Evolution Computation Based Resource Allocation for Hybrid Visible-Light and RF Femtocell

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Abstract. Incorporating visible light communication (VLC) with existing radio frequency (RF) access techniques has received widespread concern to enhance network coverage/capacity. This paper focuses on the joint downlink resource allocation (RA) in a hybrid VLC-RF network. The problem is formulated as utility maximization by jointly adjusting downlink sub-channel allocation. A Evolution Computation (EC) based centralized algorithm is developed to solve the problem. To reduce computation complexity, the algorithm is decoupled into two sub-steps. First, users are assigned to different VLC access points and the allocation is initialized in a proportional fair (PF) like method. Second, EC search procedures are iteratively operated until optimality. Through simulation, the algorithm outperforms classic PF and Round Robin RA methods in terms of throughput and user fairness.

Keywords: Visible light communication · Heterogeneous network · 5G

1 Introduction

Visible-light communication is considered as a promising technique to provide high-speed network access for future indoor users. Its main advantages include license-free operation, clean electro-magnetic interference and high network security. One primary research direction is to deploy indoor VLC attocells with symbols-based dc-biased optical discrete multi-tone modulation (DMT) signals [1]. VLC attocell refers to indoor femtocell-like VLC coverage with radius of 0.5–1.5 m. Such deployment enables VLC system to serve multiple mobile users, allowing them to move around inside a room with seamless connection to the best serving light bulb. Besides, DMT offers adaptability in modulation patterns, which have recently demonstrated excellent bit-rate performance [2].

In spite of above advantages, the main drawback of VLC is its limited coverage. Obstacles can easily cut off VLC links and then leave the service deprived.

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On the other hand, radio frequency (RF) can cover larger area up to several square kilometers. Therefore, next generation mobile communication (5G) envisions an ultra-dense small cell deployment network (UDN) on licensed and unlicensed spectrum, aggregating various access techniques including Wireless Local Area Network (WLAN), millimetre-wave, Optical Wireless (OW), etc.

Following this trend, VLC attocell may also work as part of future UDN. Many researchers have demonstrated the attraction of corporation VLC with RF because of their complementary nature in both coverage and capacity [3]. VLC provides wide bandwidth with limited coverage, while radio frequency (RF) covers large area with lower throughput. What' more, there exists no interference problem between VLC and RF. Therefore, this paper considers an indoor co-deployment of several VLC attocells and a classic RF femtocell.

Joint resource allocation (RA) is an important issue in such hybrid systems but there exist few related studies. [4] focuses on network capacity analysis in hybrid VLC-RF system. The study is built on queue theory and VLC channel is idealized as binary channel of transmission success or failure. The network capacity is evaluated by the spatial density of accessed queues. [5] proposes distributed algorithm to solve network selection problem in order to improve VLC-RF hybrid system capacity. Fundamentally, there remains missing pieces of the RA puzzle: (i) VLC channel-aware RA scheme should be elaborated with advanced modulation signals to improve RA efficiency. (ii) Small user number and less channel complexity in VLC network alleviate the backhaul load and make centralized RA possible. Compared to distributed RA, centralized RA enables flexible resource aggregation and absolves VLC APs from complex signalling process burden.

In order to address above issues, this paper proposes a joint subcarriers (subchannels) allocation of hybrid DMT-attocell and OFDM-femtocell system. A centralized algorithm based on Evolution Computation (EC) is developed to solve the problem. To reduce complexity, the algorithm is decoupled into two subsequential steps. The first step assigns users to different VLC APs and initializes the allocation in a proportional fair (PF) like method. The second step iteratively carries out EC search procedures to improve both network throughput and user fairness. The complexity is analyzed on the basis of the dimension of the searching space. Results are compared with classic RA methods of PF and Round Robin (RR).

The paper is organized as follows. Section 2 presents the system model. Problem formulation and optimization strategy are given in Sects. 3 and 4. Simulation results are presented in Sect. 5. Section 6 concludes the paper.

