Performance Modeling and Analysis for Dynamic Bandwidth Distribution Scheme Using Real-Time Probabilistic System

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ABSTRACT

The passive optical network (PON), with its inherent point to multi-point structure, allows for centralized placement of active equipment and possible extension of its boundary towards core networks. This property of the PON can be exploited for node consolidation where multiple central offices are replaced by a single one covering a larger service area. Such node consolidation is being particularly driven by the need for network operational cost saving, and is offering significant challenges to PONs. The degree of node consolidation that can be achieved is limited by the reach of conventional PON systems. In order to achieve a larger degree of node consolidation, an extension of the PON reach, beyond the conventional 20 km, is required. This article addresses the challenges of the dynamic bandwidth allocation (DBA), where increased reach results in a degradation of DBA performance and quality of service support. We use Real Time Probabilistic Systems to evaluate a typical PON systems performance. The approach is more convenient, flexible, and lower cost than the former simulation method which needs develop special hardware and software tools. Moreover, we can easily analysis how changes in performance depend on changes in a particular modes by supplying ranges for parameter values. We compare the proposed algorithm with traditional DBA, and show its advantage on average packet delay. We then analyze and optimize key parameters of the algorithm, such as initiating and tuning multiple threads, inter-thread scheduling, and fairness among users. Numerical results demonstrate the algorithms advantage to decrease the average packet delay and improve network throughput under varying offered loads.

***Keywords* -** Passive optical network; dynamic bandwidth allocation ; Real Time Probabilistic Systems; performance analysis.

I. INTRODUCTION

We target the performance analysis of systems whose behaviour incorporates both probabilistic and real-time aspects, and which include the manipulation of (potentially infinite) data variables. We analyse systems modeled as Real Time Probabilistic Systems (RTPS), whose semantics are defined as infinite-state Markov decision processes (MDPs) [1]. We introduce a formal abstraction procedure for computing minimum and maximum reachability probabilities in RTPS. This provides outer bounds on reachability probabilities (i.e., a lower bound on the minimum probability or an upper bound on the maximum). In addition, we compute dual, inner bounds, based on a stepwise concretization of adversaries of this abstract MDP, yielding upper and lower bounds on minimum and maximum probabilities, respectively. Concretization is also used for untimed models. The key difference in our work is that we aim to keep the abstraction small by using local refinement and simplification operations, so as to reduce the need for expensive operations such as Craig interpolation.

We implement our formal abstraction approach, deploy it on various large case studies, and compare to the probabilistic verification tool PRISM [2], illustrating improved performance in many cases. We are also able to verify Real Time Probabilistic Systems containing both real-time behaviour and infinite data variables, which this tool can be handle

To bring the high bandwidth of high-capacity communication systems (e.g., optical fiber) closer to the remote end users with affordable costs, the long-reach passive optical network (PON) was introduced and studied over the past few years. The development of LR-PON coincides with the momentum in the integration of metro and access networks, as well as the integration of wireline and wireless networks. It simplifies the hierarchical architecture of the telecommunication network and can significantly reduce both capital expenditure (CapEx) and operational expenditure (OpEx) by lowering the total number of active sites such as points of presence (PoPs) and local exchanges (LXs).

A typical PON consists of three parts: the optical line terminal (OLT) at the telecom central office (CO), optical network units (ONUs) located at end users premises, and remote nodes (RNs) in between, as shown in Figure 1. To provide high bandwidth to a large number of users in an LR-BAN, a hybrid architecture should be deployed, exploiting both time-division multiplexing (TDM), where a single wavelength channel is shared among multiple users and wavelength-division multiplexing (WDM), which supports multiple wavelengths to increase capacity.

