Can Terahertz Provide High-Rate Reliable Low Latency Communications for Wireless VR?

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Abstract

Wireless virtual reality (VR) imposes new visual and haptic requirements that are directly linked to the quality-of-experience (QoE) of VR users. These QoE requirements can only be met by wireless connectivity that offers high-rate and high-reliability low latency communications (HRLLC) unlike the low rates usually considered in vanilla ultra-reliable low latency communication scenarios. The high rates for VR over short distances can only be supported by an enormous bandwidth, which is available in terahertz (THz) wireless networks. Guaranteeing HRLLC requires dealing with the uncertainty that is specific to the THz channel. To explore the potential of THz for meeting HRLLC requirements, a quantification of the risk for an unreliable VR performance is conducted through a novel and rigorous characterization of the tail of the end-to-end (E2E) delay. Then, a thorough analysis of the tail-value-at-risk (TVaR) is performed to concretely characterize the behavior of extreme wireless events crucial to the real-time VR experience. System reliability for scenarios with guaranteed line-of-sight (LoS) is then derived as a function of THz network parameters after deriving a novel expression for the probability distribution function of the THz transmission delay. Numerical results show that abundant bandwidth and low molecular absorption are necessary to improve the reliability. However, their effect remains secondary compared to the availability of LoS, which significantly affects the THz HRLLC performance. In particular, for scenarios with guaranteed LoS a reliability of 99.999% (with an E2E delay threshold of 20 ms) for a bandwidth of 15 GHz can be achieved by the THz network, compared to a reliability of 96% for twice the bandwidth, when blockages are considered.

Index Terms

virtual reality (VR), terahertz (THz), reliability, performance analysis, risk.

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I. INTRODUCTION

Virtual reality (VR) is perhaps one of the most anticipated technologies of the coming decade [1]. VR systems can create a sensorimotor and cognitive activity for users in an artificially created world, thus, enabling a sense of total presence and immersion. However, relying on wired VR systems significantly limits the VR technology's application domain. Instead, the deployment of wireless VR over cellular networks, can potentially unleash its true potential [1], [2]. In order to integrate VR services over wireless networks, it is imperative to equip the wireless network with the ability to meet the stringent quality-of-service (QoS) requirements of VR applications. On the one hand, it is important to ensure reliable low latency communications [2], i.e., the instantaneous end-to-end (E2E) delay for wireless VR needs to be very low (in the order of tens of milliseconds) in order to maintain a satisfactory user experience [3]–[5]. On the other hand, along with high-reliability, wireless VR services also require high data rates in order to deliver the 360° content to their users. Unlike the established notion of ultra reliable low latency communications [6], which is conceived for sensor-based Internet of Things applications where high reliability and low latency are offered for a relatively low rate, VR requires high-rate and high-reliability low latency communications (HRLLC) where high reliability and high rates are simultaneously needed for the transmission of large VR content packets [1].

This challenge can be addressed only through the use of abundant bandwidth, available at terahertz (THz) and millimeter wave (mmWave) frequencies [7]. In addition, support of high reliability at these frequencies becomes plausible only for short distances, which is compatible with the VR scenarios. Although deploying basic VR services is possible over 5G using mmWave frequency bands, it is anticipated that a new generation of VR services, dubbed ultimate VR, will soon be deployed [8]. In ultimate VR, perceptual and haptic requirements stem from soliciting the five senses [1]. As discussed by Huawei Technologies in [9] and by the works in [2], the stringent requirements of ultimate VR dictate an uncompressed bit rate of 1911.03 Gbit/s, which warrants investigation of frequency bands beyond mmWave and brings the THz band as a natural candidate. Propagation at THz covers short range and is susceptible to blockages and molecular absorption [10]. This results to an on-off behavior of the wireless link and leads us to the hypothesis that, if properly managed, THz can potentially offer HRLLC simultaneously high rate, high reliability, and low latency for immersive VR experience. Investigation of this hypothesis is the subject of this work.
A. Prior Works

A number of recent works attempted to address the challenges of wireless VR [2], [11]–[17]. In [2], the authors discussed current and future trends of wireless VR systems. The authors in [11] investigated the use of communication-constrained mobile edge computing (MEC) systems for wireless VR. The work in [12] introduced a perception-based mixed-reality video streaming delivery system to provide the aggregate data rates needed for VR services. In [13], the authors proposed a VR model using multi-attribute utility theory to capture the tracking and delay components of VR QoS. Meanwhile, the recent works in [14]–[17] studied the problem of HRLLC for VR networks. For instance, in [14], the authors introduced an MEC-based mobile VR delivery framework that minimizes the average required transmission rate. Meanwhile, the work in [15], studied the challenge of concurrent support of visual and haptic perceptions over wireless cellular networks. The authors in [16] proposed a joint proactive computing and millimeter wave resource allocation scheme for VR under latency and reliability constraints. A novel framework that uses cellular-connected drone aerial vehicles was proposed in [17]. However, the prior works in [13]–[17] only examine the average delays and data rates; thus reflecting limited information about the wireless VR systems analyzed. In contrast, to guarantee HRLLC, it is necessary to obtain the statistics of the delay in order to properly characterize the system’s reliability. Moreover, the works in [13]–[17] do not consider the more challenging reliability problem at high-frequency THz bands. Meanwhile, in [18], the authors investigate fundamental statistical issues related to ultra-reliability of wireless networks. The work in [19] introduced the notion of probably correct reliability (PCR) that is based on the probably approximately correct (PAC)-learning framework in statistical learning. However, while interesting, the works in [18] and [19] define reliability based on an outage event, while ignoring the E2E behavior of the system. Last, but not least, we note that the use of THz has recently attracted significant attention (e.g., see [7], [10], [20]–[22]) as an enabler of high data rate applications. However, these prior works in [7], [10], [20]–[22] do not address issues of reliability or low-latency for wireless VR systems and, thus, they do not shed light on our posed HRLLC hypothesis. In fact, most of these prior THz works primarily focus on physical layer or propagation challenges. Meanwhile, in [23], we have conducted a performance analysis assessing how and when a THz network can meet the reliability, low latency and high data rate requirement. However, our work in [23] does not take into account realistic THz dynamic network conditions as it ignores the effect of self and dynamic blockages and focuses on idealized settings. Clearly, there is a lack in existing works
that study the potential of THz frequencies to deliver HRLLC VR services.

B. Contributions

The main contribution of this paper is a comprehensive performance analysis, in terms of achievable delay, reliability, and rate, for a wireless THz network operating that serves VR users. In order to assess the capability of THz network to meet the dual HRLLC, i.e., high-rate, high-reliability QoS requirements of VR users, we make the following key contributions:

- We introduce a novel VR model based on a Matern hardcore point process (MHCPP). Each VR user sends a request to its respective small base station (SBS) and the E2E delay consists of the delay needed to process the VR images, the queuing delay, and the downlink transmission delay over the THz links.

- Based on this model, to examine the instantaneous reliability of the system, we derive the tail distribution of the E2E delay via its moments, thus characterizing the performance at extreme events and providing insights on THz's potential within a short communication range given its high susceptibility to blockages and molecular absorption. Furthermore, to scrutinize the risk of an unreliable VR user experience at THz, we derive the tail-value-at-risk (TVaR) of the E2E delay based on rigorous tools from extreme value theory (EVT) and economics [24], [25].

- Our analysis shows that the probability of line-of-sight (LoS) at THz frequencies, which is influenced by the density of VR users and their mobility, plays a primary role in characterizing the moments of the E2E delay. These results allow to characterize the tail distribution of the E2E using the instantaneous VR content requests, channel, and blockage parameters. Important insights are offered by the expected worst-case E2E delay, and the confidence level associated with the reliability.

- The asymptotic analysis of reliability is tailored to the unique THz network parameters. It characterizes the E2E delay distribution by finding the cumulative distribution function (CDF) of the E2E delay after deriving the probability distribution function (PDF) of the transmission delay in a dense THz network.

To our best knowledge, this is the first work that analyzes the reliability and latency achieved by VR services over a THz cellular network.

Following these contributions, we answered the question of “Can THz provide high-rate reliable, low latency communication for wireless VR?” as follows:
• For wireless VR services over THz networks, the characterization through quantities related to average delay lead to overly optimistic performance prediction at THz. Instead, tail delays reflect the performance during extreme events, such as a deep fade or a blockage. Analysis of extreme events is fundamental, as the occurrence of any such event during a VR session will lead to a disruption of the quality-of-experience (QoE). Our results show that, during a typical VR session THz the tail of E2E delay can range from 30 ms to 90 ms leading to an unreliable VR experience, even when the average delay is 20 ms. Hence, achieving HRLLC requires new mechanisms that can guarantee LoS link and alleviate the harsh propagation conditions at THz. For example, such is the intelligent environment based on large multiple-input and multiple-output (MIMO) arrays [21], [26]–[28].

