Prioritized S-ALOHA for URLLC

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***Abstract*— Ultra reliable low latency communication (URLLC) is one of the main goals in 5G. URLLC requires highly reliable and low latency transmission of safety critical and control packets. Slotted ALOHA forms one of the widely used access schemes in cellular communication. In this paper, we study the performance of URLLC packet transmissions utilizing slotted ALOHA and propose a prioritized access mechanism to provide low latency and high reliability transmission of delay critical packets. We consider two types of traffic, namely, regular traffic and URLLC traffic. URLLC packets have stringent delay requirements, thus, they are provided high priority access to the channel. Via analytical formulation, we obtain the packet delay distribution function for both URLLC and regular packets and formulate an optimization problem to maximize the reliability of regular packets given that the URLLC packets meet their required reliability threshold. Results show that by enabling prioritized access to URLLC packets, their reliability requirements can be met, while at the same time, regular packet transmission can make most use of the remaining channel.**

***Keywords*— URLLC, Slotted ALOHA, Priority based access, Markov chain, packet delay, reliability**

I. Introduction

5G networks focus on enabling newer services with exceedingly different data rate and latency requirements. One peculiar aspect of 5G is that, not only users but intelligent machine devices can also generate huge amount of data and transmit it through the network. Massive Internet of Things (IoT), enhanced mobile broadband, critical communications are among the few focus areas of 5G. These various services can be grouped into three broad categories, namely: eMBB (enhanced mobile broadband), URLLC (ultra reliable low latency communications), and mMTC (massive machine type communications).

URLLC forms one of the salient features of 5G. As per the Third Generation Partnership project (3GPP) [1], URLLC specifies the packet transmission latency requirements of user plane data ($\approx$ 0.5 ms) with very high probability of packet reception (error rates at most 10^{-5}) [2].

Applications such as, autonomous ground vehicles, industrial IoT, factory automation, pilotless aircraft, remote surgery, etc., require stringent packet transmission latency and reception errors [3], [4]. These safety critical and control packets require extremely high reliability in their transmissions. The existing cellular systems are incapable of handling URLLC requirements. With the increase in the number of users, latency increases tremendously. On the other hand, Fourth generation (4G) systems such as, Long Term Evolution (LTE) provides better latencies and data rates. However, they cannot achieve the URLLC reliability requirements. The authors in [5] have presented the various sources of latency in LTE systems. Here, they highlight that a major source of delay in packet transmission in a cellular network is the random access delay between the user and the base station (BS), which can go up to 10 ms. The conventional slotted ALOHA (CS-ALOHA) forms one of the main access strategies in cellular communications to transmit their request to the BS. In this protocol, all nodes having a packet, attempt transmission in a slot with certain probability. When the number of nodes are fewer, latency is lower and can be acceptable for URLLC framework. However, as the number of nodes increases, the latency increases exponentially and system is incapable of handling URLLC communications.

In this paper, we address this challenge of making CS-ALOHA suitable for URLLC communications. We note that a small fraction of traffic generated in cellular network requires URLLC. One way to enable URLLC is to reserve dedicated resource for its transmission. This can ensure the desired quality of service (QoS), however, at the cost of spectrum underutilization. To alleviate this issue, we propose *prioritized S-ALOHA*, where both regular and URLLC packets are transmitted over the same channel, thus making the most use of the available resources while at the same time ensuring QoS to URLLC traffic.

In the proposed protocol, we target the uplink communication between nodes and BS, and allow prioritized access to the URLLC traffic. The key contributions of this paper are as follows:

1) We propose *prioritized S-ALOHA* to achieve a target reliability for URLLC packet transmissions.
2) We analyse our proposed protocol using Discrete Time Markov Chains formulations.
3) We obtain and study the delay distribution for regular and URLLC packet transmissions.
4) We formulate an optimization problem to maximize regular user performance while ensuring QoS for URLLC users.
5) We compare the performance of our proposed protocol with the existing art namely, CS-ALOHA and Diversity Transmission (DT) scheme [6].

Results indicate that our proposed prioritized S-ALOHA can support higher URLLC traffic, while simultaneously carry regular traffic.

Rest of the paper is organized as follows. Next section presents the related works followed by system model and

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proposed protocol in Section III. Section IV presents protocol analysis followed by optimization of prioritized S-ALOHA in Section V. Section VI presents the results and Section VII concludes the paper.

