

A Comparative Survey of Scheduling Mechanisms in the Internet

Yaser Miaji *MIEEE*

InternetWork Research Group
UUM College of Arts and Sciences
University Utara Malaysia
06010, UUM Sintok, Malaysia
ymiaji@gmail.com

Suhidi Hassan *SMIEEE*

InternetWork Research Group
UUM College of Arts and Sciences
University Utara Malaysia
06010, UUM Sintok, Malaysia
suhaidi@ieee.org

Abstract— As the Internet is rapidly growing and its popularity increases, users tend to use creative, time-conservative, entertained and economical technologies. Real-time applications such as online gaming, voice and video applications are becoming more popular. Research effort to improve scheduling mechanisms in routers is currently given less attention by network researchers. This trend is far behind in industrial implementation and standards institutions. This paper attempts to compare the development in this subject from academic, standards and industry point of views. The results show that there is an enormous difference between academic research and standards and market domains in term of the evolution of scheduling mechanism.

Keywords: *Sceduling mechanism, Queueing discipline*

I. INTRODUCTION

The pervasiveness of the Internet, and the network applications, particularly in current era, leads to a potential increase in the users' demand for more services with fewer prices. Furthermore, the emergence of new application in daily usage such as videoconferencing and voice conversation, result in a potential necessity for novel mechanism and policy to save this steep improvement in the application itself and users' need. These new applications behave entirely in different manners from the old fashion application such as File Transfer Protocol (FTP) or Telnet and hence require absolute change in the network behavior. Therefore, there should be a substantiation of the current research direction rather just toward the speed and host software, to incorporate the network construction and network core elements. In other words, the contemporary revolution of the Internet application requires much involvement in developing layer 3 elements in particular routers. This paper will contribute in stimulating researchers thinking in enhancing the queuing concepts and mechanisms in the output buffers of the routers by comparing and contrasting some of the existing mechanism in academic research with those which are implemented in industrial routers. The result will demonstrate the significance of the gap between both in different paths as it will be illustrated in the paper.

II. BACKGROUND

Real-time applications such as video and audio differ from other sort of data transmitted over the Internet in term of its QoS requirements. They require bounded end-to-end delay, low delay variation (jitter) and very low data loss. Therefore, the underlying scheduling policy and mechanism that serve such packets should be absolutely different from others that serve other type of data. Additionally, In the presence of congestion this issue is more likely to be increased.

This congestion issue could be controlled using several methods according to its major contribution. Traffic shaping is one approach to achieve the goal of flow management as well as traffic policing. Managing the queue by deciding which packet in the queue to be discarded such as Drop Tail [1] and Weighted Early Random Detect (WERD) [1] is another approach. Congestion management by using scheduling mechanism such as Weighted Fair Queueing (WFQ) [13] and Deficit Round Robin (DRR) [35] is yet another approach. Although there are subtle differences from each approach, most mechanism constructed cooperatively to fulfill the actual aim of congestion management.

So far, there is a significant disruption between the academic achievement, the standards and the actual industry implementation in regard to the scheduling mechanism in routers. This gap mostly results of implementation issues of some scheduler. The primary target of most scheduling policy is to achieve the idealized fair and fast queuing with less complexity and effective hierarchical implementation. Although some researcher such as [3], [7], [8] and [5] claim that their mechanism is close to the ideal generalized process sharing (GPS), which is described as conceptually, the ideal situation of scheduling, in simulation, this objective has not been accomplished yet specially in practical.

WFQ is the most popular in the academic, standards and industrial environment and the only timestamp scheduler which has been approved for standardization by Internet engineering task force (IETF). However, there is a significant debate in the efficiency, effectiveness, protection and fairness of WFQ in the academic sector. DRR is also common to be used in the

industry from companies such as Cisco [17]. Nevertheless, it is highly doubtful that DRR is not the proper mechanism for adequate flow management which supports QoS for real time application due to its weakness in providing proper bonded delay and its limitation with respect to packet size. To sum up, most of the current mechanism which has been used in the market particularly in Cisco routers and approved by standards organization has been developed in late 90's whereas the academic improvement is far advance. There are several novel proposed congestion control concepts which emerged in layer three of the network and proved to be much effective, in simulation, than that are used in the market place. In addition, there are novel methods have been discovered beside the WFQ principle such as the virtual clock time and rate proportional server (RPS) concept, for example, Hierarchical Packet Fair Queueing (HPFQ) [3] and Start Potential Fair Queueing (SPFQ) [26]. However, some conceptual misinterpretation and implementation issues result in unachievable accomplishment of the mechanism in the industry.

