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Master Thesis

The Tactile Control Function Protocol Based on EDCA in IEEE 802.11n for Haptic Communication in Ad Hoc Networks

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Abstract

In the future, increasingly tactile information will be transmitted over the Internet, what is the haptic communication in the tactile internet. For example, the wireless remote mobile robot in the field of engineering, medical, public safety, logistics and so on. Tactile information transmission is the basis of these applications. The biggest challenge for these applications is the round trip latency 1 ms, Long-distance or multi-hop wireless transmission will inevitably bring about delay and packet-loss. In order to ensure Quality of Experience (QoE) and optimal latency, we have improved EDCA mechanism on the basis of IEEE 802.11n, and developed an enhanced Coordination Function protocol for Haptic Communication applications, the tactile control function (TCF) protocol.

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CHAPTER 1

Introduction

In the future, increasingly tactile information will be transmitted over the Internet, what is the haptic communication in the tactile internet. For example, the wireless remote mobile robot in the field of engineering, medical, public safety, logistics and so on. Tactile information transmission is the basis of these applications. The biggest challenge for these applications is the round trip latency 1 ms, Long-distance or multi-hop wireless transmission will inevitably bring about delay and packet-loss. In order to ensure Quality of Experience (QoE) and optimal latency, we have improved EDCA mechanism on the basis of IEEE 802.11n, and developed an enhanced Coordination Function protocol for Haptic Communication applications, the tactile control function (TCF) protocol.

1.1 Motivation

With the rise of two different mobile communication technologies, cellular networks and wireless local area networks (WLAN), they made the Internet of Things possible. These both are single-hop wireless networks, although they have simple network structure, but they require expensive inflexible infrastructure to deploy and maintain. In contrast, the wireless multi-hop networks (WMHNs) are more flexible and have lower infrastructure costs.

WMHN according to different mobility of network devices can be divided into three categories [1]: are the mobile ad hoc network (MANET), the wireless sensor network (WSN) and the wireless mesh network (WMN). MANET technology has some important applications, including flying ad hoc network (FANET) and vehicular ad hoc networks (VANETs). For these applications, human-to-machine or machine-to-machine haptic communication will be widely used.

When the human-machine remote interaction technology used in these networks, Tactile Internet technology becomes particularly important. Since the network is a delay sensitive network, Long-distance wireless transmission will inevitably bring about delay. If the delay reaches people's perception range, it will degrade the Quality of Service (QoE) for users. How to minimize the delay of wireless network transmission becomes more important.

The medium control access (MAC) layer is a sublayer of the data link layer in the ISO/OSI

(International Organization for Standardization/Open System Interconnection) protocol stack model. Mac layer protocol plays an important role in WMHNs. Because it is responsible for managing and assigning transmission media to multiple devices in a distributed network. In order for multiple devices to use the same media to propagate data, the mac protocol needs to avoid potential transmission collisions, that is the coordination functions, including the distributed coordination function (DCF), the point coordination function (PCF), the hybrid coordination function (HCF), the mesh coordination function (MCF).

The operation of these coordination functions is based on different information priorities, high priority data will be transmitted firstly, like voice information. Therefore, how to improve the priority of tactile information in traffic and reduce the mean of end to end delay has become a challenge.

1.2 Task

The purpose of this paper is to enhance the IEEE 802.11 standard mac Layer protocol, develop a new access category (AC) for tactile control information in original coordination function, so that the tactile information in the transmission process to achieve the optimal delay. In this paper, will analyze the dependency of the delay and the hop-count, and the relationship between the delay of the tactile information and the traffic load situation. And based on these, evaluate the performance of the tactile control function (TCF) protocol.

Specifically, the following tasks are to be processed:

- Build a network simulation environment with Omnet++ 5.1.1 and INET framework 3.6.
- Develop the tactile control function, a new access category (AC) for tactile information transmission.
- Testing and analyzing data of exprimentations.
- Evaluate the transmission efficiency of different Coordination Functions with the tactile control function (TCF).

1.3 The Structure of The Paper

The chapter 2 is to provide the necessary foundations to wireless transmission of tactile information that contribute to the understanding of this paper. It is clarified what is Tactile Internet, how a Model Mediated Teleoperation works, which challenges exist. Then, the wireless transmission protocol is presented and explained how the communication between the layers of the reference model works. This chapter ends with a brief conclusion of the relevant literature and the latest technology.

The chapter 3 presents the concept of the tactile control function (TCF) protocol. It is clarified what requirements are imposed on the protocol, which applications communicate via the protocol and what configurations must satisfy the communication mode. We want to improve EDCA mechanism on the basis of IEEE 802.11, and develop an enhanced wireless transmission protocol for Tactile Internet applications. We present in this chapter an example of a modification of the original EDCA. We present an EDCA variant where various setting will specifically depend on both the characteristics of Tactile Internet applications and network constraints. In this context, we propose a new AC (Access Category) that allows in one hand to ensure the priority of tactile information transmission and on the other hand to ensure the balance of simultaneous transmission on both sides. Therefore, the new AC can reduce the average delay.

Chapter 4 describes how to implement our conception. This includes what kind of simulation we use to build the experimental environment; why choose this way; and how to build experimental environment. The construction of experimental environment will be elaborated from the following two aspects: the establishment of the network topology and the configuration of the network environment.

Chapter 5 will to explain the hypothesis of the whole experimentation at first. In the expermentation performing phase, it introduces the structural framework of the experiment and experiment parameters. The evaluation will be combined with the evaluation of tactile information transmission performance and the evaluation of tactile information transmission process.

Chapter 6 is the conclusion of this paper.

CHAPTER 2

Foundations

The following chapter is to provide the necessary foundations to wireless transmission of tactile information that contribute to the understanding of this paper. It is clarified what is Tactile Internet, how a Model Mediated Teleoperation works, which challenges exist. Then, the wireless transmission protocol is presented and explained how the communication between the layers of the reference model works. This chapter ends with a brief conclusion of the relevant literature and the latest technology.

2.1 The Ad Hoc Networks in the Internet of Things

The Internet of Things (IoT) is a collection of all the networks in the future that contains everything in the world of people's lives: geo-environment information, bioinformatics and various electronic device information. Every subject in the network is uniquely identifiable through its embedded computing system, and they can connect and exchange data through the Internet of Things. Vehicles are capable of exchanging information among them Vehicular Ad Hoc Networks (VANETs). Mobile devices which are equipped with wireless transceivers such as smart phones, tablets, sensors and so on, they can communication with Mobile Ad Hoc Networks (MANETs). Furthermore, the Wireless Sensor Networks (WSNs) is a reality in urban scenarios by sensing data parameters such as temperature, humidity, CO2 emissions, etc. The integration of MANETs, VANETs, WSNs and more fixed infrastructure is the Internet of Things.

With the exception of a few fixed infrastructures that connect to the Internet via a wired network, the vast majority of devices to be connected into the Internet of things need to rely on the popularity of Commercial wireless technologies such as Bluetooth, UWB, WiMAX and Wi-Fi. With these technologies, the ad hoc network describes a local, temporary wireless network. It does not rely on a pre-existing infrastructure, such as routers in wired networks or access points in wireless networks. Each node participates in routing by forwarding data for other nodes. According to different application subjects and environment, the ad hoc network can be classified into the following categories: Mobile Ad Hoc Networks (MANETs), Vehicular Ad Hoc Networks (VANETs), Wireless Sensor Networks (WSNs), Radio Frequency Identification (RFID) and Near Field Communications (NFC).

2.2 Wireless MultiHop Networks

Wireless Multi-Hop Network (WMHNs) as an ad hoc network applications and development, it shows more advantages than the traditional ad hoc networks: indirect communication, wider range and more flexibility. So the multi-hop paradigm makes the ubiquitous and seamless communications of IoT possible.

There are two metrics widely to be used in WMHN, they are hop count and Euclidean distance between the source and destination nodes. The ideal situation is to reduce the number of nodes in the link, that is, selecting the distant node and selecting the path with lower number of hops. Since too many nodes or excessive forwarding times in the transmission process will lead to serious transmission delay. Thus, an optimal solution is to develop efficient protocols and mechanisms for the distribution of information in a WMHN.

2.3 IEEE802.11n

IEEE 802.11 is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN) computer communication in the 900 MHz and 2.4, 3.6, 5, and 60 GHz frequency bands. They are created and maintained by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN Standards Committee (IEEE 802). In our case, we develop TCF based on IEEE 802.11 standard 2016.

802.11n is a wireless-networking standard that uses multiple antennas to increase data rates. The IEEE802.11n human employs OFDM modulation technique. The antenna technology used with the IEEE802.11n standard is supported as Multiple Input, Multiple Output (MIMO). Its purpose is to improve network throughput over the two previous standards—802.11a and 802.11g—with a significant increase in the maximum net data rate from 54 Mbit/s to 600 Mbit/s at a channel bandwidth of 40 MHz.

2.4 Tactile Internet

There are four types of physiological real-time constants: muscular, audio, visual, and tactile. Different sensory stimuli lead to different reaction times in humans. In the case of muscular reaction times, to unexpected stimuli a person can react within one second with muscle movements. However, if a person is prepared for it, he can process stimuli much faster. To expected acoustic stimuli a person can react within 100 milliseconds. Expected visual stimuli are processed even within 10 milliseconds. The human tactile and haptic perception and control with auditory-visual-haptic feedback is particularly responsive, here a reaction time of one millisecond is achieved [2]. Thus, in the case of haptic communications the Tactile Internet as a system which has tactile input and also audio, visual and haptic feedback, requiring extremely short latency.

The Tactile Internet will enable remote monitoring and surgery, wireless controlled exoskeletons, remote education and training, remote driving, industrial remote servicing and decommissioning, synchronization of suppliers in smart grid – among many of its application areas. However, at the very core of the design of the Tactile Internet is the 1ms-Challenge

[3], i.e. achieving a round-trip latency of 1 ms at an outage of about 1 ms per day.

2.5 Model Mediated Teleoperation

Bilateral teleoperation systems with haptic feedback allow human users to interact with objects or perform complex tasks in remote or inaccessible environments. Communication delays in teleoperation systems jeopardize system stability and transparency, leading to degraded system performance and poor user experience. The model-mediated teleoperation (MMT) has been developed by IEEE to guarantee both system stability and transparency in the presence of arbitrary communication delays.[4]

A typical teleoperation system comprises three main parts: the human operator/master system, the teleoperator/slave system, and the communication link/network. During teleoperation, the slave and master devices exchange multimodal sensor information over the communication link. The slave robot follows the received position or velocity commands sent by the master. The haptic, visual, and audio signals captured by the sensors on the slave side are sent back to the master and displayed to the operator. This teleoperation structure, sending motion (position/velocity) signals and receiving haptic signals.

The Model Mediated Teleoperation (MMT) figure 2.1 is a solution for the Tactile Internet: the user interacts virtually, he can control the haptic controller at the Host Master. The control information will be sent through the internet to the teleoperated robot at Host lave. At the same time the robot is resending the feedback information back to the Host Master. But in real-time, Master side with a digital world model can simulate the Slave feedback without roundtrip delay before the real feedback from Slave.

The solution can't really avoid time delays between more nodes through the Internet. Using this method, users can feel no delay or a few time delays with the help of the simulation and prediction pretreatment. The simulation and predictions are based on additional sensory data. For example, the time delay between each two nodes is 1ms, by 4 nodes, time delay is always required 5ms. But by locally model, the system can simulate this contact in the master side before the contact happened in the slave side. Therefore, users have no sense of time delay.

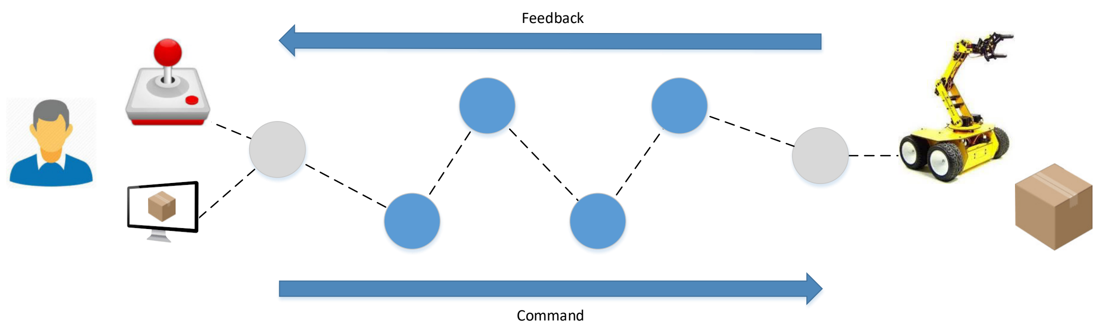

Figure 2.1: The Model Mediated Teleoperation

Depending on distance and the communication infrastructure, communication delay from a few milliseconds up to several hundred milliseconds, even increase to several seconds. Even a small communication delay or packet loss rate can jeopardizes the system's stability and transparency. To guarantee stability and to improve the level of transparency, the wave-variable transformation or the time domain passivity approach have been developed. However they have a conflict that the system gains stability at the cost of degraded transparency. MMT has been proposed to ensure both stability and transparency. In general, an MMT system requires a fast and accurate environment modeling method. These modeling methods include parametric and non-parametric approaches. Besides this, data communication, local model updating, and stable slave controlling are also important challenges for MMT.[4]

2.6 Latency

Network Latency or delay is an important performance characteristic of network communication. It is the time required for a signal to travel from one point on a network to another. It comprises four main parts like formula (2.1): Nodal Processing Delay, Queuing Delay, Transmission Delay, and Propagation Delay. These delays add up to the Total Nodal Delay. Node devices, such as routers, the time it takes to process received frame information is the Nodal Processing Delay. Queuing Delay is that sum of the queuing time of a frame during the sending and forwarding waiting for the sending of the previous frame. Transmission Delay is the time it takes to push all the frame bits to the link. The actual time of one bit in the link is Propagation Delay.

$$d_{end-end} = N(d_{trans} + d_{prop} + d_{proc} + d_{queue}) \tag{2.1}$$

- Processing delay – time routers take to process the packet header
- Queuing delay – time the packet spends in routing queues
- Transmission delay – time it takes to push the packet's bits onto the link
- Propagation delay – time for a signal to reach its destination

For a certain link of the network, the number of hosts is relatively stable, compared to the total delay of the Nodal Processing Delay is very small or even negligible. The Transmission Delay and Propagation Delay are also in microsecond in general. The main of total delay comes from the time the information is waiting in link and the time it waits for the next retransmission if it is interfered or collided. That is Queuing Delay.

