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On the Performance of Downstream Traffic Distribution Scheme in Fiber-Wireless Networks

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Abstract*—Fiber-Wireless (FiWi) access networks, have rapidly matured as a last mile Internet access network solution due to their novel combination of Ethernet Passive Optical Networks (EPON) as a backhaul and Wireless Mesh Networks (WMN) as an access network. The high bandwidth provided by the optical lines, as well as the flexibility offered by the wireless network, offers a great degree of cost-efficiency in terms of sharing an optical line with a number of simultaneous users. In a FiWi network, Gateways (GWs) located between the EPON and WMN serve both the function of an Optical Network Unit (ONU) in the EPON and a mesh router in WMN. Since all of the downstream from the EPON to the WMN and all of the upstream from the WMN to the EPON must be exchanged at GWs, traffic distribution technique between GWs is necessary to achieve efficient utilization of the network resources. Controlling the downstream traffic is a significant issue in preventing performance degradation due to network congestion at the GWs, because the bandwidth of WMN is generally narrower than that of the EPON. In addition, the number of hops from a GW to an end-user in the WMN needs to be taken into account in the traffic distribution process, because the increased number of hops results in lower communication efficiency due to mutual interferences between adjacent links and effects of cross traffic. Therefore, in this paper, we focus on the downstream controlling of FiWi networks, and propose a traffic distribution scheme which utilizes an aspect of EPON to properly distribute traffic load among GWs. A hop count limitation mechanism is adopted to avoid throughput degradation caused by increased wireless interference and effects of cross traffic in the WMN. Simulation results show a trade-off relationship between fair load balancing among GWs and high throughput for end-users, and the proposed scheme can accommodate it by regulating hop count limitation.

I. INTRODUCTION

While networks have been developed for and deployed in a variety of different environments and situations, they can generally be divided into two categories, wired and wireless networks. Wired networks provide high-speed and stable connections, at the cost of greater infrastructure requirements and lower flexibility. In contrast, wireless networks require less infrastructure and allow users to freely move around the coverage area, although performance can vary dramatically for a wide variety of reasons including signal loss and wireless interference. The advantages and disadvantages of wired and wireless networks are complementary, that is each network excels at the other's weakness. Therefore, when creating a network, after considering the many implementation factors such as service requirements, environmental conditions, and deployment costs, the best blend between wired and wireless networks should be selected.

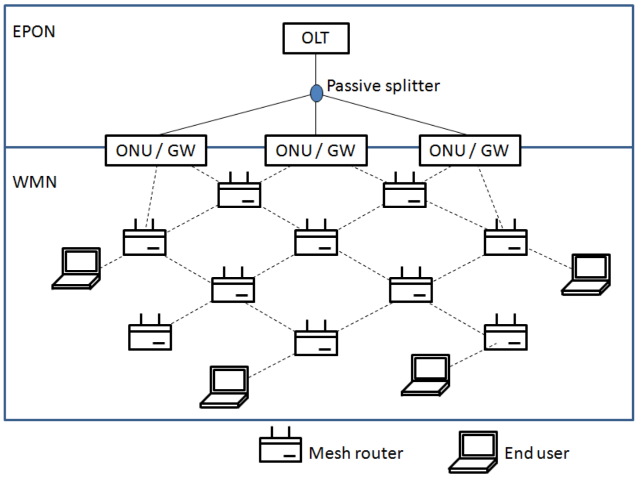


Fig. 1. Architecture of a FiWi network.