However, the relatively small span and inflexible topology of traditional PONs restrict an

Broadband Access Networks from reaching remote users. Research was thus done to extend the coverage of PONs in both directions. In the network direction, the long-reach PON (LR-PON) [3] it is no longer a passive structure has been proposed to extend the coverage from 20 to 100 km by exploiting advanced technologies such as reflective semiconductor optical amplifiers (R-SOAs) and burst-mode receivers. Instead of copying the traditional ``tree-and-branch" topology in PONs, researchers are also investigating a ``ring-and-spur" topology for LR-PONs \cite{Song1}, as shown in Figure 2, where a PON segment consists of the OLT and a set of ONUs operating on a wavelength set □ ; each PON segment exhibits a logical tree topology; several such PON segments coexist; and the OLT and ONUs are connected through a fiber ring, and RNs are deployed on the ring. Although the introduction of additional RNs increases the overall complexity of the network, an advantage of this design is that it can reuse the metro synchronous optical network / digital hierarchy (SONET/SDH) ring networks with fiber already deployed by substituting the RN equipment and thus achieve great savings in CapEx. This ring-and-spur topology can not only cover a larger area than the traditional tree topology, but also provide the broadband access networks two-dimensional coverage for failure protection, which is very important today as strict quality of service (QoS) may be specified in a user's service level agreement (SLA).

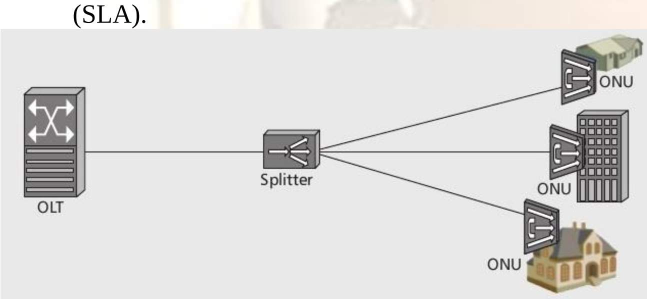

Figure 1. PON Architecture

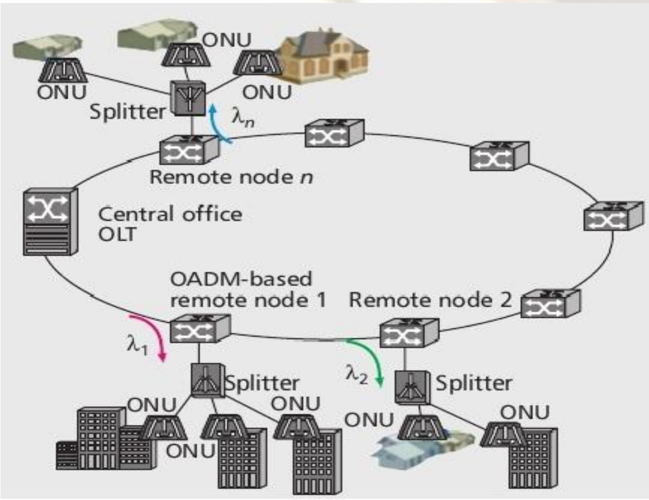

Figure 2. Ring and Spur LR-PON

Time-division multiple access (TDMA) has been adopted in both PON standards, Ethernet PON (EPON) and Gigabit PON (GPON), to share the optical capacity among subscribers by assigning different timeslots for each user. Centralized dynamic bandwidth allocation (DBA), in which the OLT at the CO arbitrates time-division access to the shared upstream channel. The performance of centralized allocation depends on the round-trip time (RTT) since it imposes a delay on the OLT-ONUs bandwidth allocation control loop. This delay is not as significant in traditional PONs as it is in LR-PONs, where the reach extension may cause the RTT to grow from today's 200 \ma \mu \am s (20 km reach) to 1 ms (100 km reach). With this increase, the performance of centralized DBA is ultimately degraded.

