Wireless Channel Condition Aware Scheduling Algorithm for Hybrid Optical/Wireless Networks

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Abstract. Recent research activities about hybrid optical wireless networks become attractive. In this paper, we provide an overview on integration of an Ethernet passive optical network (EPON) and a worldwide interoperability for microwave access (WiMAX) network. Gateway node that integrates both optical scheduling and wireless scheduling functions gains most interests. We promote a question: how the scheduler at optical network unit is affected by its wireless connections when ONUs transfer packets to optical line terminal. Scheduling algorithms have been proposed intensively in EPON system. However, the existing scheduling algorithms are only for either pure optical networks or pure wireless networks. Within this paper, we propose to design packet scheduling schemes that take wireless channel condition into account for the hybrid optical wireless networks. Our scheduling scheme is based on a cost function, which considers not only the packet transmission but also the radio link condition.

Keywords: hybrid optical/wireless networks, Ethernet passive optical networks (EPON), WiMAX, resource allocation management, dynamic bandwidth allocation (DBA), cost-function-based scheduling algorithm.

1 Introduction

Recent advances in optical and wireless communications certainly provide ample opportunities of introducing fixed mobile convergence (FMC) network architectures that benefit the broadband access transmission and allow the development of multimedia applications. The wireless access technique has shown rapid growth and future increase as major players of access network. The new-generation broadband wireless access (BWA) technology WiMAX has been, due to its easy deployment and low-cost architecture, considered an economically viable solution to provide last mile access, especially in the hard-to-reach rural area. On the optical domain, EPON has attracted many research attentions for commercial deployment recently. EPON, as a fiber-based access technology, is expected to offer a cheap solution with high bandwidth to the broadband access. The integration of the optical networks and wireless networks offers an attractive and feasible solution to broadband network access.

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Motivations behind the integration are addressed from aspects of low cost of deployment, high bandwidth provision and scalable extension of communication coverage.

- *Cost*: The economic limitation prevents fiber from directly reaching individual customers, especially for those low subscriber density areas and urban areas. In contract, wireless technique with low deployment costs alleviates such difficulty. By replacing fiber with free radio media, the cost of last-mile transmission is reduced in an integrated optical and wireless network.
- *Bandwidth*: Due to the emergence of wavelength division multiplexing (WDM) technologies, the bandwidth of backbone network has increased substantially. In the integrated optical and wireless network, EPON fills in the gap between the subscriber network and the core network. The fiber-based techniques can offer a total 1 Gb/s high bandwidth in both downstream and upstream. If there are 16 WiMAX sub-networks connecting to the EPON system, the shared upstream bandwidth requirement is up to 1.2 Gb/s, which matches the capacity of the fiber transmission.
- *Coverage*: In the integrated optical and wireless network architecture, the high-speed communication is extended by using antenna for wireless distribution. One important good feature in WiMAX technology is its scalability. Without affecting the existing customers, the service provider could install new service areas by adding new base stations as the user demand grows.

The migration requires changes in the media access control (MAC) layer and the network layer that bring services to end-users with compliable users' service level agreement (SLA). A MAC mapping scheme between the optical domain and the wireless domain is necessary to be developed in the gateway node, which is able to translate the communication between two different interfaces. To some extent, the performance of the hybrid network solution relies on the design of the gateway node, which plays an important role in the EPON-WiMAX integration.

Packet scheduling and bandwidth resource allocation are important functions in MAC design. Intensive research of upstream scheduling algorithms for EPON system has been contributed in the literature. In the hybrid optical wireless network, traffic flows arrive at the gateway node from mobile users via wireless upstream links, which are subject to signal attenuation, fading, interference and noise. Thus, these existing algorithms cannot be directly adapted without taking features of wireless links into consideration.

In this paper we first discuss three design issues about the integrated architectures. Then based on the choice of hybrid network architecture, we present a system model with detailed optical upstream scheduler functions. An improved scheduling algorithm for the integrated network is proposed, which jointly considers the packet scheduling and wireless channel conditions.

2 Background and Related Work

Recently, the integration of two greatly developed access technologies, EPON and WiMAX, has gained increasing attention. Some research activities have started to investigate and study system performances and design challenges.

