LEBANESE INTERNATIONAL UNIVERSITY (LIU)

MASTER THESIS

Timing and Synchronization Integration and Performance Analysis for 5G

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Declaration of Authorship

I, Hadi HARIRI, declare that this thesis titled, "Timing and Synchronization Integration and Performance Analysis for 5G " and the work presented in it are my own. I confirm that:

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"As we stand on the brink of the 5G revolution, we are witnessing the convergence of technological ingenuity and human ambition. 5G has the power to redefine connectivity, catalyzing breakthroughs in fields as diverse as artificial intelligence, Internet of Things, and augmented reality. Its impact will extend far beyond faster downloads, unlocking boundless opportunities for innovation, economic growth, and societal progress."

Dr. Michio Kaku

For/Dedicated to/To my…

LEBANESE INTERNATIONAL UNIVERSITY (LIU)

Abstract

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Master's degree

Timing and Synchronization Integration and Performance Analysis for 5G

by Hadi HARIRI

As the world transitions into the era of 5G networks, the demand for seamless connectivity, ultra-low latency, and high reliability becomes paramount. Timing and synchronization emerge as critical aspects in ensuring the efficient operation of these networks. This thesis explores the integration of timing and synchronization mechanisms within 5G infrastructure and conducts a comprehensive performance analysis to assess their efficacy. Through theoretical modelling, simulation studies, and practical experimentation, this research aims to provide insights into the challenges, solutions, and optimization strategies concerning timing and synchronization in 5G networks.. . .

The 5G New Radio synchronization procedure is the initial step a user must complete to access the mobile network. The synchronization signal (SS) contains the information about the PSS, SSS, PBCHand DMRS. This phase is called the initial access or cell search. in 5G NR, The initial access procedures typically include:

1. The function and procedures by which a device newly entering the new coverage area of the 5G system, discovers a newer cell.
2. The function and procedures by which a UE access the network in its idle/inactive state without any prior information, followed bya the UE requesting setting up of the connection, typically referred to as *the random access procedure.*

This involves detecting the primary and secondary synchronization signals (PSS and SSS) and decoding the physical broadcast channel (PBCH). Our objective is to study various synchronization and timing matching techniques for 5G New radio systems and how these timing and synchronization techniques can be leveraged to enhance the performance of the 5G system. The thesis plans to take advantage of the simulation environment or simulators ti study the effects of the frequency offsets, phase offsets, timing misalignments, delay spread, propagation delay and multi-path. Key areas of interest include examining impairments such as fading channels, frequency offset, and delay spread. We present our findings in terms of detection probability for PSS and SSS, and block error rate for PBCH. Our data indicates that using M-sequences for PSS provides robust performance against frequency offset. The structure of Gold sequences for SSS can be leveraged to reduce detection complexity, and different methods can be employed to enhance reliability against delay spread. Additionally, polar coding for 5G PBCH shows improved performance over the 4G coding technique but remains sensitive to frequency offset. Finally, the simulator's functionalities are validated with real 5G signal captures

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List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W (J s^{-1})
ω	angular frequency	rad

Chapter 1

Introduction

1.1 Context and Motivation

The main Context and motivation behind pursuing research in Timing and synchronization procedures and their over effect on the performance of the 5G systems is found in the basic target as set by 5G and technologies used by 5G. The 5G foundation lies on three main principles, or targets that 5G system intends to achieve, which are:

- URLLC (Ultra-Reliable Low Latency): Focuses on ultra-reliable and low-latency communications for critical applications with targets of <1 ms latency and 99.999% reliability. It targets the sue cases such as Autonomous Vehicles, remote medical procedures, industrial automation, mission-critical applications.
- eMBB focuses on providing higher data rates and improved capacity to support applications such as high-definition video streaming, virtual reality, and augmented reality. Targets:
  - Peak Data Rates: Up to 20 Gbps downlink and 10 Gbps uplink.
  - User Experienced Data Rate: 100 Mbps to 1 Gbps.
  - Mobility: Seamless connectivity at speeds up to 500 km/h.
  - Use Cases: High-definition video streaming, VR/AR experiences, high-speed internet access, smart cities.
- mMTC (Massive Machine-Type Communications) / Massive IoT : mMTC aims to connect a large number of devices with varying data needs, focusing on efficient and scalable communication for Internet-of-Things (IoT) applications.

  Targets:
  - Device Density: Up to 1 million devices per square kilo-meter.
  - Battery Life: Devices optimised for low power consumption, with battery life up to 10 years.
  - Data Rates: Typically lower than eMBB but sufficient for IoT devices.
  - Use Cases: Smart homes, smart agriculture, environmental monitoring, logistics tracking.

Now these requirements are not met unless innovative techniques and technologies such as higher frequencies, improved frame structure, beam-forming, and many other technologies to support these targets and achieve these numbers. This is where the synchronization and timing challenges start to surface. the higher, the frequencies used in 5G, the more the beam-forming is used to target specific users and increase power received by the individual users, the usage of MIMO technologies, all