II. Related Works

In this section, we survey the various contributions made towards reliability enhancement for URLLC. In [7], the authors proposed short block length channel codes to achieve low latency. In order to avoid collisions and efficiently use the available resource, the authors in [8] classified the bursty arrival process into high and low-traffic states. Thereafter, dedicated bandwidth was reserved for UEs in the high-traffic state, and the slotted ALOHA access scheme was applied for UEs in the low traffic state. Further reliability could be improved using multi-connectivity and network slicing as proposed in [9]. In multi-connectivity, a packet is transmitted over multiple parallel links, such as D2D links, relay, and cellular links. Network slicing allows the network to build multiple logical sub-networks with reserved resources for different application scenarios, e.g., eMBB, mMTC, and URLLC. In this context, URLLC service can avoid the interruptions caused by other services that share the same resources and thus help enhance QoS and user experience.

Access delay can be avoided by reserving bandwidth for each UE, however, such a method is only suitable for UEs with a high packet arrival rate. In case of low packet arrival rate, reserving bandwidth leads to a bandwidth underutilization. To address this issue, a slotted ALOHA based access protocol was studied in [6] from URLLC context. Here, the total bandwidth was divided into multiple channels. In each slot, the UEs that need to send packets choose one of the channels randomly for data transmission. If more than one UE chooses the same channel, then collision occurs. Additionally, the authors considered diversity transmission (DT) to improve the reliability of the URLLC services. They considered sending the same data multiple times to improve reliability. The authors in [10] considered a coding based slotted ALOHA wherein prior to transmission of an m-slot message, n single slot coded packets were constructed using erasure correcting codes. As a result of this any m successfully received coded packets could yield a correct reception of the message.

The current work is a novel contribution towards meeting the URLLC requirements, while at the same time making the most use of the available resources for regular transmissions. In this paper, we consider that a single channel resource is available for both regular and URLLC traffic and propose a prioritized access scheme to meet the URLLC traffic requirements while at the same time maximize resource utilization for regular traffic.

III. System Model and Proposed Protocol

A. System Model

We consider a single cell uplink scenario with multiple nodes connected to a single BS. The nodes could be either end users or machines generating packets to be transmitted. The generated packets could belong to one of the two categories depending on their application. They could either be *regular* packets suitable for transmission of voice, data, video, etc., or, they could be safety critical packets requiring highly reliable and low latency transmission for *URLLC*. It is considered that a node can generate one type of packets at a time.

Consider that there are a total of N_r nodes generating regular packets and N_u nodes generating URLLC packets. Time is considered slotted with slot duration of τ units. Nodes are considered homogeneous across each category. Packets arrive at a given node following Geometric distribution with the probability of packet arrival in each slot given as λ_r and λ_u for regular and URLLC nodes, respectively.

We consider that a single communication channel is available for the nodes to transmit their data to the BS. They use slotted-ALOHA protocol to transmit their data. Deferred first transmission (DFT) mode of slotted ALOHA is considered [11], where a newly arriving packet immediately joins the backlog nodes and packets are transmitted with a probability in each slot. Other assumptions considered in this protocol are listed below, which are inline with [12]:

1) *Collision or perfect reception*: If two or more nodes transmit in a slot, then collision occurs. Packet transmission is successful only when a single node transmits a packet in a slot. The effect of channel errors in not considered for the sake of simplicity.
2) *Immediate feedback*: At the end of each time slot, the nodes obtain feedback whether a packet was successfully transmitted, or there was no transmission in a slot, or more than one packets were transmitted resulting in collision. As we consider single hop communication, feedback can be immediately provided by the BS.
3) *No buffering*: If there is a packet waiting for transmission at a node, no new packets can arrive at that node. Thus, at a time, at most one packet can be present at a given node.

B. Prioritized S-ALOHA

Each node having a backlogged packet transmits with a certain probability at the start of a slot. Due to the different QoS requirements of various packets, we propose to provide prioritized access to nodes transmitting URLLC packets. Thus, the probability of packet transmission for regular and URLLC packets is considered different and is denoted as p_r and p_u, respectively.