WiMAX is standardized under IEEE 802.16 working group. This technology is designed to provide comparable service to traditional wireline access networks such as xDSL and cable modem networks but with much less installation cost and more rapid deployment. It adopts OFDMA/TDD in multiple access and duplex schemes. WiMAX transmits at a data rate up to 75 Mb/s and with a theoretical coverage radius of 50 km. It can be adopted as the last mile connection to both end-user and business, also a backbone for wireless local area and cellular networks.

EPON has been standardized in the IEEE 802.3ah. A typical EPON system is a tree-based architecture, which consists of one optical line terminal (OLT) functionalized as a central control station, one *1:N* passive optical splitter and multiple (N=16 or 32) optical network users (ONUs). The location of ONU is specified variously, such as inside the home (fiber to the home, FTTH), in the building (FTTB) and at the curb (FTTC). All transmissions in PON are between an OLT and an ONU. The upstream transmission originated from ONUs is in a multipoint-to-point structure, and the downstream transmission originated from an OLT is in a point-to-multipoint structure. Traffic is delivered on two separated wavelengths, typically 1310 nm (for upstream) and 1550 nm (for downstream). A multipoint control protocol (MPCP) is specified in the IEEE 802.3ah standard used as a control and signaling protocol mechanism.

A hybrid wireless-optical broadband-access network (WOBAN) was proposed by *Sarkar et al.* [1]. The integrated architecture is discussed mainly focusing on network setup, network connectivity and fault-tolerant characteristics. Authors also contribute on developing an efficient routing algorithm for the wireless front end of WOBAN [2, 4]. The wireless domain is considered as a multi-hop wireless mesh network. The routing algorithm is designed with minimized delay and reduced packet loss. *Luo et al.* [5, 6] proposed several optical wireless integration scenarios, where the wireless base station is integrated with OLT functions. Authors proposed a centralized admission control in the integrated OLT/BS node, in order to reduce the signaling transmission delay. *Shen et al.* [7] proposed architectures for the integration of EPON and WiMAX. Related control and operation issues are addressed. *Lin et al.* [8] presented an integrated wireless and SONET architecture. An optimal utility based bandwidth allocation scheme is designed for multimedia application. *H. Kim and A. Wolisz*, [9,10] proposed a radio over fiber based network architecture. A centralized MAC layer is designed with discussions on scheduling and resource sharing policy. A dynamic load balancing algorithm is proposed to achieve better resource management in the wireless domain. *K. Ho and J. Mitchell* [11] presented integration between optical networks with IEEE 802.11 wireless local area network (WLAN). The design issues containing PHY layer constraints and MAC layer integration are addressed.

3 Design Issues

In this section we list and look at three significant design issues that affect implementation performances of hybrid optical wireless networks.

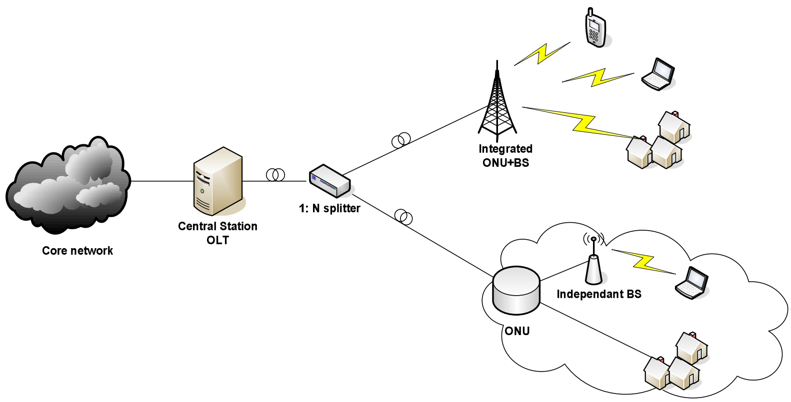

Fig. 1. Independent and hybrid architecture

3.1 Architectures

In the literature, there are several integrated network architectures proposed to the hybrid optical and wireless communication, mainly aimed at augmenting PON system with wireless transmission penetrating to the local area.

