Received July 2, 2020, accepted July 5, 2020, date of publication July 13, 2020, date of current version July 22, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3008761

Resource Allocation and Interference Management Techniques for OFDM-Based VLC Atto-Cells

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ABSTRACT In this paper, a resource partitioning scheme combined with a new multi-carrier optical modulation technique for indoor visible light communication (VLC) system is proposed. In VLC systems, the coverage area is divided into multiple atto-cells. In each atto-cell, multiple LED arrays are used as access points (APs) serving the assigned users. The coverage area of APs might be overlapped to avoid service discontinuity for mobile users. The overlapped coverage zones result in co-channel interference (CCI). We develop a shared frequency reuse (SFR) technique combined with two resource allocation algorithms to minimize interference and maximize the system throughput. This technique divides the overall bandwidth into two parts: the shared and reused bands. The shared band serves the users in the interference area while the reused band serves users in the non-interfering area. Furthermore, we propose a new multi-carrier optical modulation technique called odd clipped optical-OFDM (OCO-OFDM). This technique applies the odd symmetry on the frequency-domain OFDM to enhance the spectral efficiency compared to the asymmetrical clipped optical OFDM (ACO-OFDM) which is currently used. Then we study and evaluate the system performance in terms of the signal-to-interference and noise ratio (SINR), total throughput, and the outage probability. The proposed system achieved total throughput of up to 800 Mbps with 40 dB SINR at the cell edge. Furthermore, the outage probability can be optimized to its minimum value when the receiver field-of-view (FOV) is taken by 40° when the minimum SINR is 10 dB.

INDEX TERMS Visible light communication, OFDM, resource allocation, interference management.

I. INTRODUCTION

A visible light communication system (VLC) is an emerging optical wireless communication technology that is introduced to improve indoor coverage and provide high data rates. VLC has preferred over the radio frequency (RF) communications due to several benefits, including the broad unlicensed bandwidth, low-cost electronic devices, and the interference-less connections with the existing technologies [1]. In the VLC system, the transmitted signal is modulated on the intensity or the phase of the optical transmitter. However, intensity modulation (IM) is considered as the most suitable technique for the VLC system due to its simplicity. On the receiver side, the received intensity-modulated signal is demodulated by the optical detector using direct detection (DD) technique. The optical detector generates an electrical signal proportional to the intensity of the received signal [2]. The Optical wireless communication (OWC) systems in a range of 390–750 nm refers to a visible light communication (VLC). The VLC systems use light-emitting diodes (LEDs) for a dual-function of illumination (lighting) and communication. It employs in various applications, including indoor wireless networks, short-range outdoor communications, and vehicular networks. The OWC systems, also called free-space optical systems (FSO) when operate at near-IR wavelengths (750-1600 nm) [3], [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Mira Naftaly.

Orthogonal frequency division multiplexing (OFDM) has been proposed as the most spectrally efficient technique that provides a high data rate and significantly improves the system capacity due to its robustness to the multi-path fading [5]. A VLC system using a white LED as a communication source requires a real unipolar signal, so optical OFDM techniques have been introduced as asymmetrically clipped optical OFDM (ACO-OFDM), DC-biased optical OFDM (DCO-OFDM) [6], asymmetrically clipped DC-biased optical OFDM (ADO-OFDM) [7] and odd clipped optical OFDM (OCO-OFDM) [8]. In DCO-OFDM, Hermitian symmetry is imposed on all the subcarriers that carry the data, which produces a real bipolar signal, then DC offset is added to get the unipolar signal. While in ACO-OFDM and ADO-OFDM, only the odd subcarriers carry the data to satisfy Hermitian symmetry. However, ADO-OFDM is more optically power-efficient than conventional ACO-OFDM and DCO-OFDM [6], [9]. In OCO-OFDM, Hermitian symmetry is replaced by odd symmetry of Fourier transform, which enhances its spectral efficiency for the real-modulation technique as OCO-OFDM uses pure imaginary odd input signal to produce pure real odd output. The oddness of the output signal adds an advantage to the clipped signal, such that clipping odd real signals do not affect its amplitude, and the distortion is added on the imaginary part of the subcarrier only.

In VLC systems, the coverage area is divided into multiple atto-cells. In each atto-cell, multiple LED arrays are used as access points (APs) serving its assigned users. The coverage area of these APs might be overlapped to avoid the service discontinuity for mobile users. The overlapped zone causes co-channel interference (CCI). Hence, the interference issue is raised in VLC systems. However, several interference management techniques are developed to overcome this issue. In [10], traditional unity-frequency-reuse (UFR) is proposed, and the interference is mitigated using RF technology in the overlapped area. In [11], the authors introduce a static-resource-partitioning technique, which uses different frequencies in the adjacent cells to eliminate the interference. The static resource partitioning technique effectively eliminates the CCI at the cost of reducing the spectral efficiency. Furthermore, the interference-aware resource partitioning is investigated in [12], which depends on broadcasting a busy burst (BB) from the user intending to receive data in the next time slot. The BB adds extra complexity, but it enhances spectral efficiency. In [13], different approach of FFR is introduced as a cost-effective technique that achieves reasonable spectral efficiency with low complexity. This technique depends on assigning different frequency bands to the cell-edge users to mitigate the CCI and using the full frequency band for the cell-center user. However, frequent handovers are the main drawback of this technique.

