

Performance Analysis of NOMA for Ultra-Reliable and Low-Latency Communications

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Abstract—Grant-free non-orthogonal multiple access (NOMA) has been regarded as a key-enabler technology for ultra-reliable and low-latency communications (URLLC). In this paper, we analyse the performance of NOMA with short packet communications for URLLC. In this regard, the overall packet loss probability consists of transmission error probability and queueing-delay violation probability. Queueing-delay has been modelled using the effective bandwidth. Due to short transmission time, the infinite block-length has been replaced with finite blocklength of the channel codes which rules out the application of Shannon's formula. The achievable effective bandwidth of the system is derived, and then, the transmission error probability has been analysed. The derivations are validated through extensive simulations, which shows the variations of the signal-to-noise ratio (SNR) requirements of the system for various transmission-error probability, QoS exponent, and the transmission packet size.

I. INTRODUCTION

As compared to the previous cellular system generations, fifth-generations (5G) is considered to be more innovative while promising the seamless connectivity for massive machine type communications (mMTC) and ultra-reliable and low latency communications (URLLC) [1]. Considering URLLC, achieving a low latency in conjunction with a very high reliability is a challenging task. However, with latency as much low as 1ms and 99.999% reliability, mission critical communications can be ensured. This feature can support the ballooning demands of critical applications such as Tactile Internet, autonomous vehicles, and factory automation [2].

Non-orthogonal multiple access (NOMA) technology has been introduced to address the need for high data rate while supporting multiple users within same time/frequency resource block [3]. When compared to the orthogonal multiple access (OMA), NOMA can provide higher performance in terms of spectral efficiency and energy efficiency. The potential benefits of NOMA can be exploited while integrated it with other technologies such as short-packet communications. On the other hand, grant-free NOMA has been proposed as a potential enabler technology for URLLC to support the time-critical applications [4].

Researchers have come out with different designs paradigm to achieve the URLLC. This technology, infact, is envisioned

as a potential solution for achieving low-latency in URLLC. With the short packet communications of finite blocklength, the conventional shannon capacity has been replaced with a new formula proposed in [5].

In most of the existing studies, only the transmission delay and transmission error probability have been taken into account to model the required delay and reliability for the URLLC. However, we note that the queueing-delay could consist the highest latency in the system. In this regard, the concept of effective-bandwidth has been used to model the queueing delay of short packet communications in [2] which also considers the transmission error probability, queueing-delay violation probability, and proactive packet dropping probability. The proposed scheme proactively drops some packets to ensure the high reliability and low latency. Other designs paradigm has also been adopted to improve the transmission error probability in [6]–[9]. Particularly, the polar codes are introduced in [6] to minimize the various delays that caused from the signal processing, coding, and transmission. Various diversity schemes have also been exploited to minimize the transmission and other delays while supporting the URLLC. Spatial diversity has been used to improve the reliability in [7], while the frequency diversity has been investigated in [8]. Further, [9] shows that delay and reliability requirements for URLLC can be achieved with increased number of antennas at the BS.

On the other hand, performance of NOMA with short packet communications has been investigated in [10] where in the Transmission error probability has been translated into the block error length with finite blocklength and short transmission time. Simulations results demonstrate the effectiveness of the NOMA as compared to the OMA for reducing the transmission latency. However, the queueing-delay and queueing delay violation probability has not been taken into consideration in modelling the reliability and latency requirements in [10].

With the above background study coverage, in this paper, we aim to answer the following question:

Given the low latency and high reliability requirements of URLLC, how much latency can NOMA reduce while satisfying the given reliability constraints.

Employing the NOMA with short packet communications can result in the following advantages,

- As compared to NOMA, in conventional OMA schemes, base station (BS) has to employ the contention-based

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access scheme to mitigate the collision among multiple users. This can result into the increased delay/latency due to the increased collisions with the increased number of users. Hence, for the ultra-low latency, OMA cannot be employed.

- NOMA does not use the grant acquisition as it uses the grant-free access. This grant-free access is helpful in satisfying the required delay and reliability requirements when the number of users increases.
- NOMA can also be easily integrated with the other coding schemes such as polar codes to achieve the low latency for ultra-delay sensitive applications.

