# Performance Evaluation of the Precision Time Protocol (PTP) over a Commercial 5G Campus Network

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# Abstract

Accurate time synchronization is a fundamental requirement for industrial systems, particularly applications relying on deterministic communication and coordinated control. While the Precision Time Protocol (PTP), or IEEE 1588, can achieve a sub-microsecond accuracy in wired local networks, its performance over wireless networks such as Fifth Generation Mobile Network (5G) remains challenging due to signal propagation effects and varying wireless delays from radio scheduling.

This thesis presents an experimental evaluation of PTP performance over a commercial 5G campus network in an industrial research environment. A wired Ethernet network is used as the baseline to benchmark the impact of wireless connectivity. The study focuses on two primary key performance indicators: synchronization accuracy, represented by the mean of the time offset between PTP master and slave, and synchronization precision, represented by the standard deviation of the offset. The obtained results show that PTP over 5G can maintain synchronization accuracy close to zero microseconds under the evaluated test scenarios. However, the precision is significantly degraded as compared to wired Ethernet due to the 5G network's lack of support to compensate for the transit delay and packet delay variations.

Further analysis reveals that the dominant factor affecting time-sync performance is packet delay variation from 5G resource configuration and scheduling. The impact of message timestamping, radio signal conditions, and downlink-uplink delay asymmetry is found to be secondary as compared to the delay variability introduced by the 5G network. The findings indicate that, although PTP over 5G is able to support applications requiring microsecond-level synchronization accuracy and precision, its current performance is not sufficient for time-critical industrial applications which require a sub-microsecond precision. This work provides experimental insights into the limitations of wireless-based time synchronization and highlights the need for network-level enhancements to support deterministic communication over 5G.

# Popular Science Summary

Modern industries rely on precise timing to ensure that machines, sensors, and control systems work together correctly. In wired networks, this synchronization can be extremely accurate, often within less than one microsecond. However, as industries move toward wireless communication using 5G, maintaining this level of precision becomes more difficult.

This thesis investigates how well time synchronization works when using a private 5G network. Instead of using simulations, the study is based on real experiments conducted in an industrial research environment. The performance of wireless synchronization is compared to a traditional wired setup.

The results show that 5G can maintain overall timing alignment, meaning devices remain synchronized on average. However, the stability of this synchronization is much worse than in wired networks. In simple terms, the timing is correct on average, but it fluctuates significantly over time.

The main reason for this behavior is how 5G networks schedule data transmission. Unlike wired connections, where data is sent immediately, 5G introduces delays that vary depending on network load and resource allocation. These variations directly affect time synchronization.

The study also shows that improving hardware or signal quality alone does not significantly solve the problem. Instead, the main limitation comes from the wireless network itself.

In conclusion, while 5G can support time synchronization for less demanding applications, it is currently not precise enough for the most critical industrial use cases. Future improvements in network design and scheduling will be necessary to achieve reliable, high-precision synchronization over wireless networks.

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# List of Acronyms

**3GPP** 3rd Generation Partnership Project. 1

**5G** Fifth Generation Mobile Network. i–iv, viii, ix, 1–6, 9, 10, 12–15, 17, 18, 21–23, 28, 31–33, 35–38, 40, 41, 43, 44, 47, 50–54, 63

**BSR** Buffer Status Report. 13

**cMTC** Critical Machine-Type Communication. 17

**CQI** Channel Quality Indicator. 13

**GM** Grandmaster. 21–26, 28

**gNB** Next Generation NodeB. 13–15, 21

**GNSS** Global Navigation Satellite System. 23, 24

**gPTP** Generalized Precision Time Protocol. 18

**HARQ** Hybrid Automatic Repeat Request. 13

**IEEE** Institute of Electrical and Electronics Engineers. 1, 2, 5, 6, 9, 13, 15–18, 20, 23, 25, 35, 52

**IPv4** Internet Protocol Version 4. 22

**KPIs** Key Performance Indicators. 26, 27, 32–35, 38, 41, 44, 61, 62

**LAN** Local Area Network. 21, 22, 24, 26–28

**MAC** Medium Access Control. 12, 16

**NAT** Network Address Translation. 20

**NIC** Network Interface Card. 24, 25

**NR** New Radio. 13

**NTP** Network Time Protocol. 6

**PDV** Packet Delay Variation. 1, 5, 13, 33, 40, 47, 50

**PRB** Physical Resource Block. 51, 53

**PTP** Precision Time Protocol. i, iii, viii, 1–3, 6–12, 14–29, 31, 32, 34–36, 38, 41, 43, 44, 47, 48, 50–53, 57, 59–62, 64

**QoS** Quality of Service. 13, 19, 54

**RMS** Root Mean Square. 11, 34

**RSRP** Reference Signal Received Power. 15, 19, 30, 34, 35, 47, 51, 52, 60, 62

**RSRQ** Reference Signal Received Quality. 15, 19, 30, 34, 35, 47, 51–53, 60, 62

**RSSI** Received Signal Strength Indicator. 15

**SA** Standalone. 2, 18, 19, 23, 24, 34, 52

**SINR** Signal-to-Interference-plus-Noise Ratio. 15, 19, 30, 34, 35

**SR** Scheduling Request. 13, 18

**TA** Timing Advance. 17

**TDD** Time Division Duplex. 14, 23

**TSN** Time-Sensitive Networking. 1, 5, 16, 17

**UDP** User Datagram Protocol. 22

**UE** User Equipment. viii, 13, 15, 21, 24, 28, 31, 32, 41–43, 52, 57, 64

**URLLC** Ultra-Reliable Low-Latency Communication. 13, 15

**UTC** Coordinated Universal Time. 23, 24

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# Chapter 1
# Introduction

## 1.1 General Context and Importance

Accurate and reliable time synchronization is a fundamental requirement in modern industrial and automation systems. Applications such as power system protection, distributed control, robotics, sensor fusion, and autonomous systems rely on a shared notion of time to ensure deterministic behavior, correct event ordering, and safe operation.

In wired industrial networks, sub-microsecond synchronization accuracy is routinely achieved using PTP, standardized as Institute of Electrical and Electronics Engineers (IEEE) 1588, which has become a cornerstone of time-critical industrial systems. Furthermore, Time-Sensitive Networking (TSN) technologies increasingly rely on precise synchronization to support deterministic Ethernet communication in industrial automation systems.

## 1.2 Motivation: Wireless Communication in Industry

Industrial communication systems are increasingly adopting wireless technologies, including 5G, to facilitate flexible deployment, mobility support, and a reduction of cabling costs. Compared to traditional wired infrastructure, wireless connectivity offers advantages in network access scalability and installation flexibility.

However, wireless networks also introduce significant challenges for time synchronization. Unlike wired-only infrastructure, wireless networks are characterized by, e.g., Packet Delay Variation (PDV), uplink and downlink delay asymmetry, data retransmissions, and changing radio conditions. These characteristics violate several assumptions underlying PTP operation, particularly the assumption of stable and symmetric communication delay.

As industrial systems increasingly consider adoption of wireless, understanding the achievable time-synchronization performance over 5G becomes essential.

## 1.3 Research Gap

Although 3rd Generation Partnership Project (3GPP) has introduced mechanisms to support time synchronization within 5G systems, the practical performance of

PTP over real industrial 5G deployments remains insufficiently understood. Existing studies have primarily relied on simulation-based analysis, analytical models, or controlled laboratory environments with near-ideal conditions.

While these studies provide valuable theoretical insights, they often do not fully capture the behavior of real wireless systems operating under different radio conditions and realistic traffic load. In particular, the interaction between PTP synchronization mechanisms and practical 5G network dynamics remains insufficiently validated through experimental measurements.

Furthermore, many prior studies focus on protocol modifications or architectural solutions, while fewer works experimentally evaluate the achievable synchronization performance of standard PTP deployments over 5G campus networks in an industrial environment.

## 1.4 Scope and Focus of the Thesis

This thesis addresses the identified gap by experimentally evaluating the performance of IEEE 1588 PTP over a campus/private 5G Standalone (SA) network in an industrial research environment.

Rather than proposing new synchronization algorithms or modifications to the 5G infrastructure, this work focuses on characterizing achievable synchronization performance under realistic deployment conditions. The study investigates how wireless network characteristics influence synchronization accuracy and precision compared to a wired Ethernet baseline.

The evaluation focuses on static deployment scenarios and investigates the impact of:

- hardware and software message timestamping,
- network traffic load and resource sharing among multiple 5G devices,
- radio quality conditions, and
- delay asymmetry compensation.

The primary synchronization metrics considered in this thesis are:

- synchronization accuracy, represented by the mean value of time offset between PTP master and a slave,
- synchronization precision, represented by the offset's standard deviation value (jitter).

## 1.5 Objectives and Research Questions

The main objective of this thesis is to evaluate the performance of PTP when operating over a campus/private 5G network in industrial conditions.

Specifically, the thesis aims to:

- Experimentally assess the achievable synchronization accuracy and precision of PTP over a commercial 5G campus/private network,

- analyze the impact of wireless network conditions on synchronization performance,
- compare time-synchronization behavior between wired Ethernet and 5G,
- evaluate the influence of message timestamping, wireless signal conditions, and radio resource sharing on synchronization stability, and
- determine under which conditions PTP over 5G may be suitable for industrial applications.

Based on these objectives, the thesis addresses the following research questions:

1. How does PTP synchronization performance over a campus/private 5G network compare to a wired Ethernet baseline?
2. What are the dominant factors affecting time synchronization accuracy and precision in 5G networks?
3. How do message timestamping methods, network traffic load, and radio conditions influence synchronization performance?

## 1.6 Contributions

The main contributions of this thesis are:

- an experimental evaluation of IEEE 1588 PTP running over a real private 5G network,
- a time-sync performance comparison between wired Ethernet and 5G,
- a characterization of synchronization accuracy and precision under varying network conditions,
- an analysis of the impact of message timestamping mechanisms, resource sharing, and radio conditions on synchronization behavior,
- an analysis of the key factors affecting PTP synchronization performance over private 5G networks, providing initial guidance for industrial deployment of PTP over 5G.

Chapter 2

# Background and Related Work

## 2.1 Time Synchronization Fundamentals

Accurate time synchronization is a fundamental requirement in distributed communication and control systems. In such systems, multiple devices operate independently while cooperating to perform time-critical tasks. To ensure correct operation, these devices must operate using a shared time reference with tightly controlled synchronization accuracy. Even small timing inaccuracies may lead to incorrect sequencing of events, degraded performance, or system instability, particularly in industrial environments.

### 2.1.1 Clocks in Distributed Systems

Each node in a distributed system maintains its own local clock, typically implemented using a crystal oscillator and clock counter. Due to manufacturing tolerances, temperature variations, voltage fluctuations, and aging effects, no two oscillators operate at the same frequency or start from the same time reference. As a result, local clocks inevitably diverge over time if no synchronization mechanism is applied [4, 5].

To achieve a common time base, distributed systems rely on synchronization protocols in which one clock is selected as reference, often referred to as the master or the grandmaster clock. Other nodes, acting as slaves or followers, periodically adjust their local clocks based on timing information exchanged over the communication network. The achievable synchronization accuracy depends on both clock quality and network characteristics, such as delay, jitter, and asymmetry [1].

In this thesis, these factors are experimentally evaluated using synchronization accuracy, represented by the mean offset, and synchronization precision, represented by offset jitter, under different network conditions, including wireless transport over 5G.

### 2.1.2 Clock Offset and Clock Drift

Two key concepts are used to describe clock discrepancies in distributed systems: clock offset and clock drift. Clock offset is defined as the instantaneous time difference between two clocks at a given moment, while clock drift refers to the rate of change of this offset over time, caused by a frequency mismatch between clocks

[5]. Formal definitions and synchronization-related offset estimation equations are presented in Section 2.2.3.

Even a small frequency error can lead to a significant clock offset if it is not corrected regularly [4]. For example, a frequency deviation of a few parts per million results in microsecond-level errors within seconds. Synchronization protocols, therefore, perform periodic timing exchanges to estimate and compensate for both offset and drift [5].

### 2.1.3 Network Delay and its Impact on Synchronization

Time synchronization over packet-switched networks is fundamentally limited by network delay [4]. When timing messages are exchanged between nodes, the transmission delay introduces uncertainty in the estimation of clock offset [5]. This delay can be decomposed into fixed components, such as propagation and processing delays, and variable components, commonly referred to as packet delay variation or jitter.

Many synchronization protocols assume symmetric delays in the forward and reverse communication paths [1]. However, in practical systems, especially wireless networks, uplink and downlink delay may differ significantly. Such delay asymmetry introduces systematic synchronization errors that cannot be eliminated by simple averaging and must be addressed through protocol design or compensation mechanisms [5].

Packet Delay Variation (PDV) refers to the variation of one-way packet delay over time in a packet-switched network. It is commonly defined as the deviation of the instantaneous packet delay from its minimum or mean value over an observation interval. PDV introduces uncertainty in timestamp-based delay estimation and directly contributes to synchronization jitter in IEEE 1588 systems [6].

Delay asymmetry is defined as the difference between the forward-path delay and the reverse-path delay. Let $d_{\text{down}}$ denote the master-to-slave (downlink) delay and $d_{\text{up}}$ denote the slave-to-master (uplink) delay. The delay asymmetry is then expressed as

$$\Delta d = d_{\text{down}} - d_{\text{up}} \tag{2.1}$$

If $\Delta d \neq 0$, the estimated clock offset becomes biased by $\frac{\Delta d}{2}$, as derived in IEEE 1588 [1] and discussed in [6]. In wireless networks, delay asymmetry may arise from scheduling mechanisms, retransmissions, or different processing paths in uplink and downlink directions.

This limitation is particularly critical in wireless networks such as 5G, where scheduling and retransmissions introduce time-varying asymmetry. This effect is directly evaluated in this thesis through experimental measurements under varying load and radio conditions.

### 2.1.4 Synchronization Accuracy Requirements

Different applications impose different requirements on synchronization accuracy. While millisecond-level synchronization may be sufficient for general-purpose networking [5], industrial automation and TSN applications often require sub-microsecond or even nanosecond-level accuracy [7]. These strict requirements motivate the use of specialized synchronization protocols, hardware stamping, and network architectures optimized for deterministic timing behavior [1, 7].

## 2.2 IEEE 1588 Precision Time Protocol

The IEEE 1588 PTP is a network-based clock synchronization protocol designed to provide high-accuracy time synchronization for distributed measurement, control, and industrial automation systems [1]. Originally, PTP was primarily developed for deterministic wired Ethernet networks, where communication delays are relatively stable and symmetric. Unlike general-purpose time synchronization mechanisms such as Network Time Protocol (NTP), IEEE 1588 is specifically engineered to achieve sub-microsecond or nanosecond-level accuracy by exploiting hardware timestamping and precise delay estimation [1, 5]. However, the accuracy of IEEE 1588 strongly depends on stable and symmetric communication delay, which is difficult to guarantee in wireless networks such as 5G.

### 2.2.1 Clock Hierarchy and Roles

IEEE 1588 operates using a hierarchical clock architecture. A single clock is selected as the reference clock, referred to as the grandmaster clock, while all other clocks synchronize their local time to this reference. The selection of the grandmaster is performed automatically using the Best Master Clock Algorithm (BMCA), which evaluates clock quality parameters such as clock accuracy, stability, and priority.

PTP defines several clock types to support scalable synchronization:

- Grandmaster clock, which provides the reference time.
- Ordinary clocks, which act as end devices.
- Boundary clocks, which synchronize to an upstream clock and serve as masters to downstream devices.
- Transparent clocks, which correct timing messages by accounting for residence time within network devices.

This hierarchy allows IEEE 1588 to scale effectively in large networks while maintaining high synchronization accuracy [1].

### 2.2.2 Message Exchange Mechanism

Time synchronization in IEEE 1588 is achieved through the periodic exchange of time-stamped messages between master and slave clocks. The primary message types include sync, Follow_Up, Delay_Req, and Delay_Resp messages. Using these messages, a slave clock estimates both the clock offset relative to the master and the path delay, defined as the propagation and transmission delay between the master and slave clocks [1].

