Joint Power Allocation and Caching Optimization in Fiber-Wireless Access Networks

Zhuojia Gu, Hancheng Lu, Daren Zhu, Yujiao Lu
Department of Electrical Engineering and Information Science
University of Science and Technology of China, Hefei, Anhui 230027 China
Email: guzj@mail.ustc.edu.cn, hclu@ustc.edu.cn, darenzhu@mail.ustc.edu.cn, lyj66@mail.ustc.edu.cn

Abstract—Fiber-Wireless (FiWi) access networks have been widely deployed due to the complementary advantages of high-capacity fiber backhaul and ubiquitous wireless front end. To meet the increasing demands for bandwidth-hungry applications, access points (APs) are densely deployed and new wireless network standards have been published for higher data rates. Hence, fiber backhaul in FiWi access networks is still facing the incoming bandwidth capacity crunch. In this paper, we involve caches in FiWi access networks to cope with fiber backhaul bottleneck and enhance the network throughput. On the other hand, power consumption is an important issue in wireless access networks. As both power budget in wireless access networks and bandwidth of fiber backhaul are constrained, it is challenging to properly leverage power for caching and that for wireless transmission to achieve optimal system performance. To address this challenge, we formulate the downlink wireless access throughput maximization problem by joint consideration of power allocation and caching strategy in FiWi access networks. To solve the problem, firstly, we propose a volume adjustable backhaul-constrained water-filling method (VABWF) to derive the expression of optimal wireless transmission power allocation. Then, we reformulate the problem as a multiple-choice knapsack problem (MCKP) and propose a dynamic programming algorithm to find the optimal solution of the MCKP problem. Simulation results show that the proposed algorithm significantly outperforms existing algorithms in terms of system throughput under different FiWi access network scenarios.

Index Terms—Fiber-Wireless (FiWi) access networks, Fiber Backhaul, Throughput, Caching, Power Allocation

I. INTRODUCTION

In recent years, the growing bandwidth demand is foreseen to put tremendous pressure on access networks. Cisco predicts that global Internet traffic will increase nearly threefold over the next 5 years, and video applications will account for 82% of all Internet traffic by 2021, up from 73% in 2016 [1]. Obviously, it is crucial for future access networks to support the growing demand for Internet traffic. To cope with the severe bandwidth crunch in access networks, fiber-wireless (FiWi) access networks were proposed to provide an efficient “last mile” Internet access in 1990s and have been widely deployed, especially in the field of multimedia communications [2]. As an integration of optical access networks and wireless access networks, FiWi access networks leverage the complementary advantages of these two technologies and have attracted a great deal of research interest over the past two decades. Specifically, a FiWi access network combines optical fiber networks as its backhaul for high capacity and wireless networks as its front end for high flexibility and ubiquity [3].

In FiWi access networks, fiber backhaul bandwidth is shared by all wireless front ends. To meet the demands for bandwidth-hungry multimedia applications such as video on demand (VOD) services, access points (APs) are supposed to be densely deployed to improve network capacity in wireless front ends [4]. Moreover, the recent IEEE 802.11ac standard specifies a data rate of at least 500Mbps for higher wireless access throughput. Hence, fiber backhaul in FiWi access networks is facing bandwidth bottleneck that limits the network throughput. Some researches have focused on next-generation passive optical networks (NG-PONs), which aim to achieve higher bandwidth in optical networks. But the cost of deploying NG-PONs is very high due to the fact that existing optical network units (ONUs) and optical line terminals (OLTs) are not directly compatible with the technical requirements of NG-PONs [5], so ONUs and OLTs must be replaced or upgraded to support NG-PONs, which is a costly method at present.

At the same time, there have been growing recent researches towards data caching as an approach for alleviating bandwidth pressure in fiber networks. In [6], an architecture consisting of an ONU with an associated storage unit was proposed to save traffic in the feeder fiber and improve the system throughput as well as mean packet delays. In [7], a framework of software-defined PONs with caches was introduced to achieve a substantial increase in served video requests. In [8], a dynamic bandwidth algorithm based on local storage VOD delivery in PONs was proposed and achievable throughput levels have been improved when a local storage is used to assist VOD delivery. However, most of them mainly focus on providing storage capacity in PONs to improve the network throughput, so these methods can not be directly applied to FiWi access networks.