A FiWi network is an integrated network which provides the advantages of both a Ethernet Passive Optical Network (EPON) [1] and a Wireless Mesh Network (WMN). The high-speed cost-efficient backhaul is derived from an EPON, and is combined with the flexible access provided by a WMN. Fig. 1 shows the architecture of a FiWi network. A EPON is a reliable low-cost optical network where multiple users share the same optical line and signals are spread by a splitter without any electric processing. In a EPON, the data sent downstream from Optical Line Terminal (OLT) toward Optical Network Units (ONUs) are split at a passive splitter and simultaneously broadcasted to each of ONUs. It should be noted that each ONU receives all of downstream traffic destinated to not only itself but also every other ONU. In other words, data received by non-destination ONUs is discarded. In upstream transmissions from ONUs to the OLT, a polling technique is used as a multiple access technology to allow the ONUs to share the same optical line. ONUs are assigned time slots and they are allowed to transmit data only during the assigned time slots. A WMN is a dynamically self-organized, self-configured network where mesh routers automatically establish an wireless multi-hop network and maintain the mesh connectivity [2]. Some mesh routers equip special functions, such as Gateways (GW), which connect the WMN to external networks. In FiWi networks, each GW functions not only as a GW but also as an ONU. GWs which connect the EPON to the WMN play a significant role in controlling the traffic in FiWi networks.

Although FiWi networks are a promising solution to provide Internet access in metropolitan areas [3], some technical challenges still remain. One such issue is that the WMN tends to become a bottleneck because its wireless links are quite narrow when compared to the broadband links in EPON which exceed gigabyte speeds. In this paper, we aim to achieve a highly efficient utilization of EPON bandwidth by mitigating throughput degradation in WMN due to traffic congestion.

Moreover, the number of hops between a GW to an end-user in the WMN needs to be taken into account due to throughput degradation. In wireless networks, mutual interferences between adjacent links and effects of cross traffic reduce communication efficiency. In multi-hop wireless networks such as WMN, the increased number of hops results in lower communication effeciency because of wireless interferences and effects of cross traffic increase on each hop. Thus, we adopt a hop count limitation mechanism to avoid lower communication efficiency.

The rest of the paper is organized as follows. Section II reviews the related work. We propose our traffic distribution scheme in Section III, and its performance is validated through computer simulations in Section IV. Section V outlines the future work and Section VI concludes the paper.

II. RELATED WORK

FiWi networks have recently attracted much attention due to their potential to become the next generation of broadband access networks in near future. However, FiWi networks still face some technical challenges. One challenge lies in finding the optimum locations for the ONUs, so that the number of ONUs is minimized in order to lower the fiber, equipments, and installation costs, while simultaneously satisfying quality-of-service (QoS) requirements to meet user demand. The Modified Clustering Algorithm (MCA) [4] has been proposed to obtain a near-optimal result with a minimal number of ONUs while maintaining the network connectivity and satisfying QoS requirements. The optimization scheme [5] using Simulated Annealing (SA) and Hill-Climbing (HC) algorithms have been proposed to minimize the average distance between each wireless mesh router and its nearest ONU. This work finds a near-optimal ONU distribution which reduces the hop count and installation costs.

Another significant challenge for FiWi networks lies in the innovation of routing algorithms that control traffic for efficient communication. The Delay-Aware Routing Algorithm (DARA) [6] is designed to minimize the delay in the WMN such as propagation delay, transmission delay, queuing delay and slot synchronization delay which comes from the Time-Division Multiplexing (TDM) operation of the wireless channel. DARA computes the delay from the source mesh router to the GW and vice versa. It then chooses the path that minimizes the delay. To achieve both high throughput and the minimized end-to-end delay, Capacity and Delay-Aware Routing (CaDAR) has been proposed [7]. CaDAR is capable of reducing the network-wide average end-to-end delay through optimal capacity assignment on the wireless links and using the delay-aware routing that is similar to DARA.

The growth of applications such as the video streaming and online chatting has increased the demand for peer-to-peer communication, and this is not exception for FiWi networks. The performance improvement of peer-to-peer communication between two mesh routers in the same FiWi network have been researched [8]. The use of optical lines in PONs instead of numerous wireless multi-hop connections in WMN for the peer-to-peer communication between distantly-positioned source and destination mesh routers has been proposed [8]. By utilizing PONs for communication between source and destination mesh routers, [8] mitigates the throughput reduction and end-to-end delay increment caused by wireless interference increased by many hops in WMN.