In contrast, [14] suggested dynamic FFR splitting the cell region into two virtual classes rather than separating the users of the cells. Each cell had a supergroup covering all cell areas and a regular group covering the cell area by dividing it into three sectors. The Radio Network Controller (RNC) dynamically assigns different subcarriers to each group and its users based on the SINR of that subcarrier and based on the fairness between its users. Super and regular subcarrier groups serve both center and edge users in the entire area and the sector. In [15], the authors suggested that the dynamic strict FFR would depend on the spatial scheduling of channels that would eliminate interference. The cell is dynamically divided into sectors, unlike the strict static FFR, which divides it into three static sectors. The Joint Scheduler is used to assign channels, divide the cells into sectors, and select the best modulation and coding regime. The authors in [16] suggested FFR optical dynamics that interact with the interference graph in neighboring cells. This interference graph links all interfered access points and used dynamic FFR to increase spectral efficiency in each subgraph. Alternative optical dynamic FFR based on bidirectional double tabu list tabu search and interference graph that analyzes the potential interference between users is proposed in [17]. The author reached the optimal dynamic scheme by combining the interference graph and the bidirectional search. A static and dynamic multicolor scheduler was proposed in [18]. The authors presented a static scheduler that assigns a different color to each cell edge to mitigate ICI and dynamic color assignment based on linear programming and greedy color assignment to improve cell-edge throughput. Also, the authors in [19] proposed interference mitigation in the colored VLC cell, which assigns users to each AP based on the minimum distance principle and assigns a channel based on the weighted user graph to mitigate the ICI and improve the network throughput.

In this paper, a new shared frequency reuse (SFR) scheme combined with two resource allocation (RA) algorithms is proposed to minimize the interference and maximize the system throughput in the VLC system. The proposed scheme and resource allocation algorithms are applied over different OFDM techniques in a VLC system. The simulation results show that the proposed scheme and algorithms improved the signal-to-interference and noise ratio (SINR), total system throughput, and the outage probability. Furthermore, the resource allocation algorithms satisfy the demand rates with small computational complexity compared to the fixed-rate and max-min fairness algorithm, which are proposed in [20] and [21], respectively.

The contributions are listed as follows

- We proposed a static resource portioning technique that shows better performance than the UFR and the static FFR, although some dynamic FFR schemes show better spectral efficiency it adds some complexities as frequent handover and computational complexity.
- We adapted our optimized resource allocation algorithm proposed in [20] and the max min fair algorithm [21] to suit the multi cell optical OFDM system in both interference area and the cell area.
- Finally, we compared the proposed interference management under different modulation and resource allocation schemes.

The rest of the paper is organized as follows. In Section II, the indoor VLC system model is introduced. The proposed resource allocation algorithm is presented in Section III.

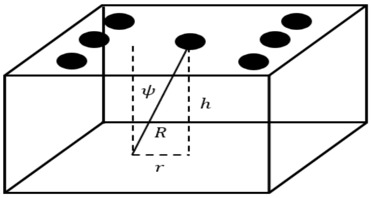

FIGURE 1. AP deployment in the simulated room.

Performance evaluation results and their significance are provided in Section IV. Finally, the conclusions are drawn in Section V.

II. SYSTEM MODEL

In this section, a system model of the optical atto-cell is presented. This model represents the downlink, which consists of one AP acting as a transmitter and multiple receivers. The AP could serve several users according to its power, available capacity, and coverage area.

A. INDOOR CHANNEL GAIN

The downlink channel between the AP and the user equipment (UE) is considered as a flat channel like a DC channel gain with considering the line-of-sight (LOS) path only and neglects the shadowing and non-line of sight (NLOS) transmission [20].

$$G = \frac{(m+1)\, A_{pd}}{2\pi d^2} \cos(\varphi)^m\, T_S(\omega)\, g_c(\omega) \cos(\omega)\,, \qquad (1)$$

where m denotes the Lambertian emission order which is given by:

$$m = \frac{-\ln(2)}{\ln\left(\cos\left(\varphi_{1/2}\right)\right)}, \qquad (2)$$

where $\varphi_{1/2}$is the angle at which the radiated power reduces to half its value. T_S is the optical filter gain, and g_c is the concentrator gain, it is given by:

$$g_c(\omega) = \begin{cases} \dfrac{n^2}{\sin(FOV)^2} & 0 < \omega < FOV \\ 0 & \omega > FOV \end{cases} \qquad (3)$$

The FOV of the receiver can be adjusted to control the coverage area of each AP. The proposed model uses several AP to cover an entire region. A user can communicate with at least one AP, as shown in Fig. 1, where ψ is the receiver angle of UE at the cell edge, r is the cell radius, R is the distance between AP and UE, and h is the distance between the plane containing the UE and the ceiling. We introduce a condition on the receiver's FOV that minimizes the interference area between the cells while keeping no dead zones. Thus, the FOV should be higher than the receiver angle of UE at the cell edge ψ, where ψ is given by:

$$\psi = \tan^{-1}\left(\frac{R}{h}\right) \qquad (4)$$

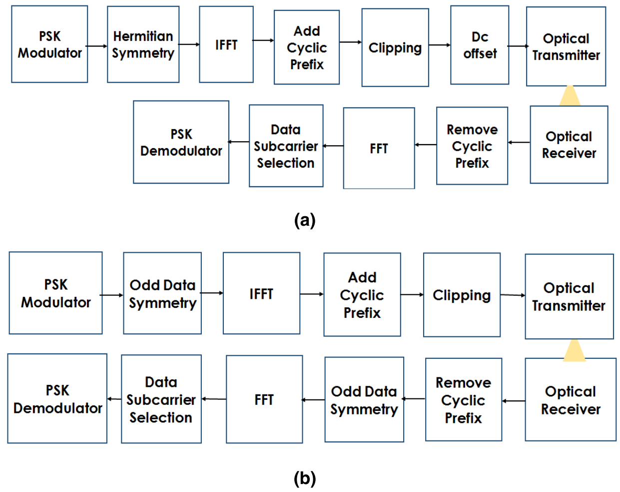

FIGURE 2. (a) DCO (b) OCO modulation techniques.