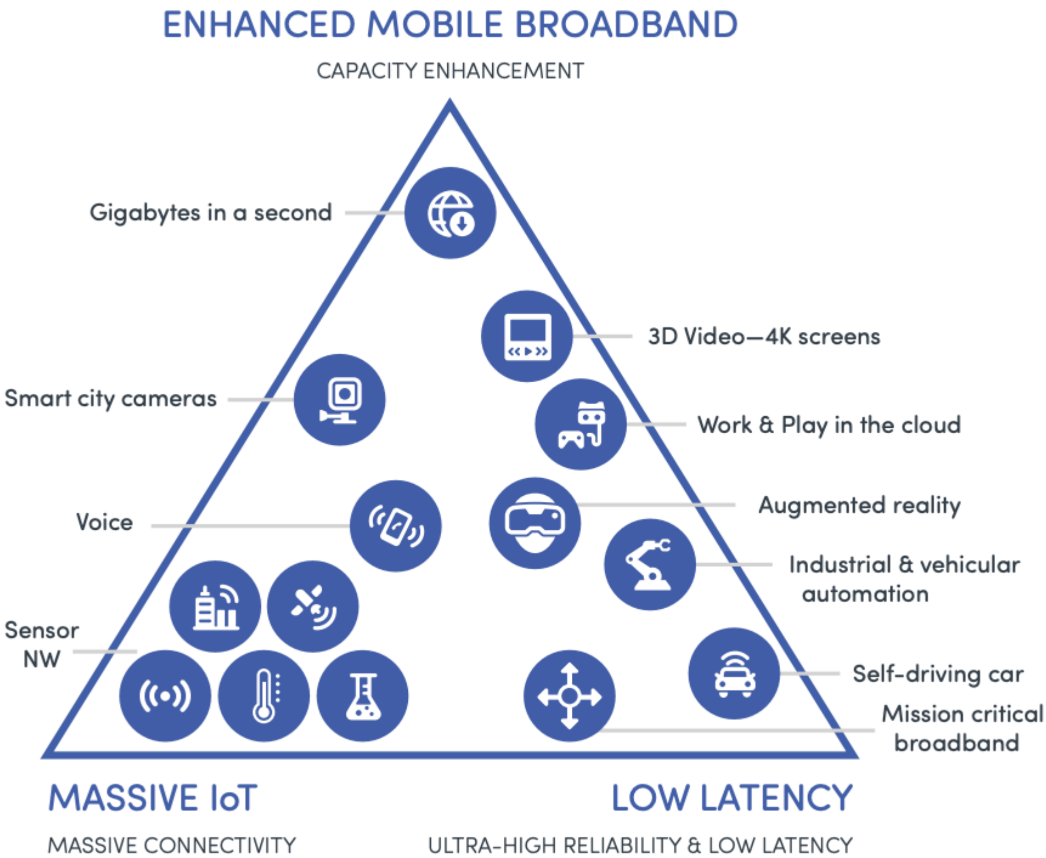

FIGURE 1.1: 5G triangle for targets and terminologies

of these technologies makes the 5G eNB and UE ecosystem more complex, resulting in significant higher timing and synchronization challenges.
For 5G, higher accuracy time synchronization requirements and increasing challenges are raised due to new services, technologies, and network architecture. Major of these technologies and services include Carrier aggregation, Coordinated Multipoint Technologies (CoMP), 5G frame structure, back haul and front haul and higher accuracy and positioning services requirements.

1.2 Objectives of the thesis

Objective of the thesis is to get thorough understanding of the 5G goals and how and from where the significant higher synchronization challenges as compared to LTE are emerging from. Researching this question lead us to the conclusion that higher the complexity and system architecture for 5G which is the need for fullfilling 5G objectives, higher the system synchronization challenges.The objective of the thesis is to understand the different forms of synchronization schems and present the escalating synchronization challenges, evaluate the performance effects of these synchronization challenges on 5G throughput, latency, data rate and other achievable targets. It is also in objectives to present and research viable solutions to overcome these challenges that improve the 5G system performance as promised by the telecommunication vendors and 5G marketers. There are three different forms of synchronization schemes in 5G and recent systems:

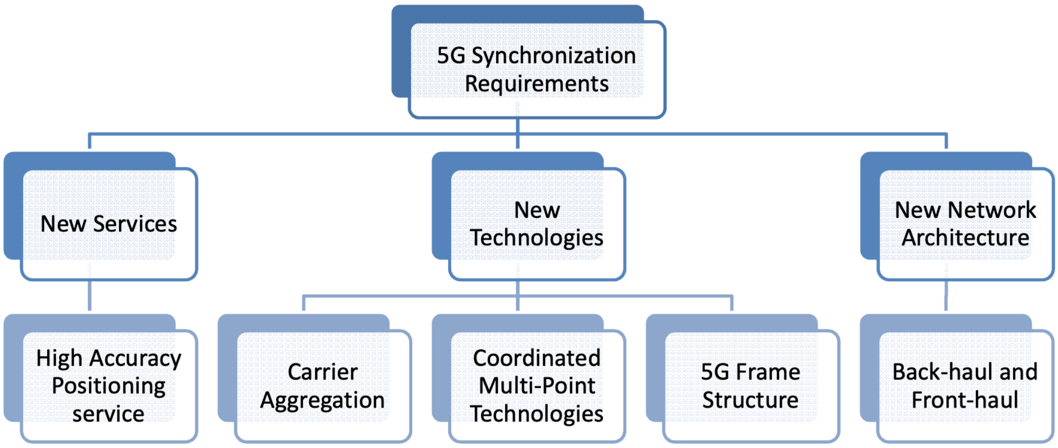

FIGURE 1.2: Technologies and Services Rising Synchronization Challenges

Frequency:
Two clocks that are aligned in terms of their repeating interval (i.e. frequency), but not in phase and time.

FIGURE 1.3: Two Clocks Aligned in Frequency but not in Phase and Time.

Phase:
Two clocks that are aligned in terms of their repeating interval (i.e. frequency), and also phase (a one-second interval) but without a common time origin.

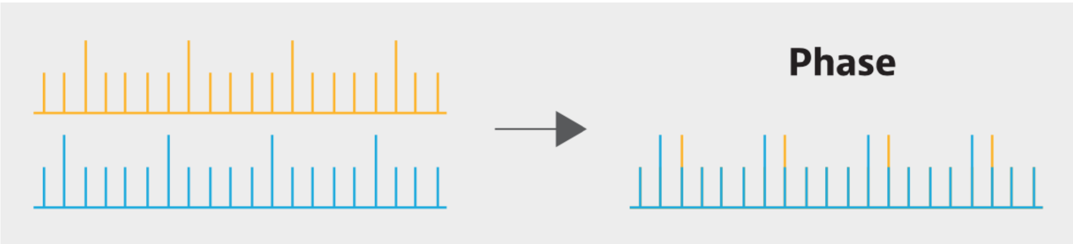

FIGURE 1.4: Two Clocks aligned in Frequency and Phase but Without Common Time Origin.

Time:
Two clocks that are aligned in terms of their repeating interval (i.e. frequency), their phase (a one-second interval) and also sharing a common time origin.
Frame:
A compatible frame structure to avoid simultaneous UL/DL transmission, which determines a specific DL/UL transmission ratio and frame length.

