Time Synchronization in XG-PON Systems: An Error Analysis

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Abstract: Synchronization in modern optical systems is of paramount importance. The sharing of a common time between different network components constitutes a crucial factor towards system stability. Latest advancements in optical access networks, such as Passive Optical Networks (PONs), allow transmission rates of 10 Gbps. Hence, a very accurate synchronization method is required in order to keep the network free of blocking and collisions. In this work, we focus on 10-gigabit-capable passive optical network (XG-PON) systems, one of the most popular standards for PONs. A rigorous analytic approach is devised so as to investigate the required precision of underlying synchronization method. Closed equations for computing the no blocking and blocking probabilities are developed. The devised analytic framework is verified using simulation methods.

1 INTRODUCTION

Passive Optical Networks (PONs) architecture effectively apply a cost-effective solution of optical technology to address the bandwidth mismatch between the backbone and the last mile (Lam, 2011). They present numerous influential assets: a) a cost-effective, optical-based solution, without needing regenerators, amplifiers, or active converters, b) a flexible infrastructure allowing scaling up at low cost, c) broad deployment which means that a PON could cover over 60 Km distance between the central office (CO) and the most distant user, and d) various, concurrent service level agreements (SLAs) enclosing heterogeneous quality of service (QoS) guarantees among numerous users withing the network (Lee et al., 2006),(Sarigiannidis et al., 2015). Indeed, there is a growing interest on optimizing the performance of many inner components and processes of the PON (Sarigiannidis et al., 2010).

Next generation PONs (NG-PONs) have been recently inaugurated in order to further empower the network capabilities (Kani et al., 2009). By delivering shared Internet access up to 10 *Gbps*, the latest standard of the telecommunication standardization sector of the international telecommunication union (ITU-T), called 10-gigabit-capable passive optical network (XG-PON), is envisioned to provide even more capabilities to even more users (ITU-T). Nevertheless, having in mind that the number of users potentially connected to a PON is growing, the responsibility of delivering data following multiple user traffic requirements becomes more pressing. Data delivery should be carried out without violating QoS agreements, while user requests should be met in time according to their Service Level Agreements (SLAs). Accordingly, users that share the same SLA should experience the same level of services. This implies that the network performance is efficient enough to provide good and fair data delivery to all users.

However, such a demanding network system requires accurate synchronization mechanisms. The Time of Day (ToD) distribution over the system should be accurate enough in order to avoid collisions between bandwidth allocations. Various techniques are available to support time synchronization, such as Global Positioning System (GPS), Network Time Protocol (NTP), and Precision Time Protocol (PTP). According to the standard specification, the Optical Line Termination (OLT), which is the main network component in the XG-PON systems, is equipped with an accurate real time clock; however, the means of provisioning an accurate clock to the OLT is left beyond the scope of the standard recommendations.

The time synchronization in XG-PON systems is the main focus of this paper. The ToD distribution method, according to the standard specification, is adopted. The Optical Network Units (ONUs) receive the ToD through downstream frames that the OLT send in a periodic manner. The ToD accuracy is crucial since it dramatically affects the bandwidth allocation schedule integrity. For example, if two ONU receive different ToD, a bandwidth allocation collision may be happened. This phenomenon may lead to network performance degradation since the collided allocations should be re-scheduled again in the forthcoming allocation opportunities, resulting in considerable delays. To this end, an analytic framework is devised in this work in order to examine the blocking probability of a burst (upstream allocation that received erroneous time from the OLT. Furthermore, the number of involved bursts is calculated under saturation conditions. Analytic results are verified using a rigorous simulation environment. The obtained results indicate the capability of various accuracy levels.

The remainder of the paper is organized as follows. Section 2 introduces several features of the XG-PON system. In Section 3 existing research efforts towards timing synchronization are outlined. A detailed description of the proposed analytic approach is provided in Section 4. Section 5 illustrates the obtained results, followed by detailed reports. Finally, conclusions are given in Section 6.

