Analysis of 5G Cellular Network and 802.11 for Industrial Automation

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Abstract

Wireless communication nowadays is playing a vital role in real-life data transmission. This communication can be machine-to-machine or human to machine communication. In each of these categories, reliability and low latency data transmission are critical factors of success transmission in case the number of devices in a certain area increases. In this thesis, I mainly investigate on smart manufacturing point of view. The Main aim is to measure the best suitable wireless technology that can satisfy the requirements for smart manufacturing. The most recent wireless communication known as 5G has the potential to support both accuracy and low latency communication.

In this thesis, three main parts have been introduced. The first part introduces a scenario which can illustrate main use cases of wireless technologies in industrial manufacturing. The second is to establish a method for statistical analyze in the latest generation of cellular network enabling comparison with IEEE 802.11AC latest version. Without a tunneling technique introduced in the method chapter industrial protocol such as Profinet cannot be transmitted over a wireless medium.

Packet structures and several features in each technology are being considered which in fact directly influence latency and reliability. Each wireless technology will be reviewed theoretically and practically. The result of this comparison will be given. 5G introduces special features such as diversity in time, space and frequency. 5G also introduces a flexible packet structure that directly enhances the ultra reliable and low latency data transmission.

Popular science

Nowadays modern technology is a considerable part of human life. From day to day usage for communication between people to massive usage in the industry. Products that are wirelessly communicative or remotely controllable are being extremely popular. Due to the fact that using wireless products is extra convenient compare to the wired facilities, in most cases provide valuable opportunities in human life with less complexity. However, designing wireless products can be more complex and challenging.

These challenges can be a number of devices that communicate with each other in a certain area. Wireless devices transmit and receive messages using high-frequency signals. By increasing these signals in a certain area they can interfere with each which has negative consequences such as the lower speed of transmission and no reliable communication.

In this thesis, my intention is to investigate new wireless technologies that have the capability to support an increasing number of devices and the quality of data transmission. This investigation contains testing in a real-time scenario to see which one of those technologies has the potential. This investigation will face new challenges such as accessing technologies and make them work to do our test In this article all the necessary methods have been explained.

As a result, I will describe each technology and statistical results will be illustrated. Meanwhile, the finest wireless technology called 5G will be explained. This wireless technology has a structure that is flexible and the range of frequency that it uses makes it possible to be used in various service categories.

Contents

1. Introduction

1.1 Foundation

Technology advancement in wireless communications is seen as one of the enablers for the industrial Internet of Things (IoT) leading the 4th industrial revolution. A large number of devices need to be interconnected in order to collect and exchange large amounts of data[1].

The so-called "smart factories" will become a major breakthrough in the way future businesses operate. The vision is to fully automate the whole procedure from material gathering to the consumer's end product. Currently, there are many competing technologies such as 5G Cellular Networks, LTE and 802.11. These technologies have the potential to become the future of wireless industrial networks, while new standards and protocols are being developed constantly as we speak. One of those, the 5G NR cellular technology, is very promising for providing everything needed for full-scale industrial automation.

What remains to be seen is whether one of these technologies will win over the other or if there will be a number of technologies coexisting in parallel, fulfilling different needs. In this thesis, my purpose is to investigate the wireless technology candidates such as 802.11, LTE and finally 5G to see in which perspective they can satisfy the smart manufacturing needs. Including ultra reliable and low latency is known as a critical characteristic of massive type of communication in smart manufacturing.

By investigating on a real-time measurement focusing on downlink transmission, I highlight the main features of different wireless technologies to see in which perspective they have the potential to satisfy the 4th generation of smart manufacturing[1].

1.2 General Knowledge

Mission-critical communication is seen as a use case of new machine type communication which will enable real-time communication in smart factory[2]. The critical aspect of smart manufacturing, massive data transmission, is latency and reliability. End-to-End delay refers to the time taken for a packet to be transmitted across a network from source to destination. End-to-End is a common term in IP network monitoring, and differs from round-trip time (RTT). This is used for equipment measurements and testing purposes, in which one can see features and the potential of the quick reliable delivery of the packets.

Low latency wireless connections with the aid of spectral efficiency are beneficial to overcome the transmission power. This feature allows industrial hardware [2] to be connected to IoT software with high availability which is known as a mission-critical in smart manufacturing. Regarding our motivation about this topic, mission critical is known as one of the numerous applications of Industrial IoT and 5G cellular networks, is inspired by HMS and their vision about connecting different industrial hardware wirelessly.

This is ideal for replacing expensive and maintenance-heavy cables without the need for special configuration. Industrial wireless connections can be extremely useful in cases of mobility, remote, hard-to-reach or hazardous locations. The goal of this thesis work is to analyze different wireless technologies in terms of suitability for industrial automation to see if they satisfy the smart manufacturing requirements. Specifically, it must be evaluated how a 5G cellular network will behave under the requirements of low latency and ultra-reliable wireless connections without any critical or synchronization problems.

1.3 Contribution

This thesis aimed to compare the capability of wireless technologies and standards for 4th industrial revolution. Two main technologies have been compared; 802.11 and LTE are the potential candidates for critical capability measurements. Deep analysis and description of both technologies are explained. This will provide a background and real-time evidence to make a conclusion about their capabilities.

A real time scenario has been imposed to illustrate latency of each technology. And makes it possible for deep analyzes of latency. This research has introduced a basic method of tunneling in cellular networks using Open vSwitch. In this technique, the data in the Ethernet protocol based network such as Profinet can be transmitted over the IP-based protocol wireless network. Without this technique data transmission wont be possible. HMS has provided us with access points accompanying with Ericsson who gave us an access to the LTE test bed.

The latency of these data transmissions will be calculated and analyzed in my research. These can be considered as main features of mission critical in 4th generation of automation in the factories. These deep analyzes give me the opportunity to create a comparison table between different technologies. The basic contributions of this research are Open vSwitch and OpenFlow for flexibility of data and quality of service management, and Python script which can analyze the statistical latency evaluation of different wireless networks.

1.4 Limitation

Explaining the limitation part of the thesis for the technologies and equipment. I had a plan to test 802.11AD and 5G test-bed in which I did not have the chance to do the measurement, instead, I explain their packet structure and perspective for a similar scenario. 802.11AD routers do not have the ability to be used as a bridge. I had limited access to LTE testbed. In the next section, the background and basic structure of technologies are being reviewed.

2. Background

2.1 Industrial Networks

In this section, the background of thesis work will be explained to see what are the potentials motivating us to use wireless technologies in smart manufacturing.

Primarily the industrial networks are used for the process of controlling and monitoring. Industrial Ethernet is different than the one we use at home or at businesses. In case of letting a user wait while a task is being performed, we should consider that a factory floor data communications needs are real-time. Both industrial Ethernet and traditional fieldbuses are growing[3], but industrial Ethernet has overtaken traditional fieldbuses in terms of new installed nodes in factory automation.

In the last decades, there has been a push for supporting Ethernet-based communications. But to meet the demands of industrial applications, it has been necessary to implement real-time functionality over Ethernet[4]. Several Industrial Ethernet protocols have been introduced and widely adopted by automation equipment manufactures. Industrial Ethernet protocols are not the fastest-growing deployed network type in new industrial installations.

Beyond the traditional industrial protocol network, there are a number of new technologies that are entering the factory floor. Wireless solutions such as WiFi and Cellular Networks are enabling manufacturing facilities[1]to eliminate cables and create more reconfigurable operations.

