

Unsourced Multiple Access With Common Alarm Messages: Network Slicing for Massive and Critical IoT

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Abstract—We investigate the coexistence of massive and critical Internet of Things (IoT) services in the context of the unsourced multiple access (UMA) framework introduced by Polyanskiy (2017), where all users employ a common codebook and the receiver returns an unordered list of decoded codewords. This setup is suitably modified to introduce heterogeneous traffic. Specifically, to model the massive IoT service, we assume that a *standard* message originates independently from each IoT device as in the standard UMA setup. To model the critical IoT service, we assume the generation of alarm messages that are *common* for all devices. This setup requires a significant redefinition of the error events, i.e., misdetections and false positives. We further assume that the number of active users in each transmission attempt is random and unknown. We derive a random-coding achievability bound on the misdetection and false positive probabilities of both standard and alarm messages on the Gaussian multiple access channel. Using our bound, we demonstrate that orthogonal network slicing enables massive and critical IoT to coexist under the requirement of high energy efficiency. On the contrary, we show that nonorthogonal network slicing is energy inefficient due to the residual interference from the alarm signal when decoding the standard messages.

Index Terms—Internet of things, unsourced multiple access, network slicing, random-coding bound, misdetection, false positive

I. INTRODUCTION

The number of connected devices has grown drastically; it reached 13.2 billion in 2022, and is projected at 34.7 billion in 2028 [2]. The data exchange between these devices gives rise to the Internet of Things (IoT) [3]. Two of the main segments of the IoT landscape are massive IoT and critical IoT [4].

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Massive IoT connectivity targets a large number of low-cost, battery-limited, narrowband devices—meters, sensors, trackers, wearables—that transmit small data volumes in a sporadic and uncoordinated manner. Critical IoT connectivity aims to deliver data under strict latency and reliability guarantees for applications such as autonomous vehicles, real-time fault prevention, and real-time human-machine interaction. In a typical scenario in critical IoT, multiple devices report a common malfunction or abnormal physical phenomenon, such as a gas leak or an out-of-range temperature, to an IoT gateway. In the fifth-generation (5G) wireless cellular standard, massive IoT and critical IoT are mapped to two separate use cases, named massive machine-type communications (mMTC) and ultra-reliable low-latency communication (URLLC), respectively [5]. This paper aims to investigate the coexistence of massive and critical IoT via an information-theoretic analysis.

1) *State of the Art*: Some of the key features of massive IoT connectivity are captured by the recently proposed unsourced multiple access (UMA) model [6]. This model differs from the classical multiple access setting in three fundamental aspects: i) all users transmit their messages using the same codebook and the decoder returns an unordered list of messages; ii) the error event is defined on a per-user basis as the event that the message transmitted by a given user is not included in the list produced by the decoder, and the error probability is averaged over all users; iii) each user sends a fixed amount of information within a finite-length frame. UMA is driven by the emergence of massive IoT applications, characterized by the deployment of millions of identical low-cost devices with codebooks hardwired in production. The common-codebook assumption eliminates the need for a codebook-assignment phase, which is implicitly assumed in classical multiple-access analyses but becomes impractical in the massive IoT setup. In UMA, the receiver decodes the list of transmitted messages without prior knowledge of the identity of the active devices [7]–[11]. Under the UMA framework, traditional as well as modern random access protocols [12] provide achievability results. In [6], a random-coding bound on the energy efficiency achievable on the Gaussian multiple access channel (MAC) was derived. Modern random access schemes exhibit a large gap to this bound. This triggered a line of research aimed at devising new coding schemes approaching the bound. Recent schemes are based on, e.g., coded compressed sensing [13]–[16], a combination of coded slotted ALOHA and conven-

tional channel codes [17], [18], random spreading [19], sparse Kronecker product [20], and tensor decomposition [21]. The UMA framework has been extended to the quasi-static fading channel [22], the frequency-selective fading channel [23], the multiple-antenna channel [24], [25], and a setting with variable-length codes and feedback [26]. An extension to the case of random and unknown number of active users was presented in [27], [28], where both misdetections (MDs), i.e., transmitted messages that are not included in the decoded list, and false positives (FPs),¹ i.e., decoded messages that are not transmitted, were considered.

Both massive and critical IoT can be analyzed under the framework of finite-blocklength information theory [29], [30]. For massive IoT, this framework accounts for the fact that the users transmit over a finite-length frame a finite number of bits. For critical IoT, finite-blocklength information theory provides accurate upper and lower bounds on the maximum information rate that can be achieved under a given latency and reliability requirements.

Different IoT traffic types typically need to coexist [4]. In [31], the authors proposed to leverage reliability diversity to perform simultaneous transmission of different traffic types (also referred to as nonorthogonal network slicing) followed by successive interference cancellation. They showed that this approach leads to significant gains over orthogonal slicing when mMTC and enhanced mobile broadband (eMBB) traffic are present, or when URLLC and eMBB traffic are present. However, they noted that nonorthogonal network slicing between URLLC and mMTC may be problematic due to the need to ensure reliability for URLLC devices in the presence of the random interference patterns caused by mMTC transmissions.

The evolution toward more complex IoT devices results in scenarios where each user generates heterogeneous traffic that can be critical or not critical. In [32], the authors investigated massive multiple-input multiple-output (MIMO) deployments for critical alarm traffic and noncritical mMTC traffic, but did not consider the coexistence of both traffic types. A first attempt to incorporate critical IoT traffic into the UMA model was undertaken in [33]. There, on top of standard messages, the users communicate a common alarm message that needs to be decoded with higher reliability than the standard messages. The authors assumed that a user drops the standard message in favor of the alarm message when both messages are present, and that the total number of active users transmitting either message is known. They showed that, in nonorthogonal network slicing, the FP probability of alarm messages dominates and significantly reduces the energy efficiency when the total number of users is large.

2) *Contribution*: In this paper, we generalize the UMA setup with common alarm message proposed in [33] and study both orthogonal and nonorthogonal network slicing. In orthogonal slicing, standard and alarm messages are transmitted in separate blocks within a frame; in nonorthogonal slicing, both messages are transmitted over the whole frame. Differently from [33], we consider a random and unknown number of

active users for both traffic types, and that both messages are transmitted if they are present. This means that, in our setup, the spectral efficiency is not automatically decreased upon the occurrence of alarm message, unlike [33], where the suppression of the standard messages directly decreases the nominal rate of information conveyed through the system. For both orthogonal and nonorthogonal network slicing, we provide a random-coding bound on the MD and FP probabilities of standard and alarm traffic, achievable on the Gaussian MAC. Note that for the alarm traffic, we need to use a different bounding technique compared to [6], [28] because the assumption of a common message transmitted by all active users is not compatible with the assumption of independent message generation used in [6], [28]. We use our bounds to evaluate the achievable energy efficiency, measured by the minimum average energy per bit (E_b/N_0) required to satisfy given requirements on the MD and FP probabilities. Specifically, we let the standard traffic operate at a larger E_b/N_0 than the minimum E_b/N_0 required when the alarm traffic is not present. We refer to the additional E_b/N_0 as backoff. We then report the minimum required E_b/N_0 for the alarm traffic.

For orthogonal network slicing, we investigate the impact of the probability that a user detects the alarm, which models the user sensitivity and limits the probability that the user transmits the alarm message when an alarm is present. We also study the impact of a constraint on the difference (in dB) between the power at which the standard and alarm codewords are transmitted, which we call the dynamic range. Through numerical results, we show that in orthogonal network slicing, a limited backoff is sufficient to transmit the alarm traffic with high energy efficiency, provided that i) the users are highly sensitive to the alarm, i.e., a large number of users detect and transmit the alarm message and ii) the dynamic range is large, i.e., the power at which the alarm message is transmitted is much smaller than that at which the standard message is transmitted. We also show that nonorthogonal network slicing is inefficient because of the residual interference from the alarm message when decoding the standard messages. Specifically, for a small E_b/N_0 backoff of the standard message, nonorthogonal network slicing cannot satisfy the reliability requirements of both traffic types unless the number of users transmitting the alarm message is reliably estimated, which occurs if all users transmit the alarm message or the transmit power of the alarm codeword is comparable to that of the standard codeword. In both cases, however, the required alarm E_b/N_0 is significantly higher than that of orthogonal network slicing. This confirms that reliability diversity [31] between critical and massive IoT is hard to exploit.

3) *Paper Organization*: The remainder of the paper is organized as follows. In Section II, we present the system model for UMA with common alarm messages and define a random-access code. In Sections III and IV, we provide a random-coding bound for orthogonal and nonorthogonal network slicing, respectively. In Section V, we present numerical results and discussions. We conclude the paper and provide some directions for future work in Section VI. The proofs of our bounds can be found in the appendices.

¹In [27], [28], the event that a message has not been transmitted but is included in the list produced by the decoder is called a *false alarm*. Here, we use the term *false positive* to avoid confusion with the *alarm* event.

4) *Notation:* We denote system parameters by sans-serif letters, such as K , scalar random variables by upper case letters, such as X , and their realizations by lower case letters, such as x . Vectors are denoted likewise with boldface letters, e.g., a random vector \mathbf{X} and its realization \mathbf{x} . We denote the $n \times n$ identity matrix by \mathbf{I}_n , and the all-zero vector by $\mathbf{0}$. The Euclidean norm and the transpose of \mathbf{x} are $\|\mathbf{x}\|$ and \mathbf{x}^\top , respectively. Calligraphic uppercase letters, such as \mathcal{A} , denote sets or events. We use $|\mathcal{A}|$ to denote the cardinality of \mathcal{A} and $\mathfrak{P}(\mathcal{A})$ the set of all subsets of \mathcal{A} , $[m : n] \triangleq \{m, m+1, \dots, n\}$, $[n] \triangleq [1 : n]$, $\mathbb{1}\{\cdot\}$ is the indicator function, $\bar{\mathcal{A}}$ is the complement of the event \mathcal{A} , and \mathbb{R} denotes the set of real numbers. We denote the Gamma function by $\Gamma(x) \triangleq \int_0^\infty z^{x-1} e^{-z} dz$, and the upper incomplete Gamma functions by $\Gamma(x, y) \triangleq \int_y^\infty z^{x-1} e^{-z} dz$. We denote the Binomial distribution with parameters (n, p) by $\text{Bino}(n, p)$, and its probability mass function evaluated at k by $\text{Bino}(k; n, p) \triangleq \binom{n}{k} p^k (1-p)^{n-k}$. Finally, $\mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ denotes the multivariate real-valued Gaussian distribution with mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$.

II. SYSTEM MODEL

We consider a MAC in which K users are given access opportunity over a frame consisting of n uses of a stationary memoryless additive white Gaussian noise (AWGN) channel. This channel model is relevant, e.g., in a time-division duplexing system where the base station broadcasts a downlink pilot signal, each user estimates its channel based on the pilot signal, and active users pre-equalize their uplink signals based on the channel estimate [34], [35]. Here, as in [35], we assume that the channel estimation and pre-equalization steps are perfect and lead to a Gaussian channel with known signal-to-noise ratio (SNR), equal across all devices. We thus focus on the uplink transmission. Let $\mathbf{S}_k \in \mathbb{R}^n$ be the signal transmitted by user k , which is $\mathbf{0}$ if the user is inactive. This signal is subject to the power constraint $\|\mathbf{S}_k\|^2/n \leq P$, $\forall k \in [K]$. The corresponding received signal is given by

$$\mathbf{Y} = \sum_{k=1}^K \mathbf{S}_k + \mathbf{Z}, \quad (1)$$

where $\mathbf{Z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_n)$ is the AWGN, which is independent of $\{\mathbf{S}_k\}_{k=1}^K$. Contrary to many UMA studies, we assume that the number of transmitting users is random and unknown to the receiver.

A. Message Generation

We let \mathcal{M}_a denote the set of alarm messages and \mathcal{M}_s the set of standard messages; both sets are common to all users. Let $M_a \triangleq |\mathcal{M}_a|$ and $M_s \triangleq |\mathcal{M}_s|$. In a frame, if an alarm event has occurred, let W_a be the corresponding alarm message, drawn uniformly from \mathcal{M}_a . Each user transmits this message with probability ρ_d . With probability ρ_s , user $k \in [K]$ generates a standard message $W_{s,k}$ uniformly over \mathcal{M}_s and independently of the other users. To summarize, each user either transmits an alarm message, a standard message, both messages, or is inactive. Fig. 1 illustrates the message generation rule. For

convenience, we denote by w_e the ‘‘null message’’, mapped to the all-zero codeword (no transmission).

Remark 1: ρ_d can be expressed as $\rho_d = \rho_{d,\max} \rho_{d,\text{trans}}$ where $\rho_{d,\max}$ is the probability that a user detects the alarm and $\rho_{d,\text{trans}}$ is the probability that, upon detecting the alarm, the user decides to transmit the alarm message. The probability $\rho_{d,\max}$ models the user sensitivity to the alarm, while $\rho_{d,\text{trans}}$ is a design parameter. Therefore, ρ_d is upper-bounded by $\rho_{d,\max}$.

Remark 2: We assume that M_s is much larger than M_a . In typical IoT scenarios, M_s is in the order of 2^{100} (see, e.g., [6] and [36, Rem. 3]), whereas M_a can be less than 10, i.e., only a few different alarm events can occur. Since reporting the alarm is crucial for the system operation, the alarm message needs to be decoded with much higher reliability than the standard messages.

Note that the number of users generating an alarm message and/or a standard message is random. We assume that this number and the identity of the active users are unknown to the receiver. Hereafter, a user generating an alarm message is called an alarm user, and a user generating a standard message is called a standard user. A user can be simultaneously an alarm user and a standard user.

B. Random-Access Code

For the standard traffic, similar to [6], all users employ the same codebook and the receiver decodes up to a permutation of the messages. Furthermore, as in [28], to address a random and unknown number of active users, we account for both MD and FP of the standard messages, referred to as SMD and SFP, respectively. An SMD occurs if a transmitted standard message is not included in the list of decoded standard messages. An SFP occurs if a message in the list of decoded standard messages has not been transmitted. We also consider MD and FP of the alarm message, referred to as AMD and AFP, respectively. An AMD occurs if an alarm event takes place but the receiver decodes the alarm message erroneously. An AFP occurs if the receiver returns an alarm message while no alarm event occurs. We define the probabilities of these events and the random-access code below.

