Massive Channel Access in Ultra Reliability and Low Latency Communication

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Md. Abir HOSSAIN

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Waseda University
Graduate School of Fundamental Science and Engineering
Department of Computer Science and Communications Engineering,
Research on Wireless Access

Md. Abir HOSSAIN

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Abstract

5G communication is going to be the next communication standards in communication era in modern world. It going to be initiate different communication services beyond current 4G communication. The 5G communication services broadly categories into three sections, Ultra-Reliable and Low-Latency Communication (URLLC), massive Machine Type Communication (mMTC), and enhanced Mobile Broadband (eMBB). Ultra-Reliable and Low-Latency Communication (URLLC) is a promising service initiated by 5G communication to ensure higher reliability of packet transmission with very low latency constraints in wireless communication. The mMTC is expected to provide massive wireless access to a large number of devices about tens of billions of low-complexity low-power MTC devices simultaneously. The eMBB communication service is designed to provide extremely high data rates by addressing specific use case requirement. The massive Multiple Input and Multiple Output (Massive MIMO) is considered as a promising technology that might ensure such requirement by utilizing a very large number of antenna elements at the base station.

The main approach of this research work is to propose Medium Access Control (MAC) which ensures URLLC‘s higher reliability of packet transmission of 99.999% at extreme low latency less than 1 ms bound. It‘s very challenging to satisfy dual requirement of reliability and latency at the same time. Now a days, researchers and engineer‘s proposed many techniques and strategies to fulfill this requirement in different application domain of URLLC. But we intend to apply URLLC’s higher Quality of Service (QoS) in a future robot’s internal communication system to replace the wire communication by a finite number of sensors in wireless communication. To make this conversion, we propose a new “Medium Access Control” (MAC) - Orthogonal Frequency subcarrier-based Multiple Access” (OFSMA). The OFSMA scheme incorporates packet diversity principle and transmits multiple copies of a packet over the massive number of subcarrier channels to ensure higher reliability of the transmission. The OFSMA scheme considers subcarrier channels orthogonal to each other to ensure interference-free communication and the subcarriers selection is random and independent. To assure low latency, the OFSMA scheme applies short

slot duration having 0.1 ms with high-speed link connectivity.

In Chapter 3, the OFSMA scheme is analyzed for a single frequency band and transmits multiple copies of the packet over a single band frequency diversity model. The performance of the OFSMA scheme is evaluated in terms of reliability, packet diversity, diverse number of subcarrier channels and air-interface latency measurement. The OFSMA scheme's reliability is measured for 2-packet duplication over the different number of subcarrier channels and 2-, 4-, and 6-packet duplication reliability for fixed channel conditions over low arrival situation. The OFSMA scheme determines the minimum number of subcarriers demands to satisfy the URLLC's expected reliability 99.999% for a different number of packet duplication over low to higher arrival condition. For the OFSMA scheme, determines the minimum packet duplication that satisfies the reliability of 99.999% for different arrival condition over the different single frequency band. Finally, the OFSMA scheme's air-interface latency is measured for different packet lengths and compared with the OFDMA system.

In chapter 4, the OFSMA scheme is analyzed for multiple frequency bands and transmits a different number of packet duplication over different band diversity and frequency diversity system models. The OFSMA scheme's performance is analyzed for packet diversity, different number of subcarrier channels, frequency band diversity, and different arrival conditions. For OFSMA scheme, determines the minimum number of subcarrier channels needed to satisfy the reliability of 99.999% for a single band, double band, and triple-band diversity system. The OFSMA scheme's reliability also evaluates for fixed channel condition and determine the reliability response for different packet duplication over different frequency band diversity models. The minimum packet duplication that satisfies the reliability of 99.999% for a different packet duplication also evaluated for multiple single-band consideration for the OFSMA scheme and presented with their normalized form. Finally, the OFSMA system's air-interface latency is measured for different packet lengths with different latency thresholds and compared with the OFDMA system.

Different from the previous in chapter 3 and 4, a new hybrid access scheme is proposed in chapter 5 to incorporate the OFSMA scheme and considers audio, video and general sensors for transmission at the same time. The general sensors transmit multiple packets over a single frequency band where the subcarriers are selected in a random fashion and the audio and video sensors transmit the single packet over the dedicated channel in a collision-free manner. The hybrid access scheme's reliability and collision probability are measured for different packet duplication. The signal propagation over the hybrid access scheme is captured using ANSYS HFSS software for different structural configurations as part of a robotic structure. The signal having fixed power is transmitted over different frequency bands and the propagation expressions are captured and compared to each other.

This research work exploits the challenges of the URLLC communication and proposed two basic MAC system to satisfy the URLLC requirement. The OFSMA and Hybrid MAC scheme is proposed to evaluate a short-range uplink communication system's performance in terms of reliability and latency for different packet duplication and different arrival condition. The simulation results depicted that our proposed systems can achieve the reliability and latency bound required by URLLC system. In future, the proposed systems might be able to replace an existing wire-based communication system as robot, vehicles and other short-range communication system to a wireless sensor-based communication system.

Chapter 1

Introduction

1.1 Introduction

This thesis studies mainly focus on random access over a single frequency band and multiple frequency bands as a robotic body backbone communication. Moreover, the signal propagation scenario inside different structure as part of a robotic body over different frequency bands are captured. In the first chapter of this thesis, we discuss the basics of 5G communication systems, services, application scenarios, open challenges, contributions, and motivations. The overall structure of the thesis is summarized at the end of this chapter. In the following subsections, "the fifth-generation communication technology" (5G) is introduced in terms of history, application, expected services, current condition, and future trends. Currently, the "fourth-generation wireless communication technology" (4G) has been providing mobile and wireless communication services. The 5G communication system is expected to lunch within 2020 and application services will be available around 2020 and beyond [1, 2]. The 5G communication has designed to provide three main categories of services as a) evolved mobile broadband (eMBB), b) ultra-reliable and low-latency communication (URLLC), and c) massive machine type communication (mMTC) [3, 4]. Different home and industrial applications, automation and adaptation in 5G services are the important research topics in current research trends. The limited radio resources utilized efficiently and in an optimized manner demands good access scheme termed as "Medium Access Control". An efficient MAC system has been a deserving research topic for many years. We end this chapter by describing the thesis structure which identifies all main sections and subsections described throughout the chapter. The rest of the chapters described the following contents in detail.

1.2 Research Background

The higher reliability of packet transmission within low latency bound during providing services for data and voice is challenging over many years in the wireless communication system. From the beginning of the wireless communication system as 1G to till 4G, the networking services and quality improvement in terms of voice services, audio and video combined services, emerging technologies and overall multimedia systems. The "first generation" (1G) was developed to provide voice services in an analog system using the frequency modulation technique termed as "Frequency Division Multiple Access" (FDMA) for radio signal transmission[5]. The "second generation" (2G) was the initialization of digital communication system designed to provide "Short Message Service" (SMS) and "Multimedia Messages" (MMS) along with voice services using two digital modulation system called "Time Division Multiple Access" (TDMA) and "Code Division Multiple Access" (CDMA)[6]. The "third-generation" (3G) was initialized high-speed mobile access with "Internet Protocol" (IP)-based services using "Wideband Code Division Multiple Access" (W-CDMA), and "Universal Mobile Telecommunication System" (UMTS)[7]. The "fourth generation wireless mobile technology" (4G) enhanced mobile broadband services quality with wireless modems and to smartphones using two popular network technology WiMAX and LTE system[8]. Nowadays, the 4G networking system controls most of the mobile networking services and provides a variety of services like online gaming, live streaming, video conferencing and so on. The upcoming 5G communication system will expect to enlarge the service area of the existing system with higher data rates and explore new services.

1.2.1 5G Communication System

The fifth-generation mobile communication termed as 5G communication will be the next generation communication standards beyond 4G communication. The researchers and engineers expect that the 5G system will achieve higher data rates, reduced packet transmission latency, low power consumption, large system capacity, enhanced spectral efficiency, denser user equipment, and massive communication

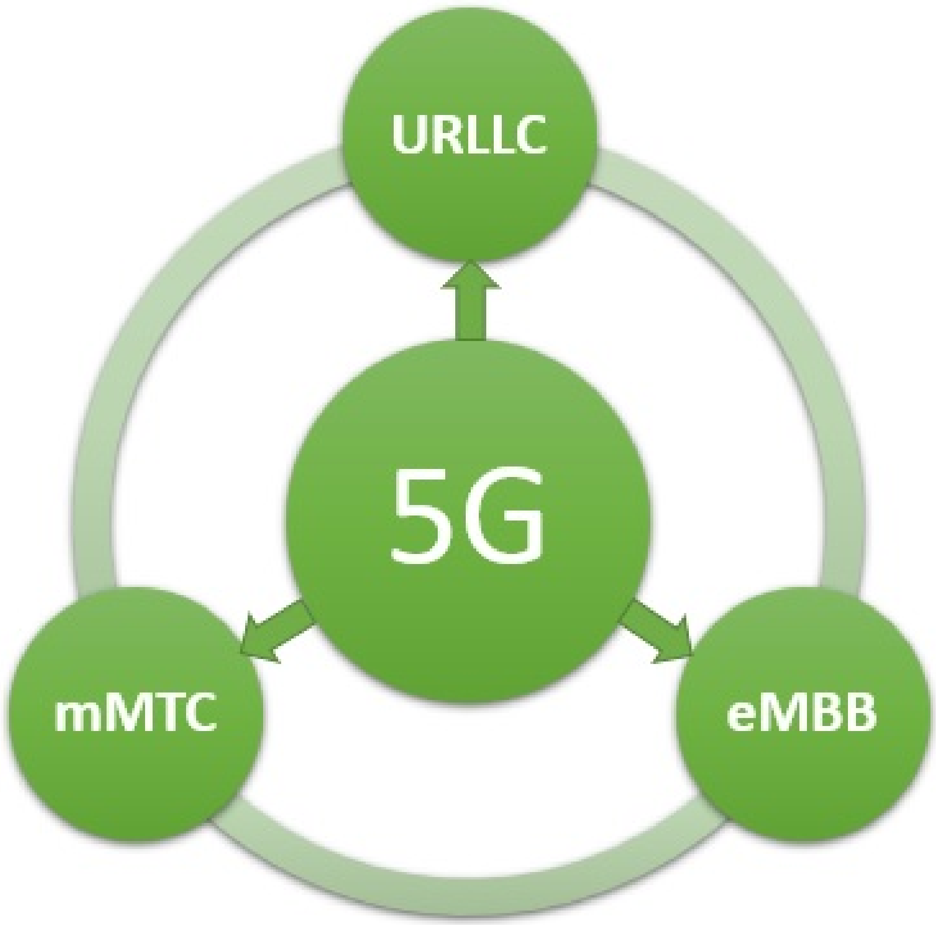

Figure 1.1: 5G services.

over 4G communication. Based on this consideration, the 5G services are broadly divided into three categories[9] presented in Figure 1.1 and listed below:

1. Ultra-Reliable and Low-Latency Communication (URLLC)

2. Massive Machine-type Communication (mMTC) and

3. Enhanced Bobile Broadband (eMBB)

1.2.1.1 Ultra-Reliable and Low-Latency Communication

The combined requirement of high reliability and low latency is termed as Ultra-Reliable and Low-Latency Communication (URLLC). The allowable packet loss rate of 10^{-5} for small packets within low latency is less than 1 ms in one-way user plane[10, 11]. This research work [12] identified a comparison of reliability in terms

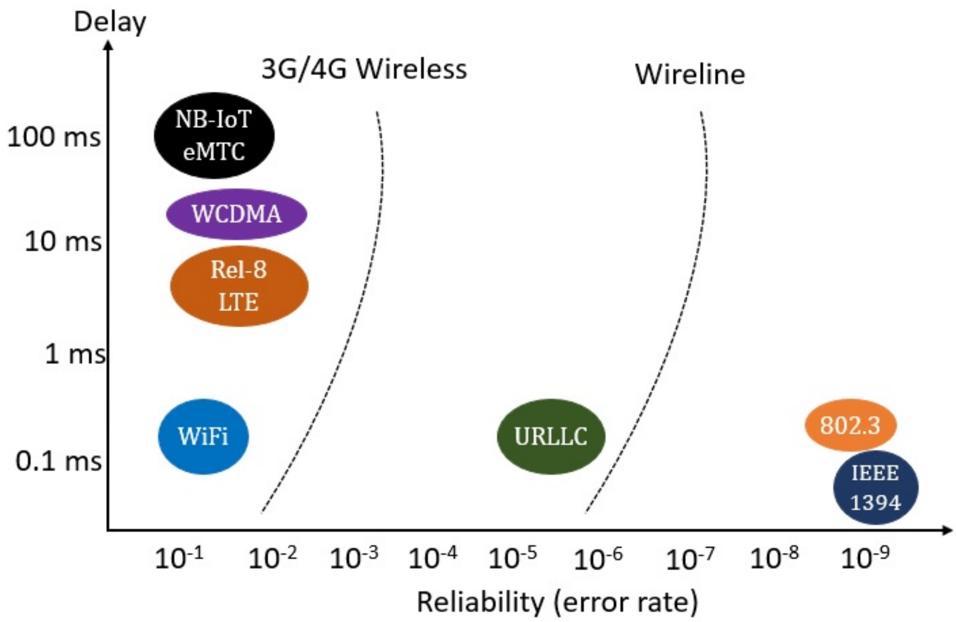

Figure 1.2: Reliability and latency comparison over different communication technologies.

of packet error rate over packet transmission latency over different communication technology in the domain of both wired and wireless system is presented in Figure 1.2. The URLLC has been considered as one of the key trends of future wireless cellular communications. The URLLC attracts more attention from the researcher community due to its innovative and extraordinary applications. The URLLC applications include reliable remote action with robots and coordination among vehicles, tactile internet, autonomous vehicles communication industry of factory autonomous systems, augmented or virtual reality (AR/VR), and unmanned aerial vehicles communications. In the future, URLLC will create a new era of the application domain that is still unthinkable by human beings.

1.2.1.2 Massive Machine-type Communication

Machine Type Communication gets access to the device (i.e., smart meters, sensors, and appliance) to directly communicate via a central MTC server or a set of MTC servers without the human intervention. Based on the distinct system requirement and challenges, the MTC is divided into two groups

1. Massive Machine-type Communication (mMTC)

2. Ultra-reliable Machine-type Communication (uMTC)

The mMTC is expected to provide massive wireless access to a large number of devices about tens of billions of low-complexity low-power MTC devices simultaneously[13]. A conventional example of mMTC is smart metering as collecting the measurements from a massive number of sensors. The uMTC provide the network services for MTDs with critical requirements of latency and reliability[14]. From the requirement point of uMTC, one example can be vehicle-to-X (V2X) communications and another is industrial control applications that demand high availability, high reliability per link communication within low latency packet transmission.

1.2.1.3 Enhanced Mobile Broadband

Enhanced Mobile Broadband (eMBB) is designed to provide extremely high data rates by addressing specific use case requirements. To ensure this high data rate services, user experienced data rate and spectral efficiency are the two most prominent key performance indicators for the eMBB networking system. The 5G radio interface must have very diverse capabilities for eMBB including a 20-Gb/s peak data rate, a 100-Mb/s user rate, a velocity of up to 500 km/h, less than a 4-ms latency, and a 100-fold improved network energy efficiency to enable the seamless delivery of large amounts of data[15]. The massive Multiple Input and Multiple Output (Massive MIMO) is considered as a promising technology that might ensure such requirement by utilizing a very large number of antenna elements at the base station. The higher number of antennas improve the spectral efficiency through high order spatial multiuser (MU) multiplexing[16]. Moreover, in the physical layer, the eMBB needs to support a higher range of code rates, code lengths and modulation orders beyond the existing 4G Long Term Evolution (LTE). The present scenarios of eMBB code lengths range from 100 to 8000 bits (optionally 12,000-64000 bits) and code rate range from 1/5 to 8/9 s[17].

1.3 Motivation

With the emerging applications in the context of 5G communication demands higher reliability packet transmission at a higher speed. Nowadays, the wireless domains gain more transmission speed, improve reliability, reduce interference and able to coverage mass communication due to significant improvement of technology by researchers and engineers. Due to this significant improvement of technology and efficient medium access control, day by day wireless converted system is increasing and being demanding by general people. A wireless system provides a set of facilities as mobility, flexibility, lightweight and easy maintenance over the wired system.

A conventional robotic structure consists of a massive number of wires to connect all elements inside it. The connecting wires inside a robot act as the primary communication medium. This huge number of wires enhance a robotic structure to gain more weight that consumes more power. The numerous wires prolong the usual shape of a robot and sometimes restrict designers to create a proper flexible configuration. Most importantly, the physical wires disconnected at the operation time because of operational speed, movement of different parts of the body, and sometimes burns due to heat. The detection of disconnected wires and maintenance is time-consuming and expensive.

Based on this above explanation and problem formulation, we expect to design a robotic structure where the wires are replaced by a finite number of sensors to resolve the defined problems. The finite lightweight sensors deployed over the robotic structure can take over the communication backbone of the wired system. The ultra-reliable and low-latency communication under the 5G communication domain is able to expect the replacement of enormous wires by a finite number of sensors.

1.4 Contributions

This thesis work consists of three main parts. The first part of the thesis proposes a new medium access control as "Orthogonal Frequency Subcarrier-based Multiple Access" (OFSMA) aiming to apply as communication protocol inside of a future robot communication system to ensure URLLC defined higher reliability and latency bound over single frequency bands. The second part of the thesis studies and analysis the OFSMA MAC over multiple frequency bands and the packet transmission latency is compared with the OFDMA system. The system includes multiple frequency bands to reflect the impacts of minimum subcarrier demands and reliability response by the system. In the third part of the thesis, a hybrid access scheme is proposed which is a combination of OFSMA random scheme and a dedicated channel scheme for audio and video sensors. The hybrid access scheme inherits OFSMA with single frequency band for limited number of general sensors and assigned dedicated subcarrier channels for audio and video sensors. Under this scheme, the system evaluates the reliability and collision probability for audio, video and general sensor‘s packet transmission. The inside robotic structure‘s signal propagation expression for multiple frequency band evaluates for different structure and shape configuration aiming to apply for a future robot‘s internal communication system.

Chapter 3 explains the OFSMA communication system with a suitable system model and a path loss design is proposed. The OFSMA system is analyzed in the presence of different packet duplication over a single frequency band. The key contribution of the first part in the thesis studies are defined below:

- We propose a new access scheme-“Orthogonal Frequency Subcarrier-based Multiple Access” (OFSMA) for future robotic short distance communication system. This OFSMA access scheme has the capability to ensure higher reliability of packet transmission within the stringent latency requirement defined by the URLLC system.

- We express a system model explains the packet equivalent signal expression and path loss design of the signal for single frequency bands.

- We evaluate the performance of our proposed OFSMA scheme for a small number of packet duplication in fixed channel conditions at lower traffic conditions.

- We determine the OFSMA access scheme performance for low to higher-order packet duplication transmitted over different traffic conditions up to 10000 pk/sec arrival rate and determine the minimum number of subcarrier channels required to satisfy the packet transmission reliability of 99.999%.

- Moreover, The OFSMA system performances also examine for determining the minimum packet duplication that satisfies the reliability of 99.999% for different arrival condition.

Chapter 4 describes the OFSMA system in terms of multiple frequency bands, single packet processing cycle, transmitted packet size, interface diversity, link reliability, and air-interface latency measurement. The major contributions of chapter 4 are listed below:

- We represent the OFSMA access scheme with the variation of a different number of frequency bands. The OFSMA scheme adopts a packet diversity principle and transmits multiple copies of the same packet over the band and frequency diversity system to improve the reliability of the transmission.

- We propose three system models regarding the frequency band's inclusion in the system. The system models explain the short-range packet signal expression, packet size, collision probability, and interface reliability to represent the system characteristics.

- We determine the minimum number of subcarriers to satisfy the reliability of 99.999% of the packet transmission for a different number of packet duplications over low to higher arrival conditions.

- The OFSMA system's reliability evaluates for fixed channel conditions over the different frequency bands for different packet duplication and different arrival conditions.

- Moreover, the air-interface latency estimates for different bit length of packets and compare the result with the OFDMA system in presence of different packet latency thresholds.

Chapter 5 presents a new hybrid access scheme considering real robot sensor applications. The hybrid access scheme considers audio, video and general sensor take into account and allow transmission on different modes. The key contribution of the thesis part explains below as a list:

- We propose a hybrid access scheme that considers audio, video and general sensors and transmits the packets over the different allocated subcarrier channels.

- A system model explains the details of the hybrid access scheme as total duplicated packet signal expression, the total number of packets transmitted in a TTI over the hybrid access scheme and the received signal along with the Gaussian noise.

- We determine the reliability and collision probability of the hybrid access scheme by assigning sensor and subcarrier channel ratio as 1:1. The reliability and collision probability evaluates based on the different number of packet duplication over a single frequency band.

- Moreover, the signal propagation expression capture for different structural conditions as part of a robotic body formation and determines for different frequency bands for fixed power transmission for a defined finite length.

1.5 Thesis Structure

The rest of the thesis is organized as follows. In chapter 2, The fundamentals of random access are presented as a summarized form. The random access operation over the basic protocol as ALOHA, slotted ALOHA, and CSMA system is briefly explained and finally, some important context of URLLC under the wireless communication domain is presented. In chapter 3, the OFSMA access scheme is presented using a single frequency band. Based on this design, we determined the packet and channel diversity impact in reliability results for different arrival conditions. In Chapter 4, the OFSMA access scheme is presented in the presence of multiple frequency bands and determine the impacts of the band and frequency diversity, packet diversity, fixed channel assignments on reliability. Moreover, the system also defines a direction for packet size and interface reliability for short-distance communication and finally evaluated the air-interface latency and compared with the OFDMA system for different packet bit length under different latency thresholds. In chapter 5, a new hybrid access scheme is presented along with the OFSMA system and considers the audio, video and general sensors into consideration to determine the reliability and collision probability of the system. Moreover, the signal propagation expression is measured for fixed power allocation over different structural configurations as part of the robotic body for different frequency bands. Finally, Chapter 6 concludes the entire thesis and provides the direction of future research.

Chapter 2

Fundamentals of Random Access and URLLC

2.1 Random Access Control

Random access defines the dynamic assignment of radio resources to a large number of users or transmitters. A central communication channel or channels access without any scheduling might be alternatively called as random access. A pure random access mechanism (Pure Aloha) is very simple and defined as in a networking system, any transmitter or user has a packet to transmit, it simply transmits without any consideration. Generally, the packet generation and transmission follow the Poisson distribution. However, Due to this direct access method in random access, there is a high probability of collision. The researchers attempt to minimize the collision in many ways by dividing the transmission time in the specific time slot (slotted ALOHA), Sense the channel before transmission (Carrier Sense Multiple Access), and reserve a future slot for transmission. There are many variations of random access protocol based on its medium access characteristics. The below section listed and described a few random access mechanism.

2.1.1 Pure ALOHA Protocol

A pure ALOHA protocol[18] is a blind transmission process where each station transmits its packet whenever it has data to transmit. If a packet is successfully received, the receiver transmits an acknowledgment. But In a transmission process, if more than one packet is transmitted, they collide with each other and finally lost. The transmitter waits for an acknowledgment for a timeout time and if not received it waits for a random time and retransmits. A pure ALOHA packet transmission, collision scenario and vulnerable periods for ALOHA protocol are presented in Figure 2.1.

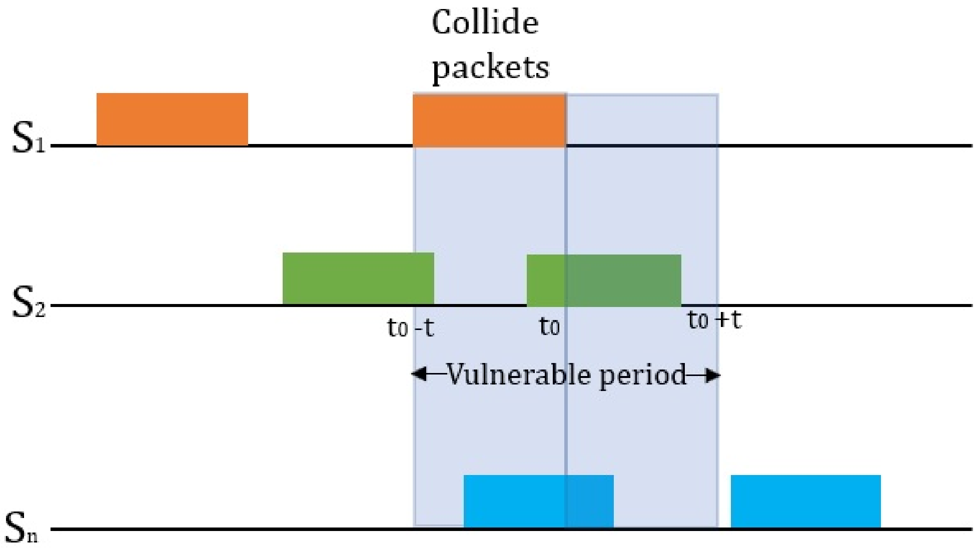

Figure 2.1: Pure ALOHA packet transmission, collision and vulnerable period.

