

# **Implementing Tactile Internet using 5G Technology to Minimise Production Time in a PLC-Driven Smart Manufacturing Environment**

by

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## **Declaration of Independent Work**

I, Humane Joseph Mokotjo, student number #####, do hereby declare that this research project submitted to the Central University of Technology, Free State, for the Degree MASTER OF ENGINEERING: ELECTRICAL ENGINEERING, is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State, and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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DATE

## **Dedication**

I would like to dedicate this work to my family and friends for bearing with me and praying for the success of my work, and further dedications to Prof. Rangith Kuriakose and his research team for the encouragement, guidance, and motivations during this study.

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## **Abstract**

Smart manufacturing involves a dynamic, autonomous, and data-centric manufacturing or processing line. This manufacturing approach is gradually replacing traditional manufacturing due to its advantages which include improved productivity, reduced labour costs, product uniformity, remote and predictive maintenance, scalability, and product customisation. Amongst others, automation of production lines is one of the key attributes which is identified in all smart plants. Moreover, Programmable Logic Controllers (PLCs) are the most predominant automation technology in smart manufacturing. The diversity of PLCs is engendered by their durability, scalability, flexibility, improved usability, and simplified fault-finding ability. To facilitate network-reliant operations like remote maintenance, data management, and digital twins in smart manufacturing, a network technology with low latency, high bandwidth, easy access, increased reliability, and the ability to multi-connect an increased number of nodes should be implemented to establish a visual presence called tactile internet. These qualities are proven to improve data synchronisation on the network link of tactile internet applications, and improved network links minimise production time in smart manufacturing plants as the plant can be maintained remotely, and collaborative decision making, at any stage of production, can be made without network interruptions. Therefore, 5G network technology, which is equipped with the ultra-low latency, broad bandwidth, maximum device density, and reliability over all commercially available network technologies at the time of conducting this study, should be adapted into smart manufacturing environment to facilitate tactile internet applications. However, most industrial-level PLCs which are diversely used in smart plants lack 5G capabilities. Hence, this study undertook the comprehensive research of improving wireless 5G capabilities in an already existing PLC-driven smart plant, implementing tactile internet using wireless 5G technology, and proving/disproving the theorised ability of 5G technology to improve production time in tactile internet applications. In this study, the Scalance MUM856-1 5G wireless router was used to enhance 5G wireless features in a PLC-driven smart water bottling. Based on measured results, 5G technology was able to decrease the latency by 99.01%, increase bandwidth (throughput) by 75.40%, improve device density by 90%, maintain 100% reliability, and improve system accessibility over 4G network technology.

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# 1. Introduction

## 1.1. Introduction to Study Environment

Traditional manufacturing lines depend on the utility of human labour and manual hand-to-hand procedures. This manufacturing process has been the backbone of many industries for centuries and is still inevitably implemented in a few industries today [1]. Due to its limitation in production speed (hence limiting production volume), limited product uniformity, and lack of flexibility, the relevance of traditional manufacturing is gradually fading out in most industries [1], [2], [3].

With the aim of addressing the deficiencies identified in traditional manufacturing to meet consumer demands and increase the competitive advantage of the manufacturing sector in the global economy [4], the manufacturing and processing sector has gradually transformed into a more advanced and dynamic manufacturing approach called smart process manufacturing, which was coined as ‘smart manufacturing’ later in 2006 at a National Science Foundation workshop [4], [5].

Smart manufacturing leverages data-driven technologies, interconnected devices, and real-time analytic diagnostics which aim to optimise the manufacturing process by facilitating product customisation, make-to-order systems, and product uniformity. As a result of all these benefits inherited by smart manufacturing, a considerable migration of the manufacturing sector from traditional to smart manufacturing has been realised in recent years [6], [7].

In smart manufacturing, production or processing lines are characterised by process automation, data storage, remote access, prediction of bottlenecks, and the ability to interrupt a physical system using digital twins [1], [8]. Over the years, the automation of smart factories has been achieved through the realisation of Industry 4.0 and Industrial Internet of Things (IIoT) with the introduction of automation-over-internet in the smart manufacturing environment [9], [10], [11].

Among these innovative transformations of automation, Programmable Logic Controllers, hereinafter abbreviated as PLCs, have the most diverse automation technology over centuries of automation history [11], [12]. PLCs contribute exceptional qualities, such as improved efficiency, precision, and flexibility, thereby bettering the manufacturing process and escalating the potential of Industry 4.0 [12], [13].

The automation of smart factories relies on a series of user-defined instruction lines, commonly referred to as the program, to govern the decision making at every stage and emerging condition (inputs/outputs) in a production line [14], [15]. On a PLC-automated smart manufacturing plant, signals from the field sensors are centralised on a PLC device and govern decision making using conditional examination functions at every stage of the production line [15].

Similarly, all the output actuator signals are generated from the PLC device and output to respective actuators according to the defined control program [15], [16]. This centralised server platform integrates field sensors and actuators on a user-defined PLC program to develop an automated Internet of Things scenario. However, for reliably storing automation data and historical performance of sensors/actuators during hardware failure, research recommends cloud storage as an optimal solution [17], [18].

Cloud storage provides an ascendible and easily attainable storage platform [17], [19]. The optimal data synchronisation between a smart factory (with data centralised in a PLC device) and a cloud storage can be achieved using a digital twin of the manufacturing line [8], [18], [19]. A digital twin is the virtual resemblance of the physical plant characterised by the bidirectional data synchronisation between the two, enhanced production performance optimisation, performance tracking, diagnostics, and prognostics [1].

For real-time data synchronisation between physical and virtual objects in digital twins, a reliable fast network link is required [2], [20]. This network can also facilitate cloud-based and remote access of smart factories for remote monitoring, maintenance and enhanced plant data access by stakeholders. However, research reveals a markable deficiency of remote access applications in PLC-automated smart factories [15].

The remote access deficiency identified in PLC-automated smart factories is caused by a lack of the latest network technologies' capabilities in most industrial-level PLCs [15]. Based on literature, the link between a PLC-driven physical system and digital object has been achieved using 3G, 4G, and 4G-LTE networks [20], [21].

However, the implementation of 3G, 4G, and 4G-LTE technologies in smart manufacturing is often hindered by limitations in network capacity (bandwidth), latency, device density, reliability, and accessibility [9]– [11]. These barriers can increase production time in smart manufacturing [15].

In the context of this research, production time is considered as the time taken to produce/process one unit of the intended product. Inadequate network bandwidth, poor network access, limited device density, low reliability, and high network latency can cause delays in data transmission and disrupt the flow of tasks and information across different processes due to interruptions in production cycles, increased downtime, and reduced efficiency, all of which can increase production time [21], [23][15], [16], [4], [6], [24].

The hypothesis is that, if the considered network factors are not optimal, the production time will be increased, which will in turn decrease production volume [15]. To address this issue, the aim of this study is to minimise production time in smart manufacturing by increasing network bandwidth, improving network access, increasing device density, increasing reliability, and minimising latency [15], [25].

This measures of improving production time involve identifying and implementing solutions to enhance the network infrastructure, reducing delays in data transmission, and streamlining the flow of information between devices and systems [12], [24]. Ultimately, this innovative improvement of transforming into an ultra-responsive network will stimulate adoption of the principle of Tactile Internet (TI) into the smart manufacturing industry [22], [26].

TI is the ability to monitor a physical system and apply interruptions to such system operation through the internet [25], [27]. This innovation facilitates visual presence and bi-directional feedback which could in turn escalate a massive growth of the manufacturing and processing sector in the global market [22]. However, this can only be achieved if the core barriers of high latency, limited network access, and low data capacity can be reduced [22].

The diversity of tactile internet applications has increased since it was formulated in 2014 [26]. Moreover, it is revealed in its definition that it requires the network to be ultra-responsive, highly reliable, more secure, and highly available, and older generations of mobile network technologies have limitations of high latency and limited bandwidth to facilitate tactile internet applications [28].

According to research, at the time of writing this dissertation, the only existing network technology which was commercially available to iron out network limitations in tactile internet applications is the 5<sup>th</sup> generation mobile communication system (hereinafter referred to as 5G) [15], [25].

5G technology is equipped with very high speed, high bandwidth, high reliability, and increased device density to multi-control various equipment at the same instance [21], [22]. Many comprehensive studies on 5G application were done in different private and public facilities, however, at the time of initiating this project, there is limited evidence on the implementation of the envisioned 5G technology to build a tactile internet application for accessing PLC-controlled smart factories.

Among other reasons limiting the implementation of 5G technology into PLC-driven smart factories' tactile internet, inadequacy of existing infrastructure to adapt to 5G technology with the aim of complimenting the envisioned future of tactile internet applications, was found to be the main reason [15], [28].

At the time of conducting this research, the 5G technology was still limited in developing countries, and it posed some formidable challenges as most of the systems used in smart manufacturing lack 5G capabilities – that is, the adaptability of most I/O network devices to 5G network is a challenge as most of them were invented before the existence of 5G [21], [22], [25].

However, the implementation of tactile internet using 5G, the feasibility of the setup, and predicted results, have been reviewed by various researchers, and this necessitated this research [10], [15]. This research is aimed at minimising production time by minimising the latency, increasing the network bandwidth, accessibility, reliability, and maximising the device density of the network link used to implement tactile internet application for a PLC-driven smart factory to decrease production time [18], [23].

The pre-existing smart water bottling plant which is driven by the Simatic S7-1200 PLC device, will be used as the case study for the project [16], [29]. The 4G network link will be developed between the remote Personal Computer (PC) and the PLC-driven smart water bottling plant, and those factors that affect production time will be measured [16], [29]. Then, a 5G network link between the remote PC and PLC-driven smart water bottling plant will be implemented. The same network performance factors will be measured, evaluated and compared with results for 4G tactile internet to conclude on the theorised ability of 5G network technology to improve production time based on the results.

## **1.2. Problem Statement**

Network connections used to implement tactile internet applications in PLC-driven smart factories have thus far been implemented using 3G, 4G, or 4G-LTE network technology. However, research revealed that the implementation of these network technologies limits the network capacity, device density, reliability, accessibility, and increase transmission latency, which will result in increased production time.

## **1.3. Research Questions**

1. Which effective and plausible amendments can be implemented on already existing PLC-driven plants to be able to adapt to 5G network technology?
2. Can the system modification ultimately be scalable to all PLC-driven systems?
3. Will the developed experiment increase bandwidth, device density, system accessibility, network reliability, and minimise network latency, which will in turn minimise production time?

## **1.4. Research Aims, Objectives, and Hypothesis**

### **1.4.1. Research Aim**

The aim of this project is to implement tactile internet using 5G network technology in a PLC-driven smart manufacturing environment to minimise production time.

### **1.4.2. Research Objectives**

In this project, the intention is to use a pre-existing smart water bottling plant as the smart factory test-bench to set up remote access for an automated processing plant using 5G network technology, and network factors that affect production time will be measured. Moreover, a 4G network setup will be developed and network factors that affect production time will also be measured for comparison purposes to complement the discussion on the theorised ability of 5G in minimising production time. These will be achieved through the following steps:

- Identify and develop a remote access setup using 4G network link on the physical object and measure network factors affecting production time.
- Identify and create a plausible solution of remotely accessing the PLC-driven smart

manufacturing factory over 5G network and measure network factors that affect production time.

- Compare and analyse the results from 4G and 5G networks set up to prove/disprove the theorised ability of 5G network technology in improving network factors that affect production time.

### **1.4.3. Research Hypothesis**

Production time in network-reliant PLC-driven smart factories is dependent on network latency, bandwidth, device density, reliability, and accessibility [15], [30], [31]. Research reveals that 5G network technology has minimal latency, high bandwidth, improved device density, high reliability, and broad network access over its predecessors, being 3G, 4G, and 4G-LTE networks [15], [32].

Hence, the hypothesis is that, with the implementation of 5G network technology to develop a tactile internet application in a PLC-driven smart factory, network latency will be minimised, bandwidth will be increased, network device density will be maximised, network reliability will be improved, and the plant will be more accessible [15]. As a result, the production time of such smart factory will be minimised, which will in turn increase production volume [15], [18], [25].

The scope of this dissertation will be limited to network factors which affect performance of the tactile internet setup being latency, bandwidth, device density, reliability, and accessibility. However, intra-network dynamics which lead changes in all mentioned performance metrics being security, network segmentation, encryption, and topology among others, were not reviewed in this study.

### **1.5. Research Methodology**

The research methodology for this study was started by an extensive literature review which engendered the following steps listed by stages:

## **Stage 1: Case study selection**

With consideration of all the features required in the project title, the case study for the project should be carefully chosen. This case study should be a smart plant which is driven by an industrial-level PLC drive and located in an area where there is a nearby 4G network link and wireless 5G network coverage. Analyse the operation of the case study to assure that it aligns with the intended tests.

## **Stage 2: Experimental setup**

The experimental setup will be executed through the following three phases:

### **Phase 1: Setting-up tactile internet using 4G network.**

Step 1: Set up an OPC server for data streaming.

Step 2: Set up tactile internet on the smart water bottling plant using 4G network.

Step 3: Measure network factors on 4G network tactile internet setup.

### **Phase 2: Implementing tactile internet using wireless 5G network.**

Step 1: Configure PLC drive for 5G setup.

Step 2: Implement tactile internet solution to the plant using wireless 5G network.

Step 3: Measure network factors on 5G network tactile internet setup.

### **Phase 3: Comparison**

Step 1: Compare measured results of network parameters from 4G and 5G network setup.

## **1.6. Case Study**

The pre-existing smart water bottling plant setup in the laboratory will be used as the smart factory case study for this study. The plant is currently operating on a centralised manufacturing protocol with three Smart Manufacturing Units (SMUs), being:

1. SMU1 – Filling unit

Fill the empty bottle with clean drinking water.

2. SMU2 – Capping unit

Cap filled water bottles.

### 3. SMU3 – Packaging unit

Package the filled and capped water bottles according to customer's order.

All data from field sensors and actuators from the three SMUs are centralised on the Simatic S7-1200 PLC drive from Siemens, and the entire plant is currently driven from wired connections.

The project aim in the case study will be achieved by developing an IoT hub enabling service-oriented intelligent manufacturing for enhanced autonomy and remote access [33]. The virtual and real space mapping will be enabled by establishing the communication protocol using both 4G and 5G network technologies for real-time synchronisation and geographic-free access of the physical plant [8].

## 1.7. Thesis Structure

### Chapter 1

This chapter introduces the study environment, explains the research title, formulates the problem statement, and necessitates the aim of the research with the intention of addressing the deficiency stated in the problem statement. To introduce and explain the research title and the study environment, some articles which possess close interest with the research title will be noted. The chapter will be concluded by directing the objectives, hypothesis, methodology to be implemented in addressing the problem statement, as well as selecting the suitable case study for the research.

### Chapter 2

In Chapter 2, publications sharing a close interest with the project title are reviewed. In these publications, key research fields of the project being smart manufacturing, industry 4.0, tactile internet, programmable logic controllers, 5G network technology, and cloud computing, are thoroughly explored. The intersections within these research fields are established with their contributions to the research title explained.

The chapter further locates the research gaps in reviewed publications and investigates the solutions of improving in such gaps. Based on research, the possible ways of implementing tactile internet using 5G are reviewed and theoretically expected result on network factors are analysed.

### **Chapter 3**

In Chapter 3, the methodology undertaken to fulfil the research aim is elaborated on. This methodology commences by thoroughly explaining the selected case study for the projects, then showcases the experimental setup for implementing tactile internet using 4G network for comparison reference. The chapter proceeds to the core aim of the study, which is to implement tactile internet using 5G technology. The final step is to scientifically measure network performance factors on 4G and 5G tactile internet applications.

### **Chapter 4**

Chapter 4 clearly showcases the experimentally measured results of network performance factors of 4G and 5G technologies' tactile internet applications. The comparison of network performance results from both tactile internet applications is detailed in graphical presentations. Moreover, calculation of percentage improvements is made to quantify improvements brought by 5G technology, if any.

### **Chapter 5**

This chapter engages in a thorough discussion on all highlighted research gaps identified in Chapter 2. The improvements that this research made to the identified research gaps and limitations are detailed in this chapter. The chapter further elaborates on the results shown in Chapter 4 and emphasises the research contribution that has emanated from this study, based on the comparison of both sets of results.

### **Chapter 6**

In this chapter, a detailed reflection is made on the research aim. In this reflection, a thorough analysis is made regarding whether the project was able to achieve the intended results, and research questions are answered. The efficiency and scalability of the implemented methodology are reviewed, and the results are examined to determine whether 5G network technology was able to improve production time in a PLC-driven smart plant, and hence, the success of the research is accentuated.

## 2. Literature Review

### 2.1. Introduction

This chapter conducts a comprehensive literature review on the study environment. The aim of this chapter is to present what researchers have presented in this area of research and thereby establish the research gap that necessitated this study. This will be done by exploring the manufacturing environment and doing a comparison between smart manufacturing and traditional manufacturing.

The chapter will then look at Programmable Logic Controllers (PLCs) and their impact on smart manufacturing environments with a special focus on the Simatic S7-1200 PLC drive as the case study for this project. An examination of different automation techniques will be conducted with merits of PLCs over other automation techniques which inspired the diversity of PLCs in the smart manufacturing environment.

The concept of tactile internet will be thoroughly explained, and the origin and evolution of tactile internet applications will be elaborated upon. Moreover, the role played by network technologies in tactile internet applications will be defined, including the adaptation of this tactile internet application in a PLC automated smart plant. The deficiency of adopting tactile technologies into PLC-driven smart plants will be identified and all possible solutions will be explored.

Based on the articles reviewed, solutions to the identified deficiency in tactile internet applications in PLC-driven plants will be introduced with special focus on 5G network. TI and 5G development, their evolution and reckonable footprints in their journeys will be highlighted, as well as the adaptation of 5G into tactile applications and PLC automated plants. The challenges underlying the introduction of 5G in smart manufacturing environments, and the possible and plausible ways of implementing 5G based on the work of various researchers.

Based on the literature review, the research gap will be identified, and the problem statement will be elaborated upon. The feasibility of the project and the limitations of the project will also be included in this chapter. At the end of this chapter, the link between smart manufacturing, PLCs, TI, and 5G network technology will be established.

## 2.2. Industry 4.0 and Smart Manufacturing

### 2.2.1. Industry 4.0

Industry 4.0 is a neologism that defines the realisation of technological transformation via the integration of smart digital technologies into manufacturing, industrial processing robotics, and autonomous systems [8], [34]. This cyber-physical transformation is characterised by haptic data acquisition between Industrial Internet of Thing (IIoT) smart devices, facilitation of cloud computing, utility of additive manufacturing, and application of Artificial Intelligence (AI) [6].

All characteristics of Industry 4.0 are constructive innovation features dedicated to the efficient operation of manufacturing, industrial processing, robotics and autonomous systems to enhance product customisation, decentralised and collaborative decision-making, make-to-order demand-reliant production, personalisation, green manufacturing, and efficient resource allocation [6], [8], [35]. Table 1 outlines some of most valuable characteristics of Industry 4.0.

*Table 1: Characteristics of Industry 4.0 and their explanations.*

<b>Characteristics of Industry 4.0</b>	<b>Explanations</b>
<b>Cyber-physical nature</b>	Allows utilisation of network technologies to facilitate machine-to-machine communication in a decentralised network.
<b>Additive manufacturing</b>	Technology models and prototypes used to enhance dynamic and predictive operations.
<b>Cloud computing</b>	Engaging centralised cloud computing platforms for reliable data acquisition, data management, storage, and ease of access.
<b>Haptic data analytics</b>	Allowing exchange of large amounts of data to complement systems' digitisation.
<b>Cybersecurity</b>	Overlays highest cryptographic security to encrypt network links and nodes against unauthorised access.

These pillars of Industry 4.0 draw a quantifiable line between Industry 3.0 and Industry 4.0 in the industrial evolution journey. This industrial evolution began in the 1760s with the first industrial revolution (Industry 1.0) which was focused on mechanical work powered by water or steam [6], [36], [37]. In the late 18<sup>th</sup> century, electrically powered mass production, named the second industrial revolution (Industry 2.0), was introduced in the manufacturing sector [6], [37].

A huge milestone was reached in the evolution of the industrial revolution in the mid-19<sup>th</sup> century when electronics, computers, IT infrastructure, robotics, and automation strategies were introduced in the industrial sector. This transformation was named the third industrial revolution (Industry 3.0) [6], [25], [36].

Next came the decentralised IIoT communications, digital twins, cloud computing, and big data analytics, referred to as the fourth industrial revolution (Industry 4.0), which was introduced in 2011 [6], [25], [35], [38]. The industrial revolution journey is demonstrated in Figure 1.

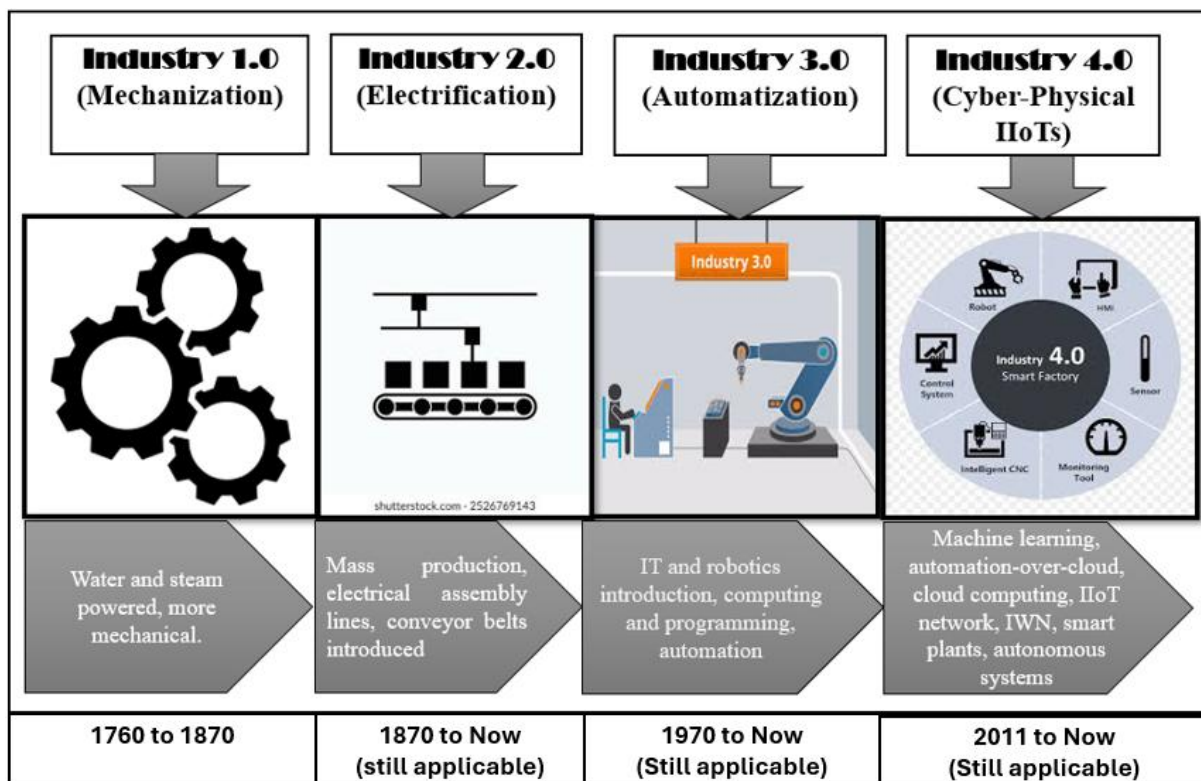


Figure 1: The evolutionary journey of industrial revolution.

With the evolutionary footprints from Industry 1.0 to Industry 4.0, more advantages were realised in the manufacturing and industrial processing sector which include mass production, collaboration with stakeholders, reliable storage, product uniformity, and advanced automation, to name a few [6], [35]. It is with these advantages that Industry 4.0 enabled the development of more intelligent applications which include mobile robots, autonomous vehicles, smart clinics, and smart manufacturing [4], [7], [39].

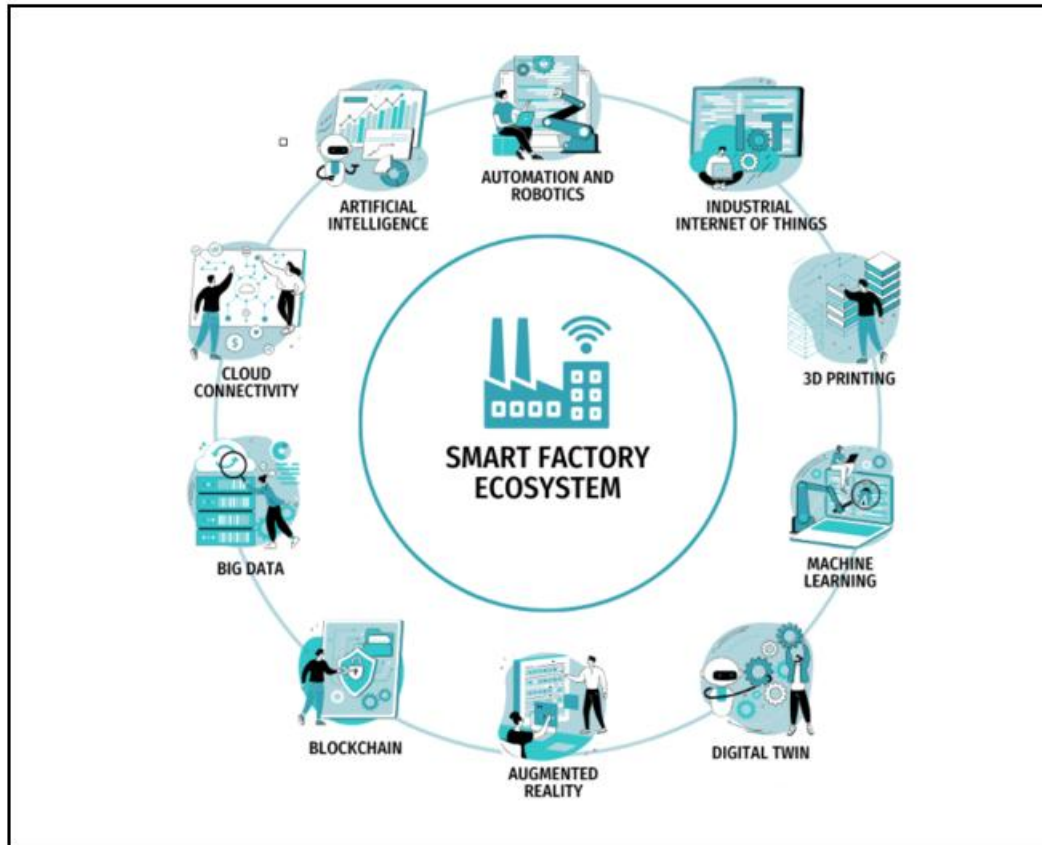
### **2.2.2. Smart Manufacturing**

Smart manufacturing is an autonomous, dynamic, and data-centric manufacturing approach which is characterised by integration of digital technologies to form an Industrial Internet of Things (IIoTs), data synchronisation between IIoT nodes, and automation of production for more efficient and effective production [4], [7]. The interoperability and digitisation of manufacturing and processing plants is achieved through the adaptation of Artificial Intelligence (AI) technologies to optimise the productivity of the sector [4], [40].