To maximize PON performance, various resource management schemes for PONs in upstream transmission from multiple ONUs to the OLT have been researched [9]. PON requires an appropriate control access mechanism in each shared wavelength, because each ONU transmits data only during its assigned time slot. The authors of [9] categorized upstream MAC layer transmission scheduling and bandwidth allocation schemes based on their features and compared their strengths and weaknesses.

A Wavelength-Division-Multiplexing (WDM) PON [10] which uses multiple wavelengths for transmission and tunable lasers can admit more traffic to the network. To achieve this goal of increasing admissible upstream traffic, research on the design of WDM PONs with tunable lasers has been done [11]. Generally, the broader the tuning ranges of the lasers, the more the traffic can be admitted to the network. However, a broad tuning range requires sophisticated technology which can imply higher costs. To achieve an optimal tradeoff between admissible traffic and cost, Zhang et al. [11] design a WDM PON by selecting lasers with proper tuning ranges for the upstream data transmission.

As mentioned above, while much research has been done to tackle various issues in FiWi networks, the effect of traffic convergence on flow throughput at certain GWs, as well as its effect on the efficiency of resource utilization in downstream transmission has not been sufficiently studied. In our research, we focus on the degradation communication efficiency due to not only wireless multi-hop relaying but also traffic convergence at GWs connecting the PON and WMN.

III. PROPOSED SCHEME

In FiWi networks, GWs serve as the bridge between the EPON and WMN, and handle downstream and upstream traffic. However, the link bandwidth capacities on either side of the EPON and WMN are completely different. Since the bandwidth capacity of wireless links in the WMN is smaller than that of the optical lines in the EPON, network congestion tends to frequently occur in the downstream direction at each

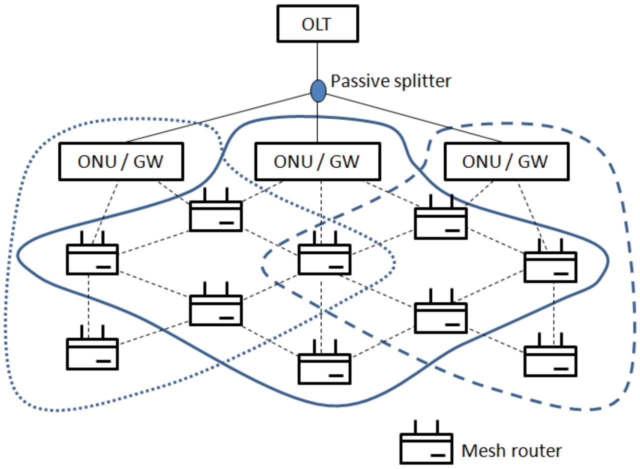


Fig. 2. Mesh router clustering based on hops from GWs.

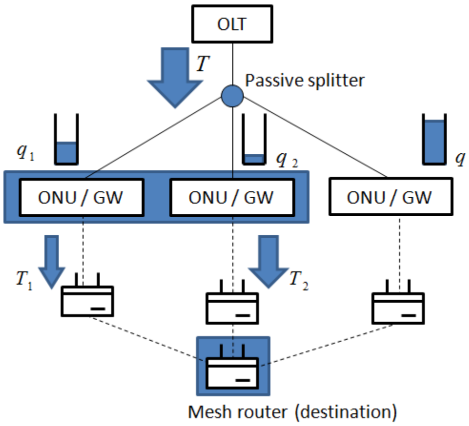


Fig. 3. Traffic distribution according to traffic load among GWs.

GW. To mitigate the performance degradation in crowded GWs due to the convergence many flows, distributing traffic fairly among GWs, including the less-congested GWs is a fundamental solution. However, it is also necessary to take into account the impact of hop count on the throughput of each flow in WMN. As mentioned in [12], the increase in the number of hops leads to an increase in mutual interferences between adjecent links and effects of cross traffic, which generally results in significant end-to-end throughput degradation. [12] showed that in a WMN where n is the total number of nodes, the per-node throughput is $O(1/n)$. This is significantly less than the results of Gupta and Kumar model $O(1/\sqrt{n})$ [13] in pure ad hoc network because a WMN has a hotspot at the GW, which all the flows to external networks flow through. Therefore, not only are traffic distribution techniques required, but hop count restriction mechanisms are needed to achieve highly efficient utilization of network resources. To cope with this issue, we propose a traffic distribution scheme using an aspect of EPON technology to balance the traffic load among GWs. The method is based on a simple clustering strategy designed to limit the hop count for all mesh routers.

