level at the hour t goes below DoD (βB_{cap}), $P_a(t)$ is assigned 1, else $P_a(t)$ is assigned 0. Utilizing the power level of the battery at the beginning of current hour, power supplied by the battery at current hour, and excess power available at the PV panel, the battery level

Algorithm 2 The OFF-PA Algorithm

Inputs:
M:Number of PV panels.
SP_s: Hourly solar power profile of a PV panel at a considered location.
P_{ONU}: Hourly power consumption profile of the ONU.
B_s: Maximum power of the battery.
T: Time (hrs) when the battery should be fully charged.
Output:
M_{min}: Minimum number of PV panels required by ONU.

for each PV panel level $SP = SP_s$ to $M \times SP_s$ **do**
  Initialize:$B_{state}(T) = B_s$
  for $t = T$ to $T + 23$ **do**
    Function `Power`$(SP, B_{state}(t), B_s, \beta)$
    $P_{PV}(t) = min(P_{ONU}(t), SP(t))$
    if $P_{ONU}(t) - P_{PV}(t) > 0$ **then**
      $\Lambda(t) = 1$
      $P_{BAT}(t) = P_{ONU}(t) - P_{PV}(t)$
      $P_{excess}(t) = 0$
      $B_{state}(t+1) =$
      $min(B_{state}(t) - P_{BAT}(t) + P_{excess}(t), B_s)$
    else
      $\Lambda(t) = 0$
      $P_{BAT}(t) = 0$
      $P_{excess}(t) = SP(t) - P_{PV}(t)$
      $B_{state}(t+1) =$
      $min(B_{state}(t) - P_{BAT}(t) + P_{excess}(t), B_s)$
    end if
    End Function
  end for
  if $B_{state}(T+24) = B_s$ **then**
    exit
  end if
end for

at the beginning of next hour is calculated as

$$B_{state}(t+1) = min(B_{state}(t) - P_{BAT}(t) + P_{excess}, B_{cap}), \tag{8}$$

since, the battery cannot be charged beyond B_{cap}, therefore, the upper limit to the $B_{state}(t)$ is kept as B_{cap}. The additional power available at the PV panel after charging the battery upto its maximum level i.e. B_{cap} is not considered. The $P_a(t)$ computed by the function `Outage()`, is then used to calculate the power outage for the hour. In case there is no outage, 24-hour communication is feasible. Thus, in order to get the minimum battery requirement at the ONU, OFF-BA algorithm selects the minimum amount of batteries required, such that 24-hour communication is feasible, i.e.,

$$\sum_{t=0}^{23} P_a(t) = 0. \tag{9}$$

2) OFF-GRID PV PANEL ALLOCATION (OFF-PA) ALGORITHM

OFF-PA algorithm as illustrated in Algorithm 2, calculates the minimum number of PV panels required so that battery is entirely charged at the T^{th} hour or the level of battery at the T^{th} hour is B_{cap}. The algorithm is given the hourly solar power profile of a PV panel (SP_s), hourly power consumption profile of the ONU (P_{ONU}), the maximum power of the battery (B_s), and the time at which the battery should be fully charged (T) as the inputs. For each PV panel level $SP \in [SP_s, \; M \times SP_s]$ an hourly analysis is performed to compute the minimum number of PV panels required by the ONU. Considering the t^{th} hour of operation, OFF-PA checks if the solar power is available at the ONU. For each hour, function `Power()` is called with arguments (SP, $B_{state}(t)$, B_s, β). Within `Power()`, the amount of solar power allocated to the ONU ($P_{PV}(t)$) is given as

$$P_{PV}(t) = min(P_{ONU}(t), SP(t)) \tag{10}$$

Depending on the solar power profile, the solar power allocated to the ONU may or may not be sufficient to fulfill the power demand of the ONU. $\Lambda(t)$ indicates the solar power sufficiency index. $\Lambda(t) = 0$ indicates that the solar power allocated to the ONU is sufficient and $\Lambda(t) = 1$ indicates that there is a need for additional power supply to fulfill the power demand of the ONU. The additional power required by the ONU is served by batteries, $P_{BAT}(t) = P_{ONU}(t) - P_{PV}(t)$. After supplying the power to the ONU, the excess solar power available at the PV panel is given as, $P_{excess}(t) = SP(t) - P_{PV}(t)$. The power level of the battery at the beginning of the next hour, which is given as

$$B_{state}(t+1) = min(B_{state}(t) - P_{BAT}(t) + P_{excess}(t), B_s). \tag{11}$$

If the battery level at $(T + 24)^{th}$ hour is equal to B_s, the algorithm stops executing, and SP/SP_s gives the minimum number of PV panels required by the ONU to provide 24-hour communication to the users.