The protocol typically assumes symmetric propagation delays in the forward and reverse paths. Under this assumption, the estimated delay and offset can be

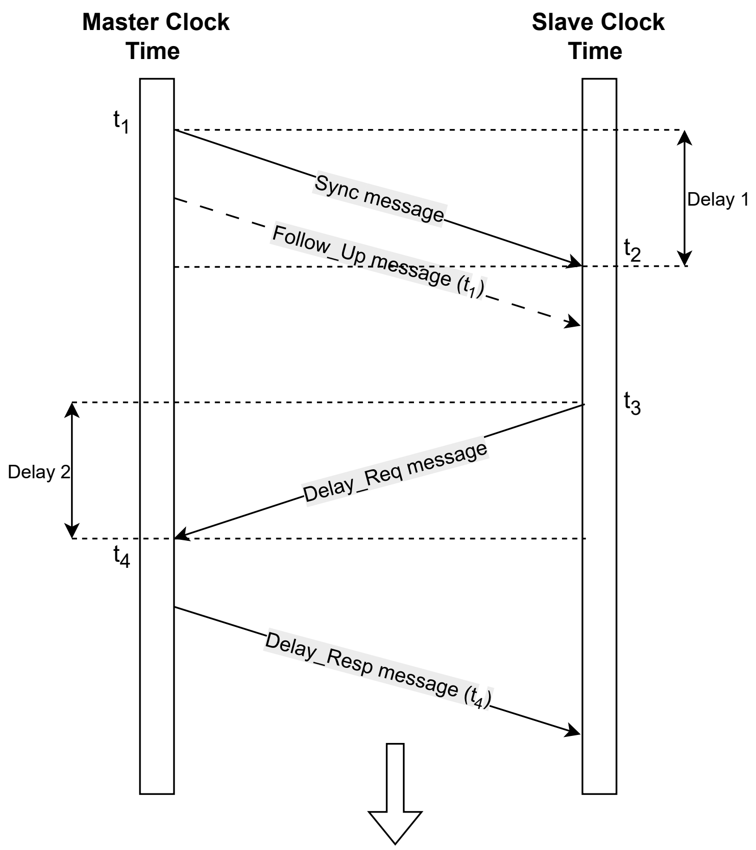


**Figure 2.1:** Message exchange and timestamping in IEEE 1588 PTP [1].

computed accurately. However, any asymmetry in the communication path results in systematic synchronization errors, highlighting the importance of controlled network conditions or compensated mechanisms [1].

In a typical two-step clock operation, synchronization is performed through the exchange of four timestamps, commonly denoted as $t_1$, $t_2$, $t_3$, and $t_4$ [1]. The timestamps are measured using the local clocks of the master and slave devices before synchronization is applied. The synchronization sequence proceeds as follows:

- The master transmits a Sync message at master clock time $t_1$.
- The slave receives the Sync message and records the reception time $t_2$ using its local clock.

- The slave transmits a Delay_Req message at slave clock time $t_3$.
- The master records the reception time of the Delay_Req message as $t_4$ using the master clock.

In two-step mode, precise transmission timestamp $t_1$ is delivered in a Follow_Up message, since the exact transmit time can only be determined after the Sync frame leaves the network interface.

Using these four timestamps, IEEE 1588 performs clock offset and path delay estimation between the master and slave clocks. The mathematical formulation of this estimation process is presented in the next subsection [1, 6].

### 2.2.3 PTP Delay and Offset Estimation

In IEEE 1588, clock synchronization is achieved through timestamp exchange between the master and slave clocks. Let the master transmit a Sync message at time $t_1$, received by the slave at time $t_2$. The slave then transmits a Delay_Req message at time $t_3$, which is received by the master at time $t_4$.

The downlink propagation delay from master to slave, denoted by $d_{\text{down}}$, is defined as

$$d_{\text{down}} = t_2 - t_1 \tag{2.2}$$

Similarly, the uplink propagation delay from slave to master, denoted by $d_{\text{up}}$, is defined as

$$d_{\text{up}} = t_4 - t_3 \tag{2.3}$$

Assuming symmetric propagation delays in the forward and reverse communication paths, IEEE 1588 estimates the mean path delay $d$ as [1, 6]

$$d = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} \tag{2.4}$$

Under the same symmetry assumption, the clock offset between the slave and the master, denoted by $\theta$, is estimated as [1, 6]

$$\theta = \frac{(t_2 - t_1) - (t_4 - t_3)}{2} \tag{2.5}$$

These expressions rely on the assumption that the propagation delay from master to slave is equal to the delay from slave to master. Under symmetric propagation delay conditions, the estimated offset corresponds to the actual clock difference between the master and slave clocks without additional bias caused by communication asymmetry.

If this symmetry assumption is violated, the estimated clock offset becomes biased by half of the delay asymmetry, resulting in systematic synchronization errors [1, 6]. The delay asymmetry, represented by the difference between $d_{\text{down}}$ and $d_{\text{up}}$, therefore directly contributes to the estimated clock offset.

### Impact of Delay Asymmetry on PTP Offset Estimation

**Table 2.1:** Illustrative comparison of delay and offset estimation for wired-like and 5G-like conditions.

| **Parameter** | **Wired-like case** | **5G-like case** |
|---|---|---|
| Downlink delay, $d_{\text{down}}$ | 10.000 $\mu s$ | 4900 $\mu s$ |
| Uplink delay, $d_{\text{up}}$ | 10.001 $\mu s$ | 5840 $\mu s$ |
| Mean path delay, $d$ | 10.0005 $\mu s$ | 5370 $\mu s$ |
| Delay asymmetry, $\Delta d$ | $-0.001$ $\mu s$ | $-940$ $\mu s$ |
| Estimated clock offset, $\theta$ | 0.0005 $\mu s$ | $-470$ $\mu s$ |
| Interpretation | Very small synchronization error | Large synchronization error caused by delay asymmetry |

Table 2.1 presents an illustrative comparison between wired-like and 5G-like delay conditions. The numerical values used in both cases are derived from representative measurements obtained in the experimental setup presented later in this thesis. The wired-like case reflects the nearly symmetric delay behavior observed in the wired Ethernet baseline measurements, while the 5G-like case reflects the millisecond-level path delay and uplink–downlink asymmetry observed in the private 5G experiments described in Section 3.4.7.

The objective of the example is to illustrate how delay asymmetry directly contributes to clock offset estimation error in IEEE 1588 PTP. In the wired-like example, the forward and reverse delays are nearly symmetric, resulting in only nanosecond-level offset bias. In contrast, the 5G-like example exhibits significant uplink and downlink asymmetry, producing synchronization offset bias in the order of several hundred microseconds.

This symmetry assumption is generally valid in controlled wired Ethernet networks, but may not hold in scheduled or wireless communication systems. In wireless systems such as 5G, uplink and downlink delays may become asymmetric due to scheduling and varying radio conditions [8, 9].

This asymmetry is one of the key challenges for accurate PTP synchronization over 5G networks.

## 2.2.4 Clock Servo Mechanism

The offset estimated from the message exchange does not directly adjust the slave clock. Instead, IEEE 1588 implementations employ a clock servo mechanism to gradually align the slave clock with the master.

Most practical implementations use a proportional-integral controller that adjusts the frequency of the slave clock based on the measurement offset. If the offset is large during initialization, the clock may be stepped. During steady state operation, the clock is typically slewed by applying a small frequency correction to ensure smooth convergence and stability.

Step correction refers to the immediate adjustment of a clock by directly changing its time value, eliminating the offset instantaneously but introducing a discontinuity in time. Slew correction refers to the gradual adjustment of a clock by modifying its frequency, allowing the clock to converge smoothly to the reference time without introducing discontinuities.

The servo mechanism continuously filters measurement noise and compensates for oscillator drift, thereby maintaining long-term synchronization accuracy.

### 2.2.5 Clock Frequency Deviation

A clock in a digital system is generated using a hardware oscillator that produces periodic timing signals. Ideally, all clocks would operate at exactly the same frequency. In practice, however, oscillator frequencies may slightly deviate from their nominal values due to temperature variations, aging, manufacturing tolerances, and hardware imperfections.

As a result, independent clocks gradually drift relative to each other over time. This phenomenon is commonly referred to as clock frequency deviation or clock skew.

A simplified clock model can be expressed as:

$$c(t) = \alpha t + \beta \tag{2.6}$$

where:

- $c(t)$ is the local clock value,
- $t$ is the reference time,
- $\alpha$ represents the clock frequency ratio (clock skew), and
- $\beta$ represents the clock offset.

When $\alpha = 1$, the local clock runs at the same frequency as the reference clock. Any deviation from this value causes the clock offset to accumulate over time.

Clock synchronization protocols such as IEEE 1588 PTP periodically exchange timestamped messages to estimate and compensate for both clock offset and clock frequency deviation between devices [1]. In wireless communication systems such as 5G, synchronization performance may additionally be affected by propagation delay asymmetry and packet delay variation [10, 9].

### 2.2.6 Synchronization Performance Metrics

While clock properties describe intrinsic oscillator behavior, synchronization performance metrics quantify the time alignment quality between network nodes [1].

#### Offset

Clock offset is the instantaneous time difference between a slave clock $C_s(t)$ and a master clock $C_m(t)$:

$$\theta(t) = C_s(t) - C_m(t). \tag{2.7}$$

This offset corresponds to the quantity estimated by the PTP delay and offset estimation process described in Section 2.2.3.

### Mean Offset

The mean offset over an observation interval $T$ is defined as

$$\mu_\theta = \frac{1}{T} \int_0^T \theta(t)\, dt. \tag{2.8}$$

Mean offset reflects a systematic bias that may arise from asymmetric communication delays. Systematic bias refers to a persistent offset in clock synchronization that does not average out over time, typically caused by asymmetric communication delays between forward and reverse paths.

### RMS Offset

The Root Mean Square (RMS) offset quantifies the magnitude of synchronization error:

$$\theta_{\mathrm{RMS}} = \sqrt{\frac{1}{T} \int_0^T \theta^2(t)\, dt}. \tag{2.9}$$

RMS offset captures both systematic and random error components. Although RMS offset is a useful metric for describing the overall magnitude of synchronization error, this thesis focuses primarily on mean offset and offset jitter to distinguish between synchronization accuracy and precision.

### Jitter

Jitter represents short-term variations of the clock offset around its mean value and is typically quantified by the standard deviation:

$$\sigma_\theta = \sqrt{\mathbb{E}\left[(\theta(t) - \mu_\theta)^2\right]} \tag{2.10}$$

Jitter primarily results from stochastic network delay variations and timestamp noise.

## 2.2.7 Timestamping Mechanisms and Network Delay Effects

The achievable synchronization accuracy in PTP strongly depends on where timestamps are generated within the communication stack. Timestamp uncertainty may originate from software execution delays, operating system scheduling, interrupt latency, and variable network delays. These effects become particularly important in wireless communication systems, where stochastic delay variations may significantly degrade synchronization precision.

### Software Timestamping

In software timestamping, timestamps are generated within the operating system network stack after packets traverse multiple software layers. Consequently, the timestamp values are affected by operating system scheduling, interrupt handling, driver execution, and buffering delays.

Because these delays are nondeterministic, software timestamping introduces additional timing uncertainty and jitter into the synchronization process. In practical wired Ethernet networks, software-based timestamping typically limits its achievable synchronization accuracy to the microsecond range. In wireless networks, additional variability introduced by radio scheduling and packet delay variation may further degrade synchronization performance[1, 5].

#### Hardware Timestamping

Hardware timestamping reduces timestamp uncertainty by generating timestamps directly at the network interface level, typically close to the physical layer or Medium Access Control (MAC) layer. Since timestamps are generated before software processing occurs, the influence of operating system and driver delays is significantly reduced.

With suitable hardware support, hardware timestamping enables much higher synchronization precision and is commonly used in industrial Ethernet systems requiring sub-microsecond synchronization performance [1, 6].

#### Network Delay Variation and Synchronization Accuracy

Even when hardware timestamping is used, synchronization performance remains affected by network-induced delay variation. Variable queuing delays, packet scheduling, retransmissions, and communication asymmetry may introduce fluctuations in packet propagation time, resulting in offset jitter and synchronization degradation.

In wired Ethernet networks, propagation delays are generally stable and nearly symmetric, enabling highly accurate synchronization. In contrast, wireless communication systems such as 5G introduce additional delay variability due to uplink scheduling, shared radio resources, retransmission mechanisms, and changing radio conditions [8, 9].

Consequently, while hardware timestamping minimizes local timestamp uncertainty, synchronization performance in wireless systems is often dominated by network-induced delay variation rather than timestamp generation accuracy alone. This effect is one of the primary challenges for achieving high-precision PTP synchronization over 5G networks.

## 2.3 5G Networks for Time-Critical Communication

Fifth-generation mobile networks 5G were initially designed to enhance mobile broadband capacity and reduce latency compared to previous cellular systems. However, beyond traditional consumer services, 5G has evolved to support time-critical and industrial communication scenarios. These include factory automation, smart grids, remote control systems, and other applications that require predictable latency and reliable data delivery.

### 2.3.1 Latency and Reliability Enhancements

5G introduces several architectures and physical layer improvements that reduce end-to-end latency. Compared to LTE, 5G New Radio (NR) supports shorter transmission time intervals, flexible numerology, and faster scheduling mechanisms. These features enable lower air interface latency and improve responsiveness.

In addition, Ultra-Reliable Low-Latency Communication (URLLC) has been defined as one of the key 5G service categories. URLLC targets very high reliability and low latency performance, making 5G suitable for mission-critical and industrial applications. While the theoretical latency targets are in the millisecond range, practical performance depends on network configuration, load conditions, and deployment architecture.

URLLC targets reliability levels above 99.999% with end-to-end latency in the order of 1 ms under ideal deployment conditions [11, 12]. While these targets are defined as system-level, practical performance depends on scheduling configuration, radio conditions, and network architecture.

### 2.3.2 5G Scheduling Mechanisms

5G New Radio (NR) employs a centralized, grant-based scheduling mechanism controlled by the base station (Next Generation NodeB (gNB). Scheduling procedures are defined in the NR MAC and physical layer specifications [2], while the overall system architecture is described in [12].

In the downlink direction, the gNB schedules data transmission to the UE by assigning time-frequency resources within specific slots. In contrast, uplink transmission is grant-based: the UE must first transmit a Scheduling Request (SR), after which the gNB responds with an uplink grant before the UE can transmit data.

This additional control exchange introduces extra delay and variability compared to wired communication. Furthermore, scheduling decisions depend on Channel Quality Indicator (CQI), Buffer Status Report (BSR), Hybrid Automatic Repeat Request (HARQ) processes, and Quality of Service (QoS) priorities. Consequently, transmission timing is not deterministic and may vary between scheduling intervals.

The evaluated private 5G network operates in TDD mode. In TDD systems, uplink and downlink transmissions utilize a common frequency band but are temporally separated according to a predefined slot configuration. Depending on the specific TDD pattern employed, the allocation of uplink and downlink resources may be asymmetric. This asymmetry can lead to differential delay between the forward and reverse communication paths.

From a time synchronization perspective, scheduling behavior directly affects PDV and uplink-downlink asymmetry. Since IEEE 1588 offset estimation assumes symmetric path delay, scheduling-induced asymmetry may bias the offset estimate, while scheduling variability contributes synchronization jitter.

Figure 2.2 illustrates the simplified dynamic uplink scheduling procedure in 5G NR. Before transmitting uplink data, the User Equipment (UE) first sends a Scheduling Request (SR) to the gNB. The gNB then allocates uplink resources by transmitting a grant message, after which the UE can transmit data. This

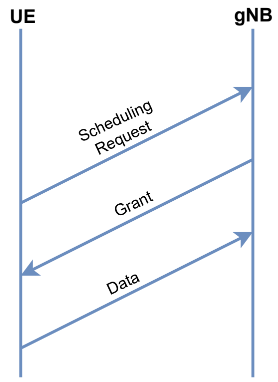


**Figure 2.2:** Simplified uplink scheduling procedure in 5G NR based on [2, 3].

additional scheduling exchange introduces delay and timing variability compared to deterministic wired Ethernet communication.

### 2.3.3 Industrial and Campus 5G Deployments

Industrial communication systems are increasingly adopting campus and private 5G deployments to support flexible connectivity, mobility, and reduced cabling requirements in industrial environments. Compared to public mobile networks, campus deployments provide improved control over network configuration, traffic prioritization, security, and latency management.

A typical industrial 5G deployment consists of a local or enterprise-integrated 5G infrastructure including the gNB, core network functions, and industrial user devices. Such deployments are intended to support industrial applications including factory automation, monitoring systems, autonomous vehicles, and distributed sensing.

Unlike wired Ethernet networks, 5G communication relies on centralized radio scheduling and shared wireless resources. As discussed in Section 2.3.2, uplink and downlink transmissions are dynamically scheduled by the gNB, introducing variable transmission delay and packet delay variation. These effects are particularly important for time synchronization protocols such as PTP, which assume relatively stable and symmetric communication delay.

In addition, 5G systems operating in Time Division Duplex (TDD) mode may introduce asymmetry between uplink and downlink transmission timing due to unequal slot allocation. The resulting uplink-downlink delay asymmetry can bias the offset estimation process described in Section 2.2.3.