Man–Machine interaction will also be improved through new communication technologies for functional safety [5], allowing operators and machines to work together side by side. Service teams will continue to leverage remote control to better predict system productivity. In this case, low latency and reliable data transmission is our motivation to see the potential capability of wireless technologies for the mentioned purpose. In the following section, I explain standards that improve the functionality of Ethernet.

2.1.1 PROFINET IO

Profinet is an open standard, which is a leading standard in automation. Profinet can use TCP/IP and real time application simultaneously, which provides more flexibility and efficiency for automation scenarios [6]. It uses Ethernet as a medium to access the devices. Currently Profinet is being used the most in industry after Ethernet/IP. The media access protocols are implemented on top of Ethernet protocols. PROFINET IO is an Ethernet-based automation standard in PROFIBUS International. Profinet defines a communication, automation and engineering model. With PROFINET IO proposed a technique allows all stations to access the network at any time. Simultaneous sending and receiving are enabled through the full-duplex operation of Ethernet. Protocol levels which are defined in Profinet are[7]:

- TCP/IP for PROFINET CBA and the commissioning of a plant with reaction times in the range of 100ms.
- RT (Real-Time) protocol for PROFINET CBA and PROFINET IO applications up to 10ms cycle times.
- IRT (Isochronous Real-Time) for PROFINET IO applications in drive systems with cycle times less than 1ms.

Some of the advantages of using Profinet are:

- Unlimited access, powerful capabilities, greater flexibility
- Full TCP/IP, internet and web compatibility, with real-time determinism
- Ethernet cabling decreases installation maintenance and diagnostics.
- Wireless and functional safety easily added.

- Easily extended and expanded as enterprise need changes.

Profinet can be fully operational on a single network cable alongside other Industrial Ethernet including Ethernet/IP and Modbus/TCP. Modbus is a serial communication protocol which is commonly used in connecting industrial electronic [8] devices. Coexistence means that it is possible to use the same network infrastructure to support multiple Industrial Ethernet.

Isochronous Real-Time (IRT)in Ethernet, by definition, is an open network that allows anyone to transmit at any time, making it a probabilistic transmission medium. Unless there is abnormally high bandwidth utilization, Ethernet is built on the assumption that nodes will probably not transmit at the same time. Ethernet calls this concept “CSMA-CD” (Carrier Sense Multiple Access – Collision Detect). It means that on a common carrier, multiple nodes can access the medium. And transmit when they like and what they are responsible for detecting a collision and retransmitting their data if one occurs.

In the next chapter wireless communication technologies will be introduced and analyzed to see if they have the capability of real time data transmission on the factory floor.

2.2 Wireless Technologies

2.2.1 Cellular Networks

When the last connection in our network is wireless, it can be called cellular network[9]. The cellular network is distributed over separate cells, and in each cell there is at least one transmitter and receiver. As is being shown in [2], [10] currently available wireless networks have several milliseconds latency. This does not fulfill the ultra-reliable and low latency. And doesn't have the potential to be in the range of the latency and reliability that can satisfy the 4th generation of smart factory requirements. Here one of my candidates for the mission-critical suitability will be future cellular networks with having more flexibility with packet structure. In the following section first I will describe the LTE latest releases and then I come to the point that explains where 5G has the potential for automation 4th generation requirements.

In the release 14 Nb Iot was introduced, to be developed for further user experience such as positioning accuracy, increased peak data rates, coverage enhancements, low power device class by 3GPP[11]. During LTE Release 13 there was a high effort for Nb IoT which will continuously be used for low latency and low power consumption. These enhancements would be more aligned in release 14, that would satisfy the smart factory requirements. So I saw it as a candidate for evaluating the exact latency for the smart factory scenario.

Generally, in LTE for TDD operation, it may be of interest to study latency reductions by increasing the number of UL-DL switches[12]. For the small packets, the effect of latency becomes visible. In the uplink (UL), medium is based on scheduling requests (SR) that are sent by the access point to request resources if data need to be transmitted.

From the physical layer perspective, the scheduling interval is shorter. The transmission delay and the processing delay will be decreased, which in the result have the potential to diminish the user plane latency. For the current TTI duration the latency is decreased to 7.5ms[11] and I have gotten similar result in table 5.1.

Latency reduction techniques are currently being considered in 3GPP in the form of an extension of semi-persistent scheduling for faster Uplink access. Reduction of handover interruption time, as well as shorter transmission intervals and processing times. In release 14 two features of Nb IoT and LTE-M were investigated. Nb IoT targets relaxed latency and data rate at the same time. Nb IoT inherits the LTE design features in an expanded area, including numerologies, channel coding, and modulation schemes. These enhancements lead to introducing 5G. 5G has the potential because of the packet structure and flexibility in the transmission time slot.

The NGMN(Next Generation Mobile Networks) proposed that 5G systems shall be able to provide 10 ms End-to-End [13](E2E), latency in general referred to as HRLLC in 3GPP, 3rd Generation Partnership Project), and 1 ms latency (URLLC) for use cases with extremely low latency requirements. It is motivating to see the flexible packet structure and the latency that matches the most with the 4th generation to see how the future of 5G can elevate the quality of service in the wireless automation process.

In 5G, the high bands expected to be deployed for 5G include the 28GHz, as well as the 26GHz, 37GHz and 39GHz bands[14]. The 28GHz band may be used in certain countries by the end of 2018 or early 2019, while the other high bands are estimated to be available in late 2019. Low bands below 1GHz are of interest due to their favorable radio wave propagation characteristics, as they provide coverage in remote areas and into buildings. A new band in the 600MHz range is expected to be made available by the end of 2018 for 5G services.

The mentioned frequency bands are unlicensed. The disturbance from other frequencies will be limited. We can increase the sub-carrier spacing and decrease the transmission time. We can have better bandwidth and adjust the packet structure for different scenarios. I describe more details in the next section. In the traditional 3G and 4G spectrum is overutilized and might not be efficient for the future of the cellular network and the quality of service.

International Telecommunication Union Standardization Sector ITU-T P.10/G.100 defines the QoE as "level of user's acceptance towards application and services is referred to as QoE". There are two main parameters that analyze the quality of experience. First one is consistency, this feature explains the continuous transmission of data with the enhanced mobility. And then signaling, the method of signal transmission for Downlink and Uplink for example which is mentioned in table 3.1.

A unique technique in 5G that helps in achieving the QoS and guarantees its reliability to a large extent is Slicing of 5G network functions (RAN and Core). Network and service resources can be dedicated and negotiated (scaling in, scaling out) dynamically in our project. I have done a slicing by using a software that I will use in the measurement section. To scale the packets and control them for a different quality of service this software will be a key.

5G network backbone will be structured on the technologies like cloud considering software defined radio (SDR) structure and in the core network (Cloud CN) with using Software Defined Network (SDN). Control and management of QoS should be covered by (NFV)[15].

Software-defined networking (SDN) is introducing a smart and programmable network backbone and splitting of network control and data planes. It targets the simplified network management. HMS has provided us with a product called SLP which one can install Open vSwitch and OpenFlow on it for encapsulation purposes. OpenFlow^{TM} protocol is a foundational element for building SDN solutions[16]. OpenFlow helps to manage the data flow and quality of service of specific packets.

