[Invited Paper] Time Gating Control Approaches for Time Critical Applications from Perspective of Wireless LANs and All Optical Networks

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***Abstract*—In recent years, with the proliferation of diverse time-critical applications, there is a growing need for technologies that can limit packet transmission delays within acceptable bounds while also maintaining low packet loss rates. This paper addresses this challenge by introducing the concept of Time-Gating Control. In particular, it aims to maintain compatibility with existing information network infrastructures like TCP/IP and CSMA/CA, ensuring low cost and high scalability. Initially, the paper focuses on wireless access networks in smart factory environments, proposing a method that introduces a hierarchical time-unit structure for periodic traffic, such as sensor data and surveillance video. This method determines time widths for the overlap-free transmission of varied periodic communications, thereby facilitating temporal load distribution. We present results from functional verification tests conducted using a software prototype in this environment. Furthermore, as a solution for non-pediodic traffic with permissive delay constraints, an overview of a virtual slot-based CSMA/CA method is introduced. In addition, targeting completely different applications, we explore the implementation of Time-Gating Control in All Optical Packet Switching Networks within Beyond 5G access-metro and data center networks. Here, we design a new TCP transmission method incorporating this control mechanism and discuss its advantages and superior performance.**

I. INTRODUCTION

In recent years, network traffic volume has been increasing, leading to performance degradation due to congestion. Furthermore, in wireless access networks, such as Wireless LANs (WLANs), Wireless Sensor Networks (WSNs), and wireless cellular networks, including smart factory environments, there is a growing prevalence of time-critical applications. These include control of mobile robots like Automatic Guided Vehicles (AGVs), autonomous driving control on roads, devices detecting human proximity, and surveillance cameras for anomaly detection in manufacturing equipment, etc.

Most MAC protocols in wireless access systems, such as WLANs and WSNs, adopt Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)-based random access protocols. While these protocols enjoy the benefits of low cost and high scalability, they sacrifice the ability to guarantee communication quality with high precision. In other words, while ensuring low cost and high scalability, it becomes challenging to strictly meet the latency and information loss requirements of time-critical applications, necessitating the development of solutions.

When seeking solutions to these problems, compatibility with the current information network infrastructure is crucial. Currently, the network infrastructure is based on packet-switching networks using TCP/IP, offering best-effort service, and wireless access MAC protocols predominantly use random access protocols like CSMA/CA. Therefore, solutions adhering to these premises are necessary.

This paper first focuses on the smart factory environment within the wireless access context and presents solutions to the aforementioned challenges. In this environment, both periodic and aperiodic traffic are anticipated. Periodic traffic includes regular transmission of sensing data and monitoring video information from devices to control servers, with numerous application examples. Aperiodic traffic includes both time-insensitive data communications and time-critical ones like alert information of equipment anomalies and human proximity detection. For example, in Smart Factory IoT communications, some data must be transferred within a permissible delay of 10 to 100 ms (refer to IEEE 802 Nendica Report [1]).

Regarding the traffic management policy in the newly proposed method, for periodic traffic, there is a need to achieve continuous low latency by equipping a control mechanism that appropriately shifts packet transmission timings in conjunction with the application. For aperiodic traffic, it is necessary to reactively keep the absolute time from packet generation at sender (sensing nodes) to packet reception at receiver (sink or control server) below the permissible delay.

Concerning the functional implementation of the proposed method, it can be controlled between the network and data link layers in the communication protocol hierarchy. This emphasizes the minimal impact on existing de facto standard protocols like TCP/IP and CSMA/CA.

It should be noted that this method can be generalized. For instance, it can be applied to general wireless access network

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environments beyond smart factory environment. Besides, we are focusing on “all optical packet switching network environments” applicable to Beyond 5G access-metro and data center networks, designing a new control mechanism based on our time-gating concept and proposing a new method applied to TCP traffic [2]. This paper introduces an overview of this method and its superior performance.

