Analysis of Water-Filling Random Resource Allocation (W-FRRA) for Energy Saving in Light Fidelity (LiFi)

Brian Pamukti, Vinsensius Sigit W.P., Arfianto Fahmi, Nachwan Mufti Adriansyah and Nur Andini

***Abstract*—In this research, we proposed the resource management based on random mobility for energy savings, called Water-Filling Random Resource Allocation (W-FRRA). To prove our intended, we simulated massive users with different channel conditions in the closed room. We consider that Access Point (AP) has a controller to collect channel state information (CSI) and give several users more power to poor channels, dynamically. We also evaluate our proposed with different maximum and minimum transmitted power. From an extensive simulation study, our results show that best energy savings and performance is obtained using maximum and minimum 3 and 0.8 Watt transmitted power, respectively. For performance, average data rates are achieved around 145 Mbps and energy saving up to 46%. A random user's location and condition affect the Fairness Index (FI) value to 53%. Using coded domain Non-Orthogonal Multiple Access (NOMA) instead of the power domain, we proved that energy saving in different transmitted power does not affect the performance significantly. The performance shows that the total user to serve is 40 for a single AP. At the end of the research, we found that using the W-FRRA algorithm as energy savings can extend the Light Emitting Diode (LED).**

***Index Terms*—channel state information; energy saving; light fidelity; water-filling random resource allocation.**

I. Introduction

The Light Fidelity (LiFi) is a technology that works by laying on the visible light's transmission data. This visible light itself has a wavelength between 400 nm - 700 nm. LiFi has received a lot of attention recently because of its promising features such as unlicensed spectrum, high speed, lower cost, easy installation, and safer data transmission [1]. This technology is very easy to use because light will fade along with increasing distance and small coverage. Also, Wireless Fidelity (WiFi) can not used in several areas, such as hospital, gas station, airplane and places that prohibit for radio frequency.

Manuscript received March 19, 2020; revised September 17, 2020.

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Research [2] developed hybrid systems on radio frequency (RF) VLC for heterogeneous networks. This research investigates not only energy-efficient but various environmental and financial considerations. The integration of RF/VLC results in better performance when compared to just RF alone. Besides, this study is limited to locations in the indoor room, with throughput and interference between RF and VLC on the Access Point (AP) is not considered.

This study [3] arises because of the limited distance for Visible Light Communication, so it needs a parallel path in the form of RF. The resource allocation algorithm applied to VLC/RF that is made hybrid proved to be able to improve power efficiency compared to just using RF itself. The performance of the hybrid system also increased almost five times in this simulation. Discrete multi-tone (DMT) is used because it is useful in the use of a single transmitter. Furthermore, research [4] reviews energy efficiency in smart buildings, with parameters testing humidity, temperature, and CO_2 levels. The study uses sensors to collect weights sent via VLC technology. Energy efficiency is obtained when the data transmitted is heterogeneous. Also, the researcher applied a machine-learning algorithm to a found number of occupants. However, this study does not discuss the number of recipients that affect the VLC system.

Using multiple transmitters increases performance and interference simultaneously. This research [5] used power allocation (PA) and multiple access (MA) to resolve interference between transmitters using heuristic optimization. The increase in VLC throughput in the closed room increases significantly with the same transmit power value. The weakness in this paper is that the power allocation algorithm does not consider the efficiency of sending power, so the MA-DMT effect on cost reduction does not exist.

The research among resource allocation, multiple access, and impact of interferences are studied in [6]. Interference that uses a lot of LEDs causes a decrease in performance on VLC. Many methods are used to reduce interference, such as frequency reuse (FR) and considering resource allocation (RA) schemes. This research proposes the vectored transmission (VP) to minimize interference, but increase the delay in communication. Furthermore, to overcome interference among multiple LEDs, this method is very high complexity.

To accommodate massive users, Non-Orthogonal Multiple Access (NOMA) is a promising method for increasing network and connectivity by fully doubling the spectrum available through sharing non-orthogonal spectrum [7]. NOMA expands many users to use optical frequency and time block in the same spatial frame through the power and code domain. Compared to basic multiple access techniques, NOMA able to serve massive users through the allocation of non-orthogonal resources and allows controllable interference.

