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Performance improvement for applying network virtualization in fiber-wireless (FiWi) access networks*

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Abstract: Fiber-wireless (FiWi) access networks, which are a combination of fiber networks and wireless networks, have the advantages of both networks, such as high bandwidth, high security, low cost, and flexible access. However, with the increasing need for bandwidth and types of service from users, FiWi networks are still relatively incapable and ossified. To alleviate bandwidth tension and facilitate new service deployment, we attempt to apply network virtualization in FiWi networks, in which the network's control plane and data plane are separated from each other. Based on a previously proposed hierarchical model and service model for FiWi network virtualization, the process of service implementation is described. The performances of the FiWi access networks applying network virtualization are analyzed in detail, including bandwidth for links, throughput for nodes, and multipath flow transmission. Simulation results show that the FiWi network with virtualization is superior to that without.

Key words: FiWi access networks, Network virtualization, Performance analysis
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1 Introduction

Fiber-wireless (FiWi) access networks, also called wireless-optical broadband access networks (WOBANs) (Sarkar *et al.*, 2009), are an optimal combination of fiber access networks and wireless access networks. FiWi access networks have been widely deployed to achieve flexibility at a low deployment cost (Kazovsky *et al.*, 2012). In the fiber subnetwork of FiWi networks, the optical line terminal (OLT) is laid in the central office (CO) and connected via fiber to several optical network units (ONUs). In its wireless part, a group of wireless routers comprise a wireless mesh network (WMN) with the ONUs. Users, whether stationary or mobile, connect to OLTs through these routers whose positions are fixed in a WMN (Feng and Ruan, 2011). FiWi networks are owned by Internet service providers (ISPs), who are also responsible for providing users with services (Feamster *et al.*, 2007).

Unlike core networks which connect domestic relay COs or different nations, access networks are responsible for connecting users and the CO. This means core networks require globalization, standardization, and unification, while access networks require localization, personalization, and diversity (Kuri *et al.*, 2012). FiWi access networks, as a type of access network, have their own characteristics: (1) front-end wireless mesh architecture and back-end tree-like architecture—because of the difference between physical links, the wireless subnetwork is the bottleneck of FiWi networks; (2) service burst in access networks—service occurrence time and duration are both random; (3) great variation of services in access networks—services hosted by access networks range from byte-level (such as message transmission)

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to GB-level (such as multimedia services) and service flow is huge during the day but less at night.

With the success of the Internet, more and more services have emerged and gained users' favor, especially video services and third-party services. Video services require higher bandwidth; thus, a new access network should be deployed to support video services, which requires much time and expenditure. Third-party services, which form most of the new services, are always the product of non-ISPs. Some third-party services are location and human action based, which are quite different from traditional network services. The open environment of the network largely promotes the development of third-party services.

In current FiWi access networks, there have been some service management schemes (such as service priority management), but they lack systematic service management. By improved service management we can deal with an increase in third-party service and systematically plan bandwidth for hosting services, which indirectly meets a higher bandwidth requirement.

We apply network virtualization in FiWi access networks to alleviate bandwidth tension and facilitate new service deployment. The main idea of network virtualization is to decouple services from infrastructure in traditional networks controlled by ISPs, and thus provide a more open environment for services. In this way, the role of traditional ISPs is separated into two entities: infrastructure providers (InPs) and service providers (SPs) (Chowdhury and Boutaba, 2009). The former manages the network infrastructure and provides abstracted virtual resource to multiple SPs rather than users in traditional networks. The latter creates virtual networks (VNs) by aggregating resources from multiple InPs and offers assembled VNs to host a specific service.

Using network virtualization, multiple VNs which may host different services are allowed to coexist upon the same network infrastructure. Each VN in the network virtualization environment is a collection of multiple virtual resources. Essentially, a VN is a subset of the underlying physical network resources (Chowdhury and Boutaba, 2010). Several testbeds are already available, such as PlanetLab, VINI, and GENI, with the help of network virtualization technology like OpenFlow (Wang *et al.*, 2013).

Network virtualization is a new way of organizing and managing network resources. In general, it is beneficial. Resources in access networks are more restrained than in core networks. Lack of systematic management and the prosperity of third-party services make the situation worse. On the other hand, FiWi access networks have the advantages of both fiber access networks and wireless access networks, including high bandwidth, high security, low cost, and flexible access. Thus, FiWi access networks are selected to apply network virtualization.

Software defined networking (SDN), as a way to build an engine, for example, is relevant to system builders. Someone would use a new way (i.e., network virtualization) of building an engine (i.e., SDN) of a car; however, customers do not buy engines, but cars (Michelle, 2013).

Our contributions in this paper are as follows:

1. Based on the hierarchical model and service model proposed by Dai *et al.* (2013), we develop a service realization process including the creation, maintenance, and removal of VNs. The overhead of setting up and removing VNs is also discussed.

2. The changes in FiWi networks are assessed after applying network virtualization, considering both the characteristics of FiWi networks and the existence of multiple VNs. The performance changes being analyzed include bandwidth for links, throughput for nodes, and multipath flow transmission.

2 Related work

Much work has been done on network virtualization. Khan *et al.* (2012) argued that network virtualization might bring nothing new in terms of technical capabilities and theoretical performance, but it provides a new way of organizing networks, which makes it possible to overcome some of the practical issues in today's Internet. Matsubara *et al.* (2013) investigated the initial standardization document given by ITU-T and concluded that network virtualization is useful in achieving service awareness. Duan *et al.* (2012) presented a review of service-oriented network virtualization to support cloud computing, from a perspective of network and cloud convergence. They also presented a framework of network-cloud convergence based on network virtualzation.

In a network virtualization environment, all operations are built on the virtual resources which are abstracted from physical infrastructure.

Belbekkouche *et al.* (2012) pointed out the importance of resource discovery and allocation. Cardoso *et al.* (2012) addressed the physical layer awareness problem in access, core, and metro networks. By means of network virtualization, they proposed a physical layer aware network architecture framework, in which the abstraction strategy has well elaborated mechanisms to handle channel impairments and requirements.

