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# Network control for ensuring haptic service performance in 5G/6G networks

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**Abstract**—Applications requiring haptic flows are expected to grow in importance for 6G networks. While the haptic codec has been recently standardized and is based on the Just Noticeable Difference (JND) principle, performance models and associated network control mechanisms are still lacking. We propose in this work a queuing theoretical control framework to minimize the cost of haptic packet delivery, in terms of network resources, while respecting constraints on consecutive packet losses, an essential metric for such applications. The framework switches between different control policies, leveraging resource reservation and/or power control, depending on the network conditions. Each set of policies is parameterized, reflecting a trade-off between system cost and performance of the haptic service. Through this adaptive approach, we derive closed-form solutions that minimize the cost while ensuring adherence to the loss constraints.

## I. INTRODUCTION

Haptic technology enables remote tactile interaction, allowing users to engage in multi-sensory exploration of real and virtual environments [1]. Real-time tactile feedback is essential in haptic communications, and consecutive data losses can severely degrade the user experience, impacting immersion, accuracy, and responsiveness. Unlike traditional Ultra Reliable Low Latency Communications (URLLC) in 5G networks, the haptic service requires then handling consecutive losses differently due to their significant impact on user experience. [2] highlights the significant degradation in smoothness experienced by users in the event of consecutively lost packets. Users reported feeling as if there were a small hole in the virtual wall. Furthermore, in [3], an experimental study was conducted to estimate the threshold at which users notice a "lost trajectory" (burst loss of packets), highlighting the sensitivity of haptic feedback to burst packet loss. In [4], the challenge of overcoming consecutive losses, termed "lost trajectories," is addressed using a predictor. Moreover, considering the remote control operations in a 5G/6G network context, [5] emphasizes the importance of mitigating consecutive packet errors or losses that could disrupt control operations. However, many research works on haptic service transport over 5G/6G networks model still focus solely on delay and reliability, treating it as either URLLC or Extreme URLLC [6] [7].

Besides the importance of consecutive packet losses, haptic applications are characterized by a particular codec designed to reduce the traffic load, where packets are generated based on Weber's Law of Just-Noticeable Difference (JND) to better align with the user's subjective experience [8], i.e., packets are transmitted only when changes in haptic feedback exceed the

user's perceptible threshold. Any haptic performance model and controller should take into considerations this particular codec. For instance, [9] introduced the Tactile Internet Metric (TIM), which, unlike conventional QoS metrics, measures perceptual quality degradation using the JND principle. In our paper, we develop a performance model for haptic services over the 5G/6G network, considering the JND-based codec and the impact of consecutive losses.

On the other hand, when the performance target of the haptic service cannot be satisfied with basic system parameters, a control approach is to be implemented for reaching the targets. Two approaches have been adopted in the literature. The first approach controls the haptic codec itself, and is based on packet rate adaptation, as in [10] where the authors propose a haptic packet rate control scheme to reduce network load by managing the burstiness of haptic data. They adaptively adjust the Deadband Parameter (DBP) based on packet transmission history and network load to maintain a target mean packet rate. However, this approach overlooks packet loss and its impact: when packets are lost, the JND threshold is likely exceeded, which can trigger further bursts if losses continue. Another approach is to compensate for the packet losses at the receiver. In [11], the goal is to prevent the system from acting on outdated information during bursts of packet losses. A threshold on the Age of Information (AoI) triggers a switch to a "safe" controller if the last received packet becomes too old. This safe controller mitigates potential damage but cannot fully maintain control accuracy during extended losses and thus controlling the network would help to prevent such burst losses. The network control scheme of [4] relies on shortened channel coding blocklengths to manage delays. In our control approach, we consider power control within a pre-specified interval and/or preempting resources from enhanced Mobile BroadBand (eMBB) users.

The contribution of this paper is twofold. First, we develop a performance model for the haptic service over 5G/6G networks. Haptic packet loss stems from two main issues: resource shortages within the delay budget due to eMBB traffic, and high Block Error Rate (BLER) from bad radio conditions. Our second contribution is then a controller that leverages two actions: preempting opportunistically eMBB resources and/or controlling transmission power to combat bad radio conditions. We formulate an optimization problem and derive closed-form solutions for the optimal policies that minimize cost while satisfying constraints on consecutive packet losses.

