Banff International Research Station, Banff, March 10-15, 2024

Grant-Free Access in 6G Networks: An Unsourced Multiple Access Perspective

Gianluigi Liva, gianluigi.liva@dlr.de
German Aerospace Center, DLR

DLR

Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

Introduction
Massive Random Access

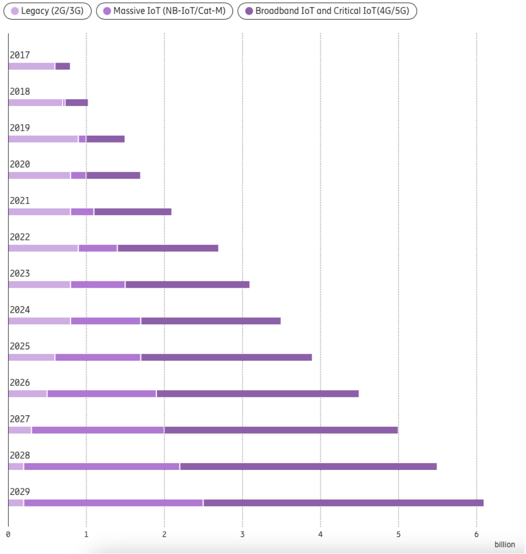
- **Machine-type communications** (mMTC) and **internet of things** (IoT) are expected to impact the **connectivity requirements** of next generation wireless systems

Introduction

Massive Random Access

- **Machine-type communications** (mMTC) and **internet of things** (IoT) are expected to impact the **connectivity requirements** of next generation wireless systems

- Large number of low-power nodes
- Sporadic transmission of small data units
- Often, relaxed reliability targets



Ericsson Mobility Report (Nov. 2023)

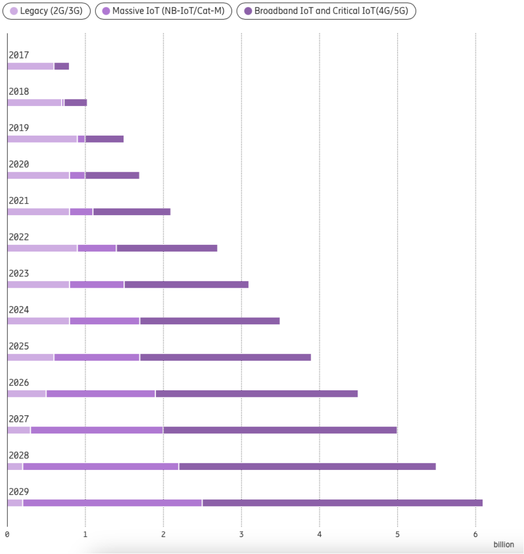
Introduction

Massive Random Access

- **Machine-type communications** (mMTC) and **internet of things** (IoT) are expected to impact the **connectivity requirements** of next generation wireless systems

- Large number of low-power nodes
- Sporadic transmission of small data units
- Often, relaxed reliability targets

Massive, energy-efficient grant-free random access



Ericsson Mobility Report (Nov. 2023)

Introduction

Massive Random Access

- **Machine-type communications** (mMTC) and **internet of things** (IoT) are expected to impact the **connectivity requirements** of next generation wireless systems

- Large number of low-power nodes
- Sporadic transmission of small data units
- Often, relaxed reliability targets

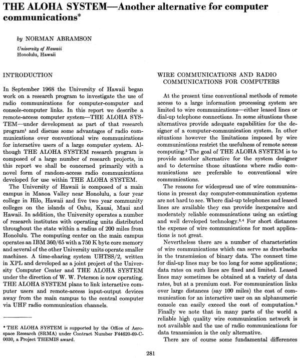
Massive, energy-efficient grant-free random access

Can cellular standards support massive random access?

Random Access: Historical Notes

First Wave
(1970-2007)

Aloha, CSMA,
Splitting Algorithms



THE ALOHA SYSTEM—Another alternative for computer communications*

by NORMAN ABRAMSON

University of Hawaii
Honolulu, Hawaii

INTRODUCTION

In September 1968 the University of Hawaii began work on a research program to investigate the use of radio communications for computer-computer and console-computer links. In this report we describe a remote-access computer system—THE ALOHA SYSTEM—under development as part of that research program[1] and discuss some advantages of radio communications over conventional wire communications for interactive users of a large computer system. Although THE ALOHA SYSTEM research program is composed of a large number of research projects, in this report we shall be concerned primarily with a novel form of random-access radio communications developed for use within THE ALOHA SYSTEM.

The University of Hawaii is composed of a main campus in Manoa Valley near Honolulu, a four year college in Hilo, Hawaii and five two year community colleges on the islands of Oahu, Kauai, Maui and Hawaii. In addition, the University operates a number of research institutes with operating units distributed throughout the state within a radius of 200 miles from Honolulu. The computing center on the main campus operates an IBM 360/65 with a 750 K byte core memory and several of the other University units operate smaller machines. A time-sharing system UHTSS/2, written in XPL and developed as a joint project of the University Computer Center and THE ALOHA SYSTEM under the direction of W. W. Peterson is now operating. THE ALOHA SYSTEM plans to link interactive computer users and remote-access input-output devices away from the main campus to the central computer via UHF radio communication channels.

WIRE COMMUNICATIONS AND RADIO COMMUNICATIONS FOR COMPUTERS

At the present time conventional methods of remote access to a large information processing system are limited to wire communications—either leased lines or dial-up telephone connections. In some situations these alternatives provide adequate capabilities for the designer of a computer-communication system. In other situations however the limitations imposed by wire communications restrict the usefulness of remote access computing.[2] The goal of THE ALOHA SYSTEM is to provide another alternative for the system designer and to determine those situations where radio communications are preferable to conventional wire communications.

The reasons for widespread use of wire communications in present day computer-communication systems are not hard to see. Where dial-up telephones and leased lines are available they can provide inexpensive and moderately reliable communications using an existing and well developed technology.[3,4] For short distances the expense of wire communications for most applications is not great.

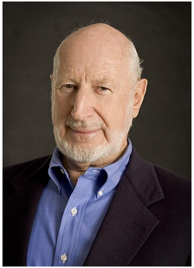
Nevertheless there are a number of characteristics of wire communications which can serve as drawbacks in the transmission of binary data. The connect time for dial-up lines may be too long for some applications; data rates on such lines are fixed and limited. Leased lines may sometimes be obtained at a variety of data rates, but at a premium cost. For communication links over large distances (say 100 miles) the cost of communication for an interactive user on an alphanumeric console can easily exceed the cost of computation.[5] Finally we note that in many parts of the world a reliable high quality wire communication network is not available and the use of radio communications for data transmission is the only alternative.

There are of course some fundamental differences

---

* THE ALOHA SYSTEM is supported by the Office of Aerospace Research (SRMA) under Contract Number F44620-69-C-0030, a Project THEMIS award.

281



Random Access: Historical Notes

First Wave
(1970-2007)

Aloha, CSMA,
Splitting Algorithms

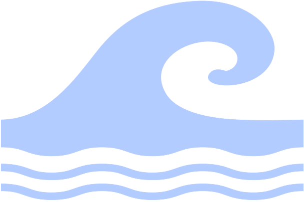
Random Access as
Layer-2 protocol [†]

[†] Notable exception: spread Aloha

Random Access: Historical Notes

First Wave
(1970-2007)

Aloha, CSMA,
Splitting Algorithms



Random Access as Layer-2 protocol †

† Notable exception: spread Aloha

Second Wave
(2007-2017)

SICTA/CRDSA/CSA
E-SSA, Frameless Aloha

Contention Resolution Diversity Slotted ALOHA (CRDSA): An Enhanced Random Access Scheme for Satellite Access Packet Networks

Enrico Casini, Riccardo De Gaudenzi, *Senior Member, IEEE,* and Oscar del Rio Herrero

***Abstract*— In this paper a new multiple access scheme dubbed Contention Resolution Diversity Slotted Aloha (CRDSA) is introduced and its performance and implementation are thoroughly analyzed. The scheme combines diversity transmission of data bursts with efficient interference cancellation techniques. It is shown that CRDSA largely outperforms the classical Slotted Aloha (SA) technique in terms of throughput under equal packet loss ratio conditions (e.g. 17-fold improvement at Packet Loss Ratio = $2 \cdot 10^{-2}$). CRDSA allows to boost the performance of random access (RA) channels in the return link of interactive satellite networks, making RA very efficient and providing low latency for the transmission of small size sparse packets. Implementation-wise it is shown that the CRDSA technique can be easily integrated in systems equipped with digital burst demodulators.**

***Index Terms*— Access control, interference suppression, multiaccess communication, satellite communication, time division multiaccess.**

I. INTRODUCTION

DESPITE having been proposed more than 30 years ago, Slotted Aloha (SA) [1], [2] and its slightly enhanced version named Diversity Slotted Aloha (DSA) [3] are today widely used in satellite networks for initial terminal access or short packet transmissions over a shared medium. The current satellite standards for interactive satellite broadband networks like the Digital Video Broadcasting (DVB) Return Channel via Satellite (DVB-RCS) [4] and the Telecommunication Industry Association (TIA) IP over Satellite (IPoS) [5] provide the capability to transmit small packets through a SA Random Access (RA) contention channel. In particular, the IPoS standard exploits the DSA protocol to enhance the RA channel capabilities. The satellite standards also include a capacity reservation mechanism, Demand Assignment Multiple Access (DAMA) [6], for longer packets transmission or for terminals offering a medium to high level of traffic aggregation. However, DAMA response time can be too long for the transmission of short bursts, which is frequent in consumer type of terminals [7]. The family of Carrier Sense Multiple Access (CSMA) [8] protocols cannot be used for satellite networks because their large propagation latency (250 ms for a geostationary satellite) prevents the exploitation of the carrier sensing mechanism.

Moving towards consumer type of interactive satellite terminals (ST), the amount of traffic aggregation at the ST will largely decrease and consequently the RA channel utilization potential will increase. In fact, although SA represents today a well established Random Access technique for TDMA satellite networks doubling the maximum throughput compared to the pure Aloha protocol [9], its utilization is typically limited to initial login, capacity request or Medium Access Control (MAC) signalling packets. This is because in practice SA works with very moderate normalized average loading (e.g. 2-5%) to ensure acceptable packets transmission delay and loss probability [10]. DSA provides better delay and throughput performance than SA under very moderate loading conditions by transmitting twice the same packet in a different TDMA slot, or a different frequency and time slot in case of Multi-Frequency TDMA (MF-TDMA) [3]. However, the throughput difference between Aloha and Slotted Aloha or Diversity Slotted Aloha is limited and quite poor in absolute terms. Another possible improvement of SA is the so called Selective Reject Aloha (SRE) protocol [11], [12]. Its main claimed advantage lies in the SRE capability to achieve throughput performance similar to the SA without the need for STs network synchronization. SRE exploits message subpacketization jointly with selective reject ARQ retransmission for partial packet overlaps occurring in practice avoiding the need for network synchronization. This advantage is however mitigated by the need for extra overhead in the packets. It is therefore pivotal to enhance the satellite RA channel performance in terms of throughput and delay with minimum impact on the existing satellite standards, currently based on MF-TDMA access scheme. The novel Contention Resolution Diversity Slotted Aloha (CRDSA) scheme described in the present paper represents an improved version of the well known SA and DSA schemes. Similarly to DSA, the CRDSA protocol generates two replicas of the same burst (in the following we will call *burst* the physical layer packet) at random time within a frame instead of only once as in SA. While the driver for DSA is to slightly enhance the SA performance by increasing the probability of packet successful transmission at the expense of increased RA load, CRDSA in addition is designed in a way to resolve most of the DSA packet contentions. Burst collisions are cleared up through a simple yet effective iterative Interference Cancellation (IC)

Manuscript received July 10, 2005; revised December 5, 2005, April 30, 2006, and August 3, 2006; accepted August 10, 2006. The associate editor coordinating the review of this paper and approving it for publication was V. Leung. This work was supported by the European Space Agency.

The authors are with the European Space Agency, European Space and Technology Center, ESTEC, Keplerlaan 1, 2200 AG, Noordwjik, The Netherlands (e-mail: enrico.casini@esa.int; riccardo.de.gaudenzi@esa.int; oscar.del.rio.herrero@esa.int).

Digital Object Identifier 10.1109/TWC.2007.05528.

Random Access: Historical Notes

First Wave
(1970-2007)

Aloha, CSMA,
Splitting Algorithms

Second Wave
(2007-2017)

SICTA/CRDSA/CSA
E-SSA, Frameless Aloha

Random Access as
Layer-2 protocol [†]

Improving Aloha
with SIC
Layer-2 ↔ Layer-1

[†] Notable exception: spread Aloha

Random Access: Historical Notes

First Wave
(1970-2007)

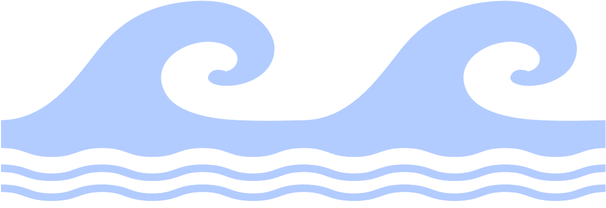
Aloha, CSMA,
Splitting Algorithms

Second Wave
(2007-2017)

SICTA/CRDSA/CSA
E-SSA, Frameless Aloha

Third Wave
(2017-now)

Coding for
the UMAC



Random Access as
Layer-2 protocol [†]

Improving Aloha
with SIC
Layer-2 ↔ Layer-1

A perspective on massive random-access

Yury Polyanskiy

***Abstract*—This paper discusses the contemporary problem of providing multiple-access (MAC) to a massive number of uncoordinated users. First, we define a random-access code for K_a-user Gaussian MAC to be a collection of norm-constrained vectors such that the noisy sum of any K_a of them can be decoded with a given (suitably defined) probability of error. An achievability bound for such codes is proposed and compared against popular practical solutions: ALOHA, coded slotted ALOHA, CDMA, and treating interference as noise. It is found out that as the number of users increases existing solutions become vastly energy-inefficient.**

Second, we discuss the asymptotic (in blocklength) problem of coding for a K-user Gaussian MAC when K is proportional to blocklength and each user's payload is fixed. It is discovered that the energy-per-bit vs. spectral efficiency exhibits a rather curious tradeoff in this case.