The Economic Resource Efficiency (ERE) is built to manage bandwidth and energy efficiency under the smart grid, and cognitive technology has been studied from the researcher [8]. This research used the Orthogonal Frequency Division Multiplexing (OFDM) technique, and the ERE is used to optimization the problem. The results showed that the efficiency obtained was useful and increased the amount of available spectrum.

In this study, we propose Water-Filling Random Resource Allocation (W-FRRA) to serve massive users. We used water-filling resource allocation to deliver different power transmit for different channel state information (CSI). CSI sent channel condition to Access Point (AP), and decision either bigger or lower power will be transmitted. After all of the user channel condition obtain with the almost equal signal to noise ratio (SNR), we use successive interference cancellation (SIC) to support NOMA. In our research, we employee coded instead of the power domain for NOMA. To create our research closer than reality, we consider using room size 5x5x3 m with 64 user equipment (UE) and no interference from sunlight or ambient light. We use data rate, fairness index, and percentage of energy-saving for performance parameters. Besides, if lower power transmits is chosen, the energy saving is obtained.

This research is managed as follows. Part II illustrates the design system for the Non-Line of Sight (NLOS) LiFi system, including the channel model and W-FRRA framework. At the same time, Part III describes the principles of the Water-Filling Random Resource Allocation. Part IV explains the results of our simulation, and closing remarks are drawn in Part V.

II. Research Method

This section discusses the uplink and downlink LiFi system adopted in this research. This research use the attocell AP that accommodates massive users, simultaneously in a different location under its coverage area. In the downlink side, we assumed that AP no interference with uplink. We also consider that uplinks have the potential to use Radio Frequency (RF) or infra-red (IR) [9], but this part is out of scope in this paper. Also, the LED as AP is considered to use channel state information (CSI) for all channel conditions of users, which is the common idea in related research [10], [11], [12]. We assume that attocell has a circular area is divided into two areas, as shown in Fig 1. The first area represents users close to AP with radius r_A, the second area in the middle area between edge and first area with r_B. We classified the user from different area that $U_A = \{U_A\}_{i=1}^{N_A}$ for cell center and second area is $U_A = \{U_B\}_{j=1}^{N_B}$. Every single user has a different channel condition according to non-Line of Sight (NLOS) like shadowing and multi-path.

A. Non-Line of Sight Model

To simulation our research, we consider using the NLOS channel model, so the study was closer to reality. We use the multipath and shadowing tragedy to explain the effect of LiFi performance. The proposed model (Fig. 1) shows that the room has the possibility of a ray path into the line of sight (LOS), reflection, and blocked rays due to any object. It illustrates the power difference in the eight users provided by the access point. With a channel that unable to be predicted, it needs power allocation and utilizes interference by encoding user power. Also, the channel impulse response (CIR) is employed for characterize the circumstances of the channel and analyze the relationship between the LED power signal in transmitter and receiver. We consider CIR in LiFi relates to the LOS (H_{LOS}), multi-path (H_{ref}), and shadowing (H_{shd}) component as given by

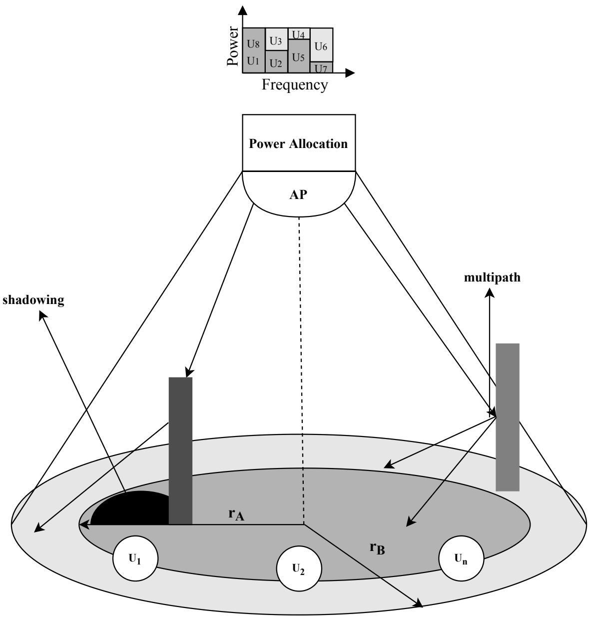

Fig. 1. LiFi system model using power allocation.