Algorithm 3 The ON-BA Algorithm

Inputs:
N:Number of batteries.
B_s: Maximum power of a battery.
P_{ONU}: Power consumed by the ONU.
SP_s: Solar power profile for a considered location.
γ: Number of hours grid power supply s available.
Output:
N_{min}: Minimum number of batteries required by ONU.
Initialize:
X: A random vector of γ elements, with values $x \in [0, 23]$.

```
for B_cap = B_s to N × B_s do
  for t = 0 to 23 do
    if x(t) ≠ 0 then
      P_grid(t) = max(0, P_ONU(t) − SP_s(t))
      P_a(t) = 0
      P_excess(t) = max(SP_s(t) − P_ONU(t), 0)
      P_PV(t) = SP_s(t)
      B_state(t + 1) = min(B_state(t) + P_excess(t), B_cap)
    else
      Outage(SP_s, B_state(t), B_cap, β)
    end if
  end for
  if Σ_{t=0}^{23} P_a(t) <= γ then
    exit
  end if
end for
```

C. ON-GRID SCENARIO

In this case, it is assumed that a limited grid power supply is available to the ONU. Thus, ONU is powered using the grid, battery as well as solar power. We propose an on-grid BA (ON-BA) and on-grid PA (ON-PA) algorithm to minimize the number of batteries and PV panels required to power the ONU respectively.

1) ON-GRID BATTERY ALLOCATION (ON-BA) ALGORITHM

Let us consider a location where grid supply is available for only γ hours in a day. For the rest of the hours, ONU relies on the other sources of power, i.e., PV panels and batteries. For such scenarios, we propose ON-BA as illustrated in Algorithm 3. The vector X represents the availability of grid power at each hour of the day. The proposed on-grid BA algorithm uses the hourly solar power profile (SP_s) and hourly power consumption profile of the ONU (P_{ONU}) as its input. The algorithm iterates over each value of the battery, up to N batteries. For each hour 0 to 23, the ON-BA algorithm checks if the grid power supply is available for the ONU. In case the grid power supply is available, it checks whether solar power is also available. In case the solar power is available, it fulfills the demand of the ONU by the available solar power and then through the grid. The power supplied by the grid is given as

$$P_{grid}(t) = max(0, P_{ONU}(t) - SP_s(t)), \tag{12}$$

Algorithm 4 The ON-PA Algorithm

Inputs:
M:Number of PV panels.
SP_s: Solar power profile of a PV panel at a considered location.
P_{ONU}: Power consumed by the ONU.
B_s: The maximum capacity of the battery.
T: Time (hrs) when the battery should be fully charged.
Output:
M_{min}: Minimum number of PV panels required by ONU.
Initialize:
X: A random vector of γ elements, with values $x \in [0, 23]$.

for each PV panel level $SP = SP_s$ to $M \times SP_s$ **do**
  Initialize:$B_{state}(T) = B_s$
  for $t = T$ to $T + 23$ **do**
    if x(t) $\neq 0$ **then**
      $P_{grid}(t) = max(0, P_{ONU}(t) - SP(t))$
      $P_a(t) = 0$
      $P_{excess}(t) = max(SP(t) - P_{ONU}(t), 0)$
      $P_{PV}(t) = SP(t)$
      $B_{state}(t + 1) = min(B_{state}(t) + P_{excess}(t), B_s)$
    else
      `Power`$(SP, B_{state}(t), B_s, \beta)$
    end if
  end for
  if $B_{state}(T + 24) = B_s$ **then**
    exit
  end if
end for

where, $P_{ONU}(t)$ is the power consumption profile of the ONU at t^{th} hour and $SP_s(t)$ is the solar power profile at t^{th} hour. If the grid power supply is available, then the battery power is not needed. Hence, the battery level will not degrade at this hour so, there will be no power outage at t^{th} hour and $P_a(t) = 0$. The excess power available at the PV panel after supplying the power to the ONU is given by

$$P_{excess}(t) = max(SP_s(t) - P_{ONU}(t), 0), \tag{13}$$

The power level of the battery at the beginning of the next hour when the grid power supply is available is given as

$$B_{state}(t + 1) = min(B_{state}(t) + P_{excess}(t), B_{cap}). \tag{14}$$

If at t^{th} hour the grid power supply is not available, the power outage will be calculated by using the function `Outage()`, this is in line with what is shown in Algorithm 1. On-grid BA algorithm selects the minimum amount of batteries required, such that 24-hour communication is feasible, i.e.,

$$\sum_{t=0}^{23} P_a(t) = \gamma. \tag{15}$$

2) ON-GRID PV PANEL ALLOCATION (ON-PA) ALGORITHM

As the grid power supply is impediment, the batteries are charged using solar power. The minimum number of PV panels required by the ONU is obtained in the ON-PA algorithm as illustrated in Algorithm 4. The algorithm is given hourly solar power profile of a PV panel (SP_s), hourly power consumption profile of the ONU (P_{ONU}), the maximum power of the battery (B_s) and time at which the battery should be fully charged (T) as the inputs. The grid power supply is assumed to be limited to γ hrs in a day. For fixed number of PV panels, the ON-PA algorithm checks the availability of grid power supply at each hour (t). If the grid power supply is available, check whether the solar power supply is available. The maximum solar power allocated to the ONU when the grid power supply is available is given by $max(0, P_{ONU}(t) - SP(t))$, where $P_{ONU}(t)$ is the power consumption profile of the ONU at t^{th} hour and $SP(t)$ is the solar power profile at the t^{th} hour. The excess solar power available at the PV panel is given as