In FiWi access networks, the functions of ONU and AP are integrated into a component called ONU-AP. To mitigate the bandwidth crunch of fiber backhaul in FiWi access networks, we equip ONU-APs with caches. Note that in FiWi access networks, the wireless front end will also make an impact on the system throughput in addition to the fiber backhaul network. Transmission power and channel conditions in the wireless front end should be taken into account, which is different from optical access networks with caches mentioned above. Particularly, transmission power of ONU-APs and channel conditions from user equipments (UEs) to ONU-APs are important factors determining the throughput in wireless access networks. When involving caches in FiWi access networks, it is challenging to properly leverage power for
caching and that for wireless transmission to achieve optimal system performance. That is because if more power is used for wireless transmission, UEs can achieve higher wireless access throughput, whereas less power is used for caching, putting more pressure on fiber backhaul load. As both power budget in wireless access networks and bandwidth of fiber backhaul are constrained, joint power allocation and caching optimization are required to maximize the throughput in FiWi access networks.

In this paper, considering fiber backhaul bottleneck and channel conditions in wireless front end, as well as the sum power constraint of integrated ONU-APs, we formulate the joint power allocation and caching optimization problem as a Mixed Integer Programming (MIP) problem. To solve the problem, firstly, we propose a volume adjustable backhaul constrained water-filling method (VABWF) using convex optimization to derive the expression of optimal wireless transmission power allocation. Then, based on the derived expression, we reformulate the problem as a multiple-choice knapsack problem (MCKP) by exploiting the highest-popularity-first property of files. Finally, we propose a dynamic programming algorithm to solve the MCKP problem.

The rest of this paper is organized as follows. We first introduce the system model in Section II. Then, in Section III, the joint power allocation and caching optimization problem is formulated, and the transformation of the optimization problem into MCKP based on the proposed VABWF method is described. Simulation results are shown in Section IV and concluding remarks are provided in Section V.

II. SYSTEM MODEL

A. Network Model

The network model we propose is shown in Fig. 1. The FiWi access network is divided into a fiber backhaul network and a wireless front end network. We adopt Passive Optical Network (PON) as the fiber backhaul network. The optical line terminal (OLT) is located at the central office (CO), connecting to an optical splitter through the feeder fiber. The optical splitter is connected to multiple ONU-APs through the distribution fiber. The split ratio of the optical splitter is usually 1:32 or 1:64. In the FiWi access network, each ONU is collocated with an AP, and the integration of the ONU and AP is called integrated ONU-AP. The ONU-APs are denoted by an index set \( N = \{1, 2, \ldots, n, \ldots, N\} \).

We assume that the feeder fiber connecting the splitter and the OLT has a capacity constraint of \( C \). At the wireless front end of the FiWi access network, \( K \) user equipments (UEs) are randomly distributed in the coverage of ONU-APs. Let \( K \) denotes the UE index set and \( K = \{1, 2, \ldots, k, \ldots, K\} \). Each UE is assumed to be fixed associated with an ONU-AP, thus we denote the set of UEs associated with ONU-AP \( n \) by \( \Phi_n, n \in N \). We assume that ONU-APs adopt orthogonal frequency-division multiple access (OFDMA) to transmit data, that is to say, an ONU-AP allocates orthogonal subcarriers to UEs, and different transmission power levels are assigned to different UEs.

The received signal-to-interference-plus-noise ratio (SINR) at UE \( k \) associated with ONU-AP \( n \) can be expressed as

\[
\gamma_{nk} = \frac{g_{nk}P_{nk}}{\sum_{m \in N \backslash \{n\}} g_{mk}P_{mk} + \sigma^2},
\]

where \( N \backslash \{n\} \) denotes all ONU-APs except ONU-AP \( n \), \( P_{nk} \) denotes the transmission power allocated to UE \( k \) by ONU-AP \( n \), \( g_{nk} \) denotes the Rayleigh channel gain from ONU-AP \( n \) to UE \( k \) which follows the exponential distribution. \( \sigma^2 \) characterizes the background noise power level.

We assume that non-overlapping channels are assigned to adjacent ONU-APs, and ONU-APs that reuse the same spectrum are deployed far away from each other. Thus, the co-channel interference is negligible, namely, \( g_{nk} = 0, m \in N \backslash \{n\} \). The wireless transmission rate from ONU-AP \( n \) to UE \( k \) is given by the Shannon’s theorem

\[
R_{nk} = B \log_2(1 + \frac{g_{nk}P_{nk}}{\sigma^2}),
\]

where \( B \) is the subchannel bandwidth for each UE.

