High Accuracy Timing and Synchronisation for a Telecom Infrastructure

By

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A thesis submitted to
the University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

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University of Birmingham
July 2024

ABSTRACT

The scientific community is performing groundbreaking experiments to develop the best clocks in the world. Recently, strontium-based optical lattice clocks have been reported to provide stability and precision to 10^{-18} levels. In addition to that, the research community has been developing compact transportable optical lattice clocks, with the aim of bringing them out of research labs to real network environments. These clocks might be an alternative solution to satellite technologies in the near future for positioning, navigation and timing services. They are capable of providing timing and synchronisation to sub-nanosecond or picosecond levels in future networks through terrestrial networks. However, there is a lot more to investigate regarding challenges incurred while disseminating the clock output across the fibre networks. These challenges can be the factors affecting frequency and phase stability, network configuration, long-term stability and accuracy and much more.

At present, the telecommunication infrastructure relies on microwave-based atomic clocks and satellite-based technologies for accurate phase, frequency and time of day at the network core. Optical atomic clocks are the next generation of atomic clocks capable of replacing microwave-based atomic clocks and satellite-based technologies at the network core in the coming years. The research work delves into the practical applications of optical lattice clocks in telecommunication networks, particularly in disseminating time and frequency at a national scale. This report outlines the initial steps towards this goal, which includes the development of a time dissemination simulation platform at a national scale with sub-nanosecond level timing accuracy, with optical atomic clocks at the core nodes of telecom infrastructure. The simulation model investigates various novel architectures to identify the best possible way to connect optical atomic clocks to a telecom infrastructure in future. The research also explores the use of FPGAs to synchronise multiple nodes to picosecond scale precision. The implementation of a time-to-digital converter module on an FPGA along with the novel technique for offset calibration aids to synchronise multiple nodes to picosecond scale precision. The need for high-accuracy clocks and improved transport schemes is crucial to transport high-accuracy timing from the core to the access node in a telecom infrastructure. The PhD work focuses on the intricacies of transporting timing signals within sub-nanosecond or picosecond timescales in telecom infrastructure, highlighting the practical implications of this research.

DEDICATION

You could call it a matter of dedication,
I'd say it's time for the citation,
It's been a long while on this station,
I'd like to start with my dear mother's blessing,
Her presence was a rare finesse,
Her actions needed no adjection,
Her love bowed one and all into submission,
An impact so deep,
If I perspire, you'll see her in it's reflection,
Her prayer to do me well, my daily invocation,
My father's wishes and admiration,
My grandfather's an inspiration,
My grandmother's love ties this generation,
My dear aunt and uncle, hearts lined with invitation,
By my side stays my siblings inclination,
To my husband a salutation,
To do right by them all, my aspiration
Learnt much on this vocation,
The team at BT for my integration,
The University of Birmingham's allocation
To them all a special mention,
Have many words left for recitation,
Hereby ends my felicitation.

ACKNOWLEDGMENTS

It is a matter of pleasure for me to acknowledge my deep sense of gratitude to my supervisors, Dr Andrew Lord and Prof. Yeshpal Singh, for giving me an opportunity to explore my abilities in this research area and leading me with valuable guidelines throughout the work. I would like to convey my sincere gratitude to the MoSaiQC consortium for the opportunity and the European Commission for funding the research program. I am thankful to the Optical and Quantum Networks Research Team in British Telecommunications PLC and members of the Alkaline Group at the University of Birmingham for the support and encouragement required for the progress of this research work. I would like to express my gratitude to Mike Gilson and the Timing and Synchronisation Specialist Platform Team at British Telecommunications PLC for helping me enrich my practical knowledge in the research area.

My sincere gratitude to the team members in Research and Network Strategy at British Telecommunications PLC and faculty members at the University of Birmingham for helping me in my research work in one way or another. I would like to thank Peter Winzer from Nubis Communications and High-Performance Networks Group at the University of Bristol for providing me with the guidelines and environment to complete the secondment work as part of the research programme. My sincere gratitude to Dr. Marco Menchetti for his moral support and guidance during the earlier stages of my research work. My sincere appreciation for Dr. Zoe Davidson for being a great support during the final stages of my research work.

Special thanks to my husband for being a solid pillar and making me feel easy throughout the research period. My sincere gratitude goes to my beloved family members and friends who have always encouraged, supported and cared for me throughout my life. I would also like to thank my fellow early-stage researchers involved in the MoSaiQC project for being very helpful in sharing their knowledge and for their valuable assistance. I would like to thank British Telecommunications PLC and the University of Birmingham for providing me with a congenial environment to work in.

There are a lot of people who helped me throughout the journey. By reading this, please be assured that you all are being thanked.

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Glossary

Accuracy It is the degree of closeness between the measured value and the actual or standard value. 4

Asymmetry It refers to any factor that contributes or adds an error value to a timing signal. 60

Backhaul It is the transmission link that connects the remote or edge sites to the central or core node. 7

Carrier Aggregation It is a technique used in wireless communication where multiple frequencies are allocated to the same user to increase the data rate per user. 2

CoMP A technique used from the fourth generation of telecommunication network where multiple base stations co-ordinate to manage the interference and enhance the user experience. 2

Dead time It is the time interval after the occurrence of a pulse for which the counter is insensitive to record the events. 86

eCPRI It is an interface for data transmission connecting the remote radio units to the baseband units in a network. 14

eICIC It is an interference control technology used from the fourth generation of telecommunication networks to minimise the inter-cell interference, mainly at the cell edge to enhance the user experience and allow the coexistence of macro and small cells in the network. 2

FDD It is a communication technique where different frequencies are used for the transmission and reception of the signal. 8

Flicker frequency noise It is a type of electronic noise affecting the frequency component of a signal. 86

FPGA slice It is a group of logic elements that is part of the configurable logic blocks in an FPGA. 104

Frequency synchronisation It is the process of disciplining the frequency of the slave device to match with the frequency of the master device. 5

Fronthaul It is the transmission link connecting the remote radio units or the remote radio head units with the cloud radio access network. 7

Grandmaster It is a device that can only act as a master device and not as a slave device. 13

Guard period It is the time period between multiple transmission to avoid interference or overlapping of signals. 2

Holdover It refers to the time period that an equipment can continue providing an accurate time even when the reference fails or is unavailable. 4

HPBC It is a device that has more than one port in the IEEE1588 clock domain where one port acts as a slave clock port and multiple ports act as master clock ports. 8

Instantiate It is the process of creating the first instance of a TDC. 108

Isotope Different forms of an element that have same number of protons but different number of protons in the nuclei, therefore exhibit similar chemical properties but differ in atomic mass. 28

Jamming It is a type of attack where the attacker disrupts the data flow from a sender to a receiver by creating noise in the communication channel. 14

Jitter It refers to the high-speed variations in a timing signal that falls above 10Hz. 4

Joint transmission It is a technology that refers to the transmission from multiple transmission points to a single device. 2

Metastability It is a phenomenon that occurs due to the variations in the setup and hold-time in flip-flops, which results in an unpredictable output state. 106

Midhaul It is the transmission link connecting the distributed unit with the centralised unit of the baseband unit. 7

NTP It is for clock synchronisation between computer systems. 5

OTN It is a transmission technology that allows the transport of data traffic over the fibre networks using the wavelength division multiplexing. 5

Path length stabilisation A technique to improve the frequency stability of a signal transmitted over fibre by compensating for the error induced during transmission. 80

PDH It is a telecommunication technology for transmission which worked with large frequency rate. 3

Phase noise It is the noise due to rapid, random, short-term fluctuations in the phase component of a signal eventually degrading the quality of a signal. 86

Phase synchronisation It is the process of disciplining the phase of the signal generated by the slave device to the master so that both waveforms are identical frequency and phase in each cycle. 5

PRC It is a component in the telecommunication network that serves as the primary source for stable frequency. 4

Precision It is the degree of closeness between the measurements taken on a particular device multiple times. 49

Primitives They are general purpose or dedicated components included in an FPGA which help in the design of specialised tasks. 100

PRTC It is a component in the telecommunication infrastructure that serves as the primary source for accurate and stable time information. 5

PSTN It is a traditional telecommunication technology for the voice communications. 3

PTP It is an ITU-T standard protocol used to synchronise different clocks in a network to a reference source. 5

Resiliency The ability or capacity to recover quickly from a failure scenario. 14

Resonant frequency It is defined as the natural frequency at which the medium vibrates at the highest amplitude. 27

Second The International System of Units defines the second as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Caesium-133 atom" [30]. 19

Spoofing It is a type of attack where the attackers set up fake access points in high traffic locations, where the users would connect to, giving access to user information. This information can be forged or used to spread malware through forged mails, infected links or attachments etc. 14

SSU It is a high-quality clock used in the telecommunication infrastructure. They have a very narrow bandwidth and support holdover, thereby providing reference in the event of temporary loss of a timing signal. 4

Stability It defines the degree of consistency of the measurements taken from a particular device. 50

STM It is a standard for data transmission over the SDH or SONET transmission networks. 4

SyncE It is an ITU-T standard protocol that allows the transmission of clock signals over the Ethernet medium. 5

Synchronisation Operating multiple clocks at the same rate as the reference clock. 1

Syntonisation It is the process of tuning the frequency of one device with respect to the frequency of another device. It is the other term for frequency synchronisation. 11

TC It is a device that adds hardware timestamps to a sync message received or transmitted from the device. 8

TDD It refers to duplex communication technique where the uplink and downlink are allocated with different time slots in the same frequency band. 2

TDM It is a multiplexing technology where the signals are transmitted and received over the network by means of synchronised switches and allows multiple data signals to be transmitted over the same communication channel in different time slots. 5

Telegraph It is a low bitrate data service which sends information by creating and breaking an electrical connection. 3

Thermometer code The N-bit long code generated after the sampling the cock period. 108

Wander It refers to the slow-speed variations in a timing signal that falls below 10Hz. 4

White noise It is defined as a type of noise which is a mixture of electrical signals or frequencies which consist of the electrical signals or frequencies over a wide range or spectrum. 86

Acronyms

ADC Analog to Digital Converter. 103

ADEV Allan Deviation. 86

AI Artificial Intelligence. 62

AOM Acousto-Optic Modulator. 80

ASIC Application Specific Integrated Circuit. 99

AVAR Allan Variance. 86

AXI Advanced eXtensible Interface. 112

BC Boundary Clock. 13

$C-RAN$ Core-Radio Access Network. 102

CA Carrier Aggregation. 2

CTE Constant Time Error. 14

CoMP Coordinated Multipoint. 2

DCF Dispersion Compensation Fibre. 60

DSAC Deep Space Atomic Clock. 46

DSP Digital Signal Processing. 60

DWDM Dense Wavelength Division Multiplexing. 54

FIFO First In First Out. 60

FPGA Field Programmable Gate Arrays. 16

GEO Geosynchronous Equatorial Orbit. 39

GLONASS Global Navigation Satellite System. 29

GM Grandmaster. 13

GNSS Global Navigation Satellite System. 8

GPS Global Positioning Service. 29

GSO Geosynchronous Orbit. 39

GbE Giga bit Ethernet. 112

HDL Hardware Description Language. 100

HPBC High Performance Boundary Clock. 59

IP Intellectual Property. 100

IRNSS Indian Regional Navigation Satellite System. 29

IoT Internet of Things. 2

JPL Jet Propulsion Laboratory. 46

LEO Low Earth Orbit. 39

LORAN Long Range Navigation. 41

LTE Long Term Evolution. 58

LTE − A Long Term Evolution - Advanced. 54

MEO Medium Earth Orbit. 39

MHz Mega Hertz. 58

MIMO Multiple Input Multiple Output. 102

ML Machine Learning. 62

MOT magneto optic trap. 48

NASA National Aeronautics Space Administration. 46

NIST National Institute of Standards and Technology. 25

NMI National Meteorology Institutes. 46

NPL National Physical Laboratory. 46

NTC National Timing Center. 46

NTP Network Time Protocol. 5

OCP Open Compute Project. 44

ORS Optical Reference System. 83

OTN Optical Transport Network. 5

PDH Plesiochronous Digital Hierarchy. 3

PID Proportional Integral Derivative. 80

PLD Programmable Logic Device. 99

PNT Position, Navigation and Timing. 15

PPS Pulse Per Second. 58

PRC Primary Reference Clock. 4

PROM Programmable Read Only Memory. 99

PRTC Primary Reference Time Clock. 8

PSTN Public Switched Telephone Networks. 3

PTB Physikalisch Technische Bundesanstalt. 46

PTP Precision Time Protocol. 5

QZSS Quasi-Zenith Satellite System. 29

RF Radio Frequency. 91

RNSS Regional Navigation Satellite System. 29

SDH Synchronous Digital Hierarchy. 4

SEC Synchronous Equipment Clock. 4

SFP Small Form Pluggable. 110

SIUnit International System of Units. 19

SONET Synchronous Optical Networking. 4

SSP Single Shot Precision. 114

SSU Synchronisation Supply Unit. 4

STM Synchronous Transport Module. 4

SyncE Synchronous Ethernet. 5

$T-BC$ Telecom Boundary Clock. 54

TAP Time Appliance Project. 44

TC Transparent Clock. 13

TDC Time to Digital Converter. 99

TDD Time Division Duplex. 2

TDM Time Division Multiplexing. 5

TE Time Error. 14

THz Terahertz. 58

TSC Time Slave Clock. 13

UDP User datagram Protocol. 10

URLLC Ultra-reliable Low Latency Communications. 7

UTC Universal Co-ordinated Time. 26

VHDL VHSIC Hardware Description Language. 100

VHSIC Very High-Speed Integrated Circuit. 100

WDM Wavelength Division Multiplexing. 54

WR White Rabbit. 11

cnPRTC Coherent Primary Reference Time Clock. 8

dTE Dynamic Time Error. 14

eCPRI enhanced common public radio interface. 14

eICIC Enhanced Inter-cell Interference Cancellation. 2

eLORAN Enhanced Long Range Navigation. 41

ePRTC Enhanced Primary Reference Time Clock. 59

mHz Millihertz. 58

ns Nanosecond. 63

ppb Parts per Billion. 9

ps Picosecond. 97

Chapter One

Introduction

Time is an entity that we all care about and worry about as it frames the routines of our daily lives. Everyone observes the ticking of a clock at all times of the day, irrespective of whether being at work or home or relaxing with family and friends. However, the main centre of interest for civilisations around the world over many centuries has been how to measure time. Similar to measuring quantities like length and mass, time is a parameter that needs to be accurately measured. Time measurement has a long, deep history. The history narrates the facts on the measurement of time in ancient times and how the measurement techniques evolved gradually. It also adds knowledge on various devices and techniques invented by humans to measure time accurately and precisely. All these facts underline the importance of timekeeping and the necessity of precise and accurate time measurements in the current era.

Timing and synchronisation are fundamental to a telecommunication infrastructure supporting high-speed data transmission and ultra-reliable low-latency services. Synchronisation is often taken for granted and is effectively invisible, primarily when the network is functioning well. However, timing and synchronisation is one of the critical enablers for different aspects related to the transfer of voice and data. Distribution of a reference signal across different layers is essential to support the applications and services on the network and ensure reliable network operation. Lack of synchronisation will affect the operation of various technologies supported by the network and, therefore, result in a poor end-user experience such as dropped calls, poor data connectivity etc. Poor synchronisation between network elements results in issues such as lower data throughput, improper handover between cell sites, poor network connectivity, data buffering and poor signal strength. A telecommunication infrastructure relies on various technologies to ensure the reliable operation of a network. Technologies such as Coordinated Multipoint (CoMP), Enhanced Inter-cell Interference Cancellation (eICIC), joint transmission, and carrier aggregation (CA) demand tight synchronisation to ensure reliable operation of the network. Poor synchronisation at the radio units results in the misalignment of Time Division Duplex (TDD) frames with the guard period . It interferes with the adjacent cell sites, thereby creating time shifts, resulting in interference and performance issues.

In the present era of modern telecommunications networks, the advancement towards the fifth generation signifies the need for higher data speeds, better connectivity and low latency. Synchronisation plays a crucial role in achieving the desired performance from these networks. The fifth generation of telecommunication networks deploys edge computing where data processing is close to the end-user. Additionally, the proliferation of Internet of Things (IoT) devices across the network enhances the importance of accurate timing and tight synchronisation across network devices. In a nutshell, poor synchronisation results in poor quality of service, poor performance, and poor connectivity. Stringent timing and proper synchronisation are essential for seamless connectivity, integration of multiple portable and fixed network devices into the network, proper monitoring of the network, and supporting automotive and real-time services in a network.

1.1 Evolution of Synchronisation in a Telecommunication Infrastructure

Telecommunications began with the telegraph services during the 1830s. Telegraph service is a low-bitrate data service which sends information by creating and breaking an electrical connection. Synchronisation concepts started to be considered in the design of telecommunication infrastructure with the introduction of Plesiochronous Digital Hierarchy (PDH) in the transport networks and digital switches in the Public Switched Telephone Networks (PSTN) . Figure 1.1 shows the evolution of synchronisation technology across the various generations of telecommunication networks.

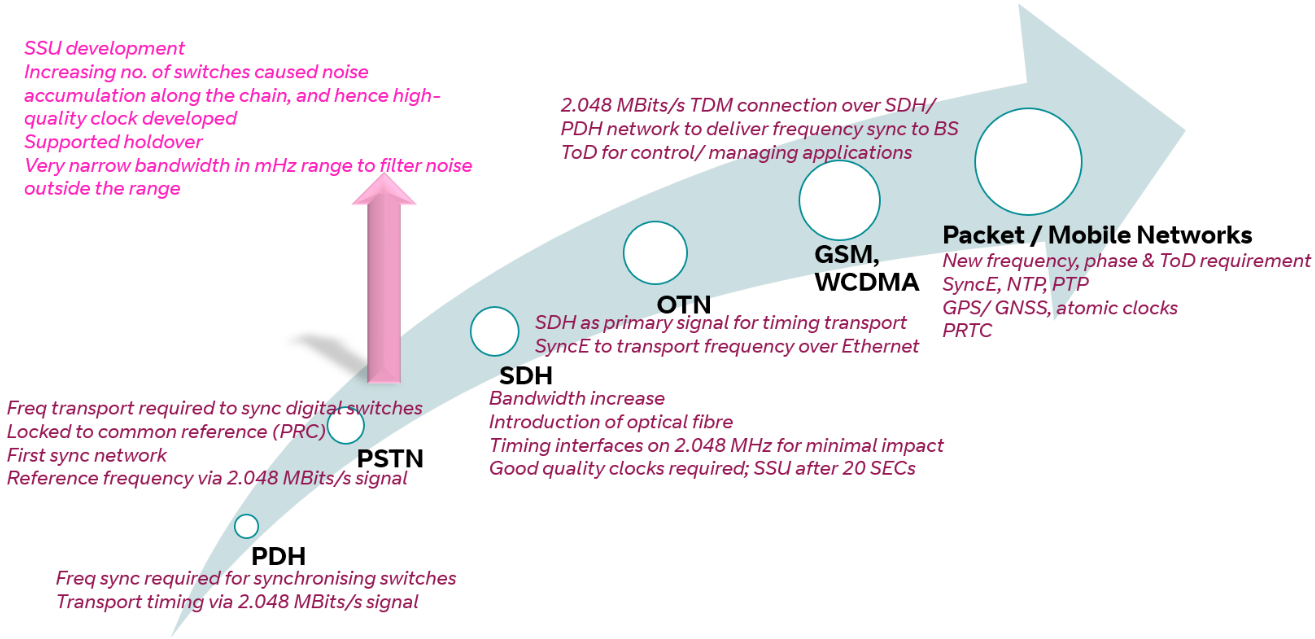


Figure 1.1: Evolution of synchronisation from traditional to modern telecommunication networks

The PDH network worked with a high frequency rate, and therefore, PDH networks did not demand synchronisation by themselves. The transport network was capable of transporting timing as it implemented the 1 bit justification process. The multiplexers in the network assume that the data transmission occurs at the maximum supported speed and, therefore, expect the next bit to arrive at the appropriate time. However, it is implausible that the bits arrive at the exact expected time. In this case, one bit is added to the data stream to maintain the bit rate for the outgoing data. This is known as the bit justification or stuffing process in a PDH network. The bit justification process aids in meeting the required jitter and wander performance. The introduction of PSTN into the telecommunication infrastructure demanded frequency transport to synchronise digital switches in the network. A 2.048 MBits/s signal transported the reference signal for frequency synchronisation. This resulted in the design of the first synchronisation network for a telecom infrastructure.

The devices across the network are locked to a Primary Reference Clock (PRC) . The long-term accuracy of a PRC is 1 part in 10^{11}. However, the growth of the infrastructure on a broader scale resulted in the use of more switches. Therefore, the level of noise that accumulated along the chain became high and affected the synchronisation quality. This resulted in the development of high-quality clocks known as the Synchronisation Supply Units (SSU). The SSUs had a very narrow bandwidth in the mHz range to filter out the noise lying outside the range of the passband. These high-quality clocks support holdover, which means they are capable of providing a reference signal where there is a temporary loss of a timing signal.

The increasing demand for higher bandwidth and new optical fibre technology resulted in the implementation of Synchronous Digital Hierarchy (SDH) / Synchronous Optical Networking (SONET) technology. A new clock terminology named Synchronous Equipment Clock (SEC) was defined. However, the timing interfaces were still maintained as the 2.048 MBits/s signal. This ensured a smooth transition from PDH to SDH technology and the replacement to have less impact on the synchronisation architecture. SDH allowed direct access to the Synchronous Transport Module (STM) line frequency rate, which generates a 2.048 MBits/s signal. This signal can be fed onto external equipment to transport timing across the network. Noise is one of the main factors limiting the quality of a timing signal, and the proliferation of devices such as SECs and switches resulted in the accumulation of noise that degraded the quality of the timing signal. Specific design rules were introduced for designing a synchronisation architecture to limit the quantity of noise affecting the quality of a timing signal, such as having an SSU after 20 SECs to improve the quality of existing technologies.

The Optical Transport Network (OTN), defined in the 2000s, was capable of carrying different types of signals across the network. OTN relied on SDH as the primary signal to transport timing signals across the network devices. The Synchronous Ethernet (SyncE) protocol was introduced to support synchronisation and transport timing signals for the data networks over the Ethernet medium. In the earlier generations of mobile networks, the base station controller connects to the base station via a 2.048 MBits/s signal over the SDH or PDH networks to deliver frequency synchronisation. Frequency synchronisation was a requirement to ensure proper handover between the base station and cells. The time of day information and phase synchronisation was essential for the control and management services related to the network operation. Protocols such as SyncE, Precision Time Protocol (PTP), Network Time Protocol (NTP), and high accuracy PTP are widely used along with technologies such as Global Navigation Satellite Systems (GNSS), atomic clocks, Primary Reference Time Clocks (PRTCs), to ensure accurate timing and synchronisation across devices in a telecom infrastructure.

Time Division Multiplexing (TDM) network divide the communication channel into time slots allowing the transmission and reception of multiple signals over the same physical medium. Synchronising the transmission of multiple signals is essential to ensure proper data transmission, uninterrupted operation of the network, proper data extraction, and prevention of collision of data frames for an error-free communication. Distribution of the reference signal from a master clock (primary reference clock or synchronisation supply

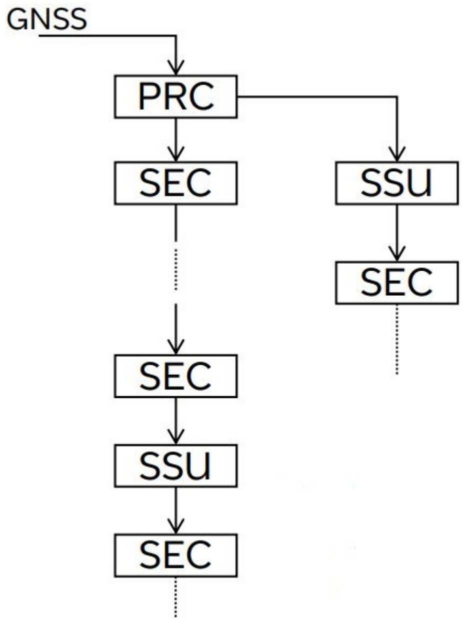


Figure 1.2: Synchronisation architecture for a TDM network

unit) to the network devices disciplines the clocks in the network devices (synchronisation equipment clock) to operate at the same rate, thereby preventing discrepancies that lead to data distortion or loss. In a TDM network, frame synchronisation is essential for identifying the time slots accurately and allocating them to different channels without misalignment. At a microscopic level, bit synchronisation allows the proper interpretation of the bits within a specific timeslot. Figure 1.2 illustrates the traditional synchronisation architecture that uses a physical layer signal (2.048 MBits/s signal) to transport frequency over the SDH network from the PRC. SSUs and SECs aid in distributing frequency down the hierarchy. SSU is one of the key devices capable of providing a stable and reliable reference to other devices in the network. SSUs rely on GNSS or atomic clocks as an accurate source of time and distribute the timing signals throughout the network through SSUs and SECs. SSUs are present in stratum 1 and stratum 2 in the synchronisation architecture. The stratum is classified based on the level of accuracy. Highly accurate timing sources or synchronisation devices occupy stratum 1 in the hierarchy. SECs are specialised cards present in devices such as routers and switches that handle the synchronisation functionality. These cards do support standardised protocols such as PTP to distribute the timing across different network elements.

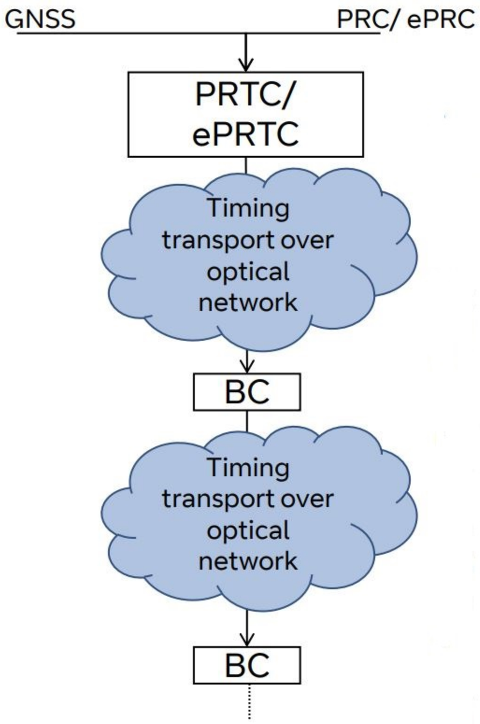


Figure 1.3: Synchronisation architecture for a modern telecommunication network

In modern networks, timing and synchronisation are essential for achieving the low latency communication and high performance promised by the technology. In a 5G network, ultra-reliable low latency communications (URLLC) demand stringent synchronisation to minimise the delays in communication. Accurate and precise timing ensures that the transmissions occur at the right time interval, thereby aiding applications such as autonomous vehicles and real-time monitoring and control systems in working efficiently. In the 5G architecture, synchronisation needs to be maintained across the backhaul , midhaul and fronthaul to ensure coordination and proper data flow across different network elements or segments. The introduction of small cells into the network demands tight synchronisation to improve efficiency and minimise interference. Network slicing creates virtualised networks for different applications, and they demand tight synchronisation to ensure each network slice achieves its desired performance for applications with varying latency and requirements.

The fifth generation of telecommunication networks supports a vast number of connected devices ranging from IoT sensors to smart devices, and synchronisation is essential to manage the communication between these devices to ensure reliable communication and efficient operation of these devices to cater for the needs of a wide range of applications and services supported by the technology. Figure 1.3 illustrates the distribution of a timing signal across a modern telecommunication network. The network consists of Primary Reference Time Clocks (PRTC) and high-performance boundary clocks to distribute time. PRTCs are highly accurate clocks that act as the primary reference. They receive timing information from the Global Navigation Satellite System (GNSS) and atomic clocks. They are stratum 1 devices. The high-performance boundary clocks (HPBCs) can act as masters or slaves to transport high-accuracy timing signals across the network. The networks also use transparent clocks for synchronisation. These clocks only forward the incoming PTP messages and provide the corrections for the residence time on the device and, therefore, cannot act as a master or a slave device. Coherent PRTCs (cnPRTC) and virtual PRTCs (vPRTCs) are technologies under development to improve the accuracy of the existing systems. Additionally, the factors that contribute to timing errors, termed as asymmetries are one of the factors that degrade the quality of a timing signal. Therefore, the network looks into reserving a dedicated wavelength for transporting the timing signal to minimise the effect of asymmetries.

1.2 Sync Delivery

Earlier generations of telecommunication networks, such as 2G and 3G, used Frequency Division Duplex (FDD) for transmission. This technology uses different frequencies for the upstream and downstream communication. Hence, there were stringent requirements on frequency synchronisation to utilise the frequencies in the spectrum range effectively.

Moreover, frequency synchronisation ensures the improvement of the quality of service across the network, such as smooth handover and cell coordination. Frequency synchronisation is characterised by the deviation of the measured frequency from the actual frequency and is measured in parts per billion (ppb). The frequency error in mobile networks should be within 50 ppb [27] at the air interface of the radio access network. The frequency error in the backhaul transport network should be within 16 ppb [27]. When networks evolve to 4G-LTE and 5G, the radio access network supports functionalities such as interference cancellation, coordinated multipoint, joint transmission and multiple input multiple output antennas. Hence, phase and time synchronisation is a necessity. The TDD technology helps to support the increasing traffic in the evolving networks. In this technology, the upstream and downstream communication utilise the same frequency, but different services utilise different time slots. Devices in the network need to be synchronised in frequency and phase to enable seamless connectivity between the radio units, baseband units and core units of the network. Phase synchronisation, measured in seconds (microseconds, milliseconds, nanoseconds, or picoseconds), is the time difference or phase difference between the measured signal and the reference signal. In addition to phase and frequency synchronisation, devices need to have accurate time of day information for accurate time stamping [27].

Distributing phase, frequency and time of day information across networks is equally important as having an accurate source as a reference. There is a wide range of standardised protocols, such as Precision Time Protocol (PTP), Synchronous Ethernet (SyncE), and Network Time Protocol (NTP), that aid in the distribution of frequency, phase and time of day information across the network. SyncE protocol provides a synchronisation signal to the resources in a network. It is an ITU-T standard used mainly for computer networking. It aids in transferring the clock signals over the physical medium, which is the ethernet. The signals are referenced to an external clock within the network. The external clock acts as the master clock, and clocks present within the network configured to the master act as slave clocks.

Network Time Protocol (NTP) is one of the oldest networking protocols that helps synchronising clocks in computers connected in a packet-switched network with variable latency. This protocol works in systems modelled in a client-server and peer-to-peer topology, where the servers or peers are considered as an accurate time source. The time stamps are sent and received through a User Datagram Protocol (UDP). This protocol works well in broadcasting and multicasting methods where clients listen to the time updates after the initial round trip of messaging. The different levels of hierarchy within the network are known as stratums. Stratum 0 is the starting point and consists of a highly precise time reference device that acts as the master clock. Commonly used Stratum 0 devices in the network are either synchronisation supply units or sync servers with GNSS connectivity. The protocol can synchronise time to a few milliseconds over the Internet network and even better over the local area networks. Stratum 1 consists of devices in synchronisation with the Stratum 0 devices within a few microseconds. They act as primary time servers. The maximum limit of the stratum is Stratum 15. A device in Stratum 16 is not in synchronisation with the reference in Stratum 0.

Precision time protocol (PTP) synchronises the phase, frequency and time of day components of a timing signal. The accuracy of this technology ranges from microsecond to nanosecond level. PTP is used within the network if phase synchronisation and time-of-day information are required or if better synchronisation accuracy is essential than that provided by existing synchronisation protocols. The protocol eliminates time error between master and slave by computing the offset between the slave and the master. The protocol uses a master clock as a reference to synchronise the slave clock. The master clock in the network shares a broadcast message periodically to the slave devices within the network. Once the broadcast message is received, the slave device will take note of its local time. Then, the master will broadcast a message with an accurate timestamp. The slave device uses this information to calculate its deviation from the master. PTP uses a set of four messages to synchronise the slave clock to the master:

- Sync message
- Follow-up message
- Delay request message
- Delay response message

Some of the factors that affect the accuracy of the protocol are the length of the link between master and slave, the transit time taken by the sync messages to propagate from master to slave, and the exchange time in the handshake process.

A high accuracy PTP (known as the White Rabbit (WR) protocol) is a combination of the PTP and the Sync-E synchronisation protocol. The synchronous Ethernet (SyncE) protocol is an ITU-T standard to achieve network wide synchronisation by transporting clock signals over the Ethernet physical medium. High accuracy PTP allows slave clocks to synchronise with their master within the sub-nanosecond level of accuracy. In comparison with independently running PTP or Sync-E, this protocol has advantages over time precision, distance range, scalability, robustness and auto-calibration. The White Rabbit protocol follows a set of procedures to synchronise the slave to the master. It includes setting up the link, syntonisation (frequency synchronisation), calibration of the physical layer, measuring coarse delay and phase, determining link asymmetry, computing one-way delay and clock offset, correcting the offset change, and measurement of phase and compensation of delay variations. Syntonisation refers to calibrating the frequency of the local clock to its master. The delay aids in estimating the variations due to the effect of asymmetries. It also reveals information related to the transmission circuit and the physical medium. Some of the factors contributing to asymmetry include propagation delay generated from the electronic circuits and PCB, delay generated in the transceiver components, different fibre for transmission and reception, length of the link and temperature variations.

There are a wide variety of technologies that aid in keeping the devices within a network in tight synchronisation with respect to each other. Different strategies and technologies need consideration from the perspective of network design and the type of application. These technologies vary depending on the geographical area in which the network provides connectivity and services. In the case of a wider topological area, the timing signal can be from satellite sources such as GNSS or GPS. The devices within the network can have a GPS receiver embedded into them, which derives the timing information from the satellites.

In some cases, the GPS signals may have little coverage over the area, which makes it difficult for the network devices to rely on the satellites for timing information. In such scenarios, GPS receivers are in centralised locations, and the timing signals can be transferred to other devices within the network through the transport technologies over the fronthaul, midhaul or backhaul. Suppose neither of the above-suggested strategies works, then the timing signals can be transferred through a separate synchronisation delivery network; for example, a terrestrial network using optical clocks for time and frequency dissemination. A combination of different functionalities, design criteria and performance characteristics aid in achieving the desired quality of synchronisation. They are required to maintain the slave clock within the required network budgets to achieve the overall quality of the network. Poor synchronisation can result in poor management of frequency within the radio access network, hence leaving the spectrum not fully utilised. Functionalities such as carrier aggregation, interference cancellation schemes, and coordinated multipoint and joint transmission may go out of alignment, creating colossal disruption to the services handled by the network.

Synchronisation of network elements relies on phase, frequency and time of day synchronisation. Frequency synchronisation ensures that the frequency of the local clock is similar to the frequency of the master clock. The time interval between the signals needs to be similar, but they do not need to start at the same time. In the case of phase synchronisation, the pulses need to start at the same time. The time of day ensures that the slave clock has the same time information as the master. In 5G, synchronisation is not only dependent on the increasing network requirements but also on the design processes. Synchronisation and timing requirements need to be considered when designing the fronthaul, midhaul, and backhaul of the network. The hierarchical network consists of different types of clocks to achieve the required accuracy at each level, namely grandmaster (GM), boundary clock (BC), transparent clock (TC), and time slave clock (TSC). ITU-T G.8266 standard details the timing characteristics of a grandmaster clock for frequency synchronisation [38]. ITU-T G.8273.2 standard details the timing characteristics for telecom boundary clocks and telecom slave clocks with full timing support from the network [38]. ITU-T G.8273.3 standard details the timing characteristics for telecom transparent clocks with full timing support from the network [38]. The grandmaster clock is a highly precise clock at the core node, mainly located at the PRTC. It is the master clock and starting point of the PTP domain. A boundary clock is generally configured as a slave clock and synchronises itself to the GM clock in the hierarchy. It will act as a master clock to the clocks below it in the hierarchy. A transparent clock can compensate for internal delay by estimating the delay created by the device itself. The synchronisation accuracy achieved with this clock is less when compared to a boundary clock. The time slave clock is the lowest device in the hierarchy to receive clock information. These clocks sit in the distributed unit or the radio unit of the network.