$$P_{excess}(t) = max(SP(t) - P_{ONU}(t), 0). \tag{16}$$

Since, at t^{th} hour the grid power supply is available, therefore, there is no outage at time t and $P_a(t) = 0$. Further, at t^{th} hour the battery supply is not required therefore, the power state of the battery at the beginning of the next hour is

$$B_{state}(t + 1) = min(B_{state}(t) + P_{excess}(t), B_s). \tag{17}$$

If at t^{th} hour the grid power supply is not available, the power level at the end of each hour will be calculated by using the function `Power()`, in a similar way as shown in Algorithm 2. ON-PA algorithm select the minimum amount of PV panels required by the ONU if the following condition is fulfilled

$$B_{state}(T + 24) = B_s. \tag{18}$$

IV. PERFORMANCE EVALUATION

This section presents the performance evaluation results for the proposed algorithms for both off-grid as well as on-grid scenarios. We consider a network with a single ONU connected to WiFi-AP with a point-to-point link. The work presented can be extended to multiple ONU FiWi network by appropriately changing the incoming traffic parameters. As mentioned earlier, we consider an average hourly solar power profile for the three locations Phoenix, New Delhi, and Rome. The average throughput requirement per ONU is classified into three categories, namely, 20 Mbps, 40 Mbps, and 60 Mbps. The analysis is performed for a single ONU on an hourly basis. Throughout this article, unless otherwise stated, we consider battery capacity (C_B) of 86.4 Whr for 8 hrs [25], i.e., each battery supplies a power of 10.8 W and DC power rating of the PV panel is 12 W [26].

TABLE 2. Resource allocation for an ONU for the off-grid scenario.

a) The minimum battery level required by the ONU						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	110.91	11	185.86	18	217.08	21
New Delhi	156.92	15	224.74	21	244.51	23
Rome	193.43	18	237.60	22	280.8	26

b) The minimum PV panel dimension required by the ONU						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)
Phoenix	18.50	4	20.75	5	23.00	5
New Delhi	20.75	5	25.25	6	28.5	6
Rome	25.25	6	29.75	6	32.00	7