## II. PERFORMANCE MODEL

### A. Service model

Haptic data, typically requiring over 1,000 updates per second [12], has a packet size determined by the Degree of Freedom (DoF) of the application. The kinesthetic data can be described by 24 DoF, while the tactile data can involve even more dimensions. As a result, the packet size is at least 480 bytes as shown in [12]. In our scenario, a haptic device, whose codec is based on the JND [1], sends intermittently packets over a wireless link towards a human operator.

The haptic packet has a delay budget of  $d$  ms, meaning that this packet can remain unserved in the system for up to  $d$  ms without being considered in outage. After exceeding its delay budget, it will expire and thus be in outage. We define consecutive losses as a device experiencing  $m$  consecutive packet losses—that is,  $m$  packets are in outage consecutively. Note that if a user experiences a first packet loss (i.e., it is in outage), then the device will systematically send packets afterwards to overcome that loss, as the status of the device is no more up-to-date at the receiver.

### B. Resource allocation model

Radio resources are organized into Physical Resource Blocks (PRBs), slots and mini-slots. We define  $\delta$  as the delay budget for a packet in terms of the maximum number of mini-slots a haptic packet can remain in the system before it is considered in outage. For a delay budget of  $d$  ms and a mini-slot duration of  $\Delta$  ms, the number of possible retransmissions for a single haptic packet is  $\delta = \frac{d}{\Delta}$  mini-slots. If the packet is not received within this delay, it is dropped at the transmitter and a new packet is generated and new transmissions are attempted. The haptic performance is considered degraded if  $m$  consecutive packets are dropped.

While the haptic packets are served on a mini-slot basis, we assume that other eMBB users are present and are served on a slot basis. The baseline resource allocation considered in this paper is a non-scheduled one, as haptic packets are generated on the fly. The eMBB traffic is however pre-scheduled and it may happen that the slot resources are already in use and the haptic packet cannot be sent. Otherwise, if the resources are available, the packet is transmitted on a mini-slot basis and may be lost due to bad radio conditions or to interference from other base stations. We then differentiate between several loss cases:

- 1) The haptic packet is generated for the first time, and cannot be sent because resources are occupied by eMBB. This happens with probability  $p$  that we will compute next. The network is then aware of its presence and can, if the controller decides so, preempt resources for some of the next slots (within the budget  $m$ ).
- 2) Resources are available for the packet. The delay budget  $d$  is generally smaller than the slot duration (typically 1 ms), so that the  $\delta$  transmissions fall within the slot. Each time the haptic packet is transmitted, it may be lost with probability  $q$  due to bad radio conditions. We make here

the realistic assumption that the feedback is not instantly received so that the packet is transmitted  $\delta$  times within the slot, but the device is aware at the end of the slot if its packet went through or not. The model can be easily extended to rapid feedback cases. In the event of loss, the device may adjust its transmission power for the next slots for enhancing its success rate.

### C. Computing channel availability

We now develop models for the channel, from the haptic device point of view, in the baseline case with no control.

1) *eMBB impact assessment*: In order to compute the channel unavailability due to eMBB activity, we need to model the eMBB traffic. Let  $u_j = Pr[y(t) = j]$ ,  $j \in \mathbb{N}$ , denote the probability of having  $j$  new eMBB packet arrivals during a slot. Let  $R$  be the amount of resources available in one slot in the frequency dimension, where a resource is defined as a bloc of PRBs needed for serving one eMBB packet. In slot  $t$ , the eMBB buffer length after scheduling, denoted by  $B(t)$ , is the amount of backlogged packets after using all the resources of slot  $t$ , and is given by:

$$B(t) = (y(t) + B(t-1) - R)^+, \quad (1)$$

where  $(x)^+ = \max(0, x)$ .  $y(t)$  is the amount of resources needed for serving new packets arriving in slot  $t$ , and  $y(t) + B(t-1)$  is the total amount of resources needed for serving all the backlogged packets from previous slots plus the new packets. As there are  $R$  resources available in each slot, at most  $R$  among the required resources are used, and the remaining packets, if any, are backlogged in the next slot. The resource state, as seen from the haptic device, is then described by:  $B(t), r(t)$ , where  $r(t)$  is the amount of free resources at slot  $t$ , equal to 0 if  $B(t) > 0$ , and having a positive value otherwise. If the arrival process of eMBB packets is iid, this state evolves following a Markov chain.

