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Digraph-Based Joint Routing and Resource Allocation in Software-Defined Backhaul Networks

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***Abstract*—By decoupling the control plane from the data plane and providing programmability for network applications, software-defined network (SDN) is positioned to offer more efficient management, higher flexibility and better performance. Routing and resource allocation are two closely related applications in wireless networks. With close cooperation, better performance and lower complexity can be achieved in an SDN architecture. However, work that jointly studies routing and resource allocation is rarely seen. In this paper, the joint routing and resource allocation problem is investigated in OFDMA-based software-defined backhaul networks (SDBN). To exploit the SDN programmability, an SDBN system model is proposed, where the control panel can use high complexity algorithms in configuration phase in order to simplify algorithms in operation phases. Then the joint routing and resource allocation problem is formulated as a system throughput optimization problem. By constructing the interference digraph of the network and analysing the vertex degree characteristics, a digraph-based greedy algorithm (DBGA) is proposed. Simulation results have shown that, the proposed DBGA works well to increase the system throughput.**

***Index Terms*—Software-defined backhaul network, joint routing and resource allocation, graph theory.**

I. INTRODUCTION

Owing to its simplified management, high flexibility and improved performance, software-defined network (SDN) has drawn considerable attention in recent years [1–3]. By separating the control plane and the data plane, SDN can offer logical centralization of network management and introduce the programmability, which open up new approaches to control functions in the application layer. Routing and resource allocation are main functions of wireless networks. Traditionally, routing and resource allocation designs are based on distributed approaches, which may confront problems such as high complexity and performance limitations. With the introduction of SDN, problems can be broken into tractable pieces and decisions can be made based on global network information.

Several works have been presented to utilize the SDN features for better routing and resource allocation designs separately. In [4], the authors built a model and developed algorithms for load balancing with packet forwarding rules. By migrating traffic from heavy loaded switching devices to lightly loaded ones, the proposed algorithm in [5] achieved load balancing routing reactively. Multipath routing, where traffic can be forwarded with multiple paths, was exploited in [6] to provide load balancing and improve network throughput. In [7], a novel method was proposed to build multicast topology in SDN. In [8], a price-based joint allocation model of network resource in SDN is built by introducing the price for each of the resources, which can get the proportional fair allocation of link bandwidth and Sthe minimum global delay at the same time. However, work that jointly considers both routing and resource allocation is rarely seen in SDN.

Strong interactions exist between routing and resource allocation procedures. For instance, to hold the forthcoming traffic, the available spectral resources of the different links should be considered. In return, when all routes are settled, the spectral resources are assigned based on the traffic amount in each link. Especially with interferences existing in the network, the routed traffic may impact the resource allocation strategy and further affect the capacity of the network. Hence, jointly considering routing and resource allocation is of fundamental importance to increase the reusability of spectrum to load the explosively growing traffic over wireless networks [9].

In this paper, we investigate joint routing and resource allocation in an OFDMA-based software-defined backhaul network (SDBN), where multi-hop transmission and mesh topology are applied. We proposed an SDBN system model for routing and resource allocation functions in consideration of SDN features. Based on our system model, we formulated the joint routing and resource allocation problem as a system throughput optimization problem. To solve the problem in a decomposition manner, an interference digraph was constructed. Through analysing the indegree and outdegree of vertices in the digraph, a low complexity greedy algorithm was proposed, which has been proven by simulations to work well to improve the system throughput.

The remainder of the paper is organized as follows. In II, we propose the SDBN system model in detail. Then, the joint routing and resource allocation problem is formulated in III. Next, we analyse the problem on an interference digraph

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basis and propose our digraph-based greedy algorithm in IV. Simulation results and analyses are presented in V. Finally, we conclude this paper in VI.

II. SYSTEM MODEL

A. Software-Defined Backhaul Network

Backhaul network is considered in this work, in which basic SDN architecture is adopted. It includes two parts: SDN controller in the control plane and switching devices in the data plane. The SDN controller is a centralized software-defined control unit, which communicates with all switching devices through control panel. Switching devices or nodes for simplification are responsible for collecting and sending network status to controller and processing data packets based on rules provided by the controller. It is worthy noticing that communications between any two nodes may be required with caching techniques [10]. N nodes and L directional links are considered in this paper.