2.7 Mac Layer Protocol

Mac layer protocol provides transmission medium access control. For the WMHNs, it uses for Collision detection and avoidance, the Coordination Function is the most important mechanism to management Medium. The architecture of the MAC sublayer, including the distributed coordination function (DCF), the point coordination function (PCF), the hybrid coordination function (HCF), the mesh coordination function (MCF). The coordination function is a logical function that determines when a station is permitted to transmit protocol data units via the wireless medium. In the following context, we will briefly introduce the DCF and HCF. The PCF mechanism is obsolete, it might be removed in a later revision of the standard [5], so in our case we don't talk about PCF.

The Distributed Coordination Function (DCF)

In the 802.11 protocol, the fundamental mechanism to access the medium is called distributed coordination function (DCF). This is a random access mechanism, based on the carrier sense multiple access with collision avoidance (CSMA/CA) and a random backoff time following a busy medium condition. In addition, all individually addressed traffic uses immediate positive acknowledgment (Ack frame), in which retransmission is scheduled by the sender if no Ack frame is received. The CSMA/CA protocol is designed to reduce the collision probability between multiple stations accessing a medium, at the point where collisions would most likely occur. Just after the medium becomes idle following a busy medium is when the highest probability of a collision exists. This is because multiple stations could have been waiting for the medium to become available again. This is the situation that necessitates a random backoff procedure to resolve medium contention conflicts.

For a station to transmit, it shall sense the medium to determine if another station is transmitting. If the medium is not determined to be busy, the transmission may proceed.

The CSMA/CA distributed algorithm mandates that a gap of a minimum specified duration exists between frame exchange sequences. A transmitting station shall verify that the medium is idle for this required duration before attempting to transmit. If the medium is determined to be busy, station may defer until the end of the current transmission. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the station shall select a random backoff interval and shall decrement the backoff interval counter while the medium is idle. A refinement of the method may be used under various circumstances to further minimize collisions—here the transmitting and receiving station exchange short Control frames after determining that the medium is idle and after any deferrals or backoffs, prior to data transmission. [5]

The Hybrid Coordination Function (HCF)

Quality of service (QoS) is the description of customer satisfaction for a service from a device performance, such as a telephony or computer network or a cloud computing service, particularly the network performance by the users. To quantitatively measure quality of service, several related metrics of the network service are often considered, like packet loss, bit rate, throughput, transmission delay, availability, jitter and so on. If a device can work with QoS function, we call that a QoS-device.

The QoS-devices includes an additional coordination function called HCF that is usable only in QoS network configurations. The HCF shall be implemented in all QoS stations except mesh stations. Instead, mesh stations implement the MCF. The HCF combines functions from the DCF and PCF with some enhanced, QoS-specific mechanisms and frame subtypes to allow a uniform set of frame exchange sequences to be used for QoS data transfers during both the contention period and contention free period. The HCF uses both a contention based channel access method, called the enhanced distributed channel access (EDCA) mechanism for contention based transfer and a controlled channel access, referred to as the HCF controlled channel access (HCCA) mechanism, for contention free transfer [5]. Because our protocol is based on contention, so at here we only consider EDCA as our study object.

The Enhanced Distributed Channel Access (EDCA)

The EDCA mechanism provides differentiated, distributed access to the wireless Medium for stations using eight different User Priorities (UPs): from 1 up to 7. The EDCA mechanism defines four access categories (ACs): AC_BK, AC_BE, AC_VI and AC_VO, that provide support for the delivery of traffic with UPs at the stations. There is one enhanced distributed channel access function (EDCAF) per AC. EDCAF is a logical function in a quality of service (QoS) station that determines, using EDCA, when a frame in the transmit queue with the associated AC is permitted to be transmitted via the wireless medium. The transmit queue and AC are derived from the UPs as shown in the following Table.

UP	AC	Designation
1	AC_BK	Background
2	AC_BK	Background
0	AC_BE	Best Effort
3	AC_BE	Best Effort
4	AC_VI	Video (alternate)
5	AC_VI	Video (primary)
6	AC_VO	Voice (primary)
7	AC_VO	Voice (alternate)

Table 2.1: UP-to-AC mappings

2.8 Simulation Environment

OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. "Network" is meant in a broader sense that includes wired and wireless communication networks, on-chip networks, queueing networks, and so on. Domain-specific functionality such as support for sensor networks, wireless ad-hoc networks, Internet protocols, performance modeling, photonic networks, etc., is provided by model frameworks, developed as independent projects. OMNeT++ offers an Eclipse-based IDE, a graphical runtime environment, and a host of other tools. There are extensions for real-time simulation, network emulation, database integration, SystemC integration, and several other functions.

INET Framework contains IPv4, IPv6, TCP, SCTP, UDP protocol implementations, and several application models. The framework also includes an MPLS model with RSVP-TE and LDP signaling. Link-layer models are PPP, Ethernet and 802.11. Static routing can be set up using network auto configurators, or one can use routing protocol implementations. The INET Framework supports wireless and mobile simulations as well.

In the chapter 4, we will introduce the installation of Omnet++ and INET framework, and the configuration about our TCF networks.

2.9 Related Work

From 2000 until 2017, there have been a lot of researchers have studied various optimizations based on the existing ACs in EDCA mechanism:

Ibukunoluwa Akinyemi and Shuang-Hua Yang [6] propose a dynamic feedback based control algorithm (FCA) that assesses the WLAN and outputs contention window value with respect to number of active nodes on the WLAN. Kosuke Ozera, Takaaki Inaba, Shinji Sakamoto and Leonard Barolli [7] in order to deal with the problem with user priority, propose a Fuzzy-based Admission Control System (FACS). They compare the performance of WLAN and WLAN Triage systems considering throughput parameter. The experimental results show that the implemented testbed performs better than conventional WLAN. Mohand, Djamil and Louiza [8] aim at extending the Markov chain models proposed for the IEEE 802.11e-EDCA network, in order to especially model the TXOPLimit, the PF and the Packet Error Rate. Besides, they elaborate a mathematical model to compute the saturation throughput of Access Categories, Voice, Video, Best Effort and Background. The achieved numerical results indicate, for the first time that, the PF permits boosting the TXOPLimit efficiency under noise-related losses. Thus, the saturation throughputs of both Voice and Video access categories are substantially enhanced. This paper of M. K. Alam, S. A. Latif1, M. Akter, F. Anwar and Mohammad Kamrul Hasan [9] introduces an enhanced EDCA resource allocation parameter named dynamic transmission opportunity (TXOP) limit that regulates according to the variation in traffic load over WCN. This work also employs a mathematical modelling approach for the proposed parameter and numerical analysis of the existing and proposed parameters.

From the above conclusions, most researchers give a dynamic variables processing, optimized performance for normal data transmission in a general network. But they did not mention the performance of haptic communication in a wireless multi-hop network with IEEE802.11n MIMO model. Therefore, in this paper we should give haptic communication data higher transmission priority than normal data to ensure the quality of service and optimal overall performance.

CHAPTER 3

Conception

This chapter presents the concept of the tactile control function (TCF) protocol. It is clarified what requirements are imposed on the protocol, which applications communicate via TCF and what configurations must satisfy the communication mode.

We want to improve EDCA mechanism on the basis of IEEE 802.11n, and develop an enhanced wireless transmission protocol for Tactile Internet applications. We present in this chapter an example of a modification of the original EDCA. We present an EDCA variant where various setting will specifically depend on both the characteristics of Tactile Internet applications and network constraints. In this context, we propose a new AC (Access Category) that allows in one hand to ensure the priority of tactile information transmission and on the other hand to ensure the balance of simultaneous transmission on both sides. Therefore, the new AC can reduce the average delay.

3.1 Requirement

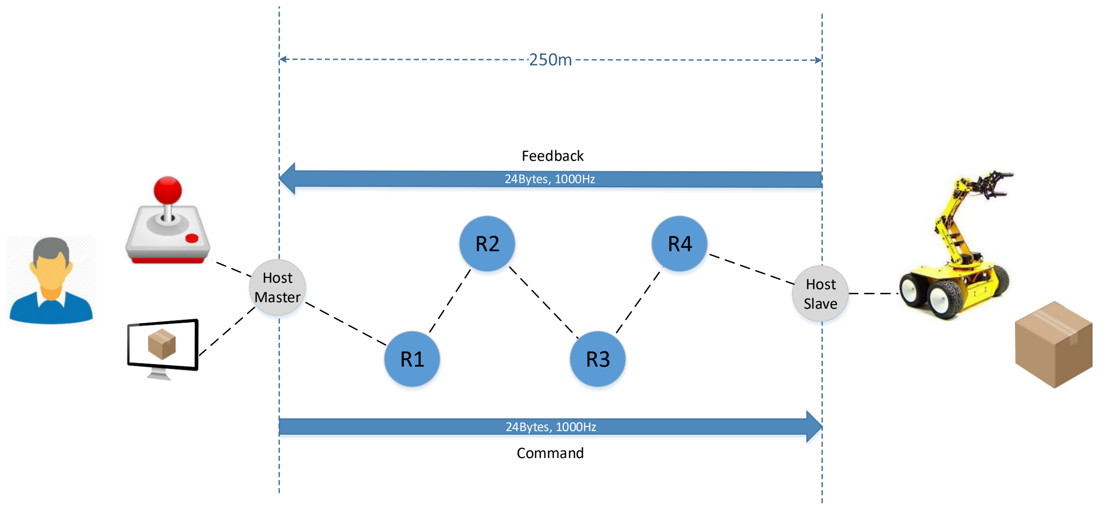

Figure 3.1: Teleoperation System

The object of investigation in this paper is a teleoperation system for a mobile robot (see picture 3.1). The goal is the development of a demonstrator: The user is supposed to be able to remotely control a robot, which may operate at a very great distance. The tactile information will be sent with 1000 Hz from both sides to the other at the same time, each packet has 24 Bytes. The user gives the control handle a command, this command through the local host at the master side into control information and send to the slave side. The robot's sensor sends the received status information to the host at the master side end via the slave computer. The entire communication process will be wirelessly transmitted through 5 Ad hoc networks with different hop count 1 - 5 and Euclidean distance from 50 meters up to 250 meters. Jitter and latency of the communication system directly affect the operator's perception, so it is important to minimize it.

The best solution is to optimal the Coordination Functions (CFs) in the MAC-Layer protocols. With this demonstrator, the two most widely used CF protocols (DCF and HCF) will be tested to transmitt tactile information. All the performance metrics, particular latency behavior of tactile information, will be investigated. The investigated results will help to modify and develop the Tactile Control Function (TCF) protocol. TCF as an additional coordination function of HCF to enhance the efficiency of the haptic communication, its development should follow the following principles:

- The proposed TCF solution is an enhancement to HCF, i.e. all applications that can run with HCF also run with TCF (with/without adaptation).
- The proposed TCF will allow regular data flow of all formerly present HCF access categories (VO, VI, BE, BK).
- The proposed TCF solution does not change the behavior of the network when there is no Tactile data flow present. TCF behaves exactly as HCF in this case.

In this section, the requirements of the teleoperation system for a mobile robot will be introduced with different metrics, like latency and jitter, signal frequence, hop count, Euclidean distance, bitrate and bandwidth.

3.1.1 TCF Networks Topology

In order to test the support of different coordination function protocols (DCF and HCF) on the low latency of tactile network, our experiment needs to gradually increase the hop count to observe the network performance with different Euclidean distances under different protocols. And in order to expand the application range of the wireless network in the future, we need to optimize the coverage area of the WMHNs with as many hops as possible.

However, on the other hand, the delay of wireless networks increases with the hop count. And with the increase of the number of forwarding, the probability of collision increases with the increasing of packet-loss probability. Therefore, the maximum hop count in a wireless multi-hop network should be limited.

In our case, we set the maximum hop count up to 5 and the radiation distance up to 250 meters.

In practice, the topology of each node may be different devices, and the real topology should be showed as figure 3.2, such as hosts, routers, mobile phones and so on. These devices have different network cards, network cards have different network settings, resulting in delay and other performance will be different. In order to facilitate the experimental measurement, we set here all the nodes and the host exactly the same.

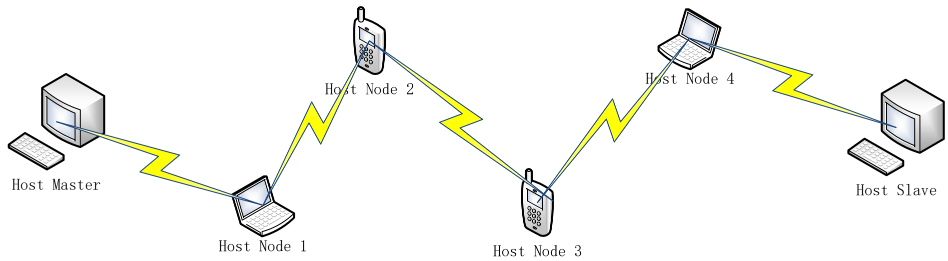

Figure 3.2: Real Teleoperation System Network Topological Structure

3.1.2 The Application Layer

At the application layer in figure 3.1, the application in the host master will send the user command signals with 1000 Hz to the host slave in the form of a packet. The command from user received by the haptic controller (a joystick). Every command is a frame of message length 24 Bytes. After the host master receives the command, it immediately calculates and predicts the robot's reaction, and reflects the virtual audio and virtual video results on the host display, with virtual tactile feedback on the joystick.