I. INTRODUCTION

An interesting technological challenge for the next generation of wireless standards is to provide coexistence over the same band of a massive number of infrequently communicating devices. This problem has attracted attention in the world of the licensed spectrum (3GPP and 5G-PPP) under the name of *mMTC* (massive machine-type communication), and i the world of unlicensed spectrum under the name *LP-WANs* (low-power wide-area networks).

One may be inclined to dismiss the novelty of challenge by refering back to the classical multi access channel (MAC) question. There are, howe several interesting and new aspects of this reincarn tion of the problem: small size of the payload lea to *finite-blocklength* (FBL) effects [1], only a sma fraction of users are active at any given time (*random access*), but the total number of active users can still be comparable with the overall blocklength (*massive multiple-access*) and users access channel without any prior resource requests to the base station (*grantless* or *grantfree* [2]).

Various subsets of these issues have been observed and discussed in the past. The FBL questions for a K-user MAC have been studied in [3], but their bounds and normal approximations require evaluating probabilities in 2^K-dimensional spaces, and thus are only computable for very modest values of K. Classical literature on the topic of multiple-access may roughly be split into three categories: information theoretic (Ahslwede-Liao [4], [5]), the

MAC [11], [12]). Already 30 years ago R. Gallager [13] called for "a coding technology that is applicable for a large set of transmitters of which a small, but variable, subset simultaneously use the channel." It appears (to this author) that this call has not been completely answered still. One reason for this could be that the models in each of three categories are different and thus solutions are not directly comparable. Our first goal, thus, is to define a notion of random-access code that would appeal to all three communities. This we do next.

Fix integer $K_a \geq 1$ – the number of active users – and let $P_{Y|X} = P_{Y|X_1,\dots,X_{K_a}} : \mathcal{X}^{K_a} \to \mathcal{Y}$ be a memoryless MAC satisfying permutation invariance condition: the distribution $P_{Y|X_1,\dots,X_{K_a}}(\cdot|x_1,\dots,x_{K_a})$ coincides with $P_{Y|X_1,\dots,X_{K_a}}(\cdot|x_{\pi(1)},\dots,x_{\pi(K_a)})$ for any $x^{K_a} \in \mathcal{X}^{K_a}$ and any permutation π.

Definition 1. An (M, n, ϵ) random-access code for the K_a-user channel $P_{Y|X^{K_a}}$ is a pair of (possibly randomiz the encoder $f : [M] \to \mathcal{X}^n$ and the) – satisfying:

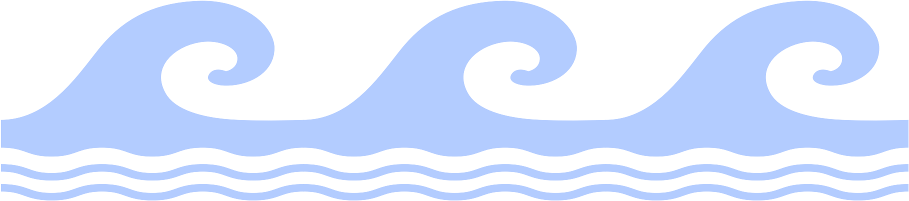
ϵ,

$\mathcal{Y}^n)\} \cup \{W_j =$
user error event,
uniform on $[M]$

generating code-
d the decoder's
transmitted list.
action of correctly
ces from the usual
a) users are
fo decoding is
do ror event
is d
Befor
make te
In the r
on the G
$Y =$
In thi

[†] Notable exception: spread Aloha

Random Access: Historical Notes



First Wave
(1970-2007)

Aloha, CSMA,
Splitting Algorithms

Random Access as
Layer-2 protocol [†]

Second Wave
(2007-2017)

SICTA/CRDSA/CSA
E-SSA, Frameless Aloha

Improving Aloha
with SIC
Layer-2 ↔ Layer-1

Third Wave
(2017-now)

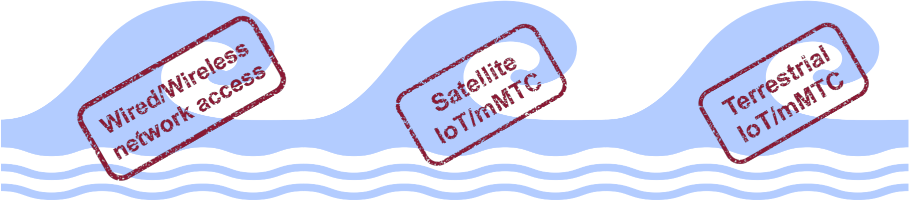
Coding for
the UMAC

Random access as
a coding problem
Layer-1

[†] Notable exception: spread Aloha

Random Access: Historical Notes

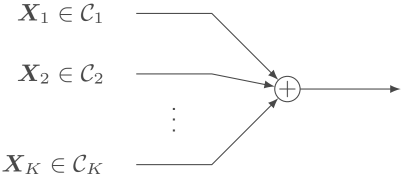
First Wave (1970-2007)	**Second Wave (2007-2017)**	**Third Wave (2017-now)**
Aloha, CSMA, Splitting Algorithms	SICTA/CRDSA/CSA E-SSA, Frameless Aloha	Coding for the UMAC
Random Access as *Layer-2 protocol* [†]	*Improving Aloha* *with SIC* *Layer-2 ↔ Layer-1*	*Random access as* *a coding problem* *Layer-1*



[†] Notable exception: spread Aloha

Coordinated K-User Multiple Access Channel

- Assign different codebooks to users
- Different codebooks allow (a) to identify users and (b) to "separate" them



$\boldsymbol{X}_1 \in \mathcal{C}_1$

$\boldsymbol{X}_2 \in \mathcal{C}_2$

$\vdots$

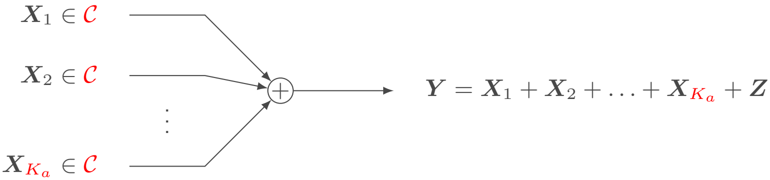
$\boldsymbol{X}_K \in \mathcal{C}_K$

$$\boldsymbol{Y} = \boldsymbol{X}_1 + \boldsymbol{X}_2 + \ldots + \boldsymbol{X}_K + \boldsymbol{Z}$$

- Typically, K is small

Random, Uncoordinated Access

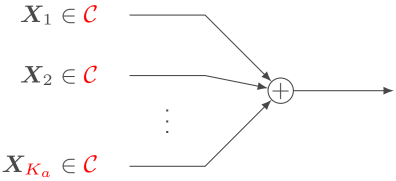
- Large user population (large K)
- User activity sporadic and unpredictable ($K_a \ll K$ active users)
- Each user transmits a short message of k bits
- Impractical to assign a different codebook to each user (receiver complexity)



Random, Uncoordinated Access

- Large user population (large K)
- User activity sporadic and unpredictable ($K_a \ll K$ active users)
- Each user transmits a short message of k bits
- Impractical to assign a different codebook to each user (receiver complexity)

huge coordination overhead!



$X_1 \in \mathcal{C}$

$X_2 \in \mathcal{C}$

$\vdots$

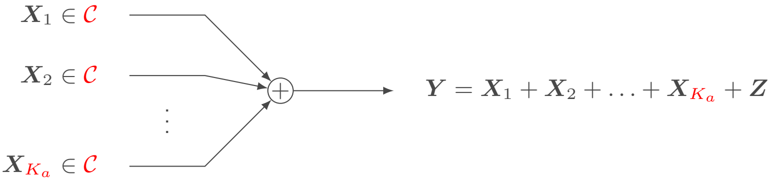
$X_{K_a} \in \mathcal{C}$

$$\boldsymbol{Y} = \boldsymbol{X}_1 + \boldsymbol{X}_2 + \ldots + \boldsymbol{X}_{K_a} + \boldsymbol{Z}$$

Random, Uncoordinated Access

- Large user population (large K)
- User activity sporadic and unpredictable ($K_a \ll K$ active users)
- Each user transmits a short message of k bits
- Impractical to assign a different codebook to each user (receiver complexity)

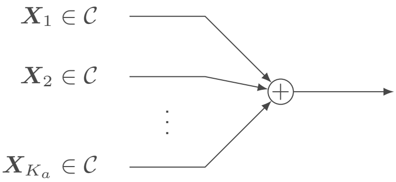
huge coordination overhead!



- **Even if users embed their identity in the message (partitioning the codebook), the decoder cannot make use of this information:** *Unsourced* Multiple Access (UMAC)

Unsourced Multiple Access

- The decoder outputs a list of codewords $\mathsf{D}(\boldsymbol{Y})$



$\boldsymbol{X}_1 \in \mathcal{C}$

$\boldsymbol{X}_2 \in \mathcal{C}$

$\vdots$

$\boldsymbol{X}_{K_a} \in \mathcal{C}$

$$\boldsymbol{Y} = \boldsymbol{X}_1 + \boldsymbol{X}_2 + \ldots + \boldsymbol{X}_{K_a} + \boldsymbol{Z}$$

- Per-user probability of error (PUPE)

$$\mathsf{PUPE} := \frac{1}{K_a} \sum_{i=1}^{K_a} \mathbb{P}[\boldsymbol{X}_i \notin \mathsf{D}(\boldsymbol{Y})]$$

Unsourced Multiple Access

Connection to Compressive Sensing (CS)

- Stack the $M = |\mathcal{C}|$ codewords in the

$$n \times M \text{ sensing matrix } \boldsymbol{C}$$

- Re-write

$$\boldsymbol{Y} = \boldsymbol{C}\boldsymbol{A} + \boldsymbol{Z}$$

- $\boldsymbol{A}$ is a length-M sparse binary activity vector, $A_i = 1$ if the ith codeword is transmitted
- Decoding $\equiv$ estimating the support of $\boldsymbol{A}$

Unsourced Multiple Access

Connection to Compressive Sensing (CS)

- Stack the $M = |\mathcal{C}|$ codewords in the

$n \times M$ sensing matrix $\boldsymbol{C}$

- Re-write

$$\boldsymbol{Y} = \boldsymbol{C}\boldsymbol{A} + \boldsymbol{Z}$$

- $\boldsymbol{A}$ is a length-M sparse binary activity vector, $A_i = 1$ if the ith codeword is transmitted
- Decoding $\equiv$ estimating the support of $\boldsymbol{A}$

Curse of dimensionality: M is huge already for moderately-short messages (e.g. $k = 100$–500 bits)

Number of protons in the observable universe $\approx 2^{266}$ *(Eddington number)*

Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

5G New Radio and Narrowband IoT
Four-Step Random Access

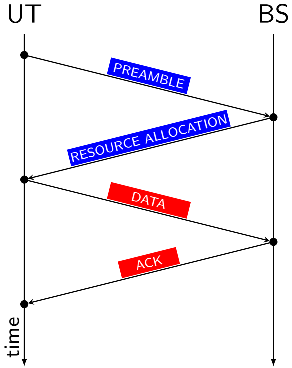
- Building on the legacy of LTE, 5GNR and NB-IoT employ “four-step random access”
- The procedure decouples random access and data transmission:

msg 1: random access via preamble transmission to identify users

msg 2: resource allocation provided by the base station

msg 3: data transmission over resources that are orthogonal for the identified users

msg 4: final acknowledgment



- No grant-free transmission

5G New Radio

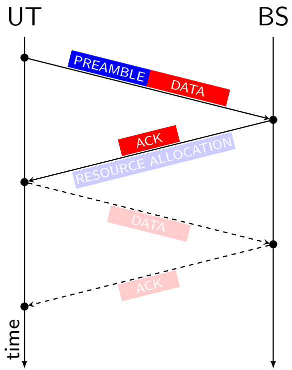
Two-Step Random Access

- With Rel. 16 of 5GNR, “two-step” random access

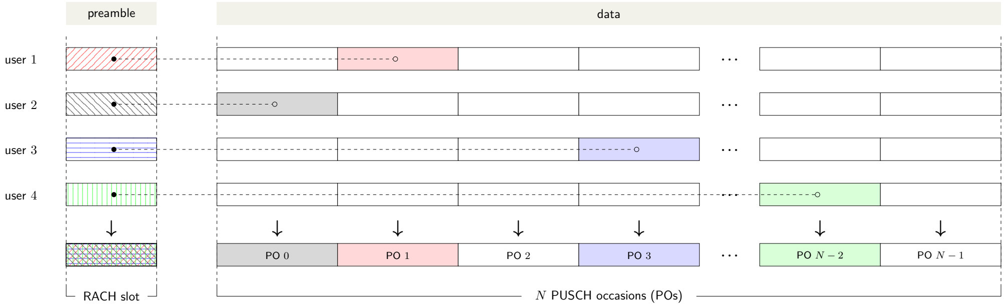
  msg A: preamble transmission, *announcing* the resources used for data transmission, data transmission follows

  msg B: acknowledgment

- If decoding fails, four-step random access is resumed
- Grant-free *(in part)*
- Focus: How does two-step random access perform?

