This article has been accepted for publication in IEEE Wireless Communications Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LWC.2024.3352705

Proactive Resource Allocation for Aggregated VLC/RF Networks with Outdated CSI

Dimitrios Bozanis, Nikos G. Evgenidis, Vasilis K. Papanikolaou, *Member, IEEE*, Alexis A. Dowhuszko, *Senior Member, IEEE*, Sotiris A. Tegos, *Member, IEEE*, Panagiotis D. Diamantoulakis, *Senior Member, IEEE*, and George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—In this paper, the case of an aggregated VLC/RF network is presented, where the users can be served simultaneously by both a visible light communication (VLC) carrier and a radio-frequency (RF) carrier to increase their achievable data rate. The optimal resource allocation in the network is dependent on always having accurate channel state information (CSI), otherwise, in the case of outdated CSI, the system is prone to sub-optimally allocating resources and, due to the limited coverage of VLC, users may also experience outage. A closed-form expression for the coverage probability is presented for a user moving randomly in the cell. Using this, a proactive resource allocation algorithm is proposed that takes into account outdated CSI which can occur due to user movement, and ensures the outage probability is low in the network without diminishing the average achievable data rate of users. Finally, simulation results validate the proposed analysis and showcase the effectiveness of this approach.**

***Index Terms*—proactive resource allocation, aggregated VLC/RF networks, outdated CSI**

I. Introduction

The escalating demand for wireless communication services, propelled by the widespread proliferation of mobile devices, the ubiquity of the Internet of Things (IoT), and the growing reliance on data-driven applications [1], has given rise to an exponential upsurge in data traffic. Within this context, the domain of optical wireless communications (OWC), which includes visible light communication (VLC), has arisen as an enticing pathway to mitigate the inherent constraints of conventional radio frequency (RF)-based networks [2].

While VLC offers enticing benefits such as license-free bandwidth and immunity to radio-frequency (RF) interference, its pragmatic implementation grapples with challenges pertaining to limited coverage and the prerequisite for unobstructed line-of-sight communication. The fusion of VLC with RF networks has emerged as a strategy to effectively surmount these limitations, harnessing the synergistic attributes of both technologies [3]. In [4], an extended analysis of a selection RF-VLC network was furnished, underscoring its merits over a traditional RF network and performing resource allocation under power, bandwidth, and quality of service (QoS) constraints. Concurrently, [5] embarked on a comparative exploration of diverse network configurations, incorporating the proportional fairness metric to allocate resources [6]. This encompassed standalone RF, standalone VLC, selection-based VLC/RF, and aggregation of VLC/RF networks. The study demonstrated that the carrier aggregation technique, which has been previously employed in wireless networks [7], surpasses other configurations in terms of both fairness and overall performance.

Notwithstanding the potential of integrated networks, the efficient deployment of such frameworks necessitates resource allocation strategies that are adaptable to the dynamics of channel conditions, while also mitigating the repercussions of outdated channel state information (CSI) on system efficiency [8]. The use of proactive handover within a dynamic mobile environment has been studied for an VLC/RF network implementing radio access technology selection [9], while [10] built upon this groundwork by demonstrating experimentally an RSSI-based handover. In a similar scenario, a Q-learning approach was proposed for VLC/RF selection in [11].

The crux of this research endeavor lies in the proposition of a proactive resource allocation scheme for aggregated VLC/RF networks in scenarios marked by outdated CSI. The situation is particularly precarious when a user positioned at the edge of a VLC cell exclusively receives VLC resources, or very limited RF, and subsequently relocates outside the coverage area. Our main goal is to point out and mitigate the problems that outdated CSI induces in this kind of network. To this end, we strive to explore innovative methodologies that can overcome the limited CSI to optimize resource allocation. Our contributions are two-fold: firstly, the formulation of a proactive resource allocation algorithm with the utilization of a CSI estimation based on the delay and with the calculation of the probability of the user staying inside the VLC cell, and secondly, a performance evaluation across a spectrum of VLC cells. We intend to not only address the problems posed by outdated CSI in the context of aggregated VLC/RF networks, which were never studied before for VLC/RF integration at the MAC layer, but also to provide a robust foundation for superior network performance in dynamic scenarios.

II. System Model and Problem Formulation

The hybrid communication system under consideration, which utilizes VLC/RF carrier aggregation to provide indoor wireless access, is illustrated in Fig. 1. It comprises a Remote Radio Unit (RRU), a Remote Optical Unit (ROU), and a scheduler in charge of the management of communication resources

D. Bozanis and N. G. Evgenidis are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece (e-mails: dimimpoz.ece.auth.gr, nevgenid@ece.auth.gr).

V. K. Papanikolaou is with the Institute for Digital Communications, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), 91054 Erlangen, Germany (e-mail: vasilis.papanikolaou@fau.de).