A. *Limiting hop count by clustering*

In WMNs, communication efficiency can be dramatically reduced by an increase in the number of hops due to the increase in wireless interference of relaying data and effects of cross traffic. Therefore, it is necessary to limit the maximum number of hops in the WMN to ensure efficient communication in FiWi networks. In the proposed traffic distribution scheme, mesh routers are clustered according to the hop counts of each GW as shown in Fig. 2. Mesh routers located within the coverage area of the same GW are clustered together, that is if their hop counts are no more than a predefined certain threshold, θ. Additionally, some mesh routers may belong to multiple clusters. By not allowing GWs to communicate with mesh router outside of their cluster, the maximum number of hops in the WMN is limited to θ or less. Hop counts information can be obtained from the employed routing protocol. We assume that the Hybrid Wireless Mesh Protocol (HWMP) [14] which is the default routing protocol of IEEE 802.11s [15][16], is used as a routing protocol in WMNs. Cluster information about which mesh routers belong to which clusters is notified to the OLT by the GWs, and the OLT then accordingly determines a destination GW for each mesh router while considering the load balance among GWs. In this way, the proposed scheme is able to maintain communication efficiency by keeping smaller hop counts for all mesh routers.

B. *Load-balancing by traffic distribution*

By using the above method to limit the hop count, the OLT will have knowledge about the set of GWs which can deliver traffic to a destination mesh router within an acceptable number of hops. If each mesh router is covered by only one GW, then there is no leeway to balance the traffic load among GWs. However, if the hop count threshold is moderate, some mesh routers will belong to multiple clusters, which creates the opportunity for traffic to be distributed among several GWs. In such situation, the proposed scheme distributes traffic according to the degree of network congestions at each GW. In other words, traffic destined for the same mesh router is distributed over some of the available GWs in regards to the amount of queuing at each downstream GW. For example, when a mesh router belongs to N clusters, the traffic destined to the mesh router, T, is distributed over n GWs, where n is less than N and N_{max}. N_{max} is defined according to the size of the network and the total number of GWs. n GWs are selected starting with the least busy. The traffic volume is assigned to the ith GW, T_i, is calculated by the following equation;

$$T_i = \frac{q_i^{-1}}{\sum_{j=1}^{n} q_j^{-1}} \cdot T \tag{1}$$

q_i indicates the latest buffer occupancy ratio averaged over the last certain time duration, t_u, at ith GW. The traffic