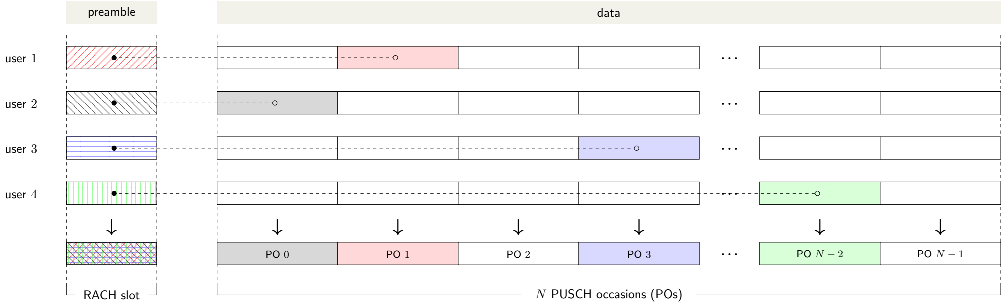


Two-Step Random Access



- Preamble dictionary: 64 Zadoff-Chu sequences, length 139 (*short preambles*) or 839 (*long preambles*), possibly repeated
- Each preamble points to a *physical uplink shared channel* (PUSCH) *occasion* (PO)
- One-to-one mapping vs. many-to-one mapping
- We denote by N the number of POs

Two-Step Random Access



- Within a PO, transmission through (n_c, k) LDPC codes (5GNR)
- Pilot field appended to each codeword (*demodulation reference signal*, DMRS)

Gaussian MAC

Model and Notation

- UMAC code $C(n, M)$, information message of $k = \log_2 M$ bits

$$\boldsymbol{Y} = \boldsymbol{X}_1 + \boldsymbol{X}_2 + \ldots + \boldsymbol{X}_{K_a} + \boldsymbol{Z}$$

with

$$||\boldsymbol{X}||_2^2 \leq nP \qquad\qquad \boldsymbol{Z} \sim \mathcal{CN}\left(\mathbf{0}, \boldsymbol{I}\right)$$

- Per-user signal-to-noise ratio

$$\frac{E_b}{N_0} = \frac{nP}{k}$$

Quasi-Static Rayleigh Fading MAC

Model and Notation

- UMAC code $C(n, M)$, information message of $k = \log_2 M$ bits

$$\boldsymbol{Y} = H_1\boldsymbol{X}_1 + H_2\boldsymbol{X}_2 + \ldots + H_{K_a}\boldsymbol{X}_{K_a} + \boldsymbol{Z}$$

with

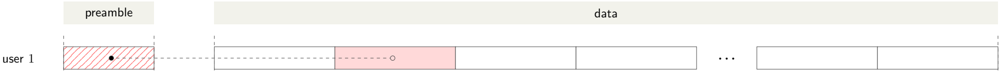
$$||\boldsymbol{X}||_2^2 \leq nP \qquad \boldsymbol{Z} \sim \mathcal{CN}(\boldsymbol{0}, \boldsymbol{I}) \qquad H_i \sim \mathcal{CN}(0,1) \quad \text{(i.i.d.)}$$

- Per-user average signal-to-noise ratio

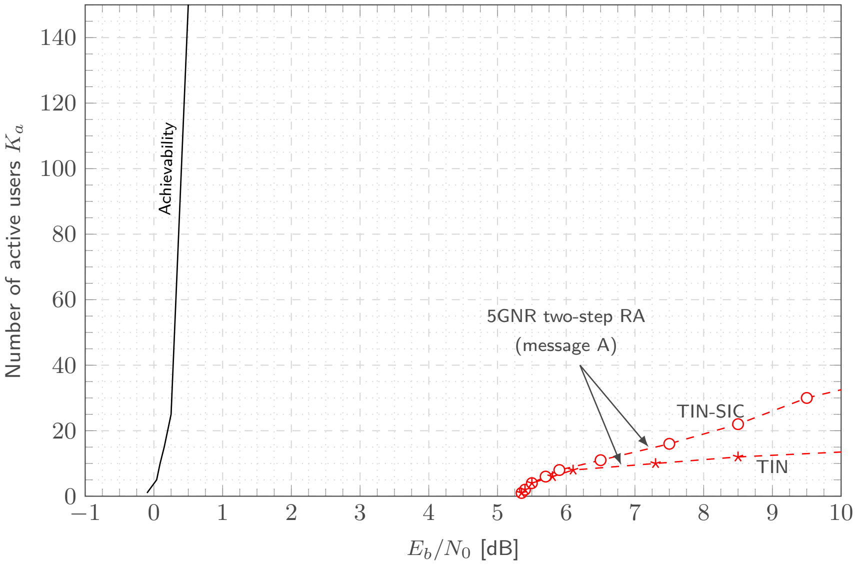
$$\frac{\bar{E}_b}{N_0} = \frac{nP}{k}$$

Two-Step Random Access
Simulation Setup

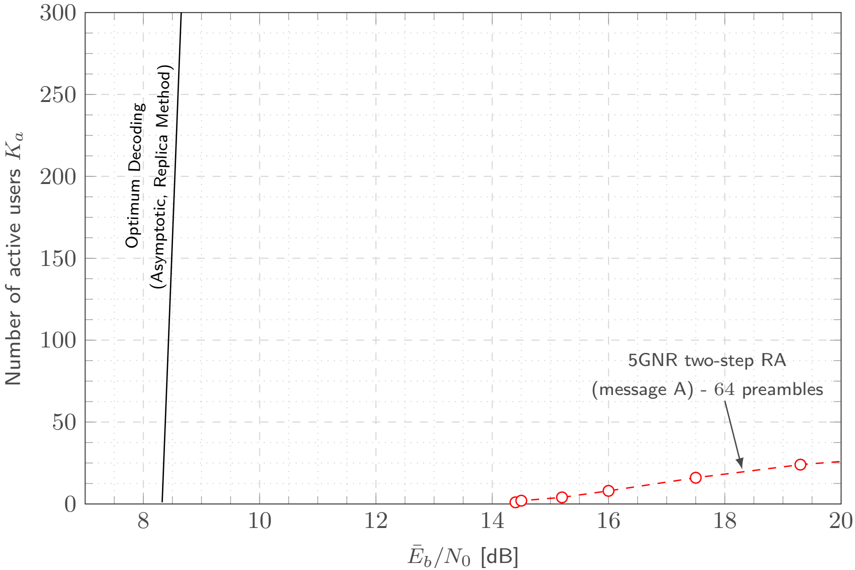
- Preamble length $= 2 \times 139$ (*A1 configuration*)
- $(500, 100)$ LDPC code (5GNR base graph 2) with QPSK modulation
- Pilot-free (AWGN) or 50 pilots (quasi-static fading)
- Decoding: treat-interference-as-noise (TIN) w/wo successive interference cancellation
- $N = 64$ POs (one-to-one mapping)
  - ☐ AWGN: $n = 16278$
  - ☐ Quasi-static fading: $n = 19478$



Two-Step Random Access: Gaussian MAC



Two-Step Random Access: Quasi-Static Rayleigh Fading MAC



Study Group on Random Access for 6G
Objective

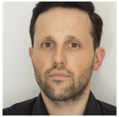
Leaning on lessons from the UMACs framework, identify directions to upgrade existing 3GPP protocols (*two-step random access*)


Krishna Narayanan


Jean-Francois Chamberland

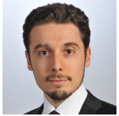

Zoran Utkovski


Johannes Dommel


Patrick Agostini


Yury Polyanskiy


Federico Clazzer


Andrea Munari

Study Group on Random Access for 6G

Objective

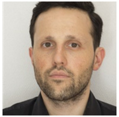
Leaning on lessons from the UMACs framework, identify directions to upgrade existing 3GPP protocols (*two-step random access*)


Krishna
Narayanan


Jean-Francois
Chamberland

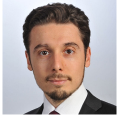

Zoran
Utkovski


Johannes
Dommel


Patrick
Agostini


Yury
Polyanskiy


Federico
Clazzer


Andrea
Munari

6G-RIC
Research and
Innovation
Cluster


Slawomir
Stanczak

Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

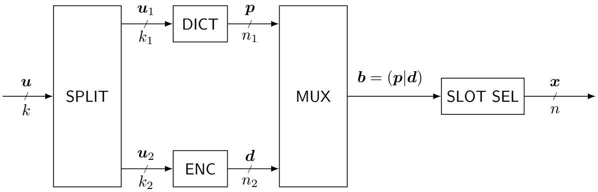
UMAC Emerging Architectures

- Several excellent schemes: very hard to provide a comprehensive survey...
- Four dominant architectures:
  - ☐ Slotted Aloha with multipacket reception (MPR)
  - ☐ Preamble-based
  - ☐ Coded compresses sensing (CCS)
  - ☐ Spreading-based

UMAC: Emerging Architectures

Slotted Aloha with MPR

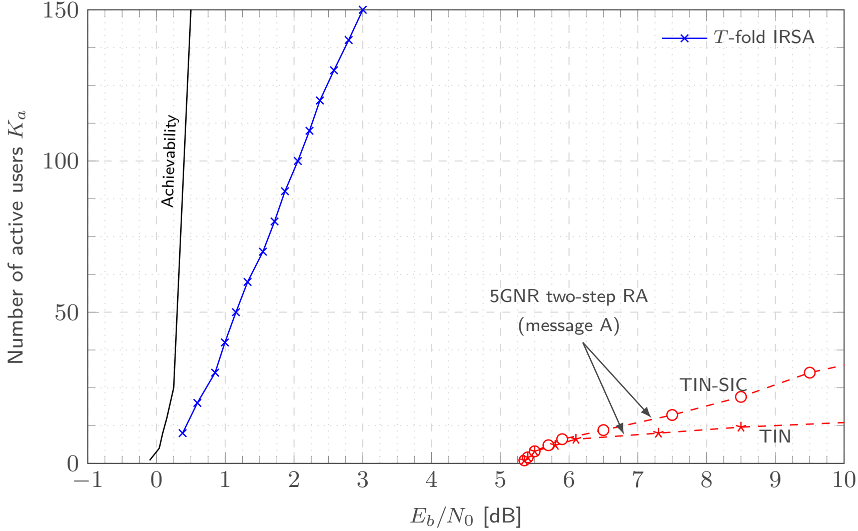
- **Principle:** Turn a UMAC channel with many transmissions in a several UMAC channels with fewer transmissions
- **Ingredients:** Low-rate error correcting codes, data-driven pilot selection, joint decoding or SIC



- O. Ordentlich and Y. Polyanskiy, “Low complexity schemes for the random access Gaussian channel,” in *Proc. IEEE Int. Symp. Inf. Theory*, 2017.
- A. Vem, K. R. Narayanan, J.-F. Chamberland, and J. Cheng, “A user-independent successive interference cancellation based coding scheme for the unsourced random access Gaussian channel,” *IEEE Trans. Commun.*, 2019.
- E. Marshakov, G. Balitskiy, K. Andreev, and A. Frolov, “A Polar Code Based Unsourced Random Access for the Gaussian MAC,” in *Proc. IEEE Vehicular Technology Conference Fall*, 2019.
- A. K. Tanc and T. M. Duman, “Massive random access with trellis-based codes and random signatures,” *IEEE Commun. Lett.*, 2021.
- S. S. Kowshik, K. Andreev, A. Frolov, and Y. Polyanskiy, “Energy efficient coded random access for the wireless uplink,” *IEEE Trans. Commun.*, 2020.
- K. Andreev, E. Marshakov, and A. Frolov, “A Polar Code Based TIN-SIC Scheme for the Unsourced Random Access in the Quasi-Static Fading MAC,” in *Proc. IEEE Int. Symp. Inf. Theory*, 2020.
- M. J. Ahmadi, M. Kazemi, and T. M. Duman, “Unsourced Random Access Using Multiple Stages of Orthogonal Pilots: MIMO and Single-Antenna Structures,” *IEEE Trans. Wireless Commun.*, 2023.
- M. Ozates, M. Kazemi, and T. M. Duman, “A Slotted Pilot-Based Unsourced Random Access Scheme with a Multiple-Antenna Receiver,” *IEEE Trans. Wireless Commun.*, 2023.
- A. Fengler, O. Musa, P. Jung, and G. Caire, “Pilot-Based Unsourced Random Access With a Massive MIMO Receiver, Interference Cancellation, and Power Control,” *IEEE J. Sel. Areas Commun.*, 2022.