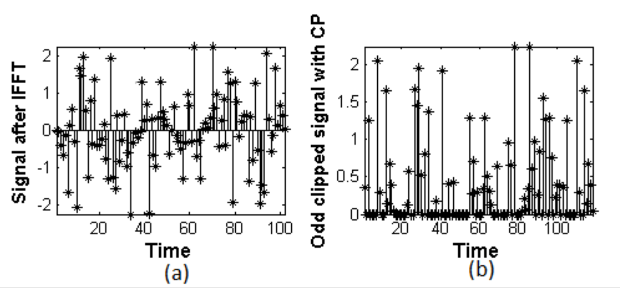

FIGURE 3. (a) Unclipped signal (b) OCO clipped signal.

B. OPTICAL OFDM MODULATION AND MULTIPLE ACCESS

Intensity modulation with direct detection (IM/DD) technique has been proved to be the most suitable technique for indoor VLC systems due to its simplicity and the low-cost end devices since the IM/DD technique is a real value unipolar signal.

In the DCO-OFDM shown in Fig. 2 (a), Hermitian symmetry is applied on the frequency domain OFDM frame X[k] before the inverse fast Fourier transform (IFFT) operation [6]. The Hermitian symmetry requires:

$$X[k] = X\,[\text{N-k}]\,, \qquad (5)$$

$$X[0] = X\left[\frac{N}{2}\right] = 0, \qquad (6)$$

The DCO-OFDM signal is made positive by adding a DC bias and after the IFFT is given by:

$$X'(t) = X(t) + DC_{\text{offset}} \qquad (7)$$

The DCO-OFDM has relatively high spectral efficiency as all subcarriers carry information. However, it has a low power efficiency as the optical (P_{opt}) to electrical (P_{elec}) power conversion γ is affected by the DC_{offset} and given by [22], [23]:

$$P_{\text{elec}} = \frac{P_{\text{opt}}^2}{\gamma^2} \qquad (8)$$

In OCO-OFDM technique shown in Fig. 2 (b), a real unipolar signal is produced by applying odd symmetry on the frequency domain OFDM frame before the IFFT operation [8]. The odd symmetry requires that:

$$X[k] = -X[N-k] \tag{9}$$

After the IFFT and clipping circuit, the unipolar signal can be generated which is represented as:

$$X_C(n) = \begin{cases} X(n) & X(n) > 0 \\ 0 & X(n) < 0 \end{cases} \tag{10}$$

As can be seen, the clipping distortion does not affect the unipolar real information carried by the subcarrier [23].

$$P_{elec} = \pi * P_{opt}^2 \tag{11}$$

C. PERFORMANCE METRICS

1) SIGNAL TO INTERFERENCE AND NOISE RATIO (SINR)

SINR for user k in AP u is given by:

$$\mathrm{SINR}_{k,u} = \frac{R_{pd}^2 G_{k.u}{}^2 P_{\mathrm{elec}}}{\sum_{i=1.i!=u}^{i=AP} R_{pd}^2 G_{k.i}{}^2 P_{\mathrm{elec}} + N_o B_T} \tag{12}$$

where N_o is the noise spectral density, R_{pd} is the photodector and B_T is the system bandwidth.

a: SYSTEM THROUGHPUT

A system throughput is defined as the sum of all rates that are required by the users. These required rates are computed bounded by the Shannon-Hartley formula. The total rate (R) is defined as the sum of the K user's rates and it is given by [12].

$$R = \rho * \sum_{k=1}^{K} N_K * B * log_2 (1 + P_{Kn} * g_k) \tag{13}$$

where B is the bandwidth of a sub-carrier, ρ is the capacity utilization, g_k is the DC optical channel gain for user k and P_{Kn} is the power assigned for user k on subcarrier n.

b: THE OUTAGE PROBABILITY OF THE SYSTEM

The outage probability of a system is the likelihood of the SNR being below the threshold SINR_{th} and it denoted as:

$$P_{outage} = P_r (SINR < SINR_{th}) \tag{14}$$

III. RESOURCE ALLOCATION AND INTERFERENCE MANAGEMENT

In this section, we introduce a radio resource allocation algorithm that provides reasonable high capacity while satisfying the user rate requirements for the indoor VLC system. Then, we propose a shared-band interference management algorithm that compromises the performance of the UFR and the PFR algorithms.

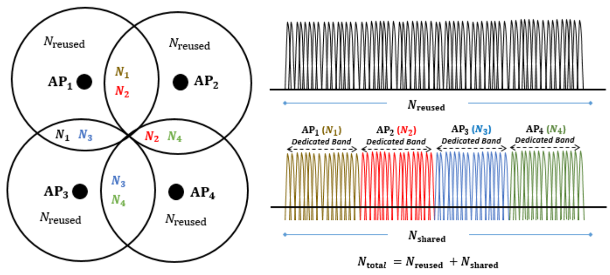

FIGURE 4. Resource partitioning of 4 APs.

