Centralized vs Decentralized Resource Analysis of Green FiWi Networks

Kinshu Kumar, Akshita Gupta, Vivek Ashok Bohara and Anand Srivastava
Wirocomm Research Group, Department of Electronics & Communication Engineering,
Indraprastha Institute of Information Technology Delhi (IIITD), New Delhi 110020, India.
Email: kinshu17161@iiitd.ac.in, akshitag@iiitd.ac.in, vivek.b@iiitd.ac.in, anand@iiitd.ac.in

***Abstract*—Fiber Wireless (FiWi) networks have recently emerged as one of the preferred solutions for high-speed internet as they provide large capacity, high stability, and user mobility. This paper considers a real-time campus wireless local area network (WLAN) deployment scenario. The resource allocation framework to power the FiWi network components such as optical network units (ONUs) and access points (APs) is analyzed. Specifically, an off-grid scenario is considered wherein the ONU and AP collectively called 'ONU-AP' is powered through photovoltaic (PV) panels and batteries. We propose a three step iterative algorithm (TSIA) to compute the minimum resource requirement of the ONU-AP. A comparative analysis of resource requirements for two network setups is presented, namely, a) decentralized setup- where each remotely located ONU-AP has its own power source and b) centralized setup- where the ONU-APs are powered by the centralized power unit. The results presented show that the centralized power setup for the FiWi network is more power-efficient compared to the decentralized setup. Furthermore, a carbon footprint analysis to compare the carbon dioxide (CO_2) emissions for the centralized and decentralized setups is also presented in the paper.**

***Index Terms*—FiWi, ONU-AP, centralized setup, decentralized setup, WLAN**

I. INTRODUCTION

The recent advancements in telecommunication systems require the networks to be bandwidth-efficient, energy-efficient, while providing low latency and low packet drop rate. In order to fulfill the aforementioned demands, fiber-wireless (FiWi) network is recently gaining a lot of attention. FiWi networks combine the advantages of the wireless network with the fiber backhaul network. The fiber network provides high bandwidth, and the wireless frontend gives the flexibility to connect to multiple users simultaneously [1]. The FiWi network consists of a passive optical network (PON) with wireless fidelity (WiFi) or Worldwide Interoperability for Microwave Access (WiMAX) network at the frontend [1], [2]. Moreover, in order to increase the energy efficiency of the network, green energy sources, such as solar and wind power, are increasing utilized in addition to non-renewable alternatives such as, diesel generators or fossil fuels. The green sources of energy reduce the dependence on non-renewable resources and have a lower carbon footprint [3].

The 5^{th} generation (5G) mobile communication networks requires an expected capital expenditure (CAPEX) of $1 trillion by 2025 [4]. CAPEX will increase further as the demand for seamless connectivity and ubiquitous coverage increases. In order to reduce the setup cost, one of the possible solutions is the use of centralized setup. Although the centralized setup has higher transmission loss compared to the decentralized setup, but there are certain advantages of a centralized setup such as better power efficiency, in addition to reduction in system size and cost of network deployment [5], [6]. Considerable amount of prior literature has deliberated the pros and cons of deployment of the centralized and decentralized setups. For instance the authors in [7] optimized the location for centralized placement of PV (photovoltaic) panels and batteries to enhance the energy sharing among the producers and consumers of energy. The authors claimed that the proposed model not only improves the energy sharing but is also economically viable. The authors in [5] compared the techno-economic analysis for the centralized setup and decentralized setup for a residential community for the on-grid scenario. The authors compared the advantages of centralized and distributed PV setup installation in three metrics, namely, the cost of deployment of the models, the energy production from the two systems, and the reliability of the system during peak power. The results showed that the centralized system required less number of batteries to store the surplus power. The authors in [6] focused on direct current (DC) microgrid for residential power requirements on distributed and centralized setup. The authors considered a locality of five houses drawing parallel load and then compared it with the centralized and distributed solar supported microgrid. The analysis showed that there is a reduction in the dependence on the PV panels by 0.31% and battery by 1.55%. Further, the analysis showed a reduction in energy losses by 1.47% and capital cost by 4.71%. However, to the best of our knowledge, the comparative analysis for the resource allocation of centralized and decentralized green FiWi network setups has not been performed yet.

