Unobtrusive, Accurate, and Live Measurements of Network Latency and Reliability for Time-Critical Internet of Things

Koushik Bhimavarapu, Zhibo Pang, Ognjen Dobrijevic, and Pawel Wiatr

Abstract

Time-Critical Internet of Things (TC-IoT) applications place very stringent communication requirements on underlying networks in terms of latency and reliability. To verify experimentally if wireless networks can fulfill those, an appropriate method to measure latency and reliability needs to be developed. State-of-the-art methods are either obtrusive to and dependent on application setup, or insufficient in accuracy. In this work, we propose a new solution called Unobtrusive Latency Tester (ULT) to measure the latency and reliability of wireless networks for TC-IoT applications. The ULT can be seen as unobtrusive to time-critical applications since the insertion delay is shorter than 1 µs and the accuracy of latency measurements is 40 ns. We apply the ULT in a real-life motion control testbed that uses Wi-Fi 6 and 5G networks. The presented results show the feasibility of the proposed approach. We also provide some initial observations on the latency and reliability of current Wi-Fi 6 and 5G technologies and the possibility of their use for TC-IoT applications.

Introduction

The emerging wireless networks with low latency and high reliability will play prominent roles in Time-Critical Internet of Things (TC-IoT) in, e.g., process automation, factory automation, motion control, robotics, power grids, transportation, healthcare, and energy infrastructure [1, 2]. The required latency of those TC-IoT applications spans from 10 µs to 100 ms, with reliability up to 99.999999 percent and even higher [2]. Recently, cellular technologies, especially 5G [3], and the Wi-Fi standard, especially Wi-Fi 6 [4], have achieved considerable progress towards low latency and high reliability, encouraging the industry verticals to pursue integrating the 5G and Wi-Fi 6 technologies into their TC-IoT applications [5].

However, industrial users are cautious about the promised latency and reliability of wireless technologies due to the lessons learned in the past two decades [1]. Systematically evaluating the latency and reliability of the Ultra Reliable Low-Latency Communication (URLLC) technologies that are integrated into real TC-IoT systems is still an open question and of high priority among major players, such as Ericsson, Nokia, Intel, Siemens, and Bosch [5–9]. The quality of the evaluation method and its results are crucial for the industrial users to make strategic decisions that are not just about the destiny of a certain product but also about the overall strategy (i.e., yes, or no) and roadmap (i.e., what, when, and where) on wireless, mainly because the promises, expectations, and bets are too big to afford any failure.

In particular, the evaluation method is required to be accurate enough to address the required latency and reliability of the TC-IoT applications. The method is also expected to be unobtrusive to the applications so it can be easily added to or removed from a functional realistic testbed with real traffic and run for a long time, instead of using synthetic traffic or hard-coding measurement functionalities in the application. Moreover, the evaluation platform needs to be applicable to a large number of protocols in the world of industrial networks. Unfortunately, the literature survey and discussions with leading wireless vendors suggest that existing evaluation methods are either obtrusive (i.e., introducing additional communication and computing loads and thus affecting the behavior of the application) or even do not provide enough accuracy to address the latency and reliability levels required by those TC-IoT applications.

In this article, we introduce a novel method called Unobtrusive Latency Tester (ULT) to measure communication latency and reliability for TC-IoT over wireless networks. The ULT introduces less than 1 µs insertion latency and assures 40 ns accuracy of latency measurements, which are short enough to address the required latency of the TC-IoT use cases in the contexts of the automation industry. It is transparent to the applications and independent of the amount or type of monitored traffics. It can measure the network latency and reliability at the Data Link Layer or a higher layer of the Open Systems Interconnection (OSI) model irrespective of the underlying networks. It can support mainstream Industrial Ethernet (IE) protocols, such as PROFINET, Modbus/TCP, Ethernet/IP, OPC UA, and more can be extended easily in the future. The ULT is validated by implementation in a real-life automation testbed that uses two different wireless technologies, namely 5G and Wi-Fi 6.