2 System Model

2.1 Scenario Description

In Fig. 1, several light-emitting diode (LED) APs and a RF femto are co-located to cover the whole room area. LED signal is DMT based: the whole bandwidth is divided into subcarriers that can be allocated to multiple users. In order to realize the full potential of DMT, subcarriers can be densely reused among different APs [6]. RF signal is OFDM based. In our model, mobile terminal (MT) is indexed by m and $\mathcal{M}$ denote total MT set. VLC AP is indexed by k and $\mathcal{K}$ denote total VLC AP set.

The work is based on following assumptions: (i) VLC APs and RF femtocell are linked with each other through wired backbone for exchanging signalling information. (ii) The network is converged in Internet Protocol (IP) layer. So the physical difference between VLC and RF sub-channel is ignored. MTs are capable of scheduling multiple heterogeneous or homogeneous sub-channels simultaneously. (iii) Transmit power on every VLC and RF sub-channel is constant, subject to total power constraint.

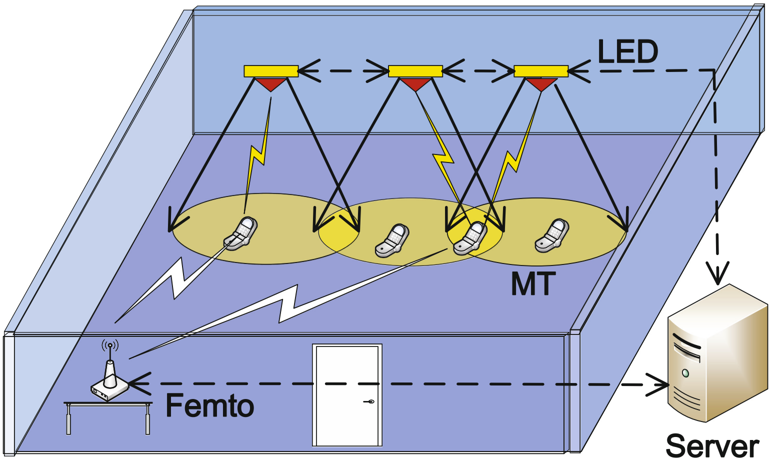

Fig. 1. Indoor VLC-RF hybrid network.

2.2 VLC Channel Model

VLC channel consists of two parts: line-of-sight (LOS) and non-line-of-sight (NLOS) components [7]. The LOS DC (Direct Current) gain between transmitter k and receiver m is given by:

$$h_{k,m} = \begin{cases} \frac{A}{d_{k,m}^2} I_w(\phi_{k,m}) \cos(\varphi_{k,m}), & 0 \le \varphi_{k,m} \le \varphi_c \\ 0, & \varphi_{k,m} > \varphi_c \end{cases} \quad (1)$$

where A is the size of the receiver, $d_{k,m}$ is the distance between transmitter k and receiver m. $\varphi_{k,m}$ is the angle of incidence of light at the receiver. φ_c is the receiver field-of-view (FOV). The light signal can be detected only when the incidence angle is no more than receiver's FOV. $I_w(\phi_{k,m})$ is the Lambertian radiant intensity profile of order w that models LED radiation pattern.

Reflective responses (NLOS channel) have similar forms with LOS components and can be calculated recursively in terms of (1). LOS and first-reflective path are considered in our work since these two components account for more than 97% of the total received energy. Readers may consult [8] for details.

3 Problem Formulation

3.1 User Rate Calculation

Subcarrier of VLC AP is indexed by v and $\mathcal{V}$ denote total VLC subcarrier resource set of the corresponding AP. The SINR of user m on channel v can be calculated by [6]:

$$\gamma_{m,v} = \frac{\sum\limits_{k\in\mathcal{K}} \rho_{k,m,v} p_{k,m,v} \left|h_{k,m,v}\right|^2}{\sum\limits_{k\in\mathcal{K}} (1-\rho_{k,m,v}) p_{k,m,v} \left|h_{k,m,v}\right|^2 + \sigma_{VLC}^2} \tag{2}$$

where $\rho_{k,m,v}$ is subcarrier allocation indicator. $\rho_{k,m,v} = 1$ only when subcarrier v of transmitter k is allocated to MT m. Otherwise, $\rho_{k,m,v} = 0$. $p_{k,m,v}$ denotes the transmit power on subcarrier v, $h_{k,m,v}$ is the channel gain between transmitter k and MT m on subcarrier v. σ_{VLC}^2 is the variance of Gaussian noise. Note that the numerator represents the desired signal that might come from different VLC APs in synchronous time sequence, which is unproblematic among neighboring APs linked through wired backhauls. The interference in the denominator represents unexpected signals from interfering APs on the same sub-channel.