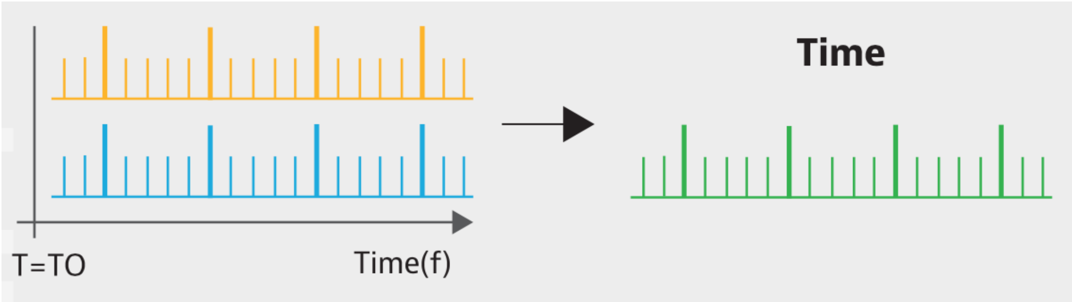

FIGURE 1.5: Two Clocks aligned in Frequency, Phase and Common Time Origin.

1.3 Importance of timing and synchronization in 5G networks

Synchronization and timing challenges fall in three different categories, which are timing synchronization, frequency synchronization, and phase synchronization. Timing synchronization refers to the correct and exactly same time-slot usage by the UE and eNB so that they can communicate to each other simultaneously and the messaging is not slipping into the next time slot being used by the next user avoiding interference to this next user. The time-slot concept arises from TDD, that is used in 5G as the duplex technology. FDD (Frequency Division Duplex) uses different frequency for both uplink and downlink where uplink refers to the communication from UE to eNB and downlink refers to the communication from eNB to the UE. The data rate is not symmetric between the uplink and downlink as user download more than they upload. Hence, more adoptable scheme such as TDD is needed to adjust the resources as per the imbalanced data rate requirements. TDD uses the same frequency for uplink and downlink but uses different time-slots for both uplink and downlink communication streams.

The frequency synchronization refers to the mismatch between the clock in the oscillators used by the UE and eNB. Oscillators by design use components that drift the frequency of the UE and eNB. Temperature, humidity and environmental variations are also contributing to the frequency drift. The downside of not matching clocks is exactly the same, the interference to the neighbouring channel and time-slot.

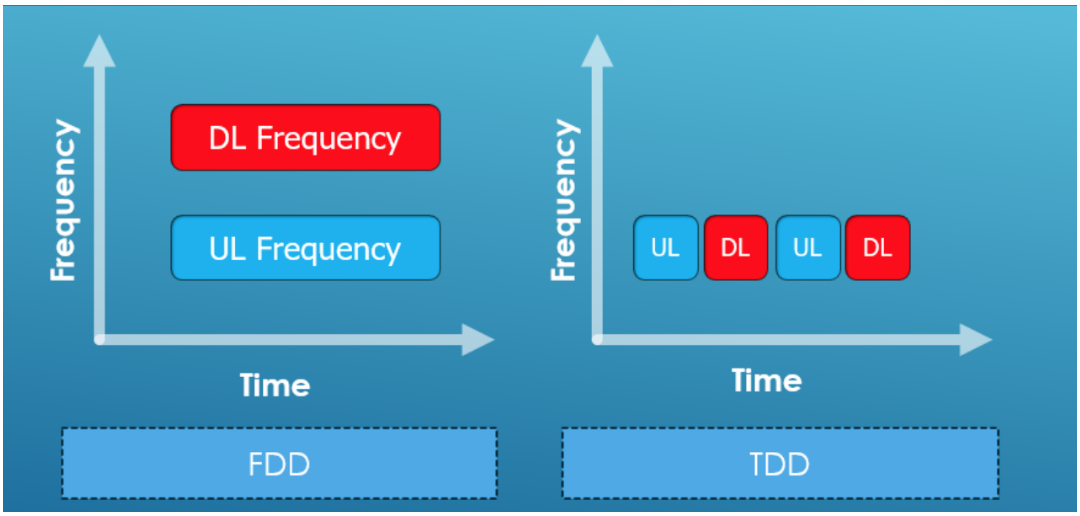

FIGURE 1.6: The FDD vs TDD for 5G massive MIMO and beamforming

The phase misalignment and errors are also originating due to similar issue including the oscillator instability, imperfect initial synchronization during initial cell search, propagation delays which is the signals traveling at different speeds, reaching at destination out of sync, causing phase misalignment and multi-path effect which is the signal taking different paths to reach the receiver, hence reaching at different times and causing phase inaccuracies.
the importance of the synchronization can be emphasised with the fact that by getting synchronization right in the system, there is a distinct possibility to get interference out. Although, getting synchronization right and in ideal condition is not possible due to factors such as oscillator design deficiencies, mullti-path and propagation delay and other factors that contribute to synchronization, hence a complete elimination of interference might not be possible in LTE and 5G system. However, interference that is generated in LTE and 5G systems that arises in two different forms, Inter-symbol interference (ISI) and Inter-carrier interference (ICI) is best illustrated by the Figure 1.8. This figure also illustrates the importance of timing and

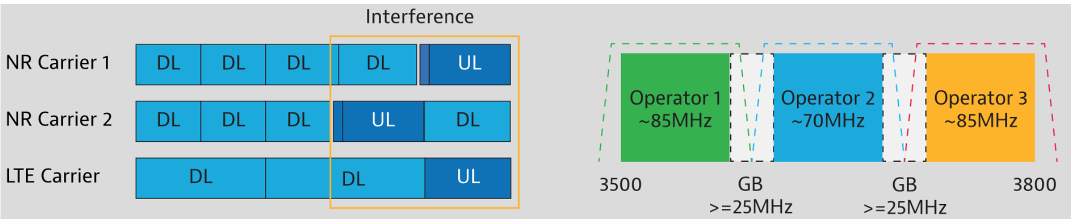

FIGURE 1.7: Interference Generation between Adjacent Carriers in Without Synchronization Case.

synchronization in 5G and LTE network. alternatively, if UL/DL or gNB and UE are perfectly synced, the situation might look like as in Figure below in an interference free environment.