$$H = H_{LOS} + H_{ref} + H_{shd}. \tag{1}$$

The channel gain for LOS propagation H_{LOS} using LED as AP with Lambertian radiation pattern is given by [13]

$$H_{LOS} = \frac{A_{det}(m+1)}{2\pi d_k^2}, \cos^m(\phi) T_s(\theta) G_c on(\theta) \cos(\theta), \tag{2}$$

where A_{det} is photodetector area, $T_s(\theta)$ is optical filter, $G_c on(\theta)$ is optical gain concentrator, d_k is propagation distance in the midst of transmitter and receiver, ϕ and θ is incidence angle of light, respectively. The m is Lambertian emission order that relates on the semi-angle half illuminance $\Phi_{1/2}$ from AP and is followed

$$m = \frac{\ln(2)}{\ln(\cos(\Phi_{1/2}))}. \tag{3}$$

We assume that Lambertian reflection from object like walls has multi-path impulse response medium after the r^{th} reflections is followed [13]

$$H_{ref} = \frac{(m+1)}{2\pi} \sum_{j=1}^{Rr} A_j \rho_j \cos^m(\phi_j) \frac{\cos(\theta)}{d_j^2} rect\left(\frac{2\theta}{\pi}\right), \tag{4}$$

where R_r is number of object that reflect the ray, $j\epsilon[1,R_r]$ is index of reflector, ρ_j is surfaces reflection coefficient including walls with j^{th} reflector, A_j is region of the j^{th} reflector, $rect()$ is function of rectangular for sign that photodetector discovered rays below the incidence angle not more than $\frac{\pi}{2}$ and h_{ref}^{r-1} is ordered impulse.

TABLE I
PARAMETERS FOR THIS RESEARCH.

Parameter	Value
Attocell radius r_B	4 m
Attocell-center radius r_A	2 m
Room size	4 x 4 x 3 m
Range transmitted power	2-3 W
Transmitter semi-angle	50°
FOV of photodetector	70°
Photodetector responsivity	0.55 A/W
Area of photodetector	1 cm^2
Power nose spectral density	10^{-21} A^2/Hz
Optical filter	1
Bandwidth of AP	20 MHz
The number of user	64

Also, the shadowing effect able to lead to (4) by involving the probability of blocking O_i as

$$H_{shd} = \frac{(m+1)}{2\pi}\sum_{i=1}^{N_t} A_i \rho_i \cos^m(\phi_i)\frac{\cos(\theta)}{d_i^2} rect\left(\frac{2\theta}{\pi}\right) O_i. \tag{5}$$

If p_v is declared as a probability blocking transmission path from the obstacle (v), with the possible value of the number of obstacles creating N shadowing, then the shadowing distribution can be written as [14]

$$O_i\left[\Pi_{v=1}^{N_t}\left(1-p_v\right)\right] = \exp\left[-E\left(p_v\right)\epsilon t\right]. \tag{6}$$

We also consider natural shot noise from sunlight or ambient light and noise from thermal component to influence the LiFi system. We use total noise variance σ_{tot}^2 as

$$\sigma_{tot}^2 = \sigma_{shot}^2 + \sigma_{th}^2, \tag{7}$$

where σ_{shot}^2 is shot noise and σ_{th}^2 is thermal noise variance. Natural ray such as ambient light or the sun light affects the shot noise, as followed [13]

$$\sigma_{shot}^2 = (I_p + I_{bg} + I_2)2qB_w, \tag{8}$$

where I_p, I_{bg}, and I_2 are primer, background and noise-bandwidth factor, respectively. q is electron charge, B_w is noise bandwidth. We also inspired [13] for thermal noise as

