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Empirical Analysis of 5G TDD Patterns Configurations for Industrial Automation Traffic

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***Abstract*—The digital transformation driven by Industry 4.0 relies on networks that support diverse traffic types with strict deterministic end-to-end latency and mobility requirements. To meet these requirements, future industrial automation networks will use time-sensitive networking, integrating 5G as wireless access points to connect production lines with time-sensitive networking bridges and the enterprise edge cloud. However, achieving deterministic end-to-end latency remains a challenge, particularly due to the variable packet transmission delay introduced by the 5G system. While time-sensitive networking bridges typically operate with latencies in the range of hundreds of microseconds, 5G systems may experience delays ranging from a few to several hundred milliseconds. This paper investigates the potential of configuring the 5G time division duplex pattern to minimize packet transmission delay in industrial environments. Through empirical measurements using a commercial 5G system, we evaluate different TDD configurations under varying traffic loads, packet sizes and full buffer status report activation. Based on our findings, we provide practical configuration recommendations for satisfying requirements in industrial automation, helping private network providers increase the adoption of 5G.**

***Index Terms*—5G, Industry 4.0, TDD pattern, testbed**

I. Introduction

The integration of recent advancements in IoT, Cyber-Physical Systems, cloud computing, and Artificial Intelligence into industrial production is already transforming traditional industries, laying the groundwork for Industry 4.0 [1]. This requires network platforms that enable efficient, low-latency and reliable communication across all components. To address this, IEEE introduced Time-Sensitive Networking (TSN), a set of standards that enhance industrial networks with synchronization, stream reservation, traffic shaping, scheduling, preemption, traffic classification, and seamless redundancy [2]. However, wired industrial networks are limited in scalability and flexibility due to the complexity of adding or relocating equipment, restricting mobility and coverage to cabled areas.

To overcome these issues, researchers are exploring the integration of the 5th Generation (5G) system as TSN bridges within TSN networks [3]. In this setup, production lines in a factory connect wirelessly to the 5G system, which then interfaces with the enterprise edge cloud through TSN bridges [4]. This integration presents challenges due to the differences between TSN and 5G technologies [5]. One key challenge is maintaining deterministic End-to-end (E2E) communications, which refers to ensuring the packet transmission delay remains consistently below a predefined threshold with very high reliability. This is difficult to achieve due to the non-deterministic latency and jitter caused by the time-varying wireless channel in the 5G system. While TSN bridges typically have latency in the hundreds of microseconds [6], 5G systems can experience delays ranging from milliseconds to several hundred milliseconds [5].

In this regard, the use of Non-Public Networks (NPN) allows for customized 5G network configurations, which present the challenge of adapting network performance to the service needs of each vertical industry [7]. To minimize packet transmission delay in the 5G system, NPN operators can customize the Time Division Duplex (TDD)[1] pattern, which involves controlling the allocation of transmission slots between Uplink (UL) and Downlink (DL) and optimizing the frequency of switching between sending and receiving data [9]. The challenge in configuring TDD is to meet strict latency requirements while considering factors such as the lack of real-world deployment studies, the range of possible parameter combinations and the strong dependence on network load.

A. Related Works

Recent research on TDD has focused on dynamic configurations to optimize UL/DL time slot allocation using machine learning. For example, the authors of [10] use convolutional long short-term memory models combined with Deep Reinforcement Learning (DRL) for real-time adjustments, while the authors of [11], [12] propose a DRL-based approach to address challenges like buffer overflow and varying traffic demands. TDD configurations have also been explored for network slicing [13], enabling service-specific resource allocation. However, these studies rely on simulations, which may overlook practical implementation challenges. For a broader overview of dynamic TDD pattern configurations, we refer to the comprehensive survey in [9].

In contrast, some works have implemented solutions in commercial base stations. For instance, the authors of [14]

[1]5G networks predominantly use TDD over Frequency Division Duplex (FDD) because it offers greater spectral efficiency, flexibility in asymmetric traffic management, and better resource utilization [8].