2 BACKGROUND

The XG-PON framework defines a point-to-multipoint optical access infrastructure that provides (nominal) 10 Gbps data rate in at least one direction. According to the standard specifications (ITU-T), the resource allocation process is designed to satisfy specific downstream and upstream requirements, while specific principles are met. Typically, the XG-PON system has a physical tree topology with the Central Office (CO) located at the root and the subscribers connected to the leaf nodes of the tree. The main network entities of a PON are the ONUs, providing to users connection to the network, and the OLT, providing to ONUs access to the backbone. A passive optical splitter/combiner connects the OLT and ONUs, receiving a single optical fiber from the OLT and distributing the incoming signal to multiple single optical fibers and vice versa. Figure 1 illustrates a typical XG-PON architecture.

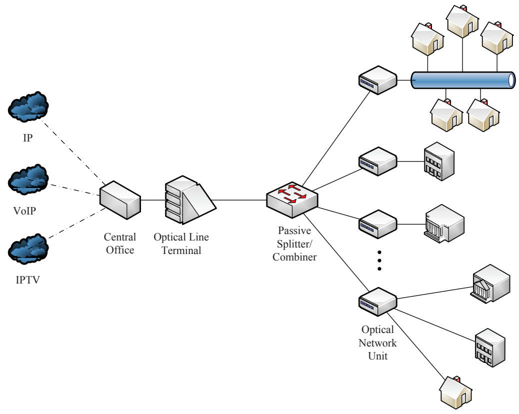

Figure 1: A typical XG-PON architecture based on a tree topology.

The XG-PON transmission convergence (XGTC) layer thoroughly describes the functional protocols and procedures, including resource allocation and QoS provisioning. Specifically, the XTGC layer is responsible for receiving service data units (SDUs) from the upper layers and providing an uninterrupted bitstream at the nominal interface, supporting a 9.95328 *Gbps* (nominal) data rate in the downstream direction and a 2.48832 *Gbps* (nominal) data rate in the upstream direction. Downstream and upstream frames of the same duration (125 μsec) are defined; this corresponds to a downstream frame size of 155520 bytes and an upstream frame size of 38880 bytes. Both downstream and upstream frames contain control information. Specifically, considering the downstream frame, the physical synchronization block field (PSBd) includes a synchronization bitstream, the PON identification number, counters and other control information. Additionally, BWmap, an important control field comprised in XGTC header that follows, is associated with the bandwidth allocation process. Specifically, it is used by the OLT to inform the ONUs about the granted transmission opportunities; it defines the start time of the transmission opportunity and the grant size of each recipient of the allocation within each ONU. In essence, the OLT continuously broadcasts data to ONUs, including requested data delivery, messages and bandwidth allocation information. Considering the upstream frame, the physical synchronization block field (PSBu) contains the preample and delimiter fields. Then the XGTC burst follows that includes XGTC header and trailer. Dynamic Bandwidth Report (DBRu) determines the adopted resource allocation process. Two options are defined by the standard, namely, a) the status reporting (SR) method, according to which each allocation encloses the DBRu header and reports to the OLT its buffer status a d b) the traffic monitoring (TR) method, according to which the OLT monitors the idle upstream frames to perceive the bandwidth pattern of each recipient. According to the specifications, the XG-PON OLT should support both techniques in a separate way or even combined. An interested reader could refer to (Effenberger, 2010) for more information.

In order to provide an uninterrupted and effective upstream schedule, the OLT should apply an accurate time synchronization method to the connected ONUs (Topliss et al., 1995). In essence, the OLT informs the ONUs about the ToD using specific downstream XGTC frames. The ONUs receive the ToD information by reading the ONU Management and Control Interface (OMCI) channel, which allows OLT and ONUs to exchanges control messages. The ToD distribution process implies a master-slave clock relationship, where the OLT maintains the master clock, whereas the ONUs are synchronize their slave clocks to the OLT's master clock by monitoring certain downstream XGTC frames which are used as timing reference. In any case, a 64-bit guard time is considered between upstream bursts from different ONUs to prevent allocation overlaps. Nonetheless, the master clock of the OLT is considered accurate while the clock implementation details are considered beyond of the scope of the standard recommendations. In this work, we try to shed light to the case that the master clock is not fully accurate using analytic techniques. In addition, the upstream allocation block probability is calculated by considering multiple accurate clock levels.