III. RESEARCH MOTIVATION

From the previous discussion, it appears that the gap between the academic achievement, the representation of this achievement in the industry and the standardization of this achievement is getting wider as the development of the scheduling mechanism in the academic domain dramatically increases. In addition, this leakage could lead to degradation in the academic improvement. Since the implementation issues in the simulation environment are different from those in the actual routers; there will be a few improvements in the scheduling technique. Therefore, there should be a critical involvement of the industry in the implementation of the new proposed mechanisms to improve the network capability from QoS point of view. Furthermore, the network and Internet institution such as IETF and the Institute of Electrical and Electronics Engineers (IEEE) should consider the new mechanism.

There are two major objectives of this paper. Firstly, it attempts to demonstrate current scheduling mechanism in the academic, standards and the industry domains. This is followed by an identification of the similarities and the differences between the three domains. The first objective will be accomplished by demonstrating the requirement for designing scheduling mechanism which is then followed by a description of the academic, standards and industry position. This description will include the current direction of each of them separately. Moreover, the development in each market will be addressed. The next stage is to compare and contrast the achievements of all the sectors in term of some criteria which will be defined later. Finally, the gap will be identified.

Since there are many firms which manufacture routers in the industry, this paper will use the routers which developed by one major company in the market namely, Cisco. Also, in the academic perspective, there are many proposed mechanism which could not be possibly covered in this paper. Hence, the paper will present the most supposed as critical mechanism

such as HPFQ [3], SRR [8] and W2FQ [5]. The comparison and contrast will include the following aspects; flexibility, protection, fairness, complexity, delays bounding and implementation issues.

IV. PROPERTIES OF SCHEDULER TO ENHANCE QOS FOR REAL TIME APPLICATION

The designer of scheduler should consider some properties before the establishment of his design. Those properties could be summarized in fairness, flexibility, protection, bounded delay and low complexity. The most important element of scheduling in routers is the fairness. The definition of fairness in the router is still ambiguous. However, there is a relatively reliable definition by Demers [13] which is referred to as Max-Min fairness definition. In this article, the fairness is defined as the maximization of the allocation for the most poorly treated session (maximize the minimum).

The second property is the flexibility which regularly refers to the ability of the scheduler to accommodate the diversity of the packet either in size or in behavior. For instance, voice packet requires strict end-to-end delay, packet loss and delay variation (jitter), and in contrast hypertext transfer protocol (HTTP) is tolerant to packet loss and end-to-end delay. Furthermore, there is a subtle difference in packet size between the voice and the video packets.

Thirdly, the scheduler should provide a protection for well-behaved source against the malicious and greedy host [ref possibly Kurose textbook]. Resource allocation mechanisms do not, so far, provide full protection from the occupation of the bandwidth from the misbehaved users who consume most of the network resources. This issue is still far behind in its solution in scheduling area.

The next property is bounded delay. Delay bounding is one important factor which affects the QoS for real time application. There are two delays that should be bounded; the end-to-end delay and the delay variation (jitter). The employment of some underling traffic condition (policing and shaping) could slightly improve the task. However, it is the scheduler responsibility to insure the reduction of the delay particularly for real time application.

The last property is simplicity of the scheduler implementation. This property is far to be achieved particularly in practical environment. As will be described later, there are many mechanisms claimed to be less complex but they could not provide a proper implementation. It is worth mentioned that there are some implementation issues which prevent the scheduler from being implemented practically.

V. SCHEDULING DISCIPLINE IN ACADEMIC DOMAIN

A. *Timestamp scheduler*

First Come First Serve (FCFS) which provide no fairness and distinction between the packets in the transmission process is the conventional mechanism in all routers. Therefore, it will not provide any sustainability for real time application. Internet is a resource sharing environment which

involves contentions. Scheduling is one obvious solution for solving this contention by fair distribution of the bandwidth and providing performance guarantees. There are two primary functions for the scheduling; deciding the service order and managing queue of service request. Consequently, after the recognition of congestion control problem by Negle [30], the research community initiated a comprehensive study of the issue to manipulate the problem specifically with the increase use of the network in the public.

