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Dual-layer efficiency enhancement for future passive optical network

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Abstract Ever-increasing demands on bandwidth compel us to improve the bandwidth utilization of access networks. It is more important to enhance the efficiency of passive optical networks (PON) than other access technologies, as they are the primary solutions to various access scenarios. To satisfy the demands of improved bandwidth efficiency, we propose a dual-layer (data link layer and network layer) efficiency enhancement scheme for future PON system. Under this architecture, a data-link-layer flexible coding scheme is introduced to extend the downstream link throughput, and a network-layer centralized active queue management (AQM) scheme is introduced to increase bandwidth efficiency. Both of these technologies are designed to suit the future centralized cooperative control mode. The results of an experimental demonstration of the network coding PON scheme reveal the efficiency of the proposed architecture. The results of simulations show that the centralized AQM scheme has a positive influence on queuing delay and jitter. To the best of our knowledge, this is the first time that a data link layer mechanism and a network layer policy have been integrated to provide high efficiency and quality of service in access networks.

Keywords passive optical network, bandwidth efficiency, network coding, active queue management, centralized control

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1 Introduction

High-definition video, file sharing, and other Internet services have stimulated an explosive growth in demand for bandwidth. As shown in Figure 1 (a) and (b), Cisco's Visual Networking Index (forecast and methodology (released in 2014) and global mobile data traffic forecast update (released in 2015)) indicates that, by 2018, total traffic will reach 131.6 exabytes per month, which is three times larger than it was in 2013, and that global mobile data traffic will grow tenfold from 2014 to 2019, reaching 24.3 exabytes per month. This ever-growing demand for bandwidth applies huge pressure to an entire network, especially at the entrance of network traffic-the access network.

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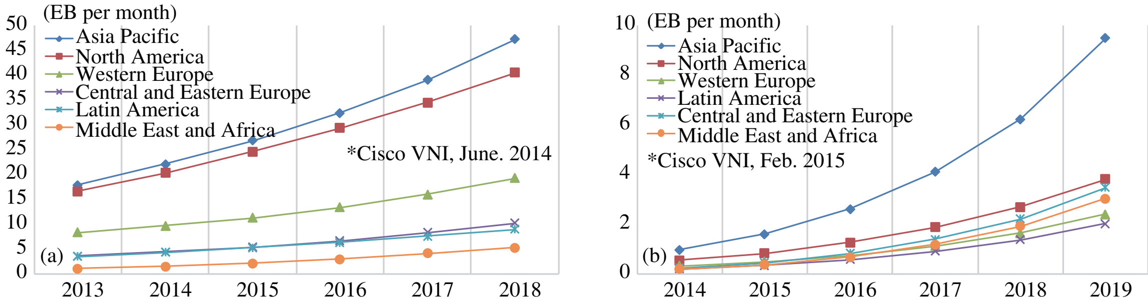

Figure 1 (Color online) Global traffic forecast (by geography). (a) Global IP traffic, 2013-2018; (b) global mobile data traffic, 2014-2019.

Key technologies have been analyzed at the whole optical network level to satisfy diverse bandwidth-intensive applications' demands [1]. And passive optical networks (PON) have been widely deployed in many kinds of access scenarios to alleviate pressure on bandwidth, because of their ability to provide higher bandwidth at lower cost [2, 3]. Higher-capacity PON technology, such as Time- and Wavelength-Division Multiplexed PON (TWDM-PON) and Orthogonal Frequency-Division Multiplexing PON (OFDM-PON) have already been proposed to further expand access bandwidth [4, 5].

However, their cost-sensitive nature, as well as their limitations on optical fiber transmission capacity [6], prevents us from persistently using simple frequency-division multiplexing or space-division multiplexing methods for expanding the capacity of a PON system. The bandwidth efficiency of the PON system must be improved to fulfill the ever-increasing demands on bandwidth.

Meanwhile, the traditional PON-based access network operation mode is extensive but inefficient, and Over-The-Top (OTT) services have seized the telecommunications operators' market. Thus, operators must improve their quality of service and capability of their operations in order to meet users' expectations and prevent further declines in profits.

Based on the factors mentioned above, the goal of future PON system development should be the improvement of bandwidth efficiency, which includes enlarging the existing bandwidth and efficiently using fixed bandwidth resources. Considering that distributed optical line terminal (OLT) deployment increases the difficulty of management, as well as the emerging trend of OLT clustering and optical distribution network (ODN) flexibility in future PON system, performing an overall collaborative optimization on both the data link layer and the network layer of PON system can be a favorable solution.

In this paper, we propose a multi-OLT-oriented dual-layer efficient PON (MODE-PON) architecture. A data-link-layer flexible coding scheme and a network-layer centralized active queue management (AQM) selection scheme are introduced to the MODE-PON in order to enlarge the existing bandwidth and service quality, respectively, and thus to increase the bandwidth efficiency. Using this architecture, both of the bandwidth optimization schemes are demonstrated. We build a 10G Ethernet PON (EPON) experimental platform to verify the data-link-layer coding scheme, and a simulation environment on NS2 to verify the network-layer AQM scheme. The experimental results demonstrate that the downstream link throughput exceeded the predefined limitations and thus improved the bandwidth efficiency. The simulation results show that using the network-layer centralized AQM selection scheme can lead to major performance improvements in latency and jitter.

The rest of the paper is organized as follows. Section 2 describes the architecture of the MODE-PON. Sections 3 and 4 describe the flexible data-link-layer coding scheme and the network-layer centralized AQM scheme of the MODE-PON, respectively. Section 5 introduces the experimental platform for the network coding PON (NC-PON) and analyzes the results of the simulation of the AQM algorithms. Finally, Section 6 presents the conclusion.