The proposed work aims to optimize the resource allocation of the FiWi network. The centralized and decentralized placement of the energy source such as PV panels and batteries are presented. The decentralized placement refers to dedicated energy resources for individual optical network unit (ONU) and access point (AP) setup. The main contributions of the papers are summarized below:

1) We compare the resource allocation required to power ONU-AP for centralized and decentralized setups.
2) Considering a real-world throughput profile for wire-

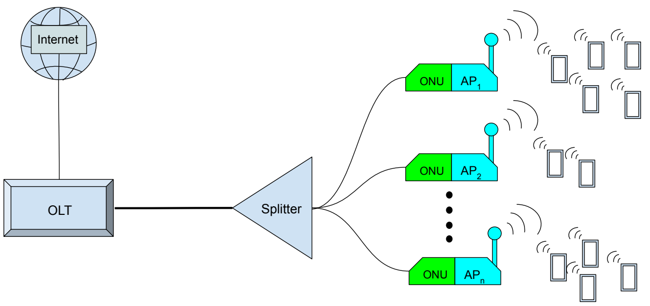


Fig. 1: FiWi Network Architecture

less local area network (WLAN) campus scenario, the resource allocation scheme is used to calculate the resources, i.e., the number of batteries and PV panels required to power the ONU-APs.

3) We propose the three step iterative algorithm (TSIA) to calculate the minimum number of PV panels and batteries required to power the ONU-AP setups.

4) Moreover, in order to explore the environmental benefits, carbon footprint analysis in terms of carbon dioxide (CO_2) emissions are compared for both the cases.

The results show that the centralized setup is beneficial compared to the decentralized setup as it has potential surplus power that can be used significantly without compromising the power requirement of the network and offers environmental benefits in terms of CO_2 emissions.

The rest of the paper is organized as follows, in Section II, we discuss the network model, in Section III, we discuss the performance analysis. Section IV discusses the comparative results for centralized and decentralized setups. The final section V concludes the paper.

II. SYSTEM MODEL

A. *Network Architecture*

The network architecture for the considered FiWi network is shown in Fig. 1. The network architecture consists of a 10 Gigabit capable passive optical network (XG-PON) connected with WLAN at the frontend. The ONUs and APs collectively known as ONU-APs are connected to the users via wireless links. The bandwidth provided by the optical line terminal (OLT) is split among the ONUs via a passive splitter.

Fig. 2 shows the energy flow for the ONU-AP setup. An off-grid scenario is considered where the resource required to power the ONU-APs and charge the batteries is generated by the PV panels at the appropriate daylight hours. The battery stores the energy to power the ONU-APs during non-solar hours. In this paper, each PV panel and battery is considered to be of DC rating of 5W [8], [9].

B. *Decentralized and Centralized Setup structure*

In this paper we consider a simplistic scenario where the ONU-APs are considered to be equidistant from each other. For the decentralized setup, the PV panels and the batteries are dedicated to one ONU-AP and deployed along with ONU-APs, as shown in Fig. 3a. For the centralized setup, the PV panels and batteries are assumed to be located equidistant from ONU-APs as shown in Fig. 3b. The PV panels and batteries are considered to be located at the centroid of the triangle[1] formed by three distributed ONU-APs, whereas for the decentralized case, the PV panels and the batteries are at the vertices of the triangle.

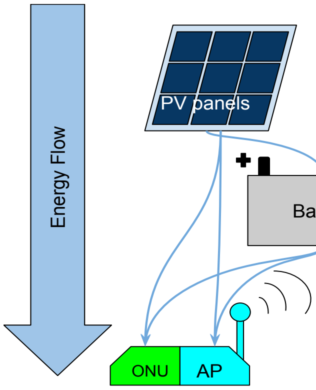
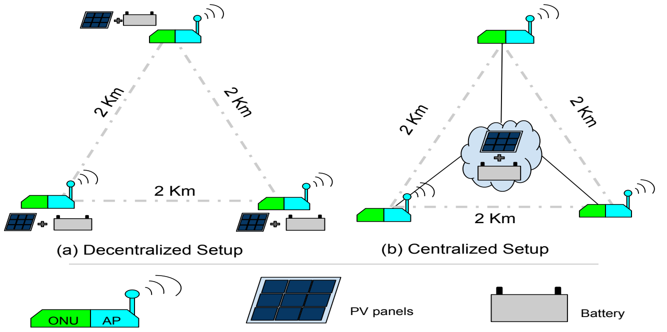