- *Independent architectures*: Shown in the lower part of Fig.1, the ONU directly connects the WiMAX base station (BS) via a common standardized interface. There is no direct wireless link between the ONU and the subscribed stations (SS). The main advantage of this architecture is the independent deployment of the two access networks. However, as two domains are separated, communication between ONU and BS, which exchanges information, is unavoidable. Such control signaling messages may suffer a delay and cause traffic overhead.
- *Hybrid architectures*: In the hybrid architecture shown as the upper part of Fig.1, an ONU and a WiMAX BS are integrated in a single device, functionalized as a gateway connecting to both PON and WiMAX access networks. The gateway contains separate buffers for the upstream and downstream traffic. Compared to the independent architecture, this hybrid architecture provides close connection between ONU and BS. Therefore, ONU and BS are aware of the details of network conditions of each other. It enables the integrated bandwidth allocation and packet scheduling scheme to optimize the whole system performance, such as end-to-end service QoS and network throughput.
- *Radio-over-fiber (RoF) architecture:* RoF based wireless access technology has been researched and proposed as a promising alternative to broadband wireless access network. Depicted in Fig.2, the RoF architecture consists of a central head-end and a remote antenna unit connected by an optical fiber link, on which the microwave signals are distributed. The advantages of RoF architecture include its low attenuation loss, immunity to radio frequency interference and reduced power consumption. However, because RoF involves analogue modulation and analogue signal transmission, the signal impairments such as noise and distortion become challenging issues in RoF systems. [7]

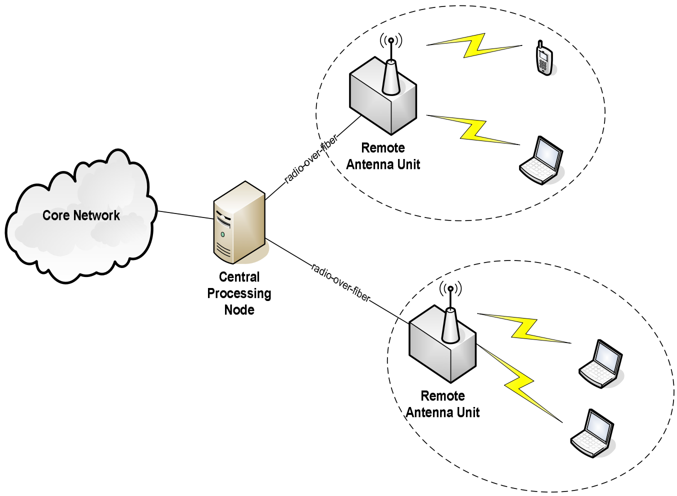

Fig. 2. Radio over fiber architecture

3.2 Topology Management

One major issue is the efficient topology management to minimize network deployment cost without sacrificing the quality of service (QoS) performance for the local and relay connections. In [1] the problem of network setup was solved by finding an optimal deployment of ONUs. Various algorithms are investigated, such as random and deterministic approach, greedy approach, combinational and joint optimization approach.

3.3 Resource Management and QoS Support

In the hybrid optical wireless network, resource management is implemented in centralized architecture, where an intelligent control mechanism in OLT polls and allocates bandwidth to all gateway nodes. There are several methods that can be used to achieve efficient resource management, such as using dynamic bandwidth allocation algorithms and admission control schemes. The resource management functions should be designed with consideration of the end-to-end QoS, such as packet delay, network throughput and so forth. In the hybrid optical wireless network, the resource management is composed of two stages. The first stage is the optical resource allocation among attached gateway nodes in the optical domain. The second one is the radio resource allocation among connected SSs in the wireless domain. Appropriate cooperation and integration of resource allocations in two domains are crucial to investigate in. The node that locates on the common boundary of two domains needs an advanced resource management so as to coordinate the communication between optical and wireless domains.

Current EPON scheduling schemes show favor only to the priority of variant arrival traffic flows. Combined with the hash wireless environment, it is possible that bad channel quality invalidate the theoretical fairness of bandwidth assignment and

QoS support. Thus, it is crucial to import the channel status awareness into the scheduling policy.

