Wireless Time Sensitive Networking for Industrial Collaborative Robotic Workcells

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***Abstract*—In this paper, we describe a collaborative robotic workcell testbed enabled by Wireless Time Sensitive Networking (WTSN) technologies and discuss deployment, performance measurement, and management guidelines challenges. We detail the methodologies for implementing and characterizing the performance of key WTSN capabilities (time synchronization and time-aware scheduling) over IEEE 802.11/Wi-Fi. We deployed WTSN capabilities on the National Institute of Standards and Technology (NIST) collaborative robotic workcell testbed consisting of two robotic arms that emulates a material handling application, known as machine tending. We further explore configurations and measurement methodologies to characterize Quality of Experience (QoE) of this use case and correlate it to the performance of the wireless network.**

***Index Terms*—Wireless TSN, IEEE 802.11, Collaborative Robotics**

I. Introduction

Sharing computing and network resources between physical Operational Technology (OT) and digital Information Technology (IT) in smart manufacturing applications needs strictly time-synchronized and deterministic low latency communications [1]. Time Sensitive Networking (TSN) [2] and its wireless counterpart [3] are developed to achieve precise time synchronization and timeliness in a network shared by time-critical traffic and other types of traffic. This paper studies the feasibility of a wireless collaborative robotic workcell application enabled by wireless TSN.

A collaborative robotic workcell testbed was constructed at the National Institute of Standards and Technology (NIST), with service requirements that are representative of a typical machine tending application. The testbed characterizes deterministic and reliable communication needs between workcell components. The testbed baseline design over a wired network has been introduced in an earlier publication [4], while experiments with a 2x2 Multiple-Input Multiple-Output (MIMO) wireless IEEE 802.11ac technology is added in this work.

Extension activities of TSN capabilities [5] to wireless domain are described in [6]. Since Wi-Fi is an IEEE 802 Local Area Network (LAN) technology, TSN link layer capabilities can be mapped seamlessly from Ethernet to Wi-Fi. However, achieving the same wired time synchronization performance over IEEE 802.11 involves many open research questions. In this paper, we focus on characterizing and assessing the performance of two major TSN features that have been extended into IEEE 802.11, namely, time synchronization (IEEE 802.1AS) and time-aware shaping (IEEE 802.1Qbv).

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II. Wireless TSN Overview

In this section, we introduce an overview of Wireless TSN (WTSN) capabilities and various system components. Fig. 1 illustrates a typical hybrid TSN network architecture where TSN capabilities in the wired segment is extended into a Wi-Fi segment of the network. It is assumed that the network is centrally managed, which is the case in most industrial internet of things (IoT) deployments that are relevant for the applications considered in this paper.

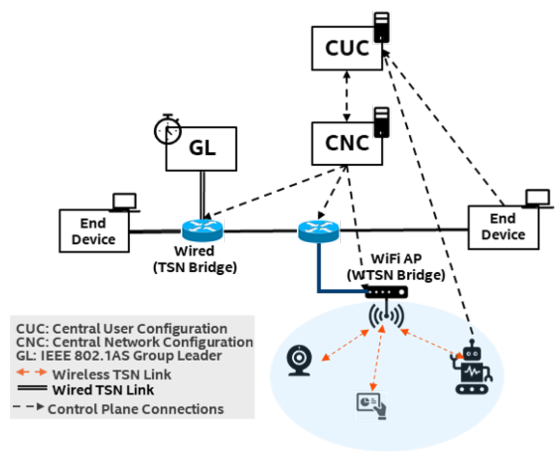

Fig. 1. Wired-Wireless hybrid TSN network architecture.

In a TSN network, every traffic stream is centrally managed and configured. This function is performed by two functional entities namely, the Central User Configuration (CUC) and the Central Network Configuration (TSN-CNC[1]) as specified by IEEE 802.1Qcc. The CUC collects traffic stream information from all the end devices and provides the information to the TSN-CNC. The TSN-CNC, using its discovered knowledge of the network topology, configures resources on each network element on the path to meet the timing requirements of the traffic streams. This may include configuring IEEE 802.1Qbv schedules at the bridges in the infrastructure.