In this paper we review and analyze multi-thread polling and inter-thread scheduling, which is a recently proposed bandwidth allocation algorithm for LR-PONs, and compare it with traditional interleaved polling. Unexpectedly, we find that the overall packet delay performance of the latter is better than the recently proposed multi-thread polling scheme. Our investigation highlights how multi-thread polling looks compelling for LR-PONs compared to single-thread polling only when the latter is assumed to be scheduled offline. This is because offline scheduling using a single thread leaves a long idle period that the multi-thread scheme utilizes by creating additional threads. However, while traditional inter-thread polling is a single-thread scheme, it exploits online scheduling with extremely small idle times. One of the key results of this paper is the demonstration that inter-thread polling with online scheduling better reduces the overall packet delay in addition to better utilizing the upstream channel. In the paper, we also point out some inaccuracies in the multi-thread algorithm, and suggest some modifications.

The rest of the paper is organized as follows. In Section II we give a brief introduction to Real Time Probabilistic Systems. Next, we review PRISM Probabilistic Model Checker in Section III, explaining how its performance analysis is highly affected by extending the network span. In Section IV, we review multi-thread polling and discuss the different aspects of its algorithm, highlighting its major differences from enhanced inter-thread scheduling.

II. REAL TIME PROBABILISTIC SYSTEMS

In this section we review the definition of real time probabilistic system, a modelling framework for real-time systems exhibiting both nondeterministic and stochastic behaviour. The formalism is derived by extending classical timed automata with discrete probability distributions over edges. First, we introduce standard notation for clocks and zones of timed automata, and then we proceed to the definition of probabilistic timed automata [4-6]. Syntax and Semantics of Real Time Probabilistic Systems

We now present the formal syntax of Real Time Probabilistic Systems.

Timed Action

A timed action is a tuple $< \alpha, \lambda, T >$ consisting of the type of the action α , the rate of the action λ and temporal constraint of the action T . The type denotes the kind of action, such as transmission of data packets, while the rate indicates the speed at which the action occurs from the view of an external observer. The rates are used to denote the random variables specifying the duration of the actions. The actions can be defined in different types of probability distribution function such as Exponential, Poisson, Constant, Geometric and Uniform distribution. Moreover, each transition is also bounded by a temporal constraint. In this section, some basic notations and operation semantics about Real Time Probabilistic Systems are briefly introduced. The syntax of Real Time Probabilistic Systems is defined in the following:

$P ::= stop \mid < \alpha, \lambda, T > . P \mid P + Q \mid P \oplus_{r,T} Q \mid P \triangleright\triangleleft_{L,T} Q \mid P\ \nabla\Delta_{P,T}\ Q \mid P/L \mid A$

The conventional stochastic process algebra operators and the additional operations are described in the following:

- stop is an inactive process.
- $< \alpha, \lambda, T > . P$, which stands for a prefix operator, where the type of the action is a probability distribution function (pdf) type α , with the activity rate denoted by λ , and the temporal constraint of component is T . It subsequently behaves as P. Sequences of actions can be combined to build up a time constraint for an action. The time constraint T is defined as above.
- P + Q is choice combinatory capturing the possibility of competition or selection between different possible activities. It represents a system which may behave either as P or as Q. All the current actions P and Q are enabled. The first action to complete distinguishes one of the processes. The other process of the choice is discarded. The system will then behave as the derivative resulting from the evolution of the chosen process.
- $P \oplus_{r,T} Q$ denotes the probabilistic choice with the conventional generative interpretation, thus with probability r the process behaves like P and with probability $1 - r$ it behaves like Q bounded with the time constraint T .
- $P \otimes_{L,T} Q$ is a cooperation, in which the two actions P and Q are parallel, synchronizing on all activities whose type is in the cooperation set L of action types. The lifetime of two actions is the time constraint T . These two actions are disabled when the time constraint expires. Any action whose type is not in L will proceed independently. As a syntactic convenience the parallel combinatory is defined by $\otimes_{\phi,T}$, where the cooperation set L is empty and the lifetime of two actions is T .
- $P\ \nabla\Delta_{P,T}\ Q$ is a unary operator which returns the set of actions that meet the temporal predicate condition specified by T . Pconsists of several predicates combined with the boolean connectives: 'And' ,'Or', Exclusive-Or (EXOR)' and 'Not'. $\nabla\Delta$ And, T means both actions can occur during the interval T . $\nabla\Delta$ Or, T means that one or both actions can occur during the interval T . $\nabla\Delta$ EXOR,T means that one of these actions occurs; it immediately determines whether P or Q can subsequently occur during the triggered interval T . $\nabla\Delta_{Not,T}$ means that both actions do not occur during the interval T .
- P/L is a hiding operation, where the set L of visible action types identifies those activities which are to be considered internal or private to the component. These activities are not visible to an external observer, nor are they accessible to other components for cooperation.
- A := P is a countable set of constants.

