MODERN RANDOM ACCESS FOR GRANT-FREE CELLULAR NETWORKS

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Indo-French Seminar
"6G Wireless Networks: Challenges and Opportunities »
9-10-11 October 2024

Outline

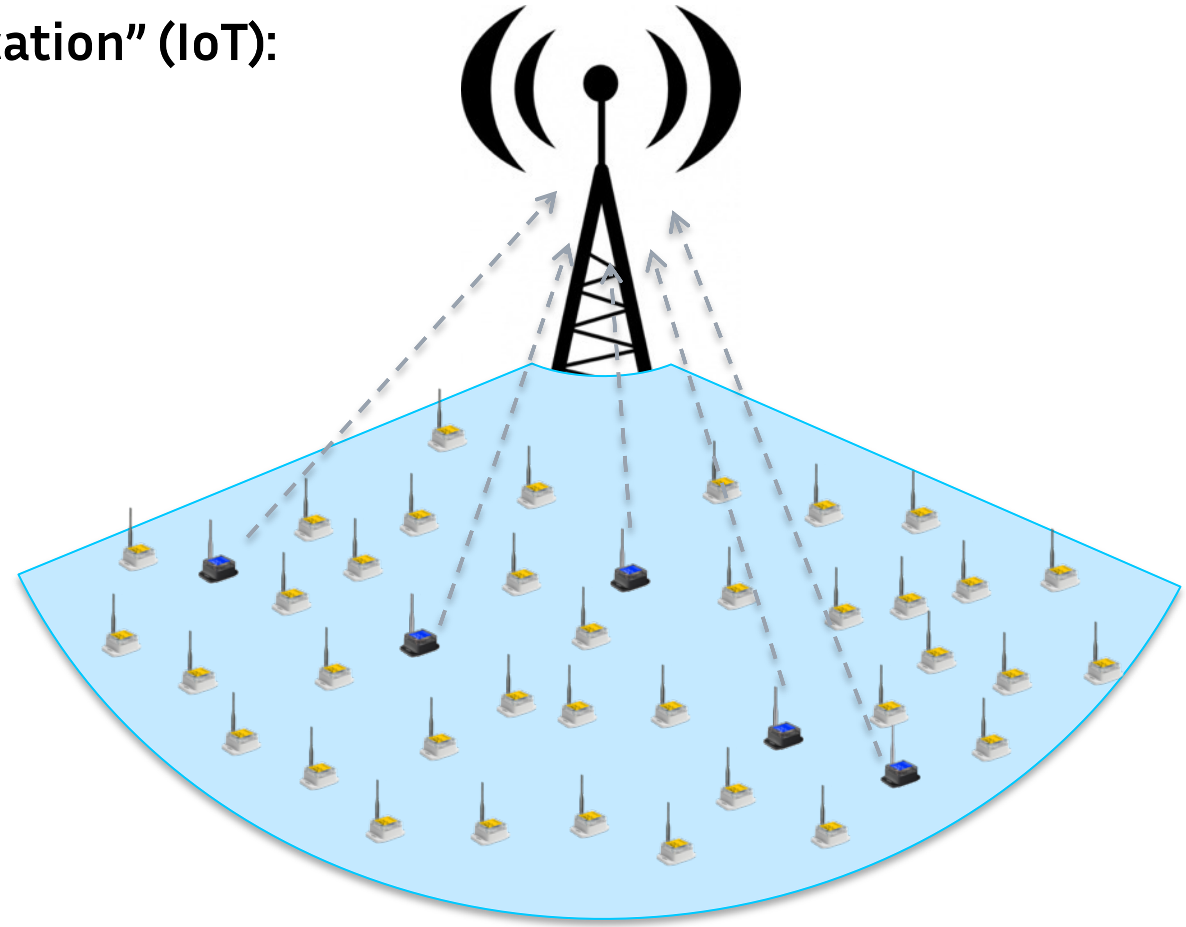
1. Introduction
2. Tutorial: Satellite Communications
   (Towards Modern Random Access)
3. Classical Modern Random Access
   (Irregular Repetition Slotted ALOHA, IRSA)
4. Towards More Realistic IRSA?
5. AI/ML-Aided Modern Random Access (i.e. with DRL)

01
Introduction

Grant-Free Access in Cellular Networks

Massive "Machine Type Communication" (IoT):

- Upstream traffic
- Low volume traffic (1/hour)
- Small packets (10-100 bytes)
- Many devices (~10000[00])
- <u>Uncertainty about transmitters</u>



Grant-Free Access in Cellular Networks

Massive "Machine Type Communication" (IoT):

- Upstream traffic
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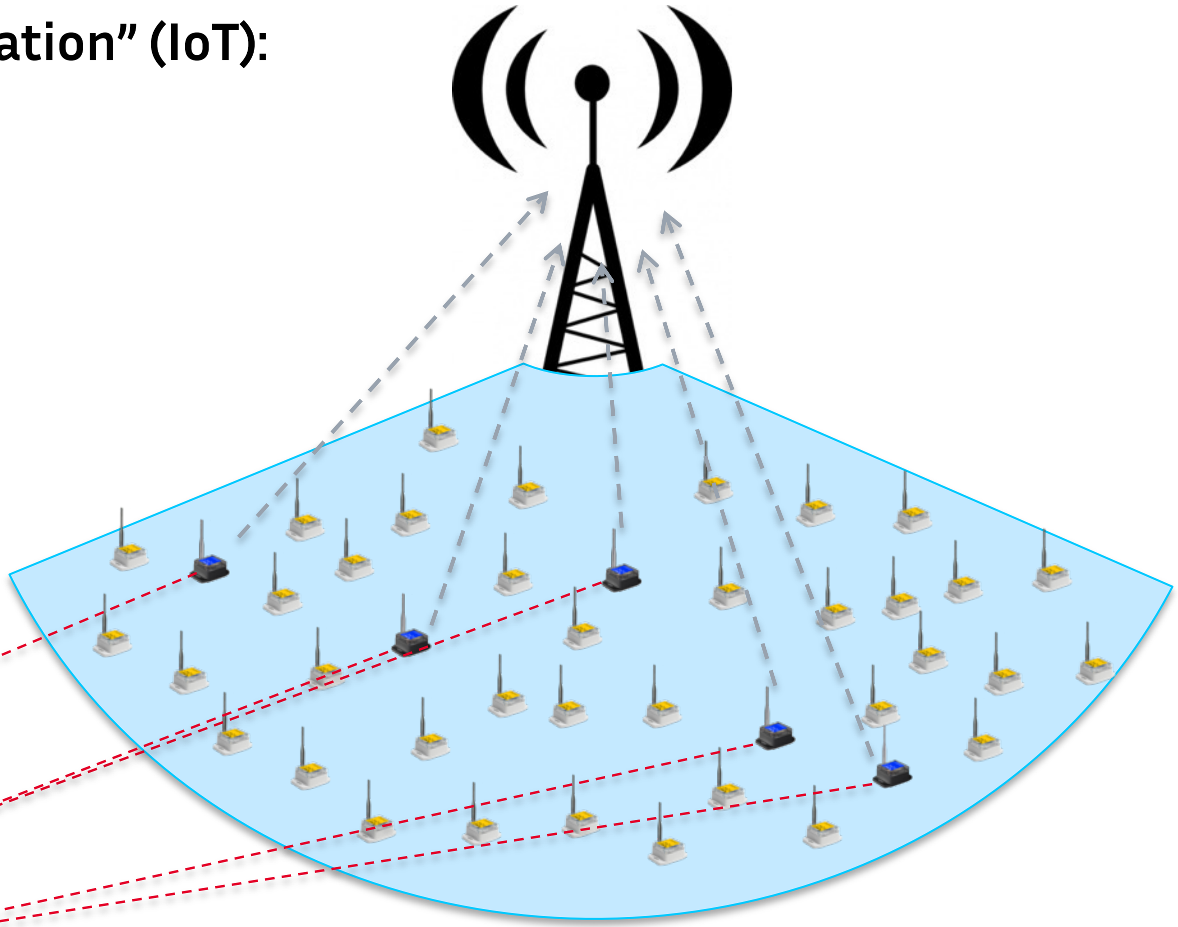
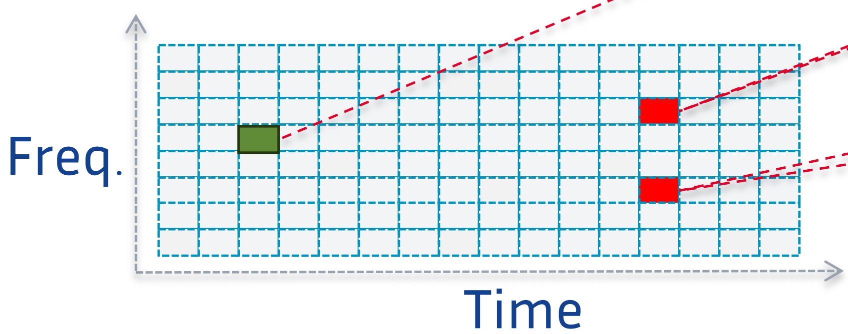
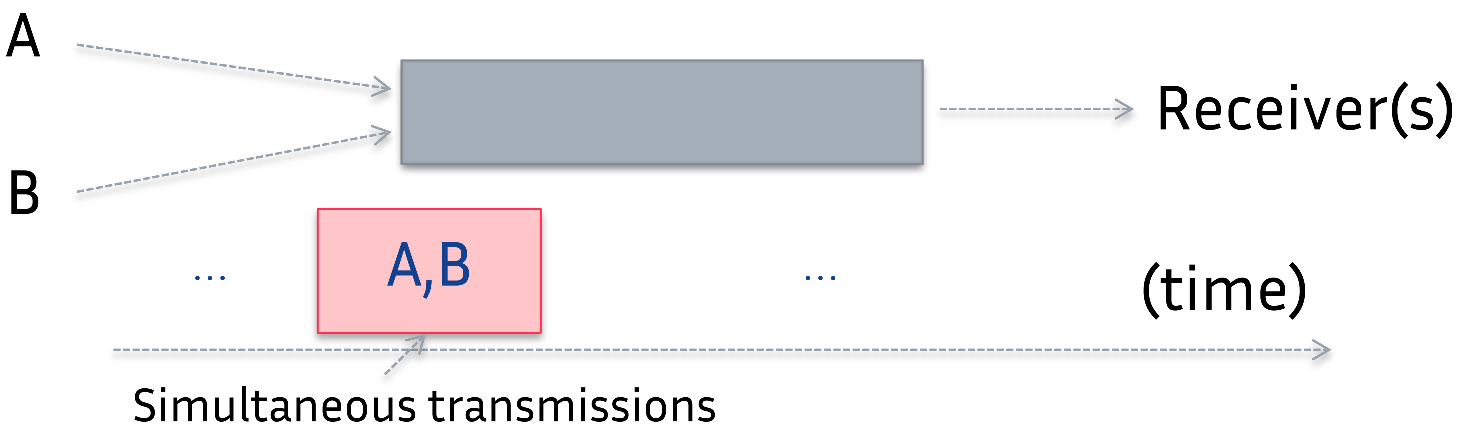
- Non-Orthogonal Multiple Access? (NOMA)

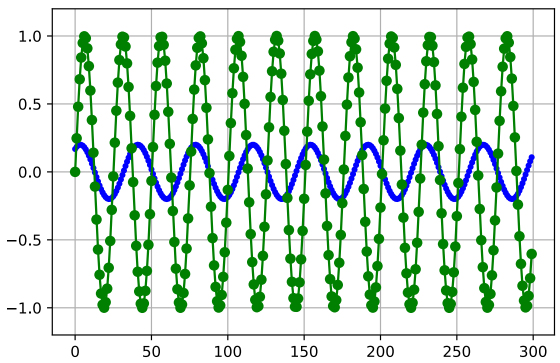




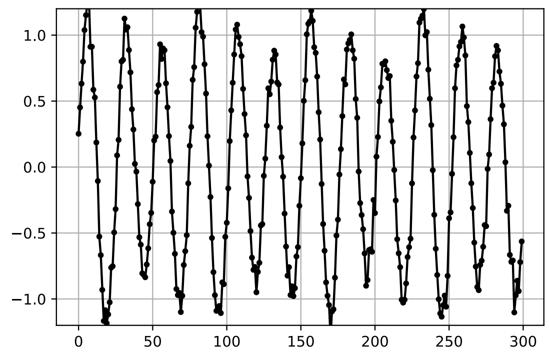
Textbook: MAC (Multiple Access Channel) Classical Theory



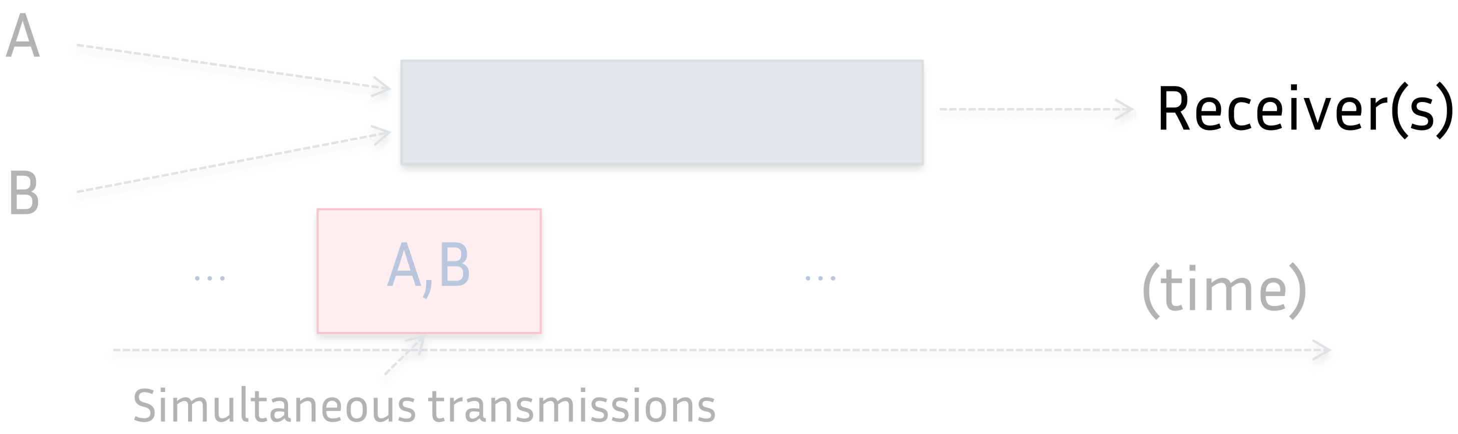
S_A and S_b simultaneous



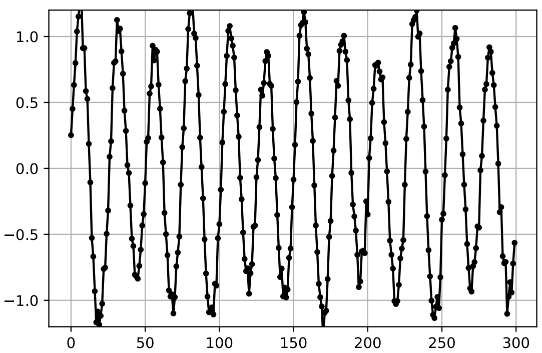
$Y=S_A+S_b+noise$



Textbook: MAC (Multiple Access Channel)
Successive Interference Cancellation

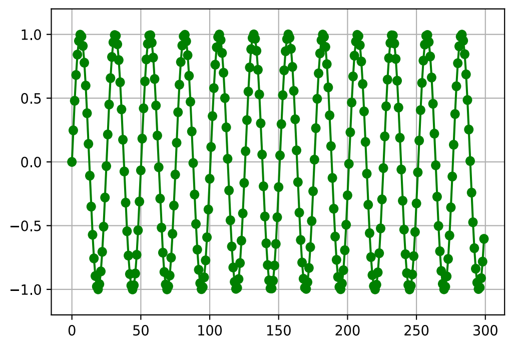


$Y = S_A + S_b + noise$



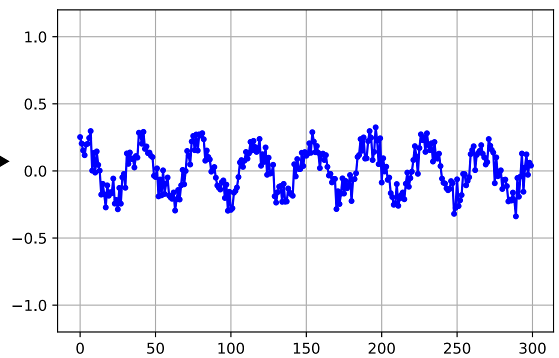
→ Recover message from A →

Reconstructed signal of A



SIC →

S_b [+noise] = $Y - S_A$



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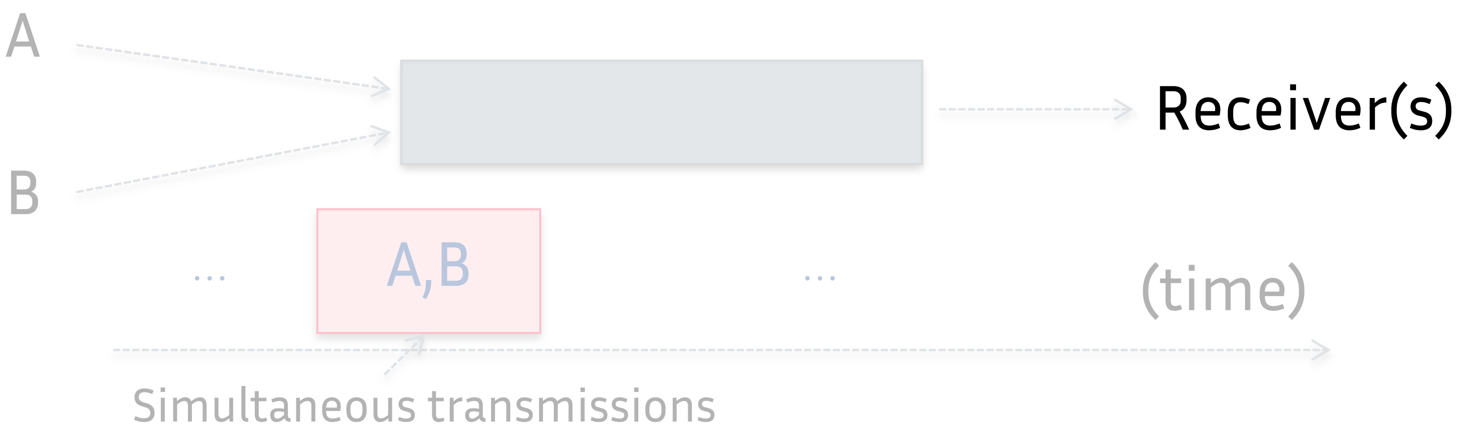
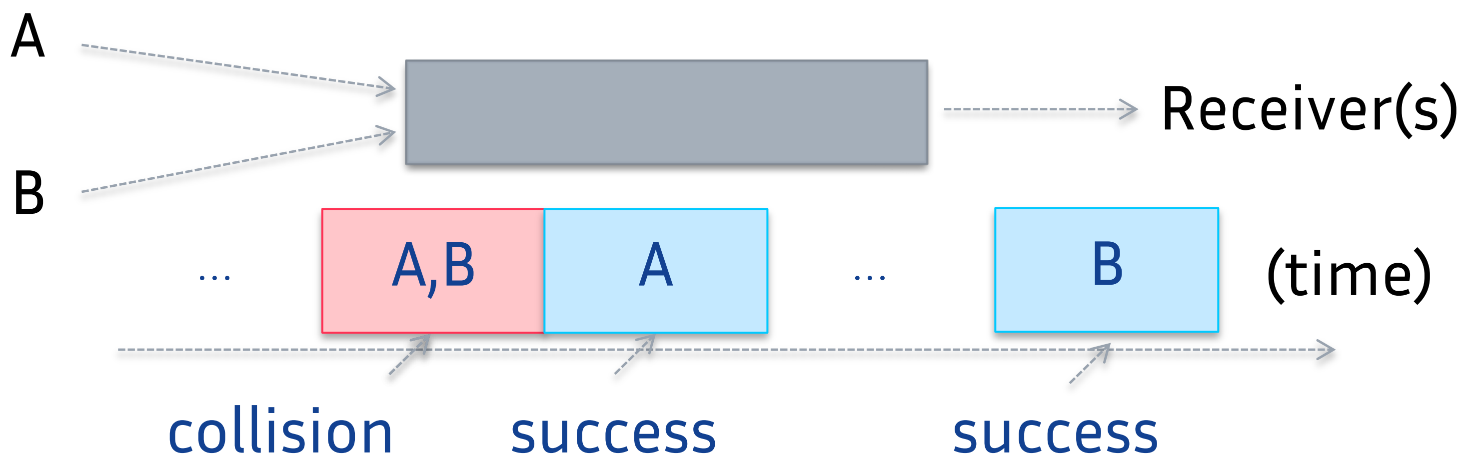


NOMA Power Domain
or all variants, e.g. [2], [3], [4], etc.