The ITU-T G.8273.2 standard outlines the time error limits for different classes of boundary clocks [38]. A Class A boundary clock is specified to have a maximum time error limit of 100 ns whereas a Class B boundary clock has a maximum time error limit of 70 ns. A Class C boundary clock has a maximum time error limit of 30 ns and a Class D boundary clock has a maximum time error limit of 5 ns. The midhaul and the backhaul networks are advised to have boundary clocks of class B or C. These networks have IP-based domains, and hence, in order to meet the synchronisation requirements within the network, routers need class B or class C boundary clocks. Time error (TE) measures the deviation of the measured time from the actual time. TE is either dynamic or constant. The dynamic time error (dTE) originates either from devices in the IP layer or from the devices in the Ethernet layer. However, these errors need to be managed and should be within the limit specified by the network requirements. One of the reasons for the generation of constant time error (cTE) across the network can be the link. For example, taking the longest routing path when the shortest routing path has failed. However, similar scenarios need to be managed and should lie within the range as per the network requirements. Fronthaul networks are based on the enhanced common public radio interface (eCPRI) or Ethernet devices and have to achieve the relative as well as absolute phase error requirements. dTE and cTE need to be managed in every part of the network and should lie within the network requirements to maintain the desired performance.

Every strategy has its own positive and negative aspects. These aspects need careful consideration while designing the network to develop a resilient infrastructure meeting the network requirements. Over the years, the security of satellite-based technologies has been questioned and is considered to be a severe threat. The signals from the satellites are low in strength; hence, it is easy to mimic a low-strength GPS or GNSS signal. This has increased the jamming and spoofing attacks, causing the networks to be vulnerable to security attacks and degrading their resilience. In addition to security threats over satellite-based technologies, the number of cell sites is increasing as the network upgrades to 5G and beyond 5G networks. 5G aims to provide connectivity to every corner of the earth. However, achieving this aim with satellite-based technologies looks challenging. The coverage from these sources needs to be large enough to cover every part of the earth. Urban environments with 5G networks need millimeter-wave small cells. These cells can provide very high bandwidth over a short distance range. Therefore, future networks need to be highly resilient and reliable as they support a vast number of devices and real-time services. The interference of GNSS signals can lead to havoc within the network, affecting multiple real-time services and thereby degrading the quality of service.

Recent research investigates finding the best alternative to GNSS. This brings up the necessity of having network-based synchronisation solutions. In older network generations, the network-based synchronisation methods were used as the backup technology to support the network in case of GNSS failure. However, recently, with rising concerns on coverage, security and tight requirements, evolution is happening to bring network-based synchronisation technologies as the primary method of transferring time, frequency and phase components of the timing signal. The secondary source of reference can be satellite technologies or similar alternative position, navigation and timing (PNT) technologies. With the current trend and network requirements, the trend is more towards the network-based synchronisation with the new generation of atomic clocks, which are the optical atomic clocks.

1.3 Aim of the Research Work

The research work focuses on methodologies aiding in achieving high-accuracy time transfer across a telecommunication infrastructure. These methodologies range from emerging technologies as sources of accurate time to novel techniques for the transport of timing signals across the network. The research focuses on building a software model which replicates the existing telecommunication infrastructure. The modelling work looks into the timing accuracy achieved at the metro nodes when the network has optical atomic clocks at the stratum 1 layer. Another dimension of research work looks into novel techniques for the transport of timing signals. This includes building a novel technique to disseminate ultra-stable frequency over a telecom fibre. It is challenging to maintain unprecedented levels of accuracy from the optical clocks to the end user node, especially when the network is complex and hierarchical. The research work also investigates achieving high precision at the radio units using Field Programmable Gate Arrays (FPGA) boards.

1.4 Dissemination

The following are the technical talks and papers that have been published during the PhD period. The talks presented at the TOP and ITSF conferences are based on the research work and results detailed in Chapter 3 of this report. The papers published at the IEEE Photonics Society Summer Topicals Meeting Series and EFTF/IFCS conferences are based on the research work and results detailed in Chapter 4 of this report. The paper published at the ONDM conference is based on the research work and the results detailed in Chapter 5 of this report.

1. L. Rajagopal, A. Lord and M. Menchetti, "Ultrastable Frequency and Timing for Future Telecom Networks," 2022 IEEE Photonics Society Summer Topicals Meeting Series (SUM), Cabo San Lucas, Mexico, 2022, doi: 10.1109/SUM53465.2022.9858243.

2. L. Rajagopal, Technical talk on "Application of Optical Atomic Clock in a Timing Network", 2022 Telecommunications, Optics and Photonics Conference (TOP 2022), London, United Kingdom.

3. L. Rajagopal, Technical talk on "Optical Atomic Clocks for Time Dissemination in a Telecom Network", 2022 International Timing and Sync Forum (ITSF 2022), Dusseldorf, Germany.

4. L. Rajagopal, A. Lord, M. Gilson and Y. Singh, "Dissemination of Optical Frequency

for Future Telecom Networks and Applications," 2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), Toyama, Japan, 2023, doi: 10.1109/EFTF/IFCS57587.2023.10272108.

5. L. Rajagopal, R. D. Oliveira, A. Lord, Y. Singh, R. Nejabati and D. Simeonidou, "Experimental Demonstration of High Precision Time Transfer in FPGA for 5G and 6G Networks," 2024 International Conference on Optical Network Design and Modeling (ONDM), Madrid, Spain, 2024, doi: 10.23919/ONDM61578.2024.10582719.

1.5 Outline of the Thesis Report

Technical background, aims and outline of the research are vital part of the work as detailed in the introductory chapter. The introductory chapter elaborates the evolution of synchronisation architecture in a telecommunication infrastructure along with techniques for delivering high accuracy frequency, phase and time of day in a mobile network. The report consists of six chapters, including the introduction chapter.

The second chapter focuses on the technologies for accurate timekeeping. The chapter details a wide range of technologies that existed in the past to present, as well as some of the technologies in the developing phase that have the potential to serve as the primary or secondary standard in the infrastructure in the near future. This chapter gives a detailed picture of the working and current state of art of the optical atomic clock technology.

The third chapter details the research work on network modelling. The network model simulated investigates the feasibility of using an optical atomic clock in the network core. The modelling work looks into the challenges such as the number of clocks required to disseminate time at the national scale, different architectures that aid in implementing optical clocks at the network core, and compute the timing accuracy achieved in each case.

The work also helps to identify the most appropriate technique and architecture to connect optical atomic clocks to the core of the telecom infrastructure.

The fourth chapter looks into a novel technique of disseminating ultra-stable frequencies over a fibre infrastructure. The work detailed in this chapter uses an ultra-stable reference system to disseminate frequency over the fibre. Moreover, since the ultra-stable reference system resembles an optical clock in functionality, the chapter also details the results for the frequency stability comparison between the ultra-stable reference system and an unsteered caesium clock. Despite having a good source, it is still challenging to achieve high precision at the radio nodes.

The fifth chapter details a novel technique that helps to synchronise remote nodes to the central node to picosecond level precision using FPGA technology. The chapter details the implementation of a time-to-digital converter module in an FPGA along with offset calibration schemes to synchronise multiple nodes to a picosecond scale precision.

The sixth chapter concludes the report, followed by a brief description of future research work in this direction.

Chapter Two

Sources of Accurate Time

The International System of Units (SI Unit) of time is the second. The International System of Units defines the second as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Caesium-133 atom" [30]. Timekeeping devices have a deep history from the period of ancient civilisations. Humans in that era measured time by observing changes to the astronomical bodies such as the sun and moon. Techniques to measure time evolved over the past years, resulting in numerous innovations in timekeeping devices, from sundials, water clocks, and mechanical clocks to present-day atomic clocks. The history narrates innumerable facts on the evolution of time measurement, adding knowledge on accurate and precise techniques. These innovations underline the importance of timekeeping and the necessity of precise and accurate measurements in the era in which we are living.

2.1 History of Timekeeping

Shadow clocks or sundials are among the first chronometry devices used for timekeeping. Figure 2.1 shows a sundial. The device uses the direction of sunlight to indicate the time of

Figure 2.1: Image of a sundial or a shadow clock [41]

day. They consist of a gnomon and a dial. The dial is a surface of flat, cylindrical, spherical, helical, or other shapes with a gnomon on top, that casts a shadow from the sunlight onto the dial. The shadow falls on the dial in a fashion similar to an hour hand in the clock, depending on the movement of the sun in the sky. The base part of the sundial consists of markings of the time. The shadow of the gnomon indicates the current time of the day. The shadow length provides information on the sun's position, revealing what phase of the day it is. The sun is at its highest point of the sky at noon, hence shorter shadows and thus longer shadows when the sun is rising or setting. The oldest known sundial belongs to Eqypt [32].

Water clocks as shown in figure 2.2, are a type of timekeeping device where the measurement of time depends on the flow of water in or out of a vessel. The simplest model of the device consists of a stone vessel to allow the inflow or the outflow of the liquid. These clocks existed across different parts of the world, such as Egypt, China, India, Greece, and Rome. There are two main types of water clock: The outflow water clock and the inflow water clock. The outflow water clock consists of a container with water. The water drains out of the container. The markings indicated on the container correspond to the elapsed time. The inflow water clock operates in a similar principle; the only difference is that water flows into the container. The most common model that existed was the outflow water

Figure 2.2: Replica of a waterclock in Yeouido Park, South Korea [69]

clock. In this type, the stone bowl had sloping sides that allowed the liquid to drip at a constant rate, and the markings on the vessel indicated the time elapsed. These clocks aided in astronomical calculations. Inaccuracies in timekeeping were a concern as evaporation and temperature variations affected the speed of water flow and, ultimately, the accuracy of timekeeping. Mercury instead of water was among the solutions identified to improve the accuracy.

Figure 2.3: Image of an ancient Chinese incense clock [28]

The incense clocks originated in China. These clocks consisted of incense sticks. The burning of these sticks relates to the passage of time. These sticks are made of different materials and rolled to different patterns depending upon the duration of time intended to be measured. The sticks are straight in shape to measure short periods and spiral in shape to measure longer periods. The length of the path burnt by the incense stick corresponds to the hours elapsed. Figure 2.3 shows the image of an ancient Chinese incense clock. These clocks are safe to use indoors as burning these sticks does not produce flames.

Figure 2.4: Image of an ancient candle clock [67]

Candle clocks were commonly used in China and Japan as a timekeeping device. These devices consist of a candle enclosed in a casing, as shown in figure 2.4. The casing has markings spaced at equal intervals to indicate the elapsed time based on the burning of the candle. The clock placed indoors determined the time during the night. The candles are made of the same material, identical in height and thickness, to maintain accuracy in timekeeping. However, factors such as the rate of burning and the quality of wax used for the candle affected the accuracy of the system.

The use of an hourglass for timekeeping became popular during the fifteenth century and was common in churches, the sea, for cooking, industry, and homes. An hourglass is also known as a sand glass, a sand clock, or a sand timer. An hourglass consists of two glass bulbs. However, factors such as the texture and quantity of sand used, the size of the bulb and the width of the passage connecting these bulbs determined the accuracy of the system. Mechanical clocks driven by gravity, weights, and striking clocks in public spaces were a few of the innovations in the field of time measurement before the introduction of pendulum clocks in the 1600s.

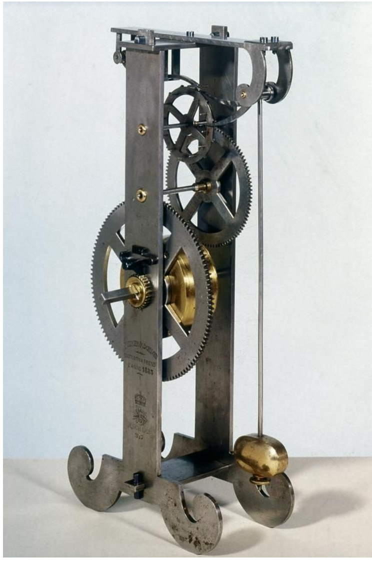


Figure 2.5: Image of a pendulum clock designed by Galileo [61]

Pendulum clocks are among the most accurate timekeeping devices in the history of clocks. These clocks operated on harmonic oscillation, where the object oscillates when restoring force acting on the object acts to bring it to its equilibrium position. A Dutch polymath, Christiaan Huygens, invented the pendulum clock in 1656 [67]. Figure 2.5 shows the image of a pendulum clock designed by Galileo [61]. Factors such as the physical characteristics of the oscillator and temperature affected the accuracy of these clocks. Several inventions, such as the use of multiple metals with good expansion properties to manufacture the length of the pendulum connecting the bob at the end, use of a bob made from glass material filled with mercury, use of alloys for manufacturing the rod and bob of the pendulum, all looked to compensate for the temperature variations that caused the expansion of the clock components to minimise the inaccuracies introduced into the system.

Figure 2.6: Image of H4 chronometer developed by Harrison [52]

The invention of marine chronometers aided in determining the position of a ship in the sea. Navigational errors resulted in the damage of ships, and it was necessary to build better clocks to help with navigation. The Board of Longitude established in England examined the proposals for developing a marine clock. The clockmaker Jeremy Thacker was among the first to use the name chronometer in his published work [52]. The first sea clock built by Huygens worked well when placed in the ship in a horizontal position. However, sudden movements of the ship in the water affected the performance of the clock, and it stopped working. In 1715, Harrison, a carpenter, constructed a wooden clock. With the help of the Board of Longitude, he built a marine chronometer. They tested it in the sea in 1736 [52]. The sea clock initially developed by Harrison consisted of rollers to overcome friction, different metals to mitigate the problems related to the expansion of the metals when the temperature fluctuates, wooden parts to eliminate the necessity of lubrication, and a grasshopper escapement which is a technique to maintain the periodic oscillations in a pendulum.

The electric clocks are electrically powered. These types of clocks became popular in the 1890s. Electric clocks exist in various types, such as electromechanical clocks, electric remontoir clocks, electromagnetic clocks, synchronous clocks, tuning fork clocks, quartz clocks and radio-controlled clocks. Sir Francis Ronalds invented the first electric clock in 1814. The increase in demand for higher accuracy in time measurement resulted in the development of watches with hour-hand, minute-hand, and second-hand measurements.

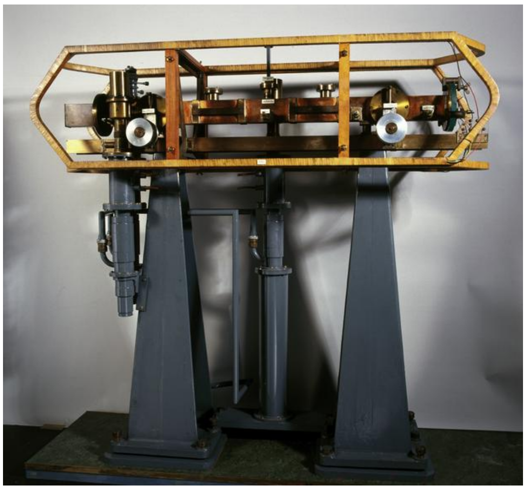


Figure 2.7: Image of a Caesium atomic clock [34]

By the 1960s, the development of atomic clocks helped to accelerate the interest in timekeeping across the world. In 1955, Louis Essen and Jack Parry developed the world's first atomic clock in the National Physical Laboratory in London [44]. The clock used the oscillations of a Caesium-133 atom to measure time. The atomic clock was accurate to a second in a few 100 million years [9]. Atomic clocks find potential applications in deep science, astronomy, interferometry, telecommunications, scientific study, and satellite technologies. They are used in satellites for accurate timing as they aid the receiver stations on Earth in calculating the position information required by the navigation services supported by the networks.

Further innovations in atomic clocks aim to reduce the size of the clock, improve accuracy, and lower the power these clocks consume. Advancements in producing a chip-scale atomic clock offer a compact and low-power atomic clock. This device, which the National Institute of Standards and Technology (NIST) developed, is fabricated using microelectromechanical systems. Although there are several solutions for building portable atomic clocks, most of the solutions operate by using the microwave transitions of caesium or rubidium atoms to generate a stable frequency. Approximately 400 atomic clocks in the National

Metrology Laboratories worldwide contribute to Universal Co-ordinated Time (UTC) [47]. In addition to caesium atoms, atoms such as aluminium, strontium, mercury, calcium, and iodine are a few commonly used to develop atomic clocks.

The story of accurate and precise timekeeping continues. Researchers worldwide are in a race to build the best clocks. The atomic clocks based on optical transitions offer more stability and accuracy than those operating with microwave transitions. Therefore, optical atomic clocks are emerging as the next generation of atomic clocks. This brings us to the new era of optical atomic clocks. The optical atomic clocks use the oscillations from an optical transition of an atom for precise time measurement. The optical atomic clocks are accurate to 10^{-18} levels, with an error of less than a second in the age of the universe [25]. However, the complex structure of atomic clocks makes it challenging to use them in out-of-lab environments. Numerous research activities aim to solve the challenges mentioned above and focus on building compact and transportable optical atomic clocks that aid their usage on a broader scale in the future [25].

The remainder of this chapter focuses on the current state of the art of various technologies that can act as an accurate source of time and find potential applications in networks. In a network, the architects identify reliable sources that can act as primary and secondary reference standards. Different applications have varying timing requirements. Hence, it is the responsibility of the architects to choose the ideal source per the application requirements. This chapter includes details on various technologies widely used by different applications at present. It also looks into some of the technologies that are in the developing phase but have immense potential to support time-critical applications in the era of high-accuracy timekeeping in the near future.

2.2 Present Technologies

A good number of technologies can provide accurate time for the positioning, timing and navigation services required by the network. Over the years, multiple technologies evolved into different forms, each aiming to provide better accuracy and precision comparable to the UTC. Researchers are continuously investigating how to improve the accuracy of these clocks to cope with the increasing frequency, phase and time of day synchronisation requirements put forward by future networks. This section details some of the technologies used in the current networks as a potential source for high accuracy time in various applications.

2.2.1 Atomic Clocks

An atomic clock uses the property of resonant frequency of atoms to measure time. Atomic clocks have been capable of providing accurate time since the 1960s. They are accurate to within a second over 100 million years [33].

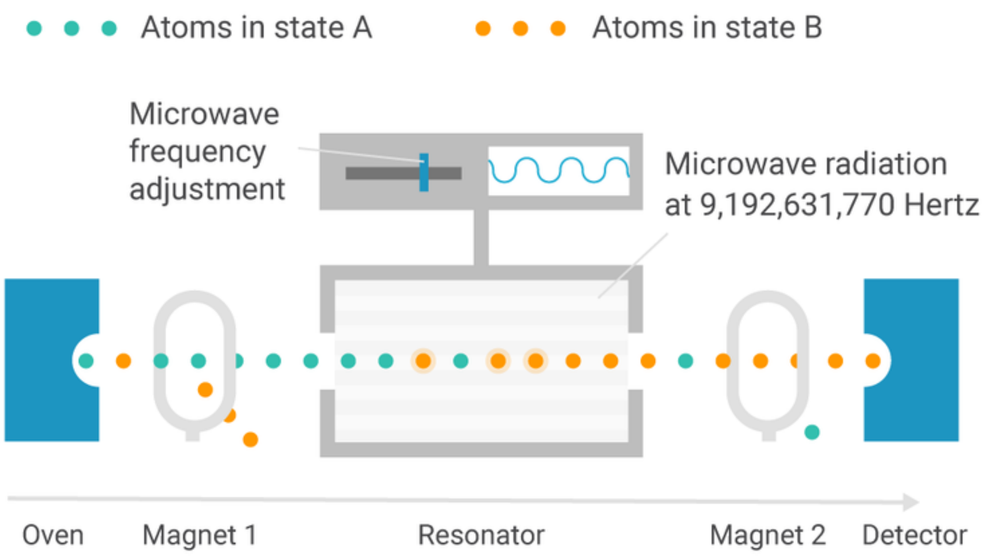


Figure 2.8: Illustration of the working principle of a Caesium atomic clock [33]

Atomic clocks differ from conventional clocks as they are based on the oscillation of atoms to measure accurate time. The natural oscillations of the atom resemble the oscillations of a pendulum. Challenges such as temperature, weight and material of the bob and loosening of the gears driving the oscillations should be absent in this case. The frequency of oscillation in an atom depends on the structure of the atom, mainly on the mass of the nucleus, gravity and the force binding the electrons surrounding the nucleus. The fact is, atoms are identical, and hence, inaccuracies due to variations in the material used to manufacture the clock, as in previous cases, are never a concern now. Atomic clocks are of different types depending on the design and the type of atom used, but the fundamental principle remains the same. The commonly used atomic clocks are caesium atomic clocks, hydrogen atomic clocks and rubidium atomic clocks.

Caesium 133 is a stable isotope of a caesium atom most commonly used in the atomic clocks. Figure 2.8 shows the working principle behind the caesium atomic clocks. The oven heats the caesium atoms present in it and are emitted from an aperture in the oven, forming a beam. Upon heating, the atoms enter into a different energy state. The beam of atoms from the oven passes through a magnetic field. The magnetic field aids in selecting the atoms with the right energy state and eliminates the rest. The atoms flowing out of the magnetic field enter a resonator and are subject to microwave radiation. The frequency of the microwave radiation is equivalent to the resonant frequency of the atom, which is 9,192,631,770 Hz. When the caesium atom receives this frequency, it excites to a different energy state. The second magnet sits after the resonator to eliminate the atoms that have not changed their energy state. The detector, placed after the second magnet, detects the number of atoms striking it. The number of atoms changing their energy state depends on the frequency of microwave radiation. The detector shows peaks in the output when the frequency of the microwave radiation is correct. The information from the peak can help correct the frequency in the resonator to tune it to the right frequency when it drifts by a small amount. The microwave frequency is tuned to the oscillation of atoms, yielding a second after 9,192,631,770 oscillations [33].

The long-term accuracy of some of the best caesium clocks is approximately 1.7×10^{-15} [39], which corresponds to an error of a second once every twenty million years. The National Company in Massachusetts developed the first commercial atomic clock [39]. Several manufacturers are developing commercial atomic clocks, such as Microchip, Adtran, Hewlett Packard and many more. However, laboratory-based atomic clocks are far more accurate than the commercially available ones.

2.2.2 Satellite Technologies

Satellite technologies comprise a system that utilises satellites to provide positioning, timing and navigation services. The growing interest in autonomous applications, navigation services, tracking applications, smart transportation systems, emergency callers or SOS applications, and location-based services results in increased interest in the positioning, timing and navigational services the satellites provide. The technology allows a user to locate the position of their device with a high accuracy level of a few centimeters or meters. The satellite constellation aims to provide global and regional coverage. They comprise GNSS for global coverage and Regional Navigation Satellite System (RNSS) for regional coverage. Global Positioning Service (GPS) of the United States, Global Navigation Satellite System (GLONASS) of Russia, BeiDou from China and Galileo from the European Union constitute the GNSS constellations. The Quasi-Zenith Satellite System (QZSS) of Japan and the Indian Regional Navigation Satellite System (IRNSS) or NaVIC of India constitute the RNSS constellations. Figure 2.9 shows the list of satellite constellations deployed for global and regional coverage. As per the 2023 update, the numbers of active satellites in the GNSS constellations is shown in figure 2.10.

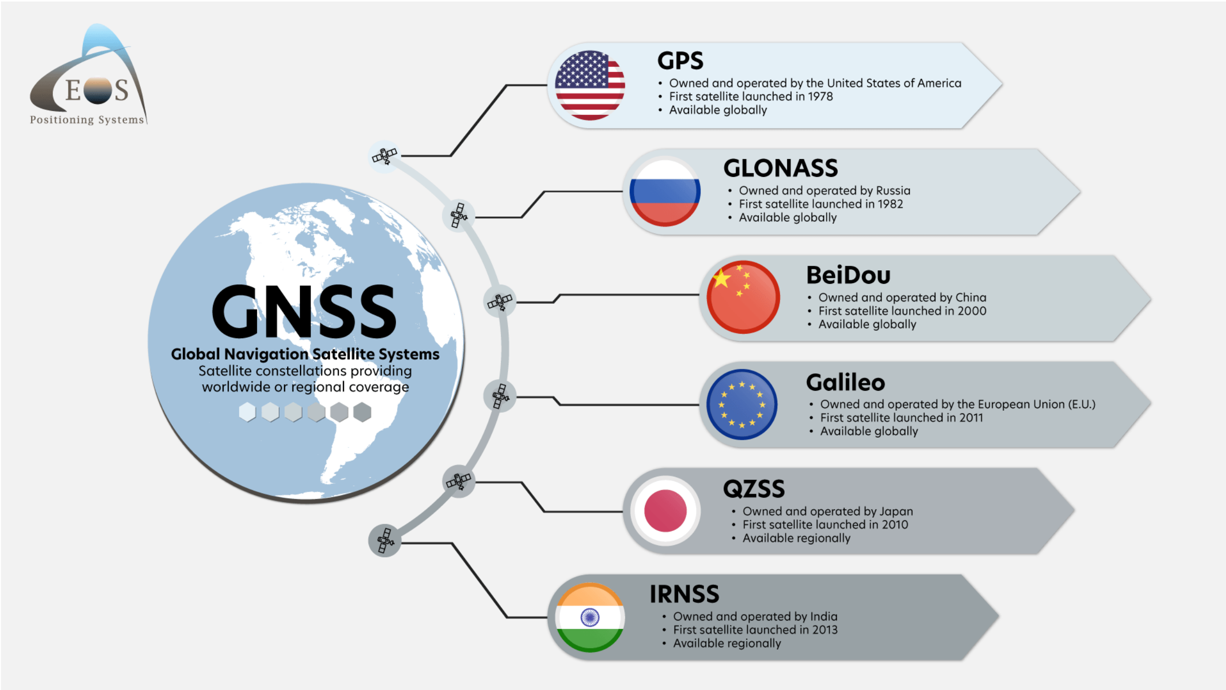


Figure 2.9: Image of satellite constellations launched by different countries to contribute to global and regional coverage [73]

The performance of a satellite system is evaluated using the following four criteria:

- Accuracy: The difference between the actual and the measured time or position of the receiver device
- Integrity: Capability of the system to generate accurate data
- Continuity: Capability of the system to perform well without any interruption
- Availability: Ability to produce signal with good strength and maintain the required levels of accuracy at all times

GPS was a project started by the Department of Defense in the US in 1973. The initial constellation of GPS consisted of 24 satellites, providing service to the military only. It was around the 1980s when civilians started using the GPS service. The system provides location and time information to a receiver device anywhere on the Earth. Nevertheless, the device must be within the line of sight of GPS satellites. The user can access the service without transmitting any data to the satellite; therefore, the system is accessible to the public with a GPS receiver. Hence, it plays a vital role in civil and commercial services. The satellite carries highly stable atomic clocks in synchronisation with each other and with the reference clocks in the ground station. The time the signal takes to propagate from the transmitter in the satellite to the receiver in the ground station is proportional to the distance between the satellite and the ground station. The distance information from the ground terminals aids the satellite system in calculating its coordinates. The GPS satellites broadcast this position and time information. With the help of GPS receivers, the end user device calculates its position and time information from the broadcast messages. The broadcast signal consists of a pseudorandom code and a message. The receiver knows the pseudorandom code, and the message includes the position of the satellite and the time of transmission. The receivers monitor the time of arrival of the broadcast message. The time of transmission and arrival aids the receiver in computing the position and time information.

GPS satellites consist of three main segments:

- Space Segment: Developed, operated and maintained by the Space Force in the United States and consists of the satellite system
- Control Segment: Developed, operated and maintained by the Space Force in the United States and consists of the master control stations, alternate control stations, dedicated ground antennas and monitoring stations
- User Segment: Consists of several million users ranging from military to civil and commercial applications using the system

GLONASS, developed by Russia, is an alternative to GPS and is the second-best

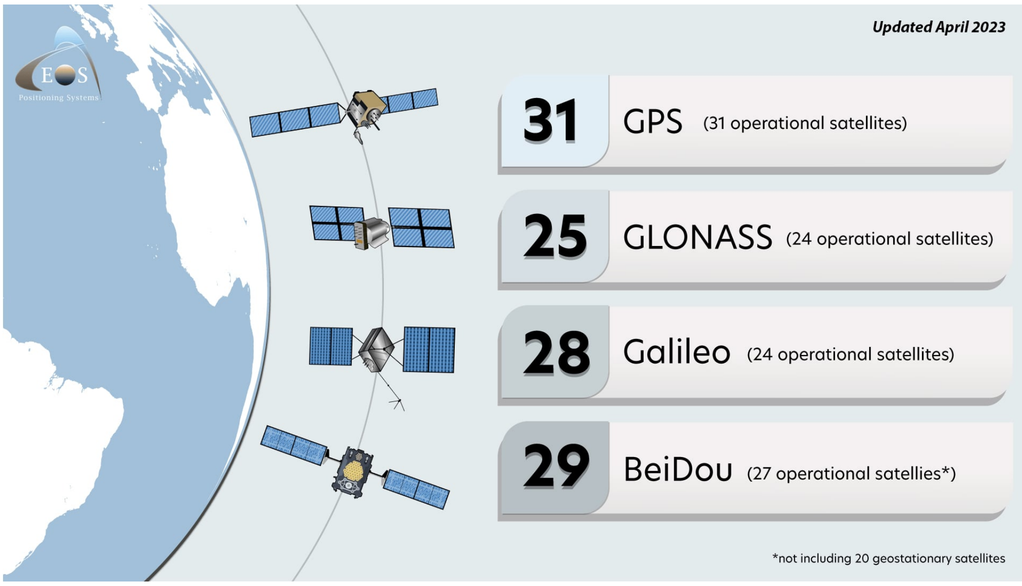


Figure 2.10: Number of active satellite contributing to global coverage [73]

satellite system to provide global coverage and precision comparable to GPS. Receivers supporting GLONASS and GPS will have more satellites in the vicinity, therefore, better positional and timing accuracy. GLONASS supports military and commercial applications. The satellite transmits an open standard precision signal and an obscured high precision signal. The obscured high-precision signals are for military applications. The positional accuracy of this system is within a few meters, approximately 5 to 10 meters. The satellite system consists of space segments and ground controls. The satellites constitute the space segment. The ground controls consist of the control centre, tracking, telemetry and command centres, monitoring and measuring stations and laser ranging stations.

BeiDou is a satellite technology developed by China for position, navigation and timing service. Galileo is the satellite system developed by the European Union with the help of the European Space Agency. The key motive in building the Galileo system was to reduce the dependency on GPS and GLONASS satellite systems, especially for military applications. Galileo is accessible to the public. A highly encrypted version of the signal is available to the authorised government officials. The regional navigation satellite systems cover the geography of a country. The satellites in this constellation orbit in a geosynchronous orbit.

2.2.3 Hydrogen MASER

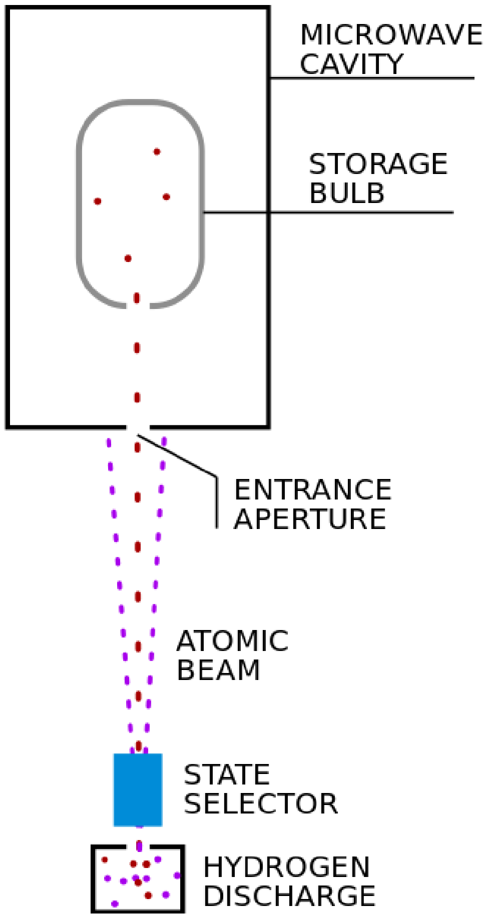


Figure 2.11: Illustration of the working of a hydrogen maser [54]

A hydrogen maser is an atomic clock that uses hydrogen atoms to measure time. The working principle of a hydrogen maser is similar to an atomic clock, where it sends the hydrogen atoms through a magnetic chamber that eliminates atoms with a different energy state. The word maser stands for microwave amplification by stimulated emission of radiation. These clocks operate at the resonant frequency of the hydrogen atom, 1,420,405,752

Hz [54]. Hydrogen masers have good short-term stability of approximately 1 part in 10^{12} [54] and demonstrate good short-term stability compared to caesium atomic clocks. In the longer term, the frequency stability from hydrogen masers degrades due to the change in the resonance of the cavity.

A schematic diagram showing the working principle of a hydrogen maser is shown in figure 2.11. A small container stores hydrogen molecules. These hydrogen molecules are subject to an electric arc and dissociate to form hydrogen atoms. The atomic beam of hydrogen atoms passes through a magnetic beam to eliminate atoms with a different energy state. The atoms then pass into a storage bulb. The storage bulb is made of quartz and internally coated with polytetrafluoroethylene. The coating reduces any absorption, reaction or changes to the atomic state when the hydrogen atoms come in contact with the surface of the bulb. These coatings are durable for approximately 20 years. The bulb is within a microwave cavity. The cavity is cylindrical and tuned to the resonant frequency of hydrogen atoms, $1,420,405,752$ Hz. Some hydrogen atoms drop to a lower energy state in the storage bulb and release microwave-frequency photons. These photons stimulate the rest of the atoms in the bulb to drop their energy state and release photons. In this way, a microwave field builds up in the storage bulb. This results in a microwave signal locked to the resonant frequency of the hydrogen atom. The process continues as long as new atoms flow into the bulb from the storage container [54].

The hydrogen masers are of two types: active hydrogen masers and passive hydrogen masers. An external 1.420 GHz frequency signal tunes the cavity in a passive hydrogen maser. The external frequency is tunable. An active hydrogen maser has no external signal tuning the cavity. The cavity requires a higher density of hydrogen atoms to sustain oscillations. Active hydrogen masers are more complex and expensive than passive hydrogen masers. However, they demonstrate better short- and long-term stability than the passive hydrogen masers.

2.2.4 Chip Scale Atomic Clocks (CSAC)

The atomic clocks have evolved in size and precision over the years. Chip-scale atomic clocks are compact and consume a very low amount of power. The device fabrication uses microelectromechanical systems and a low-power semiconductor laser system. Although there are multiple techniques for developing a portable atomic clock, most of the devices operate using microwave transitions in caesium and rubidium atoms. These clocks are present in wireless communication devices to improve network synchronisation and improve network security by providing better anti-jamming capability. The GNSS receivers used in vehicles aid in improving the precision of navigation techniques. They are present in the motherboards of computers or processing systems, aiding in better timekeeping in such devices. Symmetricom introduced the first commercial chip-scale atomic clock in 2011 [51]. Symmetricom's chip-scale atomic clock is approximately $4 \times 3.5 \times 1.1$ cm and weighs about 35 gms. It consumes approximately 115 mW power and is accurate to approximately half a microsecond per day [51]. The miniature clock, as shown in figure 2.12 consists of a caesium-133 cell and buffer gas, which is heated to form a caesium vapour distributed across the cell. The dense vapour formed across the cell is illuminated with a laser light modulated to the frequency of natural oscillations of a caesium atom. As the laser light strikes the atoms, they change to an oscillating state, and the photons emitted determine the frequency resembling that from laser modulation and atomic resonance. The precise output of the clock depends on the locking of these two frequencies [51].

