Time-Aware Deterministic Bandwidth Allocation Scheme for Industrial TDM-PON

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Abstract *For Industrial Internet with TDM-PON, we propose a time-aware deterministic bandwidth allocation (TA-DBA) scheme that allocates proper transmission windows based on flow arrival time and cycle. Simulation results show that TA-DBA can achieve deterministic transmission, and the average bandwidth efficiency is 20.4% higher than FBA. ©2022 The Author(s)*

Introduction

Programmable logic controller deployed in the cloud or edge cloud (cloud PLC) contributes to the flexible and scalable industrial manufacturing processes. The Industrial Internet is requiring communication technology to connect factory and cloud PLCs. Time division multiplexing passive optical network (TDM-PON) has become one of the alternative technical solutions due to its passive features, large bandwidth, and low-cost characteristics, as shown in Fig. 1(a). Industrial applications such as motion control, and mobile robotics impose strict latency (100μs-2ms), and jitter requirements (1μs) on TDM-PON systems in pursuit of deterministic transmission capabilities, e.g., deterministic delay, and jitter[1-3]. However, traditional bandwidth allocation schemes in TDM-PON (i.e., FBA and DBA) are designed for residential and business users, which are not suitable for transmitting industrial applications with deterministic transmission requirements.

On one hand, fixed bandwidth allocation (FBA) guarantees strict delay requirements of a flow by reserving periodic time slots (i.e., transmission window, TW), where the period is also called as service interval (SI). To simplify configuration, the SI is designed to be a multiple of or a divisor of the PON frame duration (125μs). The SI of FBA under this design principle ignores the period of the industrial flow, which leads to a mismatch between the period of the flow and the SI, which causes unexpected jitter[4]. As shown in Fig. 1(b), the period of an industrial flow is not a multiple of SI (i.e., mismatches), which makes the waiting time of packets 1, 2, and 3 different (i.e., $t_w^1 \neq t_w^2 \neq t_w^3$), resulting in indeterministic jitter. On the other hand, dynamic bandwidth allocation (DBA) only guarantees the size of TW, but there is no constraint on the position of TW in SI, which may cause indeterministic delay and jitter. As shown in Fig. 1(c), the TW sizes of packets 1, 2, and 3 are sufficient for transmission, but the position of each TW is uncertain, which results in the waiting time (t_w^3) of packet 3 does not meet the delay requirement τ of flow (e.g., indeterministic delay). In addition, the waiting time of packets 1, 2, and 3 are different (i.e., $t_w^1 \neq t_w^2 \neq t_w^3$), which also causes indeterministic jitter. Since both traditional FBA and DBA ignore the flow arrival characteristics (i.e., arrival time, cycle, etc.) when allocating TW, the deterministic delay and jitter of industrial flows cannot be guaranteed.

In this paper, we propose a time-aware deterministic bandwidth allocation (TA-DBA) scheme for the Industrial Internet with TDM-PON. The TA-DBA scheme specifies the position of the TW according to the flow arrival characteristics to guarantee the deterministic transmission capabilities. The simulation results show that our proposed scheme can achieve bounded delay and jitter, and the average bandwidth efficiency is 20.4% higher than FBA.