Given SINR and a target bit error rate (BER), the bit rate of MT m on subcarrier v of AP k can be approximated by:

$$r_{m,v} \approx \log_2(1 + \gamma_{m,v}/\mathit{\Gamma}) \tag{3}$$

where $\mathit{\Gamma} = -\ln(5\mathrm{BER})/1.5$ and BER can be typically set to 1.5×10^{-3} [6].

RF femtocell sub-channel is indexed by f. $\mathcal{F}$ denote total RF femtocell channel resource set. The SNR of user m on channel f is calculated by:

$$\gamma_{m,f} = \frac{\rho_{m,f} p_{m,f} \left|h_{m,f}\right|^2}{\sigma^2} \tag{4}$$

where $\rho_{m,f}$ denotes channel allocation indicator. $p_{m,f}$ and $h_{m,f}$ respectively represent transmit power and channel gain of MT m on sub-channel f. The achievable rate $r_{m,f}$ can be estimated for a target BER under adaptive modulation.

3.2 Utility Function Definition

The utility function can be defined in (5a) as follows:

$$u_m = r_m d_m \tag{5a}$$

$$r_m = \sum\nolimits_{v\in\mathcal{V}} r_{m,v} + \sum\nolimits_{f\in\mathcal{F}} r_{m,f} \tag{5b}$$

$$d_m = \overline{R}/(R_m + \delta) \tag{5c}$$

$$\overline{R} = \left(\sum\nolimits_{m\in\mathcal{M}} R_m\right)/M \tag{5d}$$

where r_m represents the total achievable data rate of MT m as defined in (5b). d_m indicates the service status of MT m in (5c). Note that δ in (5c) has a small value that prevents d_m from being ∞. R_m is the average throughput of MT m over a certain time-window. $\overline{R}$ is the average throughput across all MTs given in (5d). A rate deprived user will have higher service status indicator and vice versa.

Thus the problem is formulated as utility maximization by adjusting channel allocation indicator ρ:

$$\begin{aligned}
&\max_{\rho} \sum_{m \in \mathcal{M}} u_m \\
&\text{subject to:} \\
&\forall m \in \mathcal{M}, v \in \mathcal{V}, f \in \mathcal{F}, \\
&\rho_{k,m,v} \in \{0,1\}, \textstyle\sum_{m \in \mathcal{M}} \rho_{k,m,v} \leq 1 \\
&\rho_{m,f} \in \{0,1\}, \textstyle\sum_{m \in \mathcal{M}} \rho_{m,f} \leq 1
\end{aligned} \tag{6}$$

where the constraints declare that each subcarrier or sub-channel can be simultaneously allocated to one MT at most. The problem in (6) includes the nonlinear optimization of both $|\mathcal{M}| \times |\mathcal{K}| \times |\mathcal{V}|$ integer variables ($\rho_{k,m,v}$) and $|\mathcal{M}| \times |\mathcal{F}|$ integer variables ($\rho_{m,f}$). Its optimal solution by means of an integer nonlinear programming solver is exceptionally complicated and computationally intractable for evaluation within reasonable time [8]. Note that $|\cdot|$ represents set's cardinality.

4 Evolution Computation Based RA Algorithm

In this part, Evolution Computation (EC) is introduced to solve problem (6). EC is widely adopted as a general concept for solving difficult discrete optimization problems. Though its global search characteristic has been confirmed, the computation task complexity is greatly increased. Therefore, the allocation algorithm is split into two sequential steps to reduce computation complexity, as given in Algorithm 1.