5G makes it easy to satisfy the smart factory requirements. Enhancement of the new wireless communication is based on the worldwide known standards, energy-savings and economies of scale system deployment. Features mentioned below are suggestive network features in 5G to be targeted at a functional level [17]:

- Data rate of 1000 times higher for a specific dimension of area.
- More users support about 100 times higher.
- End-to-End latency of less than 1ms on specific scenario
- End-to-End latency of 10ms

LTE networks, as well as 5G networks, offer several different kinds of parameter classes and parameters which are used as tools to implement traffic prioritization. Long Term Evolution is a standard for broadband communication for mobile devices[18], previous 4G generation technologies (LTE/LTE Advanced) provide flexible quality of service management based on the division of data transfer characteristics into 9 classes. Unfortunately these LTE technological advances in the field of QoS only take a part in end to end user in particular 5G-5G. If there is a quality management it cannot be extended to 5G subscriber, with the 2G/3G 4G and fixed stations. One of the main keys in managing network in 5G is SDN(Software-Defined Networking).

Software-Defined Networking (SDN) is an architecture that is flexible, manageable, low-cost and adaptable and has a dynamic nature of massively used applications. This architecture decouples the network control and forwarding functions. Moreover enables the network control to become directly programmable. The OpenFlow protocol is a foundational element for building SDN solutions[16]. According to the ONF, some features of SDN architecture are:

- Controlling Network is directly programmable due to it is decoupled from forwarding devices.
- Abstracting control from forwarding lets administrators dynamically adjust network-wide traffic flow to meet changing needs.
- Network brain is (logically) centralized in software-based SDN controllers that keep up with a general view of the network. This appears to applications and policy engines as a single, logical switch.
- SDN lets network managers configure and manage, secure, open standards-based and vendor-neutral protocols. When implemented through open standards, SDN simplifies network design and operation. Because instructions are provided by SDN controllers instead of multiple, vendor-specific devices and protocols.

In the three layers that SDN introduces, the SDN system architecture is defined by source ONF which has some key concepts in the three layers. The first one is forwarding devices or data plane. In a pure SDN switch, all of the control functions of a traditional switch (i.e., routing protocols that are used to build forwarding information bases) are run in the central controller. The functionality in the switch is restricted entirely to the data plane. The second controller plane is in charge of providing data up to the SDN applications. The third is business applications which are directly accessible by users. Possibilities include video conferencing, supply chain management and customer relationship management.

SDN controller sends LLDP packets or other specialized packets to see where they are and the information about their neighboring. Presence of SDN network can slice the network for different workloads, each of them can utilize the network depending on their traffic. It is important to know that SDN controller has different clusters which increase the scalability and availability[19]

SDN enables centralized control of base stations. An SDN controller will have a global view of the current power and sub-carrier allocation profile of base stations. In addition, an SDN controller running on a commodity server would have much more computing resources [19] than most base stations. As a result, an SDN controller can make a more efficient allocation of radio resources to handle new users.

2.2.2 IEEE 802.11

My next candidate is 802.11 standard. Which uses 5Ghz frequency and support multiple antenna and also multi-user transmission. Despite the fact that 802.11 works in unlicensed frequency its functionality for a specific scenario because of CSMA/CA would be considerable. Distribution coordination function (DCF) is a main practical component of MAC layer in 802.11. DCF applies CSMA/CA carrier sense multiple access which has binary backoff algorithm. A station must sense the status of the wireless channel before transmitting. The station senses the situation of the channel for DIFS DCF interface space [20]interval. If the channel found a busy station, it would postpone the transmission.

While having more number of users, when the users back off they can find the channel usable at the same time. Here is where the collision happens since users simultaneously sieze the channel. DCF has another alternative short RTS(Request to send) and CTS(Clear to send). If it finds the medium capable of transmitting then it starts transmitting the frame, DCF uses a considerable airtime.

The way one can calculate the SIFS is DIFS=SIFS+(2*SlotTime) [20]which in 802.11 is 34micro seconds. SIFS is the microseconds needed for a wireless interface to process the received packet to response with a respond frame. SIFS time is 16 microseconds for 802.11 AC which frequency of transmission has 5Ghz.

A transmitter waits until the backoff time is finished, then it transmits. If the destination has successfully received the packet it hangs on for SIFS period of time and then it will transmit the Ack packets. This can significantly increase the latency of the system in critical scenarios because we are using CSMA. In case of collision, the retransmission can occur.

The backoff counter is chosen uniformly between[0,Wi-1] where i is the back off stage and W is the current contention window size. The contention window starts with W. After an unsuccessful transmission, it will be doubled. ACK will be transmitted after a successful transmission. In this case if we increase the number of users we will increase the latency directly. But the positive aspect is, if we have a limited number of users it can be quite fast since they can transmit when needed.

The original IEEE 802.11 standard introduces two OSI layers for WLANs. The Physical (PHY) and the Medium Access Control (MAC). The PHY layer is responsible for modulating and transmitting data[21]. The MAC layer is responsible for controlling transmission among the clients in BS. In each wireless technology, the quality of service is the parameter which describes the behavior of each technology effecting the packets transmission.

Generally, the admission control and scheduling are the main features of MAC layer for providing the QoS[22]. The MAC layer provides the functionality of addressing, framing, reliability check, and access coordination to the wireless interface[23]. Some of the main MAC layer properties are described as following. In Priority Queueing, the stations which have the access to channel will segregate the data packets in the queue and transmit the one whích has the highest priority. Hereby we have used OpenFlow to prioritize our packets in IP based network. Usually the highest priority is the most critical like management commands[22]. A drawback for this technique is its implementation complexity.

In DCF (distributed fair scheduling)its not fair to create a priority for a specific traffic. Instead we allocate more weight to a traffic in order to get more bandwidth. DFS uses back off mechanism in which stations with high priority have shorter back off[22]. There are other techniques which have different functionality like Blackburst. In this technique every station get access to the medium for a certain amount of time[24]. Once it gets the channel, it jams the channel for the certain amount of time.

The basic idea of traffic shaping is to limit the amount of packets per station[22]. It has a significant affect on the performance of the system. The original MAC was designed for one to one communication but from the 802.11AC the AP could transmit to different clients simultaneously. Significant changes have been done to the MAC layer, one of the main modification is enhanced aggregation. In enhanced aggregation several MSDUs are concatenated to create an A-MSDU which have the same destination address. The A-MSDU is encapsulated within a MPDU. Many MPDUs are aggregated to form an A-MPDU.

Here I review two members of of 802.11 standard. To overcome the issue of one-to-one communication in IEEE 802.11N, a new standard IEEE 802.11AC was introduced. The main PHY layer enhancements are, the 80MHz bonding technique, 8*8 multiple antenna, and Downlink Multi-User

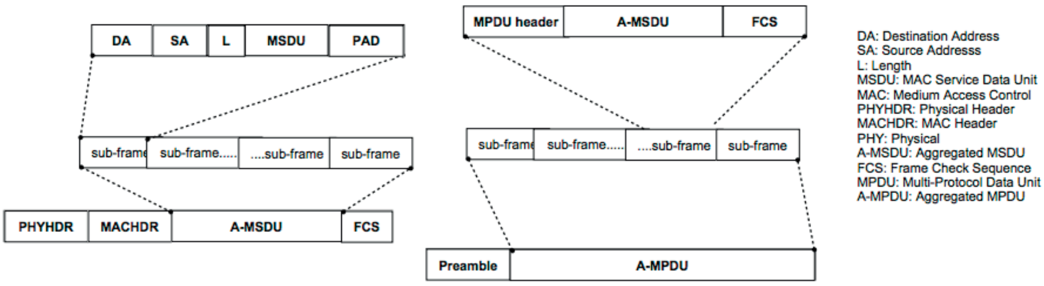

Figure 2.1: Aggregation

MIMO (DL-MUMIMO) which allows an AP to send a frames simultaneously to different receivers through multiple spatial streams[25]. Channel widths of 20Mhz, 40Mhz, 80Mhz, and 160 Mhz is supported in 802.11AC. In the previous 802.11 standards the maximum channel bandwidth was 40Mhz. Denser modulation method to 256QAM, which increases the throughput compares to the 64QAM.

