RAN Slicing Performance Trade-offs: Timing versus Throughput Requirements

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Abstract—The coexistence of diverse services with heterogeneous requirements is a fundamental feature of 5G. This necessitates efficient radio access network (RAN) slicing, defined as sharing of the wireless resources among diverse services while guaranteeing their respective throughput, timing, and/or reliability requirements. In this paper, we investigate RAN slicing for an uplink scenario in the form of multiple access schemes for two user types: (1) broadband users with throughput requirements and (2) intermittently active users with timing requirements, expressed as either latency-reliability (LR) or Peak Age of Information (PAoI). Broadband users transmit data continuously, hence, are allocated non-overlapping parts of the spectrum. We evaluate the trade-offs between the achievable throughput of a broadband user and the timing requirements of an intermittent user under Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA), considering capture. Our analysis shows that NOMA, in combination with packet-level coding, is a superior strategy in most cases for both LR and PAoI, achieving a similar LR with only slight 2% decrease in throughput with respect to the upper bound in performance. However, there are extreme cases where OMA achieves a slightly greater throughput than NOMA at the expense of an increased PAoI.

Index Terms—Age of Information (AoI), Heterogeneous services, Non-Orthogonal Multiple Access (NOMA), Reliability, Slicing.

I. INTRODUCTION

The fifth generation of mobile networks (5G) aims to support three main service categories: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). eMBB is the direct evolution of the 4G mobile broadband service with higher data rates, along with greater spectral and spatial efficiency. Even though eMBB use cases mainly occur in the downlink (e.g., video streaming or file download) novel eMBB use cases in the uplink are quickly gaining relevance. These include remote driving and live-video streaming in, for example, tactile internet applications and sport and cultural events. URLLC services, on the other hand, usually involve exchange of small amounts of data, but require latency in the order of a few milliseconds and high reliability guarantees, e.g., a packet loss ratio below 10^{-5}. Finally, mMTC also involves transmissions of small amounts of data per device, but consist of hundreds or thousands of devices in the service area. The main challenge in mMTC is to design access networking mechanisms that maximize the success probability while maintaining an adequate timing in data delivery and resource efficiency.

The main strategy for service co-existence adopted by 3GPP is network slicing, which refers to the allocation of subsets of the network resources to the active services. The idea is to provide performance guarantees by limiting the mutual impact among services and/or service categories. Arguably, in the context of the radio access network (RAN) the most natural form of slicing is frequency division multiple access (FDMA), which provides a high degree of isolation between services in different frequency bands. However, while FDMA slicing works well for high throughput services that are constantly demanding resources, it yields low utilization for intermittent services that are active only a fraction of the time. This motivates the search for alternative slicing schemes that are more suitable for heterogeneous services types.

In general, RAN slicing can be implemented in the form of Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA). OMA schemes, such as FDMA, time division multiple access (TDMA), and code division multiple access (CDMA), have been extensively studied and implemented in commercial and cellular systems. Moreover, OMA seems to be the approach preferred by 3GPP for 5G and beyond 5G systems, contextualized in the concept of bandwidth part. On the other hand, in NOMA the same time-frequency resources are assigned to multiple services or users. This allows, for example, to increase the number of served users with the available resources and/or the spectral efficiency of the system. To enable communication in shared time-frequency resources, NOMA is usually accompanied by multi-user detection techniques, like separation of the users in the code domain, or in the power domain accompanied with successive interference cancellation (SIC) where the individual signals are in turn decoded and subtracted from the received composite signal.

The difference between OMA and NOMA slicing is illustrated in Fig. Here, it can be seen that TDMA and NOMA achieve higher resource utilization than FDMA when the intermittent service transmits infrequently, while the difference will be less pronounced when the intermittent service transmits frequently. In the latter case, NOMA may even be inefficient due to the high amount of interference introduced to the broadband service. Further, TDMA faces the challenge of carefully dimensioning the allocated resources to the intermittent service, which is essential to achieve an acceptably low amount of idle resources (i.e., empty slots) and waiting time for transmission.
Despite this apparent trade-off between efficiency and timeliness of the slicing schemes, only a few studies have compared the performance between TDMA and NOMA with heterogeneous services \([9]–[11]\). On the other hand, OMA and NOMA slicing has been widely studied in the presence of multiple users of the same service type \([6], [12]–[14]\). For instance, the trade-offs in achievable data rates for eMBB services are characterized in an additive white Gaussian noise (AWGN) channel with OMA and power-domain NOMA \([13], [14]\). In our previous work, we derived the performance trade-offs with heterogeneous services with TDMA and NOMA with packet-level coding in a simplified collision channel model, which provides conservative results for NOMA \([11], [15]\). Some results with capture, obtained by simulation, were provided in \([11]\), which served as one of the main motivations for this study, as these illustrated the potential gains of NOMA. The aim of this work is to provide an extensive and exact analytical treatment of OMA and NOMA slicing in an uplink scenario with two different service types: broadband and intermittent users with throughput and timing requirements, respectively. Because the trade-off between TDMA and NOMA is least apparent, this combination is our primary focus and include FDMA as benchmark that neglects resource efficiency. Furthermore, to ensure a realistic evaluation, we consider a channel model with capture, which inevitably occurs in practice.

As mentioned, we assume that broadband users transmit data continuously and are primarily interested in achieving a high throughput. In contrast, intermittent users transmit short packets sporadically and are primarily interested in the timeliness of their data, according to the underlying application. To consider packet-level and flow-level timing requirements, we have selected two different Key Performance Indicators (KPIs). The first KPI, which reflects flow-level requirements, is Peak Age of Information (PAoI), relevant for users that send updates of an ongoing process in which the freshness of information is the most important objective. PAoI measures the time elapsed since the generation of the last received update until a new update is received \([16]\), and it is therefore determined by the transmission latency, reliability and the update generation pattern. PAoI-focused applications can tolerate individual packet losses, as there are no strict reliability requirements and new updates can supersede old ones. The second KPI, which reflects packet-level requirements, is denoted by latency-reliability (LR) and captures the probability of delivering individual packets within a given latency threshold \([17]\). For this, we use the distribution of latency where lost packets are defined to have infinite latency. LR captures, for example, URLLC traffic with strict constraints on the reliability of communication within a maximum latency. Our specific focus will be on computing high percentiles of LR and PAoI, which can be used to design systems with probabilistic reliability guarantees.

The scenario assumed in this paper comprises a single frequency band (i.e., bandwidth part in 5G New Radio (NR) terminology) sliced in time to accommodate one broadband and one intermittent user.\(^1\) We study OMA, focusing on TDMA but also including FDMA, and NOMA with SIC. In the latter case, SIC can be applied (1) in conjunction with the capture effect, such that the colliding packets are immediately resolved, and (2) coupled with the packet-level coding, such that after decoding of the broadband user block, the interference is removed and past packets from the intermittent user can be recovered. We analyze the achievable performance and the inherent trade-offs, providing closed-form expressions for throughput of the broadband user and timing of the intermittent user. The derivations are contextualized for a simple fading-based channel model, however, the elaborated approach is general and easily transferable to other settings.

In particular, the main contributions of this paper are the following.

- We provide exact expressions that allowed us to analyze the operating regions and trade-offs with OMA and NOMA with a realistic channel model that includes the possibility of capture. The results with this model show fundamental differences when compared to the analyses

\(^1\)The scenario is inspired by the latest non-orthogonal multiplexing approaches in the uplink studied by the 3GPP \([18]\).
carried out in our previous work and confirm the trends observed through simulations [11], [15].

- We analyze the impact of the wireless conditions of the intermittent user, including distance from the base station (BS) and path loss, in the performance of NOMA.
- We provide design guidelines for selecting the multiple access scheme and its parameters, depending on:
  1) The requirements and features of the different types of services in the system.
  2) The available bandwidth.
  3) The wireless conditions of the intermittent user.

We observe that, while FDMA provides the upper bound in performance, NOMA schemes offer significant benefits w.r.t. OMA when the target KPI for the intermittent user is LR. Specifically, NOMA can achieve similar performance trade-offs as FDMA but with a much higher resource utilization. On the other hand, the potential gains of NOMA w.r.t. TDMA decrease when the target KPI is PAoI, with TDMA outperforming NOMA in extreme cases where throughput is maximized in exchange for a longer PAoI.