Although 5G introduces several mechanisms intended to support low-latency communication, including URLLC, flexible numerology, and scheduling optimization, the achievable synchronization performance in practical industrial deployments remains strongly affected by scheduling behavior, network load, and wireless delay variability.

Therefore, experimental evaluation of PTP over industrial 5G deployments is necessary to determine whether wireless communication can satisfy the synchronization requirements of industrial and time-critical applications.

### 2.3.4 Radio Quality Metrics in 5G

Radio link quality in 5G networks is commonly characterized using reference-signal-based measurements reported by the user equipment (UE). Reference signals are predefined radio signals periodically transmitted by the serving gNB to support synchronization, channel estimation, and radio quality measurements. The most widely used metrics are Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Signal-to-Interference-plus-Noise Ratio (SINR) [13].

**RSRP** is defined as the linear average of the received power of downlink reference signals transmitted by serving gNB. It reflects the received signal strength and is typically expressed in dBm. Higher (less negative) RSRP values indicate stronger radio coverage.

**RSRQ** combines signal strengths and total received wideband power. It is defined as the ratio between RSRP and the Received Signal Strength Indicator (RSSI), providing insight into channel quality and cell load conditions.

**SINR** represents the ratio between useful signal power and the sum of interference and noise power. SINR directly reflects link reliability and achievable modulation and coding performance.

Variations in these radio metrics influence the scheduling behavior, retransmission, and packet delay variation in 5G networks, which in turn may impact IEEE 1588 synchronization performance.

### 2.3.5 Challenges for Time Synchronization over 5G

Although 5G improves latency performance, wireless communication introduces additional challenges for precise time synchronization.

First, the uplink and downlink paths may experience different delays due to scheduling, retransmission, and radio resource allocation. Consequently, the forward-path delay $d_{\text{down}}$ and reverse-path delay $d_{\text{up}}$ may become asymmetric. As discussed in Section 2.2.3, this delay asymmetry introduces an offset estimation bias proportional to the delay difference $\Delta d = d_{\text{down}} - d_{\text{up}}$.

Second, packet delay variation caused by radio channel conditions, retransmissions, and network load may degrade synchronization stability. Since IEEE 1588 assumes relatively stable propagation delay for accurate offset estimation, stochastic delay variations directly increase synchronization jitter and reduce timing precision.

Therefore, evaluating the achievable synchronization accuracy in IEEE 1588 over a 5G network is essential to determine whether wireless transport can satisfy time-critical communication requirements.

## 2.4 Related Work

### 2.4.1 PTP Fundamentals and Ethernet-Based Synchronization

Precise time synchronization in industrial networks is commonly achieved using the IEEE 1588 PTP and its profile IEEE 802.1AS, which forms the basis of Time-Sensitive Networking (TSN) [1, 14]. In wired Ethernet networks, PTP can achieve sub-microsecond or even nanosecond-level accuracy due to full-duplex links, low and deterministic delay, and widespread support for hardware-based timestamping at the physical or MAC layer. These properties allow PTP to reliably estimate path delay and clock offset, assumptions that are fundamental to its design. As a result, Ethernet-based TSN has become the reference solution for deterministic industrial communication, against which wireless approaches are typically compared.

### 2.4.2 Early Industrial Work on PTP over Wi-Fi

Early research on PTP over Wi-Fi investigated how wireless delay variation affects synchronization performance in nondeterministic communication environments. Raittila [15] proposed an adaptive clock servo mechanism based on Kalman filtering to improve synchronization robustness under varying wireless delay conditions. Instead of modifying the underlying communication infrastructure, the work focused on adapting the internal control behavior of the synchronization algorithm to compensate for delay variation and clock drift.

The study demonstrated that adaptive servo techniques can improve synchronization stability in Wi-Fi networks. However, the synchronization performance remained constrained by software-based timestamping and the inherent nondeterministic behavior of Wi-Fi communication links.

A more fundamental analysis of time synchronization over Wi-Fi is presented in the work by Mahmood et al. [16], which investigates the impact of hardware and software timestamping on synchronization performance in IEEE 802.11 networks. This study provides detailed experimental and simulation-based evidence that software timestamping is a primary bottleneck for achieving high synchronization accuracy. The authors show that operating system scheduling, interrupt handling latency, and CPU architecture introduce microsecond-level timestamping errors, which directly translate into synchronization offsets. While IEEE 802.11v introduces timing measurement mechanisms with hardware-assisted timestamping, the paper demonstrates that timestamp resolution, quantization, and transport of accurate timestamps to higher layers remain limiting factors. Importantly, this work highlights that timestamp precision alone is insufficient; synchronization performance also depends on oscillator stability, synchronization interval, and clock servo design. These findings establish a key insight that precise wireless time synchronization requires dedicated hardware support rather than purely software-based solutions.

Earlier work by Wu [17] investigated whether the conventional clock servo and control loop mechanisms within PTP could be adapted to compensate for varying wireless delays in Wi-Fi networks. The study focused on improving synchronization robustness under nondeterministic wireless communication conditions without modifying the underlying network infrastructure.

The work combined protocol analysis with practical measurement techniques to evaluate synchronization accuracy, pulse-per-second (PPS) alignment, and timing behavior in industrial communication environments. The results highlighted several persistent challenges in wireless synchronization, including packet delay variation, asymmetric communication paths, and timestamping limitations. In particular, the study showed that although wireless synchronization solutions can achieve functional synchronization, their timing performance remains significantly less deterministic than wired Ethernet-based industrial TSN systems.

### 2.4.3 Time Synchronization over 5G Networks

To overcome the limitations of Wi-Fi, several studies have explored time synchronization over 5G networks, motivated by the scheduled and centrally controlled nature of cellular access. Unlike Ethernet links, however, the 5G air interface introduces additional sources of timing uncertainty related to reference time indication, Timing Advance (TA) granularity, and asymmetric uplink and downlink scheduling procedures.

Mahmood et al. [18] analyze device-level synchronization requirements for Critical Machine-Type Communication (cMTC) in 5G and identify key over-the-air timing error sources, including reference time quantization, TA estimation error, and uplink/downlink asymmetry. Their analytical study shows that TA granularity and propagation delay estimation directly hit the limit of achievable synchronization accuracy at the user equipment. Similarly, Shi et al [10]. Evaluate over-the-air time synchronization for 5G-TSN integration using simulation-based modeling, highlighting the impact of scheduler behavior, propagation delay variation, and TAresolution on end-to-end synchronization performance. Although these works establish theoretical limits on the accuracy of OTA timing, they do not evaluate full PTP-based synchronization in practical deployments.

Building on this foundation, simulation-based work by Muslim et al. [19] evaluates IEEE 802.1AS synchronization over 5G networks and shows that time-slotted scheduling can reduce delay variation compared to contention-based Wi-Fi. Similarly, Morato et al. [20] assess PTP performance over mmWave 5G New Radio, indicating that high data rates and deterministic scheduling can improve synchronization accuracy under idealized conditions. However, these studies are largely based on simulations or preliminary assessments and often assume simplified delay models or ideal timestamping, limiting their ability to capture real-world implementation challenges.

Further investigation into the architectural implications of integrating TSN and 5G is presented by Striffler and Schotten [21], who model the 5G system as a logical TSN Transparent clock . Their simulation-based analysis reveals that syntonization errors and frequency mismatches between the clock at the 5G entry point and the clock at the 5G exit point within the 5G bridge can introduce additional residence-time estimation errors. Even small frequency offsets accumulate over synchronization intervals and may violate sub-microsecond TSN requirements.

Although this work provides important insight into structural timing challenges, it does not consider real radio dynamics or hardware-induced variability.

Addressing one of the fundamental limitations of PTP over 5G, Muslim et al. [8] later propose a modified Generalized Precision Time Protocol (gPTP) mechanism that compensates asymmetric uplink and downlink latency by incorporating MAC-layer timestamps of the SR and grant procedure into the propagation delay calculation. Simulation results show a significant reduction in synchronization error under asymmetric conditions. Nevertheless, the evaluation remains simulation-based and does not assess performance under real 5G deployments, mobility, and varying radio channel conditions.

Experimental evaluations of time synchronization over 5G remain comparatively limited. Thi et al.[22] investigate IEEE 802.1AS over both Wi-Fi and 5G mobile networks using hardware testbeds and a reference-based measurement methodology. Their results show that while 5G outperforms Wi-Fi in terms of synchronization stability, direct application of IEEE 802.1AS over wireless links still results in significant accuracy degradation compared to wired Ethernet. More recently, Kalniņš et al.[9] present one of the first hardware-based studies of PTP synchronization over a private 5G SA network. Their measurements reveal millisecond-level synchronization errors caused primarily by delay asymmetry and propagation delay estimation inaccuracies. However, the evaluation is conducted under static conditions and does not systematically investigate mobility, network load variation, or radio channel dynamics.

Overall, existing literature demonstrates that time synchronization over 5G is feasible but remains challenging due to over-the-air delay variability, asymmetry, and synchronization effects. Most prior work relies on simulation-based analysis or evaluates specific architectural solutions such as transparent clocks or asymmetry compensation mechanisms. Comprehensive experimental studies that characterize PTP performance over private 5G networks under dynamic industrial conditions, including mobility, varying network load, and radio channel variability, remain scarce. This thesis addresses this gap by providing an experimental evaluation of PTP-based time synchronization over a private 5G network, with emphasis on industrial applicability and performance-limiting factors.

Chapter 3

# System Model and Methodology

## 3.1 Research Design

### 3.1.1 Methodological Approach

This thesis adopts an experimental and quantitative research methodology to evaluate the performance of IEEE 1588 Precision Time Protocol (PTP) over a campus/private 5G SA network in an industrial research environment. The evaluation is conducted at ABB Corporate Research in Västerås, Sweden, enabling the analysis of synchronization performance under realistic operating conditions rather than relying on a simulation-based model.

The 5G network is treated as a transport infrastructure, and no modifications are applied to the internal radio or core network parameters. This approach reflects practical industrial deployment scenarios, where the network operator typically manages the wireless infrastructure.

A wired Ethernet configuration is used as a baseline reference to establish the lower bound of achievable synchronization error under stable and controlled network conditions. The performance of PTP over the 5G network is then compared against this baseline to quantify the impact of wireless-specific effects, such as packet delay variation, scheduling, and uplink-downlink asymmetry.

### 3.1.2 Research Variables

The experimental design is structured around a set of independent, dependent, and controlled variables to enable systematic evaluation of synchronization performance.

The independent variables represent factors that are intentionally varied during the experiments. These include radio quality conditions, network load levels, timestamping mechanisms, and QoS configuration in the 5G network. Radio quality is characterized using standard 5G metrics such as RSRP, RSRQ, and SINR, which are introduced in Section 2.3.4 and are known to influence scheduling behavior and transmission reliability.

The dependent variables correspond to the measured synchronization performance metrics. These include time offset, jitter, path delay, and frequency deviation, which are derived from PTP logs collected at the slave node. Time offset and jitter correspond to the synchronization metrics defined in Section 2.2.6, while path delay corresponds to the propagation delay estimation described in Section 2.2.3. These metrics are used to quantify synchronization accuracy, stability, and robustness under different experimental conditions.

The controlled variables are parameters that are kept constant throughout all experiments to ensure consistency and comparability of results. These include the PTP configuration (e.g., message intervals and delay mechanism), hardware platform, and underlying 5G networks configuration. By controlling these factors, the observed variations in synchronization performance can be attributed to the experimental factors under investigation.

Although mobility scenarios were initially considered in the experimental design, they are excluded from the scope of this thesis to focus on static conditions and to isolate the impact of network-induced delay variation. Mobility-related effects are therefore left for future work.

### 3.1.3 Experimental Constraints and Assumptions

Several practical constraints and assumptions are considered in the experimental design to reflect the limitations of the deployed private 5G network.

First, PTP communication is implemented using unicast transmission only. Although IEEE 1588 commonly supports multicast communication, multicast transport is not available in the investigated 5G deployment due to limitations in network configuration and user equipment capabilities.

Second, the user equipment (UE), implemented as an industrial 5G router, operates with Network Address Translation (NAT) enabled. This reflects the default configuration in the deployed network and may introduce additional processing delay and jitter in the communication path. A constant NAT-related delay component could theoretically be compensated as part of the delay asymmetry correction. However, the variable processing delay introduced by NAT cannot be easily separated from the overall network-induced packet delay variation in the performed end-to-end measurements. Therefore, NAT-related effects are treated as part of the practical deployment conditions rather than as an independently evaluated factor.

Third, the 5G network is treated as a black-box system, meaning that internal parameters such as scheduling algorithms, resource allocation strategies, and timing mechanisms are not modified. This assumption ensures that the evaluation reflects realistic industrial usage conditions.

Finally, no artificial radio interference is introduced. Variations in radio conditions are achieved through controlled device positioning within the coverage area.

These constraints ensure that the experimental results are representative of practical industrial deployments, while still allowing systematic evaluation of the key factors affecting time synchronization performance over 5G.

## 3.2 Evaluation Testbed

This section presents the experimental testbed used to evaluate PTP synchronization over a private 5G network. Section 3.2.1 introduces the overall system architecture and communication path. Section 3.2.2 describes the wired Ethernet baseline configuration, which serves as the reference scenario for synchronization performance evaluation. Finally, Section 3.2.3 presents the wireless 5G setup and the associated network configuration.

### 3.2.1 Architecture

The experimental setup is designed to evaluate end-to-end time synchronization performance across a private 5G network. The system consists of a PTP Grandmaster (GM) node, a PTP follower/slave node, an enterprise Local Area Network (LAN), a 5G core network, a 5G base station (gNB), and a UE device implemented as an industrial 5G router.

The Grandmaster node is connected to the enterprise LAN and serves as the primary reference clock for the PTP domain. The slave node is connected to the UE router, which provides connectivity to the 5G network and the core network. The synchronization message is transmitted from the Grandmaster to the slave through the 5G user plane, forming a complete end-to-end synchronization path.

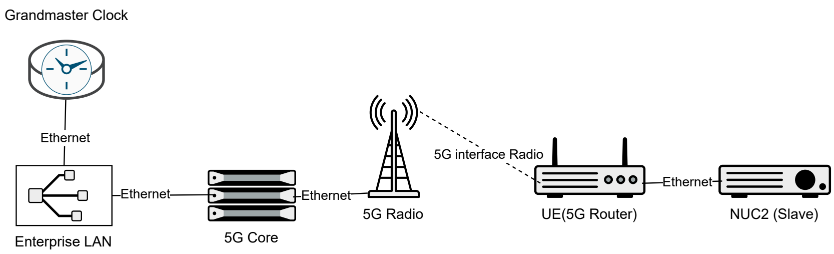


**Figure 3.1:** Overall architecture and end-to-end communication path used for PTP synchronization over the private 5G network.

Figure 3.1 illustrates the overall system architecture and the end-to-end communication path used in the experiments.

This architecture reflects a realistic industrial deployment scenario in which time synchronization must be maintained across a heterogeneous network, including both wired and wireless components.

### 3.2.2 Wired Baseline Setup

To establish a reference for synchronization performance, a wired baseline configuration is implemented using a direct Ethernet connection between the Grandmaster and the slave node. In this setup, as show on the Figure 3.2, both devices are connected to the LAN enterprise, eliminating the influence of wireless transmission, scheduling delay, and network-introduced asymmetry.

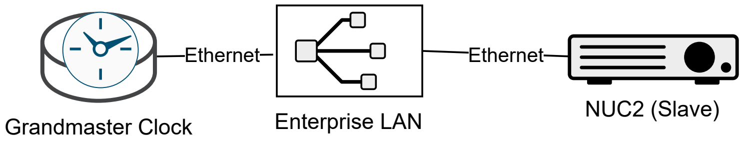


**Figure 3.2:** PTP Wired Setup.

The wired baseline serves as a benchmark for evaluating the intrinsic performance of the PTP implementation under stable and controlled conditions. It provides the minimum achievable synchronization error, allowing the impact of the 5G network to be evaluated in later experiments.

### 3.2.3 5G Setup

In the wireless configuration, PTP messages are transmitted over the private 5G network using User Datagram Protocol (UDP)/Internet Protocol Version 4 (IPv4). The GM node is connected to the enterprise LAN, which provides connectivity to the private 5G network. The communication path follows the 5G user-plane architecture and can be described as Figure 3.3.