UMAC: Emerging Architectures

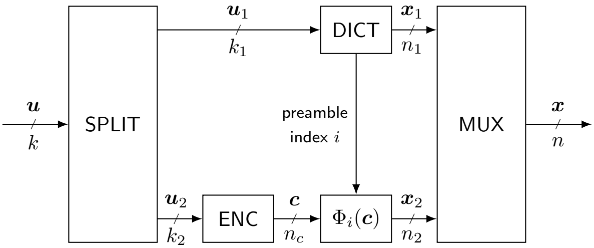
Slotted Aloha with MPR: Gaussian MAC



UMAC: Emerging Architectures

Preamble-based

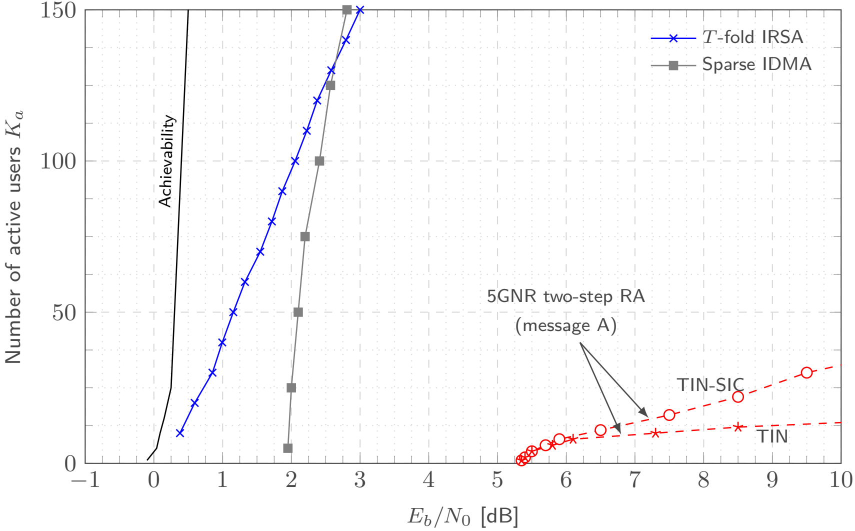
- **Principle:** Use an initial UMAC phase (preamble) to signal the resources that will be used in the second phase
- **Ingredients:** CS-based preamble detection, repetition/interleaving, sparse access patterns



- A. K. Pradhan, V. K. Amalladinne, A. Vem, K. R. Narayanan, and J.-F. Chamberland, "Sparse IDMA: A Joint Graph-Based Coding Scheme for Unsourced Random Access," *IEEE Trans. Commun.*, 2022.
- D. Truhachev, M. Bashir, A. Karami, and E. Nassaji, "Low-complexity coding and spreading for unsourced random access," *IEEE Commun. Lett.*, 2021.
- E. Nassaji, M. Bashir, and D. Truhachev, "Unsourced Random Access Over Fading Channels via Data Repetition, Permutation, and Scrambling," *IEEE Trans. Commun.*, 2022.
- M. Ozates, M. Kazemi, and T. M. Duman, "Unsourced Random Access Using ODMA and Polar Codes," *IEEE Wireless Commun. Lett.*, 2024.

UMAC: Emerging Architectures

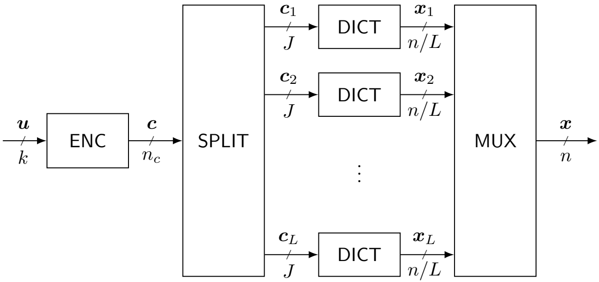
Preamble-based: Gaussian MAC



UMAC: Emerging Architectures

Coded Compressed Sensing

- **Principle:** Divide&conquer approach to CS by transmitting message sub-blocks over parallel UMAC channels
- **Ingredients:** CS-based detection for each sub-block, codes for the A-channel (tree codes)

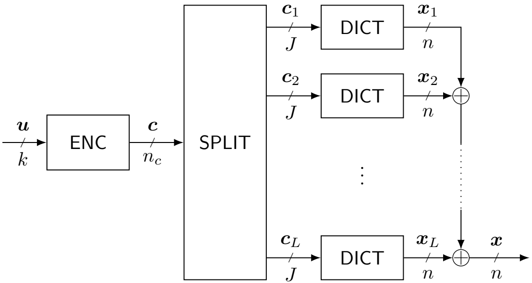


- V. K. Amalladinne, J.-F. Chamberland, and K. R. Narayanan, "A coded compressed sensing scheme for unsourced multiple access," *IEEE Trans. Inf. Theory*, 2020.
- R. Calderbank and A. Thompson, "CHIRRUP: a practical algorithm for unsourced multiple access," *Information and Inference: A Journal of the IMA*, 2019.
- A. Fengler, P. Jung, and G. Caire, "SPARCs for unsourced random access," *IEEE Trans. Inf. Theory*, 2021.
- J. R. Ebert, V. K. Amalladinne, J.-F. Chamberland, and K. R. Narayanan, "A hybrid approach to coded compressed sensing where coupling takes place via the outer code," in *Proc. IEEE Int. Conf. Acoustics, Speech and Signal Processing*, 2021.
- V. K. Amalladinne, A. K. Pradhan, C. Rush, J.-F. Chamberland, and K. R. Narayanan, "Unsourced random access with coded compressed sensing: Integrating AMP and belief propagation," *IEEE Trans. Inf. Theory*, 2021.
- J. R. Ebert, V. K. Amalladinne, S. Rini, J.-F. Chamberland, and K. R. Narayanan, "Coded Demixing for Unsourced Random Access," *IEEE Trans. Signal Process.*, Jun. 2022.
- P. Agostini, Z. Utkovski, and S. Stanczak, "BiSPARCs for Unsourced Random Access in Massive MIMO," *arXiv*, 2023.

UMAC: Emerging Architectures

Coded Compressed Sensing

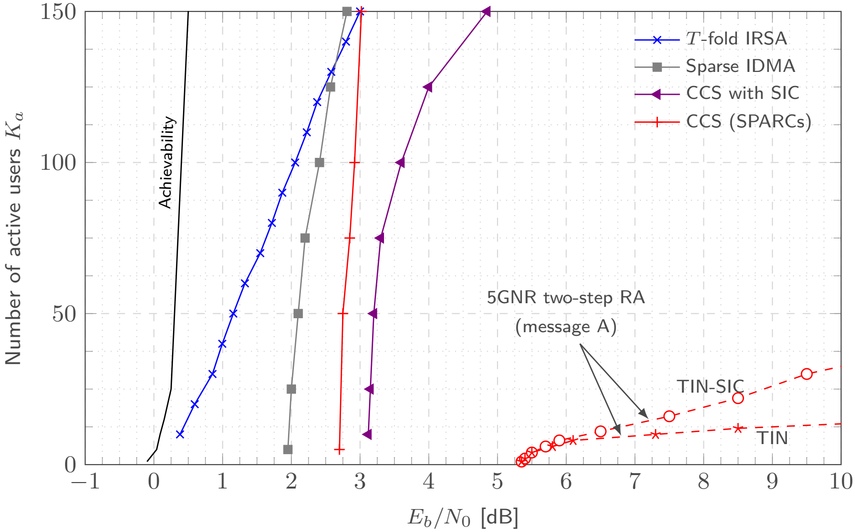
- **Principle:** Divide&conquer approach to CS by transmitting message sub-blocks over parallel UMAC channels
- **Ingredients:** CS-based detection for each sub-block, codes for the A-channel (tree codes)



- V. K. Amalladinne, J.-F. Chamberland, and K. R. Narayanan, “A coded compressed sensing scheme for unsourced multiple access,” *IEEE Trans. Inf. Theory*, 2020.
- R. Calderbank and A. Thompson, “CHIRRUP: a practical algorithm for unsourced multiple access,” *Information and Inference: A Journal of the IMA*, 2019.
- A. Fengler, P. Jung, and G. Caire, “SPARCs for unsourced random access,” *IEEE Trans. Inf. Theory*, 2021.
- J. R. Ebert, V. K. Amalladinne, J.-F. Chamberland, and K. R. Narayanan, “A hybrid approach to coded compressed sensing where coupling takes place via the outer code,” in *Proc. IEEE Int. Conf. Acoustics, Speech and Signal Processing*, 2021.
- V. K. Amalladinne, A. K. Pradhan, C. Rush, J.-F. Chamberland, and K. R. Narayanan, “Unsourced random access with coded compressed sensing: Integrating AMP and belief propagation,” *IEEE Trans. Inf. Theory*, 2021.
- J. R. Ebert, V. K. Amalladinne, S. Rini, J.-F. Chamberland, and K. R. Narayanan, “Coded Demixing for Unsourced Random Access,” *IEEE Trans. Signal Process.*, Jun. 2022.
- P. Agostini, Z. Utkovski, and S. Stanczak, “BiSPARCs for Unsourced Random Access in Massive MIMO,” *arXiv*, 2023.

UMAC: Emerging Architectures

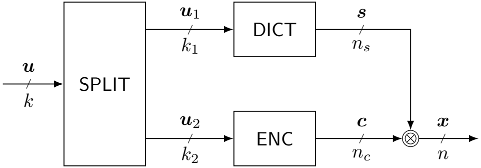
Coded Compressed Sensing: Gaussian MAC



UMAC: Emerging Architectures

Spreading-based

- **Principle:** Simplify user separation by means of information-dependent spreading
- **Ingredients:** CDMA toolbox, joint decoding or SIC, properties of rank-1 tensor decomposition

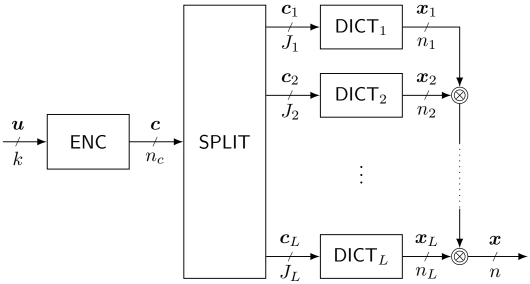


- A. K. Pradhan, V. K. Amalladinne, K. R. Narayanan, and J.-F. Chamberland, “Polar coding and random spreading for unsourced multiple access,” in *Proc. IEEE Int. Conf. Commun.*, 2020.
- A. Decurninge, I. Land, and M. Guillaud, “Tensor-Based Modulation for Unsourced Massive Random Access,” *IEEE Wireless Commun. Lett.*, 2021.
- Z. Han, X. Yuan, C. Xu, S. Jiang, and X. Wang, “Sparse Kronecker-Product Coding for Unsourced Multiple Access,” *IEEE Wireless Commun. Lett.*, 2021.
- M. Gkagkos, K. R. Narayanan, J.-F. Chamberland, and C. N. Georghiades, “FASURA: A Scheme for Quasi-Static Fading Unsourced Random Access Channels,” *IEEE Trans. Commun.*, 2023.

UMAC: Emerging Architectures

Spreading-based

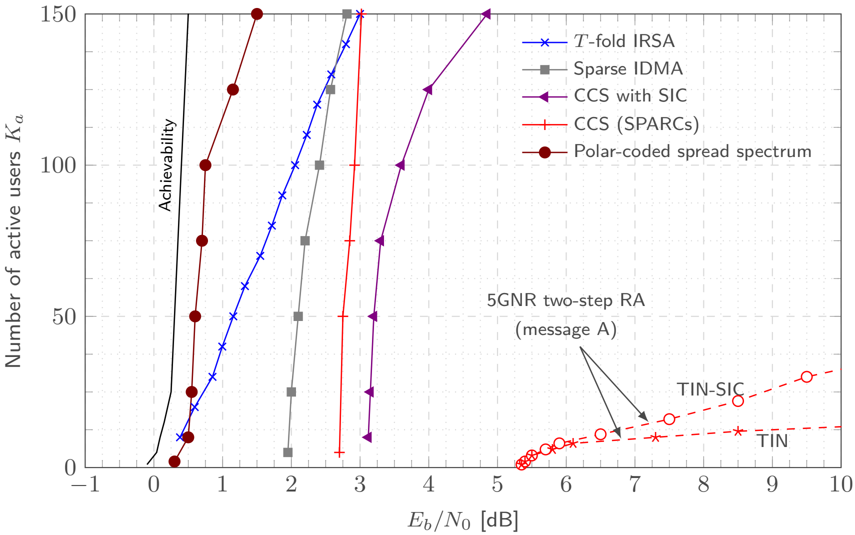
- **Principle:** Simplify user separation by means of information-dependent spreading
- **Ingredients:** CDMA toolbox, joint decoding or SIC, properties of rank-1 tensor decomposition



- A. K. Pradhan, V. K. Amalladinne, K. R. Narayanan, and J.-F. Chamberland, “Polar coding and random spreading for unsourced multiple access,” in *Proc. IEEE Int. Conf. Commun.*, 2020.
- A. Decurninge, I. Land, and M. Guillaud, “Tensor-Based Modulation for Unsourced Massive Random Access,” *IEEE Wireless Commun. Lett.*, 2021.
- Z. Han, X. Yuan, C. Xu, S. Jiang, and X. Wang, “Sparse Kronecker-Product Coding for Unsourced Multiple Access,” *IEEE Wireless Commun. Lett.*, 2021.
- M. Gkagkos, K. R. Narayanan, J.-F. Chamberland, and C. N. Georghiades, “FASURA: A Scheme for Quasi-Static Fading Unsourced Random Access Channels,” *IEEE Trans. Commun.*, 2023.