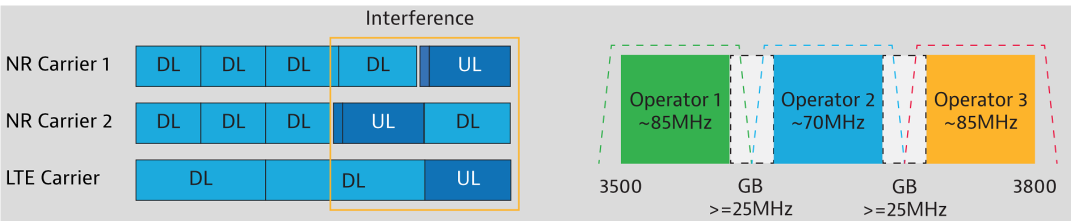

FIGURE 1.8: No Interference Generation between Adjacent Carriers in perfect Synchronization Case.

1.4 Research Question and Problem statement

In 5G systems, precise synchronization and timing are crucial for maintaining efficient communication and optimizing network performance. The frame structure of 5G networks relies on specific synchronization signals and channels, such as the PSS, SSS, and PBCH, to ensure accurate timing alignment and seamless connectivity. However, the impact of these synchronization procedures on the overall performance and reliability of 5G systems is not fully understood. This study aims to investigate the effects of synchronization and timing mechanisms on 5G system performance, focusing on how inaccuracies or delays in these processes can lead to

reduced efficiency, increased latency, and potential connectivity issues. By analyzing the role of PSS, SSS, PBCH, and other synchronization subframes, this research will provide insights into optimizing synchronization procedures to enhance 5G network performance.
The research question that this thesis mainly investigates is to first understand the frame structure and signals that are essential for understanding of the synchronization issues increasing with the complexity of the 5G system and emerging technologies to accommodate higher rates, latency and coverage requirements. This requires understanding PSS (Primary Synchronization Signal), SSS (Secondary Synchronization Signals), SS (Synchronization Signal), PBCH (Physical Broadcast Channel) and DMRS (Demodulation reference signals).

- Physical Broadcast Channel (PBCH): The PBCH provides slot and radio frame synchronization, carries the Master Information Block (MIB), and identifies the transmitted beam direction.

- Primary Synchronization Signal (PSS): The PSS is a specific physical layer signal used for radio frame synchronization. When a UE powers on and tunes to a specific frequency, it first searches for the PSS. Upon successfully detecting the PSS, the UE begins decoding the entire SSB.

- Secondary Synchronization Signal (SSS): The SSS is associated with the cell identity group N_{ID}^{1} and the cell identity within the group N_{ID}^{2}. By successfully demodulating the PSS, you can obtain N_{ID}^{2}. UsingN_{ID}^{2}, you can then demodulate the SSS to obtain N_{ID}^{1}. The physical cell identity, N_{ID}^{cell} is defined by the equation:
$$N_{ID}^{cell} = 3N_{ID}^{1} + N_{ID}^{2} \tag{1.1}$$
where N_{ID}^{1} is the physical layer cell identity group (0 to 167). and N_{ID}^{2} is the identity within the group (0 to 2).

1.4.1 Tracing the Origin for Frequency Drift Errors.

Hence, the research question lies in three different areas.
The Oscillator Design details and frequency drifting phenomenon study:
The oscillator is responsible for frequency errors. In terms of oscillator design, accuracy and resulting offset in frequency, this research aims at answering questions like:

1. The oscillator currently in operation by LTE standard results in higher frequency offset, in numbers, it is 60 KHz for 6 GHz. Although more accurate oscillators are rather expensive and difficult to design, they are a crucial need in 5G systems with lower ppm and lower frequency offset.

2. What is the minimum acceptable error of offset in terms of frequency, timing and phase set as standard for 5G systems.

3. Research the states-of-the art commercial oscillators and how they are suitable for 5G NR systems and requirements. How does these oscillators differ from

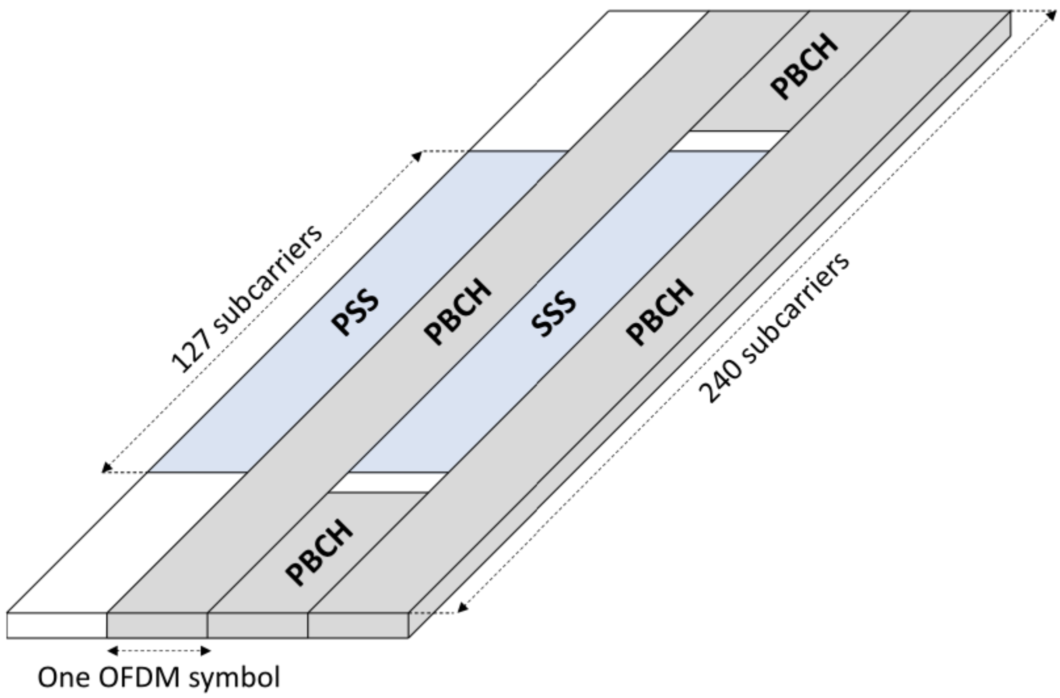

FIGURE 1.9: The time-frequency structure of a single SS Block, consisting of PSS, SSS and PBCH.

the ones used in LTE systems.