In addition, TXOP sharing mechanism was introduced in 802.11 AC [26]. The results illustrates the higher flexibility of QoS showed in 802.11AC networks in comparison to legacy EDCA. In IEEE 802.11AC, enhanced distributed channel access (EDCA) is the common channel access mechanism. However, the functionlity is diminished due to the unpredictable delay caused by its inefficient backoff procedure[21].

802.11AC has been established to fulfill the demands of bandwidth-intensive and latency sensitive application[27]. These new technologies can offer higher bandwidth. Low latency can provide better user experience. Hence, there is a demand for improved transmission techniques that can support increasing network loads and reduced transmission delays. The improvements in this standard compared to IEEE802.11N is the 256 modulation scheme and Downlink MuMIMO. These features makes it possible to transmit to separate users. Further it works in 80MHz excepts 20MHz and 40MHz. Enhanced MAC layer has three features which make it to be able to transmit up to 1Gbps.

IEEE 802.11AD using frequency bands between 57 – 66 Ghz (center 60GHz) with bandwidth of 2.16 Ghz. Latency is approximately 7ms. It can support data rates of 7 Gbps to 8 Gbps (theoretically has potential to go beyond 40-50 Gbps depending on the modulation scheme). WiGig expands the Wi-Fi experience for virtual reality, multimedia streaming, gaming, wireless docking, and enterprise applications requiring high speed, data-intensive connections. WiGig allows Wi-Fi devices to access the uncongested 60 Ghz frequency band with wide channels to transmit data efficiently at multi-gigabit per second speeds. Users benefit from expanded capacity and focused transmission between devices to reduce interference, even in crowded environments. And also specifies an adaptive beam forming option to minimize interference and optimize the data rate and link reliability. This will be one of our candidates for lower latency scenarios in which the latency will be diminished to 7ms[28]. 57-66Ghz is the only unlicensed band which can provide the intensive band-width for replacing HDMI.

WiGig was not initially made to be used for industrial environments but rather as an HDMI replacement and for transferring large amount of data. But since as being shown in the [28], it does not sound reliable to be used for motion control in an industrial network scenario. The primary target is to achieve 1Gbps with supporting multi-user access feature. The second requirement aims to enable up to 7Gbp with the transmission support of 60GHz band that provides the opportunity for much wider band channels.[29]

57-66GHz is the only unlicensed band which can provide the intensive bandwidth for replacing HDMI and also for the industry sync-go[29]. One key advantage of IEEE 802.11AD over the other standardization is activities in the 60GHz arena which can build on the already existing strong market presence of Wi-Fi in the 2.4/5 GHz bands. Based on the user expectation, five traffic models are used for evaluation of IEEE 802.11AD proposals [30]. These five traffic models include uncompressed video, lightly compressed video, local file transfer, web browsing, hard disk file transfer. The only 802.11AD router that I have the the access to is R9000 Netgear provided by HMS connectivity in Halmstad-Sweden. In the following sections I will explain what were the difficulties to do the measurement with our real time scenario.

IEEE 802.11 WLAN technology is structured on the datagram delivery model of IP, simple, flexible and fault resilient network, they are ill-suited to QoS provisioning. The mentioned datagram model of IP is a best-effort service CSMA/CA which does not satisfy the critical applications. Layer-wise explanation and survey of techniques adopted for ensuring QoS in the IEEE 802.11 networks will be explained in the following section.

IEEE 802.11AC was proposed with significant changes in the PHY and MAC layer 8*8 MIMO with spatial streaming able to communicate with various receivers at the same time for one AP which this was difficulties for the

IEEE 802.11N. IEEE 802.11AD enhances the physical layer by MCS, and to be able to perform in very high throughput and to support directionality of antenna layer, there has been enhancements in the mac layer like bidirectional aggregated Ack, TDMA directional collaboration and beamforming. Beamfroming is a processing transmission technique for directional communication in which the combination of arrays to achieve spatial diversity.[31]

IEEE 802.11AD MAC supports both 802.11 basic MAC layer and the enhanced MAC to support both high throughput and beamforming and directional association TDMA. In the enhanced MAC there are many features which will be focused and the beacon frame which is designed for the directional association and beamforming for operating in 60 GHz. IEEE 802.11AD introduces new transmission periods with a target of enhancing the performance IEEE802.11AD beacon format which are listed as below.

In BT period the AP/PCP propagates the directional beacons while the stations are looking for the directional beacons and followed by the beamforming in the A/BFT period. The continuity of beamforming for launching the directional transmission between the base station and the PCP/AP and an initial beamforming training is done in A/BFT. During the beamforming the devices will adjust their antenna for the desired direction. Millimeter waves can be considered here since we can launch more antennas. Management of request response between base stations and APs is done in Announcement time.

In CBP/frame aggregation and aggregation of Ack period, the access during CBP is inspired by the 802.11E, each access is following CSMA/CA 802.11. And is designed for the high data rate transmission and also it guarantees the 60GHz and related delay. In the transmission period the frame aggregation and ACK aggregation is done in CBP period. VA-MSDUs consist of MAC header, MAC sub-header HCF (Check sequence) and MSDUs with sub-frame FCs.

We utilize the SPs for the specific users in SP/TDMA part. For different applications we need various QoS. For example when monitoring wirelessly we need better efficiency, due to sensitivity with the delay and jitter of applications we want. When we talk about CSMA/CA, its omni-directional and its not suitable for the scenarios where the stations are changing dynamically towards different directions. 802.11, to support CSMA/CA the MAC extend the layer by adding TDMA in the way that the STAs to know when are they suppose to wake up. Now we use TDMA for better QoS like video application while in the fast changing applications we need CSMA/CA since it provide lower latency than TDMA. In the next chapter I will compare the different wireless technologies mentioned above that will bring us closer to the conclusion and the way I can explain the measurement results.

3. 802.11 AC/AD and Cellular Network Comparison

In this section the theoretical feature of wireless technologies is being provided. And is followed by the enhancements done by 5G which can hopefully lead to our requirements for smart manufacturing explained in the section one. 5G is being standardized in the form of two radio technology components: A novel radio interface denoted as New Radio (NR), and long-term evolution (LTE). For enabling low-latency communications, new short slot structures enable faster Uplink (UL) and Downlink (DL) transmission for URLLC, called minislot for NR and short transmission time interval (TTI) for the LTE radio interfaces[12]. In factory the opportunity for small packet transmission is needed. Although mechanisms to increase the reliability of URLLC services, such as robust coding and modulation, and various diversity schemes, are being promoted in accordance with the LTE and NR designs.

There exist number of PHY techniques for achieving URLLC that we can divide them to three categories:

- Structure-based: Shortening the TTI and reducing the symbol duration.
- Diversity-based: Applying diversity by repetition of time/frequency/space/code
- Resource-reuse-based techniques: Time/Frequency/Space more precisely Structure based.

Frame structure is important in the design of 5G PHY aspects, and the ability of achieving lower latency has an intrinsic correlation with frame structure.