Fig. 2: Flow of Energy within the system



(a) Decentralized Setup (b) Centralized Setup

Fig. 3: Setup Structures

III. PERFORMANCE ANALYSIS

In this section the performance analysis for the FiWi network in terms of throughput profile, power consumption model, transmission loss, solar profile, resource allocation scheme is discussed.

A. *Throughput Models*

The following subsection explains the throughput model considered in the paper:

1) Throughput model: In order to get better insights of centralized and decentralized setup we consider a real-time campus scenario where spatio-temporal traffic for the campus can be modelled as given in [10]. The authors estimated the traffic with respect to time and location of the end-users. The traffic estimation at first, models the session arrivals i.e.,

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[1] Triangular architecture has been considered for ease of analysis, however the insights obtained from this paper can be extended to any other architecture as well.

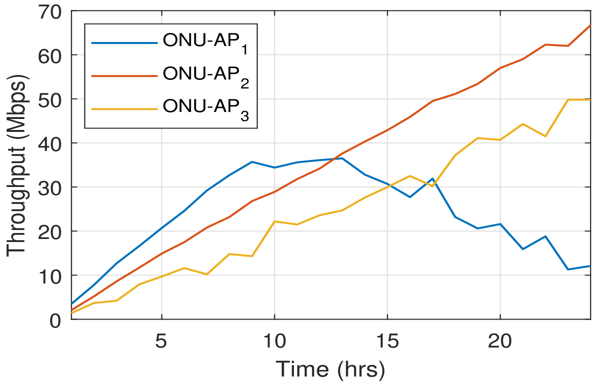

Fig. 4: Spatio-temporal traffic for WLAN campus scenario

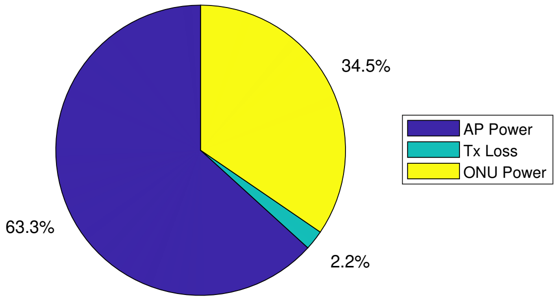

Fig. 5: Power consumption distribution for ONU-AP$_1$

number of sessions/connection alive in the network in a span of 0.1 hours [10], using time-varying Poisson distribution. Afterwords, session AP preferences are modeled using Lognormal distribution for the number of sessions associated to each AP. Then the number of flows per session are estimated, this estimates the frequency of data transaction happening from the connected user to the network, via BiPareto distributions [10]. Finally, the authors estimated the flow size that enumerates the size of each data packet in bytes corresponding to the flow. The flow size is modelled with BiPareto distribution. The values of the parameters for the various distributions are given the Table I.

The authors in [10] offered sub-models listed above that imitates the traffic of WLAN of the campus of University of Northern Carolina. The campus has 40000 users on a daily basis with a network of 600 APs. For the scenarios discussed in this paper the model has been scaled down to 3 APs and 600-700 sessions. The authors have simulated the same model for Dartmouth and proposed the model can be adjusted according to different institutions by adjusting the parameters accordingly. The model in [10] has a resolution of 0.1 hours. For this paper an hourly analysis is done therefore, the traffic has been added up for each hour to compute an hourly traffic profile. Fig. 4 shows the throughput profile considered in this paper. We consider a 3 ONU-APs scenario, where, the number of users are considered to be 1000 and the availability of the users connected to each ONU-AP is a time varying poisson distribution. The users or session are associated to one of the 3 ONU-APs. The association is decided by the lognormal distribution under ONU-AP preference for every user. Thus, the throughput profile at the three test locations are different, i.e., the number of users connected to ONU-AP$_1$ increases till 12 noon and then decreases, while, for ONU-AP$_2$ and ONU-AP$_3$, the throughput increases linearly depicting a scenario where the number of users increase as the day ends and reaches peak at the night time. Further on a statistical note, the aggregated throughput for a day for ONU-AP$_1$, ONU-AP$_2$, and ONU-AP$_3$ are 572.7, 853.4, and 594.5 Mbps, respectively.