The rest of the paper is organized as follows. Sec. II presents the related work on AoI and slicing-based access for heterogeneous user classes. The system model and KPIs are specified in Sec. III. We then derive the analytical distributions of those metrics for OMA and NOMA in Sec. IV and Sec. V respectively. Sec. VII presents simulation results and discussion of the performance of the different access schemes. Finally, Sec. VIII concludes the paper.

II. RELATED WORK

Non-orthogonal slicing, in the form of NOMA, offers the possibility of increasing the spectral efficiency and the number of supported users with respect to OMA in exchange for a greater decoding complexity at the receiver to perform SIC [5], [19] or other multi-user detection techniques. Hence, NOMA has been widely studied in the literature in systems with a single service type [5], [6], [12]–[14]. NOMA often assumes user separation in the power domain such that the benefits of SIC can be fully exploited. However, different performance gains have been observed for NOMA in the uplink and in the downlink. In particular, the effect of power control in the uplink can be eclipsed by the channel conditions of the users in combination with imperfect channel state information [19].

A particularly interesting approach towards heterogeneous service coexistence with NOMA is presented in [6], which emphasizes the importance of power control in NOMA and formulates resource allocation as a non-cooperative game and as a matching problem. While not addressing them directly, this non-cooperative game may be able to handle heterogeneous service types, as each user defines and attempts to maximize its own utility.

One of the first studies that addresses the coexistence of heterogeneous services in OMA and NOMA was presented in [10], considering different combinations of 5G services in an uplink scenario. Specifically, eMBB users are allocated orthogonal resources between them; these coexist with either one URLLC user or with mMTC traffic, which follows a Poisson distribution. It was observed that NOMA may offer benefits with respect to OMA depending on the rate of the eMBB users and on the type of coexisting traffic. Specifically, these benefits were evaluated in terms of the achievable rates for eMBB and URLLC traffic and the achievable eMBB rates as a function of the arrival rate of mMTC packets. This work was later extended to a multi-cell scenario with strict latency guarantees for URLLC traffic [20], where it was observed that NOMA leads to a greater spectral efficiency w.r.t. OMA. This same conclusion was drawn by Maatouk et al. [12] in an uplink scenario with two users with and one service type. The aim of the latter study was to minimize the average AoI, however, it was also observed that a greater spectral efficiency does not directly translate in a lower average AoI.

AoI is a relatively new performance metric, but it has been rapidly adopted due to its relevance in remote control tasks [21]. Most papers in the literature have examined it in the context of queuing theory, often in ideal systems with Markovian service [22], because of the relative simplicity of the analysis, but a few have considered the effect of physical layer issues and medium access schemes on it. Recent works compute the average AoI in Carrier Sense Multiple Access (CSMA) [23], ALOHA [24] and slotted ALOHA [25] networks, considering the impact of the different medium access policies on the age.

Another important missing piece in the AoI literature is the worst-case performance analysis: while studies on average AoI are common, the tail of its distribution is rarely considered [26], limiting the relevance of the existing body of work for reliability-oriented applications. The analytical complexity of deriving the complete distribution of the age is a daunting obstacle; only recently, advances have been made in this line. A recent work [27] uses the Chernoff bound to derive an upper bound of the quantile function of the AoI for two queues in tandem with deterministic arrivals. Using a more analytical approach, the PAoI distribution was computed over a single-hop link with fading and retransmissions in [28]. We also mention the work in [29], where different service classes are defined and the system is modeled as an M/G/1/1 clocking queue with hyperexponential service time. However, in the latter, only the service rate is different among classes. Then, the classes can adapt the arrival rate to minimize the AoI. Finally, for a more detailed overview of the literature on AoI, we refer the reader to [30].

III. SYSTEM MODEL

We consider an uplink scenario with a set of users \( U \) transmitting data to a BS through an Orthogonal Frequency-Division Multiple Access (OFDMA) system whose time-frequency resources are divided into time slots and bandwidth parts as in 5G NR [31]. A bandwidth part is defined as a set of contiguous resource blocks in the frequency domain. We consider the case where the users transmit up to one packet per time slot, occupying the whole bandwidth part. Herein, we consider the case where two heterogeneous users must be allocated resources. The options for the BS are 1) allocate the users in the same bandwidth part and define how
the resources should be shared among them or 2) allocate a

different bandwidth part for each of the users using FDMA.

User 1 is a broadband user following the eMBB model: it is a full-buffer user, that is, it always has data to transmit, and maintains an infinite transmission queue. To counteract potential packet losses due to fading and noise, the broadband user implements a packet-level coding scheme, where blocks of packets are encoded to generate a frame of N coded packets. The coded packets are transmitted in the same bandwidth part, one after the other, and have a zero probability of linear dependence, which can be achieved, for example, with Maximum Distance Separable (MDS) codes. Hence, the block of packets is decoded when any K packets from the same frame are received without errors.

User 2 is an intermittent user that, with a (relatively low) probability \( \alpha \), may generate a short packet at each slot. Each generated packet is transmitted just once at the next available time slot. User 2 maintains up to \( q \) of the generated packets in a transmission queue. We denote by \( q_t \) the length of the queue at time slot \( t \). If a new packet is generated when \( q_t = Q \), user 2 discards the oldest buffered packet and adds the newly generated one at the end of the queue.

When both users are allocated to the same bandwidth part, the BS must allocate the time slots that are available for the transmission of each of the two users. For this, we define the resource allocation set \( A_i \subseteq U \) as the subset of users that can access the bandwidth part at slot \( t \). We define the following three types of slot allocations.

1) Broadband: The slot is reserved for the broadband user. Hence, \( A_i = 1 \).

2) Intermittent: The slot is reserved for the intermittent user and may use it if it has one or more packets in its queue. Hence, \( A_i = 2 \).

3) Mixed: Both users are allowed to access the slot, implying that the signals will overlap if the intermittent user transmits. Hence, \( A_i = \{1, 2\} \).

Building on these, we define the following different access schemes.

1) TDMA: Both users are allocated resources in a single bandwidth part with separate broadband and intermittent slots. Specifically, the intermittent user has a reserved intermittent slot once every \( T_{int} \) slots, while the rest of the slots are reserved for the broadband user. As such, this is a non-orthogonal slicing in the frequency domain but orthogonal in the time domain where there is no interference among the users.

2) NOMA: Both users are allocated resources in a single bandwidth part with only mixed slots. Hence, the intermittent user may transmit at any slot. The two users interfere any time the intermittent user transmits, but the packets can be recovered through SIC by decoding one of the signals immediately or at a later time slot. More details on the operation of SIC are given in Section III-A.

3) FDMA: The users are allocated resources in different and non-overlapping bandwidth parts. Hence, one of the

bandwidth parts contains only broadband slots and the other bandwidth part contains only intermittent slots.

The frame structures for these access schemes are illustrated in Fig. 3. Naturally, FDMA can only take place when there are two bandwidth parts available. Needles to say, the bandwidth part allocated to the intermittent user with FDMA is likely to be under-utilized, as \( \alpha \) is relatively small. Hence, this approach results in a low resource efficiency, and is used here only as a benchmark scheme in which the performance of the users is fully independent of each other.

A. Channel model

We consider a block fading channel, where the received signal by the BS at time slot \( t \) is given as

\[
y_t = \sum_{u \in \{1, 2\}} h_{u,t}a_{u,t}x_{u,t} + z_t
\]

(1)

where \( h_{u,t} \in \mathbb{C} \) is the random fading coefficient for user \( u \) and \( z_t \) is the circularly-symmetric Gaussian noise with power \( \sigma^2 \). The variable \( a_{u,t} \) is an activity indicator, equal to 1 if the user is active in slot \( t \) and 0 otherwise. A user is active at time \( t \) if and only if \( u \in A_t \) and if its packet queue \( q_{a,t} \) is not empty

\[
a_{u,t} = I(u \in A_t)I(q_{a,t} > 0),
\]

(2)

where \( I(\cdot) \) is the indicator function, equal to 1 if the condition is true and 0 otherwise. Let \( P_u \leq P_{max} \) be the selected (i.e., fixed) transmission power for user \( u \), where \( P_{max} \) is the maximum transmission power. The signal-to-noise ratio (SNR) of user \( u \) is given as

\[
    \text{SNR}_{u,t} = \frac{|h_{u,t}|^2P_u a_{u,t}}{\sigma^2} = \frac{|h'_{u,t}|^2P_u a_{u,t}}{\ell_u \sigma^2},
\]

(3)

where \( \ell_u \) is the constant large-scale fading, including path loss, and \( |h'_{u,t}| \) is the envelope of the channel coefficient due to fast fading. The path loss is a function of the distance of user \( u \) to the BS \( r_u \), the carrier frequency \( f_c \), and a path loss exponent \( \eta \). We assume the standard path loss model

\[
    \ell_u = \left(\frac{4\pi f_c}{c^2}\right)^\eta r_u^\eta,
\]

(4)

where \( c \) is the speed of light.

