Bandwidth Management for SDN-enabled Wireless Networks

Kuei-Li Huang, Mu-Liang Wang, Chin-Tien Huang

Abstract—This paper proposes a dynamic bandwidth management method for SDN-enabled wireless networks, where users join and leave a small cell frequently. The proposed mechanism takes the user group priority into account. A user of a high-priority group is always allocated more bandwidth than a user of a low-priority group. Under this criterion, the proposed mechanism addresses the issue on how to provide dynamic bandwidth management in an SDN-enabled wireless network while reducing control signaling for bandwidth management. Simulation results show that the proposed method reduces 60% of signaling overhead compared with the method in which every occurrence of user join or leave triggers a bandwidth adjustment operation. The experimental results verify the feasibility of the dynamic bandwidth management method and its correctness with respect to the intra-group and inter-group bandwidth management behavior.

Index Terms— Software-Defined Network; Wireless Network; Bandwidth Management

I. Introduction

BANDWIDTH requirement in the next wireless communication generation is expected to increase dramatically up to tera scale [1]. However, current guiding direction on wireless technology development points to the macro cell capacity improvement, which is foreseen fail to meet the bandwidth requirement at that moment. Instead, many research findings give three new directions to the capacity improvement, i.e., spectrum refarming [17], device-to-device direct communication [18] and ultra-dense network[19]. Among these directions, building an ultra-dense network is comparatively much earlier to be realized in the near future. An ultra-dense network is a wireless network in which small cells such as Femto base stations, Wi-Fi APs, etc., are densely deployed, say one thousand small cell base stations per square kilometers [2].

An ultra-dense network is usually deployed in a dense population area such as a campus, a park for a big company, etc. A backhaul network which connects small cells to the core network is required and should be able to tackle a considerable amount of mobile data traffic. In addition, as users move, sources of mobile data traffic move. This implies a backhaul network should be able to deal with traffic dynamicity. As shown in Fig. 1, small cells are connected to a backhaul network and users belonging to various groups are served. In a company, users can be classified into Staff, Guest or Bring-Your-Own-Device (BYOD) [3] groups. From viewpoint of a company, different groups should be treated differently with respect to bandwidth and provision of quality of service (QoS). In other words, an ultra-dense network should be able to manage the bandwidth of the groups separately.

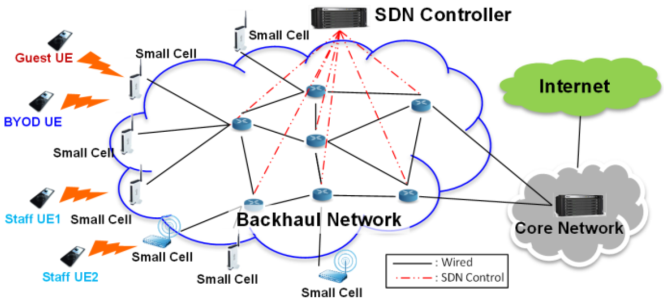

Fig. 1. SDN-enabled Wireless Network

Software-defined network (SDN) is a new concept that the routing behavior of a network is programmable, which can meet the aforementioned requirements of a backhaul network in the next generation [4][5]. As shown in Fig. 1, in such an SDN-enabled wireless network, SDN controller can dynamically control the routing behavior of switches and the packet scheduling behavior of small cells and switches in the backhaul network. In addition, the granularity of bandwidth control can be fine to flows, implying that the bandwidth management can distinguish users of different groups and provide different groups different bandwidth management policies.

This paper addresses the issue on how to provide dynamic bandwidth management in an SDN-enabled wireless network while reducing control signaling for bandwidth management. Therefore, a dynamic bandwidth management method is proposed for an SDN-enabled wireless network.

The remainder of this paper is organized as follows. The related work in the second section introduces the software-defined network, and reviews works in the literature. The proposed dynamic bandwidth management method then is detailed in the third section. The fourth section describes and discusses the performance evaluation of the proposed method. Finally, the fifth section concludes this work.

II. Related Work

A. Software-Defined Network

SDN technology has been used to address the low utilization problem happened in backbone network at internet-based companies such as Google and Internet2 [6]. In an SDN architecture, network logic is centrally managed by a programmable SDN controller. The foundation for building SDN solutions is the OpenFlow protocol standard published by the Open Networking Foundation (ONF) [7]. ONF partitions the SDN architecture into three logical layers: the Application Layer, the Control Layer, and the Infrastructure Layer [5], where the Application Layer includes applications regarding network behavior management intelligence, the Control Layer consists fundamental networking and maintenance functions, and the Infrastructure Layer is formed by a number of SDN switches.

An SDN switch consists of one or more flow tables to perform packet lookup and forwarding. A flow table consists of a set of flow entries [8]. Each flow entry has three main fields: Match, Instruction, and Counter. The Match field includes a set of "match fields" for matching packets. The Instruction field consists of a set of instructions to apply to matched packets such as forwarding the packets to a designated port, sending the packets to a queue obeying certain traffic control policies, dropping the packet, etc. The Counter field contains a set of counters to track packet statistics. If a packet matches a flow entry in a flow table, the instructions associated with the specific flow entry are applied to the matched packet. Such instructions include packet forwarding and packet modification. If a packet matches no flow entry in the flow table, the packet is either sent to the controller, or processed by the next flow table.