A. A. Dowhuszko is with the Department of Information and Communications Engineering (DICE), Aalto University, 02150 Espoo, Finland (e-mail: alexis.dowhuszko@aalto.fi).

S. A. Tegos and P. D. Diamantoulakis are with the Department of Applied Informatics, University of Macedonia, 54636 Thessaloniki, Greece (e-mails: sotiristegos@ieee.org, padiaman@ieee.org).

G. K. Karagiannidis is with with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece and also with the Artificial Intelligence & Cyber Systems Research Center, Lebanese American University (LAU), Lebanon (e-mail: geokarag@auth.gr).

The work of S. A. Tegos and P. D. Diamantoulakis was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers” (Project Number: 7280). This work was based upon work from European Union’s Horizon 2020 COST Action CA19111 (European Network on Future Generation Optical Wireless Communication Technologies, NEWFOCUS).

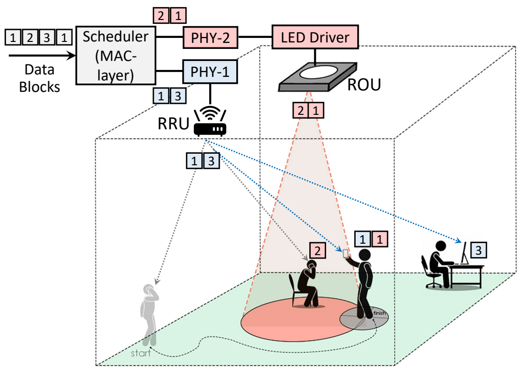

Fig. 1: System model.

on both RF and optical carriers to serve N users. Note that the illumination of the room is not obligatory based on this ROU, which can also be in the Infrared (IR) band, while other LEDs could be used for illumination only. We focus on the downlink direction of communication, where the fixed or moving users with index n in set $\mathcal{N} = \{1, ..., N\}$ have the possibility to receive data simultaneously over both RF and VLC carriers. Without loss of generality, all mobile users are equipped with single RF antennas and optical photodetectors (PDs). The RRU provides coverage in the whole room, whereas the ROU provides coverage in the central part, inside a circular cell of radius R_v. Co-channel (inter-cell) interference coming from RRU/ROU in adjacent rooms is assumed negligible, while with the usage of Orthogonal Multiple Access (OMA) intra-cell interference is also avoided. Hence, co-channel interference is assumed negligible with respect to the noise.

A. Achievable data rate on VLC/RF with CSI feedback delay

When the carrier aggregation approach is used to define the scheduling weights on both RF and VLC carriers, and there is a delay in reporting the CSI estimated in the user terminals to the CPU that makes the scheduling decisions, the aggregate data rate that user n can achieve in Transmission Time Interval (TTI) with index i is given as

$$R_n[i] = \alpha_{n|i-1}\, r_n^{(\mathrm{RF})}[i] + \beta_{n|i-1}\, r_n^{(\mathrm{VLC})}[i], \tag{1}$$

where $r_n^{(\mathrm{RF})}[i]$ and $r_n^{(\mathrm{VLC})}[i]$ are the actual data rates that are achievable when all the communication resources from the RRU and ROU are allocated to user n, respectively, whereas $\alpha_{n|i-1}$ and $\beta_{n|i-1}$ are the scheduling weights applied in transmission at time instant i. Note that $\alpha_{n|i-1}, \beta_{n|i-1} \in [0, 1]$ are the fraction of the orthogonal multiple access resources that the RRU and ROU allocate to user n when *outdated* CSI is used to solve the optimization problem that defines the allocation of resources on the carriers. The presence of outdated CSI in (1) is explicitly represented with the *conditioned* sub-index $i - 1$ that is included in the notation of the scheduling weights. A more generalized approach would be using $i - d_n$, which is equivalent to a variable feedback delay due to users moving at different speeds. However, for simplicity, we assume that $d_n = 1$, considering that the speed of moving users indoors is not notably different.

The data rate and Signal-to-Interference-plus-Noise Ratio (SINR) on RF carrier for user n at time instant i becomes

$$r_n^{(\mathrm{RF})}[i] = B\log_2\left(1+\gamma_n^{(\mathrm{RF})}[i]\right), \quad \gamma_n^{(\mathrm{RF})}[i] = \frac{L_n[i]|g_n[i]|^2 P}{I_n^{(\mathrm{RF})}[i] + N_0^{(\mathrm{RF})}B}, \tag{2}$$

respectively, where $L_n[i]$, $g_n[i]$, P, and B denote the path loss attenuation [12], the normalized fast fading coefficient, the mean transmission power, and the full communication bandwidth of the RRU, whereas $I_n^{(\mathrm{RF})}[i]$ and $N_0^{(\mathrm{RF})}$ identify the co-channel interference power (which is assumed negligible) and the spectral power density of the Additive White Gaussian Noise (AWGN) in the RF receiver at user n, respectively.