B. ONU-AP Caching Model

Each ONU-AP is cache-enabled, and the cache size of ONU-AP \( n \) is denoted by \( Q_n \). Requested files are denoted by an index set \( J = \{1, 2, \ldots, j, \ldots, J\} \). If ONU-AP \( n \) already caches a requested file, it will respond to the request directly. Otherwise, the file should be fetched from the Internet via capacity-limited fiber backhaul. We assume all files have the same size, which is denoted by \( s \). The file popularity distribution of \( J \) files is modeled as Zipf distribution, so the probability of the \( j \)-th ranked file being requested by UEs is \( p_j = \frac{1}{j^\delta} \), where \( \delta \) is a shape parameter that shapes the skewness of the popularity distribution. Let \( p_{hit}^n \) denote the probability that files requested by UEs are cached at ONU-AP \( n \) (i.e., cache hit ratio), and \( p_{miss}^n \) denote the probability that files requested by UEs are not cached at ONU-AP \( n \) (i.e., cache miss ratio), where \( p_{hit}^n + p_{miss}^n = 1 \). Given the cache decision on the \( j \)-th file at ONU-AP \( n \) as \( x_{nj}, x \in \{0, 1\} \), the cache hit ratio at ONU-AP \( n \) can be written as

\[
p_{hit}^n = \sum_{j \in J} x_{nj}p_j = \frac{\sum_{j \in J} x_{nj}j^{-\delta}}{\sum_{j \in J} j^{-\delta}}.
\]
Note that files requested by UEs that are not cached at ONU-APs should be fetched from the Internet via fiber backhaul. According to the cache miss ratio $p^{\text{miss}}_{nk}$ at ONU-AP$_n$, the average fiber backhaul bandwidth occupied by UE$_k$ at ONU-AP$_n$ can be written as $p^{\text{miss}}_{nk} R_{nk}$, thus the backhaul constraint of all $K$ UEs should be satisfied as

$$\sum_{n \in N \ k \in \Phi_n} p^{\text{miss}}_{nk} R_{nk} \leq C. \quad (4)$$

### C. Power Consumption Model

The total power consumed by an ONU-AP$_n$ can be expressed by extending the typical wireless network power consumption model to include caching power consumption as follows

$$P^{\text{total}}_n = \sum_{k \in \Phi_n} \rho P_{nk} + P^{\text{ca}}_n + P^{\text{cc}}_n, \quad (5)$$

where $P^{\text{ca}}_n$ denotes the power consumed at ONU-AP$_n$ for caching. $P^{\text{cc}}_n$ denotes the power consumed by circuits, which is a constant that depends on the circuit design. $\rho$ is a coefficient that measures the impact of power amplifier, power supply and cooling. We use an energy-proportional model for caching power consumption [10] [11], which has been widely adopted in content-centric networking for efficient use of caching power. In this model, the consumption of caching power is proportional to the total number of bits cached at an ONU-AP, which can be expressed as $P^{\text{ca}}_n = \omega \Omega_n$, where $\omega$ is a power coefficient related to caching hardware that reflects the caching power efficiency in watt/bit. In this paper, we consider the common caching device, high-speed solid state disk (SSD), for caching files at ONU-APs. The value of $\omega$ for SSD is 6.25 $\times$ 10$^{-12}$ watt/bit.

For each ONU-AP, it can adjust the transmission power and the caching power to achieve higher throughput without violating the maximum power constraint $P_{M}$, namely, $P^{\text{total}}_n \leq P_{M}$. For notational convenience, the circuit power $P^{\text{cc}}_n$ is omitted for it is a constant.

### III. PROBLEM FORMULATION AND SOLUTION

#### A. Problem Formulation

Our objective is maximizing the downlink wireless access throughput for UEs by optimizing power allocation and caching strategy at ONU-APs in the FiWi access network. This is formulated as follows:

**PI:** \(\max_{x, P} \sum_{n \in N \ k \in \Phi_n} B \log_2 \left(1 + \frac{g_{nk} P_{nk}}{\sigma^2}\right)\) \quad (6a)

s.t. \(\sum_{k \in \Phi_n} \rho P_{nk} + \omega \sum_{j \in J} x_{nj} \leq P_{M}, \forall n \in N\) \quad (6b)

\(\sum_{n \in N \ k \in \Phi_n} p_j \left(1 - x_{nj}\right) R_{nk} \leq C \) \quad (6c)

\(\sum_{j \in J} x_{nj} \leq Q_n, \forall n \in N\) \quad (6d)

\(P_{nk} \geq 0, \forall n \in N, \forall k \in K\) \quad (6e)

\(x_{nj} \in \{0, 1\}, \forall n \in N, \forall j \in J\) \quad (6f)

Constraint (6f) makes sure that the sum power consumed by each ONU-AP does not exceed the maximum power constraint $P_{M}$. Constraint (6c) ensures that the backhaul occupancy by uncached files should not be greater than the capacity constraint of fiber backhaul $C$. Constraint (6d) makes sure that the total size of files cached at ONU-AP$_n$ should not exceed the cache capacity $Q_n$. Constraint (6b) guarantees that the transmission power is non-negative. Constraint (6a) means that the cache decision on the $j$-th file at ONU-AP$_n$ is a binary variable $x_{nj}$.