Challenges and Architecture

To measure the communication latency of a Network Under Test (NUT) between two devices A and B, one needs to know the time when a packet enters and exits the NUT. Such a measurement can be achieved by introducing probes with special features before and after the NUT. Figure 1 shows the main components of the measurement architecture together with key features required to achieve precise and unobtrusive latency measurements. Both probes provide a hardware-timestamped copy of every packet for further processing on a separate device

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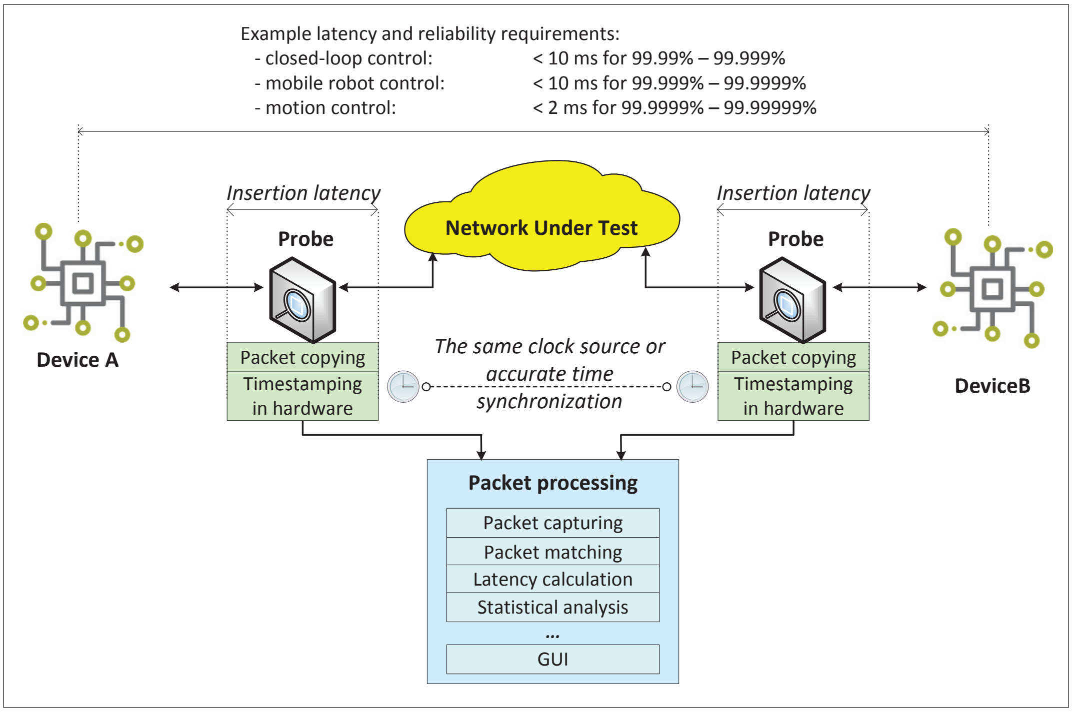

FIGURE 1. Components necessary for precise latency measurements — general view.

(PC). As the copies of the packets are already timestamped, the order they are received for packet processing may not have stringent requirements. Having two timestamped copies of the same packet, one before entering and one after exiting the NUT, allows for calculating the packet latency introduced by the NUT.

To assure the unobtrusiveness of the measurements, the probes should have only a negligible impact on the traffic. The packets passing through a probe and their order must be unchanged (i.e., first-in-first-out) and the latency introduced by the probe itself, referred to as insertion latency, must be deterministic (preferably constant) and negligible as compared to the communication requirements of TC-IoT applications (Fig. 1). A significant delay or its variation, in that case, may cause, e.g., motion control packets with commands and feedback to miss their intended arrival deadline. Therefore, one should avoid using consumer-grade network equipment as probes, as they often use a store-and-forward packet-sending approach, which introduces variable insertion delay. Instead, equipment that uses cut-through forwarding, which guarantees the latency inserted by a probe is constant, should be used. The probes must be transparent from carried traffic, this means that copying and timestamping functionality cannot be affected by the type of carried traffic.