III. MULTI-THREAD SCHEDULING SCHEME OF DYNAMIC BANDWIDTH ALLOCATION

In this section, we briefly describe two different inter-thread scheduling algorithms presented in [10–12] in Figure 1. The one proposed in [12] is referred to as newly arrived plus (NA+), which aims to overcome the over-granting problem in multithread schemes. We name the reviewed algorithm (i.e., in [10]) as subsequent requests plus (SR+), since it is able to reduce grant delay by utilizing the information regarding the requests received in the overlapped subsequent DBA processes. Furthermore, we integrate the key advantages of these two existing approaches and propose an enhanced inter-thread scheduling (EIS) algorithm in order to further improve the DBA performance.

A. Newly Arrived Plus

Over-granting can be a serious performance issue in a typical LR-PON scenario when a multi-thread DBA scheme is used. To overcome this problem, NA+ has been proposed in the literature [12]. The main idea of NA+ is that each thread is mainly responsible for the bandwidth allocation for the traffic that has arrived since the initiation of the last DBA process. In this way load is evenly distributed among the different threads. NA+ can compensate for the backlogged traffic at a specific ONUi in DBA process n using the information gathered from some previously completed DBA process. A compensation mechanism for backlogged traffic is important because a DBA allocation process may not be able to cater for all the requested bandwidth in a given DBA process. Furthermore, EPON does not support frame fragmentation, and unused time slots (UTS) may occur. NA+, presented in [12], also includes a compensation mechanism for the UTS in EPONs. The effectiveness of NA+ can be clearly observed from [12] , where an over-reporting problem is eliminated by allocating bandwidth only once. For instance, the first arrived packet (i.e., the black packet) is reported in both $R_{i,1}$ and $R_{i,2}$, but the corresponding bandwidth granting is only performed once (i.e., in $G_{i,1}$) because $R'_{i,2}$ excludes the bandwidth of the black packet, which has already been granted in $G_{i,1}$. This allows improving network throughput as well as delay and jitter.

$$ONU_i := < sent, \lambda_1 > .Report(R)_{i,1} \otimes_{L_1} < get, \lambda_1 > .OLT$$

$$ONU_i := < poll, delay_i > .Report(R)_{i,2} \otimes_{L_2} < get, \lambda_2 > .OLT$$

$$ONU_i := < grant_{NA+}, delay_{NA+_i} > .Data_i \otimes_{L_3} < get, \lambda_3 > .OLT$$

$$ONU_i := < sent, delay_i > .Report(R)_{i,3} \otimes_{L_4} < get, \lambda_4 > .OLT$$

$$ONU_i := < queue, delay_i > .Data_i \otimes_{L_5} < get, \lambda_5 > .OLT$$

The operation in DBA Scheme for OLT specified as follows:

$$OLT := < sent, delay_1 > .Result(G)_{i,1} \otimes_{L_1} < get, \lambda_1 > .ONU_1$$

$$OLT := < sent, delay_2 > .Result(G)_{i,2} \otimes_{L_2} < get, \lambda_2 > .ONU_2$$

$$OLT := < sent, delay_3 > .Result(G)_{i,3} \otimes_{L_3} < get, \lambda_3 > .ONU_3$$

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