#### B. Optimal Transmission Power Allocation

Problem PI is a typical Mixed Integer Programming (MIP) problem, which is non-linear and non-convex. However, the problem becomes a convex optimization problem for fixed \(\{x_{nj}\}\). By deriving the Karush-Kuhn-Tucker (KKT) conditions, we can get the optimal solution to transmission power allocation.

The Lagrangian of PI is given as

\(\mathcal{L}(P, \lambda, \mu, \varepsilon) = -\sum_{n \in N \ k \in \Phi_n} R_{nk} + \varepsilon_{nk} P_{nk} + \lambda \left(\sum_{n \in N \ k \in \Phi_n} p^{\text{miss}}_{nk} R_{nk} - C\right)\)

\(+ \sum_{n \in N} \mu_n \left(\sum_{k \in \Phi_n} \rho P_{nk} + \omega \sum_{j \in J} x_{nj} s - P_{M}\right) - \sum_{n \in N \ k \in \Phi_n} \varepsilon_{nk} P_{nk}\)

where $\lambda$, $\mu$, $\varepsilon$ are Lagrangian multipliers.

**Proposition 1.** Problem PI becomes a convex optimization problem for a given solution to the caching strategy \(\{x_{nj}\}\).

**Proof.** The objective function (6a) is a strictly concave and increasing function with respect to $P_{nk}$, the inequality constraints (6b) and (6c) are convex for a given caching solution \(\{x_{nj}\}\). Therefore, problem PI becomes a convex optimization problem for fixed \(\{x_{nj}\}\). \(\square\)

The KKT conditions can be expressed as

\[\frac{\partial \mathcal{L}}{\partial P_{nk}} = \frac{g_{nk}}{\sigma^2} + g_{nk} P_{nk} \ln 2 \left(1 + \lambda \sum_{j \in J} B p_j (1 - x_{nj})\right)\]

\[+ \rho \mu_n - \varepsilon_{nk} = 0 \quad (8a)\]

\[\lambda \left(\sum_{n \in N \ k \in \Phi_n} \sum_{j \in J} p_j (1 - x_{nj}) R_{nk} - C\right) = 0 \quad (8b)\]

\[\mu_n \left(\sum_{k \in \Phi_n} \rho P_{nk} + \omega \sum_{j \in J} x_{nj} s - P_{M}\right) = 0 \quad (8c)\]

\[\varepsilon_{nk} P_{nk} = 0, \forall n \in N, \forall k \in K \quad (8d)\]

\[\lambda, \mu_n, \varepsilon_{nk} \geq 0, \forall n \in N, \forall k \in K \quad (8e)\]

where (8a) is a necessary condition for an optimal solution, (8b), (8c) and (8d) represent the complementary slackness, and (8e) represents the dual feasibility.

**Proposition 2.** The downlink throughput in the FiWi access network is maximized when the ONU-APs consume the maximum power, i.e., satisfy

\[\sum_{k \in \Phi_n} \rho P_{nk} + \omega \sum_{j \in J} x_{nj} s = P_{M}, \forall n \in N \quad (9)\]

**Proof.** Suppose that there exists $n \in N$ which satisfies $\sum_{k \in \Phi_n} \rho P_{nk} + \omega \sum_{j \in J} x_{nj} s < P_{M}$, then ONU-AP$_n$ can increase its caching power to $P_{M} - \sum_{k \in \Phi_n} \rho P_{nk}$ for a
higher cache hit ratio without reducing the sum rate of UEs associated to ONU-AP\(_n\). Through proof by contradiction, we get the conclusion that the downlink throughput of the FiWi access network is maximized when the ONU-APs consume the maximum level of power.

By using Proposition 1, 2 and the KKT conditions mentioned above, we can obtain an expression for the optimal transmission power \(P^*_nk\) with respect to Lagrangian multipliers \(\lambda_n, \mu_n\)

\[
P^*_nk = \left( \frac{B - \lambda B \sum_{k \in F_n} p_j (1 - x^\circ_{nj}) - \sigma^2}{\rho \mu_n \ln 2} \right)^+ g_{nk},
\]

with \((\cdot)^+ = \max(\cdot, 0).