[2] 3GPP TR 38.812, "Study on Non-Orthogonal Multiple Access (NOMA) for NR," Dec. 2018.
[3] M. Vaezi, Z. Ding, H.V. Poor (Eds) "Multiple access techniques for 5G wireless networks and beyond", Springer, 2019
[4] MB Shahab, T Abbas, M Shirvanimoghaddam, SJ Johnson "Grant-free non-orthogonal multiple access for IoT: A survey" IEEE Communications Surveys & Tutorials, May 2020

Textbook: The other MAC (Medium Access Control) Classical Theory - Random Access



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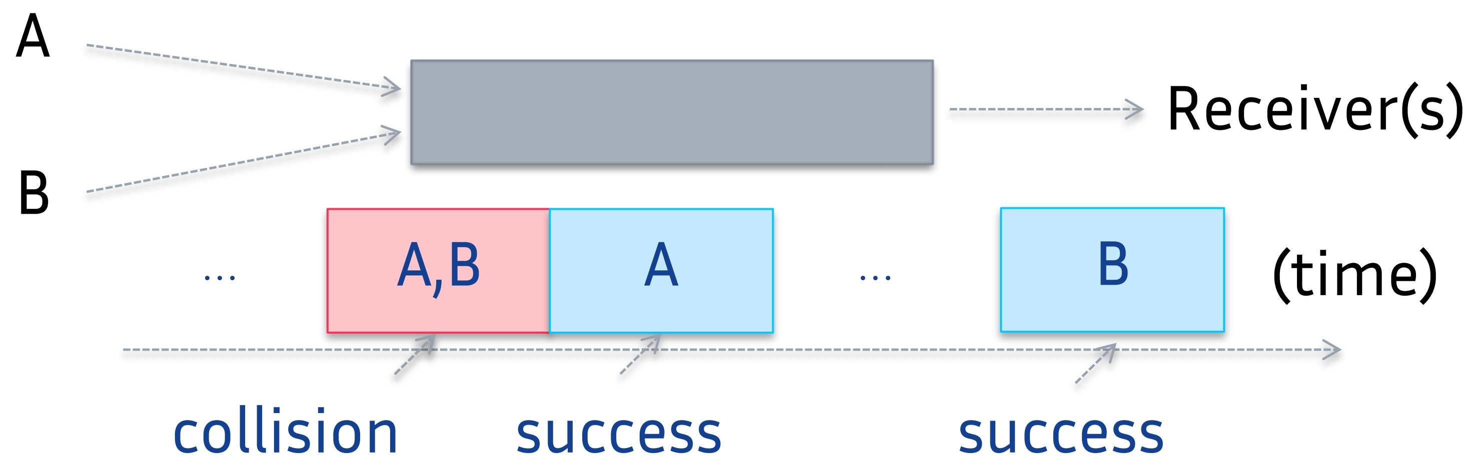
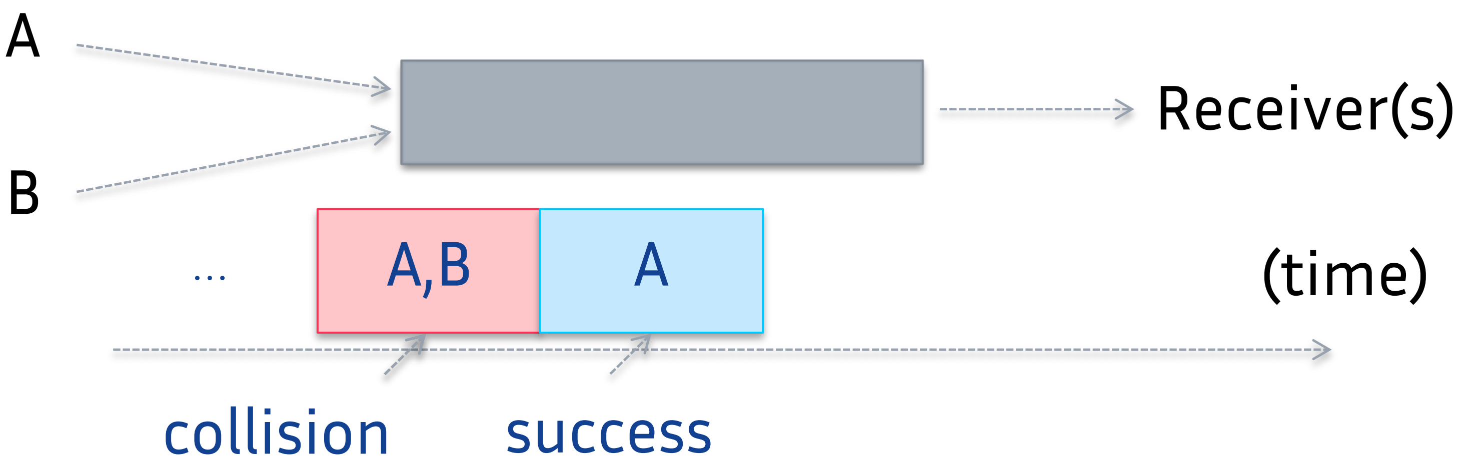
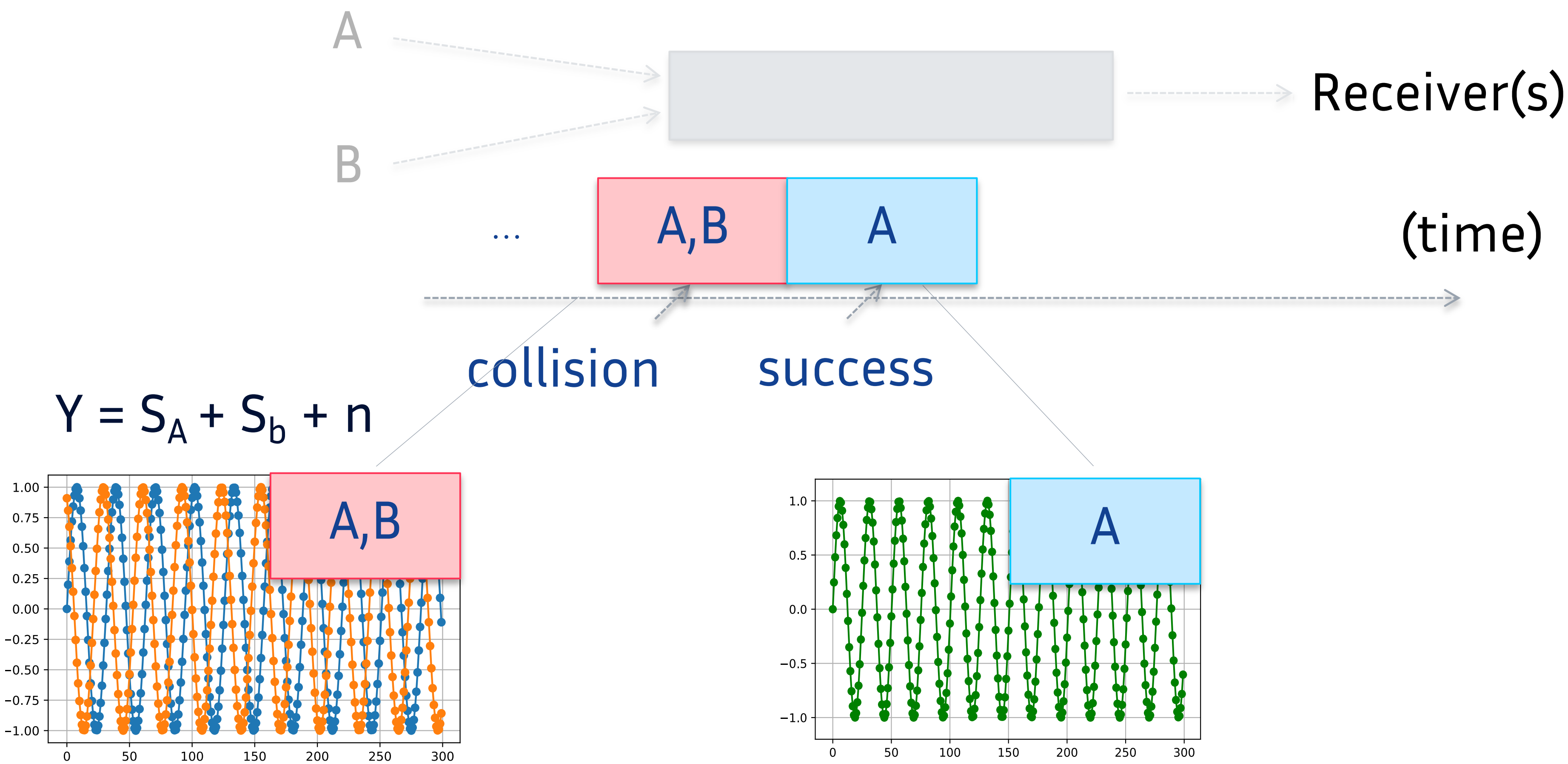


- With feedback: random access protocols (e.g. slotted ALOHA, tree collision resolution, ...)
  - Performance: ALOHA = 0.367... ; FCFS = 0.487(1) ; Bounds: 0.5 (FIFO), 0.568 (any access)
- Alternate: sensing to avoid collisions (CSMA)

Principle of "Modern" Random Access

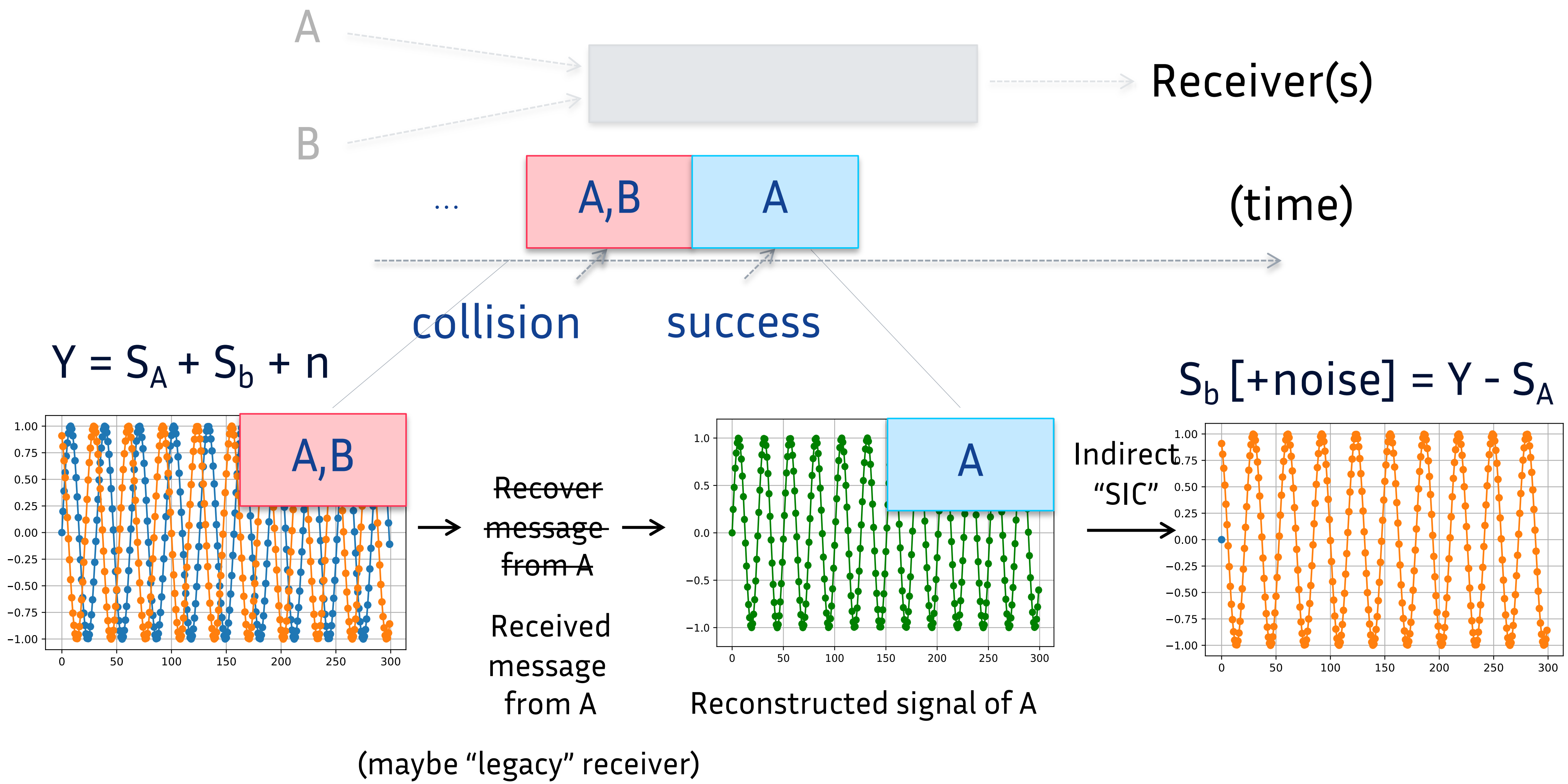


Principle of "Modern" Random Access



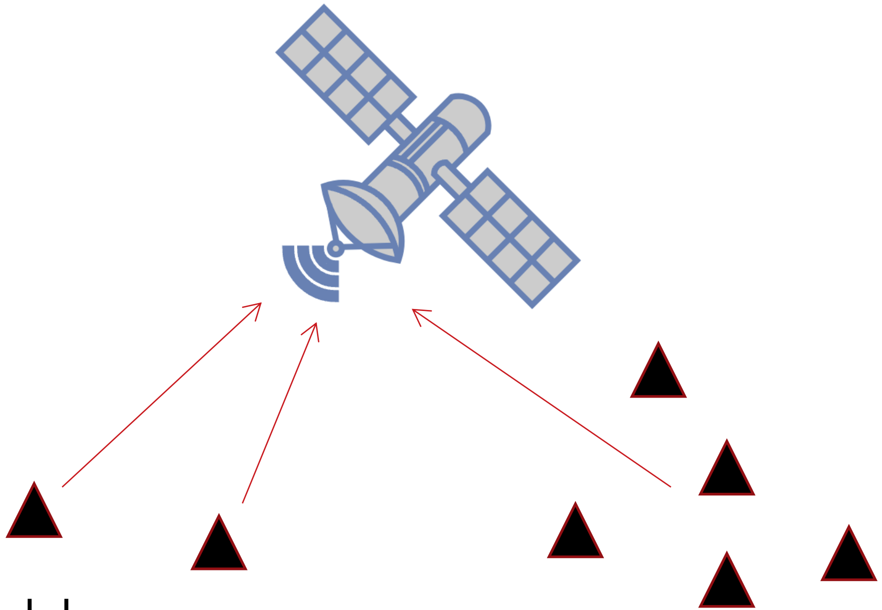
$$Y = S_A + S_b + n$$

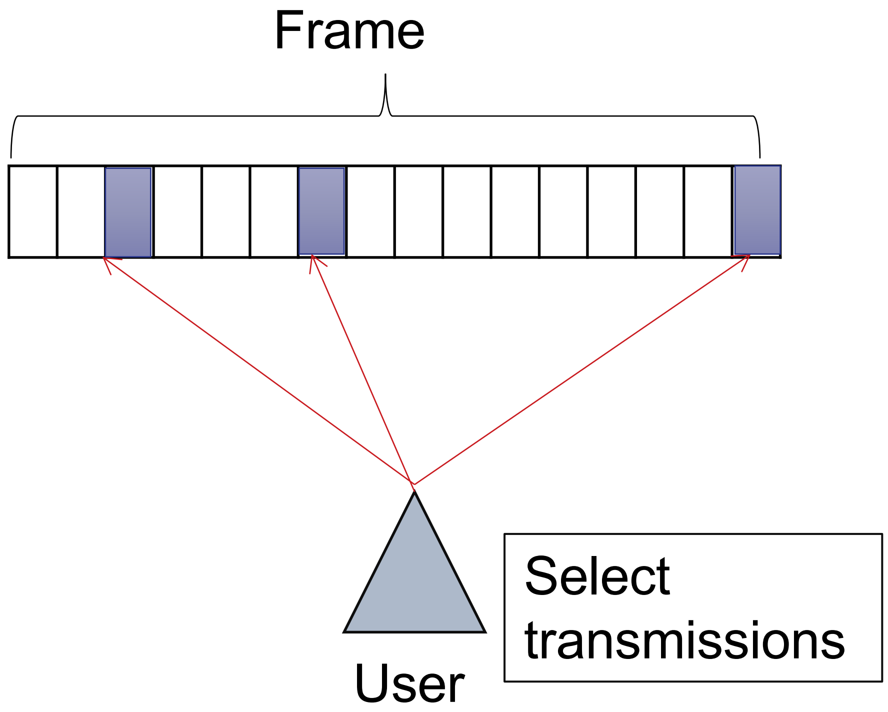
Principle of "Modern" Random Access
Interference Cancellation at another location



02
Satellite Communications
(Towards Modern Random Access)

Classical Model





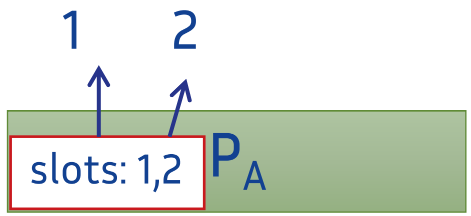
- Model:
  - Active users transmitting to a satellite (upstream)
  - Fixed-size frame with time slots ("slots")

- Previous: Diversity Slotted ALOHA (DSA)

[1] G. Choudhury, S. Rappaport, "Diversity ALOHA - A random access scheme for satellite communications" IEEE Transactions on Communications, 1983

Contention Resolution Diversity Slotted ALOHA (CRDSA)

- Satellite communications (physical layer simulations)
- Slotted Aloha with frame of time slots, and 2 transmissions
- Inter-slot Successive Interference Cancellation (SIC)
- Pointers in packet headers

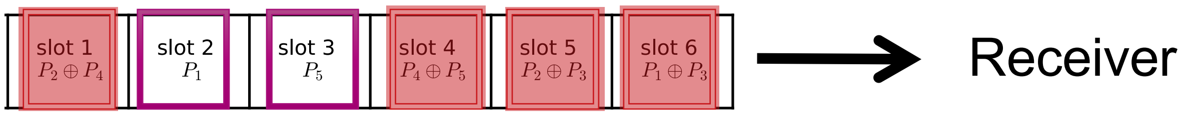


	slot 1 $P_2 \oplus P_4$	slot 2 P_1	slot 3 P_5	slot 4 $P_4 \oplus P_5$	slot 5 $P_2 \oplus P_3$	slot 6 $P_1 \oplus P_3$
Node 1		P_1				P_1
Node 2	P_2				P_2	
Node 3					P_3	P_3
Node 4	P_4			P_4		
Node 5			P_5	P_5		