2 Multi-OLT-oriented dual-layer efficient PON architecture

Figure 2 shows the multi-OLT-oriented dual-layer efficient PON architecture. In this architecture,

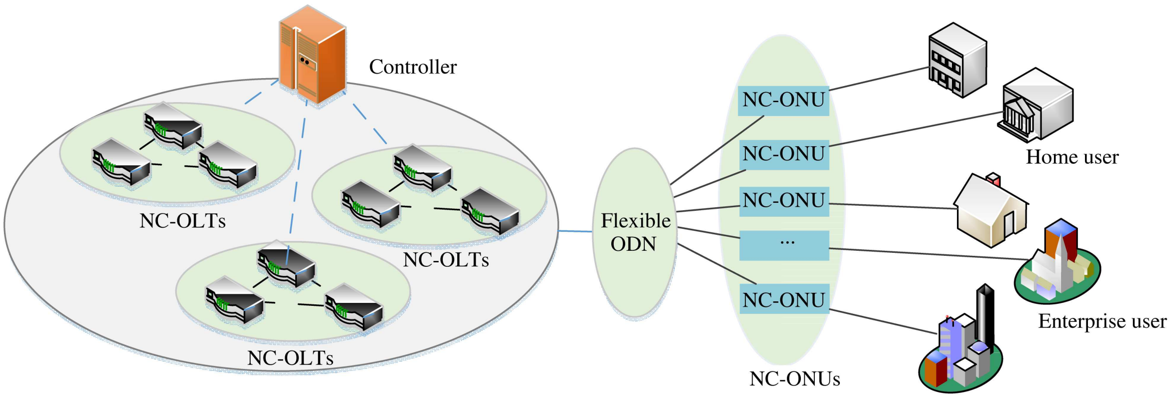

Figure 2 (Color online) Multi-OLT-oriented efficient PON architecture.

multiple OLTs are deployed together to provide sufficient bandwidth for the end users, and the OLTs can be partitioned into several individual clusters according to their access coverage. Meanwhile, the OLTs have the capability of data switching and different OLTs can be connected to each other for external communications and further pooling support.

To improve the bandwidth efficiency, efficiency enhancement schemes are proposed for each of the two layers. At the data link layer, network coding technology is introduced into the PON system, and it can compress data information to enlarge the throughput of the network. Because of the downstream broadcast feature of PON system, the peer-to-peer (P2P) traffic in the local network will clearly be optimized. At the network layer, AQM is introduced into the OLTs to improve the service quality and thus improve the efficiency under a fixed bandwidth situation. AQM can control queuing behavior by detecting incipient congestion and maintaining proper latency and jitter to offer satisfactory link utilization.

Owing to the disadvantages of current network coding technology in PON system and AQM technology, we deployed a centralized controller in the central office to provide a unified management capability. Current research into network coding technology in PONs has mainly focused on a single PON system [7, 8], which means that only optical network units (ONUs) under the same OLT can participate in network coding, and this is unsuitable for multi-OLT scenarios because it prevents maximal network coding pairs from being found and it influences optimization results. AQM faces the same problem too. As only local information on network statistics is available for each switch device, the localized view rather than the global view influences traditional AQM's ability to perform suitable adjustments within the changing global network status [9, 10].

The centralized controller is introduced to address this issue, and we found that the concept of Software Defined Networking (SDN) [11] matches our centralized control demands. Besides the unified southbound interface, the programmable control layer feature of SDN can effectively shield the differences between the underlying devices, provide unified management of various devices, and give the capability to choose the optimization algorithm and other value-added applications.

The OLTs in this architecture should provide the capability for network coding and AQM, and should also supply a unified southbound interface protocol such as Multi-Point Control Protocol (MPCP) or OpenFlow to communicate with the controller. Under the unified control, each OLT can obtain the whole network status, and follow the instructions to perform network coding or AQM procedures.

At the user side, a flexible ODN is deployed to provide flexible affiliation between multiple OLTs and ONUs, which can provide more choices for the network coding ONU pairing. The flexible ODN, which has been shown to provide fine support for further optimization [12], can also be controlled by the controller, and it can be composed by large-scale optical switches. Considering the efficiency introduced by the network coding technology, the cost of building an active ODN is reasonable. The ONUs in this architecture are designed to support network coding and some other basic functions to communicate with the OLTs.

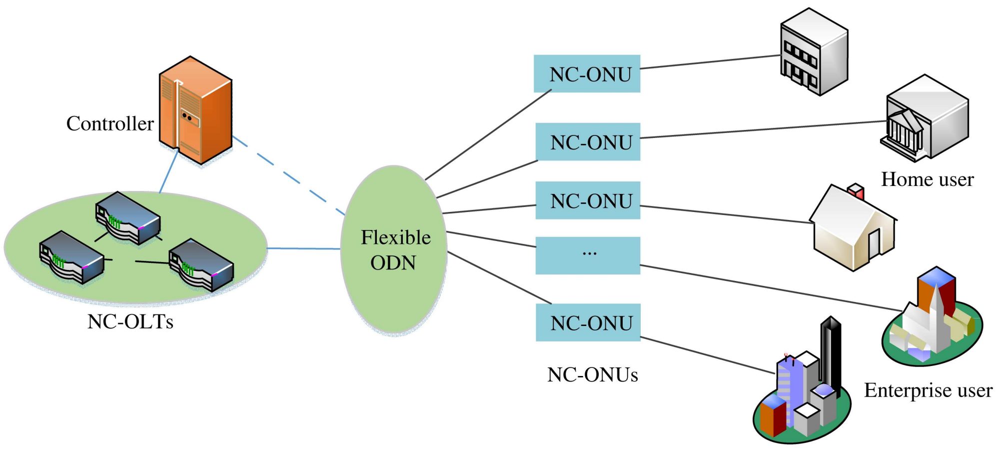

Figure 3 (Color online) Operating scenario for the data-link-layer flexible coding scheme in the MODE-PON.