**Proposition 3.** For problem \(\text{PI}\), the optimal transmission power \(P^*_nk\) allocated to UE\(_k\) by ONU-AP\(_n\) can be expressed as

\[
P^*_nk = \left( \frac{B}{\rho \mu_n \ln 2} - \frac{\sigma^2}{g_{nk}} \right)^+,
\]

and the corresponding Lagrangian multiplier \(\mu_n\) can be expressed as

\[
\mu_n = \frac{|\Phi_n|B}{P_M + \sum_{k \in F_n} \frac{\rho}{{g_{nk}}} - \omega} \ln 2
\]

\[\text{Proof.} \quad \text{Eq. (11) holds if the backhaul constraint (5c) is neglected (i.e., } \lambda = 0). \text{ Substituting Eq. (10) into Eq. (9), we obtain Eq. (12). What we need to prove is that the conclusion still holds with the backhaul constraint (5c). Suppose the optimal solution to problem \(\text{PI}\) is } \{P^*_nk, x^\circ_{nj}\}, \text{ then } \sum_{k \in F_n} P^*_nk + \omega \sum_{j \in J} x^\circ_{nj} s = P_M. \text{ Let } \{P^0_{nk}, x^\circ_{nj}\} \text{ denote the solution that satisfies Eq. (11), which indicates the maximum sum rate of UEs associated to ONU-AP\(_n\) without the backhaul constraint and is expressed as}

\[
\sum_{k \in F_n} \log_2 \left( 1 + \frac{g_{nk} P^0_{nk}}{\sigma^2} \right) \geq \sum_{k \in F_n} \log_2 \left( 1 + \frac{g_{nk} P^*_nk}{\sigma^2} \right)
\]

\[
\sum_{k \in F_n} P^0_{nk} \leq \sum_{k \in F_n} P^*_nk
\]

From Eq. (9) and Eq. (13a), we obtain \(P^0_{nk} \geq P^*_nk\), which means that \(\{P^0_{nk}, x^\circ_{nj}\}\) gets a higher cache hit ratio without reducing the sum rate of UEs associated to ONU-AP\(_n\). Therefore, Eq. (13a) also holds with the backhaul constraint, so \(\{P^0_{nk}, x^\circ_{nj}\}\) yields the optimal solution which is obtained by using Eq. (11).

In Eq. (11), \(\frac{\sigma^2}{g_{nk}}\) is the inverse of channel gain normalized by the noise variance \(\sigma^2\). Eq. (11) complies with the form of water-filling method [12, Chapter 6]. Think of a vessel whose bottom is formed by plotting those values of \(\frac{\sigma^2}{g_{nk}}\) for each subchannel \(k\). Then, we flood the vessel with water to a depth \(\frac{B}{\rho \mu_n \ln 2}\). Note that the volume of water is not fixed and it depends on the caching solution \(\{x^\circ_{nj}\}\). For a given caching solution, the total amount of water used is then \(P_M - (\omega \sum_{j \in J} x^\circ_{nj} s)\). The depth of the water at each subchannel \(k\) is equal to the optimal transmission power allocated to the channel. Proposition 3 guarantees that the optimal solution to transmission power allocation still holds with the backhaul constraint, so this method is called volume adjustable backhaul-constrained water-filling method (VABWF).

**Theorem 1.** On the condition of total power constraint, files with higher popularity should be cached preferentially for maximizing the throughput in the FiWi access network.

**Proof.** Suppose that \(\{P^*_nk, x^*_{nj}\}\) is the optimal solution to problem \(\text{PI}\) with the corresponding downlink throughput \(R^\text{dl}\), and \(\{x^*_{nj}\}\) violates the popularity based caching policy mentioned in Theorem 1. Let \(\{P_{nk}, x^\circ_{nj}\}\) be another set and \(\{x^\circ_{nj}\}\) satisfies

\[
\left\{ x^\circ_{nj} | x^\circ_{nj} \geq x^0_{nj(j+1)}, \sum_{j \in J} x^\circ_{nj} = \sum_{j \in J} x^0_{nj}, \forall n \in N, \forall j \in J \right\}
\]

Namely, \(\{x^\circ_{nj}\}\) is a caching solutions that obey Theorem 1. As \(p_j\) is monotonically decreasing in \(j\), the cache miss ratio satisfies

\[
\sum_{j \in J} p_j (1 - x^\circ_{nj}) < \sum_{j \in J} p_j (1 - x^*_{nj}).
\]

Note that \(\{P^0_{nk}, x^\circ_{nj}\}\) satisfies \(\sum_{j \in J} x^\circ_{nj} = \sum_{j \in J} x^0_{nj}\). With constraint (2), we can obtain a set of transmission power solution that satisfy \(P^0_{nk} = P^*_nk\). With \(\{P^0_{nk}, x^\circ_{nj}\}\) is ensured to satisfy the constraint (5c), so \(\{P^0_{nk}, x^\circ_{nj}\}\) is a solution to problem \(\text{PI}\), with the corresponding downlink throughput \(R^\text{dl}\). By the optimality of \(\{P^0_{nk}, x^\circ_{nj}\}\) to problem \(\text{PI}\), we have

\[R^\text{dl} - R^\text{dl}^0 \geq 0.\]

Since \(P^0_{nk} = P^*_nk\), the equality in (13) must hold, which concludes that \(\{P^0_{nk}, x^\circ_{nj}\}\) yields the optimal solution to problem \(\text{PI}\).