With the advent of AI technologies in smart manufacturing environments, more beneficial proactive operations, data collaboration platforms, and dynamicity of production/processing lines have been realised in smart plants through the adaptation of digital twins, cloud computing, and Make-To-Order (MTO) advancements, amongst others [6], [37]. According to research, these advancements have improved the competitiveness of manufacturing sectors in global markets [2].

The manufacturing and processing sector gradually improved by adopting new emerging technologies over the past decades [4], [6]. However, a clearer footprint in the history of the manufacturing sector was realised in 2006 when the term ‘smart manufacturing’ was coined in the National Science Foundation (NSF) workshop on Cyberinfrastructure to symbolise an advanced, data-centric, automated, and dynamic manufacturing approach [5].

Since 2006, smart manufacturing has become a topic of interest on both academic and industrial platforms because of its ability to converge with cutting-edge ICT technologies in building smart manufacturing ecosystems [6], [41], [42]. A smart manufacturing ecosystem is a collaborative globalisation of intelligent technologies, organisations, and skilled professionals in a production process, as illustrated in Figure 2.



*Figure 2: Smart manufacturing ecosystem. Adapted from [43].*

All smart manufacturing characteristics demonstrated in Figure 2 collaborate with the common goal of improving accessibility, efficiency, and dynamicity of the production line [4]. This collaboration is called a smart manufacturing ecosystem [6]. In a smart manufacturing ecosystem, some of the features in Figure 2 can be lacking, but the ecosystem will still be considered as smart manufacturing [4], [6]. However, if all these features are lacking, the production line is considered to be traditional manufacturing [3].

### **2.2.3. Smart Manufacturing vs. Traditional Manufacturing**

Unlike traditional manufacturing, which utilises labour-intensive and low-end mechanisms, smart manufacturing improves precision, product uniformity, efficient resource utilisation and production volume which will in turn boost competitiveness and increase global economy [3], [44].

Table 2 outlines the advantages of smart manufacturing over traditional manufacturing.

*Table 2: Comparison between smart and traditional manufacturing.*

<b>Characteristics</b>	<b>Traditional Manufacturing</b>	<b>Smart Manufacturing</b>
<b>Resource utilisation</b>	It is dependent on manual labour, hence inefficient in resource utilisation.	Deploys data-driven technologies which improve resource utilisation.
<b>Production volume</b>	The production volume is comparatively low.	Production volume can increase accordingly, depending on the demand.
<b>Product uniformity</b>	Limited product uniformity as it relies on human decision at every stage of production.	The automation facilitates product uniformity.
<b>Data management</b>	Lacks data management and the records are done manually.	Enables improved data management as it is integrated with storage facilities.
<b>Technology integration</b>	Lacks technology integration as most work is done manually.	It is equipped with enhanced technological integration.
<b>Labour cost</b>	High labour costs.	Low labour costs.

#### **2.2.4. Characteristics of Smart Manufacturing**

For a manufacturing line to be classified as smart manufacturing (SM), there are key features that should be identified in such a production line, which help researchers and industrial engineers to distinguish between smart and traditional manufacturing [3]. Some of these key characteristics are the automation of the production line, data storage, data-driven decision making, energy efficiency, and interconnectivity of manufacturing units [3], [4].

According to Mittal *et al.*, the collaboration of production-facilitating equipment to form a production line is categorised as a smart manufacturing unit only if it possesses five basic characteristics, which are modularity, heterogeneity, interoperability, awareness, and compositionality [4].

With all these characteristics, the human ingenuity in customising smart factory processing design is emphasised, hence, human input is not replaced by artificial intelligence and production automation [4], [12]. Behind this innovative production approach, smart engineering on the system design and minimal human interaction with the system on the operation is achieved.

Amongst all key characteristics of smart manufacturing, statistics reveal that automation is identified in all smart manufacturing setups, unlike other smart manufacturing features [11], [45]. This feature (automation) was introduced in the earliest stages of smart manufacturing evolution, and it is still one of most vital features in the smart manufacturing ecosystem currently [9], [11], [12], [46].

With automation accentuated at the centre of smart manufacturing, there are numerous technologies used in automation. However, research indicates that PLCs are the most diverse automation technology used in smart manufacturing environments [9], [12].

## **2.3. Programmable Logic Controllers**

### **2.3.1. Introduction to Programmable Logic Controllers**

Programmable Logic Controllers, hereinafter referred to as PLCs, are special-purpose built-in computer devices designed for automating industrial processes [47]. According to Stankovski *et al.*, the first market-oriented PLC drive was a Modicon 184 drive which was introduced in 1969; this intelligent microprocessor was aimed at automating industrial processing and minimising manual labour [46], [47].

However, a significant milestone in industrial automation and PLC evolution was realised in the 1990s upon the development of networking modules over fieldbus to synchronise the PLC drive with other field instruments [46]. In recent years, the versatility and diversity of PLCs in automating manufacturing sectors and various related applications like energy management, chemical processing, mining, environmental management, and automotive assembling, has increased rapidly [46], [47].

This versatility and diversity were realised because of the PLCs' built-in reliability, flexibility, modularity, scalability, cost efficiency, and easy customisation, among other advantages [15], [46], [48]. Moreover, one of the key identifiers in the development of PLCs is the presence of built-in functions, libraries, and standardised programming languages which ease the programmer's job [46], [49].

For sequential and repeating tasks, PLCs underlie a vital role owing to the loop-oriented nature of its built-in functions, as this nature culminates in real-time conditions altering the state of the physical plant[50]. This effect is referred to as real time simulation (RTS) in instrumentation articulation and it has been inherited by most industrial level PLC manufacturers [50].

To fulfil the above-mentioned RTS in PLCs, developers have come up with intrinsic control engineering using the MATLAB/SIMULINK design platform [13]. The most significant innovation of Open Platform Communication (OPC) technology has been endorsed by one of the international PLC giants, Siemens. This endorsement opens up the possibility of data synchronisation between the MATLAB environment and Siemens-based PLC [13], [51].

Some researchers may defend the cost efficiency of soft PLCs (also known as virtual PLCs) over hard PLCs, but the limitation of virtual PLCs in ultra-processing capacity recurrently urges inventors to choose hard PLCs over virtual PLCs [52], [53]. This choice led to the development of edge computing in hard PLC-driven processes for improved control and data management [41].

Edge computing is the systematic data storage and processing architecture at the edge of the network, that is bringing data processing to a closer and more easily accessible position to the data utilising equipment and intended user [41]. This architecture deploys features like Supervisory Control and Data Acquisition (SCADA) for secure monitoring, improved data analysis using trends, and user-friendly application of human interactions on a live production, hence, bringing the PLC computing to the user level [54].

### **2.3.2. OPC Servers and their Role in PLC-Driven Plants**

Open Platform Communication (OPC) servers are a server-based industrial communication standard which overwrites the individual IIoT communication compatibility by forming a data tunnel to accommodate multi-vendor IIoT devices integrated into one system [50], [55]. The read/write capabilities in OPC servers are facilitated by the activation of OPC client capabilities which are packaged and bridged into a centralised communication server [56].

With the usage of OPC servers in tactile internet applications, sensation and actuation signals from different IIoT devices used in smart plants can be processed in the same data sets for analysis and comparison purposes [51], [57]. Hence, the individual vendors' data sets are bridged, and the raw values are extracted and tunnelled into a centralised server where they will be converted to the desired data type [56].

For efficient communication in smart manufacturing environments, the OPC foundation developed an advanced gateway management solution called Unified Architecture (UA), hence, the most implemented communication tunnel is referred to as OPC UA [58], [59]. This communication bridge requires IIoT vendors to align with the communication standard, irrespective of the software installed in individual devices, to facilitate remote access of plant data [58], [59].

Once the plant data can be accessed remotely, the smart functionalities of the considered smart plant can then be taken beyond automation [60]. This means more functionalities can be adopted by network-based remote access, which include automation-over-cloud, cloud-based manufacturing, remote access, remote monitoring, and data sharing with authorised stakeholders [9], [46]. These innovative features can improve production time in smart manufacturing [15].

PLC devices, as the over-ruling automation solution in current smart plants, are mostly the intended beneficiaries of OPC UA servers, and the development of OPC servers was intended to solve the automation and cloudification challenge of data compatibility in PLC autonomous plants [50]. Hence, most industrial-level PLC devices have standard communication protocol to adapt to OPC UA servers [58].

### **2.3.3. PLC-Automation vs. Non-PLC-Automation**

For the flexibility and ease adaptation to a rapidly changing process in real-time automation of smart factories, the PLC automation has transpired as a cornerstone in industrial processing [12]. This PLC technology is equipped with advanced reliability, consistency, quick programming, and high precision [49]. These qualities which are inherently integrated in PLC-automated smart factories situate PLCs as a superior solution compared to non-PLC-automated smart factories [49].

Non-PLC-automated processes are processes which utilise industrial PCs, microcontrollers, or distributed control systems for automating industrial processes instead of PLC devices. These alternative approaches are mostly suited to applications with dynamic and continuously evolving production lines where adaptive control systems are required, while other automation approaches are suited for applications with averagely low data [48], [49].

### **2.3.4. Industrial PCs**

Industrial PCs (Personal Computers) are built-in computers which are designed to automate and control industrial processes. These PCs are hard-shielded and more humid resistant to withstand harsh conditions as they are mostly located close to the equipment intended to control [61], [62]. The industrial PCs are usually used as field-mount Human-Machine-Interface (HMI) panels and built-in Supervisory Control and Data Acquisition (SCADA) systems [61].

These PCs are designed specifically for the intended application of bearing all the requirements of such application. Some of the key qualities considered in such designs are listed in Table 3.

*Table 3: Qualities to be considered when designing an industrial PC.*

<b>Qualities</b>	<b>Clarification</b>
<b>Modular design</b>	The design should allow easy upgrade and customisation based on the process requirements.
<b>Redundancy and fault tolerance</b>	The PC must be tolerant of hardware failure impacts, unplanned power cuts and storage failures.
<b>External environmental conditions resistant</b>	The PCs should be designed to withstand external environmental conditions like rain, extreme temperatures, vibration, and sunlight exposure as they are field-mounted.
<b>Reliability and longevity</b>	The PC should be reliable and able to operate for the longest period without maintenance or replacement to minimise downtime in production.

### **2.3.5. Microcontrollers**

Based on the scale of automation, the connectivity adaptations, and functionality specifications, different microcontrollers can be used to automate different processes. A thorough study on the intended processes should be done before engineering the control circuit for the automation process [63]. Table 4 shows some microcontrollers and their suitable application specifications.

*Table 4: Different microcontrollers and their functional merits in automation.*

<b>Microcontroller</b>	<b>Specification</b>
<b>Microchip PIC and dsPIC series</b>	This microchip family is equipped with many communication interfaces, analog-to-digital conversion, and ability to automate industrial processes.
<b>Arduino Industrial 101</b>	The Arduino board supports Wi-Fi connection and industrial communication protocol.
<b>STMicroelectronics STM32 Series</b>	This microcontroller family is equipped with low-power consumption, high performance, and diverse communication compatibility for improved automation.
<b>Raspberry Pi</b>	The Raspberry Pi FPGA module has high processing speed, general purpose input/output pins, and diverse communication compatibility.
<b>Infineon XMC series</b>	This FPGA family has real-time capabilities and supports industrial communication protocols.

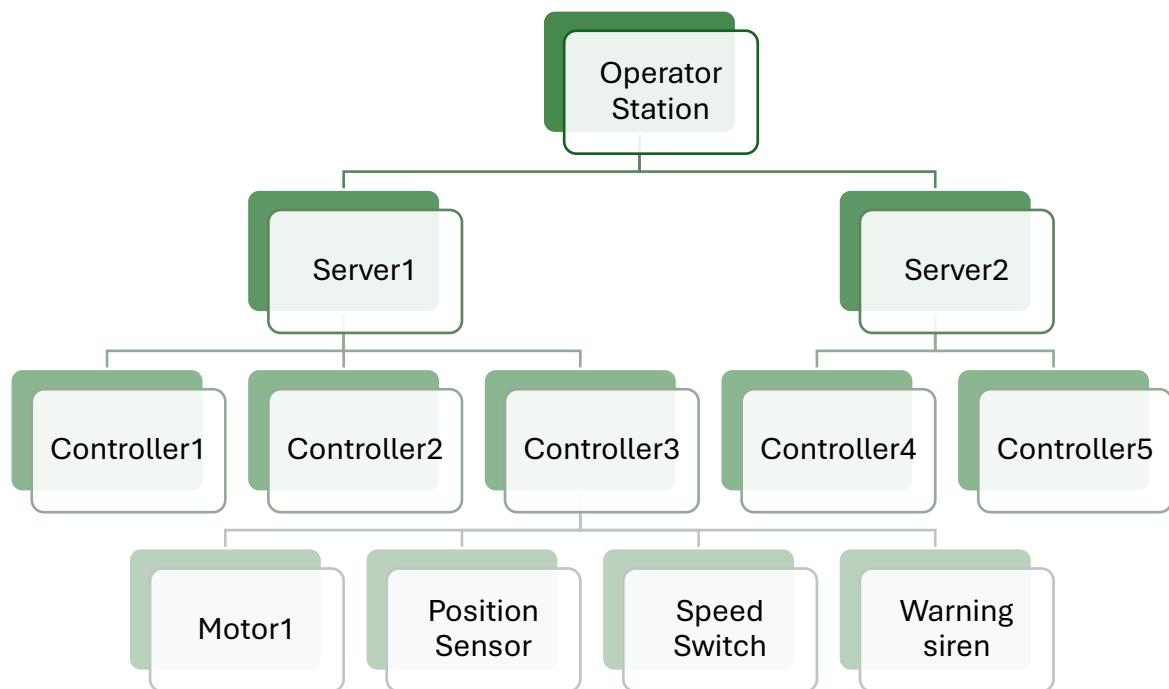
The cost-efficiency and modular design of microcontrollers in industrial automation are considered as the major advantages; however, research revealed some recognisable drawbacks in processing power, real-time performance, and memory limitations inherited by the usage of microcontrollers in smart factories [63].

### **2.3.6. Distributed Control Systems**

For increased reliability, scalability, and flexibility, system developers have created an ultra-modern approach to industrial automation in which multiple controllers are introduced to the processing system for increased decentralisation of the system [64]. This intelligent architecture is called Distributed Control Systems (DCSs), and it is more appropriate in complex systems where more comprehensive data management is required and modular expansion is foreseen [64], [65].

In this Industrial Control System (ICS), the processing plant is divided into sub-sections and a nodal control is developed for each section. Each plant section is assigned to a controller or controllers with a healthy communication network linking each controller to the server, and the server should be linked with the operator station to provide the graphical presentation of the plant for monitoring and interruptions [66]. Figure 3 indicates the detailed architecture of the DCS [65].

If the controllers used in DCSs are PLC devices, the system is called a DCS-PLC Hybrid system, and it inherits all the merits of a PLC-driven plant while the distributed nature imports more flexibility, advanced data acquisition, easy fault-finding by isolation, and a wider room for modular expansion [66]. The selection on the automation will depend on the scale of automation, plant size, need for comprehensive data management, and the budget as the DCS can be more costly as they require numerous controllers [66].



*Figure 3: The nodal presentation of the DCS architecture.*

### 2.3.7. Programmable Automation Controllers

Programmable Automation Controllers (PACs) are all industrial automation controllers which are equipped with the capability to execute higher-level instructions in an Industrial Control System (ICS) [60]. Based on the level of automation and data acquisition, higher-level instructions are considered as more complex, the ability to run custom programs, easy connectivity to databases, and compatible communication over different networks [60].

Unlike traditional PLCs, PACs are considered as an ‘all-in-one’ solution to all industrial automation applications due to their enhanced computational capabilities, multiple control strategies, and improved communication capabilities. These controllers are mostly distinguished by their ability to support higher-level programming languages like C, and C++ which are tailored to the specification of the intended processes [67].

*Table 5: Detailed analysis of merits and drawbacks of PACs over traditional PLCs.*

Qualities	PACs	PLCs
<b>Integration with IT systems</b>	Easy integration	Mostly lack compatibility
<b>Communication capabilities</b>	Enhanced communication	Lack most communication protocols
<b>Data acquisition</b>	Advanced data acquisition	Lack of data management
<b>Scalability</b>	Easily scalable	Lack scalability
<b>Reliability</b>	Lack of reliability to some extent	More reliable
<b>Industrial standard</b>	Lack some industrial standard	PLCs are designed based on industrial standards
<b>Examples of applications</b>	Renewable energy system, chemical processing plants, automated packaging systems, etc.	Traffic light control systems, water treatment plants, manufacturing assembly lines, etc.

From Table 5, an overlap in characteristics between PACs and PLCs can be noted, however, the choice between the two will depend on the need for data management and availability of IT infrastructure in system design [46], [49]. A trade-off can be made on the cost, simplicity of design, and ability to incorporate higher-level programming languages as they are less-determining factors in industrial automation compared to advantages of traditional industrial-level PLC devices [46], [49].

With some of the significant innovations in the PLC automation landscape, including adaptation of RTs and development of OPC servers, as explained in Section 2.3.2, the industrial capacity can be maximised as these features facilitate improved data management [50], [55]. However, management of large datasets requires reliable data storage and backup facilities catered for possible physical infrastructural failures [14], [17].

This need for reliable storage facilities accentuates cloud storage as core topic of interest in the smart manufacturing evolutionary journey [17], [19]. Hence, in every research study which contributes to the continuous development of the smart manufacturing landscape, cloud computing will always be considered [68]. This introduction of cloud computing in smart manufacturing environments developed into the commonly used terminology of Cloud Manufacturing [19].

## **2.4. Tactile Internet and 5G Technology**

### **2.4.1. Tactile Internet**

Tactile internet is explained as the network facility which creates a visual presence by facilitating the ability to access, monitor, and apply interruption to the physical plant in real time using the internet [26], [28]. According to Rico et al., tactile internet is the innovative transformation which is characterised by ultra-low latency with extremely high reliability owing to the path selection in the implementation of Multi-connection Tactile Internet Protocol (MTIP) [69].

The vision of tactile internet was developed early in 2012 by Professor G. Fettweis at the Technical University of Dresden in Germany [70]. Over the years, this idea was taken over in an evolutionary leap by numerous researchers with the aim of improving compatibility in connectivity, minimising network latency, and customising the open-end room for scalability and close-to-ideal incorporation of the idea in smart manufacturing [70].

Since its origin, the concept of tactile internet has been developed over the years and concrete revolutionary footprints have been realised on the concept. These steps include the incorporation of mobile networks to enhance mobility and geographical-free access, standardisation of communication protocols to enhance scalability, and progressive updating with the new technological trends and emerging infrastructure for better network performance [25], [28].

Tactile internet, which facilitates the virtual presence in smart manufacturing, can only achieve the intended aim if the network used has high reliability, availability, security, and has minimal latency. If the network has minimal latency, it will be fast enough to enable synchronisation in real-time [22], adequately reliable and available network will enable full-time and undisturbed monitoring of real-time applications and user-defined interactions when required [28].

This innovative transformation in smart manufacturing has evolved in recent years owing to its ability to support numerous applications, such as remote maintenance, operation and changing parameters, increased collaboration with stakeholders, and the MTO systems which result in optimal resource allocation [70], [71]. The intrinsic diversity of tactile internet globally has improved the adaptation of IIoT applications and smart manufacturing efficiency in alignment with the Industry 4.0 pillars [25].

#### **2.4.2. Network Factors**

Smart manufacturing leverages a network of interconnected field sensors, I/O nodes/modules, drive storage facilities, operating station PCs, engineering station PCs, intelligent sales websites, and stakeholders access interfaces, operators and engineers collaborated to form a distributed heterogeneous Industrial Internet of Things (IIoT) [4], [7].

In smart manufacturing, the Artificial Intelligence (AI) transformation of integrating the service-oriented and technological smart components for an improved data acquisition, business intelligence, feedback-reliant automation, and demand-based production management forms a smart ecosystem known as Internet of Everything (IOE) [5], [40], [72]

In the IOE setup, communication between smart sensors and the plant drive the coordination of data between the plant drive and storage facility for continuous data update, feedback-correlated automation, and accessibility of plant data over the internet for demand-reliant production. All these operations depend on the network communication and are the key features which distinguish smart manufacturing from its predecessor, traditional manufacturing [72], [73].

The adaptation of communication networks in the digitisation of the smart manufacturing environment locates the network facility at the centre of the Industry 4.0 evolution [4], [8]. This digitisation of the manufacturing industry has improved the competitiveness of such sectors in the global economy by enhancing modular responsiveness and autonomy of the production line [9]. However, the efficiency of the network in a smart manufacturing environment is a key feature to be considered [32].

In the assessment of the network for efficiency of an IIoT setup, responsiveness, accessibility, and the ability of the smart manufacturing setup to synchronise data in close to real time are key performance features of interest [74]. These are key drivers to the evolution of Industry 4.0 and the increased amount of innovative research on further developments pervasively available on various research platforms resulting in the achievement of the envisioned digitalisation of smart factories [1], [8].

Nevertheless, the significance of the role played by network parameters in an industrial revolution are seldom considered in both educational and industrial explorations [32], [69], and this hinders the vision behind Industry 4.0 of leveraging technology and cloud computing to achieve real-time automation and improved data accessibility to authorised stakeholders pioneering to the revolutionization of the smart factories [37].

The pivotal determination of this research is therefore to garner more research interest in network factors with significant impact on production time in smart manufacturing environments. However, this scrutiny can only be initiated if a detailed observation can be made of close research fields to identify the possible research gaps in that journey.

The research gap was identified in a study by Abdullah *et al.* which analyses factors affecting the Management Service Organisations (MSOs) in a manufacturing sector at business level using the fuzzy Demental dissecting curve; however, the research omits the analytic model on the effects of network parameters on production speed [75].

Another study was conducted by Ng *et al.*, on the analysis of the envisioned potential of Industry 4.0 to realise the digital ecosystem through the facilitation of data exchange; in this study, however, network selection to complement the cloud computing and accommodation of big data and analytics was not clarified [34].

Among other factors that Kim *et al.* considered in the adoption and modelling of smart manufacturing systems, network effect is one of the key research interests as the network resides as a technological pivot in the transformation paradigm to advocate the intelligence of the envisioned AI application and complement the Industry 4.0 mission; however, the research did not elaborate meticulously on specific network parameters with significant impact in smart manufacturing [76].

Even though the significance of network parameters is omitted by many authors, contrariwise, there is adequate research in which the impact of network parameters in smart manufacturing environments are carefully explored with the drawbacks and vagueness of bad network selection identified.

Atutxa *et al.* remark on the inefficiency of an IIoT application when the response time is high and the bandwidth is congested; however, he proposes the minimisation of response time in time sensitive IIoT applications through the adaptation of data plane programming and edge computing [32].

In a survey of incorporating edge computing in a smart manufacturing environment, Qi *et al.* outlined network unavailability, overloaded bandwidth, and high latency as three main obstacles which limit the expansion of smart manufacturing as they delay or completely prohibit data synchronisation between the cloud storage and smart factory [42]. O'Connell further outlines the significance of minimal latency and high bandwidth in an IIoT network selection to fulfil the real-time synchronisation in a cloud-based manufacturing line [77].

According to Kabir *et al.*, the fundamental requirements of the network topology adaptation to advocate for real-time synchronisation between the real and virtual reality in digital twins are minimal turnaround latency and extra broadband [38]. A survey study by Noor-A-Rahim *et al.* further emphasised the significance of low latency, high bandwidth, and wireless nature of network in the fourth industrial revolution [78].

Based on research, there are many factors to consider in assessing an internet facility which interconnects the IIoT technological nodes [27], [30], [79]; however, there are five main properties which have a significant impact on the production time in smart grids. These five factors are: latency, bandwidth, device density, reliability, and network accessibility [40].

### **2.4.3. Latency**

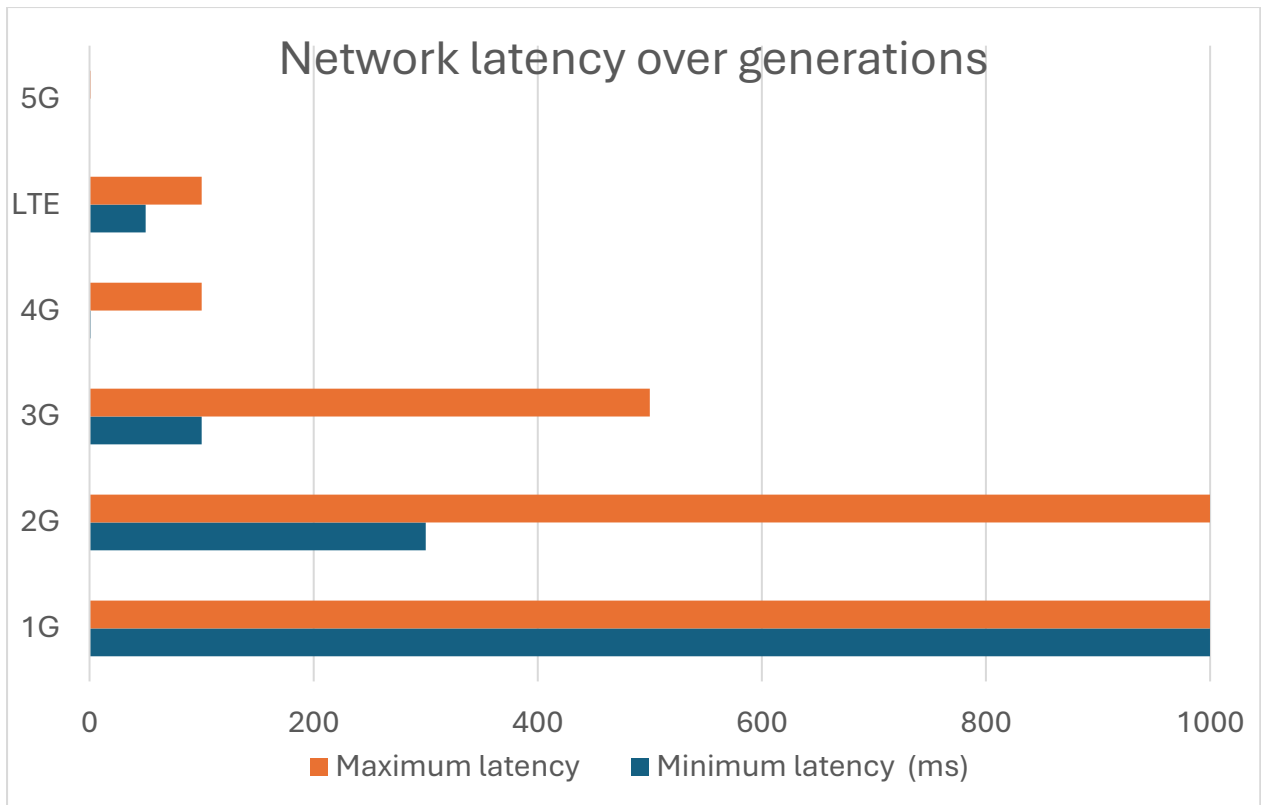
Network latency is defined as the time delay taken for a bit of an information packet between the transmitting network node to the intended destination. This time can be dissected into transmission delay, propagation delay, jittering delay and reception delay [27], [30]. This network delay is measured in milliseconds (ms), and it is commonly referred to as the responsiveness or speed of the network [30].