• From our results, we observe that increasing the bandwidth and reducing the THz molecular absorption coefficient can reduce the risk of worst-case extreme events, but are not sufficient to sustain a reliable experience. Moreover, guaranteeing a TVaR with confidence levels (i.e. the reliability during extreme events) above 90% is only possible at tail delays of 100 ms, even at a significant bandwidth of 30 GHz.

• One of the most fundamental challenges to THz’s reliability is the availability of LoS component. Overcoming this challenge, ensures that THz can provide HRLLC via network densification and significant bandwidths. In particular, our results show that, if one can ensure that the THz network can continuously operate at LoS a reliability of 99.999% (with an E2E delay threshold of 20 ms) is achievable along with data rates of 18.3 Gbps, thus delivering promising rates to support ultimate VR’s needs.

The rest of the paper is organized as follows. Section II introduces the system model. Sections III and IV, respectively, present the reliability analysis and asymptotic analysis of reliability. Section V presents the simulation results and conclusions are drawn in in Section VI.

II. SYSTEM MODEL

Consider the downlink of a small cell network servicing a set $\mathcal{V}$ of $V$ wireless VR users via a set of small base stations (SBSs) operating at THz frequencies and densely distributed in a confined indoor area according to an isotropic homogeneous MHCPP with intensity $\eta$ and a minimum distance $\epsilon$ [29]. This process is a special thinning of the Poisson point process (PPP) in which the nodes are forbidden to be closer than a minimum distance $\epsilon$, as in practice the distance between adjacent SBSs cannot be arbitrarily small. Hence, this process can adequately capture the distribution of VR SBSs in a confined area. In our network, SBSs can also perform MEC.
functions for VR purposes. As discussed earlier, THz bands are a necessity for advanced and ultimate VR applications, where the creation of artificial environment is not limited to buildings and surroundings, but to real persons, i.e., their facial expressions and gestures [30]. This requires a higher rate than those provided by other high frequency (HF) bands, such as mmWave [1].

### A. Blockage and Interference Model

We consider an arbitrary VR user in V located at a constant distance \( r_0 \) from its serving SBS. The chosen VR user and its serving SBS are referred to as **tagged** receiver and transmitter respectively. The interference surrounding this VR user stems from a set \( M \) of \( M \) non-negligibly interfering SBSs that are located within a radius of \( \Omega \) around this user. Henceforth, SBSs that are at a distance \( r \geq \Omega \) add no interference on the link between the VR user and its associated SBS. \( \Pi \) refers to the region of non negligible interference of the network. It is important to note that interference occurs because we consider a highly dense THz network whose SBSs are located at very close proximity [31]–[33]. Moreover, in such a dense environment, THz bands require a very narrow pencil beamforming (even narrower than mmWave). Such beamforming architectures face major practical challenges given that they require a high available signal-to-interference-
plus-noise-ratio (SINR) link and a narrow beamsteering angle, while providing localization and tracking of the user equipment (UE) [34], [35]. This also leads to higher susceptibility towards mobility, and does not completely solve the interference problem, given the difficulty to perform beam re-alignment in a very short time [36].

Another key challenge facing THz communications in such a dense network is the inability to penetrate solid objects. In fact, the electromagnetic properties of THz are different than conventional bands, i.e., their penetration losses are higher whereas their reflection coefficients are reduced [37]. Subsequently, the susceptibility of THz to blockage jeopardizes its reliability, thus, highlighting the importance of studying the probability of blockage, that further provides insights about the tunable parameters needed to guarantee a LoS link between the SBS and the VR user. Since we consider an indoor setting, two type of blockage are considered: self-blockage and dynamic blockage. Self-blockage arises when a user blocks a fraction of SBSs by its own body. We assume that each user makes an angle $\omega$ with the blocked SBSs $\omega$ determines the orientation of the user and is assumed to be uniformly distributed in $[0, 2\pi]$, as shown in Fig. 1. Thus, the self-blockage zone is defined as the sector of a disc of radius $B$ having an angle $\omega$. Without loss of generality, hereinafter, we assume that $B = \Omega$, i.e., the blockage disc and the region of non-negligible interference coincide, and, thus, we will use $\Omega$ to refer to this region. Thus, an SBS is considered to be self-blocked if it lies in the self-blockage region of the considered VR user. Hence, the probability of self-blockage will be [38]: $P(B_s) = \frac{\omega}{2\pi}$, where

1This behavior is similar to mmWave bands but is more pronounced for THz. For instance, while the molecular absorption effect might be negligible for mmWave frequency bands, it is more significant at THz frequencies and it needs to be taken into consideration.
$B_s$ is a random variable that captures self-blockage event.

The second type of blockage is *dynamic blockage*, which captures the event in which the LoS signal between the considered **VR** user and its corresponding **SBS** is interrupted by other **VR** users. The **VR** users contributing to dynamic blockage are moving in a blockage area of radius $\Omega$ within which a set $Q$ of $q$ **SBSs** are susceptible to blockage. The **VR** users in this region are referred to as *dynamic blockers*, and they are distributed according to a homogeneous **PPP** with density $\nu_B$. The dynamic blockers move in a random direction in this area with velocity $v_B$. Subsequently, the overall dynamic blockage process can be modeled as an M/M/$\infty$ queuing system, as explained in [38]. The first M stands for a Poisson arrival process of blockers with a rate of $\kappa_B$ blockers/sec, and the second M stands for a blockage duration that is assumed to be exponentially distributed with parameter $\nu$ blockers/sec for mathematical simplicity and tractability. The overall dynamic blockage process can be modeled as an alternating renewal process with exponentially distributed periods of blocked and unblocked intervals, similar to [39]. For mathematical tractability while modeling blockage, and given that, in our dense network, the distance between **SBSs** is fairly small, the **MHCPP** can be approximated by an equivalent **PPP** of intensity $\eta_P$, with an approximated probability mass function $P_Q(q) = \frac{(\eta_P \pi \Omega^2)^q}{q!} e^{-(\eta_P \pi \Omega^2)}$.

A simultaneous blockage event by two or more dynamic blockers for the same LoS link is a negligible event, and, thus, it is assumed to be a null event. Let $r \triangleq (r_i)_{i=0,1,\ldots,q}$ be a row vector, where $r_0$ denotes the distance between the VR user and the associated SBS, and $r_i$ denotes the distance between the VR user and the blocked SBS $i \in Q$. The **SBS** distances to the VR user are independently and identically distributed (i.i.d.) with distribution $f(r_i|q) = \frac{2r_i}{\Omega^2}$. Hence, the probability of dynamic blockage is given by [38]: $P(B_d|r_i, q) = \frac{\kappa_B}{\kappa_B r_i + \nu}$. Considering both self and dynamic blockage, the probability of simultaneous blockage of all LoS links is given by:

$$P(B|q, r_i) = \prod_{i=1}^{q} P(B_i|q, r_i) = \prod_{i=1}^{q} [1 - (1 - P(B_s))(1 - P(B_d))] = \prod_{i=1}^{q} (1 - \frac{1}{1 + \frac{\Delta}{r_i}}),$$

where $\Delta$ is the probability that a random **SBS** is not self-blocked and $\Delta = \frac{2}{\pi \nu_B v_B} \frac{(h_B-h_R)}{v_T}$ where $h_B$, $h_R$, and $h_T$ are, respectively, the height of the dynamic blocker, the height of the considered **VR** user, and the height of the **SBS**. Also, $\Delta$ is related to the blockage rate by the following $\Delta = \frac{\kappa_B}{r_i}$. The channel and data rates of THz links are modeled next.