Chip scale atomic clock monitor time based on the 9,192,631,770 Hz signal emitted due to the transition between the hyperfine energy levels in the caesium atom. The clock utilises micromachining techniques to fabricate liquid caesium into the semiconductor material. A quartz crystal fabricated on the chip acts as an oscillator. The liquid caesium in a sealed cell is subjected to high temperature. Caesium vaporises, and the laser fabricated

Figure 2.12: Image of a microwave-based chip scale atomic clock [36]

on the semiconductor material shines a beam of infrared light from the oscillator onto the cell to generate two electromagnetic fields. The atoms enter a state where they stop absorbing and emitting light, increasing the output from a photodetector. The output from the photodetector feeds back into the quartz oscillator to lock the frequency, forming a feedback loop. The output frequency from the photodetector is downconverted to form a 10 MHz or 1 PPS signal.

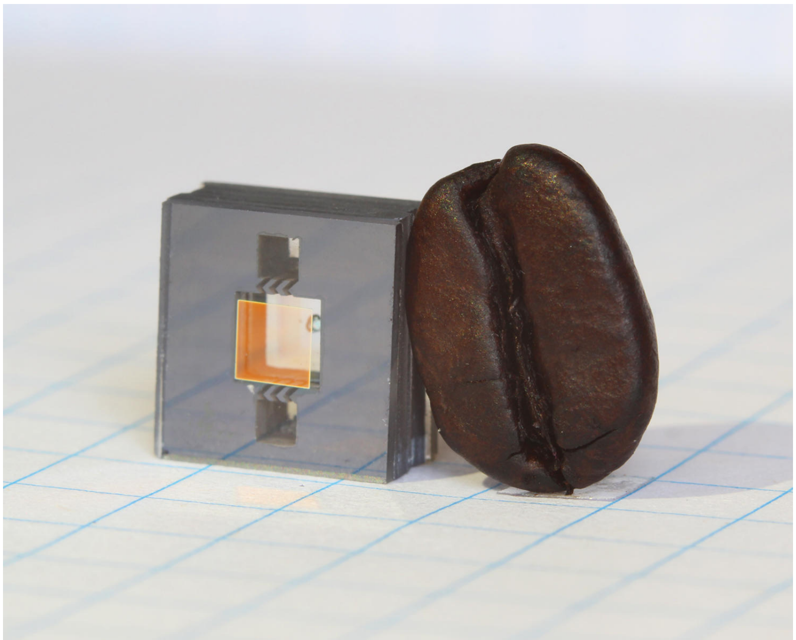


Figure 2.13: Image of an optical-based chip scale atomic clock and a coffee bean [37]

Figure 2.13 shows the image of a next-generation optical-based chip scale atomic clock. This clock operates at GHz frequencies and is more stable and accurate than the previous generation of chip-scale atomic clocks [37]. The design consists of a sealed cell with rubidium atoms on a chip. Frequency combs fabricated on the chip translate the high-frequency optical signal to microwave frequency. The highly accurate optical clocks are expensive and occupy ample space and volume, making them unfit for commercial or field applications. The next generation of chip-scale atomic clocks finds potential applications in areas such as quantum timing, calibration of GNSS signals, navigation, power grid, defence and military [37].

2.2.5 Oscillators

An oscillator uses the resonance of a crystal to generate an electrical signal with accurate frequency. The common type of crystal used is a quartz crystal. Oscillators are mainly of three types:

- Oven-controlled crystal oscillators (OCXOs)
- Temperature compensated crystal oscillators (TCXOs)
- Voltage-controlled crystal oscillators (VCXOs)

They compensate for the variations due to the influence of environmental factors. These oscillators provide good short-term stability. The long-term stability of these devices is limited by various factors like the ageing of the crystal and limitations from the electronic components [70]. They are good enough to provide short-term stability of 1 part in 10^{12} and longer-term stability of 1 part in 10^8 [70].

OCXOs consist of an SC-cut crystal and critical circuit. A critical circuit is a type of circuit that requires continuous operation to verify the safety of the associated structure and

Figure 2.14: Image of an oven-controlled oscillator designed for space mission applications [1]

components. The SC-cut is a stress-compensated cut to minimise issues related to elastic effects in common crystal cuts and compensate for the thermal transient and planar stress effects. The circuitry and the crystal help maintain the temperature, reducing frequency fluctuations and improving stability. It is suitable for applications demanding frequency stability in the parts per billion range, low phase noise, low holdover and short-term stability. The crystals are heated above the level expected in a typical working environment and maintained at a higher level afterwards. This results in better stability compared to a TCXO and is the fundamental working principle behind the operation of an OCXO. The oven in an OCXO consists of temperature sensors to maintain the temperature constant, thereby improving frequency stability [70]. TCXOs have good temperature stability in comparison to any other oscillators. It provides more stability, although the power consumed and cost of the device are higher than those of a standard oscillator. The TCXOs internally use a voltage-controlled crystal oscillator with a temperature sensor. The sensor helps to detect tiny fluctuations in the temperature and apply the correction voltage to the varactor diode. The diode produces a frequency equivalent to and opposite to the frequency change, thus cancelling out the fluctuations in frequencies due to environmental factors and thereby improving the frequency stability of the VCXOs.

2.3 Technologies for the Future

The growing requirements within the network drive the investigation and development of new technologies for high-accuracy timing. Present networks rely on satellite-based technologies and microwave-based atomic clocks for high-accuracy timing. The satellite-based sources (mainly GNSS) are low-power signals and therefore vulnerable to attacks, making security one of the major concerns in modern networks. Future networks like 6G demand sub-nanosecond accuracy or picosecond precision at the node level to support real-time and ultra-reliable low-latency applications. These levels of precision and accuracy are a challenge to satellite-based technologies. The hunt for a GNSS-independent terrestrial infrastructure to disseminate high-accuracy timing is crucial. One suitable option is to build a terrestrial infrastructure for timing distribution using optical atomic clocks. This chapter looks into some emerging technologies with the potential to deliver high accuracy and secure timing to the networks.

2.3.1 LEO Satellites

GPS or GNSS is the widely used satellite technology for timing, positioning and navigation service. They operate on the Medium Earth Orbit (MEO), Geosynchronous Orbit (GSO) and the Geosynchronous Equatorial Orbit (GEO) orbits, which are thousands of kilometres away from the Earth. Hence, the signals are weak in strength and can be easily interfered with, making them vulnerable to jamming and spoofing. Terrestrial infrastructure for timing or satellites in the Low Earth Orbit (LEO) are a few among the potential solutions that can act as a secondary or primary technology to support or replace GNSS in the near future. The prime advantage of the satellites in the low earth orbit is that they are closer to Earth, approximately 25 times [72] closer in distance when compared to the satellites in the GEO orbit. Therefore, this gives a significant advantage in terms of latency and coverage. The time required for transmission and reception of a signal between the satellite and receiver units is less, hence lower latency in communication. The signals from the satellites in the low earth orbit have more strength compared to the satellites in the GEO or MEO, approximately 30 dB more [72]. The signal strength is high, making jamming and spoofing techniques difficult and thereby offering better security when compared to GNSS. These satellites provide improved coverage as they get closer to the surface of the Earth. Additionally, since they are in the low earth orbit, they are less vulnerable to space disturbances such as solar storms, hence improving the reliability and resilience of the system [72].

Figure 2.15: Illustration of the constellation of LEO satellites revolving around the Earth [43]

OneWeb satellites are aiming to deliver a PNT solution by creating a constellation of satellites to revolve around the Earth in the low earth orbit, as shown in figure2.15. OneWeb consists of a network of approximately 648 satellites [45] travelling at a speed of 26,000 km per hour [45]. Each satellite can cover the surface of Earth from a height of 1,2000 km [45]. The satellite coverage is equivalent to the size of Alaska (663,300 sq miles) [45]. OneWeb aims to deploy a 5G-ready network at the global level. It aims to provide connectivity to every corner, ranging from mid-ocean to mid-air.

Oneweb connects the end-user device to a terminal. A terminal is a small compact device that might sit on the roof of a building or near the location of an end-user. The terminal encrypts data and hands it over to the satellites in the low earth orbit. The approximate data rate for the transmission process is estimated to be 32 Mbps [45], and the approximate data rate for the reception process is estimated to be 195 Mbps [45]. These satellites are 30 times closer to the Earth compared to the satellites in the GEO; therefore, they maintain stable real-time connectivity. The latency falls between 50 ms to 100 ms [45], which is roughly 5 to 10 times less compared to satellites in the GEO. The satellites are in continuous motion, aiding to achieve seamless coverage. The system tries to maintain high resilience. The cloud architecture gives better scalability and helps an operator control the device remotely. The data from the satellite feeds to the nearest network portal. This data re-enters into the web through one of the points of presence gateways [45]. The technology is currently under investigation to support applications in telecommunications, data centres, aviation, defence, military, and navigation services.

2.3.2 Enhanced Long Range Navigation (eLORAN)

eLORAN is an acronym for enhanced Long Range Navigation (LORAN) and is a technology used for positioning, navigation and timing services. It is an alternative source for UTC in environments with interrupted GNSS service. The eLORAN technology evolved from LORAN-C, which aimed to provide a positioning accuracy of 460 m to the sailors or mariners in the ocean [40]. The technology, LORAN, was first developed as a navigation system for the United States during World War II. A similar system named Gee existed in the United Kingdom, used by the Royal Air Force for navigation during the World War II. Both techniques used the delay between two radio signals to estimate the position of an object.

The technology lost interest with the development of GNSS for PNT services. However, it has gained interest over recent years as it could be an alternative source for accurate position and time in scenarios where GNSS fails.

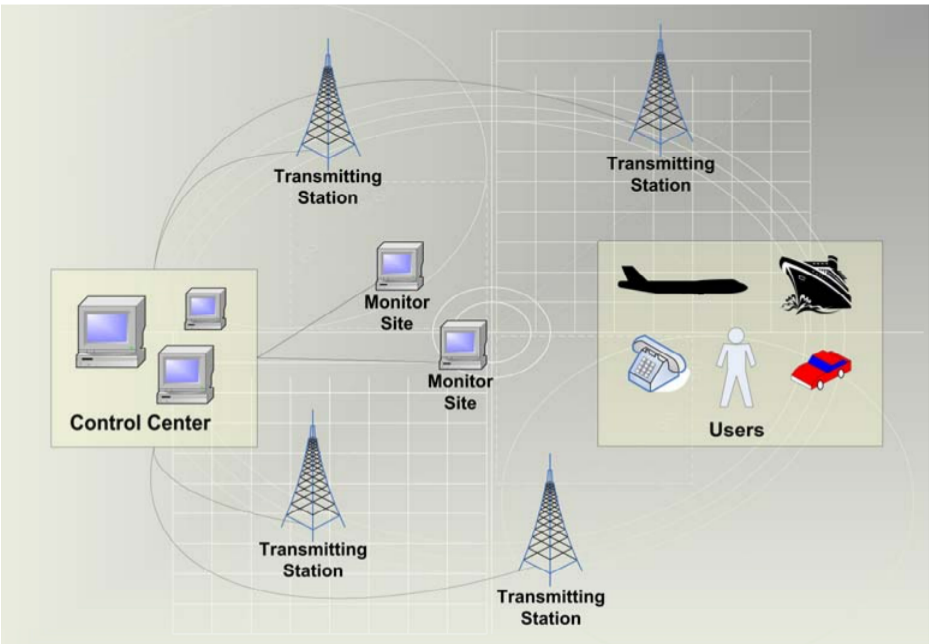


Figure 2.16: Illustration of the working of an eLORAN system [40]

The eLORAN system is compliant with the existing standards. It operates without relying on satellite-based technologies. A user with an eLORAN receiver can access the service in regions where the eLORAN service is active. The system consists of transmitters, receivers, monitors and control stations. The transmitters in the eLORAN system synchronise themselves to a trusted source of UTC separate from GNSS. This aids the transmitter in synchronising the transmissions to the UTC timescale independently without relying on satellite-based technologies. The main difference between the modern eLORAN system and the traditional LORAN system is the introduction of a data channel on the transmitted signal. This aids in improving signal integrity, applying specific corrections related to applications and conveying warnings to the receiving device. The technology can provide a time reference for the telecommunication application as per the G.811 ITU standard [40], thereby helping to reduce the need for expensive oscillators. The technology meets the performance requirements to support a wide range of applications, such as:

- Aviation and maritime navigation services
- Location-based services
- Precise time and frequency applications

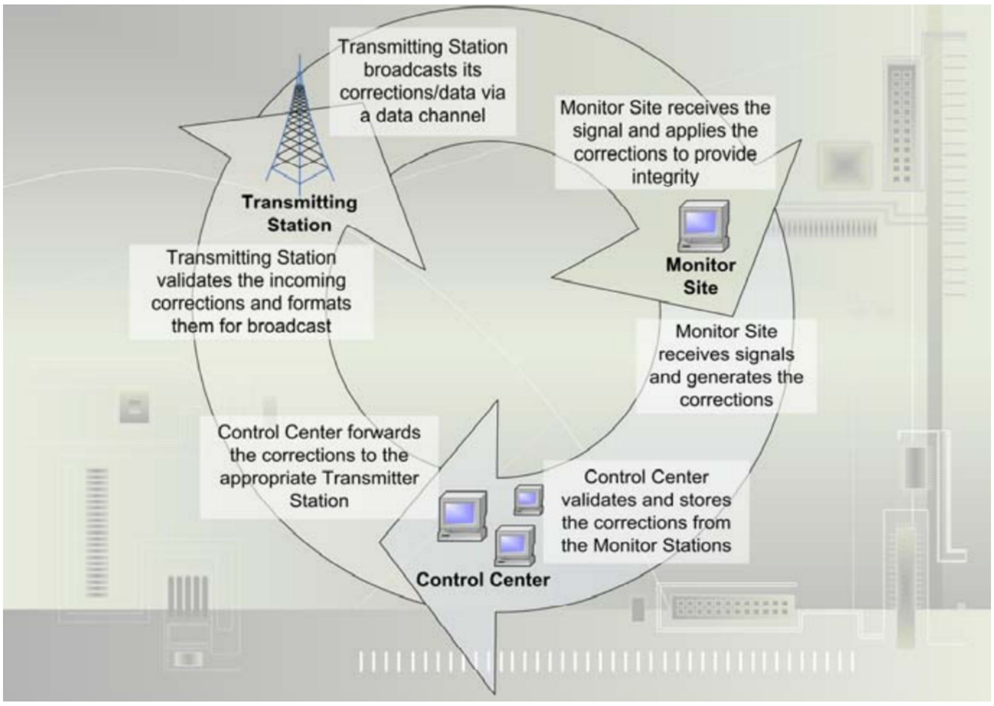


Figure 2.17: Illustration of the procedure to apply corrections in the eLORAN system [40]

eLORAN systems transmit low-frequency, high-power signals, making it difficult to interfere with and thereby giving a tough challenge for hackers to jam or spoof the signal. The combination of eLORAN and GNSS technologies aids enhanced navigation. This new technique for navigation in the sea requires reliable sources for PNT data, which is achievable by combining the two techniques mentioned above. The eLORAN signals travel over Earth's surface. These signals are subject to propagation delays due to the electrical conductivity of the ground. These delays are measured and corrected at the monitoring stations to improve the accuracy of the system. The correction messages from the reference stations or monitoring stations use one of the data channels to communicate these values to the receiver to apply corrections to the eLORAN signal.

Figure 2.16 illustrates the working of an eLORAN system. The transmitter stations synchronise themselves to the UTC without relying on GNSS. They use atomic clocks or technologies of similar quality. The transmitter stations in an eLORAN system require less monitoring. The control centres are responsible for maintaining the continuous operation of the system and immediately responding to any failure conditions to mitigate them. The monitoring stations, also known as the reference stations, monitor the eLORAN signals. They also provide real-time information on various characteristics of the signal to the control centre. A few reference stations generate data channel messages, and such sites will have high-accuracy clocks for synchronising to the UTC scale. The data channel messages aid in applying corrections to the transmitted signal. Figure 2.17 demonstrates how the systems try to perform corrections to improve the accuracy. The receivers in the eLORAN system track signals from multiple transmitting stations to derive accurate position and timing information. The receiver can receive and decode the messages in the data channels and use the information depending upon the application supported by the system, thereby providing an accurate PNT solution.

2.3.3 Timecards

The Time Appliance Project (TAP) is an Open Compute Project (OCP) which is an initiative from Meta looking onto the development of highly precise time cards for the transport of a timing signal in a data centre environment. It is a cost-effective method to achieve precise synchronisation within a data centre. The network equipment in a data centre needs to operate precisely and simultaneously; therefore, they need to be synchronised with each other

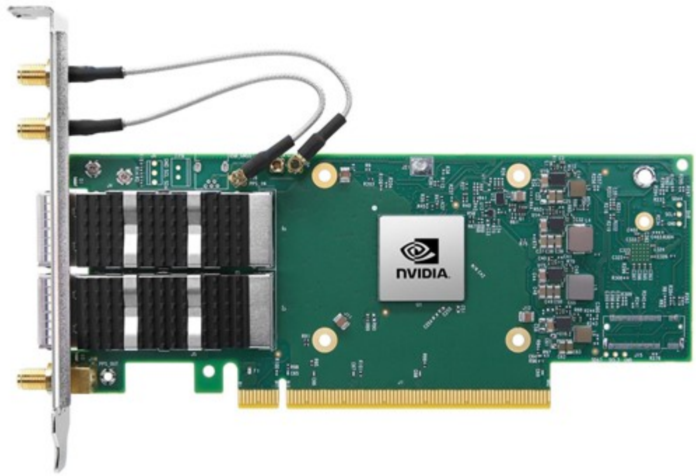


Figure 2.18: Time card unit developed by NVIDIA [58]

and have accurate timing information across them as well. Additionally, the data in one data centre must be synchronised with the data in other data centres distributed geographically to ensure consistency in the stored information. The concept behind developing a timecard is to synchronise the network elements in a data centre. The timecard comprises a GPS or GNSS receiver, a highly stable oscillator, a processing unit to process clock information, and other connectivity or interface modules. The GPS or GNSS receivers embedded within the system receive the signals from the satellites for timing information, and a network interface card embedded within the system carries out the networking-related operations. The network interface card generally has a PPS port connecting it to the timecard. This is essential for synchronising the two modules. In the early stages, the TAP project aimed for a microsecond level of accuracy [58] and could serve timing information to hundreds of servers via NTP or PTP. The processing unit is required to conduct additional computations about the timing protocols used as the network adds latency. At the same time, the signals propagate across fibre or ethernet cables. The advanced versions of timecards achieved nanosecond scale synchronisation accuracy. The unit has a miniaturised version to minimise the space occupied in the embedded system.

2.3.4 Optical Atomic Clocks

Optical atomic clocks are the next generation of atomic clocks with high precision and astonishing frequency stability. These highly precise atomic clocks are accurate to 1 part in 10^{18} [49]. Therefore, optical atomic clocks offer higher accuracy and stability than traditional microwave-based atomic clocks. These clocks have an immense role to play in applications such as geology (for sensing natural disasters, exploration of underground), meteorology, time distribution and synchronisation across networks (for the telecommunication infrastructure), astronomy (for the synchronisation of radio telescopes, gravitational wave detection), GNSS independent positioning and navigation services and many more.

There are numerous research activities taking place across the world on building the best and most accurate optical atomic clocks. In the Wuhan Institute of Physics and Mathematics, Cao et al. reported a transportable optical clock based on the $^{40}Ca^{+}$ ion. It is a single-ion optical clock with an uncertainty of 7.8×10^{-17} [26]. The California Institute of Technology developed a single ion mercury clock in the Jet Propulsion Laboratory (JPL) for the Deep Space Atomic Clock (DSAC) project led by National Aeronautics Space Administration (NASA) [14]. The Deep Space Atomic Clock uses a microwave transition and not optical transitions; hence, it is difficult to categorise it as an optical atomic clock. The clock demonstrates frequency stability of 5 parts in 10^{13} [14]. National Metrology Institutes (NMI) like Physikalisch Technische Bundesanstalt (PTB), and National Physical Laboratory (NPL) are intensely focusing on projects looking into how to disseminate time and frequency from these highly accurate optical atomic clocks over terrestrial infrastructure, how to transfer an ultra-stable frequency reference from optical clocks over a fibre infrastructure, architecture on building a national level infrastructure to disseminate secure time and potential ways to reduce dependency on GNSS. The National Timing Center Programme (NTC) led by NPL investigates into developing "UK's first nationally distributed time infrastructure" [57]. Optical atomic clocks can be primary sources for time reference, eliminating the dependency on GNSS to distribute time across networks in the UK at the national level in the near future. The time-critical applications in 5G, Beyond 5G (B5G) and future networks, smart grids and connected vehicles require more resilient, reliable, secure and accurate time and frequency signals, which are achievable with the help of a network of optical atomic clocks in the infrastructure.

Apart from telecom applications, optical atomic clocks are suitable for a wide range of applications related to deep science. A network of clocks is suitable for geodetic observations. The analysis of the fluctuations in the ultra-stable frequencies generated from these clocks positioned at different locations aids in understanding any possible drifts. Sites distributed geographically apart tend to have height differences as well. This creates a gravitational frequency redshift [59]. A network of optical atomic clocks can identify dark matter. To be used in applications in deep science, the frequency from the optical atomic clocks needs to be transmitted over a phase-stabilised fibre link. Phase-stabilised fibre links help to compensate for the noises accumulated over the fibre and help in ultra-stable frequency transfer. The variations in the frequency transmitted reflect an incident or a disaster. When a dark matter object passes across the network of optical atomic clocks, the network synchronisation gets interrupted, thereby aiding detection. Space exploration helps to investigate the secrets of deep space. Radio telescopes are positioned in different locations and observe the same part of the sky. The resolution of the telescope increases as the distance between the telescopes increases. Proper telescope operation demands precise synchronisation between the local radio telescope clocks over the longer term. The challenge increases as the distance between these telescopes increases. This is where optical atomic clocks can be advantageous.

The figure 2.19 illustrates various components included in an optical atomic clock. They consist of an atomic sample and an ultra-stable optical cavity. The quantised energy levels of the atoms relate to the energy levels of the atoms that translate to the frequency

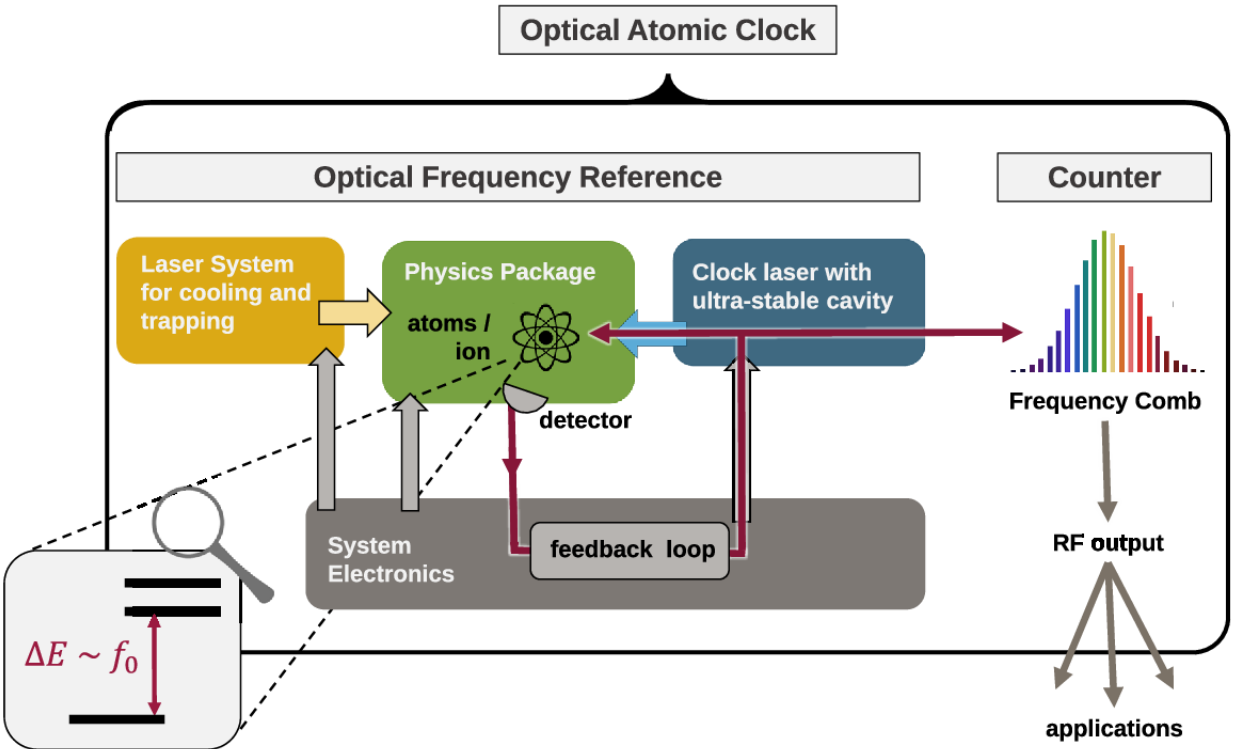


Figure 2.19: Illustration of the components in an optical atomic clock [14]

references. The atomic transitions of the atom are the primary factor that aids in building a precise clock. In order to have a better clock, the atomic transition needs to have a high frequency with narrow linewidth, and the optical transition needs to be in the mHz linewidth range. It is ideal to use a gas of atoms, as the atoms will remain undisturbed and also aid in producing a significant signal. The atoms heated in the oven form an atomic beam that emerges out of the oven. The atom beam travels at a velocity of a few hundred meters per second through the chamber. It is essential to reduce the velocity of the atoms. The high-velocity atoms slow down when subjected to a counter-propagating laser. The counter-propagating laser slows down the atomic beam by absorbing photons from the beam. Additional laser beams aid in pushing the atoms to the centre of the vacuum chamber where they are cooled down inside a magneto-optic trap (MOT). After they are cold enough, the atoms deposit in a magic wavelength. Magic wavelength is a term used in atomic physics, which refers to the particular wavelength of light that has minimal impact on the energy levels of atoms. This wavelength helps experiments requiring manipulation or control of individual atoms or ions with less external interference.

The atomic transitions are spectroscopically interrogated to emit a stable frequency in the THz range. This frequency is high and cannot be fed into any application. Hence, a frequency comb aids in translating this frequency to the frequency required per the use case, usually in the microwave range. A downconverter module aids in translating the frequency in the microwave range to radio frequency range, 10 MHz or 1 PPS signal, an ideal input for the telecom timing equipment. The main factors that determine the performance of the clock are accuracy and precision. Accuracy is the deviation of the measured transition frequency from the natural transition frequency.

The optical atomic clock is an upcoming technology in its development phase. These clocks are highly precise and stable. However, there is much scope for research on areas such as how to make these clocks compact, how to make these devices less power-hungry, and how to disseminate time and frequency from the clocks to build a GNSS-independent resilient timing infrastructure. These potential scientific applications require ultra-stable frequency from these precise clocks and much more. The clocks are precise such that they can lead to the redefinition of the second in the SI units in the future [60]. As networks evolve, there is more focus on reliability and low latency, increased capacity, integration of millions of endpoints, low power operation, and security. The network must maintain stringent timing requirements to cater to the needs mentioned earlier. A higher order of accuracy, precision and stability with minimal timing error is the aim of the synchronisation domain. The current synchronisation topology uses GNSS as the primary source of timing. Real-time applications supported by 5G networks can be drastically impacted if the GNSS signal gets interfered with even for a short duration of time.

Optical clocks developed in the laboratory have higher orders of precision, accuracy

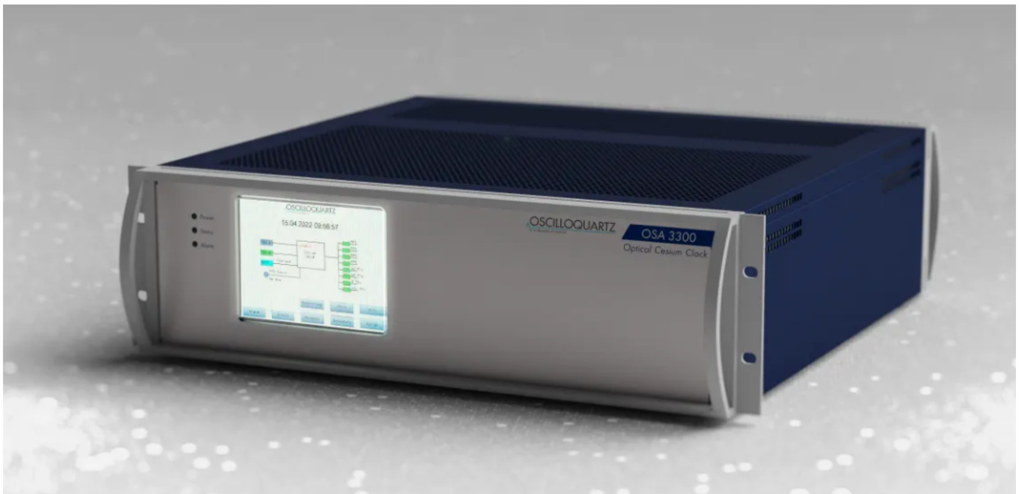


Figure 2.20: 19 inch 3U rack-based design of a commercially available optical atomic clock [48]

and frequency stability. However, the current developments restrict the use of these clocks in out-of-lab environments due to their size. There is active research on how to develop a transportable optical atomic clock. This solves challenges such as reducing the size of these clocks, reducing the complexity of the system and reducing the amount of power consumed to enable them to operate well in a natural environment. Recent focus in the field of optical clocks is on how to commercialise the clocks. The Adtran commercial optical atomic clock achieves the performance level suitable for the use cases in the field of metrology [2]. Figure 2.20 shows a photo of a commercially available optical clock unit [2]. However, additional challenges need further investigation, such as how to distribute the highly precise signal over the fibre and maintain network accuracy and precision of the timing signal. The distribution of the timing signal starts from the core and passes through multiple hierarchies to reach the tier nodes in a telecom infrastructure. The synchronisation accuracy needs to be at the nanosecond scale or even less. The current focus looks into using optical clocks to replace GNSS to serve as the primary reference source of timing and support the low latency applications in a 5G network. The next chapter in this thesis details possible ways to bring this technology into the infrastructure to cater to future requirements.

2.4 Conclusion

The chapter details various past, present, and future technologies for improving timekeeping accuracy. Accurate timekeeping techniques are essential to support various applications and services across multiple domains. Microwave-based atomic clocks utilise consistent vibrations from atoms to monitor time. These atomic clocks achieve high accuracy standards and contribute towards international time standards such as UTC. Satellite-based technologies such as GNSS have atomic clocks embedded in the satellites orbiting around the Earth. The receiver stations on the ground constantly monitor these signals to predict accurate position and time information. The atomic clocks embedded in the satellites are in synchronisation with each other and the clocks in the receiver stations on the ground to achieve higher levels of accuracy. Computer networks utilise protocols like NTP and PTP to synchronise clocks across multiple devices, where synchronisation is essential for services such as data logging and financial transactions.

Optical atomic clocks, such as the optical lattice atomic clocks, are the next generation of atomic clocks based on quantum technologies. These clocks trap atoms or ions in a lattice and interrogate them with a laser to achieve unprecedented accuracy and stability. The concept of quantum entanglement opens new research opportunities to achieve high-precision timekeeping in the future. Technologies such as machine learning are being thoroughly analysed to understand how they can help improve synchronisation in the existing systems. The predictive algorithms aid in analysing asymmetries, data patterns, and their effect on timing errors and generate the ability to predict and adjust the timing inaccuracies accordingly. Machine learning or artificial intelligence-based techniques suit well in scenarios where the application demands real-time synchronisation. The technologies for accurate timekeeping evolve and redefine the standards for measuring time and continue to advance, shaping various applications in science and technology. The thesis focuses on a similar scenario that looks at connecting optical atomic clocks to a telecom infrastructure. The work also looks into various novel techniques that aid in transporting high-accuracy frequency signals from the optical atomic clocks into the network. Despite having ultra-stable clocks at the core of the network, achieving high-precision synchronisation at the node level is challenging due to the proliferation of the nodes in the infrastructure and the effect of asymmetries that degrade the quality of a timing signal. The work also looks into FPGA-based techniques to overcome the challenges mentioned above to achieve high precision at the node level.

Chapter Three

Optical Atomic Clocks in a Telecom Infrastructure

Mobile networks have evolved rapidly over the past years. Over recent years, the fifth generation of telecommunication networks (5G) has become a topic of intense interest. The upcoming increase in the number of users, devices, and services across various platforms has led to the formation of a 5G framework to facilitate the coalescing of today's fixed, mobile, satellite, internet of things, robotics, and sensor technologies. Synchronisation allows multiple platforms and services to operate without any glitches. Numerous services can be affected when devices are out of synchronisation. Poor synchronisation over the air interface leads to poor frequency stability. The base stations in a telecom infrastructure are in synchronisation with the nearby base stations and user equipment. Therefore, poor synchronisation could result in operational challenges, poor handover among base stations, call drops and degradation of the signal strength. Figure 3.1 details different components used for synchronising multiple network devices over the years. The technologies marked in blue and green indicate their maturity and operation at a broader commercial scale.

Synchronous Digital Hierarchy (SDH) or Synchronous Optical Networking (SONET)

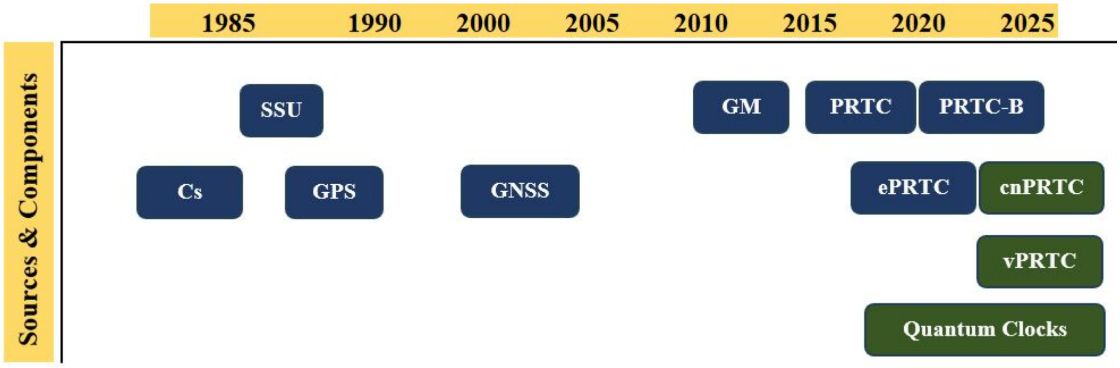


Figure 3.1: Components used for synchronisation in a telecommunication infrastructure. The components marked in blue are actively used within the infrastructure. The components marked in green are emerging technologies with immense potential for supporting the infrastructure in future.

was the core transmission technology used in most of the existing networks. Fundamentally, SDH transported over fibre should be the same as SDH transported over the Wavelength Division Multiplexing (WDM) network. However, due to longer transmission distances and temperature changes, fibre delay and wander could be impacted. Optical switching reroutes network traffic to different paths. All these factors add challenges to synchronising multiple devices across the network and eventually build up cTE in a Dense Wavelength Division Multiplexing (DWDM) layer due to asymmetries. Class D T-BCs are required at the intermediate nodes on long Dense Wavelength Division Multiplexing (DWDM) links to achieve the targeted sync performance.

Timing requirements are becoming stringent as generations of networks evolve. Technologies (such as eICIC and CoMP) that demand microsecond-level accuracy in Long Term Evolution - Advanced (LTE-A) are moving towards nanosecond-scale accuracy in 5G for better performance and to support new requirements [13]. The requirements become tighter for Beyond 5G (B5G) networks. On top of this, the security and resiliency of the networks is gaining importance as 5G aims to support mission-critical applications, machine-to-machine communication and enhanced broadband services. These services require ultra-reliable networks and ultra-low latency, bringing timing, synchronisation, security and resiliency to be top priorities in network engineering. Though GNSS or GPS-based systems are accurate to above the hundreds of nanosecond scale, they are vulnerable to attacks such as jamming and spoofing mainly due to low power transmission signals, interference and poor coverage. GNSS-based systems, the primary source for traceability to UTC, upon interference, can cause havoc to time-critical applications or services running over the network. Over the years, atomic clocks have provided better holdover performance when jamming, spoofing or interference degrades the strength of a GNSS signal. Coverage, interference and security challenges limit the use of Global Navigation Satellite Systems in future generations of networks. Recent advancements in technology and the rising importance of finding an alternative PNT solution have pushed researchers to think of using optical atomic clocks as an alternative to GNSS in the future.