The expected SNR for a transmission by user \( u \) is

\[
    \text{SNR}_u = \frac{E[|h_{u,t}|^2]}{\sigma^2} = \frac{E[|h'_{u,t}|^2]}{\ell_u \sigma^2},
\]

(5)
By using the standard assumption of treating the interfering signal as AWGN noise, the signal-to-interference-plus-noise ratio (SINR) for user \( u \) in the considered scenario is

\[
\text{SINR}_{u,t} = \frac{|h_{u,t}|^2 P_u o_{u,t}}{\sigma^2 + |h_{v,t}|^2 P_v o_{v,t}} = \text{SNR}_{u,t}, \quad \text{s.t. } v \neq u.
\]  

(6)

B. Reception model

Let \( X \) be the random variable (RV) of the number of packets from user 1 that belong to the same block and are received without errors. The success probability of user 1, denoted as \( p_{s,1} \), is defined as the probability of receiving \( K \) or more packets out of the \( N \) that comprise the block. That is,

\[
p_{s,1} = \Pr \{ X \geq K | N \}.
\]  

(7)

We define \( \gamma_u \) as the threshold in the SINR to decode a packet transmitted by user \( u \). In practice, the threshold is mainly a function of the modulation and coding scheme and the receiver sensitivity. In the following, we consider the case in which the fading envelope \( |h_{u,t}| \) is Rayleigh distributed and define the erasure probabilities for the two users.

Erasure probability for the broadband user: The BS has collected sufficient channel state information (CSI) about the broadband user so that the appropriate transmission power \( P_1 \leq P_{\text{max}} \), blocklength, and data rate (i.e., modulation and coding) to achieve a target erasure probability \( \varepsilon_1 \) are signaled back to the broadband user. Therefore, user 1 transmits with power

\[
P_1 \leq P_{\text{max}} : \Pr \{ \text{SNR}_{1,t} < \gamma_1 \} = \varepsilon_1
\]  

(8)

Erasure probability for the intermittent user: Due to the infrequent transmissions, the CSI of this user at the BS is insufficient to perform a precise selection of parameters as done for the broadband user. Instead, the user always transmits at \( P_2 = P_{\text{max}} \) and its erasure probability \( \varepsilon_2 \) is determined by its path loss \( \ell_2 \) and by \( \gamma_2 \). Hence, the erasure probability for user 2 is calculated from (5) as

\[
\varepsilon_2 = \Pr \{ \text{SNR}_{2,t} < \gamma_2 \} = 1 - e^{-\frac{\gamma_2}{P_o}} = 1 - e^{-\frac{\gamma_2}{\ell_2}}
\]  

(9)

since \( \mathbb{E} \{ |h_{u,t}'|^2 \} = 1 \) for unitary Rayleigh fading.

Based on these probabilities, we define six different outcomes for the cases where both users transmit in the same time slot. These outcomes are ordered pairs \( \{o_1, o_2\} \) where \( o_u \in \{I, E, R\} \) indicates the outcome of user \( u \)'s signal, described in the following.

- \( I \): Either 1) the signal of interest has sufficient SINR to be immediately decoded or 2) the other signal has sufficient SINR to be immediately decoded, its interference is removed through SIC, and the signal of interest has sufficient SINR and is decoded.
- \( E \): The signal has insufficient SINR to be decoded, even if the interference from the other signal is removed.
- \( R \): None of the signals has sufficient SINR to be decoded immediately, but the signal of interest has sufficient SINR to be decoded if interference from the other is removed. The probability of each of the outcomes, denoted as \( \pi_{o_1,o_2} \), is derived in the following based on the operation of SIC and under Rayleigh fading.

- \( (I, I) \): The signal with the highest SINR is decoded and its interference is immediately removed through SIC. Then, the second signal is decoded. This occurs with probability

\[
\pi_{II} = \Pr \left[ \frac{\text{SNR}_{1,t}}{1 + \text{SNR}_{2,t}} \geq \gamma_1 \land \frac{\text{SNR}_{2,t}}{1 + \text{SNR}_{1,t}} \geq \gamma_2 \right] + \Pr \left[ \frac{\text{SNR}_{2,t}}{1 + \text{SNR}_{1,t}} \geq \gamma_2 \land \frac{\text{SNR}_{1,t}}{1 + \text{SNR}_{2,t}} \geq \gamma_1 \right] = \frac{\text{SNR}_1}{\gamma_1} e^{-\frac{\gamma_1}{\text{SNR}_1}} e^{-\frac{\gamma_2}{\text{SNR}_2}} \left( 1 - e^{-\frac{\gamma_1}{\text{SNR}_1} + \frac{\gamma_2}{\text{SNR}_2}} \right) + \frac{\text{SNR}_2}{\gamma_2} e^{-\frac{\gamma_2}{\text{SNR}_2}} e^{-\frac{\gamma_1}{\text{SNR}_1}} \left( 1 - e^{-\frac{\gamma_1}{\text{SNR}_1} + \frac{\gamma_2}{\text{SNR}_2}} \right).
\]  

(10)

- \( (I, E) \): The signal with the higher SINR is decoded and its interference is immediately removed through SIC. However, the second signal cannot be decoded due to the impact of noise, i.e., a low SNR. These outcomes occur with probabilities

\[
\pi_{IE} = \Pr \left[ \frac{\text{SNR}_{1,t}}{1 + \text{SNR}_{2,t}} \geq \gamma_1 \land \frac{\text{SNR}_{2,t}}{1 + \text{SNR}_{1,t}} < \gamma_2 \right] = \frac{\text{SNR}_1}{\gamma_1} e^{-\frac{\gamma_1}{\text{SNR}_1}} \left( 1 - e^{-\frac{\gamma_2}{\text{SNR}_2}} \right) \left( 1 - e^{-\frac{\gamma_1}{\text{SNR}_1} + \frac{\gamma_2}{\text{SNR}_2}} \right). \tag{11}
\]

- \( (E, I) \): The SNR of both signals is insufficient and, thus, neither can be decoded even if the interference from the other user was removed. This occurs with probability

\[
\pi_{EI} = \Pr \left[ \frac{\text{SNR}_{2,t}}{1 + \text{SNR}_{1,t}} \geq \gamma_2 \land \frac{\text{SNR}_{1,t}}{1 + \text{SNR}_{2,t}} < \gamma_1 \right] = \frac{\text{SNR}_2}{\gamma_2} e^{-\frac{\gamma_2}{\text{SNR}_2}} \left( 1 - e^{-\frac{\gamma_1}{\text{SNR}_1}} \right) \left( 1 - e^{-\frac{\gamma_2}{\text{SNR}_2}} \right). \tag{12}
\]

- \( (E, E) \): The signal from user 2 has insufficient SNR, while the signal from user 1 has a sufficient SNR but insufficient SINR. Since the system cannot remove the interference from user 2 without decoding it first, both packets remain undecoded. This outcome occurs with probability

\[
\pi_{EE} = \Pr \left[ \frac{\text{SNR}_{2,t}}{1 + \text{SNR}_{1,t}} < \gamma_2 \land \frac{\text{SNR}_{1,t}}{1 + \text{SNR}_{2,t}} < \gamma_1 \right] = \left( 1 - e^{-\frac{\gamma_1}{\text{SNR}_1}} \right) \left( 1 - e^{-\frac{\gamma_2}{\text{SNR}_2}} \right). \tag{13}
\]

- \( (R, R) \): In this case, none of the signals can be immediately recovered but the signal from user 2 could...
be decoded if the interference from user 1 is removed via SIC after decoding the block of user 1. Therefore, this outcome includes the cases \((E, R)\) and \((R, \bar{R})\), and occurs with probability

\[
\pi_{\bar{R}} = 1 - \pi_{EE} - \pi_{IE} - \pi_{EI} - \pi_{EE} - \pi_{RI}. \quad (14)
\]

Note that the cases \((I, R)\) and \((R, I)\) are not feasible, as outcome \(I\) indicates that a signal is immediately decoded and that its interference to the other signal is removed.