Let us now model the communication on VLC, where

$$h_n[i] = \frac{(m+1)A_{\mathrm{pd}}\cos^m(\phi_n[i])\cos(\psi_n[i])T_{\mathrm{o}}g_{\max}}{2\pi\, d_n^2[i]}, \quad 0 \le \psi \le \Psi_{\mathrm{c}}, \tag{3}$$

is the gain of the optical wireless channel between the ROU and user n at time instant i. Note that in (3), A_{pd} is the sensitive area of the PD, $m = -1/\log_2\left[\cos(\Phi_{1/2})\right]$ is the Lambertian order of the LED that is related to its semi-angle at half power ($\Phi_{1/2}$), and $\phi_n[i]$, $\psi_n[i]$, and $d_n[i]$ are the angle of irradiance, angle of incidence, and Euclidean distance between the LED and the PD of user n at time i, respectively. Finally, T_{o}, $g_{\max}$, Ψ_{c} are the transmittance of the optical filter, the gain of the optical concentrator, and the Field-of-View (FOV) semi-angle of the PD, respectively.

In this case, the feasible data rate and SINR on the VLC carrier for user n at time instant i can be approximated as

$$r_n^{(\mathrm{VLC})}[i] = W\log_2\left(1+\frac{\gamma_n^{(\mathrm{VLC})}[i]}{2\pi/e}\right), \gamma_n^{(\mathrm{VLC})}[i] = \frac{(\eta\, h_n[i]\, p)^2}{I_n^{(\mathrm{VLC})}[i] + N_0^{(\mathrm{VLC})}W}, \tag{4}$$

respectively, where p and W are the optical power and the electrical communication bandwidth of the ROU for data communications, whereas η, $I_n^{(\mathrm{VLC})}[i]$, and $N_0^{(\mathrm{VLC})}$ are the PD responsivity, the co-channel interference (which is assumed negligible), and the variance of the AWGN noise in the VLC receiver of user n, respectively. Note that the right-hand side of (4) is the lower bound for the capacity of an intensity-modulated direct-detected optical wireless channel [13].

B. Optimization problem for VLC/RF resource allocation

Let $\boldsymbol{\alpha} \in \mathbb{R}^{1\times N}$ and $\boldsymbol{\beta} \in \mathbb{R}^{1\times N}$ denote the weight vectors that contain the fraction of the resources that the Scheduler allocates to the users on the RF (α_n) and the VLC (β_n) carriers, respectively. By employing the proportional fair utility function we provide a trade-off between maximizing the overall sum data rate and ensuring fairness, which could be negatively affected by the diversity of such networks in terms of resource allocation among the users. This metric is widely used in various works such as [4], [5], [6], i.e., $u_{\mathrm{sum}}(R_1, \ldots, R_n) = \sum_{n\in\mathcal{N}} u_n(R_n) = \sum_{n\in\mathcal{N}} \ln(R_n)$, the following optimization problem results:

$$\begin{aligned} \max_{\boldsymbol{\alpha},\boldsymbol{\beta}} \quad & \sum_{n\in\mathcal{N}} \ln\left(\alpha_n\, r_n^{(\mathrm{RF})} + \beta_n\, r_n^{(\mathrm{VLC})}\right) \\ \text{s.t.} \quad & \mathrm{C}_1 : \|\boldsymbol{\alpha}\|_1 \le 1; \quad \mathrm{C}_2 : \|\boldsymbol{\beta}\|_1 \le 1 \\ & \mathrm{C}_3 : 0 \le \alpha_n, \beta_n \le 1, \; \forall n \in \mathcal{N}, \end{aligned} \tag{5}$$

where $\|\cdot\|$ is the norm 1 of the vector. Note that in (5), constraints C_1 and C_2 are due to the allocation of orthogonal resources when serving users in the RF and VLC carriers, respectively, whereas constraint C_3 states that scheduling weights in both carriers must be positive and (in total) no larger than the available ones in the remote units. Then, if a mobile user $n \in \mathcal{N}$ is out of range or does not receive any communication resources from the RRU (ROU), the corresponding scheduling coefficient α_n (β_n) is equal to zero. The interdependence of the scheduling weights, α and β, in the objective function justifies that the problem is coupled over both RF and VLC bands, with the aim of ensuring a proportional fair provision of data rate amongst the users.

It can be shown that the optimization problem presented in (5) is convex and that the optimal solution corresponds to the global maximum of the sum proportional fairness utility function of the aggregate VLC/RF system. For simplicity, the time indexes i were omitted when presenting the optimization problem. We note that the actual challenge is not the derivation of an optimization algorithm to solve (5), but rather its transformation into another optimization problem that not only mitigates the impact of outdated CSI in the presence of fragmented VLC coverage, but also ensures fairness when scheduling resources jointly on the RF and VLC carriers.

