Multiband Massive Channel Random Access in Ultra-Reliable Low-Latency Communication

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ABSTRACT

Ultra-Reliable Low-Latency Communication (URLLC) is challenging due to its extremely higher reliability requirement with stringent short latency packet transmission. In order to overcome this reliability and latency bound, a communication access scheme needs to assure almost error-free and high speed packet transmission. In this paper, a new multiple-access scheme—Orthogonal Frequency-Subcarrier-based Multiple Access (OFSMA)—is proposed with URLLC’s high requirement adaptation. In this scheme, the packet diversity concept is incorporated to achieve the expected packet transmission reliability and a diverse number of the duplicated packet are processed with a set of operations and transmitted over randomly selected orthogonal subcarrier frequency channels. Performances of the OFSMA system are measured in terms of applying several numbers of frequency bands, a massive number of subcarrier channels, a different number of packet duplications, and a diverse rate of traffic arrival conditions. We determined the minimum number of subcarrier channels requirement to satisfy the reliability of 99.999% for different packet duplication in presence of different frequency bands. The reliability response for a fixed number of subcarrier channels is evaluated for different frequency band conditions. Finally, the air interface latency of the OFSMA system is measured for single packet uplink transmission and compared with that of a traditional OFDMA system. The performance results in terms of reliability and latency express that the OFSMA scheme can assure the expected reliability and latency defined by URLLC.

INDEX TERMS

URLLC, reliability, latency, random access, OFSMA, OFDMA, short-distance communication.

I. INTRODUCTION

A. MOTIVATION

5G technology has intended to facilitate three broad categories of service: evolved mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine type communication (mMTC) [1]. Among these services, URLLC is specially designed for mission-critical services, target-oriented service, and next-generation network services which aims to prioritized high reliability and low latency packet transmission. URLLC is a category of machine type communication (MTC) which mainly focus the communication demands among machines and devices [2]. URLLC provides services to devices with high reliability as 99.999% of packet transmission within strict latency bound as 1 ms [3], [4]. URLLC has diverse applications, such as reliable remote action with robots and coordination among vehicles [5], autonomous vehicles communication [6], the tactile internet [7], augmented or virtual reality (AR/VR) [8], unmanned aerial vehicles [9] and industrial internet of things (IIoT) applications include factory autonomous systems [6], [10]. In the future, URLLC will explore new dimensions of application that are still unthinkable by human beings.

A robot consists of multiple elements, and many wires are usually required as the communication backbone among attached different elements [11]. These numerous wires increase the conventional weight of a robot structure, thereby increasing the power consumed by the robot structure during the robot’s usual movement. Incorporating many wires sometimes turns a robot into an improper configuration. Occasionally, wires lose their connectivity due to heat, a loose connection or speed of operation. In such a situation, maintenance becomes complex and time consuming.
time is expected to range from 1 ms to 100 ms. Soon, mobile latency ranges from 250 µs to 1 ms to 10 ms, and the total processing time is expected to range from 1 ms to 100 ms. Soon, mobile latency ranges from 250 µs to 1 ms to 10 ms, and the total processing time is expected to range from 1 ms to 100 ms.

According to [15], the packet loss rate covers up to 10⁻⁸ for different MCS to ensure 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, mobile latency ranges from 250 µs to 1 ms to 10 ms, and the total processing time is expected to range from 1 ms to 100 ms. Soon, mobile latency ranges from 250 µs to 1 ms to 10 ms, and the total processing time is expected to range from 1 ms to 100 ms.

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protocol having a short 5 ms time slot. A wireless-sensor-
network-based structural health monitoring system for an
airplane is studied in [28] and in this system, a few sensor
nodes monitoring the health status of an airplane are deployed
during the whole aircraft. Those nodes 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. We study a real-time elderly healthcare monitor-
ing system [29] that utilize a wireless sensor network where
bracelet-type devices are equipped with sensors that received
data in real time and stored in a centralized server for monitoring
and analysis. A sensor-based structural health monitoring
early earthquake warning system is proposed in [30] that
presented a monitoring and warning generation system in
presence of seismic events in the 5G communication domain.
Moreover, a few random accesses in slotted ALOHA have been studied to achieve the expected reliability and
latency of our system. An asynchronous contention resolution
slotted ALOHA studied in [31] where virtual framing,
time offset strategy, and multiple replicas of the packet forwarding strategy are used to improve the throughput of
the system. A multi-packet messaging system incorporated in a cluster-based environment analyzed in [32] where the
multiple packets transmitted into different slots and having
independent frequency and transmitters are grouped to improve the system throughput level. Multichannel random
access in an OFDMA wireless network is analyzed in [33], that proposed a fast retrial algorithm to forward a packet
into a frequency diversity system after a collision in a slotted
ALOHA system.