This paper will be a first attempt to analyse the performance limitations of NOMA in short packet communications for URLLC. The major contributions of our work can be summarized as follows:

- A performance analysis of NOMA for URLLC has been provided while considering the queueing-delay, error-rate, and packet sizes.
- Transmission error probability and queueing-delay violation probability with finite blocklength codes has been taken into consideration to ensure the overall reliability.
- Analysis of effective-bandwidth for the NOMA in URLLC has been provided. This analysis is then used to find the required SNR for the given latency and error-rate.
- Extensive simulations have been carried out to investigate the performance of NOMA for URLLC while taking into consideration the required SNR, transmission-error probability, delay exponent, and different packet sizes.

The rest of the paper is organized as follows. Section II provides the system model and problem formulation. Section III shows the performance evaluation of the proposed analysis, and Section IV concludes the paper with future research directions.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a two users power-domain NOMA operation. Out of the two users, one user is getting a better channel condition such that,

$$|h_1|^2 \geq |h_2|^2, \quad (1)$$

where h_i is the channel coefficient between the user k_i and the BS, where $i = \{1, 2\}$. According to the NOMA operation, the broadcast signal from the BS to the users can be defined as:

$$x = \sum_{i=1}^2 \sqrt{\alpha_i P} m_i, \quad (2)$$

where α_i is the power allocation coefficient, P is the transmitted power, and m_i is the message of user k_i . The received signal at user i is hence given by

$$y_i = h_i \sum_{i=1}^2 \sqrt{\alpha_i P} m_i + n_i, \quad (3)$$

where n_i is the additive white Gaussian noise at user i . According to the conventional NOMA operation, k_2 decodes the m_2 first. The resulting signal-to-interference-plus-noise ratio (SINR) at k_2 to decode m_2 , hence can be approximated as follows,

$$\gamma_{22} = \frac{\alpha_2 |h_2|^2}{(\alpha_1 |h_2|^2 + \frac{1}{\rho})} \quad (4)$$

where ρ is the transmit signal-to-noise ratio (SNR). Similarly, k_1 first decodes m_2 . The received SINR at k_1 for decoding first the m_2 is given as follows,

$$\gamma_{12} = \frac{\alpha_2 |h_1|^2}{(\alpha_1 |h_2|^2 + \frac{1}{\rho})}, \quad (5)$$

after successfully decoding the m_2 , the received SNR at k_1 to decode m_1 is,

$$\gamma_{11} = \alpha_1 \rho |h_1|^2. \quad (6)$$

The overall reliability is the overall packet loss probability ε_D of a single user which is the combination of transmission error probability and queueing-delay violation probability:

$$\varepsilon_D = \varepsilon_C + \varepsilon_Q, \quad (7)$$

where ε_C is the transmission-error probability and ε_Q is the queueing-delay violation probability. Normal operation of NOMA revolves around the principle of superposition coding (SC) at the transmitter and interference cancellation at the receiver. After considering the queueing delays and successive interference cancellation at the two users, the overall reliability can be summarized as follows,

$$\varepsilon_D = \varepsilon_{C_{ij}} + \varepsilon_{Q_{ij}}, \quad (8)$$

where $\varepsilon_{C_{ij}}$ and $\varepsilon_{Q_{ij}}$ are the transmission error probabilities and queueing-delays violation probabilities of user k_i to decode the message m_j , where $i, j = \{1, 2\}$. In this paper, we use the concept of effective bandwidth which models the performance of the system when taking into consideration the queueing-delay violation probability. Effective bandwidth can be defined as the minimal constant service rate while satisfying a certain queueing delay constraint for a given arrival process. It can be derived through large-deviation approximation. For poisson arrival process $\{A_p\}$, the effective-bandwidth can be defined as [11]

$$E_{ij}^B(\theta_{ij}) = \frac{1}{T_f \theta_{ij}} \ln \{ \mathbb{E} [\exp(\theta_{ij} A_p)] \}, \quad (9)$$

where θ_{ij} is the quality-of-service (QoS) exponent for the user k_i to decode the message m_j , smaller value of θ_{ij} indicates the larger queueing-delay bound. T_f is the frame duration and $\mathbb{E}[\cdot]$ is the expectation operator. If the arrival rate is constant then the queueing-delay violation probability can be derived as [12]