B. SDN-based Bandwidth Management Methods

The concept of bandwidth slicing was proposed by Yap and et. al., where bandwidth can be sliced into fractions [9][10][11]. Such bandwidth isolation can be achieved in an SDN network. Following up is Lam and Varghese who proposed NetShare which provide throughput guarantee to multiple users [12].

These works were done in wired networks. Huang and et. al. further extended the SDN-based bandwidth management to the area of wireless networks [13], in which Wi-Fi APs are transformed into SDN-capable devices by flashing the operating system of the Wi-Fi APs into an embedded Linux system, called OpenWrt [14]. Such a small cell base station is able to communicate with SDN controller via an OpenFlow client through the OpenFlow protocol. In addition, the OpenFlow client is able to relate the OpenFlow operation to the underlying queueing system running in the kernel space of the OpenWrt operating system so as to realize the bandwidth control of guaranteed bitrate and maximum bitrate for each data traffic flow. However, the queueing behavior for bandwidth management on the small cell base station is manually configured. There is no intelligence in such a system. This paper aims at building intelligence in this system to realize dynamic bandwidth adjustment, which is illustrated and detailed in the following sections.

III. Proposed SDN-based Bandwidth Management Mechanism

The design philosophy of a bandwidth management mechanism can vary. In order to prevent from bandwidth starvation while best lowering down the signaling cost, the design philosophy of the proposed bandwidth management mechanism is to provide at least an amount of guaranteed bandwidth to a user according to the user's group priority. In addition, since users dynamically join or leave a small cell, an objective is set to take a less signaling cost to maintain the "guaranteedness."

In order to provide the bandwidth adjustment intelligence in an SDN-based wireless network, we first define the problem to bandwidth management and then illustrate the principles of the proposed bandwidth management mechanism. Finally, we detail the bandwidth management algorithm.

A. Problem Formulation

To reach the cost target while satisfying the design philosophy, we first formulate three criteria as follows. Assume the total available bandwidth is G and the number of user groups is m. To provide a guaranteed bandwidth to a user, the minimal guaranteed bandwidth is defined as g. The minimal guaranteed bandwidth means a user of any group should be provide at least g unit of bandwidth. Suppose the number of users of group i is n_i and the total guaranteed bandwidth of group i, i.e., the bandwidth granted to group i, is denoted as g_i. To assure that a priority group receives more bandwidth, three criteria should always hold at any moment.

Criteria 1: $\forall i, 0 \le i \le m-1 \ni \frac{g_i}{n_i} \le \frac{g_{i+1}}{n_{i+1}}$;

Criteria 2: $g \le \frac{g_0}{n_0}$

Criteria 3: $\sum_{i=0}^{m-1} g_i \le G$

Criteria 1 ensures a priority group receives a larger piece of bandwidth, where a larger value of group index i means a higher group priority; Criteria 2 assures that users in the lowest priority group should be granted on average at least g unit of guaranteed bandwidth; Criteria 3 pledges the total guaranteed bandwidth would not exceed the total available bandwidth. When the three criteria are satisfied, the situation at that moment meets the design philosophy. However, users join or leave a small cell dynamically, which may again break down the criteria satisfactoriness. Consequently, a bandwidth adjustment operation is required. After the operation, the three criteria are again to be satisfactory.

The problem addressed in this paper is how to design a dynamic bandwidth management method so that the three criteria always hold while the number of bandwidth adjustment operations is low to a certain degree.

Beside the bandwidth granted to all users, the rest available bandwidth is shared among groups. The sharing policy is equal sharing in the proposed method.

B. Design Principles

To minimize the signaling cost, the design of the proposed method entails two main design principles: 1) batch grant and 2) lazy adjustment. The batch grant principle means the guaranteed bandwidth is granted to a group a piece more than a minimal need. In this way, a user join does not always trigger a bandwidth adjustment operation. The lazy adjustment principle

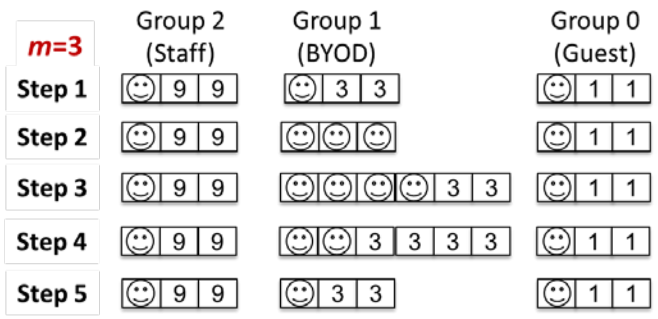

Fig. 2. Illustrative Example for Batch Grant and Lazy-Adjustment Principles

means that adjustment is only required when one of the criteria is broken. Therefore, a user leave does not always cause a bandwidth adjustment operation.