In steady-state, let  $v_b$  be the probability that the queue length is  $b \geq 0$ . Setting a maximal queue length  $\hat{B} \gg R$  and defining the space of states  $\mathcal{S} = [0, \hat{B}] \times [0, R]$ , we write the following system of linear equations:  $\mathbf{v} = \mathbf{v}\mathbf{V}$ , where  $\mathbf{V}$  is the transition matrix with elements  $V_{(j,r),(b,l)}$ ,  $j$  and  $b \in \mathcal{B}$ , and  $r$  and  $l \in \mathcal{R}$  designating the transition probabilities between states  $(j, r)$  and  $(b, l)$ .  $\mathbf{v}$  is the vector of state probabilities, with  $v_{(j,r)}$  denoting the probability of state  $(j, r)$ . The elements of the transition matrix  $\mathbf{V}$  are given by:

$$V_{(j,r),(b,l)} = \begin{cases} u_{b+R-j}, & b \in ]0, \hat{B}[ , l = 0 \\ \sum_{i \geq b+R-j} u_i, & b = \hat{B}, l = 0 \\ u_{R-l-j}, & b = 0, l \in [0, R] \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Adding the normalizing equation  $\mathbf{v}\mathbf{v}^T = 1$ , the system of equations can be solved and the average channel availability for the haptic user computed by:

$$1 - p = \sum_{r>h} v_{(0,r)} \quad (3)$$

$h$  is the amount of resources for serving the haptic packet.

2) *Fading and interference impact*: When the resources are available, the transmitted packet may be lost due to bad radio conditions. This BLER depends on fading, interference, and the power used to transmit the packet, through the Signal-to-Interference-plus-Noise Ratio (SINR)  $\gamma$  given by

$$\gamma = \frac{P_t \cdot \eta}{I + N} \quad (4)$$

where  $P_t$  is the transmit power,  $\eta$  is the path loss, accounting for distance and fading,  $I$  is the interference from other base stations and  $N$  is the noise. For URLLC-like short packets, the BLER is given by [13]:

$$q = \begin{cases} 1, & \text{if } 0 \leq \gamma \leq \zeta_w, \\ c_w \exp(-d_w \gamma), & \text{if } \gamma \geq \zeta_w, \end{cases} \quad (5)$$

where  $c_w$  and  $d_w$  are Modulation and Coding Scheme (MCS)-dependent constants, and  $\zeta_w = \frac{\ln(c_w)}{d_w}$  is the SINR threshold beyond which the BLER decreases exponentially.

### D. Haptic performance model with no control

The state of the haptic device evolves following a discrete-time model, with  $\delta$  slots representing the time unit. The state of the haptic device at time  $t$  is represented by  $i(t)$ , where  $i(t) \in \{0, 1, \dots\}$  indicates the number of consecutive packet losses experienced by the user. At state  $i = 0$ , only packets exceeding the user's perceptible threshold will be put in service. This happens with probability  $s$  (based on JND). For  $i > 0$ , the system will have experienced a loss, prompting a new packet to request service, as previously described.

Knowing probabilities  $p$  and  $q$ , the performance of the haptic service can be computed as the probability of experiencing  $m$  consecutive losses after the packet has been generated. This is the probability of reaching state  $i = m$  at time  $t = \delta m$  starting from an initial state  $i = 0$  when there has been a packet generation, denoted by  $\eta_m$ :

$$P(\eta_m) = (p + (1-p)q^\delta)^m \quad (6)$$

### III. OPTIMAL CONTROL

In scenarios where the performance target for the haptic service is not achieved, i.e., when the performance degradation of equation (6) is larger than the maximal limit:

$$(p + (1-p)q^\delta)^m > \epsilon, \quad (7)$$

where  $\epsilon$  is a small positive constant, the network should be controlled, either by reducing the impact of eMBB traffic, or by combating interference and fading. We next define a generic control policy, and then specialize to specific actions.