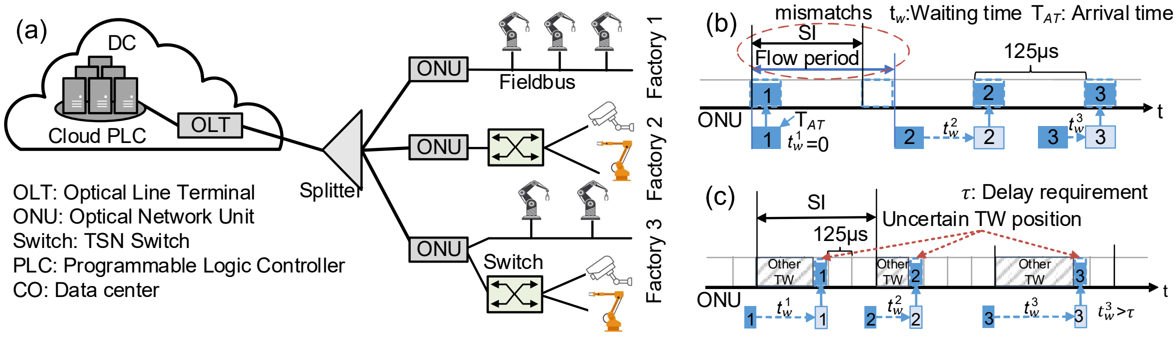


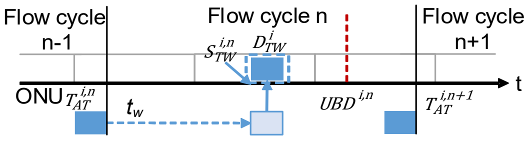
Fig.1 (a) Indestrial internet with TDM-PON; (b) Tranditional FBA scheme; (c) Tranditional DBA scheme.

Proposed TA-DBA scheme

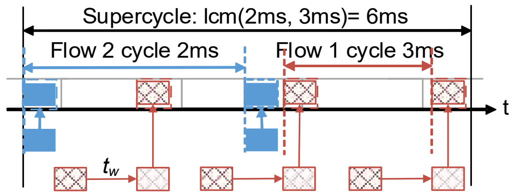
Industrial flows can be roughly classified as isochronous, cyclic, and burst flows[5]. Both isochronous and cyclic flow types are periodic data transmissions. As shown in Fig. 1(a), the isochronous flow is usually connected to the optical network unit (ONU) via the Fieldbus. The cycle and arrival time of an isochronous flow is pre-configured. Unlike isochronous flow, the arrival time of cyclic and burst flow cannot be pre-configured, so they need to be shaped by TSN switch into periodic flows, which can be achieved by time-aware shaper in TSN[6]. Therefore, the industrial flow entering the ONU can be regarded as a periodic flow.

In the TA-DBA scheme, the optical line terminal (OLT) is aware of the arrival time and cycle of a flow through the external interface, such as the cooperative transport interface (CTI)[7]. Based on flow arrival characteristics, and the delay and jitter requirements of a flow, TA-DBA constrains and specifies the position of each TW. As shown in Fig. 2(a), the "position" is the difference between the start time of the TW ($S_{TW}^{i,n}$) and the arrival time of the packet ($T_{AT}^{i,n}$) in each flow cycle. For the TW of each cycle of flow i, the deterministic delay can be guaranteed by the constraint that the TW position does not exceed the upper bound of delay (UBD). Deterministic jitter can be guaranteed if the difference between the maximum and minimum TW positions for different cycles does not exceed the jitter requirement of flow i. Computing the start time of each TW for each flow according to the above constraints can be achieved by Satisfiability Modulo Theories (SMT) solver[8].

We denote the input set of flows by S and a flow $s_i \in S,\ i = 1, \dots, N$. TW is allocated for each flow s_i, and the TW per cycle of each flow is scheduled within a supercycle, which is the least common multiple (LCM) of all flow cycles, as shown in Fig. 2(b). The packets of each cycle of flow i have a corresponding TW and ensure that the TW size (D_{TW}^i) is large enough to guarantee the bandwidth of the flow. The parameters appearing in the constraints are shown in Tab. 1, in which all parameter is represented by the number of time slots. Following are some scheduling constraints for TW start time:



(a) TA-DBA delay constrain



(b) Supercycle of multiple flows

Fig. 2 Time-aware deterministic bandwidth allocation

Tab. 1: Parameters of constraints

$T_{AT}^{i,n}$	Arrival time of flow i in the n^{th} cycle.
T_P^i	Cycle of flow i.
T_{DT}^i	Delay tolerance of flow i from industrial equipment to cloud PLC.
T_{JT}^i	Jitter tolerance of flow i.
D_{TW}^i	Size of TW for flow i.
$S_{TW}^{i,n}$	Start time of the TW for the n^{th} cycle of flow i in supercycle.
h^N	Supercycle for all flows.
t_{Proc}	Processing delay of ONU/OLT.
t_{Prop}	Propagation delay between ONU and OLT.
t_G	Guard bandwidth between two TW.