Achieving precise time synchronization across all the devices in the network is foundational to any TSN capable

[1]According to the TSN standard, this entity is abbreviated as CNC but since we have other entities having the same abbreviation in this paper, we will henceforth refer to this entity as TSN-CNC.

network. The IEEE 802.1AS standard is the protocol defined for time distribution in a TSN network and it can operate over Ethernet and Wi-Fi (IEEE 802.11) [7]. The IEEE 802.11 specification has defined mechanisms to support the propagation of time as specified in IEEE 802.1AS. These mechanisms are based on exchange of precisely timestamped action frames between nodes to propagate a reference time. The WTSN implementation [6], used in this paper, uses the Timing Measurements (TM) feature in the IEEE 802.11 specification.

Another fundamental TSN feature is Time Aware Shaping which enables delivery of time-critical data within deterministic time windows, without being impacted by other background/interfering traffic sharing the network. Time Aware Shaping implements a time-division multiple access (TDMA) scheme of scheduling packets by giving packets of different traffic classes access to the communication medium within different time slots [2]. In this paper we evaluate our implementation of the concept of IEEE 802.1Qbv over IEEE 802.11 using an industrial workcell testbed.

III. NIST Collaborative Robotic Workcell Testbed

In this section, we present a brief description of the industrial wireless testbed design. We also present the modifications performed to the testbed to enable the WTSN. We use a collaborative workcell testbed, which was developed and implemented at NIST. We extended the testbed with WTSN and precise measurement capabilities to be able to characterize and measure the use case's physical and network performance. For brevity, the design of the testbed itself, the equipment used, as well as the information data flows are detailed in [4], and are not included in this paper. This paper will discuss the modifications made to enable WTSN.

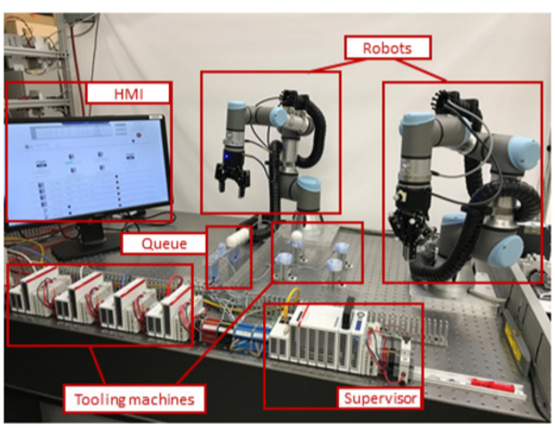

Fig. 2. Collaborative robotic workcell testbed.

At a high level, the industrial wireless testbed emulates a collaborative industrial workcell, which is shown in Fig. 2. There are two robots, operator (OPT) and inspector (INS), which move and inspect parts within the work zone. There is a supervisor programmable logic controller (PLC) that coordinates the operations in the testbed by sending commands to the robots, as well as receiving inputs from the four computerized numerical control (CNC) emulators, which are able to sense the presence of the acrylic balls in the work zone. A grand leader clock (GL) is used to synchronize all times of measurement devices and the wireless access point. A previous work that uses a similar testbed configuration and implements a graph database approach for performance evaluation without TSN can be found in [8].

To enable WTSN, wireless networking is introduced using a Wi-Fi access point (AP) and two Wi-Fi stations for each robot. These three wireless nodes are equipped with a WTSN software stack, which extends TSN features into the Wi-Fi domain. These nodes are Intel-based next unit of computing (NUC) systems (Onlogic ML100G-51) equipped with an Intel 9260 IEEE 802.11ac Wi-Fi card [9]. The AP node synchronizes its time with the GL in the network over IEEE 1588 Precision Time Protocol (PTP). The AP propagates this time over Wi-Fi to the two stations using the IEEE 802.1AS time synchronization protocol.