For service requests, a subset of virtual resources is allocated to form a VN which hosts requested services. Papagianni *et al.* (2013) provided a unified resource allocation method for network virtualization. The optimal networked cloud mapping problem was formulated as a mixed integer programming (MIP) problem, considering cost efficiency of resource allocation and the quality of service (QoS) requirement of users. The principles of different resource allocation methods differ, including hierarchical auction mechanisms (Tang and Jain, 2012), greedy randomized adaptive search heuristic algorithms (Pages *et al.*, 2012), game theory (Zhou *et al.*, 2010), bankruptcy games (Liu and Tian, 2013), Nash equilibria (Pacifici and Dan, 2012; Kakhbod and Teneketzis, 2012; 2013; Sharma and Teneketzis, 2012), and biological species competition models (Balasubramaniam *et al.*, 2011).

Allocated VNs must be mapped upon physical infrastructure, specific nodes and links. Yu *et al.* (2008) simplified VN embedding by allowing physical infrastructure to split a virtual link over multiple substrate paths and using path migration to optimize physical resource utilization. Chowdhury *et al.* (2012) proposed a VN embedding algorithm, called ViNEYard, to leverage coordination between node mapping and link mapping. Zhou *et al.* (2013) focused on the re-embedding process after the service was finished and VN removed. They demonstrated an incremental re-embedding scheme which is aimed to reduce the number of nodes that need to be re-embedded as much as possible. Leivadeas *et al.* (2012) introduced social features based metrics in the VN embedding process to fulfill the service centric function of future networks. Their work added an objective related to the social features of the physical network, minimizing the cost of embedding a request. Houidi *et al.* (2008) addressed the challenge of embedding a VN in physical infrastructure in a distributed and efficient manner.

As for the services in the network virtualization environment, Huang *et al.* (2012) proposed a model for end-to-end multimedia service delivery, in which an efficient path selection algorithm was used to traverse the network infrastructure and guarantee QoS. Rubio-Loyola *et al.* (2011) presented the architectural design of an autonomic Internet (AutoI) model which provides guaranteed services in an efficient manner and executes these services in an adaptive way.

Kokku *et al.* (2012) described a network virtualization substrate (NVS) to effectively exploit wireless resources in a cellular network. Lv *et al.* (2012) studied the network virtualization in WMNs. They designed the node in WMNs based on orthogonal frequency division multiple access (OFDMA) dual-radio architecture. Wang *et al.* (2011) discussed the application of network virtualization in multi-domain optical networks, especially public carrier networks with much dynamic background traffic. However, the real networks have heterogeneous physical infrastructures where many technologies exist. We have already proposed a general model for hybrid FiWi access network virtualization (Dai *et al.*, 2013). This paper builds on the previous work.

3 Network models

In FiWi network virtualization, some basic concepts should be introduced.

The physical infrastructure, which is also called physical resources, the substrate network, or the physical network in this paper, is provided by InPs. Physical infrastructure is the foundation of virtualization of the entire FiWi networks. Based on physical infrastructure, virtual resources and VNs are obtained and the operations among different roles realized. Physical infrastructure is composed mainly of physical nodes and physical links.

Virtual resources are generally one or more properties of physical devices, e.g., physical nodes or physical links. The information about all virtual resources, including occupied virtual resources and available virtual resources, is stored in a virtual resource pool, which is taken over by a virtual resource manager (VRM). The sufficient condition of a VN's creation is that there are enough available virtual resources to fulfill the virtual resource request of this

VNs; otherwise, the VN request will be denied.

A VN is a subset of all the virtual resources and is created to host a specific service which is provided by SPs. VNs have some unique characteristics, such as coexistence, recursion, inheritance, isolation, manageability, scalability, and stability. VNs can be created, maintained, and removed.

3.1 Hierarchical models

Because of the decoupling of physical infrastructure and the services, network virtualization provides a more open network environment for newly emerging services and indirectly alleviates bandwidth tension in FiWi access networks. The hierarchical model of FiWi network virtualization is shown in Fig. 1.

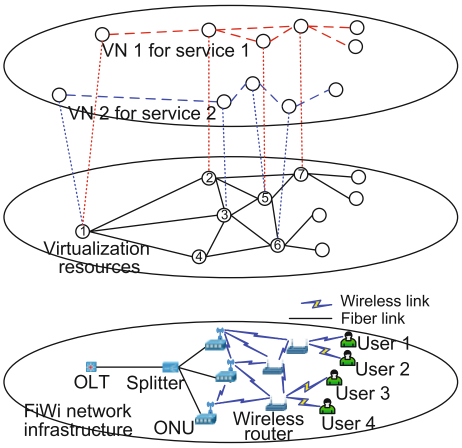

Fig. 1 Hierarchical model for FiWi network virtualization

The bottom layer is the physical infrastructure of the FiWi network, provided by the InP. To disengage services from physical network resources which have complex characteristics, network virtualization is used to abstract the physical infrastructures into virtual resources which are an independently manageable partition of all the physical resources and inherit the same characteristics as the physical resources. The capacity of the virtual resources is not infinite but bound by the capacity of network physical resources.

The middle layer in Fig. 1 is the total virtual resources in the FiWi network, from which a portion of virtual resources is allocated to an SP as a VN according to its virtual resource request. The SP loads the specific service on allocated virtual resources (i.e., VN), which means that different services may be carried by the same node or link.

The top layer in Fig. 1 shows that VNs can host different kinds of services. VN 1 is suitable for the peer-to-multiple-peer (P2MP) service. VN 2 is suitable for the peer-to-peer (P2P) service. The relationship between the VNs and virtual resources are depicted in Fig. 1. The virtual resources that comprise different VNs may come from a same device. Actually, a VN can be deployed upon another VN, which is called VNs' recursion. Due to the use of network virtualization, the differences between physical resources in the FiWi network are eliminated, which makes the FiWi network a tighter access network.

3.2 Service models

The way of providing service in FiWi network virtualization is different from that in traditional FiWi networks (i.e., the FiWi access network without network virtualization). The service model of FiWi network virtualization is shown in Fig. 2.