4 System Model and Gateway Node Functions

A hybrid optical wireless network with integrated ONU-BS gateway node (GN) is considered. The optical network is configured according to a tree-based EPON structure and a point-to-multipoint (PMP) WiMAX system is deployed in the wireless domain. The service area is partitioned based on the available GNs. For instance, there are N GNs ($GN_{1...N}$) associated with OLT and there are M SSs ($SS_{1...M}$) located in one GN. To ease and simplify our discussion, we assume the coverage of a single WiMAX network is independent and there are no overlaps between two wireless networks.

Concerning resource management, both EPON and PMP WiMAX employ a poll/request/grant mechanism for bandwidth allocation. Differences are that the resource allocation in EPON is per-queue based and in WiMAX is per-connection based.

In the integrated architecture, a central station (i.e. OLT) polls a gateway node. GN responds with requests for bandwidth requests. A grant is permitted by OLT and is sent to GNs with information of the starting time and duration of their upstream transmission. In the upstream direction, multiple GNs share the same optical channel to transmit control and data packets to the OLT. The scheduler mechanism in OLT arbitrates the upstream transmission among the associated GNs without collision.

GN contains two interfaces connecting to both wireless and optical domains. The functions of ONU and BS are both implemented. Thus there are packet schedulers required in both upstream and downstream directions. For GN, the uplink includes transmission from SSs to GN and from GNs to OLT. The downlink transmission is from OLT to GN and from GN to SSs. The scheduling function in a GN can be classified as following:

- *Upstream wireless scheduler*: pools and grants admission among its associated SSs.
- *Upstream optical scheduler*: after receiving assigned bandwidth from OLT, it allocates the aggregated bandwidth to various backlogged traffic queues.
- *Downstream wireless scheduler*: decides the order and capacity of traffic, which are destined to SSs within GN service area.

Our research focuses on the design of the upstream optical scheduler. In the following section, we first give an overview of the upstream optical scheduler in GN. Then, a cost-function based scheduling algorithm with awareness of wireless channel conditions is proposed.

5 Scheduler Design

5.1 Function Overview

The implementation of an upstream optical scheduler in a GN consists of two planes, a data plane and a control plan, shown in Fig.3 The control plane is responsible for call admission control, buffer management, and channel condition monitoring and such functions. The data plane, which is in the path of data flows, focuses on packet classifying, queuing and scheduling, and it is controlled by the components of control plane.

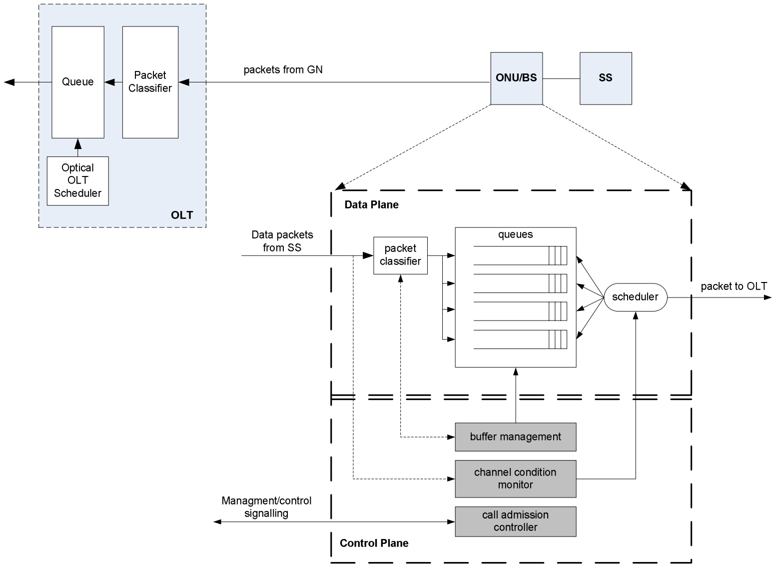

Fig. 3. Resource management functions in hybrid networks

The data plane of the Gateway Node mainly consists of three function modules: packet classifier, queue module and packets scheduler.

