

Alma Mater Studiorum Università di Bologna
Archivio istituzionale della ricerca

A Grant-Free Coded Random Access Scheme for Near-Field Communications

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Testi, E., Torcolacci, G., Decarli, N., Dardari, D., Paolini, E. (2025). A Grant-Free Coded Random Access Scheme for Near-Field Communications. NEW YORK : Institute of Electrical and Electronics Engineers Inc. [10.1109/ICC52391.2025.11161137].

Availability:

This version is available at: <https://hdl.handle.net/11585/1026784> since: 2026-04-16

Published:

DOI: <http://doi.org/10.1109/ICC52391.2025.11161137>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

A Grant-free Coded Random Access Scheme for Near-field Communications

Enrico Testi^{*‡}, Giulia Torcolacci^{*‡}, Nicolò Decarli^{†‡}, Davide Dardari^{*‡}, Enrico Paolini^{*‡}

^{*} DEI, Università di Bologna, 40136 Bologna, Italy

[†] IEIIT, National Research Council (CNR), 40136 Bologna, Italy

[‡] National Laboratory of Wireless Communications (WiLab), CNIT, 40136 Bologna, Italy

Abstract—The industrial Internet of things (IIoT) is revolutionizing industrial processes by facilitating massive machine-type communications among countless interconnected devices. To efficiently handle the resulting large-scale and sporadic traffic, grant-free random access protocols—especially coded random access (CRA)—have emerged as scalable and reliable solutions. At the same time, advancements in wireless hardware, including extremely large-scale MIMO arrays and high-frequency communication (e.g., mmWave, Terahertz), are pushing network operations into the near-field propagation regime, allowing for dense connectivity and enhanced spatial multiplexing. This paper proposes an innovative approach that combines near-field spatial multiplexing with the interference mitigation capabilities of CRA, utilizing an extremely large aperture array at the access point. This integration improves reliability and reduces access latency, offering a robust framework for IIoT connectivity in next-generation 6G networks.

I. INTRODUCTION

The industrial Internet of things (IIoT) is revolutionizing industries by enabling interconnected devices and systems that facilitate real-time monitoring, automation, and data-driven decision-making, serving as the backbone of Industry 4.0 [1], [2]. In the 6G era, these machine-type communication (MTC) systems will demand unprecedented scalability, improved battery efficiency, and diverse reliability and latency requirements [3]. Meeting these requirements necessitates innovations in medium access control (MAC) and physical (PHY) layers, particularly to support grant-free massive multiple access (MMA) protocols, which are well-suited for managing the dense and sporadic traffic characteristic of MTC. Grant-free access allows devices to transmit without prior scheduling, reducing the signaling overhead and latency but risking collisions when many devices communicate simultaneously. Recent developments in coded random access (CRA) techniques, especially those leveraging successive interference cancellation (SIC), have enhanced reliability by allowing devices to send replicas over multiple resources, significantly boosting the chances of successful decoding [4], [5]. When high carrier frequencies such as mmWave or Terahertz are adopted in conjunction with extremely large scale (XL) MIMO arrays, propagation occurs within the radiative near-field region, where devices can leverage spatial multiplexing even when operating in line-of-sight (LOS) to enhance their communication capability [6]–[8]. In this setup, multi-antenna IIoT devices can establish parallel channels (namely, communication modes), thereby

enhancing network efficiency. However, to exploit high carrier frequencies in MTC, proper multi-antenna beamforming gain at both the transmitter and receiver is required to counteract the increased path loss and exploit the spatial multiplexing capabilities, thus requiring precise channel estimation, which may be impractical due to overhead constraints [9]. Recent studies have explored leveraging the near-field region to enhance communication performance. In [10], the authors propose a beam division multiple access (BDMA) scheme for massive MIMO, organizing users into non-overlapping beams and minimizing channel estimation overhead. In [11], location division multiple access (LDMA) for near-field multiple-input multiple-output (MIMO) is introduced to improve spectrum efficiency by leveraging beam focusing. In [12], the authors address beam training in near-field communications, focusing on channel state information (CSI) acquisition. A complex bilinear inference algorithm for XL-MIMO activity detection is proposed in [13]. In [14], a QoS-aware joint user scheduling and power allocation technique for XL-MIMO systems is proposed. A beamspace modulation strategy for XL-MIMO communications that enhances spectral efficiency through spatial degrees of freedom by utilizing few radio frequency chains is introduced in [15]. Despite their contributions, all these approaches rely heavily on complex channel estimation processes, which are impractical for the sporadic traffic typical of MTC in IIoT networks.

To address this gap, in this paper we propose a novel near-field communication strategy that combines grant-free MMA with multi-modal communication in the near-field. This is performed by utilizing an extremely large aperture array (ELAA) at the access point (AP), so that multi-antenna IIoT devices can transmit across both spatial and temporal domains without extensive channel estimation procedures. By clustering received signals at the ELAA to exploit the combining gain and applying SIC, this strategy mitigates collisions and increases the overall throughput, supporting dense, uncoordinated IIoT networks with high reliability and efficiency.