Definition 1 (Random-access code): Consider the Gaussian MAC with both standard and alarm traffic described above. An $(M_a, M_s, n, \epsilon_{\text{amd}}, \epsilon_{\text{afp}}, \epsilon_{\text{smd}}, \epsilon_{\text{sfp}})$ random-access code for this channel, where M_a and M_s are the sizes of the alarm and standard message sets, respectively, n is the framelength, and $\epsilon_{\text{amd}}, \epsilon_{\text{afp}}, \epsilon_{\text{smd}}, \epsilon_{\text{sfp}} \in (0, 1)$, consists of:

- A random variable U defined on a set \mathcal{U} that is revealed to both the users and the receiver before the transmission. This random variable acts as common randomness and allows for the use of randomized coding strategies.
- An encoding function

$$f: \mathcal{U} \times (\mathcal{M}_a \cup \{w_e\}) \times (\mathcal{M}_s \cup \{w_e\}) \rightarrow \mathbb{R}^n$$

that produces the transmitted codeword $\mathbf{S}_k = f(U, W_{a,k}, W_{s,k})$ for user k , for a given alarm message $W_{a,k}$ and standard message $W_{s,k}$.

- A decoding function

$$g: \mathcal{U} \times \mathbb{R}^n \rightarrow (\mathcal{M}_a \cup \{w_e\}) \times (\mathfrak{P}(\mathcal{M}_s) \cup \{w_e\})$$

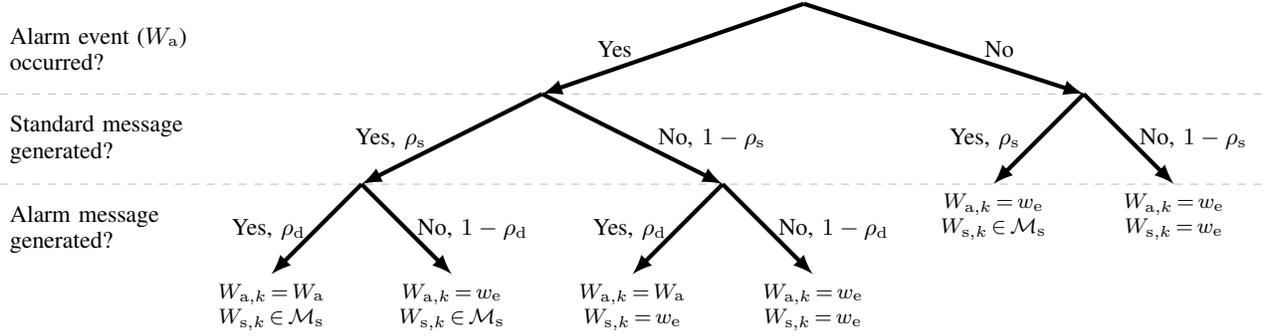


Fig. 1. A tree representation of the message generation for user k . The user generates the alarm message $W_{a,k}$ and the standard message $W_{s,k}$ indicated by the leaves. When a message is not generated, we say that the user picks the null message w_e .

that provides an estimate \widehat{W}_a of the common alarm message W_a and an estimate $\widehat{\mathcal{W}}_s = \{\widehat{W}_{s,1}, \dots, \widehat{W}_{s,|\widehat{\mathcal{W}}|}\}$ of the list of transmitted standard messages. That is, $(\widehat{W}_a, \widehat{\mathcal{W}}_s) = g(U, \mathbf{Y})$.

Let $\widetilde{\mathcal{W}}_s = \{\widetilde{W}_{s,1}, \dots, \widetilde{W}_{s,|\widetilde{\mathcal{W}}|}\}$ be the set of distinct elements of $\mathcal{W}_s = \{W_{s,k} : W_{s,k} \neq w_e, k \in [K]\}$. Let \mathcal{A} denote the event that an alarm occurs. We assume that the decoding function satisfies the following constraints on the AMD, AFP, SMD, and SFP probabilities, respectively:

$$P_{\text{amd}} \triangleq \mathbb{P}[\widehat{W}_a \neq W_a | \mathcal{A}] \leq \epsilon_{\text{amd}}, \quad (2)$$

$$P_{\text{afp}} \triangleq \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}] \leq \epsilon_{\text{afp}}, \quad (3)$$

$$P_{\text{smd}|\mathcal{B}} \triangleq \mathbb{E}_{|\widetilde{\mathcal{W}}_s|} \left[\frac{1}{|\widetilde{\mathcal{W}}_s|} \sum_{i=1}^{|\widetilde{\mathcal{W}}_s|} \mathbb{P}[\widetilde{W}_{s,i} \notin \widehat{\mathcal{W}}_s | \mathcal{B}] \right] \leq \epsilon_{\text{smd}}, \quad (4)$$

$$P_{\text{sfp}|\mathcal{B}} \triangleq \mathbb{E}_{|\widetilde{\mathcal{W}}_s|} \left[\frac{1}{|\widetilde{\mathcal{W}}_s|} \sum_{i=1}^{|\widetilde{\mathcal{W}}_s|} \mathbb{P}[\widehat{W}_{s,i} \notin \widetilde{\mathcal{W}}_s | \mathcal{B}] \right] \leq \epsilon_{\text{sfp}}. \quad (5)$$

Here, we used the convention that $0/0 = 0$ to circumvent the cases $|\widetilde{\mathcal{W}}_s| = 0$ or $|\widehat{\mathcal{W}}_s| = 0$. Furthermore, (4) and (5) hold for both $\mathcal{B} = \mathcal{A}$ and $\mathcal{B} = \bar{\mathcal{A}}$.

Our definition of a random-access code differs from that in [33, Def. 2] in two aspects. First, [33, Def. 2] applies exclusively to the case where a user drops the standard message in favor of the alarm message when both messages are present, and this does not result in a SMD. Here, we assume that both messages are transmitted if they are present. Second, while [33, Def. 2] assumes a known total number of active users and considers only MD for the standard traffic, we consider an unknown number of active users and account for both SMD and SFP.

Remark 3: Note that ρ_d should be sufficiently large to satisfy the reliability target of the alarm traffic. Specifically, P_{amd} is lower-bounded by the probability that no user transmits the alarm message, $(1 - \rho_d)^K$. Thus, to guarantee $P_{\text{amd}} \leq \epsilon_{\text{amd}}$, one must have that $(1 - \rho_d)^K \leq \epsilon_{\text{amd}}$, i.e., $\rho_d \geq 1 - \epsilon_{\text{amd}}^{1/K}$.

In the next section, we shall use a random-coding argument to obtain achievability bounds, i.e., upper bounds on the error probabilities in (2)–(5). Specifically, we will construct a codebook ensemble for which (2)–(5) hold in average. Unfortunately, this does not imply that there exists a code

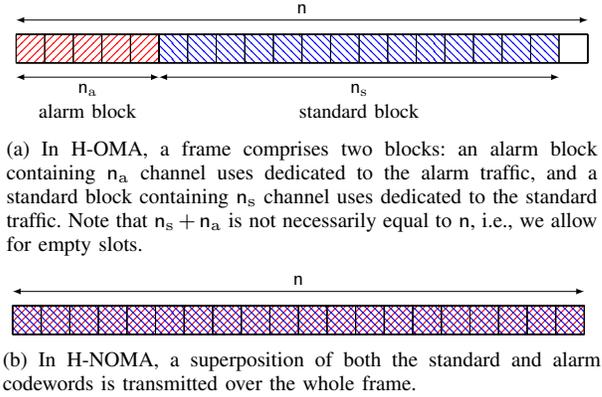


Fig. 2. Illustration of a frame in the two considered network slicing strategies, namely, H-OMA and H-NOMA.

in this ensemble that satisfies all these four constraints simultaneously. The introduction of the random variable U in Definition 1 allows us to circumvent this issue by enabling randomized coding strategies. Specifically, by proceeding as in [37, Th. 19], one can show that there exists a randomized coding strategy that achieves (2)–(5) simultaneously and involves time-sharing among at most five deterministic codes (i.e., $|\mathcal{U}| \leq 5$) in this ensemble.

III. HETEROGENEOUS ORTHOGONAL MULTIPLE ACCESS

We analyze next an orthogonal network slicing strategy, which we refer to as heterogeneous orthogonal multiple access (H-OMA). Each frame comprises two blocks: one containing n_a channel uses dedicated to the alarm traffic, and the other containing $n_s \leq n - n_a$ channel uses dedicated to the standard traffic. We illustrate the frame structure in Fig. 2(a). We next describe the signal model in each block.

A. Signal Model

We assume that the users share an alarm codebook containing M_a codewords of length n_a and a standard codebook containing M_s codewords of length n_s .

1) *Alarm Block:* If an alarm event has occurred, the common alarm message W_a is sent in the alarm block by every user that detects the alarm and decides to transmit (i.e.,

with probability ρ_d). Let $\mathbf{X}_a \in \mathbb{R}^{n_a}$ be the alarm codeword corresponding to W_a . The received signal is

$$\mathbf{Y}_a = K_a \mathbf{X}_a + \mathbf{Z}_a, \quad (6)$$

where $K_a \geq 0$ is the number of alarm users and $\mathbf{Z}_a \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_{n_a})$ is the AWGN. If no alarm event occurs, $K_a = 0$; otherwise, $K_a \sim \text{Bino}(K, \rho_d)$. We impose the power constraint $\|\mathbf{X}_a\|^2/n_a \leq P_a$. This model is equivalent to a single-user AWGN channel with random SNR $K_a^2 P_a$. The average energy per bit of the alarm traffic is upper-bounded by $(E_b/N_0)_a = \frac{n_a P_a \rho_d K}{2 \log_2 M_a}$.

2) *Standard Block*: The standard block resembles the UMA channel with random and unknown number of active users considered in [28]. The number of active users in this block is $K_s \sim \text{Bino}(K, \rho_s)$. Without loss of generality, we assume that the first K_s users are active. Let $\mathbf{X}_{s,k} \in \mathbb{R}^{n_s}$ be the standard codeword mapped from $W_{s,k}$. The received signal is

$$\mathbf{Y}_s = \sum_{k=1}^{K_s} \mathbf{X}_{s,k} + \mathbf{Z}_s, \quad (7)$$

where $\mathbf{Z}_s \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_{n_s})$ is the AWGN. We impose a power constraint $\|\mathbf{X}_{s,k}\|^2/n_s \leq P_s$, $k \in [K_s]$. The average energy per bit of the standard traffic is upper-bounded by $(E_b/N_0)_s = \frac{n_s P_s}{2 \log_2 M_s}$.

3) *Encoder, Decoder, and Power Constraint*: In accordance with Definition 1, the output of the encoding function is the concatenation of an alarm codeword and a standard codeword. The received signal \mathbf{Y} over the frame is $\mathbf{Y} = [\mathbf{Y}_a^T \ \mathbf{Y}_s^T]^T$. The decoder outputs an alarm message (or w_e) and a list of standard messages (or w_e) that are returned by the decoders operating on the two blocks, respectively. To satisfy the power constraint, we set (P_a, P_s) such that $n_a P_a + n_s P_s \leq nP$. We note that, for fixed P_a and P_s , orthogonality implies that the MD and FP in the standard traffic are independent of the alarm event, i.e., $P_{\text{smd}|\bar{A}} = P_{\text{smd}|A}$ and $P_{\text{sfp}|\bar{A}} = P_{\text{sfp}|A}$.

B. Random-Coding Bound

In the following, for a given frame split (n_a, n_s) and power allocation (P_a, P_s) , we derive a random-coding bound on the AMD, AFP, SMD, and SFP probabilities defined in (2)–(5).

1) *Alarm Block*: We fix a transmit power $P'_a \leq P_a$ and draw M_a alarm codewords $\mathcal{C}_a = \{\mathcal{C}_{a,1}, \dots, \mathcal{C}_{a,M_a}\}$ independently from $\mathcal{N}(\mathbf{0}, P'_a \mathbf{I}_{n_a})$. To convey an alarm message W_a , the alarm users transmit \mathcal{C}_{a,W_a} provided that $\|\mathcal{C}_{a,W_a}\|^2 \leq n_a P_a$. Otherwise, they transmit the all-zero codeword.² To summarize, $\mathbf{X}_a = \mathcal{C}_{a,W_a} \mathbb{1}\{\|\mathcal{C}_{a,W_a}\|^2 \leq n_a P_a\}$. Given a realization \mathbf{y}_a of the received signal, the decoder proceeds in two steps. First, it detects if an alarm is present. Specifically, it finds an initial estimate of the number of active alarm users as

$$K'_a = \arg \max_{k \in \{0\} \cup [k_{a,\ell} : k_{a,u}]} m_a(\mathbf{y}_a, k), \quad (8)$$

²This implies that, if there is an alarm, no user transmits the alarm codeword if it violates the power constraint. In our bound, we use a change of measure to account for the probability that a codeword violates the power constraint. We choose P'_a such that this probability is small.

where $m_a(\mathbf{y}_a, k) \triangleq P_{\mathbf{Y}_a|K_a}(\mathbf{y}_a|k) = (2\pi(1 + k^2 P_a))^{-n_a/2} \exp\left(-\frac{\|\mathbf{y}_a\|^2}{2(1+k^2 P_a)}\right)$. The limits $k_{a,\ell}$ and $k_{a,u}$ are chosen such that $\sum_{k=k_{a,\ell}}^{k_{a,u}} \text{Bino}(k; K, \rho_d)$ exceeds a threshold, as discussed in Remarks 4 and 5 below. If $K'_a = 0$, the decoder declares that there is no alarm, i.e., it returns the null message w_e . Otherwise, the decoder proceeds to decode the alarm message as

$$(\widehat{W}_a, \widehat{K}_a) = \arg \min_{w \in \mathcal{M}_a, k \in \{0\} \cup [k_{a,\ell} : k_{a,u}]} \|\mathbf{y}_a - k \mathcal{C}_{a,w}\|^2 \quad (9)$$

Finally, the decoder returns \widehat{W}_a if $\widehat{K}_a > 0$, or returns w_e if $\widehat{K}_a = 0$.

Remark 4: In [33], the decoding of the alarm message consists only of a step similar to (9), where the search space for \widehat{K}_a is $[0 : K]$. If there is no alarm, then $K_a = 0$, $\mathbf{Y}_a \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_{n_a})$, and $\mathbf{Y}_a - \mathcal{C}_{a,w} \sim \mathcal{N}(\mathbf{0}, (1 + P'_a) \mathbf{I}_{n_a})$. In this case, if $P'_a \ll 1$, i.e., $1 + P'_a \approx 1$, then (9) outputs $\widehat{K}_a = 1$ with significant probability. This causes a high AFP probability, which was the bottleneck in [33]. We overcome this bottleneck by adding the alarm-detection step (8), which aims to detect if $K_a = 0$, i.e., no alarm is present, or $K_a \in [k_{a,\ell} : k_{a,u}]$, i.e., an alarm is present. We also include $k = 0$ in the refined estimation of K_a in (9) to be able to detect the no-alarm state in this step.