III. Proactive scheduling with outdated CSI

In the presence of feedback delay when reporting the CSI on both VLC and RF carriers, the computation of scheduling weights α_n and β_n in the optimization problem (5) is done with the data rates dictated by (2) and (4) in a previous time instant. Without loss of generality, it can be assumed that feedback delay equals the duration of a TTI. Then, the achievable data rates to be plugged in the objective function of (5) should be $r_n^{(\mathrm{RF})}[i-1]$ and $r_n^{(\mathrm{VLC})}[i-1]$, respectively.

Then, the objective function that corresponds to the optimization problem (5) with outdated CSI can be rewritten as

$$\begin{aligned}\{\boldsymbol{\alpha}_{i-1},\boldsymbol{\beta}_{i-1}\} &= \{(\alpha_{1|i-1},...,\alpha_{N|i-1})^{\mathrm{T}},(\beta_{1|i-1},...,\beta_{N|i-1})^{\mathrm{T}}\}\\ &= \arg\max_{\{\boldsymbol{\alpha},\boldsymbol{\beta}\}}\left\{\sum_n \log(\alpha_n\, r_n^{(\mathrm{RF})}[i-1]+\beta_n\, r_n^{(\mathrm{VLC})}[i-1])\right\}, \quad (6)\end{aligned}$$

where $\boldsymbol{\alpha}_{i-1}$ and $\boldsymbol{\beta}_{i-1}$ are the vectors that contain the scheduling weights $\alpha_{n|i-1}$ and $\beta_{n|i-1}$ for users $n \in \mathcal{N}$ to be applied in transmission at time instant i, when the achievable data rates in both RF and VLC bands will be different from the ones used in the optimization problem (at time $i-1$).

However, if *proactive* scheduling were used, such that the data rates of the objective function were the estimated actual data rates at the current time instant, the objective function of the new optimization problem becomes

$$\begin{aligned}\{\widehat{\boldsymbol{\alpha}}_{i-1},\widehat{\boldsymbol{\beta}}_{i-1}\} &= \{(\widehat{\alpha}_{1|i-1},...,\widehat{\alpha}_{N|i-1})^{\mathrm{T}},(\widehat{\beta}_{1|i-1},...,\widehat{\beta}_{N|i-1})^{\mathrm{T}}\}\\ &= \arg\max_{\{\boldsymbol{\alpha},\boldsymbol{\beta}\}}\left\{\sum_n \log(\alpha_n\, \widehat{r}_n^{(\mathrm{RF})}[i]+\beta_n\, \widehat{r}_n^{(\mathrm{VLC})}[i])\right\}, \quad (7)\end{aligned}$$

where $\widehat{r}_n^{(\mathrm{RF})}[i]$ and $\widehat{r}_n^{(\mathrm{VLC})}[i]$ are the estimated data rates that would be achievable *on average* on both RF and VLC carriers, respectively, using for this estimation the available side information at the current time instant. Note that since the achievable data rate on the RF carrier is not expected to change notably between adjacent TTIs, $r_n[i] \approx r_n[i-1]$ holds, thus $\widehat{r}_n[i] \approx r_n[i-1]$ can be used in (7). Unfortunately, this is not the situation on the VLC carrier, especially when the user is moving around the cell edge since there is a high probability that the actual data rate over VLC drops to zero in the next TTI if the user steps out of the service area.

A. Achievable data rate on VLC carrier with outdated CSI

Let us assume that $q_n[i]$ is the probability that user n is inside the VLC cell at scheduling time instant i, based on the position that the user had at time $i-1$. Then, the VLC data rate that is expected at time instant i can be modeled as

$$\widehat{r}_n^{(\mathrm{VLC})}[i] = \mathbb{E}\{r_n^{(\mathrm{VLC})}[i]\} = q_n[i]\,\mathbb{E}\{r_{n|\mathrm{in}}^{(\mathrm{VLC})}[i]\} + (1-q_n[i])\,\mathbb{E}\{r_{n|\mathrm{out}}^{(\mathrm{VLC})}[i]\}, \quad (8)$$

where $\mathbb{E}\{r_{n|\mathrm{in}}^{(\mathrm{VLC})}[i]\}$ is the mean data rate that is expected for user n at time instant i assuming that it will have VLC coverage when the scheduling weights are applied. Note that the estimated data rate $\widehat{r}_n^{(\mathrm{VLC})}[i]$ varies with the position of the user at the previous time instant, and is different from zero if $q_n[i] > 0$. Note that the received signal coming from the ROU drops to zero when the position of user n is outside the VLC cell; due to that, the second term of (8) vanishes.