The OLTs and controller are all located in the central office, and the flexible ODN can communicate with the controller via in-band signaling. Based on this architecture, we introduced the data-link-layer flexible coding scheme and the network-layer centralized AQM scheme to optimize the bandwidth efficiency. Details about network coding PON and the centralized AQM frame are described below in Sections 3 and 4.

3 Data-link-layer flexible coding scheme in MODE-PON

Network coding technology can improve the throughput of a network by encoding the transmission data [13]. Because of the downstream link broadcast mechanism in conventional TDM-PON systems like the EPON/10G EPON, network coding technology can be added to reduce the downstream traffic. Considering that P2P traffic such as file sharing and data backup between WiFi base stations makes up a large part of an access network, compressing these forms of traffic can improve bandwidth utilization significantly [14]. By using simple bitwise exclusive OR operations on the P2P traffic, the two bits of original data can be compressed into one bit and thus increase the downstream throughput [15].

3.1 Data-link-layer flexible coding scenario

Although the traditional network-coding-supported PON architecture can reduce network traffic between different ONUs of the same OLT, it is inadequate for the P2P traffic between ONUs of different OLTs because of the fixed PON architecture. Under the MODE-PON architecture, the relationship between OLTs and ONUs can be reallocated dynamically.

Figure 3 shows the operating scenario for the data-link-layer flexible coding scheme in the MODE-PON. The flexible ODN (FODN) can flexibly change the connections between the OLTs and ONUs. The FODN should have an $N \times M$ architecture, which can connect N OLTs and M ONUs. In this scenario, the controller monitors the traffic between any two ONUs and reconfigures the FODN to change the connections between the OLTs and ONUs. Then any two ONUs can establish a network coding pair when they have P2P traffic, even if they are not under the same OLT.

The core process of the NC-PON is as shown in Figure 4.

1) Controller collects the information of communication flows between each ONU.

2) Controller classifies all P2P traffic between ONUs and chooses the pair of ONUs that have the largest flows as network coding ONUs (NC-ONU).

3) Controller assigns NC-ONUs into the same OLT, and then applies network coding.

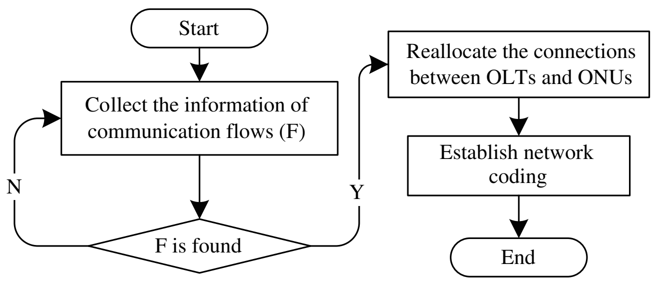

Figure 4 The flexible ONU matching process.