*Table 6: Contributing delays to the network latency.*

<b>Delay type</b>	<b>Explanation</b>	<b>Occurrence</b>
<b>Transmission delay</b>	The time taken for transmitting network node to prepare (IP tagging, sampling, encrypting, etc.) message packet until it is released into the network interface.	Transmitting node
<b>Propagation delay</b>	The time taken by the message packet to traverse through the network medium (air, fibre cable, etc.) until it reaches the next node (router).	Network medium
<b>Reception delay</b>	The time taken for an intended destination network node to detect, decode, and packet verification (error detection).	Destination network node
<b>Jittering delay</b>	The time taken for an information packet to traverse the routing congestion on network nodes.	Network routers and switches

Some researchers often classify transmission and reception delays as preparations and jittering delays as part of propagation delay, but it does not make any difference as the centre of determination is to evaluate theoretically expected delays on the network facility for an evaluation of such network [80], [81].

Depending on the network technology used and the medium through which the transmission propagates, the network latency varies and there is a vivid trend of decreasing latency with increasing generation of communication networks. This means that the first generation of communication networks (referred to as 1G network technology) has maximum latency while the fifth generation of mobile networks (5G technology) has the minimum latency, according to research [21], [27].



*Figure 4: Theoretical latency performance of different network generations.*

Based on Figure 4, an improvement of the minimisation of network latency over the evolution of network generations can be identified, and this minimisation has improved efficiency in data synchronisation and diversifying the adaptation of network facilities in the manufacturing sector to facilitate the reengineering of IWN, cloud computing, IIoT and digital twins, of which all these Industry 4.0 features have been proven to improve production time in tactile internet applications [82].

With the earlier adaptation of outmoded generations of mobile network technology in the smart manufacturing environment, the real-time synchronisation of data was often hindered by high latency. This is engendered by the increased amount of time to complete the roundtrip transmission on automation stages which are governed by field conditions for feedback [27], [83]. Hence, the decision-making process takes longer than anticipated as it must undergo high network delays before the remote program can administrate an action based on the field condition [82].

The delays incurred along the network link due to high network latency can be seen as small and irrelevant, however, the minimisation of such delays plays a vital role in the improvement of smart grids as they will add up and cause a significant impact with the IIoT network increasing which will ultimately impact production time [15].

This extremely low latency is unequivocally imperative in IWN applications, particularly in time sensitive applications. Hence, this establishes a need for migration of IIoT applications to late (recent) generations of mobile networks owing to their minimum latency [78]. Moyizere *et al.* depict the significance of impact of the network delays in smart grid management systems, where the research further analyses the network-reliant limitations of network control management systems [84].

In consideration of the different generations of mobile networks, research assertively accentuates that the fifth generation of mobile networks (5G network technology) is equipped with the lowest minimum latency ever existing in network technology over, its predecessors being 3G, 4G, and LTE network [78]. The motivation behind this project is to support the theorised low latency of 5G over its predecessors in a smart manufacturing environment which can significantly impact production time [15].

This hypothesis will be proven by enhancing already existing IIoT smart units' compatibility to a 5G ecosystem and developing a remarkable milestone in the adaptation of Industry 4.0 to the evolutionary technological trends. The final step will be to scientifically measure latency in a PLC-driven smart plant as it has been proven by prior research to have a significant impact on production time. The results will be analysed and the conclusion on the theorised ability of 5G technology to minimise production time in PLC-driven smart manufacturing plants will be drawn [15], [30].

#### **2.4.4. Measuring Latency**

The focal point in the research community recently is the minimisation of latency in IIoT applications to achieve close-to-real-time synchronisation as per the Industry 4.0 vision [85]; however, the most unsettling domain in such development direction is the ability to quantify latency accurately [81].

Hence, to facilitate further innovations of ultra-low latency attainability in TI applications, network enthusiasts should be able to quantify end-to-end latency performance of existing network technologies to track the evolution footsteps based on comparable results [86]. For the last two decades, exponential growth has been realised in technological evolution and organisational migration to digitised operations to enrich lives [78].

The transition has become more conventional in retail organisations than in manufacturing business as they leverage digital platforms to facilitate e-commerce [30], [79]. This deficiency identified in manufacturing and processing sectors was further mediated in the 20<sup>th</sup> century in both academic and industrial platforms following the progressing migration of such sectors to digital platforms for improved data acquisition with the aim of improving production time [27].

The desired data acquisition was often hindered by the inability of existing network technologies to synchronise data in real time owing to their high latencies [10], [45]. To address this high latency challenge, network engineers probed network technologies with decreased latency compared to the pre-existing technologies [30], [87], and this is a progressing challenge globally, pioneering the continuing evolution of network generations [32], [83].

However, a recognisable milestone in network evolution will only be realised if parameters to be improved can be accurately quantified on the existing technology [20], [80]. This quantification will provide network engineers with existing references and results after development to conclude on the achievement of the desired network parameter threshold, as well as future invention to attain the Predictive Quality of Service (PQoS) [20].

Latency, as one of the main network parameters considered in this evolution journey, must be accurately measured [15], [30]. Many trials in attempting to quantify latency have been endeavoured by various authors on research level, trailed by various experimental tests, hence, numerous latency test methods exist thus far.

Most of these attempts were primarily aimed at improving the online gaming industry [81]. Subsequently, the idea was further scrutinised to adopt into smart clinics, mobile robots, and autonomous vehicles as the call increased for more improvement on network latency [88]. At a later stage, the quantification of network latency was further acceded into the smart manufacturing environment with the aim of accomplishing the real-time data synchronisation [4], [40].

Along with this quantification journey, numerous methods of latency assessment were invented. These methods differ, from incorporation of external measurement devices, extra software requirements, to the accuracy of each method. Chen *et al.* took a survey to quantify the round-trip latency using a Direct3D application and EndScene () function on the summation of delays [81]. However, the procedure on such methodology was not explained and its scalability to the smart manufacturing sector is unforeseen [80], [81].

Another method by Miller *et al.* explores the validity of image latency and quantifies the delay between physical world and virtual response using video cameras or two 1D CCD sensors which are orthogonally positioned. Then, the two CCD sensors' signal from the physical and virtual are merged to assess the delay it took the motion on the physical to reflect on the virtual image [80], [89].

A similar approach was also identified in research by Mine *et al.* in which a photodiode signal change from the moving pendulum arm was used as the physical object and the diode signal received to determine the time difference between them [90]. Both approaches are still efficient in today's test experiments, however, the adaptation of such test methods to the considered smart manufacturing setup will call for more system modifications and extra resource procurement [90].

A survey by Fristone *et al.* on various latency measurement methods outlined the possibility of implementing an error-reliant distinctive motion pattern of movements using a low frequency camera [80]. In this analytic endeavour, inventors track the incidences in which two considered objects exhibit typical and noticeable movement trends, then the time frame is captured and analysed between the physical and virtual sample. This method also requires an additional camera to the setup [80].

On the other hand, Sun *et al.* validate the significance of substituting mmWave antennas with the NYUSIM simulator for quantification of 5G network parameters, including latency [86], [91]. This cutting-edge open-source method running in MATLAB applications accurately assesses 5G network parameters and it is idealised in a controlled atmospheric attenuation [35], [86].

The propitiousness of the NYUSIM simulator in broadband and MIMO system parameter assessment is dominating in 5G communication; however, the scalability of such simulation assessment method is limited in older generations in network evolution, being 3G, 4G, LTE networks, as they are not stemmed on MIMO antennas and broadband capabilities [86], [92], [93], [94].

El-salah evaluates indoor and outdoor network management through the android G-NETTRACK developed by Yuiyan Gyokov [85], [95]. This application was developed to monitor a vast number of network performance KPIs, including signal-to-noise-ratio (SNR), latency, speed, throughput, and others based on the geographical and population density of the considered location and network [85], [95].

The outcompeting merit associated with this application is the ability to evaluate all generations of mobile network technologies, including 5G. Many network enthusiasts are switching to this application, which stemmed from cell monitoring, to gain a better insight in network analysis. An additional PING feature is incorporated into this application for packet propagation analysis between distinct IP addresses and web address's location [95].

Moreover, in the survey to quantify the bandwidth performance with the aim of saving cost and minimising energy consumption by limiting network overheads, Awodele *et al.* propose the utilisation of the assessment of network traffic using the Paessler PRTG Network Monitoring Software [96], [97]. In this research, the authors indicated network speed as one the network parameters that can be measured with PRTG software [96].

A study by Mats Nordin also utilises the Paessler PRTG network monitoring software to assess network performance metrics which include latency [98]. The main advantage of the monitoring software lies in its user-friendly interface and ability to measure several key performance factors in all network technologies [96], [97], [99].

For the purposes of this project, the G\_NETTRACK and Paessler PRTG network monitoring software approach will be used to evaluate the latency performance in both 4G and 5G network setup. These approaches were selected based on their simplicity and do not require additional cameras or procurement of other components [95], [97]. The results will also be post-checked using the basic PING instruction on windows command prompt.

#### **2.4.5. Bandwidth (Data Rate)**

Bandwidth is defined as the range between higher and lower boundaries in frequency band within which the transmission medium can transmit signal. It can also be viewed as the channel broadness of the transmission medium, or spectrum width, and it is measured in Hertz (Hz) [100]. The most commonly applicable definition to bandwidth is the capacity of data that a medium or network device can transmit in a unit time, and this definition treats bandwidth as data rate as it will be measured in bits per second (bps) [100].

The synonymy between bandwidth and data-rate definitions is that with an increased capacity of a transmission channel, or the wider spectrum, the number of bits that can be transmitted in a unit time are higher, and this leaves the researchers and vendor with discretion on which definition and measurement units to use [101].

With the continuous revolutions in network generation revolutions from the first (1G) to the fifth generation (5G) [34], [40], a vivid trend of an increase in bandwidth utility and more standards of band management is observed, and this theoretically proves an ability of the late network generations to transmit large amounts of data in a unit as compared to the older generations; hence, 5G network technology has been proven to project extra-high bandwidth as compared to its predecessors, as indicated by the graph in Figure 5 [24], [78].

The continuous increase in usable bandwidth in the telecommunication industry to broadband applications led to the network society migrating the bandwidth units to Mbps and Gbps. Figure 5: The data rates performance of different network technologies. shows a graphical indication of bandwidth improvement over network generations' evolution for the 1G to 5G network technology.

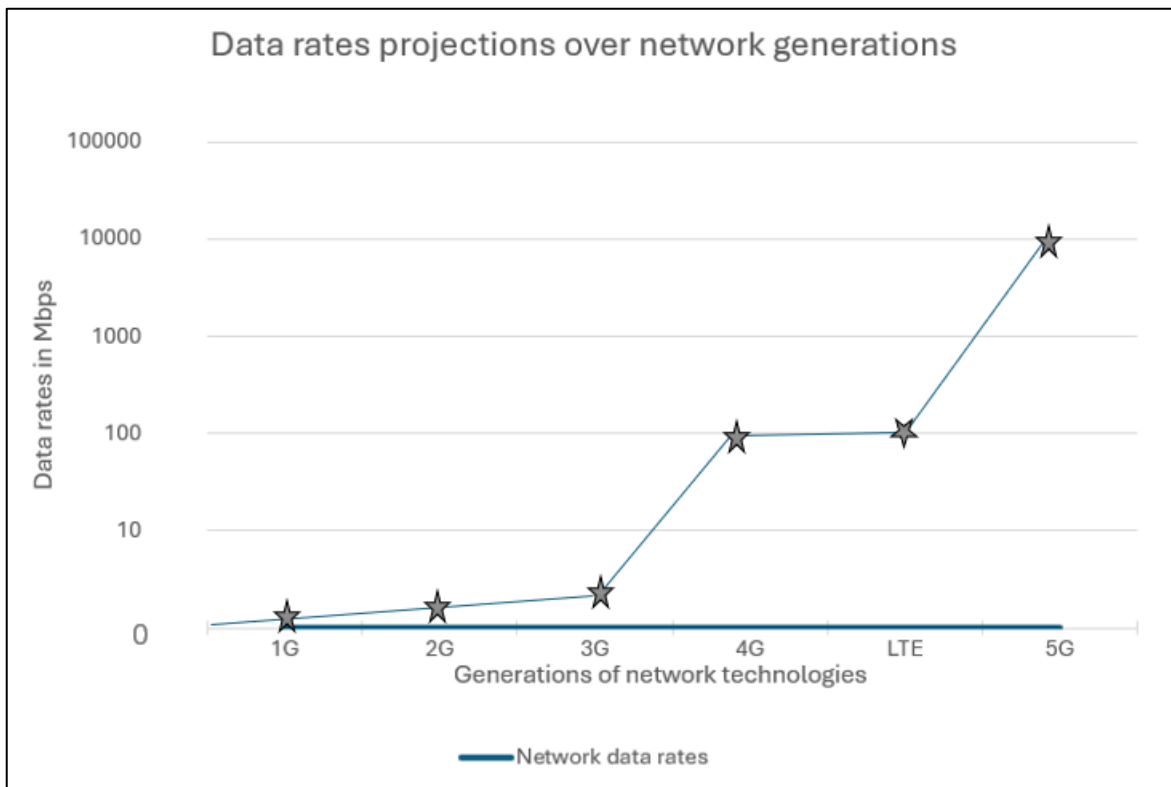


Figure 5: The data rates performance of different network technologies.

In the 20<sup>th</sup> and 21<sup>st</sup> centuries, bandwidth has been a crucial commodity to many developed and developing countries as it facilitates vast capacity of data transmission for multimedia applications and telephony [100]. This cruciality in band allocation centres on the ability to support haptic data transmission in cloud computing architecture and has enhanced the rapid evolution of the envisioned capacity of Industrial 4.0 applications.

In their study investigating the broad-spectrum need for electrical power management smart grids to cater for cryptographic data overheads, Ghanem *et al.* analysed the need for extensive bandwidth as one of the main challenges in the deployment of IWN, and they clearly depict the stringency of bandwidth consideration in the wireless network selection [102].

#### 2.4.6. Measuring Bandwidth (Data Rate)

In the evaluation of network performance metrics, there is an inevitable need to quantify such parameters pivoted at the centre of the network selection appraisal [103]. The assessment of network performance parameters is solely governed by the ability to measure such parameters prior to concluding on the selection [104].

The identical performance measures assessment further begs improvement opportunities as the existing deficiency will only be identified on the measurement results of the existing technologies. Moreover, the improvement will only be validated with reference to the existing deficiency in performance against the newly invented technology [101].

Bandwidth as one of the Key Performance Indicators (KPIs) which affect production time in a PLC-driven smart manufacturing plant governs the network selection in tactile internet applications and IoT setups. Thus, it must be accurately measured, and a detailed analysis of such factors should be carefully studied [101].

Measuring network bandwidth will provide end-user homes, individuals and tactile internet designers with proper network capacity selection, organisations with informed and surveyed choice on network bandwidth needs, and network engineers with insight and knowledge of bandwidth performance of the existing network. This will enhance innovation which will reduce production time [100], [104].

However, like all other network parameters, bandwidth performance also poses a challenge in accurate measurement due to the dynamic nature of recently available network technologies and inconsistencies in data capacity induced into such networks [101]. These inconsistencies are caused by instability of transmission throughput in network connections to overfill the transmission spectrum [100], [101].

Upon realisation of this challenge, some service providers developed a marketing ploy of misleading network end-users on the bandwidth. Subsequently, this challenge was brought under close consideration on academic platforms as a social impact challenge, resulting in researchers and network enthusiasts devising measurement methods to accurately quantify the network bandwidth [105].

The key probes in all bandwidth measurement methods are accuracy, simplicity, and accessibility as the intended beneficiaries for such methods are primarily end-users [100], [104]. These methods were experimentally tested, and every inventor maintained the efficiency of their methods, but the final preference is reliant on the end-user, depending on availability of additional measuring resources and intended application.

Jain *et al.* propose the end-to-end evaluation of the maximum available bandwidth to accommodate constant throughput without restrictions. This method is called the pathhold bandwidth measurement method [106]. The method was further developed by various authors to accommodate the throughput boundaries characterised by the transmission and receiving hosts [106]. The simplicity, accuracy, and efficiency of this method are appealing, however, it is unsuited for the tactile internet application in consideration of this project as the throughput of receiving hosts, which are the IoT devices (PLC drive in the case of this study), cannot be assessed, as it relies on the feedback-oriented transmission [104], [106].

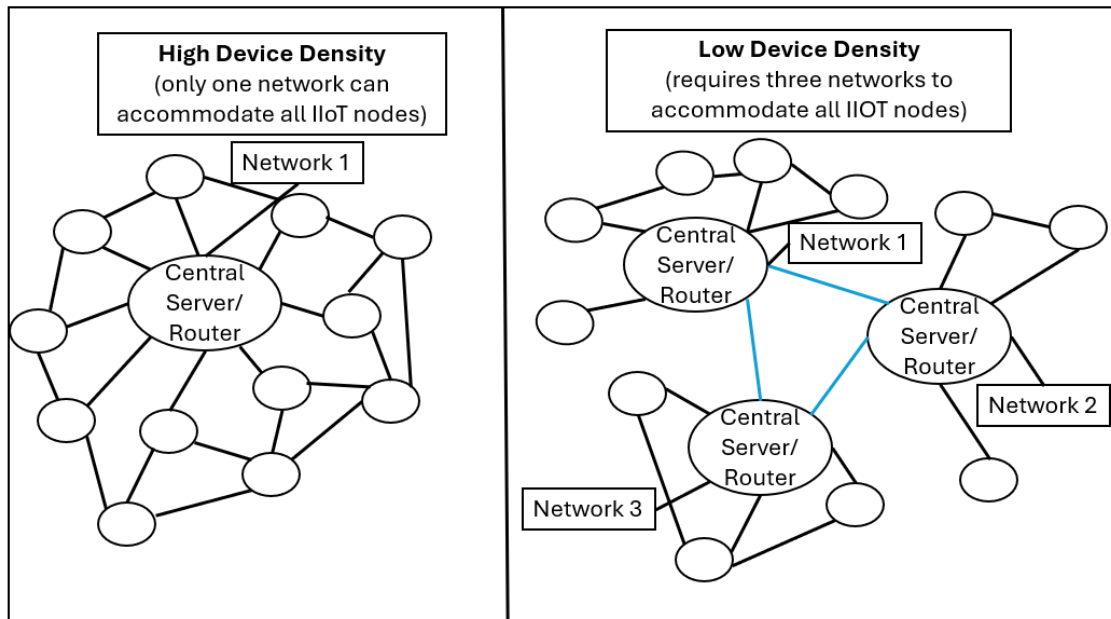
Another bandwidth measurement method is Internet Control Message Protocol (ICMP) [107]. This is the checksum error analytic exercise applicable to both TCP and IP based communication which is dependent on packet responsiveness [107], [108]. This method has mostly been explored in theoretical analysis with a recognisable lack in practical idealisation, and there is limited research on the proven applicability of such method in late generations of internet technologies, which is pivotal to this project [107].

From Section 2.4.4, the G-NETTRCK method and the Paessler PRTG network monitoring software were reviewed for the ability to measure network data rate effectively. For this research, they (G-NetTrack and PRTG network monitoring software) will also be used to measure network data rate [95]. Due to the resemblance between data rate and bandwidth explained in Section 2.4.5, the measured data rate will also reflect the bandwidth performance of the setup.

#### **2.4.7. Device Density**

Device density is defined as the number of IIoT devices that a network setup can connect to at the same time, or the ability of the network facilitating tactile internet application to multi-connect to an increased number of IIoT nodes/devices [15], [109]. Based on literature, a network that can connect to an increased number of IIoT nodes at the same time can minimise the production time as latency will decrease [15].

This network latency will be decreased by the decreased number of inter-networks switching delays; that is, with the device density maximised, more nodes will be connected, hence, a single network setup will be required in large plants [110]. If the network device density is low, more network setups will be required to accommodate large plants, and this will increase switching delays between network setups, which will in turn increase production time as demonstrated in Figure 6 [69], [110].



*Figure 6: Difference between high and low device density in an IIoT setup.*

From Figure 6, the setup on the left indicates a network with high device density. In this setup, only one network setup was able to accommodate all IIoT nodes. On the right is the network setup with low device density. Three network setups are required to accommodate all IIoT nodes, which will result in increased latency due to switching delays between different networks, and research revealed that decreased device density will increase production time in a tactile internet application [69], [111].

Moreover, if the device density of the network technology used to implement the tactile internet application is limited, it means the network technology can only multi-connect a limited number of IIoT nodes, and this will prohibit plant size expansion, or requires several plant network setups to accommodate large plants. In addition, research revealed that communication between standalone network setups increases network latency as it inherits more switching delays and limits network reliability [15], [69], [112].

To achieve an increased device density, most recently invented wireless network technologies improve space optimisation by directing the wireless signal to the intended IIoT device rather than broadcasting it [113], [114]. This beam forming direction control is mainly implemented in WiFi 6 which utilises up to eight spatial streams [113], [114], [115]. This increased number of spatial streams in WiFi 6 allows high precision in close-range devices and increased device density [114].

In these spatial streams, congestion is managed by importing the Multi-User Multiple-In Multiple-out (MU-MIMO) to focus the Radio Frequencies (RF) in unique directions using interference patterns and multiplexing two antennas [116], [117]. To avoid interference in spatial streams, different frequencies in close range IIoT devices are used for clean links. This calls for a broadband frequency need for IIoT applications contributing to increased device density in direct-mapped MIMO, which minimises production time [113], [116].

#### **2.4.8. Measuring Device Density**

Based on research, 4G network technology can accommodate up to  $2 \times 10^3$  devices/km<sup>2</sup> while the 5G network technology device density is up to  $1 \times 10^6$  devices/km<sup>2</sup>, and it is expected to be  $1 \times 10^7$  devices/km<sup>2</sup> [114], [115], [118]. These values of device density are very high, and it is not practically viable to measure them in a laboratory setup. Hence, the theoretical values will be considered for comparison purposes.

#### **2.4.9. Network Reliability**

Network reliability defines the ability of a network connection used in a tactile internet application to connect for the considered period without interruptions [83]. Hence, a network connection which can withstand inter-network disruption and external environmental conditions is considered as a highly reliable network connection [39].

Reliable network connections are suitable for tactile internet applications as the physical operation can be monitored without interruptions and network outages [27], [119]. If all tactile internet operations can be facilitated without loss of connection, production time can be improved in a tactile internet application [119].

For a network connection to be considered as reliable in an immersive virtual reality tactile internet application, it should perform optimally in six key performance aspects [27]. These aspects are capacity, resilience, redundancy, availability, monitoring and maintenance, and Quality of Service (QoS). Table 7 defines all key aspects that define network reliability.

*Table 7: Key features of network reliability in tactile internet applications.*

<b>Reliability Aspects</b>	<b>Definition</b>
<b>Capacity</b>	A reliable network should be equipped with enough capacity to accommodate high traffic congestion.
<b>Resilience</b>	A reliable network should be able to withstand interruption and to recover from network disconnections.
<b>Redundancy</b>	A network connection should be equipped with extra backup connection paths to maintain reliability.
<b>Availability</b>	A highly available network is considered to more reliable.
<b>Monitoring and Maintenance</b>	If a network is carefully monitored and scheduled maintenance executed properly, it will be more reliable.
<b>Quality of Service</b>	The ability to predict network performance for proactively conducting preventative maintenance.

In their research which investigated the evolutionary footprints of tactile internet, challenges, and predicted future of tactile internet applications, Aijaz *et al.* outlined the need for redundant communication and increased network capacity as pillars contributing to an ultra-reliable network [119]. Moreover, in their effort to analyse the performance requirements thresholds in multi-connection Tactile Internet Protocol, Rico *et al.* specified the importance of multi-connection paths to increase reliability in TI applications [112].

When redefining the application scenarios of tactile internet applications and the stringent challenges in the evolutionary paradigm, Fanibhare *et al.* accentuate network availability in the middle of network reliability in tactile internet revolutionization [71]. Yahiya and Kirci also indicate the adoption of network slicing in tactile internet's evolution journey to improve Quality of Service (QoS) and efficient resource allocation, which will in turn improve network reliability [87].

#### **2.4.10. Evaluating Network Reliability**

As the definition of network reliability in Section 2.4.9 states that it is the measure of the network resilience against interruptions and network failures causing objectives, network reliability will be measured by connecting the chosen PLC-driven smart plant to both 4G and 5G networks for the considered period of time.

Then, the Paessler PRTG network monitoring software will be activated to record any network disruptions during the considered period [96], [98]. Recorded network failures will be evaluated as a percentage of all experienced interruptions to conclude on the network reliability performance of the network technology used to implement a tactile internet application.

#### **2.4.11. Network Accessibility**

Network accessibility is defined as the simplicity of or increased chances of connecting to a particular network [82], [117], [120]. In an IIoT application, it is defined as the degree of obtainability or attainability of a particular network as a percentage factor, reliant on network strength, network range and distance diversity.

With increased network accessibility, authorised stakeholders will be able to connect to an IIoT network at different locations, and the accessibility of a particular network can differ depending on the propagation media through which the network traverses [82], [117], [121]. There are two basic network media which govern network access, namely wired and wireless network media [35], [82].

On a wired network access medium, the only link to connect to that network is through cable(s). The cable can be coaxial, copper, twisted pair, fibre optic, Cat5 cable and others [122], [123]. Cable type selection depends on the physical nature of the transmitted network signal, available infrastructure, the requirements of an application, and the physical nature can be electrical or optical (light) signals [122].

According to research, cabled network access limits the accessibility and mobility of the network as cables and wired network points cannot be extended to every location due to terrain and cost reasons. As a result [78], it will inconvenience or even delay the authorised stakeholder from accessing the smart manufacturing system at any location on demand [78].

Wireless network access refers to all network architectures propagated on radio or wireless link [123]. This exclusivity of cabling infrastructure in networks engenders more accessibility, mobility, and flexibility in network access. With an increased range of wireless transmission, a digitised smart manufacturing application can be accessed from a variety of places to facilitate remote maintenance, monitoring, operational data access and decision making, amongst others [123].

Studies revealed that wireless or radio medium increases accessibility of a network. This is mostly due to the wireless nature of propagation and access [123]. This kind of medium is mostly preferred and recommended in the selection of an IIoT access network as it reduces cable cost and terrain limitations [35], [78], [123].

Many authors may argue the vulnerability of more accessible networks to security hazards[124]. The justification applies to most smart manufacturing setups, however, the trade-off between accessibility and security must be carefully revised by the network inventors [124].