The existence of Weighted Fair Queueing (WFQ) [13] causes a perceivable achievement in the scheduling field. However, its fairness and bounded delay which depend on underlying bucket share policy, does not overcome the complexity issue. The fundamental aim of WFQ is to approximate GPS [37], which has the assumption of finite packet size. GPS is optimal method for traffic sharing but unrealistic due to its adoption of the concept of infinitesimal [5]. The emulation of WFQ is complex and handles the diversity of packet size but it still fall short from GPS. WFQ does not provide full protection to the well-behaved users since its fundamental is the source-destination flow [4]. Malicious sources could simply initiate several sessions to several source which allow them to consume much more from network resources and hence cause higher delay to others. In addition, with the presence of Max-min notion the misbehaved users could establish session with minimum to be served first according to this notion. So, once the ability to protect network users is broken the rest will so.

L. Zhang [39] demonstrates a new discipline which is called virtual clock (VC). The concept of this mechanism is to emulate the time division multiplexing (TDM) by allocating a virtual transmission time for each packet. VC failed to achieve a distinguish mechanism to replace WFQ. However, its insufficient ability to provide fairness, which considered as a primary condition for designing a scheduler, led to its supersession.

Self Clocked Fair Queueing (SCFQ) [19] shares some similarities with WFQ. It is believed that its first conceptual proposition was by Davin [12]. The principle of SCFQ that every packet is tagged prior of its involvement in the queue and the packet served as its tag increase. Despite the fact that it is simpler than WFQ, it has the sacrifice of the fairness and less end-to-end bounding delay as the number of session grows which makes it less concurrent. Consequently, Minimum Delay Self Clocked Fair Queueing (MD-SCFQ) is proposed by Ciulli [9], [10] to overcome the SCFQ bounding delay problem. Since MD-SCFQ uses virtual finishing time of the packet as the system virtual time, the complexity of calculating system virtual time is $O(1)$ [10]. Likewise, its fairness is optimal beside its bounded delay which is reliable. Nevertheless, the recalibration of the system virtual time which passed on weighted average virtual start time of all backlogged session introduces additional computation which results in more complexity.

There are two disciplines which cognitively correlated to Earliest Deadline First Scheduling (EDF); Delay Earliest-Due-Date (Delay-EDD) and Jitter Earliest-Due-Date (Jitter-EDD). However, there is a subtle difference EDF, Delay-EDD and Jitter-EDD. EDF does not provide protection to the host from misbehavior host. Delay-EDD, which is proposed by Ferrari [15] and [16] attempts to overcome this issue by assigning a rate to each flow and compute a deadline based on packet arrival time and allocate separate rate and delay. However, its lack of providing proper bounding for delay variation (jitter), results in its failure to enhance the QoS for real time application. Jitter-EDD, which proposed by Verma [38] achieves a satisfactory level of bounding delay variation and requires less buffer size. Basically, it maintains a head time which stored in the packet header and different from deadline and arriving time. This packet head time delays the packet to allow reconstruction and hence avoidance of jitter. Nevertheless, it utilizes the concept of non-conserving scheduler which is not preferred in term of providing QoS for real time application.

Worst Case Fair Weighted Fair Queueing (WF^2Q) is proposed by Bennett [5]. WF^2Q approximate GPS with high probability and difference of no more one packet. In a WF^2Q system, when the server chooses the next packet at time t , it chooses only from the packets that have started receiving service in the corresponding GPS at t , and chooses the packet among them that would complete service first in the corresponding GPS. Nevertheless, the time complexity of implementing WF^2Q is high because it based on a virtual time function which is defined with respect to the corresponding GPS system. This leads to considerable computational complexity due to the need for simulating events in the GPS system.