C. CONTRIBUTIONS

Current research works regarding the wireless sensor-based
system explained in [27]–[30]. Among the research works [27], demanded higher latency for packet transmission
as a 5 ms transmission slot and not determined the reliability
defined by URLLC. The research work presented in [28],
latency is comparatively higher as 115 ms and reliability
not defined by the system. The research work explained in
[30] satisfied the URLLC latency bound but reliability not
guaranteed. Another sensor-based elderly healthcare moni-
toring system presented in [29] not determined the reliability
and latency for their proposed system. The existing research
works are different in application environment and not suit-
able to convert robotic communication into the wireless
domain. Moreover, all the proposed sensor-based systems are not evaluated in term of reliability defined by URLLC
system. The previous research works often used Orthogonal
Frequency Division Multiple Access (OFDMA) and Time
Division Multiple Access (TDMA) scheme for packet trans-
mission. In OFDMA system, the usual packet size is getting
bigger due to its packet splitting mechanism into multiple
subcarriers which consume more time during transmission.
On the other hand, the slotted-ALOHA system is superior
for small size packet transmission compared to TDMA
system [34]. The existing works were not yet considered the
short-distance communication and high traffic performance
impact into the network. Moreover, the minimum number of
subcarriers detection to achieve reliability 99.999% for
the mass number of sensors was still absent. In addition,
the reliability response for different packet duplication over
different frequency bands was not yet evaluated. To the
best of our knowledge, no research work has been done to
transform a robot’s internal communication system into a
wireless sensor-connected system by applying an efficient
access scheme for short-distance communication. The main
contributions of this paper are summarized as follows.

- We introduce an Orthogonal Frequency Subcarrier-
based Multiple Access (OFDMA) scheme to allow ran-
dom accessing over orthogonal subcarriers to ensure
interference-free transmission.
- We propose short distance system and path loss model
which express the transmitted signals for packets,
analyze the packet size, collision probability, allow
massive connectivity, and measure link reliability of the
OFDMA communication system.
- We evaluate the minimum number of subcarrier chan-
nels to satisfy the URLLC’s 99.999% reliability in terms
of packet diversity over different number of frequency
bands from low to higher traffic condition.
- We estimate the OFSMA system’s reliability for fixed
number of subcarrier allocation and determine the vari-
ation of reliability in terms of diverse numbers of
frequency bands and packet duplication.
- Finally, we measured the OFSMA system’s air interface
latency for different packet bit length and compare it
with the OFDMA system for a single packet uplink
transmission.

The rest of the paper is organized as follows. In Section II,
the system model with signal analysis, packet size determin-
ation, 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 paper.

II. SYSTEM MODEL

We consider a short-range uplink communication system
where the non-periodic sensors are ubiquitously distributed
around the receiver. For the uplink packet transmission,
we adopt a packet diversity concept and transmit 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 reliabil-
ity of the packet transmission. For the OFSMA system, based
on the frequency band and subcarrier channel allocation,
the system model is classified into three categories:

1) Single-band frequency diversity model.
2) Double-band frequency diversity model.
3) Triple-band frequency diversity model.
The single-band, double-band, and triple-band frequency diversity model is presented in Fig. 2. The single-band frequency diversity model uses a single frequency band 2.4 GHz with multiple orthogonal subcarrier channels as presented in Fig. 2a. We assume a total $K$ number of sensors ($Sensor_1$, $Sensor_2$, $Sensor_K$), and each sensor transmits $3, 5, \ldots, d$ duplicated packets. According to the packet diversity principle, among the duplicated packets in transmission, if at least a single packet is successfully received at the receiver, it’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, $B_1, B_2, \ldots, B_n$. So, the bandwidth of each subcarrier frequency channel is $B_f = B/K$. Each frequency band has a set of maximum $C$ subcarrier channels as $f_1, f_2, f_3, \ldots, f_C$. During the transmission of a single packet from the duplicated packets, first a frequency band, $B_r$ is selected in random order where $B_r \in B_s$. Afterwards a subcarrier channel $f_s$ is also picked in random fashion where $f_s \in f_r$, is from the previously elected $B_r$ frequency band. For single-band frequency diversity model the frequency selection can be expressed as