→ Receiver

[1] E. Casini, R. De Gaudenzi, O.D. Herrero, “Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks”, IEEE Transactions on Wireless Communications, April 2007

Contention Resolution Diversity Slotted ALOHA (CRDSA)



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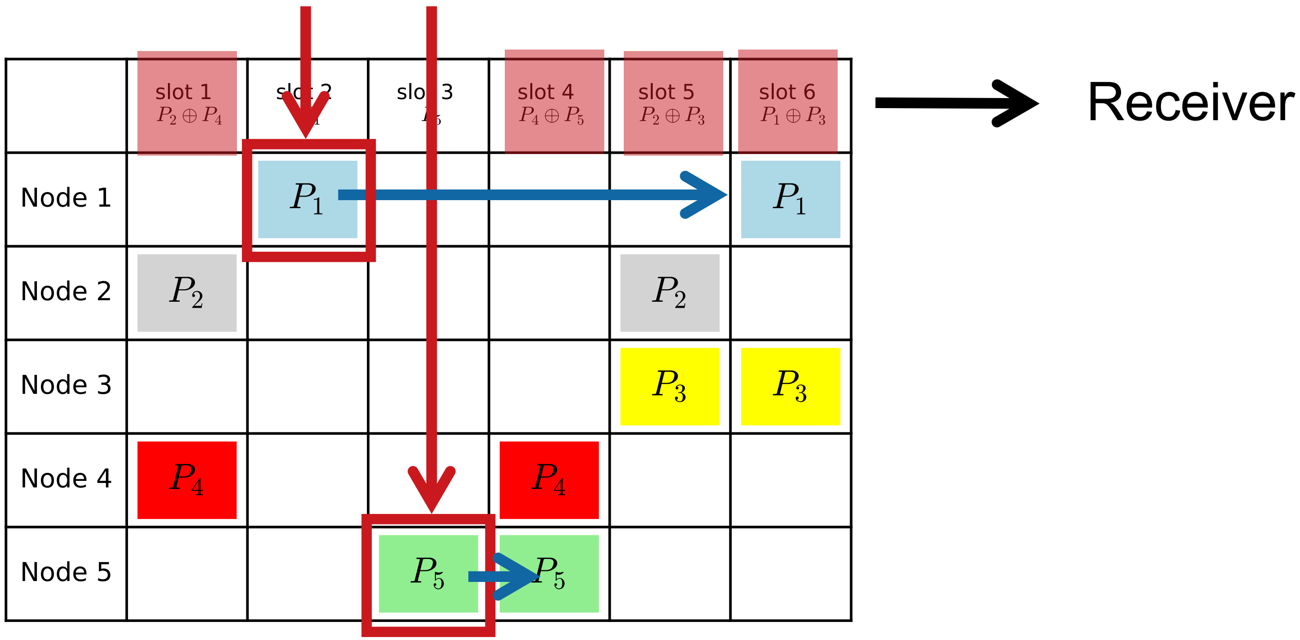
Contention Resolution Diversity Slotted ALOHA (CRDSA)

CRDSA, Iterative decoding

- Demodulating each slot of the whole frame
- Inter-slot SIC



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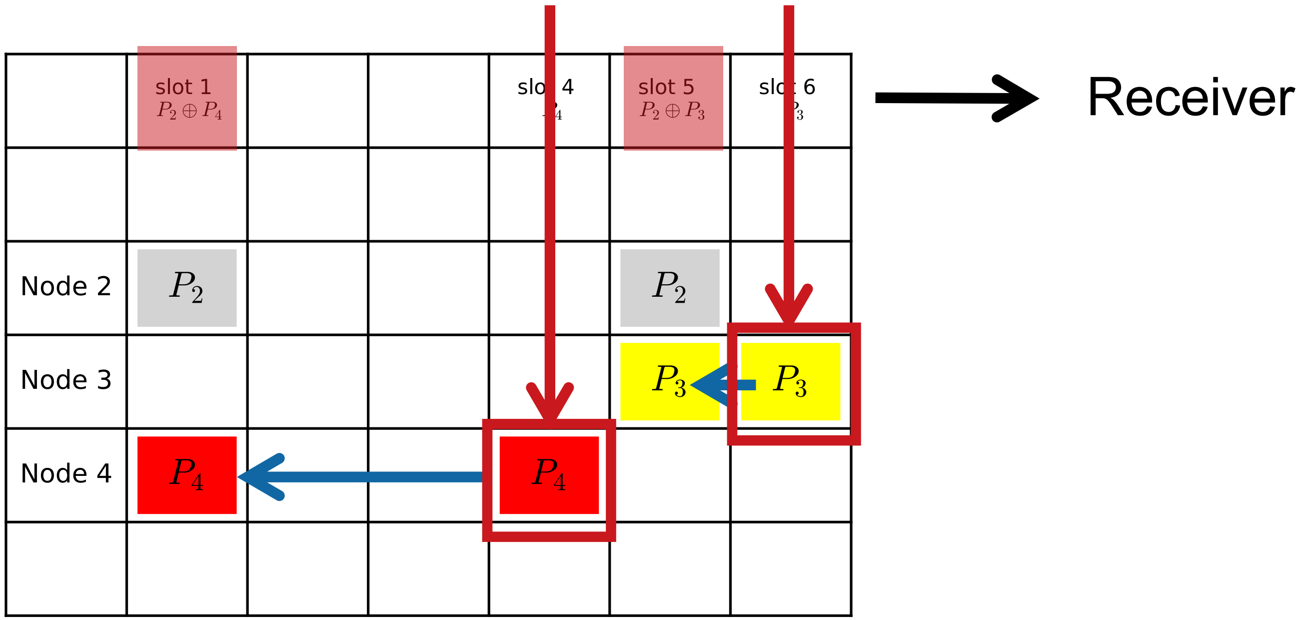

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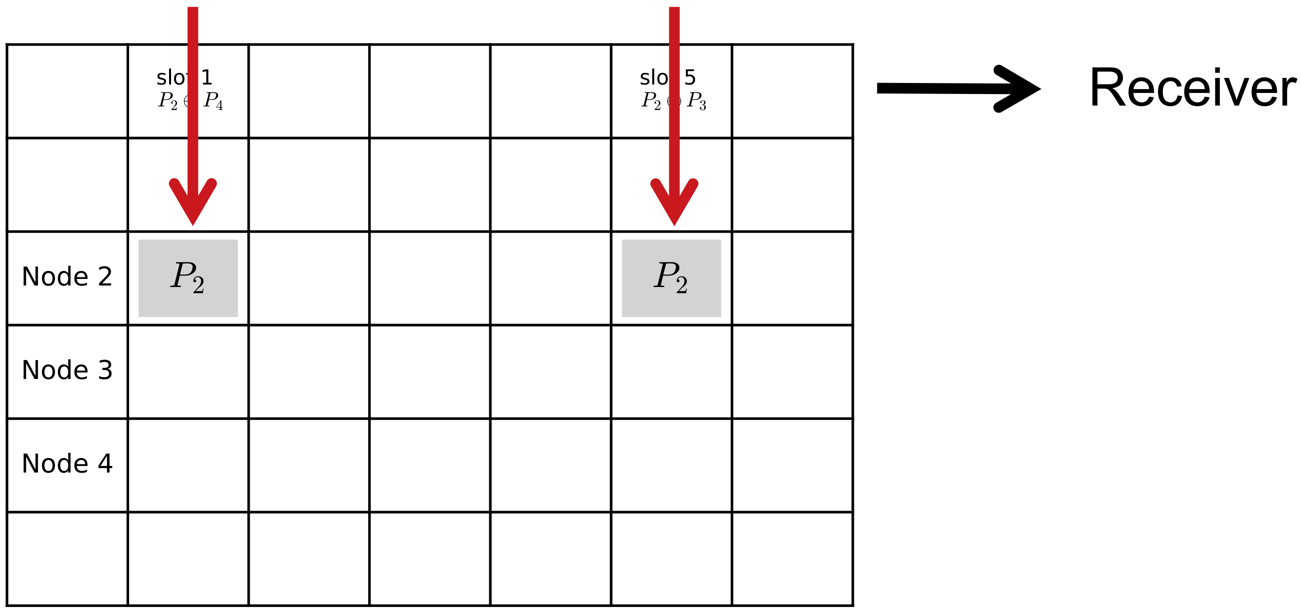

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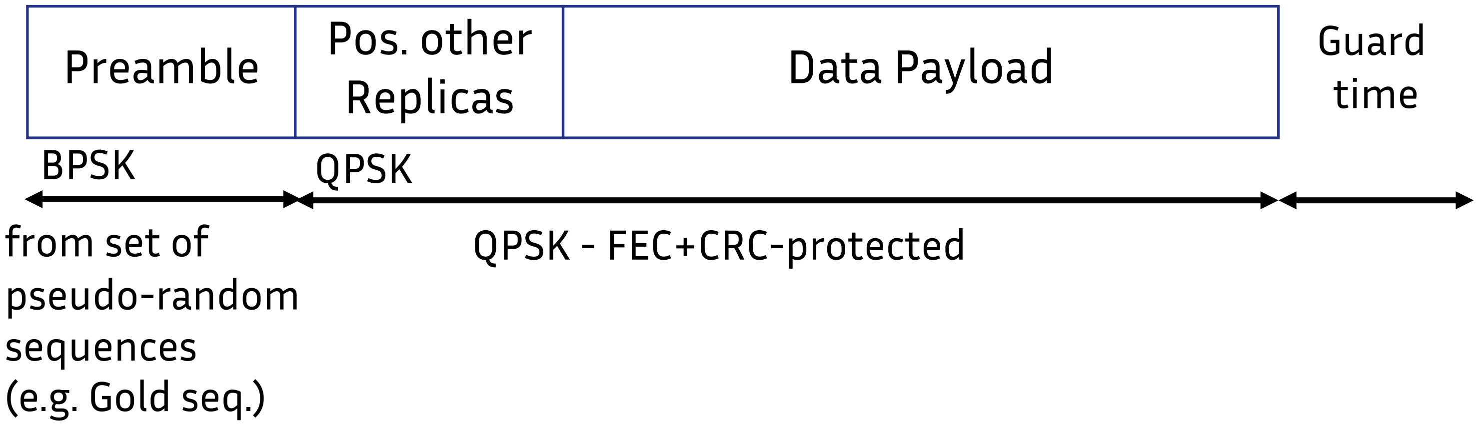

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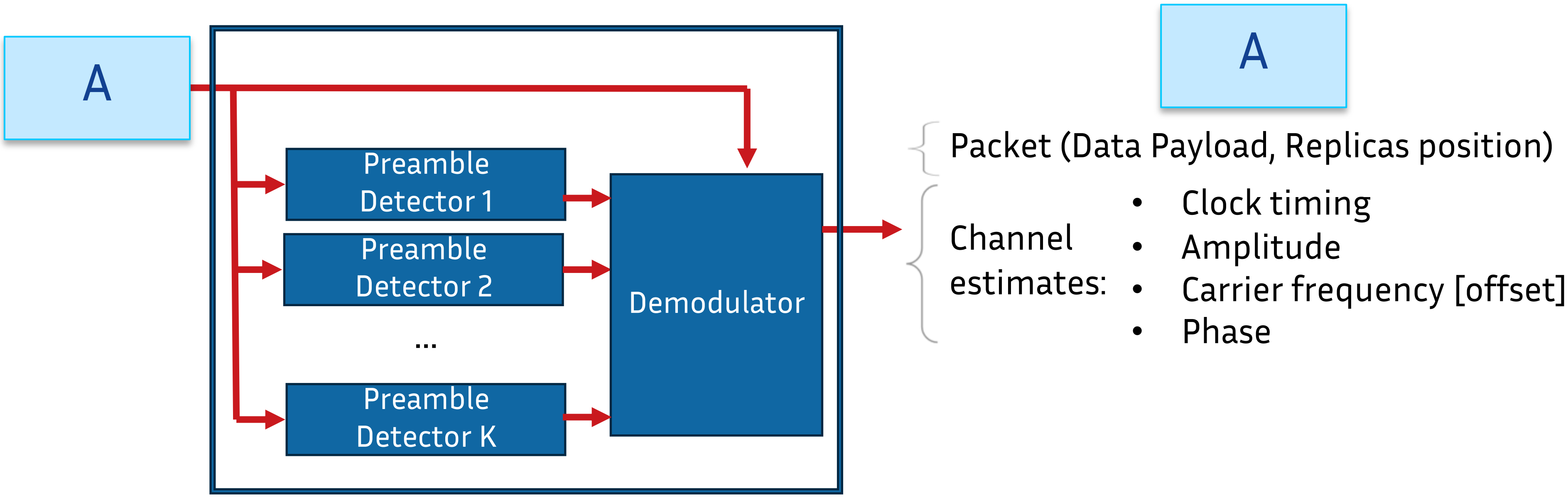
Contention Resolution Diversity Slotted ALOHA (CRDSA)

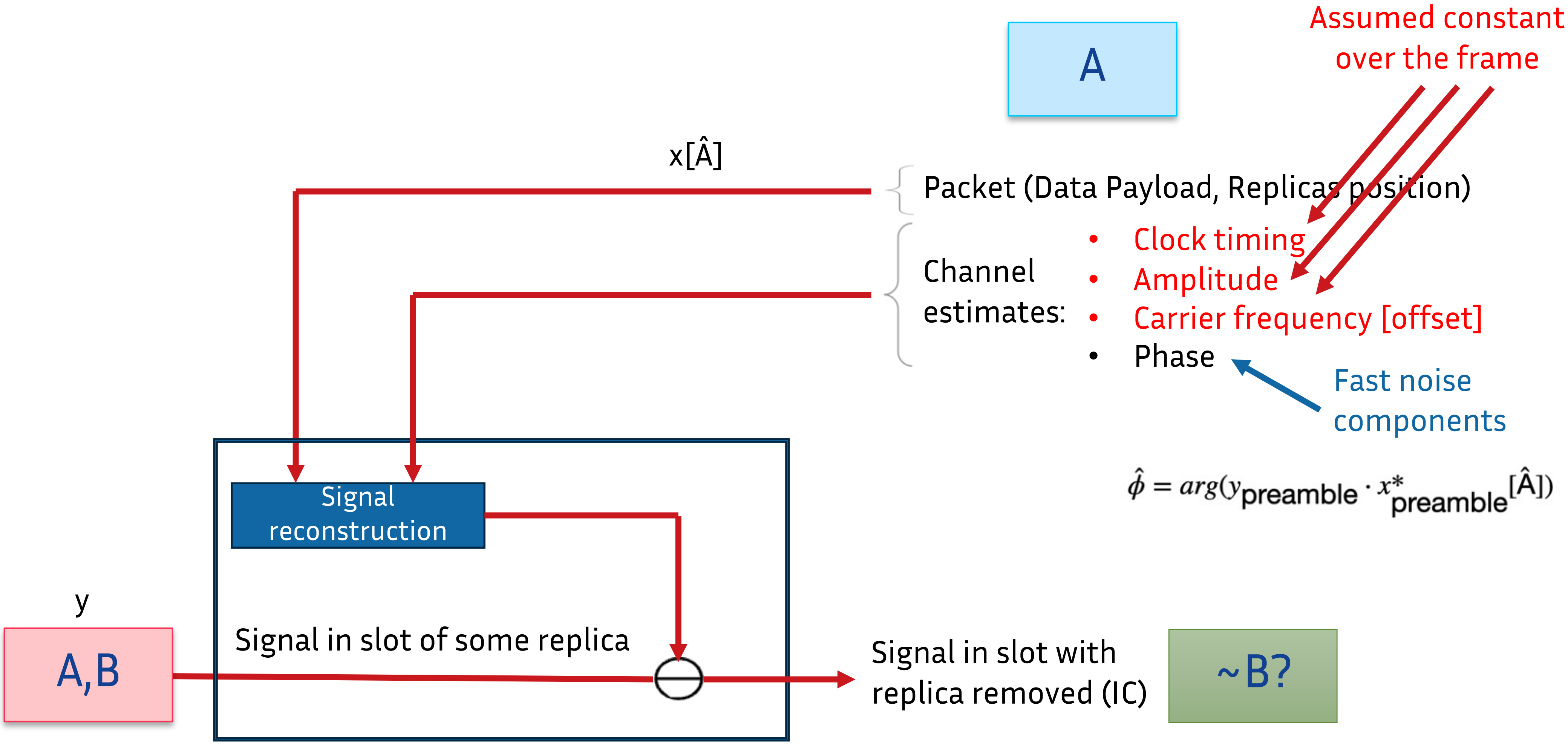
Received signal (slot per slot)



Assumptions on channel: constant during a time slot, received power follows lognormal distribution

[1] E. Casini, R. De Gaudenzi, O.D. Herrero, “Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks”, IEEE Transactions on Wireless Communications, April 2007

Contention Resolution Diversity Slotted ALOHA (CRDSA) Inter-slot SIC



$$\hat{\phi} = arg(y_{\text{preamble}} \cdot x^{*}_{\text{preamble}}[\hat{A}])$$

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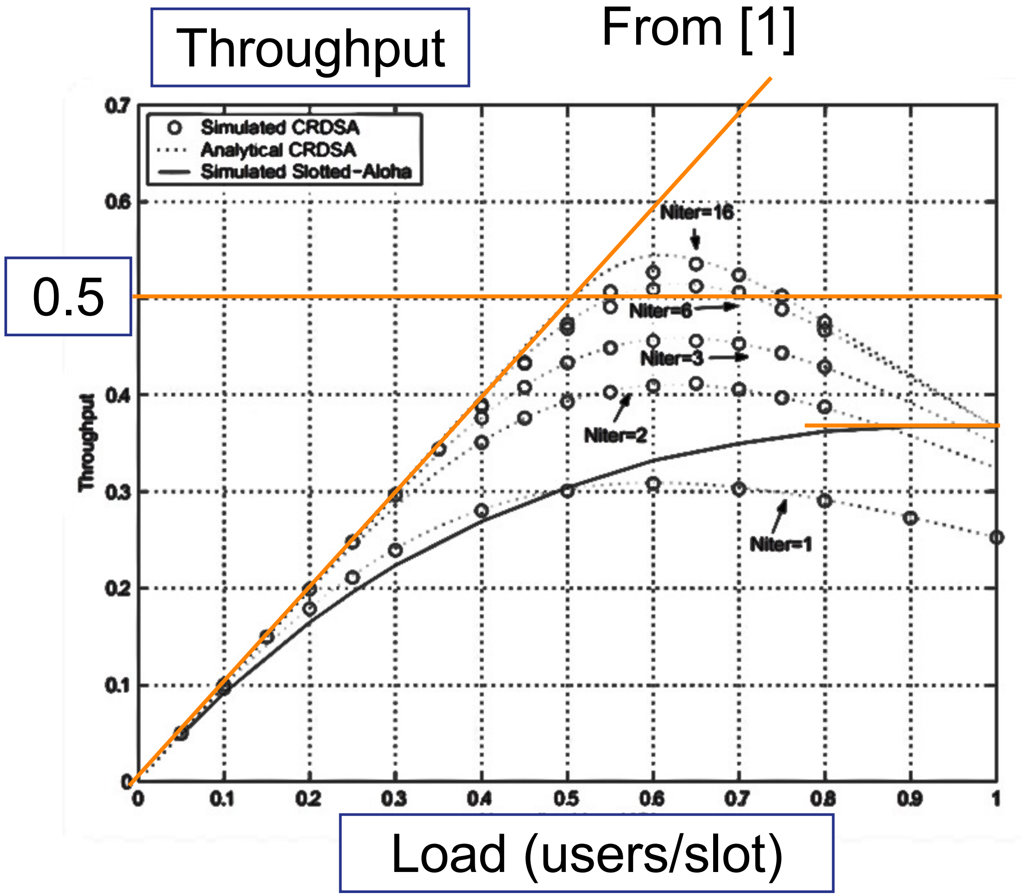
Contention Resolution Diversity Slotted ALOHA (CRDSA)