Consequently, Bennett and Zhang [3] introduced Hierarchical Packet Fair Queueing (HPFQ) which is also called enhanced WF^2Q (WF^2Q+). Their approach is similar to WF^2Q with simpler implementation. In WF^2Q+ , each flow is associated with a *weight*, such that the sum of the weights of all flows is no larger than a predefined value W . A flow's weight specifies how much share of the capacity of the output link a flow is entitled to receive. Note that if W is equal to the capacity of the link, then the weights are actual bandwidth given to each flow. By keeping track of eligible times and finishing times of flows, the packets could be scheduled according to WF^2Q+ . Ciulli and Giordano [9]_[10] simulate WF^2Q+ and compare its performance with SPFQ, which will be described later. In spite of the fairness and less complexity of HPFQ, there is an issue regarding the distribution of the bandwidth in the presence of hierarchical complex network. Moreover, the model has lack of ability to serve the multimedia traffics due to less-consideration of the diversity requirement of the multimedia traffic. It also has the inability to accommodate the dynamic flow set and insulating the similar traffic.

Since there are several issues associated with the implementation of HPFQ [3], Ju [29] introduced new method

which augments the mechanism and called novel HPFQ. The principle of the proposition is to divide the scheduling task in to four server; hard-QoS server scheduling, soft-QoS server scheduling, best-effort server scheduling and co-scheduling among the previous mentioned three servers. The rest of the algorithm is typical to the HPFQ. With this sort of division of tasks, it will involve practical complexity.

Also, Lee et al. [28] presents a new scheduling mechanism which adopts the virtual clock principle and called worst-case fair weighted fair queueing with maximum rate control ($WF^2Q\text{-M}$). $WF^2Q\text{-M}$ claimed to be consisted of packet shaping and scheduler which enforce the maximum rate constraints with low packet loss. However, the most obvious drawback of such algorithm is potential increase in the complexity which results of the combination of both scheduler and shaper.

Start Time Fair Queueing (SFQ) ([20], [22]) applies different method with different computational method as well for starting and finishing time for a packet. SFQ has finish number and start number. Start number of a packet arriving into inactive connection is the current round number otherwise it is the finish number of the previous packet. Additionally, round number is set to start number of the current packet. Hence, packets are scheduled in the increasing order of start number. SFQ is effective in variable bit rate (VBR) applications such as the video application. Its computation method is less complex compare to WFQ and WF^2Q . Nevertheless, packet sorting complexity is an implementation issue which prevents the utilization of SFQ in real routers. Furthermore, the end-to-end delay grows proportionally with the number of session [21].

New Start Potential Fair Queueing (NSPFQ) is proposed in [26] and proposed as Mean Starting Potential Fair Queueing in (MSPFQ) in [27] as an enhancement for SPFQ which is proposed in [26]. There a slight discrepancy between both algorithms. NSPFQ recalibrates the system virtual time using the maximum timestamp increment (MTI), which defines as a constant value that determine at the system setup and mathematically as the result of the division of maximum packet length and a rate, while it uses the system virtual time for a newly arrived packet as the last calibrated system virtual time added by the elapsed real time between two calibration events. Nevertheless, since the NSPFQ is actually a Rate Proportional Server (RPS), it still has the system complexity of $O \log(n)$ [26].

A new method of scheduling has proposed by Shi and Sethu [34] which called Greedy Fair Queueing (GrFQ). The concept of GrFQ is to seek of the minimization of the maximum difference in the normalized service received by any two flows when the next packet transmission completes. Obviously, this principle has been inspired by SWFQ discipline. The author uses the Relative Fairness Bound (RFB) to prove the fairness of the algorithm. In addition, according to the simulation result, the discipline bounding delay is

approximately similar to WFQ. However, its complexity is $O(\log N)$ [34] with respect to the flow which is still high.

This section has presented several scheduling discipline which proposed to overcome multiple issues associated with the implementation, fairness, delay, packet loss and complexity of a scheduling mechanism. Next section will demonstrate the innovation in the Round Robin based (RR) schedulers.

B. Round robin scheduler

In the previous section the most critical timestamp schedulers have been presented since the early beginning of the discovery of congestion issue. This section will present Round Robin (RR) schedulers.