To assure the high quality of latency calculation, the time on both probes must either use the same clock source or be accurately synchronized using, e.g., GPS or precise time synchronization protocols such as Precision Time Protocol (PTP) or Synchronous Ethernet (SyncE). The NTP protocol should be avoided as it does not provide the required accuracy. Also, it is crucial for the probes to provide high stability and accuracy of timestamping that is not impacted by any factor such as the load on the probing system. As a result, the software-based timestamping provided by, e.g., the PCAP library, should be avoided. Our observations show that PCAP may introduce errors in the order of milliseconds. Consequently, hardware-based timestamping is required to be used.

Multiple ways of implementing the illustrated architecture can be considered. For example, only one probe with multiple communication channels could be used to monitor traffic on both sides of the NUT (e.g., ET2000 [10] as implemented and verified in this work), or the hardware-based timestamping functionality could be decoupled from the probe and performed at the entry of the packet processing system (using, e.g., PF_Ring [11]). Both eliminate the challenge of precise time synchronization for the two-probes approach. However, moving the timestamping out of the probe may introduce additional challenges. Namely, the packets copied by the probe and timestamped in a separate packet-processing system must meet the same requirements as the packets going through the probe towards/from the NUT. More specifically, the probe would have to use two separate links to the packet processing system, each one carrying only a carbon copy of the traffic in a separate direction. Any other traffic, e.g., probe management traffic, would need to use a separate (third) link in order not to disturb the copied traffic.

Regardless of the implementation used, the measurements should be based on monitoring the actual industrial traffic. Any traffic injected for measurement purposes, e.g., ICMP probes or UDP packets, may disturb packet flow or even impact the network load and, consequentially, influence the results.

Furthermore, any device used in the implementation (probes and timestamping equipment) must be carefully selected to ensure no packet loss at any point over long experiments, since it may impact the stringent requirements of TC-IoT applications on reliable packet delivery (Fig. 1). That is particularly important for TC-IoT devices which may generate a substantial number of short packets (often <100 bytes). Thus, to provide live measurements, the processing of the data must be optimized toward a high number of packets.

After measuring the latency of every packet, statistics on the latency and reliability can be calculated and visualized. However, simple statistics of the overall experiment such as minimum, average, standard deviation, or maximum latency are not enough to evaluate the NUT in the context of TC-IoT requirements as they might show misleading comparisons. The Empirical Complementary Cumulative Distribution Function (ECCDF) is proposed as the most insightful way to present the latency and reliability of the NUT.

Given that time synchronization is one of the major concerns of industrial wireless networks, the timestamps added by the TC-IoT devices cannot be considered for calculating the high precision and accurate communication latency. The other reason is that not all TC-IoT devices have the capability of time-