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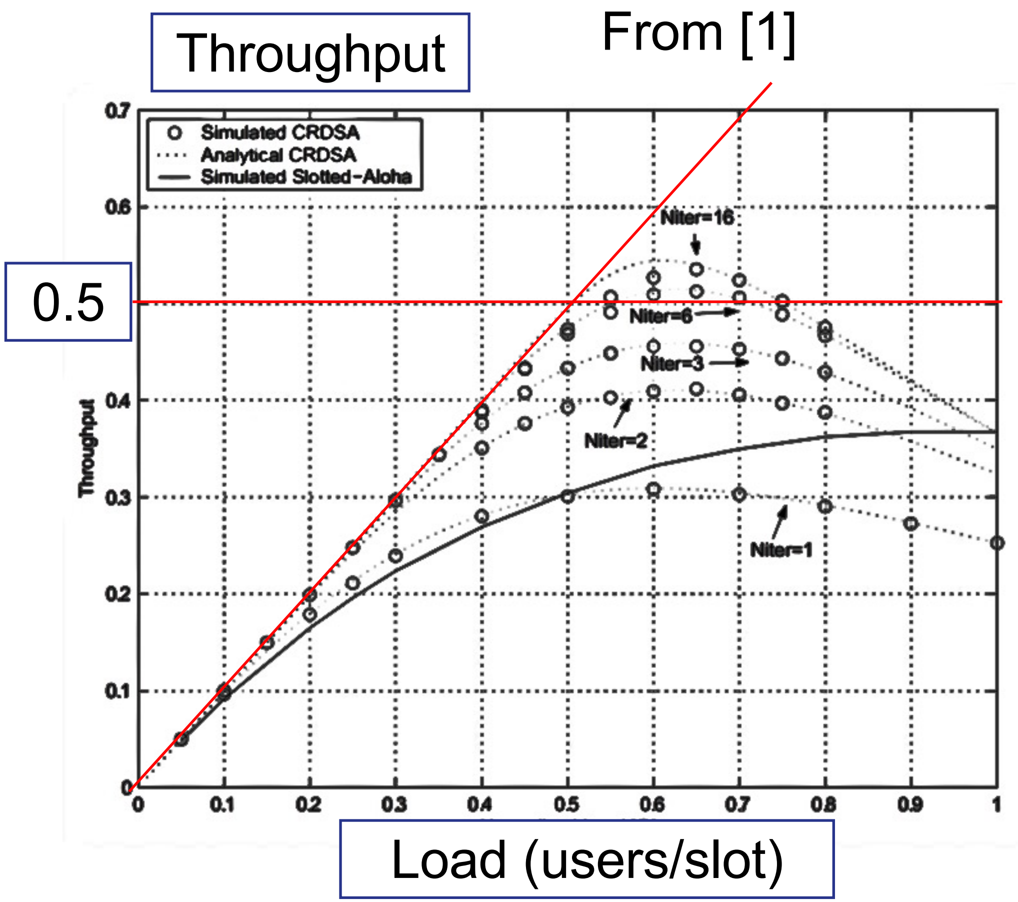
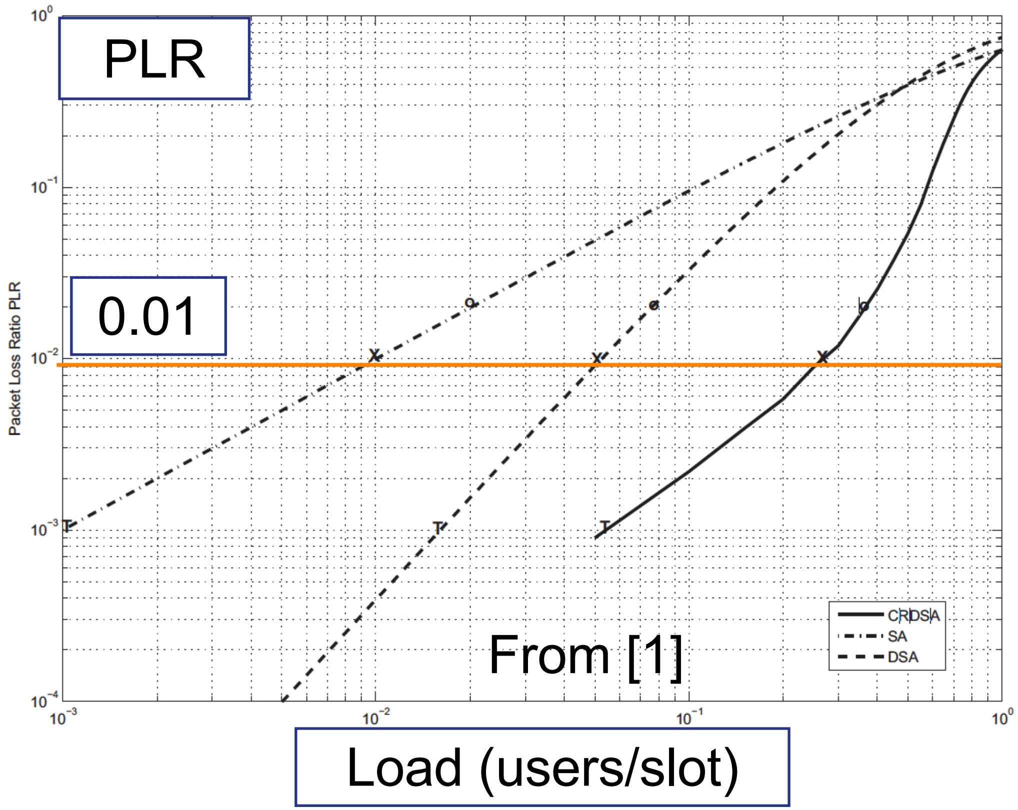
Contention Resolution Diversity Slotted ALOHA (CRDSA)

CRDSA, Throughput: peak = 0.52;
Low loss rate: at 10^{-2}, 26x more load





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Contention Resolution Diversity Slotted ALOHA (CRDSA)

Effect of estimation errors

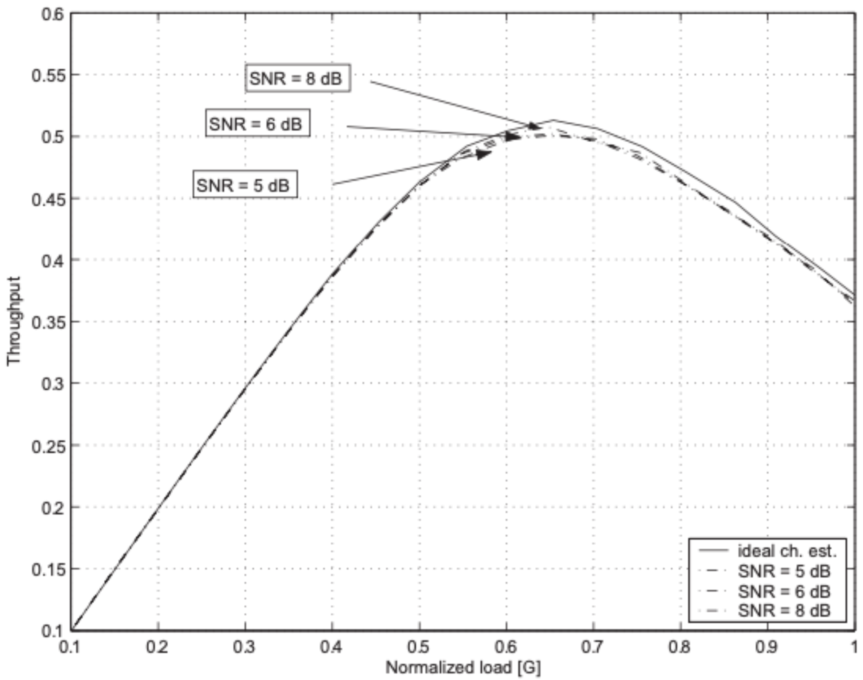


Fig. 8. Simulated ideal channel estimation (continuous line) and real channel estimation for IC (dashed dot line) results for the CRDSA throughput versus the normalized channel loading for $N_{\text{iter}} = 10$ and $E_s/N_0 = 5,\ 6,\ 8$ dB.

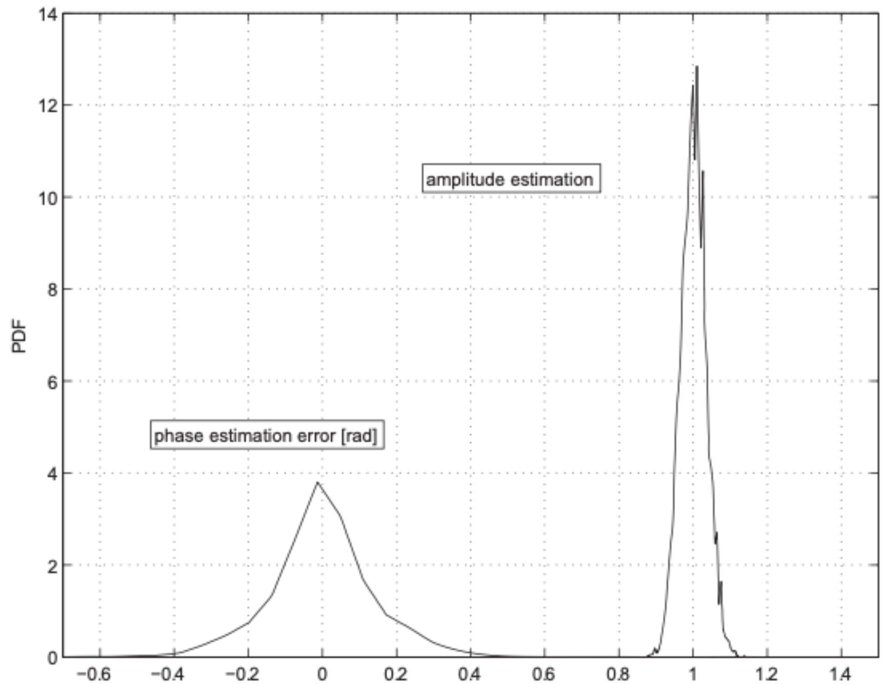
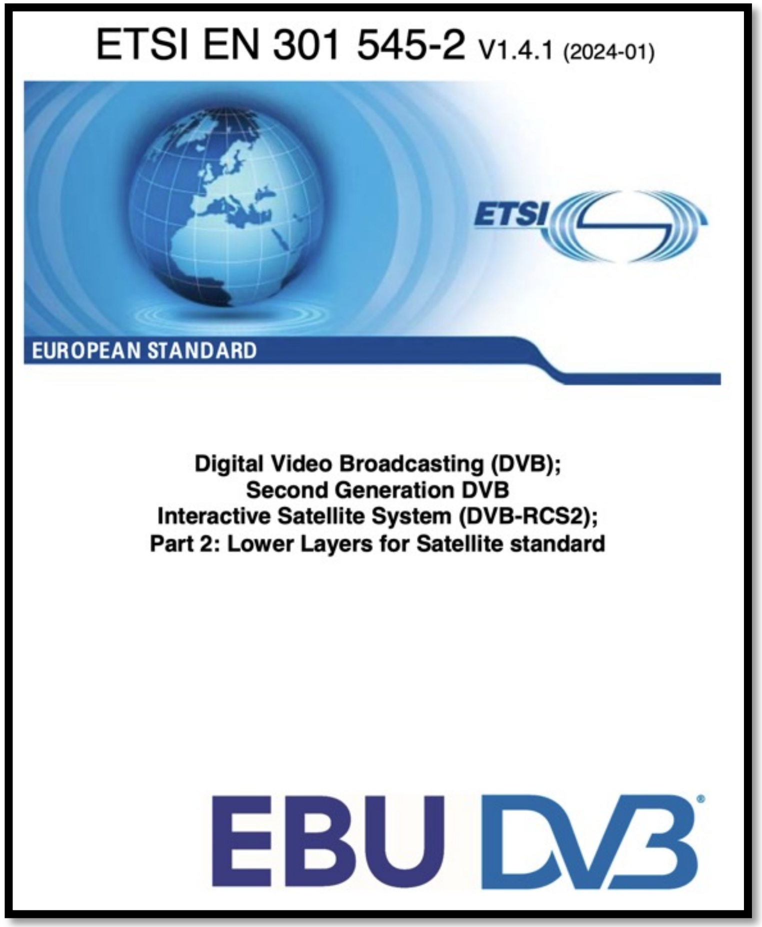


Fig. 9. Simulated CRDSA preamble amplitude and carrier phase estimation error for $N_{\text{iter}} = 10$, $E_s/N_0 = 6$ dB, G=0.4 and $N^{RA}_{\text{guard}} = 5$.

[1] E. Casini, R. De Gaudenzi, O.D. Herrero, "Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks", IEEE Transactions on Wireless Communications, April 2007



7.2.5.2.2 CRDSA (optional)

7.2.5.2.2.0 Introduction

Contention Resolution Diversity Slotted ALOHA (CRDSA) is based on the transmission of a chosen number of replicas of each burst payload by using slotted aloha in a specific transmission scheme.

There are two possible variants of CRDSA transmitter operation:

- Constant Replication Ratio CRDSA (CR-CRDSA): using a constant number of replicas of each burst;
- Variable Replication Ratio CRDSA (VR-CRDSA): using a varying number of replicas for the different bursts, where the number of replicas is determined according to a pre-defined probability distribution.

The type of CRDSA scheme (CR-CRDSA vs. VR-CRDSA) that is best to use may be chosen on the basis of a trade-off between throughput and burst loss rate. While CR-CRDSA allows low burst loss rate, VR-CRDSA allows larger peak throughput.

02
Classical Modern Random Access
(Irregular Repetition Slotted ALOHA)

Irregular Repetition Slotted ALOHA (IRSA)

Improvement and formalisation: Liva [1]

- Variable number repetitions “Irregular Repetition Slotted Aloha”
  - Choices of number of repetitions from a distribution
  - Ex. 50/50 choice between 2 repetitions and 3 repetitions:
    - $\Lambda_2=½$ and $\Lambda_3=½$
    - **“degree distribution”: $\Lambda(x) = ½\, x^2 + ½\, x^3$**

- Ideal “collision channel” model

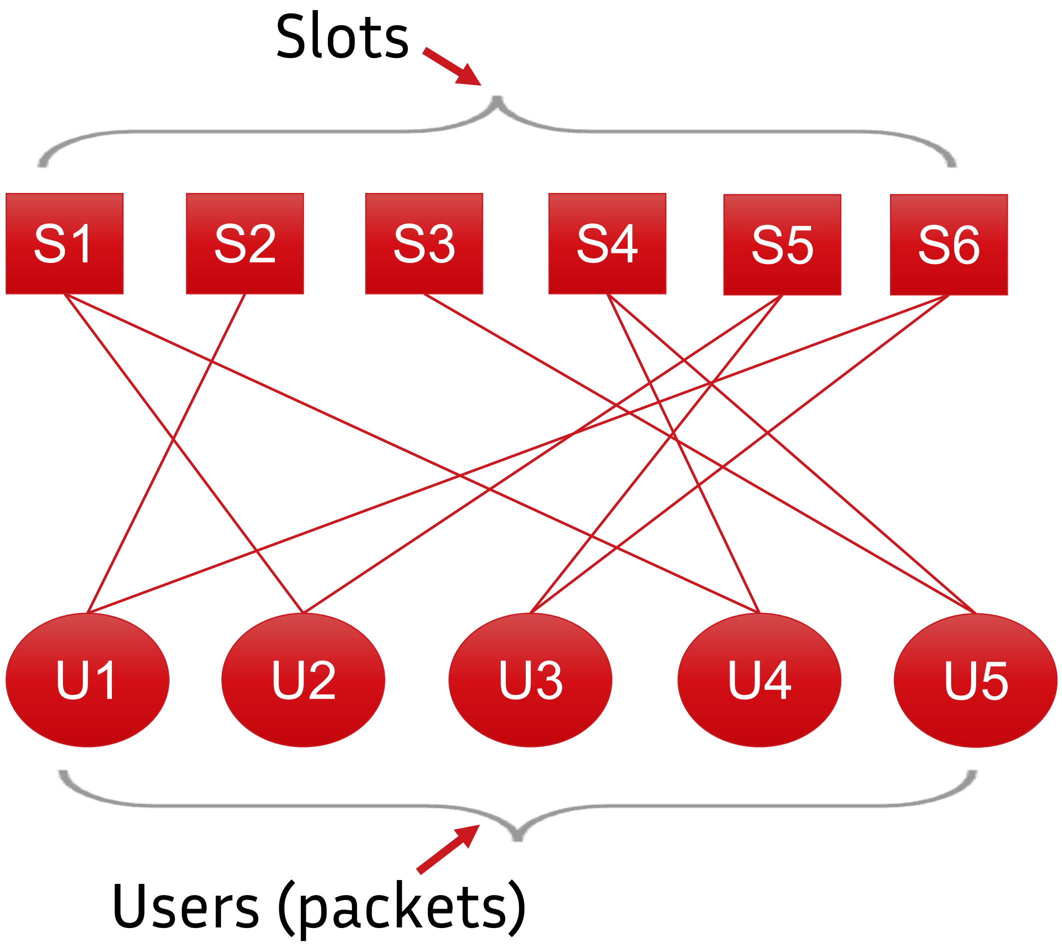
- Modeling the iterative decoding (message passing) with density evolution
  - Analogy with framework of LDPC codes / codes on graphs.
  - Binary-erasure channel

- General introduction of concept in [2]

[1] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA”, *IEEE Transactions on Communications,* 2011.