- *Packet classifier* is responsible for sorting the incoming packets into different services classes and forwarding them to the corresponding queues. In addition, the packet classifier sends information of the packets to the buffer management module in the control plane and takes the order of dropping or accepting the packets.
- *Queue block* consists of several sub-queues. It is a memory system which is responsible for packet storage and removal. The queue system stores packets according to their service class and creation source. It records the information in a two-dimensioned list and keeps the list up-to-date periodically.
- *Packet scheduler* works as a local server to the packets in the queues, which is discussed in details in next section.

The control plane is basically comprised of three function blocks: buffer management, channel condition monitor and call admission controller.

- *Buffer management* module gathers information from packet classifier and sends commands of dropping or accepting packets to the queue block. Based on the arrival time stamp of each packet, the buffer management module monitors the storage time of each packet. Once the time is longer than the maximum tolerated delay, the packet is supposed to be purged. In addition, the buffer management module should watch the queue size. To avoid increasing the packet delay, buffer manager should begin to reject packet arrivals based on the measurement of queue size or required bandwidth for completing the queuing packets. Thresholds for rejecting and re-accepting packets should be determined so as to eliminate the burst behavior and packet dropping. The threshold can be dynamic according to the statistics of the traffic. However, challenges lie in how the parameter setting of the buffer management module is configured. An appropriate configuration may result in satisfied traffic characteristics.

- *Channel condition monitor* watches the WiMAX wireless channel condition of each user connection. Wireless communication condition can be affected by multi-path fading, inter-channel interference (ICI), and Doppler effects and so on. The data rate of each channel can be examined by the channel condition monitor and the wireless condition can be evaluated. The channel condition monitor reports information of current channel conditions to the packet scheduler based on the results of monitoring. To avoid burst behavior of the channel condition evaluation, the monitor should set up a scanning window that allows a longer period of channel condition tracking instead of using immediate results. Challenges may exist in the response to the changes of channel condition and the efficiency of the reaction.
- *Call admission controller* can be used in resource management. Connection request are examined with its QoS requirements. If the QoS cannot be guaranteed, the connection request will be rejected.

5.2 Problem Statement

In the upstream optical scheduler, traffic flows are received from multiple mobile users (i.e. connections) with diverse QoS requirements and channel quality. In conventional scheduler designed in EPON system, packet and queue information, such as traffic types and queue sizes, are measured to assign priority weights. The limitation of such algorithm is the ignorance of wireless channel quality. Changes of a channel condition could possibly affect the communication, which results in unexpected effects weakening the QoS support. When the quality of a channel drops lower than a threshold value, no traffic can be transmitted. When a connection is detected suffering bad channel condition, the future incoming data rate could be predicted to decrease. Assuming that most of the traffic of a class comes from the “bad” connection, it is viewed as lightly loaded. On the contrary, those traffic classes with “good” connections are viewed as highly loaded.

The basic idea is to increase the throughput of links in good channel condition. In order to avoid that incoming data from “good” connections are dropped due to the queuing overflow, it is reasonable to first serve a highly loaded class, even if the priority is lower than a lightly loaded one. The advantage of channel-condition awared scheduling algorithm compared to priority based one is the QoS assurance of low priority classes with “good” channel condition. That is, the excessive bandwidth of a lightly loaded class is shifted to the highly loaded one to meet the urgent bandwidth demand. However, the disadvantage of such scheduling algorithm is the increase in the delay of high priority traffic class, when it is under a bad channel condition. To overcome this problem, a credit table is used to enforce a minimum delay bound.

5.3 Scheduling Algorithm

As we have stated in previous paragraphs, scheduling algorithms evaluating only traffic class and queue sizes may encounter problems. It is desirable to design a scheduling algorithm reflecting wireless channel condition as well.