4.1 Initialization

The first step **Initialization** includes line 1–10 of Algorithm 1. Line 2 allocates MTs to the highest channel gain APs. Given MT m, its allocated AP is defined by: $\mathcal{M}_k = \left\{ m_k \in \mathcal{M}_k | k = \arg\max_{k} \sum_{v \in \mathcal{V}} |h_{k,m,v}|^2 \right\}$, where $\sum_{k \in \mathcal{K}} \mathcal{M}_k = \mathcal{M}$. Line 3–7 allocate VLC subcarriers of each AP to its assigned users. Line 8–10 allocate femto sub-channel resource to users.

4.2 Evolution Computation

The second step **Evolution Computation** includes line 11–18 of Algorithm 1. EC mimics the evolution process of a population of a certain species, driving its

Algorithm 1. Evolutionary Computation based RA Algorithm for VLC Heterogeneous Network

```
1:  **Initialization:**
2:  VLC AP assignment
3:  for each $k \in \mathcal{K}$ do
4:      for each $v \in \mathcal{V}$ do
5:          Allocate subcarrier $v$ to $m_k$ of maximum $u_m$
            Update $u_m$
6:      end for
7:  end for
8:  for each $f \in \mathcal{F}$ do
9:      Allocate sub-channel $f$ to $m$ of maximum $u_m$
        Update $u_m$
10: end for
11: **Evolution Computation:**
12: $i = 0$
13: repeat
14:     $i++$
15:     Selection($\Psi$)
16:     Crossover($\Psi$)
17:     Mutation($\Psi$)
18: until $i == Generation\_number$
```

Table 1. Reflection relationship.

Parameters in our model	Reflection in evolution operators
Resource index: v or f	Gene: g
Resource set: $\{\underbrace{\mathcal{V},\cdots,\mathcal{V}}_{\lvert\mathcal{K}\rvert},F\}$	Individual: $\mathcal{G}$
Objective function	Fitness

individuals towards higher fitness for adaptation and survival. Generally speaking, EC is a periodical result of the population's selection, heredity and mutation in its genetic perspective.

The reflection relationship between model parameters and EC are given in Table 1. An individual is made up of the total genes. Each individual corresponds to a certain allocation scheme with respective fitness (objective function). The individual with the highest fitness in the population is of the optimal allocation strategy. A population Ψ consists of multiple individuals. For each generation, population Ψ carries out the following three EC operators:

Selection operator (line 15) can be used to generate new population, which emphasizes fitter individuals and preserves their genotypic information. Typically, selection can be implemented as a probabilistic operator, namely roulette wheel selection (RWS) in our paper. RWS utilizes the relative fitness (a single individual fitness divided by total individuals fitness) of the individuals within the population to determine the selection probability of generated individual. Individuals are mapped into new population based on the probability proportional to the relative fitness. Individuals with higher fitness is more likely to exist in next generation of population.

Crossover (line 16) is a basic operator for producing new individuals with differentiated genotypic information. Crossover can be described as a recombination of two parent individuals, producing offsprings that have some parts of both parent's genetic material. In this paper, a standard one-point crossover is utilized as defined in [9]. First, two individuals are chosen randomly from the population. Second, a position in the gene string is randomly determined as the crossover point. Third, an offspring is generated by concatenating the left substring of one parent and the right substring of the other parent. These procedures are executed with a fixed probability of 0.3 [9]. Crossover demonstrates disruptive nature, driving the search direction more diversified.

Maturation (line 17) is discussed as 'background operator', preventing good genetic material from getting lost during selection and crossover procedures [9]. Therefore, mutation probability should not be too high to avoid interfering with selection and crossover. In our paper, mutation probability $P_{mut} = 0.05$ [9].