[2] E. Paolini, C. Stefanovic, G. Liva, P. Popovski, “Coded random access: How coding theory helps to build random access protocols”, 2014

Irregular Repetition Slotted ALOHA (IRSA)



	slot 1 $P_2 \oplus P_4$	slot 2 P_1	slot 3 P_5	slot 4 $P_4 \oplus P_5$	slot 5 $P_2 \oplus P_3$	slot 6 $P_1 \oplus P_3$
User 1		P_1				P_1
User 2	P_2				P_2	
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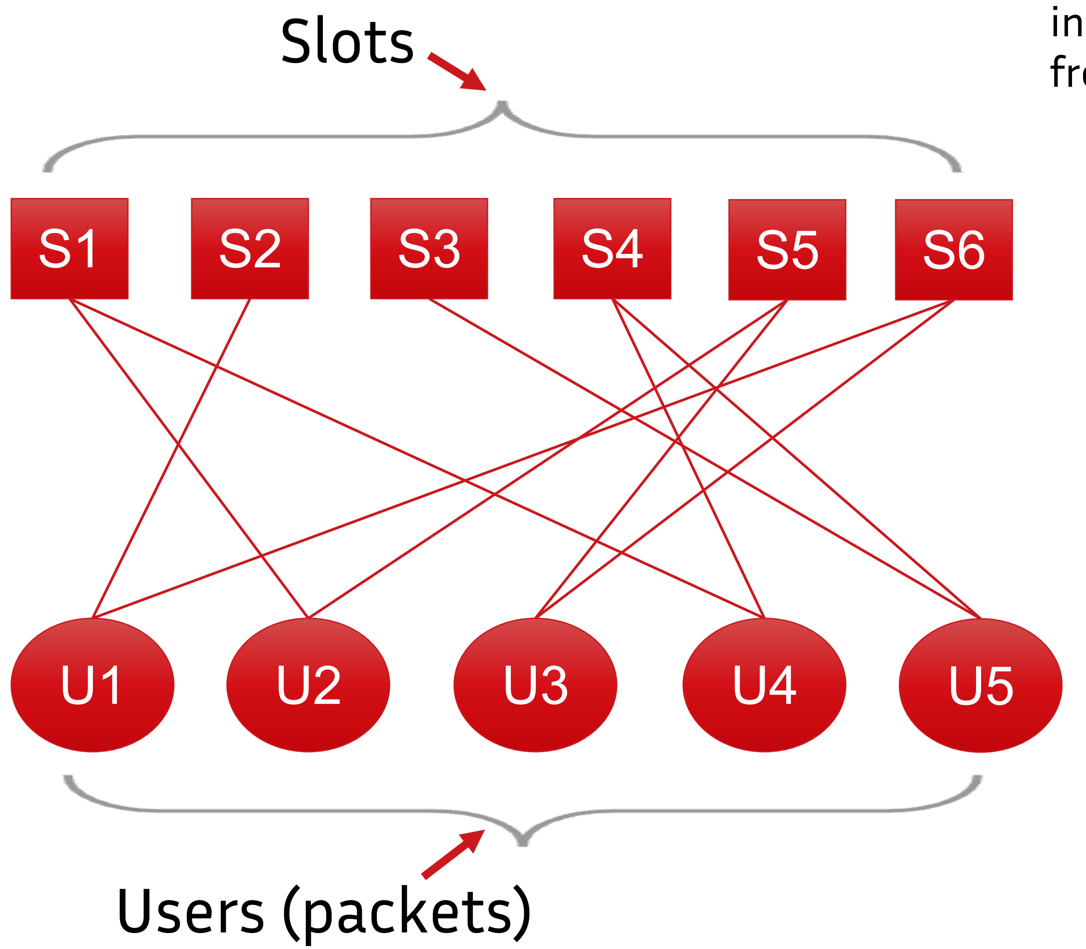
Irregular Repetition Slotted ALOHA (IRSA)



State of decoding:
indirectly represented by the proportion of edges from unrecovered slots/users at a given iteration

	slot 1 $P_2 \oplus P_4$	slot 2 P_1	slot 3 P_5	slot 4 $P_4 \oplus P_5$	slot 5 $P_2 \oplus P_3$	slot 6 $P_1 \oplus P_3$
User 1		P_1				P_1
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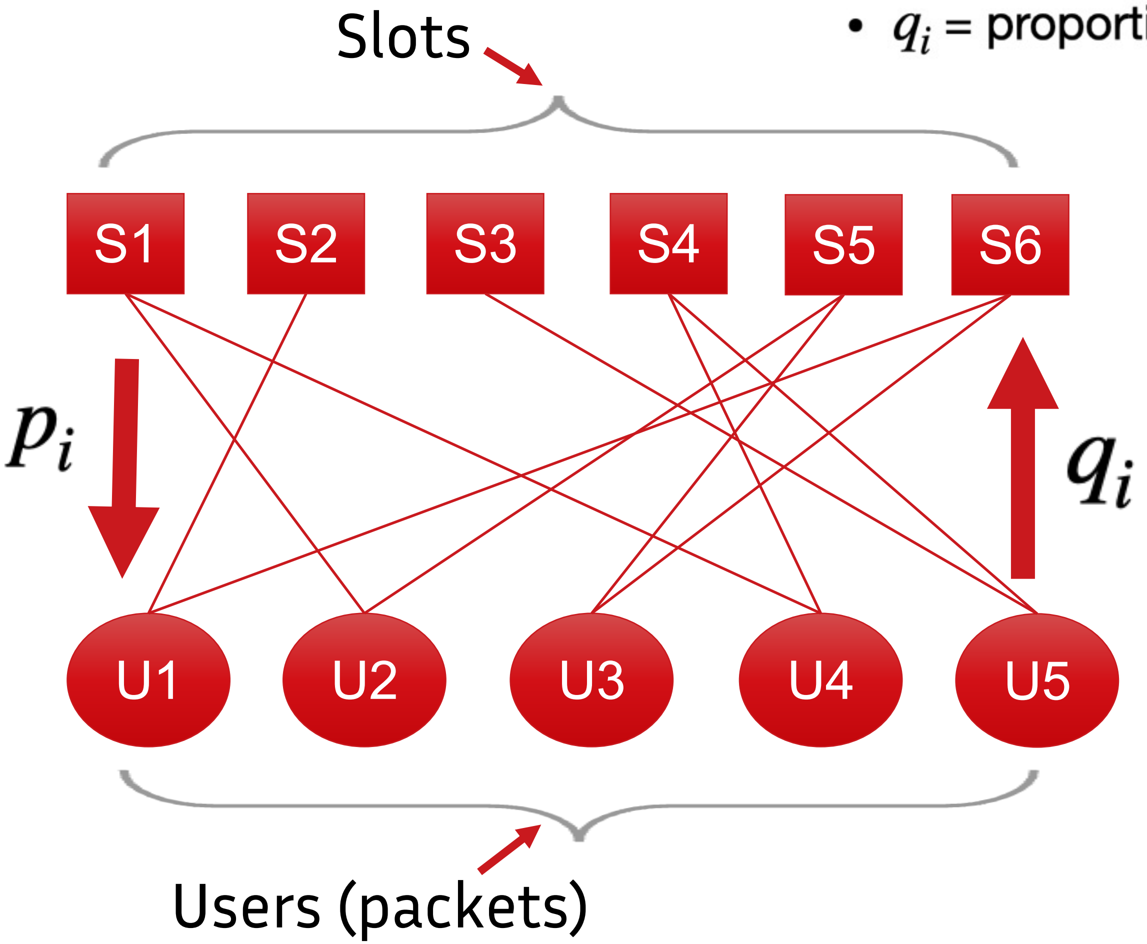
Irregular Repetition Slotted ALOHA (IRSA)

- p_i = proportion of edges from non-recovered slots
- q_i = proportion of edges from non-recovered users



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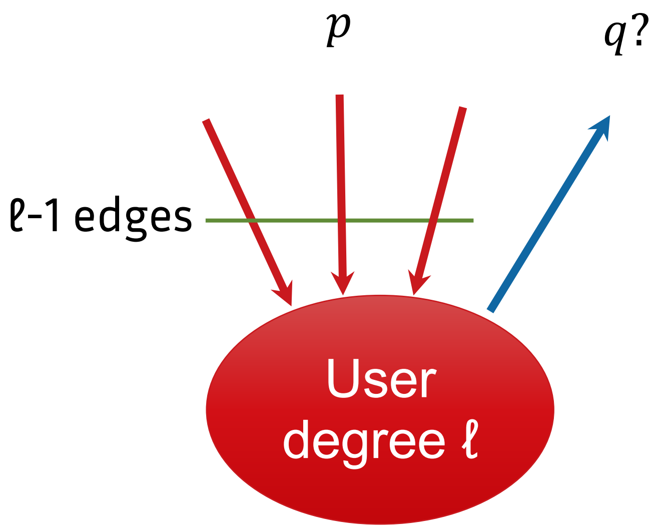
Irregular Repetition Slotted ALOHA (IRSA)

Modelisation of the decoding process

- Example:
  - User node with ℓ repetitions of a packet
  - Knowing probability that each edge is from a non-recovered slot p :
  - Probability q of that the user will not be recovered and thus the outgoing edge is going to a non-recovered user

$$q = p^{\ell-1}$$



  - Averaging over all ℓ degrees (all graphs):

$$\bar{q} = \sum_{\ell} \Pr(\text{edge from user with degree } \ell)\ p^{\ell-1} = \sum_{\ell} \lambda_\ell\ p^{\ell-1} \quad \text{with} \quad \lambda_i = \frac{i\Lambda_i}{\sum_k k\Lambda_k}$$

[1] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA", *IEEE Transactions on Communications,* 2011.
[2] M. Luby, M. Mitzenmacher, M.A. Shokrollahi "Analysis of Random Processes via And-Or Tree Evaluation", SODA, 1998

Irregular Repetition Slotted ALOHA (IRSA)

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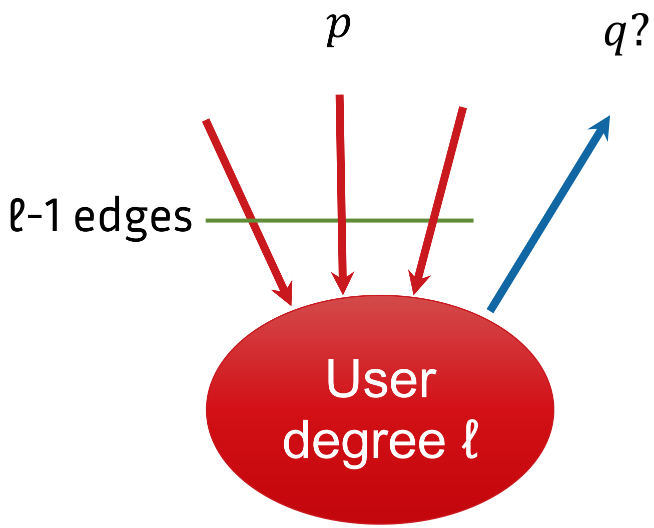

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- Overall: $q_i = \sum_{\ell} \lambda_\ell p_{i-1}^{\ell-1} = \lambda(p_{i-1})$

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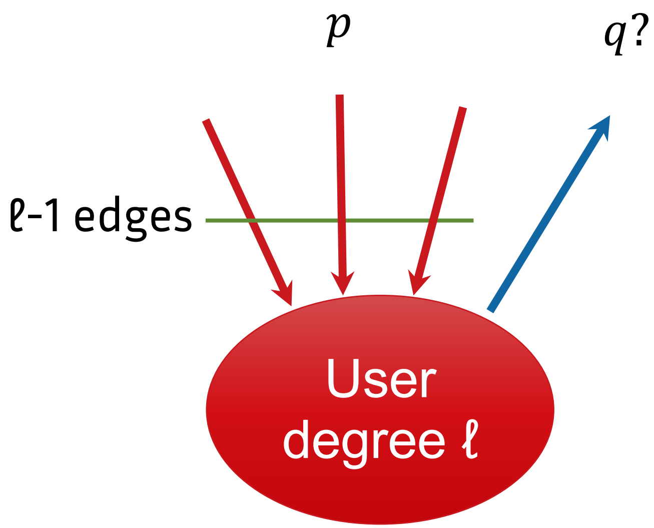
Irregular Repetition Slotted ALOHA (IRSA)

Modelisation of the decoding process

- Example:
- User node with ℓ repetitions of a packet
- Knowing probability that each edge is from a non-recovered slot p :
- Probability q of that the user will not be recovered
  and thus the outgoing edge is going to a non-recovered user

$$q = p^{\ell - 1}$$



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- Overall:

$$q_i = \sum_{\ell} \lambda_{\ell} p_{i-1}^{\ell-1} = \lambda(p_{i-1})$$

$$p_i = \sum_{\ell} \rho_{\ell}(1-(1-q_i))^{\ell-1} = 1 - \rho(1-q_i)$$

with

$$\lambda(x) = \sum_{\ell} \lambda_{\ell} x^{\ell}$$

$\rho(x)$ depends on the distribution of "collisions" on the slots

Irregular Repetition Slotted ALOHA (IRSA)
Density Evolution - A Tool for Performance Analysis

- Choice of distribution: $\Lambda(x) = \sum_{\ell} \Lambda_{\ell} x^{\ell}$
- Packet "collision" distribution: $\Psi(x) = \sum_{\ell} \Psi_{\ell} x^{\ell}$
- Establishing the density evolution equations:

$$q_i = \lambda(p_{i-1})$$
$$p_i = 1 - \rho(1 - q_i)$$

with $\lambda(x) = \frac{\Lambda'(x)}{\Lambda'(1)}$

$$\rho(x) = \frac{\Psi'(x)}{\Psi'(1)} \approx 1 - e^{-\frac{G}{R}(1-x)}$$

[1] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)

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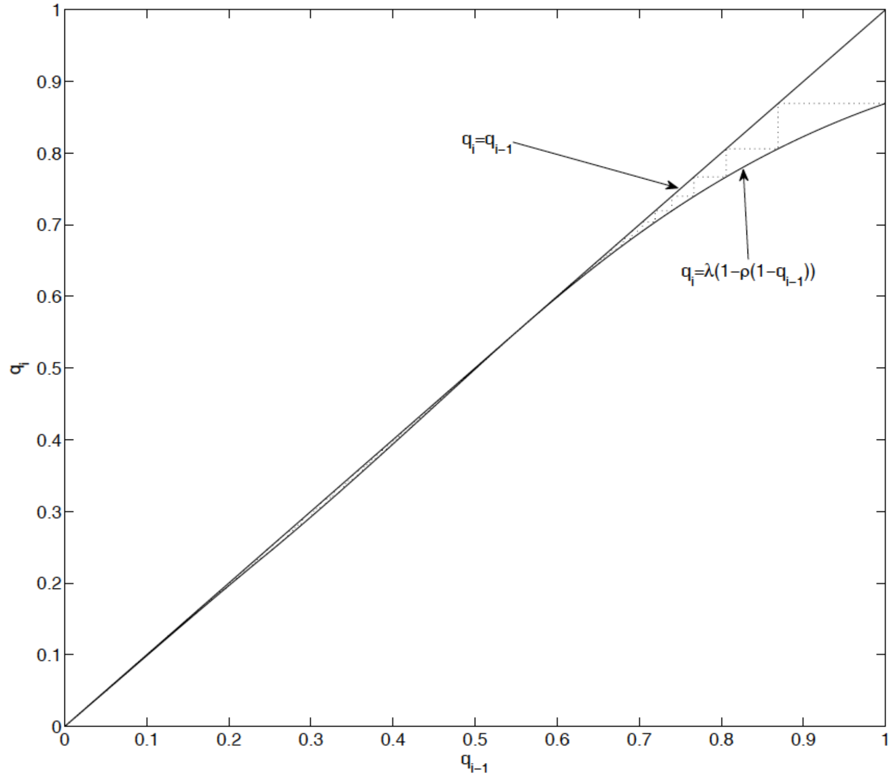
- Asymptotic performance for a given load G:

$$p_\infty = \lim_{i \to \infty} p_i \qquad \text{PLR} = \Lambda(p_\infty)$$

- Threshold G*
- What is the best $\Lambda(x)$?



From [1]: (at threshold) with Pr(d=2)=0.5; Pr(d=3)=0.28; Pr(d=8)=0.22

[1] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)

Irregular Repetition Slotted ALOHA (IRSA)
Density Evolution - A Tool for Performance Analysis

- Choice of distribution: $\Lambda(x) = \sum_\ell \Lambda_\ell x^\ell$
- Packet '
- Establis

$q_i = \lambda$

$p_i = 1$

- Asymp

$p_\infty = \lim_{i\to\infty} p_i$ PLR = $\Lambda(p_\infty)$

- Threshold G*
- What is the best $\Lambda(x)$?

Λ

Probability
to transmit 1, 2, 3, ... K copies

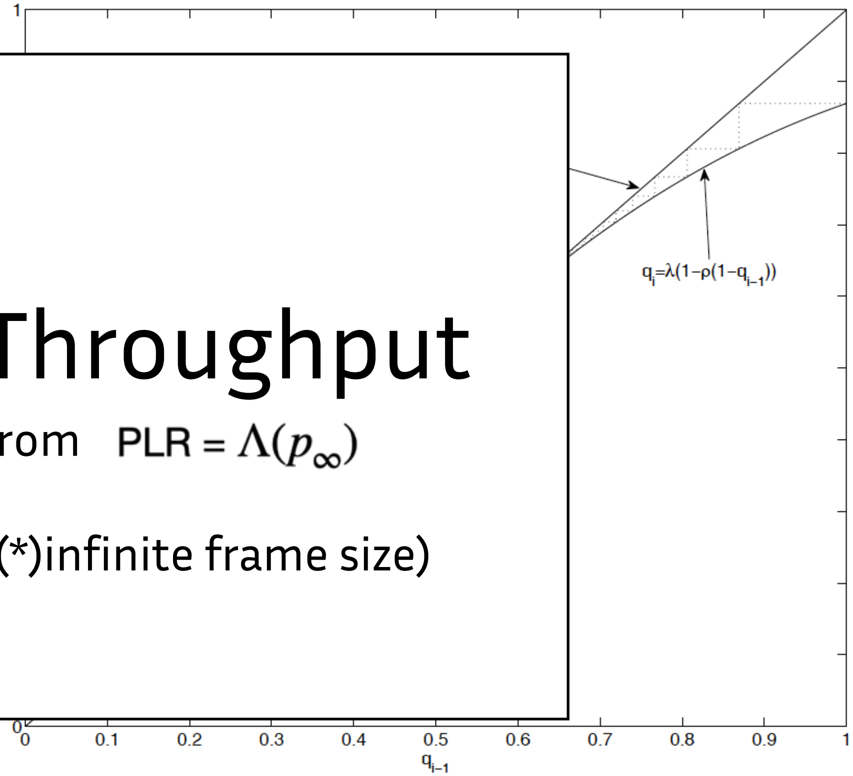
G

load (user/slot)

Throughput

from PLR = $\Lambda(p_\infty)$

((*)infinite frame size)



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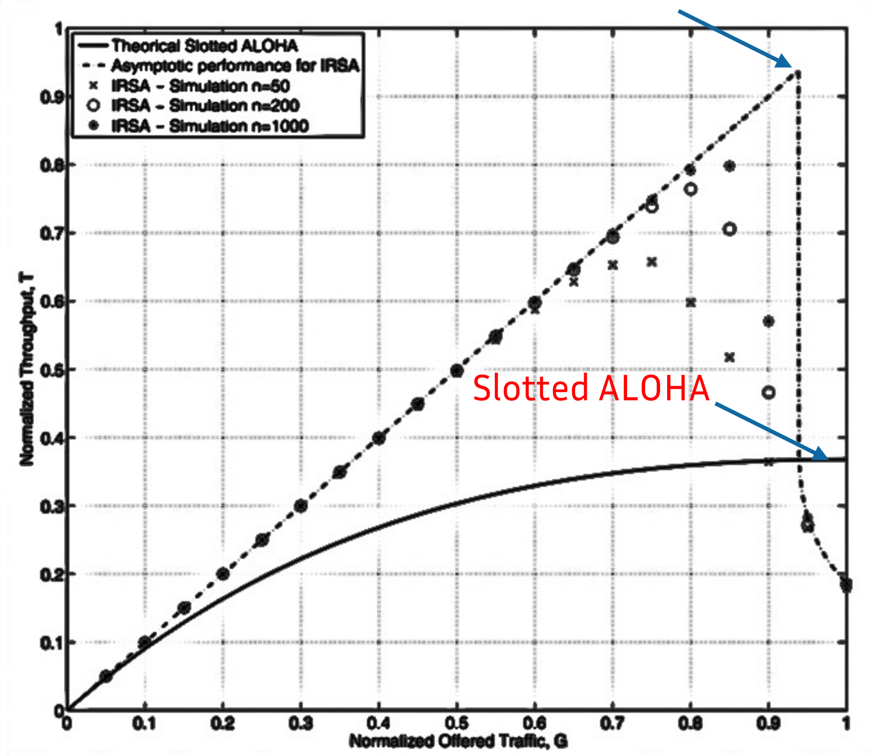
[1] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)

Inria

Irregular Repetition Slotted ALOHA (IRSA)

IRSA, numerically found distribution: 0.938



From [1]

TABLE I
THRESHOLDS COMPUTED FOR DIFFERENT DISTRIBUTIONS

Distribution, $\Lambda(x)$	G^*
$0.5102x^2 + 0.4898x^4$	0.868
$0.5631x^2 + 0.0436x^3 + 0.3933x^5$	0.898
$0.5465x^2 + 0.1623x^3 + 0.2912x^6$	0.915
$0.5x^2 + 0.28x^3 + 0.22x^8$	0.938
$0.4977x^2 + 0.2207x^3 + 0.0381x^4 + 0.0756x^5 + 0.0398x^6 + 0.0009x^7 + 0.0088x^8 + 0.0068x^9 + 0.0030x^{11} + 0.0429x^{14} + 0.0081x^{15} + 0.0576x^{16}$	0.965

From [1]: with Pr(d=2)=0.5; Pr(d=3)=0.28;Pr(d=8)=0.22

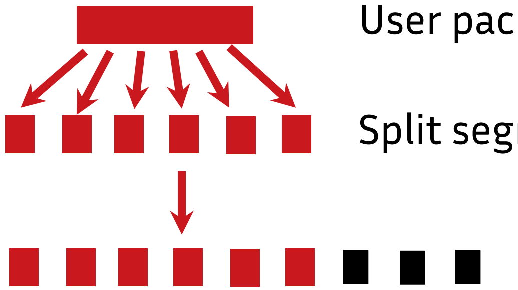
- Using an optimization method [1], differential evolution
- Good distribution: soliton distribution [2] -> towards 1 packet/slot
- (essentially p(k) ~ 1/(k (k-1))

[1] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)
[2] K.R. Narayanan and H.F. Pfister "Iterative collision resolution for slotted Aloha: An optimal uncoordinated transmission policy," 2012 7th International Symposium on Turbo Codes and Iterative Information Processing. Aug. 2012.