C. Key Performance Indicators

The broadband user (user 1) is interested on maximizing its throughput \(S\) under the constraint that the desired reliability \(p_{s,1}\) must be greater than \(1 - \varepsilon_1\). Note that increasing the reliability of the broadband user entails a reduction in the coding rate \(K/N\).

The intermittent user (user 2) is interested on the timeliness of its data, i.e., either LR or PAoI, where we have selected their 90th percentile as the main KPIs. Let \(T\) and \(\Delta\) be the RVs of LR and PAoI, respectively. Then, the 90th percentile of LR is defined as

\[
T_{90} := \min\{n : \Pr[T \leq n] > 0.9\} \quad (15)
\]

and the 90th percentile of PAoI \(\Delta_{90}\) is defined analogously. Note that the latter allows us to evaluate the tail distribution of the PAoI in a general scenario and can be used to compare the performance with different values of \(\alpha\) [32].

Since \(S\) and the timeliness of the intermittent user are interlinked, we evaluate their trade-offs for a specific activation probability \(\alpha\) and erasure probabilities \(\varepsilon_u\), via the Pareto frontier defined in the following.

**Definition 1.** Let \(C\) be the set of feasible configurations for a specific access method and \(f : C \rightarrow \mathbb{R}^2\). Next, let

\[
Y = \{(S, \tau) : (S, \tau) = f(c), c \in C\},
\]

where \(S\) is the throughput of user 1 and \(\tau\) is the timeliness of user 2; \(\tau \in \{T_{90}, \Delta_{90}\}\). The Pareto frontier is the set

\[
\mathcal{P}(Y) = \{(S, \tau) \in Y : \forall (S', \tau') \in Y : S > S' \lor \tau < \tau'\}.
\]

Besides obtaining the Pareto frontiers, we evaluate the schemes by setting a minimum requirement for \(S\), the throughput of user 2. Then, the optimal configuration of an access method is defined as the combination of parameters that minimizes the timing, either LR or PAoI while maintaining \(S\) above the minimum required.

Table I summarizes the relevant notation introduced in this section. To simplify the analysis expressions in the rest of the paper, we define the binomial function \(\text{Bin}(K; N, p)\) as

\[
\text{Bin}(K; N, p) = \binom{N}{K} p^K (1 - p)^{N-K} \quad (16)
\]

and the multinomial function \(\text{Mult}(K; N, \mathbf{p})\) as

\[
\text{Mult}(K; N, \mathbf{p}) = \frac{N! \prod_{i=1}^{|\mathbf{p}|} K_i! (1 - \sum_{i=1}^{|\mathbf{p}|} p_i)^{N - \sum_{i=1}^{|\mathbf{p}|} K_i}}{(N - \sum_{i=1}^{|\mathbf{p}|} K_i)! \prod_{i=1}^{|\mathbf{p}|} K_i!},
\]

where \(|\mathbf{p}|\) is the length of vector \(\mathbf{p}\). Finally, we denote \(\delta(x)\) as the delta function, which is equal to 1 if \(x = 0\) and 0 otherwise, and \(|x|^+ = \max(x, 0)\).

IV. Performance with TDMA

Here we derive the KPIs for the TDMA system, for a LR- or PAoI-oriented intermittent user. For LR, the length of the intermittent user’s queue is assumed to be fixed to some \(Q \geq 1\). On the other hand, for PAoI, the length of the intermittent user’s queue is set to \(Q = 1\). This is because transmitting the newest packet is the optimal strategy to minimize PAoI but packet retransmissions are not allowed.

In the assumed TDMA system, the broadband user has frames of \(N\) slots, each of which contains \(K\) data packets and \(N - K\) redundancy packets, while the intermittent user has one reserved slot every \(T_{\text{int}}\). The success probability for user 1 is easy to compute

\[
p_{s,1} = \sum_{m=K}^{N} \text{Bin}(m; N, 1 - \varepsilon_1).
\]

The expected throughput of user 1 is

\[
S = p_{s,1} \frac{(T_{\text{int}} - 1)K}{T_{\text{int}}N}.
\]

That is, the throughput measures the rate of innovative (i.e., non-redundant) packets received at the BS from user 1 per time slot. As the broadband user can only use \(T_{\text{int}} - 1\) slots for each \(T_{\text{int}}\), setting up more frequent transmission opportunities for the intermittent user reduces the throughput.

A. Latency-reliability (LR)

In order to derive the probability mass function (pmf) of LR for the intermittent user, without loss of generality, we take the origin of time to be a slot in which a transmission occurs. We define a Markov chain representing the state of the queue \(q_t\) for the intermittent user, i.e., the number of packets in the queue at time \(t\). The transition matrix of the chain is \(\mathbf{P}^{(0)}\), whose elements \(P_{ij}^{(0)}\) represent the probability of transitioning from state \(i\) to state \(j\) in the queue of the intermittent user at the end of such slot [33]. The elements \(P_{ij}^{(0)}\) are obtained as

\[
P_{ij}^{(0)} = \begin{cases} 0 & \text{if } j < i - 1; \\
\text{Bin}(j - i + 1; T_{\text{int}}, \alpha) & \text{if } i - 1 \leq j < Q; \\
\sum_{m=Q-i+1}^{T_{\text{int}}} \text{Bin}(m; T_{\text{int}}, \alpha) & \text{if } j = Q.
\end{cases}
\]

Let \(\varphi^{(0)} = [\varphi_0^{(0)}, \varphi_1^{(0)}, \ldots, \varphi_Q^{(0)}]\) be the steady-state distribution vector of the queue immediately after a transmission. From the transition matrix computed in (20), we can easily derive \(\varphi^{(0)}\) as the left-eigenvector of \(\mathbf{P}^{(0)}\) with eigenvalue 1, normalized to sum to 1 to be a valid probability metric

\[
\varphi^{(0)}(I - \mathbf{P}^{(0)}) = 0 \land \sum_{q=0}^{Q} \varphi_q^{(0)} = 1.
\]

It is easy to derive the steady-state distribution of the queue \(q_n\) (i.e., \(n\) slots after a transmission) as

\[
\varphi_q^{(n)} = \begin{cases}
\sum_{s=0}^{q} \varphi_s^{(0)} \text{Bin}(q - s; n\alpha) & \text{if } q < Q; \\
\sum_{s=0}^{Q} \sum_{m=Q-s}^{Q} \varphi_s^{(0)} \text{Bin}(m; n, \alpha) & \text{if } q = Q.
\end{cases}
\]

(22)
TABLE I: Notation summary

| Symbol   | Description                                      | Symbol   | Description                                      |
|----------|--------------------------------------------------|----------|--------------------------------------------------|
| $\mathcal{U} = \{1, 2\}$ | Set of users; $u = 1$ is the broadband user and $u = 2$ is the intermittent user | $P_u$ | Transmission power of user $u$ |
| $K$ | Size of the source block for user 1 | $\text{SNR}_u$ | Expected SNR for user $u$ |
| $N$ | Size of the coded block for user 1 | $\text{SNR}_{u,t}$ | SNR of user $u$ at slot $t$ |
| $Q$ | Maximum queue length for user 2 | $\varepsilon_u$ | Erasure probability of user $u$ |
| $T_{\text{int}}$ | Period between slots allocated to user 2 in TDMA | $o_u \in \{I, R, E\}$ | Outcome for user $u$ when signals overlap |
| $t \in \mathbb{Z}$ | Time slot index | $(a_1, a_2)$ | Outcome when signals overlap |
| $q_t$ | Length of the queue for user 2 at $t$ | $\pi_{01,02}$ | Probability of outcome $(0_1, 0_2)$ |
| $A_t \subseteq \mathcal{U}$ | Allocation of time slot $t$ | $p_{s, u}$ | Success probability of user $u$ |
| $o_{u,t}$ | Activity indicator for user $u$ at $t$; 1 if active | $S$ | Throughput of user 1 |
| $h_{u,t}$ | Fading envelope for user $u$ at $t$ | $T$ | RV of LR for user 2 |
| $\sigma^2$ | Noise power | $\Delta$ | RV of AoI for user 2 |
| $\ell_u$ | Path loss of user $u$ | $T_{90}$, $\Delta_{90}$ | 90th percentile of LR and AoI |
| $r$ | Distance between user 2 and the BS | $\delta(x)$ | Delta function, equal to 1 if $x = 0$ and 0 otherwise |