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integrate a DRL-based solution into an Open Radio Access Network (O-RAN)-supported base station, and other authors in [15] investigate the trade-off between data rate and latency in an Open Air Interface-based base station. Despite these efforts, none of these studies address the specific needs of industrial environments, where traffic demands impose strict requirements on packet transmission delay and reliability.

In an industrial context, the authors of [16] propose a service-aware TDD framework that balances latency and data rate through dynamic scheduling and reinforcement learning. While the study provides valuable insights, it is based on simulations and does not consider real-world aspects.

B. Contributions

This paper investigates the impact of different TDD patterns on 5G systems, based on empirical measurements from a commercial 5G system in a laboratory testbed. We assess packet transmission delay under varying conditions, including traffic load, packet size, and the effect of full Buffer Status Report (BSR) activation at the User Equipment (UE). The evaluation covers both UL and DL transmissions. Based on the results, we offer configuration recommendations for private industrial network operators to optimize support for diverse industrial automation traffic types. Our findings contribute to the integration of 5G into TSN-based industrial networks, paving the way for deterministic communications.

The paper is structured as follows. Section II reviews industrial traffic types and their requirements; and the concepts of 5G TDD pattern and UE BSR. In Section III, we describe our proof of concept and discuss the obtained results. We also provide recommendations for configuring TDD patterns in industrial environments. Finally, Section IV summarizes key conclusions and outlines potential areas for future work.

II. Industrial Automation Traffic and 5G Features under Evaluation

A. Traffic Types for Industrial Automation

Industrial networks involve the following traffic types as described in Table I [4]:

- *Network Control*: manages tasks like time synchronization, network redundancy, and topology detection.
- *Cyclic Synchronous*: coordinates regular synchronized user plane data exchanges between devices.
- *Cyclic Asynchronous*: involves periodic but unsynchronized user plane data exchanges.
- *Events*: trigger messages based on metric changes.
- *Mobile Robots*: include movement control, task assignment, and sensor data.
- *Augmented reality*: provides real-time video and maintenance instructions.
- *Configuration and diagnostic*: handle non-critical data like device configuration and firmware downloads.

B. TDD Patterns

The 5G-New Radio (NR) frame structure is highly flexible, supporting various services with different requirements. As shown in Fig. 1, it consists of a 10 ms frame divided into ten 1 ms subframes, each containing multiple 14-OFDM-symbol slots. The number of slots per subframe depends on the numerology parameter μ, which defines the subcarrier spacing as $15 \cdot 2^{\mu}$ KHz. Increasing μ reduces slot duration to $1/2^{\mu}$ milliseconds, enabling finer slot allocation for delay-sensitive services at the cost of higher bandwidth. The frame structure also supports mini-slots, short bursts of 2–6 Orthogonal Frequency-Division Multiplexing (OFDM) symbols, within a slot to further minimize latency.

The 5G frame structure's flexibility is further enhanced in TDD mode, where DL and UL share the same frequency band at different times. TDD patterns determine the slot allocation between UL and DL, optimizing data rate and latency based on application needs. A slot can contain DL, UL, or flexible OFDM symbols, which can be configured for either transmission type. The `TDD-UL-DL-configurationCommon` parameter, defined in 3rd Generation Partnership Project (3GPP) TS 38.331 (v18.4.0), is key to allocate slots for DL and UL transmissions. Configured at the network level, it is communicated to each UE via Radio Resource Control (RRC) signaling. Fig. 1 shows the main elements of `TDD-UL-DL-configurationCommon`:

- **Periodicity**: defines the time period over which the UL/DL pattern repeats, with the following possible values (in milliseconds): 0.5, 0.625, 1, 1.25, 2, 2.5, 5, and 10.
- **Number of Consecutive DL Slots**: specifies the number of consecutive full DL slots at the beginning of each DL/UL pattern.
- **Number of Adjacent DL Symbols**: defines the number of consecutive DL symbols at the start of the slot following the last full DL slot.
- **Number of Adjacent UL Symbols**: refers to the number of consecutive UL symbols at the end of the slot,