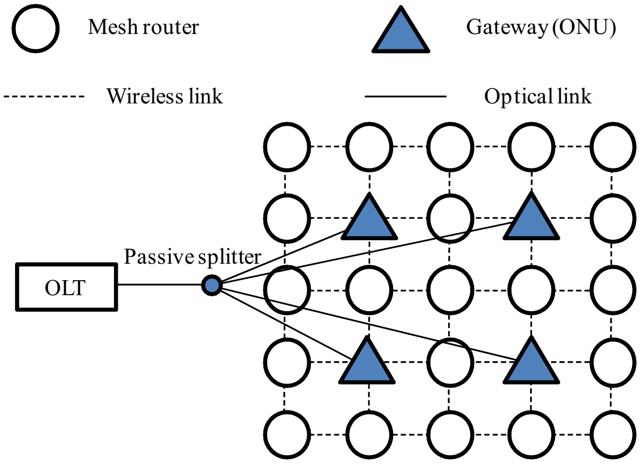


Fig. 4. Network topology

assignments for each of mesh routers are periodically updated with the interval, t_u , in order to follow the changes in traffic. The proposed traffic assignments of the simplified architecture are shown in Fig. 3. When N is 3 and N_{max} is 2, two GWs are selected starting with the least busy one. Then, traffic volume is assigned to GWs according to the traffic between two GWs. Heavy traffic is allocated in the free GW and light traffic is allocated in busy GW. In the proposed scheme, because all of the calculations to determine traffic distribution ratios is carried out at the OLT, the OLT needs to be notified of the queue occupancy information for each GW. This can be easily implemented by simply modifying the original polling mechanism of the EPONs. This is accomplished by employing Multi-Point Control Protocol (MPCP) [1] as a part of the MAC layer in order to control the upstream traffic as to avoid collisions. In MPCP, the OLT informs the ONUs of the upstream transmission window via GATE messages, and the ONUs report their queuing status at the buffer for upstream by using REPORT messages. The proposed scheme also uses this message exchange mechanism to convey the information about the downstream queues. This information is added into the REPORT messages. The queuing status reporting interval, t_r, depends on the message exchange frequency which depends on the MPCP implementation.

In order to distribute traffic by following the updated traffic assignments, the destination GW information in the MAC frames that are departing from the OLT need to be updated accordingly. Fortunately, this can be achieved without any added complication by using a preexisting mechanism in the original EPON designed to identify the destination ONU in MAC frames. In EPONs where a passive splitter duplicates optical signals and broadcast it to all ONUs, each ONU receives all of downstream traffic destined to not only itself but also every other ONU. Traffic destined to other ONUs is discarded. The destination MAC frames can be differentiated by an identifier, referred to as Logical Link ID (LLID) [1], which is written into the frame header by the OLT. So, it is in fact easy for EPONs to control the direction of downstream traffic, which can be accomplished by simply changing the LLID in each frame.

TABLE I
SIMULATION PARAMETERS

Field	1000 × 1000m
Wireless standard	802.11b
Communication range	250m
Wireless bandwidth	2Mbps
Optical line bandwidth	1Gbps
Buffer size	50kbyte
Traffic rate	200–500kbps
Communication time	20sec
Number of trails	300

IV. PERFORMANCE EVALUATION

The performance of our traffic distribution scheme was evaluated by simulation with Qualnet version 4.5.1 [17] and measured in terms of load balancing and communication efficiency.

A. Simulation environments and scenarios

To demonstrate the basic performance of the proposed scheme, a simple, symmetric FiWi network topology is used as shown in Fig. 4. Mesh routers and four GWs equipped with the ONU are placed on a grid in a square 1000m field. The communication range of each node is 250m which is sufficiently larger than the distance between neighboring nodes, 200m. Four ONUs (GWs) are connected to the OLT via a passive splitter. The propagation delay between OLT and each ONU is set to 1ms, and the bandwidth of the optical link is set to 1Gbps. Each GW has a 50kbytes buffer for the downstream. The WMN uses 802.11b and HWMP as the MAC technology and a routing protocol, respectively. The wireless link bandwidth is set to 2Mbps. Table I shows a summary of the network configuration parameters.

In each simulation, five Constant Bit Rate (CBR) traffic flows are established between the OLT and five different mesh routers which are randomly selected. CBR communication was conducted for 20sec after HWMP converges. Each simulation was conducted by varying the rate of CBR from 200kbps to 500kbps by 50kbps. The results depicted in each graph is the averaged value taken from over three hundred trials.

In the proposed scheme, two control parameters determining frequency in processings and monitoring, defined as t_u, and t_r, which are set to 20ms and 2ms, respectively. The maximum number of selectable GWs, N_{max}, is set to two. The impact of the hop count limitation threshold, θ, on the overall performance of the proposed scheme is also considered. Values of 2, 3, or 4 for θ are used. Additionally the Bellman-Ford algorithm is also used for comparison.