**B. Wireless Model and Data Rate**

As shown in [32], the signal propagation at the THz band is mainly affected by molecular absorption, which results in molecular absorption loss and molecular absorption noise. At the
THz bands, the gap between the LoS and non-line-of-sight (NLoS) links is very significant and much more drastic than at mmWave frequencies. As done in [20], given that the distance between a VR user and its respective SBS is short in our dense network, we consider only the LoS link when modeling the data rate. Consequently, the total path loss affecting the transmitted signal between the SBS and the VR user will be given by [32]:

\[ L(f, r) = L_s(f, r)L_m(f, r) = \left(\frac{4\pi fr}{c}\right)^2 \frac{1}{\tau(f, r)}, \]

where \( L_s(f, r) = \left(\frac{4\pi fr}{c}\right)^2 \) is the free-space propagation loss, \( L_m(f, r) = \frac{1}{\tau(f, r)} \) is the molecular absorption loss, \( f \) is the operating frequency, \( r \) is the distance between the VR user and the SBS, \( c \) is the speed of light, and \( \tau(f, r) \) is the transmittance of the medium following the Beer-Lambert law, i.e., \( \tau(f, r) \approx \exp(-K(f)r) \), where \( K(f) \) is the overall absorption coefficient of the medium. Let \( \mathbf{p} \triangleq (p_i)_{i=0,1\ldots,M} \) be a row vector, where \( p_0 \) represents the transmission power of the SBS servicing the considered VR user, and \( p_i \) represents the transmission power of the interference from any other SBS \( i \in \mathcal{M} \). The total noise power is the sum of the molecular absorption noise and the Johnson-Nyquist noise generated by thermal agitation of electrons in conductors. Consequently, the total noise power at the receiver can be given by [32]:

\[ N(r, p_i, f) = N_0 + \sum_{i=1}^{M} p_i A_0 r_i^{-2}(1 - e^{-K(f)r_i}), \]

where \( N_0 = \frac{W\lambda^2}{4\pi} k_B T_0 + p_0 A_0 r_0^{-2}(1 - e^{-K(f)r_0}) \), \( k_B \) is the Boltzmann constant, \( T \) is the temperature in Kelvin, and \( A_0 = \frac{c^2}{16\pi^2 f^2} \). By accounting for the total path loss affecting the transmitted signal, the aggregate interference will be: \( I(r, p_i, f) = \sum_{i=1}^{M} p_i A_0 r_i^{-2} e^{-K(f)r_i} \). The instantaneous frequency-dependent SINR at LoS will be:

\[ S_L(r, \mathbf{p}, f) = \frac{p_0^{RX}(r_0, p_0, f)}{I(r, \mathbf{p}, f) + N(r, \mathbf{p}, f)}, \]

where \( p_0^{RX} \) is the received power at the VR user from its associated SBS. Substituting each of the received power, noise, and interference terms results in the following SINR:

\[ S_L(r, \mathbf{p}, f) = \frac{p_0 A_0 r_0^{-2} e^{-K(f)r_0}}{N_0 + \sum_{i=1}^{M} p_i A_0 r_i^{-2}}. \]

Hence, with an available LoS link, given that the coherence bandwidth at THz is inherently large due to the delay spread and temporal broadening effects (e.g. 11.5 THz when measured for a distance of 10 cm) as shown in [41] and [42], we will assume that the rate shows an invariant
behavior across the THz bandwidth for all the distances considered. Thus, the instantaneous rate from the tagged SBS to the VR user at LoS can be written as:

\[ C_L(r, p, f) = W \log_2 \left( 1 + \frac{p_0 A_0 \epsilon^{-K(f) r_0}}{N_0 + \sum_{i=1}^{M} p_i A_o r_i^{-2}} \right), \]

where \( W \) is the bandwidth. Subsequently, the total instantaneous rate is given by:

\[ C_T = P(\Lambda)C_L + P(1 - \Lambda)C_N \approx P(\Lambda)C_L. \]

Here, \( C_N \) is the rate of the NLoS link and \( P(\Lambda) \) is the probability of an available LoS link between the SBS and the VR user. The approximation in (6) is based on the significant gap between the power of LoS and NLoS links, thus leading to a negligible rate for the NLoS link.

Note that, \( P(\Lambda) \) is fundamental in our analysis given that it can degrade the rate and affect the QoE of the VR users. Given the probabilities of static and dynamic blockages, in Section III, the probability of LoS will be derived in terms of the network parameters, thus providing an insight on the important factors and towards provision of a more reliable rate.

C. Interference Analysis

From (5), we can see that the only random factor is the second term in the denominator which corresponds to the interfering signals. For technical tractability, following [32], we assume that this term tends to a normal distribution [43]. Note that, it has been shown in [32] that such an approximation is realistic. Furthermore, finding the mean and variance of this term will allow us to characterize the PDF of this random interference signal, as follows:

\[ g(I) = \frac{1}{\sqrt{2\pi} \sigma_I} \exp \left( -\frac{(I - \mu_I)^2}{2\sigma_I^2} \right), \]

where \( \mu_I \) and \( \sigma_I^2 \) are the mean and variance of the interference, respectively, given by [32]:

\[ \mu_I = p A_0 \left( \frac{\ln(\Omega) - \ln(r)}{\Omega^2 - r^2} \right) \left( \frac{\pi \Omega^2 \eta}{2} \right), \quad \sigma_I^2 = (p A_0)^2 \left( \frac{\pi \Omega^2 \eta}{2} \right) \left( \frac{1}{2r^2 \Omega^2} \right), \]

where \( \epsilon \) is the minimum distance of the MHCPP, \( \Omega \) is the region of non-negligible interference, and the subscript \( i \) in \( p_i \) is omitted given that the SBSs are assumed to have the same transmission power. As shown in [32], \( \mu_I \) and \( \sigma_I \) can be derived based on the Poisson approximation for the distances between the tagged receiver and the interferers. The high bandwidth available at the THz band can provide high-rate wireless VR and, thus sustains VR with its promised visual requirement. Moreover, it is necessary to analyze whether this network can provide HRLLC guaranteeing the dual VR requirement and enabling a seamless experience. To scrutinize the performance of the THz reliability in terms of the E2E delay, we perform a rigorous analysis that characterizes the distribution of its tail, thus, outlining the worst-case performance of the
III. RELIABILITY ANALYSIS

In this section, we examine the probability of blockage and use it to derive the tail distribution of the E2E delay. Furthermore, we evaluate the TVaR of the E2E delay to scrutinize the risks pertaining to an unreliable VR experience at the THz band.

A. Blockage Analysis

Given the electromagnetic properties of THz and its susceptibility to blockage, guaranteeing a LoS path link is necessary to provide the promised high THz rate. Therefore, it is necessary to quantify the probability of an available LoS link in terms of the channel parameters, thus, characterizing the conditions needed to boost the QoE of the user. Next, given the static and dynamic blockages modeled, we derive the probability of having an available LoS link:

**Proposition 1.** In the considered network, the probability of LoS is given by:

\[ P(\Lambda) = 1 - \exp\left(\kappa \eta_p \pi \Omega^2\right), \]

where \( \Lambda \) is the event of having a LoS path, and \( \kappa = \frac{2(\nu^2 \ln(|\Delta\Omega + \nu|) - \nu^2 \ln(|\nu|))}{\Delta^2 \Omega^2} - \frac{2\nu}{\Delta \Omega}. \)

**Proof:** See Appendix A.

The probability of LoS in (9) captures the susceptibility of the THz links to blockage as an exponential function of the network parameters. We observe that an increase in the density of the VR blockers or in the region of blockage affects negatively the availability of LoS. Also, the bigger the sector of the disc of self-blockage, the lower the availability of LoS.

B. Delay Analysis

The service model of the VR image request in our wireless VR system is illustrated in Fig. 2. In this model, once a VR user requests a VR image, it goes through two queues: A first queue,
for processing a $360^\circ$ VR image, and a second queue, $Q_2$, for storing and transmitting the VR images over the wireless THz channel. We assume that the time a VR user needs for sending a request is negligible. Hence, for each VR image request, the total delay depends on the waiting and the processing time at $Q_1$ and the waiting time and VR transmission delay at $Q_2$. We consider a Poisson arrival process for the VR image requests with mean rate $\lambda_1$. The buffer of the processor is assumed to be of infinite size and the MEC processor at the SBS adopts a first-come, first-serve (FCFS) policy. The service time for each request follows an exponential distribution with rate parameter $\mu_1 > \lambda_1$, to guarantee the stability of the first queue $Q_1$. Thus, we can model queue $Q_1$ as an M/M/1 queue. According to Burke’s theorem [44], when the service rate is larger than the arrival rate for an M/M/1 queue, then the departure process at steady state is a Poisson process with the same arrival rate. Hence, the arrival of requests to $Q_2$ also follows a Poisson process with rate $\lambda_2 = \mu_1$. Similar to $Q_1$, we assume an infinite buffer size and an FCFS policy for $Q_2$. Note that, the service time of $Q_2$ is the transmission time of the SBS, that depends on the random wireless THz channel, i.e., the size of the VR content, the LoS rate, and its associated probability of LoS. Thus, different from $Q_1$, the second queue $Q_2$ is an M/G/1 queue. Our goal is to study when and how the proposed THz system can guarantee the dual HRLLC QoS requirements of VR, i.e., visual and haptic perceptions. This dual perception requires a high data rate link for visual perception and a low latency communication for the haptic. Under favorable channel conditions, THz is capable of providing high rate links, however, providing HRLLC may be challenging. Hence, our key step is to define the reliability of this system and study the fundamental performance of the VR network in terms of HRLLC requirements. This fundamental performance analysis will shed light on the capability of THz to provide a dual-metric performance for VR: high rate and high reliability.