The transmitters transmit a packet at an arrival rate of λ using the Poisson arrival process. Let a packet transmission duration is t. According to Poisson arrival process the probability of λ arrivals/ t time duration for k number of transmitters can be expressed as

$$P_r\left(k\ arrivals\ with\ an\ arrival\ rate\ \lambda\ at\ time\ t\right) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{2.1}$$

In ALOHA protocol, packet transmission is successful if no packet arrives within $2t$ times. Then equation 2.1 can be represented as

$$P_r\left(k\ arrivals\ with\ an\ arrival\ rate\ \lambda\ at\ time\ 2t\right) = \frac{(2\lambda)^k e^{-2\lambda}}{k!} \tag{2.2}$$

If there is no transmitter transmit a packet within this $2t$ then the packet transmission is marked as a success. So, the success probability equals to zero transmitters arrival within 2t time for an ongoing transmission can be rewritten as

$$P_r\left(0\ arrivals\ with\ an\ arrival\ rate\ \lambda\ at\ time\ 2t\right), or P_r\left(success\right) = e^{-2\lambda} \tag{2.3}$$

If one packet is transmitted within $2t$ time then the transmitted packet is a success. That means at arrival rate λ= 1 packet/$2t$ equals to 0.5 packet/sec ALOHA presents its best results. So, the throughput of the ALOHA at arrival rate λ=0.5 can be

$$Throughput, S = \lambda e^{-2\lambda} = 0.1839 \tag{2.4}$$

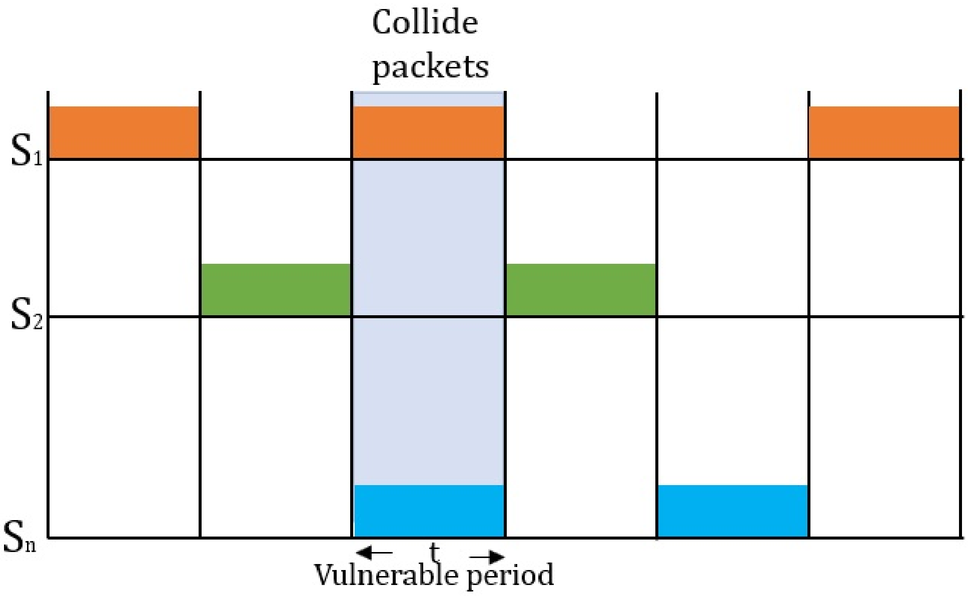

Figure 2.2: Slotted ALOHA system's packet transmission, collision and vulnerable period.

The maximum throughput of ALOHA is in arrival rate, λ=1 packet/*2t* sec is 18.39%.

2.1.2 Slotted ALOHA Protocol

A slotted ALOHA is a modified version of the ALOHA protocol where packets are transmitted at the beginning of a time slot. Due to minimize the vulnerable period of packet collision, the transmission time is divided into fixed-length transmission period and transmitters are allowed to transmit at the beginning of a transmission slot. Unlike the ALOHA protocol, the transmitters follow the Poisson arrival process for packet generation and transmission. If any transmitter generates its packet in the middle of any transmission slot, it needs to wait for the next transmission slot.

Recall the equation 2.1 for Poisson arrival process, the probability of λ arrivals/ t time duration for k number of transmitters can be expressed as

$$P_r\left(k\ arrivals\ with\ an\ arrival\ rate\ \lambda\ at\ time\ t\right) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{2.5}$$

Though the time is divided into slots, so the vulnerable period for slotted ALOHA is t. That means in a single slot duration t time if there is no other transmission that will be a success. So, the probability of success for slotted ALOHA system can be written as

$$P_r\left(success\right) = e^{-\lambda} \tag{2.6}$$

Based on the discussion, the transmission is a success if only one packet is transmitted in t time. That means the slotted ALOHA shows its best performance at an arrival rate $\lambda = 1$ packet/t duration slot. So, the throughput of the slotted ALOHA can be presented as

$$Throughput, S = \lambda e^{-\lambda} = 0.3678 \tag{2.7}$$

The maximum throughput of slotted ALOHA is in arrival rate, $\lambda = 1$ packet/t sec is 36.78%. The slotted ALOHA shows throughput twice of the ALOHA system due to divide the time into fixed transmission slots. The throughput and reliability of the slotted ALOHA system might be improved by using the packet diversity principle and transmit multiple copies of the same packet over a finite number of transmission channels.

2.1.3 Carrier Sense Multiple Access Protocol

The carrier sense multiple access is a form of random access and transmits packet before sensing the channel status(transmitter to base station) as a form of "listen before talk" form. A single packet is not allowed to transmit before sensing the channel status and if the channel is busy then wait for a random time and repeat the sensing channel. This CSMA system requires all transmitter terminals able to receive each other's signals on the transmitter to base station inbound frequency. Due to the sense the only transmitter to base station channel status, the collision happens because of hidden transmitter and termed as "hidden terminal" problem. The hidden terminal problem later resolved by another popular MAC system called "Multiple Access with Collision Avoidance" (MACA) protocol[19]. But In the wireless environment, carrier sense multiple access features are not feasible due to the magnitude of the signal attenuation [20].

2.2 Wireless Access in Ultra-Reliable Low-Latency Communication

Ultra-Reliable Low-Latency Communication (URLLC) is a special service provided by 5G communication where the system reliability and latency are prioritized. URLLC is specially designed for mission-critical communication links to ensure higher reliability within lower latency. In wireless domain ensuring such higher QoS is very challenging due to signal attenuation, multipath propagation, interference, collision, BER, and channel condition. But the researcher continues their research to resolve the problem and ensure higher QoS in the wireless domain.

2.2.1 URLLC Packet Size

URLLC is sensitive about the packet transmission latency and due to this packet size is important in the wireless application level. It is recommended to use short packet size for transmission to ensure short latency. In a networking system, the channel link rate is defined as R_{bps} and the maximum allowable transmission latency in the user plane is T. Then the packet size in bits can be defined as

$$R_{bps} = \frac{b}{T} \tag{2.8}$$

$$b = R_{bps}.T \tag{2.9}$$

But in standard information-theoretic models, the data rate is presented in terms of bits per channel uses [bpcu] and expressed as R. For a wireless communication the bandwidth is defined as B and the number of channel uses available for transmission is $2BT$, then data rate R can be expressed[21] as

$$R = \frac{b}{2BT} = \frac{R_{bps}}{2B}[bpcu] \tag{2.10}$$

2.2.2 Error probability

The b bits is transmitted over the wireless network's AWGN channel and total channel $N = 2BT$ uses for this transmission having SNR presented as γ. Then error probability of receiving b bits can be presented [22] as

$$\epsilon(N, \gamma, b) = Q(\frac{NC(\gamma) - b + \frac{1}{2}\log_2 N}{\sqrt{NV(\gamma)}}) \tag{2.11}$$

where Q is a Gaussian Q function, $C(\gamma)=\frac{1}{2}\log_2(1+\gamma)$ and $V(\gamma)=\frac{\gamma(\gamma+2)}{2(\gamma+1)^2}\log_2^2 e$ denotes the channel capacity and dispersion, respectively.

In the physical layer, the error probability of data for fixed allocation of the base station and device can be expressed as

$$\epsilon_{det} = 1 - (1 - \epsilon_{sync})(1 - \epsilon_D)(1 - \epsilon_A) \tag{2.12}$$

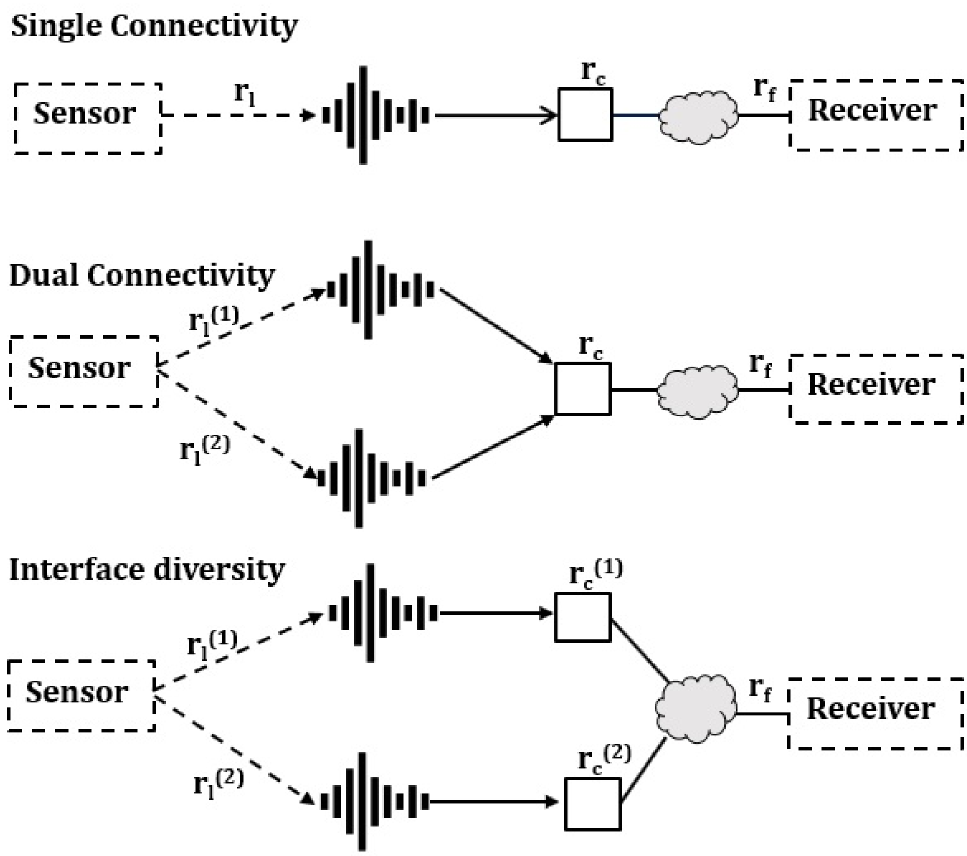

Figure 2.3: Interface diversity architecture.

Here, ϵ_{sync} is the synchronization error, ϵ_D defines the probabilities that the data is not successfully decoded by the base station and ϵ_A presents the acknowledgment is not decoded by the device.

2.2.3 Interface Diversity

In the wireless communication system, to improve the reliability of transmission, multiple copies of a data packet is transmitted. The system assigned a set of communication links for transmitting multiple packets at the same time. This network connectivity architecture is termed as link diversity or interface diversity. The different type of interface diversity architecture is presented in Figure 2.3. For single connectivity, if the link reliability is r_l, the core reliability is r_c and the interface reliability is r_f then the reliability of the single connectivity system can be presented as

$$R_{single} = r_l r_c r_f \tag{2.13}$$

For dual connectivity system, the system reliability can express as

$$R_{DC} = (1 - \prod_{i=1}^{N}(1 - r_1^{(i)}))r_c r_f \tag{2.14}$$

Here, the $r_l^{(i)}$ defines the link reliability of ith link of the connectivity. The system reliability of the interface multi-connectivity can be written as

$$R_{IFD} = (1 - \prod_{i=1}^{N}(1 - r_1^{(i)} r_c^{(i)}))r_f \tag{2.15}$$

Here, the $r_l^{(i)}$ defines the link reliability of ith link and the $r_c^{(i)}$ defines the reliability of ith core network of the communication.

Chapter 3

OFSMA MAC with Single Frequency Band

3.1 Introduction

A large number of physical wires needed to connect all internal elements of a robot that provide as main communication network. This huge number of wire insists a robot to gain high weight and sometimes unable to present an expected robotic structure. Moreover, wires sometimes disconnected during operation and the maintenance becomes complex. In order to convert a robotic physical structure lightweight, flexible, and easy maintainable, the robotic structure needs to be reviewed and suggest to change the wires by a finite number of homogeneous sensors. A typical wireless sensor-connected robot where sensors deployed different positions

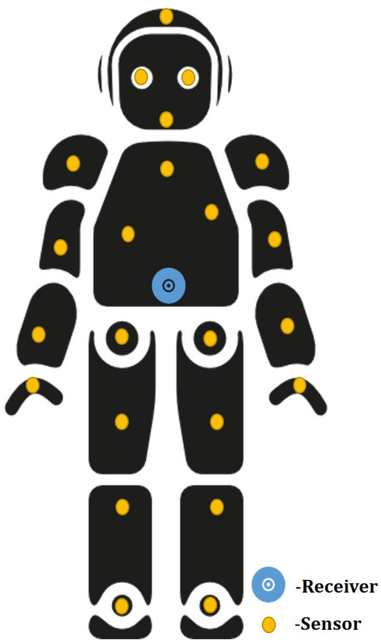

Figure 3.1: A prototype of a robot deployed with limited number of sensors to assure wireless communication over single frequency band.

of the robotic body around the receiver having a maximum radius of 1 m is illustrated in figure 3.1. But It is difficult to convert a wire-connected robotic system into a wireless system and there is a need to overcome a lot of challenges such as ensuring reliability, security, minimizing interference and latency and allowing access to spontaneous communication. The main challenges behind this transformation from wire-connected to a wireless system are high reliability and extremely short latency. The 3rd Generation Partnership Project (3GPP) fixes the URLLC system's air interface reliability of 1-10^{-5} with delay less than 1 ms for a packet transmission having size of 32 bytes [23]. In near future, the air interface latency of the robotic system is expected to be 100 μs and the round-trip processing time is bounded to be 1 ms[24].

Now a days, researchers and engineers working hard to increase the reliability, minimize the bit error rate, reduce latency, minimize the interference and avoid multi-path fading operation of a packet transmission. The higher reliability and stringent latency of the URLLC system are used to convert a wired system to a wireless sensor connection-based robot transformation. The URLLC system has different applications in 5G communication domain such as reliable robot intercommunication and action coordination, the remote operational action coordination, autonomous ground vehicles communication, Industrial Internet of Things (IoT) applications that include factory autonomous systems, pilot-less aircraft operation, remote surgery operation and so on [25], [26]. The URLLC system is specially designed under 5G communication domain to provide the next generation network services [27] that confirm ultra higher packet reliability rates in an extremely short latency communication domain.

3.1.1 Related Works

currently, few research work conducted aiming to convert wired system to wireless sensor-connected transformation oriented applications as spacecraft automation, structural health monitoring, real-time industry automated robot and so on. A spacecraft automation design is proposed [28] where sensor data are transmitted in wireless domain over the ultra-wideband networks and the payload are transmitted over diverse frequency bands in a TDMA protocol. The structural health monitoring sensor-based system for an airplane is studied in [29] where a few sensor nodes plotted over the airplane and captures the health statistics. The system determines system throughput, data dropped rate and latency for a maximum of 7 nodes as 12000 bps, 180 bps, and 115 ms, respectively. A robot aiming to automated an industry has been studied and developed in[30], and utilize advanced waveform technology polar OFDM (P-OFDM) to provide service in an industrial environment that ensure high reliability within low delay. The combined existence of URLLC and eMBB joint services in a cloud-based network system are discussed in [31], where the latency, reliability, and inter-cell power gain are evaluated among Non-Orthogonal Multiple Access (NOMA), Orthogonal Multiple Access (OMA), URLLC, and enhanced Mobile Broadband (eMBB) for diverse network traffic load by engaging puncturing and successive interference cancellation. In [32], the diverse duplicated packets are transmitted over the straight and divided carriers using more dependent channels to improve system‘s reliability and analysis the different radio resource usage in the system. A competition-based multiple channel and multiple packet diversity system has been analyzed in [33], where user equipment forwards the different number of duplicated packets over successive Transmission Time Interval (TTI) using slotted ALOHA to improve system packet transmission reliability and reduce consumed latency to satisfy the URLLC's defined requirement. An uplink transmission for the URLLC is discussed in [34] where the system transmits k number of repetitions of a packet is performed in a grant-free and grant-based strategies. In the state of the art, the research activities on few key dedications and point out some features that minimize the energy consumption in the URLLC network system which is explored in [12] and also suggests different prospects and issues that might consider in URLLC in order to make energy efficient communication system.

3.1.2 Contribution

The researchers and engineers work to optimize the network usage and ensure the packet transmission reliability and also minimize the latency at the same time which is quite challenging. The existing researchers studied factory and industry automation, spacecraft monitoring, and airplane health status monitoring system considering and analyzing for applying lower traffic and employing lower resource which is not suitable and sufficient to replace wires by sensors in a robotic system. Moreover, the system latency analyzed in previous research work was comparatively higher than URLLC requirement and reliability not determined for their proposed system. The URLLC being an advanced technology under the 5G communication system considered a lot of attention and at the same time challenging to full fill it‘s requirement. Moreover, in the robotic platform such higher reliable higher speed communication is highly desirable to achieve the higher system gain. To ensure high reliable packet transmission in an inner robotic structure within stringent latency bound is still absent in our study in the field of URLLC.

The main contributions of the research work are listed below:

- A new multiple access scheme-orthogonal frequency subcarrier-based multiple access (OFSMA)- has been proposed which inherit packet diversity principle and forwards multiple duplicated packets over massive number of subcarrier channels in order to improve the packet transmission reliability.

- A system and path loss model has been proposed to more visible of the packet signal, noise, and total received signal in the system. Moreover, the path loss system also explain and determines the received power for a packet‘s transmitted signal.

- The OFSMA system’s packet reliability response are determined in aspects of channel and packet diversity variation and also explains the concrete reason behind this reliability expression for the proposed system.

- The minimum number of subcarrier frequency channels are determined to ensure the packet transmission reliability of 99.999% defined by URLLC system. It determined for different packet duplication over diverse number of arrival condition in the network and represents the response of demanding subcarriers for different traffic arrival condition of the network.

- The air-interface latency is also evaluated for proposed OFSMA system and compared with popular OFDMA system for single packet transmission.

The rest of the research work is ordered in the following manner. Section II explains the system model. Section III covers a detailed explanation of the proposed OFSMA system aiming for robotic short-distance communication. Section IV presents the simulation results for reliability, minimum subcarrier demand and latency measurement with the packet and channel diversity concepts. Finally, Section V concludes the whole task as a conclusion.

3.2 System Model

An uplink communication system is considered in OFSMA system. An advanced receiver having capability of receive multiple packets at the same time is deployed at short-range communication system. The system model of OFSMA system is illustrated in figure 3.2. The system assumes in total K number of sensors as, $sensor_1$, $sensor_2 ... sensor_K$ in the system. Each sensor wake up based on their arrival time generated by Poisson arrival rate and transmit d duplicated packets over the total C frequency subcarrier channels. There is a set of frequency subcarrier channel, $f_x \epsilon \{f_1, f_2, f_3 . . . ..., f_X\}$. The subcarrier selection process is fully random. The system assign a total bandwidth of the system is B. Therefore, the bandwidth of a single subcarrier frequency channel is $B_{f_x} = B/K$. A packet signal is transmitted over an orthogonal subcarrier channel to avoid collision and interference. For any

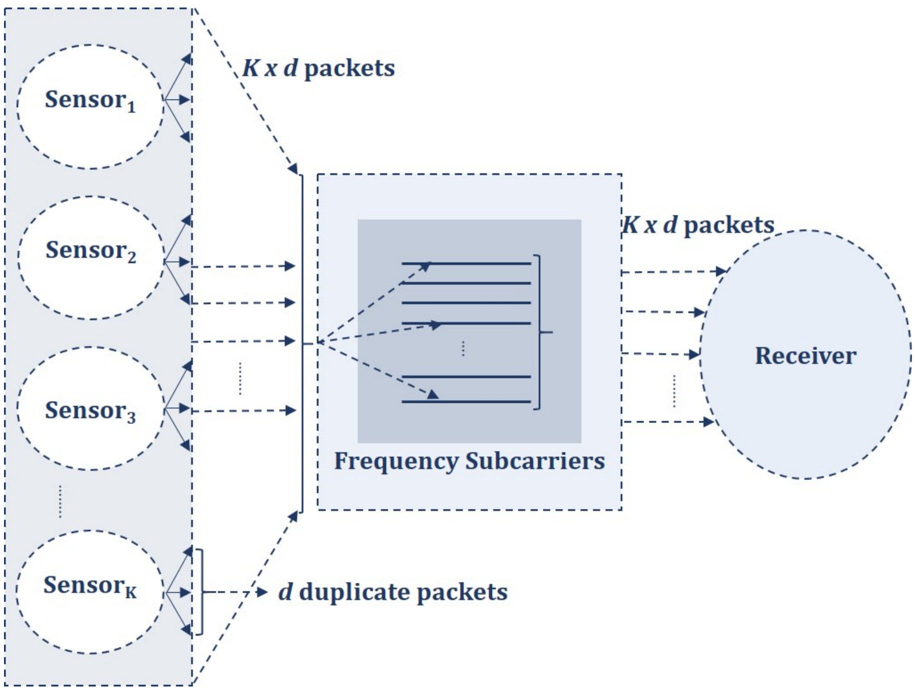

Figure 3.2: K sensors transmit d duplicated packets over the OFSMA system's single frequency band.

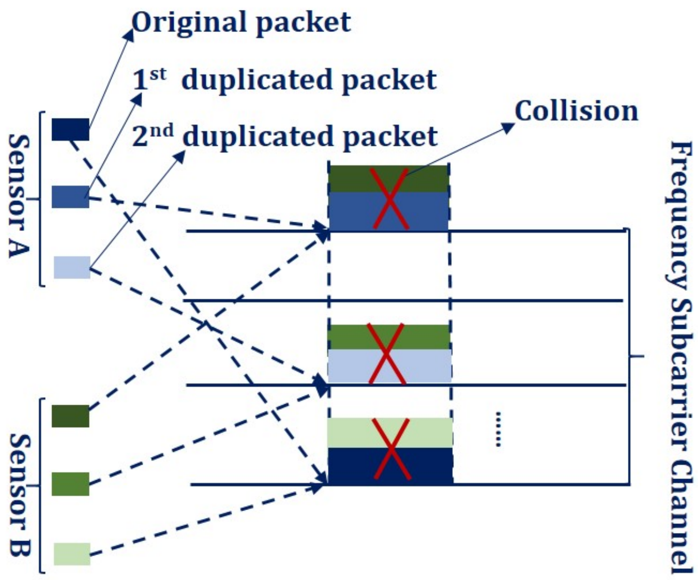

Figure 3.3: Inter-packet collision scenario in the OFSMA system.

random z-th slot, if the i=1,...,K number of sensors forwards j=1,...,d duplicated packets, then the maximum kd duplicated packets signal expression can be presented as

$$s(t) = \sum_{i=1}^{K} \sum_{j=1}^{d} u_{j,i}(t) e^{j2\pi f_x t} \tag{3.1}$$

where $u_{j,i}(t)$ is a complex baseband signal for d duplicated packet transmitting from k number of sensors having in-phase and quadrature component. Due to random subcarrier selection, there is a possibility of collision in the OFSMA system. An inter-packet collision among the packets emitted from sensors is presented in Figure 3.3 where the sensor A and B transmits 3 packet duplicated but due to random subcarrier selection all packets are collided due to select the same subcarrier channels. The probability of collision for k number of sensors transmit d duplicated packet at an arrival rate λ over C frequency subcarrier channels is given [33] as

$$\mathbb{P} = 1 - (\frac{e^{-d\lambda} + C^d - 1}{C^d})^{k-1} \tag{3.2}$$

The system assumed that the receiver has the advanced receiving and decoding capability to decode the multiple packets from different subcarrier channels at the same time. The signal is transmitted through the Aditive White Gaussian Noise channel and noise n(t) $\sim \mathcal{CN}(0, \sigma^2)$ is mixed with the signal. For any i-th slot, the received signal *r(t)* can be defined as

$$r(t) = \sum_{i=1}^{K} \sum_{j=1}^{d} u_{j,i}(t) e^{j2\pi f_x t} + n(t) \tag{3.3}$$

The OFSMA system utilized a simplified path loss model for calculating the received power signal. The system applied f=55x10^9 Hz as carrier frequency, path loss exponent γ=3[35], and the reference distance d_0=0.1 m[36]. Based on the simplified path loss model, the received signal power, p_r in dBm for OFSMA system can be calculated as

$$p_r = p_t - 77.2483 - 30\log_{10}(d_a) \tag{3.4}$$

Here, p_t is the transmit power in dBm and d_a is the distance between each sensor and receiver. The OFSMA considered the transmit power of 20 dBm at operating frequency of 55 GHz [37]. Therefore, the received power can be calculated as

$$p_r = -57.2483 - 30\log_{10}(d_a). \tag{3.5}$$

Equation (5) finally presents the OFSMA system's received power for a single packet transmission signal that directly related on the distance between transmitter and receiver. The maximum distance, d_a ranges from (0.1 $\sim$ 1) m.

3.3 OFSMA System in Single Frequency Band

The OFSMA scheme presents the sensor to receiver communication scenario and single packet processing cycle from a packet generation to the regeneration at the receiver site. The details are presented in sections below.

3.3.1 OFSMA Communication

The OFSMA is a multiple access scheme where packet signal bits are modulated, mapping and transmitted over the mass number of subcarrier channels in a random fashion. The proposed OFSMA system is presented in Figure 3.4. The packet bits that presented as bit sequence are generated and replicated for maximum of d duplication where d is a finite number as *2,3,...,d*. The d replicated packet bits are multiplied by carrier signal as a process of BPSK modulation and mapping. To avoid or significantly minimized bit error, the OFSMA system adopts BPSK modulation. An Inverse Discrete Fourier Transform (IDFT) conducts on BPSK modulated signal.

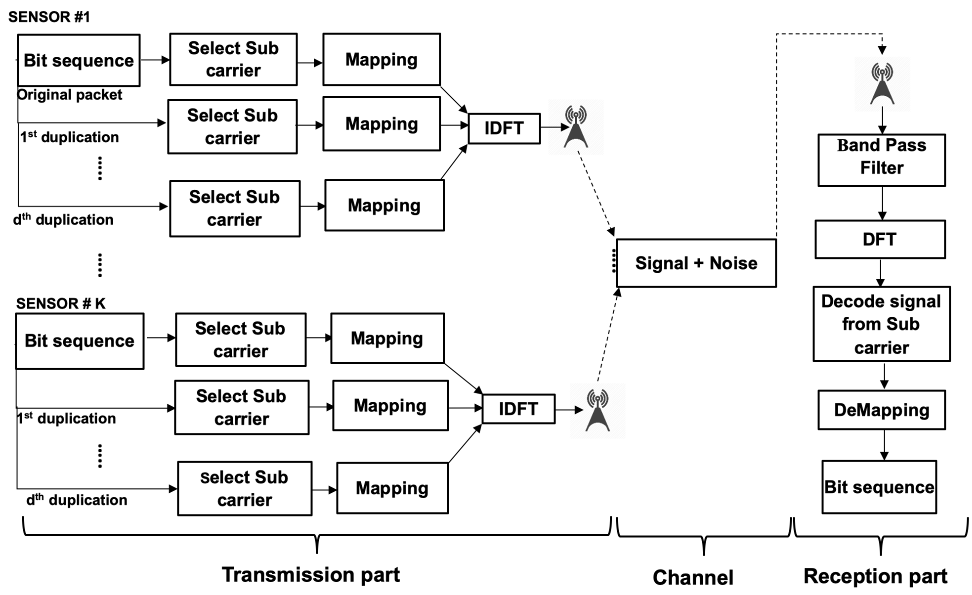

Figure 3.4: OFSMA communication system for single frequency band.

afterward, the signal is transfomr to analog domain and ready to transmit over the AWGN channel. The OFSMA system aiming to apply for a robotic short distance communication based on this consideration that the receiver able to detect more than one signal packet at a transmission time.