4.3 Complexity Analysis

Since EC is an intelligent search algorithm, the searching space greatly influences its efficiency. So this part analyzes algorithm complexity based on the dimension of searching space. Following proves the complexity of our algorithm is less than traditional EC search. First, as for VLC:

$$\begin{aligned} & g = [1, 2, \cdots, |\mathcal{M}_k|][\rho_{k,1,v}, \rho_{k,2,v}, \cdots, \rho_{k,|\mathcal{M}_k|,v}]^T \\ & Given : \rho_{k,m,v} \in \{0,1\} \wedge \textstyle\sum_{m \in \mathcal{M}} \rho_{k,m,v} = 1 \\ & \quad = m_k \in \mathcal{M}_k \end{aligned} \tag{7}$$

Second, as for RF femtocell:

$$\begin{aligned} & g = [1, 2, \cdots, |\mathcal{M}|][\rho_{1,f}, \rho_{2,f}, \cdots, \rho_{|\mathcal{M}|,f}]^T \\ & Given : \rho_{m,f} \in \{0,1\} \wedge \textstyle\sum_{m \in \mathcal{M}} \rho_{m,f} = 1 \\ & \quad = m \in \mathcal{M} \end{aligned} \tag{8}$$

Third, the dimension of the searching space is:

$$\begin{aligned} Dim = & \textstyle\sum_{k \in \mathcal{K}} |\mathcal{M}_k||\mathcal{V}| + |\mathcal{M}||\mathcal{F}| \\ & = |V| \textstyle\sum_{k \in \mathcal{K}} |\mathcal{M}_k| + |\mathcal{M}||\mathcal{F}| \\ Given : & \textstyle\sum_{k \in \mathcal{K}} \mathcal{M}_k = \mathcal{M} \\ & = |\mathcal{V}||\mathcal{M}| + |\mathcal{M}||\mathcal{F}| \\ Given : & \ |K| > 1 \wedge |\mathcal{K}| \text{ is integer} \\ & = |\mathcal{M}| \left(|\mathcal{V}| + |\mathcal{F}|\right) < |\mathcal{M}| \left(|\mathcal{K}||\mathcal{V}| + |\mathcal{F}|\right) \end{aligned} \tag{9}$$

Table 2. Simulation configuration

VLC system	Femtocell system
LED power: 20 [w]	Femotcell BS power: 0.02 [w]
LED bandwidth: 20 [MHz]	Femtocell bandwidth: 5 [MHz]
FOV: 60 [deg.]	Fast-fading: Rician
Semi-angle: 80 [deg.]	Path-loss constant: 37 [dB]
MT's receive area: 1 [cm^2]	Path-loss exponent: 3

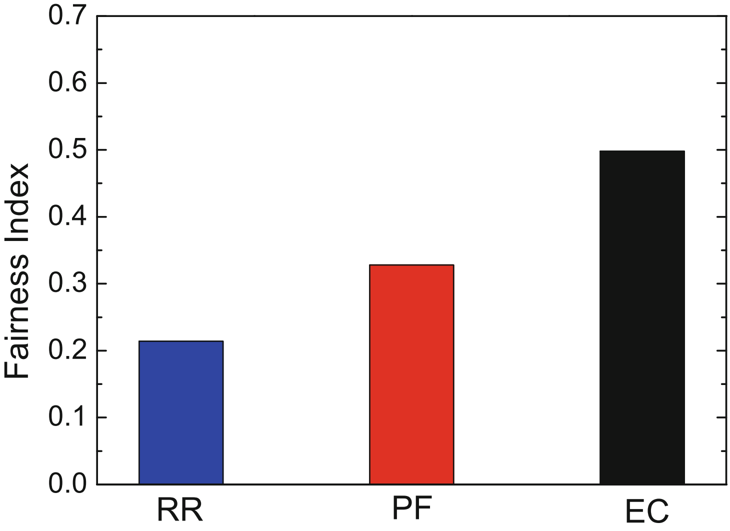

Fig. 2. Indoor VLC-RF hybrid network.

5 Simulation and Analysis

In the simulation, a 5 m × 5 m × 3 m room is considered. 30 terminals are served by 8 LED APs and a femtocell. Detailed parameters are listed in Table 2. Proportional Fair (PF) and Round Robin (RR) RA algorithms are introduced for comparison.