#### A. Performance under a generic policy

We begin by defining the sets of policies  $\mathcal{P}_n$ . Index  $n$  takes values in  $\{1, 2, 3, 4\}$  as we will define four policy sets in the sequel. A policy within  $\mathcal{P}_n$  consists of a threshold  $k_n \leq m$  specifying the device state at which control actions are initiated. When policy  $k_n \in \mathcal{P}_n$  is applied, the controller takes action  $a_i \in \{0, 1\}$  when the device is observed in state

$i$  ( $i$  consecutive losses). If  $a_i = 0$ , the baseline parameters are used, while  $a_i = 1$  indicates that the control action is taken.

Let  $Z(i, j|k_n)$  represent the transition probability from state  $i$  of the haptic user to state  $j$ , under policy  $k_n \in \mathcal{P}_n$ . If  $j = i + 1$ , this indicates a packet loss, while  $j = 0$  means a successful transmission. The steady-state probabilities of the system are denoted by  $\mathbf{z}(k_n)$ , where  $z_i(k_n)$  is the probability of being in state  $i$ . The transition probability matrix  $Z(i, j|k_n)$  is given by:

$$Z(i, j|k_n) = \begin{pmatrix} \beta(0|k_n) & \alpha(0|k_n) & 0 & 0 & 0 \\ \beta(1|k_n) & 0 & \alpha(1|k_n) & 0 & 0 \\ \beta(2|k_n) & 0 & 0 & \alpha(2|k_n) & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Here,  $\alpha(i|k_n)$  represents the probability of a failure, meaning that a packet requesting service was either not served or was served and lost, and  $\beta(i|k_n)$  represents the probability of a success.

The probability of reaching state  $m$  sequentially through intermediate states starting from state 0 is given by:

$$P(m|k_n) = \prod_{i=0}^{m-1} Z(i, i+1|k_n) = \prod_{i=0}^{m-1} \alpha(i|k_n) \quad (8)$$

The performance degradation metric is computed as the probability of reaching  $m$  from state 0, knowing that a packet has been generated (with probability  $s$ ). It is given by

$$P(\eta_m|k_n) = \frac{1}{s} P(m|k_n) = \frac{1}{s} \prod_{i=0}^{m-1} \alpha(i|k_n) \quad (9)$$

The cost of the policy  $k_n \in \mathcal{P}_n$  is denoted by  $C(k_n)$ , and will be computed next for each policy set. Thus, we are left with the following optimization problem:

$$k_n^* = \arg \min_{k_n \in \mathcal{P}_n} [C(k_n)] \quad (\text{P})$$

subject to  $P(\eta_m|k_n) \leq \epsilon$

To solve problem (P), we consider four cases, each with different set of actions.

#### B. Preempting eMBB resources

We start by the case where infeasibility in equation (7) is mainly due to a high value of  $p$  (channel unavailability). We call the set of policies in this case  $\mathcal{P}_1$ . Within this set, when an action is taken, resources are reserved for the haptic service preemptively, and the channel becomes available, generating thus a higher cost in terms of resources preempted from eMBB flows. For a policy  $k_1$ , the actions are  $a_i(k_1) = 0$ , if  $i < k_1$ , and 1 otherwise.

The probability of failure becomes  $\alpha(i|k_1) =$

$$\begin{cases} s \left[ (p + (1-p)q^\delta)(1 - a_i(k_1)) + a_i(k_1)q^\delta \right], & \text{if } i = 0 \\ (p + (1-p)q^\delta)(1 - a_i(k_1)) + a_i(k_1)q^\delta, & \text{if } i > 0 \end{cases} \quad (10)$$

and  $\beta(i|k_1) = 1 - \alpha(i|k_1)$ .

We now move to the computation of the stationary distribution of the system,

$$z_i(k_1) = z_0 \prod_{j=0}^{i-1} \alpha(j|k_1); \quad z_0(k_1) = \frac{1}{1 + \sum_{i=1}^{\infty} \prod_{j=0}^{i-1} \alpha(j|k_1)} \quad (11)$$

The probability of being in a state with no losses is:

$$z_0 = \frac{1}{1 + s \frac{A(1-A^{k_1})}{1-A} + sA^{k_1} \frac{q^\delta}{1-q^\delta}}, \quad (12)$$

where  $A = p + (1-p)q^\delta$ . This leads to:

$$z_i = \begin{cases} sz_0(p + (1-p)q^\delta)^i, & \text{for } 1 \leq i \leq k_1 \\ sz_0(p + (1-p)q^\delta)^{k_1} (q^\delta)^{i-k_1}, & \text{for } i > k_1 \end{cases}$$

Having obtained the stationary distribution, we compute the cost for controlling the system. Let  $h$  be the amount of resources the haptic packet consumes. The preemption cost is:

$$C(k_1) = \sum_{i=k_1}^{\infty} z_i h = \begin{cases} c_p h z_0 [1 + s \frac{q^\delta}{1-q^\delta}] & \text{if } k_1=0 \\ c_p h \frac{sz_0(p+(1-p)q^\delta)^{k_1}}{1-q^\delta} & \text{if } k_1 > 0 \end{cases} \quad (13)$$

where  $c_p$  denotes the cost for preempting one resource.