UMAC: Emerging Architectures

Spreading-based: Gaussian MAC

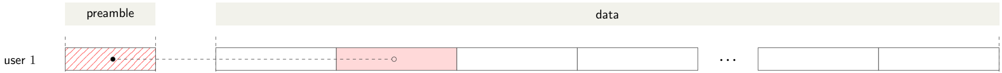


Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

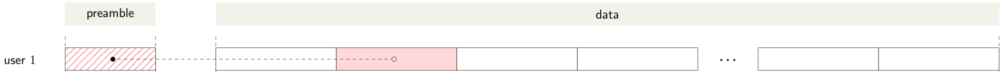
Grant-Free Access for 6G

- 5GNR two-step random access **not suitable** for massive user connectivity
- Several architectures can give **outstanding gains** over two-step random access



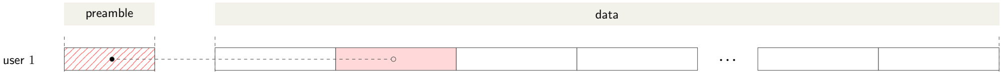
Grant-Free Access for 6G

- 5GNR two-step random access **not suitable** for massive user connectivity
- Several architectures can give **outstanding gains** over two-step random access
- To ease the adoption of advanced UMAC schemes, build on the existing two-step random access framework



Grant-Free Access for 6G

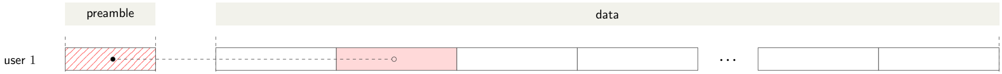
- 5GNR two-step random access **not suitable** for massive user connectivity
- Several architectures can give **outstanding gains** over two-step random access
- To ease the adoption of advanced UMAC schemes, build on the existing two-step random access framework
- **First step:** dissect two-step random access, and identify the factors that limit its performance



Two-Step Random Access

UMAC Viewpoint

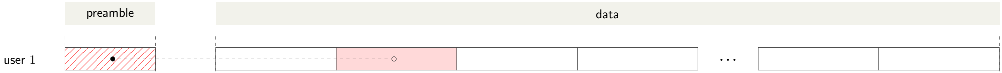
- 5GNR two-step random access: **hybrid slotted Aloha + preamble-based architecture**
- **Preambles are not required by slotted Aloha!**



Two-Step Random Access

UMAC Viewpoint

- 5GNR two-step random access: **hybrid slotted Aloha + preamble-based architecture**
- **Preambles are not required by slotted Aloha!**
- Preambles imply energy overhead...

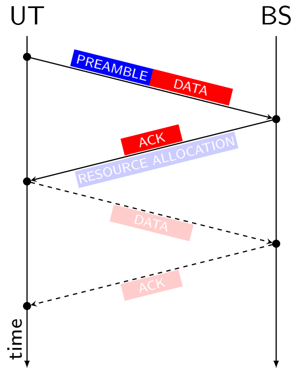


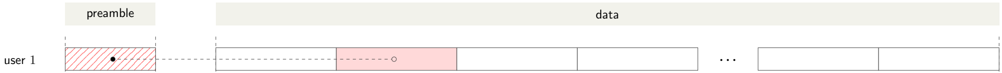
Two-Step Random Access

UMAC Viewpoint

- 5GNR two-step random access: **hybrid slotted Aloha + preamble-based architecture**
- **Preambles are not required by slotted Aloha!**
- Preambles imply energy overhead…

  …but they allow to resume the legacy four-step random access procedure

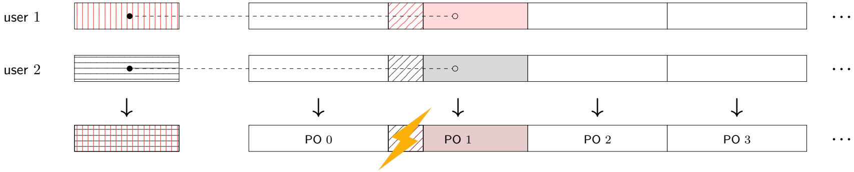




Two-Step Random Access

UMAC Viewpoint

- 64 preambles limit the performance of two-step random access
  - Only 64 *access patterns* (slots)
  - MPR hindered by channel estimation: users transmitting in the same slot with the same pilot sequence...

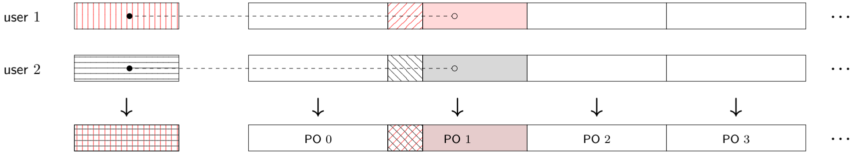


Two-Step Random Access

UMAC Viewpoint

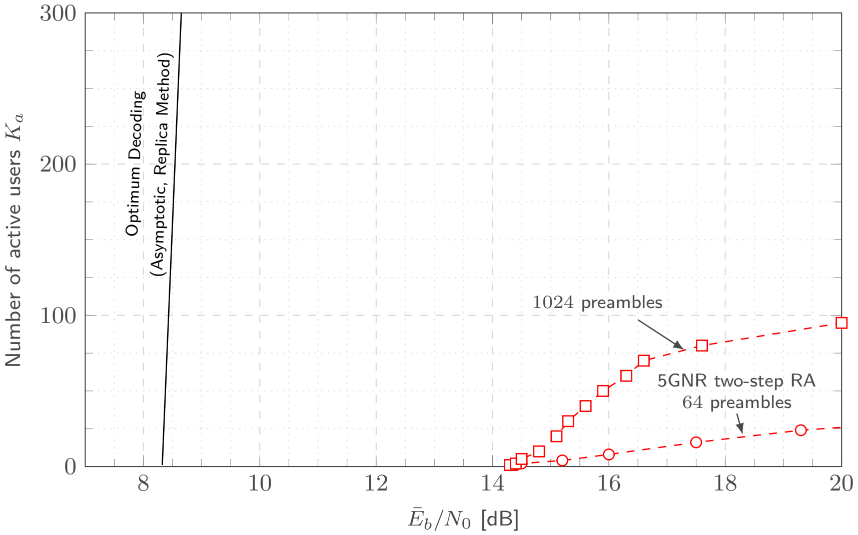
- 64 preambles limit the performance of two-step random access
  - ☐ Only 64 *access patterns* (slots)
  - ☐ MPR hindered by channel estimation: users transmitting in the same slot with the same pilot sequence...
- Possible fix: enlarge the preamble set
  - ☐ Subsets of preambles point to the same slot...

    ... but to different pilot sequences



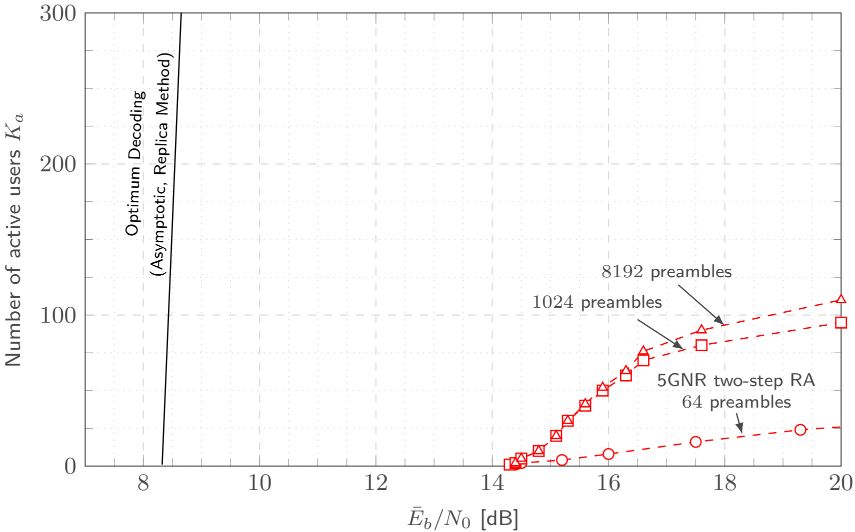
Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

Effect of Larger Preamble Sets (64 Slots)



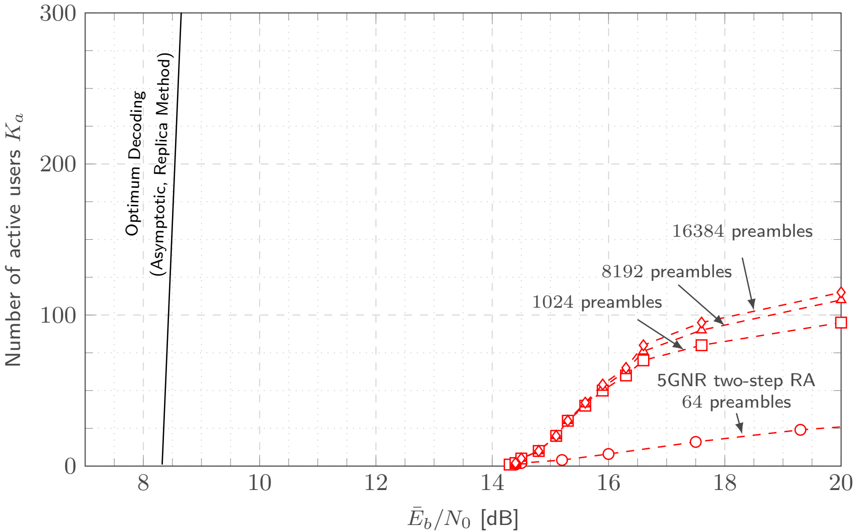
Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

Effect of Larger Preamble Sets (64 Slots)



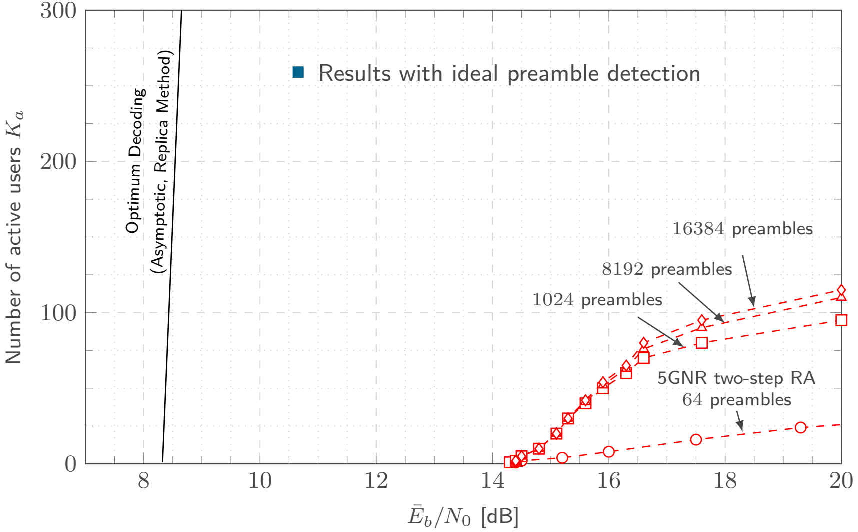
Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

Effect of Larger Preamble Sets (64 Slots)



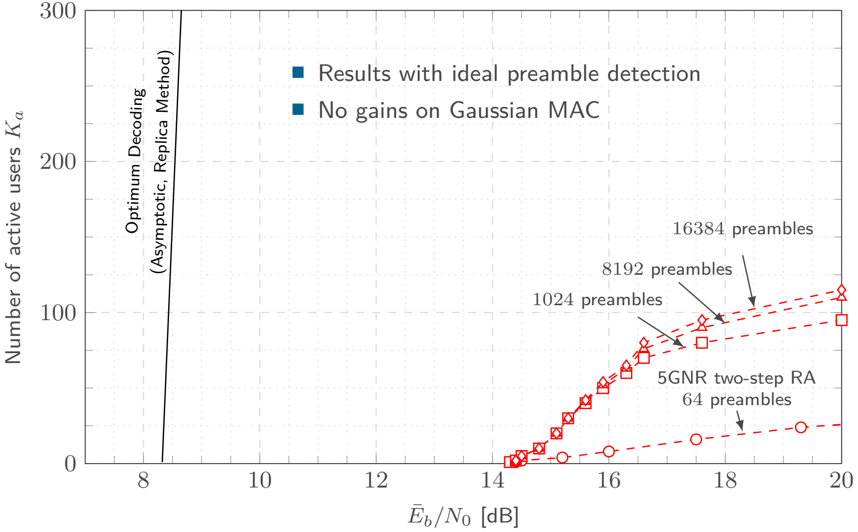
Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

Effect of Larger Preamble Sets (64 Slots)



Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

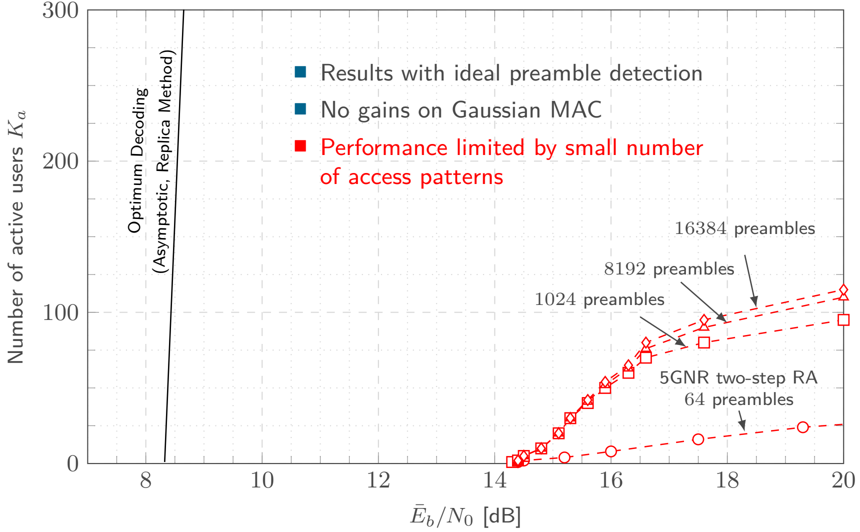
Effect of Larger Preamble Sets (64 Slots)



- ■ Results with ideal preamble detection
- ■ No gains on Gaussian MAC

Two-Step Random Access: Quasi-Static Rayleigh Fading MAC

Effect of Larger Preamble Sets (64 Slots)