URLLC requires low latency and high reliability transmission of its packets. *Reliability is defined as the probability that the packet transmission delay is below a given threshold delay (d_{th})*. Thus, if $D(t)$ denotes the probability mass function (PMF) of packet delay, then reliability $R = Pr(D(t) \leq d_{th})$. Note here that the delay considered in this work is the time taken from packet generation at a node to its successful transmission to the BS.

Our objective in this work is to analyse the reliability of both the packet transmissions (regular and URLLC) and obtain the optimal packet transmission probabilities such that our network performance is maximized (in terms of reliability of regular packet transmission), while, the QoS of URLLC packets is met. In the following section, we analytically obtain the PMF of delay in packet transmission of regular and URLLC packets and obtain the reliability of packet transmission for both the classes.

IV. Protocol Analysis

As indicated earlier, N_r nodes generating regular packets and N_u nodes generating URLLC packets transmit it to a BS. The packet arrival rate is λ_r and λ_u, respectively, for regular and URLLC nodes and their packet transmission probability is p_r and p_u, respectively.

Considering the memoryless nature of packet generation and transmission, we form a two-dimensional Markov chain with states denoted as $n(t) = (x_r, x_u)$ at time t, where x_r denotes the number of backlogged nodes transmitting regular packets and x_u denotes the number of backlogged nodes transmitting URLLC packets. The total number of states in this Markov chain is $(N_u + 1)(N_r + 1)$.

Next, we obtain the one-step transition probability matrix ($\mathbf{p_r}$, with elements $p(x_r, x_u, y_r, y_u)$) for the Markov chain. $p(x_r, x_u, y_r, y_u)$ denotes the one-step transition probability for the Markov chain going from state (x_r, x_u) to state (y_r, y_u). Note that y_r can take values from $x_r - 1$ to N_r and y_u can take values from $x_u - 1$ to N_u.

Let $\alpha_r(x_r, x_u)$ be the probability of successful transmission of a regular packet out of x_r regular packet backlogged nodes and x_u URLLC packet backlogged nodes, and $\alpha_u(x_r, x_u)$ be the probability of successful transmission of a URLLC packet out of x_r regular packet backlogged nodes and x_u URLLC packet backlogged nodes. These probabilities are given as:

$$\alpha_r(x_r, x_u) = x_r p_r (1 - p_r)^{x_r - 1} (1 - p_u)^{x_u} \tag{1}$$

$$\alpha_u(x_r, x_u) = x_u p_u (1 - p_u)^{x_u - 1} (1 - p_r)^{x_r} \tag{2}$$

Let $\beta_r(x_r, w)$ be the probability of a new packet arrival at w regular packet nodes given that x_r regular packet nodes have a backlog. This is given as:

$$\beta_r(x_r, w) = \binom{N_r - x_r}{w} \lambda_r^w (1 - \lambda_r)^{N_r - x_r - w} \tag{3}$$

Similarly, $\beta_u(x_u, w)$ be the probability of new packet arrival at w URLLC packet nodes given that x_u URLLC packet nodes have a backlog. This is given as:

$$\beta_u(x_u, w) = \binom{N_u - x_u}{w} \lambda_u^w (1 - \lambda_u)^{N_u - x_u - w} \tag{4}$$

Next, we obtain the one-step transition probability of the Markov chain in terms of $\alpha_r(x_r, x_u)$, $\alpha_u(x_r, x_u)$, $\beta_r(x_r, w)$, and $\beta_u(x_u, w)$. We divide this assignment among four cases as discussed below:

1) $y_r - x_r$=-1 and $y_u - x_u$=-1: For this case, $p(x_r, x_u, y_r, y_u) = 0$, as no two nodes can successfully transmit in a single time slot.
2) $y_r - x_r$=-1 and $y_u - x_u \geq$0: Here, $p(x_r, x_u, y_r, y_u) = \alpha_r(x_r, x_u)\beta_u(x_u, y_u - x_u)\beta_r(x_r, 0)$ as only one of the regular packet backlog node has been successful in transmitting its packet, while $y_u - x_u$ new URLLC packets are generated and are in backlog.
3) $y_u - x_u$=-1 and $y_r - x_r \geq$0: Here, $p(x_r, x_u, y_r, y_u) = \alpha_u(x_r, x_u)\beta_r(x_r, y_r - x_r)\beta_u(x_u, 0)$ as only one of the URLLC packet backlog node has been successful in transmitting its packet, while $y_r - x_r$ new regular packets are generated and are in backlog.
4) $y_r - x_r \geq$0 and $y_u - x_u \geq$0: This case is again subdivided into three parts.
   a) A regular packet is successfully transmitted: $p_1(x_r, x_u, y_r, y_u) = \alpha_r(x_r, x_u)\beta_u(x_u, y_u - x_u)\beta_r(x_r, y_r - x_r + 1)$
   b) A URLLC packet is successfully transmitted: $p_2(x_r, x_u, y_r, y_u) = \alpha_u(x_r, x_u)\beta_r(x_r, y_r - x_r)\beta_u(x_u, y_u - x_u + 1)$
   c) None of the packets are successfully transmitted: $p_3(x_r, x_u, y_r, y_u) = (1 - \alpha_r(x_r, x_u) - \alpha_u(x_r, x_u))\beta_r(x_r, y_r - x_r)\beta_u(x_u, y_u - x_u)$