B. Service-Oriented Virtual Sub-Network

In SDNs, network virtualization is a key technique which enables distinct control over different services (e.g. VoIP and download) in the very same architecture[11]. For one specific service, the SDN controller assigns nodes and links based on the demand (e.g. throughput and latency) of the service, which forms the service-oriented virtual sub-network.

In the configuration phase of one sub-network, the nodes and links can be processed to produce feasible paths between any two nodes with depth-search algorithm [12]. All feasible paths from node m to node n are recorded in set $Route(m,n)$ whose size is $F(m,n)$. The f^{th} feasible path is denoted as $Route^f(m,n)$ whose elements are link indices.

In the operation phase of the sub-network, we consider the traffic request as multi-hop transmission rate demand. For one traffic request from node m to node n, the demand is denoted by $D(m,n)$ bits/s. Further, we use D_i to denote the traffic that passes through link l_i. If traffic request $D(m,n)$ routes through link l_i, $D_i(m,n) = D_(m,n)$. Otherwise, $D_i(m,n) = 0$. The total number of traffic requests is denoted by M.

C. Resource Pool

In SDN, the controller is responsible to monitor the usage of spectral resources and control the resource allocation and the routing strategy of the network. We assume that the spectral resource is divided into W sub-channels, and there are T time slots in one second. One sub-channel w in one time slot t is called a resource block $b(w,t)$. Nodes can transmit and receive data on any combination of the resource blocks. We propose to construct resource pool P in the controller to help manage the resource usage. Each link l_i has its resource pool matrix $P_i(w,t)$. If $P_i(w,t) = \mathit{1}$, it means that the resource block $b(w,t)$ is assigned to link l_i. Otherwise, resource block $b(w,t)$ is not in use in the corresponding link.

D. Interference Model

Compared with access network, a special issue of SDBN is that the architecture and topology are stationary. Thus, it is reasonable to assume that every node and link are preconfigured with appropriate parameters that impact interferences between links. With such precondition, protocol model [13] is adopted in this paper, which simply considers that link failure occurs when nodes are out of transmission range or the transmission is interfered by nodes occupying the same resource blocks in the interference range.

With the stationary network topology and configuration, two inherent interference properties of links are certain and vital, which should be defined and recorded in the SDN controller. The set of links that interferes link l_i is denoted by A_i. Likewise, the set of links that are interfered by link l_i is denoted by B_i. A_i and B_i are called the interference sets of link l_i.

E. System Throughput

We further assume that each link has its fixed link transmission rate r_i bits/s if one resource block is assigned based on the stationary topology of SDBN. With resource blocks assigned to link l_i, the link throughput is computed by:

$$R_i = r_i \sum_{w=1}^{W} \sum_{t=1}^{T} P_i(w,t). \tag{1}$$

At the network level, the system throughput is given by the sum of throughputs of all links. If the resource allocation scheme S is applied to the network, the system throughput is computed by:

$$R_S = \sum_{i=1}^{I} R_i = \sum_{i=1}^{I} (r_i \sum_{w=1}^{W} \sum_{t=1}^{T} P_i(w,t)). \tag{2}$$

III. JOINT ROUTING AND RESOURCE ALLOCATION PROBLEM

In SDNs, routing and resource allocation are two basic and closely related issues. Different routing strategies may lead to different resource allocation schemes, which may further seriously impact the system performance. In return, resource allocation algorithms may also impact the routing decisions. In the following, we try to jointly consider the routing and resource allocation problem to improve the throughput of SDBNs.

A. Problem Formulation

In the background of traffic explosion, it is always of great interest to obtain the optimal achievable system throughput to be able to load more traffic in SDBNs. Thus, the objective function of the resource allocation problem becomes:

$$\text{Maximize } R_S = \sum_{i=1}^{I} R_i = \sum_{i=1}^{I} (r_i \sum_{w=1}^{W} \sum_{t=1}^{T} P_i(w,t)) \tag{3}$$

Meanwhile, we have the following resource block constraint:

$$\begin{aligned}&P_i(w,t)\in\{0,1\}\\&\forall i=1,2,\ldots,L\quad\forall w=1,2,\ldots,W\quad\forall t=1,2,\ldots,T.\end{aligned}\tag{4}$$

Link interference constraint is required to avoid interference between links:

$$\begin{aligned}&P_i(w,t)+P_j(w,t)\leq 1\\&\forall i=1,2,\ldots,L\quad\forall j\in A_i\\&\forall w=1,2,\ldots,W\quad\forall t=1,2,\ldots,T\end{aligned}\tag{5}$$

where A_i is one of the interference sets of link l_i.