B. Probability of VLC coverage in next scheduling slot

Let us assume that the mobile user terminal changes its position on a horizontal plane of height z, following a predefined Random Walk (RW) process in which the position in the next scheduling time instant will be uniformly distributed in a circle with radius r_{rw} (max. step size) centered in the current position [14]. When modeling this RW process in polar coordinates, it is equivalent to state that the angle of the movement of the mobile user θ_{rw} follows a uniform distribution in the interval $[0, 2\pi)$, whereas the length of the step that the user takes at any time instant L_{rw} follows a distribution that is equal to the one that corresponds to the square root of a uniform random variable in the interval $[0, r_{\mathrm{rw}}]$.

Lemma 1: The probability of having VLC coverage after one RW step with maximum length size r_{rw} is given by

$$\begin{aligned}q_n[i] &= \cos^{-1}\!\left(\frac{s^2[i]-r_{\mathrm{rw}}^2+R_v^2}{2\,s[i]\,R_v}\right)+r_{\mathrm{rw}}^2\cos^{-1}\!\left(\frac{s^2[i]+r_{\mathrm{rw}}^2-R_v^2}{2\,s[i]\,r_{\mathrm{rw}}}\right)\\ &\quad -\frac{\sqrt{(r_{\mathrm{rw}}+R_v-s[i])(r_{\mathrm{rw}}+s[i]-R_v)(s[i]+R_v-r_{\mathrm{rw}})(s[i]+r_{\mathrm{rw}}+R_v)}}{2}, \quad (9)\end{aligned}$$

where R_v is the radius of the VLC cell and $s[i]$ is the distance between the initial position of the moving user and the center position of the VLC cell. All distances are measured in the horizontal plane of height z on which the user terminal moves.

Proof: The proof is presented in Appendix A. ■

C. Expected data rate on VLC carrier in next scheduling slot

Considering the described RW process, and assuming that $r_{\mathrm{rw}} < R_v$ is verified, we study two angles of interest when the circles that describe the VLC service area (R_v) and the reachable range of the moving user after a step (r_{rw}) intersect. These angles are ψ_1 and ψ_2, which are the smallest and largest incidence angles of the position that the moving user can reach inside the VLC cell after one step, respectively. Note that when both LED and PD are pointing perfectly downwards and upwards, respectively, the incidence angle is equal to the irradiance angle (i.e., $\phi = \psi$), and $\psi_2 = \Psi_{\mathrm{c}}$ when the farthermost position after one step is on the cell edge.

Lemma 2: The angle of irradiance/incidence at which the achievable data rate on the VLC is equal to the average value of the data rate that is feasible for VLC in all the positions that are reachable by the RW process after one step is

$$\psi_{\mathrm{av}} = f^{-1}(I), \qquad f(\psi) = W\log_2\left(1+b\cos^{2m+6}(\psi)\right), \quad (10)$$

where $f^{-1}(\cdot)$ denotes the inverse of the function that determines the VLC data rate for incidence angle ψ, and

$$b = \frac{e}{2\pi}\left(\frac{(m+1)A_{\mathrm{pd}}T_{\mathrm{o}}g_{\max}\,\eta}{2\pi z^2}\right)^2\frac{p^2}{N_0^{(\mathrm{VLC})}W} \quad (11)$$

is a constant that does not depend on the incidence angle, and I is the mean data rate of the user on the VLC after one step, which is calculated as

This article has been accepted for publication in IEEE Wireless Communications Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LWC.2024.3352705

TABLE I: Simulation Parameters of the hybrid RF-VLC system.

p	1 W	n_c	1.5
η	0.53 A/W	$\Phi_{1/2}$	Ψ_c
$N_0^{(\mathrm{VLC})}$	5×10^{-22} A^2	d_{bp}	5 m
W	25 MHz	P	1 W
A_{pd}	1 cm^2	B	10 MHz
T_{o}	1	$N_0^{(\mathrm{RF})}$	4.002×10^{-21} A^2/W
z	1.5 m	f_{c}	3.5 GHz

$$I = \left\{ \int_{\psi_1}^{\psi_0} \log_2\left[1 + b\cos^{2m+6}(\psi)\right] \frac{\sqrt{r^2 - (z\tan(\psi) - s)^2}}{\cos^2(\psi)} d\psi \right.$$
$$\left. + \int_{\psi_0}^{\psi_2} \log_2\left[1 + b\cos^{2m+6}(\psi)\right] \frac{\sqrt{R^2 - (z\tan(\psi))^2}}{\cos^2(\psi)} d\psi \right\} \frac{zW}{E}, \quad (12)$$

where E denotes the area of the intersected circles, while ψ_0 is the incidence angle for the position inside the overlapping area, denoted as x_0, which is shown in Fig. 1.

Proof: The proof is presented in Appendix B. ■

IV. Numerical Results

Simulations are presented assuming three users in a room of size $5\,\mathrm{m} \times 5\,\mathrm{m} \times 3\,\mathrm{m}$: two users are stationary (one on the center and the other outside the VLC cell) and the remaining one is moving following an RW process. The simulation parameters of the hybrid VLC/RF system are summarized in Table I. We assume that $\Phi_{1/2} = \Psi_c$ to ensure fair comparisons and avoid poor VLC channel conditions for users positioned at angles between $\Phi_{1/2}$ and Ψ_c. Additionally, the maximum step size for the moving user is set to $r_{\mathrm{rw}} = 0.5\,\mathrm{m}$.