IV. Wireless TSN Evaluation

A. Measurement setup and methodology

To enable measurement and comparative analysis of WTSN, the nodes described in the previous section also function as measurement probes capturing and measuring wireless time synchronization data. Wired Ethernet Test Access Points (TAPs) installed at strategic points in the network, shown in Fig. 3, capture all network packets sent between the nodes at multiple points. Multiple 4-port Ethernet PCIe cards simultaneously capture traffic from the TAPs, shown in Fig. 3. Data is also captured from the robots through its real-time-data-exchange (RTDE) interface. The measurement methodology involves running the machine tending use case in the presence of various levels of interfering traffic and evaluating network and application performance with and without WTSN. The complete measurement setup is illustrated in Fig. 3.

To measure the network performance metrics, difference in the capture time of the same traffic at multiple points is leveraged. Moreover, the time synchronization errors between any node and the GL range from less than 1 microsecond, in the case of wired nodes, to less than 100 microseconds in the case of wireless nodes with a 99% confidence interval.

B. Key Performance Indicators (KPIs)

The KPIs and corresponding metrics were chosen while keeping in mind the goal of evaluating the performance of WTSN on the testbed. In order to evaluate the overall performance, different types of KPIs are needed. The metrics under the network performance KPIs will provide a measure of how well the network is performing with respect to the time sensitive requirements of the application. Similarly, the metrics under the application KPIs provide measures of the efficiency of the application. The metrics measured in this work, and their description are summarized in Table. I.

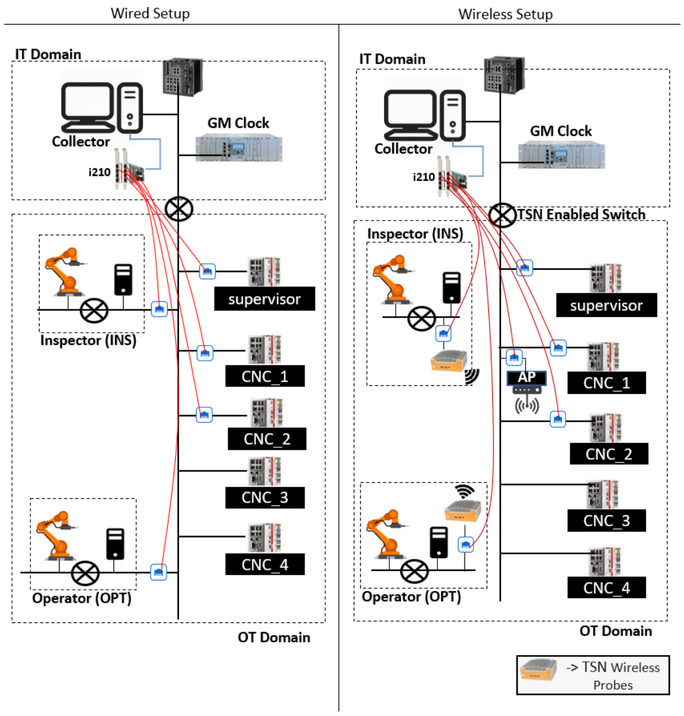

Fig. 3. Wireless TSN measurement setup of workcell testbed.