Following the two principles, the design of the proposed bandwidth management mechanism is formulated as follows. The default base of guaranteed bandwidth units is b, where b is an integer larger than 1. The guaranteed bandwidth unit of group i is denoted as b_i, where the default value of b_i is b^i*g. In this way, a user join may not need bandwidth adjustment since Criteria 1 still holds. When a bandwidth allocation is required, an amount of guaranteed bandwidth in guaranteed bandwidth unit is allocated. That is, the allocation unit of guaranteed bandwidth is a multiply of guaranteed bandwidth units. The guaranteed bandwidth allocation unit of group i is denoted as q_i, where the value of q_i is b times b_i or simply b^{i+1}*g. For example, the guaranteed bandwidth unit of Group 1 in Fig. 2 is 3 and the guaranteed bandwidth allocation unit of group 1 is 9, where the bandwidth allocation occurs in step 3.

We further denote the remainder bandwidth as R, which is the amount of rest available bandwidth.

Fig. 2 illustrates the two principles through a synthesized example, where the number of groups, m, is three and the base of guaranteed bandwidth units, b, is set to three. We start from Step 1 in which one user per group has been joined. In Step 2, Group 1 has two sequential user joins which does not cause bandwidth adjustment. This is the effect of the batch grant principle. The fourth user join of Group 1 in Step 3 triggers a bandwidth addition operation after which three guaranteed bandwidth units are allocated to Group 1. That is, an amount of the guaranteed bandwidth allocation unit of Group 1, q_1, is granted to Group 1 after this operation. In Step 4, two sequential user leaves happen in Group 1. This does not result in any bandwidth adjustment operations because Criteria 1 still holds and the lazy adjustment principle applies in this situation. Until the second user in Group 1 leaves in Step 5, which breaks Criteria 1, there triggers a bandwidth reduction operation to the bandwidth granted to Group 1.

Since the total available bandwidth, G, is limited, the amount of rest available bandwidth, R, could be insufficient in a bandwidth addition operation, especially when users are crowded. We refer this situation as the "crowded phase", whereas the situation which is not crowded refers to the "normal phase." To meet the three criteria in the crowded phase, the base of guaranteed bandwidth units, b, should be adjusted. Define the base of guaranteed bandwidth units in the crowded

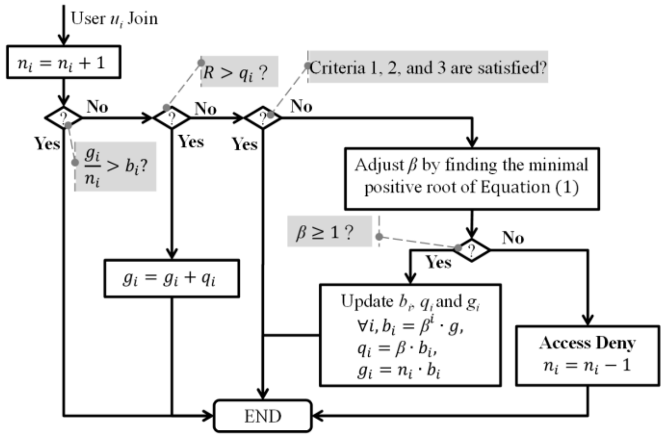

Fig. 3. User Join Bandwidth Allocation Procedure

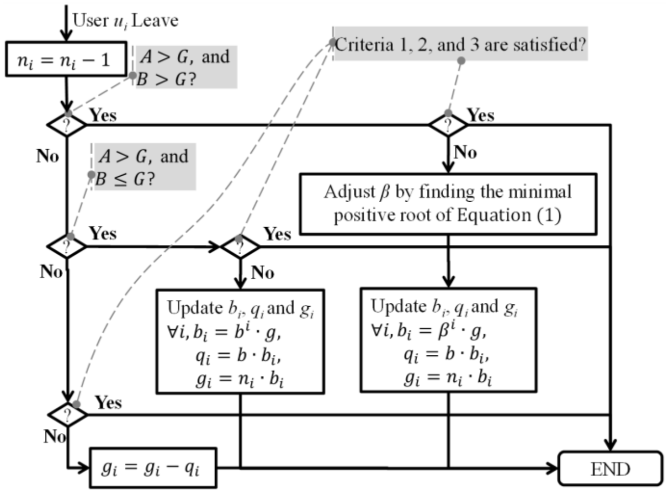

Fig. 4. User Leave Bandwidth Allocation Procedure

phase be β. We transform the base adjustment problem into a root finding problem of a polynomial and solve the problem by way of the Birge-Vieta method [15]. The root finding problem with β being the target root to be found is formulated as follows.

$$\sum_{k=0}^{m-1} a_k x^k = G/g \qquad (1)$$

where

$$a_k = \begin{cases} \lfloor n_k/2 \rfloor + n_k \bmod 2, n_k > 0 \\ 1, n_k = 0 \end{cases}.$$

Since n_k is the number of members in group k, we can compute the amount of bandwidth allocation a_k by the above equation. Therefore, the resulting minimal positive root value is the base of guaranteed bandwidth units used in the crowded phase. Consequently, related valuables need to adjust their values accordingly. That is, the guaranteed bandwidth unit of group i, b_i, is now of value β^i*g and the guaranteed bandwidth allocation unit of group i, q_i, is of value β^{i+1}*g.