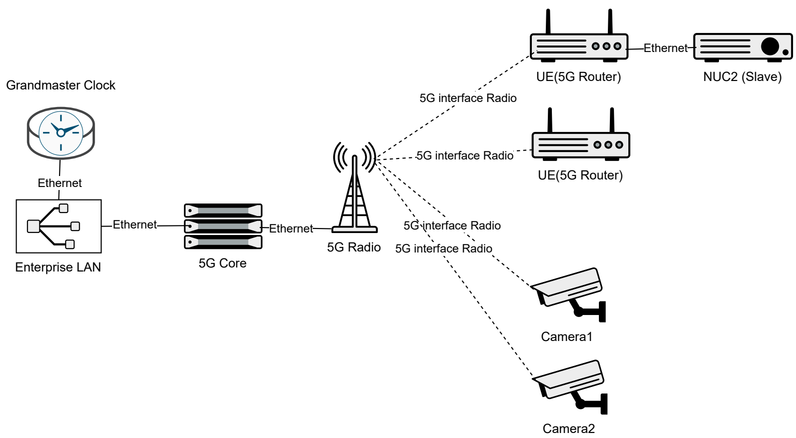


**Figure 3.3:** PTP 5G Setup.

In this setup, the Grandmaster remains connected to the enterprise LAN, while the slave node communicates through the UE router over the 5G radio interface. The 5G network introduces additional delay components, including scheduling delay, transmission delay, and processing delay within the core network and UE. Unlike the wired baseline, the wireless configuration is subject to variability in latency due to dynamic radio conditions, resource allocation, uplink and downlink asymmetry. These effects are expected to influence the accuracy and stability of the time synchronization.

### 3.2.4 5G Parameter Configuration

The radio access network operates in Frequency Range 1 (FR1) using NR band n78L in the 3.7 GHz spectrum. The configured channel bandwidth is 80 MHz.

The network uses TDD with the pattern DDDSUUDSUU. Since uplink and downlink share time resources in TDD systems, delay asymmetry may occur between the forward and reverse PTP message paths. Such asymmetry can bias the PTP offset estimate.

The gNB baseband unit is synchronized using a Global Navigation Satellite System (GNSS)-disciplined clock with configured GNSS delay compensation. This provides a stable absolute time reference for the radio access network and constrains the achievable synchronization accuracy of PTP over the 5G link.

A GNSS-disciplined clock is a local oscillator whose time and frequency are continuously corrected using signals from a Global Navigational Satellite System, such as GPS. This provided long-term stability and traceability to Coordinated Universal Time (UTC) [6]. In IEEE 1588 systems, GNSS-disciplined clocks are commonly used as grandmaster references to ensure absolute time accuracy [1].

**Table 3.1:** 5G Configuration Used in the Experiments.

| **Parameter** | **Configuration** |
|---|---|
| Network Type | Private 5G (Non-Public Network) |
| Deployment Mode | Standalone (SA) |
| Frequency Range | FR1 (Sub-6 GHz) |
| NR Band | n78L |
| Frequency Allocation | 3719.99 – 3799.99 MHz |
| Channel Bandwidth | 80 MHz |
| Duplex Mode | TDD |
| TDD Pattern | DDDSUUDSUU |
| NR-ARFCN | 650666 |
| Time Source | GNSS-disciplined clock |
| GNSS Delay Compensation | 107 ns |

## 3.3 Hardware and Software Configuration

### 3.3.1 Hardware Platform

The experimental setup consists of a GM clock, a slave device, a 5G communication system, and supporting networking equipment. The configuration is designed to emulate an industrial deployment scenario where precise time synchronization is required over a wireless network.

#### Grandmaster Clock

A professional-grade GM clock is used as the primary time reference in this study. Unlike software-based implementations, the GM is a dedicated hardware device designed for high-precision time distribution. The GM is typically disciplined by a GNSS, ensuring long-term stability and traceability to UTC.

The use of a professional GM significantly improves synchronization reliability by minimizing clock drift and timestamping uncertainty at the source. This ensures that any observed synchronization error is primarily due to network effects rather than imperfections in the time reference.

The slave node is connected to the private 5G network through an industrial 5G router, specifically the Advantech ICR-4400. The router functions as the UE and provides connectivity between the wired local network and the 5G radio access network. This setup reflects a realistic industrial deployment scenario where end devices access the network through a 5G gateway.

#### Slave Device

The slave device is implemented using an Intel NUC platform running a Linux-based operating system. The device is equipped with an Intel I219-V Network Interface Card (NIC), which supports hardware timestamping. This capability allows precise timestamping of PTP messages at the physical layer, reducing software-induced variability.

#### 5G Communication System

The wireless communication between the GM and the slave is established through a private 5G network. The setup includes:

- A 5G base station (gNB)
- A 5G core network
- A user equipment (UE) router acting as a bridge between the 5G network and the slave device

The 5G network operates in SA mode and provides the transport for PTP messages over the air interface.

#### Networking Equipment

The system is interconnected through an enterprise LAN, which connects the GM to the 5G infrastructure. Standard Ethernet switching is used without time-aware features such as boundary clocks or transparent clocks, ensuring that the impact of the wireless segment can be clearly observed.

### 3.3.2 Timestamping Capability

Accurate timestamping is critical for PTP performance. In this setup:

- The slave device uses hardware timestamping via the NIC (PTP Hardware Clock, PHC)
- Timestamping support is verified using system tools such as `ethtool`, confirming hardware transmit and receive timestamping capabilities
- The GM clock performs timestamping internally using dedicated hardware

Hardware timestamping reduces latency uncertainty and improves synchronization precision compared to software-based approaches, as discussed in prior work [15].

### 3.3.3 Software Environment

The synchronization protocol is implemented using the `linuxptp` software suite. The following components are used:

- `ptp4l`: Handles PTP message exchange and clock synchronization over the network
- `phc2sys`: Synchronizes the system clock of the slave device to the PTP Hardware Clock (PHC)

The software runs on a Linux operating system with real-time kernel support to reduce scheduling delays and improve timing determinism.

### 3.3.4 PTP Configuration

The PTP is configured according to the IEEE 1588 standard using a unicast communication model. The key configuration parameters are as follows:

- Transport protocol: udp over ipv4
- Communication mode: Unicast
- Delay mechanism: End-to-End (E2E)
- Timestamping: Hardware-based

A configured delay asymmetry compensation parameter of 1 ms is applied in all experiments to account for the expected uplink–downlink delay imbalance, as discussed in Section 3.4.7.

#### Key Parameters

- `logSyncInterval = 0`
- `logMinDelayReqInterval = 0`
- `logAnnounceInterval = 1`

These parameters are selected to provide a balance between synchronization responsiveness and network load.

### 3.3.5 System Architecture and Measurement Setup

The overall system architecture consists of two main segments:

- **Wired Segment:** The GM clock is connected to the enterprise LAN, providing a stable and low-latency reference environment.
- **Wireless Segment (5G):** PTP messages are transmitted through the 5G network from the core network to the UE router and then forwarded to the slave device.

The time offset is measured at the slave device using the output of the `ptp4l` daemon. This measurement reflects the end-to-end synchronization performance, including all network-induced effects such as delay, jitter, and asymmetry.

### 3.3.6 Design Considerations

The use of a professional GM clock ensures that the reference time source has negligible error compared to the network-induced effects. This allows the evaluation to focus on the impact of the wireless network rather than the limitations of the synchronization source.

This design aligns with industrial synchronization systems, where high-quality hardware clocks are used to meet strict timing requirements [15].

## 3.4 Measurement Methodology

### 3.4.1 Measurement Objective

The objective of the measurement is to evaluate the performance of time synchronization over a wireless 5G network using PTP. The evaluation focuses on quantifying the impact of wireless delay variation and scheduling behavior on synchronization accuracy and precision, represented by the mean offset and offset jitter, respectively.

To achieve this, synchronization performance is assessed using two primary Key Performance Indicators (KPIs): accuracy and precision.

### 3.4.2 Key Performance Indicators

Synchronization performance is evaluated using KPIs that captures both the accuracy and stability of the clock alignment.

The primary KPIs considered in this work are:

- **Accuracy**, representing the systematic synchronization error
- **Precision**, representing the variability of the synchronization error

Additional statistical metrics are also used to characterize system behavior under different network conditions. A detailed definition of the synchronization metrics and KPIs used in this work is provided in Section 3.7.1.

### 3.4.3 Measurement Point

The synchronization performance is measured at the slave device. The time offset is obtained directly from the output of the `ptp4l` daemon, which provides real-time estimates of the offset between the slave clock and the grandmaster clock.

The measurement reflects the end-to-end synchronization performance, including all network components such as the enterprise LAN, 5G core network, radio interface, and UE router.

### 3.4.4 Data Collection

During each experiment, PTP logs are recorded continuously at the slave device. The logs contain timestamped measurements of:

- Time offset (ns)
- Path delay (ns)
- Frequency adjustment (ppb)

The logging is performed at a fixed interval determined by the PTP configuration (typically one sample per second). Each experiment is conducted for a duration of 30 minutes to ensure sufficient data for statistical analysis.

### 3.4.5 Data Processing

The collected log data is processed offline using MATLAB. The processing includes:

- Extraction of time offset values from raw logs
- Removal of initialization samples (transient phase)
- Computation of mean offset (accuracy)
- Computation of standard deviation (precision)

The analysis focuses on steady-state behavior after the synchronization process has stabilized.

### 3.4.6 Measurement Scenarios

To evaluate the performance under different network conditions, multiple experimental scenarios are defined. These scenarios vary key parameters such as:

- Network load conditions
- Radio signal quality
- PTP traffic prioritization

Each scenario is measured independently, and the resulting KPIs are compared to assess the impact of wireless network conditions on synchronization performance.

### 3.4.7 Delay Asymmetry Measurement and Compensation

As discussed in Section 2.2.3, PTP assumes symmetric propagation delay between the forward and reverse communication paths. However, in wireless networks such as 5G, uplink and downlink transmission delays may differ due to scheduling behavior, retransmissions, and resource allocation mechanisms. Such delay asymmetry introduces a systematic bias in the estimated clock offset.

To estimate the uplink–downlink delay asymmetry in the experimental setup, a dedicated measurement scenario was conducted prior to the main synchronization experiments. The setup is illustrated in Figure 3.4.

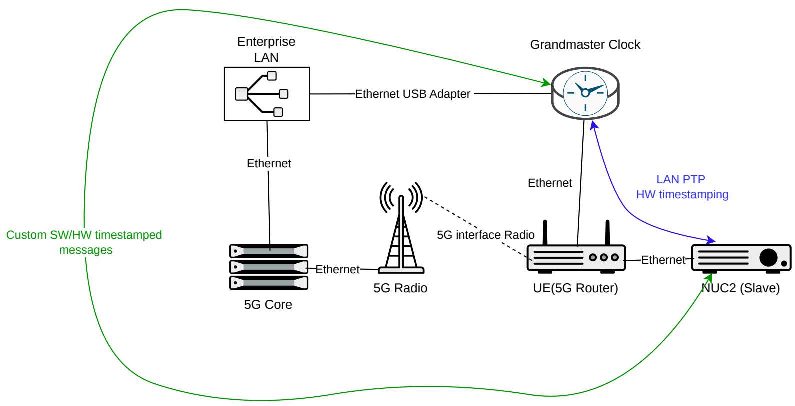


**Figure 3.4:** Setup for PTP delay asymmetry measurement.

The delay asymmetry measurement was performed in two steps. First, the GM and the slave node were synchronized using the standard PTP communication path shown in blue in Figure 3.4. This path follows the same end-to-end route used in the main experiments, traversing the enterprise LAN, the 5G core network, the radio access network, and the UE router. The purpose of this step was to establish a common time reference between the measurement endpoints.

After synchronization had been established, additional timestamped test messages were exchanged to measure one-way communication delays for the delay asymmetry estimation procedure. Dedicated hardware timestamping interfaces connected at the measurement endpoints were used to record accurate transmission and reception timestamps. These measurement messages are represented by the green arrows in Figure 3.4.

The green arrows in Figure 3.4 indicate the direction of these one-way delay measurements. One measurement sequence was performed from the GM to the slave node to estimate the downlink delay, while a second measurement sequence was performed from the slave node to the GM to estimate the uplink delay. Both measurements traversed the same end-to-end network path as the PTP synchronization traffic. Therefore, the difference between the two measurements is the transmission direction rather than the physical communication path.

By comparing the measured one-way delays in both directions, the uplink–

downlink delay asymmetry of the network could be estimated.

Based on the obtained measurements, a fixed delay asymmetry compensation parameter of approximately 1 ms was configured in the `ptp4l` implementation. The same compensation value was applied in all experimental scenarios to ensure a consistent configuration and enable fair comparison of synchronization performance across different radio conditions, traffic loads, and network configurations.

Although the actual uplink–downlink asymmetry may vary with scheduling behavior and network conditions, the objective of this work was not to optimize the compensation parameter for each individual scenario. Instead, a single representative value derived from the dedicated asymmetry measurement was used throughout the study to reduce the systematic synchronization bias caused by asymmetric uplink and downlink delays.

It should be noted that the configured compensation does not eliminate packet delay variation. Therefore, it primarily affects synchronization accuracy (mean offset), while synchronization precision (offset jitter) remains dominated by network-induced delay variation. As shown later in Section 4.7, the main conclusions regarding synchronization precision are largely independent of the applied delay asymmetry compensation.

**Table 3.2:** Measured one-way propagation delay during the delay asymmetry evaluation.

| **Measurement** | **Downlink (DL)** | **Uplink (UL)** |
|---|---|---|
| Mean delay | 4900.51 µs | 5839.80 µs |
| Standard deviation | 592.15 µs | 878.48 µs |
| Maximum delay | 10183.37 µs | 8026.88 µs |
| Minimum delay | 3818.45 µs | 3386.00 µs |
| Estimated asymmetry | 939.29 µs | |

The measurement results indicate a noticeable asymmetry between the uplink and downlink communication delays. The measured mean uplink delay was approximately 5.84 ms, while the mean downlink delay was approximately 4.90 ms, resulting in an estimated asymmetry of approximately 0.94 ms. Detailed time-series measurements and delay distribution plots for the uplink and downlink propagation delays are provided in Appendix D.

This observation supports the use of a fixed delay asymmetry compensation parameter of approximately 1 ms in the subsequent PTP experiments. The results also show significant packet delay variation in both directions, particularly in the uplink measurements, indicating that wireless scheduling variability contributes not only to static delay asymmetry but also to synchronization jitter.

### 3.4.8 Assumptions and Limitations

The use of a professional-grade Grandmaster clock ensures that the reference time source introduces negligible error. Therefore, the measured offset is assumed to be primarily caused by the network.

It is also assumed that hardware timestamping minimizes local processing delays, allowing the measurements to accurately reflect network-induced effects.

However, factors such as asymmetric delays in the wireless link and variability in 5G scheduling may still impact the results and are considered as part of the system behavior.

## 3.5 Experimental Factors and Scenarios

Synchronization performance is evaluated under two controlled experimental factors: network load and radio quality conditions.

### 3.5.1 Radio Quality Condition

Radio quality is characterized primarily using the RSRP metric reported by the ICR-4400 router. Although RSRQ and SINR were also recorded during the experiments, they were used only as supporting indicators to provide additional context regarding radio-link conditions.

The radio-condition classes used in this thesis are therefore defined based on RSRP, since it was the metric that exhibited the largest variation across the evaluated scenarios and was used to control the experimental conditions through device positioning.

Radio conditions are categorized as very good/good, medium, or weak based on measured values. Artificial interference injection is not performed. Radio condition variations are achieved through controlled device positioning within the coverage area.

**Table 3.3:** Radio Quality Condition Classification Used in the Experiments.

| **Condition** | **RSRP (dBm)** |
|---|---|
| Very Good/Good | $> -80$ |
| Medium | $-95$ to $-80$ |
| Weak | $< -95$ |

### 3.5.2 Network Load

Background traffic is generated using two IP cameras connected to the 5G radio access network. The cameras stream video to a server within the network.

Three load levels are defined:

- Idle: No active video streaming.
- Medium load: One camera streaming with fixed resolution and frame rate.
- High load: Two cameras streaming simultaneously.

The achieved throughput is recorded during each experiment to ensure repeatability.

### 3.5.3 Experimental Scenarios and Comparison Strategy

The experimental evaluation is designed to compare synchronization performance across different network configurations and operating conditions. The objective is to identify the primary factors that influence IEEE 1588 PTP synchronization accuracy and precision in 5G networks.

Table 3.4 summarizes the evaluated experimental scenarios and their corresponding configurations. A more detailed description of the experimental scenarios, including network configuration parameters and measurement conditions, is provided in Appendix A.