Remark 5: Our alarm-detection step is a relaxed version of the Neyman-Pearson binary hypothesis test between the following two hypotheses: i) \mathbf{y}_a is generated from $\mathcal{N}(\mathbf{0}, \mathbf{I}_{n_a})$ (no alarm), and ii) \mathbf{y}_a is generated from $\mathcal{N}(\mathbf{0}, (1 + K_a^2 P_a) \mathbf{I}_{n_a})$ with $K_a \sim \text{Bino}(K, \rho_d)$ (an alarm is present). This Neyman-Pearson test declares that there is no alarm if

$$\Omega(\mathbf{y}_a) \triangleq \frac{m_a(\mathbf{y}_a, 0)}{\sum_{k=0}^K \text{Bino}(k; K, \rho_d) m_a(\mathbf{y}_a, K_a)} \geq \tau$$

and that there is an alarm otherwise, for a suitably chosen threshold τ . If $\sum_{k=k_{a,\ell}}^{k_{a,u}} \text{Bino}(k; K, \rho_d)$ is close to 1, we have that

$$\Omega(\mathbf{y}_a) \approx \bar{\Omega}(\mathbf{y}_a) \triangleq \frac{\sum_{k=k_{a,\ell}}^{k_{a,u}} \text{Bino}(k; K, \rho_d) m_a(\mathbf{y}_a, 0)}{\sum_{k=k_{a,\ell}}^{k_{a,u}} \text{Bino}(k; K, \rho_d) m_a(\mathbf{y}_a, k)}.$$

With $\tau = 1$, a sufficient condition for $\bar{\Omega}(\mathbf{y}_a) \geq \tau$ is that $m_a(\mathbf{y}_a, 0) \geq m_a(\mathbf{y}_a, k)$ for all $k \in [k_{a,\ell} : k_{a,u}]$, which we use in our scheme to signify that there is no alarm. Here, we tune $k_{a,\ell}$ to control the AFP, and introduce $k_{a,u}$ to avoid large sums (up to K) in the random-coding bound. While our test is suboptimal compared to the Neyman-Pearson test, it simplifies the derivation of the bound.

An error analysis of this scheme leads to the following upper bounds on P_{amd} and P_{sfp} .

Theorem 1 (Random-coding bound for the alarm block): Fix r_a , $n_a \in [n]$, $k_{a,\ell} \in [1 : K]$, $k_{a,u} \in [k_{a,\ell} + 1 : K]$, and $P'_a < P_a$. The AMD and AFP probabilities achieved by the

random-coding scheme just described are upper-bounded by ϵ_{amd} and ϵ_{afp} , respectively, where

$$\epsilon_{\text{amd}} = \sum_{k_a=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k_a) \left(\zeta(k_a, 0) + \min \left\{ 1, \sum_{k'_a=k_{a,\ell}}^{k_{a,u}} \zeta(k_a, k'_a) \right\} \cdot \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell}:k_{a,u}]} \gamma_{\text{amd}}(k_a, \hat{k}_a) \right) + \nu_0, \quad (10)$$

$$\epsilon_{\text{afp}} = \min \left\{ 1, \sum_{k'_a=k_{a,\ell}}^{k_{a,u}} \zeta(0, k'_a) \right\} \sum_{\hat{k}_a=k_{a,\ell}}^{k_{a,u}} \gamma_{\text{afp}}(\hat{k}_a), \quad (11)$$

with $P_{K_a}(k_a) = \text{Bino}(K, \rho_d)$ and

$$\nu_0 \triangleq \frac{\Gamma(n_a/2, n_a P_a / (2P'_a))}{\Gamma(n_a/2)} + 1 - \sum_{k=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k), \quad (12)$$

$$\gamma_{\text{amd}}(k_a, \hat{k}_a) \triangleq \min_{s>0} \mathbb{P} \left[\sum_{i=1}^{n_a} \iota_s(\hat{k}_a, X'_i; Y'_i) \leq \ln \frac{M_a - 1}{V} \right], \quad (13)$$

$$\gamma_{\text{afp}}(\hat{k}_a) \triangleq \min_{s>0} \mathbb{E} \left[\frac{1}{\Gamma(n_a/2)} \cdot \Gamma \left(\frac{n_a}{2}, \frac{1}{2\beta} \left(\frac{n_a}{2} \ln(1+2\hat{k}_a^2 P'_a s) - \ln \frac{M_a}{V} \right) \right) \right], \quad (14)$$

$$\beta \triangleq s - s(1 + 2\hat{k}_a^2 P'_a s)^{-1}, \quad (15)$$

$$\zeta(k_a, k'_a) \triangleq \min_{\substack{k \in \{0\} \cup [k_{a,\ell}:k_{a,u}], \\ k \neq k'_a}} \mathbb{P}[m_a(\mathbf{Y}'_a, k'_a) > m_a(\mathbf{Y}'_a, k)]. \quad (16)$$

In (16), $\mathbf{Y}'_a \sim \mathcal{N}(\mathbf{0}, (1 + k_a^2 P'_a) \mathbf{I}_{n_a})$. In (13) and (14), V is uniformly distributed over $[0, 1]$. In (13), $[X'_1 \dots X'_{n_a}]^\top \sim \mathcal{N}(\mathbf{0}, P'_a \mathbf{I}_{n_a})$; given $X'_i = x'_i$, we have that $Y'_i \sim \mathcal{N}(k_a x'_i, 1)$; $\iota_s(\hat{k}_a, X'_i; Y'_i)$ is the generalized information density given by

$$\iota_s(\hat{k}_a, x; y) \triangleq -s(y - k_a x)^2 + \frac{sy^2}{1 + 2s\hat{k}_a^2 P'_a} + \frac{1}{2} \ln(1 + 2s\hat{k}_a^2 P'_a). \quad (17)$$

Proof: The assumption that all alarm users transmit the same codeword is not compatible with the assumption of independent codeword generation in the original UMA setup. Consequently, we need to use a different bounding technique than in [6], [28]. Specifically, the proof of Theorem 1 relies on the random-coding union bound with parameter s (RCUs) [38]. See Appendix A for details. ■

The quantity $\zeta(k_a, k'_a)$ is an upper bound on the probability that the maximum-likelihood estimation step (8) returns k'_a , given that there are $K_a = k_a$ alarm users. Closed-form expressions for $\zeta(k_a, k'_a)$ can be deduced from [28, Th. 2].

In the numerical experiments (Section V), we use $s^* = \frac{1}{4} + \frac{\sqrt{\hat{k}_a^4 (P'_a)^2 + 4\hat{k}_a^2 P'_a + 4 - 2}}{4\hat{k}_a^2 P'_a}$, which maximizes the generalized mutual information $\mathbb{E} \left[\sum_{i=1}^{n_a} \iota_s(\hat{k}_a, X'_i; Y'_i) \right] = n_a \left[-s + \frac{s(1 + k_a^2 P'_a)}{1 + 2s\hat{k}_a^2 P'_a} + \frac{1}{2} \ln(1 + 2s\hat{k}_a^2 P'_a) \right]$, as an initial value for s when performing the minimization in (13). We also use 1/4, which

minimizes an upper bound on $\gamma_{\text{afp}}(\hat{k}_a)$, as an initial value for s when performing the minimization in (14).

2) *Standard Block:* We consider the random-coding scheme proposed in [28, Sec. III-A]. Specifically, we fix a transmit power $P'_s < P_s$ and generate the M_s standard codewords $\mathcal{C}_s = \{\mathbf{C}_{s,1}, \dots, \mathbf{C}_{s,M_s}\}$ independently from $\mathcal{N}(\mathbf{0}, P'_s \mathbf{I}_{n_s})$. To convey a standard message $W_{s,k}$, the k th standard user transmits $\mathbf{X}_{s,k} = \mathbf{C}_{s,W_{s,k}} \mathbb{1}\{\|\mathbf{C}_{s,W_{s,k}}\|^2 \leq n_s P_s\}$. Given the channel output \mathbf{y}_s , the decoder first estimates the number of active users as

$$K'_s = \arg \max_{k \in [k_{s,\ell}:k_{s,u}]} m_s(\mathbf{y}_s, k), \quad (18)$$

where $m_s(\mathbf{y}_s, k)$ is a suitably chosen metric; $k_{s,\ell}$ and $k_{s,u}$ are limits on K'_s , chosen based on the distribution of K_s , i.e., based on ρ_s . Then, given $K'_s = k'_s$, the decoder chooses the output list as

$$\widehat{\mathcal{W}} = \arg \min_{\mathcal{W}' \subset [M_s]: |\mathcal{W}'| \in [\underline{k}'_s: \overline{k}'_s]} \|\mathbf{y}_s - c(\mathcal{W}')\|^2, \quad (19)$$

where $\underline{k}'_s \triangleq \max\{k_{s,\ell}, k'_s - r_s\}$, $\overline{k}'_s \triangleq \min\{k_{s,u}, k'_s + r_s\}$, $c(\mathcal{W}') \triangleq \sum_{i \in \mathcal{W}'} \mathbf{C}_{s,i}$, and r_s is a chosen nonnegative integer, which we call the *standard-message decoding radius*. Bounds on the SMD and SFP probabilities achieved by this random-coding scheme follow from [28, Th. 1]. We state these bounds in the next theorem.

Theorem 2 (Random-coding bound for the standard block): Fix $r_s, n_s \in [n]$, $k_{s,\ell} \in [0 : K]$, $k_{s,u} \in [k_{s,\ell} + 1 : K]$, and $P'_s < P_s$. The SMD and SFP probabilities achieved by the random-coding scheme just described are upper-bounded by ϵ_{smd} and ϵ_{sfp} , respectively, where

$$\begin{aligned} \epsilon_{\text{smd}} &= \sum_{k_s=\max\{k_{s,\ell}, 1\}}^{k_{s,u}} P_{K_s}(k_s) \\ &\quad \cdot \bar{\epsilon}_{\text{smd}}(M_s, n_s, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u}) + \nu_1, \quad (20) \\ \epsilon_{\text{sfp}} &= \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) \bar{\epsilon}_{\text{sfp}}(M_s, n_s, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u}) \\ &\quad + \nu_1, \quad (21) \end{aligned}$$

with

$$\begin{aligned} \bar{\epsilon}_{\text{smd}}(M_s, n_s, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u}) &\triangleq \sum_{k'_s=k_{s,\ell}}^{k_{s,u}} \sum_{t \in \mathcal{T}} \frac{t + (k_s - \overline{k}'_s)^+}{k_s} \min\{p_t, q_t, \xi(k_s, k'_s)\}, \quad (22) \\ \bar{\epsilon}_{\text{sfp}}(M_s, n_s, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u}) &\triangleq \sum_{k'_s=k_{s,\ell}}^{k_{s,u}} \sum_{t \in \mathcal{T}} \sum_{t' \in \mathcal{T}} \frac{t' + (k'_s - k_s)^+}{k_s - t - (k_s - \overline{k}'_s)^+ + t' + (\underline{k}'_s - k_s)^+} \\ &\quad \cdot \min\{p_{t,t'}, q_{t,t'}, \xi(k_s, k'_s)\}. \quad (23) \end{aligned}$$

Here, in (20) and (21), $P_{K_s}(k_s) = \text{Bino}(k_s; K, \rho_s)$ and $\nu_1 \triangleq 2 - \sum_{k=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k) - \mathbb{E}_{K_s} \left[\frac{M_s!}{M_s^{K_s} (M_s - K_s)!} \right] + K \rho_s \frac{\Gamma(n_s/2, n_s P_s / (2P'_s))}{\Gamma(n_s/2)}$.

In (22) and (23), we define $p_t \triangleq \sum_{t' \in \bar{\mathcal{T}}_t} p_{t,t'}$ and $p_{t,t'} \triangleq e^{-n_s E(t,t')/2}$ where

$$E(t, t') \triangleq \max_{\rho_1, \rho_2 \in [0, 1]} -\rho_1 \rho_2 t' R_1 - \rho_2 R_2 + E_0(\rho_1, \rho_2), \quad (24)$$

$$E_0(\rho_1, \rho_2) \triangleq \max_{\lambda} \rho_2 a + \ln [1 - \rho_2 (1 + ((k_s - \bar{k}'_s)^+ + (k'_s - k_s)^+) P'_s) b], \quad (25)$$

with $a \triangleq \rho_1 \ln(1 + P'_s t' \lambda) + \ln(1 + P'_s t \mu)$, $b \triangleq \rho_1 \lambda - \frac{\mu}{1 + P'_s t \mu}$, $\mu \triangleq \frac{\rho_1 \lambda}{1 + P'_s t' \lambda}$, $R_1 \triangleq \frac{2}{n_s t'} \ln \binom{M_s - \max\{k_s, k'_s\}}{t'}$, and $R_2 \triangleq \frac{2}{n_s} \ln \binom{\min\{k_s, k'_s\}}{t}$. We also define

$$q_t \triangleq \inf_{\gamma} (\mathbb{P}[I_t \leq \gamma] + \sum_{t' \in \bar{\mathcal{T}}_t} \exp(n_s(t' R_1 + R_2)/2 - \gamma)), \quad (26)$$

$$q_{t,t'} \triangleq \inf_{\gamma} (\mathbb{P}[I_t \leq \gamma] + \exp(n_s(t' R_1 + R_2)/2 - \gamma)), \quad (27)$$

with

$$I_t \triangleq \min_{\substack{\mathcal{W}'_2 \subset [(k_s - \bar{k}'_s)^+ + 1 : k_s], \\ |\mathcal{W}'_2| = t}} \iota_t(c(\mathcal{W}'_1) + c(\mathcal{W}'_2); \mathbf{y}_s | c([k_s] \setminus \mathcal{W}')), \quad (28)$$

where $\mathcal{W}'_1 = [k_s + 1 : k'_s]$, $\mathcal{W}' = [(k_s - \bar{k}'_s)^+] \cup \mathcal{W}'_2$, and $\iota_t(c(\mathcal{W}'); \mathbf{y}_s | c(\mathcal{W} \setminus \mathcal{W}')) \triangleq \frac{n_s}{2} \ln(1 + (t + (k_s - \bar{k}'_s)^+) P'_s) + \frac{1}{2} \left(\frac{\|\mathbf{y}_s - c(\mathcal{W} \setminus \mathcal{W}')\|^2}{1 + (t + (k_s - \bar{k}'_s)^+) P'_s} - \|\mathbf{y}_s - c(\mathcal{W}') - c(\mathcal{W} \setminus \mathcal{W}')\|^2 \right)$. Furthermore, we define the sets \mathcal{T} , \mathcal{T}_t , and $\bar{\mathcal{T}}_t$ as

$$\mathcal{T} \triangleq [0 : \min\{\bar{k}'_s, k_s, M_s - k'_s - (k_s - \bar{k}'_s)^+\}], \quad (29)$$

$$\mathcal{T}_t \triangleq [((k_s - \bar{k}'_s)^+ - (k'_s - k_s)^+ + \max\{k'_s, 1\} - k_s + t)^+ : u_t], \quad (30)$$

$$\bar{\mathcal{T}}_t \triangleq [((k_s - \bar{k}'_s)^+ - (k_s - k'_s)^+ + t)^+ : u_t], \quad (31)$$

with $u_t \triangleq \min\{(\bar{k}'_s - k_s)^+ - (k'_s - k_s)^+ + t, \bar{k}'_s - (k'_s - k_s)^+, M_s - \max\{k'_s, k_s\}\}$. Finally,

$$\xi(k_s, k'_s) \triangleq \min_{k \in [0:K] \setminus \{k'_s\}} \mathbb{P}[m_s(\mathbf{Y}'_s, k'_s) > m_s(\mathbf{Y}'_s, k)] \quad (32)$$

with $\mathbf{Y}'_s \sim \mathcal{N}(\mathbf{0}, (1 + k_s P') \mathbf{I}_{n_s})$.