As a data transfer control design policy to maximally satisfy both End-to-End permissive delay and possibly low loss rate, the question of TDMA or Random Access arises. TDMA ensures throughput without packet collisions but consumes communication capacity in dedicated manner, and requires centralized control and time synchronization among all devices, leading to higher complexity and control overhead, even under low load conditions. On the other hand, Random Access, as exemplified by CSMA/CA, is inherently decentralized, requires no special time synchronization among devices, and is widely adopted due to its low complexity and cost-effectiveness. However, as mentioned above, it has the disadvantage of increased latency under medium to high load conditions due to frame collisions and retransmissions. Our research focuses on the Random Access approach, considering its low cost and high scalability. In this approach, inherent issues arise from the increase in frame transfer delays due to backoff mechanisms and retransmissions, as well as increased frame loss rates caused by the constraints of retransmission limits in medium to high load domains. While Enhanced Distributed Channel Access (EDCA) can somewhat mitigate these issues by prioritizing control, this technique inherently provides relative and probabilistic differentiation and cannot differentiate between frame transmissions within the same priority class.

II. RELATED WORK

A. Outline of Latency-Aware MAC Protocols

Many methods based on TDMA or quasi-TDMA were presented so far. For instance, Zero-collision MAC (ZC-MAC) [3] introduces a TDMA based virtual schedule. Slot stealing MAC (SS-MAC) [4], CSMA/AP [5], and w-SHARP [6] treat aperiodic traffic delay deadline. Jin et al. [7] assume that both aperiodic and periodic packets have deadlines. These TDMA-based methods require time synchronization among nodes. As a result, nodes require higher computational power and tend to be more complicated and expensive. This is not desirable for WLANs and WSNs in which sensor nodes strongly require low cost. In addition, the TDMA-based methods are not suitable for dynamic environments in which packet flows are newly created and terminated over time.

As for the CSMA/CA-based methods, Sultana et al. [8] proposed a MAC protocol that exploits dynamic contention window (CW) sizes, depending on their priority, and new superframes in a co-existing environment of critical/emergency traffic and non-critical/normal traffic. However, this approach still follows the relative and probabilistic priority setting of adaptive CW settings, such as IEEE 802.11e EDCA.

Alternatively, in this paper, we focus on an application layer approach to control transmission timings of aperiodic and periodic packets. This has an advantage that no modification is required for the MAC layer; thus, it is advantageous that our proposed method is applicable to widely diffused MAC protocols with low cost like IEEE 802.11 and IEEE 802.15.4. In addition, the proposed method can be used in combination with such other existing MAC layer approaches in principle.

As for an application layer approach to decide transmission timings of periodic packets with different cycles, we exploit Content Score Method (CSM) [9] as the baseline.

Specifically, the CSM avoids collisions only among periodically generated packets in assumed WLAN/WSN environments where only such periodic packets exist, and do not consider collision avoidance with aperiodic packets in environments where both aperiodic and periodic packets are transferred. In contrast, our new proposal, called Discrete-time CSM (D-CSM) [10], introduces hierarchical virtual time unit structure on the CSMA/CA-based random access protocol and manages the various periodic traffic, which enhances the implementation feasibility and flexibility.

III. TIME-GATING CONTROL IN WIRELESS LAN: A GENERALIZED VIRTUAL TDMA-BASED CSMA/CA METHOD

A. Overview of System Operation and Component Configuration

We developed a prototype system of the Generalized Virtual TDMA-based CSMA/CA Method and conducted several experiments to verify its operation [10]. This control is realized with a software buffer provided just before packets are passed from the upper IP layer to the MAC layer so that existing IEEE 802.11 devices are used without replacing them.

The overall system of the proposed method is shown in Figure 1. The system consists of a coordinator (COD) and WLANs that use a same channel. Each WLAN consists of an access point (AP) and the associated STAs. The COD is connected to all the APs via wired lines and controls the transmission timings from STAs to their associated AP. Time slots with the length T_{slot} are continuously assigned on the time axis, and time slices with the length T_{slice}, each of which consists of multiple consecutive time slots, are also defined. Start time of each time slot is loosely synchronized among the COD, APs, and STAs in notified manner through beacons that are broadcast at the interval of the allocation cycle T_{table} from the COD and extended to have the information of time slot allocation to STAs. Note that there is no requirement for precise time synchronization among the COD, APs, and STAs because APs and STAs have only to manage timers upon the receipt timing of beacon message.