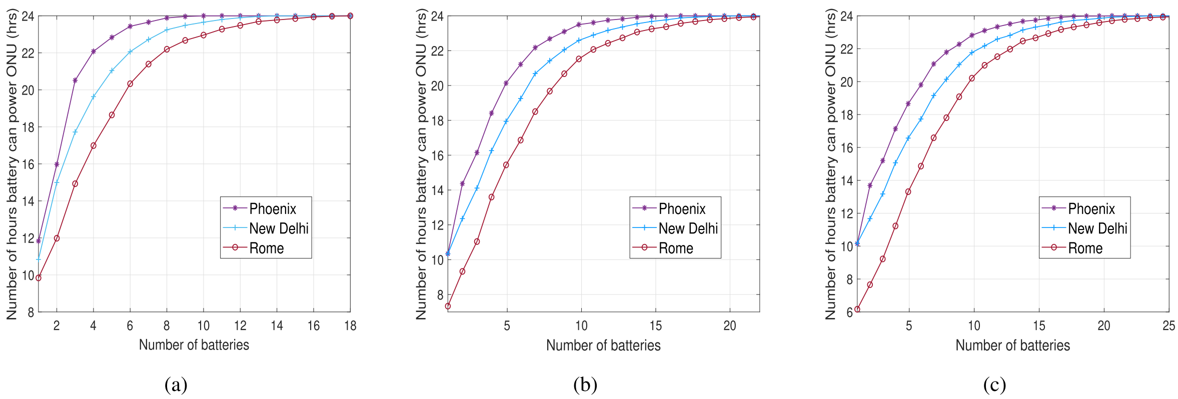


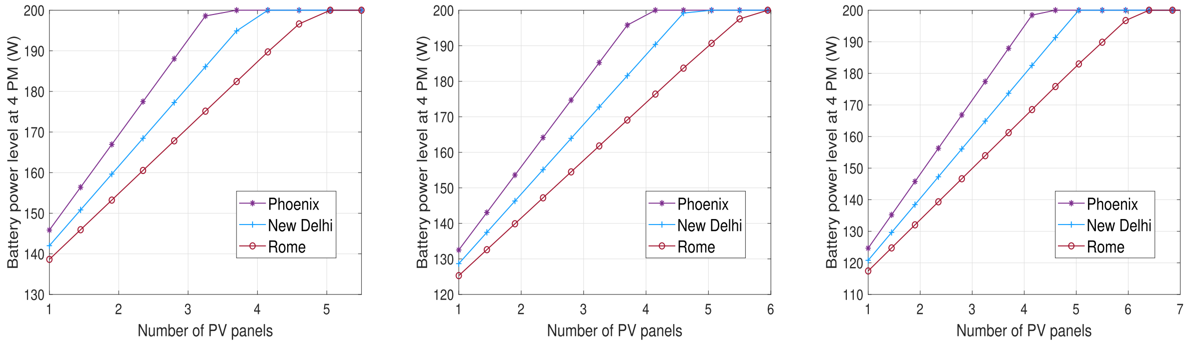
FIGURE 6. The minimum battery level required by an ONU for off-grid scenario for an average throughput of a) 20 Mbps, b) 40 Mbps, and c) 60 Mbps.

A. RESOURCE ALLOCATION FOR THE OFF-GRID SCENARIO

In this section, we provide the obtained results for the minimum number of batteries and PV panels required for the off-grid scenario. Since the grid power supply is not available, therefore the ONU is powered by the combination of solar power and battery. Moreover, solar power is also used to charge the battery.

Fig. 6 shows the total number of hours the batteries can support the power requirement of ONU with respect to number of batteries. It can be observed from Fig. 6, as the number of batteries increases, the total number of hours the batteries can support the power requirement of ONU also increases. Beyond a certain point, since the number of batteries is high enough to cater for 24 hr power requirement of the ONU, therefore, the curve flattens. Further, from Fig. 6(a), it can be observed that the number of batteries required to provide 24-hour power to the ONU increases as the solar power profile for the location decreases. For instance, Phoenix's solar power profile is better than that of New Delhi, which is indeed better than Rome. It can be observed from Fig. 6(a), that the number of batteries required by the ONU at Phoenix is less than that of New Delhi, and at Rome, the requirement is more as compared to New Delhi. In addition, as the average throughput requirement of the users increases, the number of batteries required to provide 24-hour power support to the ONU also increases. This is also evident from Table 2a), where the number of batteries and battery capacity requirements concerning different locations and average throughput requirements is mentioned. It is observed from Table 2a) that the number of batteries required by the ONU increases significantly as the throughput increases. Moreover, it can be observed that an ONU located at a place such as Phoenix may needs seven extra batteries for an increase in throughput from 20 Mbps to 40 Mbps.

Since the solar supply is limited and is only available for less than 12 hrs in a day, for the other hours, power needs to be drawn from the battery. Thus, the battery will get discharged. In order to provide 24-hour power supply to the ONU, we charge the battery using solar power and make sure the battery is completely charged at T^{th} hr of the day. For this, we calculate the minimum number of PV panels required by the ONU. Fig. 7 shows the minimum number of 5 W PV panels required to charge a battery to a maximum power level of 200 W. For analysis, it is considered that the battery is entirely charged by the PV panel at T = 4 PM. From Fig. 7(b), it can be observed that for a location with a good solar profile, i.e., Phoenix, less number of PV panels are required compared to a location with a bad solar profile. Further, as the throughput requirement increases from 20 Mbps to 60 Mbps, the number



(a) (b) (c)

FIGURE 7. **The minimum number of PV panels required by an ONU when for the off-grid scenario for an average throughput of a) 20 Mbps, b) 40 Mbps, and c) 60 Mbps.**

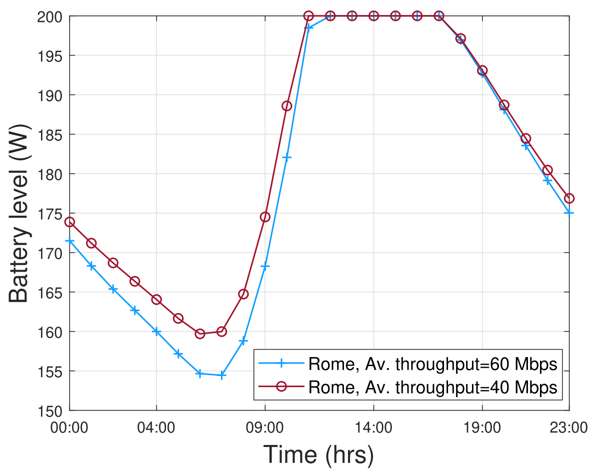


FIGURE 8. **Battery level for an ONU at different hours for the off-grid scenario at 60 Mbps load when the maximum power level of the battery is 200 W.**