TABLE I: Traffic Types and Performance Requirement

Traffic Types [4]	Periodic / Sporadic	E2E Delay bound (ms)	Typical Data Size (Byte)
Network Control	Periodic	$[50, 1000]$	Variable $[50, 500]$
Isochronous	Periodic	$[0.1, 2]$	Fixed $[30, 100]$
Cyclic Synchronous	Periodic	$[0.5, 1]$	Fixed $[50, 1000]$
Cyclic Asyncrhonous	Periodic	$[2, 20]$	Fixed $[50, 1000]$
Events	Sporadic	$[10, 2000]$	Variable $[100, 1500]$
Mobile Robots	Both	$[1, 500]$	Variable $[64, 1500]$
Augmented Reality	Both	10	Variable $[64, 1500]$
Configuration and Diagnostic	Sporadic	$[10, 100]$	Variable $[500, 1500]$
Best Effort	Sporadic	N.A.	Variable $[30, 1500]$

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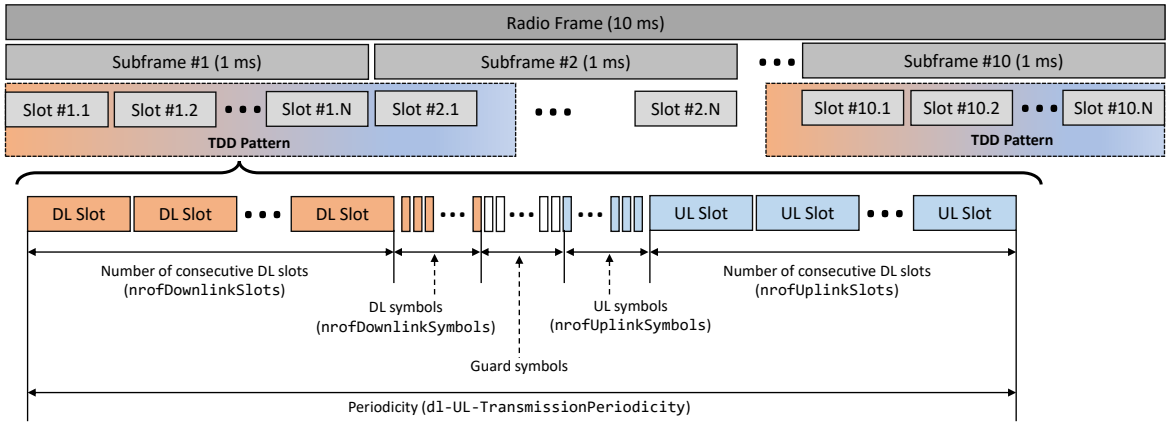


Fig. 1: 5G frame structure and TDD pattern.

preceding the first full UL slot.

- **Number of Consecutive UL Slots**: specifies the number of consecutive full UL slots at the end of each DL/UL pattern.
- **Guard Period**: necessary for the transceiver to bridge from DL to UL and allow timing advance in UL.

In this work, we evaluate different TDD pattern configurations considering various values for the periodicity, as well as the allocation of slots between DL and UL.

C. UE Buffer Status Report (BSR)

The BSR is a periodic Medium Access Control (MAC) layer message in 5G NR sent from the UE to the base station to report a quantized value of the buffered data awaiting transmission [17]. This report, reflecting data in the Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP) layers, enables the UE to request UL grants, allowing the base station to allocate the necessary radio resources for data transmission.

In particular, a special case of the BSR allows the UE to explicitly indicate that its buffer is full. This mechanism, known as full BSR, enables the base station to allocate UL time slots more aggressively, assuming the UE always has data to transmit. The full BSR may be sent only once, when the UE initially establishes communication with the base station, signaling that its buffer remains full. In our study, we analyze two BSR transmission scenarios in a 5G TDD system with a single UE. In the first scenario, the UE reports the actual data volume in its buffer, leading to dynamic UL scheduling based on real-time buffer status. In the second scenario, the UE sends a full BSR, allowing the UE to transmit user plane data as frequently as possible, minimizing latency without requiring further BSR updates.