B. Hierarchical Time Unit Structure

Figure 2 shows the hierarchical time structure, and this time structure is constructed based on the T_{table}. The time slice and time slot serve as internal components of T_{table}. In cases where an allocation extends beyond a time slice or time slot

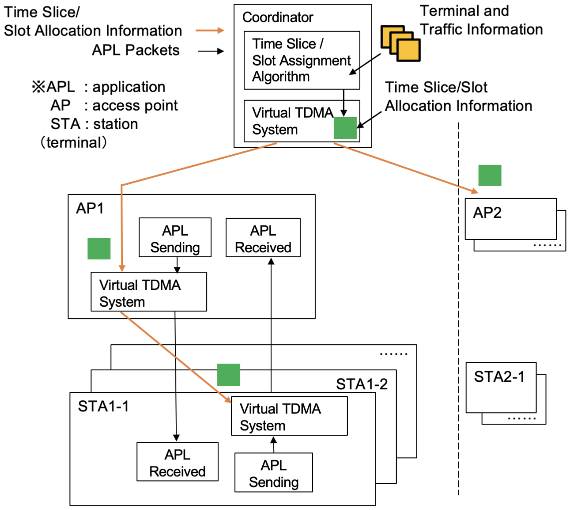

Fig. 1. Overall system of the proposed method.

boundary, the portion that exceeds the boundary is allocated in the subsequent beacon. This portion is managed as the offset information in COD, which makes any time-period of periodic traffic accommodate to WLAN.

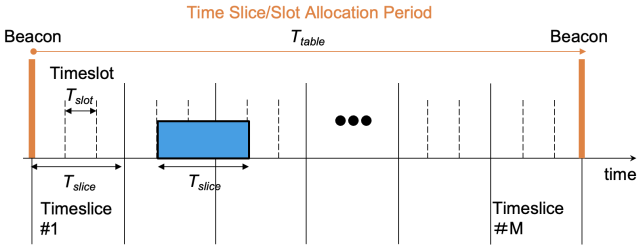

Fig. 2. Time slice/slot definition (in case that one T_{slice} is composed of three T_{slot}).

C. Method for Accommodating Periodic Traffic Using Hierarchical Time Unit Structure

Discrete-time Contention Score Method (D-CSM) adapted to hierarchical time unit structures follows the naive CSM [9]. The example of time-slice allocation algorithm is shown in Figure 3. The D-CSM operates according to the following two steps: (1) When a new periodic traffic is generated from a new terminal, CS value is calculated for each time slot; (2) The time slice position (in other words, time shift volume) with the smallest CS is allocated to the new terminal.

In D-CSM as well as CSM, when a new source node N_j starts to transmit periodic packets, the sink determines the suitable periodic packet transmission timing for N_j using contention score (CS). In Figure 3, t_{0i} and s_i are defined as the time point when traffic of node N_i first occurred, and the time shifted for node N_i, respectively. Nodes N_i and N_j are assigned the same time interval T_{slice} for the reserved transmission (blue parts in Figure 3) for simplicity. T_i and T_j are periodic packet generation intervals of node N_i and N_j.