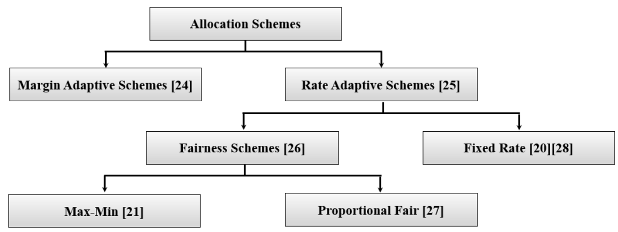

FIGURE 5. Resource allocation techniques.

A. RESOURCE PARTITIONING TECHNIQUE

A resource partitioning technique is proposed to resolve the inter-carrier interference (ICI) problem at the cell edge. In this technique, the covered area is partitioned into two regions, non-overlapped and overlapped. The whole band is distributed between the two regions. The reused band (N_{reused}) is assigned to the non-overlapped region and the shared band (N_{shared}) is reserved for overlapped region as shown in Fig. 4. The shared band is separated to small dedicated bands N_1, N_2, N_3 and N_4 and distributed on AP_1,AP_2, AP_3 and AP_4, respectively. In this design, the maximum capacity of the system is given by:

$$C_{\max} = B_T \left[\frac{MN_{\mathrm{reused}} + N_{\mathrm{shared}}}{N_{\mathrm{total}}} \right] \tag{15}$$

where M is the number of APs.

The shared band affects the outage probability as well as the overall system throughput. When this band is increased, the outage probability and the system throughput are decreased, and vice versa. Thus, a radio resource allocation algorithm is proposed to determine the optimal value of the shared band to provide better system efficiency.

B. RESOURCE ALLOCATION ALGORITHMS

Several resource allocation techniques are used to optimally assign the subcarriers of the OFDM frame to differentiate users in a multi-user environment. Fig. 5 shows the common resource allocation techniques that can be used with different OFDM modulation schemes.

Margin adaptive and rate-adaptive algorithms are the two major classes of dynamic resource allocation schemes. The margin adaptive schemes focus on minimizing the total transmission power and provisioning each user with the desired data rate [24]. The rate-adaptive schemes concentrate on maximizing the overall data rate and on satisfying the power constraints [25]. The adaptive rate schemes are classified into fairness or fixed rate requirements algorithms [26]. Resource allocation with fairness algorithms attempts to maximize the total data rate while satisfying fairness among the users. For example, proportional-fair [27] and the max-min fair [21] algorithms have been introduced to allocate the radio resources. The proportional fair resource scheduling technique provides an efficient resource to most users and improves the cell-edge user throughputs. While the max-min fairness maximizes the minimum rate of the users subject to the link-capacity constraint.

In [24], the proposed scheme assigns a single carrier to each user and increases the assigned resources to the user that has the least rate in each iteration. In contrast, resource allocation with fixed-rate algorithms maximizes the total data rate while providing each user with its rate requirements as in [28].

We assume that the users are uniformly distributed over the VLC area, and they are requesting different rates in the downlink transmission. Accordingly, we modified the previous resource allocation algorithms, where each cell assigns its radio resources to the attached users in the non-interference area. While in the interference area, the radio resources are assigned by a central unit.

As mentioned before each cell contributes with a portion of the total subcarriers N_{shared} and portion of the total power P_{shared} to serve the users in the interference area and N_{reused}, P_{reused} to serve the users in the cell area.

Algorithms 1 and 2 show the proposed adaptive max-min and the optimized resource allocation schemes, respectively. We assume users (K) distributed uniformly in the room area while they are requesting different rates. Whereas the optimized allocation begins by assigning transmission power p_k and N_k subcarriers to user k based on the channel state information and the required rate to satisfy $P_a < \left[(N_a \times P_{elec})/N\right]$, P_a: Total electrical power assigned to the users. N_a: Total assigned subcarriers, and N: Total subcarriers.

In Algorithm 1, the resource allocation proposed to service the users in the two regions (interference free, and interference areas). In the non-interference area, each user in the cell region receives a single subcarrier assigned from the N_{reused}, subcarriers, which is considered the minimum allocation bandwidth of any user. As well as, a power p_k equally distributed among subcarriers considering flat channel. This step is computing in several rounds until the user with minimum rate is served. The served user is then removed from the list, and the remaining subcarrier distributes on the rest users based on their requests. This process is repeated until the total assigned subcarriers reach N_{reused}. In the interference area, the same proceeding is repeated for the users in the interference region over the N_{shared} and P_{shared}.