II. SYSTEM MODEL

Let us consider an industrial setting, such as a manufacturing line in a factory as illustrated in Fig. 1. In this scenario, N network users (NUs), i.e., machine-type devices, randomly transmit signals towards the ceiling, where an ELAA is installed

and acts as receiving AP. Specifically, the ELAA could be realized as a linear large intelligent surface (LIS) or a so-called *radio stripe* [16], which we assume to be deployed along the y -axis. Each of the transmitting NUs is equipped with a uniform linear array (ULA) having N_T antenna elements located at $\mathbf{p}_{T,i}^{(k)} = [x_{T,i}^{(k)}, y_{T,i}^{(k)}, z_{T,i}^{(k)}]^T$, with $i = 1, 2, \dots, N_T$ and $k = 1, 2, \dots, N$. Let us denote by L_T the length of the NU's array, which we assume to be identical for all users. All NUs are considered to be located in the xy -plane, positioned parallel to the receiving AP, with no misalignment with respect to the y -axis between the arrays. Such a condition can be realized with proper deployment of the NU antennas along the machine. Regardless of the implementation strategy for the ELAA at the AP, we model it as a long ULA of length L_R encompassing N_R antenna elements, each of them located at $\mathbf{p}_{R,r} = [x_{R,r}, y_{R,r}, z_{R,r}]^T$, $r = 1, 2, \dots, N_R$. Moreover, we have $N_T \ll N_R$ and all antenna elements, both at the AP and the NUs, are uniformly spaced with an inter-element distance of $\lambda/2$, where λ denotes the wavelength.

Let us assume that the generic (say the k -th) NU, if active, transmits a sequence of N_S complex symbols $\mathbf{x}^{(k)} = [x_1^{(k)}, x_2^{(k)}, \dots, x_{N_S}^{(k)}] \in \mathbb{C}^{1 \times N_S}$, with $\|\mathbf{x}^{(k)}\|^2 = N_S$. We denote by P_T the NUs' transmit power. At the AP side, when all N users are active, the received signal $\mathbf{Y} = [\mathbf{y}_1, \mathbf{y}_2, \dots, \mathbf{y}_{N_R}]^T \in \mathbb{C}^{N_R \times N_S}$ is expressed as

$$\mathbf{Y} = \sqrt{P_T} \sum_{k=1}^N \mathbf{H}^{(k)} \mathbf{b}^{(k)} \otimes \mathbf{x}^{(k)} + \mathbf{W} \quad (1)$$

where \mathbf{y}_r represents the signal received at the r -th AP array element, $\mathbf{H}^{(k)} = \{h_{r,t}^{(k)}\} \in \mathbb{C}^{N_R \times N_T}$ denotes the complex channel matrix associated with the k -th NU, $\mathbf{b}^{(k)} = [b_1^{(k)}, b_2^{(k)}, \dots, b_{N_T}^{(k)}]^T \in \mathbb{C}^{N_T \times 1}$ is the beamforming vector of the k -th NU, $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_{N_R}]^T \in \mathbb{C}^{N_R \times N_S}$ is a matrix of additive white Gaussian noise (AWGN) samples, where $\mathbf{w}_r \in \mathbb{C}^{N_S \times 1}$ and $\mathbf{w}_r \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{N_S \times N_S})$, and t and r indicate the t -th element of the k -th NU's array and the r -th element of the AP ELAA, respectively. The noise variance is $\sigma^2 = Bk_B T_0 \text{NF}$, where B is the bandwidth, k_B is the Boltzmann constant, T_0 is the equivalent noise temperature, and NF denotes the noise figure of the receiver. In LOS free-space conditions, the elements of the channel matrix $\mathbf{H}^{(k)}$ in (1) are given by

$$h_{r,t}^{(k)} = \frac{\lambda}{4\pi d_{t,r}^{(k)}} e^{-j \frac{2\pi}{\lambda} d_{t,r}^{(k)}}. \quad (2)$$

The quantity $d_{t,r}^{(k)}$ represents the distance between the $(\mathbf{p}_{T,t}^{(k)}, \mathbf{p}_{R,r})$ antenna pairs.

Given (i) the extremely large aperture of the AP antenna array, (ii) the high operating frequency employed (e.g., mm-Waves or THz), and (iii) the short communication distances (e.g., in the same order of the AP array aperture), the system operates in the near-field regime [7]. Accordingly, in the following, we assume that all the NUs are located in the radiative near-field region of the receiving AP, where the

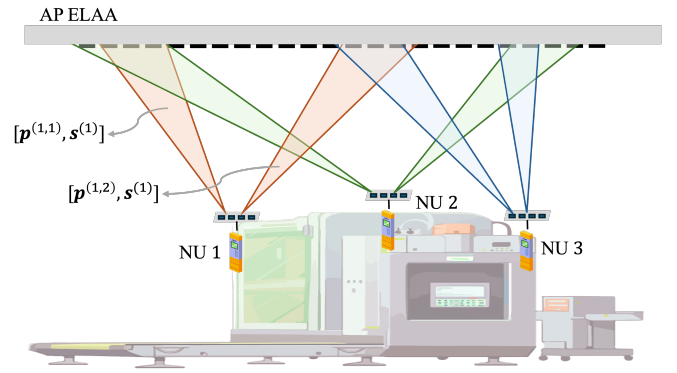


Fig. 1. IIoT scenario with three multi-antenna NUs, placed on an industrial machine, transmitting their signals towards an overhead AP equipped with an ELAA, according to the coded spatial random access scheme.