On the contrary, the late generations of mobile networks (particularly 5G network) have increased security, along with improved accessibility owing to its wireless nature. Hence, this innovation completely marginalises the significance of trade-off between accessibility and security in network selection [22], [69], [111].

Opting for these network technologies will result in the inheritance of both security and improved accessibility into IIoT applications, meaning the smart factory will be more accessible only to authorised candidates[22], [69], [125]. This accessibility to authorised candidates can also be developed into smart businesses which enhance secure access to the public for demand-reliant production in an IoE network without compromising confidential organisational data [124].

#### **2.4.12. Evaluating Network Accessibility**

In the network domain, accessibility is measured by the ability to access a network at different locations. There is no specific number of places to scientifically quantify the accessibility, nor the specific geographical arrangement set as the threshold for a network to pass the accessibility test [123]. However, for the sake of this research, the theoretically proven hypothesis which states that wireless networks are more accessible than wired network will be followed [122], [123].

The only experimental test attempting to quantify the considered network accessibility will be trying to access the PLC-driven smart manufacturing plant at various locations which have 5G wireless coverage to experiment with the ease of access on 5G network. The same experiment will be repeated using the 4G network setup on the same case study. The ease of access from these two setups will be compared to complement the argument.

In the same experiment, PLC-driven smart plant data will be accessed over a 5G coverage on a mobile setup to test the theorised reliability and mobility of 5G network, with the aim to see if connectivity to the smart factory will affect network cells' handover process. At the end of these tests, the conclusion will be drawn on the accessibility of 5G owing to its wireless nature as compared to 4G wired network.

#### **2.4.13. Current Operations and Barriers**

Based on literature, these tactile internet applications have always been achieved with the implementation of 3G, 4G, and 4G-LTE network [26], [31], [126]. However, the implementation of these network technologies to facilitate TI applications in smart manufacturing is often hindered by limitations in network capacity, accessibility, reliability, device density, and latency. Furthermore, research has revealed that these barriers can increase production time in smart manufacturing[31], [126].

Within the context of this study, production time is considered as the time taken to produce a single unit of the intended product [4], [75]. If the production time is increased, it can affect overall production volume per unit time, which will in turn affect the supply of such product negatively [127]. However, optimising production timelines in smart manufacturing will advantage the producers in maintaining constant supply which will result in supply stability [3], [4].

To minimise production time, all factors that affect production time must be thoroughly analysed in a considered network technology to be used to implement a tactile internet application [15]. Since the dawn of tactile internet, network technologies that were commercially available to facilitate tactile internet applications have been 3G, 4G, and 4G-LTE network technologies [15]. At a later stage, the 5G network technology was introduced and it broadened network options [15].

At this stage, a brief review on the operation of 3G, 4G, and 4G-LTE network technologies will be done to gain the full picture of the current operation of tactile internet applications.

#### **2.4.14. 3G Network Technology**

The third generation of wireless mobile telecommunication, usually abbreviated as 3G network, was coined by the International Telecommunication Unit (ITU) in the late 1980s as an upgrade of 2G network. In 1998, it was first tested in Japan followed by its W-CDMA (Wideband-Code Division Multiple Access) technology commissioning in 2001, and the launch of the first commercial 3G network in 2003 [94], [128].

The 3G compliance with the International Mobile telecommunication-2000 (IMI-200) standard was endorsed by ITU for adaptation to fixed wireless access, mobile internet access, wireless voice telephony, video calls, and mobile TV [94], [128]. Above the broadband innovation of 5MHz in 3G, this network technology is equipped with numerous built-in radio interfaces, including the W-CDMA operating at the widespread band of 2100 MHz, Time Division-Synchronous CDMA and High-Speed Packet Access (HSPA) yielding 56 Mb/s as peak data rate [128].

#### **2.4.15. 4G Network Technology**

As a successor of 3G network, the fourth generation of mobile broadband cellular network (4G network) was envisioned in 2002 and laid out as IMT Advanced by ITU. However, the prototype was tested by the NTT DoCoMo (Japanese Company) in 2007, followed by full commissioning in 2008 [93], [110].

Major advancements of 4G network over 3G are the inclusion of all IP-based packet switched networks, broad network band of 5-20MHz, high data rate of up to 1 Gb/s as peak rate, and smooth handover management across different network providers [93].

### 2.4.16. 4G-LTE Technology

As an upgrade on 4G network, the 4G-Long-Term Evolution (4G-LTE or LTE) communication standard was developed by the Third Generation Partnership Project (3GPP) in collaboration with Siemens Networks, Ericson, and NTT DoCoMo based on speed increment by utilising alternative radio interfaces and core network upgrades. Some researchers refer to LTE network technology as 4G-LTE or Advanced 4G [129], [130]

This network technology is characterised by scalable broadband of 1-20MHz, IP-based network architecture named Evolved Packet Core (EPC), and efficient handover management in both data and voice applications [110]. With further research, an argument can be made on the inefficiency of LTE network in IoT application due to limited data rate, however, the ITU has ruled out on the matter by classifying both 4G and LTE as equals [131]. Table 8 summarises the characteristics of 3G, 4G, and 4G-LTE network technology.

### 2.4.17. Comparison Between 3G, 4G and 4G-LTE Technologies

*Table 8: Features of 3G, 4G and LTE network technology.*

Network	Latency	Bandwidth	Security System	Minimum data rate	Maximum data rate
<b>3G</b>	100-500 ms	15-20 MHz	Kasumi block cipher and SNOW3G Cryptographic system	348 Kb/s	384 Kb/s in WCDMA
					7.2 Mb/s in HSPA
					21.1 Mb/s in HSPA+
					42.2 Mb/s in DC-HSPA+
<b>4G</b>	1-100 ms	4-20 MHz	ZUC stream cipher and AES encryption standard	30 Mb/s	100Mb/s for high mobility devices
					1 Gb/s for low mobility
<b>LTE</b>	50-100 ms	1-20 MHz	ZUC stream cipher, AES, and SNOW3G Cipher	Not specified	100 Mb/s

In smart manufacturing, inadequate network bandwidth, poor network access, and high latency can cause delays in data transmission and disrupt the flow of tasks and information across different processes [4], [37]. This can lead to interruptions and bottlenecks in production cycles, increased downtime, and reduced efficiency, all of which can increase the time needed to complete production tasks [30].

High network latency in a tactile application will result in increased amount of time taken to produce a unit product because required interruption and remote logic controls will not be accessed in time, and this can result in possible bottlenecks and increased production time [82]. This theoretical analysis was accentuated by Ura and Ghosh as they quantify the latency in both time and frequency domain to measure its significance in latency-centric signal processing application [30].

Likewise, if the network bandwidth is limited, it will prohibit the bidirectional feedback transmission of haptic signals which will result in possible bottlenecks, hence, increased production time will result as more time is required to transmit signals [32]. Finally, if the network access is limited, more time will be required to access the physical plant and to apply some operational interactions, remote maintenance, and the stakeholder's decision on the emerging conditions in production line [42], [117].

From Section 2.4.9, network reliability is defined as the ability of the considered network technology to facilitate the connection for the considered period without disruptions [15], [83], or the resilience of the network technology against external environmental and network-oriented factors that can cause communication failure. If this network reliability is high, data synchronisation in a tactile internet will be efficient, and this can minimise production time [15], [121], [132].

From Table 8, an evident improvement in network latency, bandwidth, reliability, device density, and network access were realised from 3G to 4G and 4G-LTE network technologies [20], [24]. However, research revealed that all these network factors in 3G, 4G, and 4G-LTE network technologies are still not sufficient to facilitate tactile internet applications and the envisioned standards of Industry 4.0 [6], [8], [25].

At the time of conducting this study, the fifth generation of mobile network technology (5G network technology) is the only commercially available network technology to address network limitations in tactile internet applications of high latency, limited network bandwidth (which result in low data rate), low network reliability, limited network access, and limited device density, which are proven by research to have a significant impact on production in a smart manufacturing environment [18], [21], [133].

## **2.5. 5G Technology**

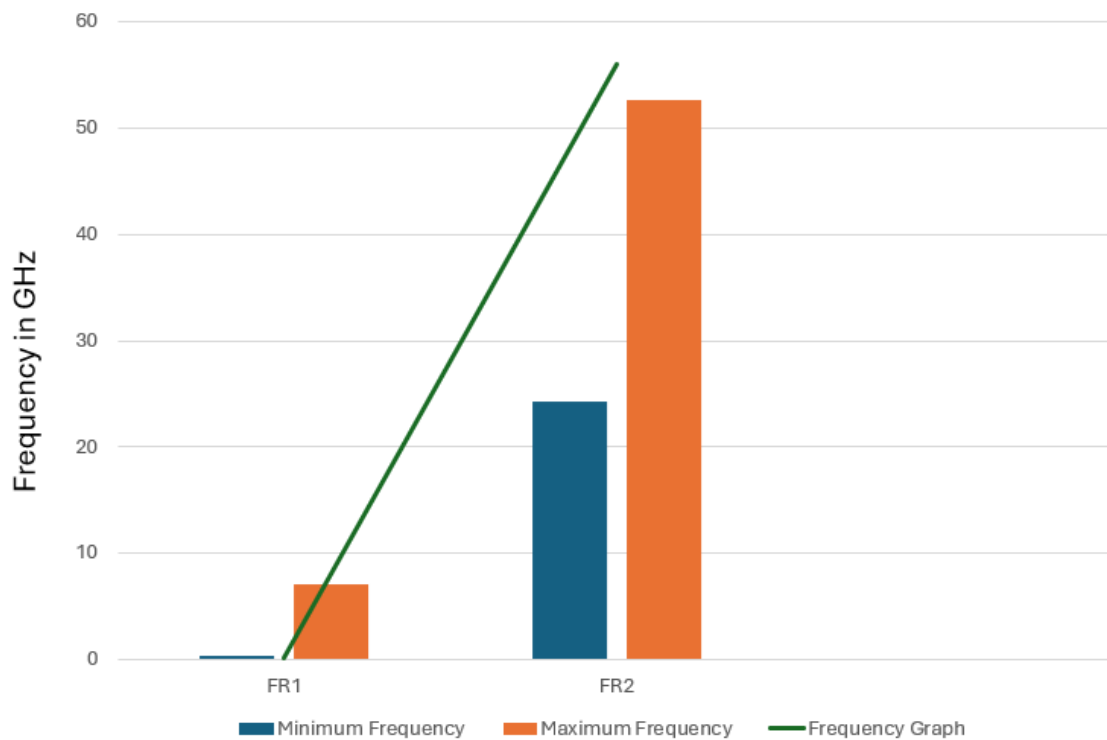
The fifth generation of mobile and wireless communication (hereinafter referred to as 5G network) was envisioned and developed by Machine-to-Machine intelligent (M2Mi) Corp in partnership with NASA as successor to the 4G and LTE network technology [132]. The study was carried over by different companies since then, based on recent technological trends, until the first commissioning commenced by South Korea and a United States technology giant called Verizon in April 2019 [132].

The 5G network study and development was centred on cell division for network distribution in small geographical areas (called cells) and millimetre wave technology [23], [121]. This millimetre wave technology is the idea of minimising the wavelength of the transmitted signal to yield ultra-high transmission frequency.

This anticipation of minimising wavelength is governed by the basic sinusoidal relation in which the frequency is inversely proportional to the wavelength to maintain the constant speed [49], [51]. In this relation, minimising the wavelength will result in increasing the frequency of such signals to maintain the constant speed and are clearly outlined in the documentation of communication standards and protocols [134], [135].

The documentation of communication standards and protocols was clearly underlaid by 3GPP with the 20 Gb/s peak download speed specified by ITU's ITM-2020 standard in all 5G communication links [136]. The IEEE clarified the infrastructure standard to 5G communication for the achievement of the network technology as the Next Generation Fronthaul Interface (NGF-I) and the diverse spectrum referred to as 5G NR frequency bands was allocated for this communication technology [136].

This 5G NR indicated 5G network operation in multi-stage frequency operation ranges is named FR1 and FR2. FR1 is the primary band for all basic application of 5G network which includes the Sub6 band (frequencies lower than 6GHz) ranging from 45MHz to 6GHz and provide a limited band at 5-100 MHz per user because of unavailability of the explored incessant spectrum insufficiency, while FR2 are frequency ranges above Sub6 band with the operating frequency range of 24.25 to 71 GHz at the bandwidth of 50-400 MHz [134], [137].



*Figure 7: The graph of FR1 and FR2 frequencies against wavelength.*

Figure 7 indicates the FR1 and FR2 frequency ranges with their maximum applicable bandwidths and their operating frequency ranges against the wavelengths. From the graph, it can be deduced that the wavelength, which is already ranging along minimum values, decreases with the increasing operating frequency to complement the millimetre wave technology proposed by Verizon Communications [138], [139].

However, the ultra-high frequency implementation in 5G network technology consequently hinders the network coverage. This is because at ultra-high frequency ranges, the rate of attenuation increases, which in turn limits the range of transmission [140]. Hence, all 5G communication links have relatively low range due to high transmission frequency. To compensate for the limited range, multiple antennas are multiplexed in 5G technology form a Multiple Input - Multiple-Output (MIMO) technology [116], [117].

For maximum resource utilisation, the 5G technology imports the idea of Massive Multiple Input-Multiple Output (Massive MIMO) by multiplexing more than one antenna in both time and frequency domains [116], [117]. This Massive MIMO idea should be implemented in both transmitting and receiving ends with the multi-access edge computing for better results [117].

Based on the above elaborated features of 5G network technology, inventors, developers, and network operators promise Ultra-Reliable Low Latency Communication (URLLC) of less than 1 ms, extreme Mobile Bandwidth (eMBB) of up to 20 GHz (up to 400 MHz at 24 GHz operating frequency for millimetre wave radio channels), and ultra-high device density of up to  $10^6$  devices/km<sup>2</sup> which is normally referred to as massive Machine Type Communication (mMTC) as a result of its ability to multiplex wireless traffic [18], [22].

These innovative features (URLLC, eMBB and mMTC) make 5G network an inevitable choice over its predecessor for IIoT applications and it is theoretically anticipated to address all network challenges in smart manufacturing. In addition, it is complemented by a high reliability rate of 99.99% and increased accessibility due to the wireless nature of 5G network technology [21], [25], [132]. This theorised ability of 5G network technology to improve network factors which affect production, is yet to be proven in this research [15].

However, an intricate challenge in proving the theoretical anticipation of 5G network technology in improving network factors that affect production time lies in the limitations of most industrial level PLC devices of adopting the wireless 5G technology [18], [22]. This is caused by the lack of 5G wireless features in such PLC devices. Hence, to prove the hypothesis, the primary goal of this research is to address the implementation challenges of enhancing 5G wireless features in a PLC-driven smart manufacturing environment [22].

### **2.5.1. Challenges Underlying 5G Implementation**

The wireless nature of 5G network facilitates enhanced mobility and increased device density in an IIoT application [141]. However, this feature imposes a formidable challenge as most of the IIoT devices used in smart manufacturing lack wireless capabilities [25], [133]. This challenge calls for integral engineering in the system to enhance wireless features. If this modification is successful, IIoT devices will be linked to 5G network technology to complement the desired mobility [137].

At the time of writing this thesis, the coverage of 5G networks is still a challenge in most developing countries, hence, this poses a formidable challenge to the complete transition of IIoT devices to be 5G capable [28], [78]. Therefore, the implementation of 5G in the smart manufacturing environment is limited by compatibility of industrial devices to 5G network as most IIoT devices lack 5G capabilities [142].

PLCs, which are used to automate most smart factories, including the case study for this project, are typical examples of the IIoT devices which lack wireless and 5G capabilities. Subsequently [12], [46], [49], a PLC-driven plant should be modified in order to adopt these wireless and 5G capabilities, and the communication link should be established with carefully defined communication protocols.

### **2.5.2. Proposed Solutions of 5G Implementation**

To overcome the two main implementation-based challenges of 5G in industrial automation mentioned in Section 2.5.1, which are the lack of wireless and 5G capabilities of IIoT devices in smart manufacturing, several researchers propose several technical setups.

Some researchers propose setups which completely substitute PLCs in industrial automation with other automation devices to achieve the intended 5G wireless capable system, while others propose the addition of some 5G wireless modules to the already existing PLC-driven system to adopt 5G wireless capabilities [18], [45], [143].

### 2.5.3. FPGA and Raspberry Pi

This technique was proposed by Siedler *et al.*, in which the authors suggest the installation of a data streaming FPGA and Raspberry Pi 4B 5G network module from Simcom for the enhancement of 5G capabilities [18], [83]. When analysing the properties of an FPGA module used on the proposed setup, the Mesa 7I76E FPGA is best suited for the application, even though the author did not specify [48].

In this setup, the PLC is phased out and the FPGA is used for data streaming, data encoding and decoding, analogue-to-digital conversion, and digital-to-analogue conversion. However, research revealed that most of the industrial-level smart factories are already automated using PLC devices, as explained in Section 2.3. Moreover, the FPGA used has limited I/O interfaces as compared to the PLC drive, thermal limitation (of up to 1.4A for 7I76E FPGA), and limitation in storage which will affect the scalability of the system to large plants [144].

The use of a Raspberry Pi network module also inherits some built-in limitations into the system, these limitations include a lack of Real-Time Clock (RTC) with backup battery, lack of analogue-to-digital converters, and unstable power consumption (load-dependent power consumption) [145]. Moreover, most industrial plants are already established, and research revealed that most of these plants are PLC driven, hence, phasing out PLCs will not be a cost-effective approach [12], [46].

### 2.5.4. User Equipment and 5G Capable IIoT Instruments

Ansari *et al.* suggest the usage of 5G User Equipment (5G UE) as the gateway between the PLC and wireless 5G network [10]. This UE can be a smart phone, tablet, or laptop. The idea was also vouched for by 5G-Smart group in their delivery report, as they propose the deployment of main computers as UE to enhance 5G adaptability for vision-based navigation of each single-arm YuMI robot [146].

However, none of these studies consider the limitation in mobility, power efficiency, and processing speed of the used UE which will be inherited into the system [41], [71]. Moreover, most UE that can be used is not industrial-level equipment, and this will shorten their lifespan [45]. This application is thus unsuited for the test considered as UE maximum data rates will define the entire setup speed.

On the other hand, Sa *et al.* propose the utilisation of 5G wireless capable industrial instruments (PLCs, sensors, actuators), but the scarcity of these 5G capable instruments in the current market makes the project less feasible [45]. In the case of the smart water bottling plant, the Simatic S7-1200 PLC does not have any 5G capabilities, and completely phasing out the PLC with the new 5G capable PLC will be costly [15], [45].

### **2.5.5. Protocol Adaptation Scheme**

Xu *et al.* propose a protocol adaptation scheme and developing a 5G-based wireless PLC prototype system based on 5G transmission on Modbus RTU and Modbus TCP to attain an Industrial Wireless Network (IWN) using 5G network [143]. This experimental study suggests the incorporation of a network adapter to a PLC drive using a RS485 cable for 5G capabilities enhancement.

The network adapter in consideration consists of a Layerscape 1046 multicore processor which supports four Cortex-A72 cores, and an industrial-level RM500U-CN 5G network Module [143]. This system is very close to the envisioned setup for this study as it does not phase out the PLC drive, however, it inherits some limitations associated with individual components [123], [143]. These equipment limitations include, but are not limited to, the limited data-rate specified as the upper bound for an RS485 transmission of 10 Mbps, the limited bandwidth of up to 100 MHz for the RJ45 cable, and maximum data rate of 2100 Kbps specified for all Layerscape FPGA family, which will bottleneck the system [63], [145].

### **2.5.6. Scalance MUM856-1 5G Wireless Router**

The other optimal solution is the incorporation of a single-unit Siemens Scalance MUM856-1 5G wireless router, which operates by bridging network layer 2 packets and transmitting them in layer 3 infrastructure to adapt to 5G technology [147]. This router is equipped with a high data-rate of up to 1 GB/s, high mobility, improved energy efficiency, and standard compatibility with all Siemens PLCs through the possession of standard ethernet interface [147].

The experimental research by Fowler *et al.* also utilises the Scalance MUM856-1 5G router to enhance wireless 5G features in an Automated Guided Vehicle (AGV) to address 5G implementation challenges [88]. This study focuses on mobile robots or AGVs rather than PLC-automated systems [39]. However, to a significant extent, it depicts the feasibility of Scalance router implementations in smart manufacturing environments. The advantages associated with incorporation of the Scalance MUM856-1 router to the smart factory drive to enhance 5G wireless features are as follows:

1. The router is equipped with a maximum data rate of 1 GB/s, which is adequately high and will not bottleneck the system.
2. Besides 5G network technology, the router can also communicate with 3G and 4G network technologies, hence the system will still be functional during 5G network outages.
3. Enhanced mobility is one of the most important advantages of the router, as it can also connect mobile networks from national service providers. This feature makes the router adaptable to mobile applications.
4. The router has an ethernet/LAN port, with standard LAN communication. Most of the drives or servers used in industrial processing also have a standard LAN interface. Hence, the router is scalable to other PLCs, DCSs, and PACs besides the Siemens drive family.
5. The router is equipped with an external memory card slot for memory supplementation in large data processing.

NOTE: At the time of conducting this research, there is limited evidence on the implementation of the Scalance MUM856-1 router in a PLC-driven smart manufacturing plant to implement tactile internet.

### **2.5.7. Comparison Between Reviewed Techniques**

*Table 9* summarises the reviewed techniques of enhancing 5G wireless features in smart manufacturing environments for different publications.

Table 9: Comparison of reviewed techniques of 5G implementation.

Author set	Proposed solution	Advantage(s)	Disadvantage(s)
Siedler <i>et al.</i> (2021) [18]	Mesa 7176B FPGA and Raspberry Pi 4B 5G network module	Mesa 7176B FPGA is both digital and analog capable.	Substitution of PLC drive Limited IOs, storage, and thermal limitations (1.4A)
Ansari <i>et al.</i> (2022) [10] 5G-Smart group (2023) [146]	5G user equipment (5G UE)	Most UE has standard interfaces User-friendly interface	Not industrial level Setup inherits limitations of UE (data rates, processing speeds)
Xu <i>et al.</i> (2023) [143]	Layerscape 1046 multicore processor and RM500U-CN 5G network module	Does not substitute PLC drive	2100 Kbps specified for all Layerscape FPGA family Upper bound for an RS485 transmission of 10 Mbps
Siemens industrial (2023), (2022), (2023) [39], [147], [148]	Scalance MUM856-1 wireless 5G router	High data rate, Enhanced mobility, Scalable, Energy efficient	Built internal Sinema RC software defined for Siemens IIoT smart devices

### 2.5.8. Theoretically Anticipated Results

In this section, the theoretical, anticipated results for latency, bandwidth (data rate), device density, network reliability, and accessibility based on research will be detailed to provide the expected behavioural performance of tactile internet application implemented using 5G network technology and 4G network technology.

From the methods reviewed, the Scalance MUM856-1 router was concluded to be the optimal solution. Hence, the theoretical evaluation will be conducted on the experiment to be implemented using the Scalance MUM856-1 router. On the other hand, the theoretical performance of the 4G network tactile internet application will be evaluated based on the wired teleservice method

### 2.5.9. Latency and Bandwidth (Data Rate)

Theoretically, the latency performance of the 4G network tactile internet application will be evaluated to be equal to or greater than the greatest latency performance amongst all components to be used along the latency route of the setup. Regardless of the minimal latency of some components to be used in the setup, the component with the highest latency will bottleneck the latency performance of the entire setup [87], [89].

Moreover, the theoretically expected data rates for the 4G tactile internet setup to be implemented in Phase 2 of the Methodology chapter will be governed by the theoretical data rates of all components along the latency route, and the component with the lowest possible data rate will bottleneck the data rate performance of the setup [105].

The latency route of the 4G tactile internet application setup will be composed of the latency and data rate performance of the remote PC processing speed, the 4G network latency, CAT6 LAN cable latency, and the S7 ethernet interface gateway latency as shown in Table 10

*Table 10: Theoretical latency of components along 4G tactile internet application route.*

Latency route component	Theoretical latency performance	Theoretical data rates performance
Remote PC – Dell intel core i5 laptop Intel(R) Core (TM) i5-8250U CPU @ 1.60 GHz 1.80 GHz	Expected latency to be less than 10 ms, but can extend as high as 1000 ms	At 1.8 GHz with 64-bit Operating System, the maximum possible data rate is 14.4 GHZ
4G network	10-100 ms	<150 Mbit/s download
Cat6 ethernet cable 3m	Open range of between 0.5 ms and 100 ms in low range of less than 30m	10 Gbps at 250 MHz frequency (Only applicable at the range which is less or equals to than 50m)
S7-1200 PLC drive ethernet interface	0.5 ms to 100 ms, it can also extend to over 100 ms depending on the transmission speed at the gateway	<100 Mbps, but it can also be higher than 100 Mbps depending on the transmission speed at the gateway

From Table 10, the highest lower boundary latency of components in a 4G tactile internet application route is the 4G network technology with the minimum latency of 10 ms [85], [110]. Hence, a conclusion can be drawn that the expected latency performance of 4G network tactile internet application should be above 10 ms [85]. However, as latency is measured as the round-trip delay, two times the expected latency can be set as the minimum possible latency that can be measured [87].

As shown in Table 10, the lowest upper bound data rate amongst all network components was realised in 4G network technology of 150 MBps [100], [105]. Hence, the maximum expected data rate from the setup should not be greater than 150 MBps [100].

Likewise, the latency performance of 5G tactile internet application to be implemented using the Scalance MUM856-1 router will be governed by the latency performance of the components on the latency route of the setup. Hence, the component with highest latency performance will bottleneck the implemented setup. Table 11 shows the latency performance of components in the latency route of the wireless 5G network tactile internet application.

In the wireless 5G network tactile internet application to be implemented, the theoretically anticipated data rates will be governed by the data rates of the components along the network transmission route. This means that network components with lowest upper bound data rates will determine the maximum possible data rate of the implemented setup [21], [83]. Table 11 shows the theoretically expected data rate performances of different components in the transmission link.

From Table 11, the lowest higher boundary latency performance was realised in the Scalance MUM856-1 router, amongst other components. This router possesses the upper bound latency of 10 ms [147]. Hence, the latency performance of the setup is expected to range below 10 ms. However, due to unforeseen network problems, the latency of the setup can spike above the expected maximum of 10 ms but with limited percentages. Moreover, the measured latency is expected to be two times the theoretically evaluated latency as it is measured as the round-trip [95].

As shown in Table 11, the component with the lowest upper bound data rate is the Scalance MUM router with the maximum data rate of up to 1 GBps on the downlink [147], [148]. Hence, the overall data rate performance of the implemented tactile internet setup is expected to be equal to or less than 1 GBps.