At the same time of command sending on the internet, the application in the slave host sends the current state of the robot with a frame of 1000 Hz 24 Bytes. It includes the current position, velocity, and the force situation of the robot. A robot in space has 6 degrees of freedom. These information can be represented by a vector with float values, i.e. 6 x 4 = 24 Bytes. The master sends control information and the slave sends feedback according to the 6 degrees of freedom.

When the robot host receives the command, it immediately executes the command to move the box and sends the current status to the host master. If the current status is different from the predicted feedback of the master, the prediction delay of the master will be corrected, if the real feedback is same as the predicted feedback, the delay of prediction is proved to be correct.

3.1.3 The Transport Layer

Designing Tactile Internet system and realizing it meets some challenges. The main challenge is the 1ms round trip (end-to-end) latency. The round trip latency can be defined as the time duration starts from the transmission of a small data packet from the transmitter's application layer and ends by the reception of the data by the receiver's application layer, including the response feedback dedicated by the communication process. Thus the round trip latency depends on the number of network nodes involved in the communication process. In order to reduce the round trip latency and achieve the 1ms latency requirement for the Tactile Internet system, the number of network nodes involved in the communication process should be reduced and bring them as near as possible to the user equipment. But in our teleoperation system, the prediction of host master will give the virtual feedback, it replaces real feedback and has no latency. Therefore, the round trip latency challenge becomes one-way latency (end to end delay of a packet). But added another challenge, jitter is 0. In other words, in the best case, the interval of signal frames from the same tactile application is constant. This is a big challenge because, on the one hand, the actual network link is dynamically changing; on the other hand, the sending collisions from multiple devices due to the number of retransmissions and retransmissions is random and indefinite, so it is difficult to ensure that the frame interval is constant .

In this case of the teleoperation system for a mobile robot, host Master and host Slave will send haptic information with 1000Hz as signal frequency to the other. That is to say, if the transmission successfully with ideal jitter 0, host master will update the robot model per 1ms (average delay), host master can predict the feedback of robot through pre-calculation. User will get a feedback from model prediction with no delay. With current technologies unable to overcome the latency challenge of 1ms, we need to optimize the transmission protocol (jitter 0) used for haptic signals as much as possible, and analyze the average delay that is required for one-way transmission based on the simulator, then predict the model feedback in how long time.

In this case at the transport layer, host Master and Slave will be at the same time produce tactile information packets, and continuously with 1000 Hz frequency transmits to the other, for updating the latest status. How to select packets transmission form depends on the requirements of the haptic communication for the transmission delay. Transmission forms include TCP and UDP. In general, the real-time applications select UDP as an efficient transport protocol. It includes the current position, velocity, and the force situation of the robot. From the content of the information, the content of the command frame includes only simple vector variables, the feedback frame includes position, force and motion vector. Although application in host master and in host slave are different, the tactile data they send is essentially the same, so their transmission frequency are the same UDP frame and the UDP capacity of 24 Bytes is enough. Thus, their UDP packets will be transported with 1000Hz, each packet with length 24 Bytes.

3.1.4 The Internet Layer

At the internet layer, since all nodes are hosts, the entire network is an ad hoc network with static route. Because different links lead to errors in the results (propagation delay), in order to ensure the accuracy of the experiment and the same propagation delay, it is required that all the networks with the same hop count use the same link for transmission.

3.1.5 The Logical Link Layer

At the logical link layer, the most important protocol is the MAC protocol, the coordination function in MAC protocol responsible for the management of transmission medium, to avoid conflict between distributed networks.

DCF: The fundamental access method of the MAC is a Distributed Coordination Function (DCF) known as carrier sense multiple access with collision avoidance (CSMA/CA).

PCF: The Point Coordination Function is a contention-free service for non-QoS stations. The PCF mechanism is obsolete. Consequently, the PCF mechanism might be removed in a later revision of the standard. And in the INET framework, the developer did not develop the corresponding module for PCF.

HCF: The Hybrid Coordination Function (HCF) uses both a contention based channel access method, called the enhanced distributed channel access (EDCA) mechanism for contention based transfer and a controlled channel access, referred to as the HCF controlled channel access (HCCA) mechanism, for contention free transfer.

MCF: The Mesh Coordination Function MCF implements the same EDCA as does HCF. In the INET framework, the developer did not develop the corresponding module for MCF.

As the haptic communication requirements, in the mash network or ad hoc network, the potential multi-group haptic communication applications have to send packets to each other with the contentions from the haptic application, so it cannot use PCF which is a contention-free service. Tactile information needs to compete with normal data, including audio data and video data, in a complex network with traffic and achieve the highest transmission priority, in order to obtain an optimal average delay. So how to get the highest priority has become a solution to reduce the delay of tactile information transmission.

3.1.6 The Physical Layer

INET can support wireless network card mode from IEEE 802.11a to IEEE 802.11n. In order to ensure the validity of our experiment in the future, we should choose the latest network card mode 802.11n for testing. This also ensures that the efficiency of the transmission protocol will not be affected by the limitations of the transmission hardware during the simulation.

802.11n is a wireless-networking standard that uses multiple antennas to increase data rates. The IEEE802.11n human employs OFDM modulation technique. The antenna technology used with the IEEE802.11n standard is supported as Multiple Input, Multiple Output (MIMO). Its purpose is to improve network throughput over the two previous standards 802.11a and 802.11g with a significant increase in the maximum net data rate from 54 Mbit/s to 600 Mbit/s at a channel bandwidth of 40 MHz.

Therefore, in this case Setting Bitrate to 600 Mbit/s and Bandwidth to 40 MHz.

3.1.7 Network Load Rate

In order to measure the transmission efficiency of tactile information in high network traffic, we need to compare two sets of experiments to compare tactile information in different coordination function transmission performance with or without background information transmission.

The first experiment is the transmission of haptic information without background information transmission. The second experiment is the transmission of haptic information when the network load rate is 50% of the background information.

The calculating of network load rate is the following formula:

$$NetworkLoadRate(\%) = \frac{MessageLength(bit) \times Frequence(Hz)}{Bitrate(mbps)} \tag{3.1}$$

With this formula we can compute that the network load rate of the tactile information 24 Bytes per 1 ms is 0.03% of 600 Mbps bitrate, and 1000 Bytes per 0.026 ms background information to fifty percent. It can be seen that the proportion of network occupied by background information is still quite high.

3.2 Protocol Purpose

The original EDCA channel access protocol is derived from the DCF procedures described in 2.3.1 by adding four independent enhanced distributed channel access functions (EDCAFs) to provide differentiated priorities to transmitted traffic, through the use of four different access categories (ACs).

We want to improve EDCA mechanism on the basis of HCF, and develop an enhanced coordination function for Tactile Internet applications. And its development should follow the following principles:

- The proposed TCF solution is an enhancement to HCF, i.e. all applications that can run with HCF also run with TCF (with/without adaptation).
- The proposed TCF will allow regular data flow of all formerly present HCF access categories (VO, VI, BE, BK).
- The proposed TCF solution does not change the behavior of the network when there is no Tactile data flow present. TCF behaves exactly as HCF in this case.

On this basis, we added a new AC, tactile control (TC), as shown in Figure 3.3. This figure illustrates a mapping from MAC Service Data Unit (MSDU) and User Priority (UP) to the transmit queues and the five independent EDCAFs.

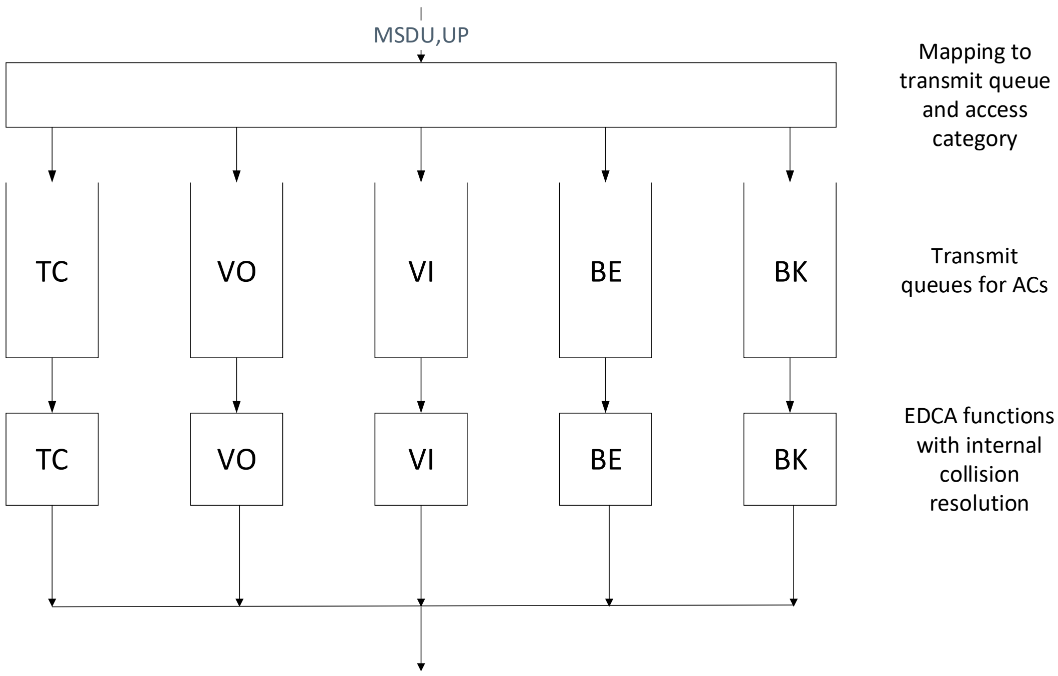

Figure 3.3: Overview of New EDCA Implementation Model

TC: Tactile Control Access Category, AC_TC.

VO: Voice Access Category, AC_VO.

VI: Video Access Category, AC_VI.

BE: Best Effort Access Category, AC_BE.

BK: Background Access Category, AC_BK.

When the Quality-Of-Service (QoS) function is enabled, the data processed by the QoS device is classified according to the type of data. Because each data type has different QoS requirements, the original HCF classifies the data types into eight access categories (0 - 7 ACs) according to the priority. For example, the voice data of voice communications requires relatively higher latency sensitivity and the priority of audio data transmission is high. The second is the video Data, its requirements for transmission are lower latency sensitivity than voice, largest volume data transmission; other data information is transmitted with best effort or as background information with lower priority. In contrast, tactile information differs from these general data in that it has highest latency sensitivity, extremely small data volume, and bi-directional transmission characteristics. So we need to add a highest priority AC (AC_TC). We propose this new AC that allows in one hand to ensure the highest priority of tactile information transmission and on the other hand to ensure the balance of transmission of tactile applications on both sides. The new AC parameters will be introduced in the following section Protocol Conception and will be compared with other ACs.

3.3 Protocol Conception

The Tactile Control Protocol conception will be introduced in this section. Which new function was added in original HCF, which parameters have modified for new function, why this modification for Tactile Internet better than original EDCA mechanism.

3.3.1 Access Category (AC)

The EDCA mechanism provides differentiated, distributed access to the Wireless Medium (WM) for stations using eight different User Priorities (Ups). The EDCA mechanism defines four access categories (ACs) that provide support for the delivery of traffic with UPs at the stations.

For each AC an enhanced variant of the DCF, called an enhanced distributed channel access function (EDCAF), like edcaf0 for background information, edcaf1 for best effort information, edcaf2 for video information and edcaf3 voice information. They contend for Transmit Opportunities (TXOPs) using a set of EDCA parameters: Inter-Frame Space (IFS), Contention Window (CW), Transmit Opportunity Limitation (TXOPLimit) and Retransmission Limitation (RetryLimit) and Queue Size Limitation (QueueSize).

The following rules apply for HCF contention based channel access:

- The minimum specified idle duration time is not the constant value (DIFS) defined for DCF, but is a distinct value, Arbitration Inter-Frame Space (AIFS) for different ACs.
- The contention window limits aCWmin and aCWmax, from which the random backoff is computed, are not fixed as DCF, but are variable and assigned by data types or by access points.
- During an EDCA TXOP won by an EDCAF a station may initiate multiple frame exchange sequences to transmit MAC management protocol data units (MMPDUs) and/or MAC service data units (MSDUs) within the same AC. The duration of this EDCA TXOP is bounded, for an AC. A value of 0 for this duration means that the EDCA TXOP is limited as defined by the rule for TXOP limit of 0.

Figure 3.4 introduces the AC parameters in the internet protocol architecture. From IP layer the data are transmit to Mac layer, these data will be at TCF in mac layer classified as five categories, from highest to lowest priorities they are tactile data, voice, video, background information and best effort information. Behind the calculating, these parameters ifs, CW, TXOP, Retry Limit and Queue Size Limit, will be used to control this frame transmission in physical layer. As the result, we can calculate the transmission Delay with delay formula. Delay of DCF depends on CW, DIFS, Retry limit and Queue Size. HCF or TCF Delay depends on CW, AIFSN, TXOP Limit, Retry Limit and Queue Size. The settings for these parameters are analyzed separately in the following sections.