Proof: We obtain ϵ_{smd} and ϵ_{sfp} directly by adapting [28, Th. 1] to the real-valued case. Here, ν_1 is obtained from a change of measure under which $k_{s,\ell} \leq K_s \leq k_{s,u}$, $\mathbf{X}_{s,k} = \mathbf{C}_{s,W_{s,k}}$ (instead of $\mathbf{X}_{s,k} = \mathbf{C}_{s,W_{s,k}} \mathbb{1}\{\|\mathbf{C}_{s,W_{s,k}}\|^2 \leq n_s P_s\}$), and the standard users transmit distinct codewords. The quantities $p_{t,t'}$ and $q_{t,t'}$ are upper bounds on the probability of having $t + (k_s - \bar{k}'_s)^+$ SMDs and $t' + (k'_s - k_s)^+$ SFPs; p_t and q_t are upper bounds on the probability of having $t + (k_s - \bar{k}'_s)^+$ SMDs. We obtain p_t and $p_{t,t'}$ based on an error-exponent analysis, while q_t and $q_{t,t'}$ follow from a variation of the dependence-testing bound [29, Th. 17]. The sets \mathcal{T} , \mathcal{T}_t , $\bar{\mathcal{T}}_t$ contain possible values of t and t' . Finally, $\xi(k_s, k'_s)$ is an upper bound on the probability that, given $K_s = k_s$ standard users, the estimation step (18) returns k'_s . ■

The limits $k_{s,\ell}$ and $k_{s,u}$ are introduced to facilitate the numerical evaluation of the bounds, since they allow us to avoid large sums (from 0 to K) over k_s and k'_s . We set $k_{s,\ell}$

to be the largest value and $k_{s,u}$ the smallest value for which $\sum_{k=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k)$ exceeds a given threshold.

Remark 6: As explained in [27], [28], when P_s is small, one should use a small r_s to avoid noise overfitting. Specifically, when the noise dominates, a large r_s seems to increase the chance that the decoding step (19) returns a list containing codewords whose sum is closer in Euclidean distance to the noise than to the sum of the transmitted codewords. To satisfy mild targets on ϵ_{smd} and ϵ_{sfp} , setting $r_s = 0$ results in higher energy efficiency than $r_s > 0$, see [28, Fig. 2].

3) *Overall Random-Coding Bound:* By combining Theorem 1 and Theorem 2, we obtain the following random-coding bound for H-OMA.

Theorem 3 (Random-coding bound for H-OMA): Fix r_a , r_s , $n_a \in [0 : n]$, $k_{a,\ell} \in [1 : K]$, $k_{a,u} \in [k_{a,\ell} + 1 : K]$, $k_{s,\ell} \in [0 : K]$, $k_{s,u} \in [k_{s,\ell} + 1 : K]$, (P_a, P_s) such that $n_a P_a + n_s P_s \leq nP$, $P'_a < P_a$, and $P'_s < P_s$. For the considered Gaussian MAC with both standard and alarm traffic, there exists an $(M_a, M_s, n, \epsilon_{\text{amd}}, \epsilon_{\text{afp}}, \epsilon_{\text{smd}}, \epsilon_{\text{sfp}})$ random-access code with ϵ_{amd} and ϵ_{afp} given in Theorem 1, and ϵ_{smd} and ϵ_{sfp} given in Theorem 2.

IV. HETEROGENEOUS NONORTHOGONAL MULTIPLE ACCESS

We consider now a nonorthogonal network slicing strategy, which we refer to as H-NOMA, where both standard and alarm codewords are transmitted over the whole frame. We illustrate a frame of H-NOMA in Fig. 2(b).

A. Signal Model

Each alarm user maps the alarm message W_a to an alarm codeword $\mathbf{X}_a \in \mathbb{R}^n$. Furthermore, the k th standard user maps its standard message $W_{s,k}$ to a standard codeword $\mathbf{X}_{s,k} \in \mathbb{R}^n$. Over a frame, user k transmits $\mathbf{S}_k = \mathbf{X}_a + \mathbf{X}_{s,k}$ if it has both a standard message and an alarm message, $\mathbf{S}_k = \mathbf{X}_a$ if it has only an alarm message, $\mathbf{S}_k = \mathbf{X}_{s,k}$ if it has only a standard message, and $\mathbf{S}_k = \mathbf{0}$ if it is inactive. The received signal (1) can be written as

$$\mathbf{Y} = K_a \mathbf{X}_a + \sum_{k=1}^{K_s} \mathbf{X}_{s,k} + \mathbf{Z}, \quad (33)$$

where K_a is the number of alarm users, K_s is the number of standard users, and we assume that the first K_s users are the standard users. As for H-OMA, $K_a = 0$ if no alarm event occurs and $K_a \sim \text{Bino}(K, \rho_d)$ otherwise; furthermore, $K_s \sim \text{Bino}(K, \rho_s)$. We impose the power constraints $\|\mathbf{X}_a\|^2/n \leq P_a$ and $\|\mathbf{X}_{s,k}\|^2/n \leq P_s$, $k \in [K_s]$, and set $P_a + P_s \leq P$ to satisfy the overall power constraint. The average energy per bit of alarm and standard traffic are upper-bounded by $(E_b/N_0)_a = \frac{nP_a \rho_d K}{2 \log_2 M_a}$ and $(E_b/N_0)_s = \frac{nP_s}{2 \log_2 M_s}$, respectively.

B. Random-Coding Bound

We fix the transmit power $P'_a < P_a$ and draw the alarm codewords $\mathcal{C}_a = \{\mathbf{C}_{a,1}, \dots, \mathbf{C}_{a,M_a}\}$ independently from $\mathcal{N}(\mathbf{0}, P'_a \mathbf{I}_n)$. Similarly, we fix the transmit power $P'_s < P_s$ and draw the standard codewords $\mathcal{C}_s = \{\mathbf{C}_{s,1}, \dots, \mathbf{C}_{s,M_s}\}$

independently from $\mathcal{N}(\mathbf{0}, \mathbf{P}'_s \mathbf{I}_n)$. The alarm message W_a is mapped to $\mathbf{X}_a = \mathbf{C}_{a, W_a} \mathbb{1}\{\|\mathbf{C}_{a, W_a}\|^2 \leq nP_a\}$, while the standard message $W_{s,k}$ is mapped to $\mathbf{X}_{s,k} = \mathbf{C}_{s, W_{s,k}} \mathbb{1}\{\|\mathbf{C}_{s, W_{s,k}}\|^2 \leq nP_s\}$. To convey $(W_a, W_{s,k})$, W_a , or $W_{s,k}$, user k transmits $\mathbf{X}_a + \mathbf{X}_{s,k}$, \mathbf{X}_a , or $\mathbf{X}_{s,k}$, respectively.

Given a realization \mathbf{y} of the received signal, the receiver first decodes the alarm message and estimates the number of alarm users similarly to the alarm block in H-OMA. The sum of the standard codewords, $\sum_{k=1}^{K_s} \mathbf{X}_{s,k}$, is treated as noise. Specifically, the receiver performs steps (8) and (9) with \mathbf{y}_a replaced by \mathbf{y} , and obtains an estimate (\hat{K}_a, \hat{W}_a) of (K_a, W_a) . Next, exploiting reliability diversity [31], the receiver performs interference cancellation and decodes the list of standard messages in a similar manner to the standard block in H-OMA. Specifically, the receiver removes the decoded alarm codeword from the received signal to obtain $\mathbf{y}_{ic} = \mathbf{y} - \hat{K}_a \mathbf{C}_{a, \hat{W}_a}$. It then performs steps (18) and (19) with \mathbf{y}_s replaced by \mathbf{y}_{ic} , and obtains an estimate \hat{W}_s of the list of transmitted standard messages.

An error analysis of the proposed scheme leads to the following random-coding bound.

Theorem 4 (Random-coding bound for H-NOMA): Fix $r_a, r_s, k_{a,\ell} \in [1 : K]$, $k_{a,u} \in [k_{a,\ell} + 1 : K]$, $k_{s,\ell} \in [0 : K]$, $k_{s,u} \in [k_{s,\ell} + 1 : K]$, (P_a, P_s) such that $P_a + P_s \leq P$, $P'_a < P_a$, and $P'_s < P_s$. For the considered Gaussian MAC with both standard and alarm traffic, there exists an $(M_a, M_s, n, \epsilon_{amd}, \epsilon_{afp}, \epsilon_{smd}, \epsilon_{sfp})$ random-access code satisfying the power constraint P for which $\epsilon_{amd} = \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) \bar{\epsilon}_{amd}(k_s) + \nu_2$, $\epsilon_{afp} = \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) \bar{\epsilon}_{afp}(k_s) + \nu_3$, $\epsilon_{smd} = \max\{\epsilon_{smd|\mathcal{A}}, \epsilon_{smd|\bar{\mathcal{A}}}\}$, and $\epsilon_{sfp} = \max\{\epsilon_{sfp|\mathcal{A}}, \epsilon_{sfp|\bar{\mathcal{A}}}\}$. Here,

$$\nu_2 \triangleq \frac{\Gamma(\frac{n}{2}, \frac{nP_a}{2P'_a})}{\Gamma(n/2)} + 1 - \sum_{k=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k) + \nu_3, \quad (34)$$

$$\nu_3 \triangleq K\rho_s \frac{\Gamma(\frac{n}{2}, \frac{nP_s}{2P'_s})}{\Gamma(n/2)} + 2 - \sum_{k=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k) - \mathbb{E}_{K_s} \left[\frac{M_s}{M_s^{K_s} (M_s - K_s)!} \right], \quad (35)$$

$$\bar{\epsilon}_{amd}(k_s) \triangleq \sum_{k_a=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k_a) \left(\eta(k_a, 0, k_s) + \min \left\{ 1, \sum_{k'_a=k_{a,\ell}}^{k_{a,u}} \eta(k_a, k'_a, k_s) \right\} \cdot \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell}:k_{a,u}]} \theta_{amd}(k_a, \hat{k}_a, k_s) \right), \quad (36)$$

$$\bar{\epsilon}_{afp}(k_s) \triangleq \sum_{\hat{k}_a=k_{a,\ell}}^{k_{a,u}} \min \left\{ 1, \sum_{k'_a=k_{a,\ell}}^{k_{a,u}} \eta(0, k'_a, k_s) \right\} \theta_{afp}(\hat{k}_a, k_s), \quad (37)$$

where $P_{K_s}(k_s) = \text{Bino}(k_s; K, \rho_s)$ and $P_{K_a}(k_a) = \text{Bino}(k_a; K, \rho_d)$. We define $\theta_{amd}(k_a, \hat{k}_a, k_s)$ similarly to $\gamma_{amd}(k_a, \hat{k}_a)$ in (13) except that n_a is replaced by n , and

given $X'_i = x'_i$, we have that $Y'_i \sim \mathcal{N}(k_a x'_i, 1 + k_s P'_s)$ instead of $Y'_i \sim \mathcal{N}(k_a x'_i, 1)$. We define $\theta_{afp}(\hat{k}_a, k_s)$ similarly to $\gamma_{afp}(\hat{k}_a)$ in (14) except that n_a is replaced by n and β is given by $s(1 - (1 + 2\hat{k}_a^2 P'_a s)^{-1})(1 + k_s P'_s)$. Furthermore, we define $\eta(k_a, k'_a, k_s)$ similarly to $\zeta(k_a, k'_a)$ in (16), except that $\mathbf{Y}' \sim \mathcal{N}(\mathbf{0}, (1 + k_a^2 P'_a + k_s P'_s) \mathbf{I}_n)$. We also have that

$$\epsilon_{smd|\bar{\mathcal{A}}} \triangleq 1 - \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) (1 - \bar{\epsilon}_{afp}(k_s)) \cdot (1 - \bar{\epsilon}_{smd}(M_s, n, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u})) + \nu_2, \quad (38)$$

$$\epsilon_{sfp|\bar{\mathcal{A}}} \triangleq 1 - \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) (1 - \bar{\epsilon}_{afp}(k_s)) \cdot (1 - \bar{\epsilon}_{sfp}(M_s, n, k_s, P_s, P'_s, r_s, k_{s,\ell}, k_{s,u})) + \nu_2, \quad (39)$$

$$\epsilon_{smd|\mathcal{A}} \triangleq 1 - \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) (1 - \bar{\epsilon}_{amd}(k_s)) \cdot \left(1 - \sum_{k_a=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k_a) \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell}:k_{a,u}]} \alpha(k_a, \hat{k}_a, k_s) \cdot \bar{\epsilon}_{smd}(M_s, n, k_s, \frac{P_s}{1+(k_a-\hat{k}_a)^2 P'_a}, \frac{P'_s}{1+(k_a-\hat{k}_a)^2 P'_a}, r_s, k_{s,\ell}, k_{s,u}) \right) + \nu_2, \quad (40)$$

$$\epsilon_{sfp|\mathcal{A}} \triangleq 1 - \sum_{k_s=k_{s,\ell}}^{k_{s,u}} P_{K_s}(k_s) (1 - \bar{\epsilon}_{amd}(k_s)) \cdot \left(1 - \sum_{k_a=k_{a,\ell}}^{k_{a,u}} P_{K_a}(k_a) \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell}:k_{a,u}]} \alpha(k_a, \hat{k}_a, k_s) \cdot \bar{\epsilon}_{sfp}(M_s, n, k_s, \frac{P_s}{1+(k_a-\hat{k}_a)^2 P'_a}, \frac{P'_s}{1+(k_a-\hat{k}_a)^2 P'_a}, r_s, k_{s,\ell}, k_{s,u}) \right) + \nu_2, \quad (41)$$

where $\bar{\epsilon}_{smd}$ and $\bar{\epsilon}_{sfp}$ are given in (22) and (23), respectively, and

$$\alpha(k_a, \hat{k}_a, k_s) \triangleq \mathbb{1}\{\hat{k}_a = 0\} \eta(k_a, 0, k_s) + \min \left\{ 1, \sum_{k'_a=k_{a,\ell}}^{k_{a,u}} \eta(k_a, k'_a, k_s) \right\} \left(1 + \frac{(k_a - \hat{k}_a)^2 P'_a}{4(1 + \hat{k}_a P'_s)} \right)^{-n/2}. \quad (42)$$

Proof: The proof follows by adapting the bounding techniques used for H-OMA to account for the interference from the standard codewords when decoding the alarm message, and the residual interference from the alarm codeword when decoding the standard messages, induced by the interference cancellation process in H-NOMA. See Appendix B for details. ■

The term $\alpha(k_a, \hat{k}_a, k_s)$ is an upper bound on the probability that the receiver estimates K_a by \hat{k}_a , given that there are k_a alarm users, k_s standard users, and W_a is correctly decoded.

