Congestion estimation technique in the optical network unit registration process

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We present a congestion estimation technique (CET) to estimate the optical network unit (ONU) registration success ratio for the ONU registration process in passive optical networks. An optical line terminal (OLT) estimates the number of collided ONUs via the proposed scheme during the serial number state. The OLT can obtain congestion level among ONUs to be registered such that this information may be exploited to change the size of a quiet window to decrease the collision probability. We verified the efficiency of the proposed method through simulation and experimental results. © 2016 Optical Society of America

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A passive optical network (PON) is a point-to-multipoint network architecture that consists of an optical line terminal (OLT) at a central office and a number of optical network units (ONUs) located at the customer's premises. The OLT performs an activation process for allowing an in-active ONU to join or resume operations on the PON. The activation process includes downstream synchronization, serial number (SN) acquisition for ONU discovery, and fiber channel ranging. During SN acquisition, all transmissions from in-service ONUs are halted for the duration of quiet window while the contending ONUs for registration respond to the OLT's SN bandwidth map. If two or more ONUs simultaneously respond, the registration fails because of a collision among the contending ONUs.

For the duration of SN acquisition, all transmissions from registered ONUs are halted, resulting in a decrease of the available upstream bandwidth. Random delay mechanisms have been used to decrease the collisions of registration requests among contending ONUs in various PONs. The size of quiet windows required to successfully register as many contending ONUs as possible should be carefully determined depending on the collision probability for their registration requests. Haduczenia *et al.* compared the efficiency of several types of collision avoidance mechanisms such as random delay, backoff, and hybrid methods in terms of the number of required discovery cycles to register ONUs [1]. Bhatia and Bartos pro-

posed a generic probability model to analyze the EPON registration scheme for identically distanced and randomly distributed ONUs [2]. They derived the probability of message collision in EPON and computed the most efficient contention window sizes for ONUs. Li el al. proposed an adaptive registration scheme in which they focused on ONU migrations due to wavelength change in Time and Wavelength Division Multiplexing PON (TWDM-PON). They used the unimodal ONU online profiles to estimate the number of newly incoming ONUs [3]. Cui et al. analyzed the throughput and efficiency of the EPON registration protocol [4]. Kamiya et al. proposed a circuitry-based technique for estimating the number of unregistered ONUs. They appended a differentiating circuit with a low-pass filter at the OLT side, and counted the changes of received signal for ONU responses to measure the number of unregistered ONUs [5]. Their simulation result showed that the discovery window size could be reduced. However, it is more desirable to estimate the number of unregistered ONUs without an additional circuitry in practice.

Fig. 1 represents an example of the timing graph of an XG-PON OLT and two ONUs in the process for the SN state when the ONUs collide [6, 7]. All unregistered ONUs receive this map and send SN response physical layer operation, administration and management (PLOAM) messages to the OLT. The OLT waits for responses from unregistered ONUs for the duration of a quiet window in which in-service ONUs cannot send any upstream data to the OLT. A random delay technique is used in order to avoid collision among ONUs during the quiet window. Each ONU can send an SN response after some random delay. In Fig. 1, W_0 is given by $W_0 = P_{min} + RT_{min} + RD_{min} + S_t + S_t$ L_{burst} , where $P_{min}(=T_a+T_b)$ is the minimum round trip delay, RT_{min} is the minimum response time of an ONU, RD_{min} is the minimum random delay, S_t is the OLT generated start time value, and *L*_{burst} is the duration of SN response burst. Similarly, W_{max} is given by $W_{max} = P_{max} + RT_{max} + RD_{max} + S_t + L_{burst}$ where $P_{max}(=T_c+T_d)$ is the maximum round trip delay, RT_{max} is the maximum response time of an ONU, and RD_{max} is the maximum random delay. In the case of a large number of contending ONUs involved in the registration process, the number of successfully registered ONUs may be extremely small, and the registration process requires a huge number of discovery cycles to complete the activation process.

If the OLT can predict the number of contending ONUs when a quiet window opens, the OLT can adjust the quiet win-



Fig. 1. Serial number acquisition timing diagram.