where $\varphi^{(q)}_k$ is the $q$-th element of vector $\varphi^{(0)}$. If a packet is queued behind $q$ others, it will be transmitted at the $(q + 1)$-th opportunity, unless new arrivals make the system drop some of the packets ahead of it in the queue: we remind the reader that, if the queue is full, the oldest packet (i.e., the first in the queue) is dropped. Let $g_i \in \{0, 1, \ldots, T_{\text{int}}\}$ for $i \geq 1$ be the number of packets generated by user 2 between the $i$-th and $(i + 1)$-th intermittent slots after the current one. Further, let $g_0$ be the number of packets generated between the current time slot and the next intermittent slot. We define

$$G_{\ell}^{(n)} = \{ [g_0 \in \{0, 1, \ldots, T_{\text{int}} - n\}; g_1, \ldots, g_\ell] \}$$  \hspace{1cm} (23)

be the set of possible vectors for the number of packets generated by user 1 given that there are $T_{\text{int}} - n$ slots until the next intermittent slot.

The probability of occurrence of each element $g \in G_{\ell}^{(n)}$ is

$$p_{\text{gen}}(g; \ell, n) = \text{Bin}(g_0; T_{\text{int}} - n, \alpha) \prod_{i=1}^{\ell} \text{Bin}(g_i; T_{\text{int}}, \alpha).$$  \hspace{1cm} (24)

At each intermittent slot, up to one packet is transmitted and, hence, removed from the queue. Other packets are removed if the number of generated packets exceeds the number of remaining spaces in the queue. For a given vector $g \in G_{\ell}^{(n)}$, the considered packet is transmitted at the $\ell$-th transmission opportunity, where $\ell$ is the first index that satisfies condition $\psi_k^{(g, q)}$ if the packet has $q$ others ahead of it in the queue

$$\psi_k^{(g, q)} = \delta \left( \sum_{i=1}^{k} \left[ q + 1 - Q + \sum_{j=1}^{i} g_j \right] + k - (q + 1) \right).$$  \hspace{1cm} (25)

We now define the set $S_{\ell}^{(n, q)}$, which contains the elements $g \in G_{\ell}^{(n)}$ for which the considered packet is transmitted at the $\ell$-th opportunity

$$S_{\ell}^{(n, q)} = \{ g \in G_{\ell}^{(n)} : \psi_k^{(g, q)} - \sum_{k=1}^{\ell-1} \psi_k^{(g, q)} = 1 \}. $$  \hspace{1cm} (26)

Since the packet is either transmitted within $q + 1$ transmission attempts or discarded, the conditioned success probability $p_{s, 2}(n, q; T_{\text{int}})$ for the intermittent user is given by

$$p_{s, 2}(n, q) = \sum_{\ell=1}^{q+1} \sum_{g \in S_{\ell}^{(n, q)}} p_{\text{gen}}(g; \ell, n) (1 - \varepsilon_2).$$  \hspace{1cm} (27)

We can now compute the latency pmf $p_T(t)$, considering the fact that it takes 1 slot to transmit the packet

$$p_T(t) = \sum_{n=1}^{T_{\text{int}}} \sum_{q=0}^{Q} \sum_{g \in S_{\ell}^{(n, \min(q, Q-1)} \frac{p_{\text{gen}} \left( g; t+n-1, T_{\text{int}} \right) \times \varphi_q^{(n-1)} \delta \left( t+n-1 - \left[ \frac{t+n-1}{T_{\text{int}}} \right] \right)}{T_{\text{int}} p_{s, 2}(n, q; T_{\text{int}})}.$$  \hspace{1cm} (28)

The success probability of the intermittent user is

$$p_{s, 2} = \sum_{n=1}^{T_{\text{int}}} \sum_{q=0}^{Q} \frac{\varphi_q^{(n-1)} p_{s, 2}(n, q; \cdot)}{T_{\text{int}}}.$$  \hspace{1cm} (29)

B. Peak age

In the PAoI-oriented case, the pmf is given by the sum of the waiting time $W$ and the inter-update interval $Z$ [21].

Since $Q = 1$, the generated packets are always sent at the first available transmission opportunity. The pmf of the waiting time $W$ for a successful transmission is given by:

$$p_W(w) = \frac{\alpha (1 - \alpha)^{w-1}}{1 - (1 - \alpha)^{T_{\text{int}}}}, \ w \in \{1, \ldots, T_{\text{int}}\}.$$  \hspace{1cm} (30)

We now compute the pmf of $Z$. Since exactly one slot every $T_{\text{int}}$ is reserved for the intermittent user, $Z$ is $T_{\text{int}}$ times the number of reserved slots between consecutive successful transmissions. This is a geometric random variable, whose probability of successful transmission is given by:

$$\xi = (1 - (1 - \alpha) T_{\text{int}}) (1 - \varepsilon_2).$$  \hspace{1cm} (31)

The pmf of $Z$ is then

$$p_Z(z) = (1 - \xi)^{\frac{T_{\text{int}} - 1}{\xi}} \delta \left( \mod(z, T_{\text{int}}) \right).$$  \hspace{1cm} (32)
The pmf of the PAoI is

\[ p_\Delta(t + 1) = p_Z(t - \text{mod}(t, T_{\text{im}})) p_W(1 + \text{mod}(t, T_{\text{im}})). \]  

(33)

V. PERFORMANCE WITH NOMA

We now derive the distributions of the KPIs in the NOMA case, in which the broadband user has frames of \( N \) slots, all of which are mixed, i.e., allocated both to the intermittent and broadband user.

First, we define \( p_1 \) as the probability that a packet from the broadband user is received in a given slot, which is given by

\[ p_1 = ((1 - \alpha)(1 - \varepsilon_1) + \alpha(\pi_{\mathcal{II}} + \pi_{\mathcal{IE}})). \]  

(34)

The probability that the block from the broadband user is decoded in the \( d \)-th slot of the frame, denoted as \( p_D(d) \), is

\[ p_D(d) = p_1 \text{Bin}(K - 1; d - 1, p_1), \]  

(35)

The Cumulative Distribution Function (CDF) of the decoding instant \( D \), \( P_D(d) \), is

\[ P_D(d) = \sum_{m=0}^{d} \text{Bin}(m; d, p_1). \]  

(36)

We then simply have \( p_{s,1} = P_D(N) \). The average throughput for the broadband user is

\[ S = \frac{K P_D(N)}{N}. \]  

(37)

A. Latency-reliability (LR)

We now analyze the latency distribution for the intermittent user. All the intermittent packets transmitted after decoding slot \( d \) – once the block from the broadband user has been decoded – can be either decoded immediately or lost. Specifically, these packets are lost with probability \( \varepsilon_2 = \pi_{\mathcal{IE}} + \pi_{\mathcal{RE}} \). On the other hand, if the intermittent user packet is sent before the decoding slot \( d \), it is decoded instantly with probability \( \pi_{\mathcal{II}} + \pi_{\mathcal{EI}} \), while it can be decoded after SIC with probability \( \pi_{\mathcal{RE}} \).