Algorithm 2 is used when a user has a constraint on the required data rate, so the radio resources are allocated while satisfying these constraints. In the non-interference area, each cell assigns the subcarriers and power for the users depending

Algorithm 1 Max-Min Fair Resource Allocation Algorithm

$g_k \rightarrow$ The DC optical channel gain for user k, $k = 1 : K$
$P_{\text{reused}} \rightarrow$ Total available electrical power for users $\in$ cell-non interference area
$P_{\text{shared}} \rightarrow$ Total available electrical power for users $\in$ interference area
$P_{\text{total}} = P_{\text{reused}} + P_{\text{shared}} \rightarrow$ Total available electrical power
$N_{\text{reused}} \rightarrow$ Total available subcarriers for users $\in$ cell-non interference area
$N_{\text{shared}} \rightarrow$ Total available subcarriers for users $\in$ interference area
$N_{\text{total}} = N_{\text{reused}} + N_{\text{shared}} \rightarrow$ Total available subcarriers
$B \rightarrow$ The bandwidth of each subcarrier
$R_k \rightarrow$ is the rate of user k

BEGIN

I. **For users $\in$ non interference area p, $p = 1 : M$**
   1. Set $N_k = 1$ for all users K
   2. Set $P_a = \sum_{k=1}^{k=K} p_k \times N_k$
   3. Set $N_a = K \times N_k$
   4. **While** $N_a < N_{\text{reused}}$ **do**
      Set $N_i = N_i + 1$ where $i = \arg\min R_k$
      End While

II. **For users $\in$ interference area**
   1. Set $N_k = 1$for all user k
   2. Set $P_a = \sum_{k=1}^{k=K} p_k \times N_k$
   3. Set $N_a = K \times N_k$
   4. **While** $N_a < N_{shared}$ **do**
      Set $N_i = N_i + 1$ where $i = \arg\min R_k$
      End While

END

on its required rate and channel gain, respectively. While in the interference area, the central unit tags the users to the cell having the maximum channel gain. Then each user is assigned radio resources from the shared portion of its cell, such that the total assigned power and subcarriers of each cell in the shared area satisfying that $P_a < \left[(N_a * P_{\text{shared}})/N_{\text{shared}}\right]$ and $P_a < \left[(N_a * P_{\text{reused}})/N_{\text{reused}}\right]$ in the cell center area.

IV. SIMULATION AND RESULTS

In this section, we present the simulation results of the resource allocation algorithms 1 and 2. We consider a $5 \times 5 \times 3$ cubic meters room with 4 APs. The users are distributed uniformly in the area. In the downlink scenario, the communication channels are assumed to be a flat time-invariant channel. We use DCO-OFDM or OCO-OFDM with 512 subcarriers. The maximum acceptable signal electrical power of 7 dB DC offset is calculated according to [10, Eq. 5]. Each cell contributes **10%** of the total bandwidth in the interference area. Simulation results are collected from random positions of 12 users over 10,000 iterations. The parameters that are used in this simulation are presented in Table 1.

Algorithm 2 Proposed Resource Allocation Algorithm

$g_k \rightarrow$ The *DC* optical channel gain for user k, $k = 1 : K$
$P_{\text{reused}} \rightarrow$ Total available electrical power for users $\in$ cell-non interference area
$P_{\text{shared}} \rightarrow$ Total available electrical power for users $\in$ interference area
$P_{\text{total}} = P_{\text{reused}} + P_{\text{shared}} \rightarrow$ Totala vailable electrical power
$N_{\text{reused}} \rightarrow$ Total available subcarriers for users $\in$ cell-non interference area
$N_{\text{shared}} \rightarrow$ Total available subcarriers for users $\in$ interference area
$N_{\text{total}} = N_{\text{reused}} + N_{\text{shared}} \rightarrow$ Total available subcarriers
$B \rightarrow$ The bandwidth of each subcarrier
$R_k \rightarrow$ is the rate of user k

BEGIN

I. **For users $\in$ non interference area p, $p = 1 : M$**

1. Set $R_{\text{ref}} = \min R_k$
2. Set $\text{rate}_{\text{ratio}} = \frac{R_k}{R_{\text{ref}}} k = 1 : K$
3. Set $\text{powe r}_{\text{ratio}} = \frac{G_k}{G_{\text{ref}}} k = 1 : K$
4. Set $p_{\text{ref}} = \frac{P/N}{\sum_{k=1}^{K} \frac{g_{\text{ref}}}{g_k} \frac{R_k}{R_{\text{ref}}}}$
5. Set $N_{\text{ref}} = \frac{R_{\text{ref}}}{B \times \log_2(1 + p_{\text{ref},n} \times g_{\text{ref}})}$
6. Set $N_k = \lceil N_{ref} \times \text{rate}_{\text{ratio}} \rceil$
7. Set $p_k = \frac{p_{\text{ref}}}{\text{Power}_{\text{ratio}}}$
8. Set $N_a = \sum_{k=1}^{k=K} N_k$
9. Set $P_a = \sum_{k=1}^{k=K} p_k \times N_k$
10. **While** $P_a > P_{\text{reused}}$ **do**
    Block *user* b, $b = \arg\ min\ R_k$
    $p_{b,n} = 0$
    $N_k = 0$
    Redo the allocation
    End while

II. **For users $\in$ interference area**

1. Set $R_{\text{ref}} = \min R_k$
2. Set $\text{rate}_{\text{ratio}} = \frac{R_k}{R_{ref}} k = 1 : K$
3. Set $\text{power}_{\text{ratio}} = \frac{G_k}{G_{\text{ref}}} k = 1 : K$
4. Set $p_{\text{ref}} = \frac{P/N}{\sum_{k=1}^{K} \frac{g_{\text{ref}}}{g_k} \frac{R_k}{R_{\text{ref}}}}$
5. Set $N_{\text{ref}} = \frac{R_{ref}}{B * \log_2(1 + p_{\text{ref},n} \times g_{\text{ref}})}$
6. Set $N_k = \lceil N_{\text{ref}} \times \text{rate}_{\text{ratio}} \rceil$
7. Set$p_k = \frac{p_{\text{ref}}}{\text{power}_{\text{ratio}}}$
8. Set $N_a = \sum_{k=1}^{k=K} N_k$
9. Set $P_a = \sum_{k=1}^{k=K} p_k \times N_k$
10. **While** $P_a > P_{\text{shared}}$ **do**

Algorithm 2 (*Continued*)

    Block *user* b, $b = \arg\ min\ R_k$
    $p_{b,n} = 0$
    $N_k = 0$
    Redo the allocation
    End while

END

TABLE 1. Interference management simulation parameters.