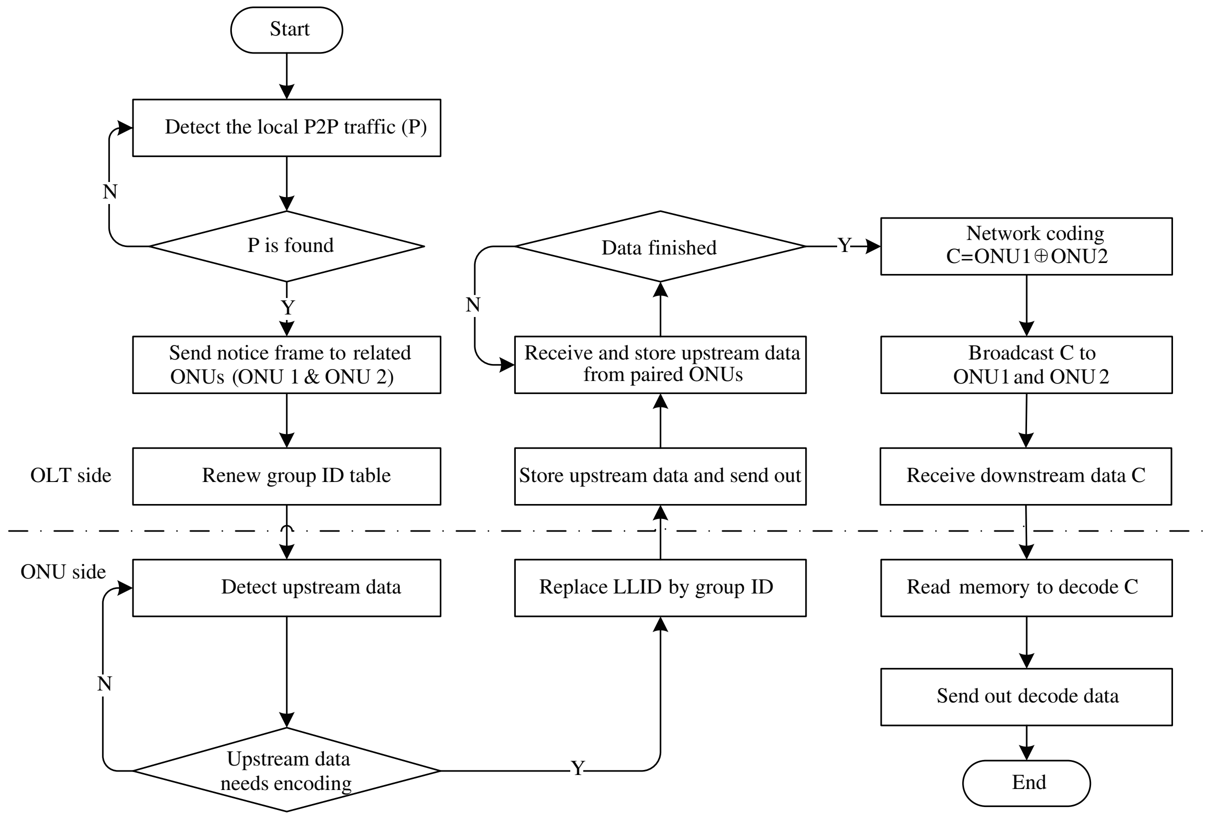

Figure 5 Flowchart of the network coding procedure in PON.

3.2 Data-link-layer flexible coding scheme

Under the operating scenario outlined above, the procedure for the data-link-layer flexible coding scheme is described as follows.

Firstly, we introduce two additional control frames (the Notice frame and the Clear frame) to control the coding procedure. The Notice frame notifies the ONUs with P2P traffic to pair with each other via a multicast, and the Clear frame demolishes the ONUs that have been paired via a broadcast. In order to identify each coding ONU pair, we define the concept of the Group ID, similar to logical link identifier (LLID) [16] defined in the EPON [17], and two ONUs with the same Group ID can participate in the coding procedure.

The procedure for network coding is shown in Figure 5. When P2P traffic is found, the Notice frame with paired information will be multicast by the OLT to the ONUs in order to build networking coding pairs. Then the Group ID Table, which saves correspondence between the Group ID and the MAC address in the ONU, will be updated. When data in upstream traffic is sent to the corresponding paired ONU, the local ONU replaces the LLID in the preamble domain with the corresponding Group ID, which is obtained from the Notice frame. At the same time, the local ONU caches the network coding data. By

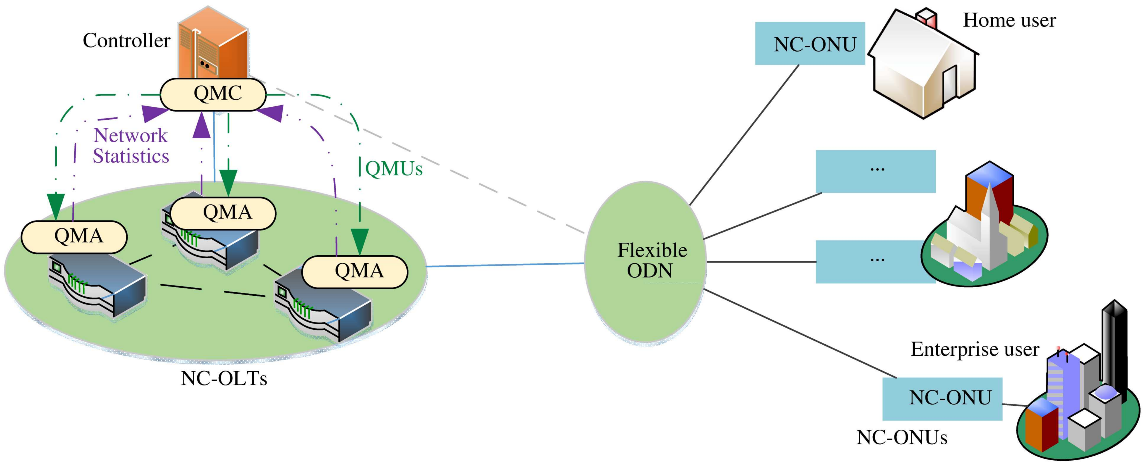

Figure 6 (Color online) Operating scenario of the network-layer centralized AQM selection scheme in the MODE-PON.

using a linear operation, such as bitwise exclusive OR, the OLT encodes the network coding data from both sides of the paired ONUs, and then sends the encoded data to corresponding ONUs. Finally, the ONUs decode the received data using the key extracted from the local cache, and then forward it to the user.

However, due to the limited computing resources, the established pairs will be removed when there is no P2P traffic. We define the maximum generation time ($T_{\max}$) of the Group ID and the cache latency time (T_{wait}) of the network coding data to enhance system robustness. When no P2P traffic between paired ONUs is detected within $T_{\max}$, the OLT will broadcast the Clear frame, which carries the Group ID and is used for clearing the Group ID Table. Then the ONUs will update its Group ID Table and replace the Group ID with LLID. The OLT will transmit the network coding data from the cache if there is no data from another paired ONU in T_{wait}.

The data-link-layer flexible coding scheme combines the advantages of SDN and network coding, which is efficient and flexible. SDN has benefits for resource scheduling and smooth upgrades. Meanwhile, network coding can improve system security by using the network coding data as the encryption key.

4 Network-layer centralized AQM selection in MODE-PON

4.1 Network-layer centralized AQM selection scenario

AQM operates on the network layer and aims to control queuing behavior by detecting incipient congestion and maintaining proper latency and jitter in order to offer satisfactory link utilization [18]. Current research into AQM has limitations because of the lack of a global perspective on the network, and it can only make decisions based on the packet arrival conditions [19]. As mainstream AQM algorithms, the Random Early Detection (RED), Random Exponential Marking (REM), and Proportional-Integral (PI) algorithms have their own specific design goals and advantages [9].