Quantum clocks are atomic clocks that utilise the principles of quantum mechanics to achieve high precision in timekeeping. Unlike optical clocks, they can operate at both microwave and optical frequencies. They utilise ions that are trapped in an electromagnetic field and cooled down to absolute zero temperature and manipulate their quantum states. They are more precise than optical atomic clocks, finding potential use in fundamental physics, mysterious universal facts such as dark matter, sensing, standard redefinition and much more. However, factors such as size, sensitivity to environmental conditions, easiness of transporting clocks without affecting performance, sensitivity to mechanical vibrations and interference, and continuity in operation restrict the clock from becoming a commercial product.

Despite numerous challenges in becoming a commercial solution, the optical atomic clock technology is attracting massive attention in a few real-life use cases, such as the telecom network. Optical atomic clocks aid in building a national-scale PNT infrastructure to deliver timing for time-critical applications over fibre networks. This will gradually reduce the dependency on GNSS or similar satellite-based systems for PNT services.

The chapter looks into identifying the best possible way to integrate optical atomic clocks into a telecommunication infrastructure. The current state of the art mainly focuses on using optical atomic clocks for scientific research. The novelty in this work lies in understanding and identifying the ways of bringing optical atomic clocks into a telecom infrastructure. This is achieved by developing a software model of the network which resembles the nodes and links present in the telecom infrastructure deployed at national scale. Multiple architectures have been modelled which investigates connecting optical clocks to the core part of the network. The core part of the network consists of nodes that carry high-accuracy timing equipment, which are traceable to UTC. The software model computes the timing accuracy achieved at the metro node (tier 3) in each case. Metro nodes are nodes that consist of timing equipment, that derives the timing information from the network core. The work detailed in the chapter compares timing accuracy with other factors, such as cost, deployment feasibility, additional link or node requirements, etc., to propose an ideal method to easily connect optical atomic clocks to the core of the telecom infrastructure in future.

3.1 Network Model to Disseminate Time

The network modelling aims to look into ways of achieving time synchronisation across networks using optical atomic clocks. The network model is identical to a telecommunication infrastructure at a national scale comprising superhubs, hubs and metro nodes. The model aims to understand the accuracy achieved at the metro node upon using optical atomic clocks in the network. The model helps to understand how an optical atomic clock fits into a telecom infrastructure. The model estimates the timing errors accumulated along the transport network and calculates the accuracy achieved at the metro node. This work aided in understanding existing technologies and techniques for synchronisation and the feasibility and challenges of integrating a new technology with an existing infrastructure. The model also aims to approximate the cost incurred to deploy optical atomic clocks in a telecom infrastructure in the near future.

The network model is built based on field information such as the location of nodes, link lengths, data traffic, transmission paths or routes. The modelling work looks into multiple architectures that aid in using optical atomic clocks as secondary and primary standards, along with their resulting accuracy in each case. It eliminates the dependency on GNSS in the near future, thereby improving the security and resiliency of the network. The network model is developed using C sharp software programming language using the data from the telecom infrastructure deployed at the national scale. The locations of tier 1 and tier 2 nodes are based on the geography of the current infrastructure. The clock and time nodes have been partially decided based on the location of core nodes or hubs in the infrastructure.

Optical atomic clocks demonstrate excellent frequency stability to a few parts in 10^{18} or beyond. There are various types of optical atomic clocks based on the principle of operation, with a prime focus on improving frequency stability. Examples include optical lattice atomic clocks, ion clocks, optical thermal clocks, super-radiant clocks, compact optical clocks using coherent population trapping, ion clocks and continuous optical clocks. Apart from the principle of operation, optical clocks differ based on the type of atoms or ions used. These clocks use different atoms, such as strontium, calcium, aluminium, caesium, ytterbium, iodine, rubidium, and magnesium. These investigations aim to build the best clock in the world regarding accuracy and stability. Researchers are in a race to make optical clocks more and more compact and transportable without compromising on frequency stability to enable their usage by a wider community [14].

The optical atomic clock built as part of the iqClock project is a strontium-based optical lattice atomic clock [49]. The clock mainly comprises a physics package, optical cavity, laser unit, control unit, frequency comb and a downconverter module. The laser signal is locked to an ultra-stable optical cavity, which results in a narrow linewidth (Hz) laser signal. The narrow linewidth laser probes a cloud of atoms which are cooled to few μK and consequently trapped in an optical lattice to provide long-term stability of a few parts in 10^{18} [13]. In most cases, the optical output from an optical clock is not compatible with telecom timing equipment or a sync box. A standard telecom timing equipment or sync box accepts 10 MHz or 1 PPS signal. Optical frequencies from optical atomic clocks are in the THz range, making it difficult to connect or interface the clock directly with the telecom equipment. A frequency comb converts the THz frequency to the MHz range (approximately 800 MHz) in the iqClock case. Figure 3.2 shows components of an optical atomic clock and the intermediate steps for frequency downconversion. The downconverter module built as part of the clock accepts frequency in the MHz range and downconverts it again to a 10 MHz/ 1 PPS signal. This downconverted signal connects to telecom equipment. The clock does provide accurate frequency and phase information. The telecom equipment still needs a GNSS receiver to obtain time of day information as the clock output is not traceable to UTC.

The timing architecture is identical to the existing fibre infrastructure. The fibre infrastructure is assumed to consist of single fibre where transmission and reception are over the same fibre cable to reduce the errors due to differential path length. Time compensation algorithms compensate for differential path length in standard timing equipment. Telecom infrastructure evolves from generation to generation, which means the existing network combines 3G, 4G (LTE) or 5G. The telecom infrastructure supports critical applications from the fourth generation, and critical services or requirements often fall into the fifth generation of telecommunication networks. Hence, the model looks into the timing accuracy for the fifth

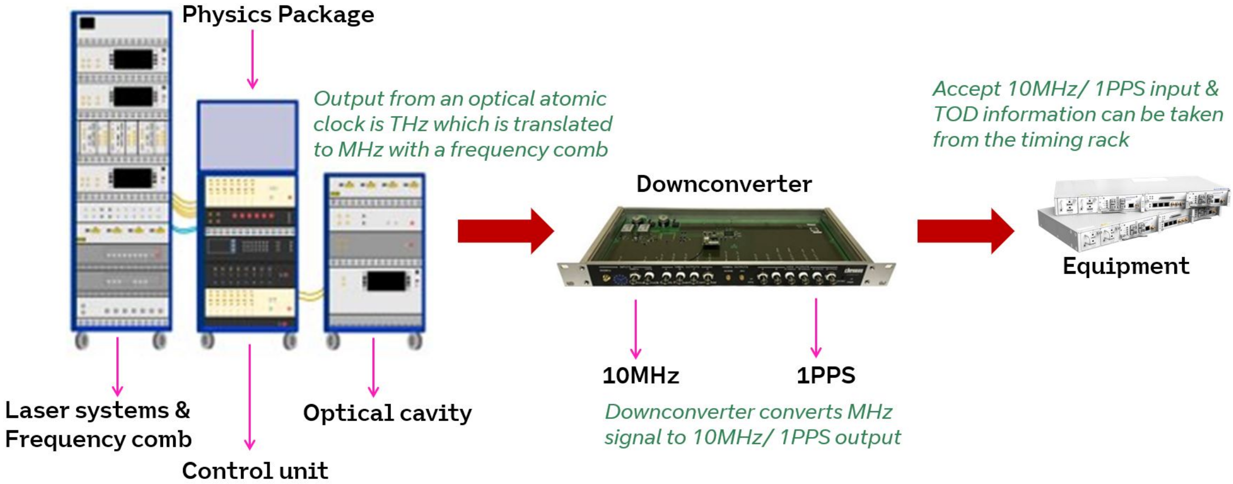


Figure 3.2: 10 MHz 1 PPS signal from an optical clock to a telecom equipment[14]

and future generations of telecom networks. The optical clock considered for the model is a strontium-based optical atomic clock with frequency stability of 1 part in 10^{18} [14]. Figure 3.2 demonstrates the physical appearance and components included in the clock. The clock is a rack-based system allowing easy transportation from one location to another. The network model computes the time error from the core (represented as tier 1) to the metro node (represented as tier 3) in the architecture. The network model includes technologies widely used over recent years, such as PRTC-B, ePRTC and HPBC. The model allows users to try different combinations of technologies. In the near future, technologies such as cnPRTC and vPRTC will help improve the accuracy of timing in infrastructure. The model is flexible enough to incorporate these technologies when required in the future. Future networks demand frequency and phase synchronisation; hence, the network model uses PTP as the synchronisation protocol. As mentioned, the network model aligns with the fifth generation of telecommunication networks. The model assumes that the network has evolved entirely to the latest generation. It helps to compute the cost incurred to deploy this technology in the near future. The cost estimated does not include expenses incurred for network upgrades.

Various factors affect the accuracy of a timing signal in the physical and transport

Contributor	***Source***	***Impact***	***Range of TE***
Fibre	Fibre length, jumper cable etc	Large and static	5 to 1000 ns of cTE
Dispersion Compensation	Asymmetry in DCF used in each direction	Very large and static	5 to $20,000$ ns of cTE
Coherent Optics	FIFO buffers and DSP components	Random and varying	20 to 130 ns of cTE
OTN Mapping	Deep FIFO buffers in OTN mapping	Random and large	20 to 1000 ns of cTE
IP Routing and Ethernet Switching	Timestamping inaccuracy, traffic congestion, buffering	Tight requirements to control impact	Maximum TE of 30 to 100 ns, cTE of 10 to 50 ns and dTE of 10 to 40 ns

Table 3.1: Asymmetries affecting the accuracy of a timing signal [31]. Dispersion Compensation Fibre (DCF); First In First Out (FIFO); Internet Protocol (IP); Optical Transport Networks (OTN)

layer. Various asymmetries contribute to errors in the timing signal, thereby degrading its accuracy. Any parameter that affects the accuracy of a timing signal by inducing some error in the signal is known as an asymmetry. These asymmetries are present at the nodes and over the fibre link. The paper [15] elaborates on components that contribute to latency in the communication process. Table 3.1 details various asymmetries contributing to timing errors in an optical transport network. The source of asymmetry helps to classify timing errors into two categories:

- Static or constant time error (cTE) refers to the predictable, static constant error sources or delays introduced into the system.

- Dynamic time error (dTE) refers to the unpredictable, variable and dynamic errors that vary over time.

Asymmetries related to fibre cable, dispersion, wavelength, optics, protocols and optical transport network contribute to cTE. Meanwhile, asymmetries related to rerouting, data traffic, switching, and environmental conditions such as temperature add to dTE. Asymmetries introduce errors to the timing signal, causing a significant variation in the measured signal from the actual. The network allocates a maximum time error budget for the transport network between time sender and receiver nodes (1000 ns between grandmaster and TSC at cell site [31]). Asymmetries within the network consume this allocated bandwidth. Asymmetries generated at the node and the link add considerable value to the allocated TE budget. Figure 3.3 details the error budget allocated for various network reference points as per the standard.

In DWDM networks, the forward and reverse transmission might be over a different fibre cable. This causes variation in the fibre length during transmission and reception and adds to time errors. Additionally, patch cables and fibre splicing also contribute to the time error. These errors are considered static but can change when fibre cables undergo repair or reconfiguration. The FIFO buffers in coherent optics generally induce a latency upon startup. These error values can differ depending on the interface and are affected by the direction of transmission and reception of a signal. Hence, it introduces a dynamic time error. It can be a constant time error over the short term but can vary over the longer term. Chips in the OTN mapping utilise the FIFO buffers, introducing time errors, especially when the system starts or restarts. Similar to the errors generated in the DSP buffers, these errors can be constant over the shorter term but vary over the longer term. The time errors introduced at the routers and switches add to timestamping inaccuracies [31]. Asymmetry management is essential. The PTP protocol corrects the timestamps, assuming the network is symmetrical.

The network model assumes the forward and reverse transmission links to be symmetrical. It means the path lengths in the forward and reverse transmissions are the same. This results in an equivalent delay and time error at the time receiver node. In a real network, it is possible to compensate for cTE with the help of time compensation modules. A time compensation module is a software logic built into timing equipment which aids in correcting known time error values. This software logic compensates for the known error value to the timing information generated by the system and thereby aids in improving the accuracy of the system. The model considers factors that contribute to cTE. However, with the increasing demand in timing requirements, dTE has created challenges, and dTE compensation is also becoming a priority. The work detailed in [65] discusses using AI or ML techniques to overcome the limitations due to dTE. These techniques help to monitor variations in TE based on link characteristics to understand the fluctuations over the longer term to train and develop a model that can predict the TE value based on changes in link characteristics. This data provides sufficient information to compensate for errors and further improve accuracy. However, this work is in the early stages and will take at least 3 more years to develop the initial proof of concept.

The total time error for a network depends on the number of hops or nodes and the link length from source to destination. It is an additive value that gets added up at each node. The general equation for computing time error is:

$$TimeError = \sum_{i=1}^{n} TimeError_{Node} + \sum_{i=1}^{k} TimeError_{Link} \tag{3.1}$$

where n is the number of nodes and k is the number of links between tier 1 and tier 3 nodes.

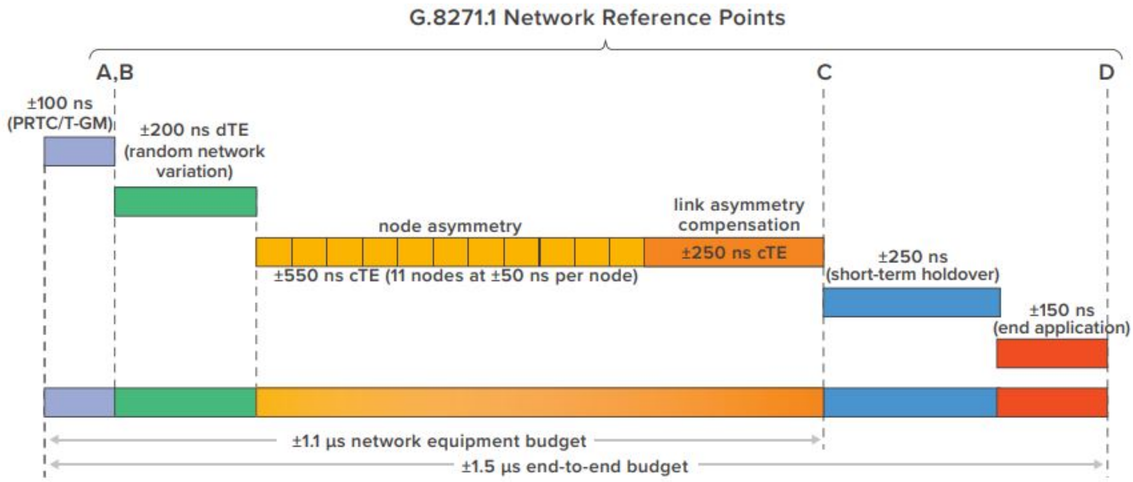


Figure 3.3: G.8271.1 time error budget and network reference points [31]. The figure illustrates the maximum time error limit at various network points for optimal continuous operation of the services. A and B are the reference points at the node level. C is the reference point after transmitting the signal over the network. D translates to the reference point at the end user side or application side.

3.2 Architecture

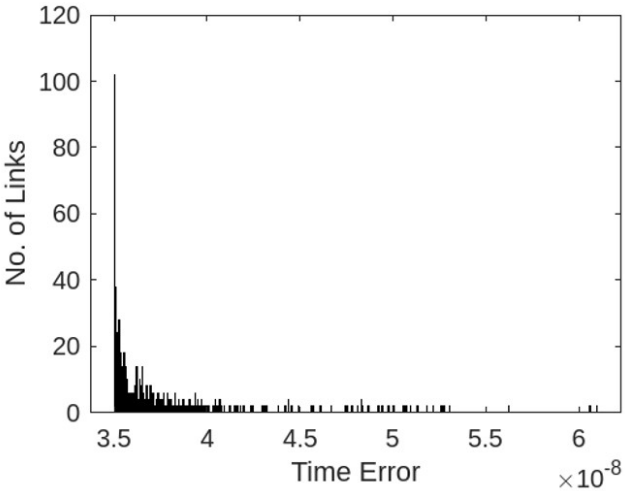
Atomic clocks have been part of the telecom infrastructure for the past few years. Upon commercialisation of the next generation of atomic clocks, the challenge lies in integrating them into an existing infrastructure. At present, atomic clocks are a secondary standard for disseminating time over a terrestrial infrastructure (Ethernet-based or fibre-based infrastructure). The atomic clocks are not traceable to UTC, which limits them from being used as a primary standard. Atomic clocks demonstrate better holdover performance when the traceability to GNSS is lost. The commercially available atomic clocks can provide 100 ns accuracy for 14 days [56] during the holdover period. Optical atomic clocks, which perform better than microwave-based clocks, should provide a better holdover period.

However, having atomic clocks in the network does not guarantee high accuracy at the edge, as the timing signal needs to flow through various layers of timing equipment before arriving at the network edge. The type of clocks, oscillators, transport mediums, and protocols used at different parts of the network and asymmetries generated limit the accuracy achieved at the network edge. Figure 3.4 aims to validate this statement. Figure 3.4 shows plots of TE accumulated over the network links upon using different types of timing equipment (which differs in performance based on the quality of the oscillator or clock). Figure 3.4a shows the plot of TE observed for over 2000 links where the network model only uses high-accuracy Class D High-Performance Boundary Clock (HPBC) to disseminate time from the core node to the metro node. Whereas, figure 3.4b depicts the plot of TE observed for over 2000 links where the network model also uses lower accuracy time slave clocks along with the high accuracy boundary clocks to disseminate time from the core node to the metro node. The time error range in the first scenario ranged from 35 ns to 64 ns (as shown in figure 3.4a) whereas the time error range for the second scenario ranged from 45 ns to 75 ns (as shown in figure 3.4b). Figure 3.4a demonstrated better accuracy due to the use of more HPBCs in the network model. However, the accuracy starts to compromise as low accuracy TSC is used in the network model as indicated in the plot 3.4b.

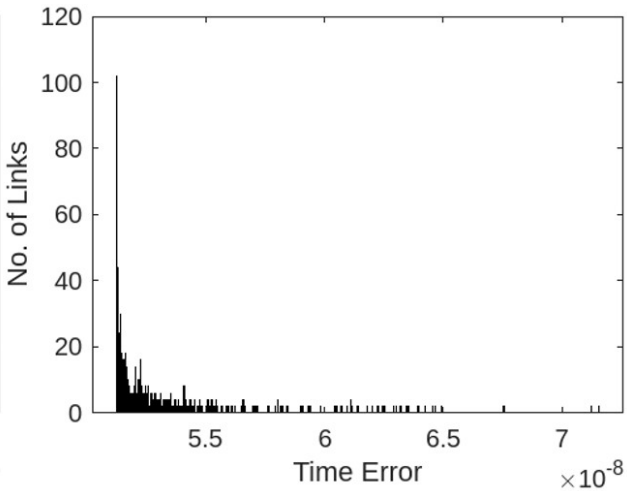
The best possible way to bring an optical atomic clock into a telecom infrastructure has always been an exciting challenge to investigate. The main driving reasons behind connecting an optical atomic clock to a telecom infrastructure are:

- To improve the existing holdover period, which aids in improving network resiliency
- To reduce dependency on GNSS, and develop a fibre-based infrastructure to disseminate UTC

The architecture shown in figure 3.5 details one of the possible ways of connecting optical atomic clocks to an existing infrastructure. The topology to distribute time is hybrid,



(a) TE achieved based on the use of high performance boundary clocks in the network



(b) TE achieved based on the use of high performance boundary clocks and telecom slave clocks in the network

Figure 3.4: The figure illustrates the difference in TE based on different clock types used in the network model. Time error varies depending on the accuracy of clocks used in the network. The x-axis indicates the time error value. The y-axis indicates the number of links in the network model that have the time error value indicated in the x-axis. Boundary clocks are more accurate than telecom slave clocks. Therefore, time error is less when only boundary clocks are present in the network.

comprising hierarchical and flat or distributed topology. The tiers at the top level of the hierarchy consist of better clocks than the lower tiers. In figure 3.5, tier 1 represents the core node, and tier 3 represents the metro node. These tiers replicate different hierarchies in a telecom network. Tier 1 represents the core node of the network which consists of a high accuracy timing equipment that is traceable to UTC. Whereas, tier 3 represents the metro node which consists of lower accuracy timing equipment that is traceable to timing equipment in tier 2 or tier 1. Tier 2 is the node in between the core node and the metro node which consists of timing equipment that is traceable to the one in tier 1. The different types of tier nodes have been modelled in the software based on their geographical location and the timing equipment residing at each node. The model uses four optical atomic clocks to distribute

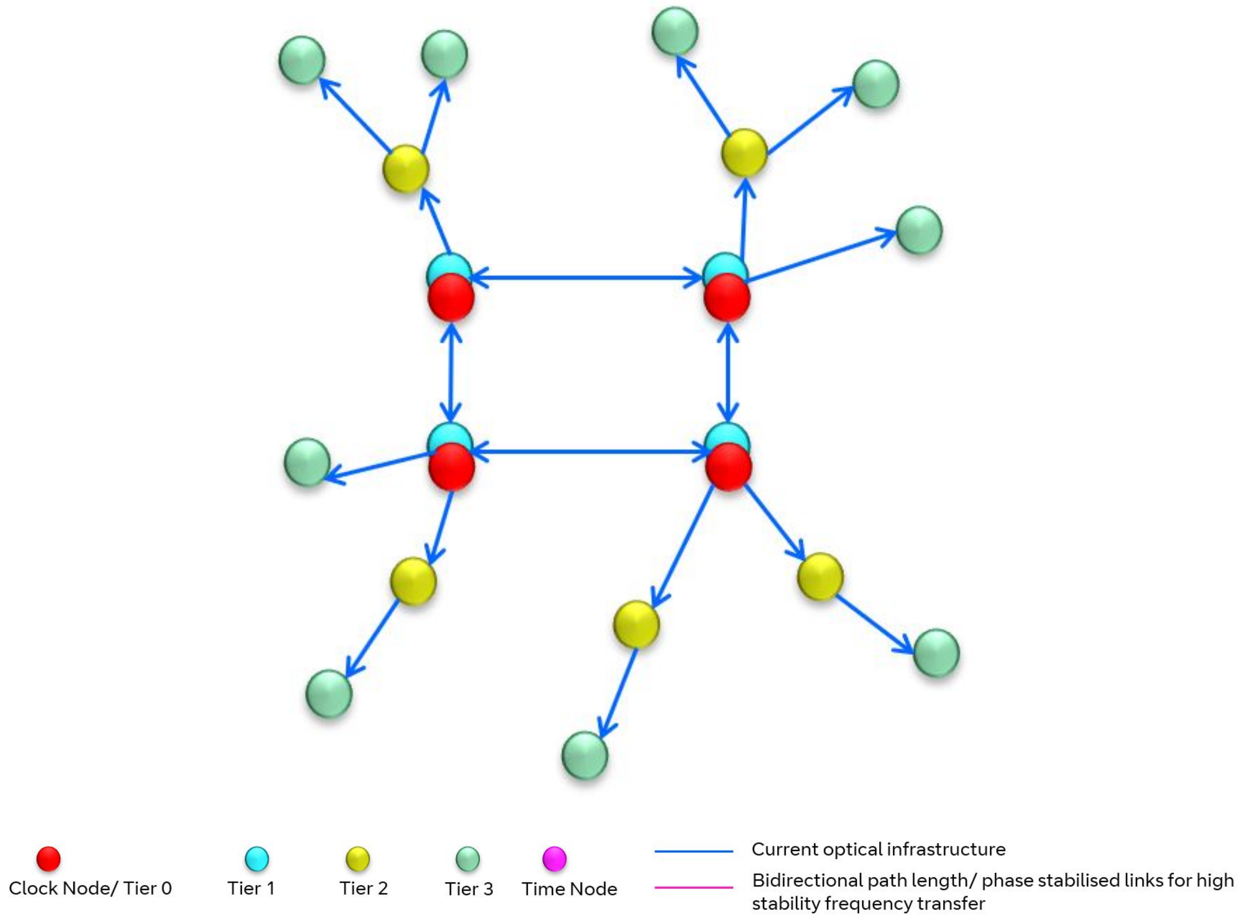


Figure 3.5: Optical clocks co-located with tier 1 nodes

time nationally. This number depends on the complexity of the architecture at different geographical locations. The first architecture looks into the positioning of clocks at the tier 1 nodes. Placing the clocks along with tier 1 nodes reduces asymmetries accumulated while transporting the signal from a different location. The timing signal from a clock feeds directly to an ePRTC device and disseminates time to lower levels in the hierarchy. This architecture fits well when tier 1 nodes are less in number. The cost of optical clocks limits them from being used in enormous amounts. This architecture does not require many changes to the existing network as the clocks lie on top of an existing infrastructure. The TE computed in this case will be equal to:

$$TimeError = \sum_{i=1}^{n} TimeError_{Node} + \sum_{i=1}^{k} TimeError_{Link} \quad (3.2)$$

where n is the number of nodes and k is the number of links between tier 1 and tier 3.

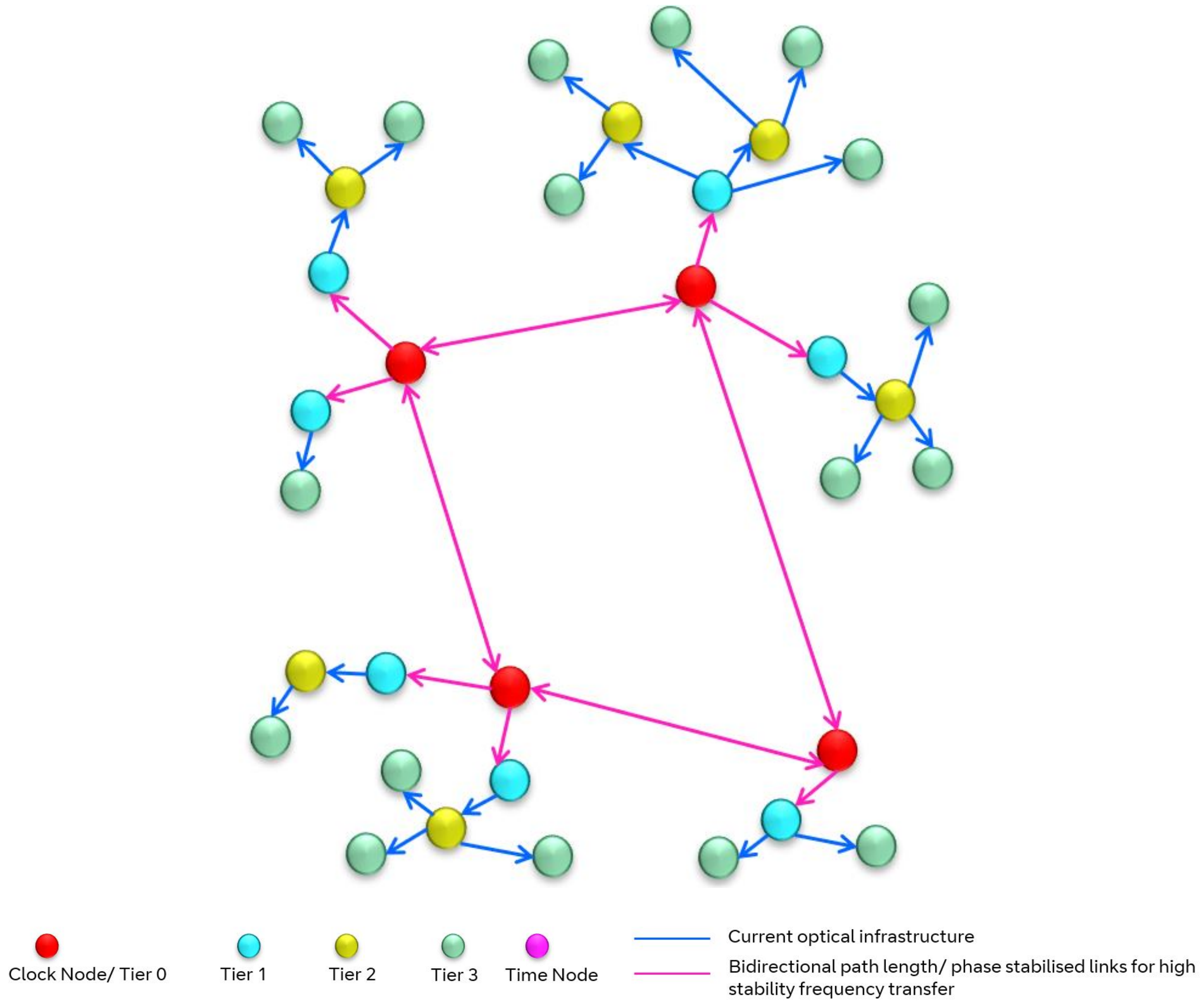


Figure 3.6: Optical clocks located away from tier 1 nodes

However, for an infrastructure with a more extensive number of tier 1 nodes, it is not practical to deploy optical clocks in every tier 1 node due to the increase in cost. In this case, clocks are deployed in different locations, and the timing signal must be transmitted to the tier 1 nodes. However, asymmetries will affect the timing signal when transferred over an optical link, eventually degrading the accuracy achieved at tier 3 nodes. The number of clocks is the same as the previous architecture; the difference is that this topology looks into supporting a more comprehensive network with the same number of clocks. ePRTCs located at tier 1 nodes receive the timing signal from optical clocks and disseminate further down to lower levels. The lower levels consist of HPBCs. This architecture requires additional links to connect clocks to tier 1 nodes and interconnect optical clocks to each other. Optical clocks are interconnected to each other to improve network resiliency. It creates a backup source to act in time when one of the clocks fails to function. The TE computed in this case will be equal to:

$$TimeError = \sum_{i=1}^{n} TimeError_{Node} + \sum_{i=1}^{k} TimeError_{Link} + TimeError_{ClockTier1Link} \quad (3.3)$$

where n is the number of nodes and k is the number of links between tier 1 and tier 3.

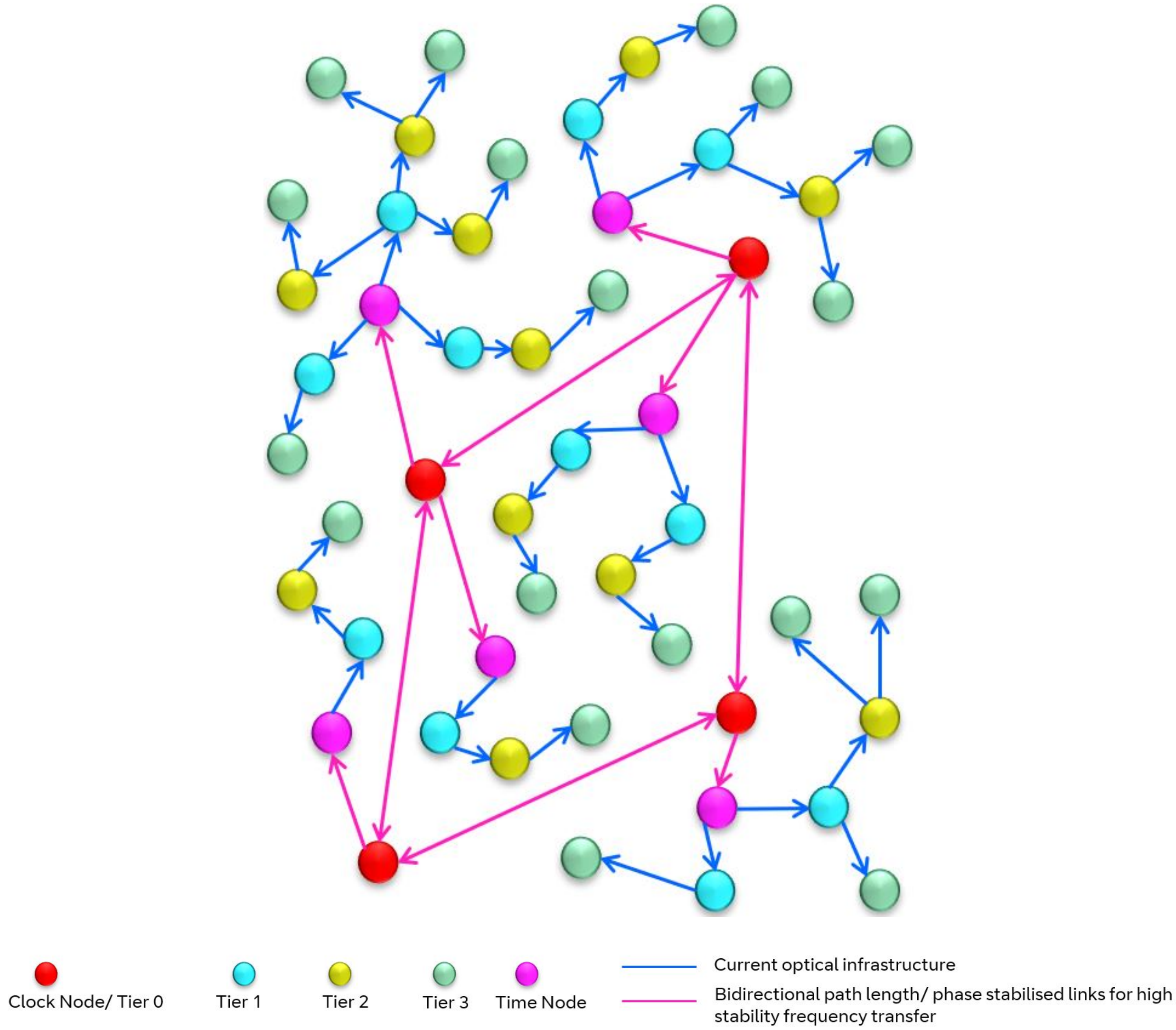


Figure 3.7: Optical clocks geographically distributed

The size of the network limits the number of links deployed to connect clocks to a tier 1 node. It turns out to be complex and costly beyond a specific limit. In such a scenario, building high-accuracy time nodes helps to connect optical clocks to tier 1 nodes. It helps to build a fibre infrastructure to disseminate time at a national scale. The high-accuracy tier nodes connect to many tier nodes, which is more cost-effective and less complex than setting up links between the clock and the tier 1 node, as detailed in the second architecture. In architectures 2 and 3, high stable optical frequency can be disseminated over fibre, which requires down-conversion before being fed into an ePRTC device at the tier 1 or time node. This architecture requires additional links to connect clocks to time nodes and time nodes to tier 1 nodes. Architectures 2 and 3 require the transportation of high frequency optical signals to nearby tier 1 or time nodes. Maintaining stable frequency over bidirectional fibre and adding time traceability at the tier 1 or time node is easier. It also helps to limit the use of PTP, which adds asymmetry due to differential path length. Hence, it will help to reduce the effect of asymmetries, eventually improving time accuracy. The time traceability is from a satellite source such as GNSS or a national laboratory such as NPL in the UK. The time error computed in this case will be equal to:

$$TimeError = \sum_{i=1}^{n} TimeError_{Node} + \sum_{i=1}^{k} TimeError_{Link} + TimeError_{ClockTimeNodeLink} \quad (3.4)$$

where n is the number of nodes and k is the number of links between tier 1 and tier 3.

Investigating the best backup technology to support the network at the time of failure is equally important while designing the network architecture. Optical clocks by themselves cannot provide a resilient infrastructure. If one of the clocks malfunctions or fails, then synchronisation for the underlying network devices will be at stake. Hence, it is equally important to provide redundancy to support the network in such scenarios. Redundancy is provided by interconnecting two optical clocks. This means that an optical clock will receive ultra-stable frequencies from two different locations to drive the frequency comb, thereby acting as a backup if required.

Moreover, GNSS will be a secondary standard in future; hence, it can also be used as an alternative source in case the optical clocks fail. The ideal situation would be to have a clock comparator circuitry, which can take time from multiple sources as input and output the signal closest to UTC. This technology is used at a small scale in timing equipment to generate the closest signal to UTC by comparing inputs from multiple feeds. It will help to improve network resiliency and mitigate sync issues due to clock failure.