$$\sigma_{th}^2 = \frac{4k_bTB_w}{R_L}, \tag{9}$$

where k_B is Boltzman constant, T device thermal, and R_L is resistance. For the k-th user, the SNR is inspired from [15] and we changed by increasing the random objects to Non-LOS

$$\text{SNR} = \frac{(\gamma P_{tx} H)^2}{\sigma_{tot}^2}, \tag{10}$$

where P_{tx} is transmitted power from k-th user and γ is photodetector responsivity. The channel capacity is obtained from transmission distance between access point and user is express [6]:

$$C_k = B_w \log_2(1+\text{SNR}). \tag{11}$$

To prove our proposed, we consider for simulation parameters that is used in this research as written in Table I.

B. W-FRRA technique

1) Resource management for power allocation: Inspired by resource allocation using the water filling (WF) technique that already implemented in Wireless Communication, this research evaluate the difference between Wireless Communication and Lifi. Lifi using light source from LED and has unipolar modulation, while RF bipolar modulation. We estimate that in AP multi-path, either slow or fast fading is present. Moreover, LED has a narrow coverage compared to WiFi and has dimming control to adjust lower or higher transmit power. Also, the WF algorithm is very urgent for LiFi technology due to the equality of data rate in any channel conditions. Algorithm 1 illustrates pseudocode that we used in this research [16]

Algorithm 1 Water filling random resource allocation.

Input: CSI $\forall$ U$_k$
Output: Avg$C_k \forall$ U$_k$
Initialisation :
$w_l, p_{tot} \leftarrow 0$
$v_{ec} \leftarrow y_k$
$p_{con} \leftarrow$ SNR constr
$t_{constr} \leftarrow 10^{-3}$
$N \leftarrow$ length(v_{ec})
Procedure
while $|(p_{con} - ptot| > t_{constr}$ **do**
$w_l \leftarrow w_l + (p_{con} - p_{tot})/N$
$p_{tot} \leftarrow \sum(\max(w_l - v_{ec}, 0)$
end while
return C_K

We use a single function from the algorithm to calculate the fairness index and data rates of users. The model of mathematical is inspirited by β-proportional fairness index as express [17]

$$\psi_\beta(x) = \begin{cases} \ln(x), & \beta = 1 \\ \frac{x^{1-\beta}}{1-\beta}, & \beta > 0,\ \beta \neq 1 \end{cases} \tag{12}$$

where x is channel capacity and β is coefficient of fairness. The formula has involve several concepts of fairness index to be the validation parameter.

2) Coded domain-NOMA: After we obtained almost the same SNR value for all users, we consider the same number of time-slot as the user. We choose the coded domain instead of the power domain due to the impact on massive users. We evaluate that the power domain-NOMA difficult to decoding in power allocation because each user has a similar power distribution. In that case, we choose the coded domain for NOMA to enhance the performance. Fig. 2 describes about uplink conditions for every channel condition. Each user has the same opportunity to give a request to access points (LED). The weight for each user is the same, as has been done power control using WF. Access points emit a signal in the form of beacons to let you know that access points will clear the user's slot. Each user randomly selects a slot that will be filled through the uplink path. This method was inspired by [18] who had analyzed the Coded Slotted ALOHA (CSA), and we used a model of irregular repetition from researchers [19]. They used CSA in indoor optical wireless communications and quite similar with our research.

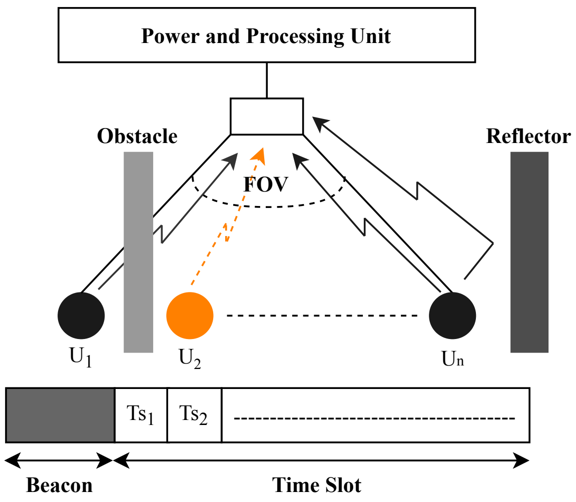

Fig. 2. Request for time-slot from each user.