The transmission timing difference between the two terminal nodes N_i and N_j, Δ_t, is

$$\Delta_t = (t_{0i} + s_i) - (t_{0j} + s_j)\,.$$

The greatest common divisor of the packet transmission period of the two terminals, d_{ij}, is

$$d_{ij} = \texttt{gcd}\,(T_i, T_j)\,.$$

The minimum traffic generation timing difference between the two terminals, δ_{ijmin}, is

$$\delta_{ijmin} = d_{ij} \cdot \texttt{frac}\left(\frac{\Delta t}{d_{ij}}\right).$$

Time (the multiple of T_{slot}) when the transmissions of N_i and N_j overlap each other (pink part in Figure 3), $t_c(i,j)$, is derived as follows:

$$t_c(i,j) = \begin{cases} 0 & \text{when } \delta_{ijmin} \geq T_{slice} \\ T_{slice} - \delta_{ijmin} & \text{when } \delta_{ijmin} < T_{slice}. \end{cases}$$

Least common multiple of the packet transmission period of nodes N_i and N_j, T_{ij}, is

$$T_{ij} = \texttt{lcm}(T_i, T_j).$$

Then, the CS of N_j, CS_j, is calculated as follows:

$$CS_j = \sum_{i=1}^{j-1} \frac{t_c(i,j)}{T_{ij}}.$$

Contention scores are calculated for some time points in $[0, T_j]$, and periodic packet transmission timing from N_j, that is s_j, is finally chosen from among the time points whose CS values are minimum. Here, if two or more same transmission timings with the same smallest CS value were found, then the nearest future time slot is selected in D-CSM differently from the center time slot selection in naive CSM.

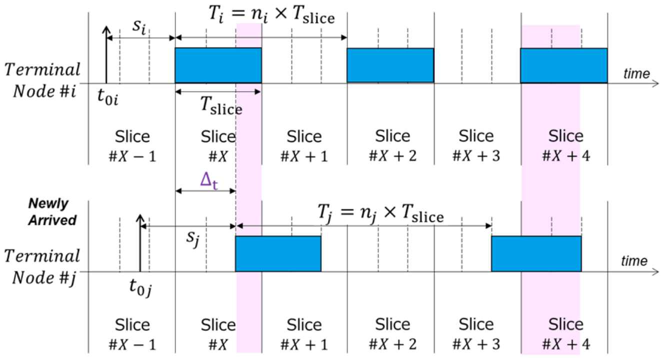

Fig. 3. Time Slice Allocation Algorithm by Discrete-time CSM.

D. Control and Evaluation of Aperiodic Traffic with Time Constraints

For periodic traffic, the framework described in the previous section allocates time slices (denoted as T_{slice}) with different cycles and widths to each other with minimal overlap. This approach facilitates temporal load balancing and enables the reduction of loss and delay, even when temporal fluctuations occur due to CSMA/CA. On the other hand, discussing a more rigorous approach, based on the aforementioned allocation in T_{slice} time units, when the gate is turned on, the transmission of accumulated periodic traffic packets in the send buffer is permitted. These packets are continuously transmitted following the CSMA/CA protocol. However, not only notifying the transmission permission terminal allocation information every T_{slot} through beacon signals but also notifying the transmission timing of each periodic traffic during T_{table} can enable time-constrained transmission of aperiodic traffic outside these specified timings for periodic traffic. Regarding transfer timing, a unit called a *Virtual Slot* is defined, which ensures a safety margin for the one-packet transmission time based on CSMA/CA, and this unit is used to understand the allocation information. It is important to note that the Virtual Slot is expected to be on the order of one packet transmission time and considerably smaller than T_{slot}. In this context, we have already proposed the CSMA/CA with Virtual Slot based Scheduling method (CSMA/CA-VS) [11]. While the details are omitted here, the main features of this method are as follows: (1) Utilization of Virtual Slots: Aperiodic packets are transmitted within these designated virtual slots, strategically placed outside the transmission intervals of periodic packets. (2) Control of Virtual Slot Selection Width Based on Packet Loss Rate: The selection width of virtual slots is dynamically adjusted based on the packet loss rate, balancing the risk of packet collisions and the increase in delays. (3) Special Consideration for Packets with Delay Constraints: Packets with permissible delays are transmitted using virtual slots selected within a limited width to meet their delay requirements.

Figure 4 shows the allocation of transmission timings for aperiodic packets within the time constraint (W) in the CSMA/CA-VS method.