3.3 Results

Time errors achieved in each case are different as they primarily depend on the location of the clock, links or nodes set up as part of the architecture, the distance between nodes and the contribution of asymmetries to time error. The locations of tier 1, tier 2, and tier 3 nodes are stationary, but the factors mentioned earlier result in the accumulation of time errors. The number of links indicated in the y-axis represents the total number of links in the network model that have the same value of time error represented in the x-axis. The x-axis of the graph will not start from 0 as there will be some value of time error associated with each link, as every link comprises at least a tier 1, tier 2 and a tier 3 node. These links represent the total path length from a tier 1 to tier 3 node and are based on the fibre infrastructure deployed at the national scale.

However, as discussed in the previous section, it is essential to understand the best possible architecture to connect the clocks to the current infrastructure. Figure 3.8 shows the plot of time error based on architecture 1, where optical clocks co-locate with tier 1 nodes. Figure 3.9 shows the plot of time error based on the second architecture where clocks are in a different location away from tier 1 nodes. Figure 3.10 shows the plot of time error based on the third architecture where optical atomic clocks are geographically distributed. The time errors for the first, second and third architecture lie between *41.8 ns and 65.1*

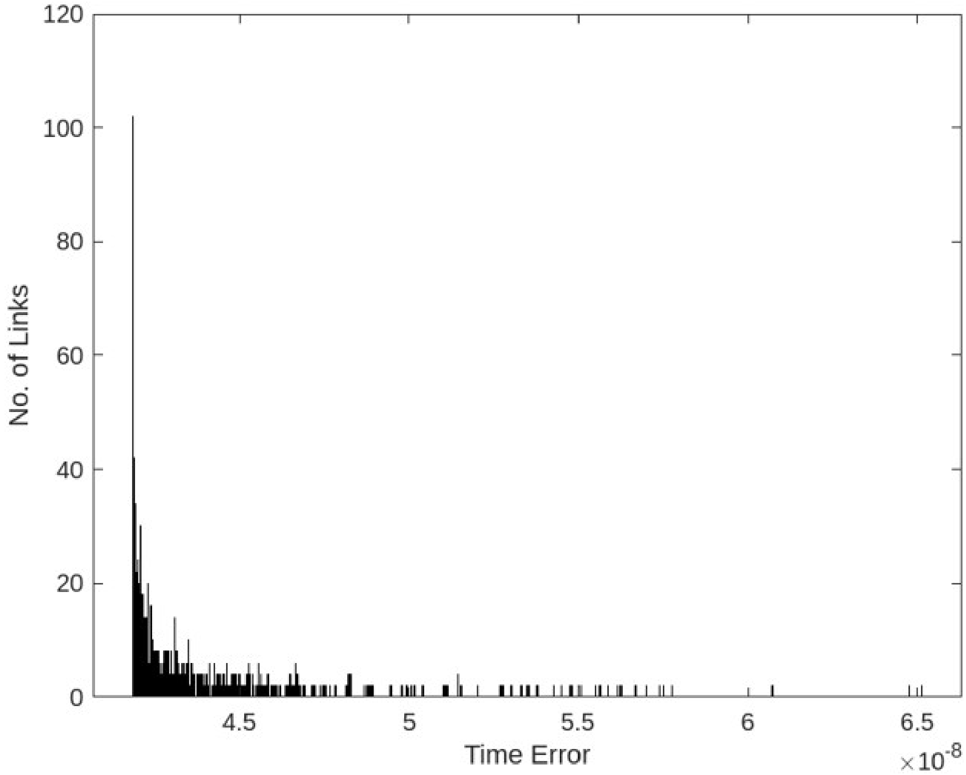


Figure 3.8: Time error for the network for the first architecture where optical clocks are co-located with tier 1 nodes. The time error for the architecture ranges between 41.8 ns and 65.1 ns.

ns, *54.8 ns and 74.1 ns* and *35.7 ns and 61.4 ns*, respectively. This is the timing accuracy achieved in each case at the tier 3 level, upon using optical clocks for distributing timing over a terrestrial infrastructure. The least time error is observed in the case of architecture 3. This is mainly because they are geographically distributed and connected by a phase-stabilised link and the timing information is fed into timing nodes and stable frequencies can be carried over the phase-stabilised links. This results in high-accuracy timing information being directly injected into the timing nodes and hence shows the least time error at tier 3 nodes. Architecture 1 also provides lower time error values. In this case, the optical clocks reside at the tier 1 node. In this case, the timing information is fed to the clocks and then to the timing equipment in tier 1 nodes. This creates an additional layer within the tier 1 node and hence the variation in the time error values. However, the time error measurements are not the only factor in deciding the best architecture. Architecture 1 investigates how easily clocks can be integrated into the current infrastructure. The second architecture looks into distributing these clocks into different locations and understanding the level of accuracy achieved at the tier 3 node level. The third architecture looks towards the future to understand the level of accuracy achieved if clocks are distributed geographically. This aids in understanding the potential of injecting various time sources which will be available in future such as the time from national laboratories which are more accurate than the satellite-based technologies.

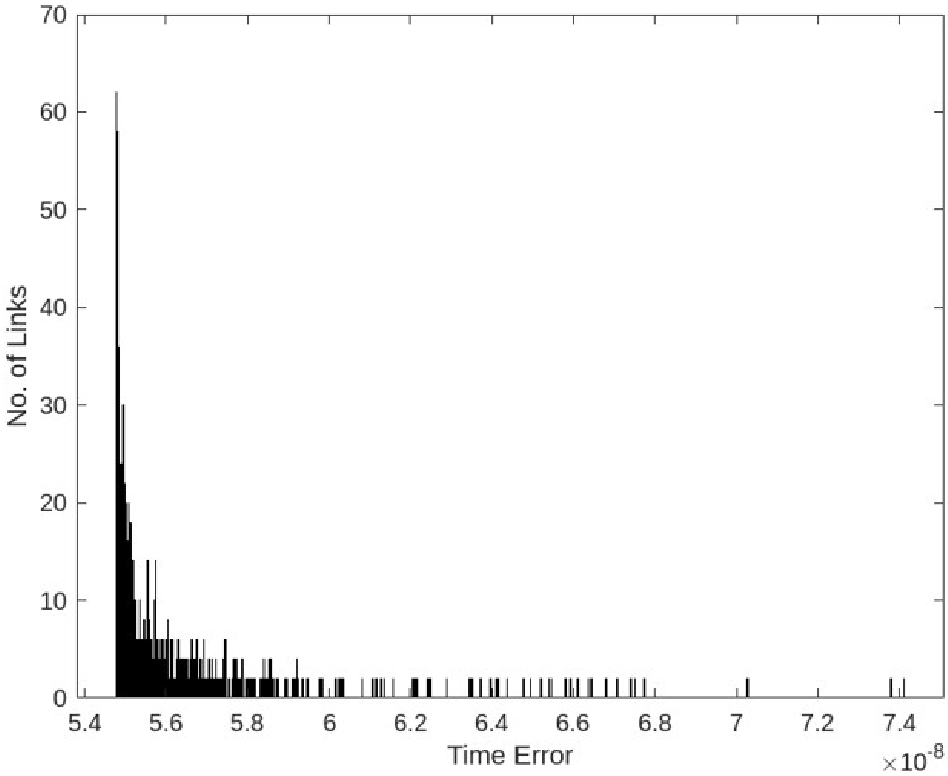


Figure 3.9: Time error for the network for the second architecture where optical clocks in a different location with respect to tier 1 nodes. The time error for the architecture ranges between 54.8 ns and 74.1 ns.

There are several other factors to consider before deciding on the best possible ar-

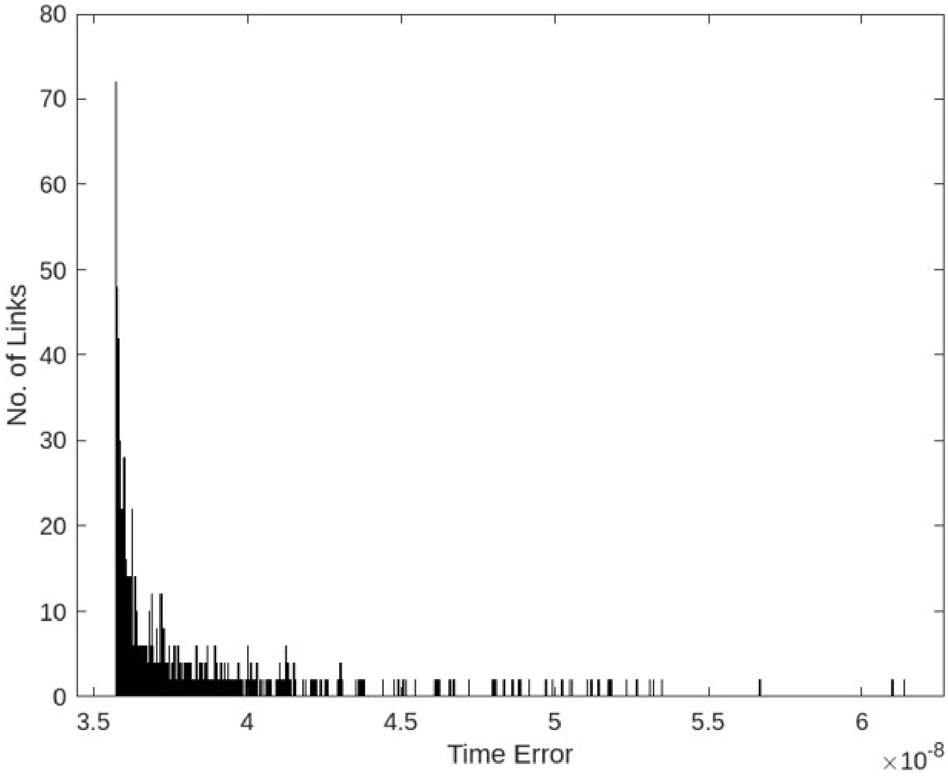


Figure 3.10: Time error for the network where optical clocks are geographically distributed. The time error for the architecture ranges between 35.7 ns and 61.4 ns.

chitecture, especially when the technology is expensive. It is difficult to comment on the exact price of the technology as it has yet to be commercially available. Nevertheless, having estimated components within these devices, the first generation might cost between £100k and £200k.

The comparison of three architectures against different criteria is detailed in table 3.2. The comparison is essential to decide the best architecture based on factors such as cost, network size, geography of the nation, ease of integrating with current infrastructure, etc. Although Architecture 3 is the best among the three in terms of time error measurements, the cost and complexity of deployment are higher than the other two. Architecture 3 demands more cost to set up additional links and time nodes, which is not required in architecture 1. The time error in Architecture 1 is better than in Architecture 2 and has no other cost apart from the cost required to buy the clocks. Since Architecture 1 looks into the co-location of clocks with the tier 1 nodes, the current infrastructure is undisturbed and focuses only on integrating the optical clocks into existing infrastructure. However, the other

Criteria	***Architecture 1***	***Architecture 2***	***Architecture 3***	***Remarks***
Deployment	Easy	Difficult	Difficult	Easiness to integrate with current infrastructure
Time Error	41.8 ns - 65.1 ns	54.8 ns - 74.1 ns	35.7 ns - 61.4 ns	Total time error from tier 1 to tier 3
Cost	Cost of clocks *(£100k - £200k per unit)*	Cost of clocks *(£100k - £200k per unit)* + Cost of new link setup *(Links for connecting clocks to tier 1 nodes and links for interconnecting clocks to serve as backup source)*	Cost of clocks *(£100k - £200k per unit)* + Cost of new link setup *(Links for connecting clocks to tier 1 nodes and links for interconnecting clocks to serve as backup source)* + Cost of TE node *(Appx. 4 in number)*	Cost estimated for the deployment of the architecture

Flexibility	Easy	Difficult	Easy	How easily can the design evolve with the next generation of technologies
GNSS independence	Can be both dependent or independent	Can be independent or dependent	Independent	GNSS dependent for traceability; Independent from GNSS if national laboratories provide UTC traceability
Geography	Apt for any geography	Apt for nations with big geography size	Apt for any geography	Size of the nation (GNSS independence is vital for all nations in future)
New links or nodes	Additional links or nodes not required	Additional links required	Additional nodes and links required	Number of additional nodes or links required for deploying the architecture

Table 3.2: Comparison of the three architectures based on different criteria

two architectures look into deploying additional links or nodes. Hence, the complexity of the architecture increases along with investment in time and money in the future. Architecture 1 is more straightforward to evolve with future generations of networks as it handles both scenarios involving traceability to UTC via GNSS or national laboratories. Current infrastructure depends on GNSS for UTC traceability. Commercialisation and standardisation of optical atomic clock technology is not far in future. UTC traceability from a national laboratory is required to set up a time node. However, this requires a massive investment in money and time, and it will take a few years to see this become a reality. Hence, Architecture 3 envisages the future. Architecture 1 handles both scenarios. Hence, considering all these factors or scenarios, Architecture 1 is an optimal way to bring optical atomic clocks into an existing telecommunication infrastructure.

3.4 Conclusion

Optical atomic or quantum clocks are a source of stable frequency of a few parts in 10^{18}, making them better than current microwave-based clock technologies. Current infrastructure depends on satellite-based technologies such as GNSS for UTC. The main challenges in using satellite-based technologies are security, poor signal strength or loss due to interference and achieving global coverage. These factors might result in poor synchronisation in the network elements, eventually affecting the critical services and technologies supported by the network. At present, atomic clocks aid in better holdover performance within the network, especially when traceability to GNSS is lost. Optical atomic clocks aid the development of the next generation of timing and synchronisation in networks by distributing time over fibre infrastructure. The infrastructure will provide traceability to UTC wherever required and provide secure time as a service in the near future.

The research work detailed in this chapter focuses on understanding the best possible way to integrate these clocks into the telecom infrastructure in the near future. Optical atomic clocks aid in building a national-scale fibre infrastructure to disseminate secure time over fibre, mitigating some of the challenges mentioned above and providing secure, uninterrupted time service to customer premises. From the network model, it is evident that advanced clocks help to improve the timing accuracy across the infrastructure. The network model examined multiple architectures for integrating optical atomic clocks into telecommunication infrastructure. The model helped to understand the feasibility and challenges of implementing this technology. The architecture where the optical clocks co-locate with the tier 1 nodes was found to be the best way to integrate this technology with the infrastructure.

However, many challenges slow the vision from becoming a reality, mainly concerning the technology (standardisation and commercialisation) and infrastructure (well-connected nationwide fibre infrastructure). Moreover, optical atomic clocks are costly. Therefore, the cost of these clocks can be a challenge to small organisations wanting to use this technology. Due to the reasons mentioned above, at present, optical clocks are mainly used for scientific studies such as the study of the universe, sensing, and many more. In the near future, optical clocks will be used in the networks to achieve improved holdover performance beyond what microwave atomic clocks are capable of. This is crucial as the network can survive longer without going out of synchronisation when the GNSS signal is lost. In the future, when there will be a well-connected fibre infrastructure and national laboratories can provide UTC, optical clocks will be a primary source for UTC in the networks. Researchers are trying to build the best clocks in the world, leaving much scope for the technology to mature in the coming years.

Disseminating time over a dedicated wavelength helps to limit timing errors generated over the DWDM network. However, this technique faces challenges in deciding the suitable wavelength. Several factors, such as Optical Time Domain Reflectometer (OTDR) monitoring wavelength, increase in data traffic, which results in the expansion of the C band to L and S bands, amplifiers in the network, fibre type and dispersion, cause difficulty in deciding the dedicated wavelength for transporting timing signal. Sometimes, clocks at the core do not help; the ability to transport the stable output frequency from these clocks over fibre is required, especially when frequency and phase synchronisation requirements arise in different tiers in the network. Chapter 4 examines a novel technique to disseminate ultra-stable frequency over dedicated telecom fibre.

Chapter Four

Demonstration of Frequency Transfer over Fibre

Optical atomic clocks achieve frequency accuracy and stability of a few parts in 10^{-18}, thereby acting as an ultra-stable source for precise frequency. Such stable frequency references are generated from atomic transitions. These clocks open an opportunity for applications demanding ultra-stable frequency. Dissemination of ultra-stable frequency over fibre is essential for precise timekeeping and frequency synchronisation. It aids in transporting high-precision frequency references over long distances of fibre, aiding applications such as sensing, interferometry, scientific research facilities, and meteorology. For example, analysis of geological phenomena for detecting changes in the gravity field, tides, ice-mass changes, volcanoes and earthquakes demands an accuracy beyond 1 part in 10^{17} [30]. The above-mentioned natural calamities change the gravity field and the geometry of mass distribution over time. It changes the height where optical atomic clocks are, and that translates to a change in frequency. The measure of frequency difference between two clocks reflects disaster. Hence, optical nuclear clocks must disseminate optical frequency over the fibre to aid in correct measurements.

Frequency dissemination over fibre is gaining much more interest recently with the wide-scale deployment of optical fibre and the demand for high accuracy and precision for various scientific experiments and applications. Fibres provide a low-loss path, thereby helping to synchronise remote systems with the reference. Frequency syntonisation is critical for non-scientific use cases as well. The finance industry demands precise synchronisation to timestamp events across distributed systems with high precision. In telecommunications, frequency syntonisation is essential for error-free data and voice transmission, leading to reliable communication. The next generation of technologies, such as quantum communication and computing, will demand even higher levels of precision.

As mentioned earlier, it is essential to transport frequency reference from a master clock to slave clocks distributed across the network. The stability in transporting a microwave signal from satellites to its ground station is limited to 1 part in 10^{16} [20]. Optical clocks being better in performance can aid in achieving stability beyond 1 part in 10^{19} over 2000 km fibre distance [20]. However, variations in path length during the transmission and reception of signals significantly impact the accuracy achieved. It is dependent on the path length to minimise phase variations. Transmission and reception of an optical signal over the same fibre gives an estimate of the accumulated phase noise. It is essential to compensate for the noise at the transmitting end to improve stability. High precision frequency and timekeeping applications demand better coherence and synchronisation. Hence, these techniques aim for stability beyond 1 part in 10^{17}. Path length stabilisation using an Acousto Optic Modulator (AOM) and a Proportional Integral Derivative (PID) is an effective technique to achieve higher stability while disseminating optical frequency over fibre [20].

Path length stabilisation is effective if the transmission and reception of the signal are over the same fibre. However, in most cases, signals are transmitted and received through different fibres in a telecommunication network. It creates differential path length; hence, the path length stabilisation technique becomes ineffective. The chapter looks into a novel method of transporting stable frequency over fibre when the transmission and reception are through different fibres. The experiment uses an Optical Reference System (ORS) as a reference. The device can generate stable frequency to a few parts in 10^{15}. Telecom applications demand clocks with good long-term stability. This ensures that the telecommunication networks remain in frequency synchronisation over longer periods of time without performing any frequency adjustments. For example, in 5G networks deviation of 1 microsecond could lead to significant data loss or connectivity loss. Hence, the experimental work also characterises the long-term stability of the ORS system by comparing it with commercially available Caesium (Cs) clocks.

4.1 Path Length Stabilisation

A path length stabilisation circuit helps to dynamically vary the frequency to compensate for the error induced while the signal propagates through the fibre. The main components include an AOM and a feedback control system using PID. The AOM modulates the frequency of an optical signal. The feedback control system uses PID to monitor variations in frequency and computes the error between the actual and received frequency. This error generates a correction factor which feeds as an input to the AOM to compensate for the fluctuations, making the optical signal more stable. Figure 4.1 shows a simplified diagram of the path length stabilisation technique to disseminate stable frequency over fibre. The optical signal feeds into a Michelson interferometer that comprises of short and long arm. The more extended arm is the fibre link connecting location A to location B for frequency dissemination. The mirror placed at location B partially reflects the transmitted signal to location A. The generated and reflected back signal is compared in the feedback control system to get an estimate of the phase noise introduced by the fibre link. The estimated error value acts as a correction signal that feeds to the AOM. The AOM shifts the frequency of the signal accordingly to cancel out the fibre-induced phase noise. However, the technique works well when the transmission and reception of the optical signal is over a bidirectional fibre cable.

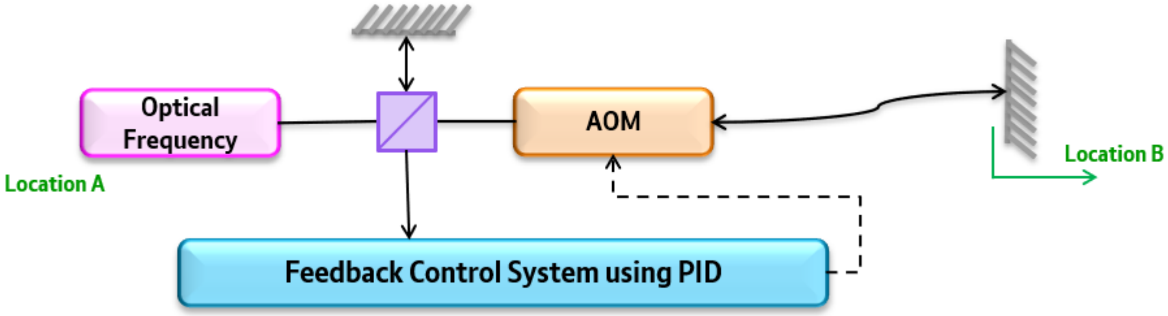


Figure 4.1: Diagram illustrating the path length stabilisation technique

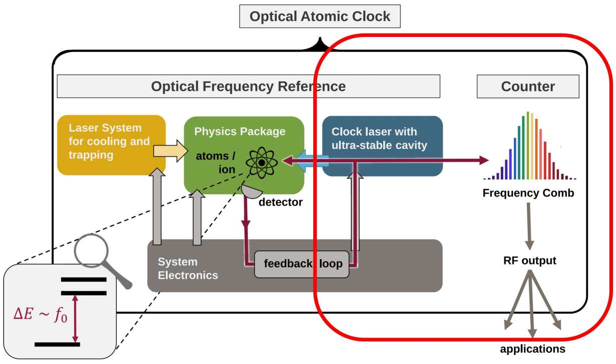
Dissemination of ultra-stable frequencies to a specific distance will help to limit the errors accumulated over the network. It is a challenge to transport ultra-stable frequencies over a telecom infrastructure. A good number of projects demonstrate frequency dissemination over fibre with good stability. One example is the REFIMEVE project [66], which aims to disseminate ultra-stable optical frequency over long distances, connecting multiple national laboratories as well. The stability achieved at present is approximately 10^{-19} [66]. The current telecom infrastructure comprises single and dual fibre working. In the case of dual fibre working, transmission and reception are along different fibres. This creates a differential path length, which challenges the techniques mentioned earlier, as it degrades the frequency stability.

In summary, path length stabilisation or phase noise cancellation techniques consist of optics at the transmitting end to compensate for the error induced. Maintaining a circuit, as shown in figure 4.1 in a telecom data centre, is quite complex due to space and environment constraints. Moreover, setting up the circuitry is challenging and costly when the number of nodes proliferates. A better technique is required to disseminate frequency over telecom fibre to aid towards the use of optical clocks in the near future. This chapter examines a novel method to transmit stable optical frequency from an Optical Reference System (ORS) over fibre. The technique uses a dual fibre to transport stable frequency. The transmission and reception are over different fibre cables, which creates a differential path length. The technique compensates for the error to achieve stability beyond 10^{-12}.

4.2 Unsteered Caesium vs Ultra-Stable Reference System

The Optical Reference System (ORS) ultra-stable laser system is a portable solution for high-precision measurements. The difference between measured frequency and actual atomic transition frequency is the uncertainty value of the system [17]. The Caesium-based atomic clocks oscillate at a frequency close to 10^{10} Hz, and their uncertainties correspond approximately to 1 part in 10^{16} [16] in the best case scenario. Optical atomic clocks, the next generation of atomic clocks, achieve uncertainty in the order of 1 part in 10^{19} [16] or beyond. An ORS is similar to an optical atomic clock but is less complex in terms of components and functionality. Figure 4.2a shows the components included in an optical atomic clock. It mainly consists of a laser system, a physics package, an ultra-stable cavity, a counter, a frequency comb and associated electronics. The components within the red box indicated in figure 4.2a are included in an ORS ultra-stable cavity system. Figure 4.2b shows an ORS ultra-stable system as a functional product.

ORS is a rack-based transportable device comprising an ultra-stable cavity, frequency comb and associated electronic components. The system uses a Fabry-Perot cavity. The high finesse cavity in the system acts as the optical reference, and it is one of the main components of the system. The cavity consists of two mirrors with high-reflectivity coatings. The surface of the mirror consists of ultra-low expansion glass to prevent changes in cavity length due to



(a) Components included in an ORS system [14]

(b) The commercially available ORS system [55]

Figure 4.2: An Optical Reference System (ORS) is not a complete optical clock but is built up of few main components of an optical clock. The figure on left has a red square box. The modules within the red square box are utilised in building a portable optical reference system. A commercially available optical reference system is shown on the right side.

temperature fluctuations. A vacuum housing encloses the cavity. The cavity, vacuum casing and ion pump form the optical reference system [16]. The system is mounted on an active vibration isolation platform and shielded from acoustic and thermal perturbations to enable the system to be transportable and operational even in rough or harsh environments [16]. The optical frequency generated from the device drives the frequency comb. The output from the comb is a stable 10MHz frequency signal.

Though an ORS ultra-stable system demonstrates good stability, it is designed mainly for applications demanding high-precision measurements and not for telecommunications. The clocks used for telecommunication applications must have good long-term stability. Since the ORS device is suitable for high-precision measurements, it is necessary to understand its stability. The device exhibits good short-term stability [55], but the long-term stability needs evaluation to understand its fitness in a telecommunication infrastructure.

Figure 4.3 demonstrates the experimental setup to evaluate the long-term stability

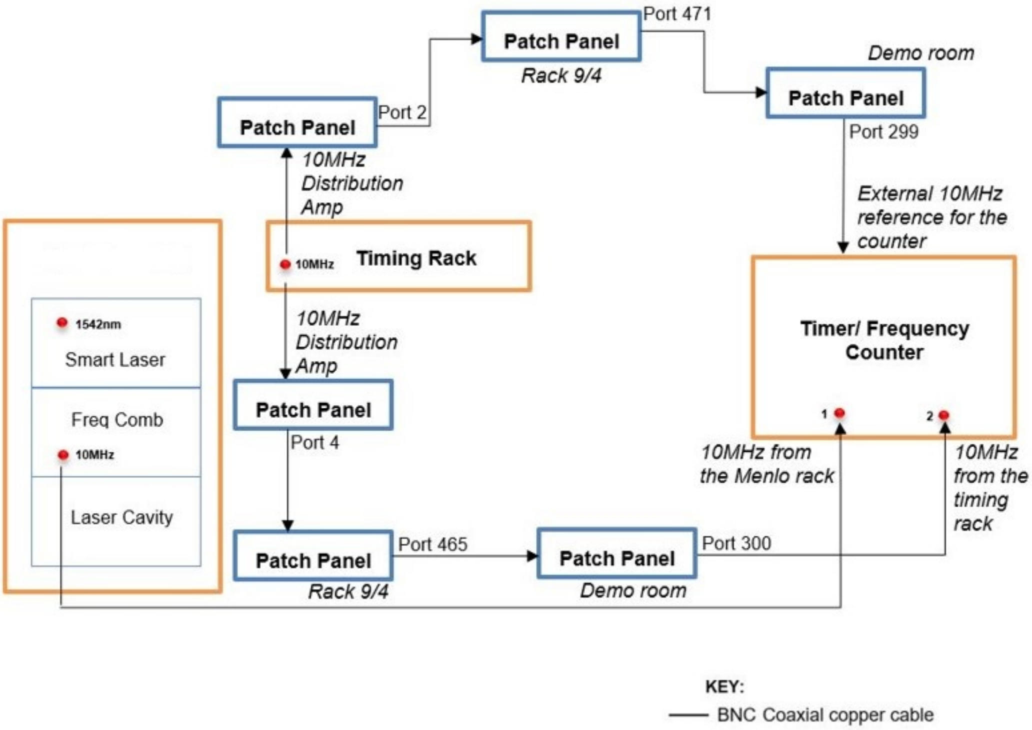


Figure 4.3: Experimental setup to understand the long-term stability of an ORS

of the device. The comparison is against the frequency output from the reference source. The reference source is a rack-based system with GNSS and atomic clocks to generate an accurate timescale. The comparison of the 10 MHz output signal from the comb against the 10 MHz signal generated from the reference rack determines the stability exhibited by the system over the long term. The outputs feed to a frequency counter to understand frequency deviations or fluctuations. The experiment ran for 42 days.

Figure 4.4 demonstrates the experimental setup to evaluate the long-term stability of a commercially available caesium device. It is an equipment developed for a telecommunication infrastructure. Hence, it should demonstrate good long-term stability. The experiment is similar to the previous case, where the frequency comparison is against the stable reference source in the laboratory. The 10 MHz signal helps to understand the long-term stability of the device. The experiment ran for 42 days. The frequency counter recorded the frequency

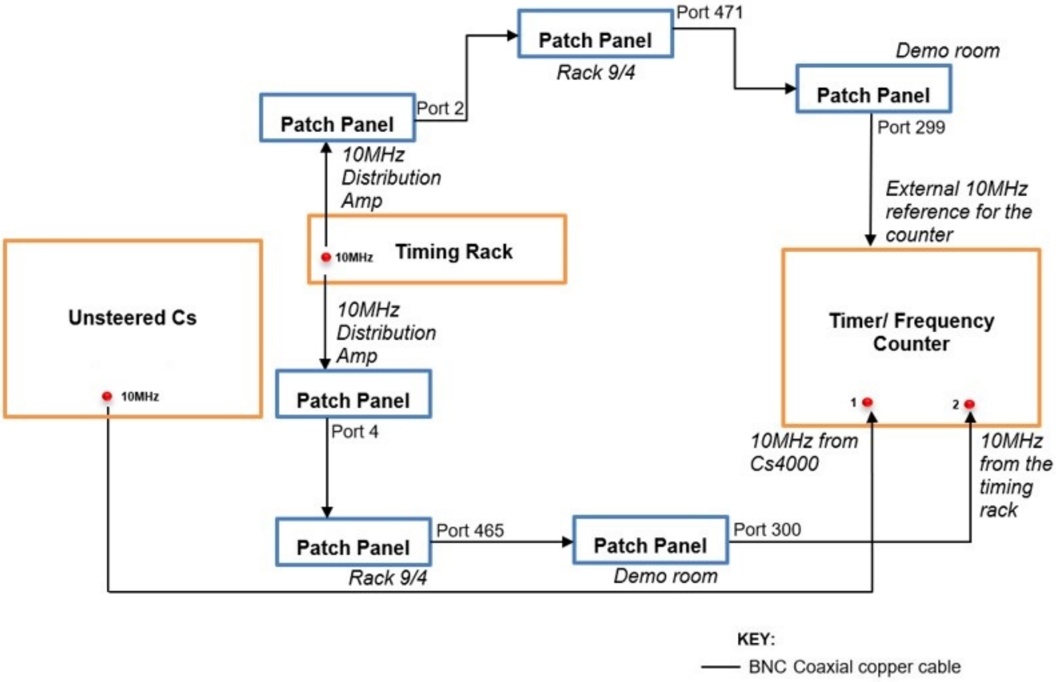


Figure 4.4: Experimental setup to understand the long-term stability of a commercially available Cs device

fluctuations. The stability of the device is evident from the Allan Deviation graphs plotted.

Allan Variance (AVAR) and Allan Deviation (ADEV) plots aids to understand the frequency stability in clocks and oscillators. ADEV ($\sigma_y(\tau)$) is the square root of AVAR ($\sigma_y^2(\tau)$), where τ is the observation time. AVAR intends to understand variations in the frequency of the device due to noise affecting the signal. The frequency stability of a clock can be affected by phase noise which comprises of flicker frequency noise and white noise. A low ADEV plot over the measured period is the characteristic of a good oscillator or clock. For example, an ADEV of 1.0 x 10^{-9} over an observation period of 1 second indicates the frequency instability between two samples observed 1 second apart. For example, analysis of a 10 MHz sinusoidal output from a clock will correspond to a 1 mHz fluctuation from the actual value over the 1 second observation period. While recording the data for similar plots, dead time used to be a concern previously. Dead time is the time interval after the occurrence of a pulse for which the counter is insensitive to record the events. The introduction of zero dead time counters helps to eliminate these limitations.

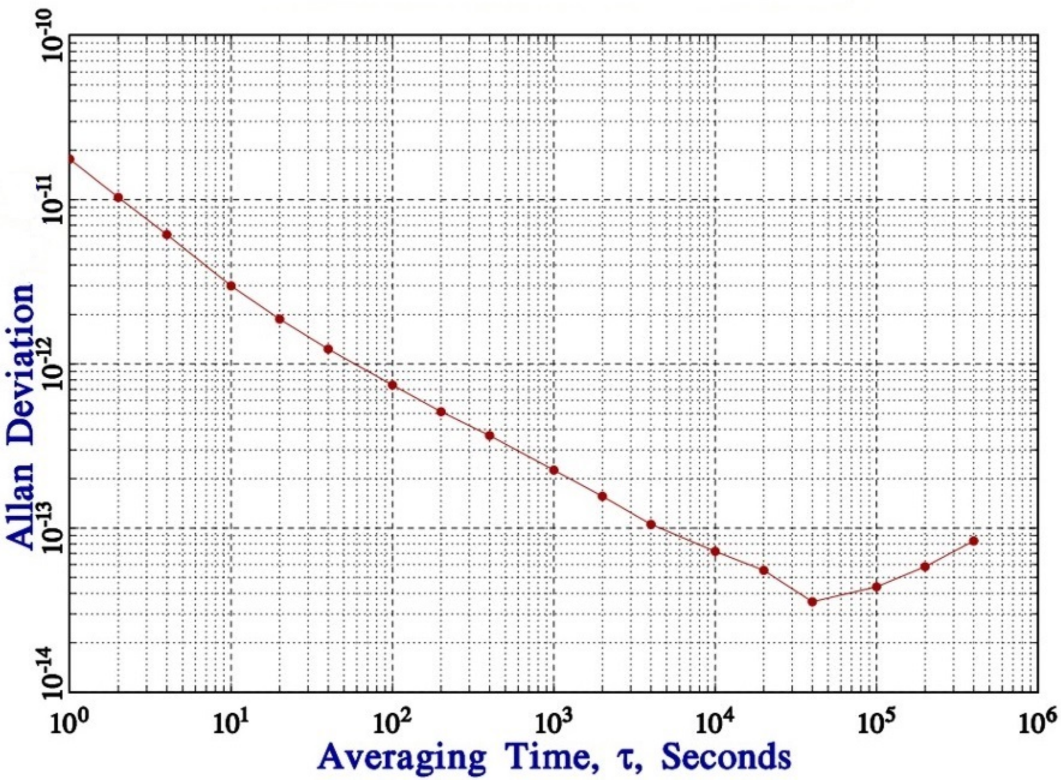


Figure 4.5: Long-term stability of an ORS device

Figure 4.5 shows the long-term stability plot of the ORS device. The device initially takes a while (approximately one hour) to stabilise, which generally refers to the warm-up period. After the warm-up period, the stability of the device gradually improves. It is evident from the graph that the stability improves over the period as it goes beyond 1 part in 10^{13}. However, the stability degrades slightly after a period (10^5 averaging time). Stability degradation over the longer term is primarily due to the limitation from the system. The system is designed for precision measurements, which demand good short-term stability. Hence, after certain period of time frequency fluctuations were observed that resulted in the degradation of stability. Therefore, the device demonstrates good stability over the short term.