This function is decreasing w.r.t to  $k_1$ , and thus the optimal  $k_1^*$ , solving problem (P), is the largest  $k_1$  that could satisfy the probability constraint, we have:

$$P(\eta_m|k_1) = (p + (1-p)q^\delta)^{k_1} (q^\delta)^{m-k_1} \leq \epsilon \quad (14)$$

$$k_1 \leq \frac{\ln \epsilon - m \ln q^\delta}{\ln(p + (1-p)q^\delta) - \ln q^\delta} \quad (15)$$

and thus

$$k_1^* = \lfloor \frac{\ln \epsilon - m \ln q^\delta}{\ln(p + (1-p)q^\delta) - \ln q^\delta} \rfloor \quad (16)$$

### C. Combating bad channel conditions

In cases where the probability of loss due to bad radio conditions  $q$  is high, and the channel availability is good (i.e.,  $p$  is small), we switch to the set of policies  $\mathcal{P}_2$ . For a policy  $k_2 \in \mathcal{P}_2$ , the action taken is to reduce the loss by increasing the transmitted power of the haptic device. The assumption here is that the transmit power can be increased from its nominal value  $P_t$ , to a higher power  $P_{t,\max}$ , reducing the loss to  $\hat{q} < q$ , while incurring an additional cost of  $\Delta P = P_{t,\max} - P_t$ . At state  $i$ , the threshold of the policy is denoted by  $k_2$  and thus if  $i < k_2$  ( $a_i = 0$ ), we transmit the packet with  $P_t$ ; and, otherwise, we transmit with  $P_{t,\max}$  ( $a_i = 1$ ). Following the same procedure as before we calculate the cost by first calculating the stationary distribution of the system state, then the cost of employing a policy. We start by

$$\alpha(i|k_2) = \begin{cases} s \left[ A(1 - a_i(k_2)) + a_i(k_2) \hat{A} \right], & \text{if } i = 0 \\ A(1 - a_i(k_2)) + a_i(k_2) \hat{A}, & \text{if } i > 0 \end{cases} \quad (17)$$

where  $A = p + (1-p)q^\delta$  and  $\hat{A} = p + (1-p)\hat{q}^\delta$ . And thus:

$$z_0 = \frac{1}{1 + s \frac{A(1-A^{k_2})}{1-A} + sA^{k_2} \frac{\hat{A}}{1-\hat{A}}},$$

and

$$z_i = \begin{cases} sz_0 A^i, & \text{for } 1 \leq i \leq k_2 \\ sz_0 A^{k_2} \hat{A}^{i-k_2}, & \text{for } i > k_2 \end{cases}$$

The cost is given as follows:

$$C(k_2) = \begin{cases} c_b \Delta P z_0 (1 + s \frac{\hat{A}}{1-\hat{A}}) & \text{if } k_2=0 \\ c_b \Delta P s z_0 \frac{\hat{A}^{k_2}}{1-\hat{A}}, & \text{if } k_2 > 0 \end{cases} \quad (18)$$

where  $c_b$  denotes the cost for unitary power boost.

We find  $k_2^*$  as follows:

$$P(\eta_m|k_2) = A^{k_2} \hat{A}^{m-k_2} \leq \epsilon \implies k_2^* = \lfloor \frac{\ln \epsilon - m \ln \hat{A}}{\ln A - \ln \hat{A}} \rfloor$$

### D. Joint power boosting and resource preemption

We now move to more challenging cases where the eMBB traffic occupies the channel frequently and the radio conditions are bad. The two sets of control actions presented above are to be applied jointly, and their order depends on the relative importance of  $p$  and  $q$  in the outage. We have here two sub-cases, depending on the order for applying the control actions.