*Table 11: The latency performance in a wireless 5G network tactile internet route.*

<b>Latency route components</b>	<b>Theoretical latency performance</b>	<b>Theoretical data rates performance</b>
Remote PC – Dell intel core i5 laptop Intel(R) Core (TM) i5-8250U CPU @ 1.60 GHz 1.80 GHz	Expected latency to be less than 10 ms, but can extend as high as 1000 ms	At 1.8 GHz with 64-bit Operating System, the maximum possible data rate is 14.4 GHZ
Wireless 5G network	Between 1 ms and 20 ms, it can also extend to less than 1 ms.	Peak speed: 20000 MBps (20 GBps) on downlink  Practically expected to reach up to 2000 MBps (2 GBps)
Scalance MUM856-1 router	<10 ms	Downlink: <1000 MBps Uplink: <500 MBps
Cat6 ethernet cable 2m	Open range of between 0.5 ms and 100 ms in low range of less than 30m	Peak speed of 10 Gbps at 250 MHz  (Only applicable at the range which is less than or equal to 50m)
S7-1200 PLC drive ethernet interface	0.5 ms to 100 ms, it can also extend to over 100 ms depending on the transmission speed at the gateway	<100 Mbps, but it can also be higher than 100 Mbps depending on the transmission speed at the gateway

### **2.5.10. Device Density**

Based on literature, the device density of 4G network technology is approximately  $0.1 \times 10^6$  devices/km<sup>2</sup> [93], [110]. The number of IIoT nodes that can be multiplexed by 4G technology are impractical to measure in a laboratory setup because the case study does not have the increased number of network compatible IIoT sensor/actuators, as explained in Section 2.4.7 and Section 2.4.8.

On tactile internet application implementation using wireless 5G technology in Section 2.4, the theoretically anticipated device density is  $1 \times 10^6$  devices/km<sup>2</sup> [1], [18]. Similar to 4G tactile internet application, this value is impractical to measure in a laboratory setup due to limited network compatible IIoT sensors/actuators, as described in Section 2.4.8.

For comparison purposes, the theoretical device density of  $0.1 \times 10^6$  devices/km<sup>2</sup> (100000 devices/km<sup>2</sup>) for the tactile internet implemented using 4G network technology will be used, and the theoretical device density of  $1 \times 10^6$  devices/km<sup>2</sup> (1 million devices/km<sup>2</sup>) for tactile internet application implemented using 5G network technology will be considered [18], [93].

### **2.5.11. Network Reliability and Accessibility**

Network accessibility is evaluated by the simplicity of connecting to such tactile internet application at diverse ranges, and based on research, wireless network links are considered to be more accessible than wired networks as they can be accessed over a wider range unlike wired network links which can only be logged into at designated network points [123], [124].

Moreover, research reveals that 4G network technology is equipped with 95-99% in low congested networks and healthy infrastructure. However, some researchers assert the possibility of 100% reliability performance in 4G technology in low range and optimal QoS facilities [79]. On the other hand, 5G network technology inventors promise 99.99% reliability in Industry 4.0 applications [79], [83]. Table 12 shows the theoretical device densities, accessibility, and reliabilities expected in wired 4G and wireless 5G technologies for tactile internet applications.

*Table 12: The theoretical device densities, network accessibility, reliability.*

<b>Factors</b>	<b>Wired 4G tactile internet</b>	<b>Wireless 5G tactile internet</b>
<b>Device Density</b>	0.1x10 <sup>6</sup> devices/km <sup>2</sup> (100000 devices/km <sup>2</sup> )	1x10 <sup>6</sup> devices/km <sup>2</sup> (1 million devices/km <sup>2</sup> )
<b>Accessibility</b>	Less accessible	More accessible
<b>Reliability</b>	Highly reliable 95-99%	Highly reliable 99.99%

## **2.6. Relationship Between Smart Manufacturing, PLCs, TI and 5G Technology**

Smart manufacturing is an IoT-integrated and fully collaborative manufacturing approach which integrates cyber, physical and human spheres to facilitate an intelligent IIoT in collaboration with all enterprise chain domains [11], [42]. Smart manufacturing is mainly characterised by the automation of production lines to ensure proper collaboration with all IIoT devices and stakeholders' input at any stage of production [4], [11].

For the automation of smart factories, PLCs have arisen as a pivot of automation in the manufacturing and industrial processing sector(s) [12]. PLCs are special-purpose built-in computer devices designed for automating industrial processes [12], [49]. These PLCs are vested with many advantages engineered to mitigate automation challenges in production plants.

However, most PLC devices have limitations in storage capacity which can lead to loss of data during hardware failure [49], [149]. In addition, the entire smart manufacturing process is subject to a lot of operational, historical, and retail-based data which requires a reliable and accessible storage facility [46], [149].

According to research, the most reliable and accessible storage facility for smart manufacturing applications is cloud storage [17], [150]. Cloud storage is a remote internet-reliant and server-based storage facility which is used by organisations and individuals to store data [33]. This facility is at the top ratings of the data storage pyramid and its utilisation is increasing rapidly [68]. To synchronise data between cloud storage and the PLC drive, a network link should be established between the two [18], [19].

The network link between cloud storage and PLC drive or between the PLC drive and the remote PC must be characterised by ultra-low latency, high bandwidth, maximum device density, and extremely high mobility to enable real-time synchronisation of data [81], [151]. Among network technologies existing at the time of writing this thesis, research revealed that 5G network is equipped with the requisite minimal latency and maximum bandwidth compared to all other existing network technologies [18], [121], [141].

If the network technology used to synchronise data between the physical system and virtual system is redundantly available, more reliable, and ultra-responsive enough to transmit large amounts of data in close-to-real-time, then the system can also adopt more time-sensitive applications like smart clinics, remote maintenance, remote operation, mobile robots, and autonomous vehicles [27], [112]. All these applications rely on creating virtual presence and are referred to as tactile internet [28], [69].

## **2.7. Limitations of Existing Research**

The aim of this research is to implement tactile internet using 5G network in a PLC-driven smart manufacturing environment. The argument has been thoroughly explored by many researchers on the possibility of implementing 5G on a PLC-driven smart factory. However, the underlying concern is on the hardware adaptation of existing IIoT devices to 5G, the uncompromised effect of the modified setup on 5G qualities which improve production time, and the resilience of the proposed system to minimise all the drawbacks inherent in 5G communication.

Several researchers reviewed the feasibility of the project and anticipated the expected results for the envisioned project. This was reviewed in research by Siedler *et al.* which demonstrated the possibility of implementing 5G network in a cloud-based environment to control a CNC machine [18]. However, this research did not describe in detail the mitigating technical factors of adopting 5G wireless capabilities in a physical CNC machine.

Segovia and Garcia-Alfaro clarified the standard approach of designing digital twins and the need for data synchronisation between the physical and virtual model [1]. Yet, this research did not thoroughly explore the accessibility of the virtual model on a reliable centralised platform (cloud storage) and reliable ultra-low latency connection for data synchronisation (5G wireless network) beyond cable connection.

Mourtizis *et al.* and Vaibhav *et al.* undertook a survey of the hardware compatibility challenges of implementing 5G in an IIoT environment[22], [25], [26]; however, this research did not provide a plausible solution to the challenge [22], [25]. This gap was also identified in research by Rico *et al.* who laid the educational test bed for the envisioned future of mobile networks in tactile internet applications without evaluating the compatibility challenge of emerging technologies to existing infrastructure in their research[69], [111].

On the other hand, some more relevant studies were examined in which the architectural setup was clearly introduced [39], [133], [143]. However, a gap was also identified as most of them do not conform to the core of the intended case study which is the PLC drive. Hence, they require other automation techniques besides PLC, while others introduce some IIoT and networking modules with limited data rates which in turn bottleneck the system and rule-out all intended merits brought by 5G into the system [18], [69], [143].

Some examples of these studies are from Siedler *et al.* in which the PLC automation is phased out with the Mesa 7176E FPGA and Raspberry Pi 4B 5G network module to introduce 5G capabilities [18], [83]; Xu *et al.* propose the development of an Industrial Wireless Network (IWN) for a PLC prototype system by building a protocol adapter which consists of a Layerscape 2046 multicore processor and RM500U-CN network module for 5G capabilities [143]; however, in this research the author did not consider the data rate bottleneck that will be brought on by the introduced components.

Another closely related study by Ansari *et al.* suggests the usage of UE with 5G capabilities to enhance 5G capabilities to the system[10]. In this research, the author did not consider how the UE used will limit the system in the terms of mobility, energy efficiency, reliability, and data rate. Sa *et al.* propose the implementation of 5G capable industrial equipment (PLCs, sensors, etc.) [45].

The idea of using 5G capable instruments would be best suited for the intended application [45]. However, the scarcity of 5G capable instruments in the market makes the proposal less feasible. In addition, the already existing PLC drive in already established smart plants including the chosen case study for this research does not have 5G or any wireless features [12], [152], [153].

Some publications which possess a similar research interest to this research were identified, such as Simsek *et al.* which showcase the deliverance of haptic signals in a tactile internet application to facilitate sharing skillset globally [154]. However, the research lacks experimentally measured results on the effects of network latency in such applications [154].

Tychola *et al.* also further investigated the merits and architectural challenges of incorporating 5G technology and Beyond (5GB) to implement a tactile internet application which facilitates the Metaverse ultimatum [155]. This research also does not showcase the experimentally measured results of the improvements brought on by 5G in the Metaverse application [155].

Moreover, Joshi P. further accentuated the significance of 5G and B5G technologies in establishing tactile internet applications which facilitate a smart clinic with the aim of diversifying skillset share in the health sector [156]. However, the research also did not clearly quantify the improvement that 5G and B5G brought to the system [156]. Moreover, Fanibhare *et al.* investigated the effects of multiplexing bi-directional signals to attain enhanced physical/virtual mapping in a tactile internet application without showcasing 5G innovation trend [157].

In conclusion, many comprehensive research projects were conducted on the need for and advantages of 5G adaptation in the smart manufacturing environment. Some researchers further discuss the merits of PLCs as a pillar of automation in industrial applications [12], [15], [47].

With recent developments on mobile wireless networks, researchers are mainly focused on the qualities that can be brought about by integrating 5G into the smart manufacturing environment which can minimise production time [15], [25], [78]. However, these studies omit the technical challenges, compatibility issues, and implementation challenges of the existing IIoT infrastructure to 5G network technology in implementing tactile internet application a PLC driven plant [15], [22], [25], and this is the root of this project.

Hence, the adaptation challenges brought on by a lack of 5G capabilities in most IIoT instruments have been an oversight to many authors, and this gap and limitation in existing publications necessitates this research. Thus, this research aims to address the 5G adaptation challenge brought on by industrial-level traditional PLC in PLC-automated smart plants.

### 3. Methodology

#### 3.1. Chapter Introduction

This chapter disseminates the methodology used to overcome the limitations of existing research, as described in Section 2.7. As discussed in Section 1.4.1, the aim of this research is to implement tactile internet to the existing PLC-driven plants by enhancing 5G wireless capabilities for the improved operation and effectiveness within the manufacturing sector which will result in the minimisation of production time [2], [28].

Tactile internet 5G technology topics have gained lot of attention at both research and application level recently. However, research revealed that PLC-driven plants have not been given enough consideration in this movement [28], [46]. This has led to a reckonable inability to adapt to 5G wireless network in PLC-driven smart plants which limits the implementation of an ultra-responsive tactile internet system into such plants.

To remediate this deficiency, it was established in Section 2.4 that the adaptation of a 5G wireless network into PLC-driven plants would improve data streaming, which will in turn minimise the production time, and thereby result in increased production capacity, enhanced collaboration with all stakeholders, and faster operation interaction as well as remote maintenance [27].

Based on the identified research gaps in Section 2.7, the methodology should answer the research questions that were postulated in Section 1.3, which are:

1. Which effective and plausible amendments can be implemented on already existing PLC-driven plants to be able to adapt 5G network technology?
2. Can the system modification be scalable to all PLC-driven systems?
3. Will the developed experiment improve all considered network performance factors which affect production time?

All these questions of interest will be answered by the ability of the system design to be able to enhance 5G wireless capabilities revealed in the methodology chapter. This will be achieved by elaborating more on the selected case study for this project, reasons inspiring the choice of the case study, key sections of interest on the case study, and additional innovative modules on the setup to achieve the aim of the project.

In line with the research aim detailed in Section 1.4.1, the research intends on implementing tactile internet application for a PLC-driven smart water bottling plant using 5G network technology to minimise production time on a network level. Production time will be minimised by improving the identified network factors in Section 2.4.2 which hypothetically have a direct impact on production time [4], [27], [32], [75].

As dissected in Section 2.5, research has indicated that the main change in these network performance metrics will be realised if the network technology used is changed to the most recent generation of network technology (which is 5G technology at the time of writing this thesis) [21], [24], [133].

To prove or repudiate the indicated hypothesis [21], 4G network, which is the older generation and diversely used in the manufacturing landscape, will be used as reference for comparison. Similar experimental setups will be assembled for both 4G and 5G networks to advocate the driven theory to be proven, and the network factors will be measured and analysed in these two setups.

Results from the 5G setup will be compared with the results from the 4G setup, and conclusions on the theorised ability of 5G network to improve production time will be drawn. This chapter starts by explaining the chosen case study for the research and the reasons which motivated the choice. It then explains how the OPC sever was set up for data tunnelling.

The chapter further explains how the plant was accessed over 4G network setup. Based on the surveyed literature, the optimal solution of enhancing 5G wireless features was introduced and the setup explained. The final step clarifies how network parameters were measured in both setups.

### **3.2. Case Study**

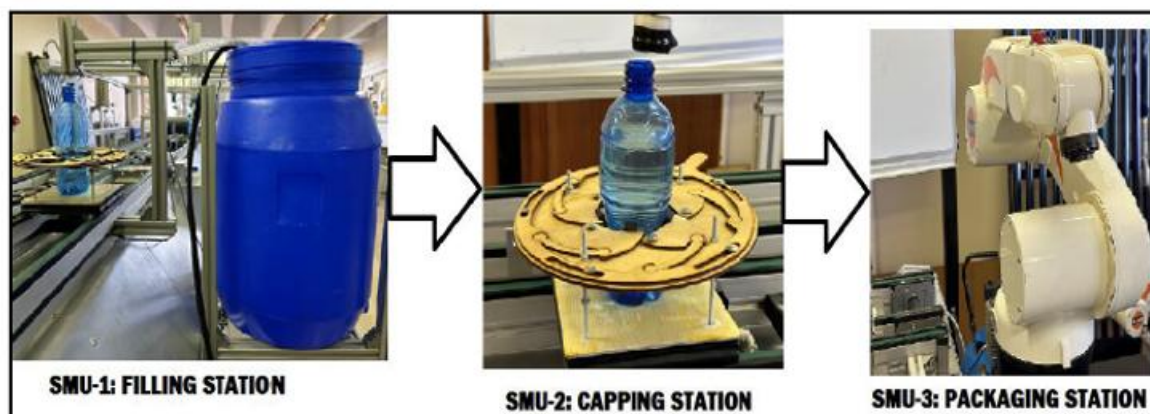
Following the selection of the case study for implementing tactile internet using 4G and 5G network, testing network factors which affect production time, and building the permanent remote access using 5G wireless network after proving the theoretical hypothesis of its (5G network) ability to minimise production by improving network factors, as considered in Section 2.4.2, the choice of the case study was made based on the key characteristics indicated in the introduction in Section 1.6. These are:

1. The case study should be fully automated.
2. The plant should be centralised and driven by the PLC drive(s).
3. The selected plant should be in a place where there is an accessible 4G/LTE network and wireless 5G network coverage (either private or public 5G network).

In consideration of the aim of the research in Section 1.4.1 and the above listed characteristics which are key requirements to accomplish the research aim, an already established smart water bottling plant in the Central University of Technology Electrical Lab was considered an optimal test bench for this research as it possesses all necessary requirements for the intended experiment [15], [29]

### 3.2.1. Plant Overview and Operation

The smart water bottling plant was set up to manufacture two sizes of water bottles, being 330ml and 500ml, fill these bottles with clean drinking water as per make-to-order criteria, cap and package these bottles on a fully automated and timed procedure. This product-varying setup was designed and modelled using MATLAB/Simulink and implemented to illustrate the mixed model stochastic assembly lines in smart manufacturing [16], [29].



*Figure 8: Smart water bottle plant showing three SMUs.*

For testing network parameters which affect production time, the three main PLC-driven sections of the smart water bottling plant shown in Figure 8 were considered as the optimal testbench. Hence, the plant section which manufactures water bottles will not be considered, only the three PLC-automated smart manufacturing units will be considered. These smart manufacturing units are the filling unit, the capping unit, and the packaging unit[29].

### 3.2.2. Plant PLC Drive

All smart sensors and actuators for the process flow on the smart water bottling plant SMUs are independently centred on the PLC drive. Hence, the governing logic can read from the smart sensors and output to modules independently from each other, only controlled by the developer's program control philosophy, thus forming a centralised automation system with the PLC drive as the central server [149], [158].

The PLC drive used to automate the plant is the Simatic S7-1200 DC/DC/DC PLC drive from Siemens. This is one of the most commonly used 24V DC powered PLC devices in industrial automation [49], [159]. Like any other Siemens drive, it supports PROFINET bus communication, TIA portal programming environment, Simatic WinCC for visualisation and is equipped with the maximum of 100 KB of programming data memory [152], [153], [160].

In the case of a large amount of programming data, the drive has one memory card slot for memory supplementation. It can be programmed through an RS485 port known as TIA-485 programming interface. It is also equipped with an ethernet RJ45 port (LAN) which can also be used for programming purposes, and built-in Inputs/Outputs Modules [152], [153], [159], [160]. This ethernet port supports the maximum of 20 Mbps [144], [159], [161].

The TIA portal programming environment which was used to set up the S7-1200 PLC drive was the TIA Portal V15.1 version, and the WinCC advanced support version was the TIA\_Portal\_Step\_7\_Pro\_WINCC\_Adv\_V15\_1 which is the TIA Portal step7 Professional WinCC Advanced V15.1. The programming of the S7-1200 drive as per intended control philosophy logic was developed on the same TIA portal environment [153], [159], [161].

### 3.3. Experimental Setup

This section demonstrates how the smart water bottling plant driving PLC was accessed over a wired 4G network and wireless 5G network. As explained in Section 2.3.2, some data tags require data tunnelling, and an illustration on how the tunnelling server was set up is also detailed in this section. The experimental setup is divided into the following three phases:

**Phase 1:** Setting up tactile internet using 4G network.

Step 1: Set up an OPC server for data tunnelling.

Step 2: Set up tactile internet on the smart water bottling plant using 4G network.

Step 3: Measure network factors on 4G network setup.

**Phase 2:** Setting up a tactile internet using 5G network.

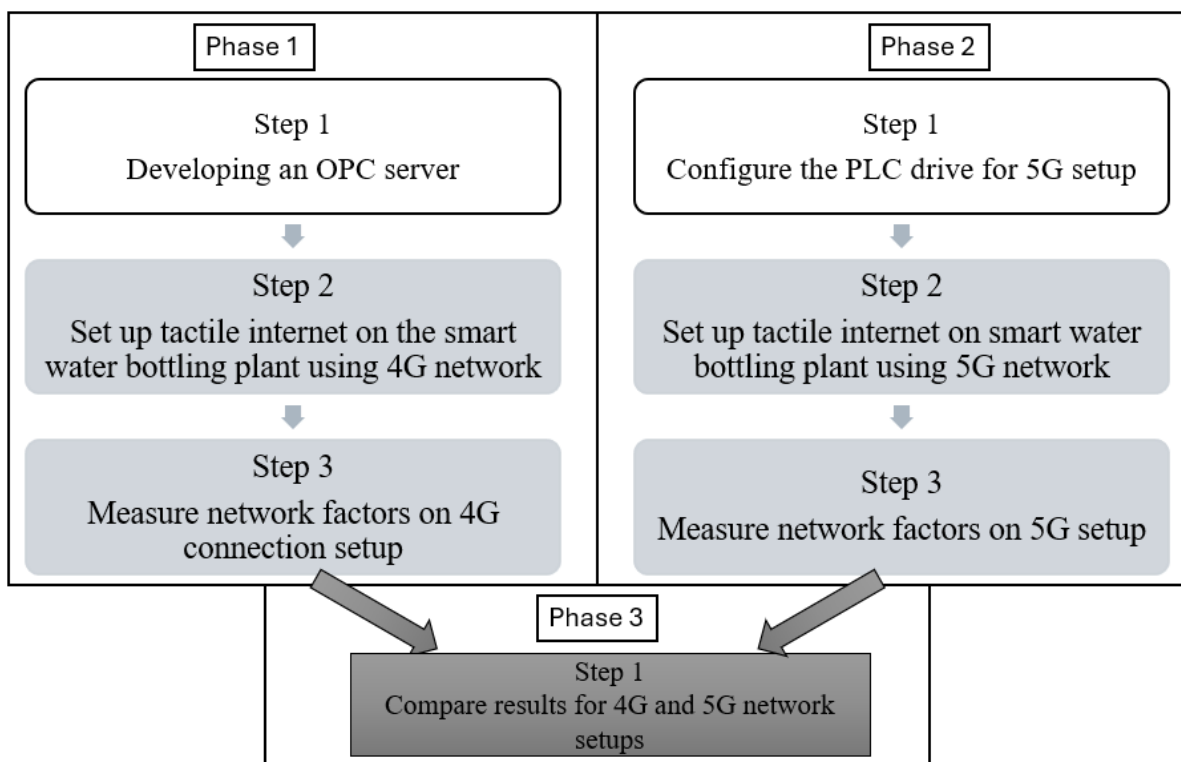
Step 1: Configure PLC drive for 5G setup.

Step 2: Configure Scalance MUM856-1 router and develop remote access to the plant using 5G network.

Step 3: Measure network factors on 5G network setup.

**Phase 3:** Comparison

Step 1: Compare measured results of network parameters from 4G and 5G network setup.



*Figure 9: The block diagram of the experimental steps.*

## **Phase 1: Setting-up tactile internet using 4G network**

In this phase, the tactile internet application will be implemented on the smart water bottling plant using the 4G network setup through the wired connection. As explained in Section 1.6, all sensors and actuators on the smart water bottling plant are centralised on the automating PLC; the underlying conclusion is that accessing the PLC drive remotely will be accessing the entire plant.

This 4G network remote access to the water bottling plant will be executed by, firstly, developing an OPC server, then configuring the PLC drive to enable the Teleservice functionalities, connecting the plant PLC drive to the wired 4G network and, finally, measuring all network factors that were discussed in Section 2.4.2 to have a significant impact on production time in tactile internet applications.

### **Step 1: Developing an OPC server**

In industrial automation, data from different vendors need interfacing for real-time data synchronisation between process control devices and software applications. To overcome this multi-vendor data compatibility challenge, Section 2.3.2 specifies that the most applicable solution is to develop a common bridge tunnelling data between windows-based software applications and process control hardware [162].

In the case of this experiment, the bridging tunnel will be an Open Platform Communication (OPC) server which uses the proprietary technology that allows the document to be linked and embedded to different vendors' devices called Microsoft's Object Linking and Embedding (OLE) technology. This OPC server facilitates data interfacing in substitution to software development by hardware manufactured to accommodate every Windows data application.

In this experimental setup, the OPC Kepware server called KEPServerEX 6 configuration platform was used [163], [164]. This is the Unified Architecture (UA) open standard server which tunnels data by eliminating the network and operating system level compatibility requirements for data streaming [163], [165].

The OPC UA client on the KEPServerEX 6 was set up by creating a new project online, configuring the communication channel which the OPC UA server was going to communicate with, which was added to the connectivity tab and configured, confirming the drive type (which is S7-1200) and setting up TCP/IP Ethernet driver for Profibus communication.

After setting up the client, the device which the channel will communicate with was set. The device type was set to S7-1200, which is the PLC drive used to automate the smart water bottling plant, and the node station set to the IP address assigned to the ethernet port of the drive [165], [166]. The summary of all these configurations on the KEPServerEX 6 client are reflected in Figure 10, and this device created will allow tags from the PLC drive to be accessible on the remote connection channel [51], [167].

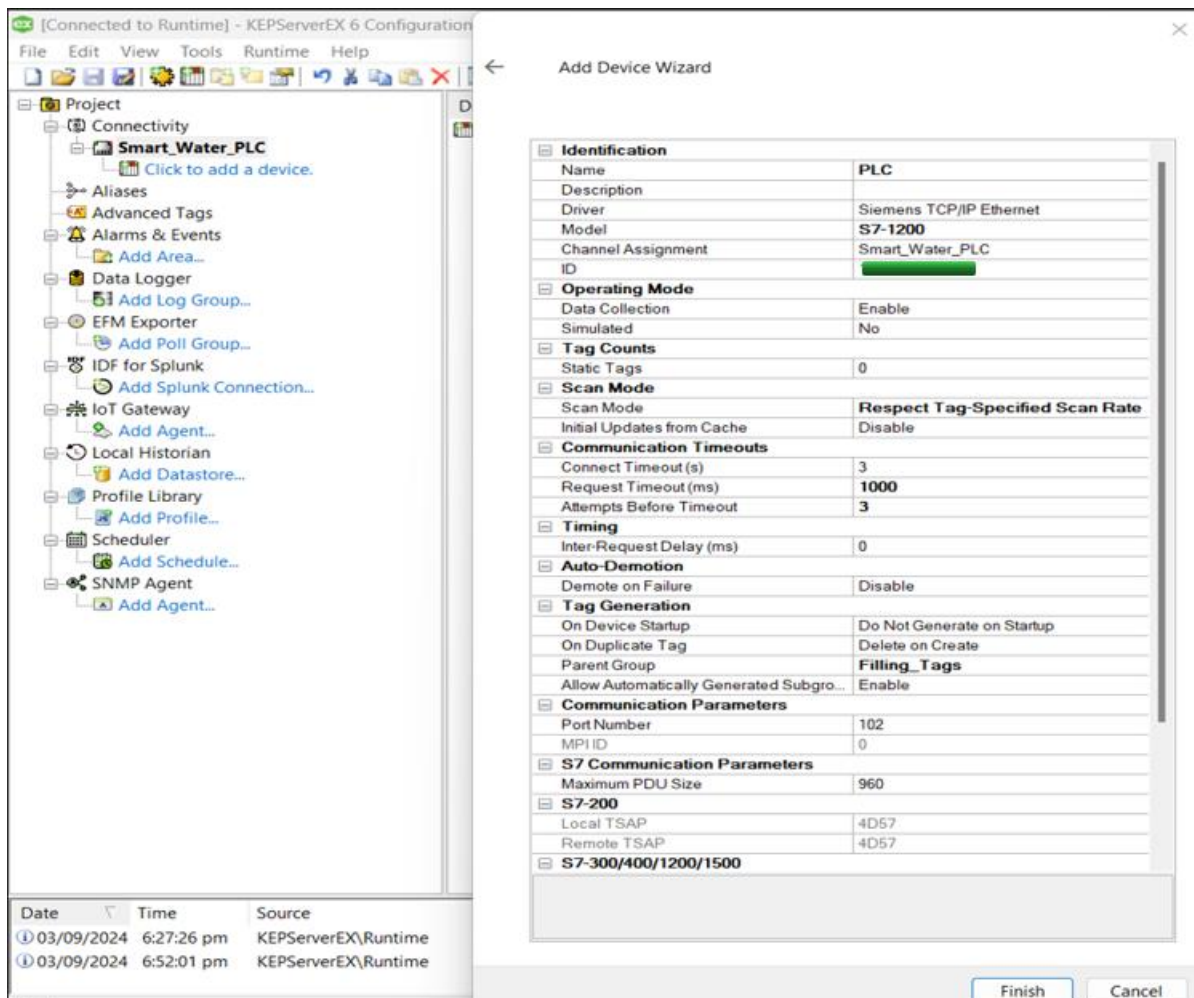


Figure 10: The configuration summary of device creation in KEPServerEX 6.