At the receiving point, the receiver receives the combined signal with AWGN channel's noise. A bandpass filter is applied to detect the signal from the signal noise mix form. The extracted signal is then shifted to a fast Fourier transform (FFT) block of operation and detected from their respective subcarrier channels. At final step, the BPSK demodulation operation is retrieved the original bit combinations.

3.3.2 Single Packet Processing Cycle

The OFSMA system also analyzed the single packet processing operation. A single packet processing cycle by the OFSMA system is illustrated in Figure 3.5. A packet bits are generated by the sensors and randomly selects a subcarrier frequency channel. A subcarrier frequency channel is a single frequency used to transmit the packet signal. The signal bits are modulated using BPSK low level modulation scheme to avoid Bit Error Rate (BER). For modulation process, the signal is multiplied with

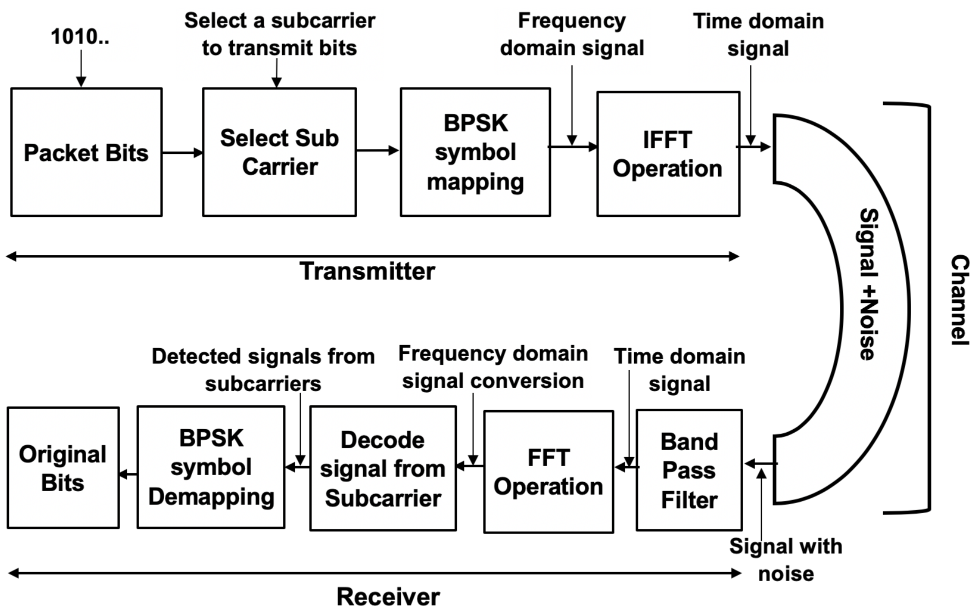

Figure 3.5: Single packet processing cycle for the OFSMA system‘s single frequency band operation.

the subcarrier signal. The subcarrier signal [38] expression can be presented as

$$CarrierSignal(CS) = \sqrt{\frac{2}{\overline{T}}} cos(2\pi f_x t) \tag{3.6}$$

where $\overline{T}$ is the symbol period time, f_x is the subcarrier frequency, and t is the duration of the signal. After the BPSK modulation process, the system performs an Inverse Fast Fourier Transform (IFFT), which converts the signal bits from the frequency domain to the time domain. A digital-to-analog converter is used to transform the signal into an analog form, and the signal is transmitted through the additive white Gaussian noise (AWGN) channel. A received signal added with noise is filtered using a bandpass filter to extract the signal part from the signal noise composite form. The processed signal is then entered into the the Fast Fourier Transform (FFT) block of operational steps to transform the signal from the time domain to the frequency domain. The frequency domain signal is then decoded by its respective subcarrier frequency and frequency bands. Finally, the signal is demodulated using BPSK demodulation process, and retieved the original bits of the packet.

3.3.3 OFSMA Distinction Over OFDMA

The OFSMA system‘s packet processing mechanism is different in comparison with the OFDMA system. In the OFDMA system, a packet is divided into multiple subcarriers and for each block of packet added extra bits as cyclic prefix which increase the usual size of a packet. On the other hand, the OFSMA system transmits the packet directly to a single subcarrier channels and the subcarrier determination is independent or random. In the OFDMA system, there is no probability of packet collision, but in the proposed OFSMA system, there is a probability of collision only when two or more packets selects the same subcarriers. The collision probability of the OFSMA system is minimized by assigning a massive number of subcarrier channels and a diverse duplicated packets.

3.3.4 Time Complexity Analysis

The time complexity of the OFSMA system is directly related to the number of sensors transmits packets over the transmission slot. In the best case scenario, only one sensors transmits d duplicated packets over the transmission slot that defines the time taken for processing the d packets. For each packet needs to perform all the n tasks (task means select subcarrier, mapping, IDFT etc.) which implies in total d.n time unit required to finished for d duplicated processing. So, the best case time complexity of the OFSMA system is $O(d.n)$. In the worst case scenario, the K sensors simultaneously transmits d duplicated packets over the transmission slot. That means the OFSMA system needs time to process in total $K.d$ packets. Therefore the worst case time complexity of the OFSMA system is $O(K.d.n)$

3.4 Simulation Results

The OFSMA system‘s reliability, latency, minimum subcarrier demands to satisfy reliability 99.999% and minimum duplicated packets which demands minimum subcarrier channels are analyzed in a system level MATLAB simulation platform. The reliability defines by the ratio of the number of successful packets at the receiver side and the total transmitted packets in a simulation time. In the simulation system, each sensors wake up and transmit packets based on the Poisson arrival process. Each sensors generates and processes the packets based on the OFSMA

Table 3.1: Simulation parameters for single frequency band operations.

Simulation parameters	**Value**
Modulation	BPSK
Center frequency f_c	55x10^9 Hz
Subcarrier bandwidth	10 kHz
System bandwidth	4 MHz
Link rate	1 Mbps
Number of transmitter	100
Bit length	30∼250 bits
Slot length	0.1 ms
Packet duplication	2∼32
Number of frequency subcarriers	25∼650
λ	0.05∼15000 pk/sec
SNR	5 dB
Bit Rate, T	1 bit/sec
Simulation Time	1000 s

system strategy and transmits through 55 GHz, 30 GHz, 10 GHz, 2.4 GHz, and 920 MHz frequency subcarrier channels. The detailed simulation parameters are listed in table 1.

The OFSMA system's reliability responses are evaluated for a different number of subcarrier channels. The system reliability is directly related to the number of frequency subcarrier channels assigned for transmission presented in Figure 3.6. The 2 packet duplications are transmitted over a slotted ALOHA multi-channel system assigning at 200, 300, and 400 channels for 100 sensors. The figure illustrates that the 400 channels achieve improved reliability percentage compared with 300 and 200 channels. Due to random subcarrier selection implies the increasing number of frequency subcarriers assignment achieved a higher reliability percentage. The 400 channels able to achieve on average 0.217 % better reliability percentage compared to 300 channels and on average 0.6036 % reliability percentage is improved compared to 200 channels.

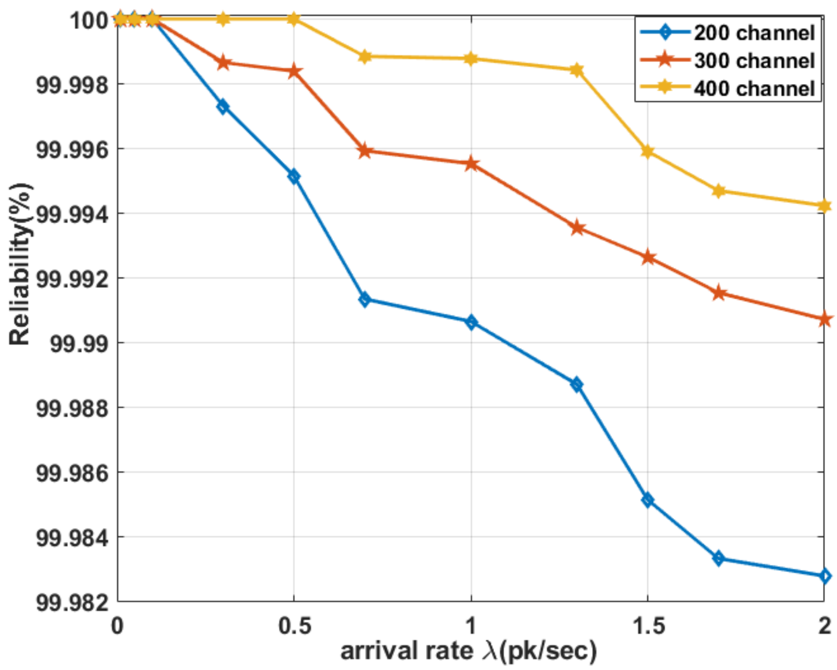

Figure 3.6: The reliability response for 2-packet duplication evaluated over 200, 300 and 400 subcarriers.

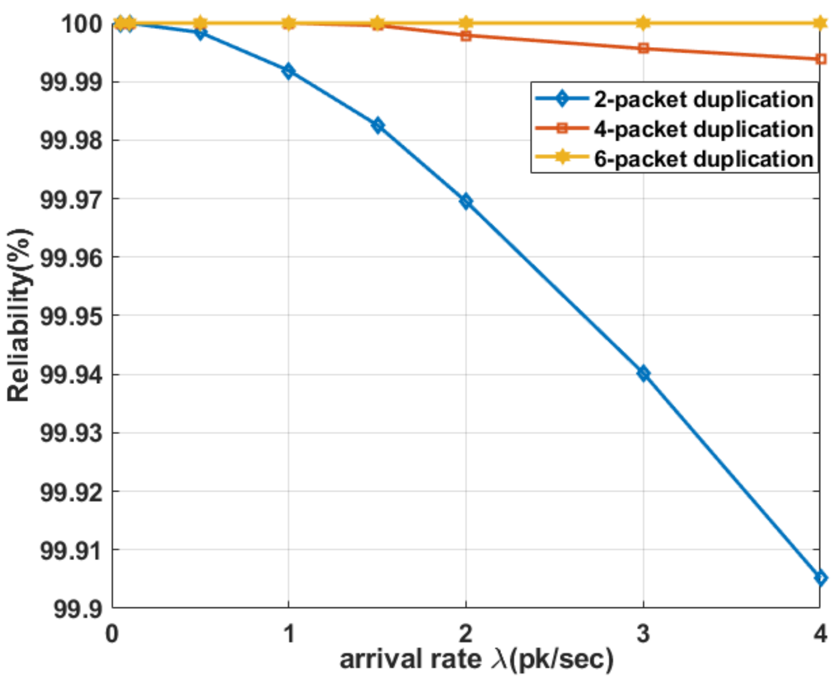

Figure 3.7: The reliability response of 2-, 4-, and 6-packet duplication over 300 subcarrier channels.

The number of packet duplications also has an important impact on the system reliability of the packet transmission. The reliability performance over different packet diversity is presented in Figure 3.7. The system considers 100 sensors allow to transmit 2, 4, and 6 packet duplications for different arrival conditions inside 300 subcarrier channels, and the reliability response is presented in Figure 3.7. The figure illustrates that the 6-duplicated packet shows the improved reliability percentage compared with the 2 and 4 packet duplication. The reliability percentage of 2 packet duplication is decreased faster compared to the 4 and 6 packet duplication because of the higher number of inter-packet collision. Moreover, due to a lower number of packet duplication, it is very easy to collide all packet duplications. The 6-packet duplication able to achieve on average 0.16305 % improve reliability compared with 4-packet duplication and on average 2.62365 % improve reliability over 2-packet duplication.

The previous results considers a short range of arrival condition for 100 sensors. The OFSMA system also considers a higher range of arrival condition for sensors and evaluate the reliability. The system determine the minimum number of frequency subcarrier channels demanded by the system to ensure the URLLC's expected reliability 99.999%. The minimum number of subcarrier to satisfy the reliability of 99.999% considering different packet duplication is presented in Figure 3.8. To determine the minimum subcarrier channels, the OFSMA system considers 3-, 4-, 5-, 7-, 8-, 14-, 16-, 21-, and 32-packet duplication. According to the result for all packet duplications, the 3-packet duplication achieved higher reliability means demanded lower subcarrier compared to 4-packet duplication because of not only for inter-packet collision but also happening of self-packet collision. In the massive transmission, it is more easier to select a single frequency subcarrier channels by 2 packets than the 3 packet duplication. At 1000 pk/sec arrival condition mark as 1 in figure, 14-packet diversity demanded the minimum subcarrier channels to full fill the URLLC's expected reliability of 99.999%. Additionally at 10000 pk/sec arrival condition mark as 2 in the figure, 5- and 7-packet diversity demanded the minimum subcarrier channels. At higher arrival condition, the number of packets exchange in a network is successively higher. The higher packet duplication at maximum arrival condition also generates too much packet for transmission. This higher number of packets also increase the probability of inter-packet collision. Due to this reason, the lower number of packet duplication (as 5 and 7 packet duplication) demands lower number of subcarrier channels compared with large number of packet duplications (as 16, 21, and 32 packet duplication). This is one of the main reason to change the packet diversity sequence from 14 packet diversity to 5- or 7- packet diversity at packet arrival condition of 10000 pk/sec. Therefore, higher number of packet duplication is not preferable at high traffic condition to gain higher reliability.

The OFSMA system for single frequency band also determines the minimum subcarrier demands for a diverse range of packet duplication to satisfy the reliability of 99.999% and indicates which packet diversity demands the minimum amount of channels at different arrival condition. The 100 sensors transmit a different number of packet duplication over 30 GHz, 10 GHz, 2.4 GHz, and 920 MHz single frequency band and evaluate the minimum subcarrier demanded packet duplication that illustrated in Figure 3.9. The figure presents that 30 GHz and 920 MHz required the same packet diversity for an arrival rate of 1∼ 100 pk/sec. For average arrival condi-

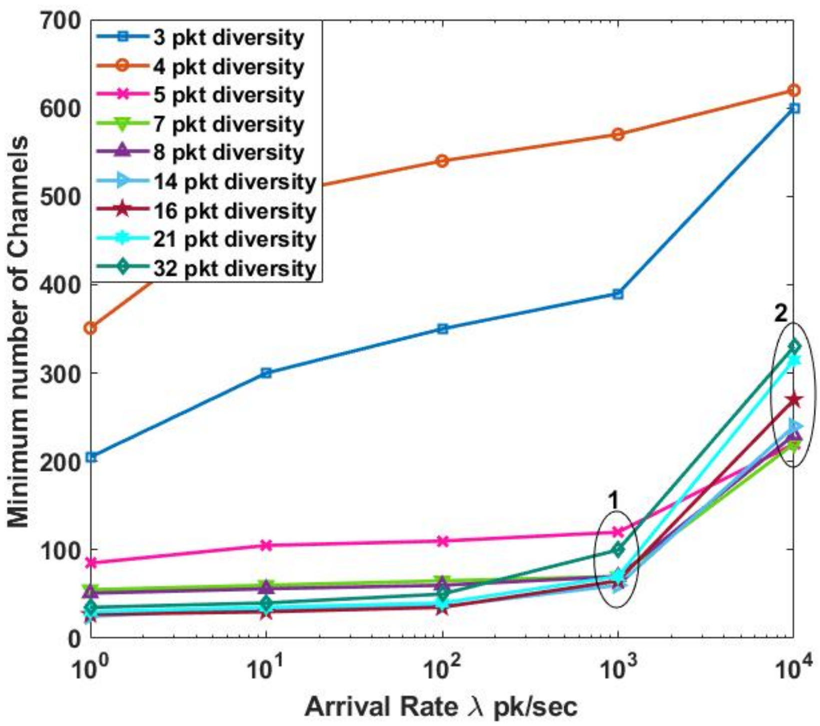

Figure 3.8: The minimum subcarrier detection to satisfy the reliability of 99.999% for diverse packet duplication over 55 GHz frequency bands.

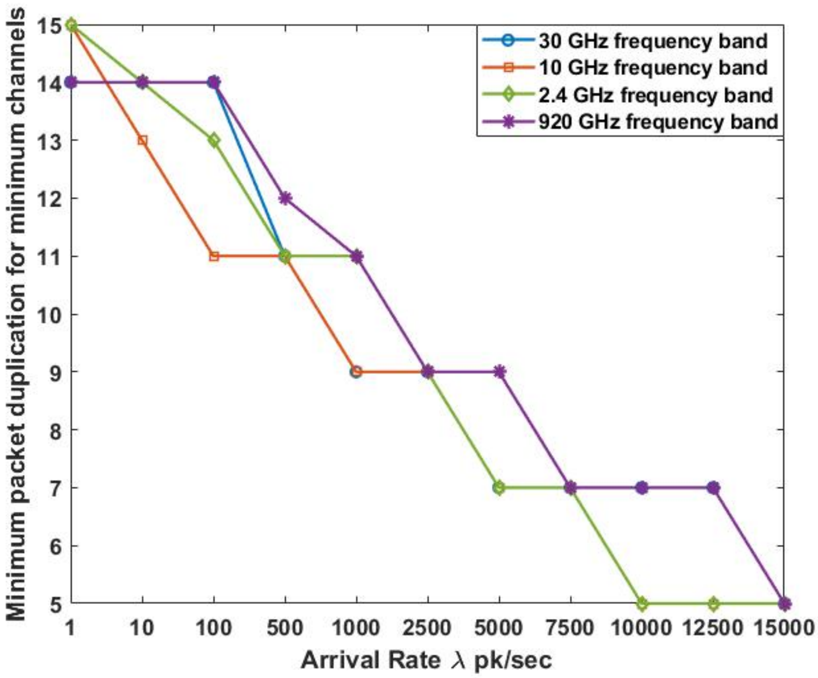

Figure 3.9: Determine minimum channel required minimum packet duplication for different traffic condition over 30 GHz, 10 GHz, 2.4 GHz and 920 MHz frequency band.

tion of 500$\sim$ 2500 pk/sec, 30 GHz and 10 GHz demanded the equal number of packet duplication and 2.4 GHz and 920 MHz have little different requirements, especially in the 500 pk/sec arrival condition. In the arrival condition of 5000 $\sim$ 10000 pk/sec, 10 GHz and 2.4 GHz have the equal packet duplication demands, but in the 5000 pk/sec arrival situation, 30 GHz and 920 MHz are a slightly different demands in evaluating the minimum number of subcarriers to satisfy the reliability of 99.999%. At higher arrival rate of 10000 $\sim$ 15000 pk/sec, 30 GHz and 920 MHz required the equal packet duplication and 10 GHz and 2.4 GHz required the equal packet duplication to evaluate the minimum subcarrier channels to full fill the URLLC's defined reliability of 99.999%. Due to the random frequency selection, there is a little variation of minimum subcarrier requirement by different packet duplication. Despite of random selection of subcarrier, the result of minimum subcarrier detection is not fluctuated at a higher order. The result illustrates an important guideline about minimum subcarrier channel demanded packet duplication considering different arrival rate situation in a slotted-ALOHA random access packet diversity system.

Finally, the OFSMA system with single frequency band evaluate the air interface

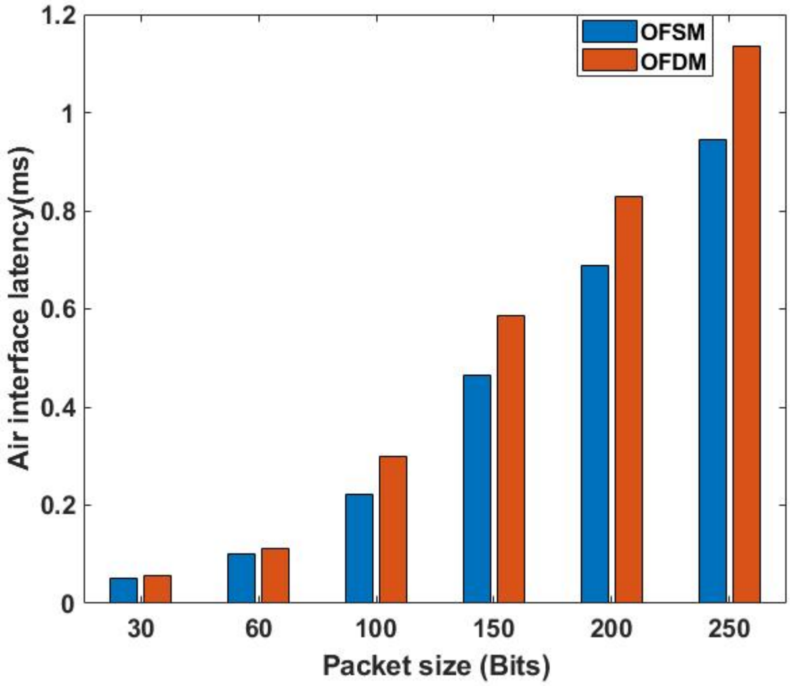

Figure 3.10: OFSMA system‘s single packet air interface latency measurement and comparison.

latency for the Orthogonal Frequency Subcarrier-based Multiplexing (OFSM) and Orthogonal Frequency Division Multiplexing (OFDM) which presents in Figure 3.10. A single packet with diverse bit lengths are transmit in an uplink communication from the sensor to the receiver and the air interface latency (ail) is determined. For the OFSMA system, if the propagation delay is l and system delay is Δ, then the air interface latency measured by the OFSMA system can be expressed as

$$ail = l + \Delta \tag{3.7}$$

The propagation delay is evaluated by the ratio of a packet length bit as B and the communication link speed of an interface as R of the system. The system delay Δ means the time consumed to transmit the bits from the sensor to the receiver via Gaussian channels and the time is measured from the simulation platform. Therefore, the ail can be rewritten as

$$ail = \frac{B}{R} + \Delta \tag{3.8}$$

The OFSMA system considered $30 \sim 250$ bits packet length for OFSM and OFDM system. The OFSM system performs better for each considered packet size compared with OFDM system due to adopt a simple packet processing system. The proposed OFSM system transmit the complete packet bits in a single subcarrier channels. On the contrary in OFDM system, the packet bits are divided into multiple subcarriers and added cyclic prefix bits into the original bits that increase the usual packet size which consumed more time to transmit over the network. In the result evaluation, up to 150 bits packet demands less than 0.5 ms and for up to 250 bits packet size requires less than 1 ms for air interface latency evaluation.

3.5 Conclusion

This research work presents a new access scheme- Orthogonal Frequency Subcarrier-based Multiple Access and considers a single frequency band in the system consideration. The OFSMA system adopts the packet diversity principle and transmits multiple copies of the same packet in the same slot over the mass number of subcarrier channels to improve the reliability of a packet transmission. The simulation results shows that the 5 and 7 packet duplications demands the minimum subcarriers at highest arrival rate to satisfy the URLLC‘s recommended reliability levels compared to all other packet duplication. Moreover,the OFSMA system also determines the air interface latency and compare with the OFDMA system. The OFSMA system shows better time efficiency compared with OFDMA system for all considered packet size. Finally, the system determines the minimum packet duplications which demands lowest subcarrier demands conducted over different frequency bands for forwarding packets. The OFSMA system achieved the expected reliability of 99.999% within latency bound less than 1 ms for specific packet size. Therefore, the OFSMA system might be used to design a lightweight, flexible robot‘s internal communication system. In the future, this scheme will investigate for more frequency bands and more time-critical communication system.

Chapter 4

OFSMA MAC with Multiple Frequency Band

4.1 Introduction

The 5G communication is going to make a revolutionary change and being standard in communication domain. It aims to provide the improved service beyond the existing 4G communication in terms of higher data rates, massive communication, mass number of device communication capability, massive IoT system and mission critical communication system. Among them the 5G facilities are broadly divided into three categories as evolved mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine type communication (mMTC) [39]. The eMBB is designed to provide the higher data rates in mobile communication devices. The URLLC is designed for mission-critical services, target-oriented service, and next-generation network services which aims to prioritized high reliability and low latency packet transmission. Finally, the mMTC is specially designed to provide communication service among devices and able to communicate a massive number of devices at the same time. The URLLC is a form of machine type communication (MTC) which mainly focus the communication reliability and latency demands among machines and devices[40]. The URLLC aiming to provide communication service with higher reliability of 99.999% in packet transmission within strict latency bound as 1 ms[41, 42]. The URLLC system has diverse applications, such as reliable remote action with robots and reliable coordination among vehicles[25], autonomous vehicles communication[26], the tactile internet [43], augmented or virtual reality (AR/VR)[44], unmanned aerial vehicles [45] and industrial internet of things (IoT) applications include factory autonomous systems[46, 26]. In the near future, URLLC will explore new domain of application that are still unthinkable by

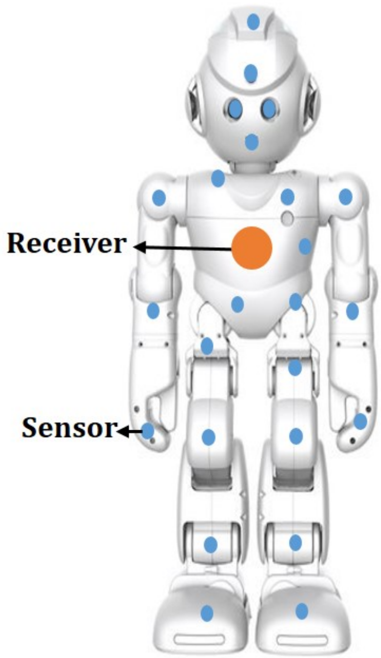

Figure 4.1: A typical humanoid sensor connected robot with finite number of sensors to ensure wireless backbone communication using multiple frequency band.

human beings.

Structurally, a robot made of multiple elements, and numerous wires are needed to serve in the communication backbone among the attached elements[47]. These enormous connective wires insist a robot to gain higher weight and results consume extra power for its regular movement. Due to attaching many wires inside the robotic structure, sometimes it is very difficult to give an appropriate structure. Moreover, the connective wires sometimes lose their connection due to a loose connection, speed of operation, and even getting burn. In that situation, the maintenance becomes complex and time consuming for a service robot.