III. Proof of Concept and Performance Results

A. Testbed Description

To validate multiple TDD pattern configurations, we implemented a testbed consisting solely of a commercial IP-based 5G system, as illustrated in Fig. 2. It comprises seven devices. A general-purpose computer equipped with a PCIe SDR50 card, referred to as 5G Amarisoft (Equip. 1), equipped with an Intel(R) Xeon(R) Bronze 3206R CPU @1.90GHz and 32GB RAM, runs the Amarisoft software to provide both the core and radio access network capabilities for a standalone 5G network. The testbed also includes one UE consisting of an Intel NUC BXNUC10I7FNH2 (Equip. 2) paired with a Quectel RM500Q-GL card in an RMU500EK evaluation board (Equip. 3). This board uses the RM500QGLABR11A06M4G firmware and the NUC is equipped with an 11th Gen Intel(R) Core(TM) i7-1165G7 @2.80GHz and 16GB RAM. Both the 5G Amarisoft and UE operate on Ubuntu 18.04.6 LTS. Since this system works in licensed bands, it is enclosed in an RF Shielded Test Enclosure, specifically the Labifix LBX500 model (Equip. 4). The last component is a SecureSync 2400 time synchronization server (Equip. 5), which distributes time using the Network Time Protocol (NTP) to ensure time synchronization across devices.

B. Experimental Setup

We considered four TDD patterns as summarized in Table II: TDD 44, TDD 36, TDD 72, and TDD 10. The numbers following TDD indicate the consecutive full slots allocated to DL and UL, respectively. All patterns have a periodicity of

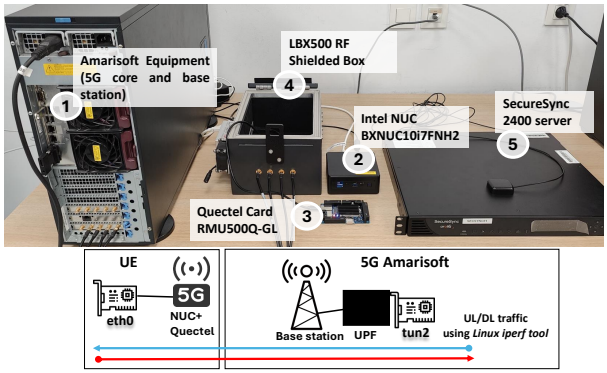


Fig. 2: Proof of concept equipment and evaluated scenario.

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10 slots between UL and DL, except for TDD 10, which has a periodicity of 2 slots. For TDD 10, although no dedicated UL slot is provided, 12 out of 14 UL OFDM symbols are used for data transmission (i.e., as `nrofUplinkSymbols`), with the remaining symbols acting guard band. For all TDD patterns, the slot duration is 0.5 ms, the minimum duration supported by the Quectel card (i.e, μ=1), allowing for the lowest possible packet transmission delay with our equipment. The base station operates with a bandwidth of 50 MHz and transmits in band n79 (4,4 GHz - 5 GHz).

We aim to measure the packet transmission delay in the 5G system for both UL and DL directions, using the outlined TDD patterns. The measurement points within the 5G system are illustrated in the bottom image of Fig. 2. Specifically, these points are the Network Interface Card (NIC) of the 5G system, via the User Plane Function (UPF), and the NIC of the UE. To measure the delay, we used `tcpdump` to capture traces from the NICs, identifying packets via the IP header's ID field. Timestamps were extracted and subtracted to calculate the delay. To emulate periodic industrial traffic, we used the Linux tool `iperf` in `UDP` mode, with the server and client configured based on traffic direction. Additionally, our work includes measurements of throughput, which refers to the data rate generated by the transmitter, and effective throughput, which represents the rate of data successfully received by the receiver.

For each TDD pattern, we considered all possible combinations of the following parameters: (a) four traffic load levels, where the same load was applied simultaneously to both UL and DL directions at 10 Mbps, 20 Mbps, 30 Mbps, and 40 Mbps; (b) two packet sizes, using either 100 bytes or 1000 bytes; and (c) two configurations for the BSR, one where the full BSR is active and another where the full BSR is not active. A total of 100,000 packets was generated in each direction for all possible scenarios to provide a sufficient number of samples to derive the distribution of the packet transmission delay.