3 SYNCHRONIZATION METHODS AND RELATED WORK

Many time synchronization protocols could be used in XG-PON systems. The NTP, defined in IETF RFC 1305, is considered a clock synchronization protocol of mature technology. It has been used for many years to ensure ToD sharing in distributed network devices. The synchronization process employed timestamps which are piggybacked in data packets to advertise the relative time. The function of NTP allows a time accuracy of milliseconds. For example, it is used in synchronous optical networking to provide alarm, billing, control, and signaling messages. However, the usage of NTP in high-speed optical access networking seems problematic due to NTP's low accuracy levels.

On the other hand, PTP, also known as IEEE 1588 standard, allows higher accuracy time distribution than NTP. NTP version 1 has been employed to provide time synchronization in Ethernet Local Area Networks (LANs). It engages time-messaging control packets between master and slave clocks, where the time information is carried using timestamps. It also included several improvements such as higher packer rate and hardware-based time-stamping. In LAN environments, it supports one microsecond accuracy. NTP version 2 has been used in Wireless Area Networks (WANs). The concepts of boundary clock and transparent clock are strong enhancements of this version. The boundary clock uses slave ports for time recovering from an upstream master; then it utilizes this recovery time as a basis for a set of master ports to synchronize downstream slave ports. The transparent clock is used as a measure device. It monitors the time a message needs to be processed and updates the clock. In PON environment, the usage of NTP seems inadequate due to link delay asymmetry (Luo et al., 2012).

The involvement of GPS systems in determining the current time is not a new concept (Lewandowski et al., 1993). Today, high precision GPS systems have been used in distributed network systems for time synchronization purposes. Recent efforts demonstrated very effective GPS clock systems using short-term frequency stability of crystal oscillator (Zhang et al., 2013). In addition, advanced memory and processing techniques are used in (Shan et al., 2014), where an accurate GPS system for mobile communications was presented. Modern GPS systems support about 100 nsec time precision; however the installation cost as well as the implementation is high.

Despite several research efforts towards time synchronization in modern network systems, the synchronization issue has not been extensively addressed, especially in modern PONs. For example, there is no evidence about the impact of a clock error in the PON operation. To be more specific, it is important to specify the impact of an clock error in the upstream allocation process, i.e., how a timing error affects the integrity of the allocation process in the upstream direction in XG-PON systems. In this paper, we intend to cover this gap by examining the synchronization deficiencies in XG-PON systems.

4 ERROR ANALYSIS

4.1 Formulation

Let $E(\mu sec)$ denotes the timing error of an ONU that received erroneous time by the OLT. Assume that the XG-PON under study consists of N ONUs. It is assumed that the error distribution follows a normal distribution, having $\mu = 0$ (Maróti et al., 2004), (Bregni and Tavella, 1997):

$$E(\mu sec) \rightarrow N(0, \sigma^2) \tag{1}$$

Due to the presence of the guard time between upstream bursts, a minor timing error could be absorbed. Based on the ITU-T recommendations, the upstream guard time is at least 64 bits. Given that the upstream transmission rate is 2.48832 Gbps, this guard time corresponds to $GT = 0.257\ \mu sec$. Thus, a timing error larger than $-GT$ and lower than GT can be absorbed. Given that Φ yields the Cumulative Distribution Function (CDF) of the standard normal distribution, the probability of error absorption, p_a is equal to:

$$
\begin{aligned}
p_a = E(-GT \leq X \leq GT) = \\
\Phi(\frac{GT}{\sigma}) - \Phi(\frac{-GT}{\sigma}) = \\
\Phi(\frac{GT}{\sigma}) - \Phi(-\frac{GT}{\sigma}) = \\
\Phi(\frac{GT}{\sigma}) - (1 - \Phi(\frac{GT}{\sigma})) = \\
\Phi(\frac{GT}{\sigma}) - 1 + \Phi(\frac{GT}{\sigma}) = \\
2\Phi(\frac{GT}{\sigma}) - 1 = \\
2(1 - \Phi(\frac{-GT}{\sigma})) - 1 = \\
1 - 2\Phi(\frac{-GT}{\sigma})
\end{aligned}
\tag{2}
$$