With the state of the art emerging applications of URLLC services and the rapid development of the sensor-oriented application, it's a time demand to replace a robot's internal communication instead of wires by a finite number of non-periodic homogeneous sensors. A conceptual design of a future wireless sensor-connection based robot is presented in Figure 4.1. This conversion is difficult and many challenges as higher reliability, stringent latency, signal fading and interference[48], and spontaneous wire-like communication need to be assured. To overcome the defined challenges in conversion process, a new access scheme-Orthogonal Frequency

Subcarrier-based Multiple Access (OFSMA) has been proposed. The OFSMA access scheme incorporated the packet diversity principle to ensure the URLLC's expected 99.999% reliability of packet transmission and allow sensors to transmit packets in a random fashion to reduce latency and keep it less than 1 ms.

4.1.1 Related Work

In the research mainstream, the researchers try to achieve the desirable reliability and latency in different wireless application environment. The URLLC able to draw attention from different researchers of state-of-the-art communication services due to its exciting and attracting applications. The wireless access in the context of URLLC is studied [21] in terms of packet reliability, latency, the trade-off between communication channel number and link rate, and probability of error in bits. This paper also highlights the impacts of link reliability, packet duplication, and interface diversity in the context of URLLC. A hybrid ARQ scheme performance and its analysis in the ultra-reliable and low-latency communication domain is studied in [49] that able to make the system more energy efficient by properly balancing the time diversity re-transmission and assure higher rate of communication over Nakagami-m block fading channels. This paper also evaluates the maximum allowed transmission attempts considering the maximum possible energy usage of the system. According to this paper [50], try to optimize the packet loss rate upto 10^{-8} for different modulation schemes to assure higher reliability. The air-interface latency ranges from 250 μs to 10 ms, and the total processing time is expected to range from 1 ms to 100 ms. Soon, the mobile broadband reliable low-latency communication (MBRLLC) is planning to deliver any demanded performance while shorten the rate-reliability-latency trade-off under the 6G communication domain[51] in near future. A field experiments trials on 5G URLLC system is studied in [52], where a new frame structure is proposed beyond the LTE-advanced frame that can achieve the URLLC defined latency and for reliability requirement over diverse packet size is analyzed under the different modulation scheme. An robot made for industry automation[30] has been proposed and utilize the advanced waveform technology (polar OFDM (P-OFDM)) to serve in a practical industrial environment as well as ensuring higher speed and higher reliability. In URLLC domain, a single OFDM symbol[53] is applied to detect a packet information, to shorten latency via differential detection and transmission prediction and able to achieve higher reliability up to 10^{-6}. A practical packet drop design in URLLC for wireless systems is analyzed in[54] and in this design, the control cost is shorten by optimizing packet drop or by optimal wireless resource allocation in a multi remote-controller system. The combined existence of URLLC and eMBB service in a cloud-based radio access network is studied in[31] and NOMA, OMA, URLLC and eMBB performances are evaluated for reliability, latency, and inter-cell power gain in terms of different network traffic loads by adopting puncturing and successive interference cancellation technique. The duplicated packets are forwarded over the connected and split carriers using dependent links to increase network reliability and analysis by employing multiple radio resource in the system[32]. A contention-based system has been studied in [33] that use slotted ALOHA system with multichannel and transmit multiple packets in consecutive transmission slots to increase the network reliability, and to minimize latency to satisfy URLLC's requirement. A grant-free uplink transmission in the context of URLLC is conducted in [34] that compared grant-free and grant-based access system performance by using the k-repetitions packet transmission principle. The energy efficieny issue in the URLLC domain is exploit in [12] and proposed few key features that helps to minimize energy consumption in the URLLC system.

An OFSMA access scheme aiming to ensure URLLC‘s higher reliability and latency requirement in a sensor-connected robot's internal communication system is proposed in[55], that considers only a single band subcarrier channels. The ultimate aim of the proposed work are to determine the minimum subcarriers to satisfy 99.999% reliability and air-interface latency for single packet communication. Similarly, few research work conducted to transform a wired system into a wireless sensor-connected system as spacecraft automation, airplane structural heath monitoring system and a wireless elderly health monitoring system. In order to design a spacecraft automated[28], sensors transmits 988 B payload over different frequency bands in an ultra-wideband frequency using a TDMA protocol having a short 5 ms time slot inside the spacecraft payload networks. A sensor-based structural health monitoring system for an airplane is proposed in[29] where a few sensor nodes observing the health status information of an airplane that deployed throughout the aircraft. These sensor nodes estimate the system throughput, the data dropped rate and the delay of the system for a maximum of 7 nodes as approximately 12000 bps, 180 bps, and 115 ms, respectively. An elderly healthcare monitoring system is studied in[56] utilizing a wireless sensor network and use a bracelet-type devices equipped with sensors that able to receive data in real time and stored in a centralized server for monitoring and analysis. A structural health monitoring and early earthquake warning system is studied in [57] that propose a monitoring and warning system in presence of seismic events in the 5G communication domain.

Moreover, several random accesses including slotted ALOHA protocol have been studied to achieve the expected reliability and latency in our survey. An asynchronous contention solution slotted ALOHA proposed in [58] that utilize virtual framing, time offset technique, and transmit multiple replicas of the same packet strategy are used to improve the throughput of the network system. A multiple packet transmission technique adopted in a cluster-based environment studied in[59] where duplicated packets forwarded into different slots selecting independent frequency and transmitters are grouped to improve the system throughput level. A multichannel random access operation in an OFDMA wireless network is studied in[60], that proposed a fast retrial algorithm to transmit multiple copies of the packet into a frequency diversity system after a collision in a slotted ALOHA system.

4.1.2 Contributions

The state-of-the-art research works related to the wireless sensor-based system studied in [28, 29, 56, 57]. These research works are not compatible to transform robotic internal communication into the wireless mode. The existing researchers frequently used Orthogonal Frequency Division Multiple Access (OFDMA) and Time Division Multiple Access (TDMA) scheme for packet transmission to assure reliability of 99.999% and bound latency less than 1 ms. But tn the OFDMA system, the packet bits split into the number of subcarrier and added cyclic prefix bits with the original packet bits. Due to this the usual packet size is getting bigger that needs more time at transmission stage. On the other hand, the slotted-ALOHA communication system shows better performance for small payload transmission over the TDMA system[61]. Moreover, the previous researchers not yet considered the short-distance communication and higher arrival rate of sensor generation performance impact into the system. Additionally, the minimum subcarriers detection to achieve reliability 99.999% for the mass number of sensors was not explored. Overall, there is a gap to analysis a short-range high reliable communication system in the URLLC domain not yet studied that can able to overcome a future robotic sensor‘s internal communication system by an effective access scheme. The main contributions of this chapter research work are summarized as follows.

- An Orthogonal Frequency Subcarrier-based Multiple Access (OFSMA) scheme has been introduced which allow massive number of sensors to transmit multiple duplicated packets randomly over orthogonal subcarriers to ensure interference-free, high reliable and low latency communication.
- A short distance system and path loss model has been presented the express transmitted packet signals, analyze the packet size in terms of link speed, collision probability analysis over number of channel assigned and packet duplication for different arrival condition, and measure link reliability of the proposed OFSMA system.
- The minimum subcarrier channels demands to full fill the URLLC's required reliability of 99.999% are evaluated for OFSMA system in terms of different number of packet diversity over the diverse frequency bands in a variation of low to higher order arrival conditions.
- The OFSMA system's reliability are evaluated for fixed subcarrier assignment and determine the variation of reliability in terms of different numbers of frequency bands and packet duplication assign in the system.
- Finally, the OFSMA system's air interface latency are estimated for diverse packet size and compared with the OFDMA system for a single packet uplink communication.

The rest of this chapter is organized as follows. In Section II, the system model with signal analysis, packet size determination, collision probability of the OFSMA system, interface reliability and a path loss design is presented. In Section III, a detailed explanation of the proposed OFSMA system is introduced. In Section IV, the simulation process and results are presented to show the performances of the proposed method. Finally, Section V summarizes the whole part of the chapter.

4.2 System Model

A short-range uplink transmission system is considered where the non-periodic sensors are ubiquitously deployed surrounding the receiver. A packet diversity principle is used and forward multiple copies of the same packet over a massive number of subcarrier channels to ensure higher reliability of packet transmission. In our proposed system, a diverse number of frequency bands and subcarrier channels are included to ensure higher reliability of the packet transmission. By considering the frequency band and subcarrier allocation, the system model of OFSMA system is divided into three types:

1. Single-band frequency diversity model.
2. Double-band frequency diversity model.
3. Triple-band frequency diversity model.

The single-band frequency diversity model adopts a single frequency band 2.4 GHz with multiple orthogonal subcarrier channels, as illustrated in Figure 4.2. We assumes a total K number of sensors ($Sensor_1$, $Sensor_2$,...,$Sensor_K$), and each sensor transmits *3,5,...,d* duplicated packets. According to the packet diversity principle, among the duplicated packets if at least a single packet is successfully received at the receiver, that‘s considered as a successful transmission. The system contains a diverse number of frequency bands for different system models. In general, the system has a set of frequency band having bandwidth B of each band as, B_s=B_1, B_2, B_3,...,B_n. So, the bandwidth of each subcarrier frequency channel is B_{f_x} = B/K. Each frequency band has a set of maximum C subcarrier channels as f_s = f_1, f_2, f_3,...,f_C. During the transmission of a single packet from the duplications, first a frequency band, B_r is selected in random order where $B_r \epsilon B_s$. Afterwards a subcarrier channel f_x is also picked in random fashion where $f_x \epsilon f_s$, is from the previously elected B_r frequency band. For single-band frequency diversity model the frequency selection can be expressed as

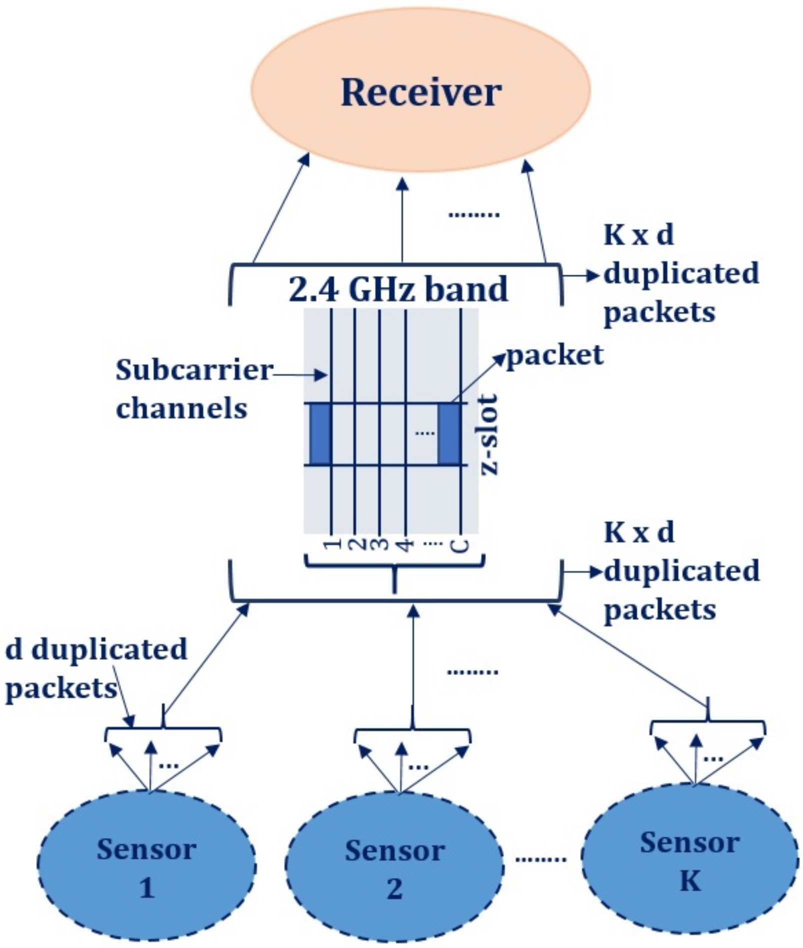

Figure 4.2: OFSMA system‘s single-band frequency diversity model.

$$f_s \overset{\mathbb{R}}{\leftarrow} f_x \tag{4.1}$$

The OFSMA scheme utilize random access for band and subcarrier channel selection in order to ensure short latency consumption. In the packet transmission steps, each sensor follows the Poisson arrival process for packet transmission and generation in the slotted ALOHA protocol. For any transmission z-th slot scenario in slotted ALOHA protocol, is presented in Figure 4.3. Due to applying the packet diversity principle, any sensor j transmits two duplicated packets over different subcarrier channels in a single slot transmission time interval (TTI).

The double-band and triple-band frequency diversity models consider more than one frequency band to forward duplicated packets. The multiband frequency diversity model is illustrated in Figure 4.4 and Figure 4.5. The double-band frequency

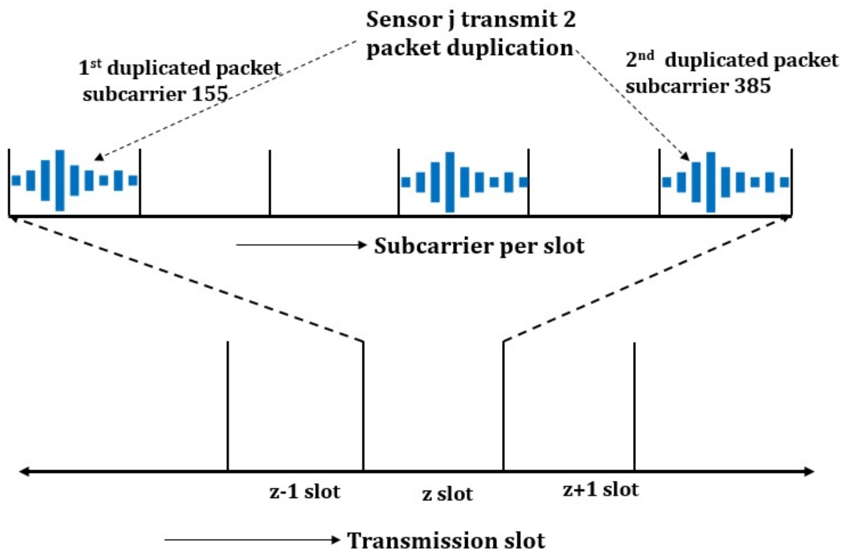

Figure 4.3: Duplicated packet transmission over single TTI Slotted ALOHA system.

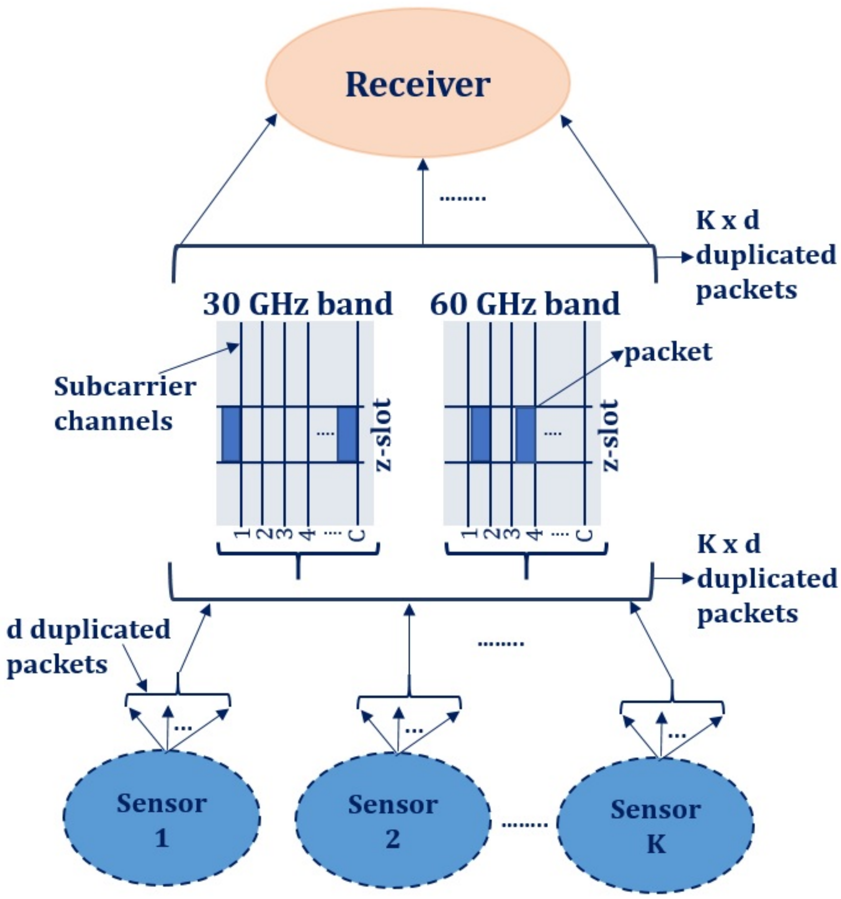

Figure 4.4: OFSMA system‘s double-band frequency diversity model.

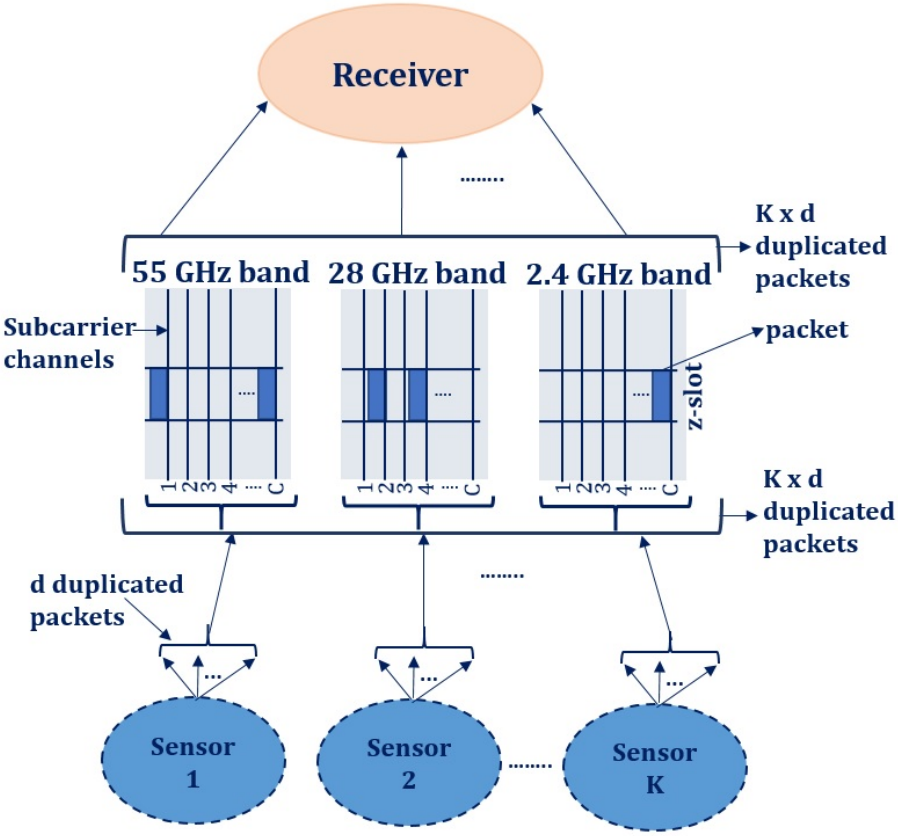

Figure 4.5: OFSMA system‘s triple-band frequency diversity model.

diversity model assign two frequency bands at 30 GHz and 60 GHz to deliver data from the sensor to the receiver's end, as presented in Figure 4.4. Each frequency band is also assigned an equal number of subcarrier frequency channels. According to the models, k number of sensors forward d duplicated packets over a randomly chosen frequency band and frequency subcarrier. The random frequency band B_r selection can be expressed as

$$B_s \overset{\mathbb{R}}{\leftarrow} B_r \tag{4.2}$$

where B_s is the set of frequency bands for double-band and triple-band frequency diversity model. The subcarrier frequency selection follows Equation (4.1). The duplicated packets are forwarded over randomly chosen one or two frequency bands and subcarrier frequency channels in the double-band frequency diversity model. The triple-band frequency diversity model, illustrated in Figure 4.5, employs three frequency bands at 55 GHz, 28 GHz, and 2.4 GHz to transmit data from the sensor to the receiver. A single packet randomly chooses a frequency band among three frequency bands and then again randomly selects a frequency subcarrier channel from the selected frequency band. The random selection procedure reduces the scheduling latency and ensures short latency packet transmission.

4.2.1 Packet Size

The 3GPP standardized the URLLC reliability requirement for one transmission of a packet size of 32 bytes is 1-10^{-5} with a user plane latency of 1ms[62],[44]. Due to low-latency requirements, the packet length should be short, and the size depends on the application environment and requirement. Consider a short-length packet of b bits and latency for b bits transmission is T. Therefore, the link or interface transmission rate R_{bps} can be shown as

$$R_{bps} = \frac{b}{T} \tag{4.3}$$

If the system's packet latency requirement is predefined, then for a given communication link rate using (4.3), we can calculate the minimum bit-length of the packet. However, the transmission rate is expressed in standard information-theoretic models in terms of bits per channel uses *[bpcu]*. For a defined bandwidth B, the number of channel needed for transmission is $2BT$. Therefore the link rate R can be expressed [21] as

$$R = \frac{b}{2BT} = \frac{R_{bps}}{2B}[bpcu]. \tag{4.4}$$

4.2.2 Packet Transmission and Collision Probability Analysis

A single packet signal is transmitted in orthogonal pattern over a frequency subcarrier f_x from C frequency channels to avoid interference. Each sensor transmits i=1,2,...,d duplicated packets to improve the reliability of the transmission. The duplicated packet signal $S(t)$ can be expressed as

$$S(t) = \sum_{i=1}^{d} u_i(t)e^{j2\pi f_{xi} t} \tag{4.5}$$

where $u_i(t)$ is a complex baseband signal for i number of duplicated packets with an in-phase and quadrature component and f_{xi} is the randomly selected frequency f_x for i duplicated packets. In the slotted ALOHA scheme, for any z-th slot, if j=1,2,...,K number of sensors transmit i=1,2,...,d duplicated packet then the total

$K.d$ number of packets transmitted in z-th slot can be presented as

$$S(t) = \sum_{j=1}^{K} \sum_{i=1}^{d} u_{i,j}(t) e^{j2\pi f_{xi} t} \tag{4.6}$$

where $u_{i,j}(t)$ is a complex baseband signal for i number of duplicated packets from j number of sensors having an in-phase and quadrature component. The OFSMA system adopted packet diversity principle and forwarded multiple copies of the packet over the different number of frequency bands and subcarriers to ensure higher reliability and error-free transmission. Due to applying packet diversity concept of transmitting multiple packets over the massive number of subcarrier channels randomly, in the system arises few collisions. The collision happens due to select the same subcarrier channel by two or more packets randomly in a transmission. How-

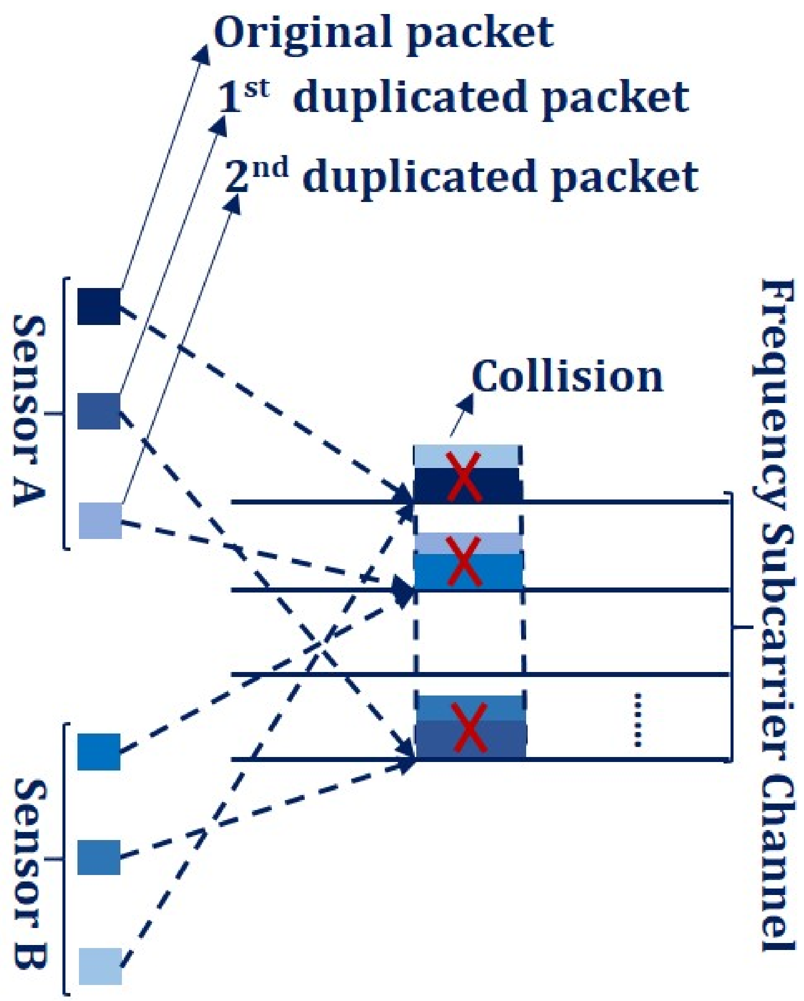

Figure 4.6: OFSMA system's inter-packet collision scenario in a TTI of a multi-channel slotted-ALOHA communication system.

ever, in a sequence of success and collide bit stream, the receiver assumed to detect the success packets[63, 22, 64, 65] and ignores duplicated packets. Moreover, the system assumed that duplicated packets emitted from a sensor have no collision means no two duplicated packets randomly choose the same subcarrier in a transmission. An example of inter-packet collision is presented in Figure 4.6. Sensors A and B forward 3 duplicated packets over the subcarrier channels, but all packets of the two sensors collide because they randomly select the same subcarrier. Due to the random selection of frequency subcarrier channels, we evaluate the probability of packet collision. The probability of random transmission events can be represented [33] as

$$\mathbb{P}_{ra} = 1 - e^{-\lambda} \tag{4.7}$$

and for d duplicated packets, the random event can be express as

$$\mathbb{P}_{ra} = 1 - e^{-d\lambda} \tag{4.8}$$

The inter-packet collision probability for K number of sensors having arrival rate of λ with d duplication packets can be shown[33] as

$$\mathbb{P}_{ipc} = 1 - (\frac{e^{-d\lambda} + C^d - 1}{C^d})^{K-1} \tag{4.9}$$

The error probability of receiving b bits of data within N=$2BT$ channels having SNR is given by γ well approximated [22, 66, 67] by

$$\epsilon(N, \gamma, b) = Q(\frac{NC(\gamma) - b + \frac{1}{2}\log_2 N}{\sqrt{NV(\gamma)}}) \tag{4.10}$$

where Q is a Gaussian Q function, C(γ)=$\frac{1}{2}\log_2(1+\gamma)$ and V(γ)=$\frac{\gamma(\gamma+2)}{2(\gamma+1)^2}\log_2^2$ e denotes the channel capacity and dispersion. The system assumes that the receiver has the capability to detect multiple user‘s packet at the same time from different subcarrier frequency channels [33]. The packet signal is forwarded through the AWGN channel, and noise n(t) $\sim \mathcal{CN}(0, \sigma^2)$ is added to the signal. For any z-th slot, the received signal *r(t)* can be defined as

$$r(t) = \sum_{j=1}^{K}\sum_{i=1}^{d} u_{i,j}(t)e^{j2\pi f_{xi}t} + n(t) \tag{4.11}$$

Equation (4.11) presents the total packet equivalent signals with noise received by the receiver.