It is important to note that, reliability cannot be defined merely on average values of delays as done in [2] and [13]. Given the stringent requirements of VR services, a full view on the statistics of the delay must be taken into account in order to design a system capable of withstanding extreme and infrequently occurring events such as a sudden user movement that changes its distance from its respective SBS or a sudden blockage between the user and the SBS which can impact reliability. To analyze reliability, next, we derive the moments of the E2E delay, these moments are further used to derive the tail distribution of the E2E delay, thus
fundamentally characterizing the worst-case performance. Given that any disruption during a VR session will lead to a low QoE analyzing the worst-case is fundamental to our performance analysis. Moreover, based on the expression of the tail distribution, the TVaR will be derived to characterize the value of the E2E delay at the tail, in the presence of a risk of an unreliable user experience.

C. Tail Reliability Analysis

Fundamentally, to guarantee reliability in the face of stochastic and dynamic wireless channels, it is necessary to analyze the instantaneous behavior of the network rather than its average [45]. Furthermore, it is necessary to examine any instantaneous exceedance of the E2E delay above a threshold that disrupts the QoS of the user. Hereinafter, given that VR services call for perceptual and haptic requirements that are directly linked to the QoE of the user; we define the reliability of the VR system as a guarantee that the instantaneous E2E delay can be maintained below a target threshold $\delta$. Formally and according to 3GPP [46], reliability is defined as the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability. Nevertheless, given that our traffic consists of VR content that needs more stringent reliability measures to ensure a seamless experience, we fortify that statement and make it more stringent by defining reliability as the probability that the E2E delay – defined as the delay incurred between the time the VR user requests a VR image to the time the image is received – remains below a stringent threshold $\delta$. Hence, the system is guaranteed to have ultra high reliability when this probability is high and tends to 1. Furthermore, to characterize the instantaneous performance, we will investigate the tail behavior pertaining to the delay distribution, thus studying the performance under the worst-case conditions, i.e., tail analysis will guarantee high reliability for a user experiencing a deep fade or a sudden blockage. Subsequently, we leverage the renowned EVT framework [24] to capture the behavior of the tails and extreme statistics of interest. The EVT theorem is formally defined as:

Definition 1. (Fisher–Tippett–Gnedenko theorem [47]) Given a sequence of i.i.d. variables $\{x_1, \ldots, x_n\}$, the distribution of $M_n = \max\{x_1, \ldots, x_n\}$ representing the maximum value of the sequence converges (for large $n$) toward the generalized extreme value (GEV) characterized by the following CDF and PDF:

$$
F_E(x; \xi_E) = \begin{cases} 
\exp\left(-(1 + \xi_E \frac{x - \mu_E}{\sigma_E})^{-1/\xi_E}\right), & \xi_E \neq 0, \\
\exp\left(-\exp\left(-\frac{x - \mu_E}{\sigma_E}\right)\right), & \xi_E = 0,
\end{cases}
$$

(10)
where \( \xi_E \) is the shape parameter, \( \mu_E \) the location parameter, and \( \sigma_E \geq 0 \) is the scale parameter. Thus for \( \xi > 0 \), the expression is valid for \( \frac{\mu_E - x}{\sigma_E} > -1/\xi \), while for \( \xi < 0 \) it is valid for \( \frac{\mu_E - x}{\sigma_E} < -1/\xi \).

\[
f_E(x) = \begin{cases} (1 + \xi_E)^{(-1/\xi_E) - 1} \exp\left(-\left(1 + \xi_E \frac{\mu_E - x}{\sigma_E}\right)^{-1/\xi_E}\right), & \xi_E \neq 0, \\ \exp\left(-\frac{\mu_E - x}{\sigma_E}\right) \exp\left(-\exp\left(-\frac{\mu_E - x}{\sigma_E}\right)\right), & \xi_E = 0. \end{cases}
\] 

(11)

In our model, the sequence of i.i.d. variables corresponds to the sequence of E2E delays experienced by the VR user; subsequently, this theorem paves the way to characterize the distribution of the maximum E2E delay that the VR user can experience, and hence the worst-case scenario. Consequently, next, we perform moment matching to match the moments of the GEV distribution to those of the moments of the E2E delay over our THz network. First, for our model in Fig. 2, given that \( Q_1 \) is an M/M/1 queue, the mean of the total waiting time at \( Q_1 \) will be \( E[T_1] = \frac{1}{\mu_1 - \lambda_1} \). Moreover, given that \( Q_2 \) is an M/G/1 queue, the mean of the total waiting time is given by:

\[
E[T_2] = \left[ \left( \frac{\rho_2}{1 - \rho_2} \right) C_\alpha^2 + \frac{1}{2} \right] E[\alpha],
\]

(12)

where \( \rho_2 = \frac{\lambda_2}{\mu_2} \) is the queue utilization, \( \alpha \) is the transmission delay, and \( C_\alpha^2 = \frac{\vartheta(\alpha)}{E[\alpha]} \) is the squared coefficient of variation. Next, we evaluate the mean of the E2E delay. This mean constitutes the first moment, that is then used to perform a moment matching between our empirical E2E delay moments and the GEV distribution, to finally characterize the tail distribution.

**Theorem 1.** The mean of the E2E delay is given by:

\[
E[T_1 + T_2] = \frac{1}{\mu_1 - \lambda_1} + \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{1}{W \log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f) \gamma_0}}{N_0 + \mu_f} \right)} \right) \right] E[\alpha] + 1,
\]

(13)

where \( E[\alpha] \approx \frac{L}{1 - \left( \frac{e^{\pi Z} - 1}{\pi Z} \right) \left( \log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f) \gamma_0}}{N_0 + \mu_f} \right) \right)} \), \( Z = \eta \eta \Omega^2 \).

**Proof:** See Appendix B.

From (13), we can see that the average E2E delay is equally influenced by the mean of the total waiting time in \( Q_1 \), the utilization of \( Q_2 \), and the mean of the transmission delay \( \alpha \) (and thus the THz environment). The waiting time in \( Q_1 \) is mainly influenced by the number of VR requests and the processing speed of the MEC server, which are beyond the control of the wireless network. Meanwhile, the transmission delay depends on the average blockage rate (which in turn is the complement of \( P(\Lambda) \) derived in (9) in Proposition 1) and the average THz
data rate. Clearly, the density of VR users, their mobility, and their requests for VR content all play a role in the average behavior of the network. Next, we derive the second moment of the $E2E$ delay, thus allowing us later to capture the $GEV$ of the $E2E$ delay and examine the instantaneous $E2E$ delay and its consequent effect on the QoE.

**Lemma 1.** The second moment of the $E2E$ is given by:

$$
\mathbb{E}[(T_1 + T_2)^2] = \left( \frac{2}{\mu_1 - \lambda_1} \right)^2 \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{1}{W\log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f)r_0}}{N_0 + \mu I} \right)} \right) V_a(Z) + 1 \right] + 1 \mathbb{E}[\alpha] + 2 \left( \frac{\mu_1 - \lambda_1}{\mu_1 - \lambda_1} \right)^2 + \mathbb{E}[\alpha^2] + \frac{\rho_2 \mathbb{E}[\alpha^3]}{3(1 - \rho_2)} + \frac{\rho_2 \mathbb{E}[\alpha^2]}{2(1 - \rho_2)} + \frac{\rho_2}{2(1 - \rho_2)} \left( \frac{\mathbb{E}[\alpha^2]}{\mathbb{E}[\alpha]} \right)^2.
$$

(15)

Proof: See Appendix C.

Having the first and second moment in (13) and (15) of the $E2E$ allows us to and characterize the moments of the highest order statistics of the $E2E$ delay to finally characterize the tail distribution. To do so, in what follows, we first order the set of $E2E$ delays and arrange them in an increasing order of magnitude. Subsequently, we model the tail of the $E2E$ delay to be the highest order statistic, i.e., the maximum of the set. Given that we have obtained the first and second moments of the parent distribution of the $E2E$ delay, we need to express the first and second moments of the highest order statistic in terms of the expectations formulated in Theorem 1 and Lemma 1. Thus, from (48), given the mean and variance of the parent distribution, we can find the highest order statistics expectation as:

$$
\mathbb{E}[(T_1 + T_2)_n] \approx \mathbb{E}[(T_1 + T_2)] + \frac{(n - 1) \vartheta (T_1 + T_2)}{(2n - 1)^{1/2}}.
$$

(16)

Given (16), next, we characterize the $GEV$ distribution of the tail after performing a moment matching and deriving its defining parameters.