**Table 3.4:** Summary of evaluated experimental scenarios.

| ID | Scenario Description | TS | Traffic Load | Priority | # of Slaves |
|---|---|---|---|---|---|
| C1 | Wired Ethernet | HW | No | – | 1 |
| C2 | Wired Ethernet + Router | HW | No | – | 1 |
| C3 | Wired Ethernet | SW | No | – | 1 |
| S1 | 5G Baseline | HW | No | - | 1 |
| S2 | 5G Loaded Traffic | HW | Yes | - | 1 |
| S3 | 5G Same Priority Traffic | HW | Yes | Yes | 1 |
| S4 | 5G Multi-UE | HW | Yes | No | 1 |
| S5 | 5G Multi-UE + Load | HW | No | - | 3 |
| S6 | 5G Multi-UE + Load | HW | Yes | Yes | 3 |

where:

- TS: timestamping method (HW = hardware timestamping, SW = software timestamping)
- Traffic Load: presence of additional background traffic
- Priority: relative network priority assigned to PTP traffic
- # of Slaves: number of active UEs participating in the experiment as PTP Slaves

The experimental comparisons performed in this thesis can be summarized as follows:

- **Wired Ethernet vs. 5G:** Comparison between wired Ethernet and 5G-based synchronization to quantify the impact of the wireless communication segment on synchronization performance.
- **Router impact:** Comparison between direct wired Ethernet and wired Ethernet through the industrial router to isolate the impact of router forwarding and processing delay without the wireless segment.
- **Hardware vs. software timestamping:** Comparison between hardware and software timestamping configurations to evaluate the importance of timestamping accuracy in PTP synchronization.

- **Traffic load impact:** Comparison between unloaded and loaded 5G scenarios to investigate the effect of background traffic and packet delay variation on synchronization stability.
- **Traffic prioritization impact:** Comparison between prioritized and non-prioritized PTP traffic to evaluate the influence of network resource allocation and traffic segmentation.
- **Multi-user impact:** Comparison between single-UE and multi-UE scenarios to investigate the influence of multiple synchronized devices sharing the same wireless network resources.
- **Radio condition impact:** Comparison between different radio quality conditions to evaluate how wireless channel characteristics influence synchronization performance.

## 3.6 Measurement Procedure

For each scenario, the following procedure is applied:

1. Establish 5G connectivity and verify radio metrics.
2. Verify that the professional Grandmaster clock is operational and synchronized to its GNSS reference.
3. Start `ptp4l` on the slave node.
4. Start `phc2sys` to discipline the system clock.
5. Allow the synchronization process to stabilize before data collection.
6. Collect synchronization logs continuously during the measurement period.

After startup, the PTP servo requires an initial transient period before stable synchronization behavior is achieved. Based on empirical observation, the first 60 s of measurements are excluded from the analysis to avoid startup transients and ensure that only stable synchronization behavior is evaluated.

Each scenario was evaluated using one continuous 30-minute measurement campaign under the specified network conditions. After removing the initial 60 s transient period, approximately 29 minutes of data are used for statistical evaluation.

## 3.7 Key Performance Indicators

To evaluate the synchronization performance of IEEE 1588 PTP, this thesis focuses on two primary key performance indicators (KPIs): synchronization accuracy and synchronization precision.

### 3.7.1 Primary (KPIs)

The primary KPIs correspond to the synchronization performance metrics introduced in Section 2.2.6. In this work, the evaluation primarily focuses on mean offset and offset jitter, representing synchronization accuracy and precision, respectively.

#### Mean Offset (Accuracy)

The mean offset represents the average signed time difference between the slave clock and the grandmaster clock during the observation interval. Since the synchronization measurements are obtained as discrete timestamp samples from the `ptp4l` logs, the mean offset is calculated using

$$\mu_\theta = \frac{1}{N}\sum_{i=1}^{N}\theta_i \tag{3.1}$$

where:

- $N$ is the total number of offset samples collected during the observation interval, and
- $\theta_i$ is the measured clock offset obtained from the $i$-th synchronization message exchange cycle.

This metric reflects the systematic synchronization error and indicates the overall synchronization accuracy between the slave and grandmaster clocks [1]. A value close to zero indicates high synchronization accuracy.

#### Offset Jitter (Precision)

Synchronization precision is quantified using the standard deviation of the measured time offset:

$$\sigma_\theta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta_i - \mu_\theta)^2} \tag{3.2}$$

where:

- $\sigma_\theta$ represents the synchronization jitter (offset standard deviation),
- $\mu_\theta$ is the mean offset, and
- $N$ is the total number of offset samples.

This metric captures short-term variations of the synchronization offset and reflects the impact of Packet Delay Variation (PDV) , timestamping noise, and wireless network dynamics. In wireless networks such as 5G, offset jitter is a critical indicator of synchronization stability and robustness.

### 3.7.2 Supporting Metrics

Additional statistical metrics may also be used to describe synchronization performance; however, they are not considered primary KPIs in this thesis. Metrics such as mean absolute offset, percentile-based offset, maximum offset, and RMS offset are used only as supporting indicators to provide additional insight into the distribution and magnitude of synchronization error when required.

The focus on mean offset and offset jitter is motivated by the objective of this work, which is to clearly distinguish between synchronization accuracy and synchronization precision. Limiting the analysis to these primary metrics simplifies the interpretation of the experimental results while still capturing the dominant synchronization characteristics of the evaluated systems.

### 3.7.3 Cross-Layer Metrics

In addition to PTP-based KPIs, selected 5G network metrics are used as explanatory variables. These include radio quality indicators such as RSRP, RSRQ, and SINR, as well as throughput measurements.

These metrics are not considered synchronization KPIs. Instead, they are used to interpret the observed behavior of PTP performance, particularly in scenarios involving varying radio conditions and network load.

## 3.8 Data Processing and Validity

PTP logs are exported and processed using offline analysis tools. The initial transient period is excluded from statistical calculations. All metrics are computed over steady-state intervals.

The 5G infrastructure parameters are treated as fixed system conditions. Artificial RF interference is not introduced. The results, therefore, reflect realistic deployment conditions of a private 5G SA network.

Chapter 4

# Experimental Results

## 4.1 Introduction to Experimental Results

This chapter presents the experimental evaluation of IEEE 1588 PTP over a private 5G network and compares it with a wired Ethernet baseline. The objective is to quantify the achievable synchronization performance under realistic industrial deployment conditions and to identify the key factors affecting accuracy and precision.

The evaluation is structured around five main aspects: baseline comparison between wired and 5G networks, impact of timestamping mechanisms, influence of network load, effect of radio conditions, and the role of traffic prioritization in the 5G network. These aspects are investigated through controlled experiments as defined in Chapter 3.

Synchronization performance is primarily assessed using two KPIs. Accuracy is represented by the mean offset, which reflects the average time difference between the slave and the grandmaster clock. Precision is represented by the standard deviation of the offset (offset jitter), which captures short-term variations caused by packet delay variation and network dynamics. Additional statistical metrics, including mean absolute offset and percentile-based values, are used to provide further insight into system behavior.

In addition to synchronization-specific KPIs, some experiments also use cross-layer performance indicators obtained from the 5G system, including radio quality metrics such as RSRP, RSRQ, and SINR, as well as throughput and latency measurements. These metrics are used to analyze the relationship between network conditions and synchronization performance and are treated as explanatory variables rather than primary performance indicators.

To ensure consistent KPIs evaluation across all scenarios, an initial transient period is removed from each measurement, following the measurement procedure described in Section 3.6. Based on empirical observation, the first 60 samples (approximately 60 s) are excluded to eliminate startup effects and ensure that only steady-state synchronization behavior is analyzed.

It should be noted that a configured delay asymmetry compensation parameter of 1 ms was applied in the PTP configuration during all experiments. The compensation value was derived from the uplink–downlink delay asymmetry measurement presented in Section 3.4.7. The parameter introduced a constant offset correction in the synchronization process. As a result, the reported mean offset values reflect the combined effect of network-caused delay asymmetry and the configured compensation. However, this configuration does not affect the relative comparison of synchronization precision across different scenarios, as jitter and percentile-based metrics are primarily driven by packet delay variation.

The result presented in this chapter, therefore, focuses on comparative analysis between scenarios, with particular emphasis on identifying the dominant factors that degrade synchronization performance in 5G networks.

## 4.2 Wired vs 5G Baseline Comparison

This section presents the baseline comparison between wired Ethernet and 5G network scenarios to establish a reference for synchronization performance. The objective is to quantify the impact of the wireless segment on PTP accuracy and precision under controlled conditions.

The wired baseline represents an ideal synchronization environment with stable and symmetric communication delay, while the 5G baseline introduced additional delay variations due to scheduling, radio transmission, and network processing. Comparing these two scenarios provides a clear understanding of the fundamental limitation of PTP over 5G networks.

The comparison is illustrated using two complementary figures. Figure 4.1 summarizes the synchronization accuracy (mean offset) and synchronization precision (offset jitter) for the evaluated scenarios. Figure 4.2 presents the distribution of the absolute offset values, highlighting the spread, median behavior, and presence of outliers.

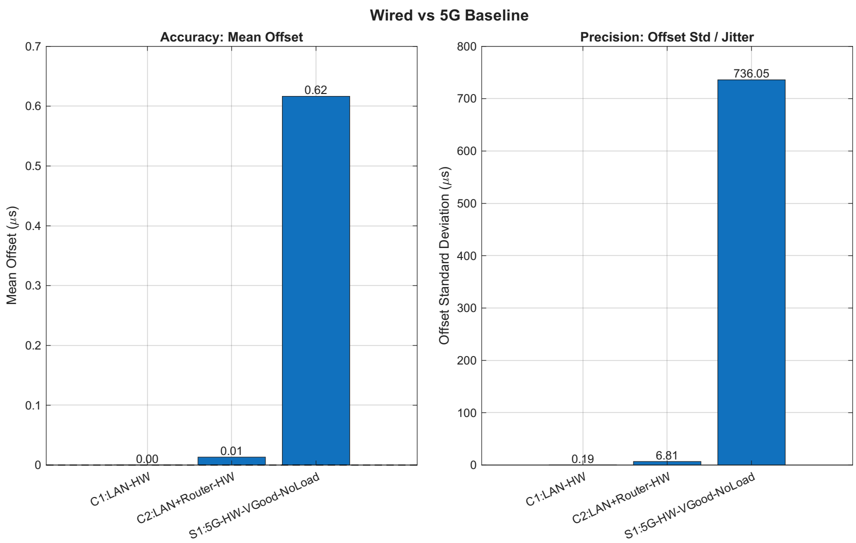


**Figure 4.1:** Comparison of synchronization performance between wired and 5G baseline scenarios.

**Table 4.1:** Synchronization accuracy and precision comparison between wired and 5G baseline scenarios.

| Scenario | Mean Offset ($\mu$s) | Offset Std. ($\mu$s) |
|---|---|---|
| LAN + HW | 0.00003 | 0.19 |
| LAN + Router + HW | 0.013 | 6.81 |
| 5G + HW + No Load | 0.617 | 736.05 |

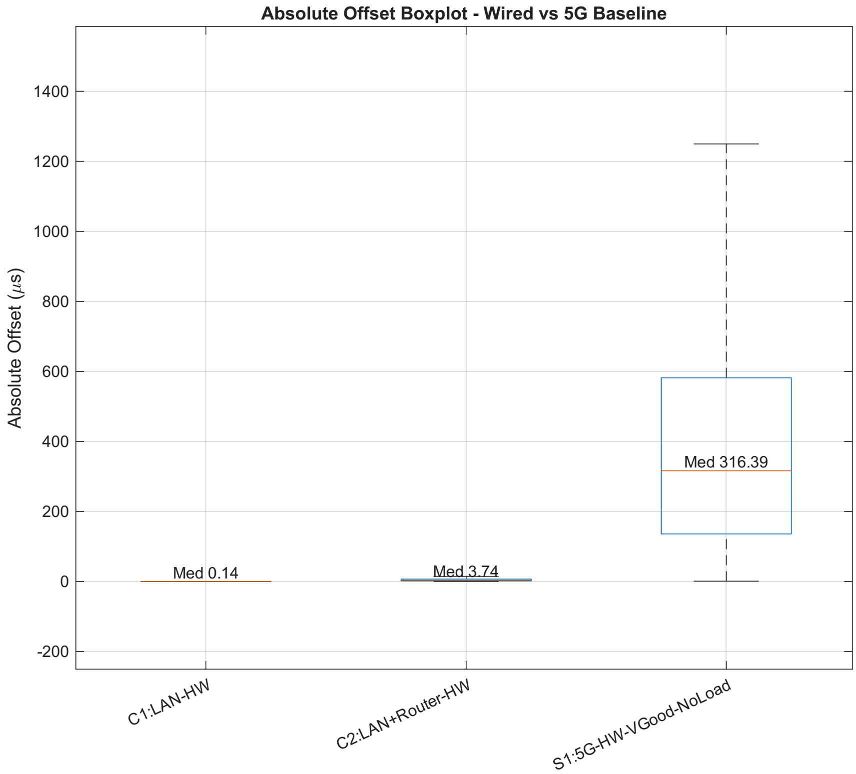


**Figure 4.2:** Absolute offset distribution for wired and 5G baseline scenarios.

### 4.2.1 Analysis of Baseline Performance

The results show a clear difference in synchronization performance between the wired baseline and the 5G scenario. As shown in Figure 4.1, the wired configurations achieve near-zero mean offset, ranging from approximately 0.03 ns in the direct wired case to approximately 13 ns when the router is included in the communication path. In comparison, the 5G baseline scenario exhibits a mean offset of approximately 0.62 µs.

Although the mean offset in the 5G scenario remains relatively small, a much larger degradation is observed in synchronization precision. The offset standard deviation increases from approximately 0.19 µs in the direct wired case and 6.81 µs in the routed wired case to approximately 736 µs in the 5G scenario. This represents an increase of more than two orders of magnitude compared to the wired baseline.

These results indicate that the primary limitation of PTP over 5G is not synchronization accuracy, represented by the mean offset, but synchronization stability over time. Although the average offset remains close to zero, the large standard deviation indicates substantial timing variability and non-deterministic behavior. Consequently, the evaluated 5G synchronization performance is not sufficient for highly time-sensitive industrial applications requiring deterministic sub-microsecond synchronization, but it may still be suitable for applications with less stringent timing requirements, such as monitoring, logging, or non-critical industrial communication.

This behavior can also be observed in the boxplot shown in Figure 4.2, where the wired cases are concentrated within a very narrow range close to zero, while the 5G scenario exhibits a substantially wider spread and larger absolute offset variation. The median absolute offset increases from sub-microsecond levels in the wired baseline to several hundred microseconds in the 5G scenario, further illustrating the significant increase in synchronization variability introduced by the wireless network.

## 4.3 Impact of Timestamping (HW vs SW)

This section evaluates the impact of timestamping mechanisms on PTP synchronization performance by comparing hardware timestamping (HW) and software timestamping (SW) under both wired and 5G scenarios.

Hardware timestamping is performed at the network interface level, providing precise timing measurements with minimal software-induced delay. In contrast, software timestamping is performed within the operating system, making it more sensitive to scheduling delays and processing variability.

The comparison is illustrated in Figure 4.3, which summarizes the key synchronization KPIs for HW and SW timestamping.