4. 5G NR works across many wide and higher frequency ranges, can these commercial oscillators provide the accuracy requirements and acceptable frequency errors for emerging 5G systems in designated frequency bands.

5. During the signalling procedure, can gNBs/eNBs and users estimate and correct the frequency offset of current commercial oscillators?

1.4.2 Time and Timing Alignment Errors:

There are three types of time and timing alignment errors.

1. Time alignment error is the timing difference between the antenna ports, measured over the air using a GPS or a common timing source as a reference. Historically, GPS receivers have been the most common timing synchronization source for the cell sites but they might not be cost effective for 5G.

2. Relative time error is the time difference between the inputs into two radio units. Relative TE error requirements are essential for advanced features including the carrier aggregation, MIMO, CoMP and location-based services.

3. Absolute-time error is the time difference between a node and PRTC which is grand master time reference. It can be measured using the precision timing protocol (PTP) for 5G-NR TDD systems. ITU-T recommends up to 1.1 microsecond up to the access point.

1.5 Outline of the thesis

TO BE ADDED

1.6 Literature Review

in this part of thesis, we dive deep into the problem statement. As the problem statement has been divided into three main parts, namely frequency synchronization, Timing synchronization, and phase synchronization and their related inaccuracies. Since the focus is on timing and frequency synchronization, the frequency synchronization origin is researched first, which turns out to be the OFDM system's limitations. The OFDM system basic structure is explained and researched and how it is susceptible to inter-carrier interference (ICI), Inter-Symbol interference (ISI). The orthogonality in the OFDM systems requires that transmitter and receiver operate at the exact same frequency, If it is not exactly the same frequency on both sides, the orthogonality is lost and this results in sub-carrie leakage which in turn introduces the phenomenon of inter-carrier interference (ICI). Putting it another way is that OFDM systems are susceptible to the frequency synchronization inaccuracies in the form of Carrier-frequency Offset (CFO).

(Evaluating the Performance of Over-the-Air Time Synchronization for 5G and TSN Integration). The performance of the real-time capabilities are targeted to be improved by the IEEE 802.1 Time Sensitive Networking (TSN). This paper [] assesses the over-the-air time synchronization mechanism from 3GPP Release 16. We analyse synchronization accuracy using the boundary clock method, considering clock drift and air-interface timing errors. We also explore frequency and scalability aspects. Our findings reveal the conditions needed to meet the 1 μs TSN time synchronization requirement.

1.6.1 Frequency Synchronization

In the first paper that is reviewed, the cooperative communication or distributed multiple-input multiple-output (DMIMO) system, combined with orthogonal frequency division multiplexing (OFDM), is considered that is an effective technology for achieving high data-rates, high link-reliability and coverage extension for 5G NR communication systems. The DMIMO system uses multiple relays equipped with either single or multiple antennas to create a virtual antenna array (VAA) between the source and destination. Transitioning from a conventional network with uncoordinated nodes to a DMIMO-OFDM system necessitates strong synchronization and tracking. The signal received at the destination experiences multiple timing offsets (MTOs), multiple carrier frequency offsets (MCFOs), and frequency-selective channel gains. This paper tackles the challenge of jointly estimating time, frequency, and channel gain for the estimate-and-forward (EF) relaying protocol. EF is good in terms of cost but provides coarse estimation, resulting in Inter-carrier interference (ICI), hence statistically improvements of EF in the form of expectation conditional maximization (ECM) and space-alternating generalized expectation maximization (SAGE) are introduces that are highly effective and iteration-based algorithms to jointly estimate MTOs, MCFOs, and channel gains in the presence of ICIs.

1.6.2 Time Synchronization

(High-precision time synchronization based on common performance clock source)

As discussed later in this chapter, it is highly crucial for the clock of all the devices in the system to be synchronized to a very-precise common clock source such as UTC.The UTX precision also might have some time synchronization inaccuracies, hence a n even better for of clock and more accurate clock source is required and hence presented in []. The accuracy of UTC clocks for time synchronization is typically within a few nanoseconds. High-precision UTC clocks, such as those used in scientific research and advanced communication systems, can achieve synchronization accuracies as tight as 10 to 100 nanoseconds.

Hence, a common-view device is presented tat consists of a A satellite card, a time interval counter, a primary control module, and the clock source and remote data transmission modules. The clock source module utilises a temperature-stabilized voltage-controlled crystal oscillator, providing an affordable clock source with standard performance. As per this research, a common package is the need of the time for the generation of time-frequency in a direct manner. This need arises from the fact that a Nanosecond-level remote time synchronization are mainly defined in the categories of satellite common view, two-way satellite synchronization, full satellite view, precise single-point synchronization, and fiber optic time transmission, among others through p-p (point-to-point) links. Now p-p is limited since it is s costly and requires constant human maintenance, accommodates fractional number of users and is not scalable and wide spread technology, due to which a better solution is required.

This paper explores an affordable, high-precision nanosecond time synchronization method based on national standard time. It uses satellite common view to directly compare user time with national standard time, effectively reproducing it for users. This method offers a practical solution for applications requiring precise time synchronization, maintaining a deviation within 10 ns by controlling a standard performance clock source.

1.6.3 Fundamentals of timing anded synchronization in telecommunications

Orthogonal Frequency Division multiplexing (OFDM) is the base technology for 4G and 5G NR. However, the OFDM based are highly susceptible to carrier frequency offsets.