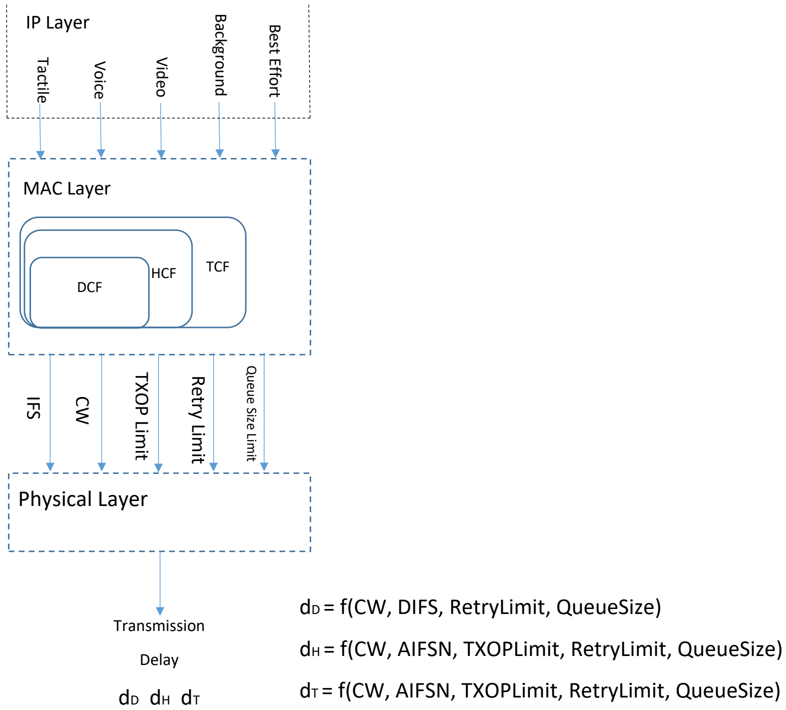

Figure 3.4: TCF Data Stream in TCP/IP

3.3.2 Inter-Frame Space(IFS)

The time interval between frames is called the Inter-Frame Space (IFS). A station shall determine that the medium is idle through the use of the carrier sense function for the interval specified. Ten different IFSs are defined to provide priority levels for access to the wireless medium. In this case, the following IFS types are more important:

Short inter-frame space (SIFS) is the shortest of the IFSs between transmissions from different stations. SIFS shall be used when stations have seized the medium and need to keep it for the duration of the frame exchange sequence to be performed. Using the smallest gap between transmissions within the frame exchange sequence prevents other stations, which are required to wait for the medium to be idle for a longer gap, from attempting to use the medium, thus giving priority to completion of the frame exchange sequence in progress.

The DCF inter-frame space (DIFS) shall be used by stations operating under the DCF to transmit Data frames and Management frames.

The arbitration inter-frame space (AIFS) shall be used by QoS stations that access the medium using the EDCAF to transmit: all Data frames, all Management frames, all Extension frames, and Control frames. The following table use to show the different between

ACs.

UP	AC	AIFSN
1, 2	AC_BK	7 Slots
0, 3	AC_BE	3 Slots
4, 5	AC_VI	2
6, 7	AC_VO	2
8	AC_TC	1

Table 3.1: Arbitration Inter-Frame Space

Setting small value of DIFS and AIFS will help to start counting down the backoff time counter faster, and increase the priority of the queue. AIFS and DIFS value can be calculated by using:

$$DIFS = SIFS + 2 \times SlotTime \tag{3.2}$$

$$AIFS[AC] = SIFS + AIFSN[AC] \times SlotTime \tag{3.3}$$

Where, AIFSN is an integer number which is used to define the number of waiting slot time. Normally, the voice and video queues have smaller values of AIFSN rather than other queues, in order to increase the priorities of real time data traffic. Therefore, the tactile information should have smaller values of AIFSN rather than voice and video, in order to take the highest priority of real time data traffic.

3.3.3 Contention Window

After this DIFS or AIFS medium idle time, the station shall then generate a random backoff period for an additional deferral time before transmitting, unless the backoff timer already contains a nonzero value. This process minimizes collisions during contention between multiple stations that have been deferring to the same event. The backoff time value can be calculated by using:

$$BackoffTime = Random() \times SlotTime \tag{3.4}$$

Where, Random() also called Contention Window (CW), CW parameter is an initial value that used to calculate the backoff time by selecting the random value between [1, CW]. The first value of CW sets to CWmin for the first transmission. If the collision happens again the CW will increase until reach CWmax. The difference between DCF and EDCA is CWmin and CWmax have different values for each AC in EDCA protocol, but DCF protocol has only one value of CWmin and CWmax. The following table use to show the different CW range between DCF and ACs in EDCA.

AC	CWmin	CWmax
DCF	15	1023
AC_BK	15	1023
AC_BE	15	1023
AC_VI	7	15
AC_VO	3	7
AC_TC	3	7

Table 3.2: Contention Window

If using a small value of CWmin will lead to get a small backoff time counter value, and the queue will be frantically accessing the media. Therefore, in the EDCA mechanism the voice queue has the smallest value of CWmin and CWmax. However, this mechanism has both advantages and disadvantages. A small value of CWmax will decrease the backoff time for a particular data type like voice data. But in the transmission contention process between these same types of data, this mechanism will increase the probability of collision. Since they have more similar values of CW, the similar values represent similar backoff times, and similar backoff times mean collisions occur, which means that all competitors (stations) have a failed sending. Thus, [3, 7] is a smallest range of CW for this medium contention process, also uses for the tactile information transmission.

3.3.4 Retransmission Limitation

The retry or retransmission limits as a basic MAC parameter are assigned to periodic traffic flows in terms of their deadline requirements. For example, periodic packets with the long deadline may be dropped because of the small retry limit although their deadline is far reached while periodic packets with the small deadline may already miss their deadline. The retry limit for the EDCA is pre-defined. If a high priority traffic with a long period is assigned with a small retry limit, the packets may be dropped even if the deadline is not reached. On the contrary, a large retry limit results in a high collision rate of the WLAN. The retransmission attempts will continue until the retry limit is reached. The contention window size is doubled in case of not only collisions but also the channel being busy. Every station maintains a station short retry count as well as a long retry count, both of which take an initial value of zero for every new packet. The different of the short retry count and the long retry count is limited by "threshold" value. When either of these limits is reached, retry attempts cease and the packet is discarded.

In the paper of P. Chatzimisios, A. C. Boucouvalas and V. Vitsas [10], they found that, the adjustment of the retry limit to a higher value results in the lowest packet drop probability and a small increase of packet drop time and delay due to the larger number of packets not being discarded and transmitted successfully.

The average delay for a successfully transmitted packet is defined to be the time interval from the time the packet is at the head of its MAC queue ready to be transmitted, until an acknowledgement for this packet is received. If a packet is dropped because it has reached the specified retry limit, the delay time for this packet will not be included into the calculation of the average delay. In their paper of 2003 [11], the average packet delay E[D]

, provided that this packet is not discarded, is given by:

$$E[D] = E[X] \cdot E[slot] \tag{3.5}$$

Where E[X] is the average number of slot times required for successfully transmitting a packet and is given by:

$$E[X] = \sum_{i=0}^{m} [\frac{(p^i - p^{m+1}) \cdot \frac{W_i+1}{2}}{1 - p^{m+1}}] \tag{3.6}$$

Where W is the contention window size, i is the backoff stage, i∈[0,m] and m represents the station short retry count. $1 - p^{m+1}$ is the probability that the packet is not dropped and $\frac{p^i - p^{m+1}}{1 - p^{m+1}}$ is the probability that a packet that is not dropped reaches the i stage.
In summary, each combination of parameters achieves an improved performance on some specific metrics compared to the standard proposed values and the choice of which set of protocol parameters should be employed depends on the specific communication requirements. There are many options for retry limit for different applications and networks. Therefore, we need to set the parameters according to the Tactile Control Function.

3.3.5 Transmit Opportunity Limitation

TXOP limit is another important parameter of the EDCA protocol that allocates the channel resource for the QoS Stations over the network. TXOP limit allows transmitting a burst of frames through the wireless medium without re-entering any traffic from other stations (a TXOP limit of null value means that a data transfer of one frame per access to the medium is authorized). In general the high value of the TXOP means the higher priority.

Due to the fixed allocation of TXOP limit in IEEE802.11, some limitations are encountered in the network. For example, during a lightly loaded network, channel bandwidth is wasted because there is no traffic to transfer but the fixed long TXOP limit occupies the channel. Conversely, when the traffic load is very high, then the traffic is not allowed to occupy the channel because the fixed short TXOP duration expires. Therefore, the M. K. Alam, S. A. Latif, M. Akter1, F. Anwar1, Mohammad Kamrul Hasan [9] come up a dynamic allocation of TXOP limit facilitates efficient bandwidth sharing and influences throughput and end-to-end delay of applications over the network.

Another limitation appears in our case, in MMT, the control information from users and the feedback from robot information is the same kind of application, they must be transmitted simultaneously, which means that they have the same priority in transmission. Thus, the TXOP on either side should not be too long. Since any side TXOP too long will lead to the other side cannot use the medium in a long time, the results will lead to an increase in average delay. Tactile applications transmit very small amounts of data, such as position vectors, velocities and pressure values. And one single frame 24 Bytes capacity is sufficient to meet its requirements. So it does not require data fragmentation and defragmentation, which means it does not take a long time to occupy the medium to transfer a large file, such as video data.

After testing, we found setting TXOP limit of AC_TC to 1 ms, which guarantees minimum packet loss on the one hand, on the other hand, it reduces the queuing delay. The following table use to show the different TXOP limit values between ACs in EDCA.

AC	TXOP Limit
DCF	0
AC_BK	0
AC_BE	0
AC_VI	3.008 ms
AC_VO	1.504 ms
AC_TC	1 ms

Table 3.3: TXOP Limit

3.3.6 Queue Size Limitation

The queuing delay is the time a job waits in a queue until it can be executed. It is a key component of network delay. In general, queueing delay depends on queue size, without considering the Throughput, the smaller the queue can bring a smaller average delay. In practice, this blocking probability often depends on the queue size. Therefore, in the paper of ANDRZEJ CHYDZINSKI carry out an analysis of the queueing system in which an arriving packet is dropped with a probability that is a function of the queue size observed upon arrival. This function is a dynamic queue size function, they found that packets loss probability is not only depends on queue size.

Queue theory is to guarantee the integrity of the transmission, to ensure that all tasks to be processed in accordance with the order. In our case, robots need to receive the commands from users with 1000 Hz, and users' computer also need to receive the feedbacks from robots with 1000 Hz. If the previous frame is not sent successfully within 1 ms, the new frame from up layer or up station will be discarded when there is no queue place. As a whole process, the smaller the queue size and the larger the packet loss rate.

After the experimental test, the packet loss rate has been declining until the queue size is 14. At this point, the packet loss rate has reached 0.1%, after that no more major changes. So we set queue size 14 as the same like default setting, it can meet the 1000 Hz requirement. The following table use to show the queue size limit values between ACs in EDCA.

AC	Queue Size Limit
DCF	14
AC_BK	14
AC_BE	14
AC_VI	14
AC_VO	14
AC_TC	14

Table 3.4: Queue Size Limit

3.3.7 Protocol Construction

This section describes the specific functions of all TCF modules and the modifications for tactile information transmission, figure 3.5 is HCF in INET Framework, the structure of all classes:

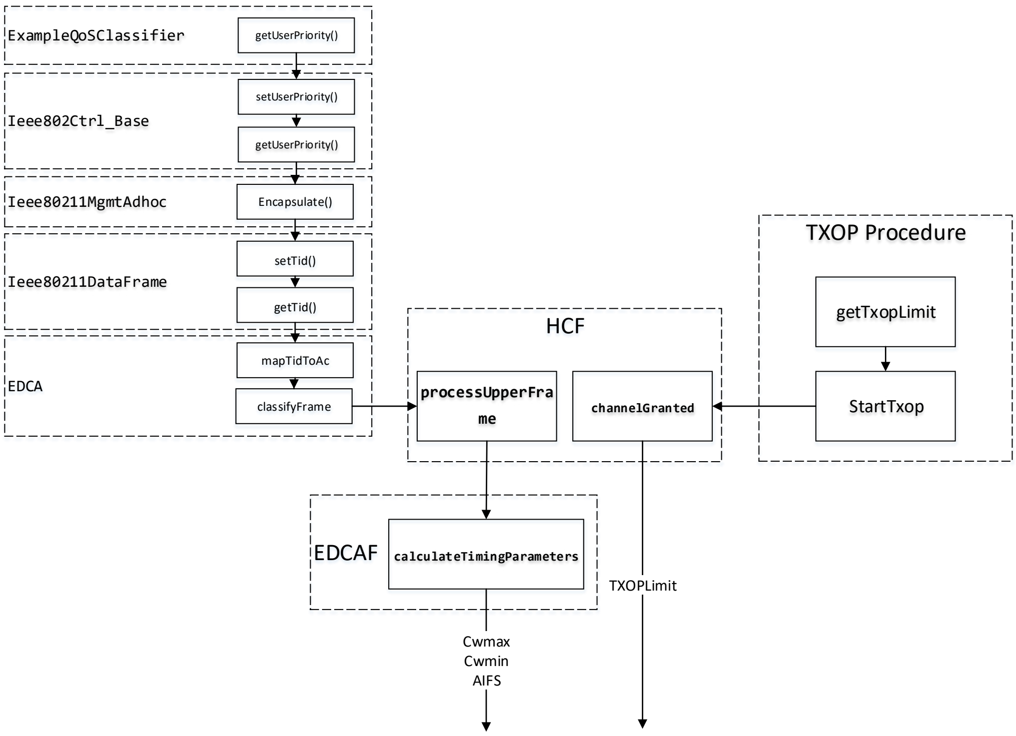

Figure 3.5: Flowchart of TCF

HCF

The processUpperFrame in the HCF is responsible for determining whether the received frame belongs to the QoS frame. If it is a QoS frame, HCF needs to determine its priority. If it is a non-QoS frame, it will be sent according to the priority AC_BE. ChannelGranted is responsible for judging the occupancy time of the channel. That is, the occupancy time according to the priority of the frame, indicated by TXOPLimit here.