distance $d^{(k)}$ between the center of the ULA of the k -th NU and the center of the AP ELAA is lower than the Fraunhofer distance [17], that is $d^{(k)} < 2L_R^2/\lambda$. This definition identifies the so-called Fresnel region, where the electromagnetic (EM) wavefront can no longer be approximated as planar and its spherical curvature must be considered instead. In this near-field condition, since we assumed the presence of multiple antennas at the NU side, it becomes possible to exploit several communication modes to communicate between each NU and the AP [6]. Specifically, this means that the channel described by the matrix $\mathbf{H}^{(k)}$ has a rank larger than one even considering LOS channel conditions and without multipath, hence allowing data communications between the NU and the AP along multiple parallel channels. It can be shown that, for a given geometry and operating wavelength under the $L_T \ll L_R$ (i.e., $N_T \ll N_R$) condition, the number of strongly coupled communication modes (i.e., with significant values of the corresponding coupling coefficients) is given by [18]

$$R_{\max}^{(k)} = \left\lfloor 1 + \frac{2L_T L_R}{\lambda \sqrt{4(d^{(k)})^2 + L_R^2}} \right\rfloor \quad (3)$$

where $\lfloor \cdot \rfloor$ identifies the floor operator. Therefore, these $R_{\max}^{(k)}$ modes can be exploited to establish orthogonal communication channels between the k -th NU and the AP.

III. CODED SPATIAL RANDOM ACCESS

In this section, we delineate the novel grant-free random access scheme, operating in the near field region, and the corresponding processing scheme at the AP.

A. Uplink Users' Transmission

Optimal communication between the k -th NU and the AP within the near-field region should be realized by exploiting simultaneously the available $R_{\max}^{(k)}$ communications modes. In this scenario, capacity maximization can be achieved by employing dedicated beamforming vectors at the NUs and corresponding combining vectors at the AP. However, this approach imposes significant challenges, including the need

for complex channel estimation, singular value decomposition (SVD) of the channel matrix, exchange of additional data (i.e., overhead), and precise synchronization between the NUs and the AP. These stringent requirements are impractical in MTC environments, particularly when dealing with a large number of sporadically active devices, as commonly observed in IIoT applications. Therefore, in the following, we propose a grant-free MMA scheme that leverages the multiple communication modes available in the near-field scenario under consideration. Specifically, it has been shown in [18] that the $R_{\max}^{(k)}$ communication modes can be easily realized considering simple beam steering vectors at the transmitting NU. This happens since NUs are equipped with much fewer antennas than the AP; thus, despite NUs being within the near-field region of the AP antenna array, it is likely that the AP is located outside the near-field region of the transmitting NUs. In such a condition, the number of well-coupled communication modes $R_{\max}^{(k)}$ corresponds to the number of orthogonal beams generated by the k -th NU capable of intercepting the AP ELAA. Thus, it can be asserted that communication modes correspond to distinct beam steering directions from the NU towards the AP. These directions must be chosen ensuring orthogonality in the angular domain among the different beams [18]. Multiple transmission directions in space will be then adopted within the grant-free MMA scheme hereby proposed; for this reason, we refer to our CRA approach as coded spatial random access (CSRA). We assume that time is slotted and, in each time slot, K out of N NUs sporadically and unpredictably wake up to transmit short information messages in a grant-free manner, competing to deliver one message each to the AP. The uplink transmission operates in a slot-synchronous mode, meaning that there is a common time reference between the NUs and the AP. This synchronization is maintained by a beacon signal transmitted by the AP at the beginning of each slot. After waking up, an active NU k waits for the beacon sent by the AP and competes to transmit one m -bit message $W^{(k)} \in \{1, \dots, 2^m\}$, within the subsequent slot. We denote by \mathcal{K} the subset of NUs which are active during a generic time slot and assume that the AP is unaware of which NU are active during any given time slot.

The access protocol operates as follows. Let us assume that all K active NUs encode their messages using the same channel encoder and map the coded bits onto the same complex constellation. Consequently, each NU obtains a data payload $\mathbf{s}^{(k)} \in \mathbb{C}^{1 \times N_D}$ consisting of N_D complex symbols. Then, each active NU selects $R^{(k)} \leq R_{\max}^{(k)}$ transmission directions and transmits a packet $\mathbf{x}^{(k,j)} = [\mathbf{p}^{(k,j)}, \mathbf{s}^{(k)}] \in \mathbb{C}^{1 \times N_S}$, with $j = 1, 2, \dots, R^{(k)}$, in such directions, where $\mathbf{p}^{(k,j)} \in \mathbb{C}^{1 \times N_P}$ is a pilot sequence drawn from a set \mathcal{P} , with $|\mathcal{P}| = P$ and $P \ll K$, of mutually orthogonal pilots. Therefore, we have $N_S = N_P + N_D$. We refer to the transmission of the k -th NU in each of its $R^{(k)}$ selected directions as a ‘‘replica’’. Moreover, each replica arriving at the AP is assumed to be perfectly synchronized with one of the designated time slots. Therefore, during uplink transmission, each NU in \mathcal{K} first sends the chosen