C. Design Principles

Fig. 3 and Fig. 4 details the two main procedures in the proposed method, respectively: the user join bandwidth addition procedure and the user leave bandwidth reduction procedure.

The user join bandwidth addition procedure in Fig. 3 is first to assure the new user u_i, who belongs to Group i, has enough guaranteed bandwidth. If it is enough, then the procedure is done. Otherwise, it further checks whether the available bandwidth is enough or not. If yes (i.e., $R \geq q_i$), the situation is in the normal phase and a piece of bandwidth, i.e., q_i, is granted to Group i. If the available bandwidth is not enough, the bandwidth adjustment in the crowded phase is executed, in which the new base, β, is computed and derived via the Birge-Vieta method. If $\beta \geq 1$, which means Criteria 2 holds, the bandwidth allocation of each group is adjusted based on the new base. In contrast, the new user join request is denied.

The user leave bandwidth reduction procedure in Fig. 4 is first to assure the phase before and after user u_i leaves. To this end, the total granted bandwidth before and after user u_i leaves are denoted as A and B, respectively, and being defined as follows.

$$A = \sum_{k=0,k\neq i}^{m-1} a_k q_k + \lfloor (n_i + 1)/2 \rfloor + (n_i + 1) \bmod 2$$

$$B = \sum_{k=0}^{m-1} a_k q_k$$

When both situations before and after user ui leaves are in the crowded phase, i.e., A > G and B > G, the lazy adjustment principle is applied. In other words, if one of the criteria is broken, it is executed the bandwidth adjustment operation with the new base, β, being computed and derived via the Birge-Vieta method. Otherwise, there is no action. When the situations before and after user u_i leaves are different, i.e., moving from the crowded phase to the normal phase, i.e., A > G and $B \leq G$, the lazy adjustment principle is again applied. Different from the previous case above, the bandwidth adjustment is with the default base, b, if required. As for the "before" and "after" situations both in normal phases, the three criteria is first checked and, if one of them is broken, a piece of bandwidth, i.e., q_i, is simply reduced from Group i.

In sum, the proposed bandwidth adjustment method handles events of user join and leave to adjust groups' guaranteed bandwidth. In general, the batch grant principle and the lazy adjustment principle should be followed. In the normal phase, the bandwidth adjustment is done by allocating or reducing a predefined amount of bandwidth to or from a group. In the crowded phase, the base of guaranteed bandwidth units is first adjusted before the bandwidth adjustment.

IV. Performance Evaluation

We evaluate the performance of the proposed bandwidth adjustment method through both simulation and implementation experiments. We first describe the simulation environment and discuss the results from simulation experiments.

A. Simulation

Fig. 5 shows the simulation environment where OpenDayLight [20] controller was selected as the SDN controller in the environment. We developed several functions in the OpenDayLight controller for simulation: 1) the Random User Join/Leave Event Generator randomly generates user