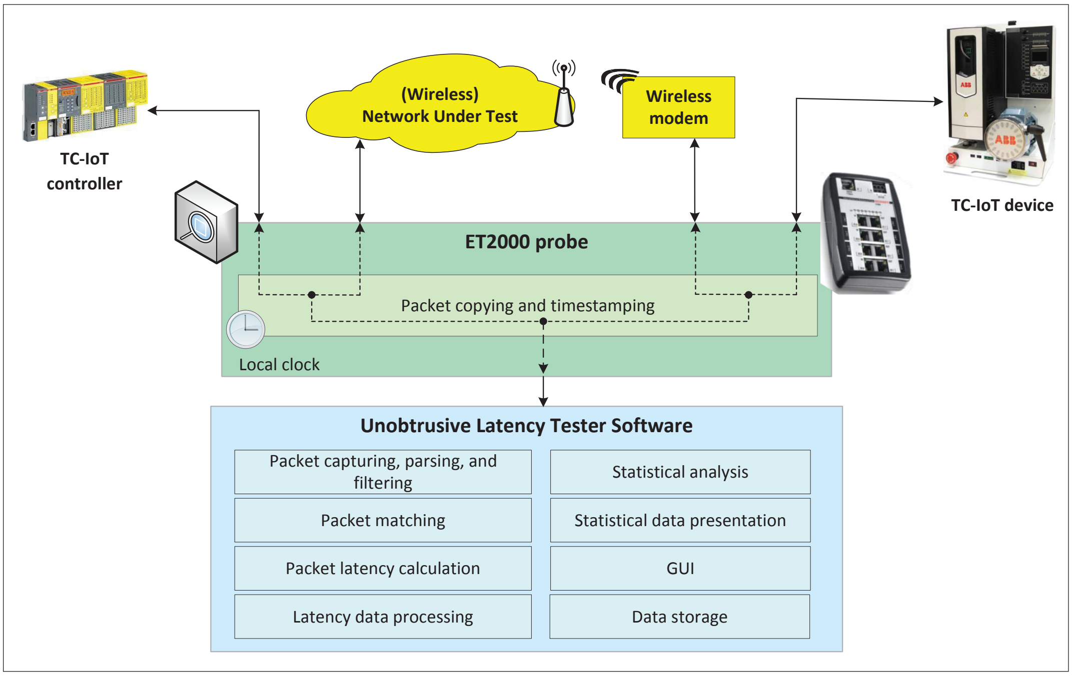

FIGURE 2. Implementation of the latency and reliability evaluation method.

stamping. So, the above proposed unobtrusive measurement architecture is very much needed to limit the dependency on any NUT and TC-IoT devices for calculating the accurate communication latency with less insertion delay.

Related Work

A team from Bosch and TU Braunschweig developed tools to investigate the latency, based on generated synthetic UDP traffic over Wi-Fi 5 and private LTE [4]. The traffic's source and destination are synchronized by the PTP over a separate Ethernet connection to enable one-way latency measurements. Comparably [6], a team from Ericsson, Bosch, and Fraunhofer measured the latency and reliability of enhanced Mobile Broadband (eMBB) 5G, an optimized eMBB, and a pre-commercial URLLC. A field programable gate array (FPGA)-based tool was developed to generate synthetic traffic, receive looped-back packets from the destination device, and calculate the latency of every packet. Although the methods described in [4] and [6] can reach high levels of measurement accuracy, the traffic generated in such a way is obtrusive to actual traffic produced by industrial devices and does not match the characteristics of the actual traffic, thus allowing only to estimate the performance of real-life TC-IoT communication.

To take advantage of flowing industrial traffic, a probe must be installed in the network at two points to capture, copy, and timestamp the packets. A team from Nokia Bell Labs and Aalborg University benchmarked the latency and reliability of public LTE and Wi-Fi 4 against Ethernet for manufacturing execution system (MES) traffic [7]. The authors claim to achieve accuracy of time synchronization of 8 μs on average. However, the possible measurement error (packet timestamping accuracy) is not discussed, neither a detailed description of the technical aspects of capturing devices is provided. In addition, the probe devices used to monitor and timestamp packets are based on a general-purpose Linux board (i.e., Raspberry Pi) which relies on software-based packet copying, timestamping, and NTP-based time synchronization. In later work on latency evaluations of Wi-Fi 5, Wi-Fi 6, and private 5G for a mobile robot application [8], the same team from Nokia Bell Labs and Aalborg University developed another Raspberry Pi-based Test Access Point (TAP) to measure the traffic latency. The insertion delay introduced to the captured packets is claimed to not exceed 0.45 ms for 99.9 percent of cases, with a jitter of 80 μs. Still, details of the packet timestamping method are not reported, suggesting that software-based timestamping is employed again. According to common experience and our experiments, software-based packet copying and timestamping often introduce unneglectable and unpredictable insertion delay, and the accuracy of NTP-based time synchronization can reach a couple of milliseconds in the worst case. In this sense, although the methods presented in [7] and [8] are capable of measuring network latency and reliability from real-life traffic, they may not assure enough precision and accuracy for high-quality measurements required by TC-IoT applications.

A team from Intel and NIST developed another method to measure the latency and reliability of a Wi-Fi 5 network with specific enhancements toward wireless time-sensitive networking. Their test application is for controlling robot joints [9]. Packet latency is measured by Ethernet TAPs, with post-processing software running on a PC. The claimed accuracy of time synchronization among the TAPs over the same wireless network under test is 100 μs for the 99 percent confidence interval. This solution eliminated the cables among TAPs, which makes it easy to use. But the expense is the interdependency between the measurement tool and the measurement object, i.e., the accuracy and stability of time synchronization (and subsequently the accuracy of latency and reliability measurement) can be affected by the latency and reliability of the wireless NUT. What we need is a measurement tool that can always guarantee accuracy regardless of the situation of the NUT.