In order to compute \( p_{s,2} \), we need to compute the conditioned probability of having \( a_d \) collisions between the two users before the broadband user block is decoded in slot \( d \), \( i_d \) of which result in an immediate decoding, while \( v_b \) are decoded after SIC, for the intermittent user. This is denoted as \( p_{A_d, I_d, V_b|D}(a_d, i_d, v_b|d) \), and given by:

\[ p_{A_d, I_d, V_b|D}(a_d, i_d, v_b|d) = \sum_{\ell = K - d + a_b}^{\min(a_d, K - 1)} \text{Bin}(a_b; d - 1, \alpha) \times \frac{p_1^{\min(i_d, \ell)}}{P_D(d)} \sum_{m=0}^{\min(i_d, \ell)} \text{Bin}(K - 1 - \ell; d - 1 - a_b, 1 - \varepsilon_1) \times \text{Mult}(\{m, i_d - m, v_b, \ell - m\}; a_d, [\pi_{\mathcal{II}}, \pi_{\mathcal{EI}}, \pi_{\mathcal{RE}}, \pi_{\mathcal{IE}}]). \]  

(38)

We can then simply take the four cases for packets from the intermittent user (transmitted before slot \( d \), in slot \( d \), after slot \( d \), or in lost frames), and compute \( p_{s,2} \). We can compute \( p_{A_d, I_d}(a_d, i_d) \), the probability that a packet from user 2 is sent and correctly decoded in the same slot as the broadband user block decoding:

\[ p_{A_d, I_d}(a_d, i_d) = \begin{cases} \frac{\alpha \pi_{\mathcal{II}}}{p_1}, & a_d = 1, i_d = 1; \\ \frac{\alpha \pi_{\mathcal{IE}}}{p_1}, & a_d = 1, i_d = 0; \\ \frac{(1 - \alpha)(1 - \varepsilon_1)}{p_1}, & a_d = 0, i_d = 0; \\ 0, & \text{otherwise.} \end{cases} \]  

(39)

We then give the probability of having \( A_a \) packets after the decoding of the broadband user block in slot \( d \), \( I_a \) of which are correctly received:

\[ p_{A_a, I_a|D}(a_a, i_a|d) = \text{Bin}(i_a; a_a, \pi_{\mathcal{IE}} + \pi_{\mathcal{EI}} + \pi_{\mathcal{RE}}) \times \text{Bin}(a_a; N - d, \alpha). \]  

(40)

Finally, we can consider the case in which the broadband user frame is not decoded: in this case, the only intermittent packets that are decoded are immediate captures. We can then compute the probability \( p_{A_a, I_a|D}(i_a, z) \):

\[ p_{A_a, I_a|D}(i_a, z) = \sum_{c=0}^{\min(K - 1 - N - a)} \text{Bin}(c; N - a, 1 - \alpha) \sum_{\ell=0}^{\min(i_a, K - 1 - c)} \text{Mult}(\{m - i_a, i_a - m, \ell - m\}; a_a, [\pi_{\mathcal{II}}, \pi_{\mathcal{EI}}, \pi_{\mathcal{RE}}]). \]  

(41)

We now know that all packets transmitted by the intermittent user at or after the decoding of the broadband block, or in frames for which the broadband block is not decoded, are either lost or decoded immediately. To compute the latency distribution, we then only need to distinguish the case in which a packet transmitted before \( d \) is decoded instantly or after SIC. The probability of a packet from the intermittent user being decoded instantly is then \( p_{r}(1) \):

\[ p_{r}(1) = (1 - p_{s,1}) \sum_{a_d=1}^{N} \sum_{i_d=0}^{\min(K, t-1)} \frac{i_a p_{A_d, I_d|D}(a_d, i_d)}{(1 - \text{Bin}(0; N, \alpha))} \times \sum_{d=K}^{N} \sum_{a_d=0}^{N - d} \sum_{i_d=0}^{a_d - i_d} \sum_{v_b=0}^{a_d - i_d} p_D(d) \times \text{Mult}(\{i_d, v_b\}; a_d, [\pi_{\mathcal{II}}, \pi_{\mathcal{EI}}, \pi_{\mathcal{RE}}]). \]  

(42)

As the delay from any packet decoded after SIC is distributed uniformly between 2 and \( d + 1 \), we can easily compute \( p_{r}(t) \):

\[ p_{r}(t) = \frac{N - d - 1}{d} \sum_{d=K}^{N} \sum_{a_d=0}^{N - d} \sum_{i_d=0}^{a_d - i_d} \sum_{v_b=0}^{a_d - i_d} \frac{p_D(d) p_{A_d, I_d|D}(a_d, i_d|d)}{(1 - \text{Bin}(0; N, \alpha))} \times \text{Mult}(\{i_d, v_b\}; a_d, [\pi_{\mathcal{II}}, \pi_{\mathcal{EI}}, \pi_{\mathcal{RE}}]). \]  

(43)

The combination of (42) and (43) is the latency-reliability pmf for the intermittent user. We then have:

\[ p_{s,2} = \sum_{t=1}^{N} p_{r}(t). \]  

(44)
B. Peak age

In order to derive the pmf of the PAoI, we first need to compute some auxiliary values. First, we derive the probability that the first decoded packet from the intermittent user in a frame is decoded in slot $f$, denoted as $p_F(f)$ and given in (45).

It is then easy to get $p_c$, the probability of decoding no new intermittent packets in a frame:

$$p_c = 1 - \sum_{f=1}^{N} p_F(f).$$  

(46)

The pmf of the number of slots $Y$ from the beginning of a given frame until the first decoded packet from the intermittent user is

$$p_Y(y) = p_c \left(1 - p_c\right)^{y-1},$$  

(47)

where $\text{mod}(m, n)$ is the integer modulo function.

We now consider the probability $p_U(u)$ of receiving an update from the intermittent user, i.e., a packet with newer information than the one already available. We have the following pmf, conditioned on the decoding slot $d$ of the broadband block. First, we consider the case in which $d < u$

$$p_{U|D}(u|d) = \sum_{a_b=1}^{d-1} \sum_{i_b=1}^{a_b} \sum_{i_d=0}^{a_b-i_b} \sum_{v_b=0}^{d-1} \frac{i_b p_{A_b,i_b|D}(a_b, i_b, v_b)}{d-1}, \quad d < u.$$  

(48)

Next, for $d > u$

$$p_{U|D}(u|d) = \sum_{a_b=1}^{N-d} \sum_{i_b=1}^{a_b} \sum_{i_d=0}^{a_b-i_b} \sum_{v_b=0}^{d-1} \frac{i_b p_{A_b,i_b|D}(a_b, i_b, v_b)}{N-d}, \quad d > u.$$  

(49)

Finally, for $d = u$

$$p_{U|D}(u|d) = \sum_{a_b=1}^{d-1} \sum_{i_b=1}^{a_b} \sum_{i_d=0}^{a_b-i_b} \sum_{v_b=0}^{d-1} \frac{i_b p_{A_b,i_b|D}(a_b, i_b, v_b)}{d-1}, \quad d = u.$$  

(50)

where $H_{M,N}(m, n)$ is the hypergeometric distribution, whose pmf is given by

$$H_{M,N}(m, n) = \binom{M}{m} \binom{N-M}{n}.$$  

(51)

We also consider the probability $p_{U|D}(u)$, i.e., the probability of receiving an update in slot $u$ if the broadband user block is not decoded

$$p_{U|D}(u) = \sum_{a_b=1}^{N} \sum_{i_b=1}^{a_b} \frac{i_b p_{A_b,i_b|D}(a_b, i_b)}{N}.$$  

(52)

By applying the law of total probability, we obtain $p_U(u)$

$$p_U(u) = \sum_{d=K}^{N} p_D(d) p_{U|D}(u|d) + (1 - p_{x,1}) p_{U|D}(u).$$  

(53)

We now compute the probability that a given update is the last in the frame, given that the decoding happens in slot $d$, denoted as $p_{L|D}(\ell|d)$. Again, we distinguish three cases, starting from $\ell < d$:

$$p_{L|D}(\ell|d) = \sum_{a_b=1}^{d-1} \sum_{i_b=1}^{\ell-i_b} \sum_{i_d=0}^{\ell-d} \sum_{v_b=0}^{d-1} \frac{i_b p_{A_b,i_b|D}(a_b, i_b, v_b)}{d-1} \times p_{A_b,i_b,v_b|D}(a_b, i_b, v_b) \times H_{\ell-1,d-2}(v_b + i_b - 1, v_b + i_b - 1), \quad \ell < d.$$  

(54)

If $\ell = d$, we have:

$$p_{L|D}(d|d) = \sum_{a_b=0}^{N-d} p_{A_b,i_b|D}(a_b, 0|d).$$  

(55)

Finally, if $\ell > d$ the probability is

$$p_{L|D}(\ell|d) = \sum_{a_b=1}^{\ell} \sum_{i_b=1}^{a_b} \frac{i_b p_{A_b,i_b|D}(a_b, i_b|d)}{(N-d) p_{U|D}(\ell|d)} \times H_{\ell-d-1,N-d-1}(i_b - 1, i_b - 1), \quad \ell > d.$$  