V. NUMERICAL EXPERIMENTS

We set the framelength n to 30000. Motivated by Remark 2, we consider $(M_s, M_a) = (2^{100}, 2^3)$, the mild target reliability $\max\{P_{\text{smd}}, P_{\text{sfp}}\} \leq 10^{-1}$ for the standard traffic, and the stringent target reliability $\max\{P_{\text{amd}}, P_{\text{afp}}\} \leq 10^{-5}$ for the alarm traffic. We set $K \in [1000 : 30000]$ and $\rho_s = 0.01$, so that $\mathbb{E}[K_s] \in [10 : 300]$, similar to the setting in [6], [28]. Let $(E_b/N_0)_s^*$ be the minimum required energy per bit for the standard traffic to satisfy $\max\{P_{\text{smd}}, P_{\text{sfp}}\} \leq 10^{-1}$ if the alarm traffic is not present. We evaluate $(E_b/N_0)_s^*$ in a similar manner as in [28], considering maximum-likelihood estimation of K_s and zero standard-message decoding radius, i.e., $r_s = 0$. Note that for the mild requirement $\max\{P_{\text{smd}}, P_{\text{sfp}}\} \leq 10^{-1}$, setting $r_s = 0$ leads to high energy efficiency since it helps to avoid noise overfitting; see Remark 6. In the remainder of this section, we address the following question: *Let the standard traffic operate at $(E_b/N_0)_s^* + \delta$ (dB) for a fixed backoff $\delta > 0$. What is the minimum required³ $(E_b/N_0)_a$?*

A. H-OMA

To address this question for the case of H-OMA, we find the minimum blocklength $n_{s,\min}$ required to satisfy $\max\{\epsilon_{\text{smd}}, \epsilon_{\text{sfp}}\} \leq 10^{-1}$ at $(E_b/N_0)_s^* + \delta$ dB. The number of available channel uses for the alarm traffic is thus $n_{a,\max} = n - n_{s,\min}$. In Fig. 3, we plot $n_{a,\max}$ as a function of K for three backoff values: 0 dB (no backoff), 0.1 dB, and 0.2 dB. We see that $n_{a,\max}$ is large for small K , and then decreases as K becomes large. For $K \leq 15000$, even with zero backoff, $n_{s,\min}$ is less than n . This shows that for a fixed $(E_b/N_0)_s$, i.e., a fixed energy $n_s P_s$, the higher transmit power P_s induced by reducing n_s is sufficient to keep $\max\{\epsilon_{\text{smd}}, \epsilon_{\text{sfp}}\}$ below 10^{-1} . For $K > 15000$, the standard blocklength cannot be shortened without a positive backoff, as a higher power is needed to counteract multi-user interference. As expected, a larger backoff leads to more available channel uses for the alarm traffic.

Next, for a given $n_{a,\max}$, we find the minimum required $(E_b/N_0)_a$ by solving

$$\begin{aligned} & \underset{\substack{n_a \in [n_{a,\max}], \\ \rho_d \in (1-(10^{-5})^{1/K}, \rho_{d,\max}), P_a > 0, P'_a \leq P_a}}{\text{minimize}} && (E_b/N_0)_a && (43) \\ & \text{subject to} && \max\{\epsilon_{\text{amd}}, \epsilon_{\text{afp}}\} \leq 10^{-5} \end{aligned}$$

with ϵ_{amd} and ϵ_{afp} given in Theorem 1. To solve (43), we apply a golden-section search sequentially over n_a and ρ_d , where for each value of n_a and ρ_d , the required $(E_b/N_0)_a$ is obtained via a binary search for the smallest power P_a such that $\max\{\epsilon_{\text{amd}}, \epsilon_{\text{afp}}\} \leq 10^{-5}$. For each n_a and P_a , we choose the transmit power P'_a such that $\frac{\Gamma(n_a/2, n_a P_a / (2P'_a))}{\Gamma(n_a/2)} < 10^{-8}$ to limit ν_0 . We choose $k_{a,\ell}$ and $k_{a,u}$ such that $k_{a,\ell} \geq 2$ and $\mathbb{P}[K_a \notin [k_{a,\ell} : k_{a,u}] | \mathcal{A}] = 1 - \sum_{k=k_{a,\ell}}^{k_{a,u}} \text{Bino}(k; K, \rho_d) < 10^{-10}$. In the following, we set $\delta = 0.1$ dB and study the minimum required $(E_b/N_0)_a$.

³Report $(E_b/N_0)_a$ for a fixed $(E_b/N_0)_s$ is meaningful because it reflects the energy efficiency of the alarm traffic even if the alarm event is rare.

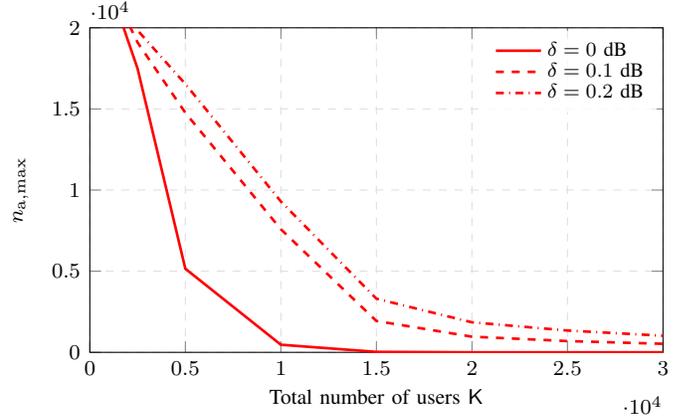


Fig. 3. The number of available channel uses $n_{a,\max}$ for the alarm traffic in H-OMA when the standard traffic operates at $(E_b/N_0)_s^* + \delta$ dB and satisfies $\max\{\epsilon_{\text{smd}}, \epsilon_{\text{sfp}}\} \leq 10^{-1}$. Here, $n = 30000$, $M_s = 2^{100}$ and $\rho_s = 0.01$.

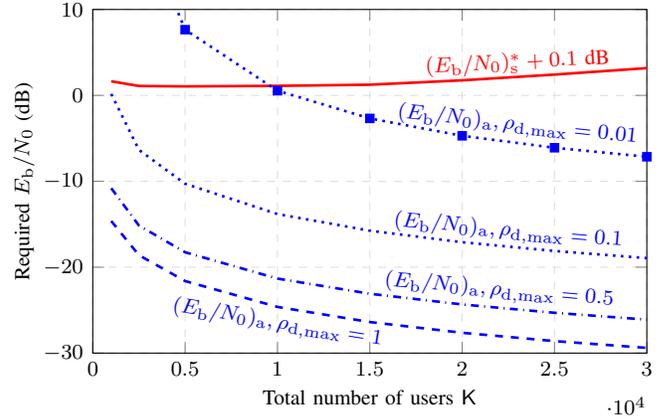


Fig. 4. The minimum $(E_b/N_0)_a$ required for H-OMA to satisfy $\max\{\epsilon_{\text{amd}}, \epsilon_{\text{afp}}\} \leq 10^{-5}$ when $(E_b/N_0)_s = (E_b/N_0)_s^* + 0.1$ dB for different values of the device sensitivity $\rho_{d,\max}$. Here, $n = 30000$, $M_a = 2^3$, $M_s = 2^{100}$, and $\rho_s = 0.01$.

1) *Impact of the Device Sensitivity:* As noted in Remark 1, ρ_d is upper-bounded by the probability that a user detects the alarm event, $\rho_{d,\max}$. To study the impact of $\rho_{d,\max}$ on the alarm-traffic energy efficiency, we vary its value and show in Fig. 4 the corresponding minimum required $(E_b/N_0)_a$ as a function of K . We also show the value of $(E_b/N_0)_s^* + 0.1$ dB for reference. We see that the required $(E_b/N_0)_a$ can be very low, especially for large $\rho_{d,\max}$. This indicates that, in H-OMA, the alarm message can be transmitted at high energy efficiency, at a cost of only a marginal backoff in the standard-traffic energy efficiency. In our numerical optimization, the minimum required $(E_b/N_0)_a$ is achieved when $\rho_d = \rho_{d,\max}$, and P_a and n_a are minimized such that $\max\{\epsilon_{\text{amd}}, \epsilon_{\text{afp}}\} \leq 10^{-5}$. That is, one should let every user that detects the alarm event transmit at a low power using only few channel uses. The reason is that, by having a large K_a (via increasing ρ_d), one achieves a high effective SNR $K_a^2 P_a$, whereas for a fixed K_a , one should minimize P_a and n_a to reduce the total energy $K_a P_a n_a$. This also explains why the required $(E_b/N_0)_a$ decreases as K or $\rho_{d,\max}$ increases, i.e., K_a increases.

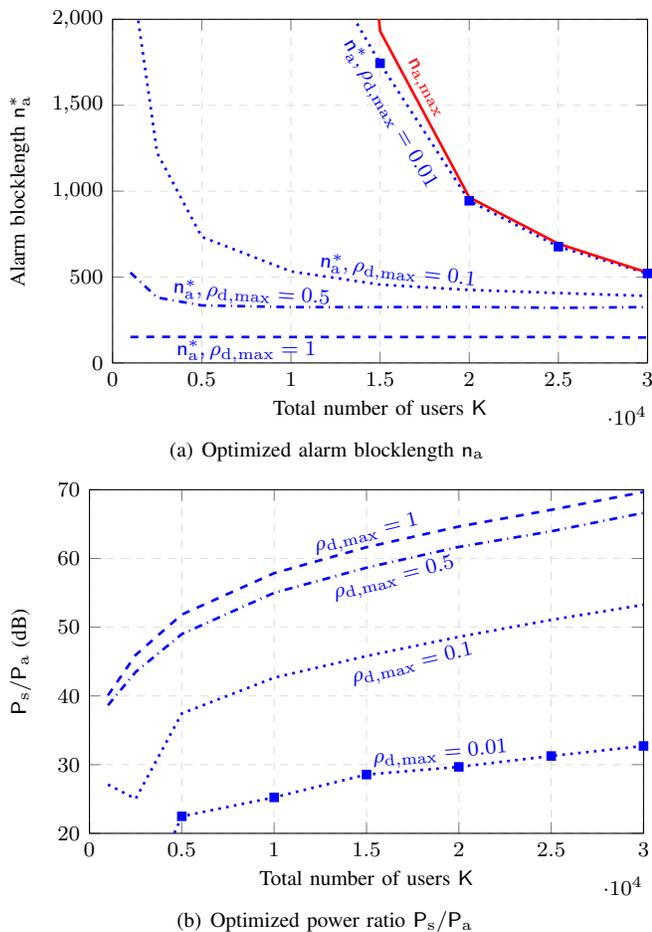


Fig. 5. The optimized alarm blocklength n_a and power ratio P_s/P_a for the setting in Fig. 4.

In Fig. 5(a), we show the numerically optimized alarm blocklength n_a^* for the considered setting. We also plot $n_{a,max}$ for reference. If the users are not sensitive (i.e., $\rho_{d,max}$ is small), the active ones should transmit alarm codewords of length close to the maximum one, $n_{a,max}$. As $\rho_{d,max}$ increases, alarm codewords of length progressively smaller than $n_{a,max}$ suffice. In Fig. 5(b), we depict the ratio P_s/P_a for the optimized alarm power P_a . We observe that the optimized P_a is much smaller than P_s , and the ratio P_s/P_a increases as K or $\rho_{d,max}$ increases. We further observe from numerical evaluation that if $\rho_{d,max}$ is high, i.e., many users transmit the alarm message, the bottleneck is to satisfy $P_{amd} \leq 10^{-5}$. However, the bottleneck becomes the AFP requirement $P_{afp} \leq 10^{-5}$ if $\rho_{d,max}$ is low, i.e., few users transmit the alarm message.

2) *Impact of the Dynamic Range:* The power difference between the alarm and the standard blocks requires the user devices to support a wide dynamic range. Recently designed transmitters for narrow-band IoT applications have the dynamic range from 34.1 dB [39] to 72.3 dB [40]. To account for the limited dynamic range of IoT devices, we impose the additional constraint $P_s/P_a \leq \psi$ in the minimization (43) of the required $(E_b/N_0)_a$. In Fig. 6, we plot the minimum required $(E_b/N_0)_a$ for $\rho_{d,max} = 1$ and $\psi \in \{0, 10, 30, 50, \infty\}$ dB. The case of infinite dynamic range corresponds to the setting

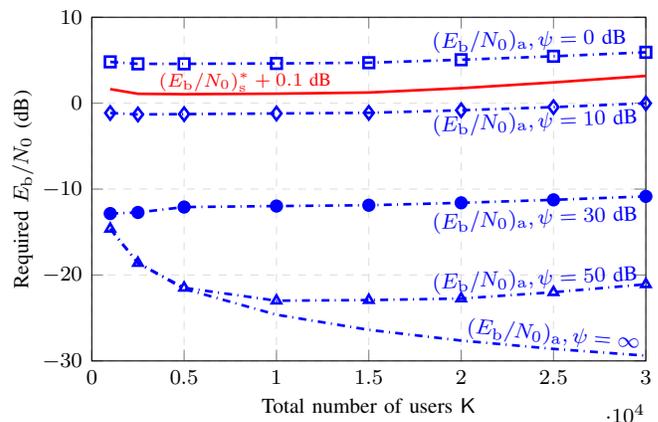


Fig. 6. The minimum $(E_b/N_0)_a$ required for H-OMA to satisfy $\max\{\epsilon_{amd}, \epsilon_{afp}\} \leq 10^{-5}$ when $(E_b/N_0)_s = (E_b/N_0)_s^* + 0.1$ dB for different dynamic range ψ . Here, $M_a = 2^3$, $M_s = 2^{100}$, $\rho_s = 0.01$, and $\rho_{d,max} = 1$.

in Fig. 4. We see that a narrower dynamic range leads to a higher required $(E_b/N_0)_a$. If the users transmit at equal power over the two blocks, i.e., $\psi = 0$ dB, the alarm traffic requires a higher energy per bit than the standard traffic.