In case that a timing error is larger than $|GT|$, the error impact is inevitable. Hence, the probability of violating the upstream transmission integrity is $1 - p_a = 2\Phi(\frac{-GT}{\sigma})$. Let UB_i denotes the length of the i^{th} upstream burst in terms of Bytes. Also, assume that the timing error affects the n^{th} upstream burst, within an upstream PHY frame of $125\mu sec$. The synchronization disorientation of this upstream burst may harm one or two other upstream bursts. For example, the n^{th} upstream burst may collide with the $(n-1)^{th}$ burst with probability $E(-GT \leq X \leq -2GT - UB_{n-1})$. In a similar way, the n^{th} upstream burst may collide with the $(n+1)^{th}$ burst with probability $E(GT \leq X \leq 2GT + UB_{n+1})$. In particular, the probability of the n^{th} upstream burst to collide with one of its neighbor bursts is as follows:

$$
\begin{aligned}
E(-2GT - UB_{n-1} \leq X \leq -GT) + \\
E(GT \leq X \leq 2GT + UB_{n+1}) = \\
\Phi(\frac{-GT}{\sigma}) - \Phi(\frac{-2GT - UB_{n-1}}{\sigma}) + \\
\Phi(\frac{2GT + UB_{n+1}}{\sigma}) - \Phi(\frac{GT}{\sigma}) = \\
1 - \Phi(\frac{GT}{\sigma}) - (1 - \Phi(\frac{2GT + UB_{n-1}}{\sigma})) + \\
\Phi(\frac{2GT + UB_{n+1}}{\sigma}) - \Phi(\frac{GT}{\sigma}) = \\
\Phi(\frac{2GT + UB_{n-1}}{\sigma}) + \Phi(\frac{2GT + UB_{n+1}}{\sigma}) \\
-2\Phi(\frac{GT}{\sigma})
\end{aligned}
\tag{3}
$$

If the timing error of an erroneous burst is slightly larger than the guard time plus the upstream length of its neighbor burst, then the erroneous burst may collide with two or more successive bursts. This depends on the burst lengths. In order to simplify our analysis, we consider identical burst lengths for all upstream bursts:

$$UB = UB_i = UB_j, \forall i, j, 1 \leq i, j \leq N \tag{4}$$

Under this assumption, the n^{th} upstream burst may collide with two other bursts at most. To be more specific, the n^{th} upstream burst collides with the $(n-1)^{th}$ and $(n-2)^{th}$ upstream bursts when the timing error is in the range $[-GT - 2UB, -2GT - UB]$. Similarly, the n^{th} upstream burst collides with the $(n+1)^{th}$ and $(n+2)^{th}$ upstream bursts when the timing error is in the range $[2GT + UB, GT + 2UB]$. At this end, the probability of the n^{th} upstream burst on colliding with its two consecutive neighbor bursts is calculated as follows:

Table 1: Notation Table.

$E(\mu sec)$	ONU Timing Error
N	Number of ONUs
GT	Guard Time (64 bits)
p_a	Probability of Error Absorption
UB_i	Length of the i^{th} Upstream Burst
F_{1b}	Single Blocking Discrete Probability Distribution
F_{2b}	Double Blocking Discrete Probability Distribution
B_{bursts}	Average Blocking Bursts
p_0	No Blocking Probability (Probability of Error Absorption)
p_1	Probability of a Single Blocking
p_2	Probability of a Double Blocking
D_{bursts}	Average Number of Discarded Bursts

$$
\begin{aligned}
&E(-GT-2UB \le X \le -2GT-UB)+\\
&E(2GT+UB \le X \le GT+2UB)=\\
&\Phi(\frac{-2GT-UB}{\sigma})-\Phi(\frac{-GT-2UB}{\sigma})+\\
&\Phi(\frac{GT+2UB}{\sigma})-\Phi(\frac{2GT+UB}{\sigma})=\\
&1-\Phi(\frac{2GT+UB}{\sigma})-(1-\Phi(\frac{GT+2UB}{\sigma}))+\\
&\Phi(\frac{GT+2UB}{\sigma})-\Phi(\frac{2GT+UB}{\sigma})=\\
&2(\Phi(\frac{GT+2UB}{\sigma})-\Phi(\frac{2GT+UB}{\sigma}))
\end{aligned} \tag{5}
$$