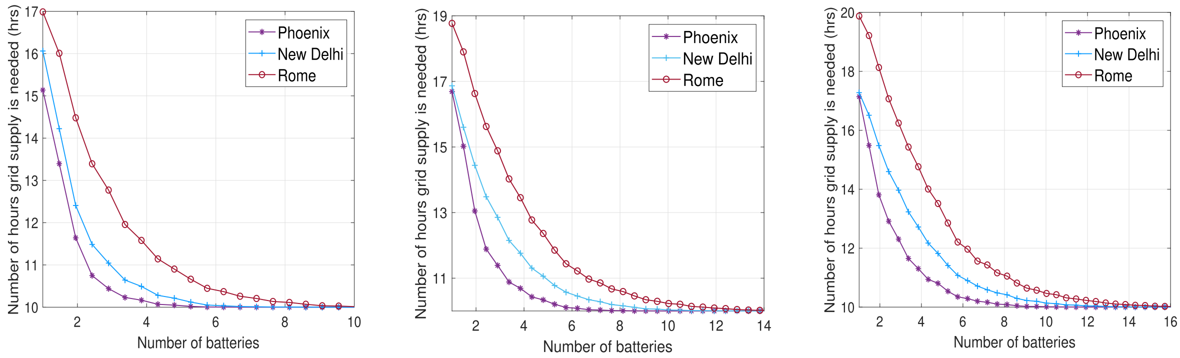
of PV panels required also increases. Table 2b) shows the number of PV panels required with respect to throughput and solar profile at different locations. It can be observed from Table 2b) that there is an increase in the number of PV panels required by the ONU as the throughput requirement increases from 20 Mbps to 60 Mbps.

Fig. 8 shows the variation of the power level of the battery for different hours for the day for the off-grid scenario when the maximum power level of the battery (B_{cap}) is 200 W. The objective is to keep the battery 100% charged at 4 PM so that the battery can cater to the power demand of the ONU at night and early morning hours when no solar power is available. It can be observed from the figure that in the initial hours up to 8 AM, the battery power level decreases due to the unavailability of solar power. For such hours, ONU is dependent only on the battery for power supply. Hence, the battery power decreases proportionally to the traffic load. After 8 AM, the PV panel starts generating the power, and thus, the battery starts charging. It can be observed that for Phoenix, at around 10 AM, the battery is fully charged, i.e., the power level of the battery is 200 W, and it is able to maintain sufficient charge till 4 PM even after supplying a fraction of its power to the load. After 4 PM, the battery power decreases as solar power starts reducing. It can be inferred from Fig. 8 that as the average throughput requirement of Rome decreases from 60 Mbps to 40 Mbps, the power level of the battery decreases. Further, it can be observed that with the decrease in throughput requirement, the number of hours that the battery can remain fully charge increases.

B. RESOURCE ALLOCATION FOR ON-GRID SCENARIO

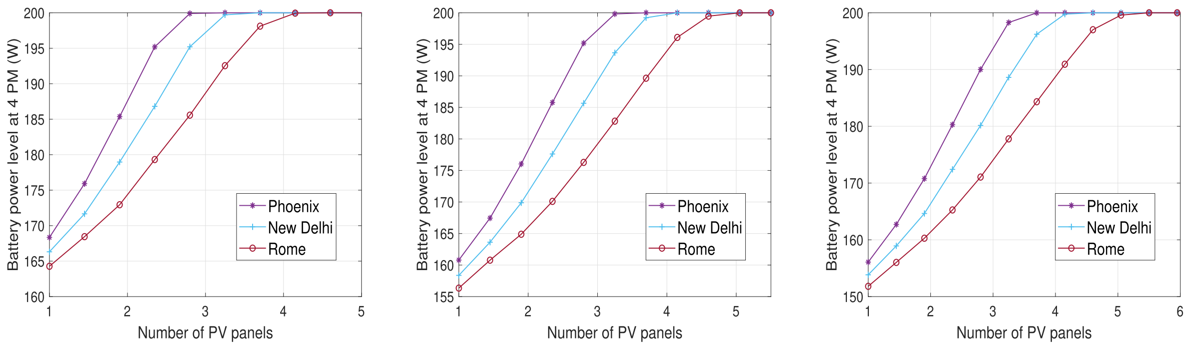
In this section, the results for the on-grid scenario are presented. For such locations, it is desirable to use solar power to reduce the reliance on grid power supply, thereby reducing the impact on the environment and making the solution green. Therefore, the grid power supply is an impediment power source. We analysed the minimum resources required by the ONU in order to provide 24-hour connectivity to the users. For simulations, the availability of grid power supply is fixed to $\gamma = 10$ hrs in a day.