To start this discussion regarding RR scheduler [24] it worth mentions the simple concept of RR in general. RR scheduler is similar to first-in-first-out (FIFO) with subtle differences by adding a preemption concept which basically means that each packet gets a small fraction of time. If this time which called time quantum is elapsed, the packet, if it has not been completely transmitted, preempted and added to the end of a queue. By this simple implementation all the properties of a scheduler will not been met. Therefore, this concept, is in the case of FQ, need to be modified in order to be met with the conditions of designing a scheduler.

Weighted round robin (WRR) [25] is an alternative for RR with an approximation of GPS. WRR implementation is simply fulfilled by assigning a weight for each connection which called a slot. In each slot the maximum size of the packet required to be transmitted. Indeed, its approximation is quite discrepant with GPS and required equal packet size. However, it could be fairly accomplished if the mean packet size is close to GPS, which is unachievable. Another weakness of this mechanism, that its fairness is highly influenced by larger connection and smaller weights. These weaknesses promote the discovery of deficit round robin (DRR).

DRR which is proposed by [35] is an attempt to remedy the fixed packets size of WRR. DRR is much less complex than WFQ and it could be implemented by specifying a quantum of bit to be served. If the Head Of Line HOL packets consist of less or equal to the quantum plus the credit it will be directly sent and save the excess otherwise save entire quantum and reset the counter. However, in term of providing fairness particularly for real time application, DRR does not provide QoS [2]. Also, there is no guarantee for protecting any host from malicious users. Furthermore, it introduces waste of bandwidth even with its simplicity. Therefore, it is not the adequate discipline for QoS support.

Smoothed Round Robin (SRR) [8] has proposed to address the issues of fairness and burstiness which is coped with the implementation of DRR. SRR composes of a set of matrix. The columns of each matrix represent the flow service time a cross entire round, whereas each row corresponds to one traffic flow. Therefore, each flow is a weight factor. The operation SRR is as follow; each weight spread sequence

(WSS) (the column) will be scanned from left-to-right then the traffic will be sequentially served from flows in matching column and then move to the next entry of WSS and so. SRR provides fairness and protection similar to WFQ but its end-to-end delay bound is less.

C. Novel approaches

Since timestamp and RR scheduler failed to provide one crucial element of the scheduler which is the protection property, scholars differ their attention to accomplish the scheduling mission by using different methods and looking at the issue from different angle.

Eriksson et al. [14] presents novel method to accomplish the scheduling and QoS tasks. The main target of justice proposal is to provide protection against malicious users as well as fairness and bounding delays. The new discipline utilized the different concept by correlate each source with the bandwidth allocation rather than source-destination. However, this new concept has not been compared with others even in simulation environment which make it less approved.

VI. SCHEDULING DISCIPLINE IN STANDARDS DOMAIN

There are many institutions are correlated to the standardization of the Internet and network. Those organizations could be summarized in Figure 1.

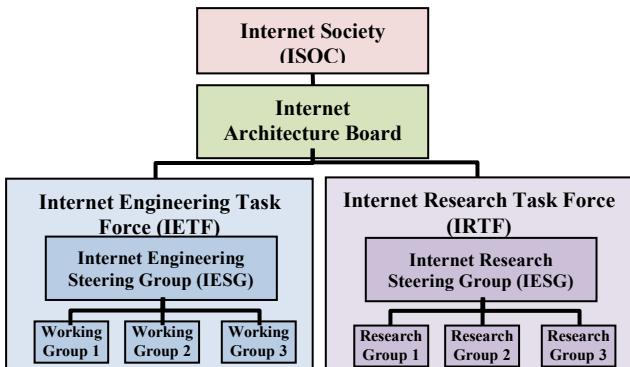


Fig.1: Internet Standards Organization

As it has been observed from the previous section that there are several scheduling discipline have been proposed in the academic domain, so, what is the case in the standards domain.

First scheduler standardized is FQ in 1948 in RFC896. This scheduler was quite simple and did not fulfill any of the scheduler properties. However, it was just the suitable discipline as that time with the absence of any other scheduler. They second scheduler is WFQ. There are several factors that lead to the success of WFQ in its standardization. Firstly, the article which presents the discipline has successfully simulated and illustrated the mechanism. Another obvious cause is the demand for such congestion control mechanism in router which replaces the conventional FIFO. The third factor is the implementation solution of the discipline in the actual router which presented in [32]. The practical implementation eventually has been accepted in IETF standard by publishing

RFC2212. In this RFC, the networking group has thoroughly illustrated the implementation of WFQ.