Parameter	Value
Room size	5 x 5 x 3
P_{opt}	8 watts
Transmitter semi angle	60°
Receiver field of view (FOV)	40°
PD Responsivity	0.28 A/W
Number of subcarriers	512
PD area	1 cm^2
Threshold $SINR_{th}$	10 dB
Refractive Index of a PD	1.5
Noise power spectral density	10^{-21} A^2/Hz
Bandwidth	20 MHz
Data subcarriers	255
FFT size	512
Cyclic prefix	16
Modulation technique	64 QAM

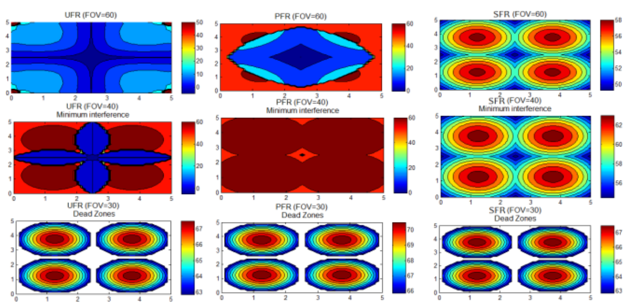

FIGURE 6. Spatial distributions of the received SINR with OCO, ACO, ADO-OFDM.

We applied UFR, PFR, and the proposed shared frequency reuse (SFR) techniques with DCO-OFDM and OCO-OFDM modulation schemes. The UFR scheme increases the ICI at the cell edge while it decreases the SINR level.

The PFR and the SFR resolve the ICI problem by assigning different frequency bands and enhance the SINR, as shown in Fig. 6 for OCO, ACO, ADO-OFDM techniques, and Fig. 7 for the DCO-OFDM. As can be seen, the FOV highly affects the SINR. The proposed system is successful in achieving an optimum value of the FOV equals 40°, which depends on the room geometry and the APs location.

Fig. 8 and Fig. 9 compare the total system throughput that is achieved while applying the different resource partitioning

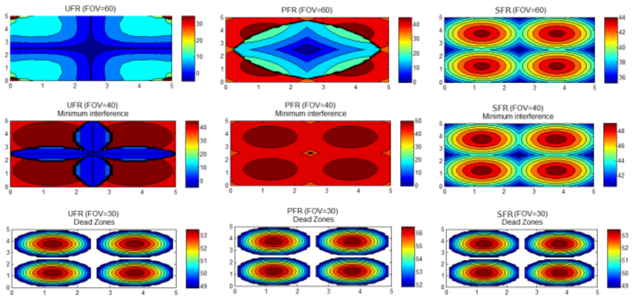

FIGURE 7. Spatial distributions of the received SINR with DCO-OFDM.

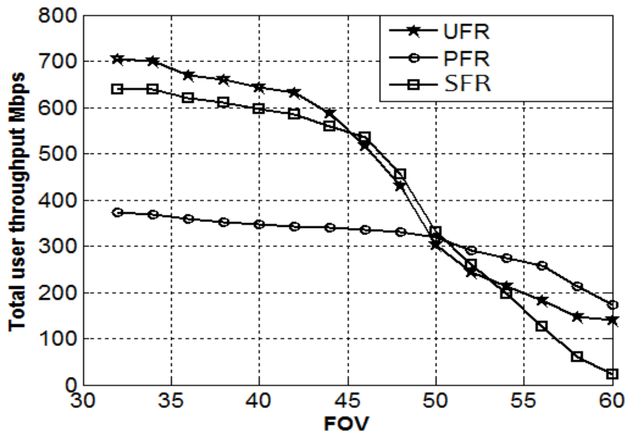

FIGURE 8. Total system throughput with DCO-OFDM.

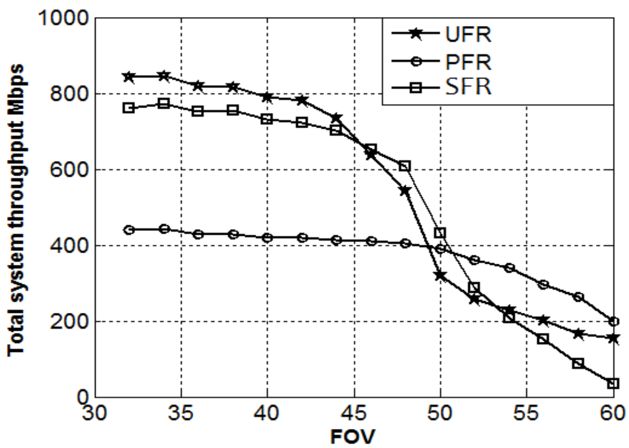

FIGURE 9. Total system throughput with OCO, ACO, ADO-OFDM.

algorithms in the DCO-OFDM and the OCO-OFDM techniques, respectively. It can be shown that the UFR and SFR enhance the overall system throughput at FOV$\leq 50^\circ$. However, the PFR enhances system throughput when the FOV$> 50^\circ$. From figures 6, 7, 8, and 9, we conclude that it is better to use the proposed UFR and SFR algorithms in the DCO-OFDM and OCO-OFDM systems with FOV equal to 40°. This configuration provides a system throughput of 650 Mbps in the DCO-OFDM and 800 Mbps in the OCO-OFDM.