Fig. 9 shows the variation of the number of hours the power supply from the grid is needed with respect to the number of batteries. It can be observed that as the number of batteries increases, the number of hours the grid power supply is required decreases. From Fig. 9(a), it can be observed that for a location with a good solar profile, i.e., Phoenix, we require fewer batteries to get a grid power supply of exactly 10 hrs whereas for a location with a poor solar profile, i.e., Rome, more number of batteries are required. The number of batteries required by the ONU at different locations and average throughput requirement is mentioned in Table 3a). It can be observed that as the average throughput of the users increases, the number of batteries required also increases. For e.g., at Phoenix the number of batteries required by the ONU increases to three as the throughput requirement increases from 40 to 60 Mbps. From Figs. 6 and 9, it can be observed that the number of batteries required for the on-grid scenario is less as compared to the off-grid scenario. This is because for the on-grid scenario, we have an additional grid power supply to cater to the load demand for ONU. Fig. 10 shows the variation of battery power with the number of PV panels at different hours of the day. It can be observed, as the



(a) (b) (c)

FIGURE 9. The minimum battery level required by an ONU for on-grid scenario for an average throughput of a) 20 Mbps, b) 40 Mbps, and c) 60 Mbps.



(a) (b) (c)

FIGURE 10. The minimum number of PV panels required by an ONU when for the on-grid scenario for an average throughput of a) 20 Mbps, b) 40 Mbps, and c) 60 Mbps.

TABLE 3. Resource allocation for an ONU for the on-grid scenario with $\gamma = 10$ hrs.

a) The minimum battery level required by the ONU

Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	67.5	7	72.36	7	103.14	10
New Delhi	82.62	8	113.40	11	149.25	14
Rome	103.14	10	139.05	13	164.70	16

b) The minimum PV panel dimension required by the ONU

Throughput	20 Mbps		40 Mbps		60 Mbps	
	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)	DC output rating of PV panel (W)	No. of PV panels (5 W DC rating)
Phoenix	16.25	4	18.50	4	20.75	5
New Delhi	18.50	4	23.00	5	25.55	6
Rome	23.00	5	27.50	6	29.75	6

throughput requirement increases from 20 Mbps to 60 Mbps, the number of PV panels required also increases. It could also be observed from Fig. 10(a) that, for a location with good solar profile, i.e., Phoenix, a lesser number of PV panels are required compared to a location with poor solar profile, i.e., Rome and New Delhi. In Table 3b), the number of PV panels required by the ONU for the on-grid scenario is mentioned. It can be observed that there is an increase in the number of PV panels required as the average throughput of the users increases. On comparing Figs. 7 and 10, it is obvious that more number of PV panels are required when no grid power supply is available compared to the case when 10 hrs grid power supply is available at the ONU.

C. POWER OUTAGE PROBABILITY

The power outage is defined as the duration of time for which no power is available at the ONU, provided the users are willing to tolerate some outage. Depending on the QoS requirement of the users, operators can afford some fraction of time in a day such that ONU is in outage. For such cases, we calculate the number of batteries required by the ONU when it is in outage for a fraction of a day. For each location, two

TABLE 4. Resource allocation for different values of power outage and battery lifetime for an ONU for the off-grid scenario.

a) The minimum battery level required for 5% outage probability						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	125.68	12	162.00	15	175.50	17
New Delhi	138.35	13	167.40	16	180.90	17
Rome	141.48	14	173.88	17	194.25	19

b) The minimum battery level required for 2% outage probability						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	156.60	15	193.43	18	216.00	20
New Delhi	166.86	16	197.10	19	219.35	21
Rome	170.64	16	202.50	19	236.62	22

TABLE 5. Resource allocation for different values of power outage and battery lifetime for an ONU for the on-grid scenario. with $\gamma = 10$ hrs.

a) The minimum battery level required for 5% outage probability						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	64.04	6	70.20	7	92.00	9
New Delhi	70.52	7	75.60	7	95.92	9
Rome	73.55	7	80.24	8	101.62	10

b) The minimum battery level required for 2% outage probability						
Throughput	20 Mbps		40 Mbps		60 Mbps	
	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)	Total battery power (W)	No. of batteries (10.8 W each)
Phoenix	86.40	8	106.94	10	118.80	11
New Delhi	91.04	9	111.24	11	121.06	12
Rome	96.01	9	118.80	11	127.55	12

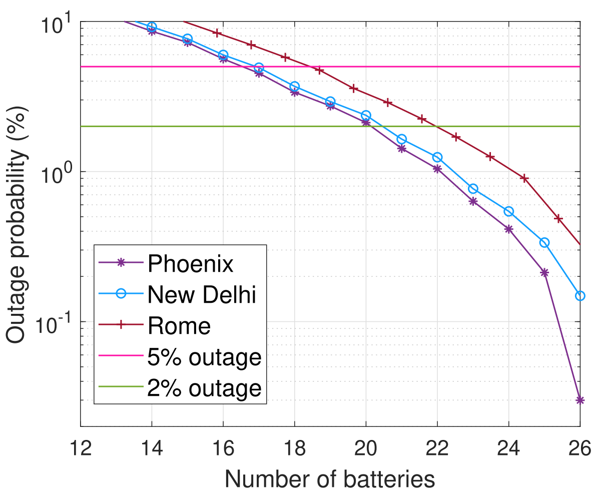


FIGURE 11. The outage probability for the off-grid scenario at 60 Mbps average throughput.