Though many feasible paths are predefined for any two nodes, only one path can be chosen. Thus, the following routing constraint should be obeyed:

$$\begin{aligned}&f\in F(m,n)\qquad D_i(m,n)=D(m,n)\\&\forall i\in Route^f(m,n)\quad\forall m=1,2,\ldots,N\quad\forall n=1,2,\ldots,N.\end{aligned}\tag{6}$$

To satisfy the traffic requests, following traffic request constraint should be considered:

$$\begin{aligned}&r_i\times|P_i|\geq D_i=\sum_{m=1}^{N}\sum_{n=1}^{N}D_i(m,n)\\&\forall i=1,2,\ldots,L\quad\forall m=1,2,\ldots,N\quad\forall n=1,2,\ldots,N\end{aligned}\tag{7}$$

To this end, an optimization problem of joint routing and resource allocation for backhaul networks has been formulated. In summary, the objective in (3) needs optimization subject to constraints in (4)-(7).

IV. DIGRAPH-BASED JOINT ROUTING AND RESOURCE ALLOCATION

As the resource allocation variable P is restricted to be an integer, the developed optimization problem is inherently NP-hard [14]. In dense wireless networks, to adapt to the dynamic traffic requests, a relatively fast algorithm is required to solve the problem. More seriously, the system may not be able to redo all the routing and resource allocation assignments globally whenever a traffic variation occurs. Thus, the algorithm should be able to work well on a single traffic request basis. Considering low computational complexity, a greedy algorithm based on interference digraph is proposed in this section.

A. Interference Digraph Construction

The network topology can be abstracted into an interference digraph $G=(V,E)$. V is a vertex set whose elements are links in the network, where $l_i\in V$. The edge set E consists of directed edges which present potential interferences between links. For instance, edge $e(l_i,l_j)$ means that link l_j is in the interference range of l_i.

In graph theory, for any vertex, the number of head ends adjacent to the vertex is defined as the indegree of the vertex, which is denoted by $deg^-(l_i)$. It presents the number of links that may cause interference to link l_i. Likewise, the number of tail ends adjacent to the vertex is defined as the outdegree of the vertex, which means the number of links that may receive interference from link l_i and is denoted by $deg^+(l_i)$.

B. Problem Analysis

The goal of the problem is to maximize the system throughput. For single traffic request, we try to make the decision of routing and resource allocation on the benefit of network throughput to approach the optimal solution.

In the interference digraph, the degrees of link clearly characterise the potential interference between links. The resource allocation of link l_i and its outdegree characteristics may impact the network throughput to a certain extent. For instance, if $deg^+(l_i)\cdot P_i$ is larger, the available resources for links in interference set B_i is smaller and so will be the network throughput. Though the above theory is not guaranteed to be always true in the global perspective, it is helpful to approach the local optimal solution by reducing $deg^+(l_i)\cdot P_i$ reasonably.

From load balancing point of view, the available resource blocks of links need consideration when routing a traffic request, which is relevant with the link indegree $deg^-(l_i)$. For example, larger $deg^-(l_i)$ means that more links interfere link l_i. Resource blocks that are assigned to such links are not available for link l_i. To characterise the resource block status of link l_i quantitatively, we introduce interference matrix $Q_i(w,t)$. If $Q_i(w,t)=1$, it means that link l_i or links in set A_i have already occupied resource block $b(w,t)$. Otherwise, resource block $b(w,t)$ is still available to link l_i.

Based on above discussion, a routing cost function for link l_i is defined as:

$$cost(l_i)=D(m,n)\cdot deg^+(l_i)+Q_i.\tag{8}$$

Thus, the cost function of path f is calculated by:

$$Cost(Route^f(m,n))=\sum_{\forall l_i\in Route^f(m,n)}cost(l_i).\tag{9}$$

During the routing process, all the links in the chosen path should be able to load the traffic. We develop $Algorithm\,1$ to check if $Route^f(m,n)$ is available.