B. Power Consumption Model

The power consumption of the network components depends on the throughput profile of the users at the location. The ONU power requirement comprises of different modes: active held, active free, doze aware, listen, sleep aware and asleep [14]. The power consumption for ONU is given as

$$\begin{aligned} P_c^{ONU} = {} & \mathcal{P}^1 \cdot P_c^{ah} + \mathcal{P}^2 \cdot P_c^{af} + \mathcal{P}^3 \cdot P_c^{da} + \mathcal{P}^4 \cdot P_c^{ls} \\ & + \mathcal{P}^5 \cdot P_c^{da} + \mathcal{P}^6 \cdot P_c^{sa} + \mathcal{P}^7 \cdot P_c^{as} + \mathcal{P}^8 + P_c^{sa}, \end{aligned} \quad (1)$$

where, $P_c^{ah}, P_c^{af}, P_c^{da}, P_c^{ls}, P_c^{as}$ and P_c^{sa} are the power consumption for ActiveHeld, ActiveFree, DozeAware, Listen, SleepAware and Asleep modes of ONU, respectively and $\mathcal{P}^1$, $\mathcal{P}^2$, $\mathcal{P}^3$, $\mathcal{P}^4$, $\mathcal{P}^5$, $\mathcal{P}^6$, $\mathcal{P}^7$, and $\mathcal{P}^8$ are stationary probability for each state given in [14].

The AP power is estimated using energy consumption per frame via the protocol stack for 802.11 devices as shown in [15]. The authors of [15] claimed that the throughput models they suggested performs better than tradition energy consumption models for similar devices. The power consumption of IEEE 802.11 AP is given as

$$P_c^{AP} = P_c^i + P_c^T T^T + P_c^R T^R + \delta^T \lambda^T + \delta^R \lambda^R, \quad (2)$$

where, P_c^i, P_c^T and P_c^R are the idle, transmission and reception power of the AP, respectively, T^T is the transmission airtime percentage, T^R is the reception airtime percentage, δ^R and δ^T are the reception and packet cross-factor as given in [15]. The values of $P_c^i = 3.68\ W$, $P_c^T = 0.4\ W$ and $P_c^R = 0.24\ W$, $\delta^T = \delta^R = 0.93 \times 10^{-3}$ [15].

C. Transmission Loss (Tx loss)

The transmission of power from the PV panels and the batteries to ONU-AP brings transmission loss. For the centralized setups, the power distance between energy sources and ONU-AP is large, hence, these transmission losses needs to be considered unlike decentralized setups. Moreover, there is a trade off between the cost of the deployed wiring at the expense of resistance [16]. The transmission loss for the ONU-AP is calculated as:

TABLE I: Probability Distribution used to model the Spatial-Temporal Throughput [10]

Constituent	Model	PDFs	Parameters
Session Arrivals	Time varying Poisson Distribution with rate $\lambda(t)$	$N : number\ of\ sessions\ between\ t_1\ and\ t_2$ $\lambda = \int\limits_{t_1}^{t_2} \lambda(t)\,dt,\ \ Pr(N=n) = \frac{e^{-\lambda}\lambda^n}{n!}, n = 0,1,2,...$ [11]	hourly rate: min-44, max-1132, median-294
Session AP Preference	Lognormal Distribution	$p(x) = \frac{1}{\sqrt{2\pi}x\sigma} e^{\left(-\frac{(ln(x)-\mu)^2}{2\sigma^2}\right)}$ [12]	$\mu = 4.0855, \sigma = 1.4408$
Number of Flows/Session	BiPareto Distribution	$p(x) = k^{\beta}(1+c)^{\beta-\alpha}x^{-(\alpha+1)}(x+kc)^{\alpha-\beta-1}, x >= k$ [13]	$\alpha = 0.06, \beta = 1.72, c = 284.79, k = 1$
Flow Size	BiPareto Distribution	$p(x) = k^{\beta}(1+c)^{\beta-\alpha}x^{-(\alpha+1)}(x+kc)^{\alpha-\beta-1}, x >= k$ [13]	$\alpha = 0.00, \beta = 0.91, c = 5.20, k = 179$