**NOTE:** For network security purposes, the IP addresses have been masked in green on purpose as it would be a violation of university network security rules to reveal the IP addresses in public documents.

## Step 2: Setup tactile internet on the smart water bottling plant using 4G network

The wired 4G setup to the smart water bottling plant was achieved through LAN ethernet cable connection between the Ethernet port on the 4G network port [159]. The PLC drive's IP address was changed to the IP address range of the 4G network used in the lab where the smart water bottling plant setup is located.

The S7-1200 PLC drive was connected to the computer using the ethernet LAN cable. On Tia portal V15, the CPU device was added, the PLC model used to automate the smart water bottling plant was chosen and added. On the project view, 'Online and Diagnostics' was selected, and the accessible devices to confirm that the PLC was visible on the TIA portal software, then the PLC settings were configured on the project view.

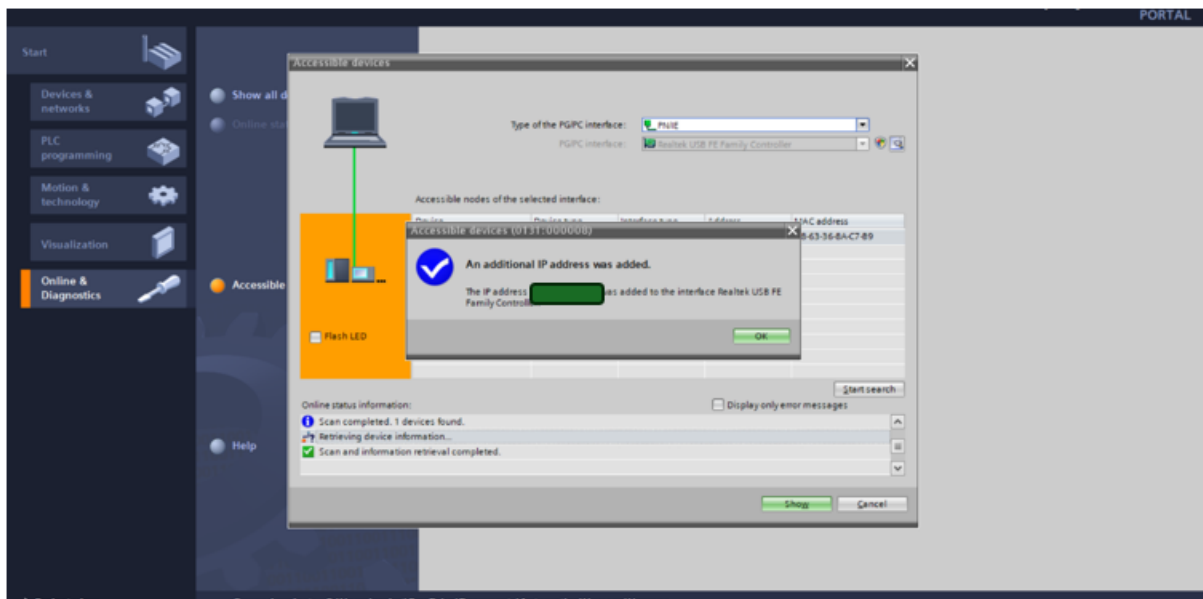
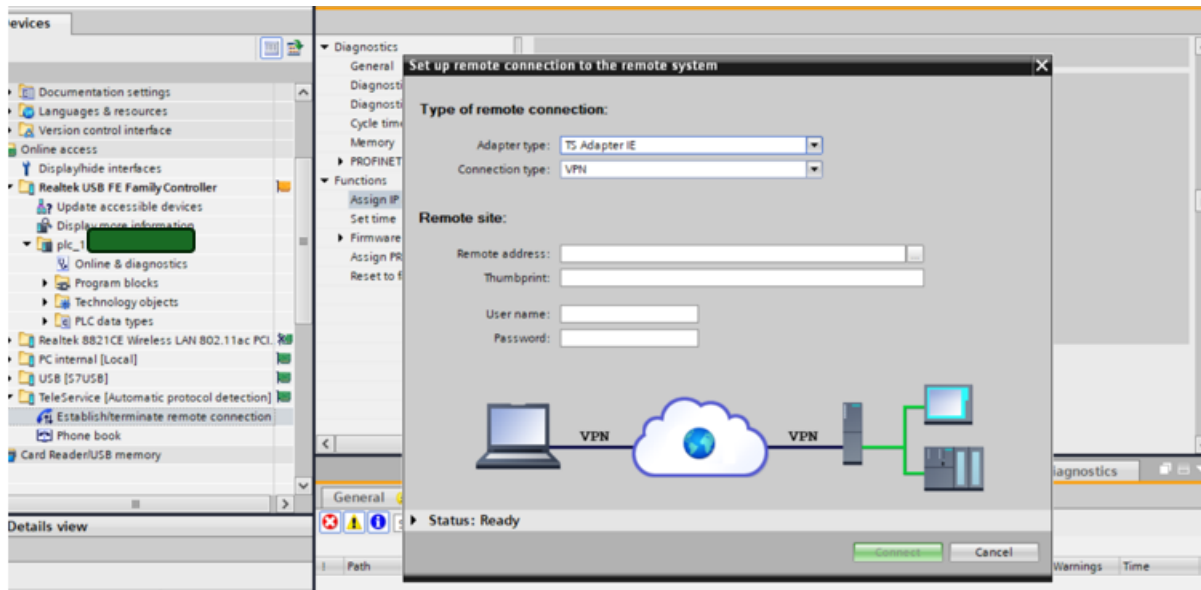


Figure 11: The portal view of the TIA Portal indicating successful change of IP address.

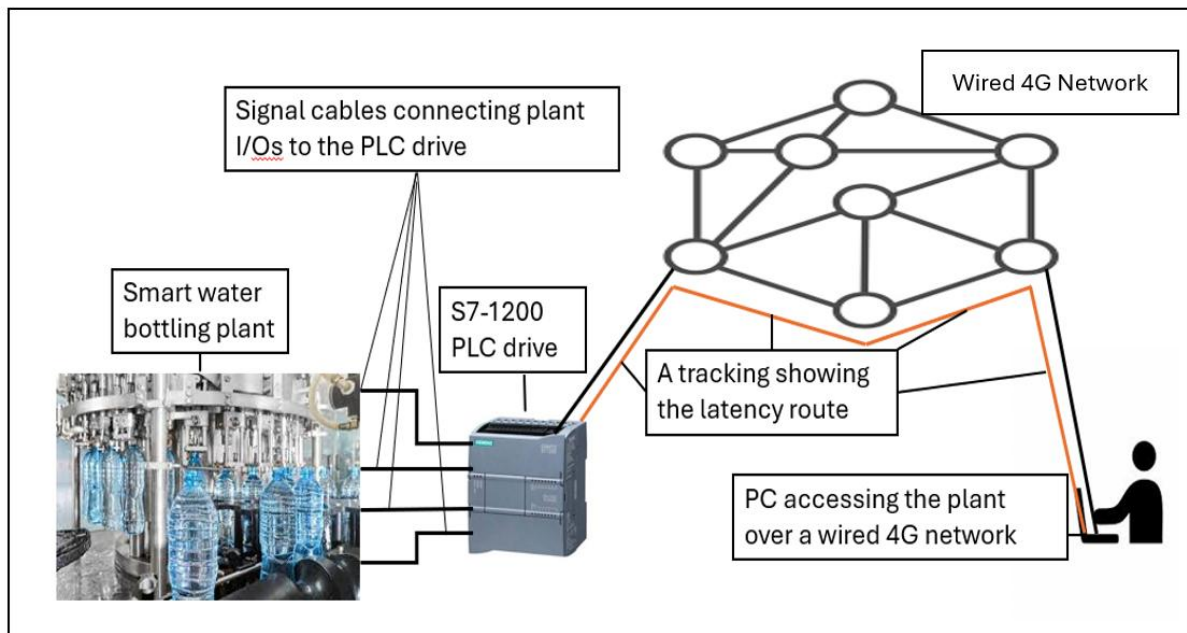
Under the functions in the 'Online and Diagnostics' tab, the IP address of the PLC drive was changed to the IP range, which is within the network to be used, as shown in Figure 11. An already developed program logic was downloaded to the PLC, then the drive was disconnected from the computer. Using the same ethernet cable, the PLC drive was connected to an ethernet port of the available 4G network [153].

The computer was connected to the 4G network using the ethernet LAN cable (assigned the dynamic host to the computer's IP address setting), the PING functionality was initiated to assure that the IP address assigned to the PLC drive is reachable on the network[168], [169]. The TIA portal Teleservice functionality was opened and the IP address of the PLC drive dialled-in to establish the remote control of the drive over 4G network[168], [169], as demonstrated by the screenshots in Figure 12.



*Figure 12: The remote connection dialup on TIA Portal Teleservices.*

After dialling-in IP address assigned to the PLC drive and thumbprint for identification and validation purposes, the remote PLC drive can be accessed. Hence, the entire smart water bottling plant can be accessed remotely over the wired 4G connection. Figure 13 shows the sketched representation of the tactile internet application on the smart water bottling plant using 4G network.



*Figure 13: The sketched representation of 4G network tactile internet.*

### **Step 3: Measure network factors on 4G network setup**

All network Key Performance Indicator (KPI) factors explained in Section 2.4.2, being network latency, bandwidth, device density, network accessibility and reliability, were measured and evaluated to complement the objectives of the study [4], [75]. Numerous sets of measurements were taken under different conditions to complement the argument in consideration.

#### **Latency**

In a 4G network setup, the IP address of the PLC drive was dialled in from the PC accessing the smart water bottling plant over the wired 4G network. The latency or the round-trip delay through the latency route indicated in Figure 13 was to average the latency behaviour of the tactile internet application [81], [89]. This exercise was repeated eight times with G-NetTrack and Paessler PRTG network monitor and the results recorded [95].

Latency measurements were also taken from the same setup with the PC connected to an ethernet port in different labs which are still within the CUT network. This was meant to monitor 4G network latency behaviour under different range accesses. Using the same latency measuring applications, eight measurements were taken and recorded.

## **Bandwidth (Data Rate)**

In Section 2.4.5, bandwidth was defined as the range between the upper and lower frequency boundaries through which the transmission medium can transmit data, or the broadness of the transmission medium [100], [136]. In the same section, the definition of bandwidth is engendered to the number of bits of data that can be tunnelled through the transmission medium in a unit time, and this definition aligned the bandwidth with the data rate. This similarity allows the measurement of data rate in substitution of the network bandwidth [105], [137].

For this experiment, the data rate through the transmission mediums was measured from the remotely accessed PC to the PLC drive wired 4G network using the G-NetTrack and Paessler PRTG network monitoring applications [95]. Similarly to the latency measurements, six sets of measurements were taken, and external affecting conditions were varied to obtain a broader analysis of data rate performances under different conditions.

In a wired 4G network, the data rate of the setup was measured by dialling-in the IP address assigned to the PLC drive in a G-NetTrack application [95]. The divergence of data rate was monitored over 48 hours. The test was then repeated six times to obtain six sets of results.

## **Network Reliability**

For evaluating network reliability, the setup was left connected with 4G network for 48 hours, after which the network disconnections were recorded and analysed. The same experiment was conducted using wireless 5G network at close range and, under minimal conditions of external factors affecting network KPIs, network disconnections were also recorded and analysed. No network disconnection was recorded over that period. Hence, reliability was considered as 100% in this experiment.

## **Device Density**

As discussed in Section 2.4.7 in the literature review, 4G network can accommodate up to  $1 \times 10^5$  devices/km<sup>2</sup> [15], [33], [151]. This number of IIoT devices which can be connected in a single network in 4G network technologies is impractical to experiment with in a laboratory setup, moreover, the case study does not have over 50 IIoT sensors.

For complementing the hypothesis in this study, theoretical values of the number of IIoT devices that can be multiplexed in a single 4G network technology facilitating the tactile internet application were considered. These theoretical values were taken from network technology inventors and standardising bodies [112].

### **Network Accessibility**

The network accessibility on the 4G setup was evaluated to be governed by the wired nature of the experiment. The wired nature of the setup makes it less accessible as it cannot be accessed at a wider range of places [122], [123]. This evaluation was derived from the proven fact that wired networks are not accessible enough as they can only be accessed from network outlet points [123], [145]. Based on this analysis, the tactile internet application using wired 4G networks was concluded to be less accessible.

### **Phase 2: Setting up a tactile internet using 5G network**

Based on the literature reviewed in Section 2.5.2, most of the applicable industrial IIoT devices, including the PLC drive used to automate the case study plant explained in Section 3.2.2, do not have 5G wireless features to adapt to 5G network technology [15]. Hence, the setup had to be modified to enhance 5G wireless features.

Among all reviewed possible methods of enhancing these features, the incorporation of the Scalance MUM856-1 5G wireless router was found to be the most plausible solution [15], [148]. For this reason, the implementation of tactile internet on the smart water bottling plant using wireless 5G network was achieved through the use of the Scalance MUM856-1 router [15].

### **Step 1: Configure PLC drive for 5G setup**

In this step, the PLC drive used to automate the smart water bottling plant was configured so that the IP address of its LAN port of the PLC drive is in the same IP range with the IP address to be assigned to the Ethernet interface of the Scalance MUM856-1 router (to be thoroughly explained in Step 2).

## Step 2: Setting up Scalance MUM856-1 router and implementing tactile internet using wireless 5G network

The Scalance MUM856-1 wireless router is a client level wireless 5G router which operates by streaming layer 2 packets over layer 3 in public and private 4G, 4G-LTE, or 5G network technology [147], [148]. The router was invented by one of the global automation technological giants, called Siemens, to address the continuously expanding demand for remote access in alignment with the most recent evolutionary milestone of 5G network in industrial applications [15], [147], [148].

It is equipped with a maximum 1000 Mbps uplink speed on the Private 5G network [147]. The router possesses two interfaces (ports), that being the Ethernet (LAN) port and wireless port. For this experiment, the wireless interface was used to access wireless 5G network and the Ethernet (LAN) interface was used to stream data to and from the PLC drive. Hence, the Ethernet interface of the router was connected to the ethernet interface of the PLC drive, as demonstrated in Figure 14.

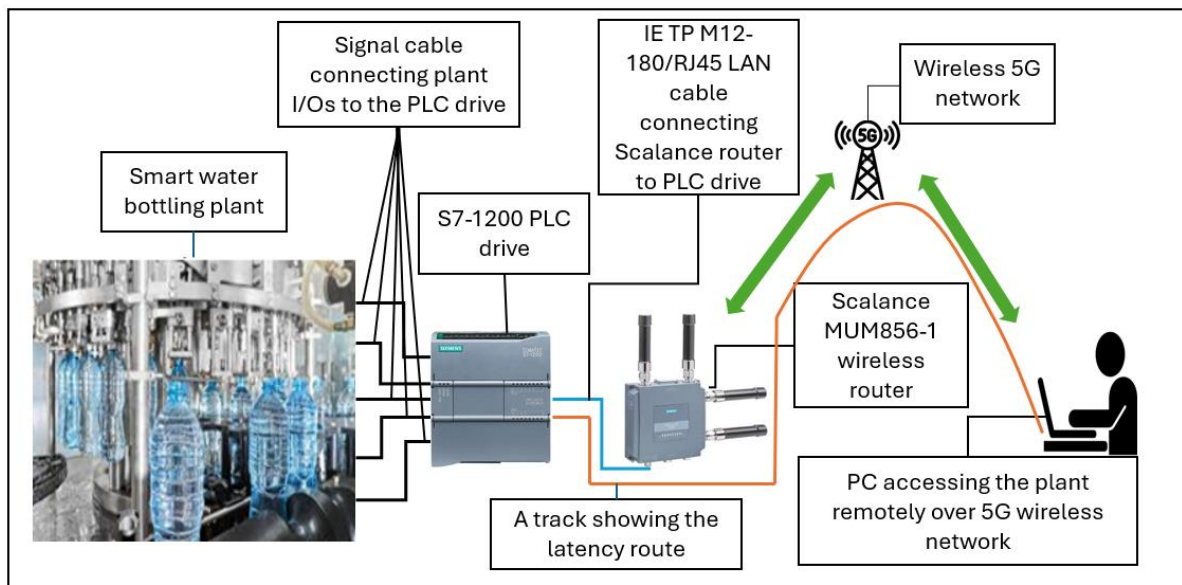


Figure 14: The sketch of experimental setup 5G tactile internet application.

For setting up the intended Industrial Wireless Network (IWN) on the Scalance router, the CLP license dongle is required for enabling the wireless port of the router. The license is procured independently, and careful selection is made which is governed by the intended features to be used. The wireless port of the router only becomes active when the wireless antennas are connected to antenna ports and the CLP license inserted [147].

The IE TP M12-180/RJ45-180 pre-assembled flexible power cable was used to connect a 2.5 amps 220VAC-24VDC power supply to the 4-pin M-socket power redundancy port (L1, L2) of the Scalance router as direct feed, which means the Power over Ethernet (POE) functionality was not used [88], [147].

Using the Siemens IE TP M12-180/RJ45-180 flexible communication cable, the Scalance M12 X-coded ethernet interface (P1LAN) port was connected to the ethernet/LAN interface of the computer. The dynamic host IP address DHCP was assigned to the computer so that the computer could attain the IP range of the Scalance router [111]

On the computer browser (Google Chrome, in the case of this experiment), the factory set IP address of the Scalance MUM856-1 router (192.172.1.1) was dialled-in to log into the router. The welcome page of the Scalance Sinema Remote Connect (Sinema RC) internally installed in the router appeared, indicating the successful logging into the Scalance router.

On the basic wizard tab, under Device, the system name, location, and contact details were set, as demonstrated in Figure 15. This name must be unique to enable improved identification of the Scalance router [147].

On this tab, the wireless interface was enabled and a unique IP address which is in the range of the wireless 5G coverage was allocated and assigned to the wireless interface. With all these configurations, both the ethernet and mobile interfaces were enabled, as demonstrated by Figure 15.

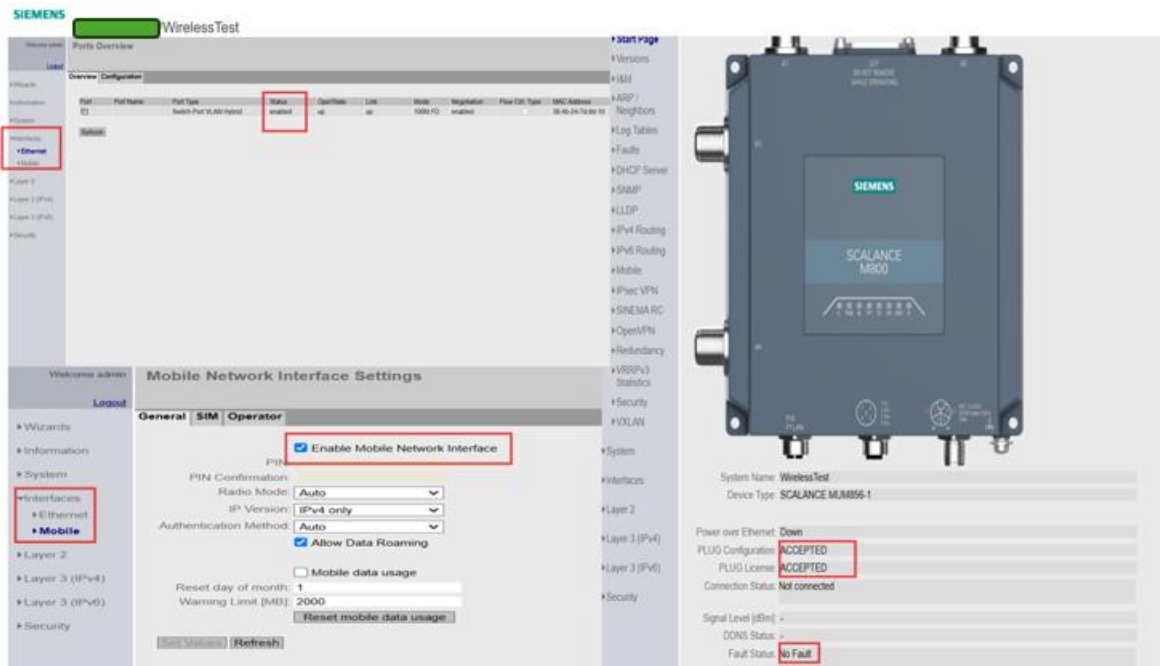
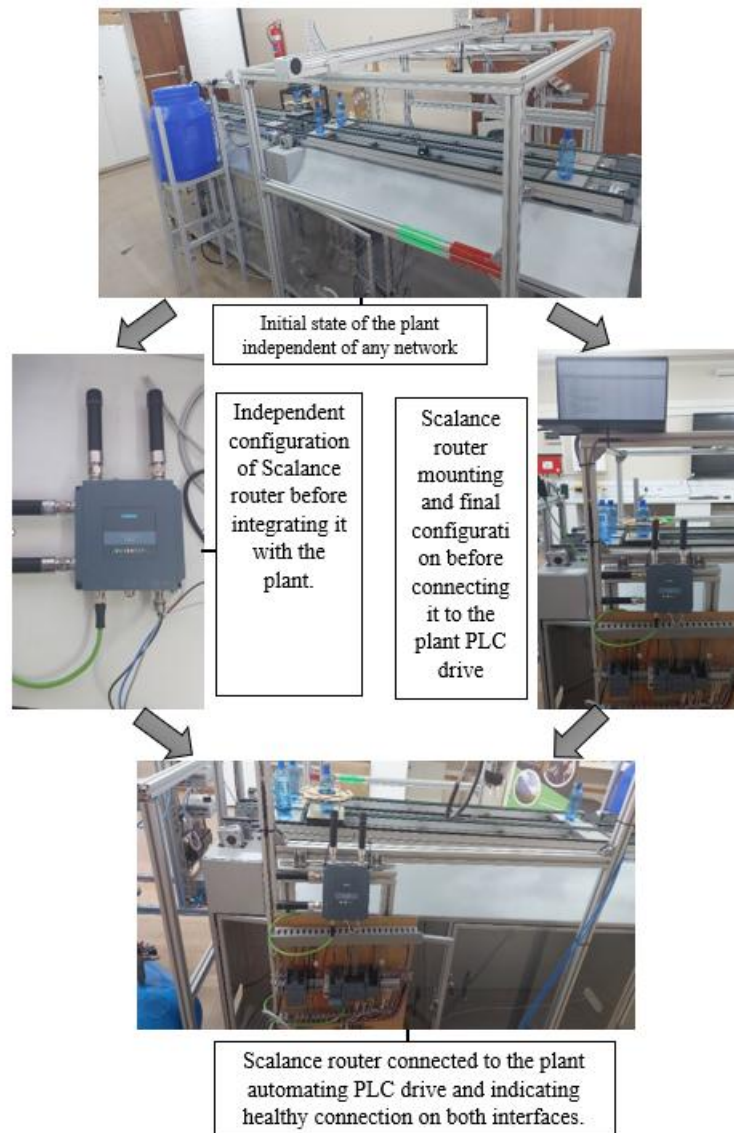


Figure 15: Screenshots of interface configurations on Sinema Remote Connect.

To achieve the intended tactile internet application illustrated in Figure 14, the computer was disconnected from the Scalance router, and the IE TP cord M12-180/RJ45 ethernet cable was used to connect the Scalance M12-LAN interface was then connected to the Ethernet interface of the PLC drive as shown in Figure 16.

On the bottom part of the picture in Figure 16, the remote Scalance router's wireless IP address was dialled in on the browser of the PC connected to the wireless 5G network. The router was accessed remotely, and on the ethernet interface of the router, the PLC drive was accessed, hence, the intended tactile internet application was implemented on the PLC-driven smart water bottling plant.



*Figure 16: Workflow wireless 5G tactile internet implementation steps.*

### **Step 3: Measure network factors on 5G network setup**

To measure all network performance metrics in a wireless network tactile internet application, the first step was to locate such node in the network which was intended to be the destination, then the measurement could be executed to such node. For this experiment, the target node was the PLC drive. Using the PRTG software, the plant-driving PLC was located and identified, as shown by the screenshot in Figure 17.

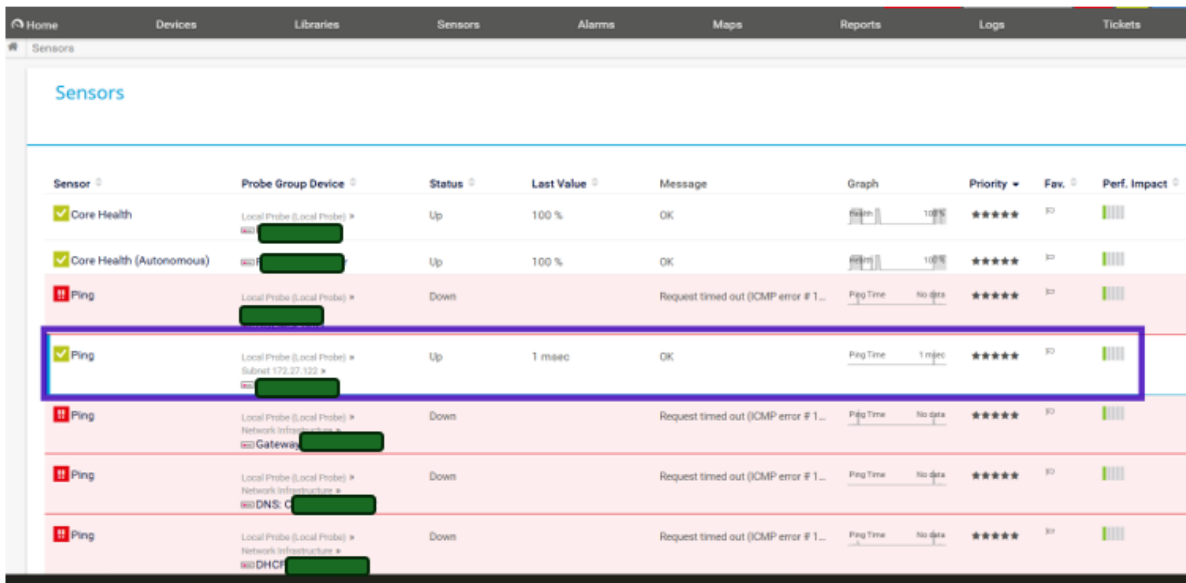


Figure 17: Screenshot of PLC drive identification in 5G tactile internet application.