B. Performance Metrics

In the performance analysis, we use the total throughput, the Fairness Index (FI) [18], and the average end-to-end delay as metrics indicating communication efficiency, fairness in load balancing, and the effect of load balancing on quality of communications, respectively. The throughput of each flow is calculated from the amount of data successfully received at each mesh router by dividing it by the duration of communication. The value of the total throughput can be obtained by integrating the throughputs each flows. FI is defined by the queue occupancy of each GW as follows;

$$FI = \frac{\left(\sum_{i=1}^{g} x_i\right)^2}{g \sum_{i=1}^{g} x_i^2} \qquad (2)$$

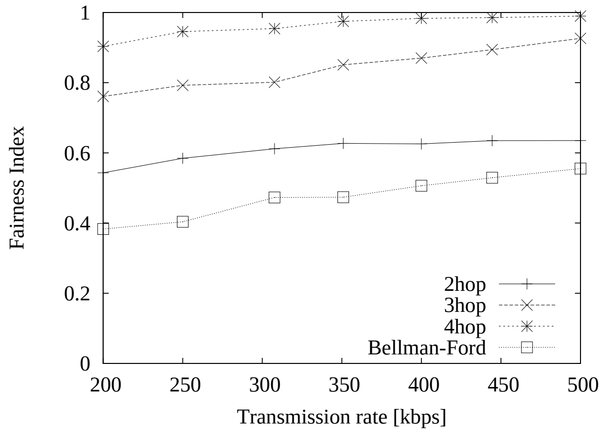
where x_i and g show the queue occupancy of ith GW and the number of GWs, respectively. FI takes a value within the range from 0 to 1, where a larger value implies more fairness. On the other hand, the averaged end-to-end delay can be easily calculated by averaging all of end-to-end delay values observed by each frame over time and flows.

C. Simulation Results

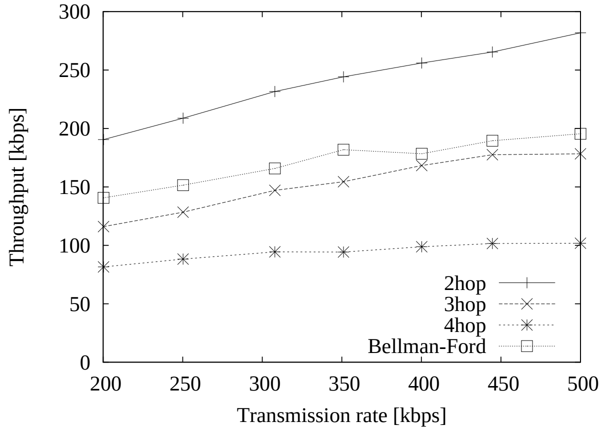
1) Fairness in load balancing: Fairness in load balancing: Fig. 5 shows the simulation results. From Fig. 5(a), we can see that the proposed scheme succeeds in improving the fairness of the traffic load distribution regardless of the hop count limitation threshold. Moreover, it is clear that the fairness tends to be improved by increasing the value of the threshold. This is because a large threshold increases the possibility of distributing the traffic load to less-loaded GWs. Especially in the case where θ is 4, because about half of mesh routers can belong to all clusters and all of mesh routers can belong to over three clusters, an enough load-balancing was conducted.

2) Changes in total throughput: Fig. 5(b) shows the total throughput for different traffic loads. In the proposed scheme, the total throughput becomes smaller as the value of the hop count limitation threshold increases, which is due to the increase in wireless interference and effects of cross traffic. While it is clear from the comparison between Fig. 5(a) and 5(b) that there is a trade-off relation between fair load balancing and communication efficiency, we need to pay more attention to the communication efficiency, i.e., when θ is 3 and 4, the total throughput is lower than that of the Bellman-Ford. From the results it is clear that the hop count limitation needs to be appropriately controlled according to not only the network size and topology, but also the MAC technologies in WMN, because the wireless interference seems to be vary with different wireless systems.