$$\text{Tx loss} = C_{loss} I^2 R \tag{3}$$

where, C_{loss} is a constant equal to 6 that comes from load of three decentralized ONU-AP setups as shown in Figs. 3a and 3b and 2 wires for $\mathrm{V_{CC}}$ and ground to each of the system [16], I is the current and R is the resistance of the wire used to connect the centralized power supply to the three ONU-AP setup. Fig. 5 shows the power distribution percentage among ONU, AP and Tx loss, illustrating the utility of the power required.

D. Solar Power Profile

The power generated by the PV panels is calculated using the data from National Renewable Energy Laboratory (NREL) site of the US Department of Energy [17]. For this paper, the PV panels are considered to be installed in south direction with a tilt angle of 33^o. The location of the installation is choosen to be New Delhi, India. Further, the PV panels consist of an inverter that converts DC to AC with ratio 1.2.

E. Resource Computation

In order to power the ONU-AP, the number of PV panels and batteries needs to be calculated. The PV panels and batteries are calculated using [2] for an off-grid scenario. The number of the PV panels and the batteries required by the different ONU-APs of the decentralized setup is calculated based on the spatio-temporal throughput. The three step iterative algorithm (TSIA) is proposed to calculate the minimum number of PV panels and batteries required to power the ONU-AP. TSIA uses an iterative process as shown in Algorithm 1 to calculate the minimum resource requirement of the ONU-AP .

Algorithm 1 The TSIA

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Initialize: The number of PV panels, $N_{PV}$ to a random integer $\in$ [1, max (Power consumption of ONU-AP$_s$)]
1: Step 1: Calculate the minimum number of batteries required to power ONU-AP given $N_{PV}$ PV panels
2: Step 2: Calculate the minimum number of batteries required to power ONU-AP and charge the $N_b$ batteries.
3: Step 3: Go back to step 1 and iterate until convergence.
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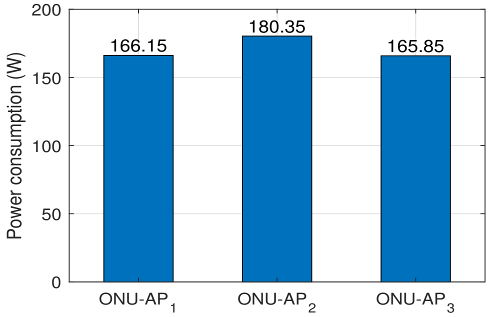
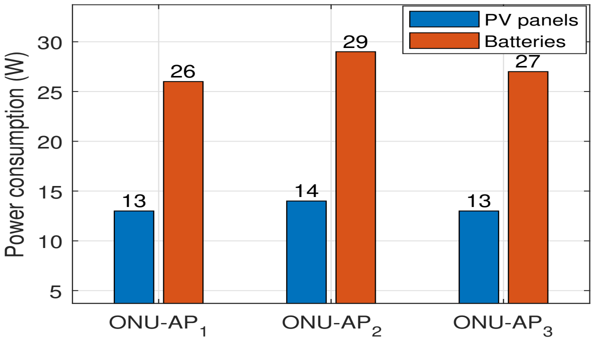
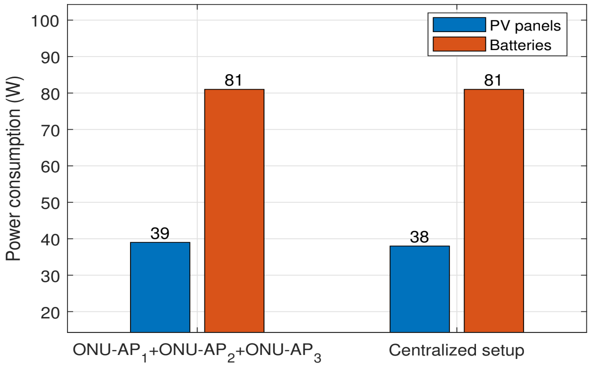