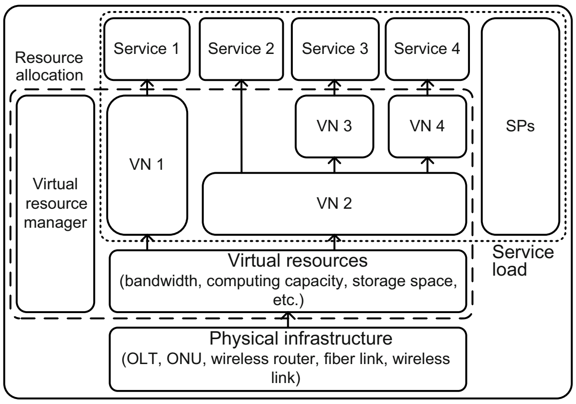

Fig. 2 Service model for FiWi network virtualization

As shown in Fig. 2, a service model is proposed for FiWi network virtualization, in which the network infrastructure resources are collected and abstracted into virtual resources. The physical resources include OLT, splitters, ONUs, wireless routers, fiber links, and wireless links. The virtual resources obtained are bandwidth, computing capacity, storage space, etc. Then, these virtual resources are allocated to SPs by VRM through network virtualization, which enables the creation of logically isolated network partitions over shared physical networks, so heterogeneous collections of the FiWi network may coexist over the same shared network. Normally, a logically isolated network partition is a VN. The specific service provided by an SP is hosted on a VN. When the provided service is finished, the occupied virtual resources will be released to VRM, waiting for the next time allocation.

3.3 Service realization process

The service realization process is as shown in Fig. 3. The details of this process are:

1. One or more users send a service request to an SP (**1** in Fig. 3a).

2. SP receives the service request, and decides whether it can provide this service by itself. If it can, then corresponding to the features required (i.e., delay-sensitive, throughput-sensitive, or others), SP sends a request which contains the virtual resources towards VRM (**2** in Fig. 3a). If not (for example, when there are too many subscribers), it returns a rejection to the user(s).

3. When the VRM receives the request from SP, it checks the available virtual resource. If the available virtual resource can fulfill the request, then the VRM gives these virtual resources' disposition to the requested SP and updates the available virtual resource (**3** in Fig. 3a). If not, it returns a rejection to the user via SP.

4. If SP's request is fulfilled, SP uses allocated virtual resources to form a VN which hosts the requested service of the user(s) (**4** in Fig. 3a). If not, it delivers the rejection from VRM to the user(s).

5. When the service is over, the user(s) will ask the SP to remove this service (**5** in Fig. 3b).

6. The SP verifies whether the service is finished. If it is finished, SP sends a confirmation back to the user(s) and a VN removal request to VRM (**6** in Fig. 3b). If not, it returns a rejection back to the user(s).

7. When the VRM receives a VN removal request from SP, it will take back the allocated virtual resource, update the available virtual resource, and send a confirmation message back to the SP (**7** in Fig. 3b).

In the above steps, steps 1–4 (Fig. 3a) are service requests and steps 5–7 (Fig. 3b) are service removals.

From Figs. 2 and 3, we can see that the VNs provided by SPs are the key portion of FiWi access network virtualization. VNs, as the bridge between physical infrastructures and services, are involved in both virtual resource allocation and service provision. To alleviate bandwidth tension and facilitate new service deployment, there are still some issues to be discussed.

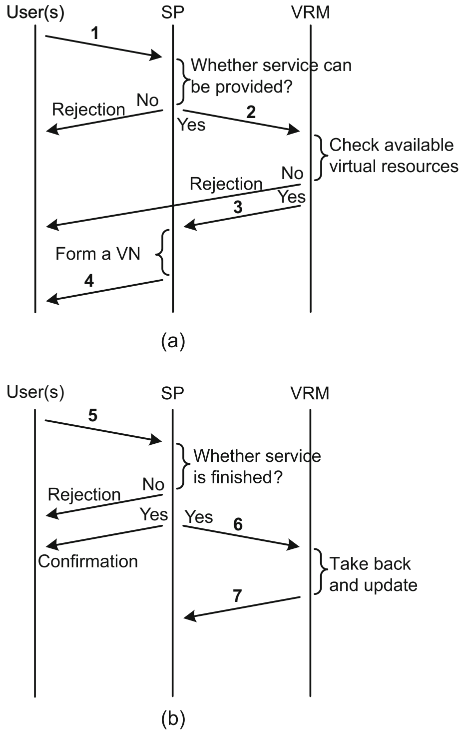

Fig. 3 The detailed process of service realization in the virtualization of FiWi networks: (a) service request; (b) service removal

Note that when a device first accesses a FiWi network, it will broadcast itself. The other devices will know the existence of this new device, which is the process of physical resource discovery. Then, the VRM will request the new device's virtual resource such as the bandwidth of connected links, the computing capacity, and storage space, and update the table of virtual resources with the returned data from the new device. Note that the update is executed once every fixed number of seconds.

3.4 Overhead of setting up and removing VNs

Setting up and removing VNs need special fields to request and release virtual resources, which will definitely entail overhead. However, the overhead does not affect the data plane, nor the control plane. The data is still transmitted under the control of the control plane.

Actually, the overhead entailed in setting up and removing VNs in network virtualization affects only the communications between the data plane and the control plane. This means that the overhead affects only a newly emerging service and service removal.

For example, for a newly emerging service flow, in the traditional FiWi network, the first ping consumes 4.59 ms and the second 0.899 ms. In contrast, in the FiWi network with network virtualization, the first ping consumes 17.6 ms and the second 0.783 ms (Zhang *et al.*, 2013). Thus, we can say that the overhead affects only the newly emerging service and service removal.

4 Performance improvement in FiWi network virtualization

In this section, we focus on the performance improvement in FiWi network virtualization, including bandwidth for links, throughput for nodes, and multipath flow transmission. We model the physical infrastructure of a FiWi network as $G^{\mathrm{S}}=\left(V^{\mathrm{S}},E^{\mathrm{S}}\right)$, where a set of physical nodes is denoted as V^{S} and a set of physical links among physical nodes as E^{S}. In addition, $V^{\mathrm{S}}=\left\{v_1^{\mathrm{S}},v_2^{\mathrm{S}},\cdots,v_N^{\mathrm{S}}\right\}$, in which N is the number of physical nodes.