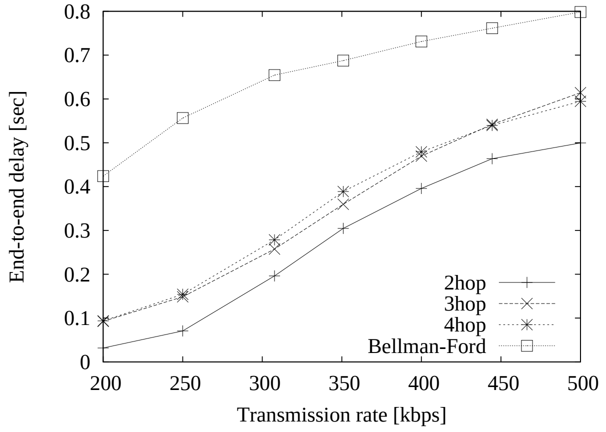
3) Changes in end-to-end delay: Fig. 5(c) shows the average end-to-end delay for different traffic loads. We can observe that the end-to-end delay is dramatically decreased by the proposed scheme, which is due to the reduction in queuing delay. Therefore, by limiting traffic convergence to certain GWs by using the traffic distribution scheme, the end-to-end delay is decreased. In our proposed scheme, increasing θ has two opposite effects on end-to-end delay, i.e., its reduction by the decreased queuing delay due to traffic distribution,



(a) Fairness in load balancing



(b) Commuinication efficiency



(c) The effect of load balancing on end-to-end delay

Fig. 5. Simulation Results

and its increment by the increased relaying delay due to hop count growing. In fact, the reason why the end-to-end delay becomes larger by increasing θ from 2 to 3 or 4, is because the effect of delay increment by hop count growth is much significant compared with that of delay reduction by traffic distribution. However, there is no significant difference between the cases where θ is 3 and 4, even though the number of hops increases. This is because the possibility of distributing traffic load to less-loaded GWs is increased drastically by the increased number of mesh routers who intend to belong to a new cluster. Actually, in the network topology as shown in Fig. 4, the four corner mesh routers can belong to only one cluster when θ is 3, although all of mesh routers can belong to over three clusters when θ is 4. Because the influence of the wireless interference, bandwitdh sharing and the queuing delay decrease is different according to the size, topology, and wireless MAC technology of the target FiWi network, the threshold needs to be appropriately determined.

V. DISCUSSION

In this paper, we proposed a traffic distribution scheme to balance the traffic load among GWs with a hop count limitation mechanism. However, the potential to develop an optimization scheme still remains. Because all of traffic goes through the OLT, and the OLT knows the state of all ONUs in EPON, all of the traffic control and calculations can be done by the OLT. If the calculation time and the control delay are negligible when the traffic changes, we can adapt an optimized traffic distribution scheme. If the traffic distribution is optimized then the communication efficiency is expected to improve further as the traffic load on GWs is effectively distributed.

However, optimizing the traffic distribution alone is insufficient to maximize communication performance in FiWi networks. The hop count limitation should be appropriately determined according to the network size, topology, and wireless interference in the WMN, since communication efficiency can suffer from large hop count even if load balancing succeeds. Also, if some ONUs have heavy traffic and some ONUs have less traffic, the hop count limitation of each ONU might have to be changed according to the traffic volume assigned to each ONU.

VI. CONCLUSION

FiWi networks offer great promise in providing cost efficient, high bandwidth, and flexible last mile Internet access for ubiquitous networking. In FiWi networks, traffic converges on GWs which connect the EPON to the WMN. This results in network performance degradation due to network congestion especially in the buffers equipped on GWs for queuing downstream, because the wireless link bandwidth in WMN is narrower than that of optical line rate of the EPON. To tackle this problem, a traffic load balancing technique is necessary. In addition, communication efficiency degradation caused by increased hop counts in multi-hop relaying in WMN needs to be also considered. In this paper, a traffic distribution scheme is proposed which is designed to appropriately distribute the traffic load among GWs. The scheme introduces a wireless hop count limitation mechanism in order to control the throughput reduction due to the inherent mutual interferences between adjacent links and effects of cross traffic. Through computer simulations, we examine the trade-off between communication efficiency and fair traffic load balancing. We conclude that the proposed scheme is able to dramatically improve both communication efficiency and fair load balancing, and its performance can be adjusted by controlling the hop count limitation.