Delay constraint: The delay constraint specifies that the TW position of the n^{th} flow cycle cannot exceed the $UBD^{i,n}$.

$$UBD^{i,n} = T_{AT}^{i,n} + T_{DT}^{i} - 2 \times D_{TW}^{i} - 2 \times t_{Proc} - t_{Prop}$$
$$\left(T_{AT}^{i,n} \le S_{TW}^{i,n} \le UBD^{i,n}\right)\ or$$
$$\left(T_{AT}^{i,n} - h^N \le S_{TW}^{i,n} \le UBD^{i,n} - h^N\right) \qquad (1)$$

where the $T_{AT}^{i,n} = T_{AT}^{i,1} + n \times T_P^i$ and the $T_{AT}^{i,1}$ is the arrival time of the 1^{st} cycle of flow i.

Jitter constraint: The jitter constraint specifies that the difference between the TW position in any two cycles cannot exceed the jitter tolerance.

$$\forall n, m \in \left[0, \frac{h^N}{T_P^i}\right], n \ne m$$
$$\left(\left|\left(S_{TW}^{i,n} - T_{AT}^{i,n}\right) - \left(S_{TW}^{i,m} - T_{AT}^{i,m}\right)\right| \le T_{JT}^{i}\right) or$$
$$\left(\left|\left(S_{TW}^{i,n} - T_{AT}^{i,n} + h^N\right) - \left(S_{TW}^{i,m} - T_{AT}^{i,m}\right)\right| \le T_{JT}^{i}\right) \qquad (2)$$

Isolation constraint: The isolation constraint specifies that there should be a guard bandwidth between the TWs of the two flows.

$$\forall n \in \left[0, \frac{h^N}{T_P^i}\right], \forall m \in \left[0, \frac{h^N}{T_P^j}\right]$$
$$\left(S_{TW}^{i,n} \ge S_{TW}^{j,m} + D_{TW}^{j} + t_G\right) \text{ or}$$
$$\left(S_{TW}^{j,m} \ge S_{TW}^{i,n} + D_{TW}^{i} + t_G\right) \qquad (3)$$

where the t_G can be either in the form of two flows belonging to the same ONUs, t_G^s, or in the form of two flows belonging to different ONUs, t_G^d.

Other constraints: The start time of TW for n^{th} cycle of flow i should be within the supercycle.

$$0 \le S_{TW}^{i,n} \le h^N - D_{TW}^{i} \qquad (4)$$

Simulation Setup and Results

We consider an XG-PON system with 4 ONUs and the maximum distance from ONU to OLT is set to 5km. We limit the reserved TW to no more than 80% of the total bandwidth to avoid starvation of other flows (e.g., best-effort flows). Other simulation parameters are listed in Tab. 2, which refers to standard G987.3[9]. In this paper, only isochronous and cyclic flow is considered, and their packet size, cycle, delay, and jitter tolerance are {80Bytes, 100μs, 100μs, 1μs} and {400Bytes, 500μs, 200μs, 200μs} respectively. The arrival time of the first cycle of flows aggregated by the TSN switch or Fieldbus follows a uniform distribution of $(0, T)$, where T is the cycle of the aggregation flow. Here we set the T of the two types of flows to be 100μs. For cyclic flows, the delay and jitter tolerance of a PON system is the delay and jitter tolerance of the flow minus T.

Fig. 3(a) shows the upstream delay of a TDM-PON. Each ONU is connected to an isochronous flow with a traffic load (ρ) of 0.1. In TA-DBA, the TW position depends on the SMT solver scheduling result, so the delay of each ONU is different. The maximum delay is 95.997μs and the maximum jitter is 129ns, which meets the 100μs delay and 1μs jitter tolerance for isochronous flow. In the FBA, the maximum delay and jitter are 87.072μs and 59.966μs respectively, where the jitter is larger than the jitter tolerance.