$$f_s \leftarrow f_r$$

We apply random access for band and subcarrier channel selection in order to ensure short latency time consumption. In the packet transmission procedure, each sensor follows the Poisson arrival process for packet transmission in the slotted ALOHA protocol. For any random $z$-th slot scenario in slotted ALOHA protocol, is illustrated in Fig. 3. Due to applying the packet diversity concept, any sensor $j$ transmits two packets duplication 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 transmit duplicated packets. The double-band frequency diversity model uses two frequency bands at 30 GHz and 60 GHz to deliver data from the sensor to the receiver’s end, as presented in Fig. 2b. Each frequency band is assigned an equal number of subcarrier frequency channels. According to the models, $k$ number of sensors transmit $d$ duplicated packets over a randomly chosen frequency band and frequency subcarrier. The random frequency band $B_r$ selection can be expressed as

$$B_s \leftarrow B_r$$
where $B_i$ is the collection of frequency bands for double-band and triple-band frequency diversity model. The subcarrier frequency selection follows Equation (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, presented in Fig. 2c, utilizes three frequency bands at 55 GHz, 28 GHz, and 2.4 GHz to forward data from the sensor to the receiver. A single packet that originated from a sensor randomly selects a frequency band among three and then again independently or randomly chooses a frequency subcarrier channel from the randomly selected frequency band. As in the single-band and double-band frequency diversity models, the subcarrier frequency channel selection procedure in the triple-band frequency diversity model is random. The random selection procedure reduces the scheduling latency and ensures short latency packet transmission.

**A. PACKET SIZE**

The 3GPP standardized URLLC reliability requirement for one transmission of a packet size of 32 bytes is $1 \times 10^{-5}$ with a user plane latency of 1ms [8], [35]. Due to low-latency constraints, the packet length is assumed to be short, and the size depends on the application requirement. Consider both a short-length packet of $b$ bits and latency for $b$ bits transmission, which is assumed to be $T$. Therefore, the link or interface transmission rate $R_{bps}$ can be shown as

$$R_{bps} = \frac{b}{T}$$  \hspace{1cm} (3)

If the system’s packet latency is predefined, then for a given transmission link rate using (3), we can calculate the minimum bit-length packet size. However, the transmission rate is expressed in standard information-theoretic models in terms of bits per channel uses [bpcu]. For a given bandwidth $B$, the number of channel used for transmission is $2BT$. Therefore the transmission rate $R$ can be expressed [13] as

$$R = \frac{b}{2BT} = \frac{R_{bps}}{2B}[\text{bpcu}]$$  \hspace{1cm} (4)

**B. PACKET SIGNAL AND COLLISION PROBABILITY ANALYSIS**

A single packet equivalent signal is transmitted orthogonally over a frequency subcarrier $f_i$ from $C$ frequency channels to avoid interference. Each sensor transmits $i = 1, 2, \ldots, d$ duplicated packets to improve the reliability of the transmission. The duplicated packet signal $S(t)$ can be presented as

$$S(t) = \sum_{i=1}^{d} u_i(t) e^{j2\pi f_i t}$$  \hspace{1cm} (5)

where $u_i(t)$ is a complex baseband signal for $i$ number of duplicated packets with an in-phase and quadrature component and $f_i$ is the randomly selected frequency $f_i$ for $i$ duplicated packets. In the slotted ALOHA system, for any $z$-th slot, if $j = 1, 2, \ldots, K$ number of sensors transmit $i = 1, 2, \ldots, d$ duplicated packet then the total $K.d$ number of packets transmitted in $z$-th slot can be expressed as

$$S(t) = \sum_{j=1}^{K} \sum_{i=1}^{d} u_{i,j}(t) e^{j2\pi f_{i,j} t}$$  \hspace{1cm} (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. We not only adopted the frequency band and frequency diversity concept to minimize collision but also incorporated packet diversity to ensure higher reliability and error-free transmission. Despite utilizing frequency and packet diversity, there are few collisions in the system. The collision happens only when the same subcarrier frequency channel is selected by two or more packets emitted by sensors. However, if at least one of the duplicated packets is successfully received by the receiver, then the packet is marked as “success” and “success” packets are encountered [36]–[39]. The system assumes that some duplicated packets emitted from a sensor have no collision in self-packet duplication. An inter-packet collision scenario is illustrated in Fig. 4. Sensors A and B transmit 3 duplicated packets over the subcarrier channels, but all packets of the two sensors collide because they select the same subcarrier through random selection. 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 [23] as

$$P_{\text{coll}} = 1 - e^{-\lambda}$$  \hspace{1cm} (7)
and for d duplicated packets, the random event can be express as

$$P_{ra} = 1 - e^{-d\lambda}$$  \hspace{1cm} (8)$$

The inter-packet collision probability for K number of sensors having arrival rate of $\lambda$ with d duplication packets can be shown [23] as

$$P_{ipc} = 1 - (\frac{e^{-d\lambda} + C^d - 1}{C^d})^{K-1}$$  \hspace{1cm} (9)$$