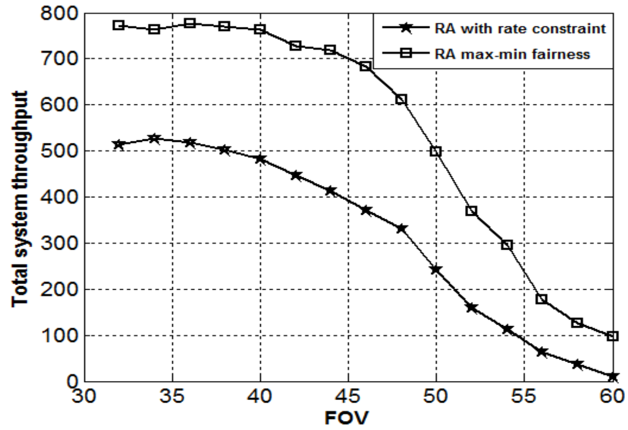

FIGURE 10. Total system throughput with different resource allocation and shared band.

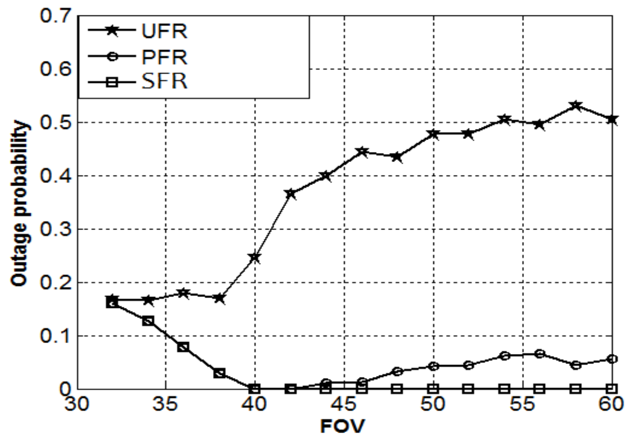

FIGURE 11. Outage probability with DCO-OFDM.

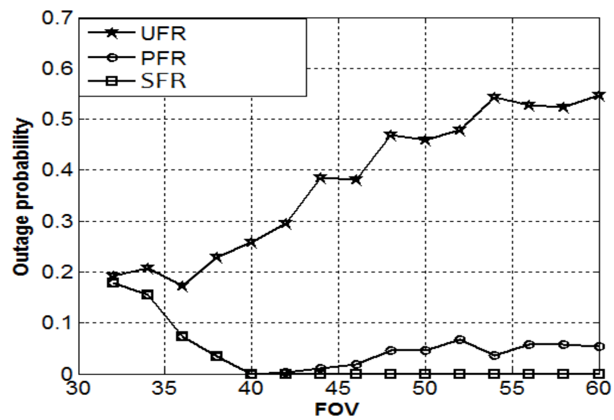

FIGURE 12. Outage probability with OCO, ACO, ADO-OFDM.

Fig. 10 shows the effect of different resource allocation algorithms by using OCO-OFDM with shared interference band, on the total system throughput. As can be seen, the overall system throughput is increased with the max-min fairness algorithm while the proposed algorithm decreases the overall system throughput due to that some users have rate constraints which cannot be satisfied, then the users will be blocked, and the capacity utilization $\rho \neq 1$.

Fig. 11, and Fig. 12 show the effect of FOV and frequency reuse techniques on the outage probability in the DCO-OFDM and the OCO-OFDM schemes, respectively. As it can be seen, the outage probability of the PFR and SFR is better than the UFR in all modulation techniques as well as, at the optimum FOV (40°) the PFR and SFR provide a zero-outage probability.

Finally, we can conclude that the PFR, which proposed in this paper with two different resource allocation schemes, can achieve a throughput of up to 800 Mbps with around zero outage probability at an optimum FOV.

V. CONCLUSION

This paper addressed the problem of interference management in a VLC indoor system with multi-user access. The performance of the system applying the SRF technique compared to UFR and PFR. The results showed that the proposed approach improves system performance in terms of total system throughput, outage probability, and SINR. It solved the problem of high SINR at the cell edge as experienced by UFR and improved the overall system throughput as compared with PFR. Moreover, the proposed technique combined with OCO-OFDM achieved total system throughput up to 800 Mbps with 12 users, and zero outage probability as it enhanced the SINR at the cell edge to 40 dB.

REFERENCES

[1] N. Komuro and H. Habuchi, "Intensity modulation direct detection optical wireless communication with nonorthogonal code shift keying," in *Proc. IEEE 8th Global Conf. Consum. Electron. (GCCE)*, Osaka, Japan, Oct. 2019, pp. 723–726.

[2] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: Opportunities, challenges and the path to market," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 26–32, Dec. 2013.