Therefore, to the best of our knowledge, no existing solutions can carry out live unobtrusive measurements on industrial automation traffic with the high accuracy required by TC-IoT, and with a low insertion delay, as the approach presented in this paper.

Implementation

Hardware Configuration

The traffic is exchanged between the TC-IoT Controller and the TC-IoT Device and uses wireless NUT in between. To monitor the traffic, we use Beckhoff ET2000 Industrial Ethernet multi-channel probe [10]. ET2000 allows the monitoring of traffic on four separate channels (X1-X4), therefore only one probe is necessary to measure NUT networks. ET2000 uses the cut-through approach to forward traffic, thus additional delay introduced for each packet is short and constant, i.e., 600 ns. In addition, the packets passing through ET2000 are copied, timestamped, and sent out using dedicated output, i.e., X5, for further analysis.

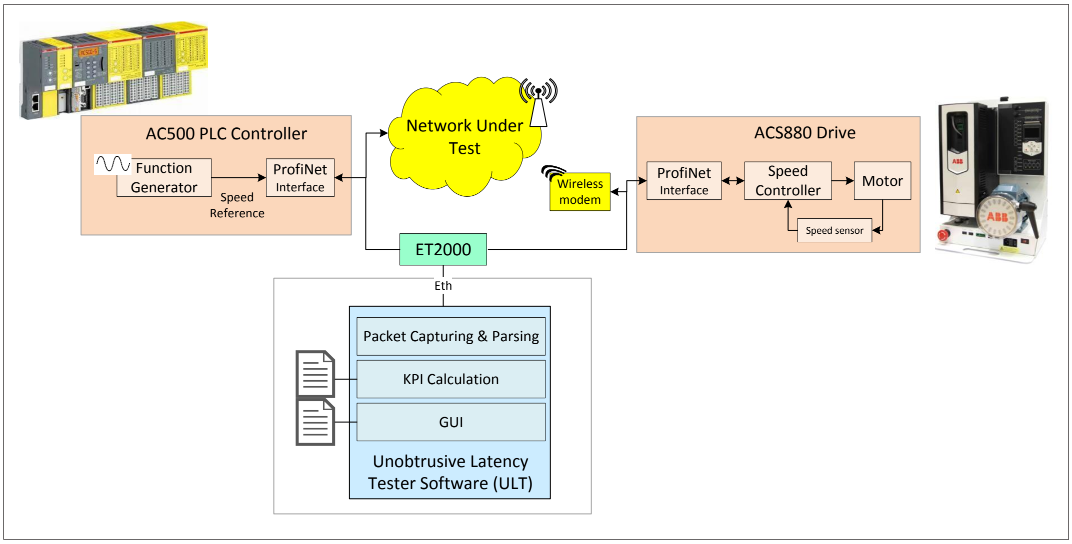

FIGURE 3. Overview of the testbed for industrial control use cases.

ET2000 timestamps every packet using its own hardware clock. The timestamp and channel input information are added to every packet (as a trailer) and then sent out onto the X5 output. The accuracy of timestamping is 40 ns and does not depend on ET2000 system load. As only one probe is used to monitor and timestamp the traffic entering and exiting the NUT, there is no need for time synchronization.

Software Configuration

The packets forwarded by ET2000 are processed by the ULT Software as shown in Fig. 2. The ULT Software is developed in Python, and it uses the WinPcap library with PCAP API for Python on a separate PC to process packets coming from ET2000. Note that the WinPcap library is used only to capture packets, its timestamping functionality is not used as it does not provide the required accuracy.

The ULT Software captures, filters, and parses the relevant packets. For each packet that passed through NUT, the ULT searches for the matching packet that was observed before entering NUT. When such a packet is found, the latency is calculated (using ET2000 timestamps), both packets are removed from the processing queues, and relevant information is passed to calculate statistics and present them using the GUI and is also saved in the file. For the remaining packets, there are no matching packets that passed NUT, because these are either still processed by the NUT or are lost when passing through the NUT. We introduce a timeout limit (significantly larger than the typical latency of the NUT), above which we mark packets as lost packets in the records and remove them from processing queues.