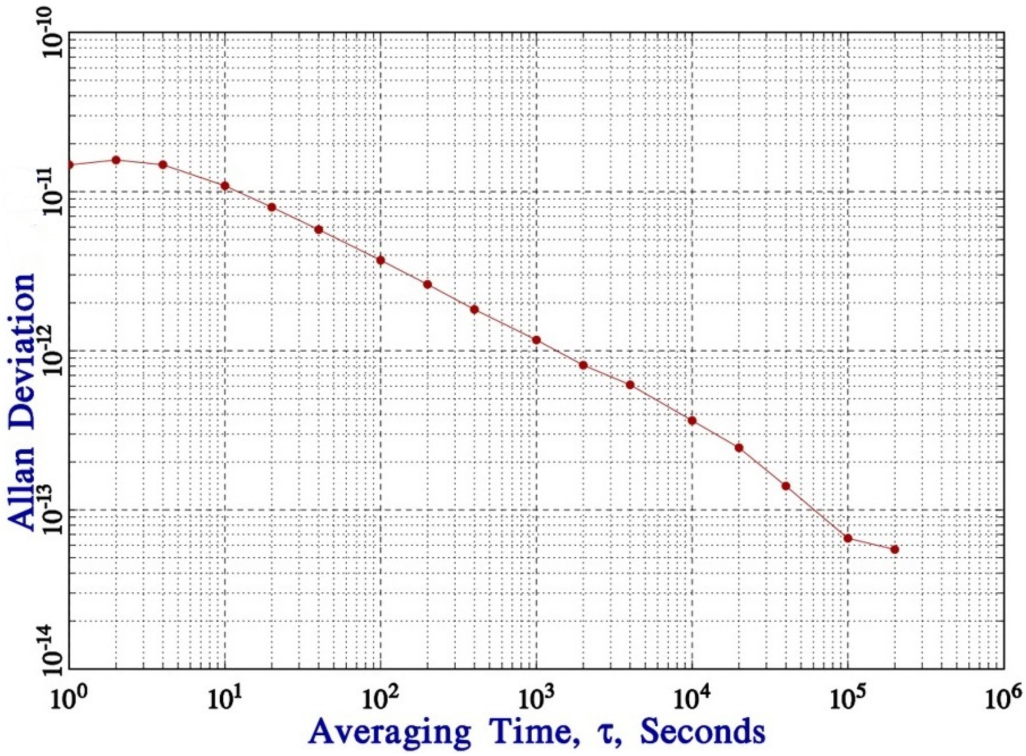


Figure 4.6: Long-term stability of a commercially available caesium device

Figure 4.6 shows the long-term stability plot of a commercially available caesium device developed for telecommunication applications. The device takes a while (approximately 20 to 30 minutes) to stabilise. After the warm-up period, the stability of the device starts to improve. The graph indicates that the device exhibits good stability beyond 1 part in 10^{13} over the period of 10^5 s averaging time. The frequency fluctuations are minimal. It is evident from the plot that the stability of the Cs device remains better even after the averaging period of 10^5 s when compared to ORS. Hence, the Cs device provides good stability over the longer term.

From the graphs 4.5 and 4.6, it is evident that the stability of the ORS device degrades after an approximate averaging time of 10^5, whereas the stability of the caesium device is maintained. Since the ORS device exhibits good short-term stability and the caesium device exhibits good long-term stability, we can conclude that the caesium device is more suitable for telecommunication infrastructure.

4.3 Frequency Dissemination over Telecom Fibre

Optical atomic clocks aid in disseminating ultra-stable frequencies over longer distances over optical fibres [66]. The work detailed in this section describes a solution which can transport optical frequency over bidirectional fibres (transmission and reception of a signal is over the same fibre) and unidirectional fibres (transmission and reception of a signal is over different fibre). The use of bidirectional fibres to transfer optical frequency has already been demonstrated [66]. Hence, this experiment focuses on understanding the frequency stability achievable if differential path lengths are created by transmitting and receiving through different fibre cables.

Synchronising various components of a telecom network refers to disciplining oscillators within the network equipment at different nodes. Frequency synchronisation is essential for proper handover between multiple cell sites and base stations. From the perspective of telecom infrastructure and the architectures detailed in the previous chapter, transportation of optical frequency from an optical atomic clock over fibre is necessary to discipline the nearest ePRTC device. Hence, transporting a stable frequency signal over the fibre is essential. However, various factors could contribute to noise and affect the frequency of the signal when it propagates through a fibre cable. There could be attenuation which results in gradual loss of strength of the signal as it propagates through the fibre. This is due to absorption or scattering of light as it navigates through the medium. Attenuation could reduce the signal power, which results in a lower signal-to-noise (SNR) ratio. Low SNR makes it difficult to distinguish the signal from noise. The frequency component could be masked by noise making it challenging to identify the frequency component. Light with different frequencies propagates at various speeds through the fibre. This will cause the signal to spread in time, broadening the pulse or overlapping adjacent pulses. The microscopic variations in the fibre material could lead to scattering of light as it propagates through the fibre and signal loss. This is termed as Rayleigh scattering. This introduces noise to the signal, which could overlap with the frequency component of the signal making it difficult to distinguish the frequency of the signal.

The experiment looks into transmitting the operative frequency as the beat frequency of a heterodyne signal. Heterodyne signals are generated by mixing two different frequencies to create new frequencies. These signals at different frequencies when combined results in new signals at the sum and difference of the initial frequencies ((f1 + f2) and (f1 - f2)), where f1 and f2 are frequencies of signals from different sources [53]. Upon transmission over fibre, both signals get affected by noise. The frequency difference detected at the receiver side (photodetector 2 in Figure 4.7) corresponds to the beat frequency. The beat frequency is unaffected by noise upon using the frequency difference (f1 - f2) and thus provides better syntonisation. The experiment looks into verifying the above-mentioned technique using an optical reference system.

Figure 4.7 shows the experimental setup for frequency dissemination. The optical clock is in one of the network exchanges. The reference frequency disciplines the timing equipment located in a different network node. The signal from an optical clock is in the terahertz range, approximately in between 100 THz to 200 THz, depending on the type of atom used and their optical transition frequency. Telecom equipment requires a 10 MHz signal for syntonisation. The heterodyne signal generated from f1 (frequency of a signal from stable laser source) and f2 (frequency of a signal from an AOM) frequencies aids in generating frequency in the radio frequency range to synchronise the timing device. The heterodyne signal is detected at the network node using a photodetector whose sensitivity range falls within the difference in the frequencies of the heterodyne signal (f1 - f2) to generate a signal

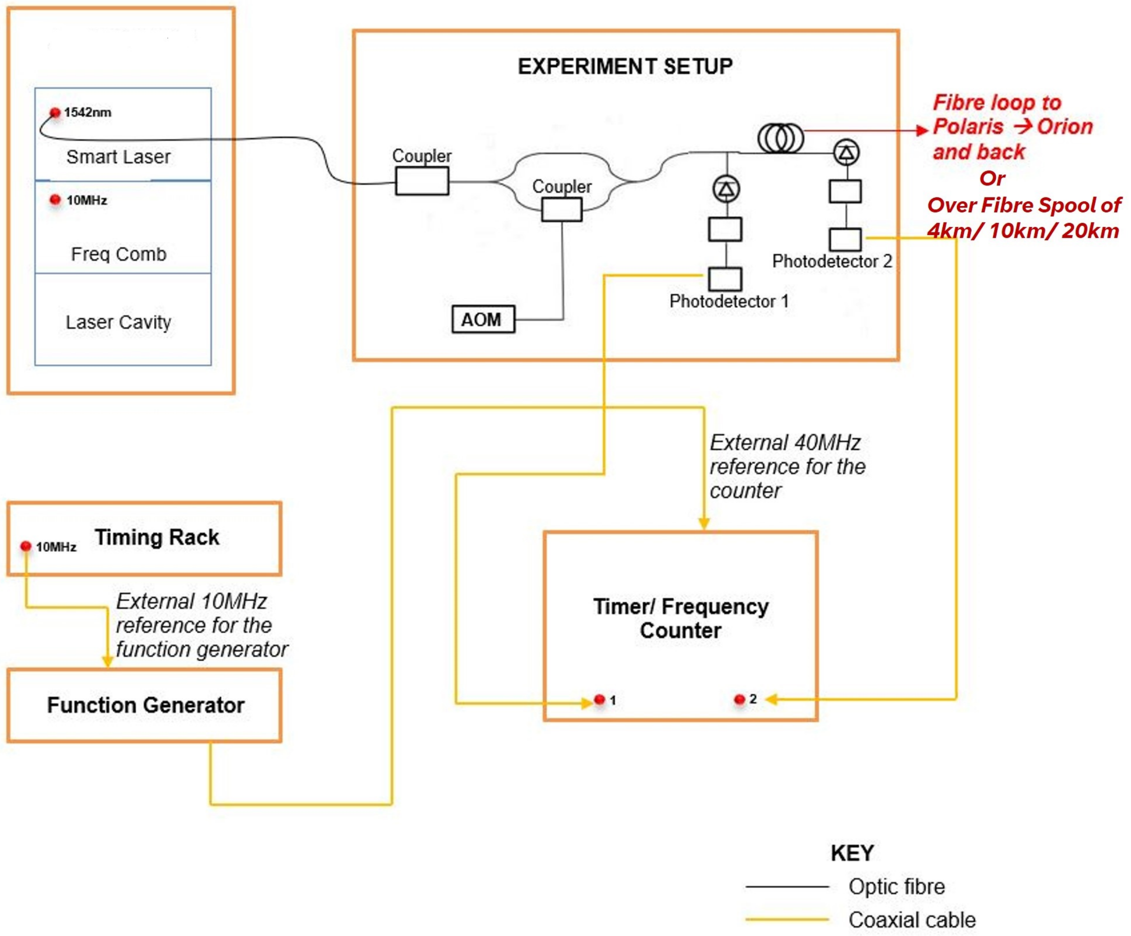


Figure 4.7: Experiment setup for the dissemination of optical frequency over fibre

in the Radio Frequency (RF) range, desirable for disciplining the oscillator in the timing device. The heterodyne signal is formed by combining two signals using a coupler. One of the signals is the output from a laser source and the second is the modulated signal using an AOM. The optical reference system used in the experiment generates a 1542 nm stable optical signal. This signal is used to drive the AOM as well.

The splitter splits the optical signal into two arms. AOM shifts the frequency of the optical signal in one of the arms. The input to the AOM is the stable optical signal from the optical reference cavity. The experiment uses a 40 MHz AOM. An ideal case requires a 10 MHz AOM. This is because the timing equipment uses a stable signal at 10 MHz to discipline the local oscillator within the equipment. The AOM aids in increasing the frequency of the signal by an amount equivalent to the frequency of the AOM. The coupler combines signals from both arms to generate a heterodyne signal consisting of frequencies (f1 + f2) and (f1 - f2). The sensitivity of the photodetectors used in the experiment is within the range (f1 - f2) and hence does not detect high-frequency signals. The second photodetector placed at the receiving end detects the received signal. Both signals are fed to a frequency counter to understand frequency variations and determine the stability achieved by the system.

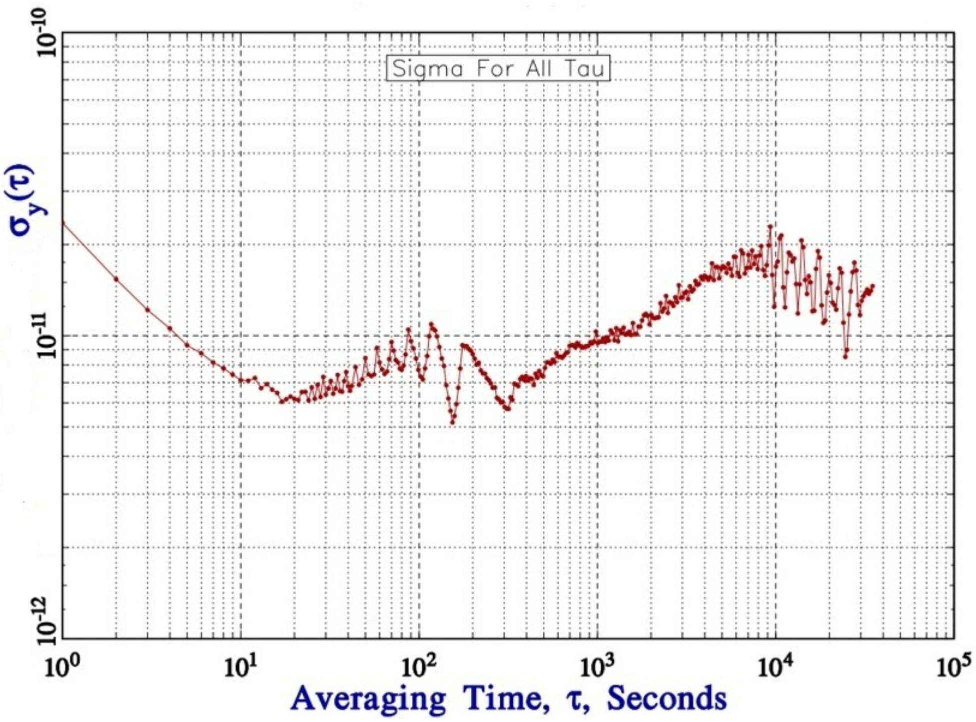


Figure 4.8: Stability over 4 km fibre spool in lab

The experiment was conducted over a 4 km fibre spool in the lab and over a 4.8 km fibre test link. The 4.8 km test link is a fibre link deployed at Adastral Park connecting two buildings across the site namely, Orion and Polaris. Since the experiment was done on dual fibre working, one of the links was 2 km long and the other was 2.8 km long, creating a differential path length. The frequency variations were monitored and this information was used to plot ADEV graphs. The ADEV plots represented in figure 4.8 and figure

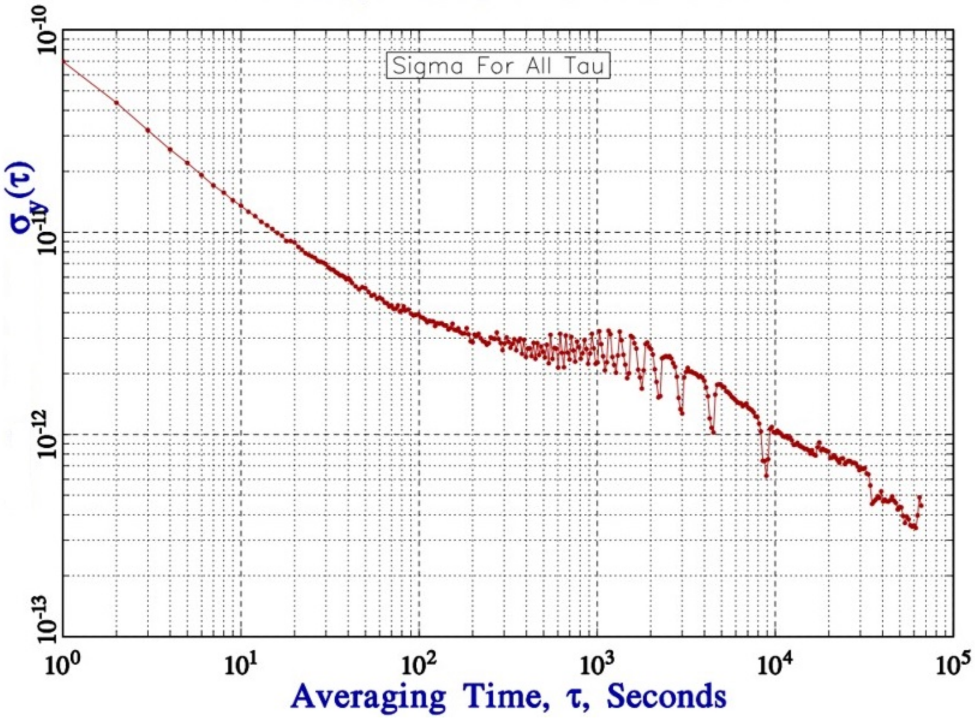


Figure 4.9: Stability over 4.8 km fibre test link

4.9 compare the frequency stability achieved in both scenarios. The graphs indicate that frequency dissemination over the fibre test link shows better stability than the fibre spool in the lab. In a fibre spool, fibres are close to each other and wound tightly. It results in interference within the fibre, causing frequency fluctuations. In the case of a fibre test link, the fibre had proper insulation and laid over the ground. It implies that it is not tightly wound as in previous instances and thus reduces interference. Hence, frequency variations were less, which aided in better stability. The optical signal is not amplified before transmitting it over the fibre. There are a few dBs of losses over patch panels, components, and connectors, but they are not considerable enough to degrade the signal quality over the link.

The results indicate it is ideal to use a proper test link to conduct experiments related to frequency transfer. The subsequent experiments were on fibre spools of 10 km and 20 km length to better understand the previous conclusion. The longer the spool is, the worse the interference will be; therefore, there will be poorer frequency stability. The frequency

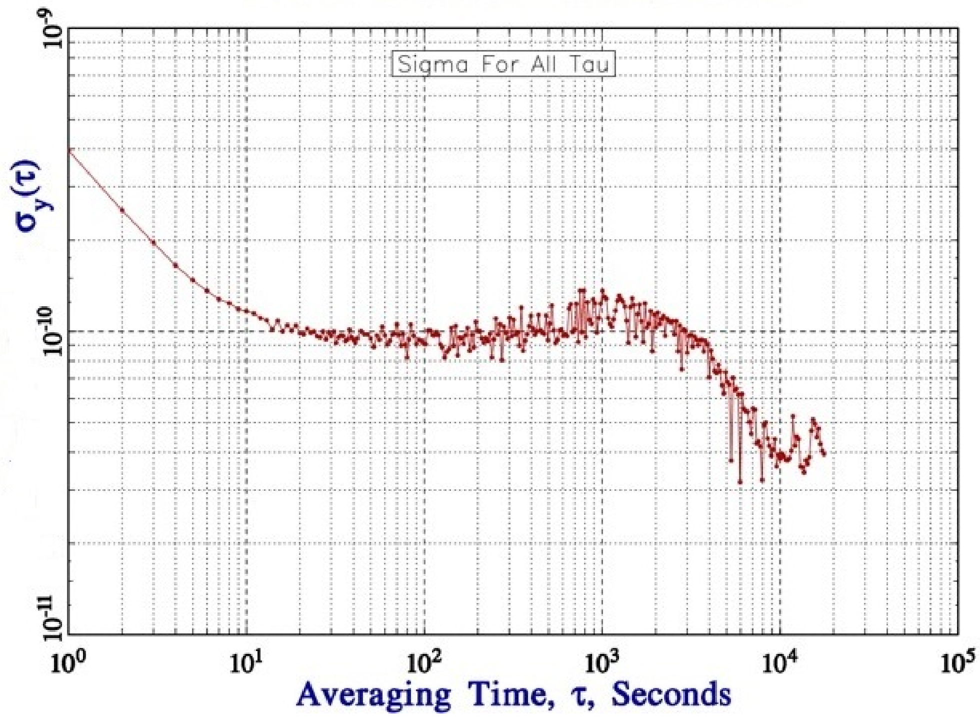


Figure 4.10: Stability over 10 km fibre spool in lab

stability plots in figure 4.10 and 4.11 show the degradation in stability when the length of the fibre winding in the fibre spool increases. The graphs indicate that frequency stability over a 4 km fibre reel is better than that achieved over a 10 km or 20 km fibre reel, and frequency stability over a 10 km fibre reel is better than the 20 km fibre reel. Therefore, it is evident that the frequency fluctuations were mainly because of the interference generated by the fibre itself. Therefore, a fibre spool is not a good option to conduct a frequency stability test. However, the experiment aimed to understand the frequency stability over the fibre link to disseminate stable frequency from reference over fibre. As the results from figure 4.9 indicate, frequency stability of 10^{-12} over 10^4 s averaging time justifies this as an effective technique to disseminate frequency over unidirectional fibres.

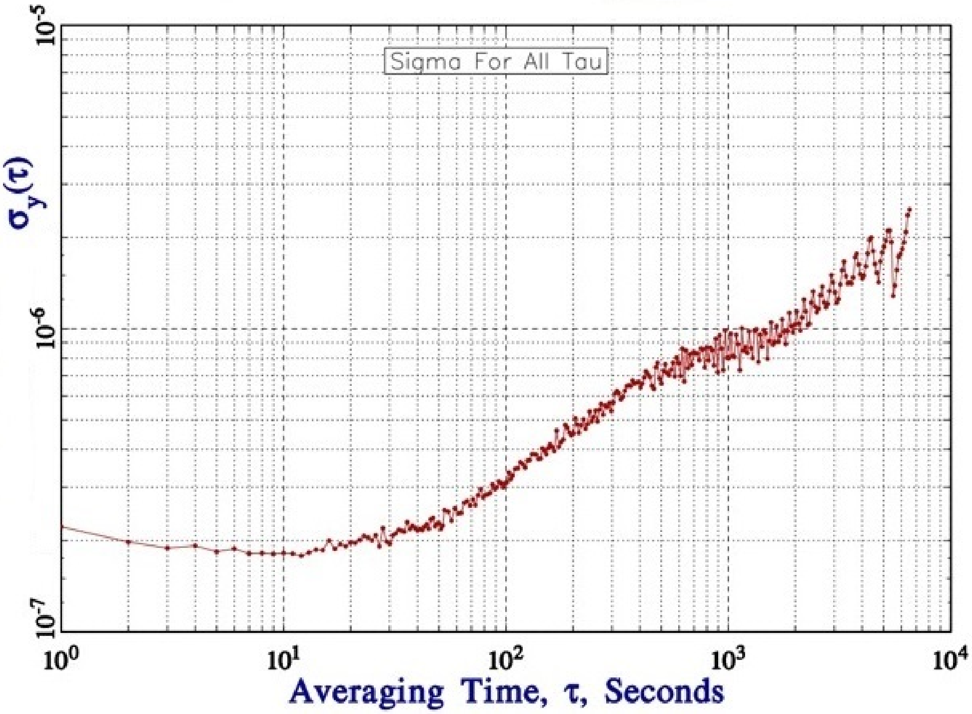


Figure 4.11: Stability over 20 km fibre spool in lab

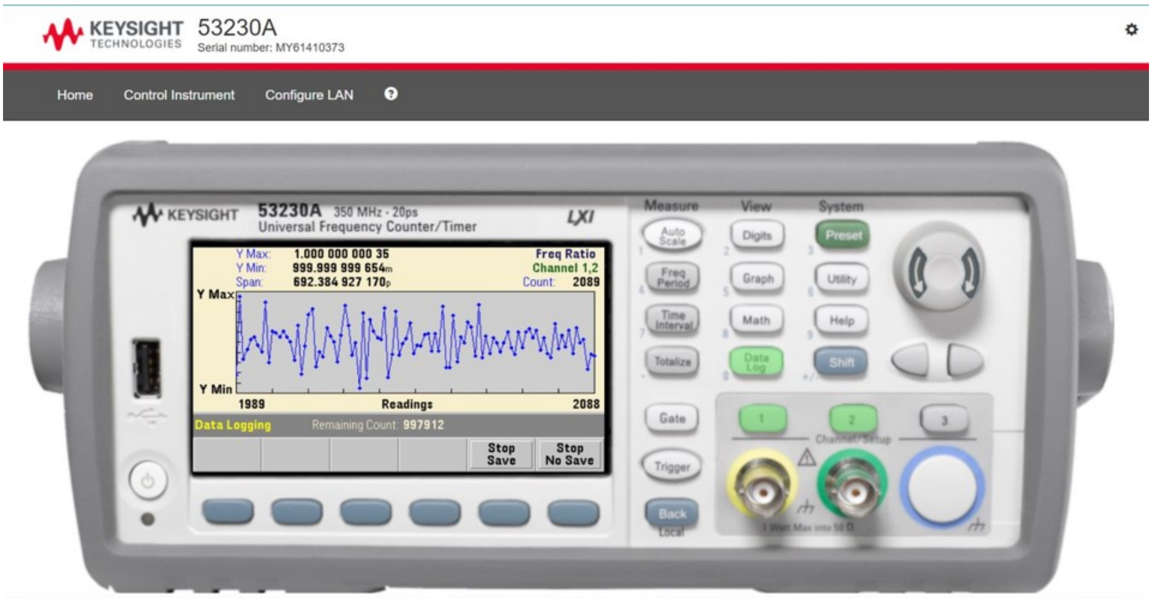


Figure 4.12: Frequency fluctuations observed in a frequency counter

4.4 Conclusion

The experiment aided in understanding the feasibility of dissemination of optical frequency over a fibre network with differential path lengths. In principle, the optical reference system resembles an optical atomic clock and generates a narrow linewidth (approximately 1 Hz) optical output at 1542 nm. The experiment helps establish the knowledge required for disseminating optical frequency over fibre infrastructure. It is an essential part of the national-level fibre-based GNSS-independent infrastructure for UTC. In the near future, optical atomic clocks will be commercially available. Therefore, the experiment helps to understand the challenges in disseminating frequency over longer distances over telecom fibres. The current state of the art looks into using bidirectional fibres to achieve higher stability. The technique does not work effectively in unidirectional fibres due to differences in the path length. A Telecom network consists of unidirectional and bidirectional fibres. The novel technique described in the chapter investigates achieving high stability in unidirectional fibre-based infrastructure.

From the experiment, it is evident that the fibre cable picks up disturbances induced on them. The optical signal suffers attenuation, dispersion, and scattering when propagating through the fibre, thereby introducing noise to the signal. These result in frequency fluctuations and challenges in distinguishing the frequency of the signal from the noise signal. Figure 4.12 shows frequency variations observed due to the effect of external disturbances introduced when testing over the 4.8 km fibre test link. The peaks in the figure correspond to frequency fluctuations due to such disturbances affecting the signal propagating through the fibre. The high peaks in figure 4.12 correspond to higher frequency drifts produced by disturbances added into the fibre. The shorter peaks in figure 4.12 correspond to the lower frequency drifts created, as the fibre was relatively stable and less affected by external disturbances. It aids in contributing to a novel interferometry technique using optical atomic clocks in the future. The experiment aided in understanding frequency dissemination over fibre and will give a better understanding of frequency transfer when optical clocks are in locations farther from the tier 1 nodes. However, the accuracy is still affected by the effect of asymmetries and other network components. Positioning best clocks at the core does not guarantee ps level precision at the edge. The following chapter details FPGA-based techniques that aid in achieving ps-level precision at the edge of the network.

Chapter Five

High Precision Time Transfer using FPGA

Time synchronisation is one of the critical aspects of 5G and future generations of telecom networks [50]. Recent advances in low-latency applications, radio technologies, automotive applications and time-critical applications have made high-precision timekeeping a fundamental requirement for a resilient and reliable network operation. In 5G-Advanced and 6G networks, absolute time is crucial to ensure critical use cases, synchronise media playout, and timestamp events for machine-learned contexts [4]. With the evolution of quantum communication systems, time distribution has become essential for synchronising and timestamping the arrival of photons [11]. At present, timing devices in a telecom infrastructure use GNSS receivers or transport techniques such as NTP, PTP and SyncE to synchronise the remote node to a reference node [21]. These systems achieve nanosecond scale accuracy. High-accuracy PTP (also known as White Rabbit) [35] is a synchronisation protocol that achieves nanosecond level accuracy and picosecond level precision. The work detailed in [8] utilises White Rabbit (WR) and digital dual mixer time difference to achieve picosecond precision for timestamping events in a Field Programmable Gate Array (FPGA) module.

The White Rabbit protocol combines phase detection and link calibration techniques with PTP and SyncE synchronisation protocols to achieve picosecond scale precision. However, these techniques require multiple and complex hardware circuitry to work efficiently. The time error added into the signal due to dynamic factors such as changes in temperature, rerouting, unknown link asymmetry and quality of syntonisation degrade the precision achieved even further [35]. These factors limit the precision achieved, especially with the proliferation of nodes in a given network. Another way to provide time measurements in the picoseconds regime is applying time to digital conversion to represent the time events digitally [10]. Time to Digital Converters (TDCs) utilise a trigger signal along with the coarse and fine counters to generate timestamps. Coarse measurements are suitable for scenarios where applications are less constrained in terms of precision. In comparison, fine measurement fits well in scenarios where the application demands higher resolution measurements. TDC architectures such as tapped delay lines and Vernier structures are apt for fine measurements. Some of these methods achieve 10 ps precision with FPGAs [22]. The work detailed in [7] applies coarse and fine counts to achieve 21.2 ps precision across two nodes. TDC implementations are commonly FPGA or Application Specific Integrated Circuit (ASIC) based.

Integrated circuits are a set of electronic circuits embedded in a flat piece of semiconductor material. FPGAs are programmable integrated circuits. They emerged from Programmable Read Only Memory (PROMs) and Programmable Logic Device (PLDs) and consists of interconnected programmable logic blocks. FPGAs are useful for aerospace, automotive, and telecommunications applications where speed, flexibility and parallel processing capabilities are required. The logic blocks within an FPGA are programmable to perform functions ranging from simple logic gates to complex combinational circuits. They consist of flip-flops as memory blocks. FPGAs are programmed using configuration files, allowing users to implement multiple logic functions without changing physical connections. They consist of synchronous circuits driven by a clock signal and have phase-locked loops to generate new clock frequencies with minimal jitter. Multiple clocks are available across different domains in an FPGA module to support complex designs that require multiple clocks. The boards also include oscillators to generate clock signals at specific frequencies.

Hardware Description Language (HDL) is mainly used for programming an FPGA. The commonly used HDLs are VHSCI (Very High-Speed Integrated Circuit) Hardware Description Language (VHDL) and Verilog. Verilog is a much more popular and simpler hardware description language, similar to the C program in style. Meanwhile, VHDL programming is similar to assembly language programming. Programming FPGAs by creating block diagrams is another way of hardware programming. Drawing block diagrams and making required connections is intricate, especially when designs are large and complex. Therefore, programming FPGAs using HDL is the best practice. Electronic software tools (such as Vivado for Xilinx boards) are available for FPGA design and programming. After programming, these tools generate a map detailing the electronic components and routes used for the design, generally called a netlist. Timing analysis, validation, and verification methods available in the software suite help validate the generated netlist.

After design and validation, the next step is to generate the binary files using vendor-specific software and licenses. The binary file configures the FPGA using a serial interface. The FPGA consists of a list of predefined functions, circuits and primitives to reduce the complexity of the design. These predefined circuits are generally known as intellectual property (IP) cores. Most of the IPs are not available for use, and those that are available are only available with proprietary licenses. FPGA programming follows a series of steps. The design needs thorough validation, as debugging the code using breakpoints, a common practice in debugging errors in software languages, is impossible. The application developer implements the design in VHDL or Verilog language. The design needs validation at different stages throughout the process. It can be a simulation-based method by creating test benches, which is an environment to validate the correctness of the design. Test benches and generated outputs help to verify the functionality of the design. Since FPGA programming results in multiple files with different logic blocks, it is always a best practice to validate the functionality of each logic block upon its completion. The synthesis and implementation process generates a netlist, which is helpful for further validation at the gate, circuit or routing level. Figure 5.1 details the internal components in an FPGA fabric.

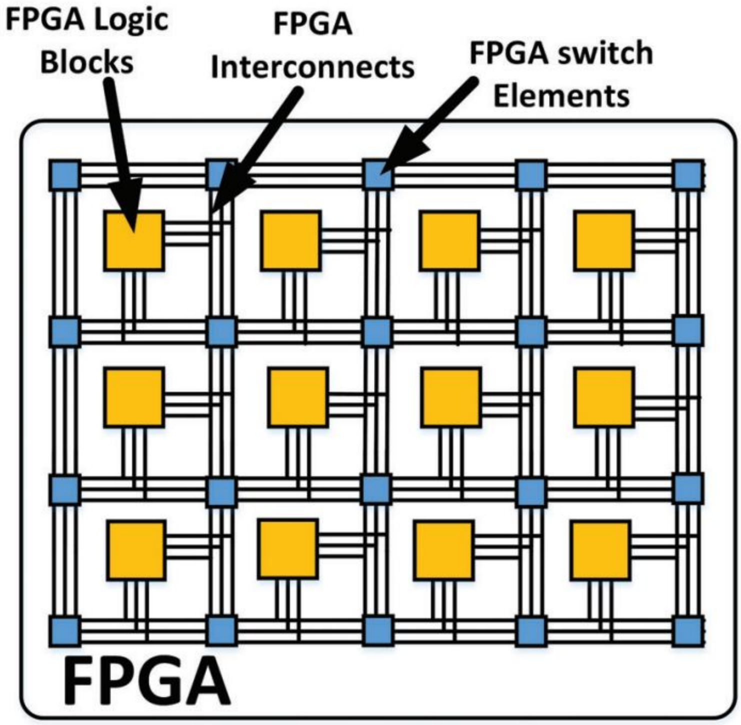


Figure 5.1: The figure illustrates the internal components of an FPGA fabric [29].

A novel architecture to distribute time with a picosecond level precision using the FPGA modules is explored in this chapter. The main idea behind this work is to design an FPGA module to capitalise on coherent transmission technology with associated measurement of phase and powerful Digital Signal Processing (DSP). A future precision timing network requires highly accurate clocks and techniques to transport clock signals over optical fibre. There could be fewer clocks if the transportation element was efficient. The FPGA-based approach discussed in this chapter leverages existing coherent transmission technology to provide a solution capable of distributing ps-level precision.

Additionally, this architecture can benefit a wide range of applications demanding precise timing, such as data centres, telecom and quantum networks. FPGAs are known as a valuable platform for network planning, especially in the 5G networks, since they can provide an accelerator for Core-Radio Access Network (C-RAN) , network slicing using Network Function Virtualization (NFV), characterisation of Massive Multiple Input Multiple Output (Massive MIMO) and cognitive radio framework [23]. Hence, it is feasible to integrate an FPGA-based solution into the hardware part of the network equipment to improve synchronisation. A high-precision timing method using FPGAs could be an effective technique for precise synchronisation at different nodes in a network. This work is a collaboration between Nubis Communications, British Telecommunications PLC and the University of Bristol. Nubis Communications helped with the high-level design. My secondment work which was an essential part of the research, was at the University of Bristol. As part of the secondment, I demonstrated the proof of concept where remote nodes in a network were synchronised to the central node to pico-second scale precision. The proof of concept was developed on an FPGA fabric. The University of Bristol instructed on the essential skills related to FPGA and provided the hardware required to set up the experiment.

The work described in this chapter details a technique to synchronise multiple nodes in a network using an FPGA-based TDC concept, which can integrate into a 5G architecture in the near future. The technique achieves picosecond scale precision upon synchronising the remote node to a central node in the network. The offset calculation and timestamp correction described in this work is a novel technique I have developed to aid increased precision. Calculation of the offset value aims to compensate for the following:

- The time difference between the timestamps generated at individual nodes
- The time taken by each node to transmit and receive a timestamp which corresponds

to link delay

5.1 Time to Digital Converters

TDCs help in precise time measurements for various applications related to science and engineering. The concept of TDC is similar to an Analog to Digital Converter (ADC) . They convert the input signal in one domain to an output signal in another domain. ADCs convert analog signals to a digital value, whereas TDCs convert time to a digital value. TDCs sample the clock signal based on a trigger signal. They find potential applications in use cases where picosecond precision measurements are necessary. TDC implementations are of two categories: Coarse TDCs and Fine TDCs. Coarse TDCs fit well in scenarios where the application does not demand high-precision measurements. Counters or variations of counters aid in implementing a coarse TDC. Fine TDCs fit well in use cases that demand high-precision measurements. The system clock does not limit the precision achieved in a fine TDC. Therefore, fine TDCs provide measurements in a sub-clock period range. In a nutshell, coarse TDCs are for low-resolution measurements. In contrast, fine TDCs are suitable for high-resolution measurements such as sub-nanosecond, picosecond, or sub-picosecond levels. The TDC implementation used in this work is the most common technique for implementing fine TDC, a tapped delay line structure [10][29].