We simulated NOMA by giving code to each user. Each user transmits a packet that has been coded to be sent through the time-slot. One time-slot can obtain several coded packets and interfere with each other. Time-slot, which only gets one coded packet, decodes and throws the package code from another user. This interference is used by SIC to reduce user code that has obtained time-slot.

Fig 3 (a) illustrates that all user initiate deliver three packets time-slot, randomly. We employ Successive Interference Cancellation (SIC) for unload singleton[1] in time-slot from user k-th. Fig. 3 (b) describes user 64-th (U_{64}) achieve time-slot-2 (T_{S-2}) and U_{64} wipes all of packets for others time-slot, stimmultanously. Afterwards, Fig. 3 (c) explains that time-slot-63 (T_{S-63}) has probability to get T_{S-64} in consequence of singleton. Nevertheless, this algorithm has a serious problem from stopping sets, where none of the time-slots can be obtained. We assume if the singleton does not present all of the time-slots, even the amount of user k-th less than time-slot, our algorithm unable be execute optimally.

III. Result and Discussion

This study uses a computer simulation by taking the random value into account, so the Monte Carlo method approach is used to analyze the simulation results. We also consider the values used in this study, as shown in Table I. The simulated power values are 2, 2.5, and 3 Watt, the detector area for all users is the same (1 cm^2), and the bandwidth of the AP is 20 MHz. Also, to represent the results of simulations and analyzes, we use test parameters such as fairness index, average rate, and percentage of energy saving.

Fig. 4 illustrates the rise in the level of the minimal amount of power that continues to increase. Star marking shows the maximum power used is 3 Watt, circle marking shows 2.5 Watt, and labelling strips represent 2 Watt power curves. Even though the average of 3 Watts is higher between 2 and 2.5 Watts, the power consumption is relatively large. Also, 3 Watts have the potential to obtain the most significant data rates due to signal to noise ratio (SNR). Besides, the difference that is not too significant makes the use of 3 Watts need to be considered.

[1]an offered packet in time-slot

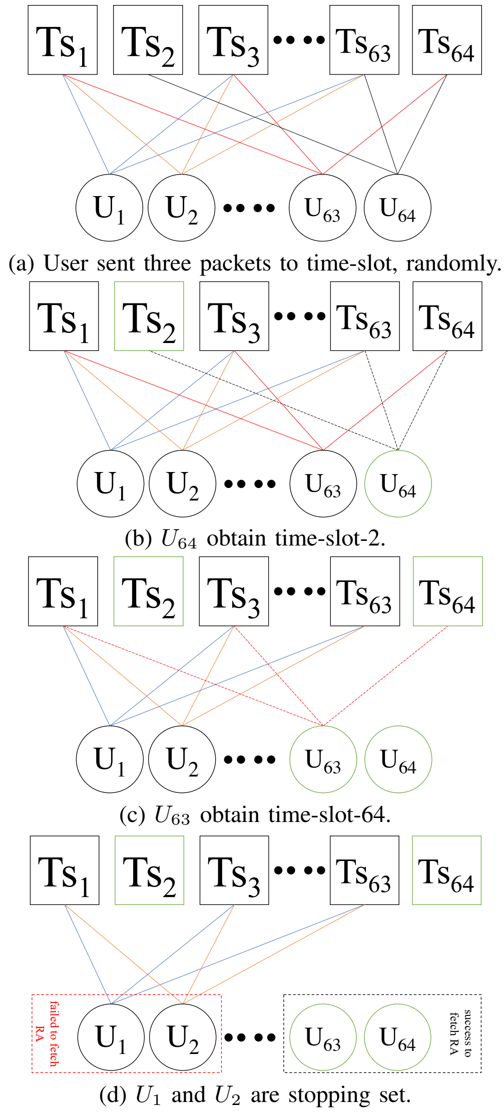

Fig. 3. The bipartite graph coded domain-NOMA technique with random distribution x^3.