**Theorem 2.** The tail distribution of the $E2E$ follows a $GEV$ distribution with a location, scale and shape parameter given by:

$$
\mu_E = \left( \frac{1}{\mu_1 - \lambda_1} \right)^2 \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{1}{W\log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f)r_0}}{N_0 + \mu I} \right)} \right) V_a(Z) + 1 \right] + 1 \mathbb{E}[\alpha].
$$

(17)
\[
\sigma_E^2 = \frac{1}{\mu_1 - \lambda_1} + \mathbb{E}[\alpha^2] + \frac{\rho_2 \mathbb{E}[\alpha^3]}{3(1 - \rho_2)} + \frac{\rho_2 \mathbb{E}[\alpha^2]}{2(1 - \rho_2)} + \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{\mathbb{E}[\alpha^2]}{\mathbb{E}[\alpha]} \right) \right]^2 \\
- \left( \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{1}{W \log_2 \left( 1 + \frac{p_0 A_0 n^2 e^{-K(f) r_0}}{N_0 + \mu I} \right)} \right)^2 V_a(Z) + 1 \right) \mathbb{E}[\alpha] \right)^2.
\]

\[
\xi_E / \Gamma(1 - \xi_E) - 1 = \frac{(2n - 1)^{1/2}}{(n - 1)}.
\]

**Proof:** See Appendix D.

Theorem 2 allows us to tractably characterize the tail of the distribution \(E2E\), i.e., the worst case distribution over all all of the possible outcomes of randomness rather than just an average value. Moreover, interestingly the tail distribution’s location \(\mu_E\) is the average of the \(E2E\) delay. Thus, the distribution of the tail of the \(E2E\) is centered around the mean of the \(E2E\) delay. Moreover, the scale of the distribution is the variance of the \(E2E\) delay. We can see that the tail variance is highly influenced by the first three moments of the THz data rate, thus characterizing the susceptible THz behavior to the dynamic environment. As for the shape, it depends on the number of VR requests in each VR session. Therefore, the moments of the \(E2E\) delay mirror variations of lower order statistics to obtain the highest order statistic distribution.

By obtaining the tail statistics and its distribution, we can further quantify the \(E2E\) value given a specific level of risk of unreliable experience. In other words, we define the notion of risk based on its confidence level: a confidence level of 99% means that we are 99% sure that the worst-case delay will not exceed a specific value. Clearly, examining tail distributions not only characterizes the worst-case scenario but also provides guarantees through risk measures, thus providing more leverage for HRLLC. To formulate these risk measures, in actuarial sciences, the value-at-risk (VaR) concept is defined as a quantile of the distribution of aggregate losses, \(\text{VaR}_{1 - \alpha} = - \inf_{t \in \mathbb{R}} \{ P(X \leq t) \geq 1 - \alpha \} \) [49]. However, VaR is an incoherent risk measure, making its analysis intractable. TVaR, on the other hand, is defined to be the expected loss conditioned on the loss exceeding the VaR [50]. Thus, TVaR not only measures the risk but also quantifies its severity, making it a superior risk measure. In our context, the TVaR allows us to scrutinize the tail of the \(E2E\) delay, at a given confidence level. Thus, if the instantaneous \(E2E\) delay follows a PDF \(\Phi(t)\), such that the \(E2E\) delay does not exceed a certain threshold \(\gamma\), we

\[3\text{A coherent risk measure is a metric that satisfies properties of monotonicity, sub-additivity, homogeneity, and translational invariance.}\]
can define the risk of an unreliable QoE to be related to the VaR as follows:

\[
\int_\gamma^\infty \Phi(t)dt = 1 - \alpha_C, \text{ where } \text{VaR}(\alpha_C) = \gamma.
\]

Subsequently, we define \( \chi \) to be the right-tail TVaR to be defined as:

\[
\chi = \frac{1}{1 - \alpha_c} \int_\gamma^\infty t\Phi(t)dt
\]  \( (20) \)

Given our knowledge about the GEV distribution, the TVaR for our network can be formally expressed in the following corollary (which follows directly from Theorem 2).

**Corollary 1.** The TVaR of the E2E \( T_e \) delay is given by:

\[
\chi = \mu_E + \frac{\sigma_E}{(1 - \alpha_C)\xi_E} \left[ \gamma \left(1 - \xi_E, -\log(\alpha_C)\right) - (1 - \alpha_C) \right],
\]

\[
= \mathbb{E}[T_e] + \frac{\vartheta(T_e)^{1/2}}{(1 - \alpha_C)\xi_E} \left[ \gamma \left(1 - \xi_E, -\log(\alpha_C)\right) - (1 - \alpha_C) \right],
\]  \( (21) \)

where \( \gamma \) is the lower incomplete gamma function defined by

\[
\gamma(s,x) = \int_0^x t^{s-1}e^{-t}dt
\]

As seen from (21), the TVaR is a tractable expression that is a function of the first and second moment of the E2E delay. These moments bring to view the fastness and robustness of THz frequency bands and the MEC server in a dynamic VR environment. Based on these moments, the TVaR provides us with the expected E2E delay conditioned on the E2E delay exceeding a specific threshold. In other words, it helps shed light on the severity of exceeding the threshold, by quantifying the expectation of the tail distribution. Thus, considering the TVaR allows us to provide the user a seamless experience with a reliability in the order of its confidence level. A confidence level of \( \alpha_C \) guarantees the maximum E2E delay to be below that threshold, \( \alpha_C \)-th of the time.

Next, we perform an asymptotic analysis for reliability under idealized conditions in which we assume the probability of LoS to be equal to 1.

**IV. RELIABILITY FOR SCENARIOS WITH GUARANTEED LOS**

Hereinafter, we assume the probability of LoS to be equal to 1, i.e., a continuous LoS is available to the VR user. Thus, this facilitates our model further making it feasible to analyze true CDFs and PDFs of the delay instead of relying on tail distributions. This special case scenario is meaningful given that it portrays cases where the number of active VR users is significantly low in the indoor area and where the user’s orientation does not vary rapidly. Subsequently, for our model in Fig. 2 given that \( Q_1 \) is an M/M/1 queue, the PDF of the total waiting time at \( Q_1 \) will be [44]:
\[ \psi_1(t) = (\mu_1 - \lambda_1) \exp\left(- (\mu_1 - \lambda_1)t\right). \]  \hfill (22)

Given that \( Q_2 \) is an M/G/1 queue and that the queuing and service time of an M/G/1 queue are independent, we find the CDF of the total waiting time:

\[ \Psi_2(t) = \Psi_{Q_2}(t) * \psi_T(t), \]  \hfill (23)

where \( \ast \) is the convolution operator, \( \Psi_{Q_2}(t) \) is the CDF of the queuing time at \( Q_2 \) and \( \psi_T(t) \) is the PDF of the transmission delay. The CDF of the total queuing time at \( Q_2 \) will be [44]:

\[ \Psi_{Q_2}(t) = (1 - \rho_2) \sum_{n=0}^{\Gamma} \left[ \rho_2^n R^{(n)}(t) \right], \]  \hfill (24)

where \( \lambda_2 \) and \( \mu_2 \) are, respectively, the arrival and average transmission rates of \( Q_2 \). Here, \( \Gamma \) is the number of states that the queue has went through, i.e., the number of packets that has passed through the queue during a certain amount of time and \( R^{(n)}(t) \) is the CDF of the residual service time after the \( n \)-th state. Note that \( R^{(n)}(t) \) can be computed by obtaining the residual service time distribution \( R(t) \) after \( n \) packets, \( R(t) = \int_0^t \mu_2 (1 - \psi_T(x)) dx \), where \( t \) is the time of an arbitrary arrival, given that the arrival occurs when the server is busy. To evaluate the PDF of the E2E delay, we need the PDF of the transmission delay which is found next:

**Lemma 2.** The PDF of the transmission delay is given by:

\[ \psi_T(\alpha) = \frac{\zeta}{\sqrt{2\pi\sigma_I}} \exp\left(- \frac{(\Upsilon - \mu_I)^2}{2\sigma_I^2}\right), \]  \hfill (25)

where

\[ \zeta = \ln \left( \frac{2}{p_{RX}^0} \right) \frac{W\alpha}{W\alpha^2 - 1}, \quad \Upsilon = \frac{(1 - 2p_{RX}^0)N_0 + p_{RX}^0}{2p_{RX}^0 - 1}. \]  \hfill (26)

**Proof:** See Appendix E.

It is important to note that the PDF in (49) does not follow a normal distribution since both \( \Upsilon \) and \( \zeta \) depend on the transmission delay \( \alpha \). Burke’s Theorem allows us to infer that \( Q_1 \) and \( Q_2 \) are independent, and, thus, the CDF of the E2E delay can be expressed as the convolution of the PDF of the total waiting time in \( Q_1 \) and the CDF of the total waiting time in \( Q_2 \). By using the dynamics in (22) and (23), the CDF of the E2E delay can formally expressed in the following theorem which is a direct result of Lemma 1.