4.1 Bandwidth for links

We select the bandwidth of links to evaluate the influence on links caused by network virtualization, so the virtualization process of physical resources can be denoted as

$$B_{\mathrm{V}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}}\right)=T\left(B_{\mathrm{S}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}}\right)\right), \tag{1}$$

where $B_{\mathrm{S}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}}\right)$ is the physical bandwidth of the link e^{S} ($e^{\mathrm{S}}\in E^{\mathrm{S}}$), which is connected to node v_i^{S} ($1\le i\le N$), $B_{\mathrm{V}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}}\right)$ is the virtual bandwidth abstracted from the link e^{S} which is connected to node v_i^{S} by network virtualization, and $T(\cdot)$ is a mapping from physical to virtual resources. Network virtualizaiton reflects the load-carrying ability of physical resources. In the process of vitualization of physical resources, the relationship between physical and virtual resources is generally one-to-many, which means that many virtual resources like bandwidth and computing capacity may be obtained from one device.

On collection of the entire FiWi network's virtualization resources, the virtual resources can be allocated to form a VN for a specific service according to the request sent by SPs. A VN is able to host a service by itself as well as multiple services by further allocation. In our proposed service model (Fig. 2), VN 1 hosts service 1 by itself, VN 2 hosts three services, namely, service 2, service 3, and service 4. Because VNs can be further allocated, VN 2 can be seen as the union set of VN 2, VN 3, and VN 4. VN 3 and VN 4 are obtained by the further allocation within VN 2. It is obvious that several VNs can be hosted by the same node, just like node 5 in Fig. 1. Fig. 4 shows node v_i^{S} and its virtual links in FiWi access network virtualization.

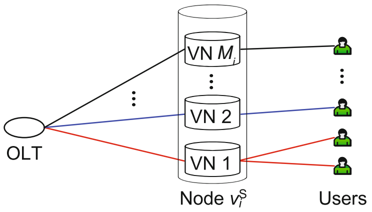

Fig. 4 Node v_i^{S} and its virtual links

In Fig. 4, it is true that all the VNs are installed based on physical resources. Therefore, for link e^{S} connected to node v_i^{S}, there is

$$\sum_{k=1}^{M_i}B_{\mathrm{V}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}},k\right)\le B_{\mathrm{S}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}}\right), \tag{2}$$

where M_i is the number of VNs hosted by the physical link e^{S} connected to node v_i^{S} ($1\le i\le N$), and $B_{\mathrm{V}}\left(e^{\mathrm{S}},v_i^{\mathrm{S}},k\right)$ is the bandwidth occupied by VN k ($1\le k\le M_i$) on link e^{S} connected to node v_i^{S}. The left side of Eq. (2) represents the virtualization resources occupied by all the VNs on link e^{S} connected to node v_i^{S}. The physical interpretation of Eq. (2) is that the total virtual resources occupied by services upon VNs cannot be larger than the physical resources. This principle limits the boundary of vitualization resource allocation and reflects the services which can be carried by physical FiWi networks. As for the service flow upon link e^{S} connected to node v_i^{S}, we have

$$\mathrm{flow}(e^{\mathrm{S}},v_i^{\mathrm{S}})=\sum_{k=1}^{M_i}\mathrm{flow}(e^{\mathrm{S}},v_i^{\mathrm{S}},k), \tag{3}$$

where $\mathrm{flow}(e^{\mathrm{S}},v_i^{\mathrm{S}},k)$ represents the service flows passing link e^{S} connected to node v_i^{S} in VN k and $\mathrm{flow}(e^{\mathrm{S}},v_i^{\mathrm{S}})$ represents the service flows passing link e^{S} connected to node v_i^{S}. The flows passing link e^{S} connected to node v_i^{S} are the sum of all the flows passing link e^{S} connected to node v_i^{S} in each VN. When the service is over, the virtual resources occupied by the services provided by SPs will be released and VRM will update the virtual resources and the available virtual resources. Through the use of network virtualization in the FiWi access network, the VN eliminates the difference of physical resources, which ensures that the resources are economically allocated to services and improves the resource utilization ratio.

Thus, after applying network virtualization in FiWi access networks, services can be provided by anyone as long as the service provider can obtain the necessary virtual resource, which is helpful for newly emerging services. A newly emerging SP who does not have enough money to build their own network for implementing service operation, can choose to obtain virtual resources for InPs. For example, MYOTee, a newly emerging third-party SP, spends only 73 RMB per month to maintain its daily service operation. Furthermore, all the network resources are controlled by the VRM that allocates virtual resources to host services. This indirectly alleviates bandwidth tension.

4.2 Throughput for nodes

We assume that the number of VNs hosted by the entire FiWi access network is M, which is different from the M_i in Eq. (2). Normally, $M_i \leq M$. There are two kinds of nodes in a FiWi access network: those that support only wireless links and those that simultaneously support wireless and fiber links. As for OLTs which support only fiber links, they are thought of as the nodes that support 0 wireless link and several fiber links. Therefore, $V^{\mathrm{S}} = V_1^{\mathrm{S}} \cup V_2^{\mathrm{S}} = \left\{v_1^{\mathrm{S}}, v_2^{\mathrm{S}}, \cdots, v_N^{\mathrm{S}}\right\}$, where V_1^{S} denotes a set of physical nodes that support only wireless links, the number of nodes of V_1^{S} is denoted as N_1, and V_2^{S} denotes a set of physical nodes that simultaneously support wireless links and fiber links, including OLTs. The number of nodes of V_2^{S} is denoted as N_2, $N_1 + N_2 = N$. We know that a physical node can host multiple VNs. In other words, multiple virtual nodes can be rooted in one same physical node. VN m $(1 \leq m \leq M)$ is denoted as $G^m = (V^m, E^m)$, where the number of virtual nodes is $|V^m|$ and the number of virtual links is $|E^m|$.