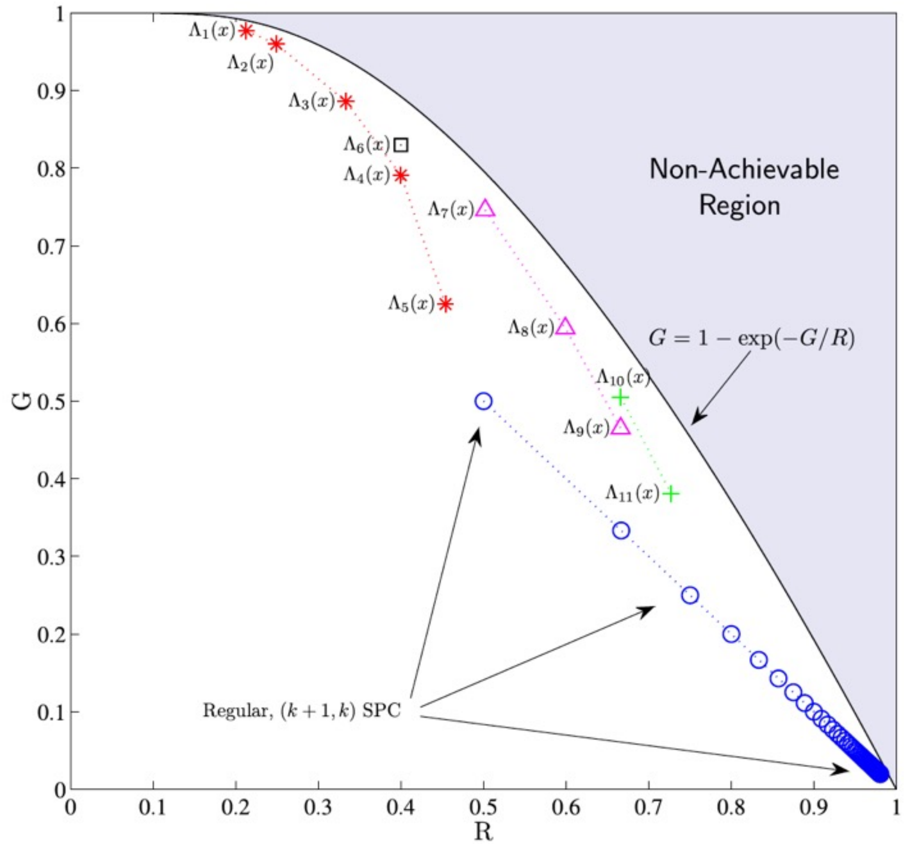
Variants, e.g. Coded Slotted Aloha

Variants

- "Coded" Slotted Aloha [1]
  - General error coding instead of repetition "code"
  - More codes-on-graphs: density evolution and EXIT charts
  - More distributions (with codes)
  - Bounds



From [1]



- Considering combining with capture and classical (same slot)-SIC

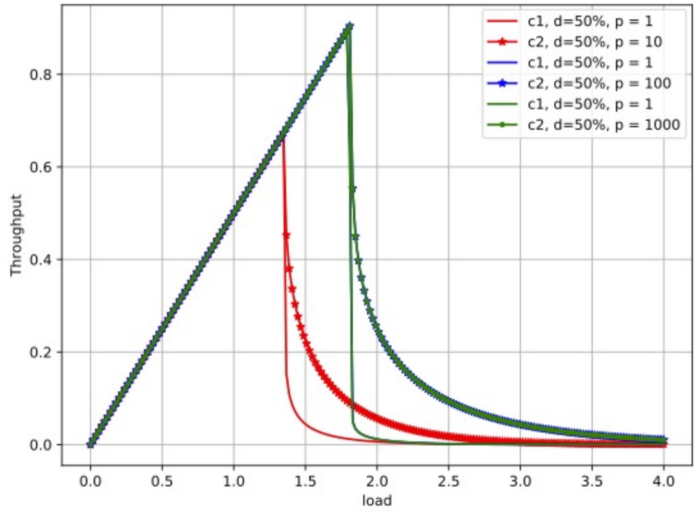
[1] Paolini, E., Liva, G., & Chiani, M. (2015). Coded slotted ALOHA: A graph-based method for uncoordinated multiple access. IEEE Transactions on Information Theory, 61(12), 6815-6832.

Variants, e.g. with fading/capture effect

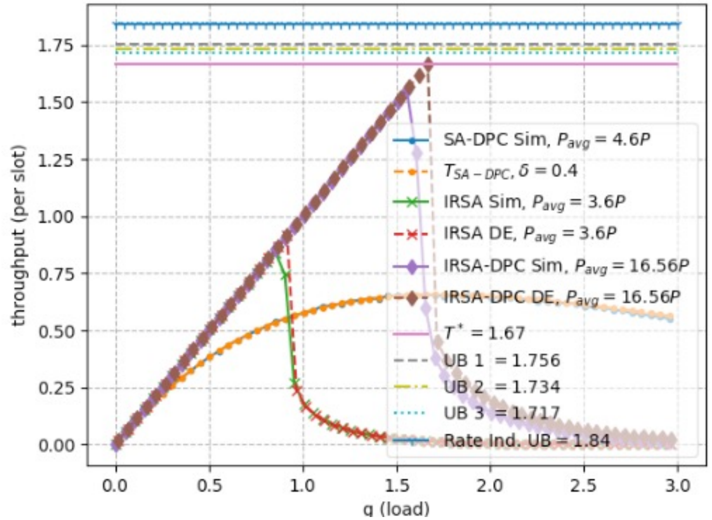
Variants

- ▶ What about taking into account capture effect ?
  - I.e. intra-slot SIC in addition to inter-slot SIC
  - I.e. power-domain NOMA
- ▶ Rayleigh Fading in [1]
- ▶ Near-Far Effect in [2]
- ▶ Density evolution [3] and optimization [4]

[3]



[4]



[1] C. Stefanovic, M. Momoda, P. Popovski, "Exploiting Capture Effect in Frameless Aloha for Massive Wireless Random Access", WCNC 2014
[2] E. E. Khaleghi, C Adjih, A. Alloum and P. Mühlethaler, "Near-Far Effect on Coded Slotted ALOHA", PIMRC 2017
[3] I. Hmedoush, C. Adjih, P. Mühlethaler, L. Salaün, "Multi-power irregular repetition slotted ALOHA in heterogeneous IoT networks", PEMWN 2020
[4] A. Kumar, P. Hegde, R. Vaze, A. Alloum, C. Adjih, "Breaking the Unit Throughput Barrier in Distributed Systems", NCC 2023

Irregular Repetition Slotted ALOHA with Diversity

With Multiple Packet Reception (K-MPR),

from [1]: $$p_i = 1 - \sum_{k=0}^{K-1} \frac{q_{i-1}^{k-1} \rho^{(k)}(q_{i-1})}{k!}$$ changed ←

$$q_i = \sum_r \lambda_r p_i^{r-1} = \lambda(p_i)$$

What are good $\Lambda(x)$?

Can we reach K packets per slot ?

[1]. Ghanbarinejad and C. Schlegel, “Irregular Repetition Slotted ALOHA with Multiuser Detection,” in Wireless On-demand Network Systems and Services (WONS), March 2013, pp. 201–205.
[2]. C. Stefanovic, E. Paolini, and G. Liva, “Asymptotic Performance of Coded Slotted ALOHA With Multipacket Reception,” IEEE Communications Letters, vol. 22, no. 1, pp. 105–108, Jan. 2018.
[3] I Hmedoush, C Adjih, P Mühlethaler, V. Kumar “On the Performance of Irregular Repetition Slotted Aloha with Multiple Packet Reception”, IWCMC 2020
[4] S.L. Shieh, S.H. Yang, “Enhanced irregular repetition slotted ALOHA under SIC limitation”, IEEE Transactions on Communications, 2022
[5] M Fernández-Veiga, ME Sousa-Vieira, A Fernández-Vilas, RP Díaz-Redondo, “Irregular repetition slotted Aloha with multiuser detection: A density evolution analysis”, Computer Networks, Oct. 2023

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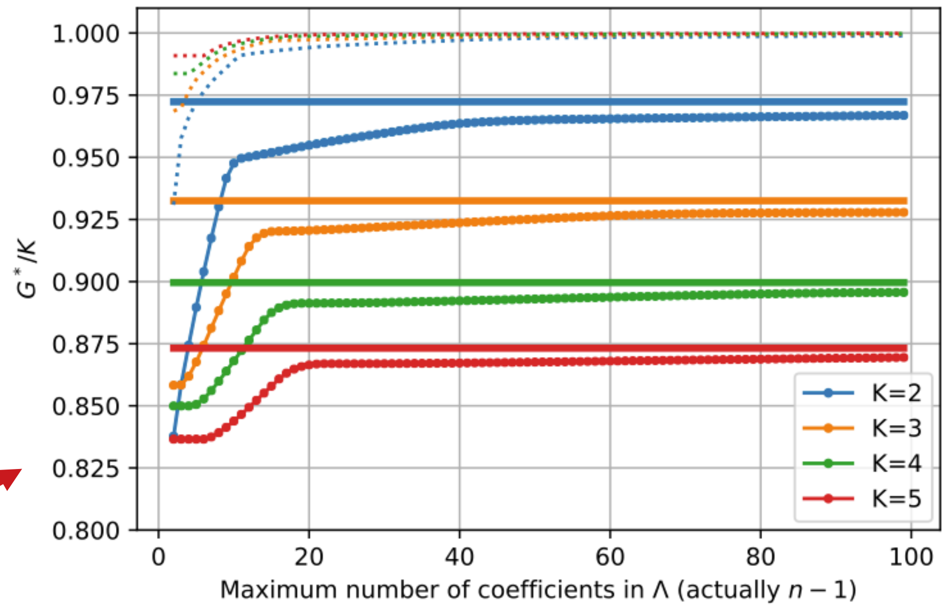

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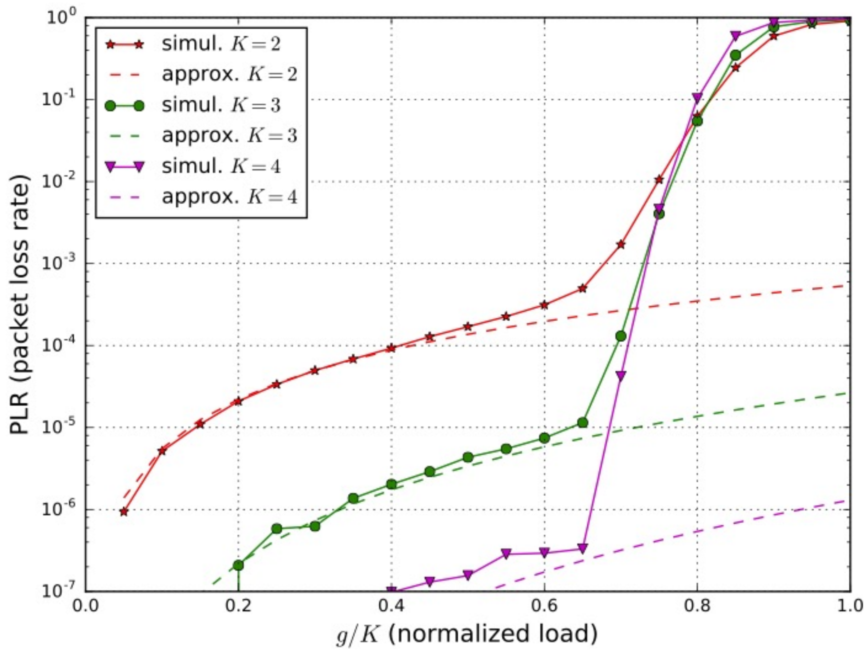

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[4] S.L. Shieh, S.H. Yang, “Enhanced irregular repetition slotted ALOHA under SIC limitation”, IEEE Transactions on Communications, 2022

[5] M Fernández-Veiga, ME Sousa-Vieira, A Fernández-Vilas, RP Díaz-Redondo, “Irregular repetition slotted Aloha with multiuser detection: A density evolution analysis”, Computer Networks, Oct. 2023

NOMA

2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)

Throughput Analysis of PDMA/IRSA under Practical Channel Estimation

Chirag Ramesh Srivatsa and Chandra R. Murthy

IEEE COMMUNICATIONS LETTERS, VOL. 23, NO. 4, APRIL 2019

NOMA-Based Irregular Repetition Slotted ALOHA for Satellite Networks

Xinye Shao, *Student Member, IEEE*, Zhili Sun, *Senior Member, IEEE*, Mingchuan Yang, *Member, IEEE*, Sai Gu, and Qing Guo, *Member, IEEE*

Towards More Realistic IRSA?

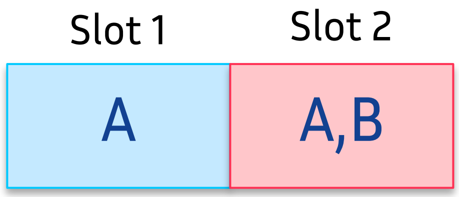
- Two issues with IRSA
  - Perfect SIC is not realistic
  - Density evolution is for large frame sizes
  - (*)

- Ideal models: upper bound
  - More realistic models?
  - Implementation: lower bound

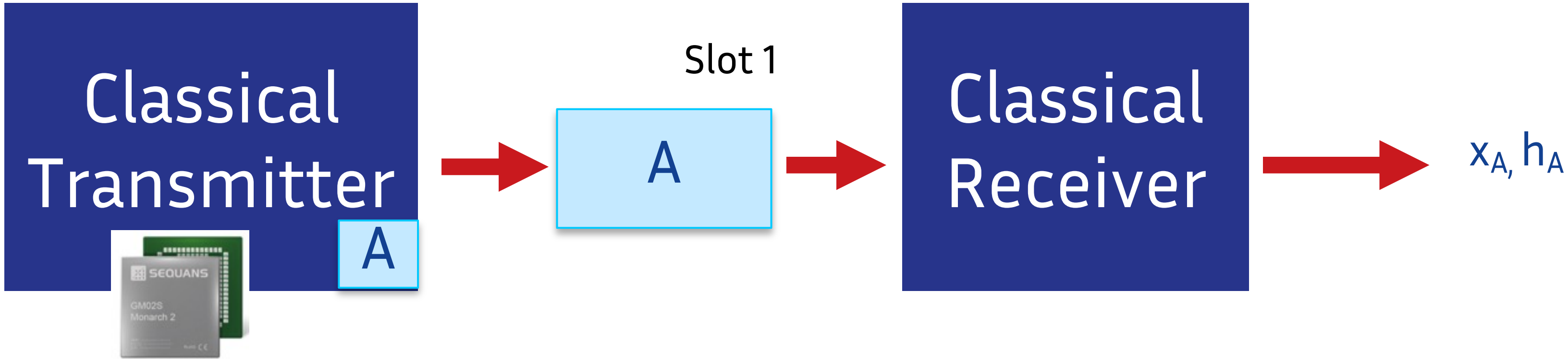
(*) Also arrivals are Poisson

03
Towards More Realistic IRSA?

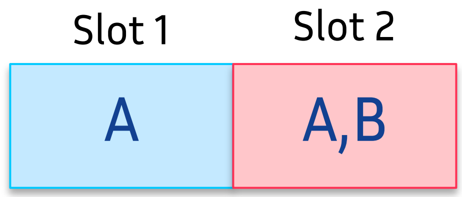
« Receiver-Only » IRSA?



- Idea: keep a traditional transmitter, and change only the receiver
- Question: what is the performance?



« Receiver-Only » IRSA?



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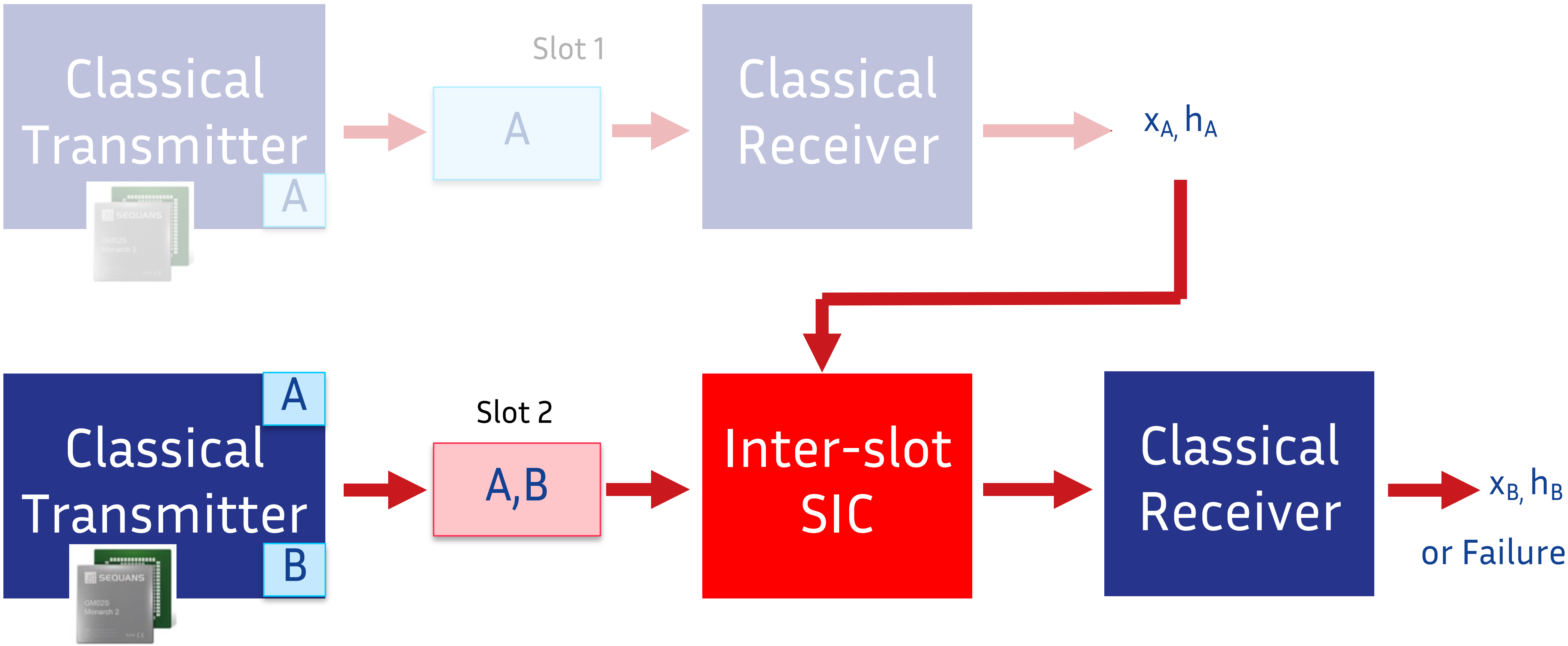
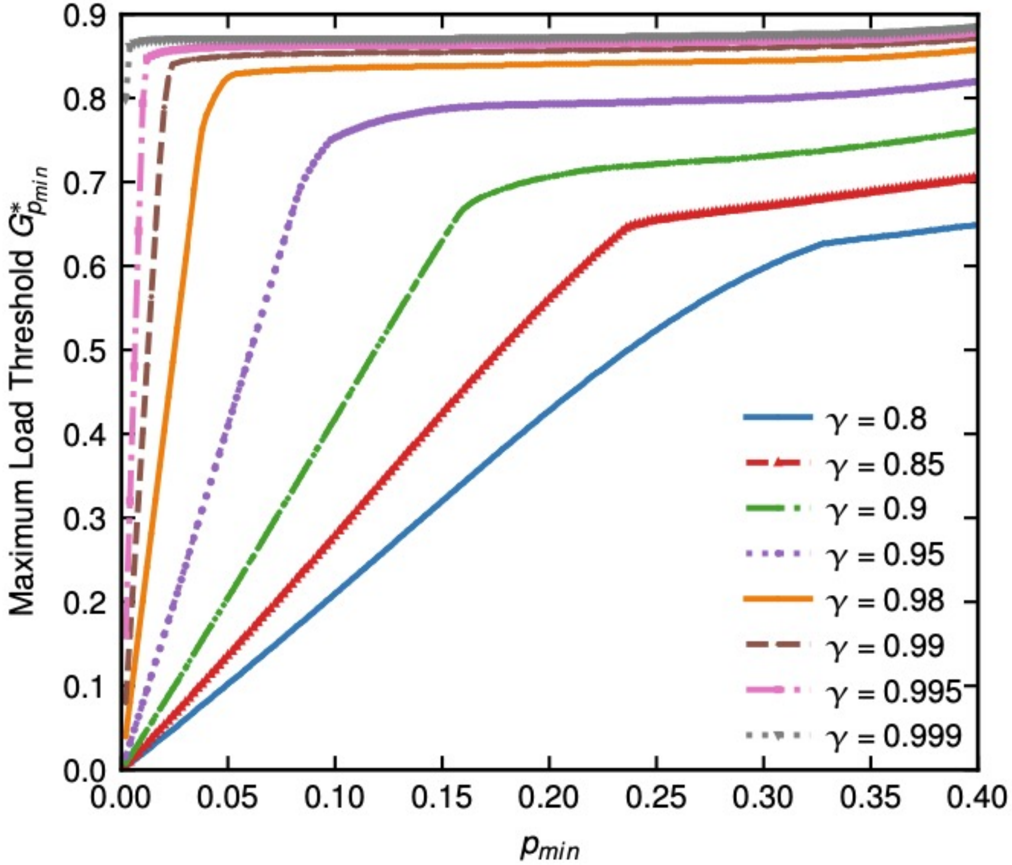


Towards More Realistic IRSA?