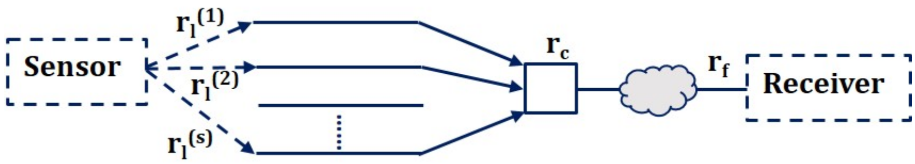

Figure 4.7: OFSMA system‘s connectivity scenario between the sensor and receiver.

4.2.3 Interface Reliability

A communication system's packet transmission reliability depends on several factors, such as a link or the interface reliability, interface diversity, packet diversity, device synchronization, interference, core network reliability, and traffic condition. The OFSMA system adopt packet diversity principle which allow sensors to forward multiple duplicated packets over massive subccarier channels in the same TTI slot to improve the reliability up to URLLC's expected level. A connectivity scenario involving a single sensor for the OFSMA system is illustrated in Figure 4.7. The proposed OFSMA system's packet reliability is related to its interface reliability r^i, core network reliability r_c and link r_f to the receiver. Therefore the system reliability can be expressed[21] as

$$R_{system} = (1 - \prod_{i=1}^{N} (1 - r_1^{(i)}) r_c r_f) \tag{4.12}$$

4.2.4 Signal Propagation

The OFSMA system considers a simplified propagation model for calculating the received signal power at the receiver side. Based on the simplified path loss model, the received power, p_r in dBm, can be presented as

$$p_r = p_t + X - 10\Gamma \log_{10} \frac{d_a}{d_0} \tag{4.13}$$

where p_t is the transmit signal power, X is an unitless constant and can be expressed as $20log_{10}\ (\lambda/4\pi\ d_0)$, λ is the wavelength of the signal measured in meters and equals c/f (in which c is the speed of light measured in meters per second and f is the signal frequency measured in Hz). The reference distance d_0 is a constant distance from the sensor to the receiver, and d_a is the actual distance between the sensor and the receiver. The Γ is a path loss exponent that varies from one environment to another. The system considered a set of carrier frequencies, which

Table 4.1: Received power, P_r for different frequency band at distance, d_a=1m.

Frequency bands (GHz)	**Received power (dBm)**
.920	-11.7276
2.4	-20.0560
10	-32.4518
28	-41.3950
30	-41.9942
55	-47.2591
60	-48.0148

are listed in table 4.1. The system considered path loss exponent Γ=2.001[68], and reference distance d_0=0.1 m[36]. After considering all of the defined parameters, the received signal power, p_r in dBm, of the simplified path loss model for the system can be evaluated as

$$p_r = p_t + 147.5482 - 20\log_{10}(f) - 20.01\log_{10}(d_a) \tag{4.14}$$

We considered the transmit power to be 20 dBm [69] for all our system models. Therefore, the received power can be calculated as

$$p_r = 167.5482 - 20\log_{10}(f) - 20.01\log_{10}(d_a). \tag{4.15}$$

Equation (15) presents the signal's received power for a single transmitted signal that directly depends on the frequency and distance between the transmitter and the receiver. The distance, d_a, ranges from $(0.1 \sim 1)$ m. The received signal power for different frequency bands is listed in table 1. This is the maximum allowed received signal power in the respective frequency bands. Any signal received above the maximum allowed received power in the respective frequency band is considered to be a collision of the packet signal.

4.3 OFSMA System in Multiple Frequency Band

The OFSMA is a random multiple access scheme which can be operated both in single band and multiple band frequency model. For Multiple frequency band, the

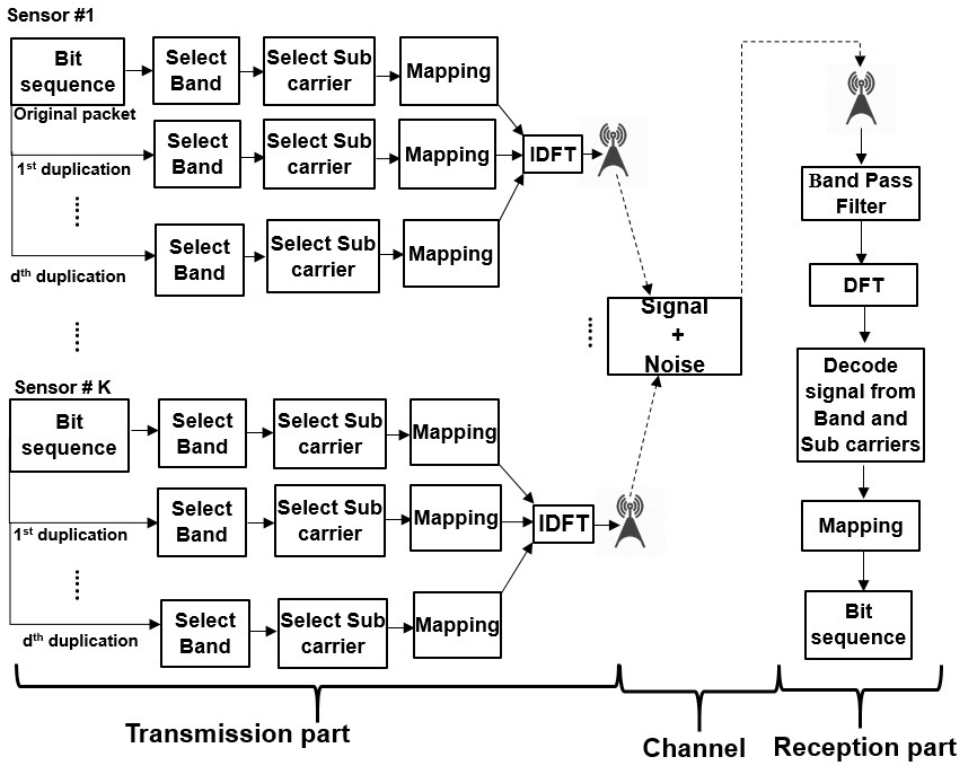

Figure 4.8: OFSMA communication system for multiple frequency band.

packet signals are forwarded over randomly selected frequency band and respective subcarrier channels. The random subcarrier selection enhances the OFSMA system to assure low latency packet communication and not let the OFSMA system to expense extra time for scheduling. The OFSMA system for multiple frequency band is presented in Figure 4.8. The OFSMA system transmits *1*,*2*,...,d duplicated packet over the multiple frequency band and massive number of subcarrier channels to improve the reliability of the transmission. In OFSMA system, each sensor need to generate a packet bits and then duplicated for d number of duplications. The d duplicated packet bits are then multiplied by the subcarrier signal. The frequency band and subcarriers are selected in random fashion. The OFSMA system applies BPSK modulation for packet mapping whereas BPSK is a low bit-level modulation scheme used to avoid or significantly minimize bit error. An inverse discrete Fourier transform (IDFT) operation is performed on the modulated mapping signal, and the signal is transform into an analog form. After a series of operations, the d duplicated packet signals are transmitted through an additive white Gaussian noise channel. The robotic system assumes that the receiver has the capability to detect

Algorithm 1: Collision Detection Algorithm

Input: subcarrier_frequency[]← stored all selected subcarrier frequencies, band_frequency[] ← stored all selected frequency bands, dup ← number of duplicated packets transmit, subcarrierlength ← 0, activeflag ← 0, pkterror ← 0, finalpkterror ← 0, receivepkt ← 0

Output: finalpkterror and receivepkt

```
subcarrierlength ← length(subcarrier_frequency[])
for i ← 1 to subcarrierlength do
    activeflag ← 0
    for j ← 1 to subcarrierlength do
        if i = j then
            Continue;
        end
        else
            if subcarrier_frequency[i]=subcarrier_frequency[j] &&
             band_frequency[i]=band_frequency[j] then
                if activeflag=0 then
                    pkterror ← pkterror+1
                    activeflag ← activeflag+1
                end
            end
        end
    end
    if i mod dup =0 then
        if pkterror = dup then
            finalpkterror←finalpkterror+1
        end
        else
            receivepkt ← receivepkt+1
        end
    end
end
```

multiple sensor‘s packet at the same time[33]. The receiver receives the combined signal added with Gaussian noise. A bandpass filter is added at the receiver side to recover the signal from the signal noise composite form. Then, the filter performs the reverse operation to regenerate the original bit patterns.

In the OFSMA system with multiple frequency band, the sensors select the frequency band and subcarriers in random pattern. Due to random subcarrier selection, there are some collisions happens in the channel of the OFSMA system. The OFSMA system applies a collision detection algorithm to determine the collision in the channels which is presented in Algorithm 1. Among the d duplicated packets, if at least one packet is successfully recovered without any error by the receiver, then the transmission marked to be successful; otherwise, it is considered as a collision. The OFSMA system assumes the sensors transmit a different number of duplicated packets over a diverse number of subcarrier channels and frequency bands in a random order. The randomly selected subcarrier frequencies and frequency bands are stored sequentially in a subcarrier frequency array and a frequency band array, respectively. Though each packet‘s selected frequency band needs to compare with other other packet‘s frequency band and subcarriers therefore the time complexity of the collision detection algorithm is $O(n^2)$

The time complexity also analyzed for OFSMA system with multiple frequency band. The OFSMA system considers multiple frequency band rather than single frequency band for duplicated packets transmission. The usual set of tasks increased by adding band selection steps beyond the previous OFSMA system with single frequency band. Therefore the time complexity appears not so much different compared with the OFSMA system with single frequency band. The best case appears only when one sensors transmits d duplicated packets over the transmission slot that defines the time taken for processing the d packets and for each packet needs to perform all the n tasks (task means select frequency band and subcarrier, mapping, IDFT etc.) which implies in total d.n time unit required to finished for d duplicated processing. So, the best case time complexity of the OFSMA system with multiple frequency band is $O(d.n)$. In the worst case situation, the K sensors simultaneously transmits d duplicated packets over the transmission slot. That means the OFSMA system demands in total $K.d$ packets processing time. Therefore the worst case time complexity of the OFSMA system with multiple frequency band is $O(K.d.n)$

4.4 Simulation Results

The OFSMA system‘s performance are evaluated in the MATLAB simulation platform. The system‘s performance are evaluated for determining minimum subcarrier channels that needed to satisfy URLLC's reliability demand of 99.999%, the reliability response in percentage for a fixed subcarrier assignment, minimum subcarrier demanding lower packet duplication which presented in a normalized form and finally the air interface latency with different latency threshold. The OFSMA system considers 100 sensors[70, 71, 72] into the simulation environment and follows the

Table 4.2: Simulation parameters for multiple frequency bands

Parameter description	**Values**
Modulation	BPSK
Signal frequency band, B_s	(60, 55, 30, 28, 10, 2.4, and .920) GHz
Subcarrier frequency bandwidth, B_{f_x}	10 kHz
Subcarrier channel, C	10∼600
Packet duplication, d	3∼32
Number of sensor, K[70, 71, 72]	100
Packet size, b	100 bits
Transmit power, p_t[69]	20 dBm
Link rate, R	1 Mbps
Path loss exponent, Γ[68]	2.001
Reference distance d_0[36]	0.1 m
Actual distance, d_a	0.1∼ 1 m
Transmission Slot duration	0.1 ms
SNR, γ	10
Bit Rate, T	1 bit/sec
Arrival rate, λ	1∼15000 pk/sec
Simulation Time	1000 s

Poisson arrival process for sensor‘s packet generation and transmission. Each sensor processes the 100-bits packet using a set of operation explained in the OFSMA system and forward the packet over 60 GHz, 55 GHz, 30 GHz, 28GHz, 10 GHz, 2.4 GHz, and 920 MHz frequency band and their respective subcarrier channels using slotted-ALOHA protocol. The simulation parameters are presented in details in table 2.

The OFSMA system's reliability, the number of subcarrier channels assignment and number of packet duplications are directly related among them. Figure 4.9 presents the minimum demanding subcarrier channels under the OFSMA system‘s single-band frequency diversity system model to satisfy a reliability of 99.999% based on different arrival conditions. The minimum subcarrier detection for single frequency band model is measured for 100 sensors, and 3-, 5-, 7-, 8-, 14-, 16-, 21- and 32-packet duplication is applied to evaluate the minimum subcarrier demanding packet duplication for different arrival conditions. The 3-packet duplication required the maximum subcarrier channels for all arrival rate because of higher inter-packet

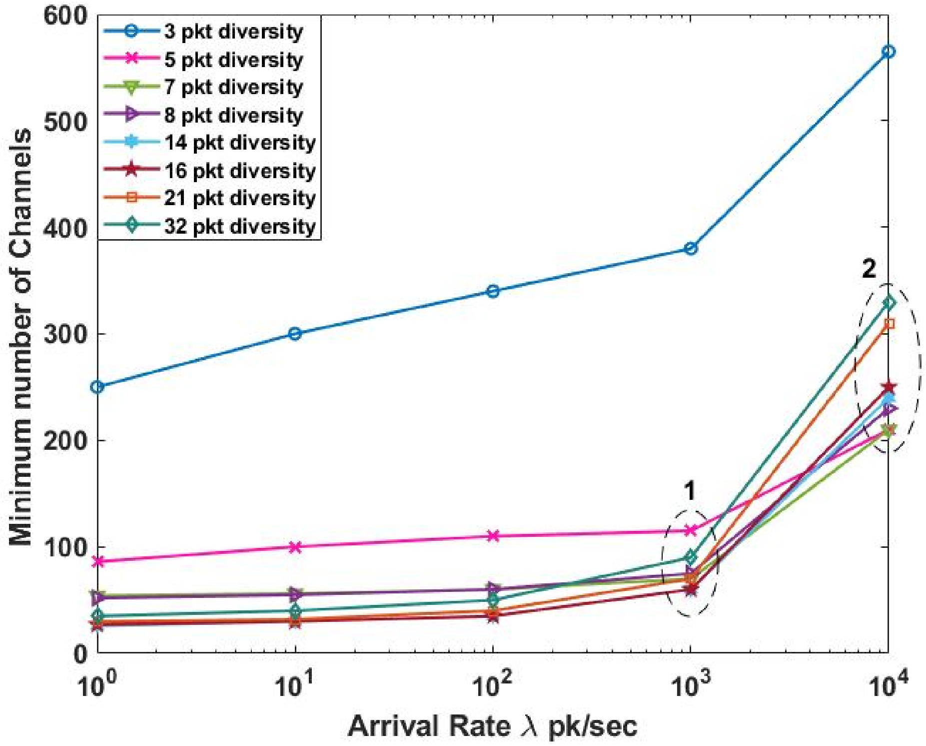

Figure 4.9: The minimum subcarrier detection to satisfy URLLC's reliability requirement of 99.999% for OFSMA system‘s single-band frequency diversity model.

collision. The 5∼32-packet duplications demanded a comparatively minimum subcarrier channels for arrival rates up to a 100 pk/sec due to the higher number of packet duplication which results a lower number of collisions. At average arrival rate of 1000 pk/sec (marked in circle 1), the 7∼21-packet duplications demanded very similar numbers of subcarrier channels to satisfy the reliability levels of 99.999%, but 5- and 32-packet duplications needed more subcarriers due to higher inter-packet collision. The minimum demanding subcarriers significantly different for higher arrival conditions, i.e., 10000 pk/sec. At a 10000 pk/sec arrival condition (marked in circle 2), the 5- and 7-packet duplication demanded minimum 210 subcarriers to full fill the reliability of 99.999%. This 210 subcarrier demands is lowest compared for all other packet duplications. The other 8∼32 packet duplication, due to increasing the number of duplicated packets in higher arrival condition faced a higher order of collision. To minimize the collision requires higher number of subcarrier channels. Therefore, at higher arrival conditions, the comparatively lower numbers (5 and 7 compared to 14, 16, 21 and 32) of packet duplications reduce the probability of

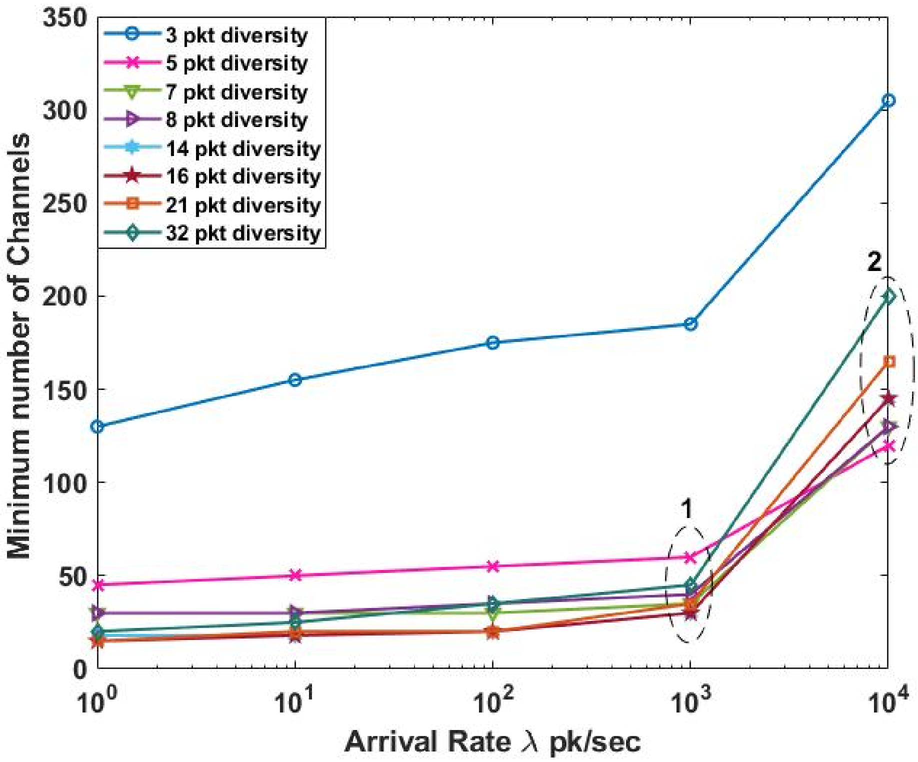

Figure 4.10: The minimum subcarriers detection to satisfy URLLC's reliability requirement of 99.999% for OFSMA system's double-band frequency diversity model.

collisions and achieve higher reliability of packet transmission.

The minimum subcarrier demands for double-band frequency diversity model in terms of diverse duplicated packets and different arrival conditions is illustrated in Figure 4.10. The 100 sensors wake up based on their arrival conditions, create the duplicated packets based on the OFSMA system and transmit the packet using the slotted-ALOHA protocol over the double 30 GHz and 60 GHz frequency bands. The double-band frequency diversity model allocate an equal number of subcarrier channels to each frequency band and applied 3-, 5-, 7-, 8-, 14-, 16-, 21- and 32-packet duplications to evaluate the minimum subcarrier demanding packet duplications to full fill the URLLC's required reliability level of 99.999%. In the double-band frequency diversity model, the 3-packet duplication demands more subcarrier frequency channels compared to other numbers of packet duplication similar like the single-band frequency diversity model. But the demanding subcarrier channels is almost half compared to the single-band frequency diversity model because of adding an additional frequency band and its subcarrier channel reduces the chance of collision. At average arrival condition, i.e., 1000 pk/sec (marked in circle 1), the demanded subcarrier channels successively increased for the 5∼32-packet duplications, but the 5-packet duplication needed a higher number of subcarriers compared with 7∼32 packet duplications. However, at a higher arrival condition, i.e., 10000 pk/sec (marked in circle 2), the 5-packet duplication demands 120 subcarrier frequency channels to satisfy the reliability of 99.999% which is minimum compared to all other packet duplications subcarrier demands. The 7∼32-packet duplications obligated a successively higher number of subcarriers because of increasing the number of duplicated packets also increased the probability of collision. In addition, URLLC's expected reliability of 99.999% is achieved, at the highest arrival rate, by employing approximately 57% of the subcarrier assignment in each band compared to the single-band frequency diversity channel. This main reason behind this achievement of increasing the frequency band and applying band diversity concept.

The minimum subcarrier demands also evaluated for triple-band frequency diversity model. Figure 4.11 presents the minimum subcarriers needed to achieve the URLLC‘s defined reliability of 99.999% applying diverse duplicated packets and different arrival condition. The OFSMA system with triple-band frequency diversity

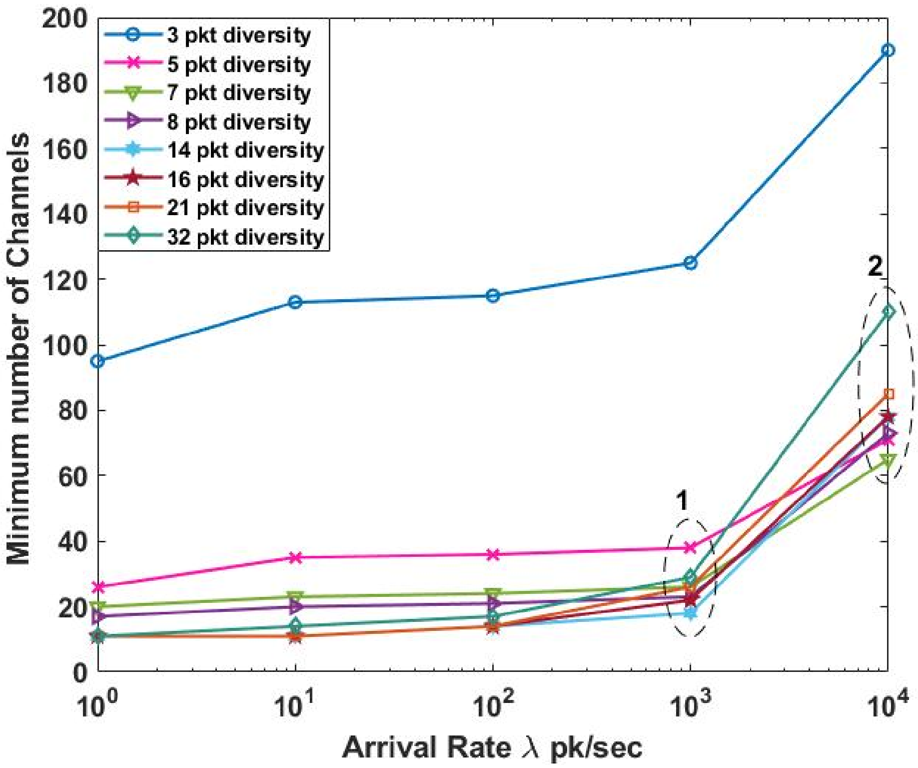

Figure 4.11: The minimum subcarriers detection to satisfy URLLC's reliability requirement of 99.999% for OFSMA system‘s triple-band frequency diversity model.

model also considered 100 sensors transmitting data with 3-, 5-, 7-, 8-, 14-, 16-, 21- and 32-packet duplication over 55 GHz, 28 GHz, and 2.4 GHz frequency bands and evaluated the minimum demanding subcarriers by each packet duplication at different arrival conditions, i.e., 1-10000 pk/sec. The OFSMA system assigns an equal number of subcarriers to each frequency band. Similar in the single- and double-band frequency diversity models, in the triple-band frequency diversity model, the 3-packet duplication demanded more subcarriers compared to all other 5∼32-packet duplications due to inter-packet collision. The 7∼32-packet duplications demanded at most 32 subcarriers to achieve the 99.999% reliability at an arrival rate of 1-1000 pk/sec, but the 5-packet duplication needed more subcarriers than the 7∼32-packet duplications because of a higher number of inter-packet collisions. Moreover, at an arrival rate of 1000 pk/sec (marked in circle 1), the 32-packet duplication demands more subcarriers compared with the 7- and 8-packet duplications due to a higher number of inter-packet collisions. At the higher arrival condition, i.e., 10000 pk/sec (marked in circle 2), the 7-packet duplication required the lowest number (65) of subcarriers compared to all other packet duplications, and the 5-packet duplication needed 71 subcarrier channels to satisfy URLLC's expected reliability of 99.999%. The 8∼32-packet duplications demanded a successive increasing number of subcarriers compared with the 7- and 5-packet duplications. The triple-band frequency diversity model able to achieve URLLC's expected reliability of 99.999% by employing approximately 31% subcarriers assignment compared with the single-band frequency diversity model and approximately 54% subcarriers allocation compared with the double-band frequency diversity model to all bands at the highest arrival condition.

The OFSMA system also analyzed the minimum subcarriers demands over different packet duplication to ensure the reliability of 99.999% and determine the minimum packet duplication that demands minimum subcarriers for different arrival conditions. The 100 sensors forward 3∼32 packet duplications over 30 GHz, 10

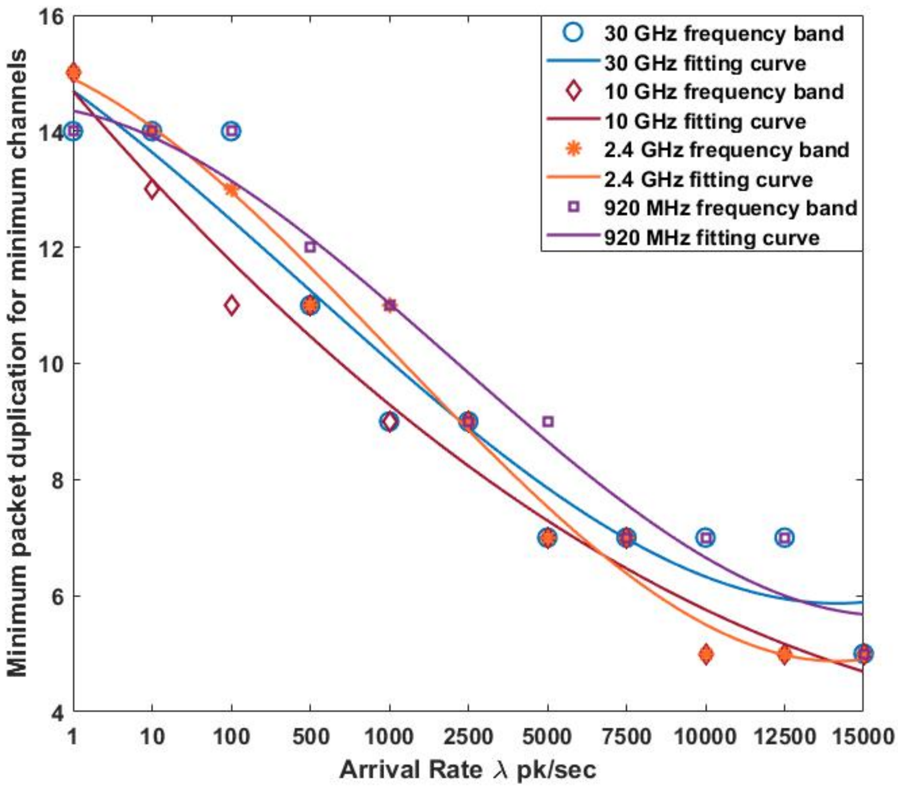

Figure 4.12: The minimum channel demanded minimum packet duplication determination for different traffic condition over 30 GHz, 10 GHz, 2.4 GHz and 920 MHz frequency band.