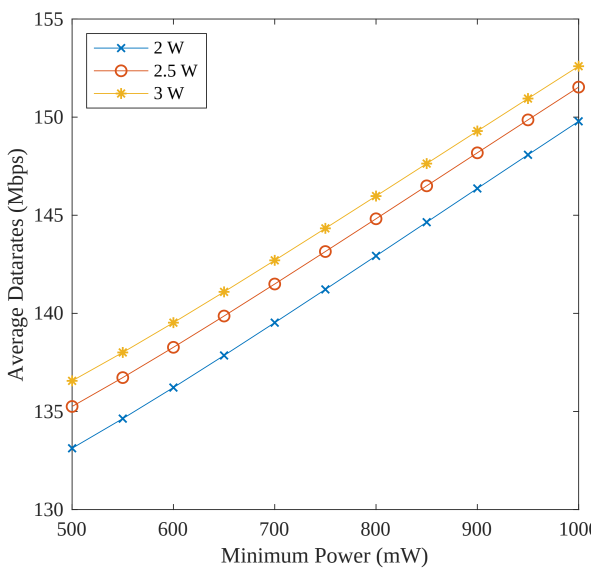

Fig. 4. Performance comparison among different maximum power transmit for average data rate.

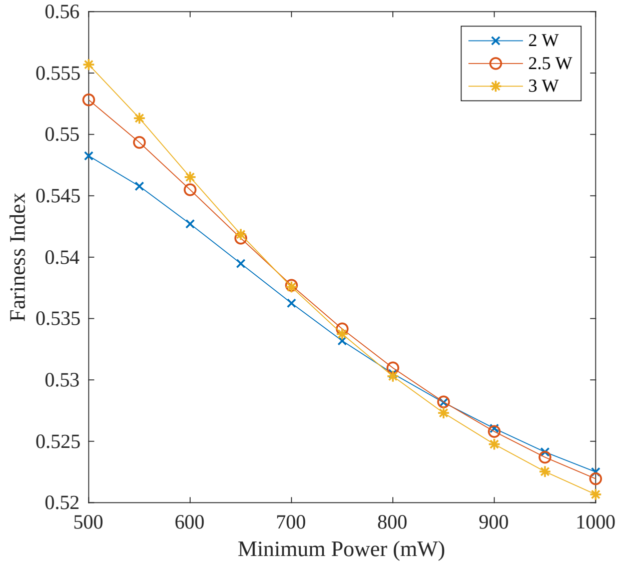

Fig. 5. Comparison of performance among different maximum power transmit for fairness index.

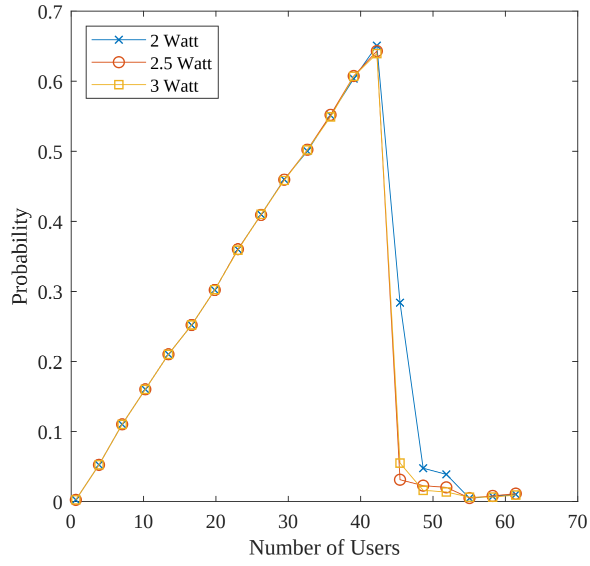

Fig. 7. Performance comparison among different maximum power transmit for probability users per time-slot.