$$\Pr \{ D_{ij}(\infty) > D_{\max}^q \} \approx \eta_{ij} \exp \{ -\theta_{ij} E_{ij}^B(\theta_{ij}) D_{\max}^q \}, \quad (10)$$

where $\Pr\{a > b\}$ shows the probability of a being bigger than b , D_{\max}^q is the delay bound, \approx shows the approximation, and η_{ij} is the probability of non-empty buffer and is approximated accurately when the queue length tends to infinity. For $\eta_{ij} \leq 1$, the queueing-delay violation probability can be,

$$\Pr\{D_{ij}(\infty) > D_{\max}^q\} \approx \exp\{-\theta_{ij}E_{ij}^B(\theta_{ij})D_{\max}^q\}. \quad (11)$$

From (10), the queueing-delay violation probability for user k_i to decode message m_j can be approximated as,

$$\varepsilon_{Q_{ij}} \approx \exp\{-\theta_{ij}E_{ij}^B(\theta_{ij})D_{\max}^q\}. \quad (12)$$

The maximum number of packets that can be transmitted to any single user in frame n can be approximated as [13]

$$s_{ij}(n) = \frac{\phi B}{u \ln(2)} \left\{ \ln \left[1 + \frac{\alpha_i P h_i}{N_o B} \right] - \sqrt{\frac{V_{ij}}{\phi B}} Q^{-1}(\varepsilon_{C_{ij}}) \right\} \quad (\text{packets}), \quad (13)$$

where ϕ is the data transmission phase, B is the bandwidth. ϕB is the block-length that can be used for the short packet communications, u is the size of packet in bits, N_o is the spectral density of noise, $Q^{-1}(\cdot)$ is the inverse of Gaussian Q-function, and V_{ij} is the channel dispersion of user k_i to decode the message m_j , that can be approximated by [14]

$$V_{ij} = 1 - \frac{1}{[1 + \frac{\alpha_i P h_i}{N_o B}]}. \quad (14)$$

If the k_{th} user is served with the constant rate, i.e., $E_{ij}^B(\theta_{ij})$, then we can approximate the number of packets transmitted in frame n using [2],

$$s_{ij}(n) = T_f E_{ij}^B(\theta_{ij}) \quad (\text{packets}). \quad (15)$$

From (4), (5), (6), and (15), the required SINR at user k_i to decode message m_j can be approximated using:

$$\ln(1 + \gamma_{ij}) = \frac{T_f u \ln(2)}{\phi B} E_{ij}^B(\theta_{ij}) + \sqrt{\frac{V_{ij}}{\phi B}} Q^{-1}(\varepsilon_{C_{ij}}). \quad (16)$$

The performance of the proposed NOMA for achieving URLLC can be compared with the OMA for URLLC. For any single user k_i , the performance of orthogonal frequency-division multiplexing (OFDM) for URLLC can be derived as:

$$s_i(n) = \frac{\phi B}{2u \ln(2)} \left\{ \ln \left[1 + \frac{\alpha_i P h_i}{N_o B} \right] - \sqrt{\frac{2V_i}{\phi B}} Q^{-1}(\varepsilon_{C_i}) \right\}, \quad (17)$$

where V_i and ε_{C_i} is the channel dispersion and the transmission error probability of the k_{ith} user employing the OMA operation. From (15) the required SNR to calculate the transmission error probability (ε_{C_i}) and queueing-delay violation probability (ε_{Q_i}) for k_{ith} user under OFDMA operation can

TABLE I
SIMULATION PARAMETERS

Frame duration T_f	0.5 ms
Overall reliability ε_D	1 - 99.999%
Queueing Delay D_{\max}	0.8 ms
Bandwidth B	100 kb/s
Packet size u	5, 15, and 25 bytes
Duration of data transmission ϕ	10^{-5} and 3×10^{-4}
Average number of events per event λ	0.01