GHz, 2.4 GHz, and 920 MHz single frequency band and determined the minimum packet duplication, as illustrated in Figure 4.12. From the figure, 30 GHz and 920 MHz demanded the same 14-packet diversity on the other hand, 10 GHz and 2.4 GHz needed different packet diversities but starting from the 15-packet duplication for an arrival rate of 1$\sim$ 100 pk/sec. At the arrival rate of 500 $\sim$ 2500 pk/sec, 30 GHz and 10 GHz demanded the same 11- and 9-packet duplications, but 2.4 GHz and 920 MHz have slightly different requirements, particularly under the 500 pk/sec arrival condition, the system required 11- and 12-packet duplication for these frequencies, respectively. However, at an arrival condition of 2500 pk/sec, all frequency bands demanded the same 9-packet duplication to ensure the reliability of 99.999%. At an arrival condition of 5000 $\sim$ 10000 pk/sec, 10 GHz and 2.4 GHz satisfied the expected reliability of 99.999% with the same 7 and 5 duplicated packets, but under the 5000 pk/sec arrival condition, 30 GHz and 920 MHz demand a little different and they required 7- and 9-packet duplication, respectively. At higher arrival conditions of 10000 $\sim$ 15000 pk/sec, 30 GHz and 920 MHz demanded the same 7- and 5-packet duplications; 10 GHz and 2.4 GHz needed the same 5-packet duplication to determine the minimum subcarriers demanded to ensure the URLLC's expected reliability of 99.999%. After evaluating the minimum packet duplication, a 3rd order polynomial curve fitting is applied to generalize the packet duplication demands over different arrival conditions. This fitting curve with actual value result illustrates an important directions about minimum packet duplication with the respective arrival condition in a single frequency band and random subcarrier selection which is successively decreased due to increasing the arrival condition.

The OFSMA system studied about the reliability response for assigning a fixed 50 subcarrier channels in the single-band frequency diversity model presented in Figure 4.13. The 100 sensors forwarded diverse duplicated packet over the OFSMA system's single 2.4-GHz frequency band.The sensors transmission over the OFSMA access scheme is simulated for 1000 sec and evaluated the reliability response in percentage. The reliability is analyzed for 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications. The red dotted line indicates the URLLC's standard reliability of 99.999%. The 3-packet duplication shows a poor reliability percentage and presented a lower reliability response compared to all the 5$\sim$21-packet dupli-

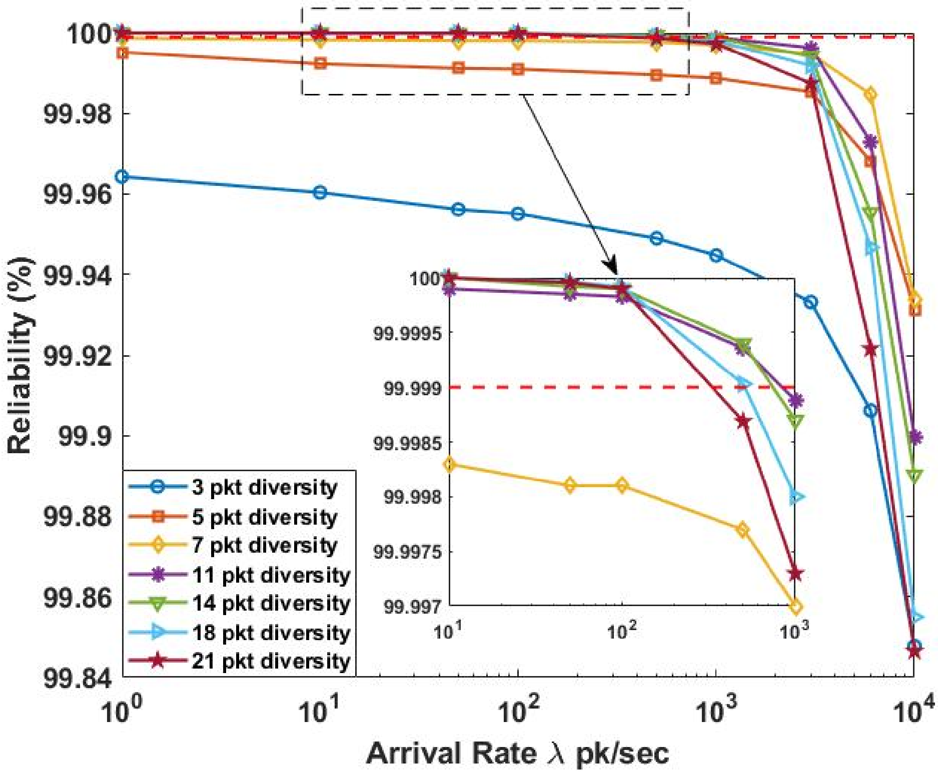

Figure 4.13: The reliability response determination for 50 channels in OFSMA system's single-band frequency diversity model.

cation due to higher inter-packet collision. The 5-packet duplication achieved a lower reliability response compared to all the 7∼21-packet duplication for a low-to-average arrival rate, i.e., 1-1000 pk/sec due to a higher number of packet collisions and not satisfying the URLLC reliability standards. The reliability response for arrival rate of 10 ∼1000 pk/sec are zoomed, and at an arrival condition of 500 pk/sec, only the 11-,14- and 18-packet duplications ensure the 99.999% reliability standard. At higher arrival conditions than 500 pk/sec, all duplicated packets able to achieve a lower reliability percentage than 99.999%. At 3000 pk/sec arrival condition, the 5- and 21-packet duplications achieved approximately similar reliability as 99.9854% and 99.9875%, respectively, and the 7∼18-packet duplications secured higher reliability. The reliability response significantly changed at the arrival rate of 6000 pk/sec, where the 7-packet duplication achieved the highest reliability percentage(99.9848%). At 10000 pk/sec arrival condition, the 7-packet duplication again secured the highest reliability percentage(99.9339%), and the 5-packet duplication gained a slightly lower reliability (99.9313%) compared to the 7-packet duplication.

The 11∼21-packet duplication reliability percentage successively decreased due to increasing in the number of duplicated packets. At higher arrival rate, due to increasing the number of duplicated packets also increase the probability of collision. In addition, at highest 10000 pk/sec arrival condition, the 3- and 21-packet duplications secured approximately similar reliability percentage of 99.8477% and 99.8465% respectively due to a higher number of inter-packet collisions compared to all other packet duplications.

The figure 4.14 presents the OFSMA system's reliability percentage for fixed 50 subcarrier assignment in the double-band frequency diversity model. The 100 sensors forward duplicated packets over 30 GHz and 60 GHz frequency bands and each band is assigned a fixed 50 subcarrier frequency channels. The OFSMA system's reliability performance is estimated for 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications. The 3-packet duplication secured lower reliability percentage compared with all other duplicated packets at an arrival conditions of 1-6000 pk/sec due to higher inter-packet collision. The 5∼21-packet duplications secured higher reliability

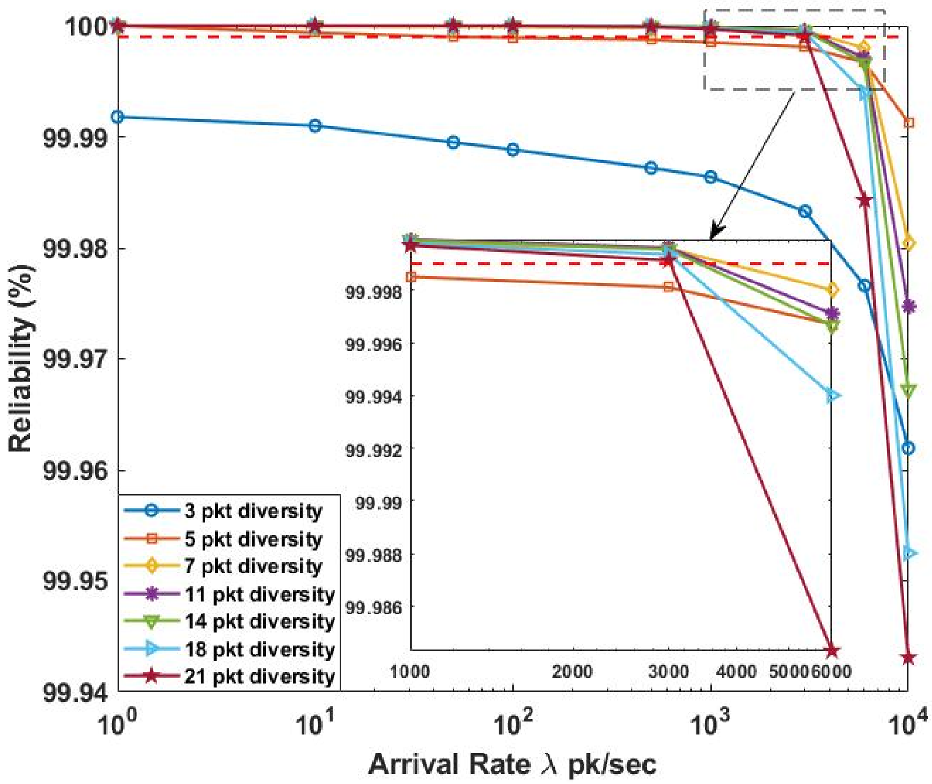

Figure 4.14: The reliability response determination for 50 channels in OFSMA system's double-band frequency diversity model.

response and the reliability results are comparatively close up to arrival conditions 1∼3000 pk/sec. The reliability percentage significantly decreased after 3000 pk/sec because the higher arrival rate introduces a higher number of packets in the network causes a higher number of collisions to happen. The reliability expression from 1000 ∼ 6000 pk/sec is zoomed and illustrates that at a 3000 pk/sec arrival rate, the 7∼21-packet duplications able to secure the reliability bound of 99.999%. At higher arrival rates than 3000 pk/sec, the reliability percentage of all packet duplications is below 99.999%. At a higher arrival rate, i.e., 6000 pk/sec, the 7-packet duplication achieved the highest reliability (99.9980%) compared to all other duplicated packets considered in the OFSMA system. The reliability expression is more scatter at a higher arrival rate, i.e., 10000 pk/sec and the 5-packet duplication able to secure the highest reliability (99.9913%). The reliability expression of the 7∼14 duplicated packets are progressively decreased compared with the 5-packet duplication due to the higher duplicated packets. Another important expression is that the 3-packet duplication achieved higher reliability percentage compared with the 18- and 21-packet duplications at an arrival rate of 10000 pk/sec because the number of packet duplication introduces higher inter-packet collisions in the system. The above explanation concludes that the comparatively lower-number of packet duplications, i.e., the 5- or 7 able to secure higher reliability percentage compares with the higher number of packet duplications (11∼21-packet duplications) in higher arrival conditions.

Finally, the OFSMA system's reliability response also measured for the triple-band frequency diversity model, as presented in Figure 4.15. In the OFSMA triple-band frequency diversity system, the 100 sensors forward 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications over 55 GHz, 28 GHz, and 2.4 GHz frequency bands. The all frequency band is equally assigned 50 subcarrier channels. Similarly as single-band and double-band frequency diversity models, also in the triple-band frequency diversity model, the 3-packet duplication express a lower reliability response compared with all the other duplicated packets for arrival conditions ranges from 1∼6000 pk/sec due to inter-packet collision. The 5∼21-packet duplications secured approximately similar reliability response for the arrival rates ranges from 1∼6000 pk/sec but progressively decreased the reliability percentage due to an in-

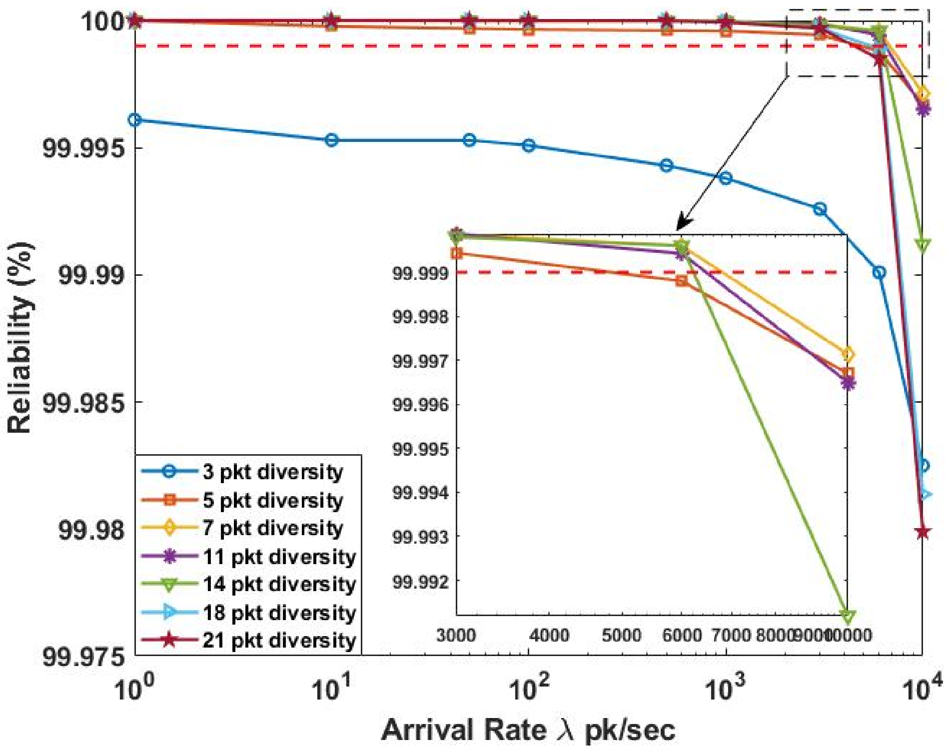

Figure 4.15: The reliability response determination for 50 channels in OFSMA system‘s triple-band frequency diversity model.

creasing number of arrival rates in the network. The reliability expression ranges from 3000 pk/sec ∼ 10000 pk/sec is zoomed and pointing at 6000 pk/sec arrival rate that the 7∼14-packet duplications achieved the URLLC‘s defined reliability bound of 99.999%. At higher arrival conditions than 6000 pk/sec, all duplicated packets reliability percentage goes below 99.999%. Moreover, At the 6000 pk/sec arrival condition, the 7-packet duplication secured the highest reliability value (99.9996%) compared to all other duplicated packets considered in the OFSMA system‘S experiment because of a small number of packet collisions. At highest 10000 pk/sec arrival condition, the 7-packet duplication again gained the highest reliability percentage (99.99714%) compared to all other duplicated packets and the 5-packet duplication secured slightly smaller reliability percentage (99.9967%) compared to the 7-packet duplication. Moreover, at the 10000 pk/sec arrival condition, the 3-packet duplication also secured higher reliability percentage compared to the 18- and 21-packet duplications due to a lower number of inter-packet collisions.

The OFSMA system‘s latency also evaluated for single packet uplink transmission and compared with popular OFDMA system that presented in Figure 4.16. In this latency evaluation, a single packet with diverse size ranges from 30 $\sim$ 250 is transmitted from the sensor to the receiver and the air interface latency is calculated in a millisecond. The air interface latency is evaluated based on the OFSMA system's propagation delay and the system delay. If the system delay of the OFSMA system is δ and propagation delay is β, then the air interface latency, α_{delay} can be presented as

$$\alpha_{delay} = \beta + \delta \tag{4.16}$$

The system delay, δ is calculated from the simulation platform and it is equivalent to the time taken to transfer the bits from the sensor to the receiver site. The propagation delay is estimated by the ratio of the packet size, b and link rate, R of the OFSMA system. So the air interface latency, α_{delay} can be expressed as

$$\alpha_{delay} = \frac{b}{R} + \delta \tag{4.17}$$

Figure 4.16 illustrated that 30-bit length of packet demanded less than 0.1 ms, the 60-, 100-, and 150-bit length of packet needed less than 0.5 ms, and the 200- and 250-bit packets expected less than 1 ms to transmit from the sensor to the receiver's

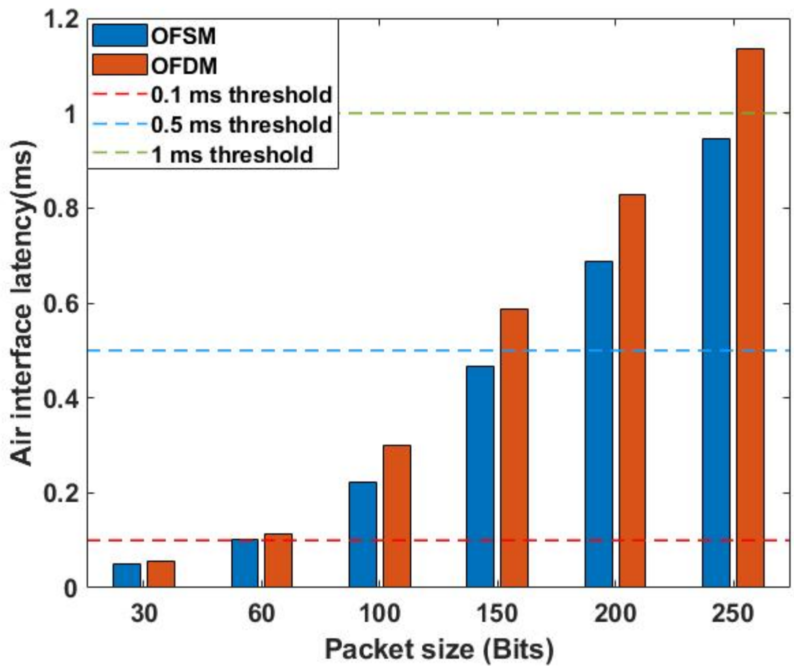

Figure 4.16: OFSM and OFDM system's single packet air interface latency measurement and comparison for different latency threshold.

end. Moreover, for each packet size comparison, the OFSMA system needed less time compared with the OFDMA system. As an example of the 100-bits packet needed 0.2234 ms in the OFSMA system, but the same packet consumed 0.30054 ms in the OFDMA system due to its packet processing mechanism. In the OFDM system, the packet bits are equally divided into the number of subcarriers, and cyclic prefix are added into the each subcarriers original bits, thereby increasing the original packet length. This is the main reason for the OFDM system to consume more time than the OFSM system.

4.5 Conclusion

A new Orthogonal Frequency Subcarrier-based Multiple Access scheme has been proposed in the presence of multiple frequency bands. The OFSMA system with multiple frequency band enables sensors to select a frequency band and subcarriers randomly due to assure low latency packet transmission. However, due to random subcarrier selection increase the probability of collision among the forwarded packets. To minimize the collisions among the transmitted packets at approximately zero levels, the system considered packet diversity principle and transmits diverse number of packet duplication over massive number of subcarriers. That results increasing the OFSMA system‘s reliability and full fill the URLLC's defined reliability requirement of 99.999%. The OFSMA system‘s minimum subcarrier demands to satisfy the reliability requirement of 99.999% for different packet duplication and experiment it over single-band, double-band and triple-band diversity communication systems. The minimum subcarrier allocation for double-band frequency diversity model demands a 57% subcarrier channels, and the triple-band frequency diversity model needs a 31% subcarrier channels compared with the single-band frequency diversity model. That concludes the increasing number of frequency band diversity decreases the minimum subcarrier demands in each of the frequency bands. Furthermore, considering the inclusions of diverse packet duplication in minimum subcarriers detection and reliability response for single and multiple frequency bands concludes that the higher number of duplicated packets may be preferable at lower arrival conditions, but for higher 6000 pk/sec $\sim$ 15000 pk/sec arrival conditions, a small number of duplicated packets is more suitable for higher reliability achievement. The

OFSMA system's air interface latency of single packet transmission is also investigated and for different packet size ranges from 30$\sim$250 bits, air interface latency is less than 1 ms for the proposed OFSMA system. Therefore, the proposed OFSMA system strongly contents the URLLC's higher reliability and short latency bound.

Due to satisfying the expected reliability and latency requirement defined by the URLLC system, we assume that the proposed OFSMA system might serve as the main communication domain in a robot. In the future, this scheme will be explored to apply for higher frequency bands and other similar time-critical and mission-critical communication domain.

Chapter 5

Hybrid MAC and Signal Propagation

5.1 Introduction

In the state-of-the-art communication system, the wireless system is getting more popular and able to draw significant attention day by day. A wireless sensor connected system's requirement increasing because of its mobility, flexibility, scalability, cost-effective and rapid deployment. Generally, a robot made of different elements and connected by the enormous numbers of wires. The wires are mainly responsible to provide the main communication domain. But the wires used in a robot not only persist to gain higher weight but also consume extra power for its regular movement. Moreover, sometimes the internal wires disconnected due to speed of operation, heat, or any other reason and instant maintenance become complex during it's service time. By addressing the problems in wired system and considering the demands of wireless system, A robot with wireless internal communication system is proposed by a hybrid access scheme. A metaphor of wireless sensor connected robot is presented in Figure 5.1. As presented in Figure 5.1, there are three types of sensors (Audio, video and general sensors) plotted ubiquity over the robotic formation and apply Hybrid Access Scheme (HAS) to assure higher reliability and lower latency defined in Ultra-Reliable Low Latency Communication (URLLC). The 3GPP already exposed the standard for URLLC system's reliability demand for single packet transmission having size of 32 bytes is 1-10-5 (alternatively 99.999%) with an air interface latency of 1ms [44, 62]. In order to assure this higher reliability and short latency, the *HAS* system incorporates packet diversity principle and forwards the packet and/or packets over a massive number of subcarrier channels in an almost error-free and interference-free manner. The *HAS* system assumed to assign a

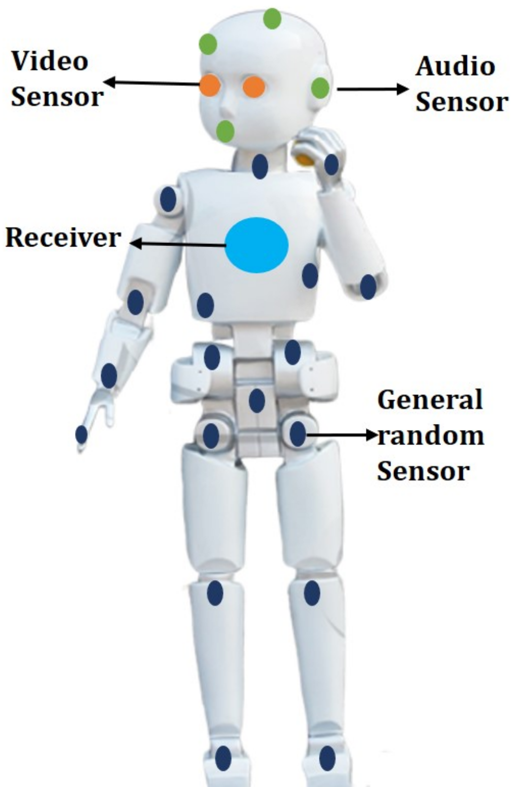

Figure 5.1: A typical humanoid robot with finite number of audio, video and general sensors.

massive number of orthogonal subcarrier channels to forward general sensors packet and assign dedicated channels to transmit audio and video sensors packet to the receiver's end. Due to considering very short area inside a robotic formation, the *HAS* system assign a massive number of channels and assumes this channel assignment will not interfere with the central mobile bandwidth assignment.

5.1.1 Related works

Recently, researchers and engineers work restlessly to develop wireless converted systems, and several significant research works already been done in the wireless sensor conversion system. In the 5G communication domain, a sensor communication based structural health monitoring and early earthquake warning system is studied in [57] that provides and explains of the monitoring and alarm generation system in the presence of seismic activities. A sensor-based health monitoring system of different parts in an airplane is analyzed in [29] where several sensor nodes deployed and monitoring the health status and evaluate throughput, the data dropped rate and the delay for a maximum of 7 nodes as approximately 12000 bps, 180 bps, and 115 ms, respectively. An older people's health care monitoring and the central observing system is studied in [56] that incorporate a wireless sensor network and use a bracelet-type device equipped with sensors. This device attached each patient's body and covers under the monitoring and networking system of the healthcare that continuously received data in real time and stored in a centralized data server. In order to aiming spacecraft automation and ensure wireless communication using a finite number of sensors is analyzed in [28], which forward payload having a size of 988 B over the Ultra Wide Band frequency in a spacecraft networks and assign different frequency bands for signal transmission using a TDMA protocol having a short 5ms time slot. A sensor-connected robot's internal communication system using OFSMA MAC protocol is studied in [55], which taken only a single frequency band into their consideration and transmit packets randomly over the single subcarriers.

A several random access protocol with slotted ALOHA system studied and analyzed to achieve the targeted reliability and latency defined in URLLC. A contention-based slotted ALOHA system has been proposed in [33] that incorporates multiple channels, multiple packets into their system, and forward multiple copies of the transmitted packets in the consecutive slots to improve the system reliability, and to reduce latency to satisfy URLLC's conditions. A multiple channel random access system using OFDMA is studied in [60], that propound a fast retrial algorithm and after having a collision the algorithm forward a packet into a frequency diversity system to improve the reliability of the transmission. A cluster-based multiple packet messaging communication system is studied in [59] that forward multiple packets into different TTI slots and having ability to select a frequency independently to improve the system performance.

5.1.2 Contributions

The previous research work in not appropriate to convert our proposed objective to convert a robot's internal communication connected by sensors. To establish our proposed aim, a hybrid access scheme has been proposed. The main contributions of the research work are listed below:

- A new Hybrid Access Scheme (HAS) is proposed to assure the higher reliability of the audio, video, and general sensors packet transmission.