A tapped delay line consists of N cascaded delay line elements with carry units and flip-flops. An external signal, named the trigger signal, initiates the whole process. The trigger signal is a square wave generated from a signal generator. The carry units generate an output with 1s and 0s. The D-type flip-flops in the design capture these output values. The output generated out of the delay line elements is called thermometer code. The length of the thermometer code is equivalent to the number of delay elements used in the TDC design. Priority encoders help to convert thermometer codes to digital codes. Figure 5.2 illustrates a tapped delay line structure. The tapped delay line TDC samples the clock signal with respect to the rising edge of the trigger signal. The resolution of a TDC defines the smallest time-measurable interval by the system. If the number of delay line elements is N, then the resolution of TDC is given by:

$$Resolution_{TDC} = ClockPeriod/N \tag{5.1}$$

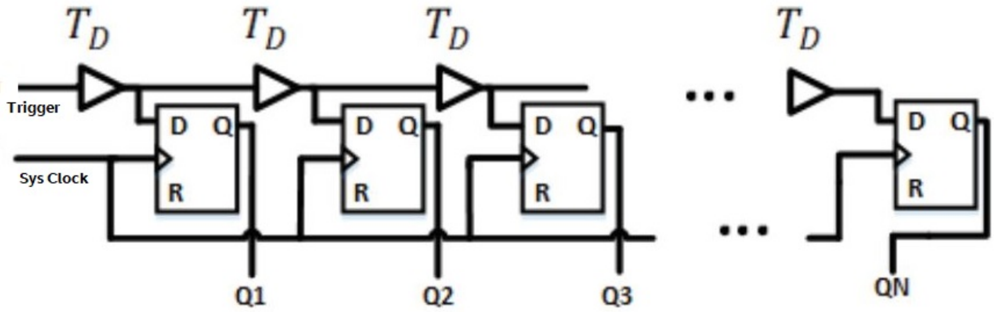


Figure 5.2: The figure illustrates a tapped delay line structure consisting of cascaded delay line elements, which comprises carry units and associated flip-flops [29].

TDCs make use of carry chain units within an FPGA SLICE. Each carry chain structure is a fast carry logic unit and consists of a series of adders, MUXes and XORs. The carry chain units interconnect through dedicated routes to perform complex functions. For the implementation of a TDC, carry chain structures aid in cascading the trigger signal from Carry-In (CIN) to Carry-Out (COUT) (CI to CO in figure 5.3). Each carry element generates a 1 bit output. The flip-flops within the slice capture the output. Figure 5.3 illustrates an FPGA slice. The bits saved in the flip-flops form the thermometer code. Cascading multiple slices forms a more extended delay line structure that generates longer output code. The COUT pin connects to the next slice via the CIN pin.

For every input, TDCs have unique values and identical steps between adjacent codes. In a TDC, the term code represents the measured time interval digitally. A time-to-digital

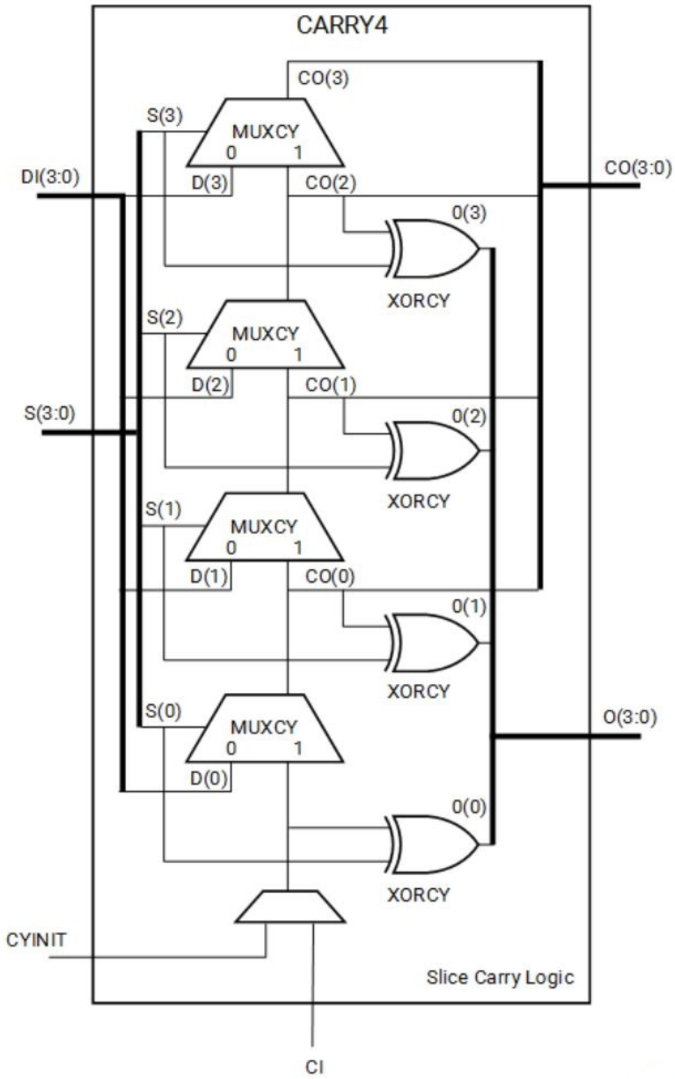


Figure 5.3: Representation of an FPGA slice [74]

converter module converts the time difference between two events into a binary format. This output is termed a code. A TDC module will measure the time interval between two pulses and output a binary value corresponding to the time interval, which is termed as the code. Hence, the input and output codes are linear. However, in a practical scenario, this is different. Due to factors such as temperature fluctuations, power variations and differential internal routing paths, the relationship between input and output codes is non-linear. Therefore, sampling the clock signal creates non-uniform bins.

In some cases, this may also result in missing bins. To overcome these effects, TDC needs calibration. There are multiple ways to calibrate a TDC to reduce the effect of non-linearities and improve the precision of the whole system. The zero-hit bins also affect the linearity of the TDC as they appear as missing codes and are thus invalid. Calibration helps to reduce the number of missing codes, improving the linearity of the whole system. Apart from the non-linearity effects, metastability is another phenomenon that degrades the precision of the TDCs, as they are asynchronous. Metastability occurs due to variations in the setup and holdtime in flip-flops, which results in an unpredictable output state [7]. The output oscillates between '0' and '1'. Eliminating issues due to metastability is impossible, but specific techniques can be implemented to help control them. To overcome the limitations caused by metastability, I have increased the number of synchronising stages in the design by cascading flip-flops to create a one-stage synchroniser. This creates a complete clock period to resolve the metastable events in the first flip-flop.

5.2 High Precision Time Transfer Solution

Figure 5.4 illustrates the high-level design of the solution. The design aims to synchronise central and remote nodes to very high precision. The nodes contain FPGA modules, which receive signals from a common source. The solution achieves high precision through the following main steps:

- Generation of timestamps on individual nodes
- Synchronisation of two nodes by applying offset correction

The signal from the source drives both FPGAs to generate timestamps. The central and remote node generates their timestamps upon receiving the trigger signal from the source.

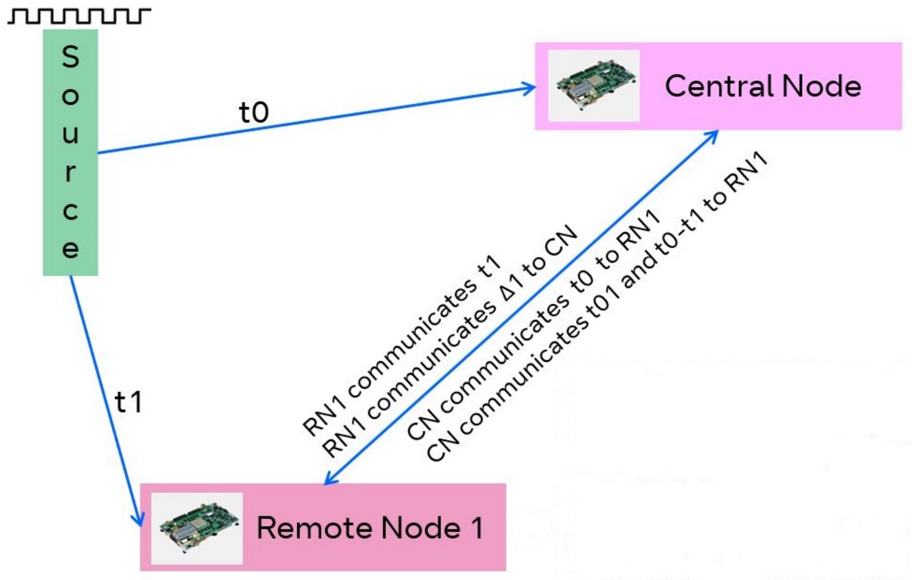


Figure 5.4: Illustration of high precision time transfer solution

The timestamps are different since they are generated independently from different TDC components, this results in poor sync quality. The nodes must be in synchronisation with each other. The exchange of timestamps between central and remote nodes aids in improving synchronisation between the two nodes. The central node transmits its timestamp to the remote node and vice versa. Once both nodes receive their second set of timestamps, they calculate the delta value, which indicates the deviation of one timestamp from the other. This process helps compensate for the differences in timestamps and also provides an estimate of the time taken by each node to transmit and receive a timestamp. This information helps compute the offset value, the correction factor used to correct timestamps at each node to achieve high precision.

Each node consists of an FPGA, which contains a TDC implementation. TDCs generate individual timestamps at every node. Figure 5.5 illustrates a time-to-digital converter module within an FPGA. As described in the previous section, TDC comprises a delayline structure based on carry chain logic units and D flip-flops. The initial phase of TDC implementation was on a student development board, Zedboard. The TDC architecture design on

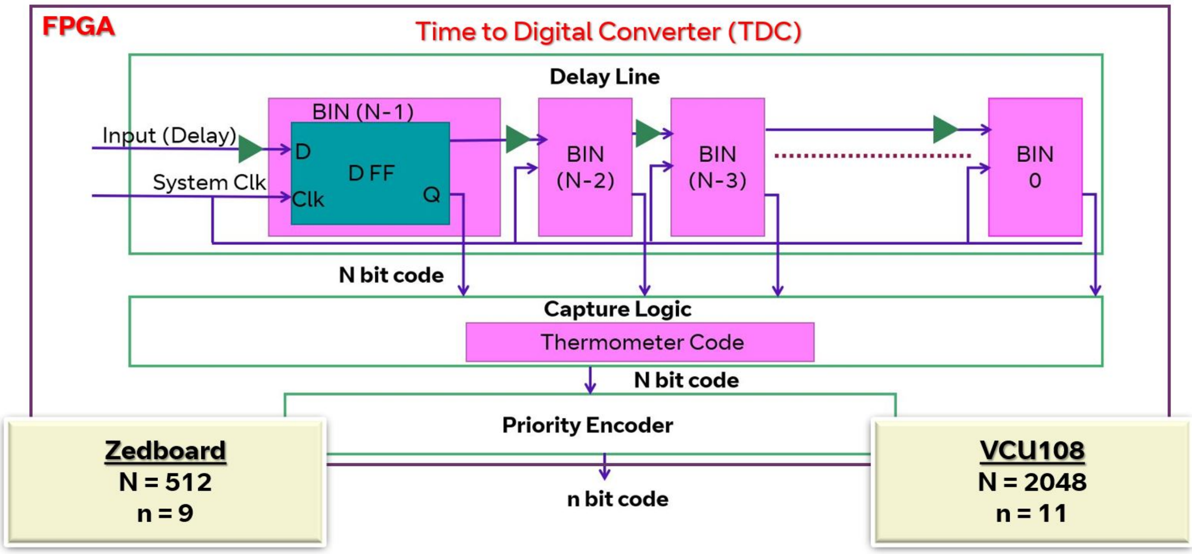


Figure 5.5: Illustration of a time to digital converter

this board consists of a 512-bit CARRY4, a carry chain primitive by Xilinx. The TDC uses 125 MHz as the clock frequency. A 1 MHz signal from the source (as mentioned in figure 5.4) is the trigger signal that instantiates the carry chain structure. The delayline samples the clock period into small bins to generate a 512-bit thermometer code. The priority encoder uses the 512-bit thermometer code to generate a 9-bit raw timestamp by applying a logarithm to the number of 1s in the thermometer code. Analysis of the raw timestamps helps to understand the resolution of the TDC implemented on the Zedboard.

The telecom equipment consists of ultra-scale fast FPGA boards to support high-speed communications. Hence, implementing TDC on an ultrascale board could be better, and therefore, the second part of the experiment was on the Xilinx Virtex Ultrascale (VCU108) board. Ultrascale boards support high-speed communication and possess faster internal routing capability when compared to Zedboards. Moreover, the VCU108 board is more advanced than Zedboard regarding internal components, routing, connectors, and serial communication. The figure 5.6 illustrates the architecture design of a time to digital converter module in an FPGA. The TDC architecture comprises a delayline structure con-

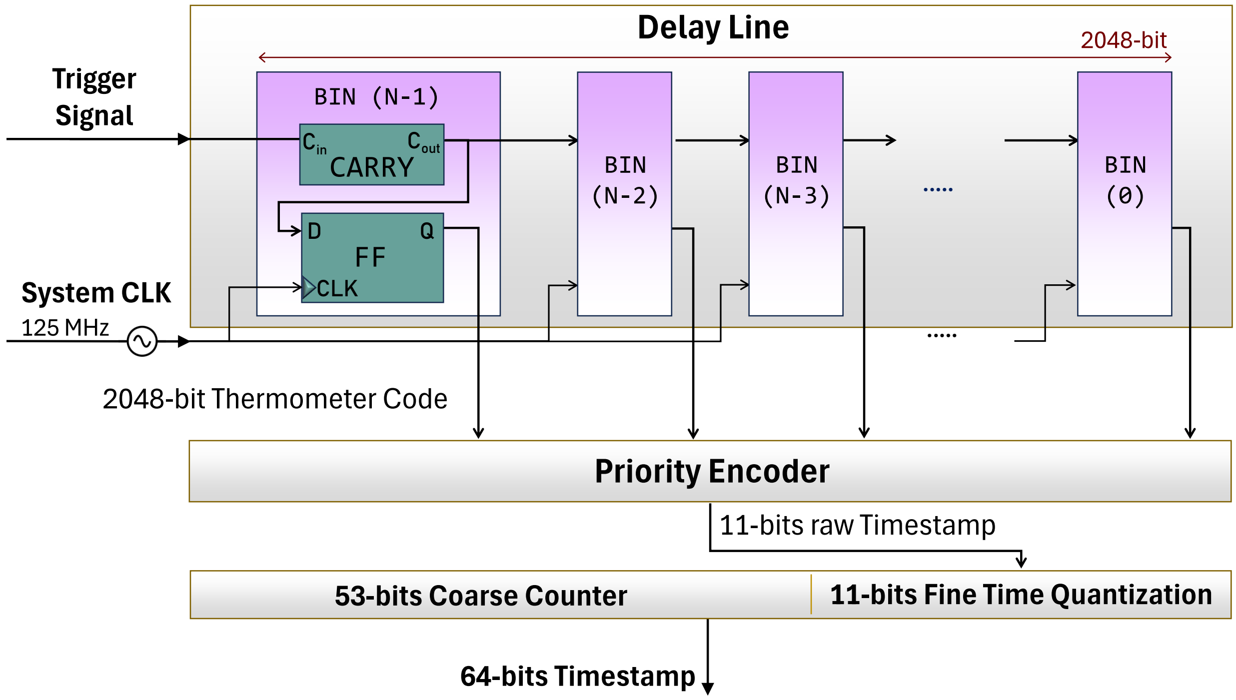


Figure 5.6: Illustration of a functional architecture design time to digital converter in an FPGA with carry chain as a delay line structure.

sisting of carry chains and D flip-flops. The board has Xilinx CARRY8 primitive as the carry chain structure. The carry chain primitives in the VCU108 board are different from the carry chain primitives in Zedboard. They are faster and composed of 8 adder units, 4 more than the Zedboard. Faster carry chain primitives result in increase in signal propagation speed within the FPGA, hence more delayline elements get a hit and therefore better resolution. The system clock used is once again a 125 MHz clock. This clock signal is generated from the in-built clock module present within the FPGA. A 1 MHz trigger signal instantiates the TDC to generate timestamps. The delayline samples the clock period into smaller bins to generate a 2048-bit thermometer code. The priority encoder uses the 2048-bit thermometer code to generate an 11-bit raw timestamp by applying a logarithm to the number of 1s in the thermometer code. The raw timestamps help compute the TDC resolution implemented on the VCU108 board. The length of the thermometer code justifies the internal speed on both boards. The signal propagates across more carry chain units in a VCU108 board, yielding a 2048-bit thermometer code. At the rising edge of the clock, raw tags are subtracted from the coarse counter value to generate a 64-bit timestamp. The precision of the timestamps helps to understand the precision of the complete system.

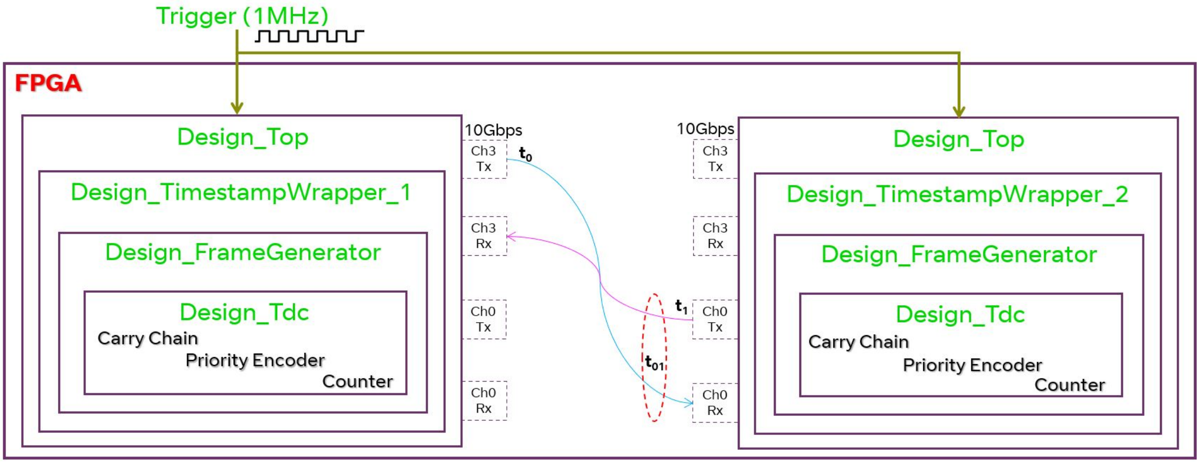


Figure 5.7: Illustration of a high precision time transfer solution on a single FPGA chip

Figure 5.7 illustrates the experimental setup to demonstrate the high-precision time transfer solution. The network consists of an FPGA-based central and remote node to carry data between the open radio unit (O-RU) and open distributed unit (O-DU). The central and remote nodes are within the same FPGA and contain two instances of TDC to generate individual timestamps for both nodes. Fibre-based 10 GbE SFPs connects the remote node to the central node. The central node receives the timestamp from TDC instance 2, the remote node. It also estimates the time to transmit and receive a timestamp, which constitutes the path or link delay. These values aid in calculating the offset to correct the timestamps, thereby improving precision.

The first experiment examined the precision achieved across a network comprising of a central and remote node by creating multiple instances of TDC within the same FPGA. The second experiment setup looks into understanding the precision achieved across a network comprising a central and remote node physically separated on different FPGA boards. It implies that TDC instances are on different FPGA boards. Figure 5.8 illustrates the solution

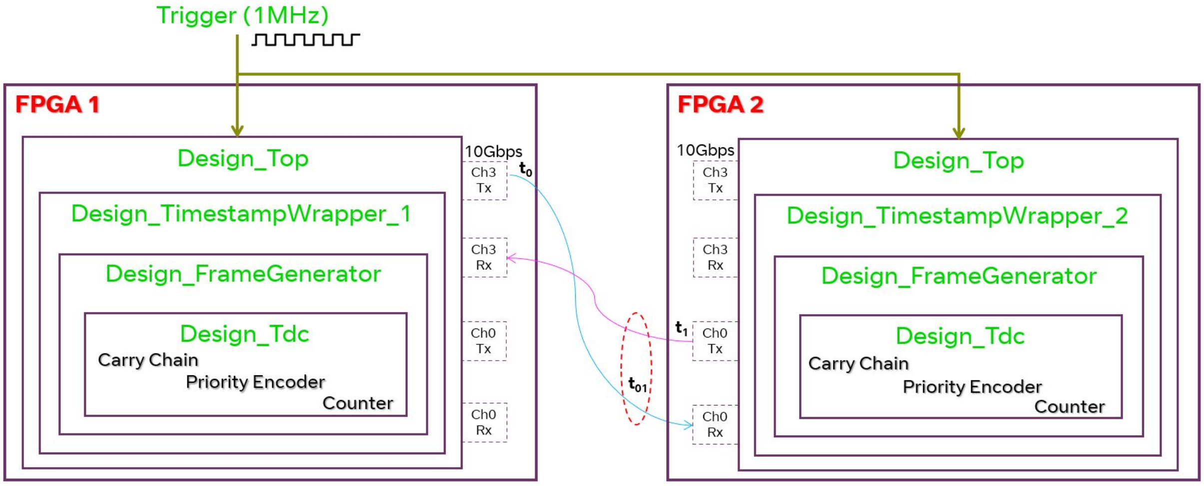


Figure 5.8: Illustration of a high precision time transfer solution on two FPGA boards

on different FPGAs. In this case, the trigger signal arrives at the FPGAs at different instances of time, which could impact the precision achieved. The experiment investigates the precision achieved while synchronising the remote node to the central node. In this case, the central and remote nodes are close to the source. It is interesting to understand the impact of distance on the precision achieved. To explore this scenario, the distance between the source and remote node is increased by 10m using a longer cable, as illustrated in figure 5.9. The trigger signal to the remote node is delayed, which implies that the TDC in the remote node is instantiated at a different time to the central node.

Both of the nodes receive the trigger signal from a common external source. The trigger signal to the central and remote nodes instantiates the TDCs to generate timestamps. After timestamp generation, the nodes transmit and receive the other timestamp over fibre. After calculating the offset at the central node, the nodes correct the timestamps based on an offset value generated periodically over time to improve the precision of the system. This creates the correction factor that compensates for the time error and improves the precision of the system. The central node calculates the offset value. The remote node receives the offset value to adjust its local timestamps.

Additionally, the time the node takes to transmit and receive a timestamp is used for the offset calculation to reflect the network behaviour. The AXI-Stream FIFOs save the timestamps from individual nodes and encapsulate them to form a frame structure before transmission. The timestamps are transmitted and received between the FPGAs via 10 GbE SFPs. The time taken by each node to transmit and receive a timestamp used for calculating the offset (t_{01} indicated in the figure 5.9) is as per the results in [18].

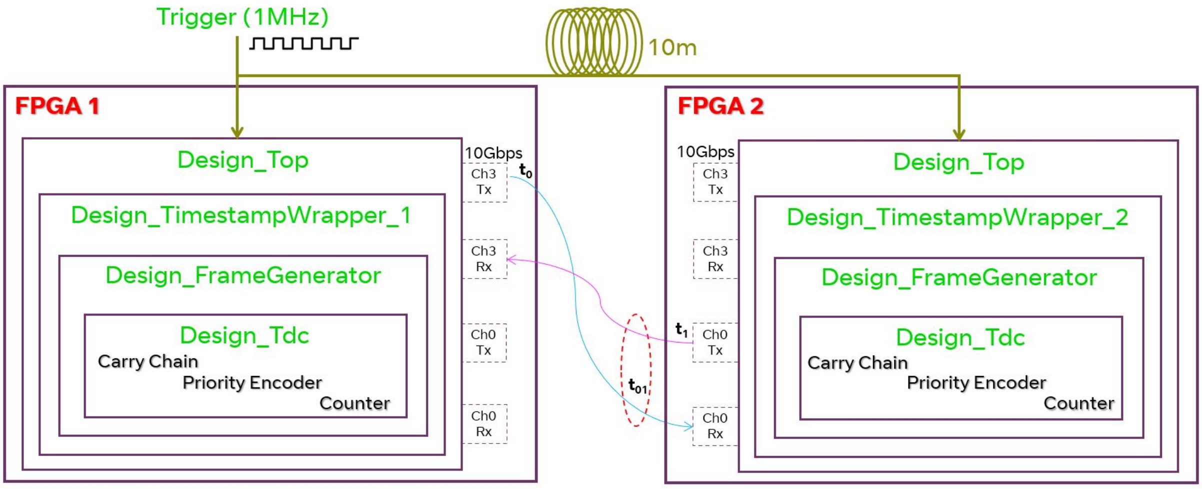


Figure 5.9: Illustration of a high precision time transfer solution on two FPGA boards upon delaying the trigger signal

5.3 Experimental Results

5.3.1 Comparison of TDC design: Zedboard vs Ultrascale VCU108 FPGA board

The initial design and implementation of a TDC was on a Zedboard. The frequency of the clock signal is 125 MHz, which corresponds to a clock period of 8 ns. 1 MHz square pulse (trigger signal) instantiates the TDC to generate timestamps. As mentioned in the previous section, the asynchronous trigger signal samples the clock period into smaller bins. In an ideal case, the bin widths should be equal in size, but practically, they are not. The trigger signal samples the clock signal with the rising edge of the trigger signal. It generates non-uniform bins, which results in varying bin counts in each cycle. Bins refer to the discrete time intervals used to quantify time measurement. Each bin represents a specific time range and the time-to-digital converter module allocates the measured time interval to one of these bins. Since the bin widths are unequal, the bin counts lie between values 0 to N, where N is the number of delay elements. The number of delay elements in the case of a Zedboard is equal to 512 (N = 512). The value of N is always a number that corresponds to n^{th} power of 2. For example, $2^9 = 512$. In an ideal case, sampling the clock signal in equal intervals generates constant bin counts. Therefore, the TDC should always generate 512 bins. The histogram illustrated in figure 5.10 indicates a range of values from 0 to 447. It implies that the bin widths differ in each cycle and are unequal. The maximum value of the bin count gives an idea of the number of delay elements getting a hit and helps calculate the resolution of TDC. The width of the bin determines the resolution of a time-to-digital converter module. Narrow bins provide higher resolution and hence more precise measurements. Using equation 5.1, the resolution of TDC implemented on Zedboard is given by,

$$Resolution_{TDC} = 8ns/447 = 17.8ps \tag{5.2}$$

The resolution of TDC indicates the lowest value measurable by the system. After analysing the resolution of the TDC, the next step is to generate timestamps. The bin counts generated represent 9-bit raw time tags from the priority encoder (n-bit code as indicated in figure 5.5). The raw time tags are subtracted from the counter value to generate a 64-bit timestamp. The precision of the TDC implemented is understood by analysing the 100, 000 timestamps generated. A histogram and standard deviation help to understand the spreading of time difference. The plot in figure 5.11 illustrates the precision achieved for the TDC implemented on a Zedboard. The plot indicates the histogram plot of the

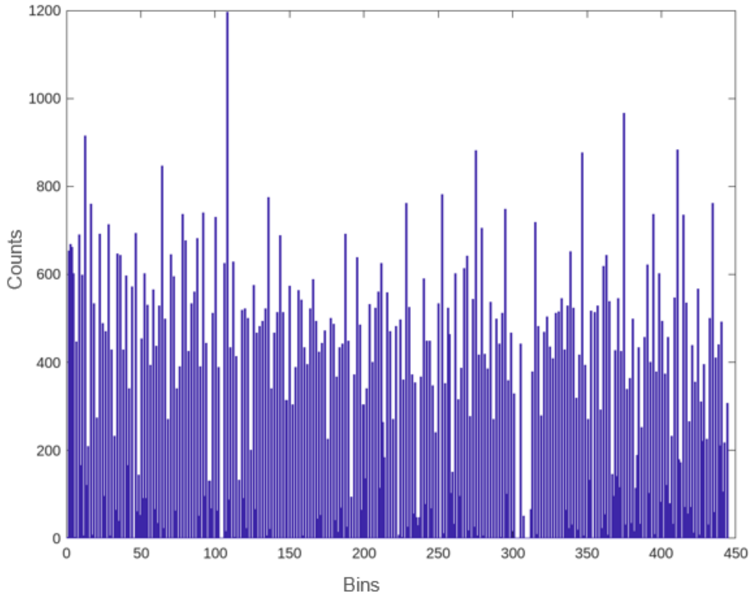


Figure 5.10: Plot of bins generated from TDC on a Zedboard

time differences observed between consecutive timestamps generated, and as observed, they spread across the nanosecond regime. The computed standard deviation is $\sigma = 430$ ps. Single Shot Precision (SSP) of TDC is given by,

$$SSP = \sigma/sqrt(2) = 304.05ps \tag{5.3}$$

Radio devices require high precision; hence, they use ultrascale FPGAs. Therefore, the further steps in relation to the development of a high precision time transfer experiment were not done on the Zedboard. TDC and the proof of concept was implemented on a Xilinx Ultrascale (VCU108) FPGA board. The frequency of the clock signal and the trigger signal are 125 MHz and 1 MHz, respectively. Figure 5.12 shows the histogram plotted for the bins generated. In a VCU108 FPGA board, CARRY4 primitives are replaced with CARRY8, and the speed of signal propagation in the board is higher than in Zedboard. Hence, the signal propagates through more delay elements than in the previous case. The number of delay elements used in this case is 2048 ($2^{11} = 2048$). The bin widths are smaller than in the previous case, generating more bins. Therefore, the resolution of the system will be better

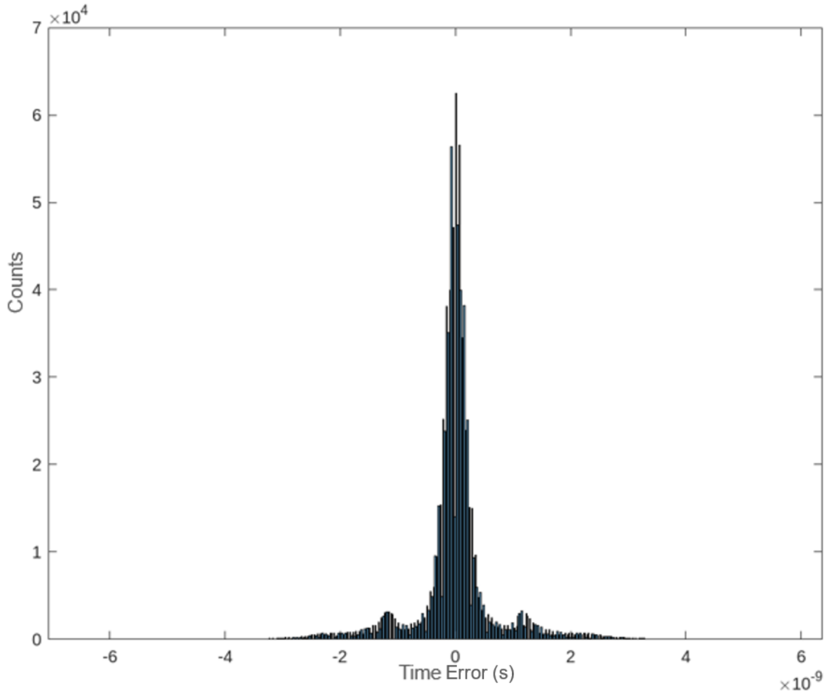


Figure 5.11: Precision of timestamps generated from TDC on a Zedboard

compared to the previous case. The histogram plot 5.12 indicates a range of values from 0 to 1609. The number of delay elements getting hit helps to calculate the resolution of TDC. Using equation 5.1, the resolution of TDC implemented on VCU108 is given by,

$$Resolution_{TDC} = 8ns/1609 = 4.97ps \tag{5.4}$$

After analysing the resolution of the TDC, the next step is the generation of timestamps. The bin counts generated represent 11-bit raw time tags from the priority encoder (n-bit code as indicated in figure 5.6). The raw time tags are subtracted from the counter value to generate a 64-bit timestamp. The precision of the TDC is determined after analysing 100,000 timestamps. A histogram and standard deviation help to understand the spreading of time difference. The plot in figure 5.13 illustrates the precision achieved for the TDC implemented on a VCU108 board. The histogram plot indicates the time differences between consecutive timestamps, and as observed, they spread across the picosecond regime. The

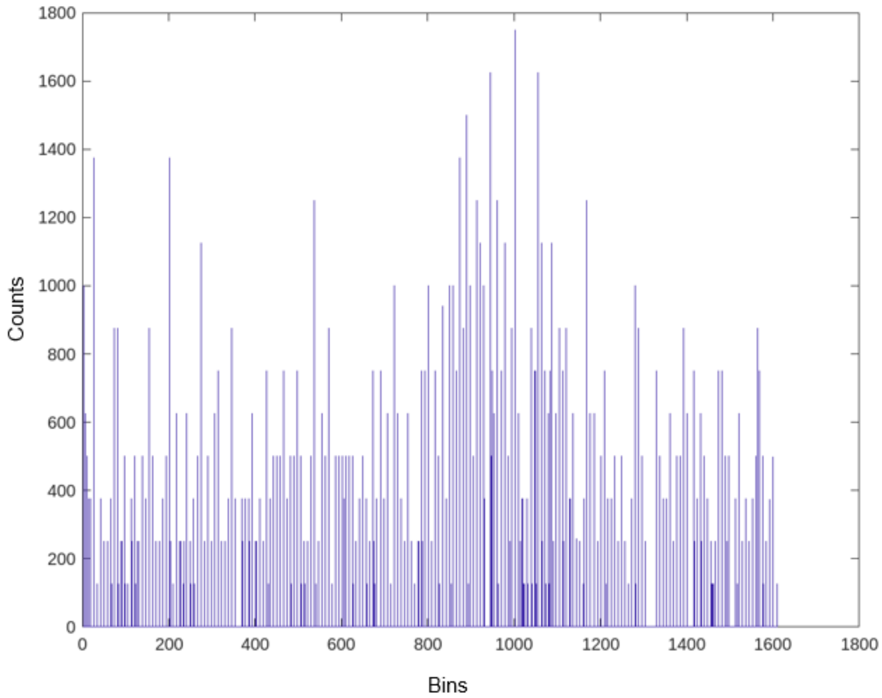


Figure 5.12: Plot of bins generated from TDC on VCU108 FPGA board

computed standard deviation is $\sigma = 60.8$ ps. Single Shot Precision of TDC is given by,

$$SSP = \sigma/sqrt(2) = 42.9ps \tag{5.5}$$

5.3.2 Implementation of TDCs on single VCU108 FPGA chip

The first experiment demonstrated in figure 5.7 defined the precision achieved with multiple TDC cores on a single FPGA chip. As part of this experiment, two TDCs were instantiated from a single VCU108 FPGA chip to generate timestamps. The timestamps were exchanged across the central and remote nodes via 10 G SPFs to compute the offset. One hundred thousand timestamps were recorded after offset correction, and the difference among them was analysed. Equations 5.6 and 5.7 illustrate offset calculation to compensate for the differences in timestamp and delay in the link. Figure 5.14 details a histogram plot of the time difference achieved. The interval for time error lies between 10.4 ps to 180 ps. Hence,

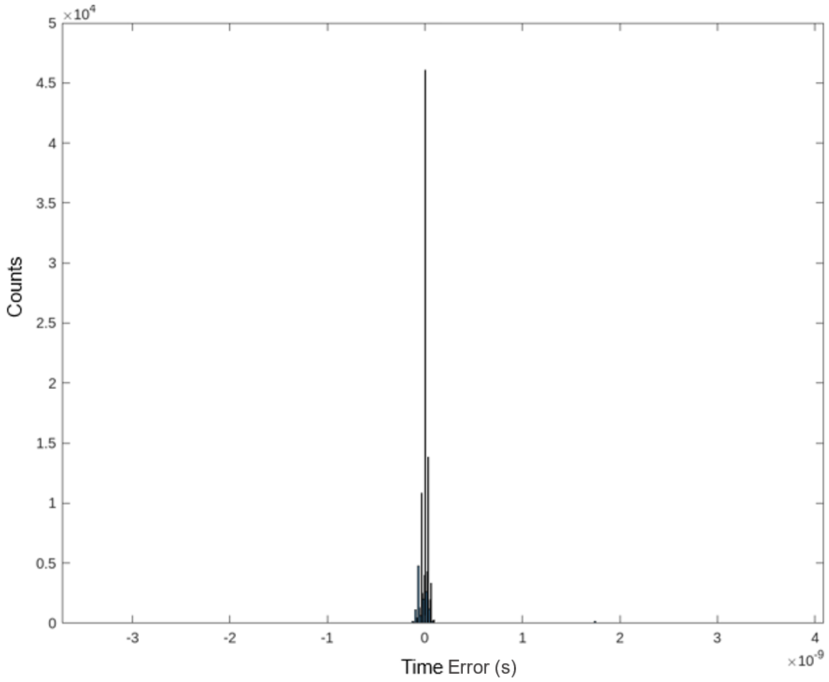


Figure 5.13: Precision of timestamps generated from TDC on VCU108 FPGA board

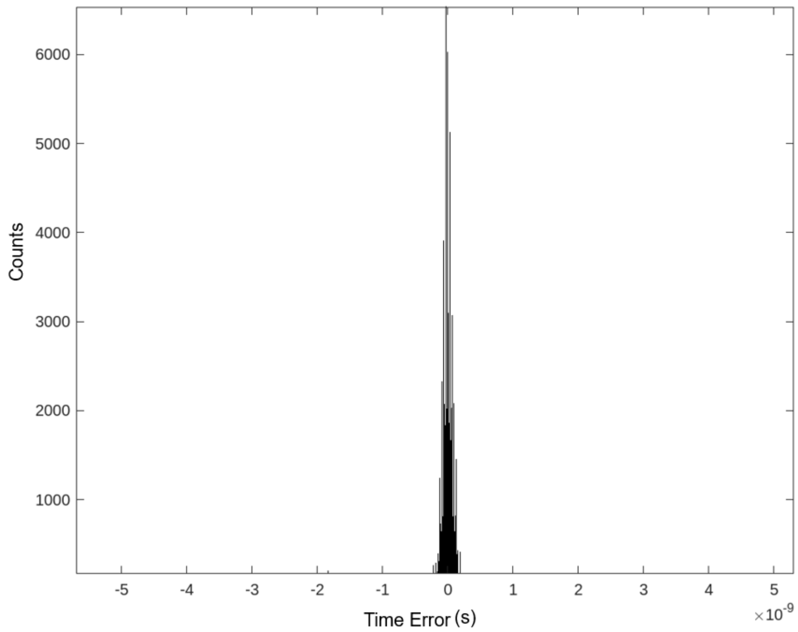


Figure 5.14: Time error on single VCU108 FPGA chip

the highest precision achieved for synchronising frames over a single FPGA chip was 10.4 ps.

$$\Delta_0 = t_0 - (t_1 + t_{01}) \tag{5.6}$$

$$\Delta_1 = t_1 - (t_0 + t_{01}) \tag{5.7}$$

5.3.3 Implementation of TDCs on different VCU108 FPGA boards

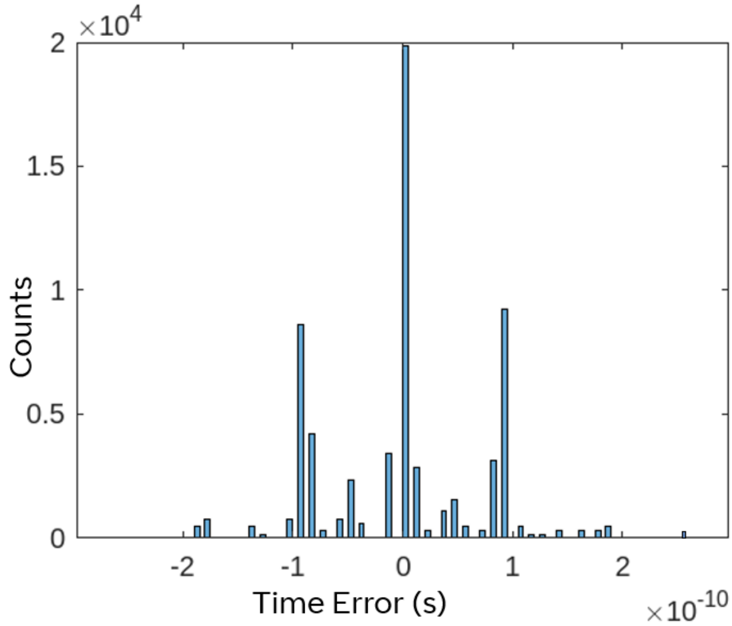


Figure 5.15: The figure illustrates a histogram plotted for the time error obtained when the remote node is synchronised to the central node. The interval for time error lies between 11.7 ps to 269.1 ps.