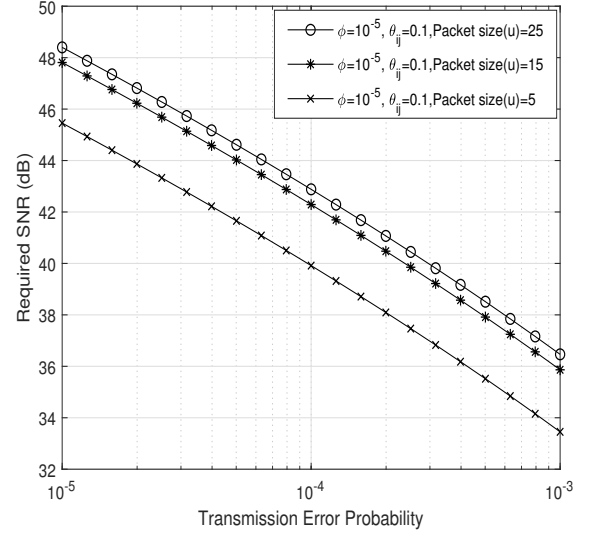


Fig. 1. SNR requirements for the given transmission error probability (10^{-5} to 10^{-3}) with different packet sizes.

be described as follows:

$$\ln(1 + \gamma_i) = \frac{2T_f u \ln(2)}{\phi B} E_i^B(\theta_i) + \sqrt{\frac{2V_i}{\phi B}} f Q^{-1}(\varepsilon_{C_i}), \quad (18)$$

where γ_i is SNR and $E_i^B(\theta_i)$ is the effective-bandwidth with θ_i as the QoS exponent of the k_{ith} user.

III. PERFORMANCE EVALUATION

In this section, we analyse the effective-bandwidth of NOMA for URLLC. Simulations have been performed to find the required SNR/SINR for a certain error-rate and latency requirement. Simulation parameters have been described in Table I, unless otherwise specified in different simulation results.

For a given transmission-error probability and queueing-delay violation probability, the required SNR for the NOMA user has been analysed in detail. Queueing-delay with extremely short delay bound has been derived from the effective bandwidth using the Poisson process. In Fig. 1, SNR requirements for the given transmission error probability ($\varepsilon_D = 10^{-5}$ to 10^{-3}) and delay QoS exponent ($\theta_{ij} = 0.1$) with different packet sizes are shown. The required SNR is small with small packet size and as the packet size increases the required

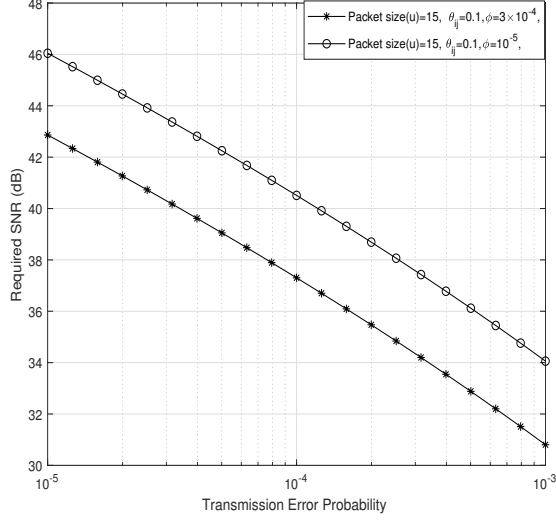


Fig. 2. SNR requirements for the given transmission error probability (10^{-5} to 10^{-3}) with different duration of data transmission (ϕ).

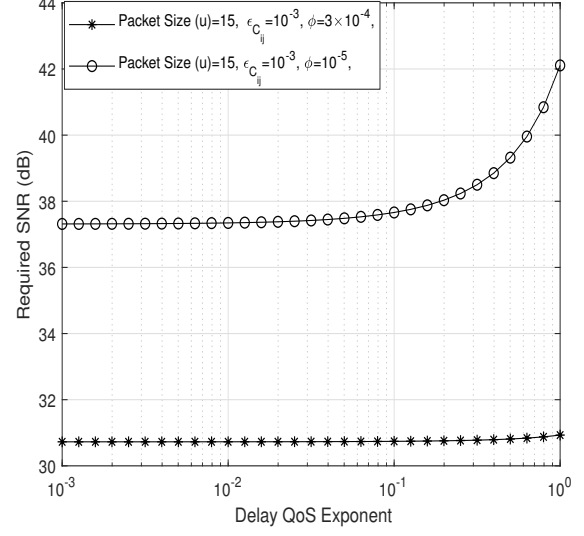


Fig. 4. SNR requirements for the given delay QoS exponent ($\theta_{ij} = 10^{-3}$ to 1) with different duration of data transmission (ϕ).