**C. Problem Reformulation and Solution**

By using Theorem 1 and the VABWF method mentioned previously, the solution space of problem \(\text{PI}\) is greatly reduced. We denote the solution space of problem \(\text{PI}\) by \(\mathcal{A}\), thus we have that

\[
\mathcal{A} = \{P_{nk}, x_{nj}\} | P_{nk} = \left( \frac{B}{\rho \mu_n \ln 2} - \frac{\sigma^2}{g_{nk}} \right)^+ \quad x_{nj} \geq x_{nj(j+1)} \quad \forall j \in J
\]

The element of \(\mathcal{A}\), denoted \(A_{nj}\) is \(\{P^0_{nk}, x^\circ_{nj}\} \in \mathcal{A}\), should satisfy

\[
\sum_{j \in J} x^\circ_{nj} = j.
\]

Let \(\mu(A_{nj})\) denote whether \(A_{nj}\) is chosen to be the solution, which can be expressed as

\[
\mu(A_{nj}) = \begin{cases} 
1, & \text{if } A_{nj} \text{ is chosen to be the solution} \\
0, & \text{otherwise}
\end{cases}
\]

Define \(\omega(A_{nj})\) to be the backhaul bandwidth occupied by ONU-AP\(_n\) with respect to solution \(A_{nj}\)

\[
\omega(A_{nj}) = \sum_{k \in F_n} P^\text{miss}_{nk} R_{nk} |(P_{nk}, x_{nj}) = A_{nj}| \mu(A_{nj}) = 1
\]

\[
, \mu(A_{nj}) = 0
\]
Likewise, define \( \nu(A_{nj}) \) to be the sum rate of UEs associated to ONU-AP \( n \) with respect to solution \( A_{nj} \)

\[
\nu(A_{nj}) = \begin{cases} 
\sum_{k \in \Phi_n} R_{nk} | \{ p_{nk}, x_{nk} \} = A_{nj} |, & \mu(A_{nj}) = 1 \\
0, & \mu(A_{nj}) = 0 
\end{cases}
\]

Then problem P1 can be converted into the problem of determining the value of \( \mu(A_{nj}) \) with the aim to maximize the downlink wireless access throughput of the FiWi access network as follows,

**P2:** \[
\max_{\mu(A_{nj})} \sum_{n \in N} \sum_{j \in J} \nu(A_{nj}) \\
s.t. \sum_{n \in N} \sum_{j \in J} \omega(A_{nj}) \leq C \\
\mu(A_{nj}) \leq 1, \quad \forall n \in N, \forall j \in J \\
\mu(A_{nj}) \in \{0,1\}, \quad \forall n \in N, \forall j \in J
\]

Problem P2 is in the form of a multiple-choice knapsack problem (MCKP) [13] Chapter 11. The problem is to choose no more than one item from each class such that the profit sum is maximized without exceeding the capacity \( C \) in the corresponding backhaul limitation. Considering an optimal solution to the MCKP problem, it is obvious that by removing any class \( n \) from the optimal MCKP packing, the remaining solution set must be an optimal solution to the subproblem defined by capacity \( C - \omega(A_{nj}) \) and class set \( N \setminus \{n\} \). Any other choice will risk to diminish the optimal solution value. Hence, problem P2 has the property of an optimal substructure as described in [14] Section 15.3. We design an optimal and efficient algorithm through dynamic programming based on VABWF method as outlined in Algorithm 1. Define \( R(n,c) \) to be the maximum downlink throughput of the FiWi access network on the condition that there exist only the first \( n \) classes with backhaul limitation \( c \). Then we can consider an additional class to calculate the corresponding maximum throughput and the following recursive formula describe how the iterative method is performed

\[
R(n,c) = \max \left\{ \left\{ R(n-1,c-\omega(A_{nj})) + \nu(A_{nj}) \right\} \cup \left\{ R(n-1,c) \right\} \mid c - \omega(A_{nj}) \geq 0, \forall j \in J \right\}.
\]

Note that the constraint (17c) is satisfied by placing the recursive formula in the innermost loop. At each iteration, we choose the optimum solution to the given number of classes \( n \) and bandwidth limitation \( c \). The running time of Algorithm 1 is dominated by the \( c \) iterations of the second for-loop, each of which contains at most \( J \) iterations where a new solution of a subproblem is computed. Considering \( N \) ONU-APs in the FiWi access network, there are \( N \) subproblems to be computed, so the overall time complexity is \( O(NCJ) \).