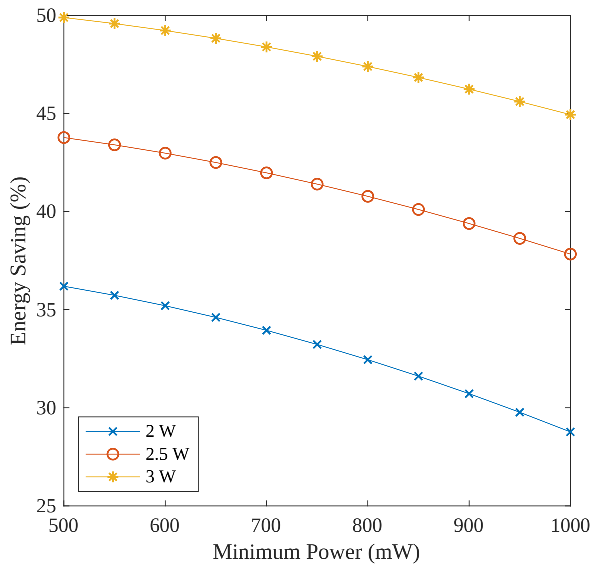

Fig. 6. Performance comparison among different maximum power transmit for energy saving.

We evaluated the fairness index after power allocation is used for 64 users. We found that using dynamic power allocation for different channel conditions have several results. Fig. 5 describes the fairness index curve for the three types of maximum acceptability. Using a minimum power of 500 mW, the difference in fairness index is relatively the same and is in the range of 0.545 to 0.555. An iteration of up to 500 times is done so that accuracy is obtained, to get the same fairness index point at a minimum power of 800 mW. Also, the fairness index curve continues to decline as the minimum power transmitted is transmitted. It has happened due to low power allocation for energy savings, and several users achieve less power. Even though the fairness have similar result around 50/

We investigated the energy saving after power allocation is used for 64 users. We found that using dynamic power allocation for different channel conditions have several results. Fig. 6 explains the comparison of energy-saving obtained from changes in power. Receive power delivered by a maximum power of 3 Watt has the most significant efficiency value from a minimum power of 500 to 1000 mW. By dynamically changing the sending power, resulting in a maximum power saving value of 50% at a minimum power of 500 mW. Due to the channels are different in each place, it takes a different transmit power value according to the condition of the channel. If the LOS channel, then minimal power is considered to deliver. However, if the channel is terrible due to multi-path and shadowing, then the maximum power is transmitted.

We analyzed the probability user per time-slot after coded is used for 64 users. We found that using repetition coded for different channel conditions have similar results. Fig. 7 shows the probability of users obtaining time-slot under various conditions for a different user number. We also show the evidence that W-FRRA in any transmitted power has the same result. The results illustrate that a bigger number of users, better performance, is performed. Although, in 40 users, the stopping set has occurred and Fig. 7 shows asymptotic curve in 0.7 probability. In consequence of the decoding technique in random allocation grants power domain only when the one time-slot has particular channel circumstances, i.e., one located in the cell center. At the same time, the other is tended close to the cell edge.

IV. Conclusion

This paper proposed Water-Filling Random Resource Allocation (W-FRRA) as the random multiple access to serve massive users in future technology. We have simulated this research for resource management systems under any channel conditions. We also investigated the Light Fidelity (LiFi) system behavior using parameter validations of average data rate, fairness, and energy-saving as the power domain parameter. To prove our proposed, we employed Successive Interference Cancellation (SIC) to improve W-FRRA for random multiple access. The probability packet for the massive user is tested and showed that among transmitted power have the same result. We found that power allocation as a water-filling advantage and coded NOMA domain produce significantly better performance and energy savings. We ensure that the proposed algorithm can support "anything as a service" in the future 5G platform. Also, LiFi has significant potential extended to combinations of various technology sectors.

Acknowledgements

We gratefully acknowledge support from the Ministry of Research, Technology, and Higher Education of the Republic of Indonesia.

References

[1] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is lifi?" *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1533–1544, 2016.

[2] M. Kashef, M. Ismail, M. Abdallah, K. A. Qaraqe, and E. Serpedin, "Energy efficient resource allocation for mixed RF/VLC heterogeneous wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 883–893, 2016.