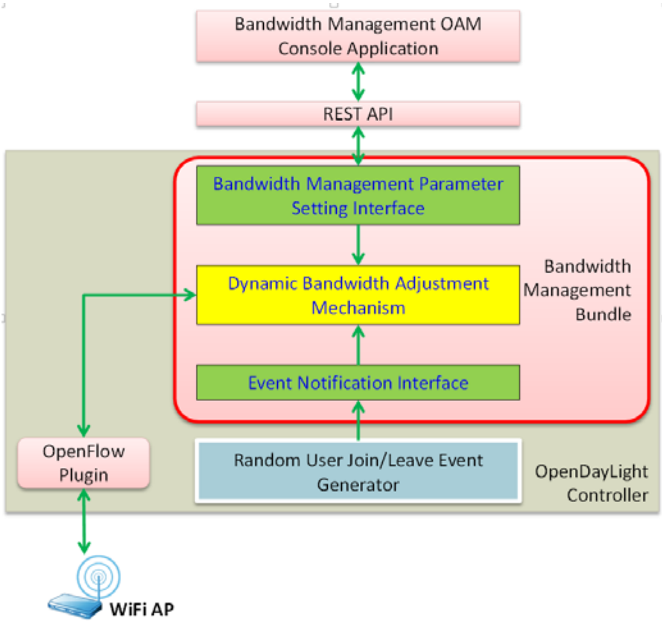

Fig. 5. Simulation Environment

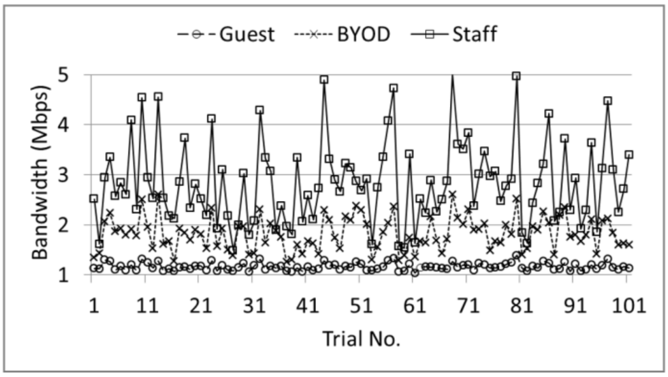

Fig. 5. Simulation Result – Granted Bandwidth Per User

TABLE I
Parameter Settings in Simulation Experiment 1

Parameters	Values
Maximum Guaranteed Bandwidth	30 Mbps
Minimal Guaranteed Bandwidth	1Mbps
User Group Number	3(*)
Default Base of Guaranteed Group Bandwidth	1, 2, 4
Initial Guaranteed Group Bandwidth	2, 4, 8
Number of User Joins/Leaves	3000
Number of Trials	100

(*): Guest, BYOD, Staff

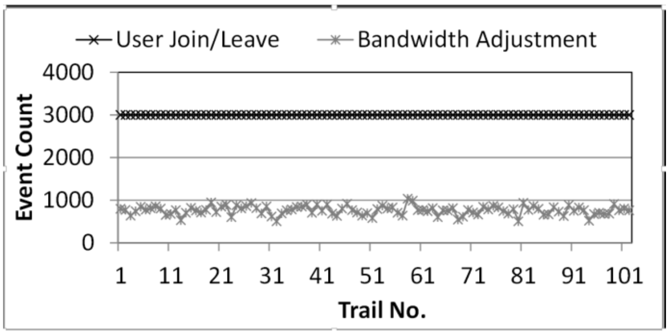

Fig. 6. Total Event Statistics for Signaling Overhead

joins and leaves; 2) the Dynamic Bandwidth Management bundle provides the dynamic bandwidth management method described in the previous section which configures the Wi-Fi AP bandwidth through OpenFlow Plugin after computing the bandwidth adjustment result; 3) the Bandwidth Management OAM Console Application provides an interface for an SDN-enabled wireless network to configure parameters of the dynamic bandwidth management method such as the number of groups, the default base of guaranteed bandwidth units, etc. The details of how to enable the OpenFlow capability of a Wi-Fi AP are illustrated in Reference [13].

In the simulation experiment, we set the number of user groups to three (Staff, BYOD, Guest) and designate their priorities. That is, Staff is with the highest priority, BYOD is in the second place and Guest is with the lowest priority. The detailed experimental settings in listed in the Table I. The experimental result of granted bandwidth per user is shown in Fig. 5, indicating that the high-priority group users (Staff users) are of more bandwidth than users of a low-priority group (Guest users). This implies that the three criteria holds.

Fig. 6 to Fig. 8 show the event statistics for signal overhead. In Fig. 6, the number of events of bandwidth adjustment operations is around one third of the number of events of user joins or leaves. In other words, the proposed method reduces around 60% of the signaling overhead compared with the method in which each user join or leave triggers a bandwidth adjustment operation. Because the batch grant and lazy-adjustment principles work, approximately three contiguous user join/leave events trigger one bandwidth adjustment operation. We further investigate the signaling overhead in the normal phase and crowded phase, separately. Fig. 7 shows the event statistics and signaling overhead in the normal phase. On average, a bandwidth adjustment operation happens after around ten contiguous events of user joins or leaves. The signaling overhead is much less than that in the crowded phase. Fig. 8 shows the signaling overhead versus the number of events of user joins or leaves. Around every two occurrences of user joins or leaves result in one bandwidth adjustment operation.