User Priority (UP) to Transmission Process Identification (Tid)

Tid is user priority in the transmission process identification. User priority is classified by destination port of the target host. For example, when an application selects a 5500 port for transmission, the frame is transmitted with the priority of tactile information, AC_TC.

Tid to AC

HCF needs to use classifyFrame function to determine the priority of QoS frames. ClassifyFrame calls mapTidToAc to classify frames with different Tid according to the Access Category map. Finally, the priority AC of QoS frame is passed back to HCF.

TXOP Procedure

Txop Procedure Select TxopLimit according to the priority AC and the physical mode of wireless transmission.

EDCAF

EDCAF according to the priority and user settings to calculate CW and AIFS, this process is caculateTimingPrarameters.

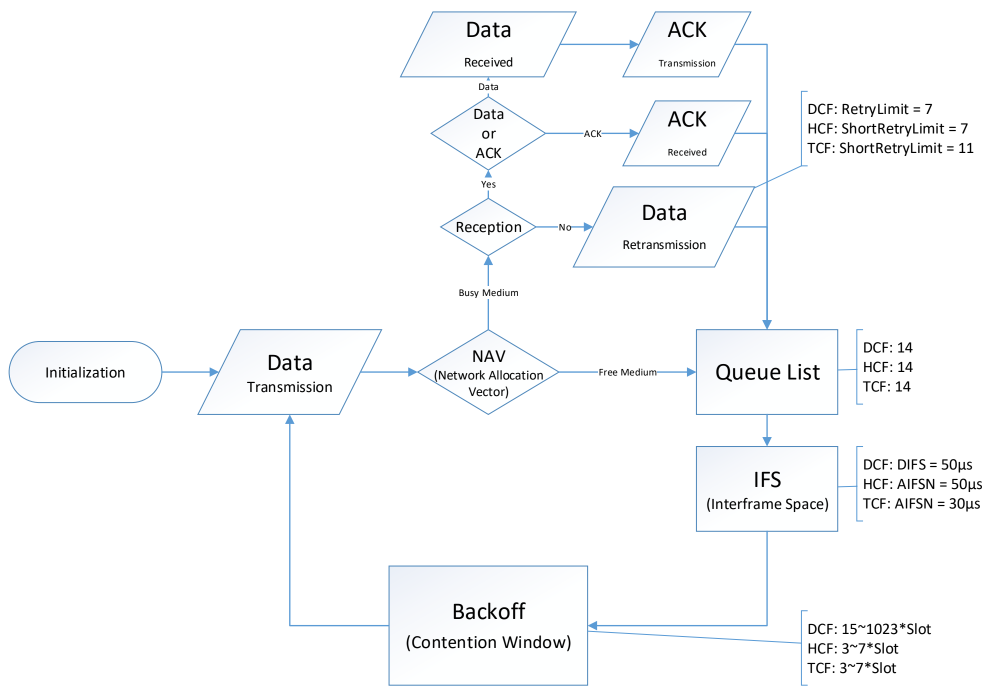

Figure 3.6: The Cycle of EDCA Mechanism

EDCA logic structure as shown in the figure 3.6 of EDCA cycle. Take the master as an example, it enters the data transmission cycle after each initialization. After completion of transmission into the NAV state immediately, if the medium is free, after the IFS is to begin competition for the next time data transmission. If the channel is busy, then wait and receive data, if the received data from the Slave, send acknowledgement to confirm that the data has been received; if it receives an acknowledgement indicates that the transmission is successful, ready to send the next packet; if it did not receive ACK then enter the retransmission. In addition to CW, AIFS and TXOP, the number of retransmissions and queue size are most important for the delay in this process.

3.4 Limitations of the Protocol

This section is mainly from a few variables were described original HCF protocol limitations, they are traffic condition, TXOPLimit, CW and AIFS. The numbers of real time application users affect the QoS parameters, as the end to end delay and packet loss. So there is a limitation in EDCA protocol caused by increasing the collision inside the network. EDCA parameters such as CW and AIFS are fixed for each access category, and trying to make these values flexible depending on the number of collisions inside network may solve this limitation.

Depending on these results, EDCA protocol has limitations when increasing the number of voice or video applications. This means when the numbers of real time application increase, the internal and external collision will rise and lead to high values of end to end delay and packet loss. So there is a limitation when used EDCA protocol with real time application because EDCA can tolerate a specific number of voice and video applications in the same network.[12]

CHAPTER 4

Implementation

This chapter describes how to implement our conception. This includes what kind of simulation we use to build the experimental environment; why choose this way; and how to build experimental environment. The construction of experimental environment will be elaborated from the following two aspects: the establishment of the network topology and the configuration of the network environment.

4.1 Selection of Experimental Tools

4.1.1 Comparing Simulator and Testbed

On the one hand, simulator have many advantages that can hardly be replaced by testbed. In simulator, network scenarios can be easily constructed and modified, and data can be easily collected. More importantly, simulations can model large scale network topologies which would be very expensive in testbed experiment, that would require hardware and labor resources. Moreover, testbed experiment results are heavily affected by the testing environment, which is often highly random and uncontrollable. For example, a little, tiny change surrounding a wireless communication parties such as temperature increases, or a door is closed, can affect the communication quality, and thus change their throughput.

On the other hand, wireless network simulators have their own limitations. Due to the inadequacy of models, especially at the PHY layer, simulators are often accused of not being able to provide as trustworthy results as real testbed does [13].

In our case, due to the hardware limitations and high costs in testbed experiments, simulator can play a more important role for the tactile control function protocol development, different coordination functions performance evaluation, and wireless traffic analysis.

4.1.2 Comparing Simulators

Currently there are many network simulators that have different features in different aspects. A short list of the current network simulators include OPNET, NS-2, NS-3, OMNeT++:

OPNET is a popular simulator used in industry for network research and development.

NS2 are the most popular one in academia because of its open-source and plenty of components library.

NS-3 is an active open-source project and it is still under development. It has several simulator features designed to aid current Internet research. It is also a community-based development and maintenance model, which needs more people and organizations to participate to contribute before it become good enough for the Internet research community.

OMNeT++ is being used in the academia as well as in industry. It is designed to provide a component-based architecture, the models or modules of OMNeT++ are assembled from reusable components. Modules are reusable and can be combined in various ways which is one of the main features of OMNeT++. As the key feature of OMNeT++ for our case, it represents a framework approach, like INET framework that has the Enhanced IEEE 802.11 MAC from version 3.6.0. That is to say, in our case the wireless multi-hop networks can use the MIMO mode of IEEE 802.11n.

4.2 Construction of Simulation of Ad Hoc networks

This section will detail to explain the process to build the experimental Ad hoc networks for TCF, called TCF networks. The specific construction process is divided into two parts, TCF networks topology (network description NED file) and TCF networks configuration (INI file).

4.2.1 TCF Networks Topology in Experimentation

Network definition file (NED) created by OmniNET++ with C++. It is a software package used for building network simulators, stores the network topology structure and used for describing the logical structure of the network that will be simulated in the software.

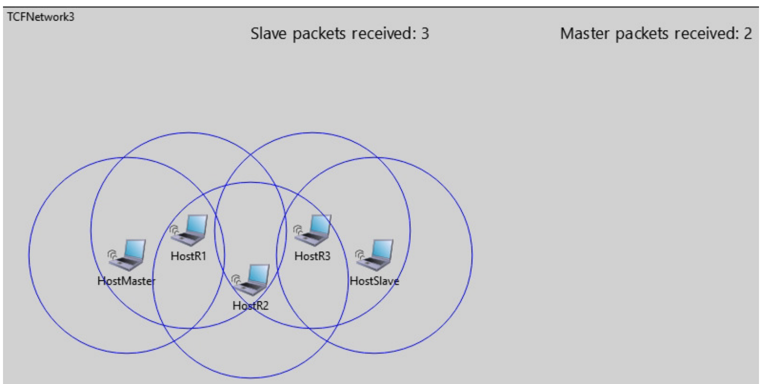

Figure 4.1: An Example of 4 Hops TCF Network Topology

Radio Definition

All networks must rely on the media as a carrier for the transmission of information, such as a wired network requires physical media as the link cable as information carrier. For example, wireless networks requires the radio waves as a carrier. The INET framework classifies 802.11 Radio in several flavors, differing with their Medium and their level of detail, as follows:

802.11 Raido Types	Radio Medium Types	Detail
Ieee80211Radio	Ieee80211RadioMedium	Ieee80211 Radio basic modes
Ieee80211IdealRadio	IdealRadioMedium	Ideal analog representation
Ieee80211ScalarRadio	Ieee80211ScalarRadioMedium	Scalar transmission power

Table 4.1: The IEEE 802.11 Radio Models

In this case, here we choose the last type of Radio model as a test model, it extends IEEE 802.11 Radio and uses scalar transmission power in the analog representation. And it must be used in conjunction with the "Ieee80211ScalarRadio" model.

Hosts and Nodes Definition

According to our experimental purposes and development purposes, at first determined the entire network does not require a wired transmission device, the entire TCF multi-hop network should be constituted by a number of wireless transmission device. There are many types of wireless device models, their transmission performance depends on their Network Interface Card (NIC) type. However, selecting multiple different types of wireless devices may result in inaccurate experimental results. Therefore, all nodes in the network should select the same type of wireless devices "WirelessHost" (a standard wireless host type) and set the same NIC for transmission. Because our protocol is based on IEEE802.11 standard, so we should choose the corresponding NIC to test. The INET framework classifies 802.11 network cards in several flavors, differing in their role (ad-hoc station, infrastructure mode station, or access point) and their level of detail, as follows:

NIC Types	Description
Ieee80211Nic	a generic (configurable) NIC
Ieee80211NicAdhoc	for ad-hoc mode
Ieee80211NicAP, Ieee80211NicAPSimplified	for use in an access point
Ieee80211NicSTA, Ieee80211NicSTASimplified	for use in an infrastructure-mode station

Table 4.2: The Network Interface Card (NIC) Classification

Both types of network cards: "Ieee80211Nic" and "Ieee80211NicAdhoc" are in line with our testing requirements. In order to facilitate the later adjustment of variables, such as setting the management of NIC as an ad hoc host or a router, so here we choose the first. In addition we also need to choose a type of NIC management for station, also differing in their role (ad-hoc station, infrastructure mode station, or access point). As the haptic application client hosts, host master and slave should choose "Ieee80211MgmtSTA" (a NIC management type for station); all other nodes as access points, only responsible for forwarding, so choose "Ieee80211MgmtAP" model (a NIC management type for access point).

Hosts and Nodes Definition

The ideal environment or application scene for our testing should be:

- Outdoor without walls or obstacles: Because indoor walls or doors will interfere with the signal. Indoor experiment targeted relatively strong, only suitable for a particular housing structure. Therefore, in order to test the general applicability, we choose the outdoor scenes without obstacles.
- Multi-hop network communication distance increases with the hop count increases: In order to facilitate comparison between experiments, when the hop count increase one node, the distance between the two ends of the increase of 50 meters, as shown in the following figure:

Hop Count	Euclidean Distance
1 Hop	50 m
2 Hops	100 m
3 Hops	150 m
4 Hops	200 m
5 Hops	250 m

Table 4.3: The Hop Count and The Euclidean Distance of TCF Networks

- The unique Link: Since the effective transmission range is much larger than the coverage of the TCF network, we need a unique static routing link to guarantee a certain number of hops.
- Delayed Challenges: The biggest challenge for haptic networks is the 1 millisecond delay between roundtrips, so the ideal delay for one hop transmission is 1 millisecond. In theory, the ideal delay for a 5-hop network is 5ms. Because too many forwardings can cause significant delays, humans can perceive this delay, so in this case the execution of the network is not available. Therefore, we control the maximum number of hops to 5.
- Fairness of Transmission Competition: Tactile interaction is a pair of bidirectional peer-to-peer transmission applications that require equal status between competing hosts, such as the same distance, the same frequency, and the same power. In order to ensure the fairness of competition of transmissions from both sides in the simulation, we set the topological structure as a axisymmetric structure. All nodes in the network are symmetrically distributed with each other. The physical distance will directly affect the propagation delay. In order to make the propagation delay of tactile information from both sides the same, here we choose to distribute all nodes symmetrically.

In summary, all node coordinates in the TCF network are set according to the following table (taking 5 hops as an example):

Host name	x-axis coordinates(m)	y-axis coordinates(m)
Master	100	200
R1	150	250
R2	200	150
R3	250	250
R4	300	150
Slave	350	200

Table 4.4: An Example of 5 Hop Network

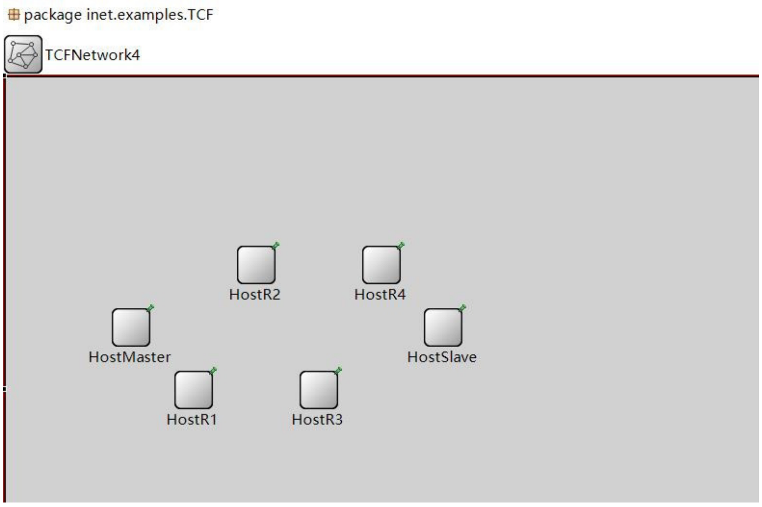

Figure 4.2: An Example of 5 Hops TCF Network Topology in NED File

This topology design as shown figure 4.2 in the IDE of Omnet++, basically completed the construction of tactile network infrastructure. In the following section, all the devices will be set up specifically.