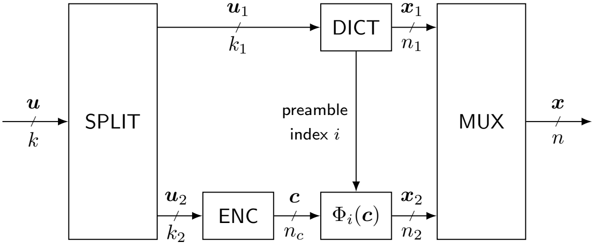
- Results with ideal preamble detection
- No gains on Gaussian MAC
- Performance limited by small number of access patterns

Embracing Preamble-based Architectures

- **Two-step random access:** Performance limited by the size of the preamble set and by the limited number of access patterns
- With a larger preamble set, we may increase the number of access patterns
  - Keep a slotted structure (facilitates channel estimation)
  - Keep the overall number of resources (total number or channel uses) unmodified

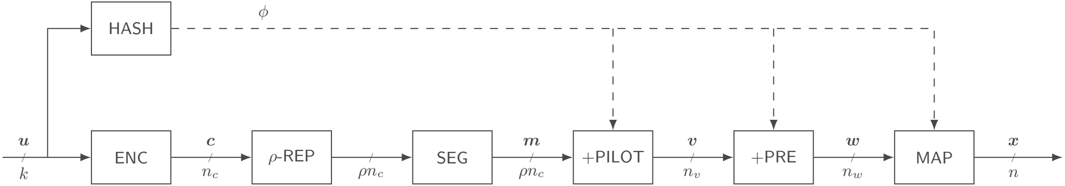
Embracing Preamble-based Architectures

- **Two-step random access:** Performance limited by the size of the preamble set and by the limited number of access patterns
- With a larger preamble set, we may increase the number of access patterns
  - ☐ Keep a slotted structure (facilitates channel estimation)
  - ☐ Keep the overall number of resources (total number or channel uses) unmodified
- **Inspired by the sparse IDMA construction**[*]: *sparse block IDMA*

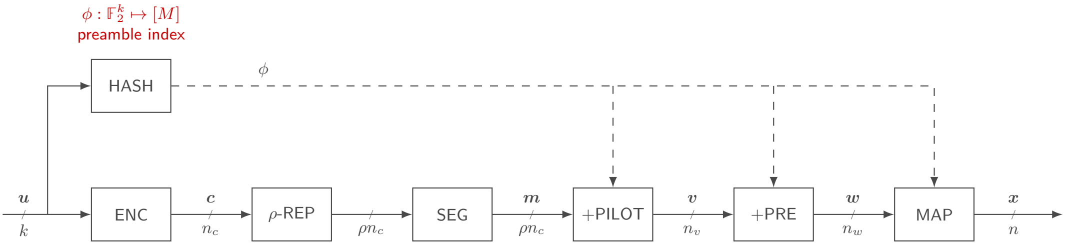


[*] A. K. Pradhan, V. K. Amalladinne, A. Vem, K. R. Narayanan, and J.-F. Chamberland, "Sparse IDMA: A Joint Graph-Based Coding Scheme for Unsourced Random Access," *IEEE TCOM*, 2022.