The ULT Software is organized in multiple threads with multiple queues to improve its performance and ensure its functioning in heavy traffic conditions.

The Testbed

As shown in Fig. 3, the main components of the testbed implemented at ABB premises are the AC500 Programmable Logic Controller (PLC) and the ACS880 Variable Frequency Drive (VFD) — a frequency controller for motors which we refer to in the article as Drive. The PLC and the Drive communicate over NUT using PROFINET protocol. The ET2000 device captures the packets before and after passing through NUT, then ULT Software processes packets in real-time as described in the previous section.

The PLC is configured to send a reference signal of the motor control loop, i.e., motor speed (rpm) that varies over time, to the Drive. The Drive receives the signal and assures appropriate electrical parameters (i.e., frequency, voltage, and current) for the motor to reach the required speed. The NUT in standard industrial implementations uses wired Ethernet which we refer to as a *Reference Scenario*, while for test NUTs we use 5G and Wi-Fi 6 networks. The configuration parameters of the 5G and Wi-Fi 6 networks are described in Table 1.

As the 5G R15 does not support Ethernet Protocol Data Unit (PDU) sessions [13] unlike Wi-Fi 6, an Ethernet over IP tunneling needs to be introduced to transmit the PROFINET traffic. Two dedicated GRE-TAP tunneling devices that encapsulate/decapsulate Ethernet packets into/from IP packets are deployed before and after the 5G network, respectively. In such a way, the 5G network together with the IP tunneling devices can act as one Ethernet segment to deliver the PROFINET traffic. The ET2000 probes are placed in between tunneling devices and end devices (PLC, Drive), therefore our measurements of the 5G network include the latency introduced by IP tunneling devices since they are necessary parts to formulate a workable PROFINET link over our 5G R15 system as of today. Furthermore, to evaluate 5G latency only, the dual connectivity, allowing the traffic to be sent over 5G and LTE at the same time, is disabled. We name the traffic from PLC to Drive as downstream (DS), and the traffic from Drive to PLC as upstream (US) from the application point-of-view.

Experimental Results

In this section, we present the results for the Reference NUT Scenario, 5G R15, and Wi-Fi 6 networks. We would like to emphasize that the purpose of our article is to tackle the problem of latency measurements of wireless networks, and it is not our intention to compare 5G and Wi-Fi 6 technologies in detail. Such comparison would require a more extended study and include multiple cases with different traffic, user equipment, radio conditions, or even particular configurations of a wireless network. Therefore, the results shown should be only taken as an illustration of the measurements provided by the presented test case.

Accuracy Results — Reference NUT Scenario

In the Reference NUT Scenario, the NUT is represented by a simple Ethernet cable. The measured latency is constant and independent of traffic conditions. For a short Ethernet cable (i.e., of 1m) we observe constant latency of 600ns which increases proportionally with the increase of cable length. We observe 40ns measurement granularity as declared in ET2000 specification [10]. This confirms the unobtrusive feature (insertion delay < 1µs) and high accuracy feature (latency error <40ns) of the ULT.

ECCDF Envelope

The details of latency distribution is illustrated with the ECCDF curves. An ECCDF curve presents the latency distribution by

Parameter	5G	Wi-Fi 6
Generation of standard	3GPP Release 15 (R15), eMBB profile	IEEE 802.11ax
TC-IoT Controller	AC500 PLC	
TC-IoT Device	ACS880 Drive	
Deployment mode	Non-standalone (NSA)	Mesh mode
TDD slot pattern	DDSU	—
User Equipment/Access point	WNC SKM-5xE	TP Link Deco X60 AX3000 Mesh
Frequency band(s)	LTE: 1875-1880 MHz 5G: 3720-3800 MHz	5 GHz
Industrial Ethernet protocol	PROFINET RT	
Distance of the wireless link	≤ 10 m	
QoS at network and user equipment levels	No	
Network type	Private network in office building	
Application cycle time	16 ms	
Packet rate	62.5 packets/sec in each direction (from Controller to Drive and vice versa)	
Packet length	76 bytes	
Timeout limit of packet matching	300 ms	
Experiment duration	112 hours	
Other parameters	Line of sight (LoS) between user equipment and base station, radio resource pre-allocation enabled	LoS between access points

TABLE 1. Configuration parameters of 5G and Wi-Fi 6 test setups.

showing the probability of the latency is larger than a specific value during the measurement window. One can easily determine the reliability for a given latency constraint, or inversely the latency with given reliability constraints.