## Latency

In a wireless 5G network tactile internet setup implemented using the Scalance MUM856-1 wireless router, demonstrated in Figure 14, the latency behaviour was measured through the round-trip as the transmitting PC also received the transmitted test bit(s) [80], [89]. The PC initiated the signal, transmitted it through the wireless 5G link, to the wireless 5G network, then through a wireless link to the Scalance MUM856-1 router, which then transmitted the signal through the PILAN interface with the ethernet cable to the PLC [95].

Using the G-NetTrack network assessing software and the Paessler PRTG network monitoring software, the IP address of the PLC drive was dialled-in on the remote PC and the latency performance behaviour of the setup was recorded. The test was repeated eight times at different locations and different weather conditions to attain a clear picture of the latency performance.

## Bandwidth (Data Rate)

As explained in Section 2.4.6, the bandwidth performance of the experiment was only determined by the data rate of data transfer according to the explained synonymity. Data capacity through the tactile interned application was maximised and the data rate was recorded. The test was repeated six times to attain the thorough data rate performance of the setup.

### **Network Reliability**

On the tactile internet implementation using wireless 5G network on the smart water bottling plant, the network reliability was also evaluated by remotely connecting to the plant for 48 hours and recording any disconnection occurred during that period. No disconnection was recorded, hence, the network reliability for the setup was considered to be 100%.

### **Device Density**

Based on research, the theoretical device density of 5G network technology is  $1 \times 10^6$  devices/km<sup>2</sup> maximum, and it is impractical to measure this network performance factor in a laboratory setup due to limited IIoT devices. As a result, theoretical values were considered for comparison purposes to complement the argument considered.

### **Network Accessibility**

From Section 2.4.11, it was established, based on conducted research, that wireless networks are more accessible than wired networks. The tactile internet application implemented using wireless 5G network also inherited this advantage. This inherited advantage was confirmed by remotely accessing the plant at different places with wireless 5G network coverage, and the plant was successfully accessed. Hence, the conclusion is that tactile internet implemented using wireless 5G network is more accessible.

## **3.4. Chapter Conclusions**

Based on the research aim, which is to implement tactile internet using 5G network in a PLC-driven smart manufacturing environment to minimise production time, this chapter was intended to showcase the conducted experiment(s) to achieve the aim. All the steps taken to achieve the intended aim were thoroughly elaborated on and explained. To complement the study achievements, the current operational state of tactile internet applications, which is implemented using 4G technology, was also tested for comparison purposes.

The chapter commenced by choosing the case study for the research. Based on the explained features in Section 3.2, the pre-existing smart water bottling plant was chosen to be the research case study because it is a smart manufacturing plant which is driven by an industrial level PLC drive and located at a place with 5G network coverage [15], [16], [29].

Then, the chapter proceeded to implement the experimental setup. The first phase of this experimental setup was to implement a remote access connection to the smart water bottling plant using 4G network [28], [71]. Next, network factors which were reviewed to have significant impact on production time were measured on this setup [15]. This phase was meant to illustrate the current operation of tactile internet applications in smart manufacturing environments [25], [71].

As per the project title, the chapter proceeded to the second phase in which the plausible solution of implementing tactile internet using 5G network was executed on the smart water bottling plant [143], [146]. This solution resulted from the reviewed methods in Section 2.5.2. In the final step of this phase, network factors that were reviewed to have a significant impact on production time in Section 2.4.2 were measured and recorded.

In conclusion, the methodology chapter successfully showcased the experimental setup fulfilling the research aim. However, the underlying questions at this stage are: Based on measured results, was the aimed improvement on considered network factors achieved? Was 5G network able to portray its theoretical hypothesis of minimising production time by improving network factors as discussed in Section 2.4.2? This will be answered in Chapter 4.

## **4. Results and Analysis**

### **4.1. Chapter Introduction**

In Chapter 3, the reviewed and selected methodology of implementing wireless 5G network in a PLC-driven smart plant was implemented. The chapter commenced by explaining the case study selected for this research and reasons motivating the choice. It further focused on building a 4G tactile internet application on the setup for comparison purposes and reconstructing the tactile internet using 5G technology as per the research aim. Finally, it showcased the steps taken to measure all network factors that were reviewed, based on research, to impact production time.

Chapter 4 will showcase all the measured results for both 4G and 5G network tactile internet setups, scientifically categorise graphical representation of collected data, and draw a distinct variation between both data sets (from 4G and 5G network tactile internet applications) in one presentation for detailed comparison in all measured and evaluated network factors reviewed in Section 2.4.2.

### **4.2. Latency Results**

To substantiate or invalidate the theoretical results showcased in Section 2.5.8, the performance of network latency as one of the key factors which were reviewed in Section 2.4.2 to have significant impact on production time were measured and recorded on the tactile internet applications that were experimentally implemented in Section 3.3.

#### **4.2.1. Latency Results of 4G Setup**

In a tactile internet application implemented using wired 4G network in a smart water bottling plant, network latency was measured and evaluated. The results from the Paessler PRTG network monitoring tool and G-NetTrack network measuring software of the 4G network tactile internet application implemented in the PLC-driven smart water bottling plant were measured, as demonstrated in the screenshot in Figure 18.

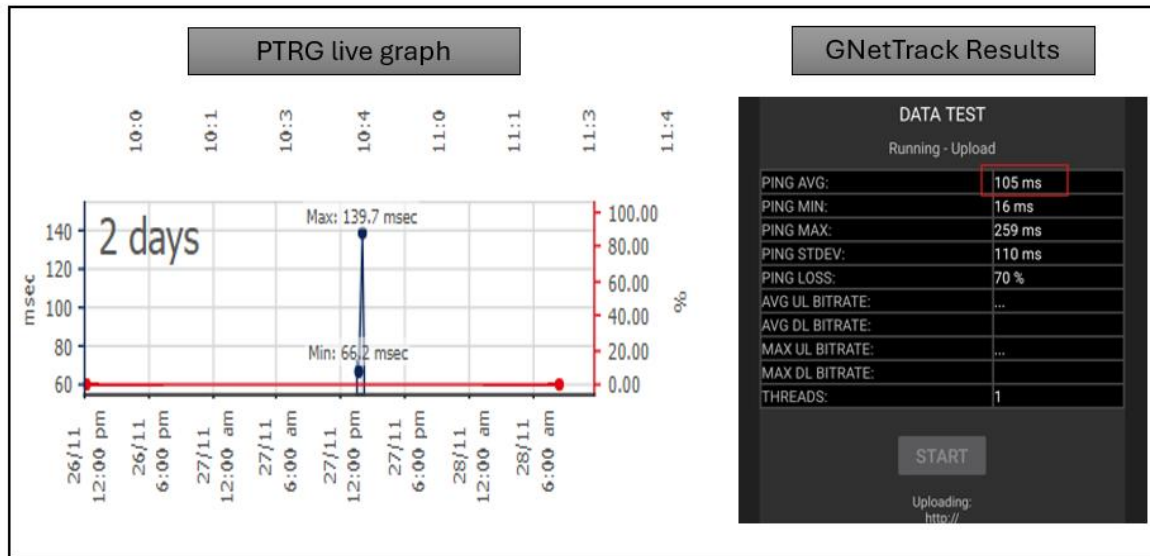


Figure 18: Screenshot of measured latency in 4G setup.

In Figure 18, eight measurements were taken at different ranges and external environment conditions. The measurements were also taken at different times to gain a thorough picture of performance metrics under different network congestion periods. The G-NetTrack results averaged at 105 ms while the Paessler PRTG results averaged at 100.1 ms, and the total average latency performance of the setup was 102.53 ms as shown in Table 13.

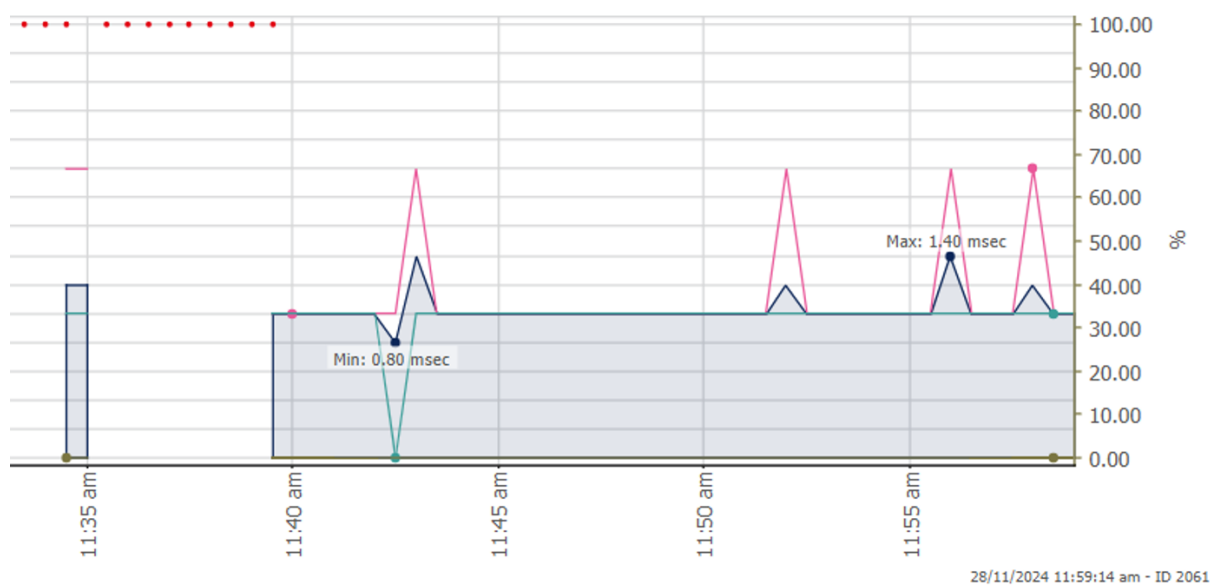
Table 13: 4G setup latency results.

Attempts	G-NetTrack Results	Paessler PRTG Results	Average Latency
1 <sup>st</sup> Attempt	62 ms	66.2 ms	64.1 ms
2 <sup>nd</sup> Attempt	89 ms	93.1 ms	91.05 ms
3 <sup>rd</sup> Attempt	108 ms	70.4 ms	89.2 ms
4 <sup>th</sup> Attempt	91 ms	90.3 ms	90.65 ms
5 <sup>th</sup> Attempt	112 ms	124.5 ms	118.25 ms
6 <sup>th</sup> Attempt	119 ms	98.5 ms	108.75 ms
7 <sup>th</sup> Attempt	124 ms	117.8 ms	120.9 ms
8 <sup>th</sup> Attempt	135 ms	139.7 ms	137.35 ms
<b>Average</b>	<b>105 ms</b>	<b>100.1 ms</b>	<b>102.53 ms</b>

#### 4.2.2. Latency Results on 5G Setup

The latency performance of the tactile internet implementation using wireless 5G network technology on the PLC-driven smart water bottling plant was measured by dialling-in (PING) the IP address assigned to the PLC drive from the remote PC accessing the tactile internet application, as demonstrated in Section 3.3.

On the G-NetTrack software and Paessler PRTG network monitoring software, the setup latency was measured as the round-trip delay through the latency route indicated by the screenshot of the live-graph on Figure 19.



*Figure 19: 5G setup latency screenshot.*

Eight measures were taken to gain the thorough latency performance of the setup under different conditions which could possibly affect the network performance. Table 14 shows the experimental results collected on the 5G network tactile internet setup.

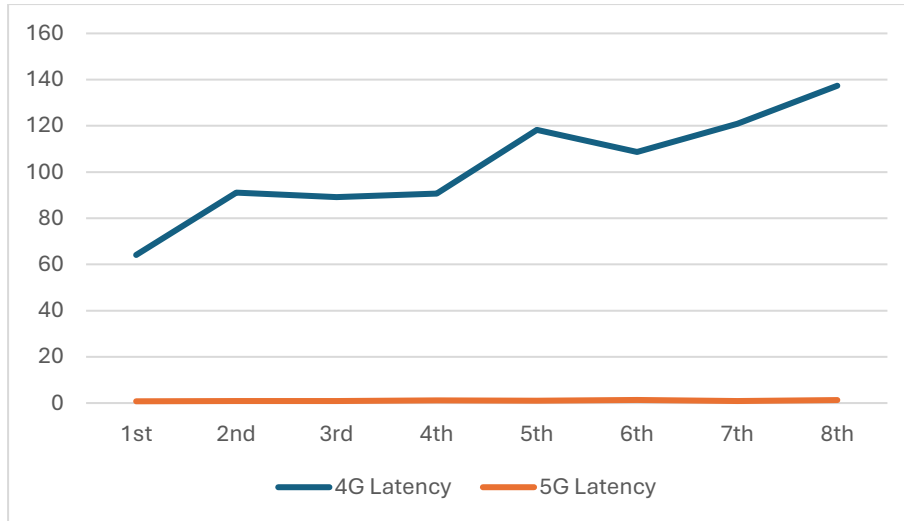
*Table 14: 5G latency results.*

<b>Attempts</b>	<b>G-NetTrack Results</b>	<b>Paessler PRTG Results</b>	<b>Average Latency</b>
1 <sup>st</sup> Attempt	0.49 ms	1.02 ms	0.76 ms
2 <sup>nd</sup> Attempt	0.91 ms	0.80 ms	0.86 ms
3 <sup>rd</sup> Attempt	0.63 ms	1.08 ms	0.86 ms
4 <sup>th</sup> Attempt	1.46 ms	0.93 ms	1.20 ms
5 <sup>th</sup> Attempt	0.91 ms	1.03 ms	0.97 ms
6 <sup>th</sup> Attempt	1.27 ms	1.40 ms	1.34 ms
7 <sup>th</sup> Attempt	0.85 ms	0.93 ms	0.89 ms
8 <sup>th</sup> Attempt	1.14 ms	1.31 ms	1.23 ms
<b>Average</b>	<b>0.95 ms</b>	<b>1.06 ms</b>	<b>1.01 ms</b>

From Table 14, the latency performance of 5G tactile internet on the PLC-driven smart water bottling plant ranges from 0.49 ms to 1.46 ms on the G-NetTrack. On the other hand, the Paessler PRTG network monitoring result ranges from 0.80 ms to 1.40 ms. Hence, the average latency performance of the G-NetTrack results is 0.95 ms while the Paessler PRTG network monitoring application results on average at 1.06 ms, and the total average latency of the 5G set up is 1.01 ms.

#### **4.2.3. 4G and 5G Setup Latency Results Comparison**

From Table 13 and Table 14, the average latencies were plotted in a graphical presentation in Figure 20 to compare the two sets of results.



*Figure 20: 4G and 5G latency results comparison.*

From Figure 20, a reckonable reduction (minimisation) in latency performance from 4G tactile internet application to 5G technology tactile internet application can be observed, hence the theorised ability 5G network technology in minimising latency in tactile internet applications has been proven. However, this improvement must be quantified by evaluating the percentage of improvement. This can be achieved by computing the average difference as a percentage of the original (4G) average as demonstrated in Equation 1.

$$Improvement(\%) = \frac{(4G\ Average - 5G\ average)}{4G\ Average} \times 100 \quad \text{Equation 1}$$

From Table 13 and Table 14, the average latency performance measured in a 4G network tactile internet application is 102.53 ms while the average latency measured in 5G setup is 1.01 ms, using these values in Equation 1 results in 99.01% improvement latency performance. In conclusion, the 5G technology implementation in tactile internet application of the PLC-driven smart water bottling plant was able to improve network latency by 99.01% on the measured results.

### 4.3. Bandwidth (Data Rates)

#### 4.3.1. Data Rates Results of 4G Setup

From the experimental setup of tactile internet application implemented using 4G network as demonstrated in Section 3.3, the data rate performance of the setup was measured using the G-NetTrack software and the Paessler PRTG network monitoring application. Figure 21 shows the screenshot of the measured maximum uplink data rate and downlink data rate.

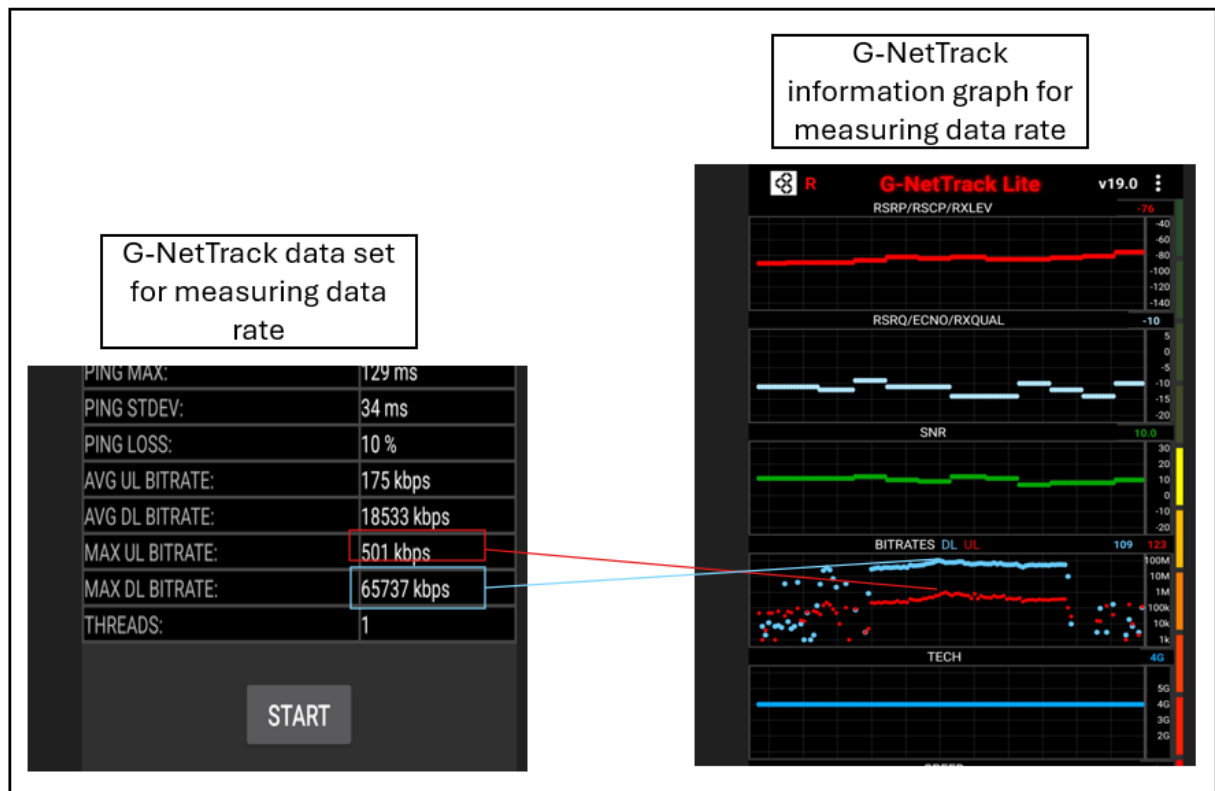


Figure 21: Screenshot of measured data rates on 4G setup.

These tests were repeated eight times to observe the thorough performance behaviour of the setup. Table 15 shows the data rate results measured on the 4G tactile internet setup.

Table 15: The data rate results of the 4G setup.

Attempts	G-NetTrack Results (Mbps)		Paessler PRTG Results (Mbps)	
	Uplink (UL)	Downlink (DL)	Uplink (DL)	Downlink (DL)
1 <sup>st</sup>	0.32	65,72	0.50	60.82
2 <sup>nd</sup>	0.81	92,81	0.38	77.38
3 <sup>rd</sup>	0.23	34.50	0.29	50.11
4 <sup>th</sup>	0.19	27,06	0.32	71.08
5 <sup>th</sup>	1.07	77,98	1.47	18.42
6 <sup>th</sup>	0.39	96.11	1.22	39.96
<b>Average</b>	<b>0.502</b>	<b>65.70</b>	<b>0.70</b>	<b>54.63</b>

From Table 15, the quantifiable difference is observed between the uplink and downlink data rates, however, the performance of the measured tactile internet application still falls within the margins specified by the theoretical expectations in Section 2.5.8. The results reflected the average of 0.502 Mbps on the uplink and 65.7 Mbps on the downlink with the G-NetTrack application, while the PRTG network monitoring application reflected 0.70 Mbps on the uplink and 54.63 Mbps on the downlink.

For results analysis and comparison purposes, the G-NetTrack and Paessler PRTG application results were averaged to get a single set of results. Moreover, only the downlink average results were used as they reflected the highest possible data rate performance in every network transmission. Hence, Table 15 was reduced to more manageable data, as demonstrated in Table 16.

*Table 16: Average 4G data rate results.*

<b>Trials</b>	<b>Average Data rate (only downlink) in Mbps</b>
1 <sup>st</sup>	63.27 Mbps
2 <sup>nd</sup>	85.10 Mbps
3 <sup>rd</sup>	42.30 Mbps
4 <sup>th</sup>	49.07 Mbps
5 <sup>th</sup>	48.20 Mbps
6 <sup>th</sup>	68.04 Mbps
<b>Average</b>	<b>59.33 Mbps</b>

From Table 16, the average data rate performance of the tactile internet implemented using 4G network ranged from 42.30 Mbps to 85.10 Mbps. Overall, the average downlink data rate performance in 4G tactile internet application was 59.33 Mbps.

#### **4.3.2. Data Rates Results of 5G Setup**

Like 4G network tactile internet application, the data rate performance of the tactile internet implemented using wireless 5G network technology was measured by streaming data between the remote PC and plant PLC drive in the setup, as demonstrated in Figure 14. As explained in Section 3.3, the G-NetTrack software and Paessler PRTG network monitoring application were used to record data rates of transmission.

These tests were done six times to gain a more detailed understanding of the data rate performance of the setup. Also, testing times were varied to test data rate performance under different network congestion levels. Table 17 shows the data rate performance of 5G network tactile internet applications.

*Table 17: 5G data rate results.*

Attempts	G-NetTrack Results (Mbps)		Paessler PRTG Results (Mbps)	
	Uplink (UL)	Downlink (DL)	Uplink (DL)	Downlink (DL)
1 <sup>st</sup>	41.03	100.89	32.68	130.50
2 <sup>nd</sup>	0.89	219.78	11.32	310.70
3 <sup>rd</sup>	24.37	506.01	0.95	420.00
4 <sup>th</sup>	41.90	88.09	43.08	180.08
5 <sup>th</sup>	18.00	406.87	18.47	97.01
6 <sup>th</sup>	12.38	214.90	24.22	219.41
<b>Average</b>	<b>23,10</b>	<b>256.09</b>	<b>21.79</b>	<b>266.28</b>

From Table 17, the G-NetTrack results range between 0.89 Mbps and 41.09 Mbps on the uplink and between 88.09 Mbps and 506.01 Mbps on downlink, while the Paessler PRTG results range between 0.95 Mbps and 43.08 Mbps on the uplink and between 97.01 Mbps and 420.00 Mbps on downlink. These values align with theoretically expected results in which downlink ranges were between 0 Mbps and 1 GBps (1000 Mbps), as explained in Section 2.5.8.

For reduced manageable data, the G-NetTrack and Paessler PRTG results were averaged to one set of results. Moreover, only the downlink results were considered for analysis and comparison purposes as reflected in Table 18.

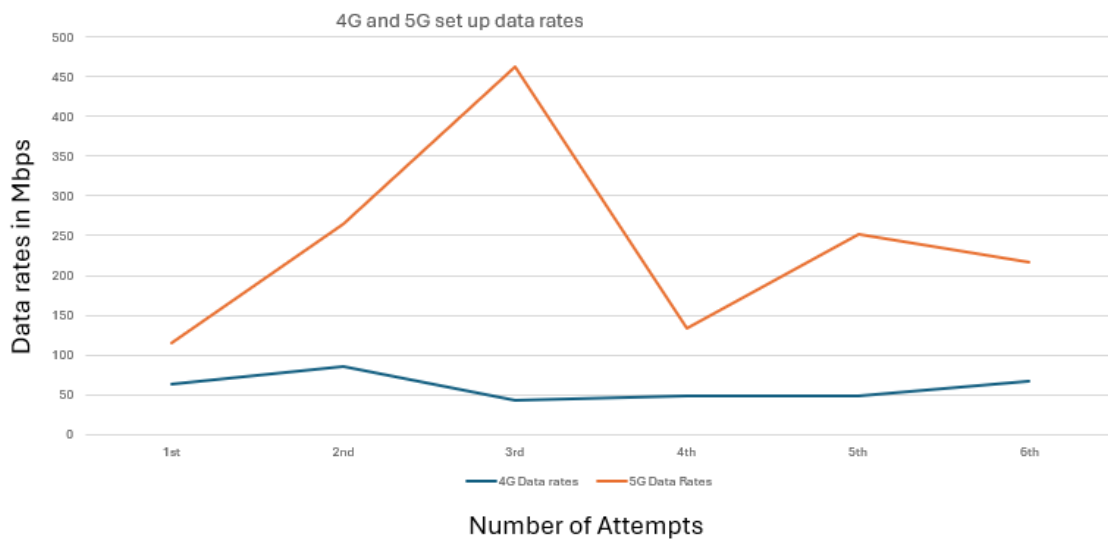
*Table 18: Average data rate results for 5G setup.*

<b>Trials</b>	<b>Average Data rate (only downlink) in Mbps</b>
1 <sup>st</sup>	115.70 Mbps
2 <sup>nd</sup>	265.24 Mbps
3 <sup>rd</sup>	463.01 Mbps
4 <sup>th</sup>	134.09 Mbps
5 <sup>th</sup>	252.0 Mbps
6 <sup>th</sup>	217.16 Mbps
<b>Average</b>	<b>241.20 Mbps</b>

From Table 18, the average downlink data rate ranged from 115.70 Mbps to 463.01 Mbps, and these were evaluated into the total data rate average of 241.20 Mbps for the tactile internet implemented using 5G technology in the PLC-driven smart water bottling plant.

#### **4.3.3. 4G and 5G Setup Data Rates Results Comparison**

Based on the average downlink data rate performance of both 4G and 5G network tactile internet setups showcased in Table 16 and Table 18, respectively, the average data rate of the 4G setup was found to be 59.33 Mbps on the downlink, while in the 5G setup, the average data rate was 241.20 Mbps on the downlink. Figure 22 shows the graphical presentation of average download data rates in both 4G and 5G tactile internet setup.



*Figure 22: Comparison between 4G and 5G data rates.*

From Figure 22, a calculable increase in data rate performance is identified in the 5G setup as compared to the 4G setup. To quantify this improvement, the average data rates were used in an improvement relation illustrated in Equation 1. Upon computation, the average data rates showed that the 5G setup was able to yield a 75.40% improvement. In conclusion, the implementation of 5G technology in a tactile internet application was able to improve the data rate performance by 75.40%, based on measured results.

#### **4.4. Device Density**

As indicated in Section 2.4.8 and Section 2.5.10, the device density of 4G and 5G technologies in a tactile internet application are extremely high and impractical to measure in a laboratory setting. Moreover, it was concluded that, for comparison purposes, the theoretical device densities of  $0.1 \times 10^6$  devices/km<sup>2</sup> would be used for 4G setup and the theoretical device density of  $1 \times 10^6$  devices/km<sup>2</sup> for 5G setup would be used [93], [132].