The core concept of OFDM involves dividing a high-rate data stream into multiple lower-rate streams, which are then transmitted simultaneously across various subcarriers. While the overall channel exhibits frequency selectivity, each subchannel experiences flat fading. To handle Inter-Block Interference (IBI), OFDM systems use a cyclic prefix (CP) added after IFFT modulation at the transmitter. The CP length is chosen to be longer than the FIR channel memory to eliminate IBI. However, a major drawback of OFDM is its increased sensitivity to carrier frequency offset (CFO) compared to single carrier modulations. CFO leads to two main issues: a reduction in signal amplitude and the introduction of inter-carrier interference (ICI) from other carriers, both of which significantly degrade Bit Error Rate (BER) performance.

As new radio technologies and network architectures develop to enhance efficiency and support complex 5G use cases, the necessity for synchronization in the

RAN has increased. Although the basic synchronization requirements haven't become stricter with 5G, the importance of precise time synchronization has significantly heightened. (Ericsson paper)

1.6.4 Overview of Timing Synchronization Protocols.

Timing synchronization is defined as the time standard uniformity and being exactly same across all devices or parts in a communication system. Eventually, this time standard Across all devices has to be matched to the Co-ordinateg Universal Time (UTC). Timing sycnhronization has gone widespread to eventually effect many fields such as High-frequency trading within the finance industry, coordination in distributed computing across data centres, frame alignment in video streaming, and precise time synchronization among devices in extensive scientific experiments, such as those involving atomic physics accelerators.
4G and beyond systems such as 5G are using Time division duplex (TDD) technology to effectively use the same frequency on the down link and uplink. This enhances the bandwidth usage efficiency of the mobile devices. the requirement for time synchronization accuracy for TDD systems is set to be +/-1.5 µs.
To make maximum usage of the spectrum provided by the ITU-T to every telecom operator, the system without the inter-guard band between the adjacent operators is used. This makes timing synchronization even more critical, because if it increases, the radio interference between the operators may occur.

Figure 1.10 suggests that if the time synchronization error goes beyond the allowable limits, the uplink and downlink frame patterns may be reversed, this will also result in interference but now with other than neighbouring operators. This problem can only be solved by synchronizing operators to a highly accurate standard such as GPS (Global Positioning System) and it also calls fro needing to unify the uplink and Downlink TDD frame structure. NTT japan presented these interference issues and their main cause due to time synchronization error and In January 2020, ITU-T Study Group (SG) 15 reviewed these considerations and incorporated them into the time synchronization requirements outlined in Recommendation G.8271.
Time Sensitive Networking (TSN) has been standardised by IEEE (Institute of Electrical and Electronics Engineers) as an industrial Ethernet standard, it facilitates real-time monitoring and control by ensuring low latency and precise time synchronization. The standards for time synchronization are specified in IEEE 802.1AS.

1.6.5 Precision Time Protocol (PTP), Timing Synchronization Protocol.

Precision Time Protocol (PTP) is the main time synchronization protocol for obtaining the target for highly-precise time synchronization. It exchanges particular packets for achieving time synchronization that contain embedded time-sync information. IEEE1588 is the standard that represents basic PTP. Various industrial fields rely on IEEE 1588, with standardization organizations and research institutes maintaining compatibility and adapting the protocol to meet the specific requirements of different use cases.

Paper: [Network Time-Synchronization in TDD Based LTE-Advanced Systems]: This paper described the network time synchronisation method in TDD based systems such as LTE and 5G. Two types of synchronisations are discussed. Full Synchronisation:
Loose Synchronization

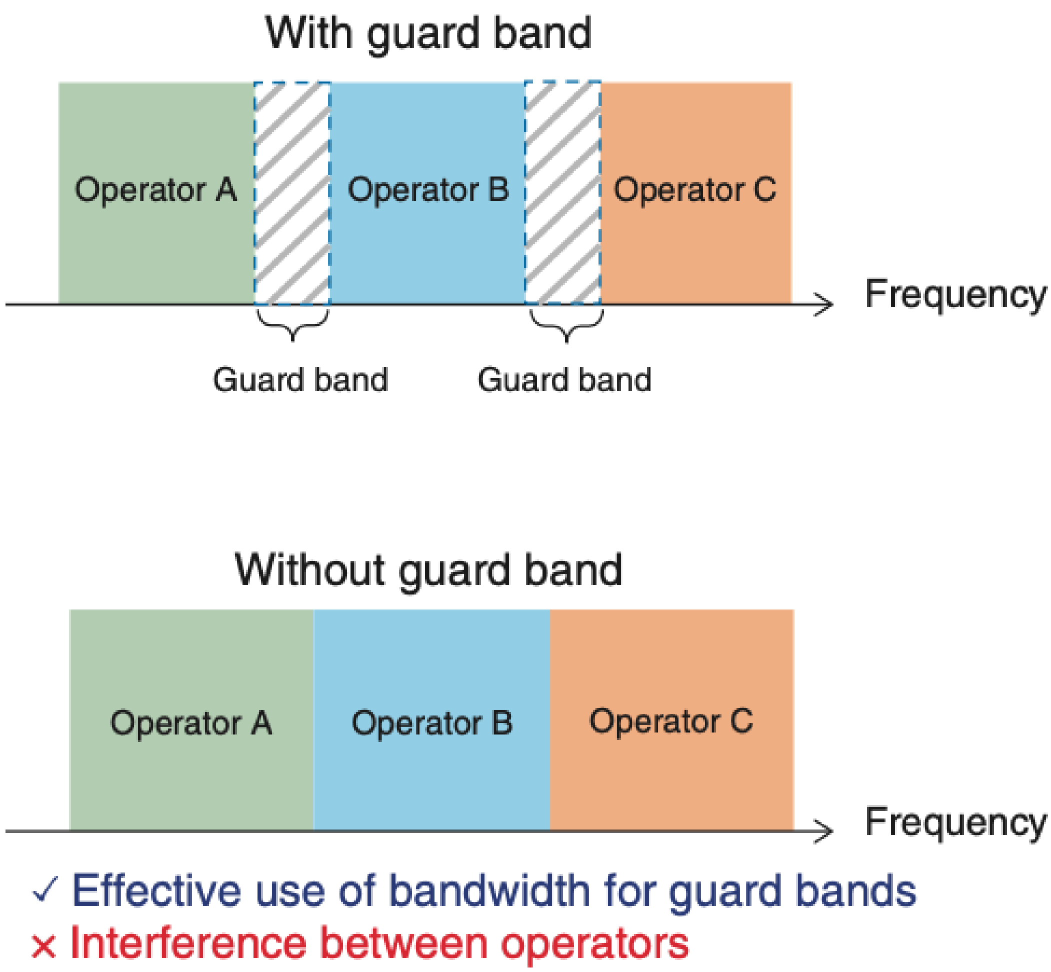

FIGURE 1.10: The interference situation with and without guard-band.