The dataset is made available to foster reproducibility[2].

C. Performance Results

Fig. 3 shows the Cumulative Distribution Function (CDF) of packet transmission delay for 100-byte packets with full BSR disabled, under varying traffic loads. First, without full BSR, DL delay is significantly lower than UL. It is due to the UE periodically sending BSR to request resources, thereby wasting transmission slots in the control plane. Second, among different TDD patterns, TDD 36 (green curves) has the highest DL delay and the lowest UL delay, due to allocating more timeslots for UL. In contrast, TDD 63 (red curves) shows the opposite effect, with the highest UL delay and the lowest DL delay. TDD 44 (blue curves) exhibits intermediate behavior. TDD 10 (purple curves), with a reduced repetition period, results in much lower delays for both DL and UL at 10 Mbps, but limits base station capacity. For DL traffic at 10, 20, 30, and 40 Mbps, the effective throughput is 97.1%, 76.5%, 65.3%, and 64.0%, respectively. In UL, throughput degradation is sharper, with 98.7%, 90.5%, 30.7%, and 3.93% effective throughput, respectively. This is mainly due to the signaling needed for UE to send BSR messages and request transmission grants. As the traffic load increases, the base station takes longer to respond to these grants, exacerbating the delay. Finally, while TDD 44, TDD 36 and TDD 63 patterns show increased delays with higher traffic, they generally maintain acceptable latency for industrial automation applications in DL. However, UL latency becomes problematic, especially for TDD 36, as 10% of the packets experience a transmission delay exceeding 30 ms at 40 Mbps, which represents an excessively high ratio for some industrial applications.

Fig. 4 shows the CDF of packet transmission delay for 100-byte packets with the full BSR mechanism enabled. Notably, full BSR significantly reduces UL delay compared to DL, as the UE no longer needs to report buffer status continuously. Instead, the UE signals a full transmission buffer to the base station, which then proactively allocates UL slots for data transmission, eliminating the need for periodic reporting. Furthermore, DL delay remains unaffected by the activation of full BSR. A key drawback occurs with reduced TDD pattern periodicity, such as TDD 10. With more UL slots allocated for user plane data, the 5G system reaches its effective throughput limit with lower traffic loads than without full BSR, resulting in increased UL delays at high traffic loads.

Fig. 5 presents the CDF of the packet transmission delay considering different packet sizes under low (i.e., 10 Mbps) and high (i.e., 40 Mbps) traffic load scenarios. In this figure, the dotted curves represent the transmission of 100-byte packets, while the dash-dotted curves represent the transmission of 1000-byte packets. We observe that, for all TDD patterns, the packet transmission delay is consistently lower when using 1000-byte packets in all scenarios, except for DL under high traffic load. The lower packet transmission delay observed in most cases when using 1000-byte packets can be explained by the reduced number of Layer 3 packets that the receiver (either the UE or the base station) needs to reconstruct from the 5G transport blocks[3]. Since the data rate remains constant, using packets of greater size results in fewer packets to reconstruct. However, in DL with high traffic load, the packet transmission delay is higher when using 1000-byte packets. This is because the UE requires more processing time to construct individual packets from the transport blocks when the packets are larger in size. This behavior is explained by the fact that the processing capacity of the Quectel card is

[2]Online Available: https://github.com/wimunet/empirical_analysis_5G_tdd_patterns_for_industry_4_0

TABLE II: Evaluated TDD Patterns

TDD Pattern	DL Slots	UL Slots	Guard Band	Periodicity
TDD 44	4	4	2 slots	10 slots
TDD 36	3	6	1 slot	10 slots
TDD 72	7	2	1 slot	10 slots
TDD 10	1	12 symbols	2 symbols	2 slots

[3]A 5G transport block is a data unit transmitted at the physical layer, while a packet is a Layer-3 data unit which includes routing information.