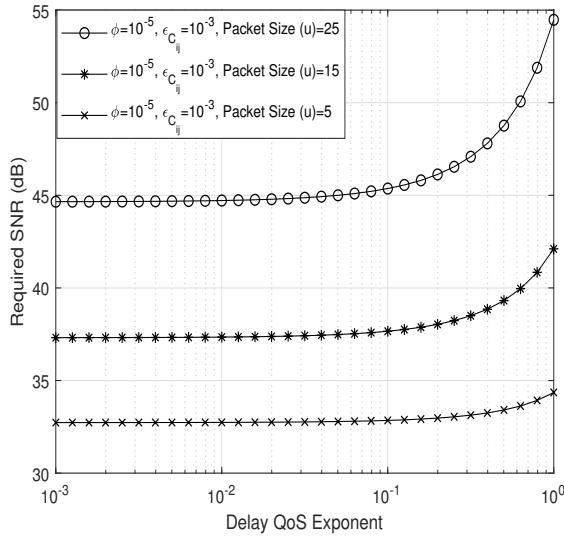


Fig. 3. SNR requirements for the given delay QoS exponent ($\theta_{ij} = 10^{-3}$ to 1) with different packet sizes.

SNR increased. However, with increase in the channel errors (transmission error probability), the required SNR decreases. It shows that, for tighter reliability requirements, a higher SNR is needed.

The duration of data transmission within one frame duration has also been analysed in Fig. 2. The increase in data transmission duration with the given frame duration of $T_f = 0.5\text{ms}$ also results into the lower required SNR. From Fig. 1 and 2, it is clear that with the short packet and short data transmission duration the required SNR decreases.

Queueing-delay for NOMA in URLLC with extremely short delay bound ($D_{\max} = 0.8\text{ms}$) has also been investigated through simulations. In Fig. 3, required SNR with the different

values of delay QoS exponent has been shown. The increased value of θ_{ij} shows the increased in the delay (more stringent delay requirements). With increased in the delay, the required SNR increased. From $\theta_{ij} = 0.1$ to 1, the delay requirements are more stringent, which shows that the SNR requirements will also be high. This trend has also been investigated with different packet size of 5, 15, and 25 bytes while keeping the data transmission duration fixed. Here, also the short packets with different delay requirements show small SNR requirements as compared to the large packets. The delay analysis for different data transmission duration with packet size of 15 bytes has been shown in Fig. 4. The short data transmissions duration seems to be more susceptible with more stringent delay requirements as compared to the slighter larger data transmission duration. For this analysis the frame duration has been kept fixed at $T_f = 0.5\text{ms}$.

From Fig. 1 to 4, the SNR requirements for the NOMA systems for ultra-reliable and low latency communications have been analysed while considering the different transmission error probability and queueing-delay violation probability. It is clear from the simulation results that employment of short packets to ensure the ultra-reliability and latency has a significant impact on SNR requirements to achieve the certain latency and error rate for NOMA in URLLC.

As a future work, we will perform an-depth performance analysis of NOMA for URLLC communications with different arrival rate and by optimizing the different resources in the system. We will also integrate other state-of-the-art technologies such as cognitive radio networks [15], [16] and wireless sensor networks [17] with NOMA-URLLC to investigate the delay-sensitive applications.

IV. CONCLUSION

In this paper, the performance of the power-domain non-orthogonal multiple access (NOMA) for ultra-reliable and low latency communications (URLLC) has been analysed with the help of effective-bandwidth. Queuing-delay and transmission delay has been considered to model the latency, while the reliability is modelled using the transmission error probability and queueing-delay violation probability. NOMA has significantly reduced the physical layer latency and improved the reliability for URLLC to support the time-critical applications. Extensive simulations have been carried out to show the SNR requirements while considering transmission error probability, delay QoS exponent, and different packet sizes.

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