A simple latency ECCDF curve calculated for the entire experiment would hide the temporal fluctuations of latency over a long experimental duration. Therefore, we divide our long experiment into 5-hour statistics windows, for each of which a separate ECCDF curve is calculated. For the clarity of illustrations, we present only the minimum and maximum values of the ECCDF of all the statistics windows, i.e., the best and worst latency/reliability, and refer to them as the ECCDF envelope. Figure 4 below shows the ECCDF envelopes for upstream and downstream, for both 5G and Wi-Fi 6.

First, Wi-Fi 6 and 5G show different latency distributions. For 5G we can observe some differences between upstream and downstream, while for Wi-Fi 6 such differences are very small. These can be explained by different radio resource assignment algorithms used by 5G and Wi-Fi. In 5G, radio transmissions are carefully scheduled into specified resource blocks within given time frames by Base Station (BS), thus the differences between upstream and downstream can be observed. In Wi-Fi 6, however, the transmissions for upstream and downstream are based on CSMA/CA.

As we can observe in Fig. 4, Wi-Fi 6 provides lower latency than 5G if the required reliability is relaxed, e.g., 99 percent or lower. However, the 5G shows more bounded latency than Wi-Fi if the required reliability is stringent, e.g., 99.9 percent or higher. Then, for the duration of the whole experiment, the 5G latency does not exceed 50 ms in both directions and we do not observe packet timeouts either. For Wi-Fi 6, on the other hand, the latency may exceed 100 ms for 0.0007 percent packets and one can even observe packet timeouts. For the whole experiment, the probability of Wi-Fi 6 packet timeouts is $1.07*10^{-6}$ and $9.47*10^{-7}$, for upstream and downstream, respectively.

Another interesting observation is the fluctuation of latency distribution over time, which could be caused by, e.g., changing radio conditions. It is represented by the width of the ECCDF envelopes for different probability levels (i.e., the difference between the maximum and the minimum ECCDF latency values for a given level of probability). We observe that for 5G upstream, the width of the ECCDF envelope is small and does not exceed 1 ms for a probability level of 10^{-5}. For the downstream, the envelope is wider but still does not exceed 2 ms for a probability level of $5*10^{-6}$. In Wi-Fi 6, however, the width of the ECCDF envelope is larger and exceeds 10 ms already for probability levels of $5*10^{-4}$.

Figure 5 presents an abstract view of achievable latency at expected reliability levels. Again, we can notice that the 5G under test offers lower latency with high-reliability levels (99.9 percent or higher). On the other hand, for applications that tolerate lower reliability levels (lower than 99 percent) Wi-Fi 6 offers much lower latency.

Conclusion and Future Work

This work presents a novel ULT method to measure the latency and reliability of wireless networks for TC-IoT applications using a real-life automation testbed. The ULT method is independent of the underlying network and industrial applications used within the tests. It provides high-accuracy measurements and has negligible impact on the communication between industrial devices. Our measurements indicate that 5G and Wi-Fi 6 networks introduce noticeable delay and thus cannot be considered as a simple replacement of wired networks for all time-critical industrial scenarios. Still, certain applications with more relaxed network latency requirements might strongly benefit from wireless networks. Wi-Fi 6 and 5G are designed with different purposes and use different algorithms (e.g., for radio resources allocation), thus introducing different latency patterns.