The error probability of receiving b bits of data within $N = 2BT$ channels having SNR is given by $\gamma$ well approximated [37], [40], [41] by

$$e(N, \gamma, b) = Q(\frac{NC(\gamma) - b + \frac{1}{2} \log_2 N}{\sqrt{NC(\gamma)}})$$  \hspace{1cm} (10)$$

where Q is a Gaussian Q function, $C(\gamma) = \frac{1}{2} \log_2(1 + \gamma)$ and $V(\gamma) = \frac{\gamma(\gamma + 2)}{2(\gamma + 1)^2} \log_2 e$ denotes the channel capacity and dispersion. The system assumes that the receiver has the multi-user detection capability to simultaneously decode the multiple packets from different subcarrier frequency channels [23]. The packet signal is forwarded through the AWGN channel, and noise $n(t) \sim CN(0, \sigma^2)$ is added to the signal. For any z-th slot, the received signal $r(t)$ can be defined as

$$r(t) = \sum_{j=1}^{K} \sum_{i=1}^{d} u_{i,j}(t) e^{i2\pi f_{a}t} + n(t)$$  \hspace{1cm} (11)$$

Equation (11) presents the total packet equivalent signals with noise received by the receiver.

![FIGURE 5. Connectivity scenario between sensor and receiver.](image)

### C. INTERFACE RELIABILITY

A system’s packet 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. We adopt packet diversity to forward multiple duplicated packets over multiple channels in the same TTI slot to improve the reliability up to URLLC’s expected level. A connectivity scenario involving a single sensor is illustrated in Fig. 5. The proposed system’s packet reliability is related to its interface reliability $r_I$, core network reliability $r_e$, and link $r_f$ to the receiver. Therefore the system reliability can be presented [13] as

$$R_{system} = (1 - \prod_{i=1}^{N}(1 - r_I^{(i)}) r_e r_f)$$  \hspace{1cm} (12)$$

### D. SIGNAL PROPAGATION

The OFSMA system utilizes a simplified propagation model for evaluating the received power at the receiver’s end. According to the simplified path loss model, the received power, $P_r$, in dBm, can be expressed as

$$P_r = P_t + X - 10\Gamma \log_{10} \frac{d_0}{d_a}$$  \hspace{1cm} (13)$$

where $P_t$ is the transmit power, $X$ is an unitless constant and can be expressed as $20 \log_{10}(\lambda/4\pi d_0)$, $\lambda$ 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 $\Gamma$ is a path loss exponent that varies from one environment to another. The system considered a set of carrier frequencies, which are listed in Table 1. The system considered path loss exponent $\Gamma = 2.001$ [42], and reference distance $d_0 = 0.1$ m [43]. 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

$$P_r = P_t + 147.5482 - 20 \log_{10}(f) - 20.01 \log_{10}(d_a)$$  \hspace{1cm} (14)$$

We considered the transmit power to be 20 dBm [44] for all our system models. Therefore, the received power can be calculated as

$$P_r = 167.5482 - 20 \log_{10}(f) - 20.01 \log_{10}(d_a).$$  \hspace{1cm} (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 ~ 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.

### III. OFSMA SYSTEM

#### A. OFSMA COMMUNICATION SYSTEM

OFSMA is a random multiple access scheme where the packet’s equivalent signals are forwarded over randomly selected subcarrier frequency channels. The random
subcarrier assignment enhances to assure short latency packet transmission and refrain to consume extra time for scheduling. The proposed OFSMA system is presented in Fig. 6. A packet's equivalent bits are generated and duplicated for \( d \) number of duplications. Each \( d \) duplicated packet equivalent bits are multiplied by the carrier signal. The frequency band and subcarrier selection are random and independent. Thus, the system performs BPSK modulation mapping. The OFSMA system utilizes BPSK modulation, a low bit-level modulation scheme, to avoid or significantly minimize bit error. An inverse discrete Fourier transform (IDFT) is performed on a modulated mapping signal, and the signal is converted into an analog form. After a series of operations, the \( d \) duplicated packet equivalent signals are transmitted through an additive white Gaussian noise channel. The robotic system assumes that the receiver has the multiuser detection capability [23] to simultaneously detect multiple signal packets. The receiver receives the composite signal with Gaussian noise. A bandpass filter is used to extract the signal from the signal noise composite form. Then, the filter performs the reverse operation to regenerate the original bit sequence.

However, in the OFSMA system, the complete data packet is directly forwarded to a single subcarrier, and the subcarrier selection is random and independent. The OFDMA system has zero probability of packet collision, but unlike the OFSMA system, collision is probable only when two or more packets are forwarded in the same subcarrier channels. This collision probability is minimized by employing a massive number of channels and a diverse number of duplicated packets.