B. Implementation

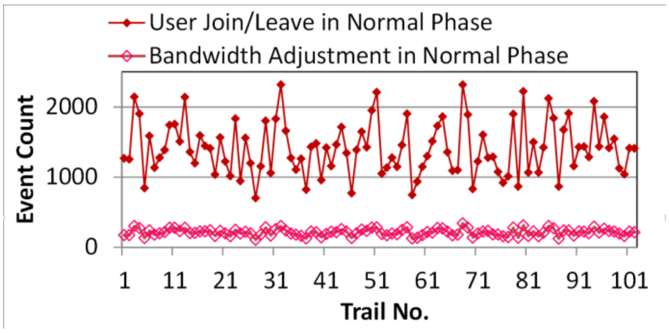

Fig. 7. Event Statistics in Normal Phase

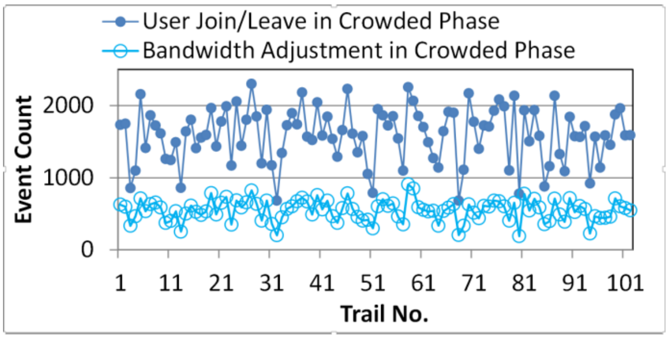

Fig. 8. Event Statistics in Crowded Phase

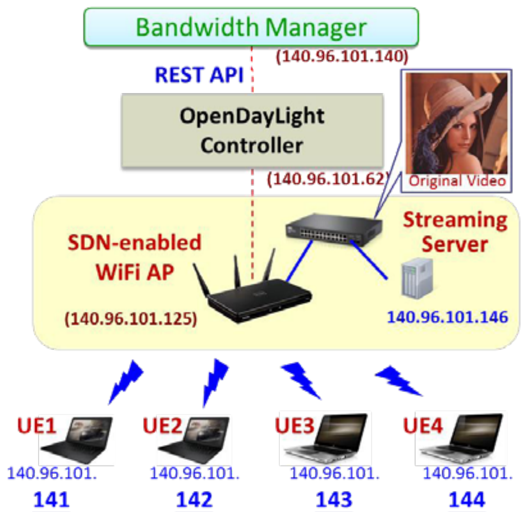

Fig. 9. Implementation Environment

TABLE II
PARAMETER SETTINGS IN IMPLEMENTATION EXPERIMENT 1

Parameters	Values
Maximum Guaranteed Bandwidth	13 Mbps
User Group Number	1 (Staff)
Default Base of Guaranteed Group Bandwidth	2
Initial Guaranteed Group Bandwidth	4

TABLE III
PARAMETER SETTINGS IN IMPLEMENTATION EXPERIMENT 2

Parameters	Values
Maximum Guaranteed Bandwidth	13 Mbps
User Group Number	2 (Guest, Staff)
Default Base of Guaranteed Group Bandwidth	2, 4
Initial Guaranteed Group Bandwidth	4, 8

TABLE IV
PARAMETER SETTINGS IN IMPLEMENTATION EXPERIMENT 3

Parameters	Values
Maximum Guaranteed Bandwidth	13 Mbps
User Group Number	2 (BYOD, Staff)
Default Base of Guaranteed Group Bandwidth	1,2
Initial Guaranteed Group Bandwidth	2,4

To verify the feasibility, we implement the dynamic bandwidth management method as well. This section describes the implementation environment and discusses the results derived from the implementation experiments. Fig. 9 shows the implementation environment in which the Bandwidth Manager provides a user interface to configure the parameters shown in Table I, except the number of user joins/leaves and the number of trials. The dynamic bandwidth management function instance resides in the OpenDayLight Controller as one of bundles (processes). The Streaming Server adopts the streaming function in the VLC media player [16], which generates unicast streams as per user's request.

In the first experiment, we verify the intra-group correctness of the dynamic bandwidth management method, where the parameter setting is shown in the Table II. Fig. 10 and Fig. 11 illustrate the implementation result, which is to verify the correctness of the dynamic bandwidth management method. In this experiment, we set the user group number as one, since verifying a group to be correct means the behaviors of all groups are correct. In step 1-2 in Fig. 10, when the third UEs joins and starts using the streaming service, the guaranteed bandwidth is increased by 4, i.e., the square value of the default base of guaranteed group bandwidth. In step 1-3 in Fig. 10, the amount of the guaranteed group bandwidth remains same, which all the Staff UEs are racing for the rest available bandwidth (i.e., the maximum guaranteed bandwidth minus the total guaranteed group bandwidth). Because the dynamic bandwidth management method does not specify any rules for allocation of the rest available bandwidth, it depends on the interactions among the Wi-Fi network interface cards on the UEs, the amount of data rate that users demand and the cleanness in the 2.4 GHz Wi-Fi operating frequency to determine how much additional bandwidth a UE can obtain from. Therefore, in a UE group, a specific UE could encounter

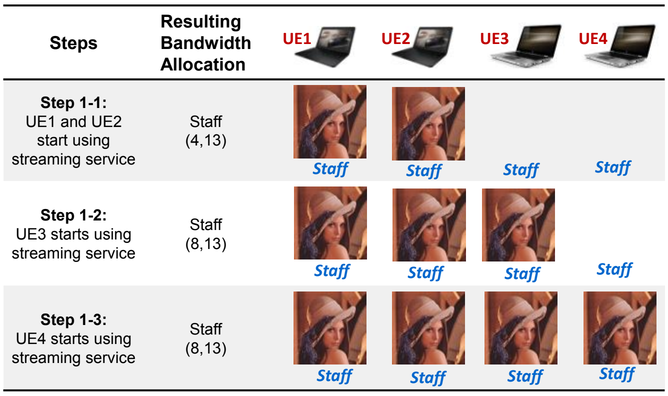

Fig. 10. Implementation Result of Experiment 1 – Verification of intra-group behavior correctness of the dynamic bandwidth management mechanism (Step 1-1 to Step 1-3)