In MODE-PON, the centralized controller can help to relieve these disadvantages of the traditional AQM, as it can gather any desired network statistics (such as flow number information for $P_{\max}$ tuning) for the AQM algorithm, so each AQM instance (i.e., the OLT) can perform suitable adjustments based on the network information it receives. Moreover, if we can choose the most compatible AQM algorithm according to the local network characteristics, the potential of these variant schemes will be fully realized. As MODE-PON is aware of the current condition of underlying network, we can dynamically switch between different AQM algorithms accordingly and the performance of AQM will be further improved.

Figure 6 shows the operating scenario of the centralized AQM architecture in the PON system. It consists of a queue management core (QMC) and some queue management agents (QMA) for each switch. The QMC runs on the centralized controller as an application and collects all network status statistics of the OLTs. The QMA is deployed on the OLTs to receive the instructions and dynamically adjust the AQM behaviors.

Queue management policies (QMP) are used to specify which statistics need to be collected in order to reach the operational goal (e.g., to maximize link utilization or to maintain a low and stable delay), the constraints that need to be satisfied, and how to map centralized AQM updates to changes in individual AQM algorithms. As part of QMPs, the operator can define a set of preconditions that need to be satisfied before any modifications are made to a specific AQM algorithm.

After receiving the network statistics, the controller generates a specific set of adaptations for the AQM algorithms. Next, the controller sends periodic queue management update (QMU) messages to the OLTs that update their adopted AQM variants and even AQM algorithms.

4.2 Theoretical comparison of mainstream AQM algorithms

The generation of a QMP relies on the performance of the stabilized AQM algorithm, and this can be analyzed in terms of many aspects, such as the packet loss rate, queuing delay, response time, and robustness. Because different AQM algorithms have different performances under various network scenarios, they do not have universal adaptability. This is the main reason preventing AQM from being universally deployed. A brief analysis of mainstream AQM algorithms (RED, REM, and PI) is provided below.

The basic idea of RED is using real-time queue length to estimate the average queue length, and use the average queue length to detect network congestion. The congestion control part of RED is a linear piecewise function that is used to determine a mapping from the average queue length to a packet loss probability. When the network congestion is confirmed by RED, the packets will be dropped. However, because of the design limitations of RED, the algorithm's parameters are largely based on manual provisions according to network conditions. A change in network conditions often leads to system instability and slow system response.

The REM algorithm successfully combines the real-time queue length and packet arrival probability as basis for judgment of network congestion, and the source transmission rate can thus be adjusted to achieve global optimization balance. It guarantees stability under different network situations and achieves a substantial improvement in performance compared to RED. However, it can only analyze steady-state performance rather than transient processes.

The PI algorithm also uses the real-time queue length as a basis for judgment of network congestion, and it introduces a lead compensator to speed up the response of the system. Compared to the RED algorithm, the PI algorithm has greatly improved performance, especially in terms of stability. However, the instability of the Transmission Control Protocol (TCP) means that the system is difficult to stabilize at a steady state when a substantial change in the network state occurs. In addition, it influences the scope of application of the algorithm model.

In this subsection, we evaluate the performance of the mainstream AQM algorithms (RED, REM, and PI) under a single-bottleneck link situation in order to provide a theoretical demonstration of the following network-layer centralized AQM selection procedure.

This theoretical derivation is based on the traditional TCP/AQM duality model, and uses the TCP Reno as an end-to-end congestion control algorithm [20]. The congestion metric P of a single-bottleneck network is given as follows [20]:

$$P = f(x_s) = \frac{3}{2x_s^2\bar{D}^2}, \tag{1}$$

where x_s denotes the data rate from the data source s, $\bar{D} = (\sum_s D_s^{-1})^{-1}$ and D_s are the equilibrium round-trip time. After getting the congestion metric P, for the specific AQM algorithm, we can get the queue length.

As shown in Figure 7, we use a single-bottleneck network topology as the simulation topology. The bottleneck link bandwidth is set to 16 Mbps with a 20 ms delay. The FTP flow number is 60, and the length of the queue buffer is set to 800. In order to compare three kinds of AQM algorithms within the

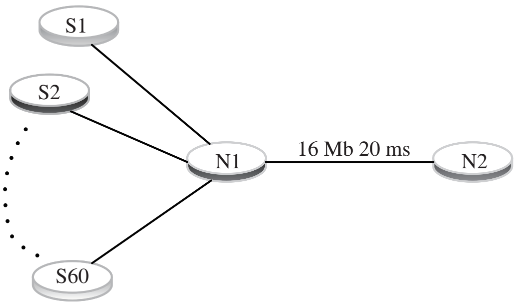

Figure 7 Single bottleneck simulation topology.

Table 1 Parameter settings for the RED, REM, and PI algorithms

AQM algorithm	Parameter settings
RED	$\min_{\rm th} = 175$, $\max_{\rm th} = 225$, $p_{\max} = 0.15$, $w = 0.005$
PI	$q_{\rm ref} = 200$, $a = 0.00001822$, $b = 0.00001816$
REM	$q_{\rm ref} = 200$, $\phi = 1.001$, $\gamma = 0.001$, $\alpha = 1$

same standards, the target queue length is set to 200. The remaining parameters are also limited to a particular range to guarantee comparability, so we choose the parameters shown in Table 1 (which are also typically used by other researchers like Sun et al [21]) from the default value database in NS2 to ensure all three algorithms have approximate the same initial input. In Table 1, $\min_{\rm th}$ is the minimum queue length threshold, $\max_{\rm th}$ is the maximum queue length threshold, $p_{\max}$ is the maximum dropping probability, w is the weight factor of the exponentially weighted moving average, $q_{\rm ref}$ denotes the target queue length, and a, b, ϕ, γ, α are all constants.