   Thus, for this case, $p(x_r, x_u, y_r, y_u) = p_1(x_r, x_u, y_r, y_u) + p_2(x_r, x_u, y_r, y_u) + p_3(x_r, x_u, y_r, y_u)$.

From the one-step state transition probability matrix, we can obtain the steady state probability of being in a state $(\pi(x_r, x_u))$ which is given as $\pi = \pi \mathbf{p_r}$.

Next, we obtain the delay distribution of a tagged node transmitting URLLC packet. This involves, first finding the delay distribution of a tagged user given that the system was in state (x_r, x_u) when the packet arrived. Thereafter, we relax this condition to obtain the delay distribution profile.

Let $n(t) = (x_r, x_u); x_u \neq 0$ be the system state at time t and let $D^u_{(x_r,x_u)}(z)$ be the z-transform of delay distribution of a tagged node having URLLC packet to transmit. $D^u_{(x_r,x_u)}(z)$ is a column vector of size $(N_r + 1)N_u$. Consider a tagged user in the backlog with system state $n(t) = (x_r, x_u)$, we define the probability $p^s_u(x_r, x_u, y_r, y_u)$ and $p^{\underline{s}}_u(x_r, x_u, y_r, y_u)$ as follows:

$$p^s_u(x_r, x_u, y_r, y_u) = Pr\{n(t+1) = (y_r, y_u), \text{tagged user successful in } t+1 | n(t) = (x_r, x_u)\}$$

$$p^{\underline{s}}_u(x_r, x_u, y_r, y_u) = Pr\{n(t+1) = (y_r, y_u), \text{tagged user unsuccessful in } t+1 | n(t) = (x_r, x_u)\}$$

These probabilities are obtained as:

$$p^s_u(x_r, x_u, y_r, y_u) = \frac{1}{x_u}\alpha_u(x_r, x_u)\beta_r(x_r, y_r - x_r) \cdot \beta_u(x_u, y_u - x_u + 1) \tag{5}$$

$$p^{\underline{s}}_u(x_r, x_u, y_r, y_u) = p(x_r, x_u, y_r, y_u) - p^s_u(x_r, x_u, y_r, y_u) \tag{6}$$

If the tagged user is successful in slot $t+1$, its delay is one slot. If it is unsuccessful, then it finds itself in backlog with y_r regular packet nodes and y_u URLLC packet nodes. Thus, its delay distribution in z-transform can be given as:

$$D^u_{(x_r,x_u)}(z) = \sum_{y_r=x_r-1}^{N_r} \sum_{y_u=x_u-1}^{N_u} z p^s_u(x_r, x_u, y_r, y_u) + \sum_{y_r=x_r-1}^{N_r} \sum_{y_u=x_u-1, y_u \neq 0}^{N_u} z\, p^{\underline{s}}_u(x_r, x_u, y_r, y_u) D^u_{(y_r,y_u)}(z) \tag{7}$$

Denote $\mathbf{p_r}^s_u$ the matrix with elements $p^s_u(x_r, x_u, y_r, y_u)$, $\mathbf{p_r}^{\underline{s}}_u$ the matrix with elements $p^{\underline{s}}_u(x_r, x_u, y_r, y_u)$, and $\mathbb{D}^u(z)$

the vector with elements $D^u_{(x_r,x_u)}(z)$. We can write (7) in matrix form as:

$$\mathbb{D}^u(z) = z(\mathbf{I} - z\mathbf{p_r}{}^{\underline{s}}_{u})\mathbf{p_r}{}^s_u\mathbf{H} = \sum_{l=1}^{\infty}(\mathbf{p_r}{}^{\underline{s}}_{u})^{l-1}\mathbf{p_r}{}^s_u\mathbf{H}z^l, \qquad (8)$$

where $\mathbf{H}$ is a column vector with all entries equal to 1.