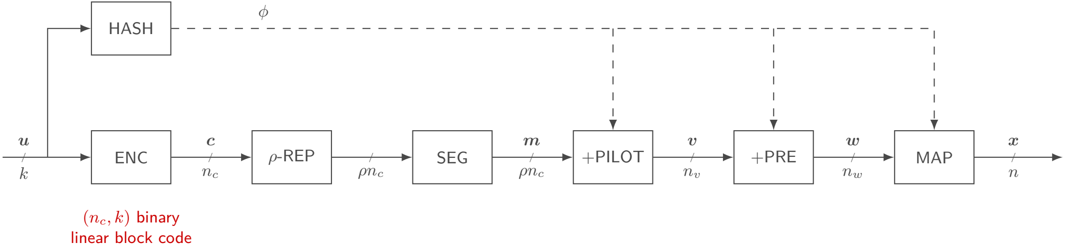
Sparse Block IDMA: Transmitter



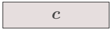
Sparse Block IDMA: Transmitter



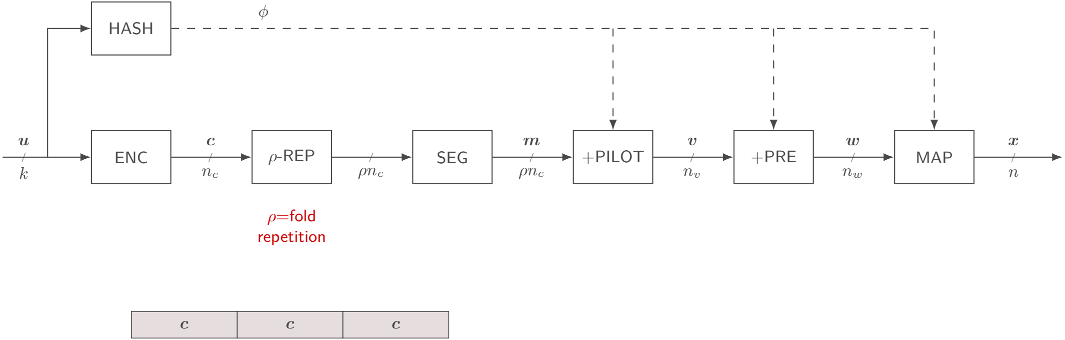
Sparse Block IDMA: Transmitter



(n_c, k) binary linear block code

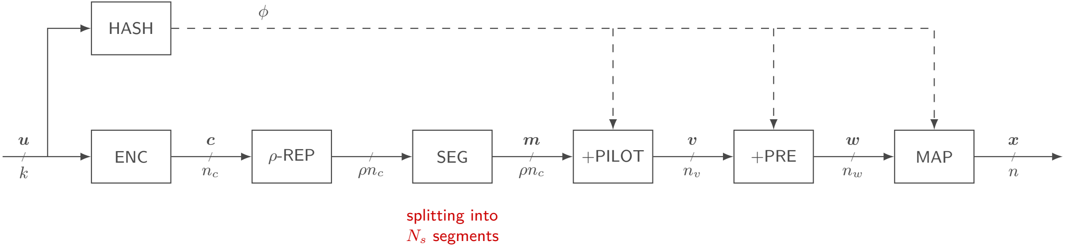


Sparse Block IDMA: Transmitter

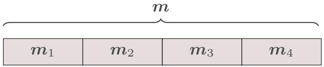


ρ=fold repetition

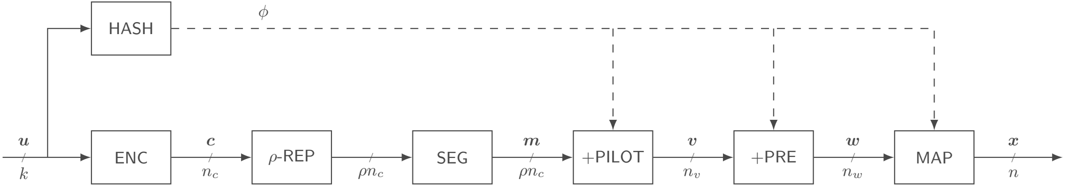
Sparse Block IDMA: Transmitter



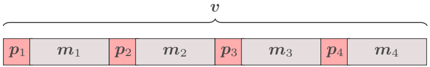
splitting into N_s segments



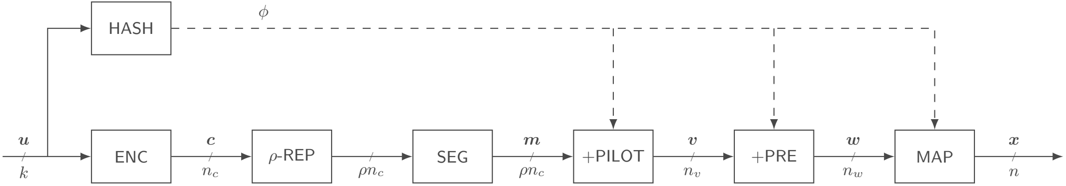
Sparse Block IDMA: Transmitter



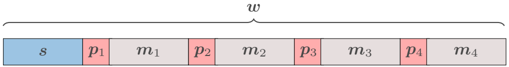
pilots insertion



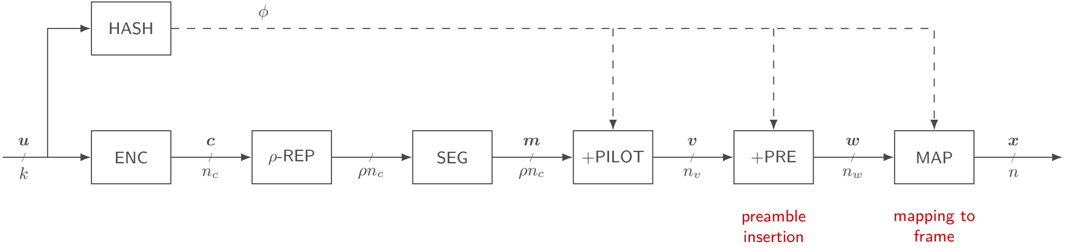
Sparse Block IDMA: Transmitter



preamble
insertion

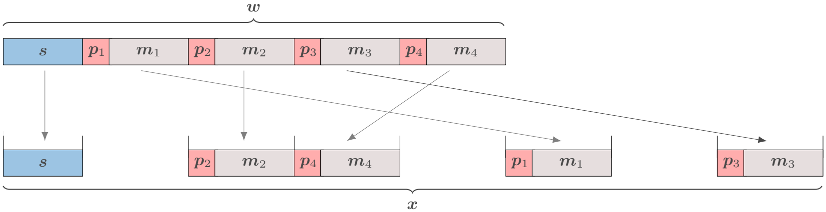


Sparse Block IDMA: Transmitter

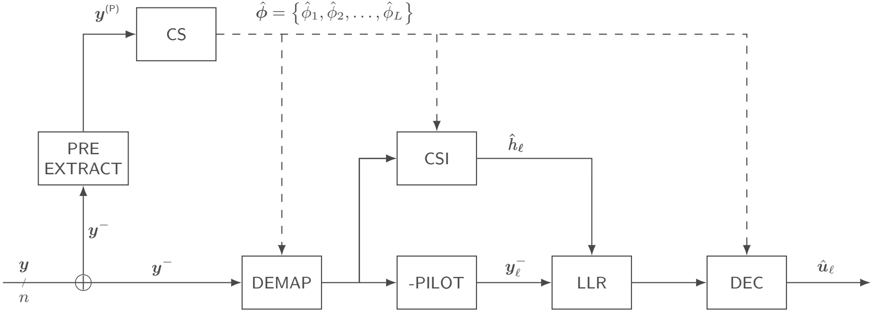


preamble insertion

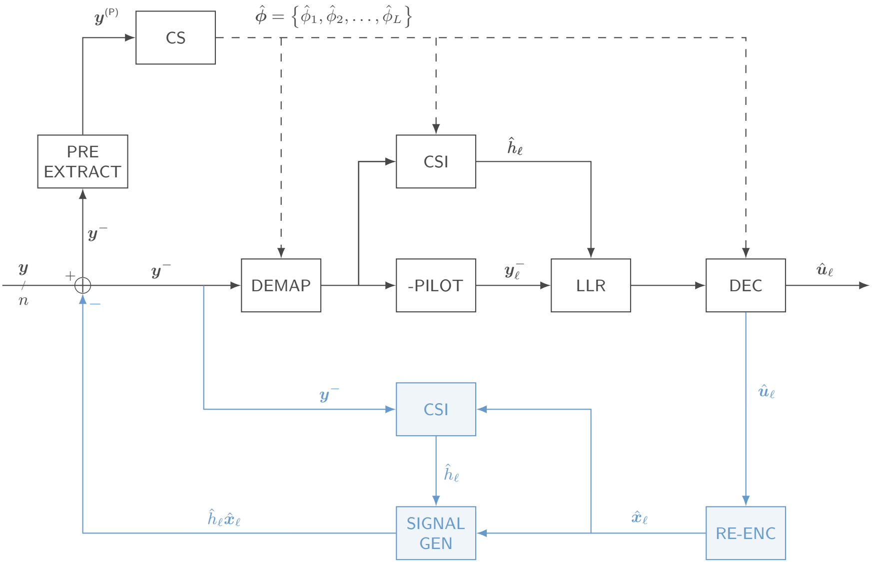
mapping to frame



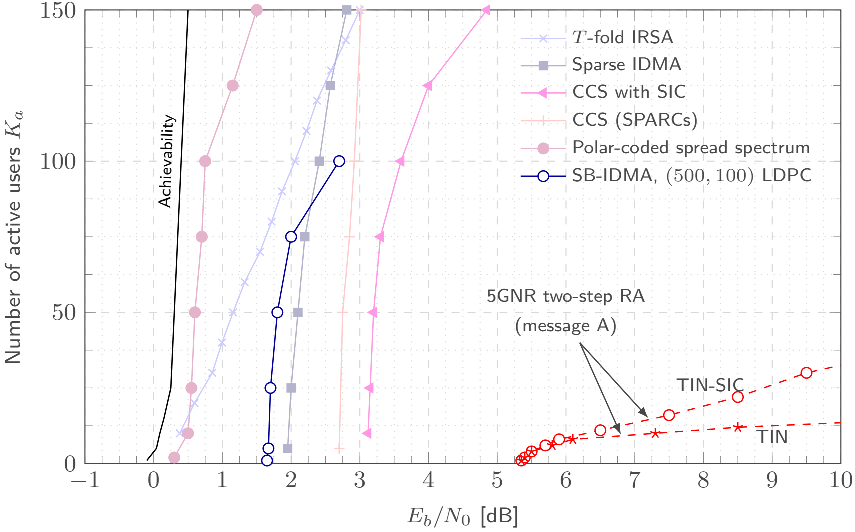
Sparse Block IDMA: Receiver



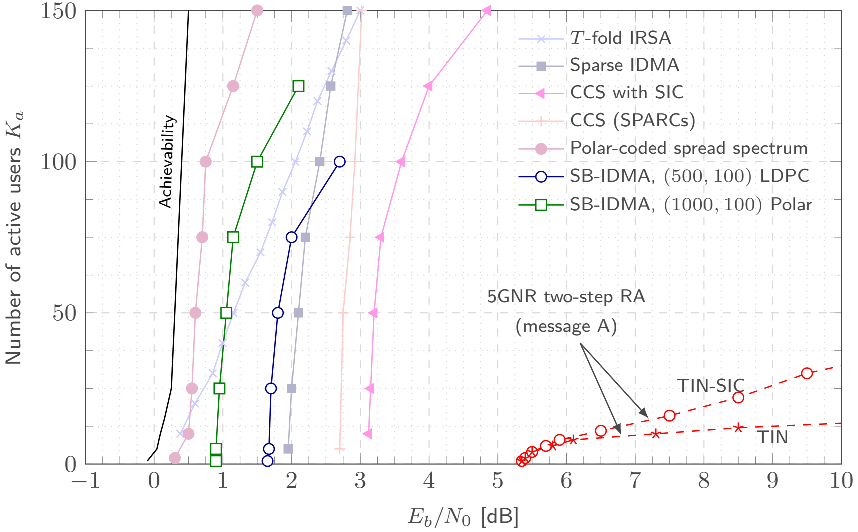
Sparse Block IDMA: Receiver



Sparse Block IDMA: Gaussian MAC

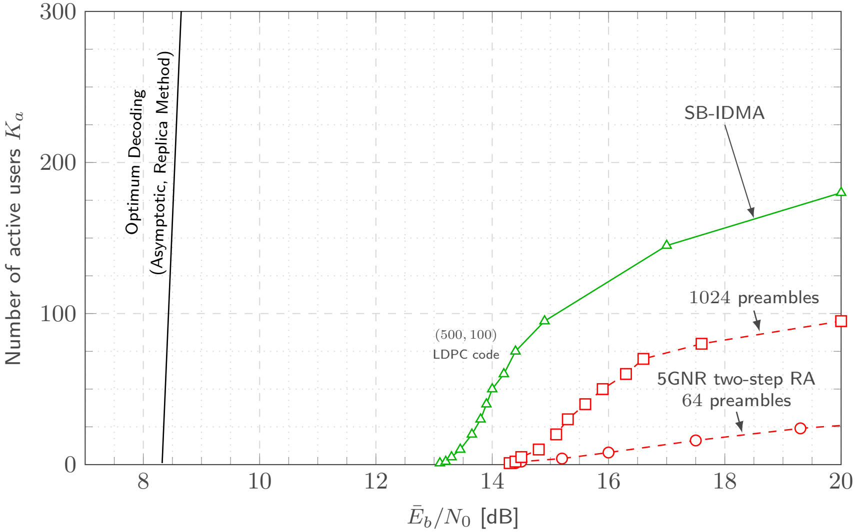


Sparse Block IDMA: Gaussian MAC



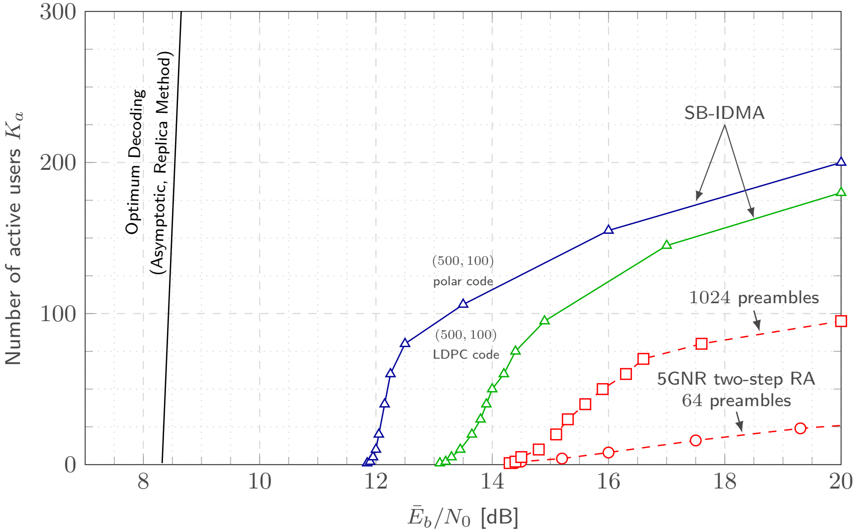
Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Single Antenna



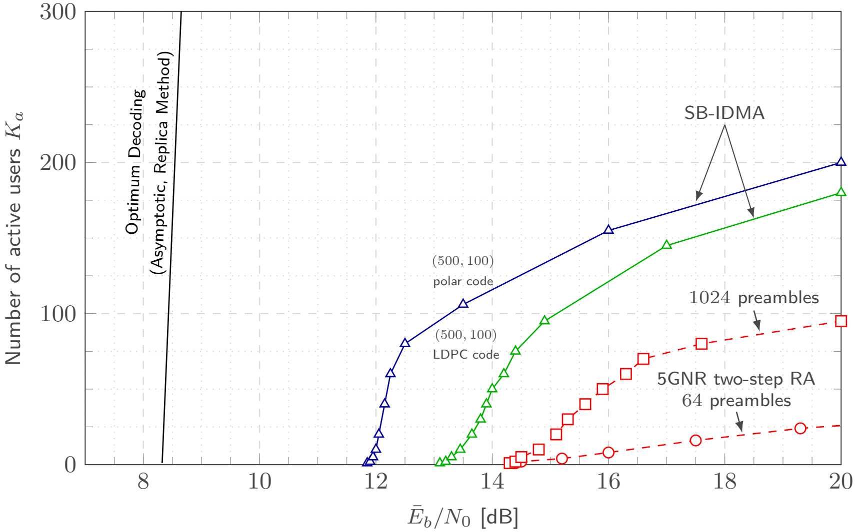
Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Single Antenna



Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

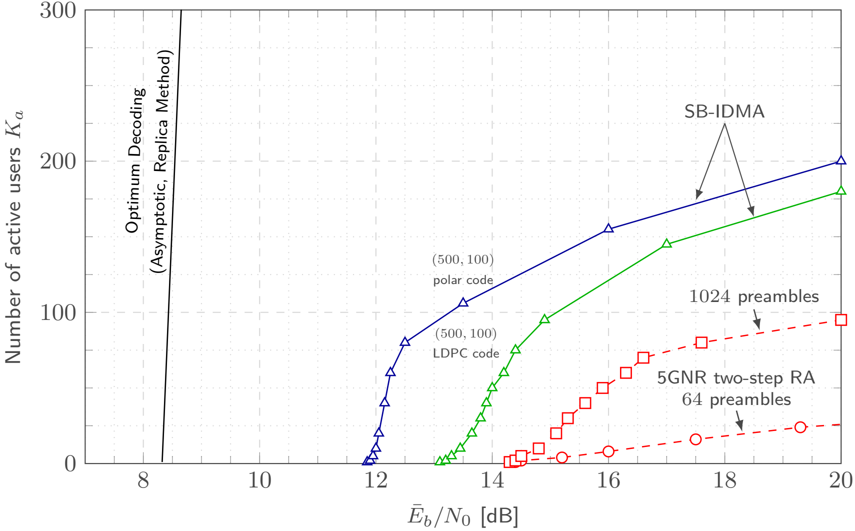
64 Slots, Single Antenna



saturation due to
number of preambles
(channel estimation)

Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Single Antenna

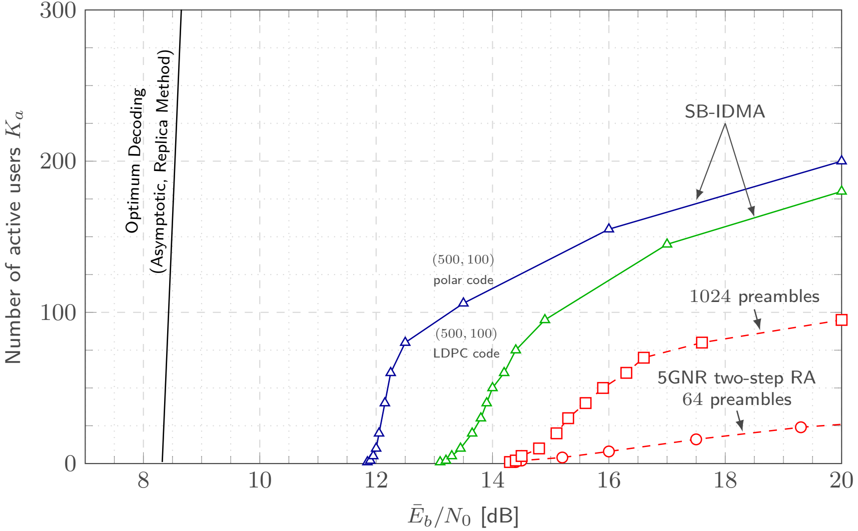


saturation due to number of access patterns

saturation due to number of preambles (channel estimation)

Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Single Antenna



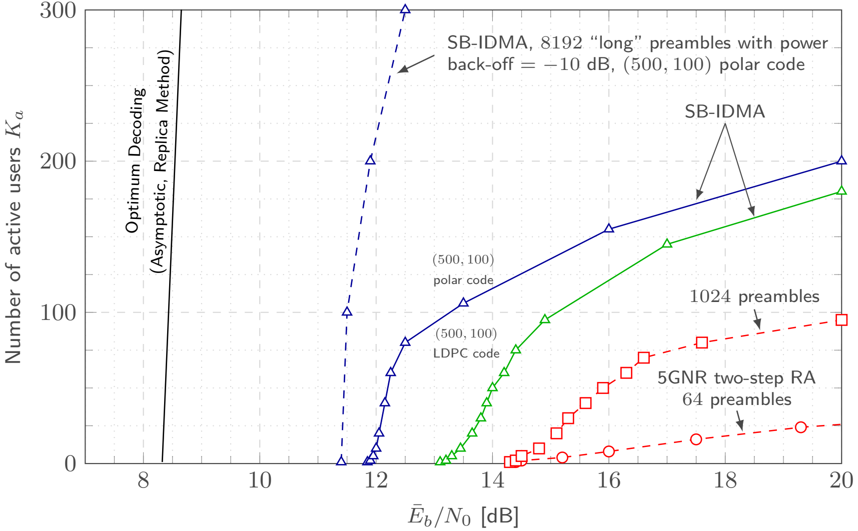
saturation due to preamble miss-detection rate

saturation due to number of access patterns

saturation due to number of preambles (channel estimation)

Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Single Antenna



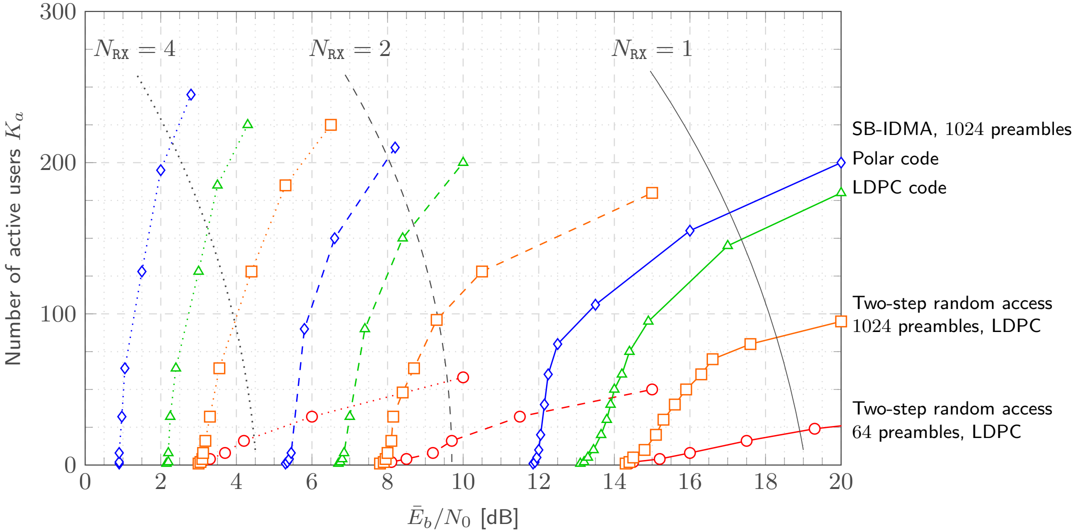
saturation due to preamble miss-detection rate

saturation due to number of access patterns

saturation due to number of preambles (channel estimation)

Sparse Block IDMA: Quasi-Static Rayleigh Fading MAC

64 Slots, Multiple Antennas

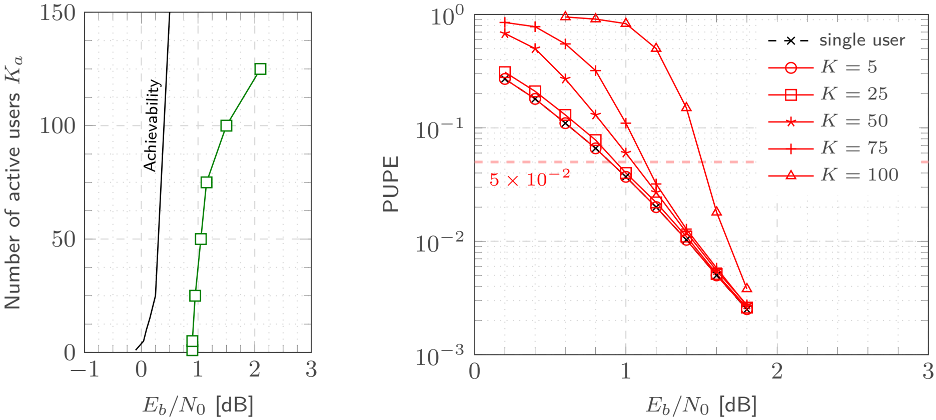


Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

Sparse Block IDMA: Analysis

- At moderate loads, adding users leads to a negligible SNR penalty
- Phenomenon that is quite common in multiuser systems*



---

* S. S. Kowshik and Y. Polyanskiy, "Fundamental Limits of Many-User MAC With Finite Payloads and Fading," *IEEE T-IT*, 2021.