[3] M.-Y. Liu, T.-L. Wang, and S.-M. Tseng, "Throughput performance analysis of asynchronous optical CDMA networks with channel load sensing protocol," *IEEE Photon. J.*, vol. 9, no. 3, pp. 1–13, Jun. 2017.

[4] S. H. Chen and C. W. Chow, "Color-shift keying and code-division multiple-access transmission for RGB-LED visible light communications using mobile phone camera," *IEEE Photon. J.*, vol. 6, no. 6, Dec. 2014, Art. no. 7904106.

[5] H. Elgala, R. Mesleh, and H. Haas, "Indoor broadcasting via white LEDs and OFDM," *IEEE Trans. Consum. Electron.*, vol. 55, no. 3, pp. 1127–1134, Aug. 2009.

[6] M. Aminikashani, W. Gu, and M. Kavehrad, "Indoor positioning in high speed OFDM visible light communications," in *Proc. 13th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Mar. 2016, pp. 1–6.

[7] S. D. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems," *J. Lightw. Technol.*, vol. 31, no. 7, pp. 1063–1072, Apr. 1, 2013.

[8] A. Ibrahim, T. Ismail, K. Elsayed, and M. S. Darweesh, "Odd clipping optical orthogonal frequency division multiplexing for VLC system," *Int. J. Commun. Syst.*, vol. 32, no. 16, p. e4150, Sep. 2019.

[9] C. Chen, W.-D. Zhong, and D. Wu, "Non-hermitian symmetry orthogonal frequency division multiplexing for multiple-input multiple-output visible light communications," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 9, no. 1, pp. 36–44, Jan. 2017.

[10] D. A. Basnayaka and H. Haas, "Hybrid RF and VLC systems: Improving user data rate performance of VLC systems," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, London U.K., May 2015, pp. 1–5.

[11] G. W. Marsh and J. M. Kahn, "Channel reuse strategies for indoor infrared wireless communications," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1280–1290, Oct. 1997.

[12] R. Mondal, M. Chowdhury, N. Saha, and Y. M. Jang, "Interference-aware optical resource allocation in visible light communication," in *Proc. Int. Conf. ICT Converg. (ICTC)*, Oct. 2012, pp. 155–158.

[13] C. Chen, N. Serafimovski, and H. Haas, "Fractional frequency reuse in optical wireless cellular networks," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, London, U.K., Sep. 2013, pp. 3594–3598.

[14] S. H. Ali and V. C. M. Leung, "Dynamic frequency allocation in fractional frequency reused OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 4286–4295, Aug. 2009.

[15] A. A. Gebremariam, T. Bao, D. Siracusa, T. Rasheed, F. Granelli, and L. Goratti, "Dynamic strict fractional frequency reuse for software-defined 5G networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[16] H. Liu, P. Xia, Y. Chen, and L. Wu, "Interference graph-based dynamic frequency reuse in optical attocell networks," *Opt. Commun.*, vol. 402, pp. 527–534, Nov. 2017.

[17] Y. Chen, S. Li, and H. Liu, "Dynamic frequency reuse based on improved tabu search in multi-user visible light communication networks," *IEEE Access*, vol. 7, pp. 35173–35183, 2019.

[18] K. Zhou, C. Gong, and Z. Xu, "Color planning and intercell interference coordination for multicolor visible light communication networks," *J. Lightw. Technol.*, vol. 35, no. 22, pp. 4980–4993, Nov. 15, 2017.

[19] F. Yunlong, L. Jianhui, L. Qing, and Z. Xiaoyi, "Downlink channel allocation of visible light communication network based on graph coloring and traffic fairness," *Procedia Comput. Sci.*, vol. 107, pp. 667–673, 2017.

[20] A. Ibrahim, T. Ismail, and K. Elsayed, "Optimized radio resource allocation scheme for indoor optical wireless communication," in *Proc. 19th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2017, pp. 1–4.

[21] W. Rhee and J. M. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation," in *Proc. 51st Veh. Technol. Conf. (VTC)*, Tokyo, Japan, May 2000, pp. 1085–1089.

[22] S. Dimitrov, S. Sinanovic, and H. Haas, "Clipping noise in OFDM-based optical wireless communication systems," *IEEE Trans. Commun.*, vol. 60, no. 4, pp. 1072–1081, Apr. 2012.

[23] J. Armstrong and B. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 343–345, May 2008.

[24] M. Vadivel and H. Ranganathan, "Optimization of dynamic resource allocation and rate adaptation in OFDMA systems," *Int. J. Comput. Appl.*, vol. 47, no. 25, p. 8887, Jun. 2012.

[25] M. Taki and F. Lahouti, "Discrete rate interfering cognitive link adaptation design with primary link spectral efficiency provisioning," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 2929–2939, Sep. 2011.

[26] S. Sadr, A. Anpalagan, and K. Raahemifar, "Suboptimal rate adaptive resource allocation for downlink OFDMA systems," *Int. J. Veh. Technol.*, vol. 2009, pp. 1–10, 2009.

[27] A. Noliya and S. Kumar, "Performance analysis of resource scheduling techniques in homogeneous and heterogeneous small cell LTE-A networks," *Wireless Pers. Commun.*, vol. 112, pp. 2393–2422, Jan. 2020.

[28] B. Ghimire and H. Haas, "Resource allocation in optical wireless networks," in *Proc. IEEE 22nd Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2011, pp. 11–14.

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