pilot sequences across its $R^{(k)}$ transmission directions, followed by the payload data. The corresponding vector of signal samples received at the r -th AP ELAA antenna element is denoted by $\tilde{\mathbf{y}}_r = [\tilde{\mathbf{y}}_r^P, \tilde{\mathbf{y}}_r^D] \in \mathbb{C}^{1 \times N_S}$, in which $\tilde{\mathbf{y}}_r^P \in \mathbb{C}^{1 \times N_P}$ is the vector of samples corresponding to the pilot and is given by

$$\tilde{\mathbf{y}}_r^P = \sqrt{P_T} \sum_{k \in \mathcal{K}} \mathbf{h}_r^{(k)} \sum_{j=1}^{R^{(k)}} \mathbf{b}^{(k,j)} \otimes \mathbf{p}^{(k,j)} + \boldsymbol{\omega}_r \quad (4)$$

where $r = 1, 2, \dots, N_R$, $\mathbf{h}_r^{(k)}$ is the vector of complex channel gains between ELAA antenna element r and NU k , i.e., the r -th row of the channel matrix $\mathbf{H}^{(k)}$, $\boldsymbol{\omega}_r \sim \mathcal{CN}(\mathbf{0}_{N_P}, \sigma^2 \mathbf{I}_{N_P})$ is the vector of AWGN noise samples, and $\mathbf{b}^{(k,j)} = [b_1^{(k,j)}, b_2^{(k,j)}, \dots, b_{N_T}^{(k,j)}] \in \mathbb{C}^{N_T \times 1}$ is the beamforming vector of NU k employed to transmit in the j -th direction, among the $R^{(k)}$ available ones. Notably, the overall beamforming vector $\mathbf{b}^{(k)}$ in (1) is $\mathbf{b}^{(k)} = 1/R^{(k)} \sum_{j=1}^{R^{(k)}} \mathbf{b}^{(k,j)}$. Similarly, the received signal samples corresponding to the payload transmission, i.e., $\tilde{\mathbf{y}}_r^D \in \mathbb{C}^{1 \times N_D}$, are

$$\tilde{\mathbf{y}}_r^D = \sqrt{P_T} \sum_{k \in \mathcal{K}} \mathbf{h}_r^{(k)} \sum_{j=1}^{R^{(k)}} \mathbf{b}^{(k,j)} \otimes \mathbf{s}(W^{(k)}) + \boldsymbol{\nu}_r \quad (5)$$

where $r = 1, 2, \dots, N_R$, $\mathbf{s}(W^{(k)})$ is the data payload of message $W^{(k)}$ transmitted by NU k , and $\boldsymbol{\nu}_r \sim \mathcal{CN}(\mathbf{0}_{N_D}, \sigma^2 \mathbf{I}_{N_D})$ is the vector of noise samples. Specifically, we have $\mathbf{w}_r = [\boldsymbol{\omega}_r, \boldsymbol{\nu}_r] \in \mathbb{C}^{1 \times N_S}$, $\mathbf{w}_r \sim \mathcal{CN}(\mathbf{0}_{N_S}, \sigma^2 \mathbf{I}_{N_S})$, where \mathbf{w}_r identifies the r -th row of the noise matrix $\mathbf{W}^{(k)}$.

B. Selection of the Transmission Directions

The complete set of orthogonal transmission directions that can be spanned by the NU antenna array can be realized by considering the classical Discrete Fourier transform (DFT)-based codebook of beamforming vectors, frequently adopted for initial access through beam sweeping [19]. In fact, the N_T antennas can span N_T different orthogonal beams (i.e., $2L_T/\lambda$) by considering as beamforming vectors

$$\frac{1}{\sqrt{N_T}} \begin{bmatrix} 1 \\ e^{-j\pi n \frac{2}{N_T}} \\ e^{-j\pi 2n \frac{2}{N_T}} \\ \vdots \\ e^{-j\pi (N_T-1)n \frac{2}{N_T}} \end{bmatrix} \quad (6)$$

for $n = \pm 1, \pm 2, \dots, \lfloor \frac{N_T}{2} \rfloor$. The different vectors correspond to the transmission directions towards angles [18]

$$\theta_n = \arcsin \frac{2n}{N_T}. \quad (7)$$

Specifically, the DFT matrix (6) for $n = \pm 1, \pm 2, \dots, \lfloor \frac{N_T}{2} \rfloor$ represents an orthonormal basis for the space \mathbb{C}^{N_T} , thus allowing to span all the space around the transmitting antenna. The characteristic of these beams is that each one points towards the null directions of all the other beams. As anticipated, the $R_{\max}^{(k)}$ communication modes correspond to the subset of these beams intercepting the receiving ELAA at the AP. According

to this strategy, all beams could be utilized if the AP is equipped with a theoretically infinite ELAA. For practical ELAA dimensions, however, each NU should select only those beams intercepting the ELAA, based on its position, thereby realizing $R_{\max}^{(k)}$ communication modes. This can be easily implemented provided that the position of NUs is fixed.