Number of symbols in one slot, symbol duration, subcarrier spacing all are connected to the frame structure. The next aspect is spatial diversity. Spatial diversity which is obtained from distributed input and output antennas, can keep transmissions almost error-free without affecting negatively the latency. The utilization of several time and frequency and space will lead to have a diversity. Recently, massive MIMO is an effective feature in 5G, due to the significant improvement in spatial diversity, supporting many users at the same time.

Meanwhile in LTE two layers are defined. Radio Link Control(RLC), the packet size is adjusted based on the latest wireless channel quality. Media Access Control(MAC), controls radio access of the packet. With considering the quality of service and wireless channel quality. On IEEE layer 1 (L1) and layer 2 (L2) technologies, these IEEE-based standards operate in the unlicensed bands (below 6 GHz) and hence suffer from potential interference from other collocated networks.

But in general cases with 3GPP licensing-based LTE standard offers the benefits of satisfying the requirement of MTC applications. 3GPP's licensing-based LTE standard brings inherent advantages to fulfill the requirements of MTC applications[10]. LTE was initially proposed for cellular macro networks with inter-site distances in the kilometer range, including support of up to 100 km. The symbol duration of IEEE-based technologies is fairly smaller, which in turn affects negatively the (e2e) latency[10].

In IEEE-based standards, synchronization preamble, control signaling, LBT (listen before talk) backoff is used for controlling channel occupation time. In specific situation like our scenario in scenario section the transmitter can transmit the packet whenever there is any data which in case of no interference will have lower latency, in which can satisfy the specific scenarios in manufacturing.

In LTE standards over frequency domain, in time symbol duration, the controlling data will be distributed. LTE will manage the multiplexing on frequency and space multiplexing. Meanwhile IEEE uses multiplexing over time, even in this case when the number of nodes start to be more the IEEE start to be inefficient[32] and cannot support the low latency scenarioes and for undeterministic medium the CSMA/CA will be insufficient when number of nodes increases.

LTE Release 13 is considering a TTI of duration 0.5ms, and even the minimum possible duration consisting of only 1 OFDM symbol 71.4 ms including the cyclic prefix). We believe that by diminishing the TTI to 1 OFDM symbol, the minimum required End to End latency of 1ms in factory automation can be accomplished[10].

LTE link layer is not designed by default to address latency-critical communication requirements. ENodeB is able to easy transmit and handle Downlink but the Uplink transmission. Users will start with Sending Request and the EnodeB will response with scheduling grant and then the user can transmit the data, this process of SR-DG-data will cause excessive delay[10]. In release 13, where the SR-SG overhead is proposed to be eliminated, the concept of so called Instant Uplink Access(IUA) was introduced, thus it will lead to shortening the TTI and lower energy consumption.

The available modulation levels in LTE are quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), 64-QAM, and 256-QAM. Using convolutional codes is preferred in the low-latency and high-reliability C-MTC use cases such as factory automation scenario the similar performance to LDPC for small block length. For factory automation we target the TTI to be on the order of 100 micro seconds to deal with the most critical cases and one OFDM symbol of 71.4 micro seconds. Control signaling and reference symboling has to be placed first to be decoded earlier

A test was done on LTE network with the the profinet protocol running on our LTE based network in Ericsson which I have tested works in band 40 ,2300MHz. The 3GPP LTE is a new standard with considerable performance targets. Therefore it is necessary to evaluate the performance and stability of this new system at an early stage to enhance its smooth and cost-efficient introduction and deployment. In general, OFDMA is an OFDM-based multiple access scheme that is utilized in the Downlink direction for both LTE.

In such a technique, each user is given a unique fraction of the system bandwidth (OFDM subcarriers) which in consequence allocate different subcarrier to different users depending on the channel condition which is known as multiuser diversity. However in LTE more number of users can be supported without significant affect on the bandwidth.

Single carrier modulation was introduced in LTE release 14. The main differnces between OFDM and Single-carrier modulation is OFDM (Orthogonal frequency-division multiplexing) modulation has a large and often unpredictable and considerable peak to average power ratio (PAPR). Which is a challenging part for the linear amplifier, on the other hand single-carrier modulation often has a low or even unity PAPR, which makes it battery-friendly. OFDM has an advantages of dealing with the distortion.

Data rates in industry is 100 Mbps[10]

Technology	802.11ac	5G	LTE Rel-14
Licensing	Unlicensed	Licensed	Licensed
Multiplexing	Time,Space	Time,Space,Frequency	T,Space,F
Antenna Support	8	?	Can 32
Frequency band	5GHz	(600Mhz-6Ghz)(28Ghz-86Ghz)	400-4Ghz
Bandwidth	20MHz-160Mhz	50Mhz-400Mhz	1.4Mhz-100Mhz
Time symb duration	3.6μs	?	71.4μs
Signaling	OFDM	UL:CPOFDM	DL:OFDMA UL:SCFDMA
Channelaccess	CSMA/CA and slotted	scheduled	Scheduled
Data rates	500Mbps-1.3Gbps[43]	?	Scheduled

Table 3.1: Theoretical Comparison

3.1 5G Enhancements

5G performance goals include high data rate, reduced latency, energy saving, cost reduction, higher system capacity and massive device connectivity. TTI is the basic unit of time scheduling the minimum data transfer time, which TTI in LTE is equal to 1ms, depending on carrier spacing the TTI can vary 15KHz carrier spacing for 1ms. And 1 TTI equals 1ms in current cellular communication, regardless of the size of the transmitted data. The latency in user plane is structured as configured latency and transmission latency, in which the configured latency is the duration of time for the BS to be allocated resource from ENodeB [33]. Latency in user plane can be divided in to different part

- Schedulig request(SR)
- ENondeB creates the scheduling grant for BSR
- Scheduling grant transmission
- UE processing delay

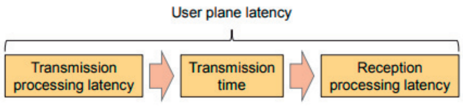

Figure 3.1: User plane

- BSR transmission
- ENodeB decodes BSR and generates scheduling grant
- UE data transmission

The main technology components for latency reduction are explained as follow. Transmission time interval, in 3GPP a very flexible frame structure was proposed in which the subcarrier spacing (SCS) can be higher in comparison to the LTE. The shorter the SCS the more number of symbol we can allocate in one TTI, in another word the reduced TTI length can be succeeded by diminishing the symbol duration (increasing the SCS) , decreasing the number of symbol per TTI. In parallel to this the number of OFDM symbol per TTI can vary as well which can be on 14 OFDM symbol or nonslot mini symbols which can vary from 1ms to 13ms. In LTE advanced 4G the user plane latency to just transmit a wireless signal is 1ms. This flexible packet structures creates a fantastic opportunity. The mini-slot length of 2, 3 or 7 symbols is in the recommendation of 3GPP.

Grant free transmission, in which the same as semi-persistent scheme can avoid regular handshake delay[34]. User plane latency is one way of a successful packet transmission and includes the time for one or more retransmission if packet reception fails.

Latency in physical layer can described in an equation, TL = Tttt + Tprop + Tproc + Tretx + Tsig. In which Tttt is the time-to-transmit latency, which corresponds to the time to transmit a packet. Tprop is the signal propagation time from the transmitter to the receiver. Tproc is the time to perform the encoding and decoding, and also the channel estimation in the initial transmission. Tretx is the time taken by retransmission. Tsig is the pre-processing time for the signaling exchange such as connection request, scheduling grant, channel training and feedback, and queuing delay.