Fig. 2 shows the Cumulative Distribution Function (CDF) of the VLC/RF aggregated data rate assuming three different VLC cell sizes (R_v), and the CDF of the feasible data rate of an RF-only network. When studying the ultra-reliability region of this CDF, it is observed the outdated CSI in (6) impacts the system performance. Note that when only VLC resources are allocated with outdated CSI to the moving user, the moving user may be out of the VLC cell once the scheduling weights are actually applied, creating this service outage situation. This is not a problem with stationary users, as their situation with respect to the VLC cell will not change at all. Thus, the actual outage probability, P_{out}, for the moving user would be three times the value depicted in Fig. 2, where $P_{\mathrm{out}} = \Pr(R_n[i] \leq R_{\mathrm{out}})$, which is equivalent to a complete communication disruption when $R_{\mathrm{out}} = 0$. Another notable finding is that the RF-only network is less affected by outdated CSI, leading to better data rate reliability when compared to the aggregated VLC/RF network with outdated CSI. However, the proactive scheme outperforms the RF-only network in terms of data rate in the ultra-reliability region, as evidenced by the substantial gap between their CDFs.

The primary concern arises when the moving user is located at the edge of the VLC cell and receives only VLC resources (or very limited RF resources) based on the outdated CSI. Then, if such a user moves out of the VLC cell once the scheduling weights are actually applied, the allocated VLC resources are wasted and communication is disrupted. Another interesting observation from Fig. 2 is that the intermediate cell radius ($R_v = 2.0\,\mathrm{m}$) exhibits the highest outage probability. This can be attributed to the statistical likelihood of being situated at the cell edge, which is higher in this radius compared to the other two. Furthermore, the proactive resource allocation on VLC/RF carriers prevents any communication disruption for various VLC cell sizes, promoting fairness among the feasible data rates for all fixed and mobile users.

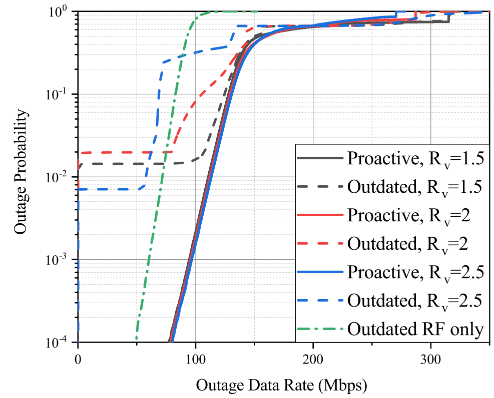

Fig. 2: CDF of the VLC/RF aggregate data rate that a fixed/mobile user can achieve with large ($R_v = 2.5\,\mathrm{m}$), medium ($R_v = 2.0\,\mathrm{m}$), and small ($R_v = 1.5\,\mathrm{m}$) VLC cell sizes.

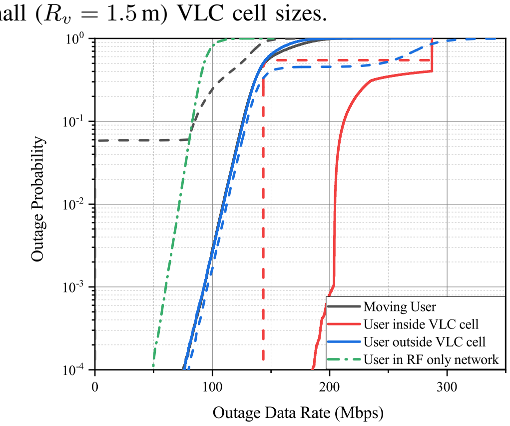

Fig. 3: CDF of the VLC/RF data rate that the mobile/fixed users achieve individually when outdated (dashed lines)/proactive scheduling is performed for a medium VLC cell size ($R_v = 2.0\,\mathrm{m}$).

Fig. 3 presents the CDFs for the average data rate that the three users can achieve individually in an aggregated VLC/RF network when the VLC cell radius is $R_v = 2\,\mathrm{m}$. As a baseline, the data rate in the case of an RF-only network is also included. The disparities between the outdated and proactive allocation schemes are evident. In the outdated CSI scenario, the moving user experiences the most unfavorable conditions, with an outage probability exceeding 6% and significantly lower data rates compared to the two fixed users. In contrast, when proactive scheduling is applied, more RF resources are given to the moving user as a backup, especially when it is in the VLC cell edge area, leading to similar performance as the one achieved by the fixed user outside the VLC cell. As an added value, the VLC resources that the moving user does not utilize can be used by the fixed user placed inside the VLC cell. This proactive scheduling approach yields a significant improvement for the moving user and offers a favorable trade-off. Furthermore, it is noteworthy that all users in both scenarios exhibit substantial performance improvements over the RF-only network. The only exception is the mobile user in the outdated scenario, who faces eventually outages resulting in poor performance in the ultra-reliability region of the CDFs. The only minor drawback is that the fixed user outside the

VLC cell experiences a slight decrease in performance, as part of the RF resources received previously with outdated CSI are used as a backup for the mobile user.