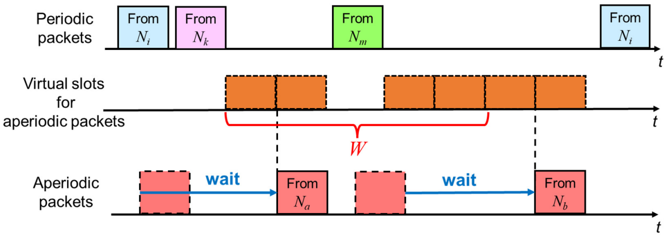

Fig. 4. Transmission of aperiodic packets with virtual slots ($W = 4$).

The CSMA/CA-VS method allows for operation within the constrained time range without concern for the usage timing of periodic traffic. In this scenario, although there is a possibility of collisions between periodic and non-periodic packets, prioritizing the transfer of periodic packets using EDCA can mitigate latency variations.

In our previous work [11], we confirmed the following results mainly. By distributing transmission timings of aperiodically generated packets from the application layer during periods when periodic packet transmissions are not scheduled, the loss rates of all the types of periodic, non-delay-bounded aperiodic, and delay-bounded periodic packets were suppressed compared with the existing method that schedules the transmissions of only periodic packets. In addition, average transfer delay of delay-bounded packets was adequately restricted within their permissible delays.

E. Experiment on Periodic Traffic Accommodation in our prototype of the Proposed Method

1) Experiment Scenarios: To evaluate the performance of our proposed method for periodic traffic, we constructed a prototype [10] as depicted in Figure 5, utilizing four Raspberry Pi (RPi) 4B units and a desktop computer. Each RPi, running Debian GNU/Linux 11 (64-bit) with a 1.5 GHz Broadcom BCM27114 processor and 8 GB LPDDR4 RAM, serves distinct roles: three as STAs and one as an AP. The desktop, powered by an Intel Core i9-10908XE processor at 3 GHz and running Ubuntu Desktop 16.04 LTS (64-bit), functions as the coordinator (COD) to manage transmission timings. In our tests, each STA produces 500 B periodic packets, transmitting them every 100 ms via the 802.11n WLAN protocol.

The evaluation in this paper encompasses two distinct scenarios, crafted to assess the system's performance under varying conditions. The first scenario involved an experiment where each STA independently generated and transmitted packets, without any control from the COD, providing a baseline for evaluating the system's functionality without COD influence. In the second scenario, the COD actively managed all STA transmissions using designated timing parameters, employing a T_{table} of 600 ms, a T_{slice} of 200 ms, and a T_{slot} of 100 ms. This setup guaranteed non-overlapping transmissions among the STAs, setting each STA's transmission cycle at 600 ms and initiating first traffic transmissions at 0 ms, 200 ms, and 400 ms, respectively.

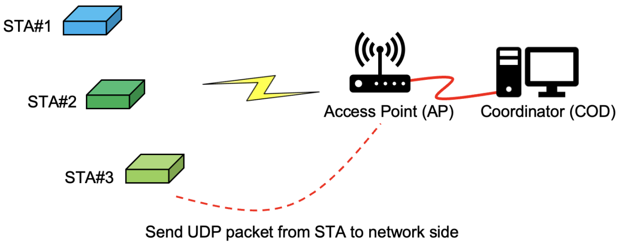

Fig. 5. The prototype's structure for the performance evaluation

2) Experiment Results: Figures 6 and 7 show 3000 ms interval graphs from scenarios 1 and 2, respectively. The vertical axis is for identification only: STA packets are uniform in height, while beacon messages are twice as tall.

In scenario 1, without COD control, each STA uses the CSMA/CA protocol for packet transmission. Packets are sent to the AP every 100 ms. Figure 6 depicts STA1's packets, colored green and sent every 100 ms as per the experiment's design. Despite equally spaced initial transmissions preventing collisions, all packets were transmitted smoothly according to CSMA/CA.