In the same way, the probability of the n^{th} upstream burst to collide with one of its neighbor bursts (Eq. (3)) becomes:

$$
\begin{aligned}
&E(-2GT-UB \le X \le -GT)+\\
&E(GT \le X \le 2GT+UB)=\\
&\Phi(\frac{-GT}{\sigma})-\Phi(\frac{-2GT-UB}{\sigma})+\\
&\Phi(\frac{2GT+UB}{\sigma})-\Phi(\frac{GT}{\sigma})=\\
&1-\Phi(\frac{GT}{\sigma})-(1-\Phi(\frac{2GT+UB}{\sigma}))+\\
&\Phi(\frac{2GT+UB}{\sigma})-\Phi(\frac{GT}{\sigma})=\\
&2(\Phi(\frac{2GT+UB}{\sigma})-\Phi(\frac{GT}{\sigma}))
\end{aligned} \tag{6}
$$

Obviously, the probability of the n^{th} upstream burst to collide with the $(n+2)^{th}$ burst will be:

$$
E(GT+2UB \le X \le 2GT+3UB) \tag{7}
$$

Based on Eq. 6 and Eq. 7, it is easy to devise the recursive probability distribution for the n^{th} upstream burst to collide with the $(n \pm i)^{th}, i \ge 1$:

$$
\begin{aligned}
&i=1, E(-2GT-UB \le X \le -GT)+\\
&E(GT \le X \le 2GT+UB)+\\
&i=2, E(-2GT-3UB \le X \le -GT-2UB)+\\
&E(GT+2UB \le X \le 2GT+3UB)+\\
&i=3, E(-2GT-5UB \le X \le -GT-4UB)+\\
&E(GT+4UB \le X \le 2GT+5UB)+\\
&\ldots+
\end{aligned} \tag{8}
$$

Based on Eq. 8, the discrete probability distribution of occurring a single blocking, F_{1b}, when an upstream burst received erroneous timer, is defined:

$$
\begin{aligned}
&F_{1b}(i)=\\
&E(-2GT-(2(i-1)+1)UB \le X \le\\
&-GT-2(i-1)UB)+\\
&E(GT+2(i-1)UB \le X \le\\
&2GT+(2(i-1)+1)UB)=\\
&2(\Phi(\frac{2GT+(2(i-1)+1)UB}{\sigma}\\
&-\Phi(\frac{GT+2(i-1)UB}{\sigma})), i=1,2,3,\ldots
\end{aligned} \tag{9}
$$

In accordance, the recursive probability for the n^{th} upstream burst to collide with the $(n \pm i)^{th}, i \ge 1$ and $(n \pm (i+1))^{th}$ is given as:

$$
\begin{aligned}
&i=1, E(-GT-2UB \le X \le -2GT-UB)+\\
&E(2GT+UB \le X \le GT+2UB)+\\
&i=2, E(-GT-4UB \le X \le -2GT-3UB)+\\
&E(2GT+3UB \le X \le GT+4UB)+\\
&i=3, E(-GT-6UB \le X \le -2GT-5UB)+\\
&E(2GT+5UB \le X \le GT+6UB)+\\
&\ldots+
\end{aligned} \tag{10}
$$

The discrete probability distribution of occurring a double blocking, F_{2b}, when an upstream burst received erroneous timer, is given as follows:

$$
\begin{aligned}
&F_{2b}(i)=\\
&E(-GT-2iUB \le X \le\\
&-2GT-(2(i-1)+1)UB)+\\
&E(2GT+(2(i-1+1))UB \le X \le\\
&GT+2iUB)=\\
&2(\Phi(\frac{GT+2iUB}{\sigma}\\
&-\Phi(\frac{2GT(2(i-1)+1)UB}{\sigma})),\\
&i=1,2,3,\ldots
\end{aligned} \tag{11}
$$