The second experiment defined the precision achieved when the nodes are physically separated. This experiment generated timestamps from a central and remote node implemented on two different VCU108 FPGA boards. The timestamps were transmitted and received via 10 GbE SFP to compute the offset. After correcting the offset, the corrected timestamps aid in understanding the time error. Figure 5.15 details a histogram of the time error obtained. The interval for time error was between 11.7 ps to 269.1 ps. Hence, the highest precision achieved for synchronising frames over two nodes was 11.7 ps.

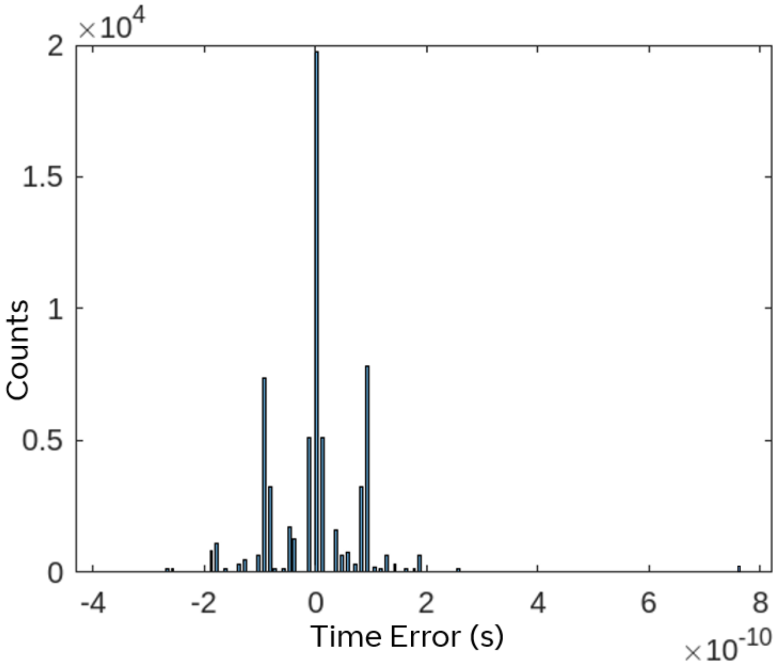


Figure 5.16: The figure illustrates the time error obtained when the remote node is synchronised to the central node. However, the trigger signal is not directly fed to the remote node, as mentioned in the second experiment. The trigger signal to the remote node is delayed using a longer cable. Therefore, the TDC module in the remote node is instantiated at a different instance. This impacts the time error, and the interval of time error observed lies between 11.7 ps and 760.5 ps

The third experiment defined the precision achieved after delaying the trigger signal (using a 10m longer cable) to the remote node. This will explain the effect on synchronisation precision achieved when the remote node is located away from the source. The trigger signal to the central and remote nodes is shifted in time (a scenario where instantiation of TDC occurs at different times). Figure 5.16 illustrates the time error observed in this case. The interval for time error lies between 11.7 ps and 760.5 ps. Thus, the highest precision achieved for synchronisation of frames was 11.7 ps. The result indicated less impact on the best case but a significant impact on the worst case.

5.3.4 TDC calibration

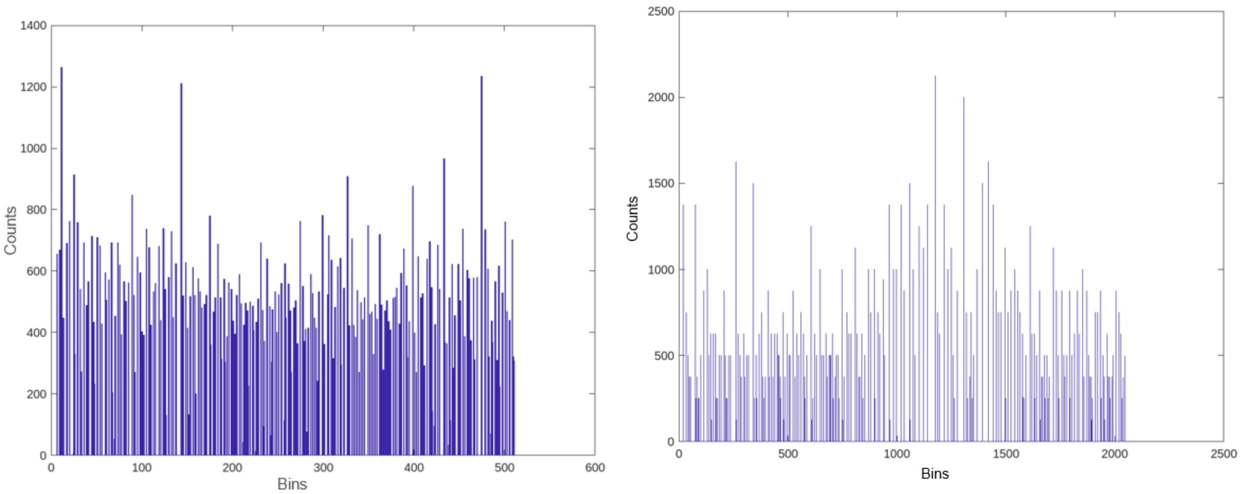


Figure 5.17: Histogram of calibrated code for Zedboard and VCU108 FPGA boards

Figure 5.10 and 5.12 illustrate histograms plotted for the 9-bit and 11-bit raw timestamp generated from the priority encoder. Upon analysing these graphs, the maximum hit in each case is 447 and 1609, while the total number of delay elements in the TDC core are 512 and 2048, respectively. The varying bin counts are due to the bin widths being unequal on every cycle. The sampling differs with the rising edge of the trigger signal. It can also result in some missing bins, as observed from the histogram plot. It could eventually affect the resolution of the TDC. Hence, bins are stretched to the maximum value to improve the resolution. The maximum value is given by the number of delay elements getting a hit. It also helps regenerate missing codes, reducing the margin between consecutive timestamps and eventually improving the precision of the system. The technique of improving the resolution of TDC by stretching the bin count is known as calibration. It is a post-processing step implemented in software language. Statistical distribution of TDC bins across delay line structure helps to calibrate a TDC, which results in a bin-by-bin calibration technique. The histogram plots indicated in figures 5.17 illustrate bin counts after calibration. The maximum bin count is stretched to 512 and 2048 for Zedboard and VCU108, respectively. Hence, the improvement in TDC resolution is given by:

$$Resolution_{TDC(Zedboard)} = 8ns/512 = 15.6ps \tag{5.8}$$

$$Resolution_{TDC(VCU108)} = 8ns/2048 = 3.9ps \tag{5.9}$$

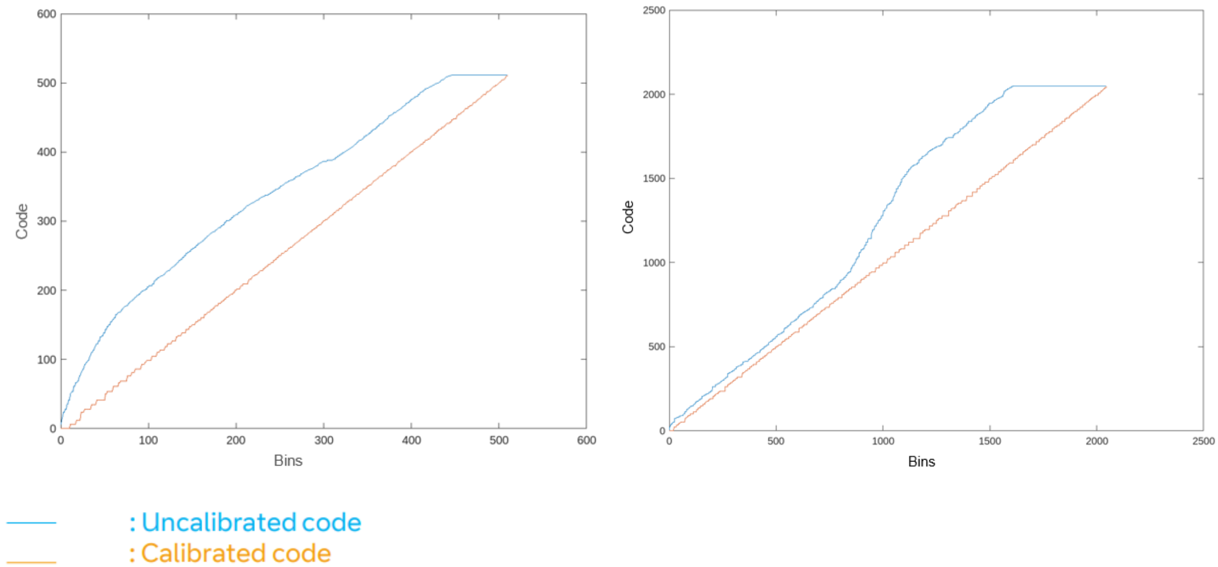


Figure 5.18: Transfer function of uncalibrated and calibrated code for Zedboard and VCU108

In a TDC, the relation between input and output should be linear. However, due to factors such as power fluctuations, differential internal routing, and temperature variations, TDC might be affected by non-linearities. The calibration technique helps to improve the linearity of the TDC. TDC calibration is implemented in software to demonstrate how it helps to improve the resolution of TDC to generate precise timestamps and thereby improve the precision of the system. Figures 5.18 shows the relation between input and output code after calibration (blue represents uncalibrated code, and orange represents calibrated code). As observed, TDC shows a linear relationship after calibration as it compensates for the non-linearities. A lower margin between the timestamps indicates that the timestamps are closer to each other. Hence, the margin between the best and worst-case scenarios is less and will improve the overall precision of the system.

The experiment results for the synchronisation precision achieved in each scenario are summarised as follows in table 5.1:

Experiment	***Precision (ps)***	***Remarks***
TDC Resolution (Zedboard)	17.8	Before calibration
TDC Resolution (VCU108)	4.97	Before calibration
TDC Resolution (Zedboard)	15.6	After calibration
TDC Resolution (VCU108)	3.9	After calibration
TDC (Zedboard)	304.05	Single Shot Precision
TDC (VCU108)	42.9	Single Shot Precision
Multiple TDC	[10.4 : 180]	On single FPGA chip
Central and Remote node	[11.7 : 269.1]	Over network on 2 FPGAs
Time-shifted trigger signal	[11.7 : 760.5]	Over network on 2 FPGAs

Table 5.1: Experiment Results

Another potential application for the high-precision timestamping is to timestamp the arrival of events in a network. The experiment examined the precision in timestamping data when transmitted from one node to another. The central and remote nodes generate their timestamps using individual TDC cores. The central node generates data and transmits the data to the remote node. The experiment aims to understand the precision to which the remote node can timestamp the data upon arrival. Figure 5.19 shows the experimental setup to demonstrate timestamping events to high precision. Channel 4 and Channel 1 are connected via 10Gbps SFPs to synchronise the remote node to the central node to ps-level precision using the solution mentioned in the section 5.2 of this chapter. Channel 5 and Channel 2 are connected to transmit data from the central node to the remote node. The data is timestamped at the remote node upon arrival. The 100,000 data samples were transmitted continuously and correspondingly timestamped at the remote node upon arrival with ps-level precision. The experiments demonstrated that the remote node is synchronised to the central node to picosecond scale precision.

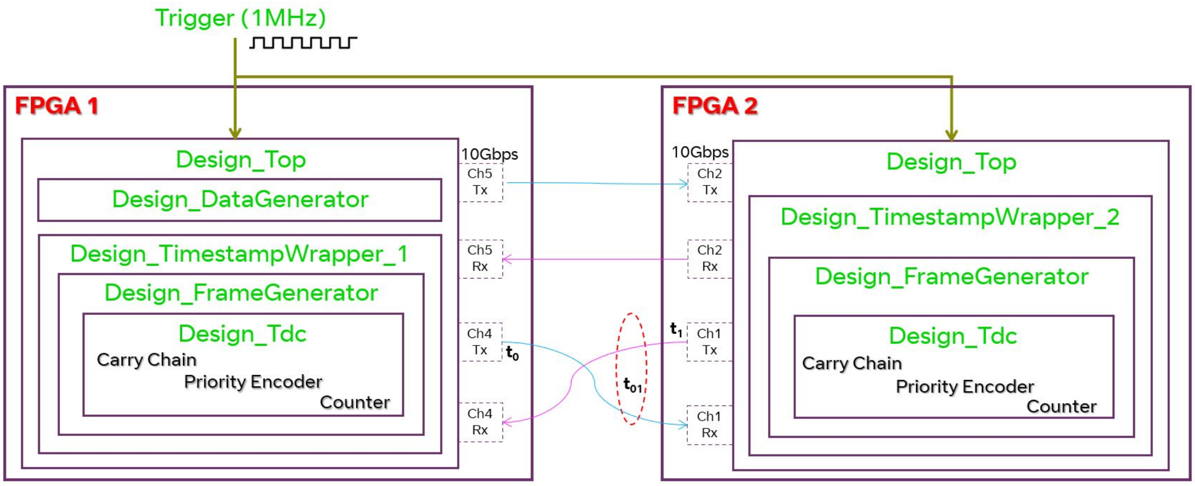


Figure 5.19: Experimental setup to timestamp events at high precision

5.4 Conclusion

The work focused on developing a proof of concept to demonstrate a high-precision time transfer solution using an FPGA module. The solution which I have developed uses a time-to-digital converter to generate timestamps on each FPGA. The offset value is a correction factor to compensate for the fluctuations, thus improving the synchronisation between two nodes. The offset value depends on the difference between the timestamps generated on individual nodes and the delay over the link, which estimates the time a node takes to transmit and receive a timestamp. This work demonstrated a prototype for high-precision time transfer using FPGA across distributed nodes. The reported TDC resolution is 4.7 ps. Software calibration improved the resolution to 3.9 ps. A precision of 10.4 ps was achieved on a single FPGA chip while central and remote nodes were synchronised to 11.7 ps. As demonstrated, bringing TDC calibration to the hardware is a suitable way to enhance the precision of the system in a real-time use case. TDC calibration has been demonstrated in the software. The experiment also demonstrated timestamping events to ps-level precision using this solution.

TDC calibration can improve the precision of the system even further by compensating for non-linearities and improving the TDC core's resolution. However, there are potential research areas that need detailed analysis. TDC calibration needs to be designed on hardware. The timestamp is transmitted as an optical signal from one node to another. It could be interesting if this clock or time information could be directly extracted from the SFPs and used to discipline another oscillator. There are also multiple ways to implement a TDC core, aside from the delay line architecture used in this solution. These are potential areas to investigate to improve the precision of the current system.

Chapter Six

Summary and Future Prospects

5G network support flexible and dynamic topologies. Ensuring the synchronisation resiliency of varying real-time configurations and connections is a huge challenge. Architecture beyond the fourth generation of telecommunication networks demands stringent timing. Any deviations in the accuracy from the time error budget can lead to performance degradation. Achieving and maintaining higher levels of accuracy in a complex and dynamic environment is challenging. In a wireless communication medium, synchronisation issues can arise due to interference, leading to signal quality degradation. Numerous factors, such as atmospheric conditions, neighbouring buildings or obstacles, and neighbouring networks, all create potential interference that can affect the accuracy of a timing signal.

Security is a significant concern, too. The use of satellite-based technologies as a primary reference time scale brings in potential vulnerabilities (such as jamming and spoofing) to the network. Emerging technologies such as Artificial Intelligence (AI) and Machine Learning (ML) demand enhanced timing accuracies, which is a promising development that instils optimism. The above-addressed challenges and concerns are a few to mention, but they eventually lead to the search for a primary standard that is capable of replacing GNSS in the near future.

6.1 Summary

Optical atomic clocks are the next generation of atomic clocks, which could be an ideal candidate to replace the GNSS systems for high-accuracy timing in the near future. Researchers are investigating to understand the potential of these clocks and working together to bring them up as a primary standard in the future. The research work detailed in the report investigates the potential ways to integrate an optical atomic clock into a telecom infrastructure. The introductory chapter details the current state of the art of various technologies used to achieve synchronisation from the second to fifth generation of telecommunication infrastructure. The second chapter details various technologies from past to current and emerging technologies that contribute to accurate timekeeping.

The software model detailed in the third chapter explores the telecom infrastructure and investigates the best architecture that aids in connecting optical atomic clocks to telecommunication infrastructure. However, having a highly accurate clock in the infrastructure does not solve all the challenges. The challenges lie in transporting the high-accuracy signal from core nodes to the access nodes in a network. The work based on the optical reference system detailed in the fourth chapter investigates a novel technique to disseminate stable frequency over telecom fibre. Despite having a good source, it is still challenging to achieve high precision at the radio nodes. The fifth chapter explores a novel technique that helps to synchronise the remote node to the central node to picosecond level precision using FPGA technology. A stable frequency from these clocks can instantiate the TDC module developed in the FPGAs to improve the precision.

The research work has explored the potential and feasibility of using optical atomic clocks in telecom infrastructure and transporting high-accuracy timing over the infrastructure. The use of optical atomic clocks in the network is justified as being one of the technologies with immense potential to become a primary reference standard capable of replacing

GNSS subsystems.

6.2 Conclusion

Optical atomic clock technology is a complex technology comprising ultra-stable lasers and control systems. The complexity of the technology makes it expensive, restricting its widescale commercial use. Additionally, these clocks are highly sensitive to environmental factors such as vibrations, electromagnetic interference, temperature variations etc. Maintaining stable environments in the lab is achievable but difficult in a commercial data centre environment, hence restricting their use for commercial applications. These clocks demand regular calibration and maintenance and therefore require high operational costs. The above-mentioned factors restrict the widescale use of optical atomic clocks, making it challenging to incorporate a significant number of them into the telecommunication infrastructure. There needs to be a balance between the cost and the number of clocks used based on the size and criticality of the infrastructure and operation of the clock technology. A dedicated set of wavelengths reserved for the transport of the timing signal across the networks will help to improve the accuracy even further. This is an effective way of transporting timing signals across an extensive infrastructure in the near future. However, with increasing capacity, changes in the type of fibre used, dispersion profile, the amplifiers used within the network, and reserving a wavelength for Optical Time Domain Reflectometer (OTDR) operation to monitor the network, it is challenging to use a dedicated wavelength of the transport of timing signal. The pitfalls mentioned above underscore the need for proper planning, monitoring, maintenance and adherence to the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) standards to build a proper synchronisation network. The gap between product research and development and the standardisation process limits the pace of downstreaming new technologies into the infrastructure. The collaborative effort among industries, stakeholders, standardisation platforms, and network operators is essential to building a resilient infrastructure that ensures seamless connectivity and reliable operation of mobile technology.

6.3 Future Work

It is still challenging to get an industrial-based compact optical atomic clock for testing in the laboratory. The initial step towards realising the use of optical atomic clocks in a telecom infrastructure will be having one of these units in the laboratory to conduct the relevant testing to understand the specifications in detail and perform required stability and time error measurements. In the near future, optical clocks will be used in the networks to achieve improved holdover performance beyond what microwave atomic clocks are capable of. This is crucial as the network can survive longer without going out of synchronisation when the GNSS signal is lost. In the future, when there is a well-connected fibre infrastructure, and national laboratories can provide UTC, optical clocks will be the primary reference time clock for the UTC timescale in the networks. In future, optical atomic clocks can be integrated into global navigation satellite systems to improve the positioning accuracy to millimetre levels thereby achieving nanosecond or sub-nanosecond accuracy. In future, optical atomic clocks could benefit the development of quantum networks by providing precise timing required for quantum protocols and quantum key distribution. Optical atomic clocks might result in bringing a change to the traditional synchronisation network which operates on a master-slave topology. Optical atomic clocks could help to build a distributed independent synchronisation architecture leveraging the high accuracy achieved by the technology.

Appendix One

ITU-T Standards

The timing and synchronisation architecture for networks is designed as per the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) standards. The standard mainly details on network architectures, clock configuration and classes, time and frequency transfer protocols and their security aspects. The table A.1 details the ITU-T standards followed for timing and synchronisation across networks.

Specification	***Summary of the contents included in the ITU-T standard***
ITU-T G.781	Frequency synchronisation for the synchronisation layer over the physical medium
ITU-T G.803	Architecture of synchronous digital hierarchy based transport networks
ITU-T G.811	The timing characteristics related to the primary reference clocks
ITU-T G.812	The timing requirements of the slave clocks that can be used at nodes to achieve synchronisation within an network

ITU-T G.813	The timing characteristics of the slave clock in a network based on synchronous digital hierarchy
ITU-T G.823	Management of wander and jitter in a digital network (2048kbits/s)
ITU-T G.824	Management of wander and jitter in a digital network (1544kbits/s)
ITU-T G.825	Management of wander and jitter in a synchronous digital network
ITU-T G.8251	Management of jitter and wander in a optical transport network
ITU-T G.8260	Definitions related to synchronisation for packet based networks
ITU-T G.8261.1	Frequency synchronisation for packet based networks
ITU-T G.8262	The timing characteristics for a synchronous equipment slave clock
ITU-T G.8262.1	The timing characteristics for a enhanced synchronous equipment slave clock
ITU-T G.8263	The timing characteristics of clocks based on packet networks
ITU-T G.8264	Distribution of timing over packet networks
ITU-T G.8265	Requirements for frequency synchronisation for packet networks
ITU-T G.8265.1	Precise time protocol for frequency synchronisation for a telecommunication profile
ITU-T G.8266	The timing characteristics of grandmaster clock for frequency synchronisation in a telecommunication network
ITU-T G.8271	Time and phase synchronisation for packet based networks

ITU-T G.8271.1	Time synchronisation for packet based networks with full timing support
ITU-T G.8271.2	Time synchronisation for packet based networks with partial timing support
ITU-T G.8272	Timing characteristics of the PRTCs
ITU-T G.8272.1	Timing characteristics of the ePRTCs
ITU-T G.8273	Framework of the time and phase clocks
ITU-T G.8273.2	Timing characteristics of the T-BC and TSC with full timing support
ITU-T G.8273.3	Timing characteristics of the TCs with full timing support
ITU-T G.8273.4	Timing characteristics of the T-BC and TSC with partial timing support
ITU-T G.8275	Architecture and requirements for time and phase distribution in packet based networks
ITU-T G.8275.1	PTP for time and phase synchronisation with full timing support
ITU-T G.8275.2	PTP for time and phase synchronisation with partial timing support
ITU-T O.171	Jitter and wander measurements for the digital systems based on PDH

Table A.1: ITU-T standards for timing requirements [38]

Appendix Two

Co-existance of Quantum and Timing Channels for Telecom Networks

Quantum and timing are two technical areas gaining extensive interest in future networks. Precise timing information is required to support ultra-reliable low latency applications in the network. On the other hand, security and data privacy are growing as major requirements from end user perspective. At present, a quantum network uses a "classical" telecom service channel to include synchronisation between the transmitter and receiver in an allocated channel [24]. This paper explores the feasibility of eliminating this dedicated service channel for synchronisation with the coexistence of quantum and timing channels over a single fibre core. Using a continuous wave signal power and wavelength, we demonstrate the variation in photon count, including different spectrum bands, to determine the optimum power and wavelength to maintain these two channels adjacent to each other with minimum crosstalk between the two signals. Moreover, based on our investigations, we quantify the tolerance of the quantum channel (in C band) to CW optical power at the O/C/L-bands. The quantum channel is 20 dBs more tolerant to optical power in the L-band than in the O-band.

The experimental setup is shown in Figure B.1. This testbed consists of a tunable laser source, a pair of attenuators connected in tandem to control the signal power from the

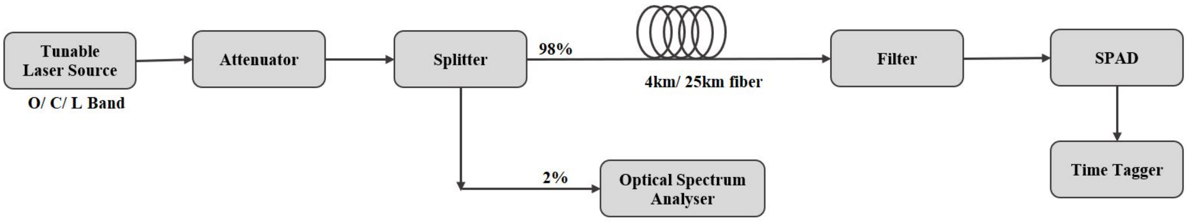


Figure B.1: Schematic of experimental setup

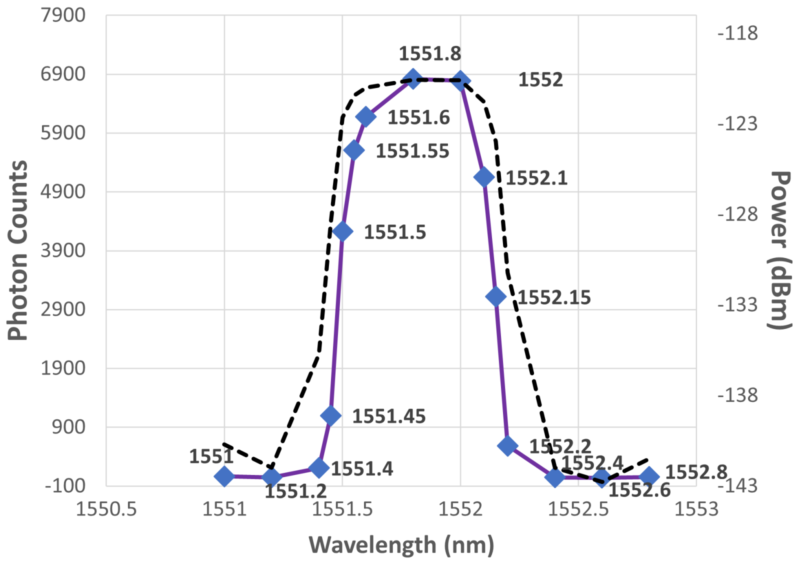


Figure B.2: Filter profile

laser, a 98/2 splitter (for monitoring), 4 km and 25 km single mode fibre spools, a narrow-band, 50 GHz-bandwidth bandpass filter centred at 1551.7 nm, a single-photon avalanche diode (SPAD) and a time tagger. Photon counts are measured using the SPAD and the time tagger at different wavelengths of the tuneable laser source over O, C and L bands. The figure B.2 shows the plot after characterising the filter by injecting a certain value of input power and monitoring the output power for varying wavelengths across the C band. The dotted black line in the figure shows the desired characteristics and the graph in purple colour shows the observed filter characteristics.

Figures B.3, B.4 and B.5 show the variation in photons detected, after passing through

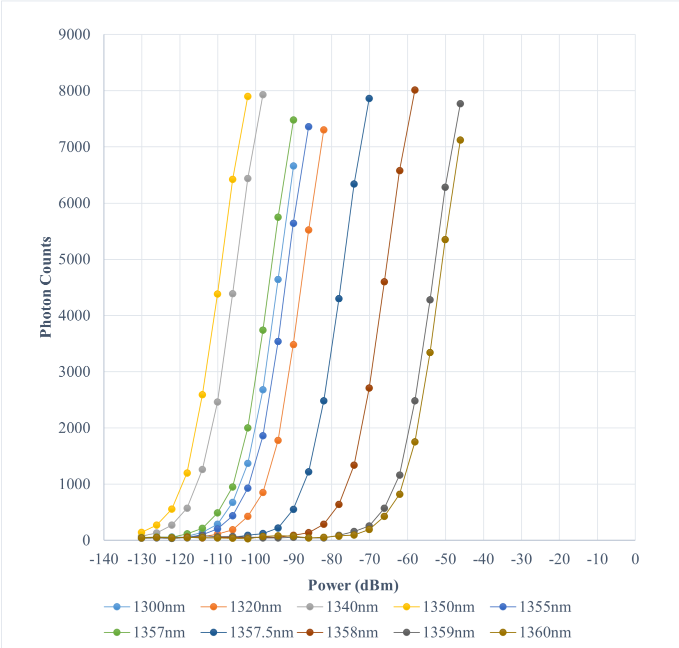


Figure B.3: Variation of photon count over O band

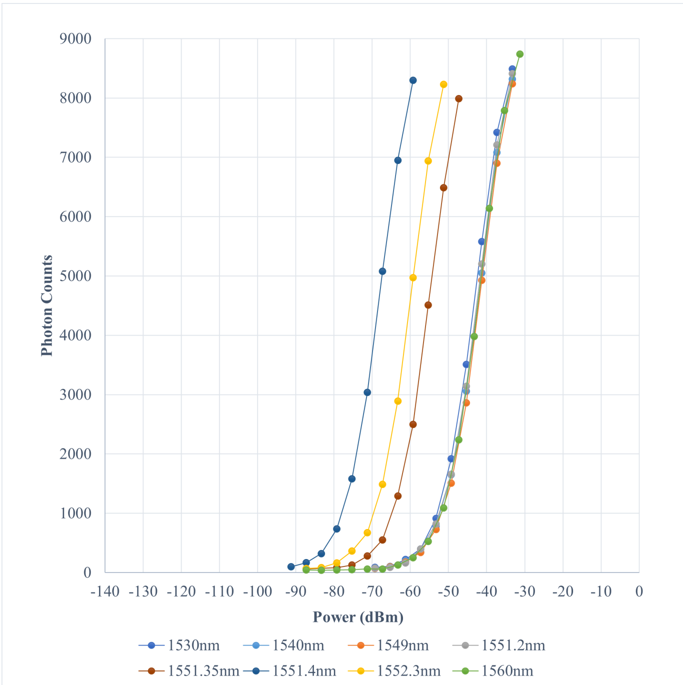


Figure B.4: Variation of photon count over C band

the 50GHz-filter centred at 1551.7 nm, against the injected CW optical power at different spectrum bands (O, C and L). As observed, 1000 photons are detected when the injected

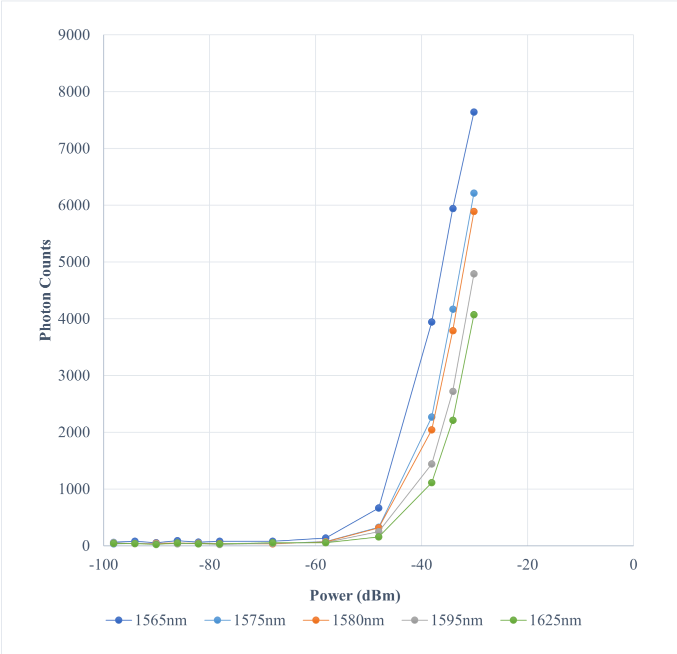


Figure B.5: Variation of photon count over L band

	Power (dBm)					
	4km Fiber Length			25km Fiber Length		
Photon Count	O-band	C-band	L-band	O-band	C-band	L-band
1000	-60	-52	-40	-58	-44	-39
2000	-58	-48	-35	-55	-40	-35
3000	-55	-45	-33	-51	-38	-32

Figure B.6: Power vs Photon Count for O/C/L bands for 4/25 km fibre

power in the O-band is between -60 dBm to -120 dBm for 4 km SMF. On the other hand, when the CW optical signal power of -40 dBm is injected in the L-band, the same number of photons are counted, proving more tolerance to optical power in the L-band than the O-band. This effect is attributed to the increased stimulated Raman scattering at longer wavelengths compared to shorter wavelengths [6]. This 20 dB tolerance to the L-band, compared to the O-band, is also repeated for a longer length of SMF of 25 km with additional 3 dBs of tolerance due to photon absorption. These results show that coexistence of "classical" signals, such as timing, with QKD channels can be achievable as long as the design considers these levels of tolerance at different bands. Moreover, this difference in power confirms that QKD signals are less affected whenever the classical timing signals are in the L band. This work is of value for the design of hybrid networks that will include quantum channels for the future quantum internet.

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