### B. SINGLE PACKET PROCESSING CYCLE

A single packet processing cycle is presented in Fig. 7. A packet of equivalent bits, initially generated by the sensor, randomly selects a frequency band and subcarrier frequency channel. The signal bits are modulated using BPSK modulation symbol mapping. For BPSK modulation, the baseband signal is multiplied with the carrier frequency signal.
The carrier signal [45] expression can be presented as

\[
\text{CarrierSignal}(CS) = \sqrt{\frac{T}{T}} \cos(2\pi f_x t)
\]

where \( T \) is the symbol period time, \( f_x \) is the carrier frequency, and \( t \) is the duration of the signal. The baseband signal is multiplied with the carrier signal and performs an inverse fast Fourier transform, which transforms the signal bits from the frequency to the time domain. A digital-to-analog converter is used to convert the signal into an analog form, and the signal is transmitted through the additive white Gaussian noise (AWGN) channel. A received signal that has some noise is filtered using a bandpass filter to extract the signal part. The processed signal is then forwarded to a fast Fourier transform (FFT) block of operation to convert the signal from the time into 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 mapping, and the original bits of the packet are retrieved.

**IV. SIMULATION RESULTS**

In this section, we evaluate the performance of our proposed system. We present the simulated results to investigate the minimum number of subcarrier channels to satisfy URLLC’s reliability requirement 99.999%, the reliability response for a fixed number of assigned subcarrier channel and the air interface latency of our proposed OFSMA system. A system-level simulation is performed on a MATLAB simulator to evaluate the performances. The 100 sensors [46]–[48] follow the Poisson arrival process for packet generation and transmission. The sensors process the 100-bit packet using the proposed OFSMA system and forward the packet through 60 GHz, 55 GHz, 28 GHz, 10 GHz, 2.4 GHz, and 920 MHz frequency subcarrier channels using slotted-ALOHA protocol. The detailed simulation parameters are listed in Table 2.

**A. MINIMUM NUMBER OF SUBCARRIERS**

The OFSMA system’s reliability is directly related to the number of subcarrier channels, the number of sensors, packet diversity and sensors arrival conditions. Fig. 8 shows the minimum number of subcarrier channels required under the single-band frequency diversity system model to satisfy URLLC’s reliability 99.999% for single-band frequency diversity model.

**TABLE 2. Simulation parameters.**

| Parameter description | Values |
|-----------------------|--------|
| Modulation           | BPSK   |
| Signal frequency band, \( f_x \) | (60, 55, 30, 28, 10, 2.4, and 920) GHz |
| Subcarrier frequency bandwidth, \( f_S \) | 10 kHz |
| Subcarrier channel, \( C \) | 10∼600 |
| Packet duplication, \( d \) | 3∼32 |
| Number of sensor, \( K \) | [46],[48] |
| Packet size, \( b \) | 100 bits |
| Transmit power, \( p_x \) | 20 dBm |
| Link rate, \( R \) | 1 Mbps |
| Path loss exponent, \( \Gamma \) | 2.001 |
| Reference distance, \( d_0 \) | 0.1 m |
| Actual distance, \( d_a \) | 0.1∼1 m |
| Transmission Slot duration | 0.1 ms |
| SNR, \( \gamma \) | 1 |
| Bit Rate,\( T \) | 1 bit/sec |
| Arrival rate, \( \lambda \) | 1∼15000 pk/sec |
| Simulation Time | 1000 s |
to satisfy the desired rate of reliability 99.999% which is lowest than that required for all other packet duplications. For packet duplications consisting of from 8∼32 packets, increasing the number of duplicated packets resulted in needing a successively higher number of subcarrier channels at an arrival rate of 10000 pk/sec due to inter-packet collision. Therefore, at higher traffic conditions, the lower numbers (5 and 7 compared to 14, 16, 21 and 32) of packet duplications reduce the chance of collision and achieve higher reliability of transmission.

FIGURE 9. Determine minimum number of subcarrier channels to satisfy URLLC’s reliability 99.999% for double-band frequency diversity model.