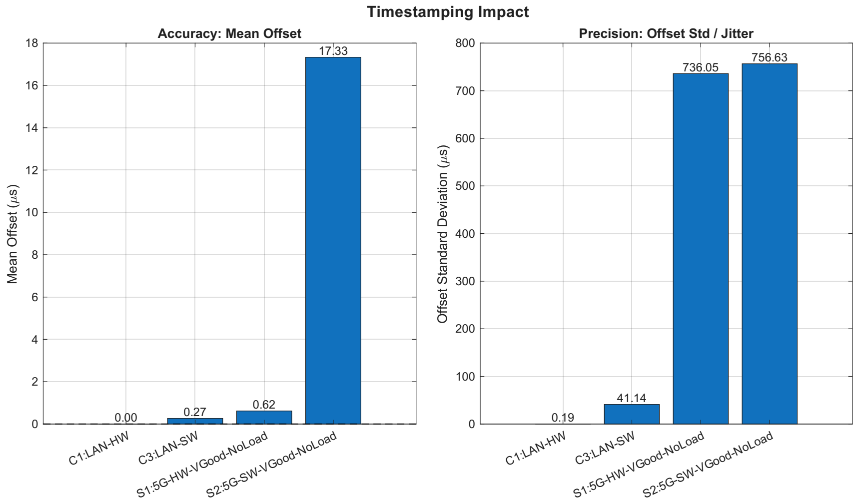


**Figure 4.3:** Comparison of synchronization performance between hardware and software timestamping.

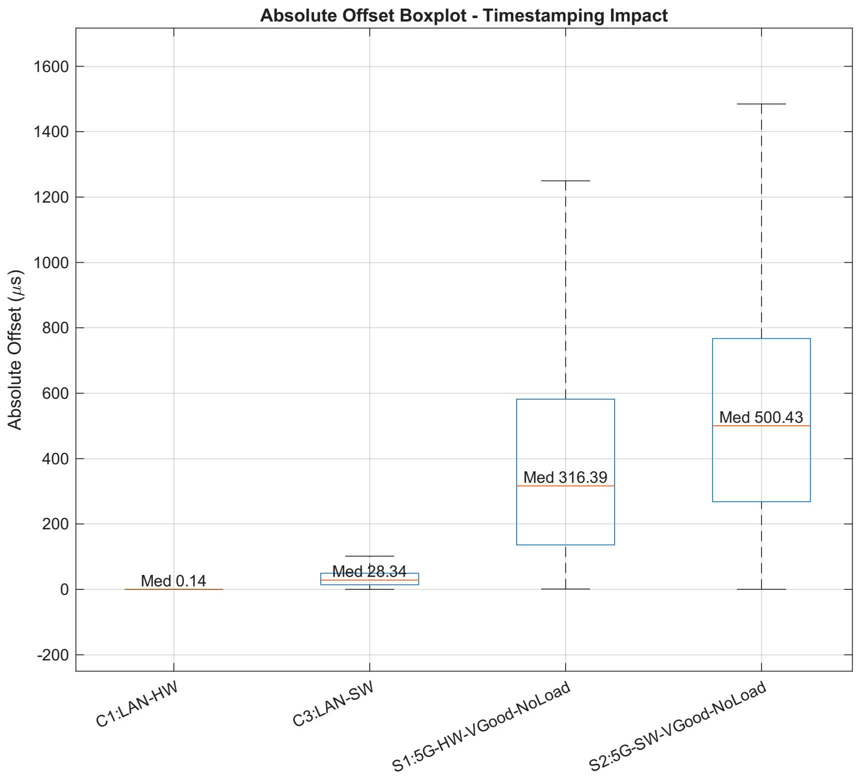


**Figure 4.4:** Absolute offset distribution between hardware and software timestamping.

**Table 4.2:** Synchronization accuracy and precision comparison between hardware and software timestamping scenarios.

| Scenario | Mean Offset ($\mu$s) | Offset Std. ($\mu$s) |
|---|---|---|
| LAN-HW timestamp | 0.00003 | 0.19 |
| LAN-SW timestamp | 0.267 | 41.14 |
| 5G-HW timestamp-No Load | 0.617 | 736.05 |
| 5G-SW timestamp-No Load | 17.33 | 756.63 |

### 4.3.1 Analysis of Timestamping Performance

The results show that timestamping mechanisms have a significant impact on synchronization performance in wired Ethernet networks. In the wired baseline, hardware timestamping achieves near-zero mean offset and very low synchronization jitter, with an offset standard deviation of approximately 0.19 µs. In contrast, software timestamping increases the offset standard deviation to approximately 41 µs, representing more than two orders of magnitude degradation in synchronization precision.

The mean offset results also indicate a degradation in synchronization accuracy when software timestamping is used in the wired setup. Although the observed mean offset remains below 1 µs, the increase compared to hardware timestamping reflects the additional timing uncertainty introduced by operating system scheduling and software processing variability. In contrast, hardware timestamping captures timestamps close to the physical transmission event, significantly reducing timestamp uncertainty.

This behavior is also reflected in the absolute offset distribution shown in Figure 4.4. The wired hardware timestamping scenario exhibits a very narrow distribution, while software timestamping shows a substantially wider spread, indicating increased variability in synchronization error.

In the 5G scenarios, hardware timestamping maintains mean offset values below 1 µs, while software timestamping results in noticeably larger mean offset values, reaching several tens of microseconds in some scenarios. This indicates that timestamping technology still affects synchronization accuracy under 5G conditions.

However, the impact of timestamping on synchronization precision becomes significantly less dominant in the 5G scenarios. Hardware timestamping under 5G conditions achieves an offset standard deviation of approximately 736 µs, while software timestamping results in approximately 757 µs. Although software timestamping introduces additional jitter, the difference between the two methods remains relatively small compared to the overall magnitude of synchronization variability introduced by the wireless network.

These results indicate that synchronization precision in the evaluated 5G setup is primarily limited by network-induced PDV, wireless scheduling behavior, and communication delay variability rather than timestamping accuracy alone.

The obtained results are consistent with previous studies reported in the literature, which show that hardware timestamping significantly improves synchronization performance in conventional wired Ethernet networks by reducing timestamp uncertainty and software processing delay [14, 16]. However, the experimental results in this thesis indicate that the relative impact of timestamping technology changes in wireless 5G environments. While hardware timestamping still improves synchronization accuracy by reducing the mean offset, its contribution to synchronization precision becomes less dominant compared to the packet delay variation introduced by wireless scheduling and network dynamics. Similar observations have also been reported in previous studies investigating PTP over wireless and cellular networks [10, 9, 18].

Overall, the results demonstrate that hardware timestamping is essential for achieving high-precision synchronization in wired networks. However, in 5G environments, synchronization performance becomes increasingly dominated by network-induced delay variation, reducing the relative impact of timestamping technology on synchronization precision.

## 4.4 Impact of Single-UE and Multi-UE Scenarios

This section evaluates the impact of resource sharing on PTP synchronization performance by comparing single-UE and multi-UE scenarios under 5G conditions.

In the single-UE scenarios, the communication resources are dedicated to one synchronized UE, while in the multi-UE scenarios, three synchronized UEs share the same network resources. This introduces additional scheduling complexity and potential contention, which can affect synchronization performance.

The comparison is illustrated in Figure 4.5, which summarizes the key synchronization KPIs, and Figure 4.6, which shows the distribution of absolute offset values.

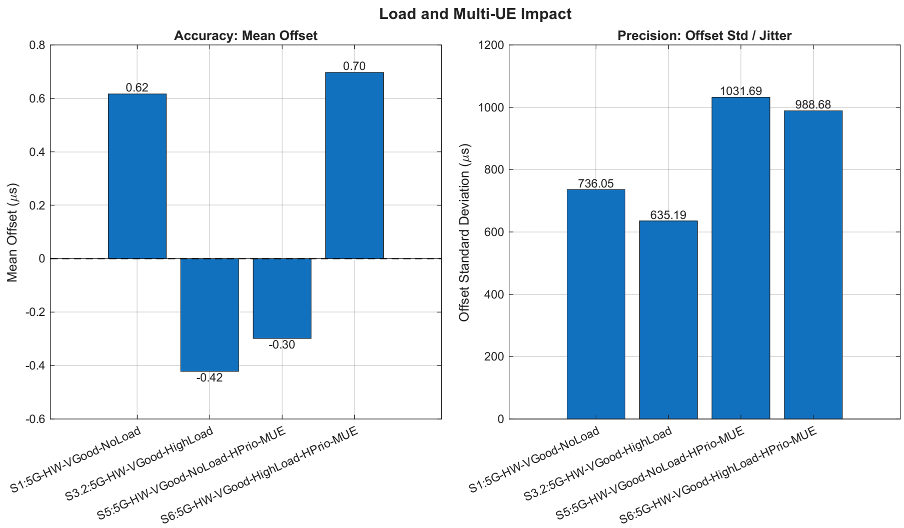


**Figure 4.5:** Comparison of synchronization performance for single-UE and multi-UE scenarios.

**Table 4.3:** Synchronization accuracy and precision for single-UE and multi-UE 5G scenarios.

| Scenario | Mean Offset ($\mu$s) | Offset Std. ($\mu$s) |
|---|---|---|
| 5G-HW TS-No Load | 0.617 | 736.05 |
| 5G-HW TS-High Load | -0.422 | 635.19 |
| 5G-HW TS-No Load-MUE | -0.299 | 1031.69 |
| 5G-HW TS-High Load-MUE | 0.697 | 988.68 |

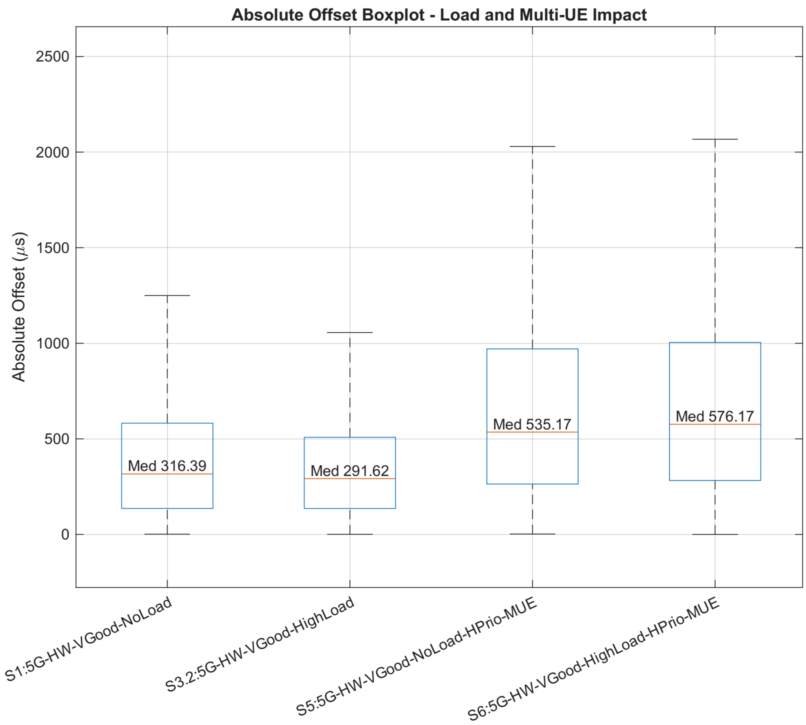


**Figure 4.6:** Absolute offset distribution for single-UE and multi-UE scenarios.

### 4.4.1 Analysis of Single-UE and Multi-UE Performance

The results show that synchronization accuracy, represented by the mean offset, remains close to zero across both single-UE and multi-UE scenarios. In all evaluated cases, the mean offset remains below approximately 1 µs, indicating that no significant systematic synchronization bias is introduced by increasing the number of synchronized devices or by adding background traffic. However, as discussed previously, the mean offset is influenced by the configured delay asymmetry compensation and should therefore be interpreted as operational synchronization accuracy rather than absolute physical synchronization error.

It should be noted that both positive and negative mean offset values are observed across the evaluated scenarios. The sign of the mean offset depends on the residual mismatch between the actual uplink–downlink delay asymmetry and the configured delay asymmetry compensation parameter, as well as the behavior of the PTP clock servo. Consequently, a negative mean offset does not indicate synchronization failure, but rather that the estimated slave clock time is slightly behind the master clock on average after compensation.

In contrast with accuracy, a more noticeable difference is observed in synchronization precision. In the single-UE scenarios, the offset jitter remains in the range of approximately 600–800 µs. The introduction of additional background traffic does not produce a substantial increase in jitter, as the synchronization precision remains within a similar range across the evaluated single-UE scenarios.

Although medium-load and high-load scenarios were configured using different numbers of video streams, both scenarios achieved similar throughput levels of approximately 60 Mbps due to limitations of the UE hardware and network setup. As a result, the effective difference in offered traffic load between the evaluated scenarios was smaller than initially intended.

**Table 4.4:** Network utilization comparison between unloaded and loaded 5G scenarios.

| **Metric** | **S1 (No Load)** | **S3.2 (Loaded)** |
|---|---|---|
| Cell DL Throughput (Mbps) | 0.006 | 60.17 |
| Cell UL Throughput (Mbps) | 0.006 | 60.17 |
| Cell DL PRB Utilization (%) | 0.80 | 21.49 |
| Cell UL PRB Utilization (%) | 4.56 | 25.26 |

As shown in Table 4.4, the measured throughput and PRB utilization results indicate that the loaded scenarios did not fully saturate the wireless network resources. Although the background traffic increased the throughput to approximately 60 Mbps, the measured PRB utilization remained around 20–25%. Consequently, the network operated under moderate resource utilization conditions, which may explain why the additional traffic produced only a limited impact on PTP synchronization precision in the evaluated experiments.

The impact becomes more significant in the multi-UE scenarios, where the offset jitter increases to approximately 1000 µs. A similar trend is observed in the absolute offset distribution shown in Figure 4.6, where the multi-UE cases exhibit a wider spread and larger median values compared to the single-UE cases. These results indicate that sharing wireless communication resources among multiple synchronized devices introduces additional packet delay variation and timing variability.

The observed degradation is attributed to increased scheduling complexity and resource contention in the 5G network when multiple synchronized UEs simultaneously compete for radio transmission opportunities.

Overall, the results demonstrate that multi-UE operation has a stronger impact on synchronization precision than background traffic load in the evaluated 5G setup. These observations are consistent with previous studies investigating wireless time synchronization, where wireless scheduling variability and shared radio resource allocation are reported as major contributors to packet delay variation and synchronization jitter [10, 19].

## 4.5 Impact of Radio Conditions on PTP Performance

This section evaluates the impact of radio signal quality on PTP synchronization performance over the commercial 5G campus network. The objective is to investigate whether variations in radio conditions significantly influence synchronization accuracy and precision.

The analysis focuses on static scenarios under both no-load and high-load traffic conditions. The evaluated radio conditions are classified according to the RSRP ranges defined in Table 3.3. RSRQ and SINR measurements are reported as supporting indicators but are not used for the radio-condition classification. The comparison is based on the primary synchronization KPIss, namely mean offset and offset standard deviation.

Figure 4.7 presents the synchronization KPIs under different radio conditions without background traffic, while Figure 4.8 shows the corresponding absolute offset distributions. Figure 4.9 presents the synchronization KPIs under different radio conditions with background traffic, while Figure 4.10 shows the corresponding absolute offset distributions. The numerical synchronization results and measured radio metrics are summarized in Table 4.5.

**Table 4.5:** Synchronization performance and RF metrics under different radio conditions.

| Case | Radio Condition | Mean Offset (µs) | Offset Std. (µs) | Avg. RSRP (dBm) | Avg. RSRQ (dB) |
|---|---|---|---|---|---|
| S1 (No Load) | Very Good | 0.62 | 736.05 | -68.43 | -11 |
| S1 (No Load) | Medium | -0.90 | 850.66 | -85.75 | -11 |
| S1 (No Load) | Weak | 0.13 | 683.53 | -101.73 | -11 |
| S3.2 (High Load) | Very Good | -0.42 | 635.19 | -67.39 | -11 |
| S3.2 (High Load) | Medium | -0.34 | 812.15 | -86.00 | -11 |
| S3.2 (High Load) | Weak | 0.98 | 647.12 | -100.07 | -11 |