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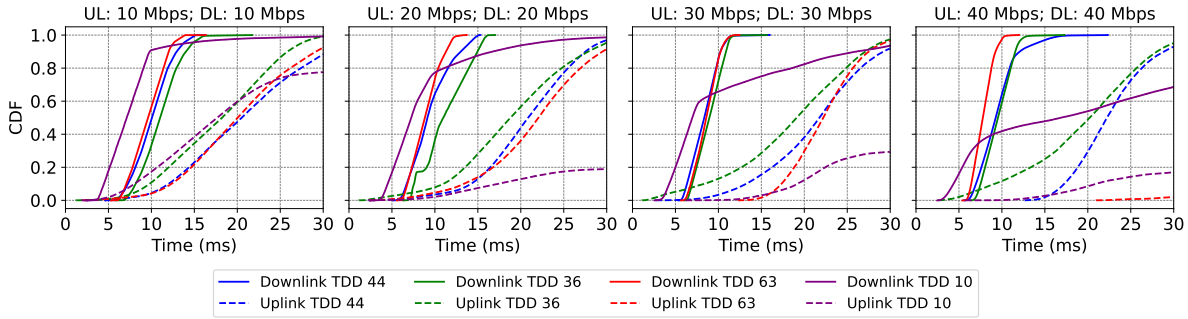


Fig. 3: CDF of the packet transmission delay for DL and UL with different TDD patterns when full BSR is not activated. The packet size is 100 bytes.

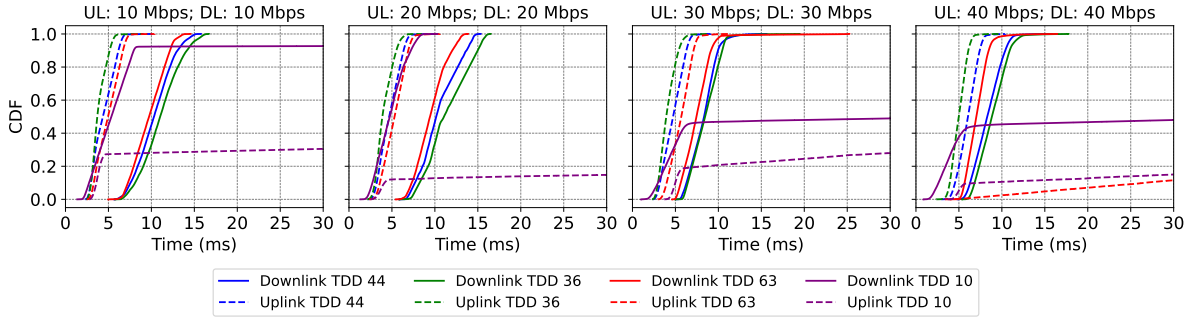


Fig. 4: CDF of the packet transmission delay for DL and UL with different TDD patterns when full BSR is activated. The packet size is 100 bytes.

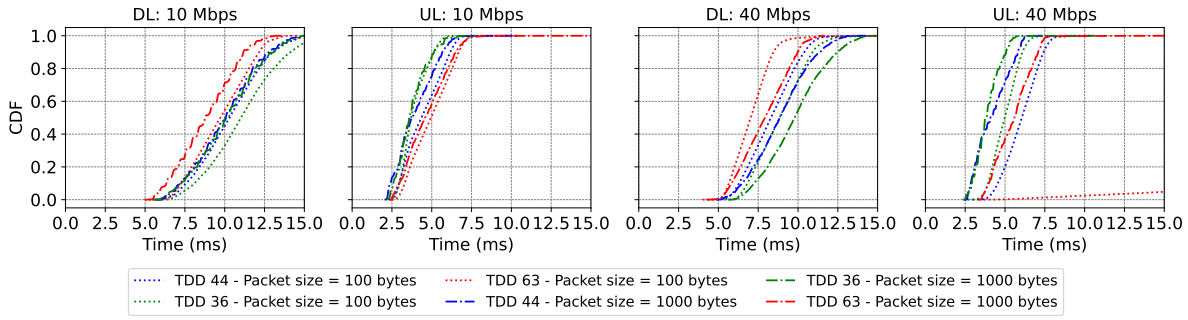


Fig. 5: CDF of the packet transmission delay for different TDD patterns, comparing 100-bytes and 1000-bytes packet sizes. Full BSR is activated.