4.2.2 TCF Network Configurations

Network configuration is about how to run the TCF network configuration file. The purpose of our experiment is to test the impact of different cooperation functions on delay and whether the network load will affect the delay of TCF Network transmission. Therefore, we need to configure different network protocols with the network configuration file to adapt to different coordination function and different network environments. This section will be described our TCF network configuration according to different protocol layers.

Application Layer Configuration

In this case, the haptic transfer application is a set of bidirectional independent transfer applications. Although it is tactile communication, in order to eliminate the delay, the model predicts virtual feedback before receiving the real feedback, so the command and the feedback are independent of each other. But in order for them to be able to send messages stably with the shortest delay and to correct the prediction in time, we need a set of the udp transport with no guarantee of delivery or duplicate protection, no handshaking dialogues and connectionless communication. As shown in Table 4.5, HostMaster.udpApp [0] represents the udp package sent by the host Master, and HostSlave.udpApp [0] represents the udp package sent by the host's Slave. The first variable is the udp send destination, the information from the master sent to the Slave, udp packets from the slave will be sent to master.

The local Port and the destination Port indicate the interface for receiving and processing information, which is closely related to the priority of the transmitted information. For details, please refer to Chapter Three. Here, in the testing of TCF coordination function, Port 5500 indicates that this tactile message will be transmitted at the highest priority of 8, which is AC_TC.

Requirements for haptic information transmitting frequency: 24 bytes of information is transmitted to the destination at a frequency of 1000 hertz. Therefore "messageLength" indicates the size of the message is 24 bytes. The transmission interval of 1ms means the frequency of 1000 Hz.

HostMaster Parameter Name	Value	HostSlave Parameter Name	Value
*.udpApp[0].destAddresses	"HostSlave"	*.udpApp[0].destAddresses	"HostMaster"
*.udpApp[0].localPort	5500	*.udpApp[0].localPort	5500
*.udpApp[0].destPort	5500	*.udpApp[0].destPort	5500
*.udpApp[0].messageLength	24 B	*.udpApp[0].messageLength	24 B
*.udpApp[0].sendInterval	1 ms	*.udpApp[0].sendInterval	1 ms

Table 4.5: The Configuration of Tactile Information in The Application Layer

In order to test the impact of network load on latency, we need to set up one or more background transport messages to take up part of the network resources. Our goal is to test the tactile transmission delays when network occupancy is 50 percent. Therefore, we need to add a set of udp applications without changing any other configuration and bring it up to 50% of the traffic load rate, as shown in Table 4.6 below. "udpApp[1]" indicates the udp application of the background information. The master and slave mutually send and receive with each other. The port for background information processing is "80" because this port is used to handle lower-priority and best-effort messages. The priority of the background information should be lower than the priority of the haptic information. Using Equation 3.1, it can be calculated that the network occupancy rate reaches 50% when the message size is 1000 Bytes and the transmission interval is 0.026 ms with Bitrate 600 Mbps.

HostMaster Parameter Name	Value	HostSlave Parameter Name	Value
*.udpApp[1].destAddresses	"HostSlave"	*.udpApp[1].destAddresses	"HostMaster"
*.udpApp[1].localPort	80	*.udpApp[1].localPort	80
*.udpApp[1].destPort	80	*.udpApp[1].destPort	80
*.udpApp[1].messageLength	1000B	*.udpApp[1].messageLength	1000B
*.udpApp[1].sendInterval	0.026 ms	*.udpApp[1].sendInterval	0.026 ms

Table 4.6: The Configuration of Background Information in The Application Layer

Network Layer Configuration

For the network layer, its configuration is very simple. Because in order to eliminate the potential transmission delays from the impact of different links, we designed only one link for transmission. Briefly, this experiment does not involve potential delays caused by network addressing.

Link Layer Configuration

The configuration of the logical link layer is one of the most important aspects of the experiment. It involves the selection of coordinated functions (DCF, HCF and TCF) and the setting of key variables (Queuing Size and Retransmission Count). As shown in the following table, the default configurations of these variables in original coordination functions (DCF and HCF) protocols are different and all coordination functions require special settings. The specific settings and descriptions are as follows:

- "qosStation" means the Quality of Service (QoS) function of a device, true means that the QoS function is enabled, and false means that it is off. In other words TCF and HCF can open QoS function, but DCF function without QoS must be closed.
- "classifierType" indicates the classification tpye of user information priority, and "ExampleQoSClassifier" indicates how the device classifies information prioritized when the QoS function is enabled. DCF does not have this feature.
- "maxQueueSize" is a basic parameter of the TCF network, which indicates the maximum waiting queue for the current device. For details, see Chapter 3. The value of the variable here is the actual value in the experiment.
- "retrayLimit" is a basic parameter of the TCF network, indicating the maximum count of retransmissions allowed by the current device. For details, see Chapter 3. The value of the variable here is the actual value in the experiment.

TCF Parameter Name	TCF Value	HCF Value	DCF Value
qosStation	True	True	False
classifierType	"ExampleQoSClassifier"	"ExampleQoSClassifier"	no
maxQueueSize	14	14	14
retrayLimit	11	7	7

Table 4.7: The Configuration in The Link Layer

Physical Layer Configuration

Physical layer configuration describes the mode of the network card transmission and the mode of Radio. The variables in the following table are the physical characteristics that can greatly affect the network structure:

- "opMode" indicates the transport protocol version, and INET can simulate IEEE 802.11 standard protocols including: 802.11a, 802.11b, 802.11g and 802.11n. We chose "n" which is 802.11n, because it has the fastest transfer bitrate and the delay will not be greatly affected by the bitrate limitation. In this mode, we can use similar bitrate of 600 mbps MIMO mode for transmission.
- In 802.11 mode, INET provides three radio modes, the "Ieee80211ScalarRadio" mode can simulate the transmission in the case of scalar power. After testing, wireless devices with 100mW can meet the outdoor scenes transmission distance more than 5000 meters. This transmission range is far greater than the coverage of the TCF network, which ensures that the transmission efficiency of haptic information is not affected by signal attenuation.

Parameter Name	Parameter Value
opMode	"n(mixed-2.4Ghz)"
bitrate	600 Mbps
radioType	"Ieee80211ScalarRadio"
transmitter.power	100 mW

Table 4.8: The Configuration in The Physical Layer

CHAPTER 5

Evaluation

This chapter will to explain the hypothesis of the whole experimentation at first. In the experimentation performing phase, it introduces the structural framework of the experiment and experiment parameters. The evaluation will be combined with the evaluation of tactile information transmission performance and the evaluation of tactile information transmission process.

5.1 Expectation of Expermentation

Experimental execution is divided into two groups, the first group of experiments is to simulate tactile information transmission without background information transmission; the second group of experiments is to simulate tactile information transmission with background information transmission. Each group of experiments will use three different coordination function protocols to test the wireless transmission efficiency of tactile information, which are DCF, HCF and TCF. According to the requirements of the experiment, each test is carried out in five network topologies with different number of nodes, from 1 hop network to 5 hops network, as shown in the experimental structure table 5.1.

The first set of experiments in order to prove the hypothesis: the network transmission delay depends on the number of nodes. The second set of experiments compared to the first set of experiments was to prove the hypothesis that the network transmission delay did not depend on the traffic load. Combined with the two sets of test data, we hope to prove that when the hop count increases, TCF transmission average delay and jitter is better than DCF and HCF, can guarantee haptic communication QoS.

5.2 Experiment Performing

Experimental Performing is divided into two groups, as shown in the experimental structure table 5.1. The first group of experiments is to simulate tactile information transmission without background information transmission; the second group of experiments is to simulate tactile information transmission with background information transmission. Each group of experiments we will use three different coordination function protocols to test the wireless transmission efficiency of Tactile information, which are DCF, HCF and TCF. According to the requirements of the experiment, each test is carried out in five network topologies with different hop count, from 1 hop network to 5 hops network.

Experiment Groups	Coordination Function	Count of Nodes
1. Tactile Information Transmission	1.1 DCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops
	1.2 HCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops
	1.3 TCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops
2. Tactile Information Transmission with Background Information Transmission	2.1 DCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops
	2.2 HCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops
	2.3 TCF	1 Hop 2 Hops 3 Hops 4 Hops 5 Hops

Table 5.1: The Table of The Experimental Structure

5.2.1 Tactile Information Transmission without Background Information Transmission

This group of experiments is to simulate tactile information transmission without background information transmission. The wireless transmission performance of three different coordination functions, which are DCF, HCF and TCF, were measured separately in five different scenarios, from 1 hop network to 5 hops network, as shown in the experimental structure table.

Parameter Name	DCF Value	HCF Value	TCF Value
Simulation Time	5s	5s	5s
Send Interval (Tactile)	1ms	1ms	1ms
Count of Packets (Tactile)	4001	4001	4001
Euclidean Distance	50m - 250m	50m - 250m	50m - 250m
Hop Count	1 - 5	1 - 5	1 - 5
Transmitter Power	100mW	100mW	100mW
NIC Mode	802.11n 2.4Ghz	802.11n 2.4Ghz	802.11n 2.4Ghz
Bitrate	600Mbps	600Mbps	600Mbps
Band Width	40MHz	40MHz	40MHz
Message Length (Tactile)	24B	24B	24B
Interface Port (Tactile)	5000	5000	5500
QoS (Tactile Information)	false	true	true
IFS	DIFS	AIFS[2]	AIFS[1]
CWmin	15	3	3
CWmax	1023	7	7
TXOP Limit	0	1.504ms	1ms
Retry Limit	7	7	11
Queue Size	14	14	14

Table 5.2: The Experiment Parameters of Tactile Information Transmission

In this set of experiments, all tests were limited to simulation time 5s, Omnet++ default all simulations start after 1s, that is, the actual simulation run time 4s. And the required interaction frequency of the haptic communication application is 1000 Hz, the transmission interval is 1 ms, that is, one frame is transmitted every millisecond. Therefore, each test, the number of packets sent in one direction is 4001, and a total of 8002 data frames are sent in both directions.

Second, the Euclidean Distance changes with the increase of the Hop Count gradually increases, the distance of each hop is 50m, so the distance of five hops is 250 meters. Transmitter Power is set to 100mW, its effective transmission range is much larger than the coverage of the TCF network, which ensures that the transmission efficiency is not reduced due to energy decay. The NIC mode is set to 802.11n 2.4GHz, the bit rate of 600Mbps and the bandwidth of 40MHz ensure that our experiments are using the best network environment, minimizing their impact on tactile transmission efficiency.

The most importantly, routing is static routing, where bi-directional haptic communication is transmitted through the same link, so they will compete with each other and may produce collisions. This contention and potential collision is the main reason for the queuing delay. Three coordination functions DCF, HCF, and TCF use different parameters and mechanisms to transmit the same data. The same aspect is the information size with 24B. The DCF does not have the QoS mechanism, so it treats all data that needs to be sent fairly, and any interface port is the same in the DCF. The HCF and TCF are different, they can use the QoS mechanism, the choice of interface port is directly related to the priority of data processing. In the HCF, the 5000 is the highest priority port, and for the best transmission performance we chose it to transmit tactile information. In the TCF in 5500 is the highest priority port, and it is designed for tactile information transmission. The contention parameters of different CFs include IFS, contention window range (CWmin and CWmax), maximum TXOP (txop limit) and queue size (Refer to Chapter 3 for the setting of contention parameters). The maximum number of retransmissions (retry limit) will be introduced in the next section.

5.2.2 Tactile Information Transmission with Background Information Transmission

Parameter Name	DCf Value	HCf Value	TCf Value
Message Length (Tactile)	24B	24B	24B
Send Interval (Tactile)	1ms	1ms	1ms
Count of Packets (Tactile)	4001	4001	4001
Message Length (Background)	1000B	1000B	1000B
Send Interval (Background)	0.026ms	0.026ms	0.026ms
Count of Packets (Background)	154001	154001	154001
Simulation Time	5s	5s	5s
Euclidean Distance	50m - 250m	50m - 250m	50m - 250m
Hop Count	1 - 5	1 - 5	1 - 5
Transmitter Power	100mW	100mW	100mW
NIC Mode	802.11n 2.4Ghz	802.11n 2.4Ghz	802.11n 2.4Ghz
Bitrate	600Mbps	600Mbps	600Mbps
Band Width	40MHz	40MHz	40MHz
Interface Port (Tactile)	5000	5000	5500
Interface Port (Background)	80	80	80
QoS	false	true	true
IFS	DIFS	AIFS[2]	AIFS[1]
CWmin	15	3	3
CWmax	1023	7	7
TXOP Limit	0	1.504ms	1ms
Retry Limit	7	7	11
Queue Size	14	14	14

Table 5.3: The Experiment Parameters of Tactile Information Transmission with Background

In this group of experiments, all haptic transmission settings are the same as in the previous group of experiments. In order to compare the transmission performance under different network loads, this set of experiments increased the network occupancy by 50% with a background information. Therefore, the test set the background information transmission capacity of 300Mbps per second from the Host slave to the Host master, sending interval 0.026ms, each frame size is 1000B. So for each test, background application sends a total of 154001 data frames.

Since the transmission mechanism of background information is different because of the setting of CF. DCF does not have the QoS mechanism and handles all data fairly. Therefore, the priority of background using port 80 and haptic information 5000 is the same in DCF.