Tttt=B/R in which B is number of bits to transmit, and R is the link data rate. In our case b is 480 bits and the link data rate is between 800Mbps to 1Gbps which is approximately 480 nanoseconds, And Tprop for one meter is 10 nanoseconds. Processing delay is often smaller than the propagation delay and the transmission delay. Average latency of URLLC (from layer 2/3, L2/L3, ingression to L2/L3 egression) should be less than 0.5ms to meet the requirement for the ITU which requires the Tttt to be order of micro second in LTE this Tttt is 1ms[12].

The critical enhancement in URLLC packet design is to diminish the processing latency Tproc or the time to-transmit latency Tttt. A square-shaped packet structure is popularly proposed to mitigate the fading channel while in 5G the frequency axis is stretched to decrease the Tttt. The main purpose in 5G NR is to create the frame structure where support the various range of services. Obviously by editing the subcarrier spacing we can reduce the symbol time. Doubling the subcarrier spacing(15khz to 30khz) will decrease the symbol length by half(from 72micro seconds to 36micro seconds) [12]. In LTE the frame contains 12 subcarriers with 15khz which is one resource block. The resource block is 180 Khz wide in frequency and 1 slot long in time.

With this technique the transmission time of one subframe will shrink to 0.5ms. We should consider that this technique of controlling the subframe spacing is suitable for the higher frequency than 6Ghz. Delay spread is small. But when the frequency is lower than 6GHz this method of increasing the subcarrier spacing will not be suitable because of large delay spread. By using mini slots we can mitigate this feature and decrease the Tttt, using minislots with 2, 3 and 7 symbols decrease the Tttt.

Wireless networks are IP protocol based networks, a Profinet protocol has datagrams without IP header. I need to encapsulate them with an IP header and do some modification on each packet to match the priority of the Profinet packet with IP based networks. Encapsulation is a the process of adding a header to an existing packet and decapsulation is to remove the added header. In the next section I will describe a method and introduce a software for applying the encapsulation. And the ways the encapsulation can be useful for the quality of service.

4. Method

Method section illustrates the technique of transmission of Profinet protocol based packets over IP protocol based wireless technologies such as 5G, 802.11 and LTE. Layer two over layer three tunneling using Open vSwitch makes this method possible. Tunneling is a communication protocol which makes it possible to transmit data from one network to another network with the so called encapsulation. I start with smart review of Profinet and bridge method used in parallel for 802.11 and then the layer three tunneling.

At the end of this section I will mention the routers I have flashed before using Open vSwitch and a brief explanation about DD-WRT which the purpose was to use it as a VPN station. Profinet allows to implement a comprehensive communications solution on Ethernet which includes peer-to-peer communication between controllers[35]. Profinet considers the scenarios from two points of view. PROFINET IO for integration of distributed I/O and PROFINET CBA (Component Based Automation) for creation of peer-to peer communication. The Profinet Real-Time Communication (RT) can enhance the cycle time up to 1-10 ms and Isochronous Real-Time Communication (IRT) enables cycle times up to 1 ms with considerable less jitter. PROFINET IO utilizes cyclic data transfer to exchange data with programmable controllers over Ethernet. Cyclic data transfer is not just a continuous transmission of data, it is also about guaranteed data transmission when there is a data to transfer.

The PROFINET IO connection can be configured for both cyclic and acyclic I/O data transfer. Cyclic I/O data is always exchanged between the PLC and anybuss communicator at the specified update time. Transmitting Profinet protocol based frames over the wireless IP protocol based network would not be possible unless the packets are being encapsulated with IP header. I Used Open vSwitch to encapsulate the packets which I explain in VPN setup. I explain some of main packets which construct the Profinet protocol. Open vSwitch is a software that can execute a virtual switch[9] which apply the programmatic control over the network.

At first Siemens LLDP(link layer discovery protocol) broadcast the 802.11 link layer discovery. LLDP packets are not data packets generated and consumed by an application running at a host. LLDP packets are to the data plane to discover the global network topology[36]. At this time HMS anybus communicators sends the PN-PTCP packets. The PROFINET IO Isochronous Real Time (IRT) implementation includes a Precision Transparent Clock Protocol (PTCP) for network-level synchronization.

The Discovery and Basic Configuration Protocol (DCP) is a protocol definition within the Profinet context. It is a link layer based protocol to configure station names and IP addresses. It is restricted to one subnet and mainly used in small and medium applications without an installed DHCP server. First the controller sends some DCP /LLDP to assign name for the anybus, the DCP protocol is defined in the standard IEC 61158,[37] its a 802.1Q virtul LAN. PNIO-CM is a Profinet specific protocol to configure the communication relations between the controller and IO devices. This will determine the amount and type of the data that will be transmitted. Our purpose here is to measure the time it takes for a packet to go from a PLC to anybus communicators as is illustrated in figure 5.1. Our first trial is to connect two routers so we can measure the 802.11AC and 802.11AD latency. Bridging will make it possible to have routers connected for data transmission between the PLC and anybus communicators. As shown in figure number 5.1. In the next section I will describe the bridging and implement VPN which at the end will end up with using Open vSwitch for encapsulation.

4.1 Bridge

Bridge subsection is introduced because the Anybus communicators and PLC cannot communicate without having one of the routers bridged to the main router. We go from data to packet to frame, so the packet which has the IP of the destination will be put in the frame with the mac address of the router or gateway, the router put the the Ip packet to the new frame with the mac address of the destination. In our scenario we used two 802.11AC routers. One of the routers is in bridge mode to create the communication

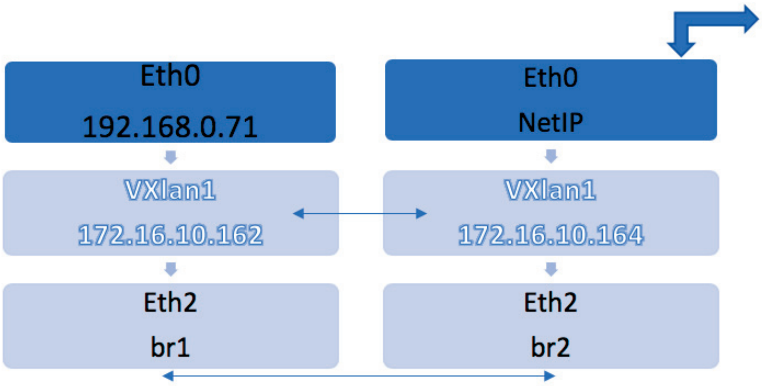

Figure 4.1: Tunneling

between the PLC and the anybusses and SLPs using Open vSwitch that will encapsulate the IRT packets to tunnel over the wireless network to reach the Anybuss Communicators.

Layer two tunneling technique sends traffic between two or more devices on a network in an encrypted tunnel, when a VPN is made all the traffic is encrypted on the clients end, sent over a network to a host creating tunnel between 2 devices. Tunneling can be done by encapsulating the private network data and the related protocol in the public network that the private data appears as the public data.

4.2 Layer 2 Tunneling

The layer two tunneling protocol creates a flexible mechanism. For tunneling layer 2 (L2) throughout a packet-oriented data network [38]. The idea of tunneling is not recent since some examples have already been used in the past. In our scenario DD-WRT, a linux based enviroment installed on the router, cannot make the layer two over layer three tunneling possible. In this case I used Open vSwitch software which could be installed on SLP small product from HMS. By Open vSwitch, we have the possibility to encapsulate the packets with IP header and send it through the IP based network.