Fig. 2. Burst signal during the serial number state.

dow size to complete the activation process as quickly as possible by reducing unnecessary discovery cycles. In [5, 8], the optimum quiet window size W_{opt} is derived as follows:

$$W_{opt} = \Delta P + \Delta RT + \Delta RD + L_{burst}(n + \frac{1}{2})$$
(1)
+ $\sqrt{L_{burst}^2(n^2 + n + 9/4) + 2L_{burst}\Delta P(n - 1)}$

where $\Delta P = (P_{max} - P_{min})$, $\Delta RT = (RT_{max} - RT_{min})$, $\Delta RD = (RD_{max} - RD_{min})$. Because W_{opt} is given by a function of n, the number of contending ONUs should be determined at each registration process. However, in practice a fixed size of quiet window in XG-PON and NG-PON2 is used, and the recommended values are 250 and 450 *us* for 20 and 40 km differential fiber distances, respectively. For efficient registration, it is essential to develop an estimation method for the number of contending ONUs, especially without additional hardware equipment.

Fig. 2 (a) and (b) show the general behavior of an OLT optical transceiver under the SN state. The transceiver generates a signal detection (SD) signal to indicate that signals are detected at the transceiver. L_{burst} from an ONU includes guard time, synchronization and header information, and an SN response PLOAM message as depicted in Fig. 2 (a), where D_r and D_f represent the rising and falling delays, respectively. When the length of the SD signal is almost the same as L_{burst} , it corresponds to a normal transmission, and the OLT accepts L_{burst} as an SN response PLOAM message. However, the length of the SD signal is longer than L_{burst} , it implies that a collision occurs.

We propose a congestion estimation technique (CET) to obtain congestion level among ONUs involved in the ONU registration process. The CET enables an OLT to estimate the number of collided ONUs by observing the length of SD signal in the SN state. The duration of an SD signal comprises synchronization and header information, and a SN response PLOAM message including the guard time. When the SD signal is longer than the length configured as normal, it indicates the case of collision, and the OLT performs CET, which calculates the number 2



Fig. 3. SD signal in case of collision.

of collided ONUs according to the length of the SD signal.

Fig. 3 depicts the analysis of the SD signal in the case of collision. We may expect that the length of the SD signal may include multiple SN responses from more than one ONU when the collision occurs. Let $X_1, X_2, ..., X_{n+1}$ be a sequence of the arrival time of SN response burst signals received from (n + 1)number of ONUs, and L_{burst} be the length of a SN response. We may assume that the arrival of each signal follows the Poisson distribution. Let $P_k(\tau)$ denote the probability that there are exactly k SN response messages during a time interval τ . Then, $P_k(\tau)$ is given by

$$P_k(\tau) = \frac{(\lambda \tau)^k}{k!} e^{-\lambda \tau},$$
(2)

where λ is the arrival rate. The arrival rate can be obtained by

$$\lambda = \frac{N_{SN} + n + 1}{T_{SN}},\tag{3}$$

where N_{SN} is the number of successfully received SN responses, T_{SN} is the time duration between the arrival time of the first and last responses, and n + 1 is the number of collided ONUs to be estimated by the CET.

Let G_k be the time difference between X_k and X_{k+1} . Then, G_k follows the exponential distribution because X_k follows the Poisson distribution. Therefore, the probability density function p_k of G_k can be expressed by $p_k(x) = \lambda e^{-\lambda x}$. Let L_{sd_col} be the duration of the SD signal when the collision occurs. L_{sd_col} is expressed by $L_{sd_col} = G_1 + G_2 + \cdots + G_n + L_{burst}$. Thus, S_n follows the gamma distribution because S_n is the sum of exponential random variables given by $S_n = G_1 + G_2 + \cdots + G_n$. The probability density function of S can be expressed as

$$P_S(S_n) = \frac{\lambda e^{-\lambda S_n} (\lambda S_n)^{n-1}}{(n-1)!}.$$
(4)