**Theorem 3.** The CDF of the E2E delay \( T_e \) is given by:

\[ \Phi(t) = P(T_e \leq t) = \psi_1(t) * \Psi_2(t) = \psi_1(t) * (\Psi_{Q_2}(t) * \psi_T(t)) \]

\[ = (\mu_1 - \lambda_1) \exp(- (\mu_1 - \lambda_1)t) * \left( (1 - \rho) \sum_{n=0}^{\Gamma} \left( \rho \Gamma R^{(n)}(t) \right) * \left( \frac{\zeta}{\sqrt{2\pi\sigma_I}} \exp\left(- \frac{(\Upsilon - \mu_I)^2}{2\sigma_I^2}\right) \right) \right). \]
Consequently, the reliability with respect to a certain threshold $\delta$, is given by:

$$\rho = P(T_e \leq \delta) = \Phi(\delta).$$  \hspace{0.5cm} (27)

The reliability defined in (27) provides a tractable characterization of the reliability of the VR system shown in Fig. 1, as function of the THz channel parameters. For instance, from Theorem 3, we can first observe that the queuing time of $Q_2$ depends on the residual service time CDF and, thus, on the transmission delay. Also, given that the processing speed of a MEC server can be considerably high, the E2E delay will often be dominated by the transmission delay over the THz channel. In general, all the key parameters that have a high impact on the transmission delay will have a higher impact on reliability. One of the most important key parameters is the distance $r_0$ between the VR user and its respective SBS; this follows from the fact that the molecular absorption loss gets significantly higher when the distance increases, which limits the communication range of THz SBSs to very few meters. Indeed, the THz reliability will deteriorate drastically if the distance between the VR user and its respective SBS increased. Also, in this special case, the PDF of the E2E delay is tractable. Thus, providing the full statistics of the E2E delay without having to examine averages and tails to scrutinize the risks pertaining to reliability. In other words, the PDF of the E2E delay provides us with generalizable information, reflecting the overall behavior of reliability in this model. Hence, while the tail reliability analyzed in Section III is mostly threatened by the probability of blockage, in this scenario, the challenges that need to be addressed to provide a robust reliability are the short communication range as result of the molecular absorption effect, and the interference stemming from the high network density. Moreover, given the QoS of a VR application is a function of the reliability, i.e., it is the reliability of the system throughout the worst case scenario. VR users’ immersion and experience will depend significantly on the reliability. Therefore, maintaining reliability is a necessary condition to guarantee the QoS for the user, thus increasing its satisfaction and yielding it a seamless experience.

V. Simulation Results and Analysis

For our simulations, we consider the following parameters: $T = 300 \text{ K}$, $p = 1 \text{ W}$, $L = 10 \text{ Mbits}$, $f = 1 \text{ THz}$, $K(f) = 0.0016 \text{ m}^{-1}$ (unless stated otherwise) with 1% of water vapor molecules as in [51]. Pertaining to $Q_1$, we consider $\lambda_1 = 0.1 \text{ packets/s}$, and $\mu_1 = 2 \text{ Gbps}$, these values are chosen to comply with existing VR processing units such as the GEFORCE RTX 2080 Ti [52]. The SBSs are deployed in an indoor area modeled as a square of size $20 \text{ m} \times 20 \text{ m}$. All statistical results are averaged over a large number of independent runs. In what follows,
we compare how the realistic scenario, i.e., when considering blockages in Section II, contrasts with the asymptotic analysis we have performed in Section IV where LoS is always guaranteed.

Fig. 3a shows that the simulation results match the distribution of the analytical result derived in Theorem 2. The small mismatch between the analytical and simulation results stems from the use of Jensen’s inequality. We can see that the tail of E2E delay is centered around 40 ms, but can reach up to 100 ms. Moreover, Fig. 3b shows that the simulation results match the distribution of the analytical result derived in (25). The small gap between the analytical and simulation results stems from the use of the normal distribution assumption for the interference. Here, we can see how that the transmission delay is low, i.e., it is, i.e., centered at 0.75 ms, owing to the high data rates at THz frequency bands.

Fig. 4 shows how each of the average, instantaneous, and tail E2E delays experienced by the user during a VR session, vary, respectively. We can see that the average E2E delay provides a positive viewpoint of the reliability of THz as its upper bound is limited by 20 ms. Moreover, for the instantaneous E2E delay, we can see how a single extreme event (a sudden blockage)
throughout the VR session can suddenly disrupt the VR experience. This is why, it is important to model the distribution of tails characterizing these extreme events. In that prospect, Fig. 4c shows a negative perspective of reliability, as the tails are lower bounded by an E2E delay of 30 ms, i.e., any extreme event will lead to a minimum E2E delay of 30 ms, thus leading to a sudden disruption of the user’s experience. Clearly, Fig. 4 reveals that average designs overlook extreme events that disrupt real-time experiences. Therefore, it is important to provide solutions that particularly improve the tail performance of THz, given that on average reliability is high.

To assess the reliability of the tails, Fig. 5a shows how the TVaR varies with respect to the confidence level $\alpha$. We can observe that while it is fairly easy to guarantee tail delays with a confidence of 80% at 30 ms, yet it is very difficult to tame low E2E tail delay with a risk percentile above 90%. In fact, at a confidence level of 99%, the tail E2E delay becomes as high as 450 ms, compared to 63 ms at a confidence level of 90%. Moreover, Fig. 5b shows the effect of bandwidth on the TVaR at a confidence level of 95%: Increasing the bandwidth reduces the risk of the occurrence of extreme events. Nevertheless, given the susceptibility of THz to the dynamic network conditions, increasing the bandwidth remains limited by a best-case TVaR of 100 ms.

Fig. 6a shows the prominent effect of the bandwidth on the delays of $Q_1$ and $Q_2$, in presence of blockages and for the idealized, guaranteed LoS scenario. We can see that, in both cases, increasing the bandwidth ensures a reliable performance, but remains limited by the processing speed at the MEC server. Nevertheless, considering blockages increases $Q_2$ delay on average from 0.3 ms to 4 ms at a bandwidth of 20 GHz. Therefore, in presence of blockage, increasing the bandwidth (as significant as 30 GHz) is not sufficient to guarantee a high reliability. In particular, Fig. 6b shows that the reliability of THz is limited to 68% and 96% for a target delay

---

**Figure 5**: TVaR Performance (a) TVaR versus $\alpha$, (b) TVaR versus bandwidth with $\alpha = 95\%$. 

---

(a)  

(b)
of $\delta = 10\text{ ms}$, $\delta = 20\text{ ms}$ at a significant bandwidth of $30\text{ GHz}$. In contrast, in the guaranteed LoS scenario, we need a bandwidth of $15\text{ GHz}$ to achieve a reliability of $99.999\%$, thus reducing significant spectrum resources when LoS is available, this also corresponds to a data rate of $18.3\text{ Gbps}$.

Fig. 7a shows the effect of the molecular absorption coefficient on the E2E delay, we can see that with a guaranteed LoS, the E2E delay increases monotonically with the molecular absorption. Nevertheless, when blockages are considered, the THz electromagnetic properties make it more susceptible to the dynamic environment as the molecular absorption coefficient increases, thus, increasing the occurrence of signal disruptions and leading to fluctuations as the molecular absorption increases. Moreover, we can see in Fig. 7b that the molecular absorption has a more pronounced effect on the reliability of the system when considering blockages, this is observed regardless of the reliability threshold $\delta$. Clearly, for a threshold $\delta = 10\text{ ms}$, the availability of LoS improves the reliability by $13\%$ (from $70\%$ to $83\%$).

Fig. 8 shows how the reliability varies as a function of the region of non-negligible interference,
Figure 8: Reliability for Guaranteed LoS versus region of non-negligible interference

in the guaranteed LoS scenario. We can see that, when the distance between the VR user and the SBS increases, the region of non-negligible interference $\Omega$ has a higher impact on the reliability, and the drop of reliability is sharper. This phenomenon is observed regardless of the reliability threshold $\delta$. Hence, even though the user can achieve high reliability, the dependence of the molecular absorption on distance limits the user to a very short distance to its respective SBS. Thus, the VR user can be guaranteed reliability regardless of the interference surrounding it, given that it is at a proximity of the respective SBS.