Router	Operating system
Asus N12	DD-wrt
Tplink wr1043	Openwrt
Tplink mr3420	Openwrt
Dlink 810l	DDwrt
TPlink WR841N	DDWRT

Table 4.1: Flashed routers

4.2.1 Open vSwitch

Open vSwitch is an open-source software in which it is implemented to be used as a vSwitch in virtualized network environments. A virtual switch forwards traffic between different virtual machines (VMs) and also forwards traffic between VMs and the physical network. Open vSwitch is open to programmatic extension and control using OpenFlow management protocol.

The SLP small has two interfaces. One for them ingresses Profinet traffic and one for the encapsulated packets output. The Profinet packets will be encapsulated and then the packets simply will be forwarded to the second bridge for the quality of service mapping. VxLAN will remove the 802.11Q header tag from the Profinet packets.

802.11Q is a networking standard that helps virtual LANs on Ethernet network 802.3[39]. This header also provides the quality for service prioritization. The reason we need two bridges is because of a bug in Open vSwitch which cannot do the encapsulation and QoS mapping at the same time. So the second bridge is needed, to create a flow that maps the QoS part with the encapsulated packets.

In table 4.1 I have mentioned the routers that I have flashed to do the encapsulation and quality of service mapping for layer two over layer three tunneling. These flashed routers can only support and create VPNs which are layer three over layer three tunnelings. There are three main issues. The first one is they cannot support both encapsulation and bridg to a router at the same time and the second one in that the only frequency support is 2.4GHz which was not in my interest. And third they lack enough memory for further packet installations.

There are some initial configuration issues which have to be fixed which I summary them as following. For example, LAN ports on Asus N12 are not functional. LAN ports connection on Dlink 810l are super unstable, and I cannot access to web interface consistently. Cisco e1200 cannot support bridge mode wirelessly and has to be upgraded, Tp links don't support Open VPN by default. But the reason I started to flash the routers was to be able to see if there is a possibility to first do the encapsulation by tunneling. And second to be able to bridge on 60Ghz. But DD-WRT and OpenWRT cannot support VxLAN and layer two over layer three tunnelings with default packet installed on them. In the scenario section I will introduce simple scenario line of sight communication over two different wireless technologies.

5. Scenario

I created a scenario in which include the method of connecting the Profinet and wireless technologies together. I can see the latency and the potential of the LTE and 802.11 for mission critical in smart manufacturing. This scenario is a typical industrial automation use case of a robot picking and placing work pieces from a moving conveyor belt. It involves sensory data inputs to a Programmable Logic Controller (PLC), and instructions from the PLC to a robot for the pick and place operation. The scenario requires communication from sensors to the PLC and from the PLC to a robot with ultra-low latency and extremely high reliability.

None of today's wireless standards is capable of satisfying these stringent communication demands. Our implementation enables industrial critical-control using wireless communication based on the 5G standard. Industrial automation and control typically involve sensors that report data to a PLC. Based on the sensory data, the PLC instructs an actuator, a robot, to perform a certain action thus forming a control loop. In industrial automation applications, these control scenarios are regarded as highly stringent with robust and real-time data communication demands. We needed several equipment which is mentioned below:

- PLC S7-1200
- Anybus Communicators
- Nightwalks N9000
- TPlink WR740N DD-WRT TPLink WR841n DD-WRT
- Hub

- Gateways
- SLP small (with Linux installed on)

Anybus communicators are connected to the first router with the wireless interface of both 802.11AC or LTE band 14. Figure 5.1 shows how I measured the scenario for different wireless technologies. For LTE test bed I used the Downlink transmission and measured it by putting the PLC on the server-side. I had two hubs to sniff traffic on the PLC side. These hubs would also add in extra latency which I have calculated and considered in the measurement chapter.

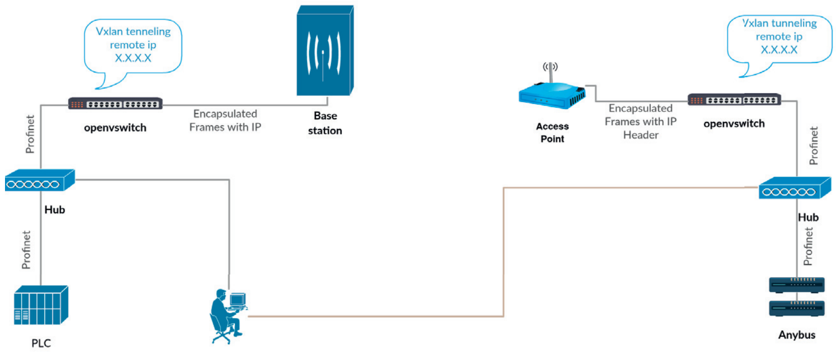

Figure 5.1: Scenario

Distance	average	maximum	0.95Confidence interval
20m	7.6ms	27ms	7.61ms-7.77ms
1m	7.8ms	20ms	7.61ms-7.86ms

Table 5.1: Measurement result

5.1 Measurments

In this section latency measurements are shown based on the scenario. LTE band 40 testbed provided by Ericsson was the only available cellular network technology which I had the possibility to access. LTE testbed release 13 with one polarized antenna band 40 which the packets will experience the internet latency. In this case, we are measuring Downlink travel time from PLC to the anybus communicators. In my Python script I have analyzed the data sniffed by the Wireshark. Some features will be described which the main one is average latency. The quality of network varies alot so I tried also to get the confidence interval, in both distance of 20 meters and 1 meter. In figure 5.1 and 5.2 both the 20 meters and the 1 meter of LTE has been shown the average latency of 7.5ms which I expected it since I had a reference[11].

The measurement was done consistently over half an hour because of our limited access to the equipment. I separated them as different batches but to do so I need to make sure they are independent. k-s test illustrates if the