The HCF and TCF are different, they use the QoS mechanism, the choice of interface is directly related to the priority of data processing. In HCF and TCF, 80 is the lower priority port compared to 5000 and 5500.

For the retry limit setting, through testing in the 5 hops TCF-Network with 50% traffic load, we have got the following vectors for the retry limit and the average delay in the table 5.4:

Short Retry Limit	Average Delay
6	3.039ms
7	2.994ms
11	2.976ms
15	2.975ms
20	3.032ms

Table 5.4: Retry Limit

In this case, we will not use retry limit less than 5, because their packet-loss rate is larger than 50%; if retry limit is bigger than 20, the average delay is too large. In the retry range 5 to 20, the lowest point is the retry limit 11 with the shorter delay 2.967ms than the default retry limit 7 with delay 2.994ms. Therefore, we chose the Short Retry Limit 11 for TCF to minimize the delay and ensure transmission success rate.

5.3 Evaluation of Tactile Information Transmission Performance

In this section, we will evaluate the impact of different coordination function protocols on the tactile internet performance by analyzing statistical results of haptic information transmission. Evaluation of transmission performance will mainly be analyzed from the following three statistical metrics: latency, jitter and throughput.

5.3.1 Evaluation of Tactile Information Transmission Latency

The experiments are divided into two groups according to the different traffic load rates: without background information transmission (traffic load rate 0%) and without background information transmission (traffic load rate 50%). The following content will be evaluated separately from these two aspects.

Tactile Information Transmission without Background Information Transmission

This group is simulation results of tactile information transmission without background information transmission. The wireless transmission performance of three different coordination functions, which are DCF, HCF and TCF, were measured separately in five different scenarios, from 1 hop network to 5 hops network, as shown in figure 5.1:

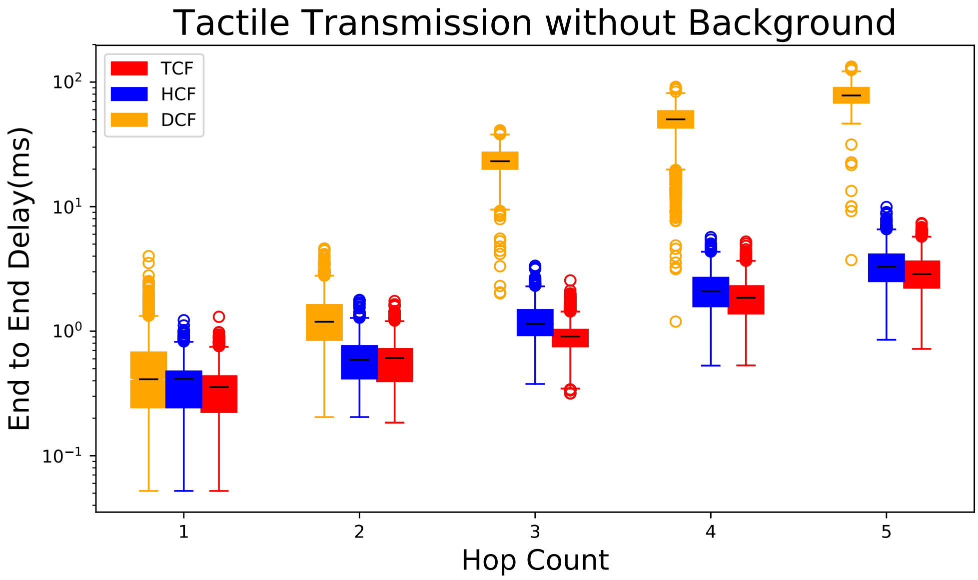

Figure 5.1: Tactile Information Transmission Delay Comparison between DCF, HCF and TCF in Boxplot

From this figure we can see that the average delay of tactile information gradually increases with the number of forwarding (hop count). The main reason for the delay increasing is the increasing of collision probability. The number of forwarding nodes means the minimum number of contention that a single frame needs to pass through. If the probability of success of each competition is P, then the probability of the success of N times forwarding is the maximum P^N. More details about the end-to-end delay result as table 5.5 below:

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	0.477ms (± 0.013)	1.285ms (± 0.025)	23.729ms (± 0.29)	48.597ms (± 1.068)	79.449ms (± 1.577)
HCF	0.379ms (± 0.006)	0.584ms (± 0.009)	1.206ms (± 0.016)	2.177ms (± 0.032)	3.419ms (± 0.05)
TCF	0.346ms (± 0.005)	0.577ms (± 0.008)	0.918ms (± 0.011)	1.890ms (± 0.027)	2.976ms (± 0.043)

Table 5.5: End to End Delay and Confidence Interval (99%) of Tactile Information Transmission

Evaluation of DCF:

For DCF, when the hop count in two, the average delay still can be accepted. When more than two hops, the average latency even more than 20ms. In addition, due to the excessive packets loss and higher standard deviation of delay, the confidence interval has become very large. Such performance is not enough to support a smooth and accurate prediction of the model.

Evaluation of HCF:

Compared with the DCF, HCF always maintained a low level of delay. This is due to EDCA mechanism and shorter backoff times.

Evaluation of TCF:

For TCF, the average delay has been handled very well as, even better, it still guaranteed within 1ms in 3 hops.

Tactile Information Transmission with Background Information Transmission

This group is simulation results of tactile information transmission with background information transmission. The wireless transmission performance of three different coordination functions, which are DCF, HCF and TCF, were measured separately in five different scenarios, from 1 hop network to 5 hops network, as shown in figure 5.2:

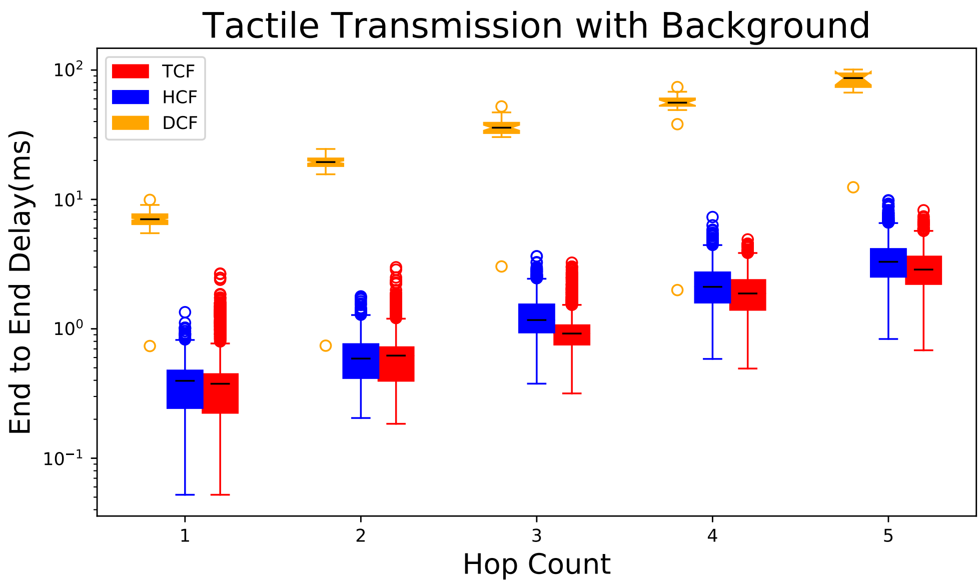

Figure 5.2: Tactile Information Transmission Delay Comparison between DCF, HCF and TCF in Boxplot

From this figure we can see that the average delay of tactile information gradually increases with the number of forwarding (hop count). The main reason for the delay increasing is the increasing of collision probability. The number of forwarding nodes means the minimum number of contention that a single frame needs to pass through. If the probability of success of each competition is P, then the probability of the success of N times forwarding is the maximum P^N. More details about the end-to-end delay result as table 5.6 below:

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	7.504ms (± 0.062)	19.220ms (± 1.012)	35.782ms (± 3.592)	54.022ms (± 10.388)	78.493ms (± 20.690)
HCF	0.373ms (± 0.006)	0.591ms (± 0.009)	1.251ms (± 0.018)	2.206ms (± 0.034)	3.422ms (± 0.051)
TCF	0.407ms (± 0.012)	0.624ms (± 0.012)	0.972ms (± 0.015)	1.938ms (± 0.029)	2.967ms (± 0.043)

Table 5.6: End to End Delay and Confidence Interval (99%) of Tactile Information Transmission with Background

Evaluation of DCF:

For DCF, when the hop count is one, the average delay is already high as 7 ms. When more than three hops, the average latency even more than 50ms. In addition, due to the excessive packets loss as 99% by traffic load 50%, the number of successful received packets is very small, the confidence interval has become huge. Such performance is not enough to support a smooth and accurate prediction of the model.

Evaluation of HCF:

HCF almost maintained the same performance as without background information, thanks to EDCA's priority mechanism.

Evaluation of TCF:

For TCF, the average delay has been handled very well as, even better, it still guaranteed within 1ms in 3 hops.

Summary of Delay Performance

Comparison between figure 5.1 and 5.2, HCF and TCF are too similar, that is to say, HCF and TCF do not depend on traffic load rate. From two group of experiments, we can get a conclusion that TCF is better than DCF and HCF on haptic internet latency challenge. The reason is that our coordination function TCF is based on the priority mechanism and has optimal setting of AC parameters. Therefore, haptic information has the highest priority, so background information does not affect haptic information.

5.3.2 Evaluation of Tactile Information Transmission Jitter

In this case, jitter represents the deviation of the actual delay from the average delay. Therefore, we use the standard deviation of End-to-End Delay as the mean of jitter, as shown in Figure 5.3 for the transmission jitter of tactile information under different CFs.

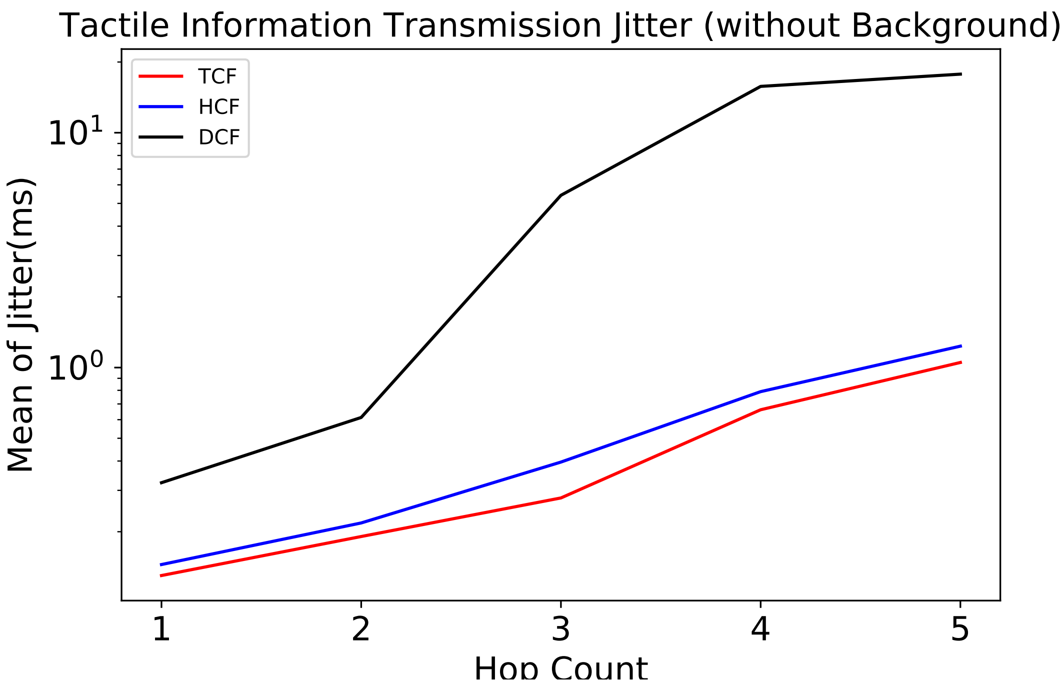

Figure 5.3: The Jitter of Tactile information Transmission without Background

When the traffic load is 0% (no background information), the jitter value of the DCF in one hop network is already quite high, and increases sharply with the increase of the number of hops. For details, refer to Table 5.7. In contrast, HCF and TCF jitter is much smaller. Although larger txop means that the better the ability of continuous transmission, but too large txop will waste transmission resources, other devices cannot use the medium for transmitting. This will increase the overall delay in bi-directional transmission and increase their jitter. Therefore, based on HCF, TCF reduces the continuous transmission time (TXOP Limit) and narrows the gap between maximum delay and minimum delay. Therefore, transmission jitter is reduced and transmission stability is optimized.

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	0.323ms	0.613ms	5.414ms	15.749ms	17.759ms
HCF	0.145ms	0.218ms	0.396ms	0.790ms	1.233ms
TCF	0.130ms	0.191ms	0.279ms	0.661ms	1.051ms

Table 5.7: Mean of Jitter with Traffic load 0%

Figure 5.4 shows the tactile transmission jitter when the traffic load up to 50%.