1) *Always transmitting with a high power:* We consider here the set of policies  $\mathcal{P}_3$ . The packet is always transmitted with high power  $P_{t,\max}$ . For any policy  $k_3 \in \mathcal{P}_3$ , if  $i \geq k_3$  ( $a_i = 1$ ), we preempt resources from eMBB traffic. We follow the same procedure for the computation of the cost and the optimal threshold  $k_3^*$ . We start as follows:

$$\alpha(i|k_3) = \begin{cases} s \left[ \hat{A}(1 - a_i(k_3)) + a_i(k_3) \hat{q}^\delta \right], & \text{if } i = 0 \\ \hat{A}(1 - a_i(k_3)) + a_i(k_3) \hat{q}^\delta, & \text{if } i > 0 \end{cases} \quad (19)$$

where  $\hat{A} = p + (1-p)\hat{q}^\delta$ . Based on this we have:

$$z_0 = \frac{1}{1 + s \hat{A} \frac{1-\hat{A}^{k_3}}{1-\hat{A}} + s \hat{A}^{k_3} \frac{\hat{q}^\delta}{1-\hat{q}^\delta}}$$

Depending on the value of  $k_3$ , we have:

$$z_i(k_3) = \begin{cases} sz_0 \hat{A}^i, & \text{for } 1 \leq i \leq k_3 \\ sz_0 \hat{A}^{k_3} (\hat{q}^\delta)^{i-k_3}, & \text{for } i > k_3 \end{cases}$$

The cost  $C(k_3)$  is given as follows:

$$\begin{cases} [c_b \Delta P + c_p h] z_0 (1 + s \frac{\hat{q}^\delta}{1-\hat{q}^\delta}); & k_3 = 0 \\ z_0 c_b \Delta P [1 + s \hat{A} \frac{1-\hat{A}^{k_3-1}}{1-\hat{A}}] + [c_b \Delta P + c_p h] s z_0 \frac{\hat{A}^{k_3}}{1-\hat{q}^\delta}; & k_3 > 0 \end{cases}$$

The optimal threshold  $k_3^*$  is then obtained by:

$$P(\eta_m|k_3) = \hat{A}^{k_3} (\hat{q}^\delta)^{m-k_3} \leq \epsilon \implies k_3^* = \lfloor \frac{\ln \epsilon - m \ln \hat{q}^\delta}{\ln \hat{A} - \ln \hat{q}^\delta} \rfloor$$

2) *Always preempting resources:* We consider here policy set  $\mathcal{P}_4$ . In this case, we always preempt eMBB resources for the haptic packets, regardless of the system's state. For  $k_4 \in \mathcal{P}_4$ , if  $i \geq k_4$  (where  $a_i = 1$ ), the decision is to boost the power by transmitting the packet with maximum power  $P_{t,\max}$ . To compute the cost and determine the optimal threshold policy  $k_4^*$ , we follow a similar procedure as outlined previously. We begin by calculating the probability distribution of the system

states and then derive the associated cost and  $k_4^*$ . The initial state probability is given by:

$$z_0(k_4) = \frac{1}{1 + s \frac{q^\delta(1-(q^\delta)^{k_4})}{1-q^\delta} + s(q^\delta)^{k_4} \frac{\hat{q}^\delta}{1-\hat{q}^\delta}}$$

The steady-state probability distribution is as follows:

$$z_i(k_4) = \begin{cases} sz_0(k_4)(q^\delta)^i, & \text{if } 1 \leq i \leq k_4, \\ sz_0(k_4)(q^\delta)^{k_4}(\hat{q}^\delta)^{i-k_4}, & \text{otherwise.} \end{cases}$$

This leads to the following expression for the cost  $C(k_4) =$

$$\begin{cases} (c_b \Delta P + c_p h)(1 + s \frac{\hat{q}^\delta}{1-\hat{q}^\delta}); k_4 = 0, \\ c_p h z_0(1 + q^\delta \frac{1-(q^\delta)^{k_4-1}}{1-q^\delta}) + s z_0 [c_p h + c_q \Delta P] \frac{(q^\delta)^{k_4}}{1-\hat{q}^\delta}; k_4 > 0 \end{cases}$$