**IV. Simulation Results**

In this section, we validate the performance of our proposed caching and power allocation algorithm under different FiWi access network scenarios. The simulation parameters are summarized in Table I. For a comparison purpose, we introduce full-cache, equal-power and random algorithms as follows,

- **Full-Cache:** Each ONU-AP fully uses the cache capacity to store the most popular files, and the classical water-filling method is used to allocate transmission power to UEs.
- **Equal-Power:** Transmission power is equally allocated to UEs. Meanwhile, each ONU-AP choose the most popular files to cache, but does not necessarily use full

| Parameter                      | Value       |
|--------------------------------|-------------|
| Number of ONU-APs              | 32          |
| UE numbers at each ONU-AP      | 20          |
| System bandwidth              | 20MHz       |
| Subchannel bandwidth          | 100MHz      |
| Thermal noise density          | $-144dBm$   |
| Number of files                | 1000        |
| Size of file                   | 100MB       |
| Cache size of each ONU-AP      | 30GB        |
| Caching power efficiency       | $6.25 \times 10^{-12}$ W/bit |
| Circuit power at each ONU-AP   | 3W          |
| Transmission power coefficient | 1.2         |
| Fiber backhaul capacity        | 2.488Gbps (unless stated otherwise) |
| Maximum total power for each ONU-AP | 7W (unless stated otherwise) |
| Zipf parameter                 | 0.8 (unless stated otherwise) |
cache capacity.

- Random: ONU-APs randomly choose files to cache and transmission power is also equally allocated to UEs.

A. Downlink Throughput and Cache Utilization of the Proposed Algorithm

As shown in Fig. 2(a), observing typical GPON downlink rate of 2.488Gbps, the corresponding downlink throughput is increased by 30% with regard to the backhaul bandwidth. Even greater improvement of the downlink throughput is observed when the backhaul bandwidth is 1.25Gbps, which is a typical downlink rate in EPON. The throughput is increased by about 2.5 times with regard to the backhaul bandwidth. As for the cache utilization shown in Fig. 2(b), we never use full cache capacity and the cache utilization is below 50% in most instances. Besides, the slope of the curves changes with different values of $\delta$.

Fig. 2(a) and Fig. 2(b) show that the downlink throughput increases with the increase of fiber backhaul capacity, whereas the cache utilization reduces as the backhaul capacity increases. This is not surprising, because the larger the fiber backhaul capacity is, the more cache miss files can be fetched via the feeder fiber from the Internet. Thus, less power for caching is used for local storage. On the other hand, the cache utilization is higher when the Zipf distribution parameter $\delta$ has a smaller value, which means the proposed algorithm choose to cache more files rather than increase transmission power for the purpose of maximizing the throughput. This is due to the fact that the file popularity becomes more decentralized with smaller value of $\delta$, so the proposed algorithm tends to cache more files to avoid the backhaul bottleneck.

B. Comparisons with the other Algorithms

Fig. 3(a) illustrates the downlink throughput with respect to maximum total power $P_M$. It is observed that the proposed algorithm outperforms the others with an increase of 10.4%, 11.8% and 25.8% in the downlink throughput, respectively. This is because the proposed algorithm can adaptively adjust the transmission power and caching power under different maximum total power values. Under the condition that the backhaul occupied by cache miss files does not exceed the backhaul limitation $C$, our proposed algorithm tries to increase the transmission power level and allocate more power to UEs with better channel conditions for higher throughput. We can observe that the interval between the proposed algorithm and full-cache algorithm becomes smaller with the increase of maximum total power available for ONU-APs. This is due to the fact that by adopting the proposed algorithm, more caching power is used when the value of maximum total power increases with the purpose of maximizing downlink wireless access throughput. Therefore, the solution to the problem using full-cache algorithm gets closer to the optimal solution using the proposed algorithm. In addition, equal-power algorithm fails to get higher throughput because the transmission power allocated to UEs is a fixed value, and the bottleneck appears when higher value of maximum total power is chosen. The worst performance occurs when random algorithm is adopted because the highest-popularity-first caching strategy is not used. Thus, the cache hit ratio is rather low, which limits the system throughput.

Fig. 3(b) illustrates the downlink throughput with respect to fiber backhaul capacity $C$. It is again observed that the proposed algorithm has much better performance than the others. It is worth noting that the downlink throughput using full-cache algorithm is considerable when the backhaul capacity $C$ is small, but never increases even if the backhaul capacity increases to a higher level. This is not surprising because the total transmission power is fixed when we use full-cache algorithm. Therefore, the throughput is never enhanced regardless of the increased backhaul capacity. On the contrary, our proposed algorithm makes full use of the backhaul capacity while increasing the transmission power level for higher throughput.