Fig. 6: Power consumption of ONU-APs



(a) Suggested PV panels and batteries for decentralized setup



(b) Comparison of total resources used in decentralized vs centralized setup

Fig. 7: Resource allocation and comparison for different setups

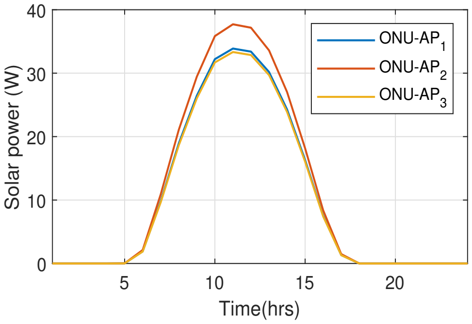


Fig. 8: Solar power generated in decentralized setup for a day

IV. RESULTS

In this section the comparative analysis of the centralized and decentralized setup is discussed. The centralized setup provides benefits over decentralised setup due to surplus energy, but there are some trade offs associated with it which will be discussed in the following subsections. For analysis, we consider the distance of each ONU-AP from the centralized setup as 1.73 km. The transmission loss is considered as 0.795 Ω/km resistance for the distance of 1.73 km [16].

A. Power consumption profile

Fig. 6 shows the power consumption of the ONU-APs for a day. It can be seen that the power consumption for ONU-AP$_2$ is the highest followed by ONU-AP$_1$ and ONU-AP$_3$. As can be inferred from (1) and (2), the power consumption of ONU-AP is proportional to the throughput profile of the ONU-AP. The throughput for the ONU-AP$_2$ is the highest and therefore, its power consumption is also the highest i.e., 180.35 W followed by the power consumption of ONU-AP$_1$ (166.15 W) and ONU-AP$_3$ (165.85) W.

B. Resource allocation

Fig. 7a compares the number of batteries and PV panels required to power the decentralized ONU-APs. It is evident from Fig. 7a that the resources required by ONU-AP$_2$ are the highest, i.e., 29 batteries and 14 PV panels. This is because the throughput requirement of the ONU-AP$_2$ is the highest, thus, the power consumption of the ONU-AP$_2$ is also the highest. Moreover, as the throughput requirement of the ONU-AP$_1$ is the least hence, it requires 26 batteries and 13 batteries. Further, from Fig. 7b it can be observed that the overall resource requirement for the decentralized setup is equivalent to centralized setup. This is due to the fact that the effective throughput at the decentralized setup is same as that in centralized setup.

Based on the resource allocation discussed above, the solar power generated by the PV panels at the different ONU-APs of the decentralized setup is shown in Fig. 8. It can be observed that the solar power is available from 6 AM to 7 PM and is maximum at 12 noon. Moreover, as the number of solar panels required by the ONU-AP are highest for ONU-AP$_2$ hence, the solar power is also highest for ONU-AP$_2$ followed by ONU-AP$_1$ and ONU-AP$_3$.