C. Proposed Algorithm

Considering the requirement of low computational complex, a digraph-based greedy algorithm (DBGA) is proposed in $Algorithm\,2$, of which the details are explained as follows. For single traffic request, the available paths are valued with the routing cost function. Then the path with minimum cost is chosen and the traffic request is assigned to each link. Lastly, available resource blocks are assigned to each link considering avoidance of interference to satisfy the demand. When more than one traffic requests occur, the one with larger rate demand is a priority to process.

The complexity of DBGA is analysed as follows. In the algorithm, there are two main variables, which are the number of feasible paths F and the number of links L. The number of links in one feasible path is also a variable, which is less than L in any case. First, the complexity of feasible path

Algorithm 1: Availability Check of Feasible Path

```
Input:
• $f^{th}$ feasible path: $Route^f(m,n)$
• Number of total sub-channels: $W$
• Number of total time slots: $T$
• Resource block status $\forall l_i \in Route^f(m,n)$: $Q_i(w,t)$
• Transmission rate per resource block
$\forall l_i \in Route^f(m,n)$: $r_i$
Output:
• Availability of $Route^f(m,n)$

if $\forall l_i \in Route^f(m,n), \quad r_i \cdot (WT - |Q_i|) > D(m,n)$
then
    $Route^f(m,n)$ is available.
else
    $Route^f(m,n)$ is not available.
```

Algorithm 2: Digraph-Based Greedy Algorithm

```
Input:
• Interference graph: $G(V,E)$
• Traffic request: $D(m,n)$
• Feasible paths: $Route(m,n)$
• Number of total sub-channels: $W$
• Number of total time slots: $T$
• Interference sets $\forall l_i \in V$: $A_i$ and $B_i$
• Resource block status $\forall l_i \in V$: $Q_i(w,t)$
• Transmission rate per resource block $\forall l_i \in V$: $r_i$
• Outdegree $\forall l_i \in V$: $deg^+(l_i)$
Output:
• Routing result for traffic request $D(m,n)$: $route(m,n)$
• Resource allocation result $\forall l_i \in route(m,n)$: $P_i$
• Updated resource block status $\forall l_i \in V$: $Q_i(w,t)$

for $f = 1$ to $F$ do
    Check availability of $Route^f(m,n)$
    if $Route^f(m,n)$ is available then
        Calculate $Cost(Route^f(m,n))$
    end
end
Choose the path with minimum $Cost$ as $route(m,n)$
forall the $i \in route(m,n)$ do
    $D_i = D(m,n)$
    for $w = 1$ to $W$ do
        for $t = 1$ to $T$ do
            if $D_i > 0 \quad \&\& \quad Q_i(w,t) == 0$ then
                $P_i(w,t) = 1$
                $Q_i(w,t) = 1$
                $D_i = D_i - r_i$
                forall the $l_j \in B_i$ do
                    $Q_j(w,t) = 1$
                end
            end
        end
    end
end
```

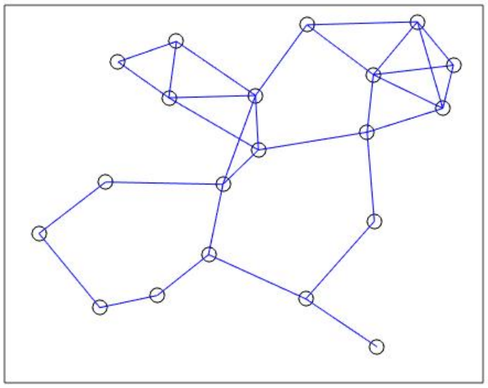

Fig. 1: Network topology

availability check and cost function calculation is $\mathcal{O}[FL]$. The selection of minimum cost path is of complexity $\mathcal{O}[F]$. Then, assigning resource blocks to one link requires $\mathcal{O}(1)$ and the update of resource block status for set B_i is of complexity $\mathcal{O}[L]$. Thus the total complexity of the algorithm is $\mathcal{O}[FL] + \mathcal{O}[F] + L \cdot (\mathcal{O}(1) + \mathcal{O}[L]) = \mathcal{O}[L(F+L)]$.

V. PERFORMANCE EVALUATION

A. Simulation Setup

The network is generated in an area of 1000 m×1000 m with 20 nodes in total. The transmission and interference range are set as 250 m and 400 m, respectively.