Table 1. Scheduling Algorithm: Pseudo-Code for Cost-Function-based Scheduling in GN

```
Initialize: (Invoked when the number of backlogged
packets exceeds the assigned)
 GrantedBW = 0;
 Threshold = SetAppropriate Threshold (AssignedBW);
 SetAllToZero (CF[i, j]);
Loop:
 while (GrantedBW < Threshold)) do
    for (i = 0; i < NumberOfTrafficClasses; i = i +1)
        W[i] = WeightOfTraffic (i);
       for (j = 0; j < NumberOfUserChannels; j = j + 1)
             C[j] = ChannelCondition (j);
               K [i, j] = CreditCondition (i, j);
               CF [i, j] = CF [i, j] + C[j] + K[i, j];
         CF[i, j] = CF[i, j] + W[i];
     SelectedBW = RequiredBW (max(CF[i, j]));
     GrantedBW = GrantedBW + SelectedBW;
 end while
```

We propose a scheduler scheme (shown in Table.1) designed based on the cost function concept, where decisions in complex situations can be evaluated by using a function of relevant features. In our case, channel condition represented by Signal-to-noise ration (SNR) and class priority. The cost function $CF_{i,j}$ is defined in Equation (1), which consists of three phases: weight function, channel function and credit function. [12,13]

$$CF_{i,j}(t) = Func(W_{channel} \cdot C_j, W_{queue} \cdot E_{i,j}, W_{credit} \cdot K_i) \quad (1)$$

where the cost function is calculated for *i-th* class with traffic arrival from *j-th* connection. C_j represents channel conditions consisting of the packet loss (*PL*) and channel interference (I_j). $E_{i,j}$ is the size of granted bandwidth in *i-th* class *j-th* connection queue. K_i represents an additional credit value which is specified in system. Three weight parameters, $W_{channel}$, W_{queue} and W_{credit}, are used to select scheduling settings.

– $W_{channel} = 1$ and $W_{queue} = 0$: scheduling algorithm make decisions based on channel conditions of incoming traffic. The fluctuation in channel quality results in a variation of the data rate, R_k, on a channel k with its PL and I_k. $R_k(t)$ is the current channel rate at time t, $\overline{R_k}$ is the mean channel rate. The factor $C_k(t)=\frac{R_k(t)}{\overline{R_k}}$ represents the mean value of channel quality for channel k. The channel is viewed in good condition when factor $C_k(t)$ is higher than a threshold value. The scheduler distributes bandwidth to queues in an order of starting with the one in the best channel condition.

$$i = \arg\max_k C_k(t), \tag{2}$$

– $W_{channel} = 0$ and $W_{queue} = 1$: scheduling algorithms are applied to grant bandwidth according to queue information, such as queue priority, queue size and so on. One possibility is that the scheduler distributes available bandwidth to queues with backlogged traffic following a weighted proportionally fair rule, from the highest queue to the lowest queue. The granted bandwidth E_i for queue i can be expressed as:

$$E_i = \alpha_i * B_{granted}, \tag{3}$$

where $B_{granted}$ is the total available bandwidth, which is delivered proportionally according to the weight α_i. The value α_i can be specified statically during system initialization. For instance, based on the traffic priorities, weights are assigned to provide different bandwidth for each queue. The bandwidth guaranteed traffic class is assigned with the highest weight value, while the Best Effort traffic is assigned with the lowest value. This static approach is simple, but it may cause the waste of bandwidth if the granted bandwidth for a queue exceeds its actual requirement. Assigning the value of α_i dynamically, bandwidth is allocated to queues to satisfy QoS requirements. The dynamic assignment method updates $\alpha_i(t)$ at time t. The weight parameter reflects the current queue status, which is adjusted in order to improve system performances, such as delay and throughput.

– $W_{channel} = 1$ and $W_{queue} = 1$: This is our proposed scheduling scheme, where both queue condition and channel condition are taken into account. Considering dynamically assigning the proportional parameter α_i, the scheduling decision is made based on the class priority, queue status and its channel condition. First sort all queues in ascending order of their queue priorities. At the same time, the current channel conditions are calculated based on the gathered PHY information. When a queue associated with bad link conditions, the allocated proportion of bandwidth is reduced to meet other queues' requirements.

– W_{credit} =1: Credit value is a system-specific value, which is set to ensure fair distribution of bandwidth among all queues. The credit K_i is initialized as zero associated with flow $m_{i,j}$ when it becomes backlogged in the system. The credit is increased when the flow is not scheduled. The cost function is increased along with the credit parameter. Thus the non-scheduled packets will be eventually served.