V. Conclusions

In this paper, an aggregated VLC/RF network with outdated CSI was studied. A proactive allocation scheme was proposed to counter the communication outage, which emanates from the VLC cell edge users. Formulas for both the probability of a user staying inside the VLC cell and the estimated VLC data rate until the next CSI report were extracted. Finally, simulation results verified the benefits and the gain in the reliability region, by completely avoiding any outage, without any loss in the mean data rate of the users.

Appendix A - Proof of Lemma 1

Let us assume two circles $\mathcal{C}_1$ and $\mathcal{C}_2$ of radius R and r centered on a horizontal plane at height z at positions $(x_1, y_1) = (0, 0)$ and $(x_2, y_2) = (s, 0)$, respectively. Let us assume that the intersection of $\mathcal{C}_1 \cap \mathcal{C}_2$ is a region shaped like an asymmetric lens consisting of two circular segments. The x-coordinate of the two intersecting points can be calculated as $x_0 = (s^2 - r^2 + R^2)/(2s)$.

Let A_1 (A_2) denote the area of circle $\mathcal{C}_1$ ($\mathcal{C}_2$) that falls outside the chord that contains x_0. Then, the probability of having VLC coverage after one RW step equals

$$\begin{aligned} q_{\text{in}} &= \frac{A_1 + A_2}{\pi r_{\text{rw}}^2}, A_1 = R^2 \cos^{-1}\left(\frac{x_0}{R}\right) - x_0\sqrt{R^2 - x_0^2}, \\ A_2 &= r^2 \cos^{-1}\left(\frac{s - x_0}{r}\right) - (s - x_0)\sqrt{R^2 - x_0^2}. \end{aligned} \quad (13)$$

After substituting x_0 and doing algebraic manipulations, we obtain the formula given in (9).

Appendix B - Proof of Lemma 2

Let us assume that the irradiance and incidence angles are equal ($\phi = \psi$). Then, by replacing $d = z/\cos(\psi)$ in (3) and clustering all the terms that are fixed and do not depend on the position of the user, we get (10). Let also $\mathcal{C}_1$ and $\mathcal{C}_2$ be the overlapping circles defined in Appendix A, where x_0 is the intersection between the chord that defines the overlapping area ($\mathcal{C}_1 \cap \mathcal{C}_2$) and the line that connects the two circle centers.

Since the two circles overlap, the minimum and maximum incidence angle the mobile user can experience after one RW step are given by $\psi_1 = \arctan\left(\frac{s-r}{z}\right)$ and $\psi_2 = \Psi_{\text{c}}$, respectively. Since the function $f(\psi)$ in (10) is a monotonically decreasing function with respect to ψ in the interval $[0, \pi/2]$, there is only one point in the diacentric line that equals the average value of the achievable data rate for all points in the overlapping area. It is vital to take into consideration that we are searching for a point on the $x-$axis while the user's movement is in polar coordinates. In order to bridge this difference, we need to introduce a cdf as a function of x for the user. If x_0 is the x-coordinate of the intersecting points, let the function f_1 be given as

$$f_1(x) = \begin{cases} \sqrt{r^2 - (x - s)^2} & s - r \leq x \leq x_0, \\ \sqrt{R^2 - x^2} & x_0 < x \leq R. \end{cases} \quad (14)$$

Now, the intersected area is given as

$$\begin{aligned} E &= \int_{s-r}^{R} f_1(x)\,\mathrm{d}x = \int_{\psi_1}^{\psi_2} f_1(z\tan(\psi))\frac{z}{\cos^2(\psi)}\,\mathrm{d}\psi \\ &= \int_{\psi_1}^{\psi_2} f_2(\psi)\,\mathrm{d}\psi, \end{aligned} \quad (15)$$

where

$$f_2(\psi) = \begin{cases} \frac{z}{\cos^2(\psi)}\sqrt{r^2 - (z\tan(\psi) - s)^2} & \psi_1 \leq \psi \leq \psi_0, \\ \frac{z}{\cos^2(\psi)}\sqrt{R^2 - (z\tan(\psi))^2} & \psi_0 < \psi \leq \psi_2 \end{cases} \quad (16)$$

and $\psi_0 = \arctan(x_0/z)$. Let $g(\psi) = f_2(\psi)/E$, then

$$\int_{\psi_1}^{\psi_2} g(\psi)\,\mathrm{d}\psi = \frac{1}{E}\int_{\psi_1}^{\psi_2} f_2(\psi)\,\mathrm{d}\psi = 1. \quad (17)$$