C. CSRA Processing at the AP

This subsection illustrates the proposed CSRA processing scheme employed at the AP. The CSRA scheme is logically divided into three phases: (i) an initial processing step that forms clusters of antenna elements based on the detected received signals; (ii) an initial decoding attempt for all identified clusters; (iii) a SIC process. The CSRA scheme is as follows.

1) *Energy detection and clustering*: Firstly, the AP performs energy detection (ED) on the channel estimates obtained from the pilot signal samples received at each antenna element. The pilot signal in (4) received at antenna element r is projected along pilot $\mathbf{p}_j \in \mathcal{P}$, $j = 1, \dots, P$, and maximum likelihood (ML) channel estimation is obtained as

$$\hat{h}_r(\mathbf{p}_j) = \frac{\mathbf{y}_r^P \mathbf{p}_j^H}{\sqrt{P_T} \|\mathbf{p}_j\|^2} \quad (8)$$

for all $r = 1, \dots, N_R$. Subsequently, ED is performed to detect if an NU is transmitting pilot \mathbf{p}_j towards the r -th antenna element as

$$\left| \hat{h}_r(\mathbf{p}_j) \right|^2 \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\geq}} \eta \quad (9)$$

where \mathcal{D}_0 represents the event that no signal is detected, while \mathcal{D}_1 is the event that a signal corresponding to the pilot \mathbf{p}_j is detected at the r -th antenna element, and η is the detection threshold. The operation in (9) is performed for all pilots $\mathbf{p}_j \in \mathcal{P}$ with $j = 1, \dots, P$, at each individual antenna element r , with $r = 1, 2, \dots, N_R$. Once the activity status of each pilot is detected at each antenna element, a clustering operation is conducted to identify the subset of antenna elements where the signal from the same NU is impinging. Let $\mathcal{C}_i(\mathbf{p}_j) = \{t_1, \dots, t_{C_{i,j}}\}$ denote the i -th cluster, which is composed of a set of contiguous antenna elements, indexed as $t_1, \dots, t_{C_{i,j}}$, that have received pilot \mathbf{p}_j with significant power—i.e., where the corresponding estimated channel coefficient exceeds the threshold in (9). We also denote by $|\mathcal{C}_i(\mathbf{p}_j)| = C_{i,j}$ the cardinality of this set. For example, $\mathcal{C}_1(\mathbf{p}_1)$ represents the first group of contiguous antenna elements that received pilot \mathbf{p}_1 with significant power. Continuing in ascending order of the antenna indices, the next group of contiguous elements that also receive significant power from pilot \mathbf{p}_1 forms cluster $\mathcal{C}_2(\mathbf{p}_1)$. The outcome of this operation is a set $\mathcal{N}_C(\mathbf{p}_j)$ of clusters for each available pilot $\mathbf{p}_j \in \mathcal{P}$, where each set comprises multiple clusters of contiguous antenna elements.

2) *Cluster-by-cluster decoding*: For each identified cluster, the AP performs signal detection and decoding based on the linear combination of the received payload signals from all the antenna elements within the cluster. Adopting the conventional

maximal ratio combining (MRC), the decoding of a user's message is attempted for cluster $\mathcal{C}_i(\mathbf{p}_j)$ starting from vector $\mathbf{z}_i(\mathbf{p}_j)$ obtained as

$$\mathbf{z}_i(\mathbf{p}_j) = \frac{\hat{\mathbf{h}}_i^H(\mathbf{p}_j) \mathbf{Y}_i^D}{\|\hat{\mathbf{h}}_i(\mathbf{p}_j)\|^2}, \quad i \in \mathcal{C}_i(\mathbf{p}_j) \quad (10)$$

where $\hat{\mathbf{h}}_i(\mathbf{p}_j) = [\hat{h}_{t_1}(\mathbf{p}_j), \dots, \hat{h}_{t_{C_{i,j}}}(\mathbf{p}_j)]^T$ is the vector of channel gains estimated over the j -th pilot at all the $C_{i,j}$ antenna elements in cluster $\mathcal{C}_i(\mathbf{p}_j)$, and $\mathbf{Y}_i^D = [(\mathbf{y}_{t_1}^D)^T, \dots, (\mathbf{y}_{t_{C_{i,j}}}^D)^T]^T$ is the matrix of aggregated received payload symbols at all the antenna elements $i \in \mathcal{C}_i(\mathbf{p}_j)$ composing the i -th cluster. If the message, sent by an NU towards the processed cluster of antenna elements using the j -th pilot, is retrieved upon successful demapping and decoding performed on $\mathbf{z}_i(\mathbf{p}_j)$, the message is pushed to a list \mathcal{L} . This operation is first performed for all pilots $\mathbf{p}_j \in \mathcal{P}$ within a fixed cluster. Afterward, the same process is repeated for each cluster $i \in \mathcal{N}_C$.