- A system model has been introduced to present the hybrid system's activity, random channel and dedicated channel access, total signal transmission of packets for a single TTI slot, and finally the received signal of packets at the receiver‘s end.
- The HAS system's reliability and collision probability for fixed channel conditions are analyzed with different number of packet duplications and diverse arrival conditions.
- Two different waveguides structural configuration are proposed as part of a robotic inner formation and analyzed signal propagation over the different frequency band.
- The signal propagation expressions for different structural waveguide medium with different variations are captured for different frequency bands and determine the success or failure signal propagation for a certain distance of signal transmission.

The remaining chapter are organized as follows: Section 2 presents the detail explanation of the hybrid access scheme. The Section 3 represents the system model of the hybrid access scheme along with the signal expression of the transmitted and received signals. Moreover, a detailed explanation about the waveguide structure and properties of the rectangular and circular transmission medium are presented in this section. The simulation results and signal propagation expression are presented in Section 4. Finally, the whole chapter work is concluded in Section 5.

5.2 Hybrid Access Scheme

The Hybrid Access Scheme (HAS) is a combination of Orthogonal Frequency Subcarrier-based Multiple Access Scheme (OFSMA) [55] and Dedicated Channel Access (DCA) illustrated in figure 5.2. The general sensors forward duplicated packets signal using the Orthogonal Frequency Subcarrier-based Multiple Access (OFSMA) scheme and the audio and video sensors transfer audio and video sensor data over the dedicated channels assigned for transmission. The OFSMA access scheme illustrated in

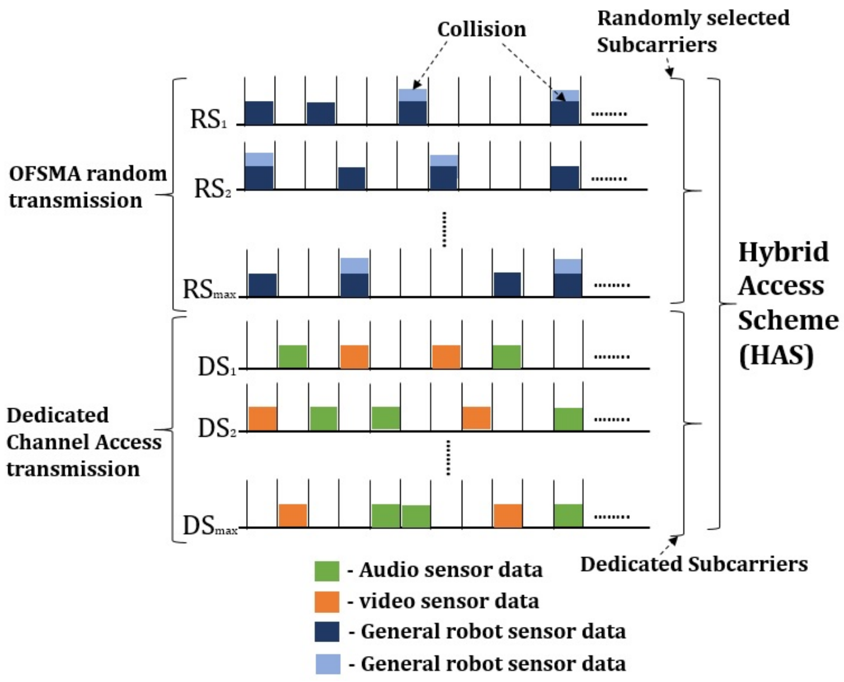

Figure 5.2: Hybrid Access Scheme.

Figure 5.3. The OFSMA scheme incorporates packet diversity concept and forwards multiple duplicated copies of the packet over different massive subcarriers in order to improve the packet transmission reliability of the system. The OFSMA system

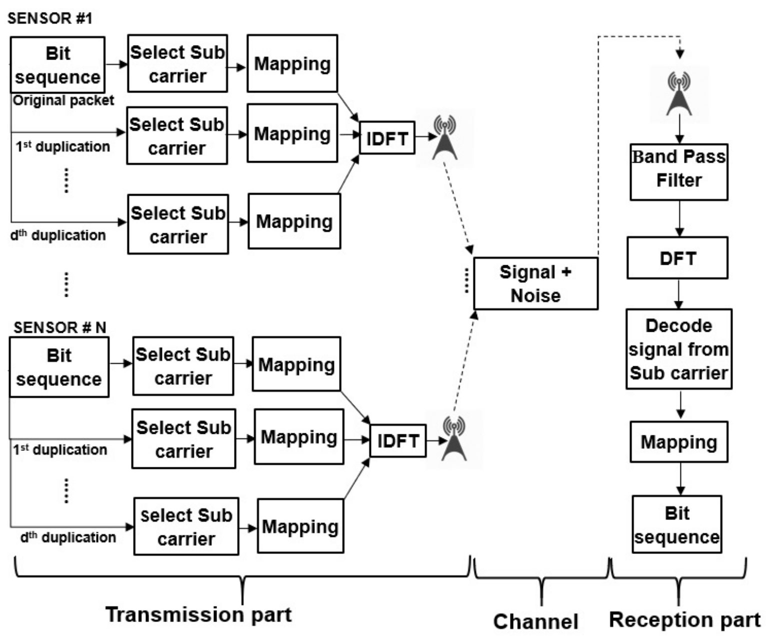

Figure 5.3: OFSMA Access Scheme for general sensors.

assumed that, there is no collision among the forwarded duplicated packets from the same sensors.

The OFSMA scheme generates a packet bits and duplicated it for up to d duplications. Each duplicated packet bits select an orthogonal subcarrier randomly and start BPSK modulation and perform mapping for transmission. Then the modulated and mapping signal bits need to process Inverse First Fourier Transform (IFFT) and transmitted over the Additive White Gaussian Noise (AWGN) channels to the receiver. Due to multiple sensors simultaneous transmission, there is a probability of collision, but the OFSMA systme minimized the collision by employing a higher number of frequency subcarrier channels. Among the replicated packet transmission, if minimum one packet is successfully received by the receiver then the transmission of the packets is considered as a successful transmission and receiver discards the other replicated copies of the same packets. The receiver utilize a band pass filter to detect the signal from signal noise composite form. The receiver performs the reverse operation and recovered the signal bits from the independent orthogonal subcarrier frequency and retrieve the original bit sequence. On the other hand, the audio and video sensors forward a single packet over the dedicated channel. Due to exclusive channel assignment, there is no probability of the collision, but a very minor number of packets might be lost due to having low signal power at the receiver side.

5.3 System Model

5.3.1 HAS System Design

A combined uplink packet transmission system is considered in our system presented in Figure 5.4. A finite number of audio, video and general sensors ubiquitously plotted around the receiver. In our proposed hybrid system, three types of sensor are considered as a) General sensor, b) Audio sensor, and c) Video sensor. The sensors transmit signal over the finite number of subcarrier channels. The subcarrier channels are also divided into two types as random accessible channel and dedicated channel. The general sensors transmit duplicated packet signal over the randomly selected subcarriers and there might be a collision due to random selection of subcarriers. To avoid the collision, the hybrid system incorporates the packet diversity principle. Based on the packet diversity principle, each general sensor needs to transmit multiple replicated copies of the same packet over the randomly selected subcarrier channels. Among the replicated copies of the packet, if at least one packet is successfully received by the receiver, then the transmission is marked as a successful transmission. The hybrid system assigned a massive number of subcarrier channels to lower the probability of the collision. The general sensors are responsible for transmitting regular small payload for communication. The dedicated subcarrier channels are allocated exclusively for audio and video sensors. There is no probability of collision in the dedicated channels for audio and video sensors transmitted packets.

The system assumes a total RK number of sensors transmitting over the randomly accessible subcarrier channels. The general sensors represented as $sensor_1$, $sensor_2$,...,$sensor_{RK}$. The general sensors are assigned a set of subcarrier channels as $f_s= f_1, f_2,..., f_c$. Each subcarrier channel f_i can be selected randomly and expressed as

$$f_s \overset{\mathbb{R}}{\leftarrow} f_i \tag{5.1}$$

Each general sensor transmitting x=*2, 3, ..., d* replicated packets over the randomly selected subcarrier channels f_i. The d duplicated packet signal $S_d(t)$ can be

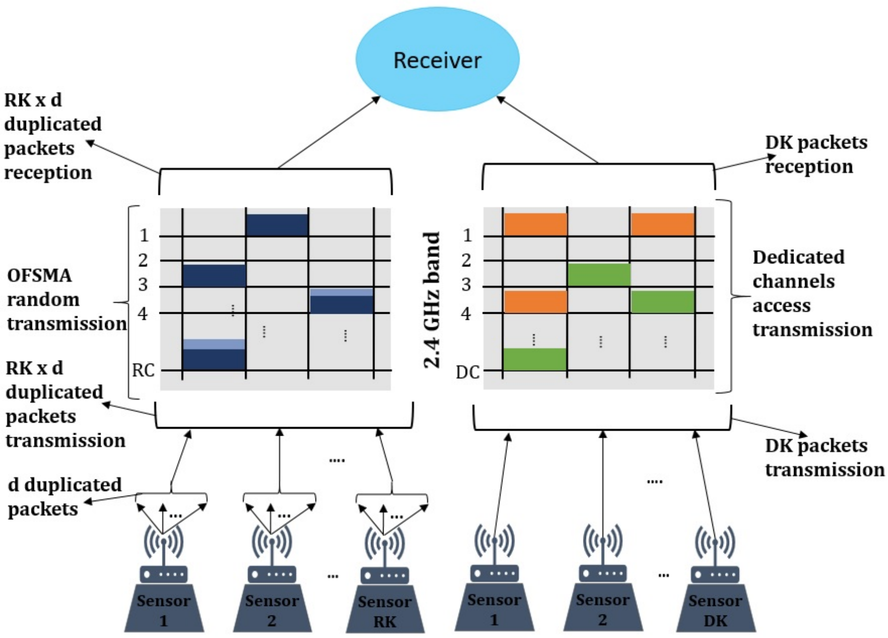

Figure 5.4: Hybrid access scheme system design.

presented [55] as

$$S_d(t) = \sum_{x=1}^{d} u_i(t) e^{j2\pi f_{ix} t} \tag{5.2}$$

where $u_x(t)$ is a complex baseband signal for x number of duplicated packets with an in-phase and quadrature component and f_{ix} is the randomly selected frequency f_i for x duplicated packets. The slotted-ALOHA protocol assigns sensors a fixed length time slot to transmit signal of data packets. For a total of *y=1, 2, ..., RK* number of general sensors transmit d duplicated equals to *RK x d* maximum possible packets can be transmit in a single TTI and it can be shown as

$$S_{RK}(t) = \sum_{y=1}^{RK} \sum_{x=1}^{d} u_{i,j}(t) e^{j2\pi f_{ix} t} \tag{5.3}$$

where $u_{x,y}(t)$ is a complex baseband signal for x number of duplicated packets from y number of sensors having an in-phase and quadrature component.

The hybrid system also considered a set of audio and video sensors which forwarded audio and video packets over the dedicated channels. For a single time slot, let's consider a maximum of DK audio or video frames are forwarded over the dedicated subcarrier channel can be presented as

$$S_{DK}(t) = \sum_{m=1}^{DK} u(t) e^{j2\pi f_m t} \tag{5.4}$$

Where *u(t)* is a complex baseband signal expression for audio or video frame with an in-phase and quadrature component, f_m is the dedicated subcarrier frequency channel for the frame and t determines the duration of the frame. So, the total frame of the audio or video sensors forwarded in a single TTI over the hybrid access scheme can be expressed as

$$S_{total}(t) = S_{RK}(t) + S_{DK}(t) \tag{5.5}$$

$$S_{total}(t) = \sum_{y=1}^{RK} \sum_{x=1}^{d} u_{i,j}(t) e^{j2\pi f_{ix} t} + \sum_{m=1}^{DK} u(t) e^{j2\pi f_m t} \tag{5.6}$$

Equation (5.6) presents the signal expression for total transmitted packet by the audio, video and general sensors in a single transmission slot. The total signal $S_{total}(t)$ is transmitted over the *AWGN* channel, and noise *n(t)* $\sim \mathcal{CN}(0, \sigma^2)$ is added to the signal. For any single time slot, the received signal $r_{total}(t)$ can be defined as

$$r_{total}(t) = S_{total}(t) + n(t) \tag{5.7}$$

$$r_{total}(t) = \sum_{y=1}^{RK} \sum_{x=1}^{d} u_{i,j}(t) e^{j2\pi f_{ix} t} + \sum_{m=1}^{DK} u(t) e^{j2\pi f_m t} + n(t) \tag{5.8}$$

The equation (5.8) presents the total received signal with noise added by the receiver. We assumed that, the system has the advanced receiving and decoding capability to receive and decode multiple copies of all the data packets at the same time.

5.3.2 Time Complexity Analysis

The hybrid system considers audio, video, and general sensors to transmit packets over the network. The audio and video sensors follow the total n steps (select dedicated subcarrier, modulation and mapping, and IDFT) and transmit over the dedicated channels. Therefore the time required for audio and video sensors packet transmission is n unit time. So, the best case time complexity of audio and video sensors is $O(n)$.

In the Hybrid scheme, each general sensor transmits d duplicated packet over the OFSMA scheme. In the best case scenario, only one sensor is transmitted d duplicated packets over the network. So, the time required for d duplicated packet processing is $d.n$. Therefore the best case time complexity of the general sensor is $O(d.n)$. The hybrid access scheme allows audio, video, and general sensors to transmit packets simultaneously in the same TTI over the differently allocated frequency subcarriers. So the total time complexity in best case scenario is $O(d.n) + O(n)$. The worst case appears in general sensors packet transmission when more than one sensor transmitting over the network. The OFSMA access scheme allows at most RK sensors to transmit in a single TTI. Therefore at worst case maximum $RK.d$ packets can be transmitted over the network. So, the worst case time complexity is $O(RK.d.n)$. The audio and video sensors transmit their packet over the dedicated channels and each sensor channel is exclusive for their transmission. So, the worst case complexity for dedicated channel access audio and video sensors is $O(n)$.

Therefore the total worst case complexity of the hybrid access scheme is $O(RK.d.n)$ + $O(n)$.

5.3.3 Signal Propagation Model Design

The hybrid scheme considers a short communication range signal propagation inside a robotic structure. The propagated signal needs to transmit 0.1m∼1m distance based on the sensor's actual deployment location from the receiver. The hybrid system considers two types of the signal waveguide as signal propagation medium as part of the robotic inner formation, rectangular transmission medium and circular transmission medium illustrated in figure 5.5. The rectangular and circular trans-

Table 5.1: Rectangular and circular transmission medium properties

Parameters	**Rectangular transmission medium**		**Circular transmission medium**
Transmit power	20 dBm		20 dBm
Carrier frequency	900MHz, 2.4GHz, 24GHz, and 55GHz		900MHz, 2.4GHz, 24GHz, and 55GHz
Structure	Width	Height	Radius
	190mm	95mm	100mm
	100mm	50mm	50mm
	50mm	25mm	25mm
	25mm	15mm	10
			5
Length	1000mm		1000mm
Delta S	0.02		0.02
Relative permittivity, air	1.0006		1.0006
Relative permittivity, iron	1		1
Relative permittivity, silver	1		1
Relative permeability, air	1.0000004		1.0000004
Relative permeability, iron	4000		4000
Relative permeability, silver	0.99998		0.99998

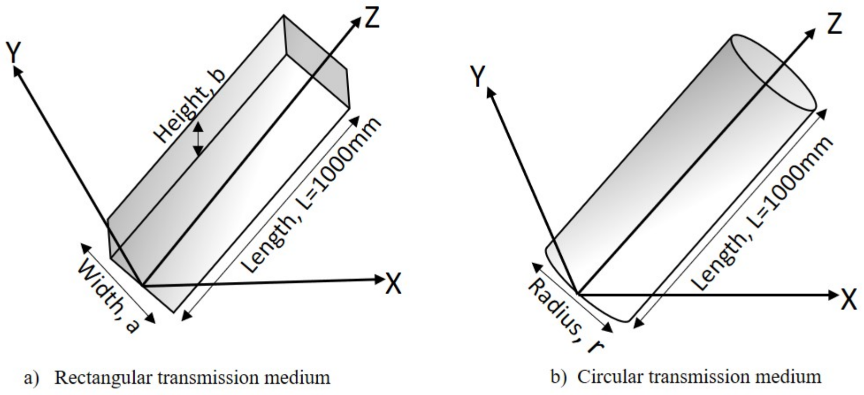

Figure 5.5: Signal transmission waveguide design, a) Rectangular shaped transmission medium, b) Circular shaped transmission medium.

mission medium design with IRON and outside coated with silver. The Z direction long tunnel in rectangular or circular structure is full of air. The hybrid system considers the following parameters listed in table 5.1 for capturing the signal propagation expression of the rectangular and circular shaped transmission medium.

5.4 Simulation Results

The hybrid system used MATLAB and ANSYS HFSS software for evaluating reliability, collision probability, and signal propagation expression over different frequency bands. The MATLAB software is used to evaluate the reliability and collision probability of the hybrid access scheme. The hybrid system utilized ANSYS HFSS software for capturing signal propagation expression. The 3-, 5-, and 7- packet duplication is forwarded duplicated packets over randomly selected subcarriers among a total of 90 subcarrier channels and determines the reliability and collision probability of the hybrid system. The hybrid system considers sensor and subcarrier ratio is 1:1. The details parameter list is presented in table 2.

5.4.1 Reliability and Collision Probability

The reliability and collision probability are evaluated for all type of sensors. The reliability defines by the ratio of the number of successful packets at the receiver side and the total transmitted packets in a simulation time and the collision probability defines by the ratio of the number of collide packets and the total transmitted

Table 5.2: Simulation properties for hybrid access scheme

Parameters	**Values**
Total general sensor	90
Total random Subcarrier channel	90
Total audio Sensor	5
Total video sensor	5
Dedicated channel	10
Carrier frequency	(0.9, 2.4, 24, and 55)GHz
Subcarrier bandwidth	10 KHz
Packet size	100 bits
Modulation	BPSK
Transmit Power	20 dBm
Link speed	1 Mbps
Packet duplication	3, 5 and 7
Arrival rate, λ	1$\sim$10000 pk/sec
Slot duration	0.1 ms
Simulation time	1000 s

packets in a simulation time. The 3-, 5-, and 7-packet duplications forwarded over randomly selected subcarriers. The audio and video sensors forwarded single packet over a single subcarrier among the 10 dedicated channels. At the receiver side, the reliability and collision probability for audio, video and general sensors are evaluated. The reliability for 3-, 5-, 7-packet duplication and dedicated channel assigned audio and video sensors is illustrated in Figure 5.6. As presented in Figure 5.6, the 3-packet duplication secured lower reliability compared to all others duplicated packets in the simulation results due to small number of duplicated packets and subcarrier channels. At higher 10000 pk/sec arrival condition, the 3-packet duplication is able to secure the reliability of 99.9578%. The 3-packet duplications failed to achieve 99.999% reliability bound for any arrival rates due to small number of packet duplications. The 5-packet duplication is able to achieve higher reliability compared with the 3-packet duplications but lower reliability response than 7-packet

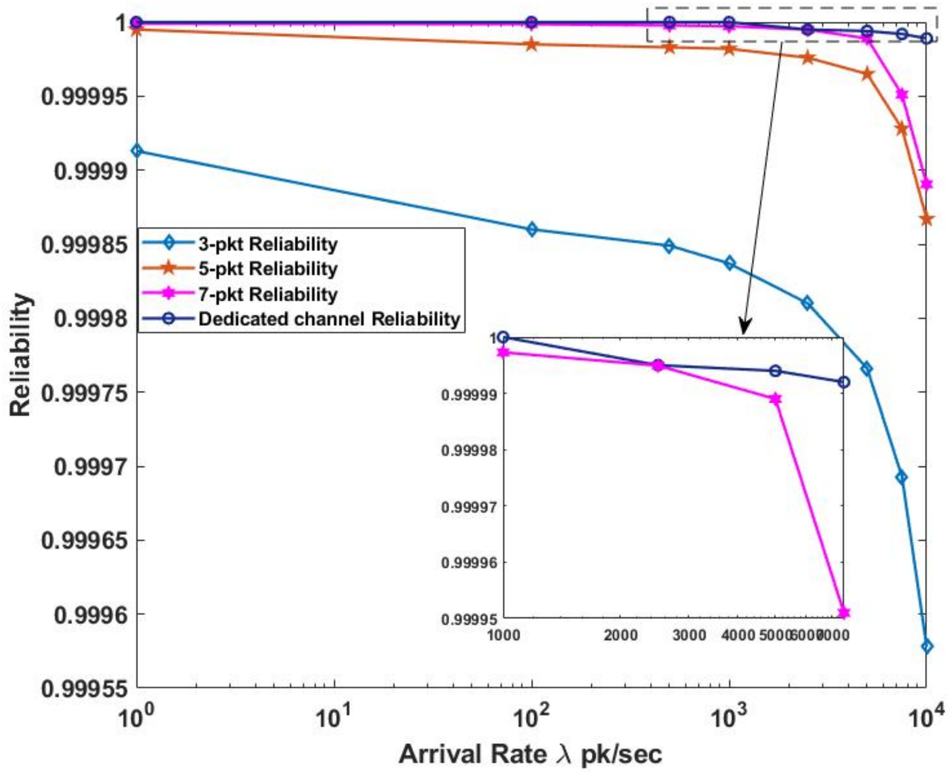

Figure 5.6: The reliability response determination for 3-, 5-, 7-packet and 10 audio and video sensors over hybrid access scheme.

and dedicated channels accessible audio and video sensors. At 1 pk/sec arrival condition, the 5-packet duplications secured 99.9995% reliability and at highest arrival condition of 10000 pk/sec, the achived reliability percentage is 99.9867%. The 10 audio and video sensors reliability response are very similar to 7-packet duplications reliability response up to 2500 pk/sec arrival conditions and after the 2500 pk/sec arrival rate, the dedicated channels improved its reliability response. The dedicated channels reliability and 7-packet reliability response are zoomed from 1000 pk/sec $\sim$ 10000 pk/sec arrival conditions. The 7-packet secure 99.9994% reliability at an arrival rate of 2500 pk/sec but after that arrival rate its reliability is decreased and lower than 99.999%. At an arrival rate of 10000 pk/sec, the 7-packet reliability response is 99.989%. The 10 audio and video sensors dedicated channel evaluated 99.999% reliability up to arrival rate 7500 pk/sec and at an arrival rate of 10000 pk/sec, the measured reliability is 99.9989%.

The 90 general sensors forward 3-, 5-, and 7-packet duplication over the 90 subcarriers and 10 audio and video sensors transmit single packet over any of the 10 dedicated channels. At the receiver‘s end, the collision probability of the hybrid system is evaluated that presented in Figure 5.7. According to the Figure, the 3-packet duplication faced higher collision probability than 5-, and 7-packet duplications due to small number of packet duplications and lower number of subcarrier channels. At higher 10000 pk/sec arrival condition, the 3-packet duplications collision probability is 0.0422%. The 5-packet duplications collision probability is comparatively lower than 3 -packet duplications but compared to higher than 7-packet duplications. At highest 10000 pk/sec arrival condition, the 5-packet duplications collision probability is 0.0133%. The 7-packet duplications collision probability is comparatively lower than 3-, and 5-packet duplications and at arrival rate of 10000 pk/sec it achieved 0.011%. Among the audio and video sensors forwarded packets, there is no collision because of exclusive channel assignment but a very small number of packets lost due to signal attenuation and appered to receiver with low power. The minimum power threshold for 2.4 GHz frequency band is set to 39.798 dBm. A packet having lower power of the threshold value is dropped by the receiver. The collision probability along with 7-packet duplication is presented inside the zoom section for 1000

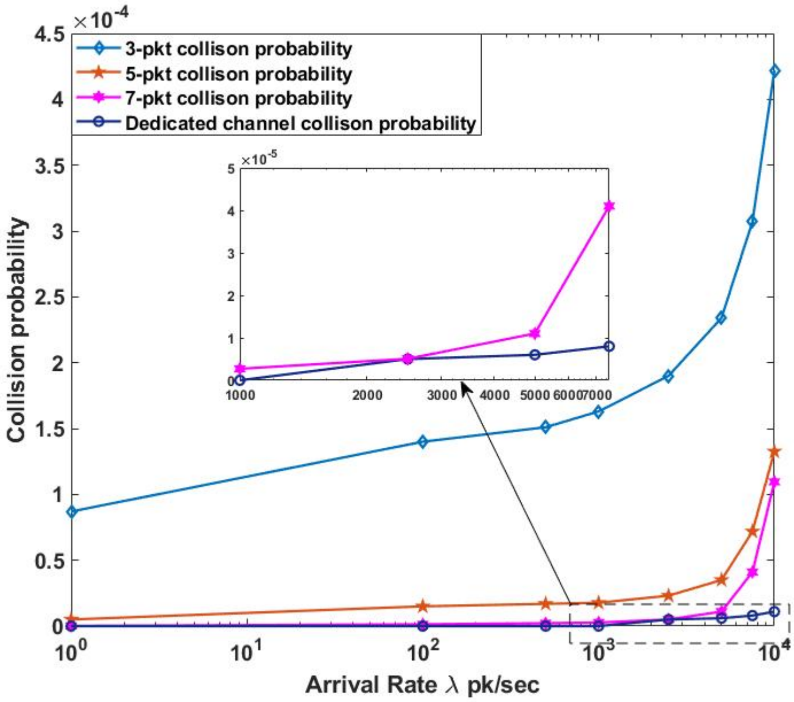

Figure 5.7: The collision probability evaluation for 3-, 5-, 7-packet and 10 audio and video sensors over hybrid access scheme.

pk/sec ∼ 10000 pk/sec arrival conditions. The audio and video sensors achieved lower collision probability than all other comparisons and at arrival rate of 10000 pk/sec, it secured 0.0011%. The *HAS* system considered there is no collision among the duplicated packets emitted from same sensor in the network. Moreover, in the received bit streams at the receiver, if there is a composite of success and collide packets bits, the receiver able to decode and extract the success packets bit sequence from the total bit sequence and ignored the duplicated packet bits.