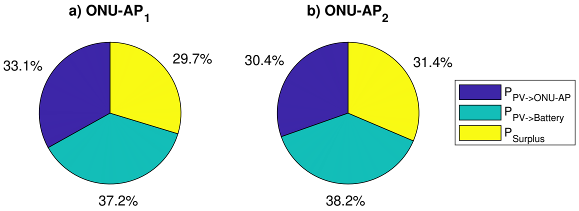


Fig. 9: Solar power requirements for (a) ONU-AP$_1$ and (b) ONU-AP$_2$

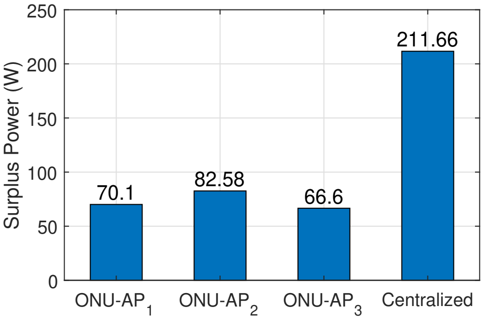


Fig. 10: Surplus power of ONU-APs and centralized setup

C. Power consumption for distributed system

The power from the PV panels is used to power the ONU-APs and charge the batteries. Let the power supplied by the PV panels to the ONU-AP be given by $P_{\text{PV}\rightarrow\text{ONU-AP}}$ and power supplied by the PV panels to charge the batteries be given by $P_{\text{PV}\rightarrow\text{Battery}}$. The surplus power available with the PV panels after powering the ONU-AP and charging the batteries is given by P_{Surplus}. Fig. 9 shows the different components of the solar power required for charging the batteries and providing the power to ONU-AP during the daytime. It is evident that surplus power available to the ONU-AP$_1$ is 29.7%. Similarly, in Fig. 9 it is observed that for ONU-AP$_2$ the surplus power available with the PV panels is 31.4%. This surplus power from each ONU-AP is not enough to charge any other ONU-AP and thus, will be wasted in distributed systems.

D. Surplus power

Fig. 10 illustrates the surplus power obtained for the decentralized and centralized setup. The surplus power generated by the PV panels is 70.10 W, 82.58 W and 66.60 W at ONU-AP$_1$, ONU-AP$_2$ and ONU-AP$_3$ respectively. Whereas, for the centralized setup, the surplus power is 211.66 W. It is obvious that in centralized set-up this generated surplus power can be used to support an extra ONU-AP that has the same power consumption profile as the highest power consuming ONU-AP, i.e. ONU-AP$_2$, while keeping the number of PV panels and the batteries same. As the number of batteries increase so does the number of PV panels required to charge it, which in turn

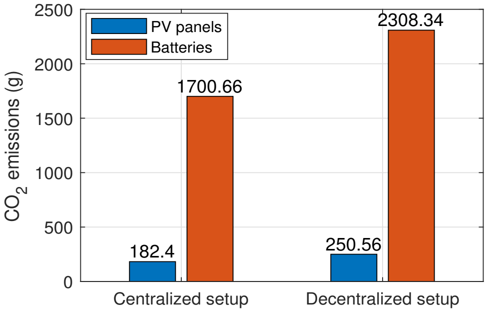


Fig. 11: CO_2 emissions from batteries and PV panels for centralized and decentralized setup

increases the surplus power, as evident from the comparison of surplus power in Figs. 9a and 9b. The surplus power being generated by the centralized setup is enough to power the most power hungry ONU-AP of all. This opens up the possibility of full-fledged deployment of a backup ONU-AP or an additional ONU-AP in centralized setup without requiring any additional power.

E. Carbon Footprint

The CO_2 emissions for centralized and decentralized setup used in this paper is shown in Table II [18]. Fig. 11 shows the comparison of the CO_2 emissions from PV panel and batteries for centralized and decentralized setup. The number of PV panels required in the centralized setup is 81 batteries and 38 PV panels as can be seen from Fig. 7, that gives a CO_2 emission of 1700.66 g and 182.40 g respectively.While for comparison since the centralized setup has the potential to power 4 ONU-APs hence, the for the decentralized setup, we consider the extra ONU-AP with power consumption equivalent to highest power consumption ONU-AP, i.e., ONU-AP_2. Thus, the CO_2 emissions for the decentralized setup is 2308.34 g and 250.86 g, respectively from batteries and PV panels as can be observed from Fig. 11 which is 26.41% higher than the CO_2 emissions from the centralized setup.

TABLE II: CO_2 Emissions [18]

	Battery	PV panel
CO_2 (g/W)	4.22	0.96

V. CONCLUSION

In this paper, we propose three step iterative algorithm (TSIA) to compute and compare the resource requirement for powering the centralized and decentralized setup of a FiWi network. Though there is no significant difference in the resource requirement by either the centralized and the decentralized setup however, the surplus power obtained through the centralized setup up has potential to for possibly powering an additional ONU-AP. Moreover, it has also been shown that there is a scope of carbon footprint reduction from the centralized setup compared to the decentralized setup.

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