Thus far, we have obtained the delay distribution of a URLLC packet when the packet finds itself in backlog state (x_r, x_u) upon arrival. Next, we relax this assumption by obtaining $\gamma_u(x_r, x_u)$, the probability that a new URLLC packet arrival finds itself in system state (x_r, x_u).

Before proceeding further, let us define probability that a URLLC packet is transmitted successfully in a slot given that the system is in state $n(t) = (x_r, x_u)$ at time t is denoted as $p^d_u(x_r, x_u, y_r, y_u)$ and is given as:

$$\begin{aligned} p^d_u(x_r, x_u, y_r, y_u) &= Pr\{n(t+1) = (y_r, y_u), \text{a URLLC} \\ &\quad \text{packet is successful in } t+1 | n(t) = (x_r, x_u)\} \\ &= \alpha_u(x_r, x_u)\beta_r(x_r, y_r - x_r)\beta_u(x_u, y_u - x_u + 1). \end{aligned} \qquad (9)$$

Similarly, the probability that a URLLC packet is unsuccessful in a slot given that the system is in state $n(t) = (x_r, x_u)$ at time t is denoted as $p^{\underline{d}}_u(x_r, x_u, y_r, y_u)$ and is given as:

$$\begin{aligned} p^{\underline{d}}_u(x_r, x_u, y_r, y_u) &= Pr\{n(t+1) = (y_r, y_u), \text{a URLLC} \\ &\quad \text{packet is unsuccessful in } t+1 | n(t) = (x_r, x_u)\} \\ &= p(x_r, x_u, y_r, y_u) - p^d_u(x_r, x_u, y_r, y_u). \end{aligned} \qquad (10)$$

Suppose that the system is in state $n(t) = (x_r, x_u)$ at time t and and transits to state $n(t+1) = (y_r, y_u)$ at time $t+1$. If a URLLC packet is not successful in slot t, then $y_u - x_u$ nodes find the system in state $n(t+1) = (y_r, y_u)$, while if a URLLC packet is successfully transmitted in slot t , then $y_u - x_u + 1$ nodes find themselves in state $n(t+1) = (y_r, y_u)$ on arrival.

Thus, the probability $\gamma_u(y_r, y_u)$ is given as:

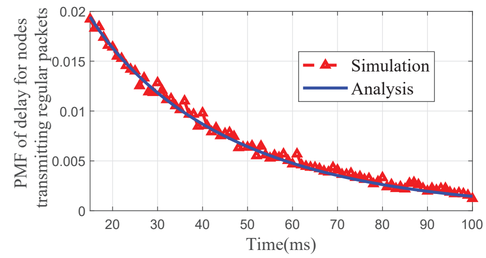
$$\begin{aligned} \gamma_u(y_r, y_u) =& K\sum_{x_r=0}^{N_r}\sum_{x_u=0}^{N_u}\pi_{(x_r,x_u)}[p^{\underline{d}}_u(x_r, x_u, y_r, y_u)(y_u - x_u) \\ &+ p^d_u(x_r, x_u, y_r, y_u)(y_u - x_u + 1)]. \end{aligned} \qquad (11)$$

Here, K is a normalization constant and is obtained by $\sum_{y_r=0}^{N_r}\sum_{y_u=0}^{N_u}\gamma_u(y_r, y_u) = 1$. Let Γ be a vector with elements $\gamma_u(y_r, y_u)$. The z-transform, $\mathbf{D}^u(z)$, of this delay distribution is given as:

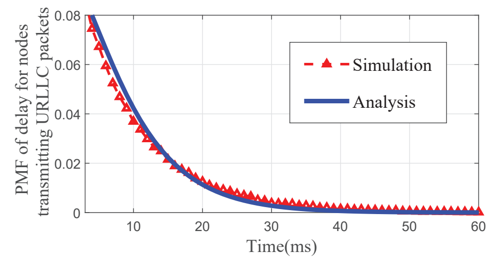
$$\begin{aligned} \mathbf{D}^u(z) &= \Gamma\mathbb{D}^u(z) \\ &= z\Gamma(\mathbf{I} - z\mathbf{p_r}{}^{\underline{s}}_{u})\mathbf{p_r}{}^s_u\mathbf{H} \\ &= \sum_{l=1}^{\infty}\Gamma(\mathbf{p_r}{}^{\underline{s}}_{u})^{l-1}\mathbf{p_r}{}^s_u\mathbf{H}z^l. \end{aligned} \qquad (12)$$

Finally, we compute the reliability, which is expressed as the probability that the delay is less than certain threshold d_{th}. This is expressed as:

$$\begin{aligned} \mathbb{R}^u &= \sum_{l=1}^{d_{th}}\Gamma(\mathbf{p_r}{}^{\underline{s}}_{u})^{l-1}\mathbf{p_r}{}^s_u\mathbf{H} \\ &= \Gamma(\mathbf{I} - \mathbf{p_r}{}^{\underline{s}}_{u})^{-1}(\mathbf{I} - (\mathbf{p_r}{}^{\underline{s}}_{u})^{d_{th}})\mathbf{p_r}{}^s_u\mathbf{H} \end{aligned} \qquad (13)$$



(a) Packet delay distribution for regular packet transmission



(b) Packet delay distribution for URLLC packet transmission

Fig. 1: Packet delay distribution plots. $N_r = 5$, $p_r = 0.1$, $\lambda_r = 0.1$, $N_u = 5$, $p_u = 0.2$, and $\lambda_u = 0.05$.

In a similar manner, we can also obtain the reliability for regular packet transmission ($\mathbb{R}^r$).

Before proceeding further, we validate our reliability analysis with the simulation results. Figs. 1 (a) and (b) present the delay distribution of regular and URLLC packets. Both simulation and analytical results are plotted. From the graphs, we observe that the delay PMF follows geometric distribution (as evident from (12)) and there is a close match between analytical and simulation PMF validating the correctness of our mathematical formulation.

V. Optimizing Prioritized s-ALOHA

A. Optimization problem formulation

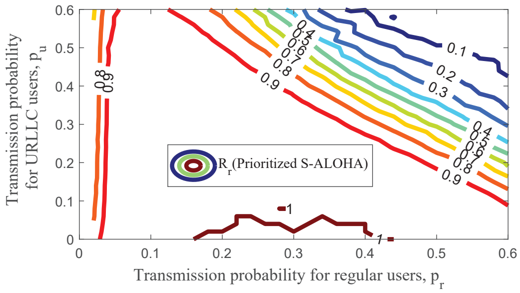
We have obtained the expressions for reliability of regular and URLLC packet transmissions. Since, reliability is a function of transmission probabilities p_r and p_u, we maximize the reliability by varying p_r and p_u. We consider the following optimization problem:

$$\begin{aligned} &\underset{p_r,p_u}{maximize} \quad \mathbb{R}^r \\ &s.t. \quad \mathbb{R}^u \geq R_{th} \end{aligned} \qquad (14)$$

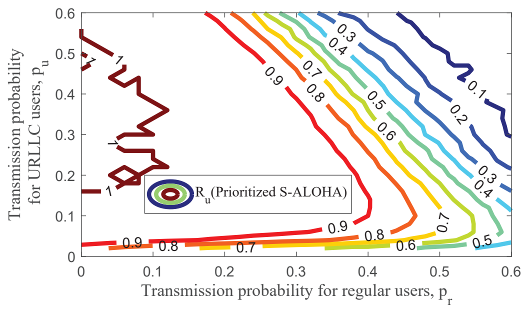
Hence, here we maximize the reliability of the regular packet transmission $\mathbb{R}^r$ such that the reliability of the URLLC packet transmission $\mathbb{R}^u$ is always above a desired threshold value.