Firstly, we estimate the performance of the three AQM algorithms in the following steps:

1) The congestion metric of the single-bottleneck link can be directly computed with Eq. (1), yielding a value of 0.0412 by substituting the network parameters.

2) According to the congestion metric, we can calculate the steady-state queue length of the three algorithms.

For the RED, the relationship between the congestion metric and the queue length is

$$p_l = G(\bar{q}) = \begin{cases} 0, & \bar{q} < \min_{\rm th}, \\ \dfrac{p_{\max}}{\max_{\rm th} - \min_{\rm th}}(\bar{q} - \min_{\rm th}), & \min_{\rm th} < \bar{q} < \max_{\rm th}, \\ 1, & \bar{q} > \max_{\rm th}. \end{cases} \tag{2}$$

The steady-state queue length $\bar{q}$=189.71 packets, when p_l=0.0412. Because of decoupling feature of the congestion metric and queue length in REM and PI algorithm, the queue length has no relationship with the congestion metric, so the queue length is estimated to the target value 200 packets.

3) Using the transfer functions of the three AQM algorithms, we can obtain the phase margin and bandwidth of the closed-loop system.

For RED:

$$P_{\rm RED}(s) = \frac{L_{\rm red}}{s/K+1}, \tag{3}$$

where $L_{\rm red} = \frac{p_{\max}}{\max_{\rm th} - \min_{\rm th}}$, $K = \frac{\ln(1-\alpha)}{\sigma}$, α is the queue averaging weight and σ is the sample time.

For PI:

$$P_{\rm PI}(s) = K_{\rm PI} \times \frac{(s/w_g+1)}{s}, \tag{4}$$

where w_g is the system gain and $K_{\rm PI}$ is the value of the PI gain.

For REM:

$$P_{\rm REM}(s) = bA + \frac{bB}{s}, \tag{5}$$

where $b = \ln\varphi$, $A = \gamma$, $B = \gamma\alpha/T$, and φ, γ, and α are constants and T is the sample time.

Table 2 Estimated results of the RED, REM, and PI algorithms

Performance index	Estimated index	RED	PI	REM
Loss probability	Congestion metric	0.0412	0.0412	0.0412
Queuing delay	Queue length (packets)	189.71	200	200
Response speed	Bandwidth (rad/s)	11.9319	0.0436	0.2728
Robustness	Phase margin (°)	3.4919	92.3713	79.4119

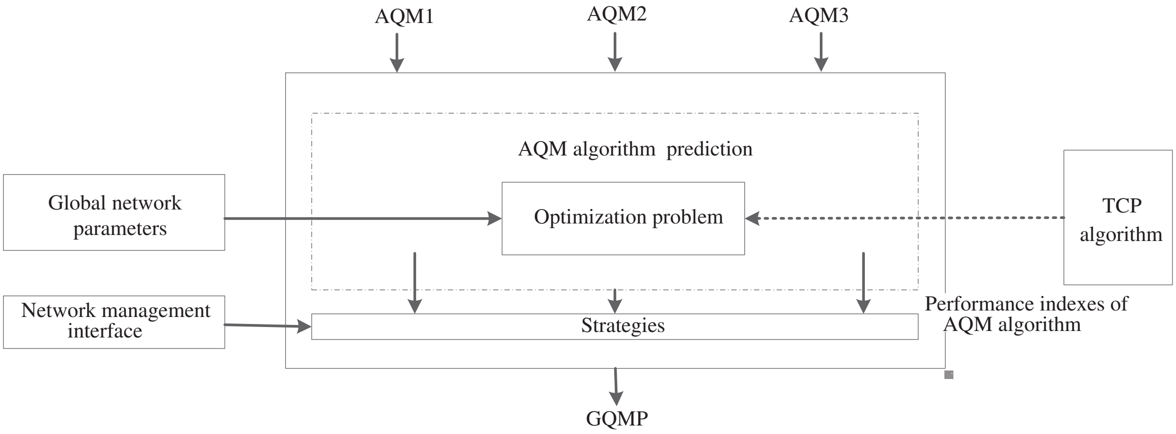

Figure 8 Procedure of the network-layer centralized AQM selection scheme.

For controlled part:

$$G(s) = \frac{K_f \times \mathrm{e}^{-sR}}{(T_1 s + 1)(T_2 s + 1)}, \tag{6}$$

where $K_f = \frac{(RC)^3}{4N^2}$, $T_1 = \frac{R^2 C}{2N}$, $T_2 = R$, R is round-tip time at the operation point, C is link capacity and N is load factor.

Then, we can easily find the phase margin and bandwidth. A summary of the estimated results is shown in Table 2. From the estimated results, we can see that the phase margin of RED is too small, so the queue will experience severe jitter; PI has a larger phase margin, which can stably maintain the queue length, but the response speed is slower than that of REM; finally, the phase margin of REM is better than that of RED, but the bandwidth is smaller. Thus, the switching of different AQM algorithms under different network situations can help to increase the overall optimization results.