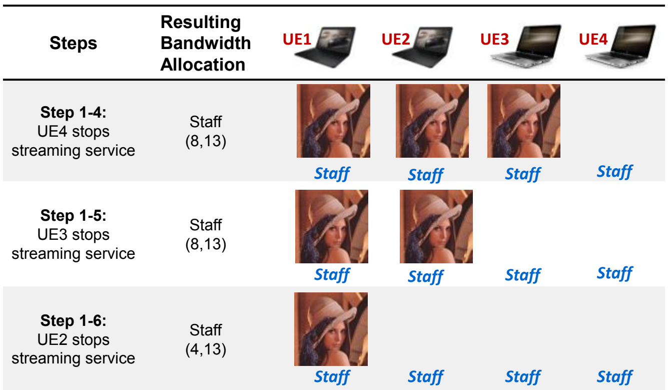

Fig. 11. Implementation Result of Experiment 1 – Verification of intra-group behavior correctness of the dynamic bandwidth management mechanism (Step 1-4 to Step 1-6)

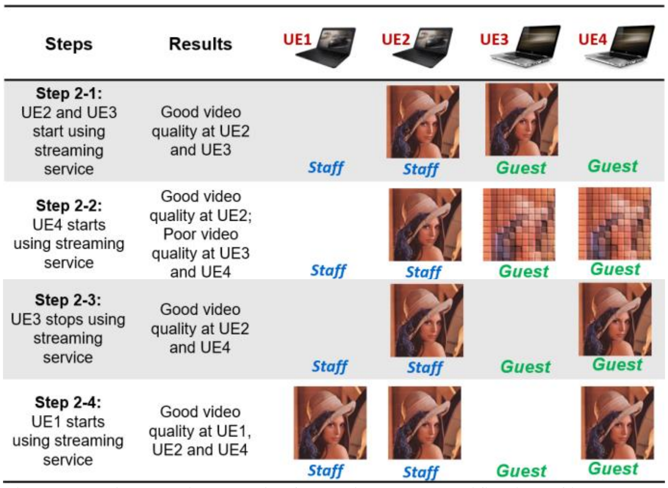

Fig. 12. Implementation Result of Experiment 2 – Verification of inter-group behavior correctness of the dynamic bandwidth management mechanism (Step 2-1 to Step 2-4)

a video quality degradation to a considerable degree for a period of time. Such phenomena happens unpredictably. However, the dynamic bandwidth management method still controls and guarantees the group bandwidth to a certain degree. When entering Step 1-4 and 1-5, the phenomena of video quality degradation becomes less as fewer group members shares the guaranteed group bandwidth. In Step 1-6, the dynamic bandwidth management method releases the guaranteed group bandwidth from 8 to 4, which could be used by other groups.

In the second experiment, we investigate the interaction among groups in order to verify the correctness of the dynamic bandwidth management method in inter-group behavior. Table III shows the implementation environment parameter settings.

Fig. 12 shows the experimental results illustratively. In Step 2-2, when the Guest member, UE4, starts using the streaming service, both Guest members, UE3 and UE4, perceives video quality degradation. While proceeding to Step 2-4, when the Staff member, UE 1, joins and starts using the streaming service, there is no and much less video quality degradation being perceived by the group members. This is because the Staff group is high priority and thus assigned more guaranteed group bandwidth than the Guest group does. This experiment result implies that the dynamic bandwidth management method can realize the prioritization with respect to bandwidth to a certain degree.

We conduct yet the third experiment to further investigate the interaction among groups. The implementation environment parameter settings is shown in Table IV.

The experimental result is shown in Fig. 13. In Step 3-2, the BYOD member joins and starts generating background (BG) traffic. Since the guaranteed group bandwidth for the Staff group is only 4, the Staff members, UE1 and UE2, would suffer from video quality degradation, expecially, when the background traffic is increased to a certain amount level. However, in Step 3-3, when a new Staff member, UE4, joins and starts using the streaming service, the video quality of the Staff group becomes better. This is because the number of the Staff member reaches 3, yielding that the dynamic bandwidth managemnt mechanism automatically allocates one additional truck of guaranteed bandwidth to the Staff group. When the Staff member, UE4, leaves in Step 3-4, the video quality perceived by the remaining members, UE1 and UE2, becomes better. The implication of this experiment is twofold. First, the amount of data traffic in a lower priority group could still impact the bandwidth allocation of a higer priority group and thus quality of service. Second, reacting to such situation properly, a higher priority group can reclaim the bandwidth back. More specific, the guaranteed group bandwidth is the key parameter to realize the priorization of groups.

V. CONCLUSION

This paper proposed a dynamic bandwidth management method for SDN-enabled wireless networks. The proposed method entails two important principles: batch grant and lazy adjustment. The principles allow the proposed method adapting to the user mobility dynamics in an ultra-dense network while controlling the signaling overhead low. The simulation results show that around every three contiguous occurrences of user joins or leaves result in one bandwidth adjustment operation. In other word, this method reduces 60% of signaling overhead compared with the method in which a user join/leave event triggers a bandwidth adjustment operation. The experimental results verify the feasibility of the dynamic bandwidth management method and its correctness with respect to the intra-group and inter-group bandwidth management behavior.