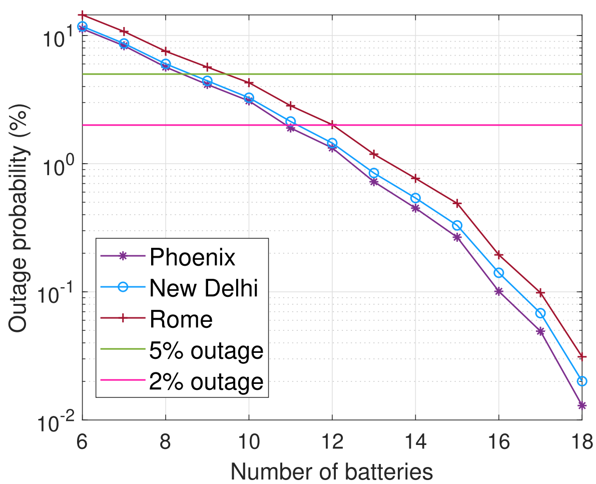


FIGURE 12. The outage probability for the on-grid scenario at 60 Mbps average throughput.

tolerable values for the outage probability, i.e., 2% and 5% are considered. An outage of 2% corresponds to 28.8 minutes per day and an outage of 5% corresponds to 72 minutes of outage per day. Fig. 11 shows the outage probability per day with respect to the number of batteries required for an average throughput of 60 Mbps. It can be observed as the number of batteries increases, the outage probability decreases. Further, it can be noted that for the same amount of outage probability, the number of batteries required for Phoenix is the least, followed by New Delhi and Rome. Table 4 shows the number of batteries required for different combinations of average throughput requirement and location. It can be observed that for the same combinations of throughput and location, the number of batteries required increases by around 2-4 as outage probability decreases from 5% to 2%.

TABLE 6. Battery lifetime for the number of batteries required at each location for no outage scenario.

a) Off-grid scenario

Throughput	20 Mbps		40 Mbps		60 Mbps	
	No. of batteries (10.8 W each)	Battery lifetime (yrs)	No. of batteries (10.8 W each)	Battery lifetime (yrs)	No. of batteries (10.8 W each)	Battery lifetime (yrs)
Phoenix	11	5.53	18	5.67	21	5.67
New Delhi	14	6.63	22	5.29	23	5.43
Rome	18	6.06	22	5.18	26	5.25

b) On-grid scenario

Throughput	20 Mbps		40 Mbps		60 Mbps	
	No. of batteries (10.8 W each)	Battery lifetime (yrs)	No. of batteries (10.8 W each)	Battery lifetime (yrs)	No. of batteries (10.8 W each)	Battery lifetime (yrs)
Phoenix	7	5.07	7	4.41	10	4.69
New Delhi	8	4.79	11	4.54	14	4.63
Rome	10	4.65	13	4.57	16	4.65

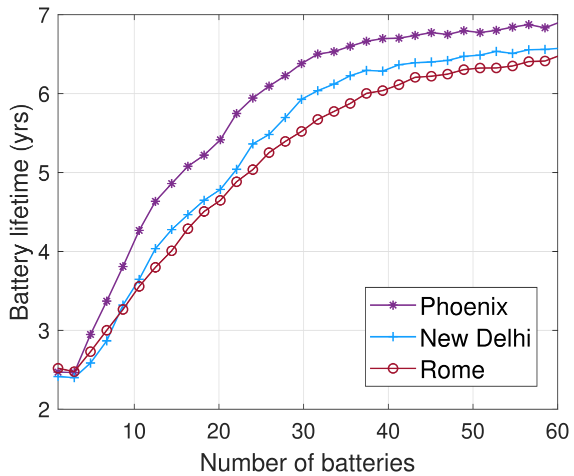


FIGURE 13. Battery lifetime for the off-grid scenario at 60 Mbps average throughput when 15 W PV panel is deployed.

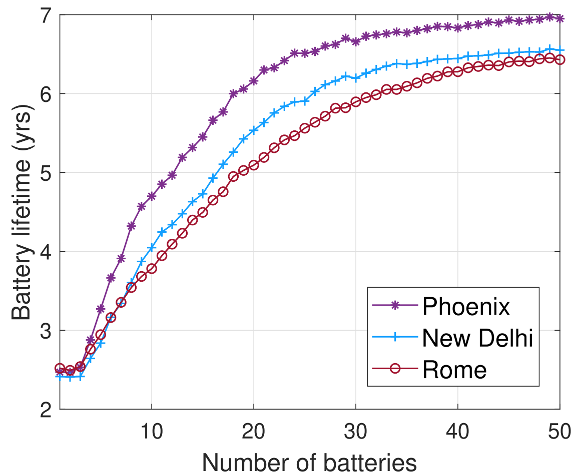


FIGURE 14. Battery lifetime for the on-grid scenario at 60 Mbps average throughput when 15 W PV panel is deployed.