We observe that for each K and n_a , if ψ is large enough such that the power ratios depicted in Fig. 5(b) are achievable, one should let $\rho_d = 1$ and use the optimized P_a for the $\psi = \infty$ case. Otherwise, the required $(E_b/N_0)_a$ is minimized with P_a equal to its minimum value P_s/ψ and ρ_d equal to the smallest value such that $\max\{\epsilon_{amd}, \epsilon_{afp}\} \leq 10^{-5}$. In Fig. 7, we show the optimized alarm blocklength n_a and optimized average number of alarm users $\rho_d K$ obtained from our numerical optimization. As shown in Fig. 7(a), when the dynamic range is limited to 50 dB and $K \geq 10^4$, the optimized alarm blocklength is significantly lower than for the case of infinite dynamic range. This is because when each alarm user transmits at a higher power, the codeword can be shortened. However, as shown in Fig. 6, this results in higher required $(E_b/N_0)_a$. Fig. 7(b) shows that as we increase ψ , the average number of alarm users increases. Indeed, a lower ψ leads to a smaller optimized n_a and ρ_d .

B. H-NOMA

For H-NOMA, we set P_s such that $(E_b/N_0)_s = (E_b/N_0)_s^* + \delta$ dB and find the minimum ρ_d and P_a required to satisfy the requirements of both traffic types. We choose $k_{s,\ell}$ and $k_{s,u}$ such that $1 - \sum_{k=k_{s,\ell}}^{k_{s,u}} \text{Bino}(k; K, \rho_s) < 10^{-10}$, and choose P'_s for each P_s such that $\frac{\Gamma(n/2, nP_s/(2P'_s))}{\Gamma(n/2)} < 10^{-5}$. It turns out that the main challenge is to satisfy the target SMD and SFP probabilities when there is an alarm. Indeed, although the alarm message W_a can usually be reliably decoded, the number of alarm users K_a is estimated incorrectly with significant probability. The probability of wrongly estimating the number of alarm users given no AMD can be computed as $\mathbb{P}[\arg \min_k \|\mathbf{Y} - k\mathbf{C}_{a,W_a}\|^2 \neq K_a]$. Note that this probability also accounts for a reestimation of K_a after correctly decoding W_a . With $K_s = 100$ and $P_a = P_s/\psi$, we have that $\mathbb{P}[\arg \min_k \|\mathbf{Y} - k\mathbf{C}_{a,W_a}\|^2 \neq K_a]$ is equal to 0.276 for

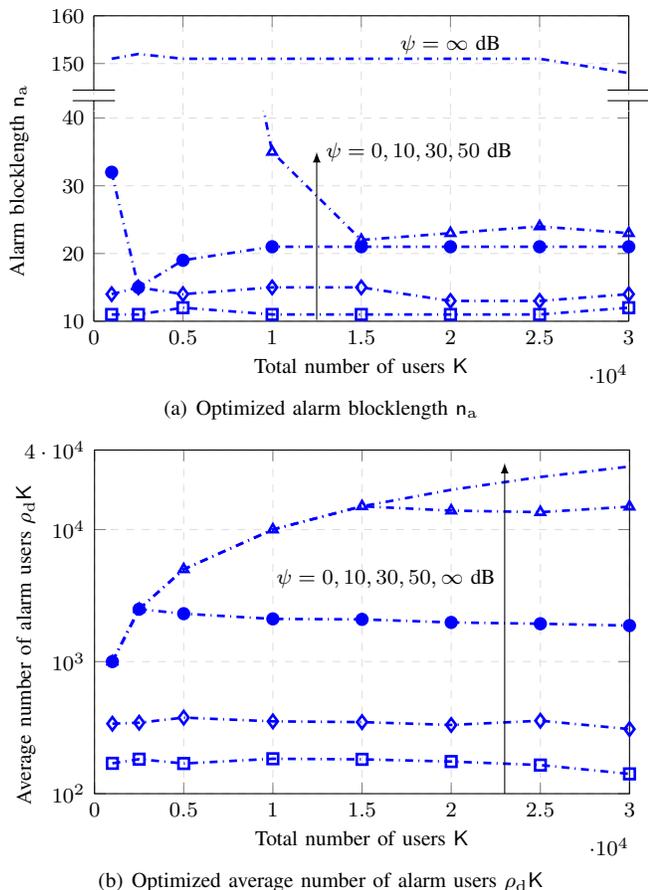


Fig. 7. The optimized alarm blocklength n_a and average number of alarm users $\rho_d K$ for the setting in Fig. 6.

$\psi = 20$ dB and 0.426 for $\psi = 30$ dB. With $K_s = 200$, this probability is 0.306 for $\psi = 20$ dB and 0.433 for $\psi = 30$ dB. (In our bound, this is reflected by the fact that $\alpha(k_a, \hat{k}_a, k_s)$ is significantly large for $k_a \neq \hat{k}_a$, especially if k_s is large.) This leads to a high residual interference $K_a C_a, W_a - \hat{K}_a C_a, \hat{W}_a$ when decoding the standard messages. We note that lowering P_{amd} and P_{afp} does not resolve this issue because, as we have seen, K_a is estimated incorrectly with significant probability even if $\hat{W}_a = W_a$.

With the same $(E_b/N_0)_s$ backoff $\delta = 0.1$ dB as considered for H-OMA, H-NOMA cannot satisfy the reliability requirements for both traffic types unless the estimation of K_a is reliable, which occurs when $\rho_d = 1$, i.e., $K_a = K$, or when P_a is high, i.e., comparable to P_s . In Fig. 8, we plot the minimum required $(E_b/N_0)_a$ for H-NOMA in these two cases. Specifically, we consider $\rho_d = 1$ and minimize P_a , and also consider $P_a = P_s$ and minimize ρ_d . As a comparison, we depict the corresponding $(E_b/N_0)_a$ values for H-OMA, which are obtained by considering the two cases $\psi = \infty$ and $\psi = 0$ dB. For $P_a = P_s$, the $(E_b/N_0)_a$ of H-NOMA is lower-bounded by $(E_b/N_0)_a = \frac{n P_a \rho_d K}{2 \log_2 M_a} \geq \frac{n P_s (1 - \epsilon_{\text{amd}}^{1/K}) K}{2 \log_2 M_a} \geq \frac{n P_s (1 - (10^{-5})^{1/K}) K}{2 \log_2 M_a}$ since $\rho_d \geq 1 - \epsilon_{\text{amd}}^{1/K}$ (see Remark 3). The minimum required $(E_b/N_0)_a$ of H-NOMA is slightly higher than this lower bound, and is much higher than the minimum required $(E_b/N_0)_a$ of H-OMA. For $\rho_d = 1$, the

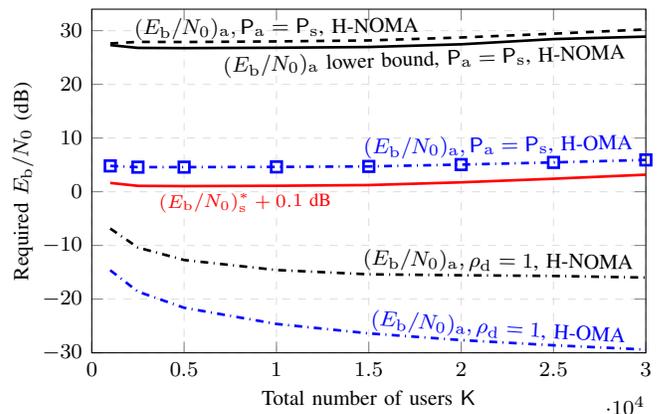


Fig. 8. The minimum $(E_b/N_0)_a$ required for H-OMA and H-NOMA to satisfy $\max\{\epsilon_{\text{smd}|\mathcal{A}}, \epsilon_{\text{smd}|\bar{\mathcal{A}}}, \epsilon_{\text{sfp},\mathcal{A}}, \epsilon_{\text{sfp},\bar{\mathcal{A}}}\} \leq 10^{-1}$ and $\max\{\epsilon_{\text{amd}}, \epsilon_{\text{afp}}\} \leq 10^{-5}$ when $(E_b/N_0)_s = (E_b/N_0)_s^* + 0.1$ dB for two cases: i) $\rho_d = 1$ and optimized P_a , and ii) $P_a = P_s$ and optimized ρ_d . Here, $M_a = 2^3$, $M_s = 2^{100}$, $\rho_s = 0.01$, and $\rho_{d,\text{max}} = 1$.

minimum required $(E_b/N_0)_a$ of H-NOMA is also significantly higher than H-OMA. In this case, the optimized P_a is similar in both schemes, but the alarm codeword length n_a in H-OMA is much shorter than that in H-NOMA (i.e., n). This leads to a significant difference in energy efficiency.

Our results suggest that reliability diversity [31] is hard to exploit in nonorthogonal network slicing between massive and critical IoT over the Gaussian MAC. This supports the claim in [31] that nonorthogonal network slicing between URLLC and mMTC may be problematic. While [31] predicted that the main challenge is to guarantee reliability for URLLC devices, we point out that reliable message decoding for URLLC devices is not enough to effectively perform interference cancellation. In our setup, the number of active URLLC devices (i.e., the number of alarm users) also needs to be estimated reliably.⁴

We further note that interference cancellation is not strictly needed for H-NOMA. Without interference cancellation, the receiver decodes the list of standard messages by treating the alarm signal as noise. Our bound in Theorem 4 can be easily adapted to this case. However, due to the interference from the alarm signal, the standard-traffic reliability requirements are difficult to achieve with a small backoff. For the setting in Fig. 8 with $\rho_d = 1$, the backoff has to be progressively increased from 0.18 to 0.89 dB as K grows from 1000 to 30000.

VI. CONCLUSIONS AND FUTURE WORKS

We investigated massive and critical IoT in a setting where both standard UMA traffic and alarm traffic are present. We considered a random and unknown number of active users and accounted for misdetections and false positives in both traffic types. For the Gaussian MAC, our results show that both traffic types can coexist with high energy efficiency by means of orthogonal network slicing, provided that a large number of

⁴H-OMA also has advantage in terms of latency for the alarm traffic since the alarm codeword occupies only a small fraction of a frame and it is decoded first.

users transmit the alarm message, and that the transmit power of the alarm message is much smaller than that of the standard message. On the contrary, nonorthogonal network slicing is energy inefficient due to the residual interference from the alarm signal when decoding the standard messages, caused by unreliable estimation of the number of alarm users. These results indicate that it is hard to exploit reliability diversity to perform nonorthogonal network slicing between massive and critical IoT, and that orthogonal network slicing is preferable.

Our conclusions pertain to the Gaussian MAC and to the considered random-coding scheme. In more general/practical settings, H-NOMA might have advantages over H-OMA. First, in this paper, we aim to satisfy the SMD and SFP requirements in both alarm and no alarm states, and the bottleneck of H-NOMA is the alarm state. If one considers average SMD and SFP probabilities over the two states, H-NOMA can still satisfy the requirements if the alarm event is rare. Second, in our setting, the detection of the alarm message benefits from the coherent addition of the common alarm codeword transmitted by many users, and thus only few channel uses suffice for the alarm traffic in H-OMA. In practice, the channel may cause a mismatch, such as a phase rotation or a scaling factor, between the signal transmitted from different users. Furthermore, multiple alarm messages with different reliability guarantees may need to be simultaneously reported. These aspects need to be taken into account. Third, one can consider dynamic power adaptation based on the presence/absence of alarm messages. For example, one can let the users increase the transmit power of the standard message if the alarm message is not present.

APPENDIX A PROOF OF THEOREM 1

The following well-known results will be used in our proof.

Lemma 1 (Change of measure [41, Lemma 4]): Let p and q be two probability measures. Consider a random variable X supported on \mathcal{H} and a function $f: \mathcal{H} \rightarrow [0, 1]$. It holds that $\mathbb{E}_p[f(X)] \leq \mathbb{E}_q[f(X)] + d_{\text{TV}}(p, q)$, where $d_{\text{TV}}(p, q)$ is the total variation distance [42, Sec. 2] between p and q .

Lemma 2 (Chernoff bound [43, Th. 6.2.7]): For a random variable X with moment-generating function $\mathbb{E}[e^{tX}]$ defined for all $|t| \leq b$, it holds for all $\lambda \in [0, b]$ that $\mathbb{P}[X \leq x] \leq e^{\lambda x} \mathbb{E}[e^{-\lambda X}]$.

Lemma 3: Let $\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \sigma^2 \mathbf{I}_n)$. It holds that

$$\mathbb{E}\left[e^{-\gamma \|\mathbf{X}\|^2}\right] = (1 + 2\gamma\sigma^2)^{-n/2} \exp\left(-\frac{\gamma \|\boldsymbol{\mu}\|^2}{1 + 2\gamma\sigma^2}\right) \quad (44)$$

for every $\gamma > -\frac{1}{2\sigma^2}$. Furthermore, if $\boldsymbol{\mu} = \mathbf{0}$, it holds that

$$\mathbb{P}[\|\mathbf{X}\|^2 > y] = \frac{\Gamma(n/2, y/(2\sigma^2))}{\Gamma(n/2)}. \quad (45)$$

Proof: Note that $\|\mathbf{X}\|^2/\sigma^2$ follows a noncentral chi-squared distribution with n degrees of freedom and noncentral parameter $\|\boldsymbol{\mu}\|^2/\sigma^2$. The results in (44) and (45) follows straightforwardly from the expressions of moment generating function and complementary cumulative distribution function, respectively, of this distribution. ■

A. Proof of the Bound (10) on P_{amd}

The AMD probability averaged over the Gaussian codebook ensemble is computed as

$$P_{\text{amd}} = \mathbb{E}_{K_a, C_a} [\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}]. \quad (46)$$

1) *A Change of Measure:* We first perform a change of measure as in [6], [28]. Specifically, we replace the measure over which the expectation in (46) is taken by the one under which $\mathbf{X}_a = \mathbf{C}_{a, W_a}$ instead of $\mathbf{X}_a = \mathbf{C}_{a, W_a} \mathbb{1}\{\|\mathbf{C}_{a, W_a}\|^2 \leq n_a P_a\}$. Furthermore, under the new measure, there are at least $k_{a, \ell}$ and at most $k_{a, u}$ users transmitting the alarm message, i.e., $K_a \in [k_{a, \ell} : k_{a, u}]$. It then follows from [44, Eq. (41)] that the total variation between the original measure and the new one is upper-bounded by $\nu_0 \triangleq \mathbb{P}[\|\mathbf{C}_{a, W_a}\|^2 > n_a P_a] + \mathbb{P}[K_a \neq [k_{a, \ell} : k_{a, u}]]$. Since $\mathbf{C}_{a, W_a} \sim \mathcal{N}(\mathbf{0}, P_a' \mathbf{I}_{n_a})$, it follows from (45) that $\mathbb{P}[\|\mathbf{C}_{a, W_a}\|^2 > n_a P_a] = \frac{\Gamma(n_a/2, n_a P_a/(2P_a'))}{\Gamma(n_a/2)}$. Furthermore, $\mathbb{P}[K_a \neq [k_{a, \ell} : k_{a, u}]] = 1 - \sum_{k=k_{a, \ell}}^{k_{a, u}} P_{K_a}(k)$, where $P_{K_a}(k) = \text{Bino}(k; K, \rho_d)$. Therefore, ν_0 is given by (12). By applying Lemma 1 to the random quantity $\mathbb{1}\{\widehat{W}_a \neq W_a\}$, we consider implicitly the new measure from now on at a cost of adding ν_0 to the original expectation in (46). That is

$$P_{\text{amd}} = \sum_{k_a=k_{a, \ell}}^{k_{a, u}} P_{K_a}(k_a) \mathbb{E}_{C_a} [\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_a = k_a] + \nu_0 \quad (47)$$

where the expectation is taken under the assumption that $\mathbf{X}_a = \mathbf{C}_{a, W_a}$.