4.3 Network-layer centralized AQM selection procedure

Based on the operating scenario described in Subsection 4.1 and the theoretical results in Subsection 4.2, we proposed a network-layer centralized AQM selection scheme in the QMC to estimate the performance of the AQM algorithm under different network statuses, and to select the optimal AQM algorithm to achieve further improvements in performance.

The specific procedure is shown in Figure 8. The solid box represents the process of collecting information, prediction of AQM algorithm performance, and final decision-making in the centralized AQM performance selection scheme. The external information that the controller requires includes the network status (such as topology, bandwidth, number of streams, and round-trip time) and the types of AQM algorithms, which can be obtained from the centralized controller. By using the corresponding utility function, combining the external information mentioned above, we can build an optimization model and obtain the system steady-state indexes, which can be used for the final decision-making.

The utility function relies on the TCP algorithm that is used in the data source. That is, once the TCP algorithm type is defined, the form of the utility function is determined. Therefore, the utility function can be imported into the system offline, and only requires external network parameters in the runtime.

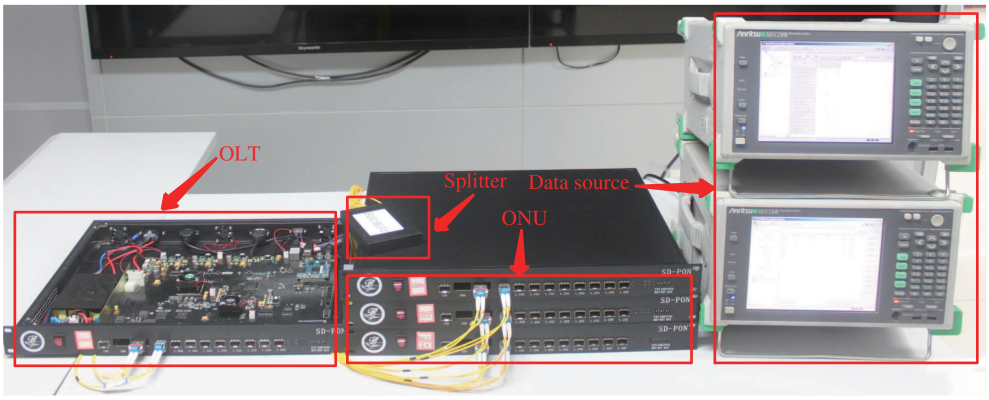

Figure 9 (Color online) The NC-PON experimental environment.

Table 3 Simulated traffic in the NC-PON

Traffic direction	Traffic size (Gbps)
Core network → ONU1	4.5
Core network → ONU2	4.5
ONU2 → ONU1	0.7
ONU1 → ONU2	0.7

5 Platform and simulation

In this section, we verify the dual-layers bandwidth optimization scheme. Firstly, we build an experimental platform based on the 10G EPON system to verify the functions of the data-link-layer coding scheme. Then we construct a simulation of the different mainstream AQM algorithms in a single-bottleneck network with NS2 simulation to validate the theoretical evaluation in Subsection 4.2. Furthermore, we perform dynamic algorithm switching by taking advantage of the mentioned algorithms to verify the network-layer AQM selection scheme. The platform results indicate that the proposed architecture is efficient. In addition, the simulation results show that a major improvement in responsiveness was achieved in our scenario.

5.1 Experimental demonstration of the data-link-layer coding scheme

As shown in Figure 9, we constructed an experimental platform based on 10G EPON. Three NC-ONUs are connected to one network-coding-supported OLT (NC-OLT); the main difference between the NC-ONUs and traditional ONUs is that it can store the coding data temporarily and use it as the key for decoding data. The OLT can also recognize and determine whether upstream data can be coded.

The data from the user side and core network are simulated using a network data analyzer (MD1230B, Anritsu). The P2P traffic transfers between user A under ONU1 and user B under ONU2. At the same time, the data of the core network transfers to users A and B. The traffic flow information is shown in Table 3.

The evaluation results of the experimental platform show that the total downstream bandwidth of the link is up to 10.4 Gbps, which is higher than a typical 10G EPON system and is without packet loss. It shows that the network coding has improved the efficiency of the PON, making the throughput greater than the line-rate.

5.2 Simulation of the network-layer centralized AQM selection scheme

5.2.1 *Performance simulation of the mainstream AQM algorithm*

For each AQM algorithm, using the same initial conditions in Table 1 of Subsection 4.2, we performed a real-time simulation with a duration of 200 s in NS2. Data for the queue length within 100 s are shown in Figure 10.

Table 4 Simulation results of the RED, REM, and PI algorithms

Performance index	Estimated index	RED	PI	REM
Loss probability	Congestion metric	0.0491	0.0389	0.0392
Queuing delay	Queue length (packets)	185.68	200.83	198.12
Robustness	Phase margin (°)	1130.04	433.156	474.002

In Figure 10, we can see the average queue length is around 200 packets for each AQM algorithm. Among them, RED has a constant amplitude, and PI and REM converge to 200 packets with small fluctuations. Taking the value after 40 s as a steady-state value, we obtain the queue lengths of the three algorithms: q_{RED}=185.68 packets, q_{PI}=200.83 packets, q_{REM}=198.12 packets, which conform to the estimates of queue length in the previous section.

The results are summarized in Table 4. Compared with the estimated results in Table 2 in Subsection 4.2, the performance prediction is comparatively accurate.

5.2.2 *Evaluation of the network-layer centralized AQM selection scheme*

The effectiveness of the duality model for predicting the steady-state performance of the AQM algorithm is verified in this last subsection. Based on the estimation values of the RED, PI, and REM algorithms, we simulated the network-layer centralized AQM selection scheme.