significantly lower than that of the PC hardware which runs the Amarisoft base station. It is reasonable to observe that a UE has lower processing capabilities compared to the base station's hardware. Finally, in most cases, the time difference between transmitting 1000-byte and 100-byte packets ranges from approximately 0.5 ms to 1.5 ms, which can be significant for isochronous and cyclic synchronous traffic.

D. Recommendations for 5G TDD Pattern Configurations

After analyzing our results, we aim to provide a series of configuration recommendations for 5G TDD patterns that will better support industrial automation traffic. They are:

R1 **Ensure Deterministic Communication for Industrial Traffic**: For industrial automation, it's crucial that packet delays remain below the threshold with a very high probability (e.g., 99.999%), ensuring reliable and timely communication. Monitor the tail of the CDF is key to confirm delays stay within the defined bound.

R2 **Perform Traffic Load Assessment for UL/DL**: It is advisable to conduct a prior study on the traffic load expected for UL/DL in the considered industrial environment. This will allow for proper allocation of time slots between UL and DL, ensuring that both directions have enough resources for efficient data transmission.

R3 **Activate Full BSR for Latency-Critical UL Traffic**:

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In scenarios where UL traffic is not critical in terms of latency, activating full BSR is not necessary. Otherwise, activating this parameter is highly recommended because it significantly reduces the signaling sent from the UE in UL, which, in turn, optimizes the available time slots for transmitting user plane data and ultimately leads to a latency reduction.

R4 **Consider Traffic Load for TDD Pattern Periodicity**: While it may seem intuitive that reducing the periodicity of TDD patterns would decrease packet transmission delay, this approach only works effectively when the 5G system's traffic load is low. In scenarios with a high traffic load, packet transmission delays can increase significantly, making this configuration unsuitable for many types of industrial automation traffic.

R5 **Consider Packet Size for Traffic with very Low Latency Requirements**: Considering the packet size of specific industrial automation traffic is key, especially when this traffic has stringent delay requirements (e.g., packet delay budget of around 2 ms or less). The packet size can significantly affect transmission delay, and optimizing this parameter is crucial to meeting the latency requirements of time-sensitive applications, particularly for isochronous and cyclic synchronous traffic.

IV. Conclusions and Future Works

In 5G-TSN-based industrial networks, ensuring deterministic E2E packet transmission delay is vital for industrial automation, requiring delays under a predefined threshold, e.g., 20 ms with 99.999% reliability. Achieving this determinism is challenging, especially in 5G systems, due to the variable delays introduced by wireless transmission. The 5G TDD pattern configuration, which allocates transmission slots between UL and DL, directly affects the packet transmission delay. Most research on 5G TDD configurations relies on simulations, neglecting real-world industrial challenges, especially the deterministic delay and reliability requirements critical for industrial automation. This paper investigates the impact of different TDD patterns on 5G systems based on empirical measurements taken from a base station in a laboratory testbed. We assess packet transmission delay under varying conditions such as traffic load, packet size, and the effect of full BSR activation at the UE. Our results yield key recommendations: *i*) Ensure deterministic communication by monitoring the CDF tail to keep delays within bounds; *ii*) Assessing UL and DL traffic load helps allocate time slots efficiently; *iii*) Activating full BSR reduces latency for UL traffic by minimizing signaling overhead; *iv*) Reducing TDD pattern periodicity can increase delays under high load; *v*) Packet size plays a crucial role in meeting the stringent latency requirements of highly time-sensitive applications.

Future work will explore additional TDD pattern configurations on our testbed, including scenarios with multiple UEs, 5G Quality of Service (QoS) flows, network slicing, multiple cell deployments and TSN bridges.

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