5.4.2 Signal Propagation Expression

The signal propagation expressions are captured for rectangular and circular transmission waveguide for a maximum of 1 m (1000mm) waveguide distance as different structure of a future robot's internal configuration. The signal propagation expression is analyzed and captured for 900 MHz[73], 2.4 GHz[74], 24 GHz[75, 76], and 55 GHz [37] frequency bands. The rectangular and circular structure considers the different parameter values listed in table 1. The rectangular transmission medium analyzed for a set of width and height configurations and captured for signal propagation expressions. The rectangular transmission medium considers a width of 190 mm and a height of 95 mm applied for capture signal propagation expression with different frequency bands presented in Figure 5.8. The signal is propagated through

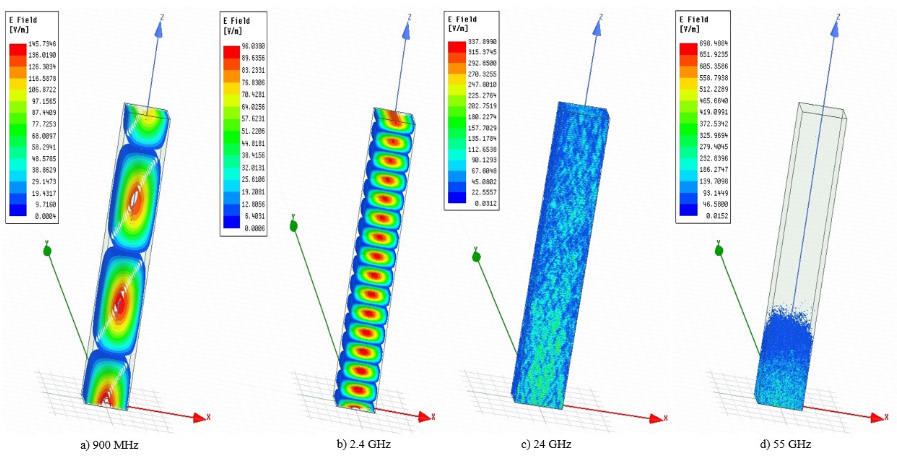

Figure 5.8: The signal propagation expression over 1000mm long, 195 mm width and 95 mm height rectangular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

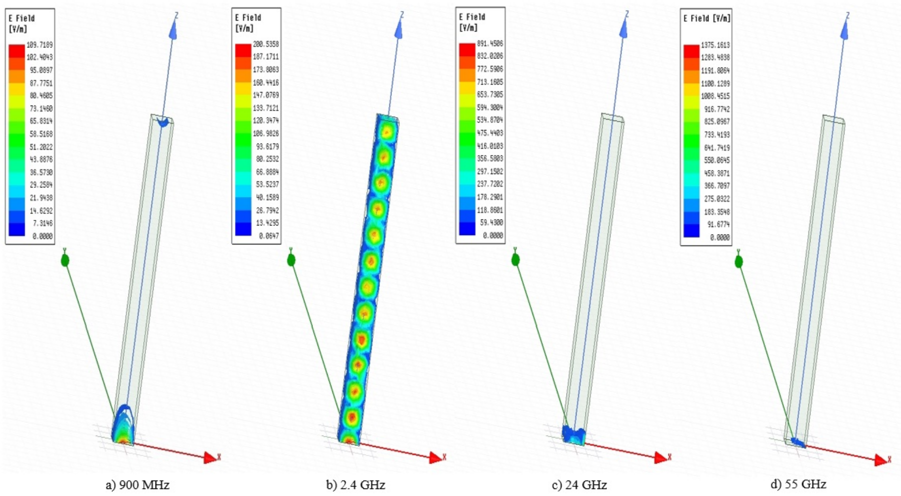

Figure 5.9: The signal propagation expression over 1000mm long, 100 mm width and 50 mm height rectangular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

the air of 1000 mm long transmission medium towards Z direction. For the defined configuration of rectangular transmission medium, a strong signal is propagated over the 900 MHz and 2.4 GHz frequency bands. But the signal is comparatively weak for 24 GHz frequency band and for the 55 GHz frequency band, the signal is unable to propagate at the end of the receiver to the Z direction.

The rectangular transmission waveguide‘s signal propagation with the configuration of width 100 mm and a height of 50 mm is illustrated in Figure 5.9. The signal unable to propagate through 900 MHz, 24 GHz, and 55 GHz frequency bands at the end of the Z direction to the receiver due to half of the size of the rectangular waveguide. But only 2.4 GHz frequency band is able to propagated the signal successfully at the receiving end towards Z direction. Moreover, the signal propagation expression over 900 MHz is comparatively strong compared to 24 GHz frequency band and the signal propagation over 24 GHz frequency band is also strong compared with the 55 GHz frequency band.

The rectangular transmission medium with the configuration of width 50 mm and a height of 25 mm signal propagation expression is illustrated in Figure 5.10. From the figure, none of the frequency band able to propagate the signal to the receiver towards Z direction for the mentioned structure. The 24 GHz frequency band expressed the comparatively strong signal expression and 900 MHz shown the most indistinct signal propagation expression among all other frequency bands transmission for the defined configuration. For the configuration of width 25 mm and a height of 15 mm of the rectangular transmission waveguide signal expression is presented in Figure 5.11. The 900 MHz and 2.4 GHz frequency band shown a dim signal expression towards Z direction. The 24 GHz and 55 GHz presents a strong signal propagation expression compared to all previous rectangular configurations. By analyzing the signal propagation expression presented in Figure 5.8-, 5.9-, 5.10-, and 5.11 for rectangular transmission medium, the higher size of width and height configuration is better for lower frequency bands, and the lower width and height size of the transmission medium showed a comparatively better signal propagation expression for higher frequency bands.

The signal propagation expression for circular transmission medium with different configuration is presented in Figure 5.12-5.16. The circular transmission waveguide‘s signal propagation expression with the configuration of radius 100 mm is illustrated in Figure 5.12. As shown in the figure, the 900 MHz and 2.4 GHz frequency bands are able to propagate the strong signal to the receiver directed towards Z direction. The signal is unable to propagate for 24 GHz and 55 GHz frequency

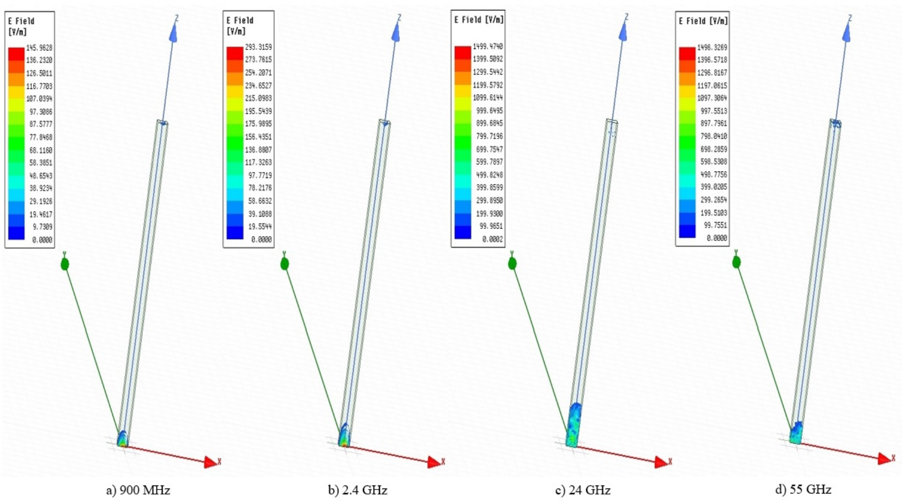

Figure 5.10: The signal propagation expression over 1000mm long, 50 mm width and 25 mm height rectangular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

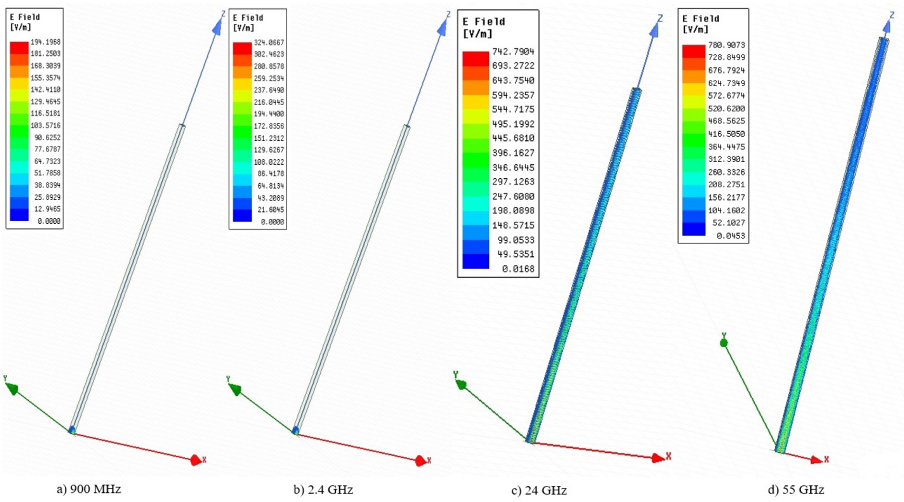

Figure 5.11: The signal propagation expression over 1000mm long, 25 mm width and 15 mm height rectangular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

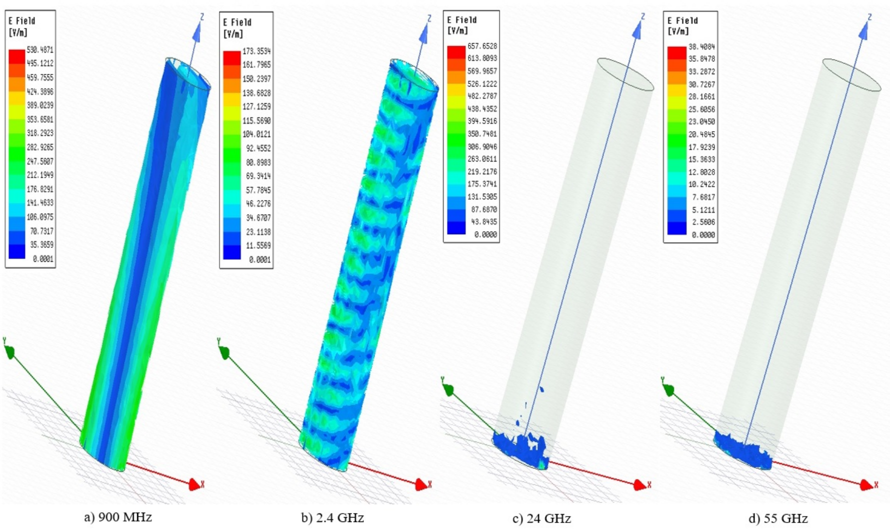

Figure 5.12: The signal propagation expression over 1000mm long, and 100 mm radius circular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

bands and the signal strength is very low compared with the 900 MHz and 2.4 GHz frequency bands signal expression.

The 50 mm radius circular transmission waveguide‘s signal propagation expression is illustrated in Figure 5.13. For this configuration, the 2.4 GHz frequency band is able to propagate the strong signal and none of the other frequency bands

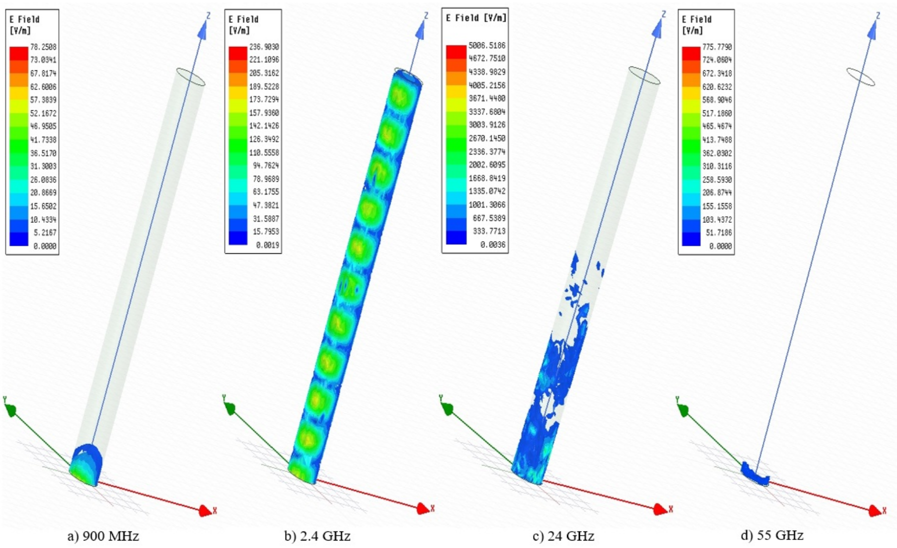

Figure 5.13: The signal propagation expression over 1000mm long, and 50 mm radius circular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

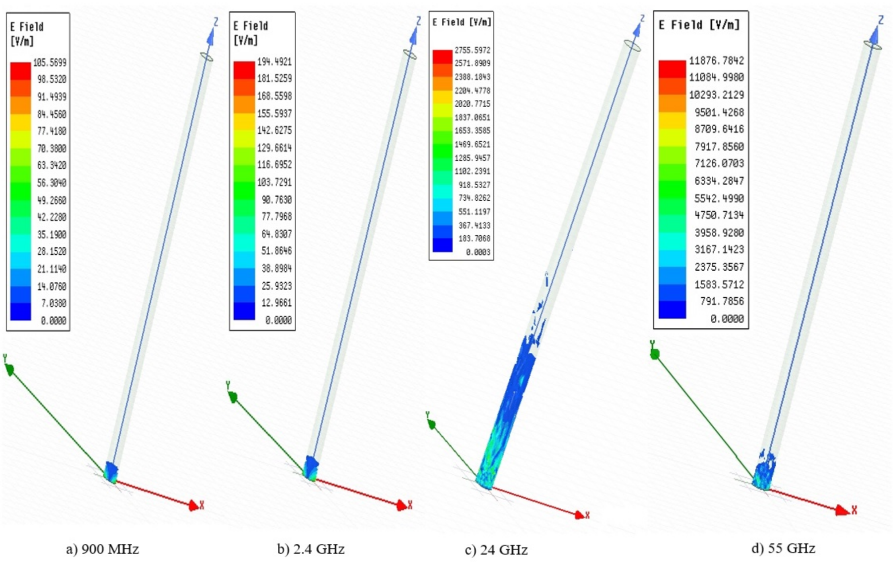

Figure 5.14: The signal propagation expression over 1000mm long, and 25 mm radius circular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

able to propagate the signal to the receiver directing in Z direction. The 24 GHz frequency band signal expression is comparatively strong with the 900 MHz and 55 GHz frequency bands. Moreover, the 55 GHz frequency band shown the weakest signal expression compared to all other frequency bands.

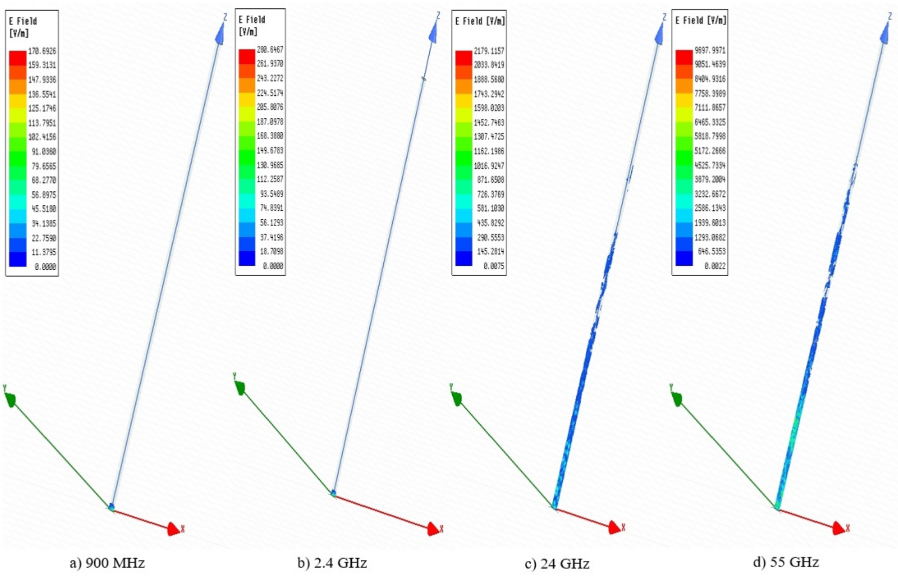

Figure 5.15: The signal propagation expression over 1000mm long, and 10 mm radius circular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

The signal propagation response for 25 mm radius circular transmission waveguide is captured and depicted in Figure 5.14. The transmitted signal is unable to propagate to the receiver towards Z direction over 900 MHz, 2.4 GHz, 24 GHz and 55 GHz frequency bands. Moreover, the signal expression strength is also too weak for almost all frequency bands compared with prior configurations. For the circular transmission medium having radius of 10 mm signal propagation response is presented in Figure 5.15. The all frequency band is failed to propagate the signal to the receiver towards Z direction. But the 24 GHz and 55 GHz frequency bands signal propagation strength are comparatively better with the prior circular waveguide configurations. The signal propagation expression for 5 mm radius of circular transmission medium is presented in Figure 5.16. The 24 GHz and 55 GHz is able to propagate the signal towards Z direction but the 55 GHz signal expression is comparatively weak. Moreover, the 900 MHz and 2.4 GHz frequency bands is unable to propagate the signal to the receiver and presented a very poor signal expression.

The circular transmission waveguide‘s signal propagation expression is experimented for five different radius configurations over 900 MHz, 2.4 GHz, 24 GHz, and 55 GHz frequency bands. The higher radius configuration (100 mm and 50 mm) of circular transmission medium is more capable to transmit strong signals

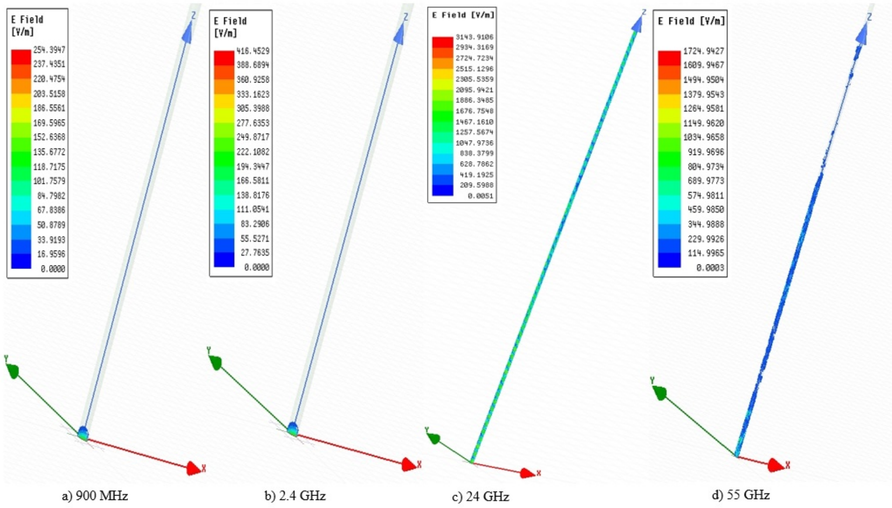

Figure 5.16: The signal propagation expression over 1000mm long, and 5 mm radius circular transmission waveguide for, a) 900 MHz frequency band b) 2.4 GHz frequency band, c) 24 GHZ frequency band, and d) 55 GHz frequency band.

to the receiver towards Z direction for lower frequency bands and vice-versa. The signal propagation expression and signal strength for different frequency bands and different structural configuration is summarized in table 5.3.

5.5 Conclusion

In this chapter work, a hybrid access scheme is proposed and analyzed for future robot's internal communication system by a finite number of sensors in replace of enormous wires. The audio, video, and general sensors transmit signals simultaneously over the hybrid access scheme. The hybrid system‘s reliability and collision probability are estimated in a system-level simulation platform by assigning a fixed channel condition. Moreover, the signal propagation expression emitted from different sensors is also simulated and captured over 900 MHz, 2.4 GHz, 24 GHz, and 55 GHz frequency bands. The signal waveguide with different configurations (width, height, and radius) of higher number is shown improved performance for comparatively lower frequency bands and vice-versa.

Table 5.3: Signal propagation results for different structural configuration over different frequency bands

	Parameters		**900 MHz**		**2.4 GHz**		**24 GHz**		**55 GHz**	
	Width	**Height**	Strength	Propagate?	Strength	Propagate?	Strength	Propagate?	Strength	Propagate?
Rectangular transmission medium	190mm	95mm	Strong	Yes	Strong	Yes	Average	Yes	Bad	No
	100mm	50mm	Bad	No	Strong	Yes	Bad	No	Bad	No
	50mm	25mm	Bad	No	Bad	No	Bad	No	Bad	No
	25mm	15mm	Bad	No	Bad	No	Strong	Yes	Average	yes
Circular transmission medium	Radius	100mm	Strong	Yes	Strong	Yes	Bad	No	Bad	No
		50mm	Bad	No	Strong	Yes	Bad	No	Bad	No
		25mm	Bad	No	Bad	No	Average	No	Bad	No
		10mm	Bad	No	Bad	No	Average	No	Average	No
		5mm	Bad	No	Bad	No	Strong	Yes	Average	Yes

Chapter 6

Conclusion and Future Works

The wireless domain getting powerful and turns into approximately equal to wired medium connectivity day by day by the continuous effort of the researchers and engineers around the world. The technical persons have been working hard and try to find their best in the different domains like frequency domain, time domain, code domain, power domain, and angular domain to explore new services and techniques to improve the communication system. In the future, the communication system will be resilient, cope with any number of users in a network and provide high-speed error-free communication in the wireless domain.

6.1 Conclusion

In this thesis, we focus on random access scheme and proposes a MAC system- "Orthogonal Frequency Subcarrier-based Multiple Access" (OFSMA) adapts with random access mechanism. The random access scheme confronts a lot of collisions in the presence of a massive number of users at higher traffic conditions. But random access is recommended while the users generate packet occasionally and the system needs to support a large number of users. Our proposed OFSMA MAC system adopts a packet diversity principle and transmits multiple copies of the same packet transmitted randomly over a massive number of subcarrier communication channels at the same time to improve the reliability at higher levels. In Chapter 1, we present our thesis briefly in the introduction. The research background covers the recent research aspects and trends towards the next communication domain and application. The 5G communication system and its services are briefly summarized under the research background section. Later, we shortly express the motivation of our research and explains the concrete contribution in the contribution section.

Finally, the chapters end with the direction of the thesis structure.

Chapter 2 introduces the fundamental study of our research work. The random operation and a few random access schemes are presented. The ALOHA, slotted ALOHA and CSMA system is studied and analyzed in terms of traffic and throughput calculation. The URLLC system and its application are briefly explained. The wireless communication in the context of URLLC is studied as packet size, error probability, collision analysis, link structure and reliability of the different interface diversity systems.

In chapter 3, we introduce our proposed OFSMA MAC system along with the random access operation. The OFSMA MAC is analyzed in the presence of a single frequency band and multiple frequency diversity patterns. The advantage of packet diversity principle in the random access operation having a large number of subcarrier channels is incorporated in the system and finally, measures the reliability of the OFSMA system. The OFSMA system determines the minimum number of subcarrier allocation required to satisfy the reliability levels 99.999% for different packet diversity mode over the variable arrival condition. The OFSMA system also determines the single band frequency diversity minimum packet duplication to satisfy the reliability of URLLC as 99.999% over different arrival conditions and gives a direction to use which packet diversity should use in which type of traffic demands to achieved URLLC prescribed reliability. Finally, air interface latency is measured and compared with the OFDMA system and discloses the reason why our proposed MAC is more latency efficient than the OFDMA system.

In Chapter 4, The OFSMA system is analyzed for multiple frequency bands. The OFSMA system designed for single frequency band, double frequency band and triple frequency band. The duplicated packets are transmitted over the respective frequency band and/or bands and the subcarrier frequency channels to improve the reliability of the system. The reliability response is measured for determining the minimum number of subcarriers demanded to ensure the URLLC reliability requirement 99.999%. The reliability response is also evaluated for assigning fixed subcarrier channels per frequency bands and compares for a diverse number of packet duplications. Moreover, the minimum number of packet duplication that satisfy the reliability 99.999% for different arrival condition and its respective 3rd order polynomial form also evaluated for different arrival condition and different packet duplications. Finally, the air-interface latency is estimated for different packet lengths and compare with the OFDMA system for different latency constraints.

In chapter 5, we propose a new hybrid access scheme incorporated with the OFSMA system applicable to robotics short distance communication. The system considers a real-life robot and takes audio, video and general sensors into their consideration for signal transmission. The research work also considers different structural configurations as part of a robot for signal propagation expression. The hybrid access scheme's reliability and collision probability are evaluated for different packet duplication over different arrival conditions. The signal propagation expression is captured for fixed transmission power over different frequency bands and transmitted over the different structural condition to determine either the signal propagation is success or failure.

In chapter 6, the main research contributions and outcomes of the thesis are summarized in a different paragraph. The thesis considers some future directions for the research work that presents in the future direction section.

6.2 Future Directions

In the world, no thesis work is complete and it requires some continuation for the next steps of the research. Every step of the research makes it more complete and forwards to its ultimate objective and/or objectives. We aiming to convert a robot's internal communication system. In order to do that, we propose an OFSMA MAC system and replace the wire by a finite number of homogeneous sensors and the sensors communicate over the OFSMA and hybrid access scheme to ensure higher reliability and reduce latency. There are some future directions related to this thesis work are listed below:

- The OFSMA system determined the minimum packet duplication for different arrival conditions over a single frequency band. The OFSMA system may consider multiple frequency bands to determine the minimum packet duplication for different arrival condition.

- In the hybrid access scheme, the reliability and collision probability is estimated for the sensor to subcarrier channels number ratio is 1:1. The hybrid access scheme's performance of reliability and collision probability may evaluate the different ratio of the sensor to the subcarrier channel number.

- The OFSMA system used the path loss exponent as 3 or 2.002 from other experimental values. The robotic internal environment is different compared to other systems. So, its recommended to evaluate a path loss exponent value of the signal propagation from a real-life robotic internal environment.

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Research Achievements

Journal papers

1. **Md. Abir Hossain,** Zhenni Pan, Megumi Saito, Jiang Liu, and Shigeru Shimamoto, **"Multiband Massive Channel Random Access in Ultra-Reliable Low-Latency Communication,"** IEEE Access 2020 vol.8, pp81492-81505.
2. **Md. Abir Hossain,** Zhenni Pan, Megumi Saito, Jiang Liu, and Shigeru Shimamoto, **"Robotic Inner Signal Propagation and Random Access over Hybrid Access Scheme,"** in International Journal of Computer Networks & Communications (IJCNC) (accepted).

Workshop paper

1. **Md. Abir Hossain,** Megumi Saitou, Zhenni Pan, Jiang Liu, and Shigeru Shimamoto, **"Orthogonal Frequency Subcarrier-based Multiple Random Access in Ultra Reliability and Low Latency Communication,"** in IEEE Consumer Communications Networking Conference (CCNC), 2nd IEEE Workshop on Cyber-Physical Networking (CPN'20).