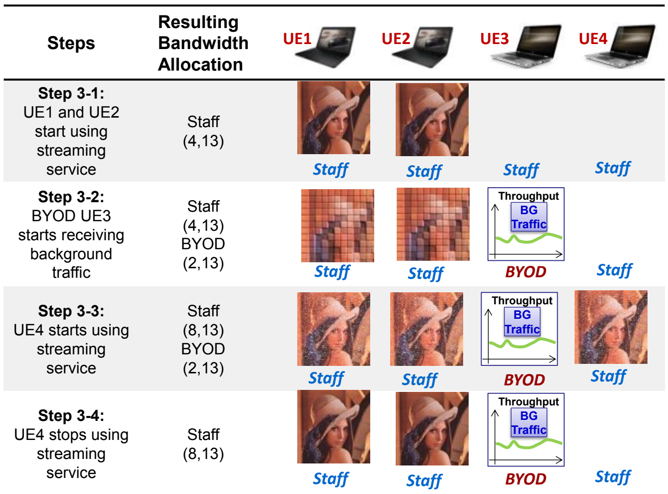

Fig. 13. Implementation Result of Experiment 3 – Verification of inter-group behavior correctness of the dynamic bandwidth management mechanism, especially on group priority (Step 3-1 to Step 3-4)

REFERENCES

[1] METIS, D. D1. 1. Scenarios, requirements and KPIs for 5G mobile and wireless system, May, 2013.

[2] A. Osseiran, et al., “Scenarios for 5G mobile and wireless communications: the vision of the METIS project,” IEEE Communications Magazine, , vol. 52, issue 5, pp. 26-35, 2014.

[3] S. Mansfield-Devine, “Interview: BYOD and the enterprise network,” Computer fraud & security, vol 2012, issue 4, pp. 14-17, 2012.

[4] N. McKeown, T. et al., “OpenFlow: Enabling Innovation in Campus Networks,” ACM SIGCOMM Computer Communication Review, vol. 38, issue 2, pp. 69-74, 2008.

[5] ONF (2012) Software-Defined Networking (SDN) Definition [Online]. Available. https://www.opennetworking.org/sdn-resources/sdn-definition

[6] F. Hu, Network Innovation through OpenFlow and SDN: Principles and Design. CRC Press, 2014.

[7] (2012) The ONF website. [Online]. Available. https://www.opennetworking.org/

[8] ONF (2012) ONF Specifications [online]. Available: https://www.opennetworking.org/sdn-resources/onf-specifications.

[9] R. Sherwood, et al., “Flowvisor: A network virtualization layer,” OpenFlow Switch Consortium, Tech. Rep., pp. 1-13, 2009.

[10] Y. Yiakoumis, et al., “Slicing home networks,” Proceedings of the 2nd ACM SIGCOMM workshop on Home networks, pp. 1-6, Aug. 2011.

[11] Sherwood, et al., “Can the production network be the testbed?,” OSDI, vol. 10, pp. 1-6, Oct. 2010.

[12] T. Lam, S. Radhakrishnan, A. Vahdat, and G. Varghese “NetShare: Virtualizing data center networks across services,” . UCSD, Tech. Rep., 2009.

[13] K.-L. Huang, C.-L. Liu, C.-H. Gan, M.-L. Wang and C.-T. Huang, “SDN-based Wireless Bandwidth Slicing,” in International Conference on Software Intelligentce Technologies and Applications, pp. 1- 5, Dec. 2014, Hsinchu, Taiwan.

[14] (2015) The OpenWrt website [Online]. Available. https://openwrt.org/

[15] T. Veerarajan and T. Ramachandran, “Numerical Methods with Programs in C,” second Edition, 2006.

[16] (2014) The VideoLAN website [Online]. Available. http://www.videolan.org/vlc/

[17] Oriol S., et al., “Cognitive pilot channel enabling spectrum awareness,” IEEE International Conference on Communications Workshops, p. 1-6, 2009

[18] Marco B., Gábor F., Andrea A., “Performance analysis of a distributed resource allocation scheme for D2D communications,” IEEE GLOBECOM Workshops (GC Wkshps), p. 358-362, 2011.

[19] Afif O., et al., “Scenarios for 5G mobile and wireless communications: the vision of the METIS project,” IEEE Communications Magazine, vol. 52, issue 5,pp. 26-35, 2014.

[20] Jan M., et al., "Opendaylight: Towards a model-driven sdn controller architecture," IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, pp. 1-6, 2014.

Kueil-Li Huang (黃貴笠)
Currently He is the engineer in Information Communications Research Laboratories. His research interest are protocol design, analysis and modeling.
E-mail: GaryHuang@itri.org.tw

Mu-Liang Wang (王慕良)
Currently She is the engineer in Information Communications Research Laboratories. Her major are WiMAX, LTE protocols and implementation.
E-mail: wml@itri.org.tw

Chin-Tien Huang (黃經天)
Currently He is the engineer in Information Communications Research Laboratories. His research interest are internet protocol design, mobile application service.
E-mail: HCT@itri.org.tw