In VN m, it is easy to obtain the adjacency matrix $\boldsymbol{A}(G^m)$ of the virtual nodes in G^m:

$$\boldsymbol{A}(G^m) = \begin{pmatrix} a_{11}^m & a_{12}^m & \cdots & a_{1N}^m \\ a_{21}^m & a_{22}^m & \cdots & a_{2N}^m \\ \vdots & \vdots & & \vdots \\ a_{N1}^m & a_{N2}^m & \cdots & a_{NN}^m \end{pmatrix}, \tag{4}$$

where a_{ij}^m $(i \neq j, 1 \leq i \leq N, 1 \leq j \leq N)$ represents the probability of establishing a link between any two virtual nodes, v_i^m and v_j^m, in G^m. Note that v_i^m and v_j^m are rooted in physical nodes v_i^S and v_j^S, respectively. When the link is a wireless link, considering a shadow fading transmission environment (Kiese *et al.*, 2009), we have

$$\begin{aligned} a_{ij}^m &= P^m\left(l_{\mathrm{w}}(i,j)\,|d(i,j)\right) \\ &= \frac{1}{2} - \frac{1}{2}\mathrm{erfc}\left(\frac{10\gamma}{\sqrt{2}\sigma}\lg\left(\frac{d(i,j)}{r_0}\right)\right), \end{aligned} \tag{5}$$

where erfc$(\cdot)$ is the complementary error function, $l_{\mathrm{w}}(i,j)$ represents an existing wireless link between two virtual nodes v_i^m and v_j^m, $d(i,j)$ represents the distance (in m) between the two physical nodes that carry virtual nodes v_i^m and v_j^m respectively, r_0 represents a normalization term specifying the maximum distance at which a link can be established in the absence of shadow fading, γ represents a path-loss exponent describing the environment where the transmission occurs and it can be derived from the Okumura-Hata model, and σ represents the standard deviation (in dB) of a zero-mean Gaussian distributed random variable (Shankar, 2011). Actually, no matter which VN the virtual node belongs to, the data is handled by the physical node. Note that $d(i,j)$ is the distance between virtual nodes v_i^m and v_j^m, which is actually equal to that between v_i^{S} and v_j^{S}. Previous work on availability in fiber networks, such as Wosinska and Chen (2007) and Kiese *et al.* (2009), has shown that fiber networks are typically highly available, much greater than 99%. If the virtual link between v_i^m and v_j^m is mapped upon a fiber link, the a_{ij}^m is

$$a_{ij}^m = P^m\left(l_{\mathrm{f}}(i,j)\,|d(i,j)\right) = P\left(l_{\mathrm{f}}(i,j)\right) \approx 1, \tag{6}$$

where $l_{\mathrm{f}}(i,j)$ represents an existing fiber link between nodes v_i^{S} and v_j^{S}. If a fiber link and a wireless link both exist between v_i^m and v_j^m, a_{ij}^m in $\boldsymbol{A}(G^m)$ is

$$a_{ij}^m = \max\left\{P^m\left(l_{\mathrm{w}}(i,j)\,|d(i,j)\right), P^m\left(l_{\mathrm{f}}(i,j)\right)\right\}. \tag{7}$$

In addition, the nodes in FiWi networks are not fixed and their positions may change with user moving, environmental change, etc. We assume that the probability of v_i^{S} away from v_j^{S} $d(i,j)$ m is denoted as $P_{d(i,j)}$. Therefore, the matrix $\boldsymbol{P}(d)$ of distance can be expressed as

$$\boldsymbol{P}(d)=\begin{pmatrix} P_{d(1,1)} & P_{d(1,2)} & \cdots & P_{d(1,N)} \\ P_{d(2,1)} & P_{d(2,2)} & \cdots & P_{d(2,N)} \\ \vdots & \vdots & & \vdots \\ P_{d(N,1)} & P_{d(N,2)} & \cdots & P_{d(N,N)} \end{pmatrix}. \quad (8)$$

Because each virtual node is mapped to a specific physical node, the distance between any two virtual nodes can be replaced by the distance between the two physical nodes that host these two virtual nodes respectively. The link matrix of single link's establishing probability is $\boldsymbol{L}^{m1}$, which can be obtained from $\boldsymbol{A}(G)$ and $\boldsymbol{P}(d)$:

$$l_{ij}^{m1}=\begin{cases} a_{ij}^{m}P_{d(i,j)}, & a_{ij}\neq 1, \\ 1, & a_{ij}=1, \end{cases} \quad (9)$$

where l_{ij}^{m1} in $\boldsymbol{L}^{m1}$ is the probability of establishing a link between its corresponding two virtual nodes, v_i^m and v_j^m, in G^m. A multi-hop route from the source node in FiWi networks can be considered as the repeat of several single links. Let $N^{mh}(j)$ denote a set of nodes that can communicate with v_j^m through h hops, in G^m. Thus, the link matrix of a single hop is $\boldsymbol{L}^{m1}$, the link matrix of two hops is $\boldsymbol{L}^{m2}$, ..., the link matrix of h hops is $\boldsymbol{L}^{mh}$, and the corresponding $N^{m1}(j)$, $N^{m2}(j)$, ..., $N^{mh}(j)$ are obtained through the multiplication of matrices. For $\boldsymbol{L}^{mh}$, its jth column vector is $\left(l_{1j}^{mh}, l_{2j}^{mh}, ..., 0, ..., l_{Nj}^{mh}\right)^{\mathrm{T}}$, which is the set of the probabilities of all the other nodes communicating with v_j^m through h hops, and the jth element in this vector is 0. The set of non-zero values' corresponding nodes in this column vector is $N^{mh}(j)$. As for v_j^m, its throughput is

$$\text{Throughput}_{v_j^m}=2\sum_{h=1}^{N-1}\sum_{i=1,i\neq j}^{N}\frac{l_{ij}^{mh}\text{sum}_{ij}^{m}}{T(i,j)}, \quad (10)$$

where $T(i,j)$ is the sum of transmission time over virtual fiber and virtual wireless links from v_i^m to v_j^m, sum_{ij}^m is the sum of the data transmitted from v_i^m to v_j^m, $v_i^m \in N^{mh}(j)$. For an undirected graph, it is doubled in Eq. (10). According to Li and Fang (2012), we can obtain the ratio of the number of lost packets to the number of sent packets in VN m:

$$P_{\mathrm{e}}^{m}(h)=\frac{1}{2}\text{erfc}\left(\frac{\sqrt{\left(\frac{CP_{\mathrm{s}}}{(1+d(i,j))^{\gamma}}\right)^{h}}}{8\left(\frac{1-\left(\frac{CP_{\mathrm{s}}}{(1+d(i,j))^{\gamma}}\right)^{\frac{h+1}{2}}}{1-\left(\frac{CP_{\mathrm{s}}}{(1+d(i,j))^{\gamma}}\right)^{\frac{1}{2}}}\right)^{2}}\right), \quad (11)$$

where C signifies a parameter related to the antenna profiles of the transmitter and the receiver, wavelength, etc., P_{s} signifies the transmission power of v_i^m, which is a constant value, and γ signifies the path loss exponent which is the same as the γ in Eq. (5).