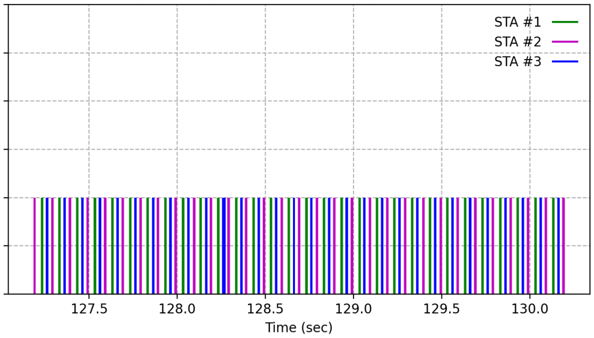

Fig. 6. Packet transmission on scenario 1.

In scenario 2, the COD directs each STA's transmission, with slot assignments remaining constant from the experiment's start to its end, as detailed in Table I. Due to identical transmission cycles for all STAs, slot allocation is consistent throughout.

As for Table I, STA1 is assigned slots 1 and 2 (first slice), STA2 receives slots 3 and 4 (second slice), and STA3 is allocated slots 5 and 6 (third slice). Each STA transmits packets following these allocations, as shown in Figure 7, across four beacon transmission cycles.

TABLE I
SLOT INFORMATION ASSIGNED BY D-CSM AT COD IN SCENARIO 2

STA	**Slot allocation**					
ID	***1***	***2***	***3***	***4***	***5***	***6***
STA#1	1	1	0	0	0	0
STA#2	0	0	1	1	0	0
STA#3	0	0	0	0	1	1

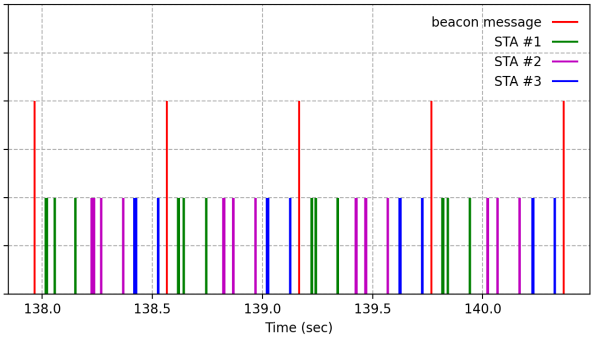

Fig. 7. Packet transmission on scenario 2.

IV. Application of Time-Gating Control to Other Environments: All-Optical Network Scenarios

A. *Proposal of TCP with Time-Gating Functionality*

In bufferless Optical Packet Switching (OPS) networks, packet loss can occur at output ports of relay nodes due to simultaneous packet arrivals, regardless of congestion. We introduce a transport protocol that autonomously controls burst transmission timing and intervals, distinct from conventional TCP modifications like congestion avoidance, window control, and pacing mechanisms. Our approach, called TCP with Timer-Triggered Transmission (TCP-T^3) maintains constant burst packet transfer intervals on a per-flow basis, yielding over 7 times higher network throughput than standard TCP, as confirmed by extensive simulations [2].

Figure 8 provides an overview of the burst transmission process in TCP-T^3, where a sender host sets a transmission timer (T^{tra}) based on the Round-Trip Time (RTT) during connection setup and a preset minimum value (T^{tra}_{min}). Unlike conventional TCP, upon establishing a TCP connection, the sender transmits an initial data burst sized to the congestion window and starts the timer, set to expire after T^{tra}. The host updates the congestion window upon receiving new ACKs but delays subsequent packet transmissions until the timer expires. At expiration, it sends a new data burst for the updated window size and resets the timer for the next burst. Thus, TCP-T^3 achieves periodic burst transmissions at intervals set by T^{tra}. If there are no packets to send at timer expiration, only the next timer is set, with no transmission.