REFERENCES

[1] F. Effenberger, D. Clearly, O. Haran, G. Kramer, R. D. Li, M. Oron, and T. Pfeiffer, “An introcution to PON technologies,” *IEEE Communications Magazine*, vol. 45, no. 3, pp. S17–S25, Mar. 2007.

[2] I. F. Akyildiz and X. Wang, “A survey on wireless mesh networks,” *IEEE Communications Magazine*, vol. 43, no. 9, pp. S23–S30, Sep. 2005.

[3] N. Ghazisaidi, M. Maier, and C. M. Assi, “Fiber-wireless (FiWi) access networks: a survey,” *IEEE Communications Magazine*, vol. 47, no. 2, pp. 160–167, Feb. 2009.

[4] Y. Liu, C. Zhou, and Y. Cheng, “Integrated BS/ONU placement in hybrid EPON-WiMAX access network,” in *Proc. GLOBECOM*, 2009, pp. 1–6.

[5] S. Sarkar, B. Mukherjee, and S. Dixit, “Towards global optimization of multiple ONU placement in hybrid optical-wireless broadband access networks,” in *Proc. COIN-NGNCON*, Jul. 2006, pp. 65–67.

[6] S. Sarkar, H. Yen, S. Dixit, and B. Mukherjee, “A novel delay-aware routing algorithm(DARA) for a hybrid wireless-optical broadband access network(WOBAN),” *IEEE Network*, vol. 22, no. 3, pp. 20–28, May–June 2008.

[7] A. Reaz, V. Ramamurthi, S. Sarkar, D. GHhosal, S.Dixit, and B. Mukherjee, “CaDAR: an efficient routing algorithm for a wireless-optical broadband access network (WOBAN),” *IEEE/OSA Journal of Optical Communications and Networking*, vol. 1, no. 5, pp. 392–403, 2009.

[8] Z. Zheng, J. Wang, and J. Wang, “A study of network throughput gain in Optical-Wireless(FiWi) networks subject to peer to-peer communications,” in *Proc. ICC*, 2009, pp. 1–6.

[9] Y. Luo, S. Yin, N. Ansari, and T. Wang, “Resource management for broadband access over time-division multiplexed passive optical networks,” *IEEE Network*, Vol. 21, No. 5, pp. 20–27, Sep./Oct. 2007.

[10] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, “Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: A review,” *Journal of Optical Networking*, vol. 4, no. 11, pp. 737–758, Nov. 2005.

[11] J. Zhang and N. Ansari, “Design of WDM PON with tunable lasers: the upstream scenario,” *IEEE/OSA Journal of Lightwave Technology*, Vol. 28, No. 2, pp. 228-236, Jan. 2010.

[12] J. C. Kuo and W. Liao, “Hop count distribution of multihop paths in wireless networks with arbitary node density: modeling and its applications,” *IEEE Transactions on Vehicular Technology*, Vol. 56, No. 4, pp. 2321–2331, Jul. 2007.

[13] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory*, Vol. 46, pp. 388–404, Mar. 2000.

[14] M. Bahr, “Update on the hybrid wireless mesh protocol of IEEE 802.11s,” in *1st IEEE International Workshop on Enabling Technologies and Standards for Wireless Mesh Networking (MeshTech 2007)*, Pisa(Italy), Oct. 2007.

[15] G. R. Hiertz, Z. Yunpeng, S. Max, T. Junge, E. Weiss, and B. Wolz, “IEEE802.11s: WLAN mesh standization and high performance extensions,” *IEEE Network*, vol. 22, no.3, pp. 12–19, May–June 2008.

[16] G. R. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, and B. Walke, “IEEE 802.11s: The WLAN mesh standard,” *IEEE Wireless Communication*, vol. 17, No. 1, pp. 104–111, Feb. 2010.

[17] Scalable Network Technologies (SNT). QualNet. [Online]. Available:http://www.qualnet.com/

[18] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, “A quantitative measure of fairness and discrimination for resource allocation and shared computer system,” Technical Report DEC-TR-301, Digital Equipment Corporation, 1984.