4.1.1 Average Number of Blocking Bursts

The average blocking bursts, when a burst receives erroneous time, is given as follows:

$$
B_{bursts} = \sum_{i=0}^{2} i p_i \tag{12}
$$

The p_i probability represents the probability of occurring no blocking ($i=0$), one blocking ($i=1$), and two blocking ($i=2$). The probability of no blocking is directly obtained by Eq. 3:

$$p_0 = -2\Phi(\frac{GT}{\sigma}) \quad (13)$$

Accordingly, the probability of occurring a blocking is given in accordance to Eq. 9:

$$p_1 = \sum_{i=1}^{\infty} f_{1b}(i) = \sum_{i=1}^{\infty}(2(\Phi(\frac{2GT+(2(i-1)+1)UB}{\sigma}) - \Phi(\frac{GT+2(i-1)UB}{\sigma}))) \quad (14)$$

In the same way, the probability of an erroneous burst to cause two burst blocking is given in accordance to Eq. 11:

$$p_2 = \sum_{i=1}^{\infty} f_{2b}(i) = \sum_{i=1}^{\infty}(2(\Phi(\frac{GT+2iUB}{\sigma}) - \Phi(\frac{2GT+(2(i-1)+1)UB}{\sigma}))) \quad (15)$$

Hence, the average blocking bursts are:

$$B_{bursts} = 0p_0 + 1 * p_1 + 2 * p_2 = p_1 + 2p_2 \quad (16)$$

Under the assumption that upstream bursts do not utilize FEC mechanisms, we consider that a blocking occurrence totally disorientates the bursts being affected. As a result all these bursts are totally discarded. Hence, an erroneous burst may discard two (single blocking) or three (two blocking) bursts including the erroneous bursts itself. In the light of the aforementioned remarks, Eq. 12 is transformed to yield the average number of discarded bursts:

$$D_{bursts} = \sum_{i=1}^{2}(i+1)p_i = 2p_1 + 3p_2 \quad (17)$$

5 PERFORMANCE EVALUATION

This section is devoted in verifying the accuracy of the proposed analytic model.

5.1 Environment

A simulation environment was implemented in Matlab in order to verify the incorporated analysis. In particular, a full XG-PON operation has been implemented. The downstream and the upstream transmission rates were set 9.95328 and 2.48832 Gbps respectively. The network operation has been examined under saturated conditions. This means that all the available upstream bandwidth is utilized by the connected ONUs. As a result, the available upstream bandwidth, which corresponds to 38880 Bytes, is equally shared to the ONUs. Thus, assuming a number of $N = 30$ ONUs, each ONU burst corresponds to 1296 Bytes including a guard time of 64 bits. Thus, $UB = 1296 - 8 = 1288$ Bytes.

For each conducted simulation experiment, an upstream burst is randomly selected as an erroneous burst. The timing error depends on the synchronization device between OLT and ONU. In order to study different synchronization methods, five accuracy levels were devised: a) Very High Accurate Synchronization (VHAS) with time precision of $\pm 10 nsec$, b) High Accurate Synchronization (HAS) with time precision of $\pm 100 nsec$, c) Accurate Synchronization (AS) with time precision of $\pm 1 \mu sec$, d) Low Accurate Synchronization (LAS) with time precision of $\pm 10 \mu sec$, and d) Very Low Accurate Synchronization (VLAS) with time precision of $\pm 100 \mu sec$. For each synchronization method the value of standard deviation (σ) is configured as its precision divided by 4, in terms of μsec, so as to maximize the cumulative percent of normal distribution values. Hence, the values of σ per synchronization method are: a) $\sigma_{VHAS} = \frac{0.01}{4}$, b) $\sigma_{HAS} = \frac{0.1}{4}$, c) $\sigma_{AS} = \frac{1}{4}$, d) $\sigma_{LAS} = \frac{10}{4}$, and e) $\sigma_{VLAS} = \frac{100}{4}$.

5.2 Results and Discussion

First, the probability of no blocking is examined for each synchronization accuracy level. Figure 2 depicts the results from both analytic and simulation frameworks. By observing this figure it is clear that VHAS and HAS are deemed as adequate to be applied as synchronization accuracy levels since they offer almost 100% time precision. On the contrary, AS, LAS, and VLAS may cause burst blocking. AS offers about 69% absorption probability, which means that it is

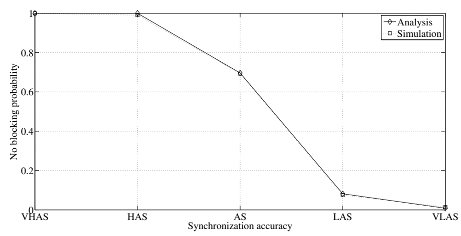

Figure 2: No blocking probability of an erroneous upstream burst.