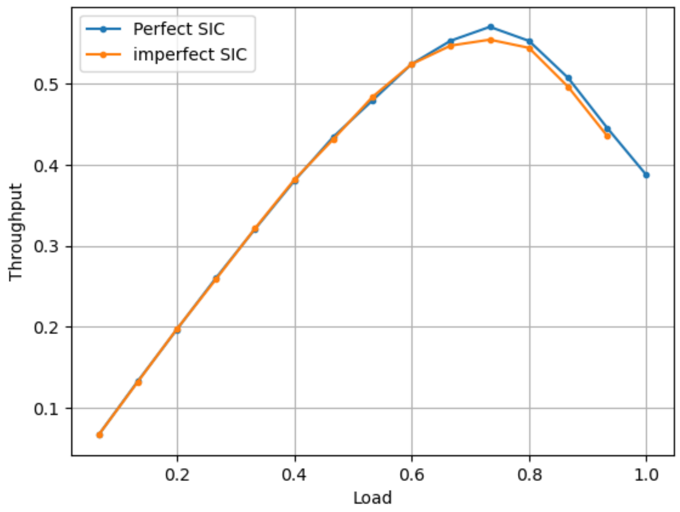
- [1] fixed probability of inter-slot SIC failure

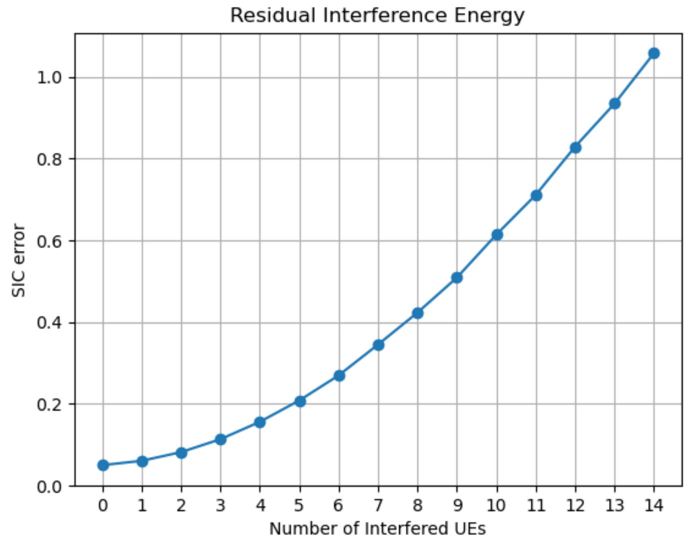


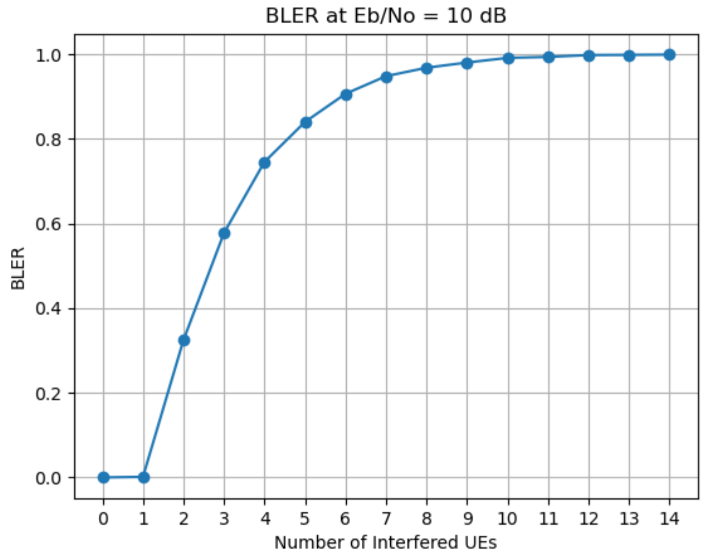
[1] C. Dumas, L. Salaün, I. Hmedoush, C. Adjih, C.S. Chen “Design of coded slotted ALOHA with interference cancellation errors” IEEE Transactions on Vehicular Technology, 2021

Simulations

- On-going work (S. Alsabbagh, A. Adouane, N. Ait-Saadi), by simulation but with « classical transmitter » (5G, OFDM, modulation, channel codes, ...) in base-band signal







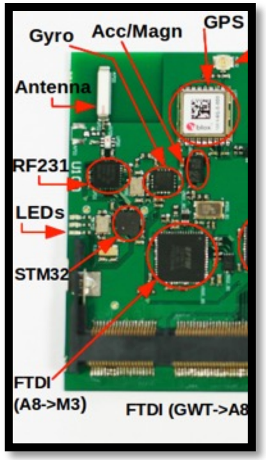
- What is the best Inter-SIC slot technique (how to model the performance)

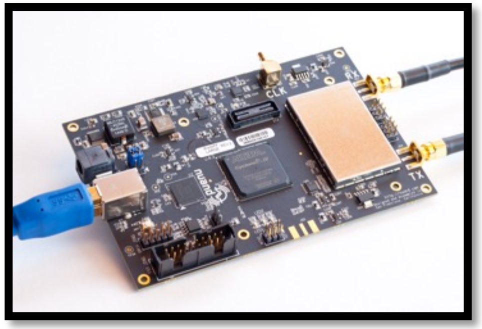
[1] C. Dumas, L. Salaün, I. Hmedoush, C. Adjih, C.S. Chen “Design of coded slotted ALOHA with interference cancellation errors” IEEE Transactions on Vehicular Technology, 2021

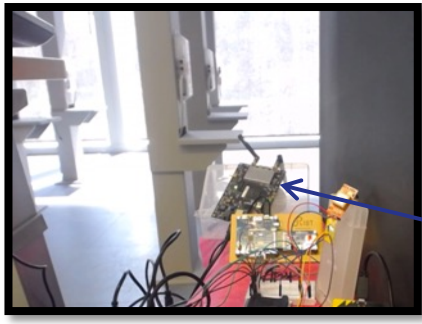
Experimenting with Irregular Repetition Slotted ALOHA (IRSA) On testbed FIT IoT-LAB (Saclay)

http://iot-lab.info/

- ▶ 21 IoT nodes of FIT IoT-LAB
  - ARM Cortex-M3 (512 kB Flash, 64 kB RAM)
  - 802.15.4 radio
- ▶ One software defined radio
  - BladeRF (16 Msps, 12 bits)
- ▶ Future choice:
  - CorteXlab (full SDR) @Lyon





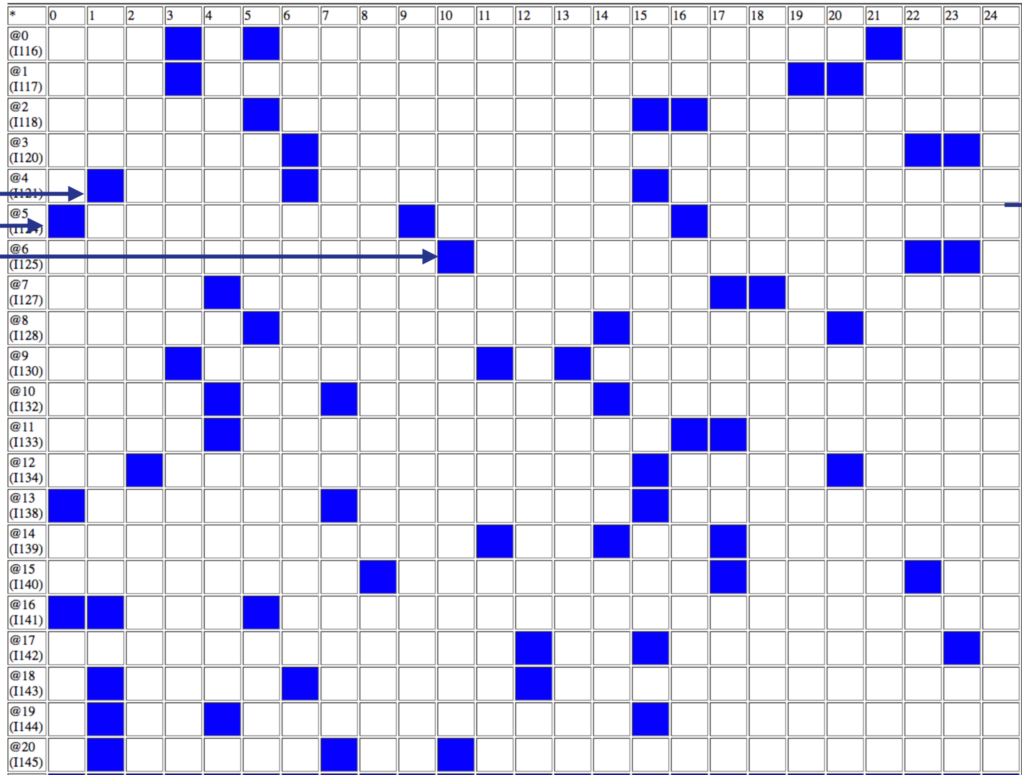


116	119	122	125	128	131	134	137	140	143
117	120	~~123~~	~~126~~	~~129~~	132	135	138	141	144
118	121	124	127	130	133	136	139	142	145

SDR

[1] https://www.silecs.net/1st-grid5000-fit-school/program/experimenting-coded-slotted-aloha-work-in-progress/

Experimenting with IRSA



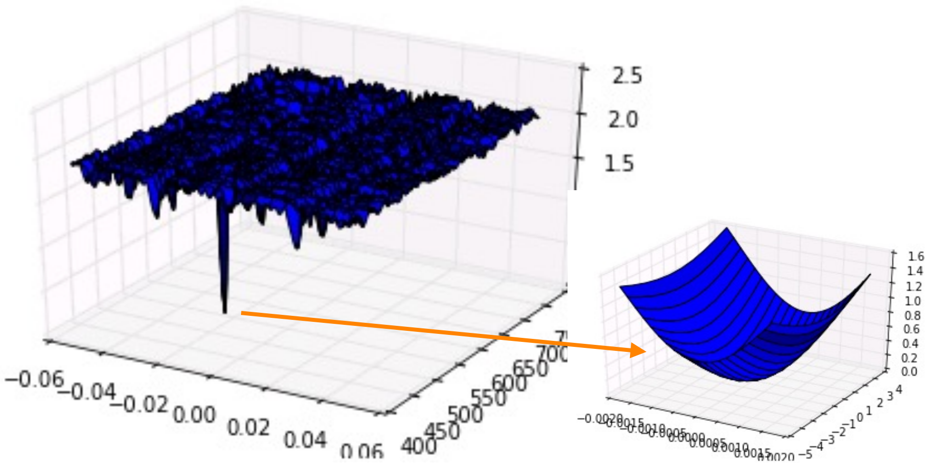
Offline (SDR) data post-processing

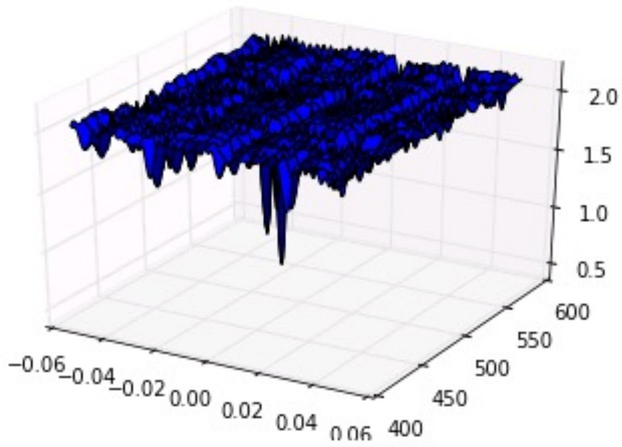
- 21 nodes
- 24 slots

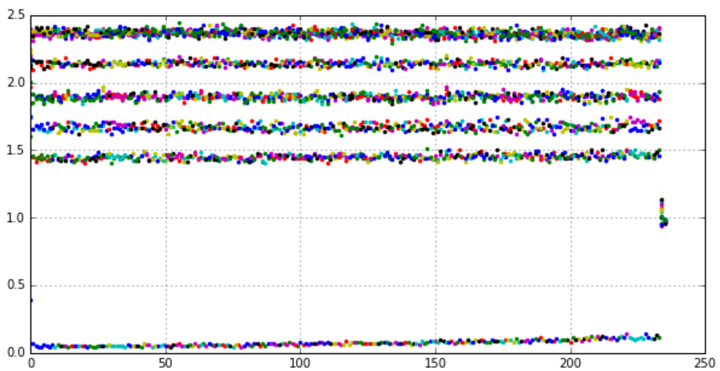
10 ms slot (actual packet: 3.744 ms)

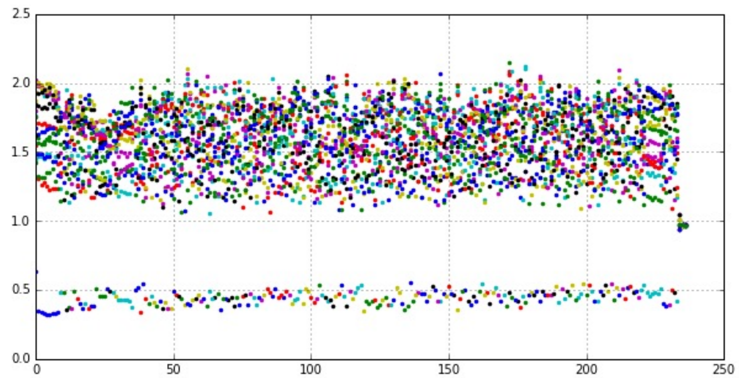
Experimenting with IRSA
Slot 2 (@12) vs Slot 11 (packet @9)

Find 802.15.4 phy header → Time Offset, Carrier Frequency Offset, Phase, Gain → Demodulation MMSE chip