3) *SIC*: The AP processes the messages in the list \mathcal{L} sequentially. Let us denote a generic message in the list as W , and by \mathcal{U}_W the subset of AP antenna elements that have received the replicas of the message W with significant power. The AP selects the first message in the list \mathcal{L} , i.e., W_1 , and performs the subtraction of the interference generated by the transmitted replicas of the decoded message, followed by a new decoding attempt, to all the antenna elements in which the replicas were transmitted. The AP can extract all of this information directly from the received message [20]. Additionally, by knowing the position of the NU, the AP can identify the indices of the antenna elements towards which the message replicas have been directed, i.e., \mathcal{U}_W . In particular, for each antenna element $u \in \mathcal{U}_W$, the AP first re-estimates the channel using the known payload, $\mathbf{s}(W)$, as

$$\tilde{h}_u^{(W)} = \frac{\mathbf{y}_u^D \mathbf{s}(W)^H}{\|\mathbf{s}(W)\|^2} \quad (11)$$

and then subtracts $\tilde{h}_u^{(W)}[\mathbf{p}(W), \mathbf{s}(W)]$ from all the received pilot and payload samples $[\mathbf{y}_u^P, \mathbf{y}_u^D]$. After canceling the interference of all replicas of the messages in \mathcal{L} , the AP performs again energy detection in each of the previously processed antenna elements, constructs new clusters of antenna elements as in step 1, and attempts decoding of new messages by performing the operations in (8) and (10) for each of the identified clusters. When a new message is decoded, it is pushed into the bottom of \mathcal{L} , and then SIC is executed again. This process is repeated for every entry of \mathcal{L} until no further messages can be decoded.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed CSRA scheme in an IIoT scenario resembling a factory line, where multiple sensors installed on machinery transmit data to an ELAA placed on the rooftop, as illustrated in Fig. 1. The evaluation is conducted through extensive simulations, comparing the proposed CSRA scheme with two alternatives: (i) a CSRA variant without SIC, and (ii) a variant in which

clustering is omitted (i.e., single-element processing is performed at the ELAA). In fact, due to the grant-free nature of the communication, the AP cannot perform a-priori channel estimation or acquire information about the active nodes, making comparisons with grant-based schemes in the literature unsuitable. Therefore, as a performance benchmark, we include a single-element variant of the CSRA scheme, labeled CSRA-SE, where the AP performs detection and decoding on each antenna element individually, without our proposed clustering operation that enables linear combining of received signals, thus beamforming gain at the receiver side.

A. Simulation Parameters

The system operates at a carrier frequency of 60 GHz. The AP features an ELAA positioned on the rooftop along the y -axis, centered at $[0, 0, h_{AP}]$, where $h_{AP} = 8$ m represents the height of the factory. To minimize edge effects during the evaluation of processing schemes, the ELAA is configured as a 20 m long radio stripe. The NUs are each equipped with a linear antenna array of $N_T = 20$ elements and are positioned randomly along a segment spanning from $[0, -3 \text{ m}, 0]$ to $[0, 3 \text{ m}, 0]$ on the y -axis. Each NUs transmits with power $P_T = 0.1$ mW, while $B = 100$ kHz, $T_0 = 290$ K, and $NF = 10$ dB. Antennas with 0 dBi gain are considered, and an overall implementation loss of 10 dB. The message length of each active NU is 421 bits. The message is encoded by a $(511, 421, 10)$ BCH code, a null bit is appended to the codeword, and finally, the encoded bits are mapped onto a QPSK constellation, yielding a data payload of $N_D = 256$ symbols. The payload is appended to a pilot sequence of $N_P = 8$ symbols to form the packet. Each NU is configured to send exactly R replicas of its packet towards the AP ELAA. In this configuration, each NU has up to $R_{\max} = 20$ orthogonal transmission directions, leveraging near-field spatial diversity. However, directions resulting in transmission beyond the ELAA boundaries are excluded, leaving each NU with $R_{\max} = 13$ usable orthogonal directions for packet replication. The clustering threshold parameter introduced in Sec. III is set equal to $\eta = 2\sigma/N_P$, ensuring robust initial signal detection and reliable performance in the proposed processing scheme. Monte Carlo simulations were conducted to evaluate the performance of the CSRA scheme in terms of packet loss rate (PLR), i.e., P_L , as a function of the number of simultaneously active devices, K , and the number of transmitted packet replicas, R .

B. Impact of the Number of Transmitted Replicas

Fig. 2 shows the PLR of the proposed CSRA scheme, both with and without SIC, as a function of the number of active NUs for various numbers of transmitted packet replicas, R . The results demonstrate the essential role of SIC in ensuring the reliability of the scheme. Without employing SIC, the system faces challenges in reaching even a packet loss probability of $P_L = 10^{-2}$ in the given scenario. The results also highlight that an optimal choice of the number of transmitted packet replicas, R , depends on the system load. This is also evident in Fig. 3, which shows the PLR of CSRA scheme varying R

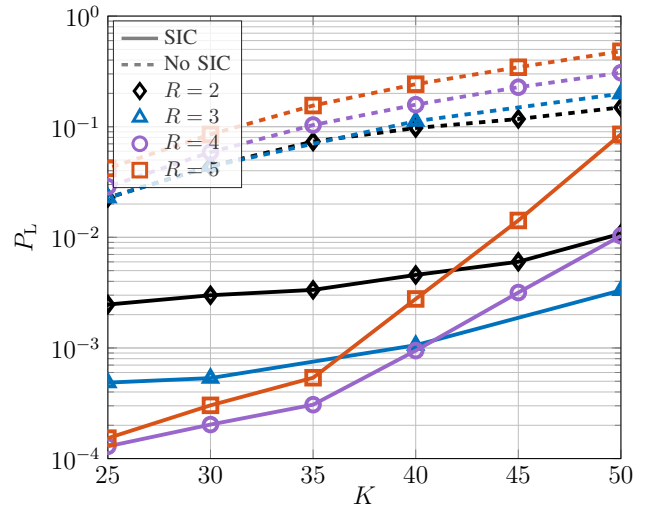


Fig. 2. Packet loss rate P_L of the proposed CSRA scheme as a function of the number of active users K , with and without SIC.