VI. CONCLUSION

In this paper, we have studied the feasibility of ensuring reliability of VR services in the THz band. To obtain an expression for the E2E delay and reliability, we have proposed a model based on a two tandem queue, in which we have derived the tail distribution of the E2E delay via its lower order moments. Subsequently, we have derived the TVaR of the E2E delay tail, characterizing the worst case scenario. Furthermore, we have conducted an asymptotic analysis where we derived the PDF of the transmission delay of a THz cellular network, based on which, we have derived the E2E delay expression along with the reliability of this system. We particularly have made the following observations regarding the reliability of THz networks:

- While it is necessary to increase the bandwidth and operate at regions of low molecular absorption, e.g., indoor areas, to provide a reliable experience; extreme events resulting from the unavailability of LoS links, disrupt the user’s QoE and increase the E2E delay significantly.
- Performance analyses based on the tail of E2E delays are fundamental to characterize the THz performance, given the insights it provides on extreme events. In that regard,
guaranteeing a LoS is of primary importance to improve the tail performance. It is thus necessary to explore directions that optimize, and increase the availability of LoS links in THz. One potential solution could be the deployment of reconfigurable intelligent surfaces (RIS) as done in our work in [26].

- After guaranteeing a LoS availability, the THz reliability remains impeded by factors such as the short communication range due to the molecular absorption effect and the interference arising due to the high network density. Consequently, it is necessary to explore new predictive mechanisms that can handle the large-scale nature of a wireless network and that is reliable in face of high uncertainty and extreme network conditions.

**APPENDIX**

**A. Proof of Proposition 1**

**Proof:** Given the probability of simultaneous blockage of all LoS paths, the conditional probability of LoS is given by:

\[ P(\Lambda|q, r_i) = 1 - \prod_{i=1}^{q} \left(1 - \frac{1}{1 + \Delta r_i} \right). \quad (28) \]

Subsequently, we need to find the marginal probability of one LoS path:

\[ P(\Lambda|q) = \int_{r_i} P(\Lambda|q, r_i) f(r_i|q) dr_1 \ldots dr_q = \int_{r_i} 1 - \prod_{i=1}^{q} \left(1 - \frac{1}{1 + \Delta r_i} \right) f(r_i|q) dr_1 \ldots dr_q. \]

Given that the SBS distances from the VR users are identically and independently distributed, we can rewrite \( f(r_i|q) = f(r_1) \ldots f(r_q|q) = (f(r|q))^q \), thus:

\[ P(\Lambda|q) = \int_{r=0}^{\Omega} \left[ 1 - \prod_{i=1}^{q} \left(1 - \frac{1}{1 + \Delta r_i} \right) \right] \prod_{i=1}^{q} \frac{2r_i}{\Omega^2} dr, \]

\[ = \prod_{i=1}^{q} \left[ \left( \int_{r=0}^{\Omega} \frac{2r}{\Omega^2} dr \right) - \left( \int_{r=0}^{\Omega} \frac{2r}{\Omega^2} \left(1 - \frac{1}{1 + \Delta r} \right) dr \right) \right], \]

\[ = \left( \int_{r=0}^{\Omega} \frac{2r}{\Omega^2} \right)^q - \left( \int_{r=0}^{\Omega} \frac{2r}{\Omega^2} \left(1 - \frac{1}{1 + \Delta r} \right) dr \right)^q. \]

The second term on the right hand side (without taking it to the power \( q \)) can be computed as:

\[ A = \int_{r=0}^{\Omega} \frac{2r}{\Omega^2} \left(1 - \frac{1}{1 + \Delta r} \right) dr = \frac{2 \left( \frac{\nu^2 \ln(|\Delta \Omega + \nu|)}{\Delta^2} + \frac{\Omega^2}{2} - \frac{\nu \Omega}{\Delta} - \frac{\nu^2 \ln(|\nu|)}{\Delta^2} \right)}{\Omega^2}. \]

Simplifying further we get,

\[ A = \frac{2 \left( \nu^2 \ln \left(|\Delta \Omega + \nu| \right) - \nu^2 \ln \left(|\nu| \right) \right)}{\Delta^2 \Omega^2} - \frac{2 \nu \ln \left(|\nu| \right)}{\Delta \Omega} + 1. \]
Consequently, \( P(\Lambda|q) = 1 - (1 + \varpi)^q \), where:
\[
\varpi = \frac{2(\nu^2 \ln(|\Delta \Omega + \nu|) - \nu^2 \ln(|\nu|))}{\Delta^2 \Omega^2} - \frac{2\nu}{\Delta \Omega}.
\] (29)

Finally, to find the marginal probability of \( \text{LoS} P(\Lambda) \):
\[
P(\Lambda) = \sum_{q=0}^{\infty} P(\Lambda|q) P(\Lambda) = \sum_{q=0}^{\infty} \left[ (1 - (1 + \varpi)^q) \frac{(\eta P \pi \Omega^2)^q}{q!} e^{-(\eta P \pi \Omega^2)} \right] = 1 - \exp(\varpi \eta P \pi \Omega^2).
\]

\text{B. Proof of Theorem 1}

\text{Proof:} Based on (5), we express the transmission delay in terms of the VR image size \( L \), \( C_L \), and \( \alpha \), as follows:
\[
\alpha = \frac{L}{P(\Lambda)C_L}, \quad \mathbb{E}[\alpha] = \frac{E(L)}{E(P(\Lambda)C_L)} \{ 1 - \frac{\text{Cov}(L, P(\Lambda)C_L)}{E(L)E(P(\Lambda)C_L)} + \frac{\partial(P(\Lambda)C_L)}{E(P(\Lambda)C_L)^2} \},
\] (30)
where the \( \partial \) operator is the variance and \( \text{Cov} \) is the covariance.

Since the VR image size is constant, and that \( P(\Lambda) \) and \( C_L \) are independent, we have: \( \mathbb{E}[\alpha] = \frac{L}{E[P(\Lambda)|E[C_L]]} \). Thus, we can now compute the expected value of \( P(\Lambda) \) and \( C_L \) respectively
\[
\mathbb{E}[P(\Lambda)] = \int_0^{2\pi} \left( 1 - \exp \left( (1 - \frac{\omega}{2\pi}) Z \pi \right) \right) \frac{1}{2\pi} d\omega = 1 - \left( \frac{e^{\pi Z} - 1}{\pi Z} \right),
\] (31)
where \( Z = \varpi \eta P \pi \Omega^2 \). Based on (5), the \( P(\Lambda) \) acts as a discount factor for the LoS rate. The LoS rate expression has only one random term in (30) which is the interference that follows a normal distribution. Subsequently, the rate is a convex function with respect to interference, and, hence, using Jensen’s inequality \( C_L(\mu_I) \leq \mathbb{E}[C_L(I)] \). As a result, given that the transmission delay is a concave function of the interference, the previous inequality sign is reciprocated. Consequently,
\[
\mathbb{E}[\alpha] \leq \frac{L}{1 - \left( \frac{e^{\pi Z} - 1}{\pi Z} \right) \left( W \log_2 \left( 1 + \frac{p_0 A \eta \pi}{N_0 + \mu} \right) \right)}.
\] (32)

Next, we need to find the variance of the transmission delay. Given that \( L \) is constant, and that \( P(\Lambda) \) and \( C_L \) are independent, according to the first-order Taylor approximation:
\[
\partial \left[ \frac{L}{P(\Lambda)C_L} \right] \approx \frac{E[L]^2}{E[P(\Lambda)C_L]^4} \partial [P(\Lambda)C_L], \quad \partial(P(\Lambda)C_L) = \mathbb{E}[P(\Lambda)^2 \mathbb{E}[C_L^2] - \mathbb{E}[P(\Lambda)]^2 \mathbb{E}[C_L]^2].
\]

We now compute the second moments of \( P(\Lambda) \) and \( C_L \):
\[
\mathbb{E}[P(\Lambda)^2] = \int_0^{2\pi} \left( 1 - \exp \left( (1 - \frac{\omega}{2\pi}) Z \pi \right)^2 \right) \frac{1}{2\pi} d\omega = 1 + \frac{e^{2\pi Z} - 4e^{\pi Z} + 3}{2\pi Z}.
\] (33)

Similarly to the first moment, the rate squared as a function of interference is convex; using Jensen’s inequality \( C_L^2(\mu_I) \leq \mathbb{E}[C_L^2(I)] \). Consequently, the transmission delay squared is a concave function of the interference, this reciprocates the previous inequality. Hence,
Moreover, to find the second moment of the E2E delay, we can first derive the second moment of the total waiting time of \( Q_1 \) as such, given that it is an M/M/1 queue: \( \mathbb{E}[T_1^2] = \frac{2}{(\mu_1 - \lambda_1)^2} \).