The minimum number of subcarrier frequency channels required under the double-band frequency diversity model in terms of different traffic conditions and different numbers of duplicated packets is illustrated in Fig. 9. The 100 sensors generate the packet using the OFSMA system and transmit the packet using the slotted-ALOHA protocol over the 30 GHz and 60 GHz frequency bands. The double-band frequency diversity model assigned an equal number of subcarrier frequency channels to each frequency band and adopted 3-, 5-, 7-, 8-, 14-, 16-, 21- and 32-packet duplications to determine which packet duplication required fewer subcarrier channels to satisfy URLLC’s target reliability of 99.999%. As in the single-band frequency diversity model, in the double-band frequency diversity model, the 3-packet duplication required more subcarrier frequency channels compared to all other packet duplications due to inter-packet collision. The 7∼32-packet duplications required at most 32 subcarrier frequency channels to achieve the reliability of 99.999% at an arrival rate of 1-1000 pk/sec, but the 5-packet duplication required more subcarrier channels compared to other packet duplications. However, at a higher arrival rate, i.e., 10000 pk/sec (marked in circle 2), the 5-packet duplication requires 120 subcarrier frequency channels that is minimal compared to the number of subcarrier frequency channels required using all other packet duplications. The 7∼32-packet duplications obligated a successively higher number of subcarrier frequency channels because 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 deploying approximately 57% of the subcarrier frequency channels assigned in each band compared to the single-band frequency diversity channel. This is achieved due to an increase in the number of frequency bands and the adoption of band diversity.

FIGURE 10. Determine minimum number of subcarrier channels to satisfy URLLC’s reliability 99.999% for triple-band frequency diversity model.

The triple-band frequency diversity model is also evaluated for minimum number of subcarrier channels. Fig. 10 shows the minimum number of subcarrier frequency channels required under this model to achieve the target reliability of 99.999% based on different numbers of duplicate packets and different arrival rate. The system 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 determined the minimum number of subcarrier frequency channels required by each packet duplication at different arrival rates, i.e., 1-10000 pk/sec. The system assigned an equal number of subcarrier frequency channels to each frequency band. As in the single- and double-band frequency diversity models, in the triple-band frequency diversity model, the 3-packet duplication required more subcarrier frequency channels compared to all other packet duplications due to inter-packet collision. The 7∼32-packet duplications required at most 32 subcarrier channels to achieve the reliability of 99.999% at an arrival rate of 1-1000 pk/sec, but the 5-packet duplication required more subcarrier channels than did the 7∼32-packet duplications due to a higher number of inter-packet collisions. Moreover, at an arrival rate of 1000 pk/sec (marked in
circle 1), the 32-packet duplication requires more subcarrier channels compared to the 7- and 8-packet duplications due to a higher number of inter-packet collisions. At a higher arrival rate, i.e., 10000 pk/sec (marked in circle 2), the 7-packet duplication required the lowest number (65) of subcarrier channels compared to all other packet duplications, and the 5-packet duplication required 71 subcarrier channels to satisfy URLLC’s expected reliability of 99.999%. The 8–32-packet duplications demanded a gradually increasing number of subcarrier channels compared to the 7- and 5-packet duplications. The triple-band frequency diversity model achieved URLLC’s expected reliability of 99.999% by deploying approximately 31% and approximately 54% of the subcarrier channels deployed by the single-band frequency diversity model and the double-band frequency diversity model, respectively, to all bands at the highest arrival rate, i.e., 10000 pk/sec.

B. MINIMUM PACKET DUPLICATIONS WITH MINIMUM SUBCARRIERS

We analyzed the minimum subcarrier channel requirement to satisfy a reliability of 99.999% considering different packet diversities and determined which packet diversity required the minimum number of channels for different arrival rates. The 100 sensors transmit different (3–32) packet duplications over 30 GHz, 10 GHz, 2.4 GHz, and 920 MHz single-band frequencies and determined the minimum packet duplication, as illustrated in Fig. 11. According to the figure, 30 GHz and 920 MHz required the same 14-packet diversity on the other hand, 10 GHz and 2.4 GHz required different packet diversities but starting from the 15-packet duplication for an arrival rate of 1~100 pk/sec. At the arrival rate of 500~2500 pk/sec, 30 GHz and 10 GHz required 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 rate, the system required 11- and 12-packet duplication for these frequencies, respectively. However, at an arrival rate of 2500 pk/sec, all frequency bands required the same 9-packet duplication. At arrival rates of 5000~10000 pk/sec, 10 GHz and 2.4 GHz satisfied the expected reliability with the same 7- and 5-packet duplication, but under the 5000 pk/sec traffic condition, 30 GHz and 920 MHz are a little different in that they required 7- and 9-packet duplication, respectively, in determining the minimum number of subcarrier channels to satisfy the expected reliability 99.999%. At higher arrival rates of 10000~15000 pk/sec, 30 GHz and 920 MHz required the same 7- and 5-packet duplications; 10 GHz and 2.4 GHz required the same 5-packet duplication to determine the minimum number of channels required to satisfy the URLLC’s expected reliability of 99.999%. After determining the minimum packet duplication, we used a 3rd order polynomial curve fitting to generalize the packet duplication over different arrival rates. The main significance of this result is that the fitting curve with actual value illustrates a direction about minimum packet duplication with the respective arrival rate in a single different frequency band and frequency diversity random operation which is gradually decreased due to the increase in the arrival rate.