B. Optimization problem solution

From (13) it is evident that the closed form expression for reliability in terms of p_r and p_u cannot be obtained. Hence, we make use of numerical optimization techniques to obtain the solution to this optimization problem. To get a better idea of



(a) Reliability for regular packet transmission, $\mathbb{R}^r$



(b) Reliability for URLLC packet transmission, $\mathbb{R}^u$

Fig. 2: Reliability contour plots. $N_r = 5$, $\lambda_r = 0.1$, $N_u = 5$, and $\lambda_u = 0.05$.

the optimization problem, we obtain the contour plots for reliability of regular and URLLC packets with variation in p_r and p_u. Figs. 2 (a) and (b) present the contour plot for reliability of regular and URLLC packets, respectively, with the change in packet transmission probability p_r and p_u. We observe that, $\mathbb{R}^r$ increases with increase in p_r up to its maximum value and then decreases on further increase in p_r. This is because at lower p_r there is hardly any packet being transmitted, while a higher p_r results in higher collisions. However, $\mathbb{R}^r$ always decreases as p_u increases, because channel is more frequently used for URLLC packet transmission giving less transmission opportunity to regular traffic. Thus, there exists an optimal transmission probability where the reliability is maximum. Similar results are obtained for $\mathbb{R}^u$.

We realize that $\mathbb{R}^r$ and $\mathbb{R}^u$ are complimentary to each other i.e., to maximize $\mathbb{R}^u$, we need to increase p_u, which in turn leads to a drop in $\mathbb{R}^r$. Thus, at the optimal point, the inequality in the optimization problem (14) will be met with equality. Thus, we form an unconstrained optimization problem using penalty function by considering equality constraint for $\mathbb{R}^u$ as follows:

$$\text{maximize } \mathcal{G}(p_r, p_u, \mu) = \mathbb{R}^r - \mu(R_{th} - \mathbb{R}^u)^2.$$

Here, μ is a small positive parameter, and the solution converges to the original solution as μ tends to a large value.

Further, the contour plots in Fig. 2 clearly show that reliability $\mathbb{R}^r$ variation with respect to p_r (for any constant value of p_u) is a unimodal function (has only one maximum point). Also, we get to observe that the variation of $\mathbb{R}^r$ with p_u (for any constant value of p_r), is a monotonic decreasing function. Hence we can make use of the two-dimensional golden section search method [13] (also referred to as 2D-GSS), to numerically maximize our penalty function $\mathcal{G}(p_r, p_u, \mu)$.

VI. Results

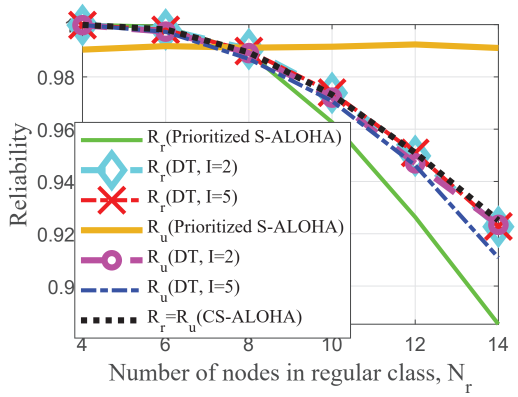
In this section, we present the reliability performance of regular and URLLC packet transmission under our proposed protocol framework and compare it with the DT scheme [6] and the CS-ALOHA. We consider the slot duration of 10 μs, and target delay threshold is considered as 1 ms as per the 3GPP specifications [2]. Reliability threshold of 0.99 is considered for URLLC packet transmission.

In the DT scheme, CS-ALOHA is employed with persistent transmission of URLLC packets. Specifically, in a slot, if a URLLC user fails to transmit a packet successfully, then it is allowed to retransmit the packet until a successful transmission occurs, for the next I consecutive slots, i.e., the diversity order for a URLLC user is I slots. If the URLLC user fails to successfully transmit a packet in I slots, then the packet is dropped and the user is no more backlogged.

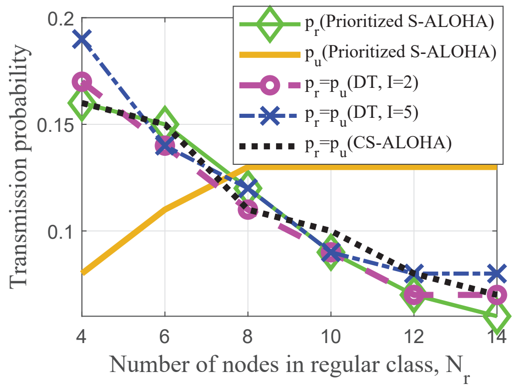
Next, we present the performance of our proposed protocol with the variation in number of nodes. We solve the optimization problem (14) and obtain the maximum value of $\mathbb{R}^r$ and the optimal transmission probabilities corresponding to both regular and URLLC nodes. We compare our prioritized S-ALOHA protocol with the CS-ALOHA and DT scheme. In both these cases, all packets are transmitted with the same probability. For these cases, we optimize the protocol performance by obtaining the optimal transmission probability that maximizes the reliability.