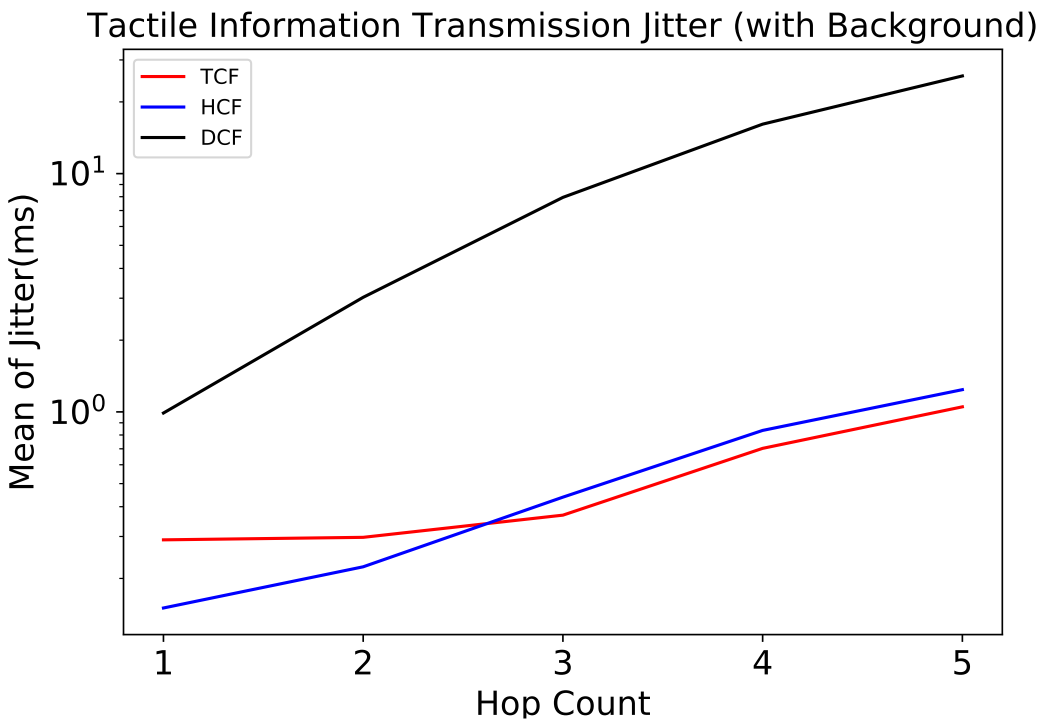

Figure 5.4: The Jitter of Tactile information Transmission with Background

As can be seen, DCF jitter has doubled, HCF jitter almost no change. Very high traffic load rate have a large impact on the jitter of TCF at low hop count. However, as the number of hops increases, the TCF jitter is gradually less than HCF. It can be said that when high traffic load, TCF still has some advantages over HCF. For details, refer to Table 5.8.

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	0.989ms	3.026ms	7.949ms	16.130ms	25.702ms
HCF	0.150ms	0.223ms	0.439ms	0.836ms	1.238ms
TCF	0.290ms	0.298ms	0.369ms	0.703ms	1.050ms

Table 5.8: Mean of Jitter with Traffic load 50%

5.3.3 Evaluation of Tactile Information Transmission Packet Loss

In the last section, we will evaluate the QoS performance of different CFs by analyzing the packet loss rate of tactile information transmission. Table 5.9 shows the packet loss when the network load is zero. At this group of experiments, since Host master and Host Slave are exactly the same, we take here master as an example for analysis. It can be seen in one hop network, all the CFs have not packet loss. In a two hop network, only one packet in DCF is lost, but this packet loss rate is negligible. However, when the number of hops exceeds two, the packet loss rate of the DCF exceeds 60%, which cannot meet the requirements of the haptic communication application. On the contrary, HCF and TCF have maintained a very small number of packet loss, which can even be ignored.

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	0	1	1724	2567	3155
HCF	0	0	1	1	2
TCF	0	0	0	1	3

Table 5.9: Tactile Packet Loss Count with Traffic load 0%

Table 5.10 shows the number of dropped packets from the Host master's haptic application at 50 percent traffic load, Table 5.11 shows the number of dropped packets from the haptic application on the Host slave at 50 percent traffic load. The main difference here is the background application that provide network load send data from the slave side to the master side, its transmission has a different effect on the both side terminals of haptic communication. However, the DCF mechanism relies on the load on the network, especially in the opposite direction.

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	3850	3940	3968	3984	3990
HCF	0	0	1	3	3
TCF	0	0	0	2	1

Table 5.10: Host Master's Tactile Packet Loss Count with Traffic load 50%

It can be seen that the traffic load has no significant effect on the haptic transmission with HCF and TCF, which shows that the transmission mechanism of HCF and TCf does not depend on the traffic load. The opposite direction of network transmission pressure makes DCF tactile transmission packet loss rate as high as 99 percent, unable to meet the requirements of tactile transmission.

Protocol	1 Hop	2 Hops	3 Hops	4 Hops	5 Hops
DCF	985	2159	2515	2941	3255
HCF	0	0	1	2	3
TCF	0	0	0	0	4

Table 5.11: Host Slave's Tactile Packet Loss Count with Traffic load 50%

Table 5.11 reflects the influence of network load on haptic transmission in the same direction. Although the dcf transmission is better than the opposite direction of the traffic load, but the packet loss rate is still higher than 80 percent, which is unacceptable by tactile transmission applications.

5.4 Evaluation of Tactile Information Transmission Process

In this section, we will evaluate the impact of different coordination function protocols on the tactile internet performance by analyzing transmission process of haptic information transmission. Evaluation of transmission performance will mainly be analyzed from the following two processes: Contention Process and Queuing Process in the worst case.

5.4.1 Evaluation of Contention Process

The contention process refers to the process of getting medium usage rights when multiple devices are preparing to send data. It is composed of three parts: Inter-frame Space (IFS), backoff process and transmitting process. As shown, DCF, HCF, and TCF by the contention process are composed of these three parts. The three component occupancy times are controlled by three variables: IFS, Backoff Slots and Data Frame Size. Figure 5.4 is a fragment of the simulation test. For ease of comparison, we cut the three CF segments together for comparison. Figure 5.5 is a fragment of the simulation test. For clear comparison, we cut the three fragments from DCF, HCF and TCF together for comparison. We assume that all three situations happen at the same time, and which coordination function is more advantageous.

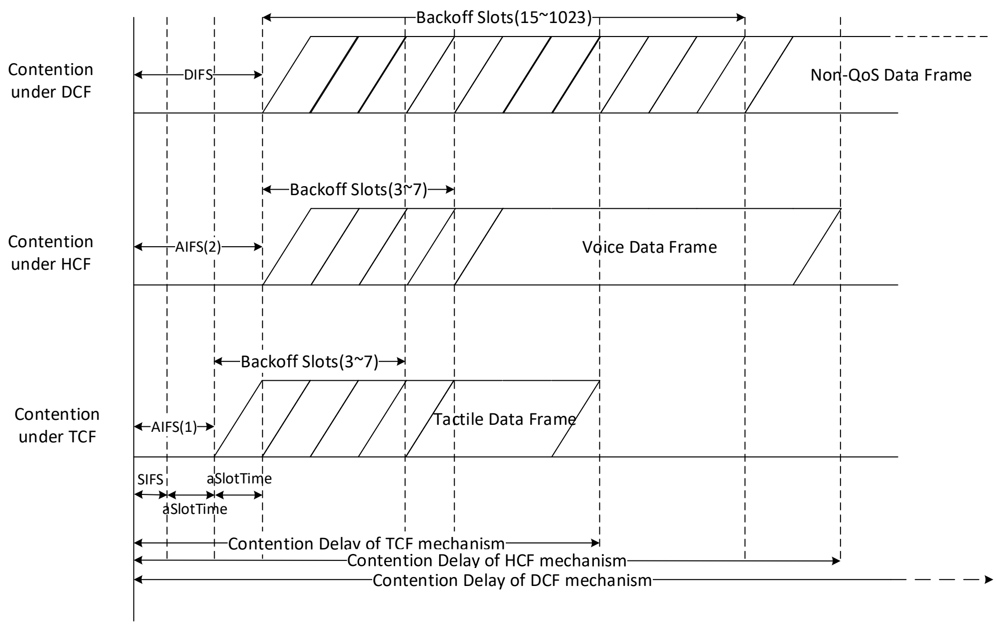

Figure 5.5: Contention Process Comparison of DCF, HCF and TCF

The first is to compare the Inter-frame Space process. As shown, DIFS is equal to AIFS[2], and they have one more slot than AIFS[1]. Therefore, in the IFS phase, the TCF delay (AIFS[1]=30μs) is shorter than DCF (DIFS=50μs) and HCF (AIFS[2]=50μs) by one slot (Calculation in 5.4.2). Shorter IFS is not impossible, may even get higher priority and shorter delay, but it will also bring some negative effects. For example, AIFS has no Slot Time, so AIFS is equal to SIFS. The SIFS shall be used prior to transmission of an Ack frame, a CTS frame or some control frames that is an immediate response. When AIFS is the same as SIFS, the tactile frame contention time is similar to these response frames IFS, it will result in these frames transmission collision and more latency.

Then they entered the backoff phase. Backoff length is determined by the range of the random contention window (CW), DCF CW range of from 15 to 1023, HCF and TCF from 3-7. DCF is significantly longer than HCF and TCF during the backoff process, which will result in huge delay in the actual transmission. And the very large range of CW values can also lead to unstable latency, that is, larger jitter, which is unfavorable to the prediction of Host master. In this regard, HCF and TCF can maintain a relatively small delay and smaller jitter.

When the backoff process ends, they are in the transmitting phase. The delay here depends on the size of the data frame, the smaller data frame and the shorter transmission-delay. In HCF, the highest priority video data is usually hundreds bytes or even a few megabytes, so the fragmentation and defragmentation process is required. And in fragmentation process, the TXOP indicates the duration of the fragments sending. It makes this device can occupy the channel for a short time, continuous transmission of multiple frames. This mechanism may help to reduce the one-way end-to-end delay, but not conducive to reducing the average delay of two-way data transmission. If during tactile transmission, other haptic devices have to wait this haptic device for its TXOP-duration, which will increase the information queuing delay form other devices, which is not allowed in the tactile network. However, TCF can solve this problem. First, in terms of frame size, haptic information requires only 24 bytes of space to represent the current state of the haptic device. Second, the TCF limits the TXOP value of the haptic information frame to 1ms, which means that after one time sending no haptic device can occupy the channel and send multiple frames continuously. Such a mechanism can shorten the average delay of two-way haptic application information.

In conclusion, through the comparison of this figure, it can be proved that under the TCF mechanism, the delay caused by the contention process will be optimized.

5.4.2 Evaluation of Contention Delay in The Worst Case

This section mainly compares the difference between different CFs by calculating the contention delay. First, the values of the parameters that affect the queuing delay in the experiment are shown in the following table:

Protocols	CW	IFS	TXOP
DCF	15-1023	DIFS	0
HCF	3-7	AIFS[2]	1.504 ms
TCF	3-7	AIFS[1]	1 ms

Table 5.12: The Parameters of Coordination Functions in The Worst Case

- DIFS = SIFS + 2 Slots = 10 μs +40 μs = 50 μs
- AIFS[2] = SIFS + 2 Slots = 10 μs + 40 μs = 50 μs
- AIFS[1] = SIFS + 1 Slots = 10 μs + 20 μs = 30 μs

First, we take the 1 frame transmission as an example to calculate the maximum contention delay required by the DCF mechanism in the worst case. The frame will be transmitted after the contention process. The contention delay is $f(c)$, includes DIFS and backoff time, the maximum backoff time is 1023 Slots. Therefore, DCF queuing delay d_{DCF} can be calculated by the following formula:

$$d_{DCF} = f(c) = DIFS + 1023Slots = 20.51ms \tag{5.1}$$

The contention delay of HCF, includes AIFS[2] and a maximum backoff time of 1023 Slots. Therefore, HCF queuing delay d_{HCF} can be calculated by the following formula:

$$d_{HCF} = f(c) = AIFS[2] + 7Slots = 0.19ms \tag{5.2}$$

The contention delay of TCF, includes AIFS[1] and a maximum backoff time of 1023 Slots. Therefore, TCF queuing delay d_{TCF} can be calculated by the following formula:

$$d_{TCF} = f(c) = AIFS[1] + 7Slots = 0.17ms \tag{5.3}$$

CHAPTER 6

Conclusion

In this paper, a new coordination function TCF has been developed. It reinforces the original HCF protocol, adds new AC for haptic communication application and tactile internet, enhances tactile information transmission performance and adds to the original standard IEEE802.11 protocol. It can not only adapt to the transmission of common data, but also can get higher priority, shorter delay and minimum jitter in the case of QoS guarantee.

The basic idea of this design comes from our robotic remote control system project. This system requires haptic communication between people and machines with through a mesh network. This communication is based on high frequency, low latency and high bandwidth networks. Therefore, we refer to the IEEE802.11 standard Mac layer protocol, HCF-based EDCA mechanism to expand, intended to adapt to the application of tactile application requirements.

TCF can coexist with HCF, i.e. TCF stations without support can still exist and do not interfere with TCF. The station without TCF-Support will not affect the prioritization of tactile access category in the network traffic. Tactile traffic (TCF) also has over all access categories of HCF and DCF. We can also use non-TCF-nodes in the radio range without interfering to the TCF process.

In order to compare and test the performance of different coordination function protocols, we have to set up a simulated network environment firstly. According to the requirements of the future tactile network, the network environment is optimized based on the development level of the simulator Omnet++. Finally, a high-power large-scale outdoor mesh network, TCF-Network, is constructed. In this network we test the most widely used two kinds of CF protocols DCF and HCF, as well as the TCF protocol we developed. Experiments have tested their transmission performance in different hop count network environments and the transmission efficiency under different network load rates.

In the experimental evaluation phase, we conducted a detailed comparison and analysis of three transmission performance metrics and the contention process. And came to the following conclusion:

- The transmission delay increases with the hop count.

- The transmission delay does not depend on the network load.
- The packet loss rate depends on the network load, but the higher priority data is not affected.
- HCF and TCF transmission efficiency is much better than DCF, TCF in the transmission delay and jitter more advantages than HCF.

Due to the current level of simulator development, we cannot rely on Omnet++ to simulate better network environments and models such as 802.11ac and ad. In future studies, further reducing the delay is still an important challenge.

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