Thus, based on Eq. (10), $\forall j$, $v_j^S \in V_1^S$, the throughput of virtual node v_j^m is

$$\begin{aligned}&\text{Throughput}_{v_j^m}\\ &=2\sum_{h=1}^{N-1}\sum_{i=1,i\neq j}^{N}\frac{l_{ij}^{mh}\text{sum}_{ij}^{m}}{T(i,j)}\\ &=2\sum_{h=1}^{n}\sum_{i=1,i\neq j}^{N}\frac{l_{ij}^{mh}D(1-P_{\mathrm{e}}^{m}(h))}{ht_{\mathrm{w}}}\\ &+\sum_{h=n+1}^{N-1}\sum_{i=1,i\neq j}^{N}\frac{l_{ij}^{mh}D(1-P_{\mathrm{e}}^{m}(h))}{ht_{\mathrm{w}}}\\ &+\sum_{h=n+1}^{N-1}\sum_{i=1,i\neq j}^{N}+\frac{l_{ij}^{mh}D(1-P_{\mathrm{e}}^{m}(h))}{(h-1)t_{\mathrm{w}}+t_{\mathrm{f}}},\end{aligned} \quad (12)$$

where i is the identifier of $v_i^m \in N^{mn}(j)$, D is the length of data flow, t_{w} is the data transmission time between two adjacent nodes over a single wireless link, and t_{f} is the data transmission time between two adjacent nodes over a fiber link. We assume that the nth hop is implemented by a fiber link. The first item of Eq. (12) is the throughput generated by the nodes within n hops. The second is the throughput generated by the nodes of the nth hop and a greater number of hops. The last is the throughput generated by those nodes through wireless-fiber-wireless links. In the case of $v_j^{\mathrm{S}} \in V_2^{\mathrm{S}}$, the situation is the same as that of $n=1$. The throughput of virtual node v_j^m is

$$\mathrm{Throughput}_{v_j^m} = \sum_{h=1}^{N-1} \sum_{i=1, i\neq j}^{N} \frac{l_{ij}^{mh} D(1-P_{\mathrm{e}}^m(h))}{h t_{\mathrm{w}}} + \sum_{h=1}^{h=N-1} \sum_{i=1, i\neq j}^{N} \frac{l_{ij}^{mh} D(1-P_{\mathrm{e}}^m(h))}{(h-1) t_{\mathrm{w}} + t_{\mathrm{f}}}. \tag{13}$$

Therefore, the throughput of v_j^{S}, no matter $v_j^{\mathrm{S}} \in V_1^{\mathrm{S}}$ or $v_j^{\mathrm{S}} \in V_2^{\mathrm{S}}$, is

$$\mathrm{Throughput}_{v_j^{\mathrm{S}}} = \sum_{m=1}^{M} \mathrm{Throughput}_{v_j^m}. \tag{14}$$

4.3 Multipath flow transmission

In FiWi networks without virtualizatioin, because of the network's mesh architecture and the use of the multipath transmission control protocol (e.g., multipath TCP), it is common that multipath flow transmission exists in P2P communications. Using multipath routing, a service flow may be flexibly divided into several sub-flows with the same destination (Prabhavat *et al.*, 2012). For instance, in Fig. 1, if user 1 attempts to communicate with OLT, there are many choices for path selection, such as $(\text{users } 1, 7, 2, \text{OLT})$, $(\text{users } 1, 7, 5, 3, \text{OLT})$, and $(\text{users } 1, 7, 5, 2, \text{OLT})$. If one of the paths breaks down, the other paths can continue flow transmission without any interruption. The existence of multiple paths makes the communication in FiWi networks more survivable at the cost of a higher overhead. Note that in FiWi networks without virtualization, all the candidate paths from the source node to the destination node are physical paths. If $(\text{users } 1, 7, 2, \text{OLT})$ and $(\text{users } 1, 7, 5, 3, \text{OLT})$ are the two paths that host the same P2P service, when $(\text{users } 1, 7, 2, \text{OLT})$ breaks down, only one path is left to guarantee the communication between user 1 and OLT as a backup path. The situation of path $(\text{users } 1, 7, 5, 3, \text{OLT})$ breaking down is similar.

The use of network virtualization largely extends the scope of multipath by increasing the number of candidate paths, due to the coexistence of multiple VNs on the same physical infrastructure. As long as there are enough virtual resources, it is possible to form a backup VN to host a service flow in the case of path failure, without completely occupying the physical links. For example, $(\text{users } 1, 7, 5, 3, \text{OLT})$ can be further allocated as sub-VN 1 and sub-VN 2. When path $(\text{users } 1, 7, 2, \text{OLT})$ breaks down, sub-VN 1 and sub-VN 2 can both continue to transfer service flows. Even if one of the sub-VNs breaks down, the remaining one is able to continue flow transmission without any interruption. Because multiple paths exist in the form of VN, the existing path will not influence the achievement of other services. The physical nodes or links involved in a service can be used for another service, as long as they can provide enough virtual resources. Thus, for a VN which is hosting a specific service, we assume that there are n_{p} physical paths existing between the source node and the destination node and m_{VN} VNs which are able to achieve the communication between the source node and the destination node. The failure probability of path is p, which means that this path breaks down with a probability of p $(0 < p < 1)$. Therefore, the availability is

$$\mathrm{Availability} = 1 - \left[1 - (1-p)^{n_{\mathrm{p}}}\right]^{m_{\mathrm{VN}}}. \tag{15}$$