Figs. 3 (a) and (b) present the reliability and optimal transmission probability, respectively, with the variation in number of regular nodes, N_r. We observe that as the N_r increases, the overall traffic increases. As the threshold reliability is to be guaranteed for URLLC packets, its transmission probability remains constant. However, the transmission probability of regular nodes is decreased to maintain the packet transmission of regular packets at a constant level, thus decreasing its reliability. In comparison, CS-ALOHA and the DT scheme can provide reliability to URLLC packet transmissions only upto certain $N_r \leq 6$. Beyond this, URLLC is not supported by both the schemes. This is because with increase in the overall traffic, the chances of a node winning over a contention in a slot decreases. This in turn decreases the transmission probability. Hence, a packet now incurs a larger delay (greater than the threshold delay) before getting transmitted. This decreases the reliability below the threshold reliability.

Figs. 4 (a) and (b) present the reliability and optimal transmission probability, respectively, with the variation in number of URLLC nodes, N_u. We observe that as N_u increases, the overall traffic increases. As a threshold reliability is to be guaranteed for URLLC packets, its transmission probability increases. However, the transmission probability of regular packets decreases to offer more channel for transmission of URLLC packets, decreasing its reliability eventually. In this case as well, CS-ALOHA and the DT scheme provide reliability to URLLC packet transmissions only upto certain $N_u \leq 8$.

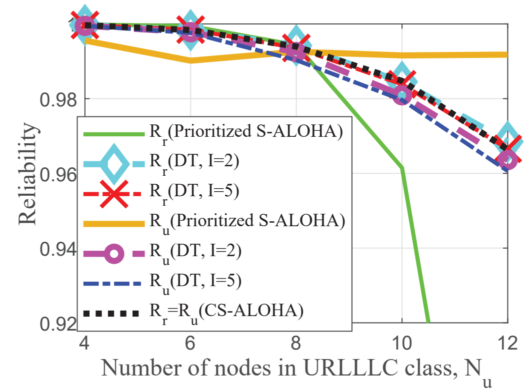


(a) Optimized Reliability

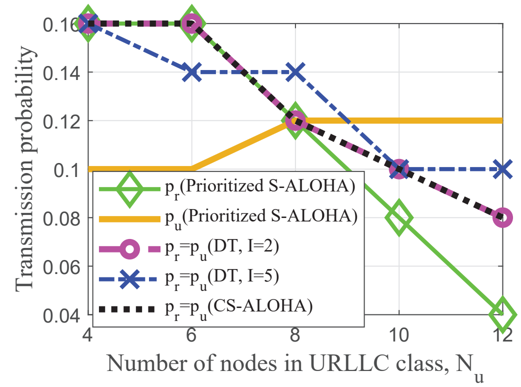


(b) Optimal transmission probabilities

Fig. 3: (a) Optimized reliability and optimal transmission probabilities with the variation in number of regular packet transmission users with $\lambda_r = 0.1$, $N_u = 5$, and $\lambda_u = 0.05$.



(a) Optimized Reliability



(b) Optimal transmission probabilities

Fig. 4: (a) Optimized reliability optimal transmission probabilities with the variation in number of URLLC packet transmission users with $N_r = 5$, $\lambda_r = 0.1$, and $\lambda_u = 0.05$.

VII. Conclusion

In this paper, we proposed a prioritized access of URLLC traffic in slotted-ALOHA and analytically evaluated the reliability of both regular and URLLC packets. An optimization problem was formulated to maximize the reliability of regular traffic subject to meeting the reliability requirements of URLLC traffic as a function of transmission probabilities. Results indicated that by suitably adjusting the transmission probavident that our proposed model gives better reliability for URLLC and regular packet transmissions than CS-ALOHA and the DT scheme. Future work includes relaxing the single packet buffer assumption in slotted ALOHA and study the stability aspects.

Acknowledgements

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