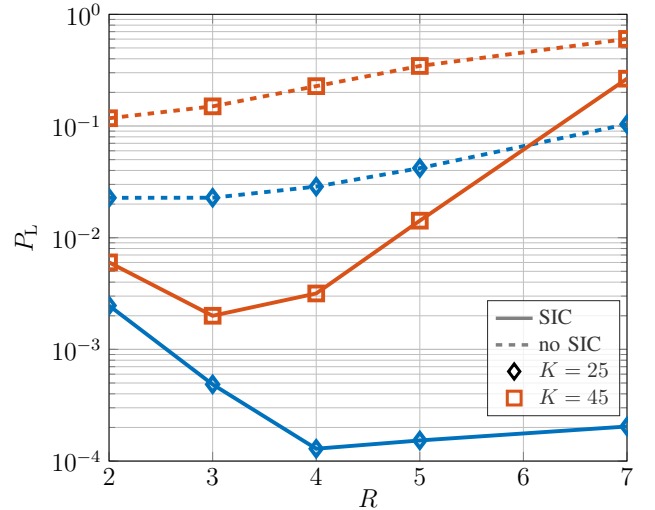


Fig. 3. Packet loss rate P_L of the proposed CSRA scheme as a function of the number of replicas R , with and without SIC.

for $K = 25$ and $K = 45$ active devices. When the number of active users is relatively low, e.g., around $K = 25$, it is preferable to set $R = 4$, which enables the system to achieve a P_L close to 10^{-4} . However, as the traffic load increases, transmitting fewer replicas reduces interference and improves overall performance. For instance, with $K = 45$ active users setting $R = 5$ yields a P_L around $3 \cdot 10^{-3}$, while $R = 4$ further reduces P_L to approximately $2 \cdot 10^{-3}$. These results suggest a dynamic configuration of R based on traffic load, balancing the benefit of additional replicas with the resulting interference. Transmitting more replicas boosts reliability in low-load scenarios but introduces more interference under high-load conditions, thus impacting P_L .

C. Comparison with CSRA-SE

Since the grant-free nature of this communication setup prevents the AP from performing a priori channel estimation or

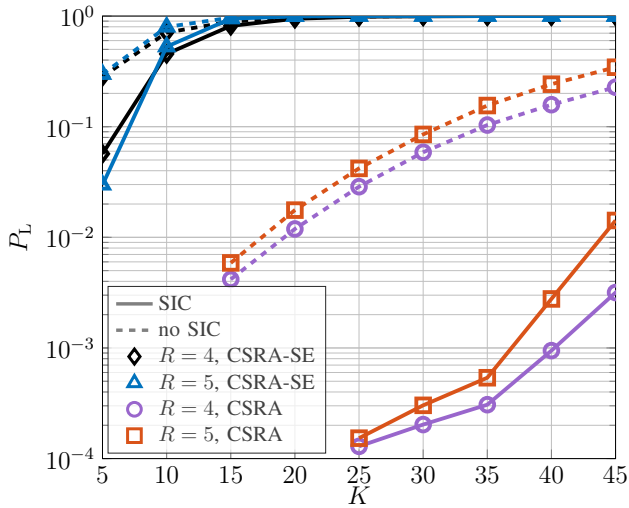


Fig. 4. Packet loss rate P_L of the proposed CSRA scheme as a function of the number of active users K , with and without SIC. Comparison with single-element (SE) processing at the ELAA.

identifying active nodes, comparisons with grant-based methods are unsuitable. Instead, we benchmark the performance against a single-element variant of the CSRA scheme, the CSRA-SE one. In CSRA-SE, detection and decoding are performed on individual antenna elements independently, without clustering, which would otherwise enable linear combining of received signals. Fig. 4 compares the CSRA and CSRA-SE schemes in terms of P_L varying K , for different numbers of transmitted replicas R , both with and without SIC. The results indicate that processing signals independently at each AP antenna element, as in CSRA-SE, leads to significantly lower performance. The CSRA-SE scheme is unable to reach $P_L = 10^{-2}$ even with only $K = 5$ active users. This drop in performance is mainly due to the system operating in a low signal-to-noise ratio regime, where sufficient performance cannot be attained without utilizing the array gain enabled by clustering and combining techniques at the receiver.

V. CONCLUSIONS

This work introduced a novel grant-free coded random access scheme tailored to meet the demands of massive MTC in IIoT networks. By leveraging an ELAA at the AP, and exploiting spatial multiplexing within the near field region, the proposed approach effectively mitigates interference and enhances reliability, even in dense, uncoordinated IIoT environments. Specifically, SIC is exploited with clustering of the signals received at multiple AP antennas, thus circumventing the need for extensive CSI estimation and effectively leveraging the beamforming gain. Extensive simulations demonstrate that the CSRA scheme significantly reduces the PLR compared to single-element processing, which cannot leverage the beamforming gain enabled by clustering. Furthermore, optimal performance is achieved by dynamically adjusting the number of transmitted replicas based on network load, balancing interference and reliability. This adaptability makes

CSRA a robust and scalable solution for next-generation IIoT applications.