WF2Q has been approved in RFC3247. It has been mentioned in this RFC that WF2Q has low latency which make it possible solution for scheduling in routers. WF2Q has been proposed for practical implementation in [36]_[9] and [10]. Similarly, DRR has been cited in the same RFC. Additionally, WRR has been supported by RFC 2598. This RFC has a comprehensive explanation of the benefit and drawbacks of utilizing WRR and priority queuing (PQ) in routers.

One last worth mention document which has been presented in IETF is flow rate fairness [6]. The Transport Area Working Group of the IEEE has introduced a novel principle to achieve the fairness in designing a scheduler. This method is quite different from previous. The Internet-Draft claims that the Internet community has been misled to the misinterpreted solution for the fairness issue [6]. They introduce the cost fairness instead of flow rate fairness. Their very basic concept is to distribute the cost of the congestion rather than the allocation of the bandwidth. Therefore, this approach should be taken in consideration by all communities.

To sum up this section, there are a few scheduling discipline that have been approved or cited in the standards domain which could be summarized in WFQ, WF2Q, DRR, WRR, and PQ as well as FIFO. The most obvious purpose of the approval of DRR and WRR is the simplicity and for WFQ and WF2Q is the comprehensive coverage of the implementation.

VII. SCHEDULING DISCIPLINE IN MARKET DOMAIN

This section will demonstrate the most utilized scheduling discipline in Cisco routers, and it will not cover all of them since there are several and multiple groups of routers under the manufacturing of Cisco.

Core Cisco routers such as Cisco 12000 [1] series uses modified DRR (MDRR). The implementation of such scheduler has been explored in [29]. The potential difference between MDRR and conventional DRR is the addition of priority queuing. The concept of MDRR is to serve a queue and de-queue some of the packet. Then the next queue will be served in round robin fashion. When the first queue served again it will be provided with extra service to compensate the dequeued packet.

Catalyst 4000 and G-L3 [17] family of switches utilize strict priority queuing and WRR. The idea of strict priority queuing is to serve the high priority queue first and the lowest later. WRR is commenced by enabling the administrator to assign a weight for each queue. Then if the queue has higher weight it permits to transmit more packets to the network.

Catalyst 6500 MSFC [17] family group occupies the WFQ with two categories. The first category is the CBWFQ which allow the user to assign a weight for the preferred class. The serves which been offered to a specific class is primarily depend on the weight of this class. By comparison low latency

queuing (LLQ) is a CBWFQ with single PQ, which receives strict priority queuing.

In summary, there are few scheduling algorithm which have been deployed in the market domain particularly in Cisco routers.

VIII. COMPARISON BETWEEN ACADEMIC, STANDARD AND MARKET DOMAINS

From the above sections it could be obviously distinguished that there is a magnificent gap between the academic domain in a side and standard and market domain in another. It seems that scholars' perceivable achievements mismatch with the standards and practical accomplishments. In the standards domain, the latest scheduler which has been approved was published in late 90's. The market domain generally uses the same scheduler which introduced in the same period except for MDRR which discovered later. In the standard domain the appearance of the informational draft [6] could be one progress toward changing the scheduling and accomplish one important property of the scheduler which is the protection. Nevertheless, the rest of the scheduler are insufficiently neither address nor improve the scheduler, despite the fact that there is improvement in the academic sector. By comparison, the market domain incorporates MDRR which support QoS regardless of scheduler proprieties and provide no enhancement for solving the leakage in other properties. As a result, there is a huge between all sectors and it seems that all not cooperate in solving the issue of scheduling which if could be covered the significance will be distinguished.

IX. CONCLUSION

This paper has demonstrated the gap between the academic, standards and market domain in the area of scheduling discipline for supporting QoS for real time applications. The results show that there is an enormous difference between the evolution in academic research and standards and market domains in term of the evolution of scheduling mechanisms. Therefore, there should be a sacrifice from both standard and market domain in adopting some novel mechanisms to keep the area evolves and then stabilizes.

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