Fig. 3(c) illustrates the downlink throughput with respect to diversity of file popularity. The proposed algorithm performs better than the others under different values of Zipf parameter $\delta$. We observe that the throughput increases with the increase of $\delta$. This is because more requests centralize on a few files with the rest of files rarely getting requested when $\delta$ is larger, thus our proposed algorithm tends to cache less files and save more caching power for increasing transmission power to achieve higher throughput. The interval between our proposed algorithm and equal-power algorithm gets smaller with the increase of parameter $\delta$, but is not
expected to be eliminated. This is reasonable because the cache hit ratio gets higher when parameter $\delta$ increases, leading to better performance of equal-power algorithm. Nevertheless, with transmission power equally allocated to UEs, the optimal solution will never be obtained. We also notice that the throughput remains unchanged using full-cache algorithm despite the change of parameter $\delta$. This indicates a waste of caching power because files rarely being requested are cached in ONU-APs. Therefore, the transmission power drops to a low level and the downlink throughput is not expected to increase.

V. CONCLUSION

In this paper, we equip ONU-APs with caches in FiWi access networks to deal with fiber backhaul bottleneck and further enhance the system throughput. To achieve the optimal downlink wireless access throughput, we propose a dynamic programming algorithm based on VABWF to perform joint power allocation and caching optimization. Simulation results show that the proposed algorithm outperforms full-cache and random algorithms as well as equal-power allocation algorithm significantly in terms of system throughput.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation of China (No.61390513, 91538203, 61771445) and the Fundamental Research Funds for the Central Universities.

REFERENCES

[1] Cisco, “Cisco visual networking index: Forecast and methodology, 2016-2021,” White Paper, Sep. 2017.
[2] J. Liu, H. Guo, H. Nishiyama, H. Ujikawa, K. Suzuki, and N. Kato, “New perspectives on future smart FiWi networks: Scalability, reliability, and energy efficiency,” IEEE Commun. Surv. Tutorials, vol. 18, no. 2, pp. 1045-1072, 2016.
[3] D. P. Van, B. P. Rimal, M. Maier, and L. Valcarenghi, “ECO-FiWi: An energy conservation scheme for integrated fiber-wireless access networks,” IEEE Trans. Wirel. Commun., vol. 15, no. 6, pp. 3979-3994, 2016.
[4] Y. Yiakoumis, M. Bansal, A. Covington, J. V. Reijendam, S. Katti, and N. McKeown, “BeHop: A testbed for dense Wi-Fi networks”, ACM SIGMOBILE Mobile Comput. Commun. Rev., vol. 18, no. 3, pp. 71-80, 2014.
[5] F. J. Effenberger, H. Mukai, J. Kani, and M. Rasztovits-wiech, “Next-generation PON — Part III: System specifications for XG-PON,” IEEE Commun. Mag., no. November, pp. 58-64, 2009.
[6] I.-S. Hwang, A. Nikoukar, C.-H. Tong, and K. R. Lai, “Scalable architecture for VOD service enhancement based on a cache scheme in an ethernet passive optical network,” IEEE/OSA J. Opt. Commun. Netw., vol. 5, no. 4, pp. 271-282, 2013.
[7] X. Li, K. Kanomakis, N. Cvijetic, A. Tanaka, C. Qiao, and T. Wang, “Joint bandwidth provisioning and cache management for video distribution in software-defined passive optical networks,” in Conf. Opt. Fiber Commun. Tech. Dig. Ser., vol. 1, pp. 4-6, 2014.
[8] S. Abeyswickerama and E. Wong, “Single-receiver dual-channel dynamic bandwidth algorithm for local storage VoD delivery,” in IEEE Glob. Telecommun. Conf. (GLOBECOM), pp. 2674-2679, 2013.
[9] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. Imran, D. Sabella, M. Gonzalez, O. Blume, and A. Fehske, “How much energy is needed to run a wireless network?" IEEE Trans. Wireless Commun., vol. 18, no. 5, pp. 40-49, Oct. 2011.
[10] N. Choi, K. Guan, D. C. Kilper, and G. Atkinson, “In-network caching effect on optimal energy consumption in content-centric networking.” IEEE Int. Conf. Commun. (ICC), pp. 2889-2894, 2012.
[11] J. Llorca, A. M. Tulino, K. Guan, J. Esteban, M. Varvello, N. Choi, and D. C. Kilper, “Dynamic in-network caching for energy efficient content delivery,” in Proc. IEEE INFOCOM, pp. 245-249, 2013.
[12] B. G. Lee, D. Park, and H. Seo, Wireless communications resource management. John Wiley & Sons Pte Ltd., 2009.
[13] H. Kellerer, U. Pferschy, and D. Pisinger, Introduction to NP- completeness of knapsack problems. Springer, 2004.
[14] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, Introduction to algorithms. The MIT Press, third edition, 2009.