(56)

The probability that an update in slot $\ell$ is the last in the frame, given that the broadband user frame is lost, $p_{L|D}(\ell)$, is

$$p_{L|D}(\ell) = \sum_{a_b=1}^{\ell} \sum_{i_b=1}^{a_b} \frac{i_b p_{A_b,i_b|D}(a_b, i_b|d)}{N p_{U|D}(\ell)}.$$  

(57)

Combining the expressions derived above, we get

$$p_L(\ell) = \sum_{d=K}^{N} p_D(d) p_{L|D}(\ell|d) + (1 - p_{x,1}) p_{L|D}(\ell).$$  

(58)

If the update is not the last in the frame, we can compute the conditioned pmf $p_{Z|U,D,L}(z|u,d)$ of the inter-update interval $Z$. We first consider the case in which $z + u < d$

$$p_{Z|U,D,L}(z|u,d) = \sum_{a_b=2}^{d-1} \sum_{i_b=2}^{a_b} \frac{i_b (i_b - 1) H_{z+1,d-3}(0, i_b - 2)}{p_{U|D}(u|d)} \times p_{A_b,i_b,v_b|D}(a_b, i_b, v_b) \times H_{z+1,d-3,1,1}(0, i_b, v_b).$$  

(59)

In this case, the only possibility to have another update after $z$ is to have two immediate captures in slots $u$ and $u+z$, without any immediate captures in between. Further, for $u > d$

$$p_{Z|U,D,L}(z|u,d) = \sum_{a_b=2}^{N-d-z+1} \sum_{i_b=2}^{a_b} \frac{i_b (i_b - 1) H_{z+1,N-d-3}(0, i_b - 2)}{p_{U|D}(u|d)(1 - p_{L|D}(d|d))}.$$  

(60)

Next, for $u = d$:

$$p_{Z|U,D,L}(z|d) = \sum_{a_b=1}^{N-d-z+1} \sum_{i_b=1}^{a_b} \frac{i_b p_{A_b,i_b|D}(a_b, i_b|d)}{(N-d)(1 - p_{L|D}(d|d))} \times H_{z+1,N-d-1}(0, i_b - 1).$$  

(61)
In all other cases, the packet is captured instantaneously, and we have

\[ p_{W|U,D}(w|u, d) = \delta(w - 1), \quad u \neq d. \]  

If the broadband user frame is not decoded, the decoding delay is always 1, as the only updates are due to immediate capture

\[ p_{W|U, D}(w|u) = \delta(w - 1). \]  

By applying the law of total probability, we get

\[ p_{W|U}(w|u) = \sum_{d=K}^{N} p_D(d) p_{W|U,D}(w|u, d) + (1 - p_{s,2}) p_{W|U,D}(w|u). \]  

Finally, we get the PAoI as the convolution of \( Z \) and \( W \) and removing the condition on \( U \)

\[ p_{\Delta}(t) = \sum_{u=1}^{N} p_u(u) \sum_{w=1}^{\min(u, t-1)} p_{W|U}(w|u)p_{Z|U}(t - w|u). \]
VI. BENCHMARK: PERFORMANCE WITH FDMA

In case of FDMA, the two users are occupying a dedicated bandwidth part each, and their KPIs are independent. The success probability for user 1 is equal to that in TDMA, given by (18). The throughput of user 1 can be computed by setting $T_{\text{int}} \to \infty$ in (19), which gives

$$S = \frac{K p_{s,1}}{N}. \quad (71)$$

For user 2, the latency for all successfully decoded packets is 1. Further, $p_{s,2} = 1 - \varepsilon_2$ and the pmf of LR is simply $p_{\Delta}(t) = \delta(t-1)$.

The PAoI for user 2 can be obtained as the latency $T = 1$ plus the inter-decoding time $Z$ when setting $T_{\text{int}} = 1$ in (31) and (32). Hence, it is simply a function of the inter-arrival time and $\varepsilon_2$. Namely,

$$p_{\Delta}(t) = (1 - \alpha (1 - \varepsilon_2))^l - 2 \alpha (1 - \varepsilon_2), \quad t \geq 2. \quad (72)$$

VII. EVALUATION

We assume that user 1 (the broadband user) selects its transmission power to achieve $\varepsilon_1 = 0.1$. On the other hand, user 2 (the intermittent user) transmits infrequently, and thus cannot get up-to-date information on the channel state. The best possible strategy for it is then to always transmit at maximum power; in this case, $\varepsilon_2$ depends on its distance from the BS $r$ and the erasure probability $\varepsilon_2$ is minimized.

For performance evaluation, we set parameters that represent a typical 5G urban scenario [1]. Namely, the carrier frequency is 2 GHz, the path loss exponent is $\eta \in \{2, 6, 3\}$ dB, the noise power $\sigma^2$ is determined by the noise temperature and the subcarrier spacing, set to a typical $\Delta f = 15$ kHz, plus a noise figure of 5 dB. The resulting noise power and other relevant parameter settings are listed in Table II. For simplicity’s sake, the SINR thresholds for decoding both users are set to the same value $\gamma_1 = \gamma_2 = 3$ dB. As a reference, the SNIR threshold when calculating the maximum coverage in 5G is 0 dB [1]. Fig. 4 show the area plots for the probability of the outcomes when both users transmit in the same slot for $\eta \in \{2, 6, 3\}$. The figure shows that a high reliability for the intermittent user is only achievable when it is close to the base station, particularly when $\eta = 3$. On the other hand, recovering packets after decoding the broadband user block is crucial, as case $(\cdot, R)$ occurs with a relatively high probability for both values of $\eta$ and is critical to achieve high reliability for the intermittent user.

An essential aspect of our analysis is to identify the values of $K$ and $N$ that maximize the throughput $S$ of user 1. These can be selected independently of user 2’s parameters for TDMA and FDMA and, hence, represent the optimal configuration for user 1 with these schemes.

Note that implementing a longer coded block size $N$ would grant a greater throughput, bounded by $1 - \varepsilon_1$ for $N \to \infty$, but would also lead to a longer decoding latency and complexity. Hence, we limit the value of $N \leq 32$ to achieve an adequate balance between $S$ and decoding latency and complexity. By restricting $N \leq 32$, the optimal configuration for user 1 for both TDMA and FDMA is $K = 26$ and $N = 32$, which leads to $p_{s,1} = 0.964$. With this configuration, FDMA achieves a throughput of $S = 0.7833$ for all cases, as user 1 operates in a separate channel from user 2 and, hence, there is no trade-off between $S$ and the KPI of user 2. On the other hand, the optimal configuration for TDMA and NOMA depends on the desired performance trade-off and, hence, these are given at the end of this section.

A. Pareto analysis

We first present the Pareto frontier for throughput of user 1 $S$ and timing of user 2, for LR $T_{90}$ or PAoI $\Delta_{90}$, which describes the best achievable trade-offs between these KPIs. We consider three different distances (50, 150, and 250 m) for the intermittent user, with three different activation probabilities. It is easy to see in Fig. 5 that NOMA easily outperforms TDMA in terms of LR and throughput in all scenarios.

Furthermore, Fig. 5a shows that $T_{90} = 1$ can be achieved with NOMA if the distance and path loss allow to immediately decode more than 90% of the packets from user 2 due to capture and the use of SIC in the same slot. In these cases, the throughput with NOMA is only up to 2% lower than with FDMA. Therefore, NOMA is the most efficient access scheme in these cases, as it achieves a similar performance to FDMA but with half the resources: one bandwidth part instead of two.