One of the limitations of our current implementation is that the probes are attached to the NUT through Ethernet cables in one point (ET2000) which makes it infeasible to cover long-distance and/or mobile applications, thus it is only suitable for testing activities instead of the operational phase. In future work, we will investigate high accuracy (e.g., sub-microsecond level) time synchronization of remote probes over wireless or using GPS which

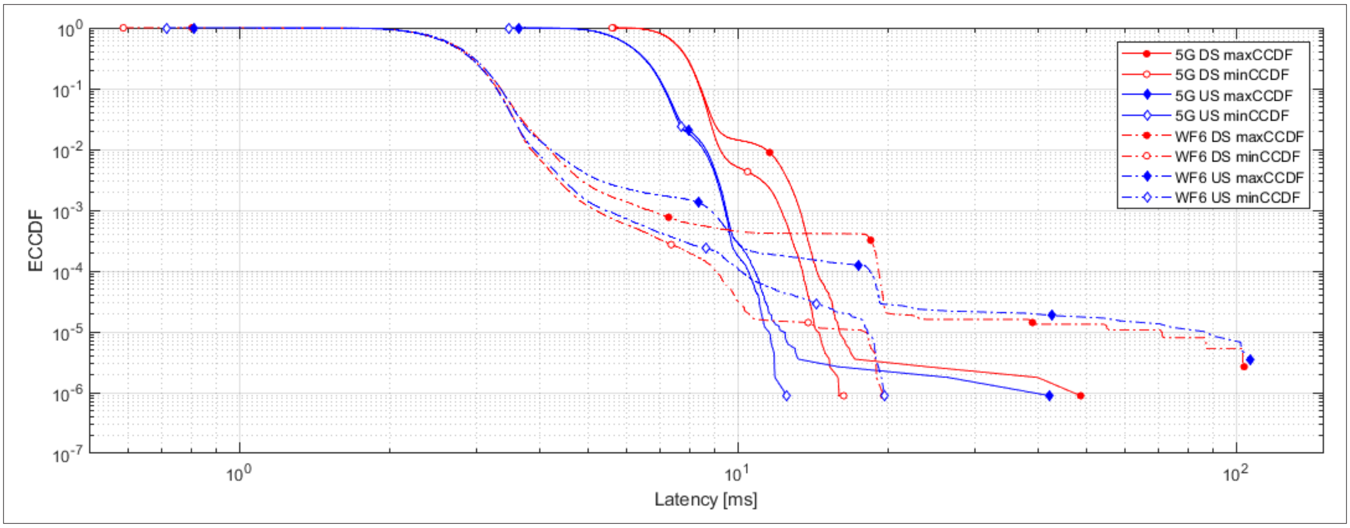

FIGURE 4. Latency distribution for 5G and Wi-Fi 6: ECCDF envelopes for both upstream (US) and downstream (DS).

could enable measurements over long distances or support mobile applications. Moreover, combining the ULT method with the emerging In-band Network Telemetry (INT) techniques in the context of Software Defined Networking (SDN) such as P4 (Programming Protocol-independent Packet Processors) [12] programable network devices, could make it possible to perform such high accuracy and unobtrusive measurements online during operation without dedicated testing devices. Online measurements would enable improvements in end-to-end experiences and resource efficiency by, e.g., the adaptive interplay between the TC-IoT applications and underlying networks. However, since the P4 requires enhancements of data plane devices, we foresee new challenges regarding compatibility with the existing Industrial Ethernet protocols.

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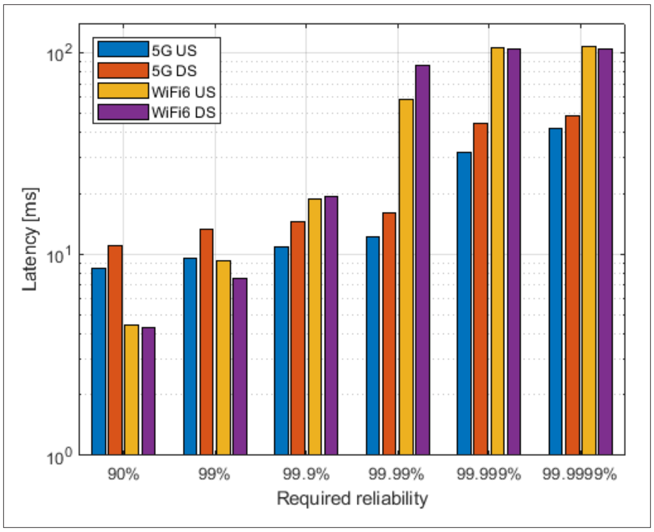

FIGURE 5. Achievable latency bound at expected reliability levels for 5G and Wi-Fi 6 for both upstream (US) and downstream (DS).

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