Moreover, to find the second moment of \( Q_2 \), we first need to express the Laplace-Stieltjes transform of the total waiting time. This transform is given by [53]:

\[
F_{T_2}^*(s) = \frac{(1 - \rho_2) F_\alpha^* (s)}{1 - \rho_2 \left( 1 - F_\alpha^* (s) \right)/s \mathbb{E} [\alpha]},
\]

(38)
By applying L'Hôpital's rule twice on the second term of $B(s)$:

$$F_{T_2}^*(s) = \frac{A(s)}{1 - \rho_2} \frac{(1 - \rho_2)F_\alpha^*(s)}{1 - \rho_2 \frac{1-F_\alpha^*(s)}{E[\alpha]}}.$$  \hfill (39)



$$\left( F_{T_2}^* \right)'' = \frac{(A'B' - B'A)B^2 - 2BB'(A'B - B'A)}{B^4},$$  \hfill (40)

$$\lim_{s \to 0} A(s) = (1 - \rho_2), \quad \lim_{s \to 0} \frac{d}{ds} A(s) = -(1 - \rho_2)E[\alpha], \quad \lim_{s \to 0} \frac{d^2}{ds^2} A(s) = (1 - \rho_2)E[\alpha^2].$$

By applying L'Hôpital's rule on the second term of $B(s)$:

$$\lim_{s \to 0} B(s) = (1 - \rho_2) \lim_{s \to 0} \left[ \frac{E[\alpha]}{E[\alpha]} \right] = (1 - \rho_2).$$

By applying L'Hôpital's rule twice on $\frac{d}{ds} B(s)$ and three times on $\frac{d^3 B(s)}{ds^3}$:

$$\lim_{s \to 0} \frac{d}{ds} B(s) = -\rho_2 \frac{E[\alpha^2]}{2E[\alpha]}, \quad \lim_{s \to 0} \frac{d^2}{ds^2} B(s) = -\rho_2 \frac{E[\alpha^3]}{3},$$

$$E[\alpha^2] \approx \frac{L^2}{1 + e^{2\pi Z - 4e^{\pi Z} + 3} \left( W \log_2 \left( 1 + \frac{p_0 A_0 - e^{-K(f)r_0}}{N_0 + \mu_I} \right) \right)^2},$$

$$E[\alpha^3] \approx \frac{L^3 6\pi z}{(2e^{3\pi z} - 9e^{2\pi z} + 18e^{\pi z} - 6\pi z - 11) \left( W \log_2 \left( 1 + \frac{p_0 A_0 - e^{-K(f)r_0}}{N_0 + \mu_I} \right) \right)^3}.$$  

Finally, we replace all the derivatives in (40), thus obtaining after mathematical manipulation:

$$E[T_2^2] = (F_{T_2}^*(s))'' = E[\alpha^2] + \frac{\rho_2 E[\alpha^3]}{3(1 - \rho_2)} + \frac{\rho_2 E[\alpha^2]}{2(1 - \rho_2)} + \left[ \frac{\rho_2}{2(1 - \rho_2)} \left( \frac{E[\alpha^2]}{E[\alpha]} \right) \right]^2.$$  \hfill (41)

Hence, we substitute the second moment of the second queue in the expression of the $E[2E]$ delay. According to Burke's Theorem, $Q_1$ and $Q_2$ are independent thus their corresponding waiting times are also independent. The $E[2E]$ is thus given by:

$$E[(T_1 + T_2)^2] = E[T_1^2] + E[T_2^2] + 2E[T_1]E[T_2]$$

$$= \frac{2}{(\mu_1 - \lambda_1)^2} + \left( \frac{2}{\mu_1 - \lambda_1} \right) \left[ \frac{\rho_2}{2(1 - \rho_2)} \left( \frac{1}{W \log_2 \left( 1 + \frac{p_0 A_0 - e^{-K(f)r_0}}{N_0 + \mu_I} \right) \left( V_0(Z) + 1 \right) + 1} \right) \right] + \left( \frac{\rho_2}{2(1 - \rho_2)} \right) \left( \frac{E[\alpha^2]}{E[\alpha]} \right)^2$$  \hfill (42)
D. Proof of Theorem 2

Proof: Given that the support of the delay is positive, the support of the GEV needs to be positive as well, thus \( \xi_E > 0 \). Consequently, we can find the first moment of the GEV:

\[
\mathbb{E}[(T_1 + T_2)_n] = \mu_E + \sigma_E \frac{\Gamma(1 - \xi_E) - 1}{\xi_E} \tag{43}
\]

Comparing (16) and (43), we can recognize by identification the following parameters of the tail of the E2E delay:

\[
\frac{\xi_E}{\Gamma(1 - \xi_E) - 1} = \frac{(2n - 1)^{1/2}}{(n - 1)}, \tag{44}
\]

\[
\mu_E = \mathbb{E}[T_e], \quad \sigma_E = (\vartheta(T_e))^2 = (\mathbb{E}[(T_1 + T_2)^2] - \mathbb{E}[T_1 + T_2]^2)^{1/2}. \tag{45}
\]

where \( n \) is the number of samples of collected E2E delays, and \( T_e = T_1 + T_2 \) is the E2E delay. After some mathematical manipulations to the moments obtained in Theorem 1 and Lemma 1, we obtain:

\[
\mu_E = \frac{1}{\mu_1 - \lambda_1} + \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \left( \frac{1}{W\log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f)]r_0}}{N_0 + \mu_1} \right) \right)^2 V_a(Z) + 1 \right) + 1 \right] \mathbb{E}[\alpha],
\]

\[
\sigma_E^2 = \frac{1}{\mu_1 - \lambda_1} + \mathbb{E}[\alpha^2] + \frac{\rho_2 \mathbb{E}[\alpha^3]}{3(1 - \rho_2)} + \frac{\rho_2 \mathbb{E}[\alpha^2]}{2(1 - \rho_2)} + \left[ \left( \frac{\rho_2}{2(1 - \rho_2)} \left( \frac{1}{W\log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f)]r_0}}{N_0 + \mu_1} \right) \right)^2 V_a(Z) + 1 \right) + 1 \right] \mathbb{E}[\alpha] \right)^2,
\]

\[
\frac{\xi_E}{\Gamma(1 - \xi_E) - 1} = \frac{(2n - 1)^{1/2}}{(n - 1)}.
\]

E. Proof of Lemma 2

Proof: Based on (5), we express the rate in terms of \( L \) and \( \alpha \) as:

\[
C = \frac{L}{\alpha} = W\log_2 \left( 1 + \frac{p_0 A_0 r_0^2 e^{-K(f)]r_0}}{N_0 + \sum_{i=1}^{M} p A_0 d_i^{-2}} \right), \tag{46}
\]

We can see that the only random term in (30) is the interference that is assumed to follow a normal distribution. Subsequently, we can express the interference in terms of the transmission delay \( \alpha \) as follows:

\[
\sum_{i=1}^{M} p A_0 d_i^{-2} = \frac{N_0 \left( 1 - 2 \frac{L}{\alpha} \right) + p_0^{RX}}{2 \frac{L}{\alpha} - 1}. \tag{47}
\]
By applying the transform for PDFs, \( g(y) = g(x) \frac{dy}{dx} \) we can find the PDF of transmission delay by transforming the PDF of interference accordingly. We let \( \Upsilon \) represent the interference and \( \zeta \) its derivative with respect to the transmission delay. Then, we have:

\[
\zeta = \frac{r \Upsilon}{r^\alpha} = \frac{\ln (2) \ln \left(2 \frac{L}{W_{\alpha}}\right)}{W_{\alpha}^2 \left(2 \frac{L}{W_{\alpha}} - 1\right)} + \frac{\ln (2) L \left(N_0 \left(1 - 2 \frac{L}{W_{\alpha}}\right) + p_{0RX}\right) \cdot 2 \frac{L}{W_{\alpha}}}{W_{\alpha}^2 \left(2 \frac{L}{W_{\alpha}} - 1\right)^2} = \frac{\ln (2) L p_{0RX} \cdot 2 \frac{L}{W_{\alpha}}}{W_{\alpha}^2 \left(2 \frac{L}{W_{\alpha}} - 1\right)^2}.
\]

Hence, the transmission delay PDF will be:

\[
\psi_T(\alpha) = g(\Upsilon) \frac{d\Upsilon}{d\alpha} = \zeta g(\Upsilon) = \frac{\zeta}{\sqrt{2\pi \sigma_I}} \exp \left(\frac{-(\Upsilon - \mu_I)^2}{2\sigma_I^2}\right).
\]

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