Sparse Block IDMA: Analysis

- At moderate loads, adding users leads to a negligible SNR penalty
- Phenomenon that is quite common in multiuser systems*

> *"optimal multiple-access architectures should be able to almost perfectly cancel all multi-user interference, achieving an essentially single-user performance for each user, provided the user density is below a critical threshold"*

---

* S. S. Kowshik and Y. Polyanskiy, "Fundamental Limits of Many-User MAC With Finite Payloads and Fading," *IEEE T-IT*, 2021.

Sparse Block IDMA: Analysis

- **Objective:** Qualitative analysis of Sparse Block IDMA under iterative TIN-SIC
- **Setting:**
  - ☐ Genie-aided preamble detection
  - ☐ Ideal interference cancellation
  - ☐ Ideal error detection at the decoder
  - ☐ Asymptotic regime with $K_a = \mu n$, $n \to \infty$

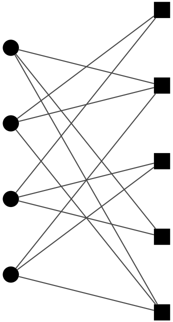
    $$\mu := \text{user density}$$

    with fixed (n_c, k) code parameters, fixed repetition rate ρ, and fixed number of segments N_s
  - ☐ *Extrinsic* interference cancellation
  - ☐ (n_c, k) random codes

Sparse Block IDMA: Analysis

Asymptotic Regime

- With fixed (n_c, k) code parameters, fixed repetition rate ρ, and fixed number of segments N_s, we can represent the collision pattern over the frame via a bipartite graph



$K_a = \mu n$

user nodes (UNs)

$N = n\frac{N_s}{\rho n_c}$

slot nodes (SNs)

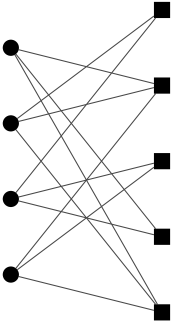
- User node degree $d_u = N_s$
- Slot node degree $\sim \mathrm{Poisson}(d_s)$ with

$$d_s = \frac{\mu \rho n_c}{N_s}$$

Sparse Block IDMA: Analysis

Asymptotic Regime

- With fixed (n_c, k) code parameters, fixed repetition rate ρ, and fixed number of segments N_s, we can represent the collision pattern over the frame via a bipartite graph



$K_a = \mu n$

user nodes (UNs)

$N = n\frac{N_s}{\rho n_c}$

slot nodes (SNs)

Sparse graph: tree-like neighborhood as $n \to \infty$

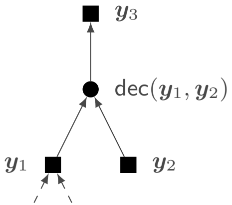
- User node degree $d_u = N_s$
- Slot node degree $\sim \mathrm{Poisson}(d_s)$ with

$$d_s = \frac{\mu\rho n_c}{N_s}$$

Sparse Block IDMA: Analysis

Extrinsic Interference Cancellation

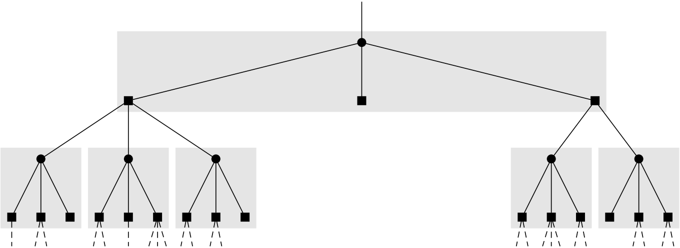
- In a given slot, decoding of a user message is performed by ignoring the specific slot observation



- Interference cancellation as a peeling process over the graph

Sparse Block IDMA: Analysis
Density Evolution

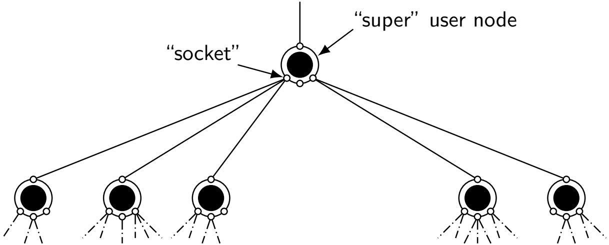
- Track the probability that a segment is decoded at the output of each user node
- Averaging over the number of collisions affecting the leaf slot nodes requires a depth-2 exploration of the graph



Sparse Block IDMA: Analysis

Density Evolution

- Equivalent graphical description:



- One super user node (SUN) for each UN
- SUNs have d_u sockets — one for each SN connected to the associated UN
- Degree of a socket: number of edges connected to it
  (= number of interfering users in the slot)

Sparse Block IDMA: Analysis

Density Evolution

- Denote by ϵ_ℓ the probability that the decoding of a segment fails at depth-ℓ
- Moreover, let $\mathbf{D} = (\mathsf{D}_1, \mathsf{D}_2, \dots)$ be the socket degrees

$$\mathsf{D}_i \text{ are i.i.d. } \mathrm{Poisson}(d_s)$$

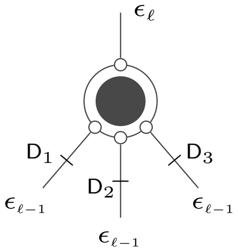
- Denote by $\mathbf{G} = (\mathsf{G}_1, \mathsf{G}_2, \dots)$ the residual socket degrees after interference cancellation

$$\mathsf{G}_i \text{ are i.i.d. } \mathrm{Poisson}((1-\epsilon)d_s)$$

- We are interested in the transfer function

$$\begin{aligned}\epsilon_\ell &= f\left(\epsilon_{\ell-1}\right)\\ &= \mathsf{E}\left[\varphi\left(\mathbf{G}\right)\right]\end{aligned}$$

where $\varphi\left(\mathbf{G}\right) := \mathbb{P}[\text{dec fails}|\mathbf{G}]$

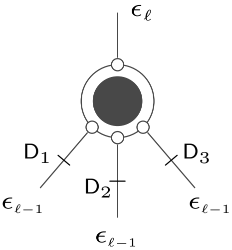


Sparse Block IDMA: Analysis
Density Evolution

- To compute $\varphi(\mathbf{G}) = \mathbb{P}[\text{dec fails}|\mathbf{G}]$ we assume each user equipped with a random Gaussian codebook
- Model the UN decoder input as $\boldsymbol{Y} = (\boldsymbol{Y}_1, \boldsymbol{Y}_2, \dots, \boldsymbol{Y}_{d_u})$
  - ☐ $\boldsymbol{Y}_i$ = observation of the ith codeword segment
  - ☐ WLOG, set $\boldsymbol{Y}_{d_u} = \mathbf{0}$ (extrinsic IC)
  - ☐ On the other edges,

$$\boldsymbol{Y}_i = \boldsymbol{X}_i + \boldsymbol{Z}_i$$

where $\boldsymbol{Z}_i$ is the noise+interference contribution whose elements are i.i.d. $\sim \mathcal{CN}(0, 1 + P\mathsf{G}_i)$



Sparse Block IDMA: Analysis

Density Evolution

- Information density (random coding)

$$\mathsf{i}(\boldsymbol{X},\boldsymbol{Y}) = \log_2 \frac{P(\boldsymbol{Y}|\boldsymbol{X})}{P(\boldsymbol{Y})} = \sum_{i=1}^{d_u} \log_2 \frac{P(\boldsymbol{Y}_i|\boldsymbol{X}_i)}{P(\boldsymbol{Y}_i)}$$

with

$$\boldsymbol{Y}_i = \boldsymbol{X}_i + \boldsymbol{Z}_i$$

for $i = 1, 2, \ldots, d_u - 1$ and

$$\boldsymbol{Y}_{d_u} = \boldsymbol{0}$$

- Evaluate $\varphi\left(\mathsf{G}\right)$ as

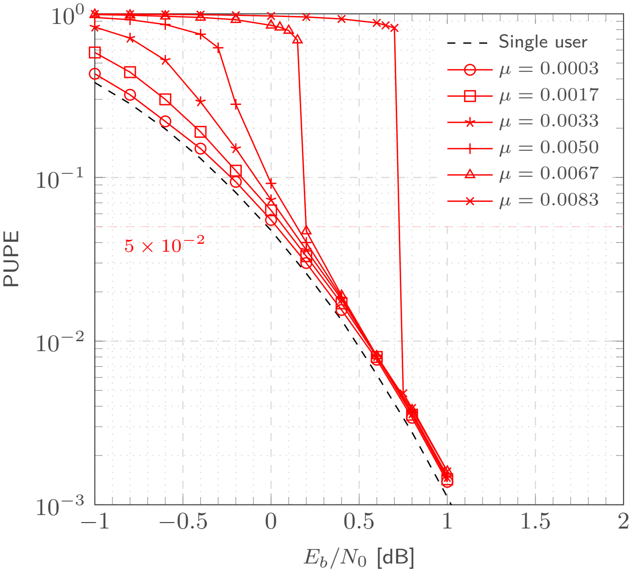
$$\varphi\left(\mathsf{G}\right) \approx \mathsf{E}\left[2^{-[\mathsf{i}(\boldsymbol{X},\boldsymbol{Y})-k]^+} \middle| \mathsf{G} \right]$$

- Averaging over **G** yields

$$f(\epsilon) = \mathsf{E}\left[\varphi\left(\mathsf{G}\right)\right]$$

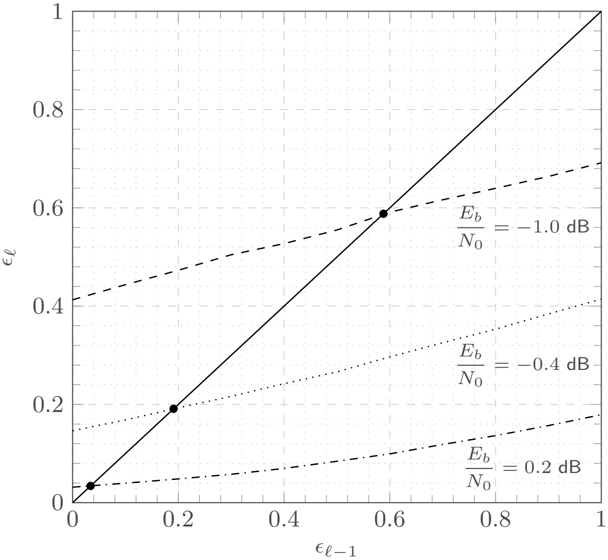
Sparse Block IDMA: Analysis

Density Evolution



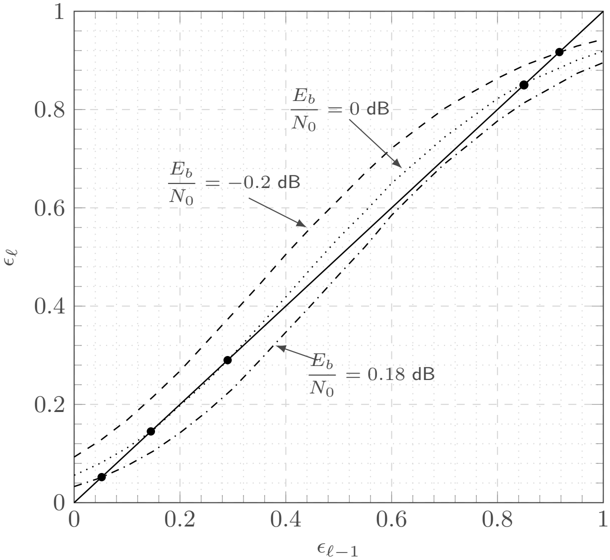
Sparse Block IDMA: Analysis

Density Evolution – $\mu = 0.0017$



Sparse Block IDMA: Analysis

Density Evolution – $\mu = 0.0067$



Outline

- Introduction
- Random Access in 5G-NR
- Architectures for the UMAC
- Grant-Free Access for 6G
- Asymptotic Analysis
- Conclusions

Conclusions

- The upcoming 6G standardization offers a unique opportunity to introduce a **massive grant-free access** mechanism in 3GPP

Conclusions

- The upcoming 6G standardization offers a unique opportunity to introduce a **massive grant-free access** mechanism in 3GPP

- We can leverage on **recent outstanding developments** in the understanding of the random access problem (UMAC)

Conclusions

- The upcoming 6G standardization offers a unique opportunity to introduce a **massive grant-free access** mechanism in 3GPP

- We can leverage on **recent outstanding developments** in the understanding of the random access problem (UMAC)

- It is possible to **build on the existing 5GNR toolbox** (two-step random access), constructing competitive solutions

Thank You!