In the simulation time interval between 60 s and 100 s, a User Datagram Protocol (UDP) flow with a constant data rate of 8 Mbps is added as a disturbance to the steady-state system. The UDP flow is an unresponsive flow, which means there is no response with the congestion metric, and it will not react to packet loss and marking. Because AQM cannot affect the source transmission rates under the stimulation of an unresponsive flow, it cannot control congestion.

RED is not considered in this subsection, because the analysis of the previous subsection shows that the RED algorithm tends to be unstable. Moreover, the steady-state performance of REM and PI are similar, while PI has a bigger stability threshold, which leads to less jitter. The bandwidth of REM is larger, which leads to a faster convergence to the steady state. Therefore, the simulation in this subsection adopted the following strategies: in the steady state, PI is used, and when interference occurs, REM is used.

Figure 11 shows the dynamic changes in queue length when algorithm is switched in the centralized AQM scheme, with the case using only PI for comparison. From Figure 11, we can see that, from 0 s to 60 s, there is no obvious difference in queue length between the two algorithms. At 60 s, because the interference flow rate increased, the algorithms began to increase packet loss probability in order to maintain the stability of the queue length. From 60 s to 100 s, as a result of switching to the REM algorithm, which has a faster convergence rate, the centralized AQM stabilizes the queue length to the target queue length using just a quarter of the time that PI costs. At 100 s, as a result of interference cancellation, the algorithms begin to reduce the packet loss probability to reduce the congestion metric on the source side, and encourage the source to transmit data. Therefore, the queue length rises gradually. The centralized AQM achieves a faster convergence speed by switching to the REM algorithm.

Overall, because of the centralized AQM performance selection scheme, the queue length of the centralized AQM is relatively stable, so it can guarantee that the delay will be relatively stable too. Therefore, the simulation results have verified that the selection scheme in centralized AQM is helpful for optimizing the performance of network.

6 Conclusion

Aiming to improve the bandwidth efficiency of future passive optical network (PON) system, we introduced network coding and active queue management (AQM) technology into PON system and proposed a multi-optical-line-terminal (OLT)-oriented dual-layer efficient PON (or MODE-PON) architecture. This architecture consists of two separate schemes on a data link layer and a network layer, and they can be

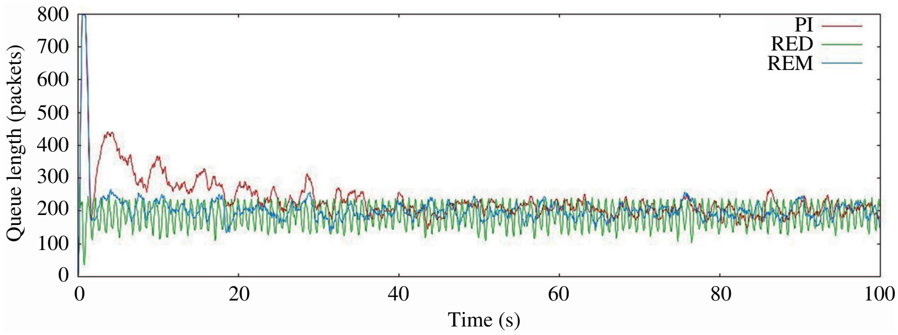

Figure 10 Queue lengths of the RED, REM, and PI algorithms.

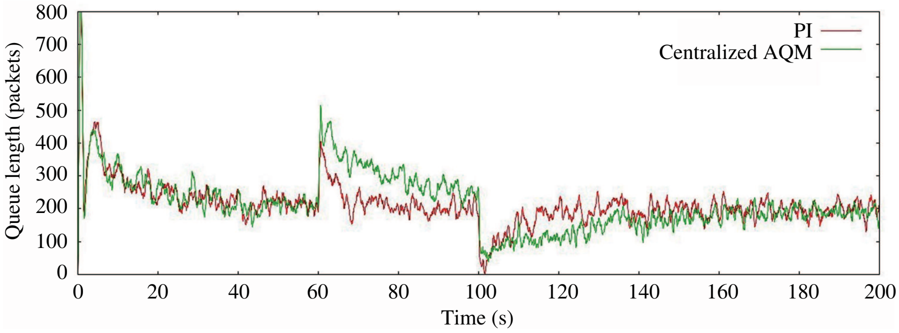

Figure 11 Comparison of queue lengths of PI and PI with centralized AQM.

deployed together on future PON system. One of the schemes is a data-link-layer flexible coding scheme that can compress P2P traffic and supports flexible affiliation between OLTs and optical network units (ONUs) to provide higher bandwidth efficiency. The other scheme is the network-layer centralized AQM performance selection scheme that dynamically updates the parameters and AQM algorithms in order to achieve the potential of various AQM schemes. In summary, these two schemes can enlarge the existing throughput to increase bandwidth efficiency at the data link layer, as well as schedule traffic into the core network to enhance bandwidth efficiency at the network layer. As far as we know, this was the first time that a data link layer mechanism and a network layer policy have been integrated to provide high efficiency and quality of service in access networks.

We carried out experimental demonstrations and simulations to verify effectiveness of the proposed scheme. The results of the experimental platform showed that network coding can improve system efficiency by enlarging the downstream link throughput. The simulation results showed that, by acquiring global network information, the performance of AQM can be improved and that it will also enjoy major improvements in delay and jitter.

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Conflict of interest The authors declare that they have no conflict of interest.

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