Note that (4) is known as the Gamma(n, λ) function. The consecutive arrival time of two SN responses should be shorter than L_{burst} to satisfy the collision condition, which is expressed by the following condition of ($G_k < L_{burst}$). This condition can be taken into consideration by replacing λ with λ_{new} as follows

$$\lambda_{new}^{-1} = \frac{1 - (1 + \lambda \cdot L_{burst})(1 - \operatorname{prob}(S_n < L_{burst}))}{\lambda \cdot \operatorname{prob}(S_n < L_{burst})}.$$
 (5)

Note that both λ and λ_{new} are a function of *n*. From (4) and (5), we can estimate the number of collided ONUs' SN responses for the given SD signal. Our goal is to find the optimal solution n_c^* for the following integer optimization problem:

$$n_{c}^{*} = \arg \max_{n} \operatorname{prob}(L_{sd_col} - \delta < S_{n} < L_{sd_col} + \delta)$$
(6)
subject to $\left\lceil \frac{L_{sd_col}}{L_{burst}} \right\rceil \le n \le r_{split}$

where r_{split} is the *split ratio* and δ is a small value for the probability computation. Note that if $\delta = 0$, the probability is always



Fig. 4. The cost function values in (6) in case of collision.

zero. Because the optimization in (6) is an integer optimization, the optimal solution can be simply obtained by evaluating the cost function for a feasible set of n. The computational complexity of CET is not high because the candidate set for n is finite and the cost function in (6) can be easily evaluated using (4) and (5).

The CET operates as follows: 1) OLT starts the activation process; 2) OLT reports L_{sd_col} , T_{SN} , and the number of successfully received SN responses during a quiet window in the SN state; 3) n_c^* is obtained by solving the optimization problem in (6); 4) the OLT updates the ONU registration success ratio that is defined by $r_{success} = n_s/(n_s + n_c^* + 1)$ where n_s is the number of successfully received SN responses. Within a single quiet window, the collided SD signals may appear more than once because collision occurs many times in the quiet window. In case of multiple collisions, the CET may work for each collision or for the summation of all L_{sd_col} . The former provides better accuracy than the latter; however, the complexity is higher than the latter. According to the CET result, the OLT may adjust the maximum random delay or use a longer quiet window to maintain higher ONU registration success ratio.

Fig. 4 plots the cost function value in (6) using Octave [9] for different values of the number of ONUs and *L*_{burst} sizes when contending ONUs are located at the same distance from the OLT. The maximum random delay is 48 *us*, and the split ratio is 128. In Fig. 4, when the number of ONUs is 20 and L_{burst} size is 64-clock length (one clock corresponds to 6.43 ns), the duration of the SD signal is 45 ms, L_{sd_col} is 1.5 ms, and n_s is 12. The number of collided ONUs is 8 as shown in Fig. 4. When n = 128 and L_{burst} = 64-clock length, the duration of the SD signal is 47.4 ms, $L_{sd\ col}$ is 17.3 ms, and n_s is 9. The number of collided ONUs is 101. When the size of L_{burst} is increased to 128-clock length and the duration of L_{sd_col} is the same, the number of collided ONUs is smaller as shown in Fig. 4, (i.e., 4 for 20 ONUs and 52 for 128 ONUs). It is also observed that as the more ONUs try to register, L_{sd col} becomes longer and the collision probability among ONUs also becomes higher. Under the CET, the optimal value for n_c^* is obtained by (6), and (n_c^*+1) is able to approximate the number of collided ONUs. Depending on the value of n_c^* , the OLT may use a bigger or smaller size when the quiet window opens the next time.

Fig. 5 shows the Octave simulation results on the comparison of the the ONU registration success ratio between the generated by collision and the estimated by the CET when the maximum random delay is 48 *us*. The split ratio is 256 and L_{burst} is



Fig. 5. Simulation result for registration success ratio.



Fig. 6. Experimental result for a single cluster.

4.11 *us.* The reported values represent the average of 1,000 trials with the standard deviations in the figure. We assumed that ONUs are located at the same distance from the OLT. The solid and dotted boxes refer to results of the simulation and CET, respectively. The CET works whenever L_{sd_col} occurs. As shown in Fig. 5, the difference in the successful registration ratio is negligibly small, thus enabling the OLT to use this information to estimate congestion level status.