Fig. 12 shows the outage probability with respect to the number of batteries required for an average throughput of 20 Mbps. It can be observed that as the number of batteries increases, the outage probability also decreases. Moreover, it is evident that for Phoenix, the outage probability is less compared to New Delhi and Rome. This is because the solar power at Phoenix is more as compared to New Delhi and Rome. For each location, two threshold values for the outage probability, i.e., 2% and 5% are underlined. In Table 5, the number of batteries required for the power outage probability of 2% and 5% are mentioned. It can be observed that as the throughput requirement increases from 20 Mbps to 60 Mbps, the number of required batteries to achieve the same power outage level increases significantly. From Figs. 11 and 12, it can be observed that there is a difference between the number of batteries required by the ONU for the on-grid and off-grid scenarios. For e.g., at Phoenix, the number of batteries required to achieve 2% outage at 60 Mbps average throughput requirement is 20 for the off-grid scenario, while for the on-grid scenario, the number of batteries required reduces to 11. This clearly indicates a saving of 9 batteries because of 10 hrs of grid power supply.

D. BATTERY LIFETIME

The battery lifetime can be calculated as given below:

$$B_{lif} = \frac{1}{\sum_{n=1}^{N} \frac{C_n}{CTF_n}}, \tag{19}$$

where, C_n is the number of cycles counted using rainflow cycle counting algorithm [27], CTF_n is the cycle to failure ratio which denotes the number of cycles a battery can have in its lifetime for a region n and N represents the number of regions in which DoD is split. Fig. 13 shows the battery lifetime with respect to the number of batteries requirement for the off-grid scenario. It can be observed that as the number of batteries increase, the battery lifetime also increases. This is due to the fact that as the number of batteries increase, the overall capacity for the battery increases, therefore the number of charging-discharging cycles decreases. Further, if the number of batteries increases beyond a certain limit, i.e., greater than 40 batteries, the battery lifetime becomes constant because the number of charging-discharging cycles becomes constant. It is also observed that for a location with a poor solar profile the battery lifetime is lower compared to the location where a good solar profile is available. This is because for a location with poor solar profile, such as, Rome, the charging-discharging cycles are more compared to a location like Phoenix. The battery lifetime for the number of batteries required for off-grid scenario at a specific location and for the average throughput per ONU is mentioned in Table 6a).

Fig. 14, shows the battery lifetime with respect to the number of batteries for on-grid scenario. Observations similar to Fig. 13 can be observed in this case as well, i.e., it can be seen that with the increase in the number of batteries, the battery lifetime also increases. In Table 6b), the battery lifetime for the number of batteries required for the on-grid scenario at a specific location and average throughput per ONU is mentioned. On comparing Figs. 13 and 14, it can be observed that for a fixed number of batteries, the battery lifetime increases for the on-grid scenario compared to the off-grid scenario due to the additional support from the grid.

The simulation results presented above show that the resources required to power the ONU vary with the insolation and throughput requirement of the users at a location. For the off-grid case, the amount of resources required to power the ONU is higher compared to the on-grid scenario. This is because of the additional grid power supply availability in the on-grid scenario. Moreover, for the scenarios where users are able to tolerate some amount of outage, it can be observed that as the outage probability increases, the resource requirement of the ONU decreases. Further, the results in terms of battery lifetime show that the lifetime of batteries increases due to fewer charging-discharging cycles for the on-grid scenarios.

V. CONCLUSION

In this article, we proposed resource allocation algorithms to cater for power requirement in ONUs for a FiWi network. Specifically, the algorithms allocate the minimum number of batteries and PV panels so that 24-hour power supply can be provided to ONUs. The proposed algorithms, BA and PA, are designed for both off-grid as well as on-grid scenarios. The results demonstrate that due to the difference in available solar power profile at different locations, the resources requirement also varies. A location with a good solar power profile requires fewer resources than a location with a poor solar power profile. Moreover, for the on-grid scenario, the requirement of resources decreases significantly due to the presence of additional power supply by the grid. In addition, to the solar power profile, the average throughput requirement of the users also affects the allocation of resources. As the average throughput increases, the power consumption of the ONU also increases. Due to the increase in power consumption, the resources required by the ONU also increases. In addition, the proposed work also calculated the battery lifetime for the batteries required by the ONU. Battery lifetime for an on-grid scenario increases as compared to the off-grid scenario because of fewer charging-discharging cycles. The results presented in the article show an improvement of around ten batteries for an on-grid scenario compared to the off-grid scenario for 60 Mbps throughput.

In addition, the proposed work also obtained the minimized number of resources required at the ONU for the scenarios where limited power outage can be tolerated. The results show that as the outage probability increases from 2% to 5%, the number of batteries required by the ONU decreases by three. In future, we plan to improve the analysis of integrated solar-powered WiFi-AP and ONU based FiWi network to conserve power both in wired and wireless part.

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