[3] M. Kafafy, Y. Fahmy, M. Abdallah, and M. Khairy, "Power efficient downlink resource allocation for hybrid RF/VLC wireless networks," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2017, pp. 1–6.

[4] Qian Huang, "Review: Energy-Efficient Smart Building Driven by Emerging Sensing, Communication, and Machine Learning Technologies," *Engineering Letters*, vol. 26, no. 3, pp. 320–332, 2018.

[5] D. Bykhovsky and S. Arnon, "Multiple access resource allocation in visible light communication systems," *Journal of Lightwave Technology*, vol. 32, no. 8, pp. 1594–1600, 2014.

[6] F. Jin, X. Li, R. Zhang, C. Dong, and L. Hanzo, "Resource allocation under delay-guarantee constraints for visible-light communication," *IEEE Access*, vol. 4, pp. 7301–7312, 2016.

[7] Opeoluwa Tosin Eluwole, Nsima Udoh, Mike Ojo, Chibuzo Okoro, Akintayo Johnson Akinyoade, "From 1G to 5G, What Next?" *IAENG International Journal of Computer Science*, vol. 45, no. 3, pp. 413–434, 2018.

[8] Baogang Li, Xuewei Wang, Wei Zhao, "Energy Efficiency and Spectral Efficiency Tradeoff in Cognitive Heterogeneous System with Economic Consideration," *Engineering Letters*, vol. 23, no. 3, pp. 215–221, 2015.

[9] Y. Liu, X. Qin, T. Zhang, T. Zhu, X. Chen, and G. Wei, "Decoupled tcp extension for vlc hybrid network," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 10, no. 5, pp. 563–572, 2018.

[10] H. Marshoud, P. C. Sofotasios, S. Muhaidat, B. S. Sharif, and G. K. Karagiannidis, "Optical adaptive precoding for visible light communications," *IEEE Access*, vol. 6, pp. 22 121–22 130, 2018.

[11] N. A. Y. Putri, A. Hambali, and B. Pamukti, "VLC system performance evaluation with addition of optical concentrator on photodetector," in *2019 IEEE International Conference on Signals and Systems (ICSigSys)*. IEEE, 2019, pp. 167–172.

[12] C. Chen, W.-D. Zhong, H. Yang, P. Du, and Y. Yang, "Flexible-rate SIC-free NOMA for downlink VLC based on constellation partitioning coding," *IEEE Wireless Communications Letters*, 2018.

[13] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*. CRC press, 2019.

[14] Z. Dong, T. Shang, Y. Gao, and Q. Li, "Study on VLC channel modeling under random shadowing," *IEEE Photonics Journal*, vol. 9, no. 6, pp. 1–16, 2017.

[15] I. Stefan, H. Burchardt, and H. Haas, "Area spectral efficiency performance comparison between VLC and RF femtocell networks," in *2013 IEEE international conference on communications (ICC)*. IEEE, 2013, pp. 3825–3829.

[16] B. Pamukti, W. V. Sigit, A. Fahmi, N. M. Adriansyah, and N. Andini, "Water-Filling Random Resource Allocation (W-FRRA) Using NOMA for Downlink LiFi System," in *2019 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob)*. IEEE, 2019, pp. 13–18.

[17] Y. Wang, X. Wu, and H. Haas, "Load balancing game with shadowing effect for indoor hybrid LiFi/RF networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2366–2378, 2017.

[18] E. Paolini, G. Liva, and M. Chiani, "Coded slotted ALOHA: A graph-based method for uncoordinated multiple access," *IEEE Transactions on Information Theory*, vol. 61, no. 12, pp. 6815–6832, 2015.

[19] D. Vukobratović and F. J. Escribano, "Adaptive Multi-Receiver Coded Slotted ALOHA for Indoor Optical Wireless Communications," *IEEE Communications Letters*, 2020.

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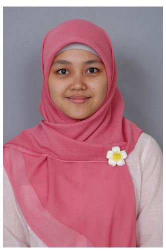

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