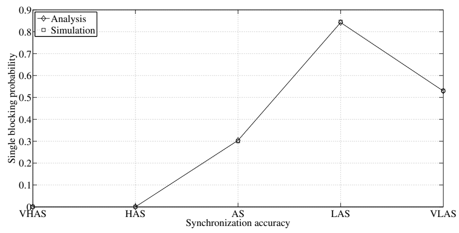

Figure 3: Single blocking probability of an erroneous upstream burst.

31% possible a blocking occurrence, and therefore burst losses. The worst performance is observed in LAS and VLAS.

It is worth mentioning that applying a synchronization device at VLAS levels, it is quite sure that a timing error will induce burst losses.

Figure 3 illustrates the single blocking probability of an erroneous upstream burst. As expected, VHAS and HAS present zero blocking probability, which means that an upstream burst that receives erroneous time from the OLT does not cause any blocking with any other burst. On the other hand, AS policy presents 30% single blocking probability. Hence, it is 30% possible of an erroneous burst to cause a single blocking, resulting in discarding two upstream bursts. LAS obtains a single blocking probability of 83%, fact that implies that in case of timing failure, the erroneous burst will probably collide with another burst. Lastly, VLAS presents a lower single blocking probability than LAS. This is attached to the fact that VLAS presents high double blocking probability.

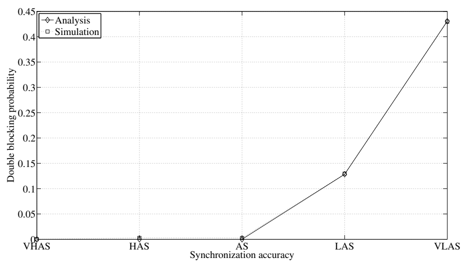

Figure 4: Double blocking probability of an erroneous upstream burst.

The double blocking probability is inspected in Figure 4. As expected, only LAS and VLAS may suffer from double blocking, which causes the disorientation of three bursts, including the erroneous one. VLAS presents the highest probability, fact that indicates its inefficiency to handle time-sensitive applications in XG-PON systems. Moreover, LAS demonstrates noticeable double blocking probability ($> 10\%$), thus LAS is also deemed as inadequate to guarantee sensitive services.

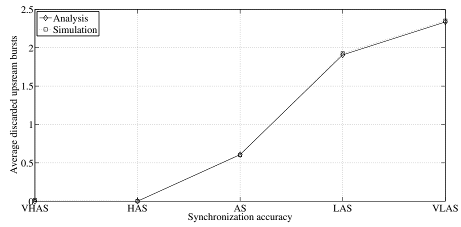

Figure 5: Average discarded upstream bursts.

The average number of discarded bursts due to an erroneous timing synchronization is depicted in Figure 5. This figure offers a clear picture of the timing error impact. VHAS and HAS are deemed as adequate synchronization accuracy levels since they minimize the impact of a timing error. On the other hand, all other schemes cause data losses. AS keeps data losses below 1 upstream burst, which means that 1288 Bytes at most are discarded in case of an error. LAS and VLAS reach high values of data drops. VLAS may cause the drop of almost 3 bursts, resulting in the loss of 3864 Bytes under saturation conditions. This loss is deemed high since sensitive services like voice and real time video may be disoriented. In a nutshell, VHAS and HAS are the synchronization accuracy levels that are suggested to handle potential timing errors in XG-PON systems.

6 CONCLUSIONS

A rigorous analytic approach for determining the impact of a timing error in XG-PON systems was proposed in this work. Several synchronization methods on sharing common time between OLT and ONUs are investigated in terms of burst blocking probability. In addition, the number of affected upstream bursts was calculated. Analytic results were verified by simulation experiments. Both results indicate that at least 100*nsec* timing accuracy is required in order to fully absorb potential burst blocking due to an erroneous burst.

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