C. RELIABILITY RESPONSE FOR FIXED CHANNEL ASSIGNMENT

The OFSMA system analyzed the reliability impact for the single-band frequency diversity model by assigning a fixed 50 subcarrier channels is illustrated in Fig. 12. The 100 sensors transmitted different numbers of packet duplication over the OFSMA system’s single 2.4-GHz frequency band. The sensors transmission operation is simulated for 1000 sec and measured the reliability in percentages. The reliability is estimated for 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications. The red dotted line indicates the URLLC’s
expected reliability of 99.999%. The 3-packet duplication depicted a lower reliability percentage compared to the 5∼21-packet duplication due to inter-packet collision. The 5-packet duplication defined a lower reliability percentage compared to the 7∼21-packet duplication for a low-to-average arrival rate, i.e., 1-1000 pk/sec due to a higher number of collisions and not satisfying the URLLC reliability requirement. At the arrival rate of 10∼1000 pk/sec, sensors reliability impacts are zoomed, and at an arrival rate of 500 pk/sec, only the 11-,14- and 18-packet duplications satisfy the 99.999% reliability requirement. At arrival rates higher than 500 pk/sec, all packet duplications achieved a lower reliability than 99.999%. At the arrival rate of 3000 pk/sec, the 5- and 21-packet duplications gained similar reliability at 99.9854% and 99.9875%, respectively, and the 7∼18-packet duplications achieved higher reliability. The higher reliability rate changed at the arrival rate of 6000 pk/sec, where the 7-packet duplication achieved the highest reliability (99.9848%). At the arrival rate of 10000 pk/sec, the 7-packet duplication still achieved the highest reliability (99.9339%), and the 5-packet duplication achieved a slightly lower reliability (99.9313%) compared to the 7-packet duplication. The 11∼21-packet duplication reliability percentage gradually decreased due to the increase in the number of duplicated packets. With higher traffic, the probability of collision increases as the number of duplicated packets increases. In addition, at an arrival rate of 10000 pk/sec, the 3- and 21-packet duplications achieved similar reliability (99.8477% and 99.8465%, respectively) due to a higher number of inter-packet collisions compared to other packet duplications.

As presented in Fig. 13, the OFSMA system’s reliability is measured for the double-band frequency diversity model. The 100 sensors transmit packets over 30 GHz and 60 GHz frequency channels. The OFSMA system’s reliability is evaluated in terms of percentages for 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications. The 3-packet duplication achieved lower reliability compared to all other packet duplications at arrival rates of 1-6000 pk/sec due to inter-packet duplication. The 5∼21-packet duplications achieved higher reliability, and the reliability results are comparatively close at arrival rates 1∼3000 pk/sec, but the reliability for these packet duplications gradually decrease because the increase in the arrival rate implies a higher number of collisions. The reliability response from 1000∼6000 pk/sec is zoomed and illustrates that at a 3000 pk/sec arrival rate, the 7∼21-packet duplications achieved the expected 99.999% reliability requirement. At arrival rates higher than 3000 pk/sec, the reliability 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 packet duplications. The reliability results scenario is different at a higher arrival rate, i.e., 10000 pk/sec; the 5-packet duplication achieved the highest reliability (99.9913%), and the reliability of the 7∼14-packet duplications gradually decreased compared to the 5-packet duplication due to the increasing number of duplicated packets. The 3-packet duplication gained higher reliability compared to the 18- and 21-packet duplications at an arrival rate of 10000 pk/sec because the number of inter-packet collisions that happened for the 18- and 21-packet duplications is higher than those that happened for the 3-packet duplication. The above explanation applies to the lower-number packet duplications, i.e., the 5- or 7-packet duplications achieved higher reliability than higher-number packet duplications (11∼21-packet duplications) in high traffic situation.