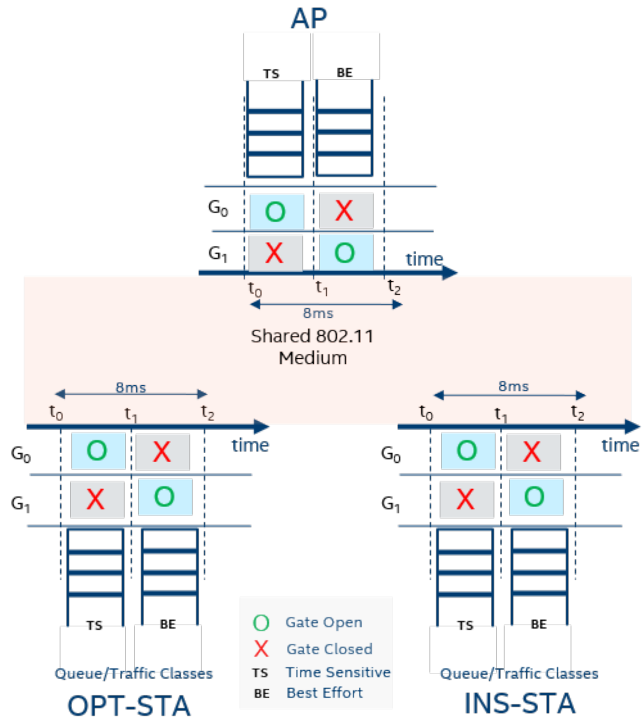

Fig. 4. WTSN Schedule in the wireless medium.

TABLE I
KPI METRICS

KPI	Description
Packet Delivery Ratio (PDR)	PDR is defined as the ratio of data packets delivered within a defined latency threshold between key points in the network.
Latency Cumulative Distribution Function (CDF)	The Latency CDF captures the distribution of latency across all data packets observed for a network flow.
Idle Time	The amount of time the robots have spent idling due to delays in updating state changes.

C. Time-aware schedule for wireless domain

The traffic between the PLC and the two robots are the two Time Sensitive (TS) traffic streams in the use case. In order to protect this traffic from interference due to any best effort (BE) traffic, the shared 802.11 link implements a time-aware (802.1Qbv) based schedule with protective slots for the TS traffic. This schedule is illustrated in Fig. 4. The schedule repeats every 8 ms to match the frequency of the two TS streams and each 8ms period is further divided into slots for TS traffic (5ms) and BE (3ms) traffic. This schedule is synchronized across all the nodes in the shared link in order to create protective periods for the TS traffic. The schedule also takes advantage of the inherent staggering between the two TS traffic streams.

The start of the application's use case and the start of the schedules are synchronized as close as possible through automated synchronization scripts. In an ideal TSN network this schedule and synchronization will be coordinated centrally by the CUC and TSN-CNC, as discussed previously. Although the protocols for coordination and resource management have been standardized, implementation and optimization of these entities are still an active area of research, especially in the wireless domain. It should be noted that the capacity available to BE traffic is reduced as a result of enabling the schedule as the BE traffic gets only 37.5% of the cycle period for transmitting. On top of that, some of that bandwidth will be further consumed by opportunistic shaping, or guard band, hence the effective rate of the medium is reduced. Note that this is an acceptable trade-off in TSN networks as the primary goal is to guarantee determinism for time-critical traffic.

V. RESULTS

In this section, we will discuss the results produced from the testbed. The measurement methodology is highlighted in section IV-A. Fig. 5 shows the PDR for packets with a measured latency of less than 5 ms. We can see a significant drop in PDR without TSN enabled, which is related to the amount of interference traffic. We can see that enabling the TSN schedule is able to bring the overall latency profile of the time sensitive streams closer to the wireless baseline benchmark (99.8%).

In Fig. 6 we show the cumulative density function (CDF) comparison of the latency distribution of operational traffic in the presence of worst-case interference traffic (20 Mbps) when the TSN schedule is both enabled and disabled. When the TSN schedule is enabled, more than 99% of time sensitive packets experience a bounded latency of less than 5ms. When