Figure 2 compares users' rate fairness. Fairness Index is defined as [10]:

$$F = \frac{\left(\sum_{m \in \mathcal{M}} r_m\right)^2}{|\mathcal{M}| \cdot \sum_{m \in \mathcal{M}} r_m^2} \tag{10}$$

F ranges from 0 (worst case) to 1 (best case). The best case corresponds to the situation that all users obtain equal data rate. Compared with RR and RF, the user fairness of our algorithm (EC) is improved 0.28 and 0.17 respectively.

Figure 3 compares system's average throughput. Compared with RR and RF, average system throughput of EC is improved 103.4% and 53.8% respectively.

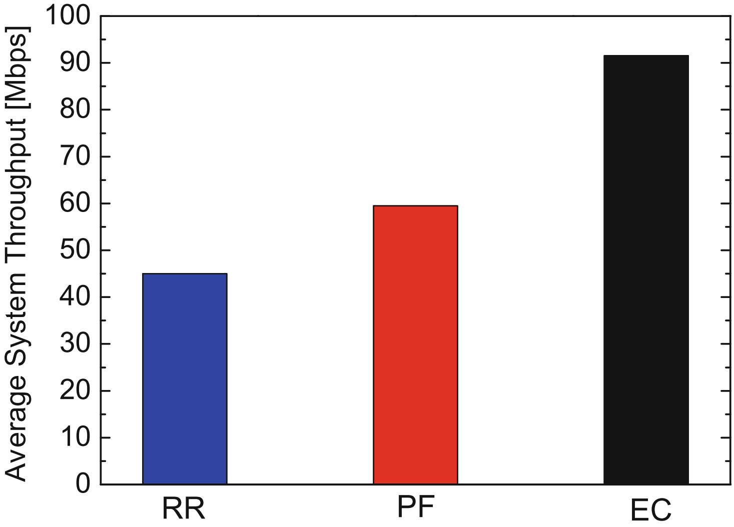

Fig. 3. Average system throughput.

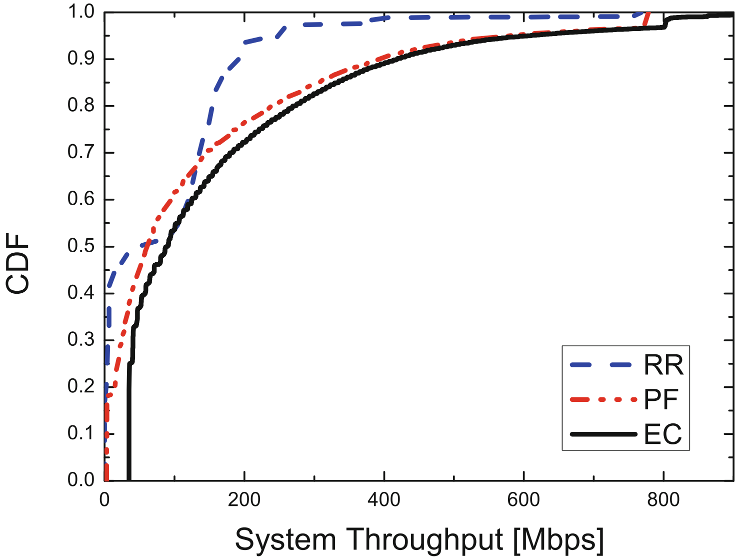

Fig. 4. Cumulative distribution function of the system throughput.

Figure 4 demonstrates the cumulative distribution function (CDF) of system throughput with different RA algorithms. RR and PF algorithms perform very poorly with regard to the lower tail of the CDF curve (especially the 30th percentile). This is due to the non-randomness of VLC channel, exceedingly subject to the distance between VLC receiver and AP. Therefore, some very poor VLC channels might be utilized by using RR and PF. On the other hand, EC promotes intelligent searching towards the point that users are allocated with possibly optimal VLC channel. In general, EC outperforms RR and PF in system throughput.

6 Conclusions

In this paper, a joint downlink resource allocation is investigated in a hybrid indoor VLC-RF network. The problem is formulated as non-linear integer optimization. An evolutionary computation based algorithm is proposed to solve the problem and the algorithm is decoupled into two subsequential steps to reduce the complexity. Through simulation, the proposed algorithm is proved to outperform classic allocation schemes in system throughput and user fairness.

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