ACKNOWLEDGMENTS

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”), and in part by the HORIZON-JU-SNS-2022-STREAM-B-01-03 6G-SHINE Project under Grant 101095738. Giulia Torcolacci was funded by an NRRP Ph.D. grant.

REFERENCES

- [1] Z. Dawy, W. Saad, A. Ghosh, J. G. Andrews, and E. Yaacoub, “Toward massive machine type cellular communications,” *IEEE Wireless Commun.*, vol. 24, no. 1, pp. 120–128, Nov. 2017.
- [2] C. Bockelmann *et al.*, “Massive machine-type communications in 5G: Physical and MAC-layer solutions,” *IEEE Commun. Mag.*, vol. 54, no. 9, pp. 59–65, Sep. 2016.
- [3] S. R. Pokhrel, J. Ding, J. Park, O.-S. Park, and J. Choi, “Towards enabling critical mMTC: A review of URLLC within mMTC,” *IEEE Access*, vol. 8, pp. 131 796–131 813, Jul. 2020.
- [4] E. Testi, V. Tralli, and E. Paolini, “Access point cooperation strategies for coded random access in cell-free massive MIMO,” *IEEE Internet Things J.*, vol. 11, no. 17, pp. 27 916–27 931, Jul. 2024.
- [5] E. Paolini, Č. Stefanović, G. Liva, and P. Popovski, “Coded random access: Applying codes on graphs to design random access protocols,” *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 144–150, Jun. 2015.
- [6] D. Dardari and N. Decarli, “Holographic communication using intelligent surfaces,” *IEEE Commun. Mag.*, vol. 59, no. 6, pp. 35–41, June 2021.
- [7] H. Lu *et al.*, “A tutorial on near-field XL-MIMO communications towards 6G,” *IEEE Commun. Surv. Tutor.*, pp. 1–1, Jan. 2024.
- [8] Z. Wang *et al.*, “A tutorial on extremely large-scale MIMO for 6G: Fundamentals, signal processing, and applications,” *IEEE Commun. Surv. Tutor.*, vol. 26, no. 3, pp. 1560–1605, 2024.
- [9] S. Cavallero *et al.*, “Terahertz networks for future industrial internet of things,” *ITU J. Future and Evolving Technologies*, vol. 4, pp. 196–208, 03 2023.
- [10] C. Sun *et al.*, “Beam division multiple access transmission for massive MIMO communications,” *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2170–2184, Apr. 2015.
- [11] Z. Wu and L. Dai, “Multiple access for near-field communications: SDMA or LDMA?” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1918–1935, Jun. 2023.
- [12] M. Cui, L. Dai, Z. Wang, S. Zhou, and N. Ge, “Near-field rainbow: Wideband beam training for XL-MIMO,” *IEEE Trans. Wireless Commun.*, vol. 22, no. 6, pp. 3899–3912, Jun. 2022.
- [13] H. Iimori *et al.*, “Grant-free access for extra-large MIMO systems subject to spatial non-stationarity,” in *Proc. 2022 IEEE Int. Conf. Commun.*, Seoul, South Korea, May 2022, pp. 1758–1762.
- [14] J. H. I. de Souza, J. C. Marinello Filho, A. Amiri, and T. Abrão, “QoS-aware user scheduling in crowded XL-MIMO systems under non-stationary multi-state LoS/NLoS channels,” *IEEE Trans. Vehicular Tech.*, vol. 72, no. 6, pp. 7639–7652, Jun. 2023.
- [15] S. Guo and K. Qu, “Beamspace modulation for near field capacity improvement in XL-MIMO communications,” *IEEE Wireless Commun. Lett.*, vol. 12, no. 8, pp. 1434–1438, May 2023.
- [16] Z. H. Shaik, E. Björnson, and E. G. Larsson, “Cell-free massive MIMO with radio stripes and sequential uplink processing,” in *Proc. 2020 IEEE Int. Conf. Commun. Workshops*, Online, Jun. 2020, pp. 1–6.
- [17] C. Balanis, *Antenna Theory: Analysis and Design*. Wiley, 2015.
- [18] N. Decarli and D. Dardari, “Communication modes with large intelligent surfaces in the near field,” *IEEE Access*, vol. 9, pp. 165 648–165 666, Dec. 2021.
- [19] D. Yang, L.-L. Yang, and L. Hanzo, “DFT-based beamforming weight-vector codebook design for spatially correlated channels in the unitary precoding aided multiuser downlink,” in *Proc. 2010 IEEE Int. Conf. Commun.*, Cape Town, South Africa, May 2010, pp. 1–5.
- [20] E. Paolini, L. Valentini, V. Tralli, and M. Chiani, “Irregular repetition slotted ALOHA in an information-theoretic setting,” in *Proc. 2022 IEEE Int. Symp. Inf. Theory*, Espoo, Finland, Jun. 2022.