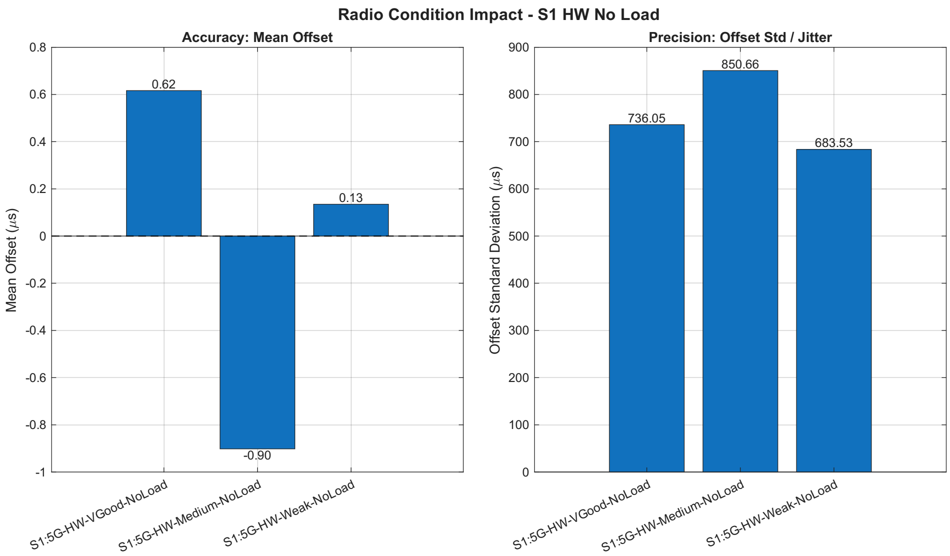


**Figure 4.7:** Impact of radio conditions on synchronization performance without background traffic.

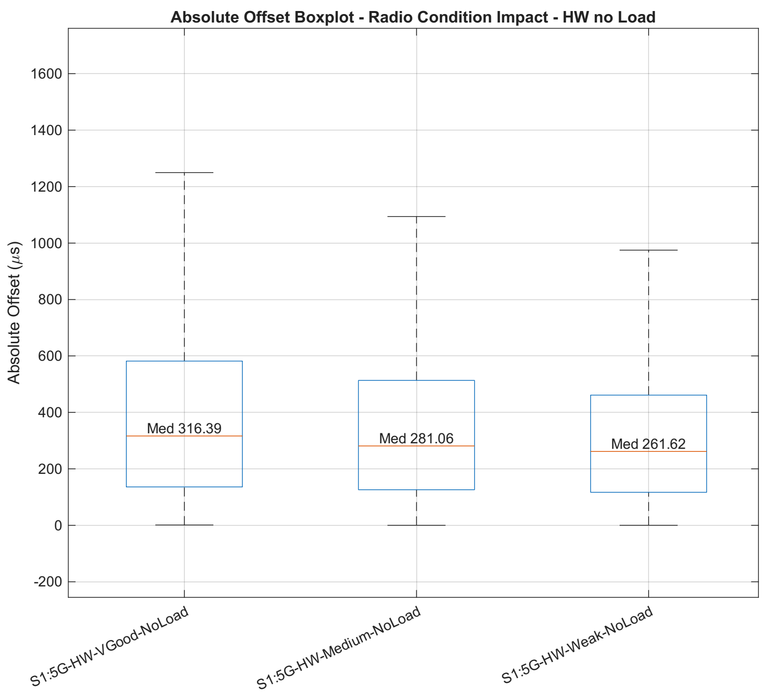


**Figure 4.8:** Absolute offset distribution under different radio conditions without background traffic.

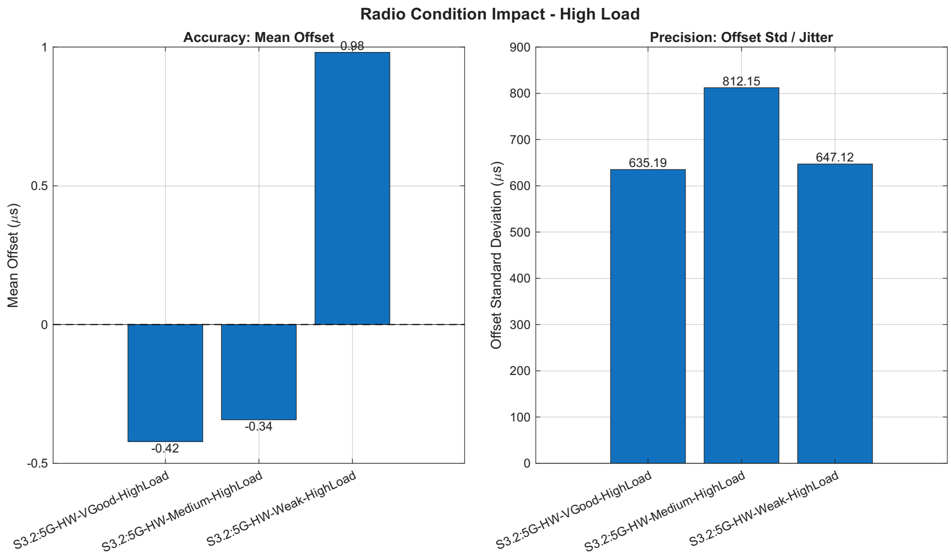


**Figure 4.9:** Impact of radio conditions on synchronization performance with background traffic.

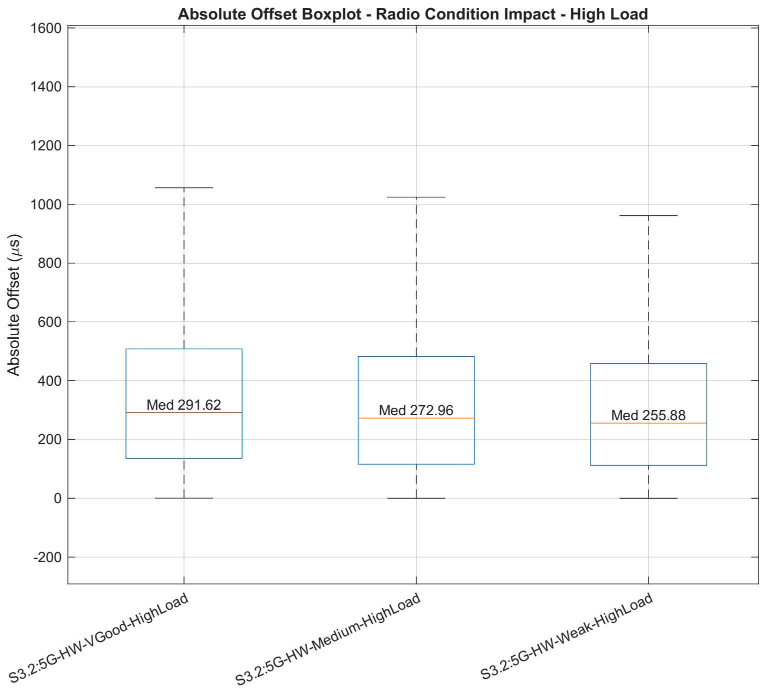


**Figure 4.10:** Absolute offset distribution under different radio conditions with background traffic.

### 4.5.1 Analysis of Radio Condition Performance

The results show that the mean offset remains close to zero across all evaluated radio conditions, indicating that synchronization accuracy remains relatively stable. In both no-load and high-load scenarios, the mean offset remains below approximately 1 µs. As discussed previously, the mean offset is influenced by the configured delay asymmetry compensation and should therefore be interpreted as operational synchronization accuracy rather than absolute physical synchronization error.

Similarly, the synchronization precision represented by the offset standard deviation does not exhibit a clear monotonic degradation from very good to weak radio conditions. Although some medium radio-condition scenarios show slightly higher offset variation, the overall differences remain relatively limited compared to the total synchronization jitter observed in the wireless scenarios.

The absolute offset distributions shown in Figure 4.8 and Figure 4.10 also demonstrate that synchronization variability remains within a comparable range across different radio conditions. While some variations in median and spread are observed, the results do not indicate a strong systematic degradation associated solely with reduced received signal strength.

The measured RF metrics summarized in Table 4.5 show that the average RSRP varies significantly across the evaluated scenarios, while the measured RSRQ remains relatively stable around -11 dB. This suggests that the experiments mainly experienced differences in signal strength rather than severe degradation in overall radio-link quality or interference conditions.

In wireless communication systems, degraded RSRP may potentially reduce modulation and coding performance and increase retransmissions or scheduling variability. However, the evaluated experiments did not exhibit severe degradation in RSRQ or unstable radio-link behavior. Consequently, the wireless network likely maintained sufficiently stable communication performance without introducing substantial additional packet delay variation for PTP traffic.

In addition, the synchronization variability introduced by wireless scheduling and network-induced PDV was already significantly larger than the additional timing variability potentially introduced by the evaluated radio-condition degradation. As a result, the influence of radio signal strength alone became less dominant compared to the overall delay variability already present in the commercial 5G network.

Overall, the results indicate that degraded radio signal strength within the evaluated operating range did not significantly worsen PTP synchronization performance compared to the variability already introduced by the wireless network itself.

## 4.6 Impact of Traffic Segregation

This section evaluates the impact of traffic segregation and prioritization on synchronization performance under high network load conditions. In the previous experiments, the background traffic generated by the IP cameras was routed through a separate segment with lower priority than the PTP traffic. This configuration was intended to reduce resource contention between synchronization traffic and non-time-critical traffic within the 5G network.

To evaluate the impact of traffic segregation, an additional experiment was performed where the background traffic and PTP traffic shared the same segment and priority level under identical radio and traffic load conditions.

Table 4.6 summarizes the synchronization performance for both configurations.

**Table 4.6:** Impact of traffic segregation on synchronization performance under high load conditions.

| Scenario | Mean Offset ($\mu$s) | Offset Std. ($\mu$s) |
|---|---|---|
| Segregated Traffic | -0.42 | 635.19 |
| Shared Priority Traffic | 0.04 | 797.09 |

### 4.6.1 Analysis of Traffic Segregation

The results show that the shared-priority configuration introduces higher synchronization variability compared to the segregated traffic configuration. In particular, the offset standard deviation increases from approximately 635 µs to approximately 797 µs when the PTP traffic shares the same segment and priority level as the background traffic.

These observations indicate that when PTP traffic shares network resources with background traffic of equal priority, synchronization precision may degrade due to increased scheduling competition and packet delay variation within the 5G network. However, the synchronization accuracy remains close to zero in both scenarios, indicating that the primary impact is on synchronization precision rather than systematic offset bias.

The results suggest that traffic prioritization and segmentation can contribute to improving synchronization stability, particularly under high network utilization conditions.

## 4.7 Effect of Delay Asymmetry Compensation

This section evaluates the impact of delay asymmetry compensation on synchronization performance by comparing PTP configurations with and without the configured compensation parameter. The applied compensation value was derived from the delay asymmetry measurement procedure described in Section 3.4.7.

For the compensated case, the LinuxPTP `delayAsymmetry` parameter was configured to approximately 1 ms. For the uncompensated case, a separate experiment was performed under the same test conditions with `delayAsymmetry = 0`. Therefore, the comparison is not obtained by subtracting a constant value from an existing offset log.

The delay asymmetry compensation is applied internally by LinuxPTP during the offset estimation process and therefore affects the offset values provided to the PTP clock servo. As a result, the compensation influences the synchronization behavior of the slave clock throughout the experiment. Consequently, the compensated and uncompensated cases represent two independent synchronization measurements rather than two versions of the same offset sequence with different post-processing corrections.

Table 4.7 summarizes the synchronization performance with and without delay asymmetry compensation for several representative scenarios.

**Table 4.7:** Synchronization performance comparison with and without delay asymmetry compensation.

| **Scenario** | **Mean Offset ($\mu$s)** | | **Offset Std. ($\mu$s)** | |
|---|---|---|---|---|
| | **Comp.** | **No Comp.** | **Comp.** | **No Comp.** |
| 5G HW No Load | 0.62 | 3.77 | 736.05 | 746.51 |
| 5G HW High Load | -0.63 | 0.68 | 787.52 | 862.48 |

### 4.7.1 Analysis of Delay Asymmetry Compensation

The results presented in Table 4.7 show that delay asymmetry compensation primarily affects synchronization accuracy rather than synchronization precision.

In both evaluated scenarios, the mean offset changes when the compensation parameter is removed, indicating the presence of systematic synchronization bias caused by uplink–downlink delay asymmetry in the 5G network. In the unloaded scenario, the mean offset increases from approximately 0.62 µs to approximately 3.77 µs when the compensation is disabled. Similarly, in the loaded scenario, the mean offset changes from approximately −0.63 µs to approximately 0.68 µs.

In contrast, synchronization precision remains within the same order of magnitude with and without delay asymmetry compensation. In the unloaded scenario, the offset standard deviation changes from approximately 736 $\mu$s to 747 $\mu$s, while in the loaded scenario it changes from approximately 788 $\mu$s to 862 $\mu$s.

The synchronization jitter is not expected to be identical between the compensated and uncompensated results. The delay asymmetry compensation is applied internally by LinuxPTP during the offset estimation process and therefore influences the offset values provided to the PTP clock servo. Consequently, the comparison is not equivalent to subtracting a constant value from an already recorded offset sequence. Furthermore, the compensated and uncompensated cases were obtained from separate measurement runs under dynamic 5G network conditions. Therefore, some differences in the measured synchronization jitter may occur even when the experimental conditions are nominally identical.

The delay asymmetry compensation was included in the experiments because IEEE 1588 PTP assumes symmetric uplink and downlink propagation delays. Without compensation, persistent delay asymmetry may introduce a systematic bias in the estimated clock offset. The applied compensation therefore aims to reduce this bias and improve synchronization accuracy.

Overall, the results indicate that delay asymmetry compensation mainly reduces the systematic synchronization bias associated with uplink–downlink delay asymmetry. However, it does not address the dominant source of synchronization degradation observed in the experiments, namely the packet delay variation introduced by wireless scheduling and network dynamics. Therefore, the main conclusions regarding synchronization precision remain unchanged regardless of whether delay asymmetry compensation is enabled.

## 4.8 Summary of Findings

This chapter evaluated the performance of PTP synchronization over wired and 5G networks under various conditions, including timestamping methods, traffic scenarios, and radio environments. The key findings are summarized as follows.

**1) Accuracy vs Precision**

Across all scenarios, synchronization accuracy, represented by the mean offset, remains close to zero relative to the observed variability. This indicates that PTP is able to maintain average time alignment even over the 5G network. However, the mean offset is influenced by delay asymmetry compensation and should therefore be interpreted with caution.

In contrast, synchronization precision shows significant degradation in 5G scenarios. While wired networks achieve sub-microsecond jitter, 5G scenarios exhibit jitter in the hundreds of microseconds range. This behavior is primarily attributed to packet delay variation (PDV) introduced by 5G scheduling and resource allocation mechanisms.

These results demonstrate that synchronization precision, rather than accuracy, is the dominant limiting factor of PTP over 5G.

**2) Impact of Network Type (Wired vs 5G)**

The comparison between wired and 5G baselines shows that the transition to 5G introduces substantial packet delay variation. This results in a large increase in offset jitter and other synchronization variability metrics, even when the synchronization accuracy remains relatively stable.

**3) Impact of Timestamping**

Hardware timestamping significantly improves synchronization precision in wired networks, reducing jitter by more than an order of magnitude compared to software timestamping. In addition, software timestamping also introduces a noticeable degradation in synchronization accuracy in several scenarios due to additional operating system and software processing variability.

However, in 5G scenarios, the difference between hardware and software timestamping becomes much smaller in terms of synchronization precision. This indicates that network-induced delay variation dominates over timestamping accuracy in the evaluated 5G environments.

**4) Impact of Resource Sharing (Single vs Multi-UE)**

The comparison between single-UE and multi-UE scenarios shows that resource sharing has a clear impact on synchronization precision. Multi-UE scenarios introduce higher jitter and larger offset variation compared to single-UE scenarios. This suggests that scheduling and contention for shared radio resources are important factors affecting PTP performance.

In contrast, the evaluated background traffic load scenarios show a more limited impact on synchronization precision. The measured throughput and Physical Resource Block (PRB) utilization indicate that the network operated under moderate load conditions, which may explain why no substantial degradation was observed in the evaluated traffic scenarios.

**5) Impact of Radio Conditions**

Within the tested range, radio conditions have a limited and inconsistent effect on synchronization performance. No clear monotonic relationship is observed between radio quality and PTP precision. Although the measured RSRP varies significantly across the evaluated scenarios, the measured RSRQ remains relatively stable, indicating that the experiments did not experience severe radio-link degradation or strong interference conditions.

These observations suggest that synchronization variability in the evaluated commercial 5G network is primarily dominated by wireless scheduling behavior and network-induced packet delay variation rather than radio signal strength alone.

**6) Impact of Traffic Segregation**

The traffic segregation experiments show that synchronization precision may degrade when PTP traffic shares the same segment and priority level as background traffic. Under shared-priority conditions, the measured synchronization jitter increases compared to the segregated traffic configuration, indicating that scheduling competition and resource contention within the 5G network can increase packet delay variation.

However, synchronization accuracy remains close to zero in both configurations, indicating that the primary impact is on synchronization precision rather than systematic offset bias. These observations suggest that traffic prioritization and segmentation can contribute to improving synchronization stability, particularly under high network utilization conditions.

**7) Impact of Delay Asymmetry Compensation**

The comparison between configurations with and without delay asymmetry compensation shows that this parameter mainly affects the mean offset. Precision-related metrics, such as synchronization jitter, remain largely unchanged between the evaluated scenarios. Therefore, the main conclusions regarding synchronization precision are not dependent on the use of delay asymmetry compensation.

The results also indicate that delay asymmetry compensation mainly reduces the static synchronization bias caused by uplink–downlink delay asymmetry, while the dominant limitation of PTP over 5G remains the dynamic packet delay variation introduced by wireless scheduling and network processing.

**Overall Insight**

The results demonstrate that PTP over 5G can maintain synchronization accuracy but suffers from significantly reduced precision due to packet delay variation. The dominant factors affecting synchronization performance are network scheduling, resource sharing, and traffic-induced delay variation, while radio conditions and timestamping methods play a secondary role in the evaluated 5G scenarios.

Chapter 5

# Conclusion and Future Work

## 5.1 Conclusion

This thesis investigated the performance of IEEE 1588 Precision Time Protocol (PTP) over a private 5G SA network in an industrial environment. The objective was to experimentally evaluate synchronization accuracy and precision under realistic deployment conditions and to identify the dominant factors affecting performance.

The results demonstrate that PTP over 5G is capable of maintaining synchronization accuracy, as the mean offset remains close to zero across all evaluated scenarios. This indicates that the protocol can preserve long-term time alignment even in the presence of wireless communication. However, synchronization precision is significantly degraded compared to the wired baseline. While wired Ethernet achieves sub-microsecond jitter, the 5G scenarios exhibit jitter in the order of hundreds of microseconds.