Un-Synchronization:

1.6.6 Background Research and Information on Frequency Synchronization in 5G networks

1.6.7 CFO Techniques and Their origin

OFDM system are particularly sensitive to the carrier frequency offset (CFO) due to doppler effects, which is movement of mobile terminals at high speed relative to Base station or relative high speed motion between transmitter and receiver, the inter-carrier interference due to the OFDM sub-carrier based systems and orthogonality being lost due to the OFDM inherent system design limitations. The cyclic-Prefix (CP) acts as the guard band between the sub-carriers to prevent inter-symbol interference (ISI) and helps sub-carriers maintain orthogonality which is essential for no leakage into neighbouring sub-carriers and avid ISI.

The ideal length of the CP is typically chosen to be slightly longer than the maximum expected delay spread of the channel. The delay spread is the time difference between the arrival of the first and the last multi-path component of a transmitted

signal.
A longer CP reduces the spectral efficiency because it increases the overhead. The length of the CP is a trade-off between robustness against multi-path interference and the efficiency of data transmission. In practical systems, the CP length is often chosen to be around 25% of the OFDM symbol duration.
The duration of the Cyclic Prefix (CP) is denoted as T_g. For an OFDM symbol, the total duration including the CP is given by:

$$T_{\text{total}} = T_s + T_g$$

where T_s is the duration of the OFDM symbol without the CP.

The CP length T_g should satisfy:

$$T_g > \tau_{\text{max}}$$

where τ_{max} is the maximum delay spread of the channel.

In practical systems, another parameter T_p might also be used to denote a typical or standard CP length, depending on the context.

To summarize:

$$\begin{aligned} T_g &\text{ - Duration of the Cyclic Prefix (CP)} \\ T_p &\text{ - Typical or standard CP length} \\ T_s &\text{ - Duration of the OFDM symbol without the CP} \\ T_{\text{total}} = T_s + T_g &\text{ - Total duration of the OFDM symbol including the CP} \\ \tau_{\text{max}} &\text{ - Maximum delay spread of the channel} \end{aligned}$$

In LTE:
Normal CP: Approximately 4.7 µs, designed to cover typical urban multi-path delay spreads. Extended CP: Approximately 16.7 µs, used for environments with longer delay spreads, such as rural areas.
In 5G:

The CP length varies with the subcarrier spacing and numerology. For instance, with a subcarrier spacing of 15 kHz (similar to LTE), the normal CP length is around 4.76 µs.

Doppler effect

CFO Estimation techniques

Paper: Carrier Frequency Offset Estimation for OFDM Systems:
The OFDM sensitivity to carrier frequency offset between the transmitter and receiver results in Inter-carrier interference (ICI). This paper derives the mathematical of OFDM system with Cyclic-Prefix (CP) and virtual sub-set carrier. The author has developed or proposed a carrier frequency offset estimation algorithm for the ESPRIT-like estimator utilising the DOA-MATRIX method. Following an initial rough estimation, it simultaneously determines the frequency offset and a matrix containing channel information, which aids in offset compensation and signal demodulation. Numerical simulations demonstrate the effectiveness of this algorithm.

From Paper: Study of the estimation techniques for the CarrierFrequency Offset (CFO) in OFDM systems.

Another research tries to tackle the frequency offset problem considering it as the major problem in OFM based systems. the papers considers the lack of local oscillator synchronization accuracy in the process of the down conversion of the receiver as the major cause of frequency offset. the CFO (Carrier frequency offset) can result in the following discrepancies in the system.

- The mismatch between the transmitter and receiver local oscillator frequencies clocks.
- The inter-carrier interference (ICI)
- Doppler effect (The relative movement or high speed movement between transmitter and receiver introducing frequency synchronisation mismatch.)

The receiver needs to know two very important factors to get it synchronized with the transmitter. the point at which it needs to sample the incoming OFDm symbol prior to the start of the FFT process. How to estimate and correct the frequency offset.

Hence, as proposed solutions, Two types of algorithms are introduced from the literature on CFO estimation which are:
1. Training based algorithm:
Training sequences can be formulated in such a way to minimise computational demands on the receiver, resulting in algorithms with low computational complexity. However, a drawback of these training-based algorithms is the need to transmit training sequences from the transmitter, which can reduce data throughput efficiency.
2. Blind algorithm and Semi-blind algorithm:

The blind algorithm title emerges from the fact that the carrier frequency offset (CFO0 is estimated using the statistical properties of the received signal, without the receiver having any information about the data or signal that transmitter have been transmitting. This results in enhanced computational complexity with the advantage that there is no over head that is being transmitted regularly, bringing throughput efficiency compared to training based algorithms.