5 Numerical results and discussions

In this section, the superiority of applying network virtualization in the FiWi network is evaluated via simulation. The FiWi network without network virtualization is implemented by radio over fiber (RoF) technology. More specifically, considering that fiber's dispersion has less impact on baseband signal, baseband-over-fiber (BoF) technology is selected (Luo *et al.*, 2012). The simulation tool is Matlab. We simulate a 20 km × 20 km area where 1 OLT, 8 ONUs, and 400 users are randomly laid. The splitting ratio of the splitter is 1:8 and each ONU covers 50 users. The users and ONUs comprise a mesh architecture in which the maximum bandwidth of the wireless link is 54 Mb/s and the maximum number of hops is 15. The maximum bandwidth of the fiber link is 10 Gb/s. The maximum processing time is 2, 5, and 10 μs for OLT, ONU, and the wireless router, respectively. The maximum communication distance of user's wireless device is 250 m.

5.1 Round trip time comparison

The FiWi network is a combination of two subnetworks, fiber subnetworks and wireless subnetworks. From the operator's point of view, it is critical that the network should be an integration rather than simple addition of two subnetworks. We select round trip time (RTT) as an index to evaluate the tightness of the FiWi network. In this scenario, RTT is the total time consumed by a test packet from the user to OLT and from OLT back to the user. For the FiWi network, RTT is the sum of processing time and transmission time; RTT is twice the sum of multi-hop wireless transmission time, time of frequency conversion from the user to OLT and OLT back to the user, photoelectric conversion time, and optical modulation time (Luo *et al.*, 2012). Without network virtualization, the processing time is consumed by several coordinating messages among multiple nodes. With network virtualization, the processing time is just the time for the VRM receiving the VN request and allocating virtual resources. The former is greater than the latter. Figs. 5 and 6 show the relationship between RTT and the number of hops and that between RTT and the distance from OLT to ONU, respectively.

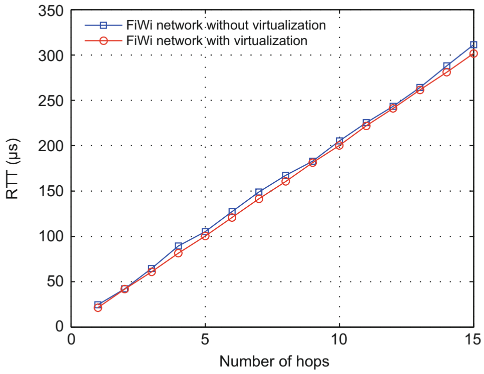

Fig. 5 The relationship between RTT and the number of hops

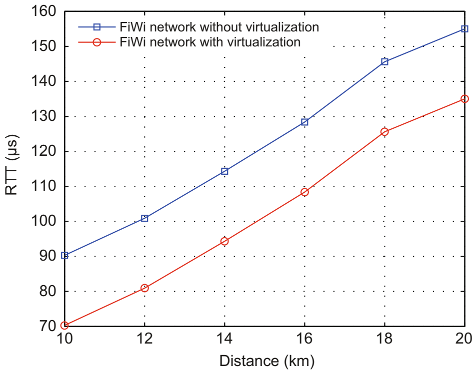

Fig. 6 The relationship between RTT for the end user and the distance between OLT and ONU

As shown in Fig. 5, in both cases RTT increases as the number of hops increases. For a fixed number of hops, RTT of the FiWi network with virtualization is always slightly smaller than that without.

As shown in Fig. 6, in both cases RTT increases as the distance between OLT and ONU in the fiber subnetwork increases. For a fixed distance, however, RTT of the FiWi network without virtualization is always larger than that without. The difference between these two scenarios is caused by the central virtual resource management in network virtualization, rather than the multi-node coordinating pattern in the traditional network.

Figs. 5 and 6 illustrate the effect of parameter variation of the wireless subnetwork and fiber subnetwork, respectively. In the FiWi network without virtualization, protocol translation is necessary, which consumes extra time; in the FiWi network with virtualization, the services are hosted by allocated unified virtual resources, and thus protocol translation is unnecessary. This is why RTT of the FiWi network with virtualization is always smaller than that without, for a fixed number of hops or a fixed distance between OLT and ONU.

Comparison of Figs. 5 and 6 shows that the RTT reduction caused by network virtualization in the fiber subnetwork is much larger than that in the wireless subnetwork. The main reason is that the wireless router performs packet handling only, while ONU performs both packet handling and protocol translation.

5.2 Resource utilization comparison

As an access network, the FiWi network is designed to provide users with qualified service using limited network resources. Therefore, it is important to use network resource as effectively as possible.

We assume that the requested bandwidth is normally distributed from 1 to 54 Mb/s, with the average requested bandwidth being 35 Mb/s. When the bandwidth of fiber link varies from 1 to 10 Gb/s, the hosted service number can be obtained (Fig. 7). To some degree, the hosted service number can be used to indicate resource utilization. With the use of network virtualization, the hosted service number is improved effectively. Because the bandwidth requested by each user is normally distributed, there is a small chance that the hosted service number in the FiWi network with virtualization is equal to that without (e.g., when the bandwidth is 5 Gb/s).

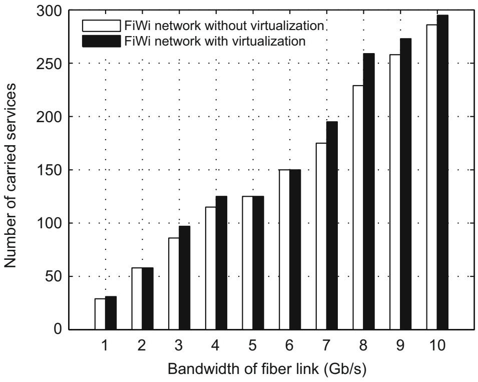

Fig. 7 Fiber subnetwork link's capacity

Fig. 8 shows the bandwidth utilization rate in two scenarios when the bandwidth requested by each service varies from 1 to 54 Mb/s. The bandwidth utilization rate fluctuates around 96% (resp. 94%) in the FiWi network with (resp. without) virtualization. The central management of abstracted virtual resources and their allocation, controlled by VRM, make this resource utilization rate improvement a reality.