Hence the optimal threshold  $k_4^*$  is:

$$P(\eta_m | k_4) = (q^\delta)^{k_4} (\hat{q}^\delta)^{m-k_4} \implies k_4^* = \left\lfloor \frac{\ln \epsilon - m \ln \hat{q}^\delta}{\ln q^\delta - \ln \hat{q}^\delta} \right\rfloor$$

#### IV. NUMERICAL EXPERIMENTS

##### A. System parameters

We consider a base station that implements a 30 kHz subcarrier spacing, where a slot consists of 14 symbols, and mini-slots allow scalable Transmission Time Intervals (TTIs). With 7-symbol mini-slots, each mini-slot lasts 250  $\mu$ s. As of the haptic service requirements, the maximum number of allowed consecutive losses is  $m = 3$ , and a packet is considered lost if it is not correctly received within 0.5 ms, leading to  $\delta = 2$ . The performance target is  $\epsilon = 10^{-5}$ .

For radio conditions, we assume that the haptic service uses robust QPSK MCS with rate  $R = \frac{78}{1024}$ , resulting in  $c_w = 1.02 \times 10^5$  and  $d_w = 73.22$  [13]. The device is located at 1 Km from the base station, with a path loss exponent of 3.5. A noise density is -174 dBm/Hz with a noise rise due to other cell interference of 12 dB. Figure 1a illustrates the packet loss  $q$  when the transmitted power increases. The power is limited to  $P_{t,max} = 1$  Watt, making the minimal BLER  $\hat{q} = 0.046$ .

For the eMBB traffic impact, we consider a Poisson arrival for eMBB packets, each bringing an equal payload so that 10 packets can be served per slot. When a haptic packet is served, it consumes 20% of the resources. Figure 1b illustrates the channel unavailability  $p$  when the eMBB traffic load, defined as the average number of new packets per slot divided by the capacity of the slot, increases from 0 to 1.

##### B. Feasibility region

We illustrate in figure 2 the values of  $p$  and  $q$  where the target performance can be attained. With the performance requirements stated above,  $q$  should be less than 0.24 and  $p$  should not exceed 0.06. However, within the acceptable range of power (less than 1 Watt), the feasibility region is delimited inside the red curve. Within this region, policy 1 can be applied to extend the feasibility regions to all the values of  $p$  (zone delimited by the dashed arrows). The blue curve delimits the feasibility region with no control and no power limitation.

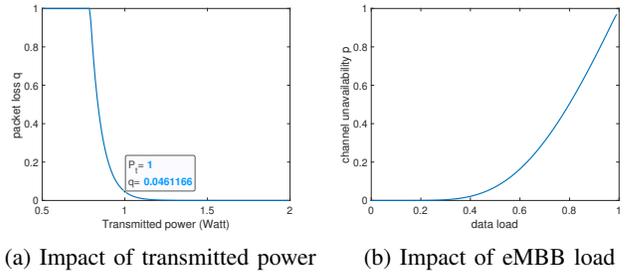


Fig. 1: Illustration of power and eMBB impacts.

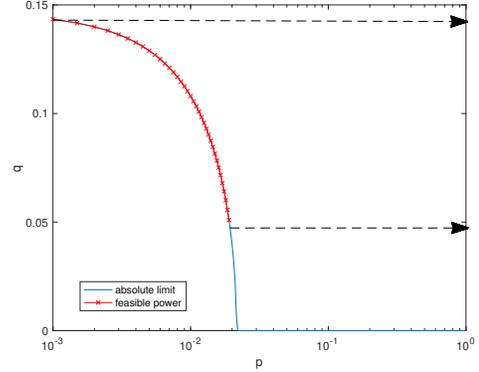


Fig. 2: Feasibility regions illustration.

##### C. Optimal policy illustration

In figure 3 we plot the threshold of the optimal policy in the set  $\mathcal{P}_1$  allowing us to respect the performance target. To be able to restrict ourselves to the set of policies  $\mathcal{P}_1$ , we choose a feasible transmit power that leads to a BLER  $q = 0.1$  and another one with  $q = 0.07$  as these are within the feasible regions as shown in figure 2. We let the channel availability take values between 0.06 and 1. We see that with the increase of the eMBB load (leading to higher values of  $p$ ), the policy starts to be more aggressive requiring preempting the eMBB packets at the initial states when  $p \geq 0.072$  and  $p \geq 0.42$  respectively when  $q = 0.1$  and  $q = 0.07$ .