The OFSMA system’s reliability also evaluated for the triple-band frequency diversity model, as illustrated in Fig. 14. The 100 sensors transmit diverse 3-, 5-, 7-, 11-, 14-, 18-, and 21-packet duplications over 55 GHz, 28 GHz,
and 2.4 GHz frequency bands, and each band is assigned 50 subcarrier frequency channels. As in the single-band and double-band frequency diversity models, in the triple-band frequency diversity model, the 3-packet duplication had a lower reliability percentage than did all the other packet duplications at arrival rates 1~6000 pk/sec due to inter-packet collision. The 5~21-packet duplications achieved a similar reliability percentage at arrival rates of 1~6000 pk/sec but gradually decreased the reliability due to an increase in the arrival rate. The reliability response from 3000 pk/sec~10000 pk/sec is zoomed, thereby illustrating that at a 6000 pk/sec arrival rate, the 7~14-packet duplications satisfy the URLLC expected higher reliability of 99.999%. At arrival rates higher than 6000 pk/sec, all packet duplications achieved a reliability rate below 99.999%. At the arrival rate of 6000 pk/sec, the 7-packet duplication achieved the highest reliability percentage (99.9996%) compared to all other packet duplications due to a lower number of packet collisions. At an arrival rate of 10000 pk/sec, the 7-packet duplication also achieved the highest reliability (99.99714%) compared to all other packet duplications, and the 5-packet duplication achieved slightly lower reliability (99.9967%) compared to the 7-packet duplication. Moreover, at the arrival rate of 10000 pk/sec, the 3-packet duplication achieved higher reliability compared to the 18- and 21-packet duplications due to a lower number of inter-packet collisions.

D. AIR-INTERFACE LATENCY

A single packet air interface latency comparison between the proposed Orthogonal Frequency Subcarrier-based Multiplexing (OFSM) and traditional Orthogonal Frequency Division Multiplexing (OFDM) is presented in Fig. 15. A single packet having different bit lengths (30~250) is transmitted from the sensor to the receiver, and the air interface latency for uplink communication is evaluated in a millisecond. The air-interface latency is computed based on the system’s propagation delay and the system delay. If the system delay of the OFSMA system is \( \delta \) and propagation delay is \( \beta \), then the air interface latency, \( \alpha_{\text{delay}} \) can be expressed as

\[
\alpha_{\text{delay}} = \beta + \delta
\]  

(17)

The system delay, \( \delta \) is estimated from the simulation platform and is equivalent to the time consumed to transmit the bits from the sensor’s end to the receiver via Gaussian noisy channels. The propagation delay is calculated by the ratio of the packet size, \( b \) and link rate, \( R \) of the system. So the air interface latency, \( \alpha_{\text{delay}} \) can be present as

\[
\alpha_{\text{delay}} = \frac{b}{R} + \delta
\]  

(18)

As presented in Fig. 17, the OFSM system’s 30-bit packet required less than 0.1 ms, the 60-, 100-, and 150-bit packets required less than 0.5 ms, and the 200- and 250-bit packets required less than 1 ms to transmit from the sensor to the receiver’s end. Moreover, for every bit-length packet comparison, the OFSM system required less time compared to the OFDM system. For example, the 100-bit packet required 0.2234 ms in the OFSM system, but the packet took 0.30054 ms in the OFDM system due to its packet processing mechanism. In the OFDM system, the packet equivalent bits are divided into the number of subcarriers, and cyclic prefix bits are added into the original bits, thereby increasing the packet length. Thus, the OFDM system takes more time than the OFSM system. On the contrary, the proposed OFSM system directly forwards the packet bits into a single subcarrier frequency channel without adding any cyclic prefix bits into the original bits.

V. CONCLUSION

In this paper, a new Orthogonal Frequency Subcarrier-based Multiple Access scheme has been proposed. The OFSMA system enables sensors to select channels randomly due to ensure short latency packet transmission. However, random subcarrier accessing increases the probability of collision among the transmitted packets. To reduce the collisions at approximately zero levels, the system employed packet diversity concept and transmit duplicated packets over multiple subcarriers. As the result, increasing the system reliability and satisfying URLLC’s expected reliability of 99.999%. We evaluated the minimum subcarrier’s demand to satisfy the reliability of 99.999% for different packet duplication and examine it over our single-band and multi-band communication system. The minimum subcarrier allocation for the double-band frequency diversity model needs a 57% subcarrier frequency channel, and the triple-band frequency diversity model requires a 31% subcarrier frequency channel compared to the single-band frequency diversity model. That implies increasing the band diversity causes decreasing the minimum subcarrier demands in each band of frequency. Furthermore, analyzing the impacts of diverse packet duplication in minimum subcarrier detection

![FIGURE 15. OFDM and OFSM single packet air interface latency comparison.](image-url)
and reliability response for single and multi-band systems concludes that the higher-number packet duplications may be better at lower arrival rates, but at higher arrival rates, i.e., 6000 pk/sec~15000 pk/sec, a lower number of packet duplications is far preferable. The OFSMA system’s packet latency is also investigated, and for packet lengths up to 250 bits, air-interface latency is less than 1 ms. Therefore, the OFSMA system satisfies URLLC’s higher reliability and stringent latency requirement.

Due to obtaining the targeted reliability and latency, we assumed that the OFSMA system can serve as the main communication medium connected by sensors inside a robot.

In the future, this scheme will be investigated to apply for higher frequency bands and other similar time-critical communication systems.

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