Fig. 3(b) shows the schedulability under different traffic load ρ. Schedulability is calculated by dividing the number of schedulable flows from the total flow. We set the ratio of isochronous flow and cyclic flow to be γ. As the ρ increases, the size of TW will increase, which reduces the schedulability of TA-DBA and FBA. Likewise, a larger TW is required to guarantee the deterministic transmission of cyclic flow, so the schedulability of both schemes decreases as γ decreases. Meanwhile, the TW cycle of TA-DBA is larger than that of FBA, so it has better schedulability.

Fig. 3(c) shows the maximum delay and bandwidth efficiency under different traffic load ρ. Suppose each ONU only accesses the isochronous flow. In the TA-DBA, the flow that is not successfully scheduled will use the legacy DBA (L-DBA) scheme. The maximum delay of L-DBA is significantly higher than that of FBA and TA-DBA when ρ<0.8. The maximum delay of FBA exceeds 100μs for the first time at ρ=0.5, and since the reservable TW is 80% of the total bandwidth, the maximum delay will increase sharply when ρ≥0.8. Since TA-DBA first appears as an unsuccessfully scheduled flow at ρ=0.8, the maximum delay rises to be comparable to L-DBA when ρ≥0.8. Bandwidth efficiency is the ratio of the bandwidth used by the ONU to the allocated bandwidth[10]. The average bandwidth efficiency of L-DBA and TA-DBA is 97.6% and 97.8% respectively, which is higher than that of FBA (77.4%). As the ρ≥0.5, there will be unsuccessfully scheduled flows in FBA, at which time all flows will reduce the bandwidth proportionally. The flow rate increases but the allocated bandwidth decreases, which makes the resource efficiency increase as the ρ increases.

Tab. 2: Simulation parameters

Parameter	Value
PON rate	9.95328Gbps
Size of time slot	12.86ns
t_G^s/t_G^d between same/different ONUs	823.04ns/ 205.76ns
SI of L-DBA	625μs
TSN switch/ Fieldbus port rate	9.95328Gbps
Processing delay in ONU/OLT	1μs

Conclusions

We proposed a TA-DBA scheme that was to constrain and specify TW position according to flow arrival characteristics. Simulation results showed that, compared with FBA and legacy-DBA, the proposed TA-DBA guaranteed bounded delay and jitter, and the average bandwidth efficiency was 20.4% higher than FBA.

Acknowledgements

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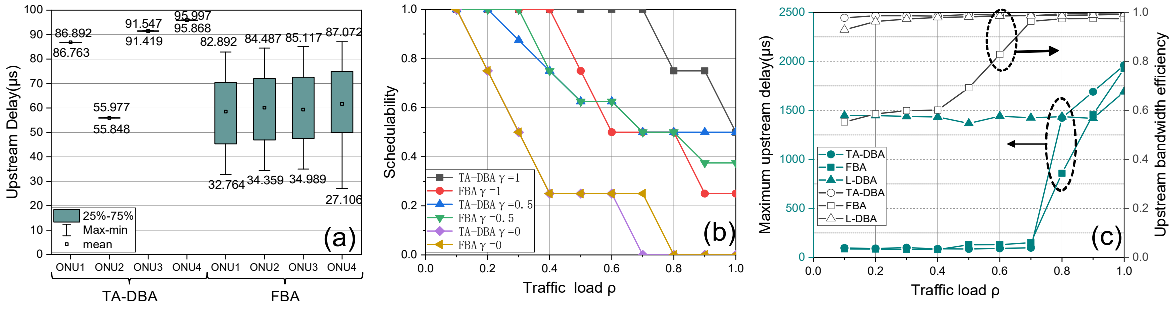

Fig. 3 (a) Minimum and maximum upstream delay of 4 ONUs; (b) Schedulability under different traffic load; (c) Maximum delay and bandwidth efficiency under different traffic load;

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