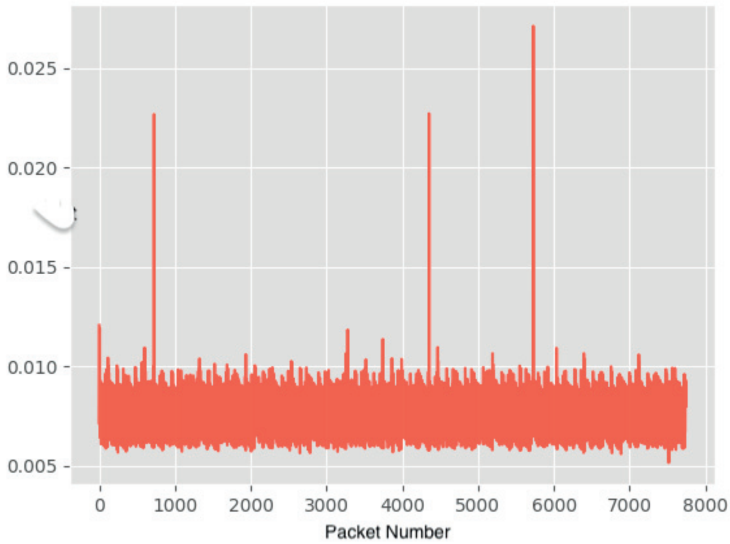

Figure 5.2: 20meter with LTE

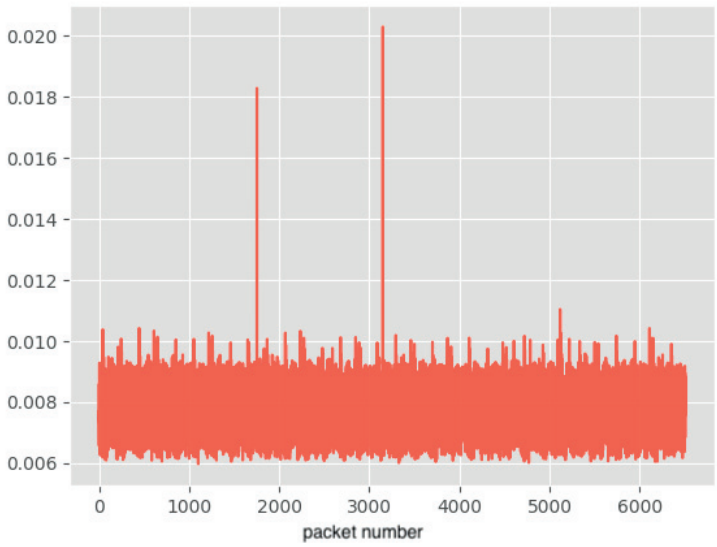

Figure 5.3: 1meter with LTE

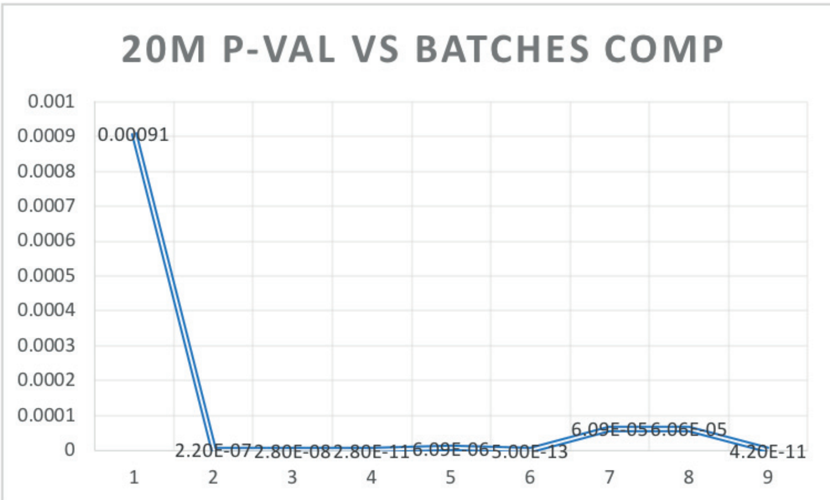

Figure 5.4: P values for 20 meter

packets are independence so I can run the confidence interval. The first time we measure the first batches is the one with 20 meter distance. As we see figure 5.4 and 5.5 the p-values are suitable for doing the confidence intervals. Since the p-values are under 0.05 the batches are independent, the confidence interval could be calculated.

The confidence intervals overlap. At the same time, the values are varied because of jitter, in consequence, we cannot claim which one of the distances have more delay. In this LTE network, the packets go through the internet, which will add extra travel time.

In the same scenario with 802.11AC, the results were considerably faster but here is the time. The delay introduced by equipment like the sniffers which introduce microseconds of delay but at the same time one user was active in this network. In figure 5.3 (In which Y is the latency and X-axis is the number of the packet)the latency of different packet in the distance of 1 meter.

There was just one active user in the network. 802.11 is more sensitive to number of users compare to LTE since CSMA/CA protocol is used. The average latency is 850 micro seconds. In which 730 micro seconds for the sniffers. The network cards should be calculated which will be approximately 1.7 ms total latency for line of sight scenario. 802.11 considering CSMA/CA protocol in case being used for the specific scenarios without any interference

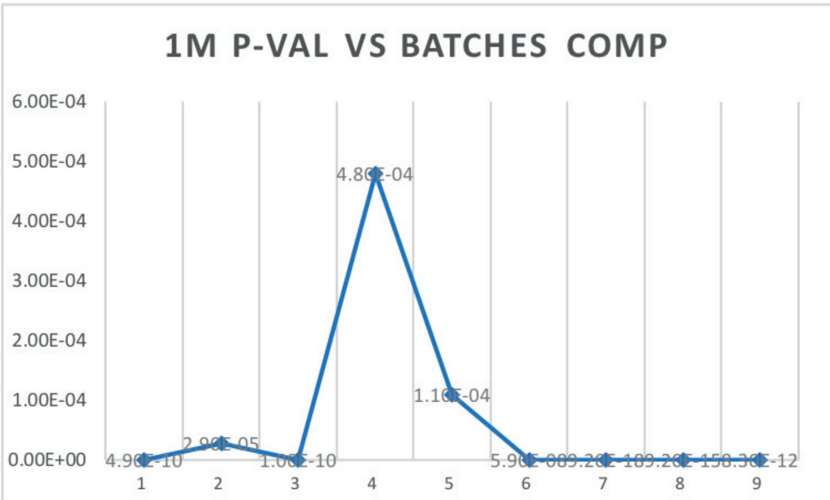

Figure 5.5: P values for 1meter

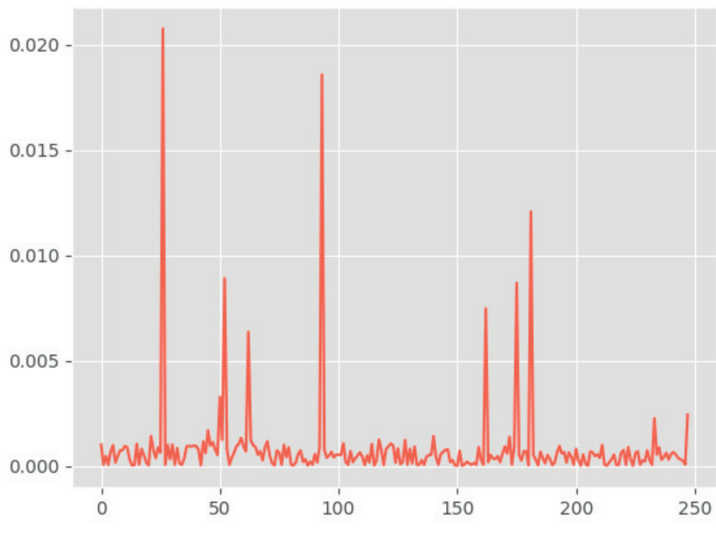

Figure 5.6: 802.11AC Latency

and a limited number of users can satisfy the latency of below 30ms for a radius of below 3 meter. Unfortunately I didn't have the opportunity to work with 5G testbed I am looking forward in the future to do the same test with 5G.

6. Conclusion

In this thesis my main goal was to measure the latency in different wireless technologies for smart manufacturing. In the future of smart manufacturing and automation the efficiency and flexibility of the work enviroment can be satisfied partially with the modern wireless technologies such as LTE and 802.11AC. But in case of critical massive communication the reliability of this technology cannot be guaranteed because they are not primarily designed for low latency transmission.

My measurements show that 802.11AC in the case of a limited number of users and interference can support an average latency of less than 5ms for the radius of 5meter. LTE latency can be guaranteed by less than 7.5ms even if with a limited number of users more than 802.11AC plus having the internet in the circuit. The solution is proposed by 5G packet structure and the flexibility of the frame structure and the diversity can hopefully bring in the support for the 4th generation of manufacturing. The perspective of 5G with the promising packet structure can satisfy the massive communication with 10ms end to end latency for the general cases.

Future work would be to measure the 5G testbed in different scenarios with a different number of users. 802.11 and LTE need to be practically measured with more number of users which will have a significant effect on their performance. In this measurement scenario, we had the internet in LTE included within return will increase the latency, so in the future using LTE without internet with more number of antennas would be an interesting to measure. As primary idea of this thesis was set by HMS network on 5G mission-critical capability measurement and more work on mission-critical with 5G testbed can be done.

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