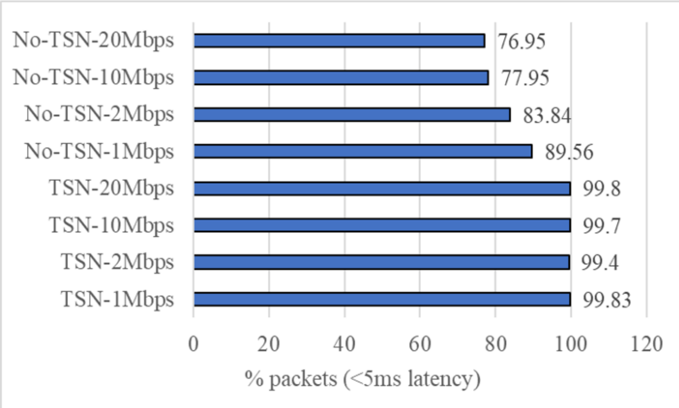

Fig. 5. Packet Delivery Ratio for latency < 5ms with TSN and no-TSN cases with varying levels of interference traffic.

the TSN schedule is disabled, the percentage of packets within the latency bound of 5ms decreases to approximately 77%.

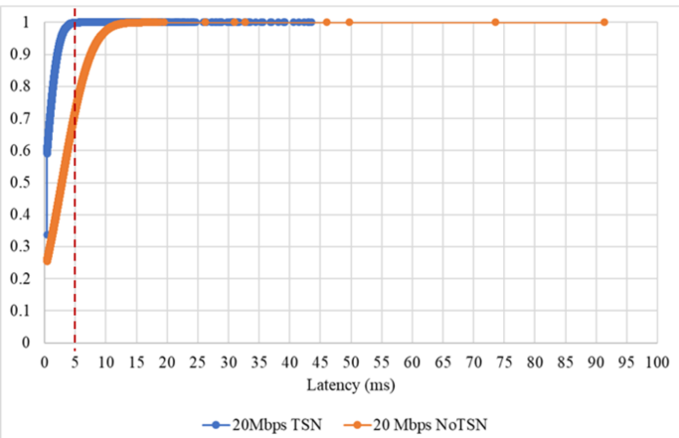

Fig. 6. Latency CDF of packets with and without TSN enabled.

The increase in the percentage of packets experiencing latency outside of tolerable bounds is also reflected in the application's performance, as shown in Fig. 7.

With TSN, the percentage of time in idle experienced by the operator robot is lower compared to the case when TSN is disabled. When TSN is disabled, there is competing BE traffic in the network with no protection for the time sensitive traffic, which increases latency, and consequently, the idle time of the operator robot as is takes more time to receive commands from the supervisor PLC. The decrease in the wireless link delay from TSN being enabled increases the efficiency of the use case, which can be desired to increase the production rate in an industrial setting where collaborative robots accomplish supervisory tasks over wireless.

VI. Conclusions

In this paper, wireless TSN capabilities were used to deliver low latency communications for an industrial collaborative robotics use case. A detailed analysis of the latency and its

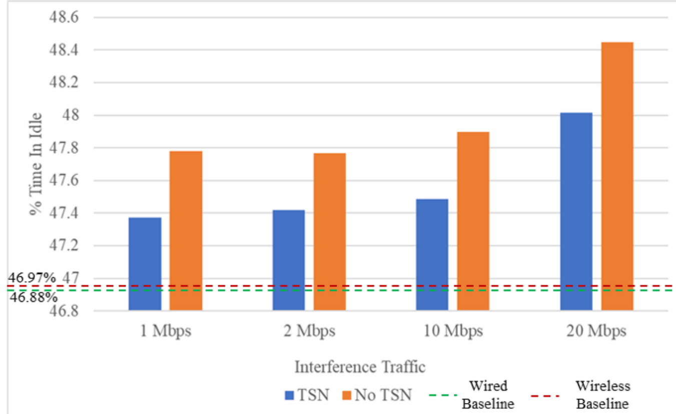

Fig. 7. Operator (OPT) Idle time across all scenarios.

correlation to the overall use case efficiency was presented. There are many challenges that should be addressed in order to fully support TSN in the wireless domain. We hope to address these challenges and revisit these experiments with new scheduling and TSN capabilities in Wi-Fi 6 and beyond.

Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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