On the other hand, there is a strict trade-off between LR and throughput for all cases with TDMA, as the only way to reduce the latency is to decrease the period between intermittent slot $T_{\text{int}}$, which decreases the resources assigned to the broadband user. The same trade-off appears with NOMA for the cases where $\pi_{T, I} + \pi_{R, I} < 0.9$ due to an increase in path loss, shown in Fig. 5d. In these, reducing the latency also requires reducing the efficiency of the code. However, the Pareto frontier for NOMA is always above and to the left of the curve for the equivalent scenario with TDMA, showing that NOMA is clearly the best choice in this scenario. The frontiers for $r = 250$ m and path loss exponent $\eta = 3$ are not shown, as

### TABLE II: Parameter settings

| Parameter                              | Symbol | Setting                        | Parameter                              | symbol | Setting                        |
|----------------------------------------|--------|--------------------------------|----------------------------------------|--------|--------------------------------|
| Coded block length for user 1          | $N$    | $\{2, 3, \ldots, 32\}$        | Source block length for user 1          | $K$    | $< N$                         |
| Erasure probability of user 1          | $\varepsilon_1$ | 0.1                           | Transmission power of user 2            | $P_2$  | 23 dBm                        |
| Activation probability for user 2      | $\alpha$ | $\{0.01, 0.05, 0.1\}$         | Period between intermittent slots in TDMA | $T_{\text{int}}$ | $\{1, 2, \ldots, 40\}$ |
| SINR threshold to decode a packet      | $\gamma_1 = \gamma_2$ | 3 dB                          | Noise power                             | $\sigma^2$ | $-127.216$ dBm                |
| Distance from user 2 to the BS         | $r$    | $\{50, 100, \ldots, 400\}$ m | Carrier frequency                       | $f_c$  | 2 GHz                         |
| Path loss exponent                     | $\eta$ | $\{2.6, 3\}$                  | Queue length in TDMA                   | $Q$    | 4 packets                     |

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This is expected, as greater values of $T$ throughput than NOMA at the expense of an increase in PAoI.

Thus, the resource efficiency of NOMA is much greater than $\Delta$ and reaches its maximum $S \approx 0.78$, which is close to the one achieved with FDMA of 0.7833. This occurs at exactly or only a few time slots later than the minimum $\Delta_{90}$. Thus, the resource efficiency of NOMA is much greater than that of FDMA and achieves similar trade-offs.

On the other hand, for $r \geq 150$ m, TDMA achieves a higher throughput than NOMA at the expense of an increase in PAoI. This is expected, as greater values of $T_{\text{int}}$ increase $S$ but also $\Delta$. Specifically, as described in Section VI, the throughput with TDMA for $T_{\text{int}} \rightarrow \infty$ is equal to that with FDMA.

Note, however, that the activation rate $\alpha$ has the greatest impact on the PAoI. This is because the interval time between consecutive packets with low values of $\alpha$ can be so long that reducing the latency for each individual packet has only a minor effect on the PAoI.

### B. Distance analysis

We now investigate the performance of the schemes as a function of the distance $r$ between user 2 and the base station. In this case, we also consider the case for NOMA with fully destructive interference and, hence, no capture, which was investigated in our previous work [11]. In this later case, we have $\pi_{\lambda, \lambda} = 1 - \varepsilon_2$ and $\pi_{\lambda, \varepsilon} = \varepsilon_2$ for any slot in which the two users collide, eliminating the possibility of instantaneous SIC. This scenario is naturally a lower bound for NOMA’s performance, as removing the possibility of capture makes the scheme perform significantly worse.
Fig. 6 shows the performance of the schemes in terms of the minimum LR $T_{90}$ that can be achieved while fulfilling a relatively high throughput requirement $S \geq 0.7$ for $\alpha = 0.01, 0.05$. In general, NOMA can outperform TDMA in most cases, but it is interesting to observe the behavior of the schemes when $\alpha$ is high. In these cases, we notice a performance drop for both TDMA, which has to allocate more slots to the intermittent user, and NOMA without capture, which has to increase the robustness of the packet-level code to protect the transmission from the additional intermittent user packets. On the other hand, capture allows NOMA to be more robust to the increased activation probability, maintaining a performance that is close to FDMA. In fact, while not shown in the figures, NOMA and, naturally, FDMA are the only schemes that can achieve $S \geq 0.7$ with $\alpha = 0.1$, while the other schemes do not achieve the required throughput for any configuration.

On the other hand, we can confirm the trend that we observed in Fig. 6 for PAoI at different distances, as Fig. 8 shows that NOMA achieves a slightly lower $\Delta_{90}$ than TDMA. However, capture is essential for the NOMA scheme with higher values of $\alpha$: without it, it performs slightly worse than TDMA for $\alpha = 0.05$, and it never reaches the required throughput for $\alpha = 0.1$. Finally, it can be seen that NOMA achieves similar values of $\Delta_{90}$ than FDMA for (1) most values of $r$ with $\eta = 2.6$ and (2) short distances $r \leq 150$ with $\eta = 3$. This demonstrates that, in the cases where the system can benefit from capture and SIC, NOMA is nearly equivalent to
Fig. 7: Minimum LR with $S \geq 0.7$ as a function of the distance between user 2 and the BS for different values of $\alpha$.

Fig. 8: Minimum PAoI with $S \geq 0.7$ as a function of the distance between user 2 and the BS for different values of $\alpha$. 
FDMA in terms of performance, even when the latter utilizes twice the amount of resources. These cases occur, for example, when pairing the broadband user with an intermittent user located near the BS and, hence, that achieves a high mean SNR.

C. Parameter analysis

We conclude by investigating the optimal configurations for the schemes as a function of the distance of user 2, under the constraint $S \geq 0.7$. Fig. 9a shows the optimal values of $K$ and $N$ for NOMA and $T_{\text{int}}$ for TDMA, for both LR-oriented and PAoI-oriented systems with $\eta = 2.6$. Fig. 9a-b, which are related to LR-oriented systems, show that the value of $T_{\text{int}}$ is always 14, independently from the distance. On the other hand, LR-oriented NOMA systems tend to slightly increase both $K$ and $N$ as the distance increases. This occurs because the capture probability decreases as the distance from user 2 to the BS increases. Increasing $N$ and $K$ then increases the robustness of the codes to errors in the transmission. This also implies that, when the capture probability is high, the NOMA system can significantly reduce the frame size, which simplifies the decoding and reduces the latency, even for intermittent user packets that need to wait for SIC.

On the other hand, if PAoI is the main objective, Fig. 9c-d show a different picture: the value of $K$ and $N$ for NOMA without capture is almost constant, as is the value of $T_{\text{int}}$ for TDMA, while the best possible values of $K$ and $N$ for NOMA are higher at some distances and lower for others. This phenomenon is likely due to the interplay between the different outcome probabilities and their effects on the PAoI.

VIII. Conclusions

In this paper, we evaluated orthogonal and non-orthogonal slicing for heterogeneous services, namely, broadband and intermittent, in the RAN. Our model considered power control and packet-level coding for the broadband user and the use of SIC at the BS. Our analyses and results highlighted the different characteristics and achievable performance of TDMA and NOMA access schemes when compared to FDMA, which utilizes double the amount of resources – two bandwidth parts instead of one for TDMA and NOMA. In addition, we observed stark differences in terms of achievable trade-offs, impact of the inter-arrival times, and optimal configuration of the access schemes between the cases where the intermittent user aims to minimize either LR and PAoI. Hence, our results highlight the importance of the considered performance indicator for the intermittent user and of its wireless conditions, which must be taken into account for an efficient user pairing in NOMA.

In particular, our results showed that, with the considered schemes, NOMA achieves a closely similar performance as FDMA if the intermittent user has a sufficiently high mean SINR as a result of a relatively low path loss. Furthermore, NOMA achieved better trade-offs between throughput and LR than TDMA in every studied scenario. Since NOMA utilized half of the resources of FDMA (the upper bound in performance), it achieved the best balance between resource
efficiency and performance when the intermittent user aims to minimize LR. Furthermore, even NOMA without capture achieved a better performance than TDMA in terms of LR.

Moreover, NOMA achieved better throughput and PAoI trade-offs in most cases. In particular, TDMA only showed a superior performance when aiming for the highest throughput possible in exchange for a longer PAoI. However, the differences in PAoI were considerably smaller than those for the LR cases, especially for short distances from user 2 to the BS. Hence, TDMA may be preferred in the cases where the intermittent user is close to the BS due to its simplicity. Finally, NOMA without capture achieved the worst performance for PAoI.

Finally, it is important to note that, since the slicing is performed independently for each bandwidth part, our model and analyses can be easily extended to the case with multiple users and multiple bandwidth parts. This is the case with multiple broadband users, each with its own bandwidth part that can be shared with up to one of the intermittent users. Further, the FDMA scheme could be used to allocate multiple intermittent users in the same bandwidth part. However, the analysis of this scenario is out of the scope of this paper as FDMA is used as a benchmark for TDMA and NOMA and it requires to define an access scheme for the intermittent users.

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