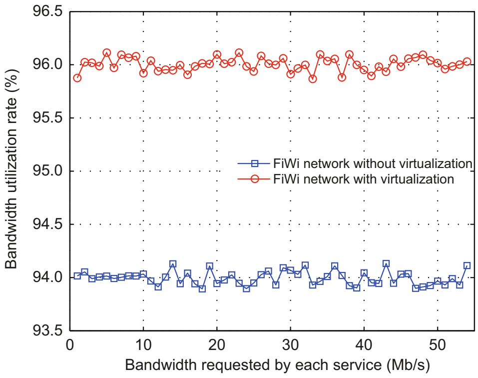

Fig. 8 Bandwidth utilization rate

In traditional FiWi networks, the resources are managed in a distributed fashion. If a node needs to learn about another node's resource utilization, it has to request and check the return message. In this pattern, the remaining available resources that cannot host a service are called offcuts. Offcuts can be exploited via resource integration, which will need much bandwidth to coordinate the available resources with other nodes. This makes cost larger than revenue. Therefore, in traditional FiWi networks, normally the offcuts are abandoned. However, in FiWi networks with network virtualization, the situation is different. Under the control of VRM, virtual resources are centrally managed. Offcuts will no longer exist, leading to a higher resource utilization rate of the FiWi network with network virtualization and thus a throughput improvement.

5.3 Throughput comparison

Throughput is considered an important indicator of network capability. Figs. 9 and 10 analyze the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ and $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$, respectively. In the simulation, the flows belonging to different VNs are calculated separately. We assume that the bandwidth requested by each service ranges uniformly from 1 to 50 Mb/s. To simplify calculation, the maximum number of VNs hosted by the FiWi network is fixed as 2.

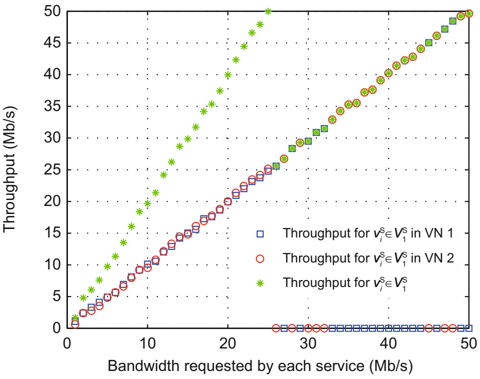

Fig. 9 Throughput for $\boldsymbol{v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}}$

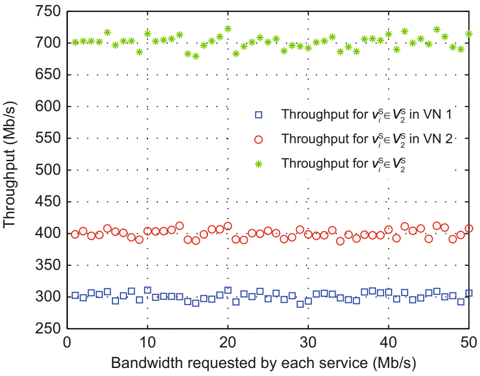

Fig. 10 Throughput for $\boldsymbol{v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}}$

In different VNs, the bandwidth requested by each service is equal. Therefore, the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 1 is the same as that for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 2, when the bandwidth requested by each service is less than approximately 26 Mb/s. When the bandwidth is larger than 26 Mb/s, however, only one of the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 1 and the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 2 is a non-zero value. Either the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 1 or that for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 2 is zero. This can be explained by reference to Section 3. The total virtual resources occupied by services upon VNs cannot be more than the physical resources. When the available virtual resources are less than the requested virtual resources, the VN request will be denied, so will the requested service. No matter which value the bandwidth requested by each service is, the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ is always equal to the sum of the throughput for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 1 and that for $v_i^{\mathrm{S}} \in V_1^{\mathrm{S}}$ in VN 2.

In Fig. 10, the throughput for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ in different VNs shows different features. No matter which value the bandwidth requested by each service is, the throughput for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ in VN 1 fluctuates around a fixed value, so does the throughput for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ in VN 2. Because $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ is able to simultaneously support wireless link and fiber link, there is sufficient bandwidth to be allocated to services. Therefore, the VRM will never deny the virtual resource request. Moreover, the throughput for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ is equal to the sum of the throughput for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ in VN 1 and that for $v_i^{\mathrm{S}} \in V_2^{\mathrm{S}}$ in VN 2.

5.4 Availability

With the use of network virtualization, we have more choices for multipath routing, which improves the availability of the FiWi network. The path failure probability here is actually the p in Section 3. In a practical environment, we assume that the path failure probability ranges from 0.01 to 0.1. By numerical calculation, we obtain the availability for the FiWi network with or without virtualization (Fig. 11).

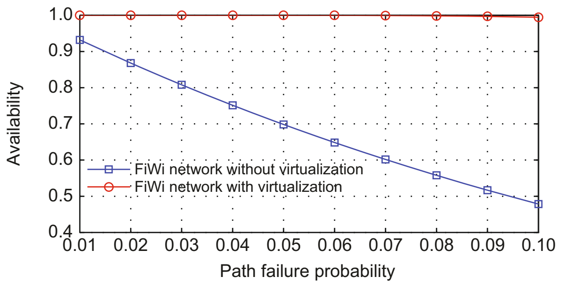

Fig. 11 Path availability

With the path failure probability increasing from 0.01 to 0.1, the availability decreases for the FiWi network without virtualization but nearly remains 1 in the FiWi network with virtualization. For a fixed path failure probability, the availability for the FiWi network with virtualization is always larger than that without.

6 Conclusions

To alleviate bandwidth tension and facilitate new service deployment, we apply network virtualization in the FiWi network, which separates the control plane from the data plane of the network. A hierarchical model and a service model are proposed to illustrate the effect of network virtualization. The performances of the FiWi network with or without network virtualization are analyzed in detail, including bandwidth for links, throughput for nodes, and multipath flow transmission. Simulation results show that network virtualization improves the performance of the FiWi network.

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