We now consider switching between two power values, nominal  $P_t$  and maximal  $P_{t,max}$ . Figures 4a and 4b illustrate the best set of policies  $\mathcal{P}_n$  for achieving minimal cost. In both figures, the x-axis shows the channel unavailability probability  $p$ , while the y-axis represents the new BLER  $\hat{q}$  after applying power boosting. We take into account the varying costs incurred to achieve these values of  $\hat{q}$  during the experiment. In figure 4a, the BLER without power boosting is  $q = 0.1$ ; in figure 4b, it is  $q = 0.15$ . We observe that with a higher initial BLER, the system adopts more aggressive policies. In figure 4a, there is a region where no control is needed, while in figure 4b, we control the system in all regions. Switching between policy sets is not straightforward. As shown in figure 4a, we start with the preemption policy  $\mathcal{P}_1$ , switch to power control  $\mathcal{P}_3$ , and then return to  $\mathcal{P}_1$ . This adaptation corresponds to the system always selecting the policy with minimal cost.

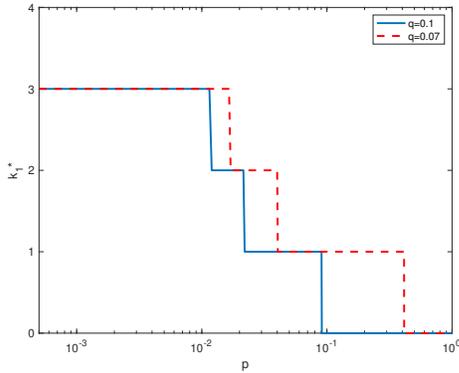


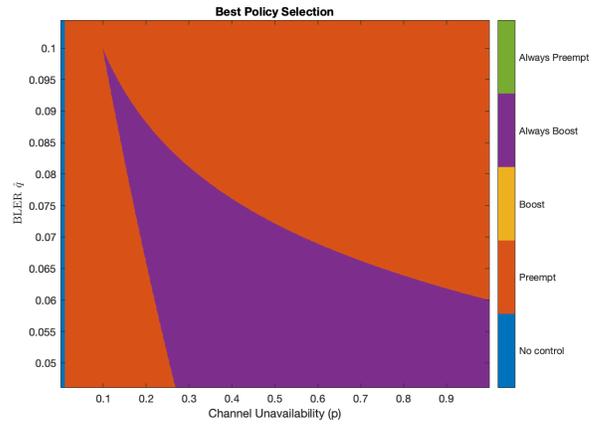
Fig. 3: The threshold of the optimal policy in set  $\mathcal{P}_1$ ,

## V. CONCLUSION

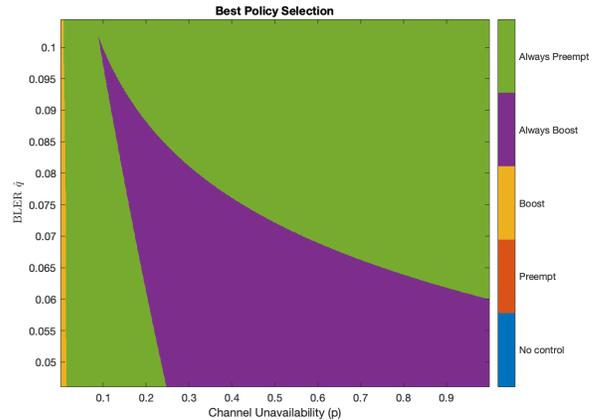
In this paper, we have developed a performance model for the haptic service over 5G/6G networks. We considered the JND-based codec that transmits packets only when a significant change is detected from the last transmitted packet. The performance metric is the probability of consecutive packet losses, the latter occurring either because of the unavailability of resources due to eMBB traffic, or because of bad radio conditions. In order to attain the target performance, we developed control schemes that preempt opportunistically the eMBB resources and/or transmit with a higher power when needed for combating bad radio conditions. We computed closed-form expressions for the optimal schemes and showed numerically their feasibility regions. We also illustrated the optimal control schemes and showed how the operator selects the policy that minimizes the overall cost.

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(a)  $q = 0.1$



(b)  $q = 0.15$

Fig. 4: Best policy selection as a function of  $p$  and  $\hat{q}$

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