The analysis shows that this degradation is primarily caused by packet delay variation introduced by the 5G network. In particular, scheduling mechanisms, resource allocation, and traffic dynamics are identified as the dominant factors affecting synchronization precision. The impact of radio conditions, within the tested range, is found to be limited and non-monotonic. Although the measured RSRP varied significantly across the evaluated scenarios, the measured RSRQ remained relatively stable, indicating that the experiments did not experience severe radio-link degradation or interference conditions. Consequently, synchronization variability remained primarily dominated by network-induced packet delay variation and wireless scheduling behavior rather than signal strength alone.

Furthermore, the results reveal that hardware timestamping significantly improves synchronization precision in wired networks, but its benefit becomes marginal in 5G scenarios where network-induced variability dominates. Similarly, multi-UE scenarios introduce additional degradation due to resource contention, highlighting the importance of scheduling behavior in shared wireless environments.

The evaluation of delay asymmetry compensation confirms that it mainly affects the mean offset, while precision-related metrics remain largely unchanged. This reinforces the conclusion that packet delay variation, rather than static delay asymmetry, is the main limiting factor for PTP performance over 5G.

Overall, the findings of this thesis indicate that while PTP over 5G is feasible for applications requiring moderate synchronization accuracy, its current performance is not sufficient for time-critical industrial applications that require sub-microsecond precision. These findings are consistent with prior studies, which report that synchronization over 5G networks is primarily limited by packet delay variation, scheduling-induced latency, and uplink–downlink asymmetry, leading to significant degradation in synchronization precision compared to wired networks [9, 18, 10, 22].

The results indicate that PTP over 5G may be suitable for industrial applications that tolerate synchronization variability in the order of hundreds of microseconds, such as monitoring, logging, and non-time-critical automation systems. However, the observed synchronization jitter remains significantly higher than the requirements of deterministic industrial applications, including motion control, protection systems, and TSN-based real-time communication requiring sub-microsecond precision.

This work contributes to the understanding of practical limitations of PTP over private 5G networks and provides experimental insights for future industrial deployment of wireless time synchronization systems.

## 5.2 Future Work

Based on the findings and limitations of this study, several directions for future work are identified.

First, further investigation is required under more challenging radio conditions. The experiments in this thesis were conducted under moderate to good signal quality, where retransmissions and packet losses were limited. Future work should include more challenging radio conditions to better evaluate the impact of radio-induced impairments on synchronization performance.

Second, the influence of network load should be studied in greater detail. In this work, medium and high load scenarios resulted in similar throughput levels, limiting the ability to draw clear conclusions. Future experiments should include controlled and higher traffic loads, as well as additional network metrics such as PRB utilization, to better characterize the relationship between network congestion and synchronization performance.

Third, future work should investigate the impact of radio interference on synchronization performance. In the experiments conducted in this thesis, the measured RSRQ values remained relatively stable, indicating limited interference conditions in the evaluated scenarios. Future experiments could therefore introduce controlled interference sources or intentionally congested radio environments to evaluate how retransmissions, degraded radio-link quality, and increased scheduling variability affect PTP synchronization stability and precision.

Fourth, mobility scenarios should be further explored. Although mobility was initially considered, it was not fully evaluated in this thesis. Future work should investigate the impact of handovers, dynamic radio conditions, and movement patterns on synchronization stability and transient behavior.

Fifth, architectural enhancements should be investigated to improve synchronization performance. This includes the integration of 5G-TSN features such as transparent clocks, boundary clocks, and time-aware network elements, which have been proposed to mitigate delay variation and asymmetry in wireless networks. Experimental validation of these approaches in real deployments would provide valuable insights.

Finally, future work should explore cross-layer optimization approaches, where synchronization performance is jointly analyzed with 5G network parameters such as scheduling policies, Quality of Service (QoS) prioritization, and latency characteristics. Such approaches may enable more deterministic behavior and improved synchronization performance in industrial wireless systems.

Overall, these directions aim to address the identified limitations and move towards achieving reliable and high-precision time synchronization over 5G networks for industrial applications.

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Appendix A

# Experimental Scenario Summary

This appendix summarizes the experimental scenarios used throughout this thesis. The scenario labels are used consistently in Chapter 4 to simplify the presentation and comparison of synchronization performance under different network conditions.

## A.1 Wired PTP Scenarios

The wired PTP scenarios were used as reference configurations to evaluate the synchronization performance under stable and controlled network conditions without wireless communication effects. These scenarios establish the baseline synchronization performance and isolate the impact of routers and software timestamping.

**Table A.1:** Baseline wired synchronization scenarios.

| ID | Scenario | Network Path | TS | Purpose |
|---|---|---|---|---|
| C1 | Baseline | GM $\leftrightarrow$ LAN $\leftrightarrow$ Slave | HW | PTP reference |
| C2 | Router | GM $\leftrightarrow$ LAN $\leftrightarrow$ Router $\leftrightarrow$ Slave | HW | Router reference |
| C3 | Baseline + SW | GM $\leftrightarrow$ LAN $\leftrightarrow$ Slave | SW | SW vs HW comparison |
| C4 | Router + SW | GM $\leftrightarrow$ LAN $\leftrightarrow$ Router $\leftrightarrow$ Slave | SW | SW vs router reference |

## A.2 5G PTP Scenarios

The 5G PTP scenarios were designed to evaluate synchronization performance over a 5G network under different radio conditions, traffic loads, prioritization configurations, and multi-UE conditions. These scenarios were used to investigate the dominant factors affecting synchronization accuracy and precision in wireless industrial networks.

| Case ID | Scenario Type | Network Path | Timestamping | Radio Condition | Traffic Load | Priority Condition | UE number | Purpose |
|---|---|---|---|---|---|---|---|---|
| S1 | Static 5G baseline | GM ↔ LAN ↔ 5G Core ↔ gNB ↔ UE ↔ Slave | HW-HW | Good / Medium / Weak | No load | Default priority | 1 | Evaluate baseline PTP performance under different radio conditions |
| S2 | Static 5G + SW timestamp | Same as S1 | HW-SW | Good / Medium / Weak | No load | Default priority | 1 | Compare software timestamping against HW baseline |
| S3 | Static 5G + high load | Same as S1 | HW-HW | Good / Medium / Weak | With load (2 cameras, multiple streams) | Different segment, PTP higher priority | 1 | Evaluate impact of heavy background traffic with PTP prioritized |
| S4 | Static 5G + medium load, same segment | Same as S1 | HW-HW | Good / Medium | With load (2 cameras, multiple streams) | Same segment, default priority | 1 | Evaluate impact of moderate background traffic without segment isolation |
| S5 | Static 5G + multiple UEs | GM ↔ LAN ↔ 5G Core ↔ gNB ↔ Multiple UEs ↔ Slaves | HW-HW | Good / Medium | No load | Default priority | 3 | Evaluate resource sharing between UEs |
| S6 | Static 5G + multiple UEs + load | Same as S5 | HW-HW | Medium / Weak | With load (2 cameras, multiple streams) | Different segment, PTP higher priority | 3 | Evaluate PTP under multi-UE loaded conditions |

**Figure A.1:** 5G PTP delay asymmetry measurement case.

## A.3 Delay Asymmetry Measurement Scenario

This appendix summarizes the experimental scenario used for the delay asymmetry measurements described in Section 3.4.7. The measured one-way delays were used to estimate the uplink–downlink asymmetry and determine the compensation parameter applied in the PTP configuration.

| Case ID | Scenario Type | Network Path | Timestamping | Radio Condition | PI servo parameters [Kp, Ki] | Load | UE number | Purpose |
|---|---|---|---|---|---|---|---|---|
| P1 | Measuring delay asymmetry | GM ↔ LAN ↔ 5G Core ↔ gNB ↔ UE ↔ Slave | HW-HW | Very good | Default | No load / medium load | 1 | Measure one-way delay in both directions in order to calculate delay asymmetry |

**Figure A.2:** 5G PTP parameter cases.

Appendix B

# LinuxPTP Configuration and Commands

## B.1 PTP Synchronization Commands

Example PTP synchronization command as a slave using `ptp4l`:

```
sudo ptp4l -i eno1 -f ptp4l-slave-unicast-5g_HW.conf -m -l 6 -H
```

## B.2 PTP slave configuration

The following configuration was used to on slave side:

```
[global]
slaveOnly               1
network_transport UDPv4
delay_mechanism  E2E
time_stamping  software

unicast_req_duration 60
inhibit_multicast_service 1
logAnnounceInterval 1
logSyncInterval  0
logMinDelayReqInterval 1

[unicast_master_table]
table_id  1
logQueryInterval 2
UDPv4   14.23.44.21
[eno1]

unicast_master_table 1
```

## B.3 RF Metric Collection

Radio quality metrics were collected from the industrial 5G router during the experiments to monitor the wireless network conditions. The collected metrics included RSRP, RSRQ, signal quality, and other modem-related parameters.

The following example command was used to periodically collect RF metrics from the router:

```
while true; do
    date
    gsminfo
    sleep 1
done >> rf_log.txt
```

The command continuously records timestamped RF measurements into a log file for offline analysis and synchronization with the PTP measurements.

Appendix C

# Example PTP Logs

This appendix presents representative PTP log outputs collected during the experiments using the `linuxptp` software suite. The logs were generated by the `ptp4l` daemon running on the slave node and were used for offline synchronization performance analysis.

The recorded logs contain timestamped measurements of synchronization-related parameters, including clock offset, path delay, and frequency correction. These values were used to compute the synchronization KPIs presented in Chapter 4.

## C.1 Example ptp4l Log Output

The following example illustrates a typical `ptp4l` log collected during a 5G synchronization experiment:

```
ptp4l[7349.844]: master offset    12445 s2 freq  -16234 path delay  196723
ptp4l[7350.844]: master offset   -27931 s2 freq  -20300 path delay  196723
ptp4l[7351.844]: master offset    13259 s2 freq  -16167 path delay  196723
ptp4l[7352.844]: master offset     5910 s2 freq  -16896 path delay  189094
ptp4l[7353.843]: master offset    36345 s2 freq  -13817 path delay  189094
ptp4l[7354.843]: master offset   -10502 s2 freq  -18512 path delay  192741
```

## C.2 Log Parameter Description

The main parameters contained in the `ptp4l` logs are summarized below:

- **master offset**: Represents the estimated time difference between the slave clock and the grandmaster clock. This value is the primary measurement used to evaluate synchronization accuracy and precision.
- **freq**: Represents the frequency correction applied by the PTP servo mechanism, expressed in parts per billion (ppb). The value indicates how the slave clock frequency is adjusted to track the grandmaster clock.
- **path delay**: Represents the estimated communication delay between the grandmaster and the slave node. The path delay includes network transmission, processing, and propagation delays.

- **s2**: Represents the synchronization state reported by the `ptp4l` daemon. This indicates that the slave clock is synchronized to the grandmaster clock.

## C.3 Log Processing

The collected `ptp4l` logs were processed offline using MATLAB scripts. The analysis workflow included:

- extraction of offset and path delay measurements,
- removal of startup transient samples,
- computation of synchronization KPIs,
- generation of statistical plots and comparison figures.

The processed metrics were then used to evaluate synchronization performance under different wired and 5G network scenarios.

## C.4 Example RF Metric Log Output

In addition to PTP synchronization logs, radio-frequency (RF) metrics were collected during the experiments to monitor the wireless network conditions throughout the measurements.

The RF logs were obtained from the industrial 5G router and included parameters such as RSRP, RSRQ, and signal quality indicators. These metrics were used as explanatory variables when analyzing synchronization performance under different radio conditions.

The following example shows a representative RF metric log collected during the experiments:

```
---- Fri Apr 24 09:59:50 GMT 2026 ----
Revision         : Rx50xxxxxxx
IMEI             : 8xx69205xxxxx
ICCID            : x93xx040xxxxx
Registration     : Home Network
Operator         : 9x9 xx EP5G
Technology       : NR5G
PLMN             : 99xxx
Cell             : 753xxx
LAC              : 00xx
Channel          : 65xxx
Band             : n78
RSRP             : -64 dBm
RSRQ             : -11 dB
CSQ              : 24
```

Appendix D

# Other Experiment Results

## D.1 Delay Asymmetry Measurement Results

This appendix presents the detailed one-way delay measurements used to estimate uplink–downlink delay asymmetry in the evaluated 5G network.

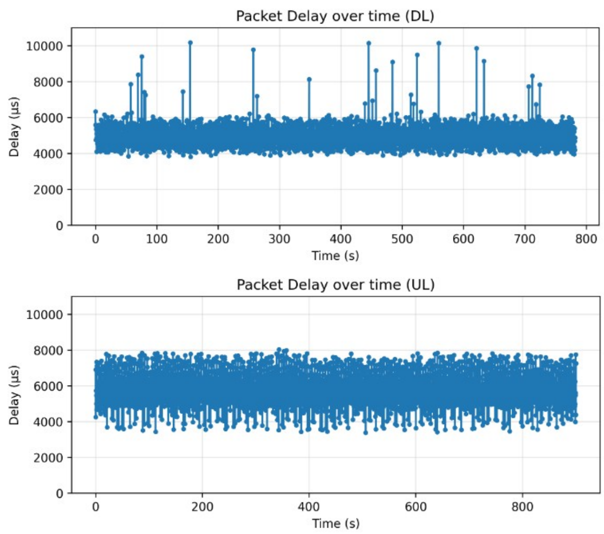


**Figure D.1:** Delay asymmetry measurement: one-way delays.

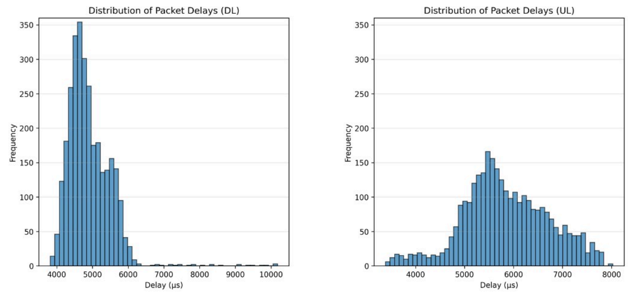


**Figure D.2:** Distribution of packet delay UL and DL.

The results show that the uplink path exhibits both higher average delay and larger packet delay variation compared to the downlink path. This behavior confirms the existence of uplink–downlink asymmetry in the evaluated 5G network and supports the use of delay asymmetry compensation in the subsequent PTP experiments.

## D.2 5G Log-scale boxplot of the Absolute offset

This figure below presents the log-scale boxplot of the absolute synchronization offset for the evaluated 5G PTP scenarios. The results are grouped according to the main experimental categories, including no-load, software timestamping, loaded, and multi-UE scenarios. The figure illustrates the large synchronization variability observed in the 5G network and highlights the impact of packet delay variation and wireless scheduling on synchronization precision.

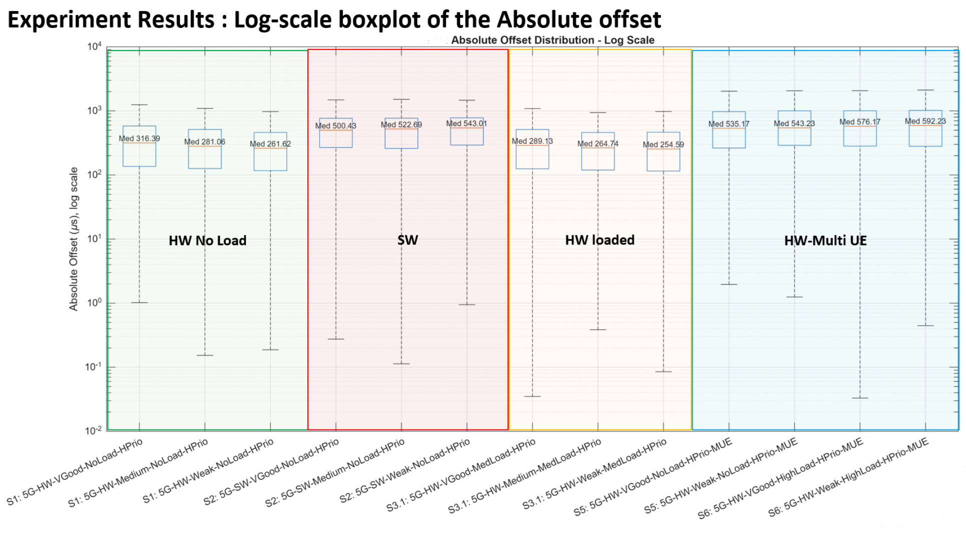


**Figure D.3:** 5G PTP Log-scale boxplot of the Absolute offset.