We implemented CET on the ETRI XG-PON system [10], which consists of the ETRI XG-PON OLT and 20 ONU. We used a 10 km fiber spool and optical splitters with 64 split ratio. Four maximum random delay values, such as 6, 12, 24, 48 us, are used to evaluate the performance of CET. The delay values are configured via a Burst_profile PLOAM message and ONUs update when they are in the SN state. The OLT system conducts the CET when the SD signal is longer than one L_{burst} which is 64-clock length, where one clock refers to 6.43 ns. The duration between the arrival time of the first and the last SN response is updated whenever the OLT opens a quiet window. The pseudo random numbers for random delay are generated by the C function of *srand* in the ONUs.

Fig. 6 depicts the experimental results by using the XG-PON system for a single cluster case where all ONUs are located in approximately 50 *m* from the OLT. The number of collided ONUs estimated by the CET tends to be smaller than measured values, and the registration success ratio is over-estimated in Fig. 6. The reason is that multiple collisions are approximated by a single collision in our XG-PON system because of a limited monitoring functionality. For example, in the case of 48 *us* maximum random delay, it was observed that there were two colli-



Fig. 7. Experimental result for multiple clusters.

sions of SD signal with 79-clock and 159-clock length. However, our system was implemented to simply report a single collision with 238-clock length in order to avoid the signaling overhead for status monitoring. Our XG-PON system is being upgraded to support a precise SD signal monitoring. Then, the accuracy of registration success ratio can be improved by applying CET to each collision in our system. It is also possible to compare the simulation result for 20 ONUs with the random delay of 48 *us* in Fig. 5 and the experiment result under the same condition in Fig. 6. It is seen that the registration success ratio for the experiment in Fig. 6 is slightly smaller than the simulation result in Fig. 5. It is perhaps due to the non-ideal signal reception capability of the OLT optical transceiver in practice, especially for short-length packets in burst [11], and the imperfect randomness of random delays used in the ONUs.

Fig. 7 shows the experimental results for a multiple cluster case where 10 ONUs are located in approximately 50 *m* and the other 10 ONUs are clustered at 10 *km* from the OLT through the fiber spool. The registration success ratios are higher than those in Fig. 6 because two groups of ONUs interfere less with each other. However, the discrepancy between the measured actual values and the estimated values by CET is larger than the case of Fig. 6. In this multiple cluster case, the assumption of Poisson distribution for the signal arrivals does not hold because there exists a long interval with no response arrivals. As a result, the estimate of λ in (3) is inaccurate. To improve the estimate accuracy, it is required to apply the proposed CET to each cluster rather than the whole interval.

Fig. 8 shows the registration completion delay for different values of the round trip delay (ΔP) and the duration of SN response burst (L_{burst}) when $\Delta RT=2 us$, $\Delta RD=48 us$, and $S_t=0$ as suggested in [6, 7]. The registration completion delay is defined as the aggregate value of quiet window sizes until all ONUs are successfully registered. In Fig. 8, we compared the registration completion delays for three schemes; (a) a fixed value of W, (b) W_{opt} in (1) when the actual value of n is given, and (c) W_{opt} when n is estimated by CET. Under the CET, W is initially set to 250 us and is updated by (1) using the estimated number of ONUs at every discovery cycle. Fig. 8 shows that the registration completion delay increases when the number of ONUs increases because of the higher collision probability. As shown in Fig. 8, the registration completion delay for the fixed W rapidly increases and is much longer than the other schemes with respect to the number of ONUs. The registration completion delay under the CET is almost the same as that of the ideal case in which the actual *n* is given.



Fig. 8. Comparison of registration completion delay.

We proposed a CET based on the length of the SD signal in the SN state. A quiet window size or maximum random delay value may be changed to decrease the collision probability for clustered ONUs. The CET can effectively help adapt quiet window size techniques or ONU side back-off to respond to SN requests for a fast activation process because the congestion information caused by contending ONUs can be accurately estimated.

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