Hence, the incorporation of 5G technology into a tactile internet application in a smart water bottling plant was able to improve device density capacity from 100000 devices/km<sup>2</sup> to 1 million devices/km<sup>2</sup>. When using these values in an improvement relation in Equation 1, the improvement result obtained showed a 90% improvement. In conclusion, the implementation of a tactile internet application using 5G network technology was able to improve device density performance by 90%.

#### 4.5. Network Reliability

For network reliability, the 4G network tactile internet application on the smart water bottling plant illustrated in Figure 13 was left connected to record any network disconnection for 48 hours. There were no disconnections or network failures during that time. Scientifically, the network reliability percentage is calculated as the difference of up-time and the downtime divided by total time and multiplied by 100% as shown in Equation 2.

$$Reliability(\%) = \frac{Up\ time - downtime}{total\ time} \times 100 = \left( \frac{48-0}{48} \right) \times 100\% = 100\% \quad \text{Equation 2}$$

In the case of the considered 4G network tactile internet application, up-time was 48 hours, down time was 0 hours, and the total time was 48 hours. Hence, the reliability result for the tested period is 100% reliability. This 100% reliability was theoretically expected based on the reviewed possible results in Section 2.5.8.

On 5G tactile internet setup, the up time was also 48 hours, down time was 0 hours, and the total time was 48 hours, and these yielded 100% reliability. In conclusion, both 4G and 5G tactile internet setups resulted in 100% reliability for the 48 hours recorded.

#### 4.6. Network Accessibility

Based on the wired nature of the setup, and the reviewed literature on accessibility of wired networks, the conclusion was drawn that the considered wired 4G network tactile internet application on the smart water bottling plant was less accessible [122], [123]. As a result, the tactile internet application implemented using wireless 5G network technology in a PLC-driven smart water bottling plant was considered to be more accessible. This is because, due to the wireless nature of the setup, the remote plant can be accessed at diverse points under 5G or any network coverage [122], [123].

#### 4.7. Chapter Conclusions

In the conclusions of the Methodology chapter in Section 3.4, the underlying result-oriented question was raised. This question was: Based on the measured results, was 5G network technology able to improve the network factors which were reviewed to have a significant impact on production time over 4G network technology? Was the theorised ability of 5G technology in improving network technology adaptation into the smart manufacturing ecosystem proven?

To answer these questions, the measured results in 4G and 5G network tactile internet applications were compared. Upon these comparisons, scientific graphical presentations were applied to the data for better analysis. As a result, a computable improvement brought by 5G network technology to tactile internet application was identified and quantified as shown in Table 19.

*Table 19: 4G and 5G setup results comparison.*

Network Factors	4G Setup	5G Setup
<b>Latency</b>	102.53 ms	1.01 ms (99.01% improvement)
<b>Data rate</b>	59.33 Mbps	241.20 Mbps (75.40% improvement)
<b>Device density</b>	0.1x10 <sup>6</sup> devices/km <sup>2</sup>	1x10 <sup>6</sup> devices/km <sup>2</sup> (90% improvement)
<b>Reliability</b>	100%	100%
<b>Network accessibility</b>	Less Accessible	Easily Accessible

This chapter was aimed at showcasing the results measured from the experimental setup of tactile internet implemented using 4G and 5G network technologies in Section 3.3. The chapter outlined the measured results from 4G and 5G network tactile internet applications in both tabulated and graphical presentation with the averages and upper margins specified for each performance metric.

With the aim of uncovering the impact brought on by the adaptation of 5G technology into the tactile internet application over 4G network, the chapter then engaged in a comparison paradigm in which the graphical presentations and averages of 4G and 5G setups were compared. In this comparison, improvements of 99.01% in latency, 75.40% in data rate, 90% in device density, 100% reliability attained, and more accessible setup were realised upon adaptation of 5G in tactile internet applications over 4G technology.

## **5. Discussion**

### **5.1. Chapter Introduction**

This chapter intends to conduct a systemic analysis of the experimentally measured results of the network factors versus the research gap that necessitated this study. The analysis determines the ability/inability of the 5G technology to improve production time over its predecessors. For this research, 4G network technology was used for comparison.

Prior to measuring the network factors that affect production time, an experimental setup was designed and implemented to unravel the reviewed incongruity of a PLC-driven plant to 5G technology. Hence, this chapter will commence by reviewing the implemented setup of incorporating 5G technology into PLC-driven plants and the scalability of the experimental set; then, it will outline the reviewed method of measuring network factors with the reasons vindicating the chosen methods and, finally, it will discuss the obtained results in depth.

### **5.2. Discussion on Experimental Setup**

Tactile internet, which is envisioned to improve operability of the smart manufacturing environment, can only be effective if network technology facilitating the tactile internet application is equipped with ultra-low latency, broad bandwidth, high reliability, high accessibility, and increased device density [87], [154].

Based on research, the network technology which possesses all these features at the time of writing this thesis is 5G technology. However, the incorporation of 5G technology in a PLC-driven plant's tactile internet application was identified as the major research gap. Upon reviewing publications, the challenge of adapting 5G technology into PLC-driven smart manufacturing plants to implement tactile internet was ascertained [1], [18], [112].

This deviation was caused mainly by the lack of 5G capabilities in most industrial level PLCs [12], [15]. Most of the publications with relatively close research interest with this study were reviewed, and the 5G technology tactile internet implementation research gaps were identified [1], [15], [22]. With this research, an improvement was made within most of the identified gaps [15].

In the research of Segovia and Garcia-Alfaro, Siedler *et al.*, Mourtizis *et al.*, Vaibhav *et al.*, and Rico *et al.*, the 5G network's potential to facilitate and improve the cloud-based operations and augmented realities in a smart manufacturing environment were demonstrated [1], [18], [22], [71], [112]. However, the methodological implementation details of enhancing 5G capabilities were not elaborated on in these studies.

An improvement on the above-mentioned gaps/limitations was made in this studies as the implementation challenges and possible solutions were reviewed in Section 2.5.1, following the dissection of the implemented methodology in Section 3.3.

Alternatively, some authors clearly introduced the methodology undertaken to implement 5G technology in Industry 4.0 applications [39], [109], [157]. A deviation was identified in these publications as they substitute PLCs with other automation technologies which does not align with the research aim as it was intended to improve 5G features on existing PLC-driven plants.

These gaps were identified in the publications by Siedler *et al.* and Ansari *et al.* in which the automation of smart operations was achieved through the implementation of FPGAs, while 5G technology adaptation protocols were achieved through implementation of network modules or completely migrating to 5G capable IIoT devices [1], [18], [22], [71], [112].

These solutions inherit the disadvantages of limited data rates and increased costs to the system [1], [18], [22], [71], [112]. To address the research gaps in these articles, this study was able to implement a scalable one-unit-solution which does not replace PLCs.

Another closely related study by Xu *et al.* in which 5G capabilities were enhanced by incorporating a protocol adaptation scheme on an existing PLC-driven plant was reviewed to have limitations in data rate [143]. To remediate the identified limitations in all these publications, this study was able to improve 5G capabilities on an existing PLC-driven plant by developing a 5G-capable communication protocol using the Scalance MUM856-1 router which is equipped with increased data rate and easily scalable to most plants that are automated using industrial level PLCs [39], [147].

Table 20 review some of the closely related articles, the research gaps identified those articles, and improvements that were brought by this study on identified gaps.

Table 20: Closely related citations, gaps, and improvements.

<b>Authors (Year)</b>	<b>Research elaboration</b>	<b>Gap/limitation identified</b>	<b>Solution (addressed in this research)</b>
Segovia and Garcia-Alfaro (2022) [1]	Development of digital twins with special focus on mapping physical and virtual objects.	Limited details on how the physical/virtual mapping will be implemented using ultra-low latency network to minimise real-time constraints.	This study was able to review 5G technology's ability to minimise real-time constraints in digital twins' data synchronisation.
Siedler <i>et al.</i> (2021) [18]	Discussed the experimental set of implementing 5G in an automation-over-internet application.	The study phases out traditional PLCs with soft PLCs.	This study was able to develop an internet reliant automated system using 5G without replacing PLCs.
Mourtizis <i>et al.</i> (2021) [22]	Reviewed and modelled the significance of low latency in tactile internet applications.	It did not elaborate how ultra-low 5G technology will integrate in existing IIoT ecosystem.	5G adaptation to tactile internet application was developed in this study.
Vaibhav <i>et al.</i> (2021) [71]	Dissects the design architecture, applications, and benefits of tactile internet.	Did not detail the communication development implementation in tactile internet.	This study established and tested the communication solution for tactile internet applications.
Rico <i>et al.</i> (2023) [69]	Establishes the MTIP standard for tactile internet applications using 5G technology.	Did not scrutinise 5G technology application challenges.	Further scrutiny into 5G implementation challenges was done.
Ansari <i>et al.</i> (2022) [10]	Provides an enhanced investigation on 5G capability to improve industrial	The research suggested the addition of 5G capable UE which will inherit	This study was able to develop 5G TI application with increased data rate

	digitalisation and automation.	their limitations (low IP rating and limited data rate) to the system.	using high industrial level device (high IP-rating).
Sa <i>et al.</i> (2019) [45]	The White Paper was intended to locate the solution of phasing out industrial level IIoTs with 5G capable devices.	The author did not consider the cost implementation and scarcity of 5G capable devices.	This research was able to innovate existing PLC-automated plants instead of phasing out existing traditional PLC devices, thereby limiting the cost factor.
Xu <i>et al.</i> (2023) [143]	Developed the protocol adaptation scheme for synchronising automated setups using 5G technology.	This setup has a limited data rate which will bottleneck the system.	This study was able to incorporate the router with increased data rate and successfully established a TI application.
Fowler <i>et al.</i> (2023) [39]	This research addressed the 5G wireless capabilities in automated-guide vehicles using the Scalance MUM856-1 router.	The study has the closest interests with this study; however, it did not consider PLC-driven plants.	This study was able to inherit the implementation of Scalance into PLC automated smart plants and showcased results.
Siemens AG (2022) [147] (2023) [148]	The publication introduced the Scalance MUM856-1 router to address 5G wireless deficiency in industrial applications.	Adaptation of the router to an automated-guided vehicle was demonstrated, however, implementation of such router to PLC automated smart plants was never introduced.	This thesis was able to successfully align the operation of the Scalance MUM856-1 router into already existing traditional PLC devices and developed a gateway to adapt 5G into TI applications.

Based on the publications listed in Table 20, the research was able to advance on existing functionalities of the Scalance MUM856-1 router by incorporating it into the pre-existing PLC-driven smart plant to improve 5G wireless features with the aim of implementing tactile internet to such a plant [147], [148]. On the implemented tactile internet application, G-NetTrack software and the PRTG network monitoring application were used to scientifically measure network performance factors which were reviewed to have impact on production time [95], [96].

### 5.3. Discussion on Experimental Setup

Publications were reviewed in which the hypothetical anticipations on the ability of 5G technology to improve network factors that affect production time in smart manufacturing were discussed [71], [109], [154], [156]. In these publications, several research gaps were identified which emanate from lack of experimentally measured results to support the hypothesis.

The research by Simsek *et al.* showcased the delivery of haptic signals in a tactile internet application to facilitate sharing skillset globally [154]. However, the research lacks experimentally measured results on the effects of network latency in such applications [154].

Tychola *et al.* further investigated the merits and architectural challenges of incorporating 5G technology and Beyond (5GB) to implement tactile internet application which facilitates the Metaverse ultimatum [155]. This research also did not showcase the experimentally measured results of the improvements brought by 5G in the Metaverse application [155].

Moreover, Joshi P. further emphasises the significance of 5G and B5G in establishing tactile internet applications which facilitate smart clinics with the aim of diversifying skillset share in the health sector [156]. However, the research also did not clearly quantify the improvement that 5G and B5G brought into the system [156]. Moreover, Fanibhare *et al.* investigated the effects of multiplexing bi-directional signals to attain enhanced physical/virtual mapping in a tactile internet application without showcasing 5G innovation trends [157].

To improve on the above-mentioned gaps and limitations in the reviewed publications, this research was able to successfully establish hypothetically expected results. In addition, the experimental setup for implementing tactile internet using 5G was experimented upon, and results on reviewed network factors were successfully measured.

*Table 21: Result citations, identified gaps, and improvements.*

<b>Author (Year)</b>	<b>Research Description</b>	<b>Identified gap/limitation</b>	<b>Improvement on this thesis</b>
Simsek <i>et al.</i> (2016) [154]	Skillset sharing as haptic signals in a tactile internet application.	No results on how 5G can improve on haptic signals transmission.	The thesis was able to showcase the improvement brought on by 5G over 4G technology.
Tychola <i>et al.</i> (2023) [109]	A review on adopting 5G and B5G into Metaverse tactile internet application.	Limited results on the quantification of 5G improvement curve.	The thesis was able to improve by clearly formulating quantitative comparison between 5G and 4G technologies.
Joshi P. (2024) [156]	Investigates the ability of 5G and B5G to facilitate TI applications in smart clinics.	Smart clinics were introduced in 4G technology times, hence, a milestone reflecting how 5G was able to improve smart clinics is missing.	This thesis was able to track the innovation journey on network KPIs between 4G and 5G technologies in automated plants, and this will reflect similar behaviour in smart clinics and automated-guided vehicles.
Fanibhare <i>et al.</i> (2024) [157]	Multiplexing signals to establish physical/virtual mapping in TI applications.	The 5G MIMO technologies was used, but the gap on quantitative innovation curve was identified.	The thesis was able to improve on that by clearly quantifying the 5G improvements on network KPIs over 4G technology.

From the experimental setup of implementing tactile internet using 4G and 5G technologies on the smart water bottling plant illustrated in Section 3.3, the scientific measurement techniques for gauging network performance factors which were reviewed in Section 2.4.2 to have significant impact on production were applied and results recorded.

Based on measured results, an improvement of 99.01% was realised on the latency performance of 5G technology over 4G network technology. This was expected as it resides close to theoretically expected results. However, slight deviations of latency performance above 1 ms were realised in the 5G setup. This behaviour might have been caused by the round-trip nature of the measuring techniques.

On data rate performance, the 4G setup was found to have the average data rate of 59.33 Mbps while 5G setup was found to have the average data rate of 241.20 Mbps, and this was computed as a 75.40% improvement. The data rate performance was analysed using the downlink data rates as they are the highest possible data rates in every bi-directional communication channel.

The device density performance for both 4G and 5G network tactile internet applications were considered to theoretical values as per network inventors [18], [117]. Hence, the device density of 4G network tactile internet applications was considered to be  $0.1 \times 10^6$  device/km<sup>2</sup> while the device density of the 5G tactile internet setup was considered to be  $1 \times 10^6$  devices/km<sup>2</sup>. This showed a 90% improvement on 5G technology over 4G network.

Network reliability of both 4G and 5G technology tactile internet applications were found to be 100% over the 48 hours period. This 100% reliability in 5G technology was theoretically expected as 5G inventors promised 99.99% reliability [83]. On the 4G network setup, the experimentally measured reliability was 100%, but 4G inventors promised 90% reliability [15], [109]. Finally, the wireless 5G network tactile internet application was considered to be more accessible than the wired 4G network tactile internet application because of its wireless nature [122], [123].

## 5.4. Chapter Conclusions

In this chapter, all publications which have close interests with the research aim were reviewed, the research gaps and limitations in such publications were re-studied, and re-located if identified gaps were answered, solved, or improved on. This was carried out by firstly reviewing the research and its gap/limitation, then showing the improvement that this research contributed to such gap/limitation.

The chapter then explained the conducted methodology as per the research aim, as well as elaborating on the research questions that were being answered by the methodology. This was also introduced by previewing all relevant citations which contributed to the methodological solution of implementing tactile internet using 5G network technology with the special focus on PLC-driven smart manufacturing plants without phasing out the driving PLC. This methodology was concluded by scientifically measuring all network KPIs on the setup.

Finally, the chapter focused on the experimentally measured results of all network KPIs reviewed in Section 2.4.2 to have a significant impact on production in a smart manufacturing environment. Upon comparison and analysis, 5G network technology was found to decrease transmission latency by 99.01%, improve transmission data rate by 75.40%, maximise device density by 90%, attain 100% reliability, and increase network accessibility over 4G network technology in a tactile internet application implemented on PLC-driven smart water bottling plant over 4G network technology.

## **6. Conclusions**

### **6.1. Chapter Introduction**

This chapter aims to reflect on the journey undertaken to intensively investigate all key research areas causative in the research title. The research commenced by introducing the study environment, then proceeded to conduct a comprehensive literature review on all contributing research areas. Furthermore, it elaborated on the implemented methodology to achieve the aims of the research. Envisaged and analysed results were then measured on the experimental setup, followed by a detailed discussion of the picture reflected by the results obtained.

### **6.2. Reflection on All Chapters**

In Chapter 1, an eye-opening introduction to the study environment was made with special focus on the key words in the project title, being smart manufacturing, tactile internet, 5G network, PLCs, and production time. This chapter went on to scientifically structure the research roadmap by highlighting some of the most significant citations which brought about this research.

Within the reviewed publications in Chapter 1, the research gap was identified, and the research aim was clearly structured. This led to the clear formulation of the research problem which engendered research objectives. It is in this chapter where the research questions were introduced based on the identified research gaps/limitations and the case study was introduced based on the planned methodology.

In Chapter 2, a comprehensive literature review was conducted. The literature review conducted was superintended by key words in the research title. Moreover, a technical link was established between smart manufacturing, tactile internet, cloud computing, 5G technology, production time, and PLCs. It is within this technical circle where the deficiency was identified on 5G adaptation into PLC-driven smart manufacturing plants to implement tactile internet with the aim of reducing production.

To address this deficiency, numerous possible methods from different authors were reviewed, amongst which most possessed the least feasible solution of completely substituting PLC devices with other automation mechanisms. Among all the reviewed techniques, the incorporation of the Scalance MUM856-1 router to enhance 5G capabilities to already-existing industrial-level PLC devices was found, and based on research it was deemed to be the most plausible solution.

The chapter (Chapter 2) went on to review network factors that can have a significant impact on production time and how they influence the considered production time. This review was accompanied by a detailed investigation into how these network factors can be measured to quantify the improvement brought on by 5G technology tactile internet applications. This chapter was concluded by further dissecting close citations in which the research gaps were identified and outlining the identified gap(s).

Chapter 3 guided the implemented methodology of the experiment to achieve the research aim and objectives. The chapter began by thoroughly explaining the case study selected for the research, which was the smart water bottling plant. In this explanation, reasons inspiring the choice, operations of the case study, and the PLC drive automating the smart water bottling plant were introduced.

The chapter then proceeded to the first phase of the methodology (Phase 1) in which the tactile internet was implemented on the smart water bottling plant using 4G network technology. The aim of this phase was to provide a reference for comparison purposes on 5G setup. Then, Chapter 3 went on to detail the key experiment of the research, which was to implement tactile internet on the smart water bottling using 5G technology.

At this juncture, it is significant to point out that the Scalance MUM856-1 router, which was found to be the most plausible solution to enhance 5G capabilities on an existing PLC drive instead of replacing it, was used to implement 5G network tactile internet application on the smart water bottling plant. Moreover, the G-NetTrack and Paessler PRTG network monitoring applications used to measure reviewed network performance factors were found, based on research, to be the most effective measuring platforms for the intended setup.

In Chapter 4, the results of all network performance factors measured on the experimental setup of tactile internet applications of both 4G and 5G were scientifically presented in tables and graphs. A detailed comparison was made on results to prove or disprove the ability of 5G technology to improve production time, upon which it was proven by experimental results that 5G network technology was able to improve production time in a PLC-driven smart manufacturing environment over 4G network technology.

In Chapter 5, a detailed discussion on the picture evinced by the results portrayed in Chapter 4 was raised. In this discussion, the percentages of improvements were technically presented on performance of latency, bandwidth (data rate), device density, reliability, and accessibility. Moreover, a comprehensive overview of the latest reviewed citations in which the research gap was identified was conducted, and the improvements contributed by this research on each identified gap were stated.

### **6.3. Overall Conclusions**

Smart manufacturing, which is a dynamic manufacturing approach characterised by automation of a production/processing line, connectivity of IIoT nodes, digitisation of the plant through digital twins and augmented realities, and product customisation [4], [5], [7], is gradually replacing traditional manufacturing due to its advantages. These include increased data management, product uniformity, increased production volume, and effective resource management, to name few [3], [5], [7].

To facilitate remote operations which include data synchronisation, remote maintenance, predictive maintenance, remote operation, and data transparency amongst all authorised stakeholders, a visual presence termed tactile internet must be established to the plant using network connection [27], [70], [71].

For this tactile internet to be effective, the network connection used must be equipped with low latency, high bandwidth, increased device density, high reliability, and easy access [27], [69], [154]. Among all network technologies that were commercially available at the time of writing this thesis, research revealed that 5G technology is equipped with the lowest latency, highest bandwidth, maximum device density, high reliability, and is easily accessible over its predecessors, being 3G, 4G, and 4G-LTE technologies [15], [25], [69], [154].

Automation, which is one of the key features which distinguish smart manufacturing from traditional manufacturing, is achieved through the usage of Programmable Logic Controllers in most smart manufacturing plants, based on researched statistics [9], [11], [15]. However, research also revealed that most industrial level PLC devices automating the smart manufacturing and processing plants nowadays lack 5G capabilities [9], [15], [39]. To address this limitation, this research undertook the journey to improve 5G capabilities on already existing PLC-driven plants to implement tactile internet.

The hypothesis was that, if the project aim, to implement tactile internet using wireless 5G technology in a PLC-driven smart manufacturing plant, could be achieved successfully, production time would be minimised [15]. This would be due to improved data synchronisation on the tactile internet routed as the network technology has low latency, increased bandwidth, ability to multi-connect an increased number of IIoTs, being more reliable, and being easily accessible [15], [16].

To fulfil this aim, the pre-existing smart water bottling plant setup automated by an industrial level PLC was selected to be the case study, and a detailed review of possible ways to enhance 5G wireless features on the case study were researched. In this journey, the incorporation of the Scalance MUM856-1 router was found to be the most plausible solution as it does not phase out the existing PLC drive [147], [148].

The Scalance MUMU856-1 router solution was implemented in a pre-existing smart water bottling plant to experiment with tactile internet applications using wireless 5G technology [15], and the intended tactile internet application was successfully implemented using wireless 5G technology on the smart water bottling plant.

To validate the improvements by comparison, the reference was induced by implementing the tactile internet using wired 4G network technology on the same case study and the results of network key performance factors which were reviewed to have significant impact on production time were measured. To prove/disprove the ability of 5G technology to improve production time, network factors were also measured on the tactile internet application implemented using wireless 5G network technology.

Upon comparison of wireless 5G technology results with wired 4G tactile internet results, it was concluded that 5G technology can reduce latency by 99.01%, increase data rate performance by 75.40%, improve device density by 90%, maintain 100% reliability, and increase accessibility in a tactile internet implemented on a PLC-driven smart water bottling plant over wire 4G network technology.

The research questions to be answered were:

1. Which effective and plausible amendments can be implemented on already existing PLC-driven plants to be able to adapt to 5G network technology?
2. Can the system modification ultimately be scalable to all PLC-driven systems?
3. Will the developed experiment improve all considered network performance factors which affect production time?

The answers to these research questions are:

1. The incorporation of the Scalance MUM856-1 router to an already existing PLC-driven smart factory was concluded to be the most effective solution to enhancing 5G wireless capabilities on the plant without phasing out the already existing PLC drive with the aim of implementing tactile internet.
2. Yes, the router was connected to the PLC through standard LAN/Ethernet communication. Hence, this solution is scalable to all PLC devices which are equipped with standard LAN/Ethernet interface.
3. Yes, based on measured results, the implemented tactile internet using 5G technology was able to improve network performance factors which affect production time. Hence, implementing tactile internet using 5G technology was able to minimise production time in a PLC-driven smart water bottling plant.

In conclusion, this research successfully explored the intended study environment, and tactile internet was successfully implemented on the PLC-driven smart water bottling plant using wireless 5G technology. Network factors were scientifically measured and compared. The comparison revealed that the wireless 5G network can improve production time over its predecessors in a PLC-driven smart manufacturing environment.

#### 6.4. Future Work

This research was one of the innovative pillars branching from the series of Industry 4.0 research that stemmed from the smart water bottling plant located in the Central University of Technology (CUT), Free State, laboratory. As new technologies emerge and innovative ideas are discovered around the globe, the smart water bottling plant setup should also transform to keep with the evolution in real time.

The most immediate furtherance considered and foreseen from this research is to explore the innovative idea of wireless tactile internet in other most-used PLC devices in the smart manufacturing industries within and outside the Siemens family. The intention is to bring the recent network generations compatibility awareness to PLC production companies and possibly to design and produce PLC devices which also support 5G and B6G routers into the industry as automation and networking are becoming inseparable in the envisioned future of Industry 4.0.

Another envisioned future work considered as the media is briefing about the launching of 6G technology in near future will be to investigate and proactively align the adaptation of widely used PLC devices in smart manufacturing plants to communication protocols proposed for 6G technology and Beyond (B6G). The cyber-security and energy efficiency performance and improvement of tactile internet applications can also be explored as part of the future work.

#### 6.5. Research Outputs

From this research, four articles were submitted to international conferences – two were already published, and the remaining two have already been accepted and are awaiting publishing.

- Kuriakose, R.B., Mokotjo, H.J. (2024). Implementing Tactile Internet Using 5G Network for Cloud Manufacturing in a PLC-Driven Water Bottling Plant. In: Iglesias, A., Shin, J., Patel, B., Joshi, A. (eds) Proceedings of World Conference on Information Systems for Business Management. ISBM 2023. Lecture Notes in Networks and Systems, vol 833. Springer, Singapore. [https://doi.org/10.1007/978-981-99-8346-9\\_29](https://doi.org/10.1007/978-981-99-8346-9_29)

- Humane J. Mokotjo and Rangith B. Kuriakose, “Adaptation of 5G Technology in Programmable Logic Controller Automated Smart Manufacturing Plants to improve Network Factors that affect Production Time” 2025. (ISBM 3<sup>rd</sup> World Conference 2024, Bangkok, Thailand). The paper has been accepted and presented.
- Humane J. Mokotjo and Rangith B. Kuriakose, “Designing and Testing an Experimental Setup for Incorporating 5G wireless network in a PLC Automated Smart Manufacturing plant” 2025, (Intelligent Systems Conference (IntelliSys) 2025) Accepted and awaiting presentation on the 28-29 August 2025.
- Humane J. Mokotjo and Rangith B. Kuriakose, “Experimental Setup and Results Analysis of Tactile Internet Implemented using 5G Technology” (ICTIS Conference 2025, Bangkok, Thailand) Accepted and awaiting presentation on the 4<sup>th</sup> to 6<sup>th</sup> April 2025.

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