From the first mean value theorem for definite integrals, it is known that the average value of a function is given at a point $\psi_{\text{av}} \in [\psi_1, \psi_2]$, where

$$f(\psi_{\text{av}})\int_{\psi_1}^{\psi_2} g(\psi)\,\mathrm{d}\psi = \int_{\psi_1}^{\psi_2} f(\psi)g(\psi)\,\mathrm{d}\psi. \quad (18)$$

which could be further analyzed by combining $g(\psi)$ with (16) and (17). This results in $f(\psi_{\text{av}}) = I$ as it's given in (12), from which ψ_{av} can be found after taking the inverse of f. This integral can be calculated with arithmetic methods. Finally, the x-coordinate can be calculated to be $x_{\text{av}} = z\tan(\psi_{\text{av}})$.

References

[1] C.-X. Wang, J. Huang, H. Wang, X. Gao, X. You, and Y. Hao, "6G Wireless Channel Measurements and Models: Trends and Challenges," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 22–32, Oct. 2020.

[2] P. Dwivedy, V. Dixit, and A. Kumar, "A Survey on Visible Light Communication for 6G: Architecture, Application and Challenges," in *Proc. Int. Conf. on Comput., Electron. & Elect. Eng. & Appl.*, Jun. 2023, pp. 1–6.

[3] H. Abuella, M. Elamassie, M. Uysal, Z. Xu, E. Serpedin, K. A. Qaraqe, and S. Ekin, "Hybrid RF/VLC Systems: A Comprehensive Survey on Network Topologies, Performance Analyses, Applications, and Future Directions," *IEEE Access*, vol. 9, pp. 160 402–160 436, Nov. 2021.

[4] V. K. Papanikolaou, P. D. Diamantoulakis, P. C. Sofotasios, S. Muhaidat, and G. K. Karagiannidis, "On Optimal Resource Allocation for Hybrid VLC/RF Networks With Common Backhaul," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 1, pp. 352–365, Jan. 2020.

[5] D. Bozanis, V. K. Papanikolaou, A. A. Dowhuszko, K. G. Rallis, P. D. Diamantoulakis, J. Hämäläinen, and G. K. Karagiannidis, "Optimal Aggregation of RF and VLC Bands for Beyond 5G Mobile Services," in *Proc. 18th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2022, pp. 75–80.

[6] L. Yang, Z. Huang, X. Yi, H. Wang, L. Li, and S. Lyu, "Improved Proportional Fairness Algorithm in Visible Light Communication / WiFi Hybrid Networks," in *Proc. 19th Int. Conf. Opt. Commun. Netw.*, Aug. 2021, pp. 1–3.

[7] F. Khoramnejad, R. Joda, A. B. Sediq, G. Boudreau, and M. Erol-Kantarci, "AI-Enabled Energy-Aware Carrier Aggregation in 5G New Radio With Dual Connectivity," *IEEE Access*, vol. 11, pp. 74 768–74 783, Jul. 2023.

[8] I. Abdalla, M. Rahaim, and T. Little, "Investigation of Outage Probability and AP Placement for Mobile Users in Indoor VLC System Design," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2019, pp. 1–6.

[9] Y. Wang and H. Haas, "Dynamic Load Balancing With Handover in Hybrid Li-Fi and Wi-Fi Networks," *J. Light. Technol.*, vol. 33, no. 22, pp. 4671–4682, Sep. 2015.

[10] R. N. Sathisha, F. Ahmed, and V. Raghunathan, "Demonstration of RF-VLC Hand-over using Receiver side Channel Selection," in *Proc. 15th Int. Conf. Commun. Syst. & Netw.*, Jan. 2023, pp. 382–386.

[11] S. Shao, Z. Khan, G. Liu, A. Khreishah, M. Ayyash, H. Elgala, T. D. Little, and M. Rahaim, "Poster Abstract: Optimizing Handover Parameters by Q-learning for Heterogeneous RF-VLC Networks," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2019, pp. 1069–1070.

[12] 3GPP. (2018) Study on channel model for frequencies from 0.5 to 100 GHz (3GPP TR 38.901 version 15.0.0 Release 15).

[13] J.-B. Wang, Q.-S. Hu, J. Wang, M. Chen, and J.-Y. Wang, "Tight Bounds on Channel Capacity for Dimmable Visible Light Communications," *J. Light. Technol.*, vol. 31, no. 23, pp. 3771–3779, Dec 2013.

[14] S. Baroudi and Y. R. Shayan, "Outage probability in a circle with uniformly distributed users," in *Proc. 25th IEEE Canadian Conf. Elect. Comput. Eng. (CCECE)*, Apr. 2012, pp. 1–4.