2) *Expanding $\mathbb{E}_{C_a}[\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_a = k_a]$:* We denote by $\{k_a \rightarrow k'_a\}$ the event that $K_a = k_a$ and the initial estimation of K_a in (8) outputs k'_a . According to (8),

$$\begin{aligned} & \mathbb{P}[k_a \rightarrow k'_a] \\ &= \mathbb{P}[m_a(\mathbf{Y}_a, k'_a) > m_a(\mathbf{Y}_a, k), \forall k \in [k_{a, \ell} : k_{a, u}] \setminus \{k'_a\} \\ & \quad | K_a = k_a] \\ &\leq \min_{k \in \{0\} \cup [k_{a, \ell} : k_{a, u}] \setminus \{k'_a\}} \mathbb{P}[m_a(\mathbf{Y}_a, k'_a) > m_a(\mathbf{Y}_a, k)]. \end{aligned} \quad (48)$$

Under the new measure, $\mathbf{Y}_a \sim \mathcal{N}(\mathbf{0}, (1 + k_a P_a') \mathbf{I}_{n_a})$. Thus the right-hand side of (49) is given by $\zeta(k_a, k'_a)$ defined in (16).

Given $k_a > 0$ and $k_a \rightarrow k'_a$, an AMD $\{\widehat{W}_a \neq W_a\}$ occurs if $k'_a = 0$, or if $k'_a \in [k_{a, \ell} : k_{a, u}]$ but the decoder (9) returns the wrong alarm message. The latter event occurs if some scaled version of a wrong alarm codeword is closer to the received signal than the correct alarm codeword, i.e.,

$$\|\mathbf{y}_a - \hat{k}_a \mathbf{C}_{a, \widehat{w}}\|^2 < \|\mathbf{y}_a - k_a \mathbf{C}_{a, W_a}\|^2, \quad (50)$$

for some $\hat{k}_a \in \{0\} \cup [k_{a, \ell} : k_{a, u}]$ and $\widehat{w} \neq W_a$. We denote by $F_{\text{amd}}(\hat{k}_a)$ the set of \widehat{w} such that (50) holds for a given \hat{k}_a . It

follows that $\mathbb{E}_{\mathcal{C}_a}[\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_a = k_a]$ is bounded as

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}_a}[\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_a = k_a] \\ & \leq \mathbb{P}[k_a \rightarrow 0] \\ & \quad + \mathbb{P}[k_a \rightarrow k'_a, k'_a \in [k_{a,\ell} : k_{a,u}]] \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell} : k_{a,u}]} \mathbb{P}[F_{\text{amd}}(\hat{k}_a)] \\ & \leq \zeta(k_a, 0) \\ & \quad + \min \left\{ 1, \sum_{k'_a = k_{a,\ell}}^{k_{a,u}} \zeta(k_a, k'_a) \right\} \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell} : k_{a,u}]} \mathbb{P}[F_{\text{amd}}(\hat{k}_a)]. \end{aligned} \quad (51)$$

3) *Bounding* $\mathbb{P}[F_{\text{amd}}(\hat{k}_a)]$ *Via the RCUs:* It remains to bound the probability $\mathbb{P}[F_{\text{amd}}(\hat{k}_a)] = \mathbb{P}[\bigcup_{\widehat{w} \in \mathcal{M}_a \setminus \{W_a\}} \{\|\mathbf{Y}_a - \hat{k}_a \mathbf{C}_{a,\widehat{w}}\|^2 < \|\mathbf{Y}_a - k_a \mathbf{C}_{a,W_a}\|^2\}]$. We do this using the RCUs [29, Th. 16], [38]. Specifically, by applying a tightened version of the union bound, we obtain

$$\begin{aligned} & \mathbb{P}[F_{\text{amd}}(\hat{k}_a)] \\ & \leq \mathbb{E} \left[\min \left\{ 1, (M_a - 1) \cdot \mathbb{P}[\|\mathbf{Y}' - \hat{k}_a \widehat{\mathbf{X}}\|^2 < \|\mathbf{Y}' - k_a \mathbf{X}'\|^2 | \mathbf{X}', \mathbf{Y}'] \right\} \right] \end{aligned} \quad (53)$$

where $\{\mathbf{Y}', \mathbf{X}', \widehat{\mathbf{X}}\}$ has the same joint distribution as $\{\mathbf{Y}_a, \mathbf{C}_{a,W_a}, \mathbf{C}_{a,\widehat{w}}\}$. That is, $\mathbf{X}' = [X'_1 \dots X'_{n_a}]^\top$ follows $\mathcal{N}(\mathbf{0}, \mathbf{P}'_a \mathbf{I}_{n_a})$; given $X'_i = x'_i$, we have that $\mathbf{Y}' = [Y'_1 \dots Y'_{n_a}]^\top$ with $Y'_i \sim \mathcal{N}(k_a x'_i, 1)$; and $\widehat{\mathbf{X}} = [\widehat{X}'_1 \dots \widehat{X}'_{n_a}]^\top \sim \mathcal{N}(\mathbf{0}, \mathbf{P}'_a \mathbf{I}_{n_a})$, independent of both \mathbf{X}' and \mathbf{Y}' . Next, by applying the Chernoff bound in Lemma 2, we obtain that

$$\begin{aligned} & \mathbb{P}[\|\mathbf{Y}' - \hat{k}_a \widehat{\mathbf{X}}\|^2 < \|\mathbf{Y}' - k_a \mathbf{X}'\|^2 | \mathbf{X}', \mathbf{Y}'] \\ & \leq \frac{\mathbb{E}_{\widehat{\mathbf{X}}}[\exp(-s\|\mathbf{Y}' - \hat{k}_a \widehat{\mathbf{X}}\|^2)]}{\exp(-s\|\mathbf{Y}' - k_a \mathbf{X}'\|^2)} \end{aligned} \quad (54)$$

for every $s > 0$. Substituting (54) into (53), we obtain that, for every $s > 0$,

$$\begin{aligned} & \mathbb{P}[F_{\text{amd}}(\hat{k}_a)] \\ & \leq \mathbb{E} \left[\min \left\{ 1, \exp \left(\ln(M_a - 1) \right. \right. \right. \\ & \quad \left. \left. + \ln \frac{\mathbb{E}_{\widehat{\mathbf{X}}}[\exp(-s\|\mathbf{Y}' - \hat{k}_a \widehat{\mathbf{X}}\|^2)]}{\exp(-s\|\mathbf{Y}' - k_a \mathbf{X}'\|^2)} \right) \right\} \right] \\ & = \mathbb{E} \left[\min \left\{ 1, \exp \left(\ln(M_a - 1) \right. \right. \right. \\ & \quad \left. \left. - \sum_{i=1}^{n_a} \ln \frac{\exp(-s(Y'_i - k_a X'_i)^2)}{\mathbb{E}_{\widehat{X}_i}[\exp(-s(Y'_i - \hat{k}_a \widehat{X}_i)^2)]} \right) \right\} \right]. \end{aligned} \quad (55)$$

We define the generalized information density as $\iota_s(\hat{k}_a, X'_i; Y'_i) \triangleq \ln \frac{\exp(-s(Y'_i - k_a X'_i)^2)}{\mathbb{E}_{\widehat{X}_i}[\exp(-s(Y'_i - \hat{k}_a \widehat{X}_i)^2)]}$. After some manipulations using (44) in Lemma 3, we deduce that

$\iota_s(\hat{k}_a, x; y)$ can be written as in (17). Using $\iota_s(\hat{k}_a, X'_i; Y'_i)$, we can rewrite (56), upon optimizing over s , as

$$\mathbb{P}[F_{\text{amd}}(\hat{k}_a)] \leq \min_{s>0} \mathbb{E} \left[\min \left\{ 1, \exp \left(\ln(M_a - 1) - \sum_{i=1}^{n_a} \iota_s(\hat{k}_a, X'_i; Y'_i) \right) \right\} \right]. \quad (57)$$

Next, by observing that, for every positive random variable Q , it holds that $\mathbb{E}[\min\{1, Q\}] = \mathbb{P}[Q \geq V]$ where V is uniformly distributed on $[0, 1]$, we obtain that

$$\mathbb{P}[F_{\text{amd}}(\hat{k}_a)] \leq \min_{s>0} \mathbb{P} \left[\sum_{i=1}^{n_a} \iota_s(\hat{k}_a, X'_i; Y'_i) \leq \ln \frac{M_a - 1}{V} \right]. \quad (58)$$

Finally, by substituting (58) into (52) and (52) into (47), we complete the proof.

B. Proof of the Bound (11) on P_{afp}

Consider the case where no alarm event occurs (thus $k_a = 0$) and the estimation step outputs k'_a . An AFP occurs if $K'_a > 0$ in the initial estimation step (8) and $\widehat{K}_a > 0$ in the message decoding step (9). The latter event occurs if an alarm codeword, scaled by some $\hat{k}_a \in [k_{a,\ell} : k_{a,u}]$, is closer to the received signal, which consists just of additive noise, than the all-zero codeword, i.e.,

$$\|\hat{k}_a \mathbf{C}_{a,\widehat{w}} - \mathbf{Z}_a\|^2 < \|\mathbf{Z}_a\|^2 \quad (59)$$

for some $\widehat{w} \in \mathcal{M}_a$. Let $F_{\text{afp}}(\hat{k}_a)$ denote the set of \widehat{w} such that (59) holds for a given \hat{k}_a . Then, the AFP probability is given by

$$\begin{aligned} P_{\text{afp}} & = \sum_{k'_a = k_{a,\ell}}^{k_{a,u}} \mathbb{P}[0 \rightarrow k'_a] \sum_{\hat{k}_a = k_{a,\ell}}^{k_{a,u}} \mathbb{P}[F_{\text{afp}}(\hat{k}_a)] \\ & \leq \min \left\{ 1, \sum_{k'_a = k_{a,\ell}}^{k_{a,u}} \zeta(0, k'_a) \right\} \sum_{\hat{k}_a = k_{a,\ell}}^{k_{a,u}} \mathbb{P}[F_{\text{afp}}(\hat{k}_a)]. \end{aligned} \quad (60)$$

Next, we use again the RCUs to bound $\mathbb{P}[F_{\text{afp}}(\hat{k}_a)]$. Specifically, we first apply a tightened version of the union bound to obtain

$$\begin{aligned} & \mathbb{P}[F_{\text{afp}}(\hat{k}_a)] \\ & \leq \mathbb{E}_{\mathbf{Z}_a} \left[\min \left\{ 1, M_a \mathbb{P}[\|\mathbf{Z}_a - \hat{k}_a \widehat{\mathbf{X}}\|^2 < \|\mathbf{Z}_a\|^2] \right\} \right] \end{aligned} \quad (62)$$

where $\widehat{\mathbf{X}}$ is identically distributed to $\mathbf{C}_{a,\widehat{w}}$, i.e., $\widehat{\mathbf{X}} \sim \mathcal{N}(\mathbf{0}, \mathbf{P}'_a \mathbf{I}_{n_a})$. We then apply the Chernoff bound in Lemma 2, and conclude that, for every $s > 0$,

$$\begin{aligned} & \mathbb{P}[\|\mathbf{Z}_a - \hat{k}_a \widehat{\mathbf{X}}\|^2 < \|\mathbf{Z}_a\|^2] \\ & \leq e^{s\|\mathbf{Z}_a\|^2} \mathbb{E}_{\widehat{\mathbf{X}}} \left[\exp(-s\|\mathbf{Z}_a - \hat{k}_a \widehat{\mathbf{X}}\|^2) \right] \end{aligned} \quad (63)$$

$$= e^{s\|\mathbf{Z}_a\|^2} \frac{\exp\left(-\frac{s\|\mathbf{Z}_a\|_2^2}{1+2\hat{k}_a^2 \mathbf{P}'_a s}\right)}{(1+2\hat{k}_a^2 \mathbf{P}'_a s)^{n_a/2}} \quad (64)$$

$$= \exp\left(\beta \|\mathbf{Z}_a\|_2^2 - \frac{n_a}{2} \ln(1+2\hat{k}_a^2 \mathbf{P}'_a s)\right) \quad (65)$$

with $\beta \triangleq s(1 - (1 + 2\hat{k}_a^2 P'_a s)^{-1})$. Here, to obtain (64), we computed the expectation in (63) using the identity (44) in Lemma 3. Substituting (65) into (62), we obtain

$$\begin{aligned} & \mathbb{P}\left[F_{\text{afp}}(\hat{k}_a)\right] \\ & \leq \mathbb{E}_{\mathbf{Z}_a} \left[\min \left\{ 1, M_a \exp \left(\beta \|\mathbf{Z}_a\|^2 - \frac{n_a}{2} \ln(1 + 2\hat{k}_a^2 P'_a s) \right) \right\} \right] \end{aligned} \quad (66)$$

$$= \mathbb{P} \left[M_a \exp \left(\beta \|\mathbf{Z}_a\|^2 - \frac{n_a}{2} \ln(1 + 2\hat{k}_a^2 P'_a s) \right) \leq V \right] \quad (67)$$

$$= \mathbb{P} \left[\|\mathbf{Z}_a\|^2 \geq \beta^{-1} \left(\frac{n_a}{2} \ln(1 + 2\hat{k}_a^2 P'_a s) - \ln \frac{M_a}{V} \right) \right] \quad (68)$$

where V is uniformly distributed on $[0, 1]$. Recall that $\mathbf{Z}_a \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_{n_a})$. By applying (45) in Lemma 3 to (68), we obtain that

$$\begin{aligned} \mathbb{P}\left[F_{\text{afp}}(\hat{k}_a)\right] & \leq \min_{s>0} \mathbb{E}_V \left[\frac{1}{\Gamma(n_a/2)} \right. \\ & \left. \cdot \Gamma \left(\frac{n_a}{2}, \frac{1}{2\beta} \left(\frac{n_a}{2} \ln(1 + 2\hat{k}_a^2 P'_a s) - \ln \frac{M_a}{V} \right) \right) \right]. \end{aligned} \quad (69)$$

Finally, we substitute (69) into (61) to complete the proof.