6 Simulation Results

In this section, we provide the simulation results based on the proposed scheduling algorithm. Multiple wireless communication channels are simulated under specific traffic characteristic. We define that the traffic is sorted into four classes, A. B, C and D. Class A is assigned the highest priority and Class D the lowest. Four wireless channels are set up to transmit data to the GN.

We implement both strict priority algorithm and the propose cost-function based scheduling algorithm in two GN separately. To ensure the identical input traffic to the GN nodes, traffic is generated from the same source and is forwarded to both nodes.

We assume that the process capacities of both nodes are the same, 5000 bps, and the queue capacities are both set to 1000 bits. Packet length of each traffic class is 100 bits in total. Thus, the queue can only hold 10 packets and this setting causes a great amount of dropping packets. The traffic source starts to generate packets at t = 0.0 and the two servers of GN nodes begins to serve the backlogged packets at t=1.0 s (simulation time). Packet inter-arrival time is exponential distributed with mean equals to 0.01 second. The assigned bandwidth for each class in strict priority algorithm is set to: Class A 35%, Class B 25%, Class C 25%, and Class D 15%. The channel condition of Channel 2 turns bad during 10s to 60s. To examine the algorithm more clearly, we set the traffic as, 80% of the traffic from Channel 1 and 2 belongs to Class B and 20% belongs to Class A; 80% of the traffic from Channel 3 and 4 is Class C and 20% is Class D.

At t = 10s, the channel condition of Channel 2 becomes infected, thus a considerable amount of Class B traffic is reduced, while Class C and D traffic remain unchanged. The cost-function algorithm intends to re-allocate more bandwidth resource to the lower classes with good channel conditions, i.e. Class C and D in this simulation scenario.

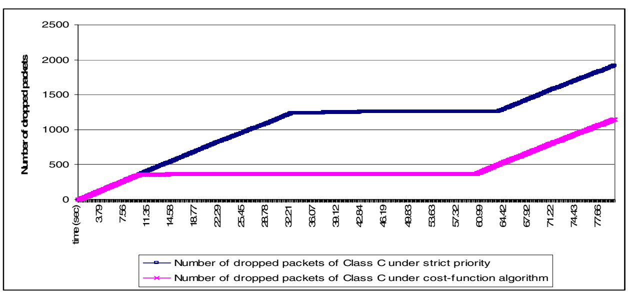

Fig. 4. Number of dropped packets of Class C

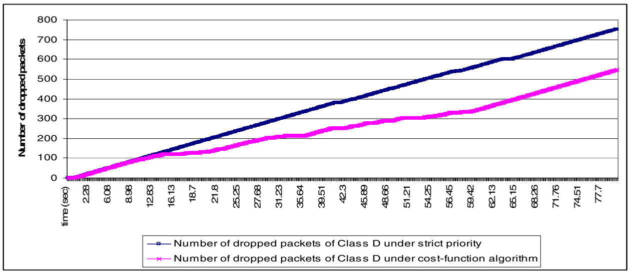

Fig. 5. Number of dropped packets of Class D

Fig.4 and Fig.5 show an increase of accepting packets when the cost-function based algorithm is adopted. Compared to the strict priority, the cost-function based scheduling distributes more fairness among the traffic classes, and the classes with lower priority could utilize more bandwidth. Although the absolute number of dropped packets is very large, it is the relative ratio with total number of transmitted packets that counts. The comparison between two curves shows a trend that more packets are accepted under the cost-function algorithm.

7 Conclusion and Future Work

In this paper, we present an overview of hybrid optical wireless networks. Design issues are addressed in terms of network architecture, topology management and resource management. Efficient use of network resources while supporting QoS for multiple services is significant and challenging. Due to the nature of wireless communication, an integrated scheduler implementation should take the variation of wireless channel condition into account so as to ensure fairness and efficient resource allocation.

We proposed a channel condition aware scheduling algorithm on a cost function basis. The sketchy algorithm is introduced and evaluated by simulation work. The idea of the cost function based scheduling needs more future work on the channel condition measurement and function improvement in order to set up an efficient scheduling system which applies more fairness in the hybrid network.

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