For the resource block settings, the whole spectral resource is divided into 50 sub-channels and one time slot is set as 5 ms. In this work, link transmission rate is not a variable that impacts on the results. So we simply assume that all links achieve 0.1 Mb/s rate with one resource block assigned.

Four services are considered in the simulations. The rate requests of the four services are set as 0.5, 1, 1.5, 2 Mb/s, respectively. The service-oriented virtual sub-network is constructed by selecting random connected nodes. The traffic requests are randomly generated between 2 nodes in the corresponding sub-network. Feasible paths are produced with depth-first search algorithm in advance.

B. Performance Analysis

The performance of network throughput with increasing traffic requests in one topology-fixed network is our primary concern. Fig. 1 shows the topology of the network for this simulation. Typical star, chain, tree and ring topologies can all be found in this topology, which makes it suitable for our performance evaluation. Two commonly used and effective algorithms, which are least hop routing algorithm (LHRA) and load balancing routing algorithm (LBRA), are compared with the proposed DBGA. To check the network throughput performance of these algorithms, we gradually add new traffic requests to the network. Fig. 2 shows the simulation results. In the beginning, all algorithms work well to route the traffic

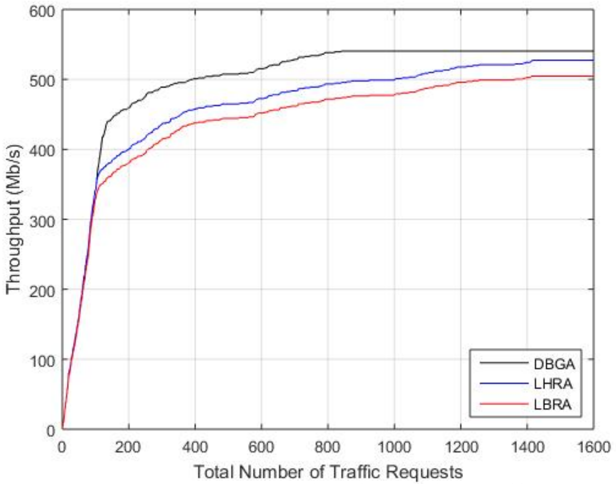

Fig. 2: System throughput against increasing traffic requests

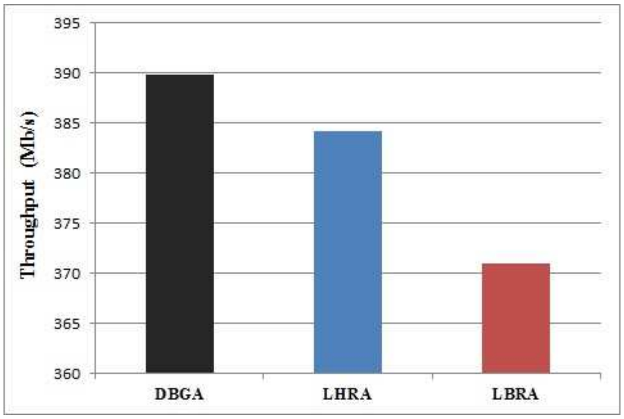

Fig. 3: Average system throughput performance

requests. Then the lines separates when some traffics are not successfully routed. At last all lines become steady as the network cannot load more traffic. As can be seen, the line of DBGA ends up higher than other algorithms. Then, we employ genetic algorithm to obtain a near-optimal solution. The result shows that the system throughput can achieve 550.5 Mb/s, which is only slightly larger than the proposed DBGA. As a conclusion, our proposed algorithm improves the ability to load traffics and achieve fair network throughput compared to the near-optimal benchmark.

Lastly, to verify the generality of our algorithm in different network topologies, we run another 25 sets of simulations with randomly generated networks. We show the average network throughput of the algorithms in Fig. 3. The results also show that our proposed DBGA is better in terms of increasing network throughput.

VI. CONCLUSIONS

In this paper, the joint routing and resource allocation problem in OFDMA-based SDBN is investigated. Based on the proposed SDBN system model, the problem is formulated as a system throughput optimization problem. Considering real time computational complexity, a digraph-based greedy algorithm is proposed through analysing the relationship between degree of vertices in the constructed interference digraph and the system throughput. Simulation results have shown that, the proposed DBGA works well in terms of improving the ability of traffic load bearing and increasing system throughput.

VII. ACKNOWLEDGEMENT

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