APPENDIX B PROOF OF THEOREM 4

A. Proof of the Bounds (36) and (37) on P_{amd} and P_{afp}

The AMD probability is computed as $\mathbb{P}[\widehat{W}_a \neq W_a | \mathcal{A}] = \mathbb{E}_{K_a, K_s, c_a, c_s} [\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}]$, where $K_a \sim \text{Bino}(K, \rho_d)$ is the number of alarm users and $K_s \sim \text{Bino}(K, \rho_s)$ is the number of standard users. We change the measure to the one for which i) $\mathbf{X}_a = \mathbf{C}_{a, W_a}$ instead of $\mathbf{X}_a = \mathbf{C}_{a, W_a} \mathbb{1}\{\|\mathbf{C}_{a, W_a}\|^2 \leq nP_a\}$, ii) $K_a \in [k_{a, \ell} : k_{a, u}]$, iii) $\mathbf{X}_{s, k} = \mathbf{C}_{s, W_{s, k}}$ instead of $\mathbf{X}_{s, k} = \mathbf{C}_{s, W_{s, k}} \mathbb{1}\{\|\mathbf{C}_{s, W_{s, k}}\|^2 \leq nP_s\}$, iv) $K_s \in [k_{s, \ell} : k_{s, u}]$, and v) the transmitted standard codewords are distinct. This is done at a cost of adding a constant bounded by ν_2 , given in (34), to the original expectation. Under the new measure, the only difference with Appendix A-A is that n_a is replaced by n , and the equivalent noise is now $\bar{\mathbf{Z}} = \sum_{k=1}^{K_s} \mathbf{X}_{s, k} + \mathbf{Z} \sim \mathcal{N}(\mathbf{0}, (1 + K_s P'_s) \mathbf{I}_n)$. Given $K_s = k_s$, by adapting the steps in Appendix A-A to codeword length n and noise variance $(1 + k_s P')$, we bound $\mathbb{E}_{K_a, c_a, c_s} [\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_s = k_s]$ by $\bar{\epsilon}_{\text{amd}}$ given in (36). Finally, by averaging over K_s , we conclude that $\mathbb{P}[\widehat{W}_a \neq W_a | \mathcal{A}] \leq \sum_{k_s=k_{s, \ell}}^{k_{s, u}} P_{K_s}(k_s) \bar{\epsilon}_{\text{amd}}(k_s) + \nu_2$.

The AFP probability is computed as $\mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}] = \mathbb{E}_{K_s, c_a, c_s} [\mathbb{1}\{\widehat{W}_a \neq w_e\} | \bar{\mathcal{A}}]$. We change the measure to the one for which i) $\mathbf{X}_{s, k} = \mathbf{C}_{s, W_{s, k}}$ instead of $\mathbf{X}_{s, k} = \mathbf{C}_{s, W_{s, k}} \mathbb{1}\{\|\mathbf{C}_{s, W_{s, k}}\|^2 \leq nP_s\}$, ii) $K_s \in [k_{s, \ell} : k_{s, u}]$, and iii) the transmitted standard messages are distinct. This is done at a cost of adding a constant bounded by ν_3 given in (35). From here, the only difference with Appendix A-B is that, in the case of no alarm, the received signal is $\mathbf{Y} = \sum_{k=1}^{K_s} \mathbf{X}_{s, k} + \mathbf{Z} \sim \mathcal{N}(\mathbf{0}, (1 + K_s P'_s) \mathbf{I}_n)$ instead of just noise. Given $K_s = k_s$, by adapting the steps in Appendix A-B to this output distribution,

we bound $\mathbb{E}_{c_a, c_s} [\mathbb{1}\{\widehat{W}_a \neq w_e\} | \bar{\mathcal{A}}, K_s = k_s]$ by $\bar{\epsilon}_{\text{afp}}$ given in (37). Finally, by averaging over K_s , we conclude that $\mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}] \leq \sum_{k_s=k_{s, \ell}}^{k_{s, u}} P_{K_s}(k_s) \bar{\epsilon}_{\text{afp}}(k_s) + \nu_3$.

B. Proof of the Bounds (38) and (39) on $P_{\text{smd}|\bar{\mathcal{A}}}$ and $P_{\text{sfp}|\bar{\mathcal{A}}}$

For convenience, we set $E_{\text{smd}} \triangleq \frac{1}{|\widehat{\mathcal{W}}_s|} \sum_{i=1}^{|\widehat{\mathcal{W}}_s|} \mathbb{P}[\widehat{W}_{s, i} \notin \widehat{\mathcal{W}}_s]$. We use the law of total probability to expand and then bound $P_{\text{smd}|\bar{\mathcal{A}}}$ as follows:

$$\begin{aligned} P_{\text{smd}|\bar{\mathcal{A}}} & = \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}] \end{aligned} \quad (70)$$

$$\begin{aligned} & = \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a \neq w_e] \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}] \\ & \quad + \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a = w_e] \mathbb{P}[\widehat{W}_a = w_e | \bar{\mathcal{A}}] \end{aligned} \quad (71)$$

$$\begin{aligned} & \leq \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}] \\ & \quad + \left(1 - \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}]\right) \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a = w_e] \end{aligned} \quad (72)$$

$$= 1 - \left(1 - \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}]\right) \left(1 - \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a = w_e]\right) \quad (73)$$

$$\begin{aligned} & \leq 1 - \sum_{k_s=k_{s, \ell}}^{k_{s, u}} P_{K_s}(k_s) \left(1 - \mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}, K_s = k_s]\right) \\ & \quad \cdot \left(1 - \mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a = w_e, K_s = k_s]\right) \\ & \quad + \nu_2. \end{aligned} \quad (74)$$

Here, we obtained (72) by assuming that one cannot decode the standard messages if an AFP occurs. In (74), we made the same change of measure as in the bound of P_{amd} , and the probability and expectation therein are computed with respect to the new measure. In Appendix B-A, we have bounded $\mathbb{P}[\widehat{W}_a \neq w_e | \bar{\mathcal{A}}, K_s = k_s] = \mathbb{E}_{c_a, c_s} [\mathbb{1}\{\widehat{W}_a \neq w_e\} | \bar{\mathcal{A}}, K_s = k_s]$ by $\bar{\epsilon}_{\text{afp}}(k_s)$. Furthermore, when there is no alarm and no AFP, the standard message list is decoded as in the standard block of H-OMA. Therefore, $\mathbb{E}[E_{\text{smd}} | \bar{\mathcal{A}}, \widehat{W}_a = w_e, K_s = k_s]$ is upper-bounded by $\bar{\epsilon}_{\text{smd}}$ in Theorem 3, adapted to the codeword length n . Finally, using these bounds in (74), we conclude that $P_{\text{smd}|\bar{\mathcal{A}}} \leq \epsilon_{\text{smd}|\bar{\mathcal{A}}}$ with $\epsilon_{\text{smd}|\bar{\mathcal{A}}}$ given in (38). The bound $\epsilon_{\text{sfp}|\bar{\mathcal{A}}}$ of $P_{\text{sfp}|\bar{\mathcal{A}}}$, given in (39), follows similarly.

C. Proof of the Bounds (40) and (41) on $P_{\text{smd}|\mathcal{A}}$ and $P_{\text{sfp}|\mathcal{A}}$

By following similar steps as in (70)–(74), we obtain that

$$\begin{aligned} P_{\text{smd}|\mathcal{A}} & \leq 1 - \sum_{k_s=k_{s, \ell}}^{k_{s, u}} P_{K_s}(k_s) \left(1 - \mathbb{P}[\widehat{W}_a \neq W_a | \mathcal{A}, K_s = k_s]\right) \\ & \quad \cdot \left(1 - \mathbb{E}[E_{\text{smd}} | \mathcal{A}, \widehat{W}_a = W_a, K_s = k_s]\right) \\ & \quad + \nu_2. \end{aligned} \quad (75)$$

In Appendix B-A, we have bounded $\mathbb{P}[\widehat{W}_a \neq W_a | \mathcal{A}, K_s = k_s] = \mathbb{E}_{K_a, C_a, C_s} [\mathbb{1}\{\widehat{W}_a \neq W_a\} | \mathcal{A}, K_s = k_s]$ by $\bar{\epsilon}_{\text{amd}}(k_s)$. We next bound the term $\mathbb{E}[E_{\text{smd}} | \mathcal{A}, \widehat{W}_a = W_a, K_s = k_s]$ as

$$\begin{aligned} & \mathbb{E}[E_{\text{smd}} | \mathcal{A}, \widehat{W}_a = W_a, K_s = k_s] \\ & \leq \sum_{k_a = k_{a,\ell}}^{k_{a,u}} P_{K_a}(k_a) \sum_{\hat{k}_a \in \{0\} \cup [k_{a,\ell}, k_{a,u}]} \\ & \quad \mathbb{P}[\widehat{K}_a = \hat{k}_a | \widehat{W}_a = W_a, K_a = k_a, K_s = k_s] \\ & \quad \cdot \mathbb{E}[E_{\text{smd}} | \mathcal{A}, \widehat{W}_a = W_a, \widehat{K}_a = \hat{k}_a, K_a = k_a, K_s = k_s]. \end{aligned} \quad (76)$$

Given $(\widehat{W}_a, \widehat{K}_a, K_a) = (W_a, \hat{k}_a, k_a)$, the residual interference plus noise after interference cancellation is $(k_a - \hat{k}_a)\mathbf{C}_{a,W_a} + \mathbf{Z} \sim \mathcal{N}(\mathbf{0}, (1 + (k_a - \hat{k}_a)^2 \mathbf{P}'_a)\mathbf{I}_n)$. The receiver decodes the standard messages under this effective noise. Therefore, $\mathbb{E}[E_{\text{smd}} | \mathcal{A}, \widehat{W}_a = W_a, \widehat{K}_a = \hat{k}_a, K_a = k_a, K_s = k_s]$ is bounded by $\bar{\epsilon}_{\text{smd}}$ in Theorem 3, adapted to codeword length n and noise variance $1 + (k_a - \hat{k}_a)^2 \mathbf{P}'_a$.

It remains to bound $\mathbb{P}[\widehat{K}_a = \hat{k}_a | \widehat{W}_a = W_a, K_a = k_a, K_s = k_s]$.

Given $(\widehat{W}_a, K_a, K_s) = (W_a, k_a, k_s)$, if $\widehat{K}_a = \hat{k}_a > 0$, it must hold that i) the estimation step returned $k'_a \in [k_{a,\ell} : k_{a,u}]$, and ii) $\|\mathbf{Y} - \hat{k}_a \mathbf{C}_{a,W_a}\|^2 \leq \|\mathbf{Y} - k_a \mathbf{C}_{a,W_a}\|^2$ or, equivalently, $\|(k_a - \hat{k}_a)\mathbf{C}_{a,W_a} + \overline{\mathbf{Z}}\|^2 \leq \|\overline{\mathbf{Z}}\|^2$, where $\overline{\mathbf{Z}} = \sum_{k=1}^{k_s} \mathbf{X}_{s,k} + \mathbf{Z} \sim \mathcal{N}(\mathbf{0}, (1 + k_s \mathbf{P}'_s)\mathbf{I}_n)$. If $\widehat{K}_a = \hat{k}_a = 0$, either both conditions above hold, or the estimation step returned $k'_a = 0$. Therefore,

$$\begin{aligned} & \mathbb{P}[\widehat{K}_a = \hat{k}_a | \widehat{W}_a = W_a, K_a = k_a, K_s = k_s] \\ & \leq \mathbb{1}\{\hat{k}_a = 0\} \mathbb{P}[k_a \rightarrow 0] \\ & \quad + \mathbb{P}[k_a \rightarrow k'_a, k'_a \in [k_{a,\ell} : k_{a,u}]] \\ & \quad \cdot \mathbb{P}[\|(k_a - \hat{k}_a)\mathbf{C}_{a,W_a} + \overline{\mathbf{Z}}\|^2 \leq \|\overline{\mathbf{Z}}\|^2] \quad (77) \\ & \leq \mathbb{1}\{\hat{k}_a = 0\} \eta(k_a, 0, k_s) \\ & \quad + \min \left\{ 1, \sum_{k'_a = k_{a,\ell}}^{k_{a,u}} \eta(k_a, k'_a, k_s) \right\} \\ & \quad \cdot \mathbb{P}[\|(k_a - \hat{k}_a)\mathbf{C}_{a,W_a} + \overline{\mathbf{Z}}\|^2 \leq \|\overline{\mathbf{Z}}\|^2]. \quad (78) \end{aligned}$$

Using the Chernoff bound, we bound $\mathbb{P}[\|(k_a - \hat{k}_a)\mathbf{C}_{a,W_a} + \overline{\mathbf{Z}}\|^2 \leq \|\overline{\mathbf{Z}}\|^2]$ by $\left(1 + \frac{(k_a - \hat{k}_a)^2 \mathbf{P}'_a}{4(1 + k_s \mathbf{P}'_s)}\right)^{-n/2}$. Substituting this into (78), then (78) into (76), and finally (76) into (75), we conclude that $P_{\text{smd}} | \mathcal{A} \leq \epsilon_{\text{smd}} | \mathcal{A}$, with $\epsilon_{\text{smd}} | \mathcal{A}$ given in (40). The proof that $P_{\text{sfp}} | \mathcal{A} \leq \epsilon_{\text{sfp}} | \mathcal{A}$, with $\epsilon_{\text{sfp}} | \mathcal{A}$ given in (41), follows similarly.

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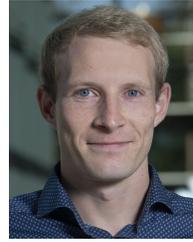


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