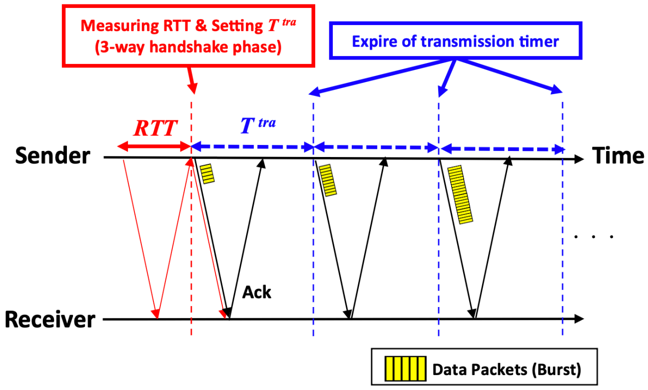

Fig. 8. Overview of data transmission in TCP-T^3.

B. *Simulation Evaluation*

We implemented TCP-T^3 on network simulator ns-3 and conducted simulation experiments. Simulation topology follows so-called dumbell topology with an core link of 100 km, and access links are distributed between 1 to 10 km, and n source-desitination node pairs communicate in parallel. The greater the increase in n, the greater the network load. For simplicity, all links with transmission speed of 10 Gbps were bidirectional, and the number of channels in each link was assumed to be one. If two optical packets collided at the output port of the relay node, the latter was lost. We compared TCP-T^3 with conventional TCP, represented by NewReno, setting the initial retransmission timer (T_{ini}^{ret}) to 1 s, and also examined a modified parameter scenario reducing T_{ini}^{ret} to 1 ms. TCP-T^3's congestion control algorithm matched NewReno's one. The minimum transmission timer (T_{min}^{tra}) was 100 µs, with S set to 10. Both TCP versions had an initial window of 10 segments and a maximum window of 64 KB. The maximum transmission unit (MTU) was 1500 bytes, and the SACK option was enabled. TCP connections began transmitting data randomly between 0.0 and 1.0 s from simulation start, continuing for the total 50 s duration.

Figure 9 compares network throughput, defined as total data received per unit time at the application layer, across different n values. TCP-T^3 consistently outperformed NewReno in throughput, regardless of the initial retransmission timer setting. Notably, TCP-T^3 (T_{ini}^{ret}=1 ms) performed best under low to medium network loads, peaking at n=30 with throughputs 11.4 times and 5.07 times higher than NewReno's two settings. At n=100, TCP-T^3 (T_{ini}^{ret}=1 s) achieved the highest throughput, 8.70 and 3.45 times higher than NewReno's respective settings. This variation in TCP-T^3's performance, influenced by the initial retransmission timer values, is attributed to network congestion.

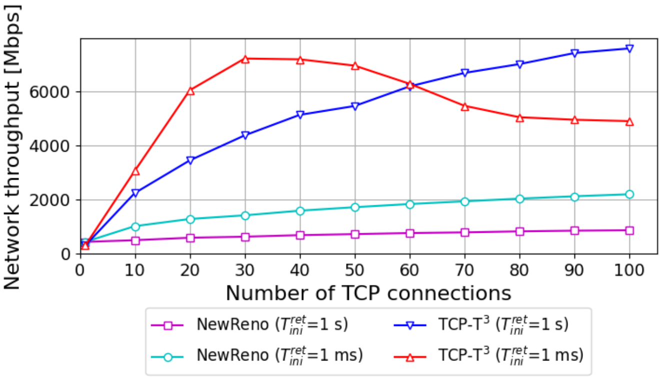

Fig. 9. Number of TCP connections vs. Network throughput.

V. CONCLUSION

In this paper, we tackled the challenge of reducing packet transmission delays and maintaining low packet loss rates for time-critical applications by introducing Time-Gating Control. This approach, compatible with existing TCP/IP and CSMA/CA infrastructures, was particularly effective in wireless access networks for smart factories, where it managed periodic traffic like sensor and surveillance data through a hierarchical time-unit structure. The method proved successful in ensuring maximally overlap-free transmission and effective load distribution, as confirmed by tests with a software prototype. Additionally, we addressed non-periodic traffic with permissive delay constraints using a virtual slot-based CSMA/CA method. Expanding our scope, we applied Time-Gating Control to "all-optical packet switching networks" in Beyond 5G environments, creating a novel TCP transmission method that demonstrated superior performance.

ACKNOWLEDGEMENT

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