Paper: Carrier Frequency Offset Estimation in 5G NR: Introducing Gradient Boosting Machines

Another effective approach that has been used for CFO estimation in 5G NR systems is the use of Machine learning techniques, specifically Gradient Boosting Machines (GBM) have been use for CFO estimation in certain conditions such as a UE is required to accept or initiate a call in low Signal-to-Noise (SNR) condition i.e. -10 dB with one antenna and zero frequency diversity, hence intensifying the signal synchronisation challenges. This situation presents major challenges to timing ad frequency synchronization, specifically CFO estimation. Maximum Likelihood based on Cyclic Prefix is one choice, but there are limitations to this method and it turns out the machine learning techniques such Gradient- Boosting Machines (GBM) have excellent results in terms of CFO estimation given the received PSS (Primary

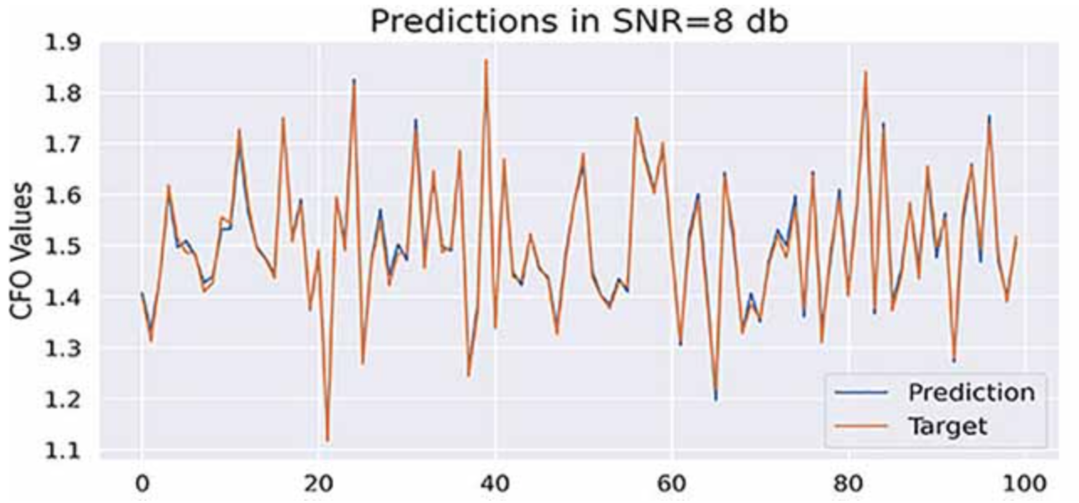

FIGURE 1.11: We used a GPM to predict CFO, training the model on 80% of the data and testing it on the remaining 20%. The training set was split into training and validation subsets. The figure shows the model's prediction accuracy for a 100-point test sample, demonstrating that the GPM accurately predicts CFO. This success is due to the ensemble model's power and the boosting technique used..

Synchronization Signal) and SSS (Secondary Synchronization Signal). There is extensive literature available and research conducted on CFO estimation and it can be read from the given referees some of which are [A Research on Carrier Frequency Offset Estimation for 5G Telecommunication], [Residual Frequency offset Estimation Scheme for 5G NR System.], [Study of the estimation techniques for the Carrier Frequency Offset (CFO) in OFDM systems.], [Carrier frequency offset estimation in OFDM systems], [OFDM Carrier Frequency Offset Estimation]

1.6.8 Identification of gaps in knowledge

The main limitations or critical issues that need to be solved in timing and synchronization procedures in 5G and their performance analysis lies in:

1): Improving oscillator synchronization accuracy.
2): the inherent limitations in the CFO estimation algorithms such as autocorrelation and cross correlation, maximum Likelihood estimator (MLE), and other algorithms such as pilot assisted and joint estimation algorithms.
3): Phase noise which is mainly produced from the oscillator design shortcomings and instability and is contributed by thermal instability, component ageing and power supply fluctuations.
Inherent Limitations in CFO Estimation Algorithms: the first two algorithms worth noting are auto-correlation, cross-correlation and maximum likelihood (MLE).
Autocorrelation and Cross-Correlation: *Noise Sensitivity:*
These methods are highly sensitive to noise, which can lead to inaccurate estimations, especially in low Signal-to-Noise Ratio (SNR) conditions.
Multipath Effects:
The presence of multipath can distort correlation peaks, making it difficult to distinguish the correct frequency offset.

Non-linearities: Correlation methods can be affected by non-linearities in the system, leading to bias in the estimation.
Maximum Likelihood Estimator (MLE):
Complexity:
MLE involves complex calculations and iterative methods, making it computationally intensive.
Convergence Issues: MLE can suffer from convergence problems, especially in the presence of large frequency offsets or noise.
Initial Estimates: MLE requires good initial estimates to converge to the correct value, which might not always be available.
Other Popular Algorithms for CFO Estimation:
Pilot-Aided Estimation: Utilizes known pilot symbols to estimate the CFO, providing high accuracy but requiring additional bandwidth for pilot symbols
Subspace Methods: These methods, such as MUSIC and ESPRIT, leverage the signal subspace for CFO estimation, offering good performance but at the cost of high computational complexity.
Kalman Filtering:
Employs a recursive approach to estimate the CFO over time, which can be efficient but relies on accurate modelling of the system dynamics.
Frequency Domain Methods: These methods analyze the frequency domain representation of the received signal, providing robust performance but requiring fast Fourier transforms (FFT) and additional processing.
Timing Error Estimation Algorithms:
Early-Late Gate: A simple method that compares early and late samples of the received signal to estimate timing errors, but it can be sensitive to noise and multipath.
Gardner Timing Error Detector: Provides a robust estimate of timing error using interpolated samples, widely used in digital communication systems.
Mueller and Müller Detector: A decision-directed method that adjusts the sampling time based on symbol decisions, offering good performance in various conditions.
Phase Noise Synchronization Issues:
Phase noise refers to the rapid, short-term fluctuations in the phase of a signal, which can significantly impact the performance of communication systems.

Importance of Phase Noise:
Signal Integrity: Phase noise can degrade the quality of the transmitted signal, leading to increased error rates and reduced communication reliability.
Carrier Synchronization: Accurate carrier synchronization is crucial for coherent demodulation, and phase noise can disrupt this process, causing demodulation errors.
Interference: Phase noise can spread the signal's spectrum, causing interference with adjacent channels and reducing spectral efficiency.

Appendix A

Frequently Asked Questions

A.1 How do I change the colors of links?

The color of links can be changed to your liking using:
`\hypersetup{urlcolor=red}`, or
`\hypersetup{citecolor=green}`, or
`\hypersetup{allcolor=blue}`.
If you want to completely hide the links, you can use:
`\hypersetup{allcolors=.}`, or even better:
`\hypersetup{hidelinks}`.
If you want to have obvious links in the PDF but not the printed text, use:
`\hypersetup{colorlinks=false}`.