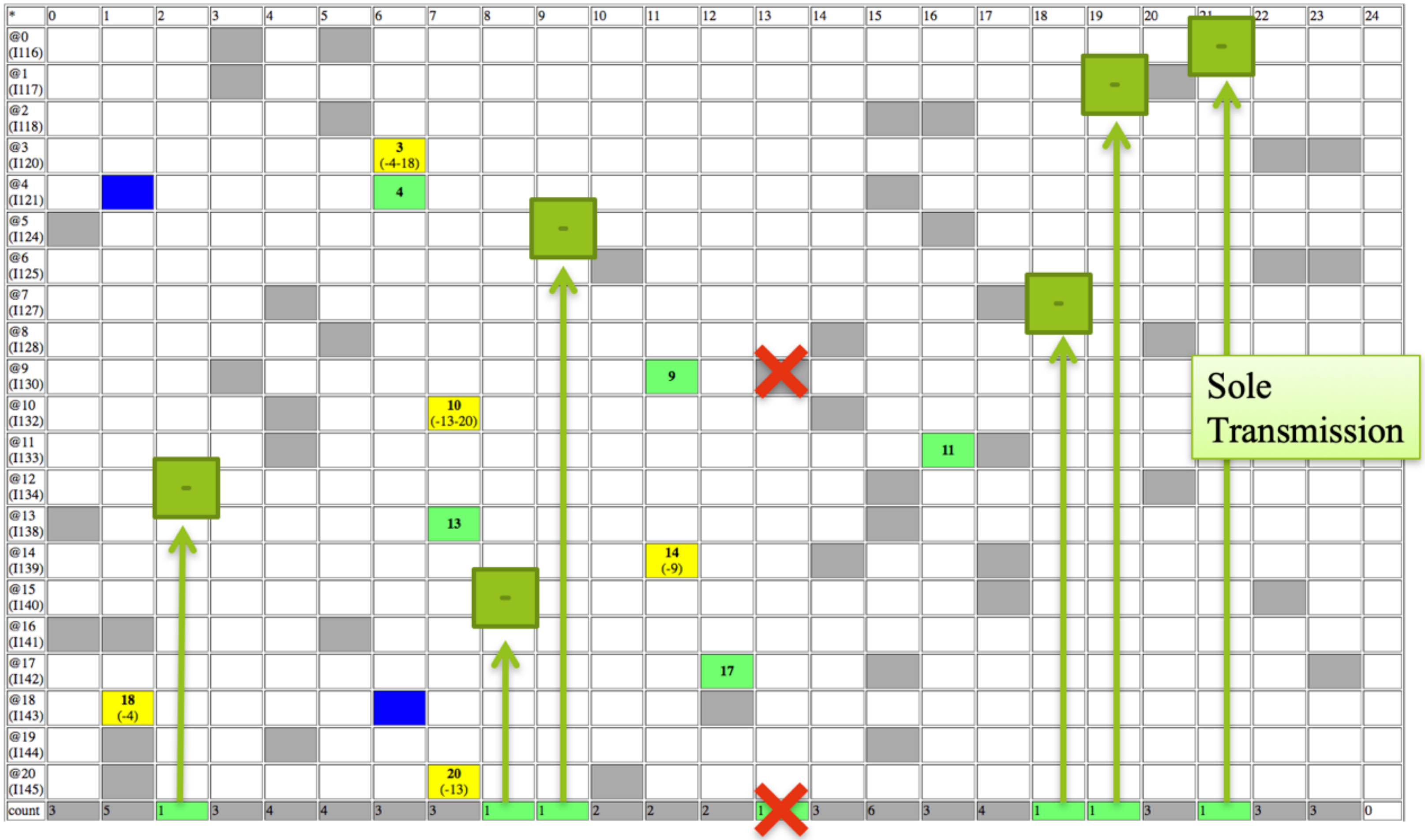




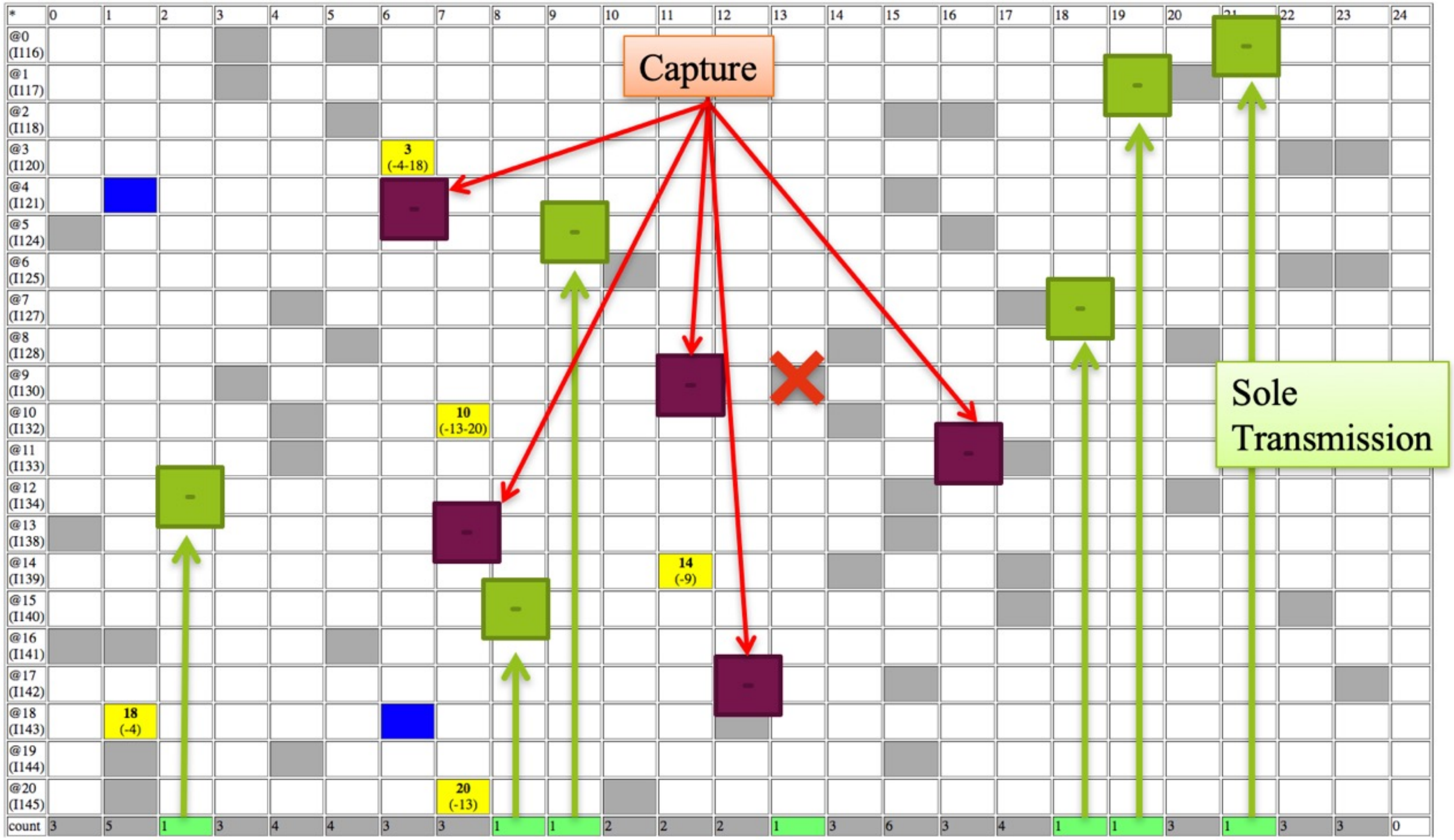




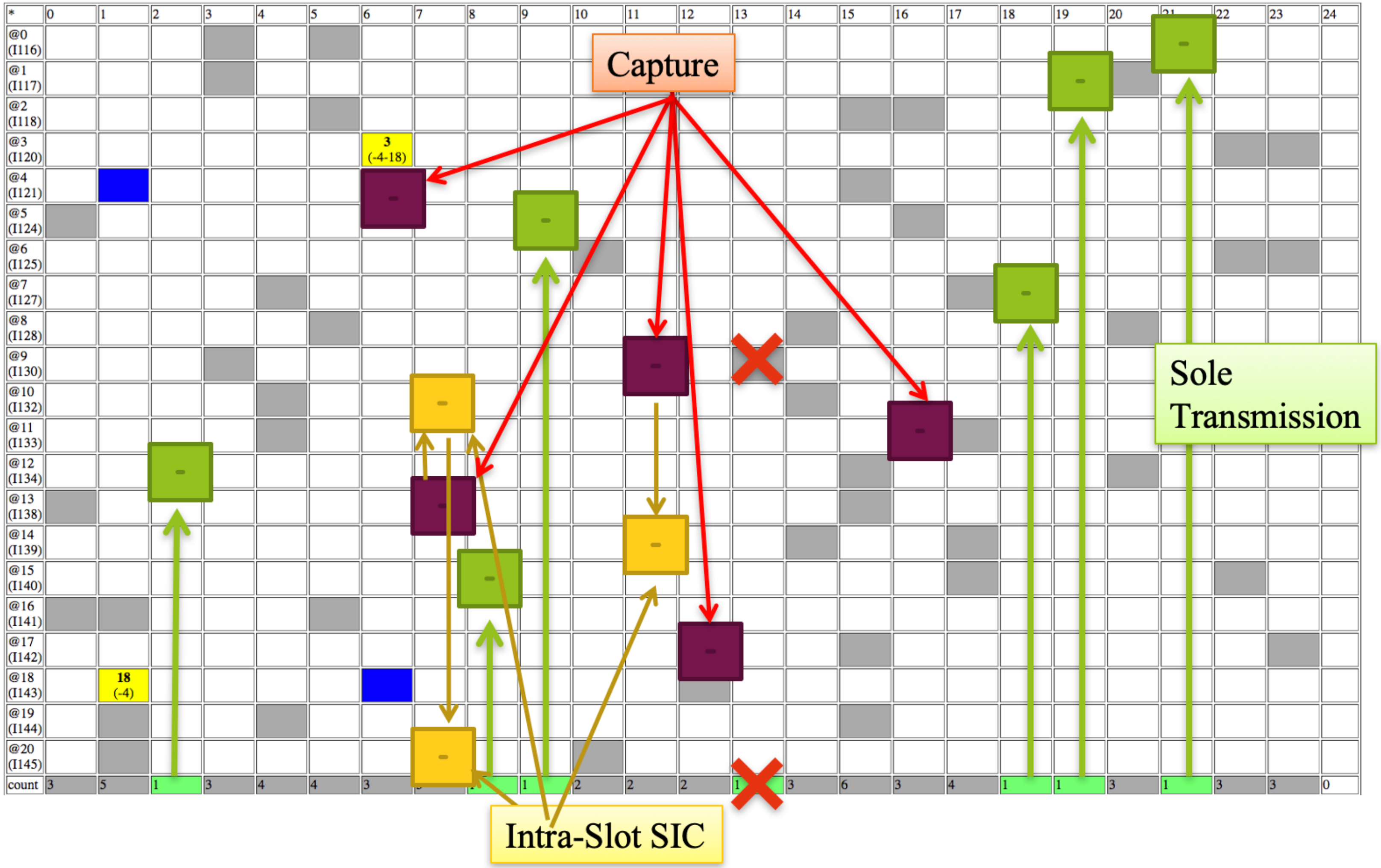
Experimenting with IRSA – Recovered 6 (/21)



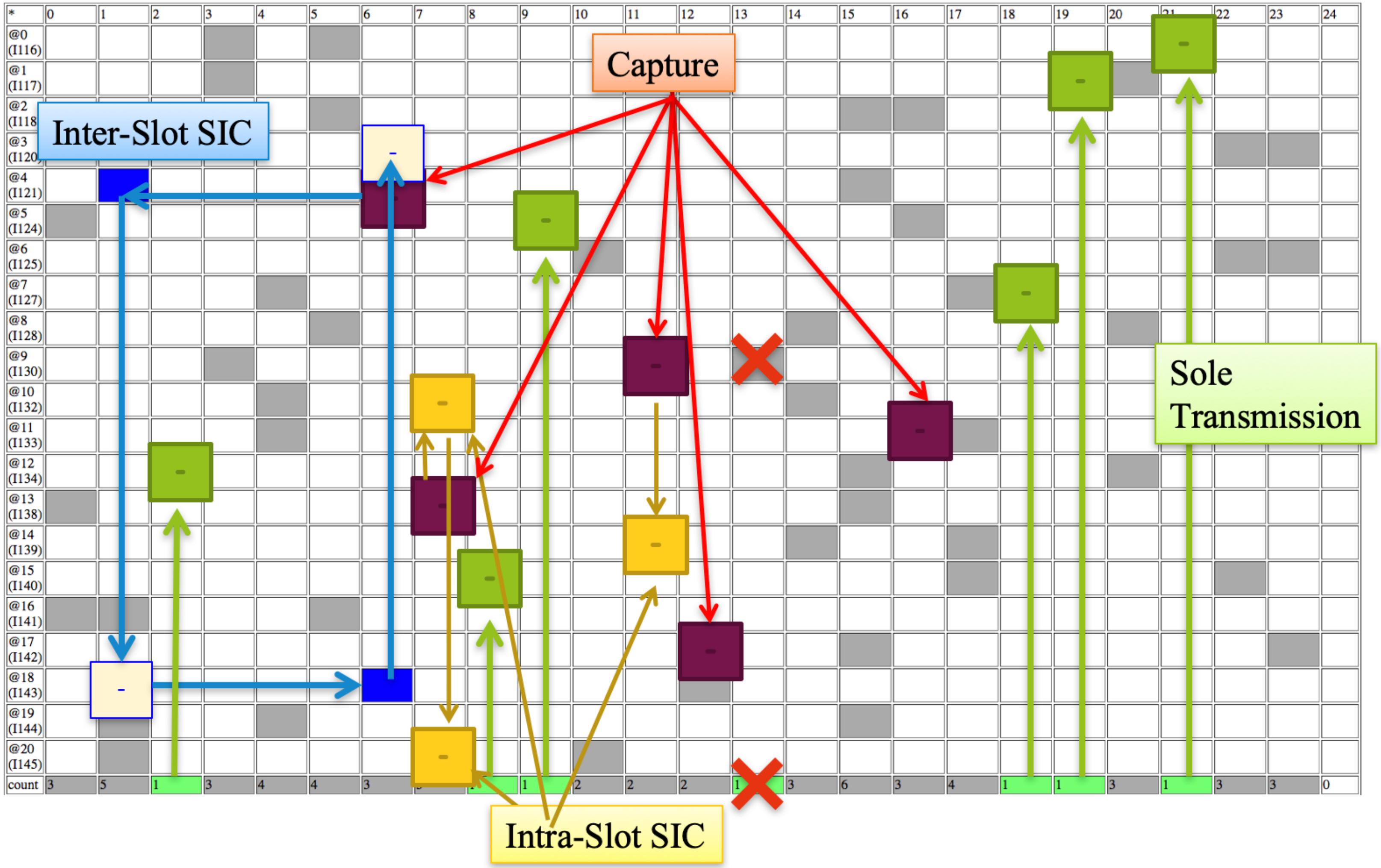
Experimenting with IRSA – Recovered 6+5 (/21)



Experimenting with IRSA – Recovered 6+5+3 (/21)



Experimenting with IRSA – Rec. 6+5+3+[1+1] = 16 (/21)



Towards More Realistic IRSA?

Objectives

- More realistic model of IRSA for cellular, in particular ,
  - Actual evaluate: similarity multiple repetions of the packets (channel, rx/tx), and frequency selectivity
  - Inter-slot SIC and residual errors [1]
- Possibly explore (better) inter-slot SIC methods, and IRSA variants

Experimentations

- CortexLAB

Complementary external work

- Simulations with realistic channel

04

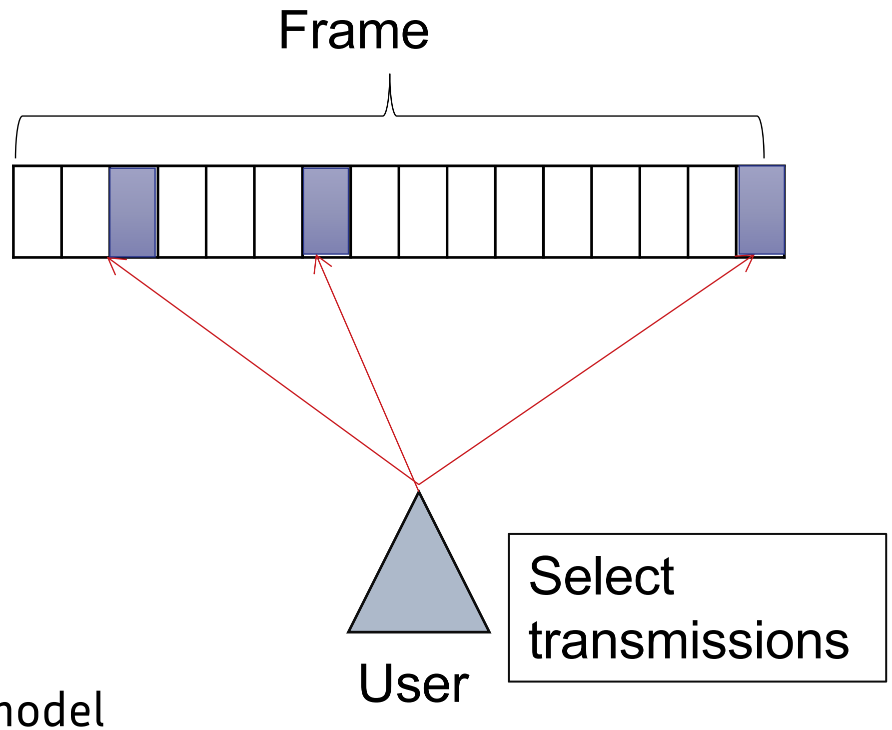
AI/ML-Aided Modern Random Access*

* with Deep Reinforcement Learning

Motivation for AI/ML-Aided Modern Random Access

Why AI/ML ?

- Performance issues
  - Especially in shorter frames, Poisson Traffic, etc.
- Beyond degree distributions: codebooks
- Improving performance with side information
  - Passively (e.g. Frameless)
  - Actively (e.g. Interacting)
- Methods that can be adapted to any channel/SIC model



Motivation for AI/ML-Aided Modern Random Access

Several Approaches:

- Many in the literature, including with AlphaSeq

- Reinforcement Learning (Regret Minimization) for degree distribution (and classes of user) [1]
- Deep Reinforcement Learning (DRL) and degree selection (and classes of user) [2]
- DRL+ Slot selection (codebook) [3]
- DRL + Slot interaction protocol + slot selection [3,4]
- DRL + Slot selection with multi-power (i.e. intra-slot SIC) [5]

[1] I. Hmedoush, C. Adjih and P. Mühlethaler, “A Regret Minimization Approach to Frameless Irregular Repetition Slotted Aloha: IRSA-RM, International Conference on Machine Learning for Networking”, Nov. 2020, France.
[2] Ibrahim Ayoub, Iman Hmedoush, Cédric Adjih, Kinda Khawam and Samer Lahoud, “Deep-IRSA: A Deep Reinforcement Learning Approach to Irregular Repetition Slotted ALOHA", PEMWN 2021, Nov. 2021.
[3] I. Hmedoush, C. Adjih, P. Mühlethaler “Deep learning, sensing-based IRSA (DS-IRSA): Learning a sensing protocol with deep reinforcement learning”, Inria Research Report RR9479, sept 2022
[4] I. Hmedoush, P. Gu, C. Adjih, P. Mühlethaler & A. Serhrouchni “DS-IRSA: A Deep Reinforcement Learning and Sensing Based IRSA”, GLOBECOM 2023,
[5] Jia Cao, “Design of Random Access Protocols with Neural Networks for the Internet of Things”, ENSTA Internship Report, unpublished, Aug. 2023

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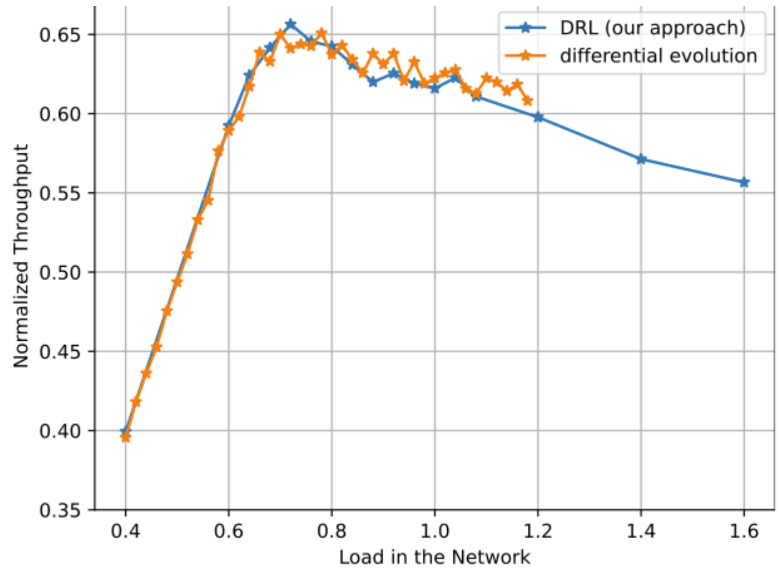
Frame size = 50



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[2] Ibrahim Ayoub, Iman Hmedoush, Cédric Adjih, Kinda Khawam and Samer Lahoud, "Deep-IRSA: A Deep Reinforcement Learning Approach to Irregular Repetition Slotted ALOHA", PEMWN 2021, Nov. 2021.

[3] I. Hmedoush, C. Adjih, P. Mühlethaler "Deep learning, sensing-based IRSA (DS-IRSA): Learning a sensing protocol with deep reinforcement learning", Inria Research Report RR9479, sept 2022

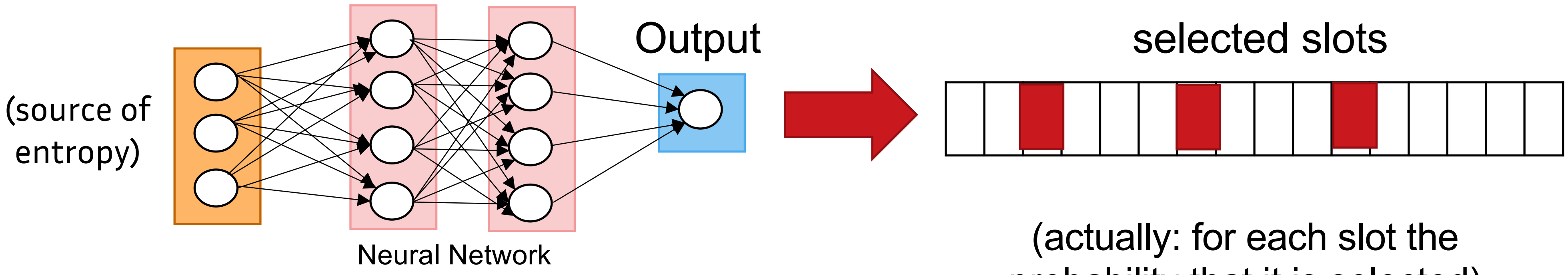
[4] I. Hmedoush, P. Gu, C. Adjih, P. Mühlethaler & A. Serhrouchni "DS-IRSA: A Deep Reinforcement Learning and Sensing Based IRSA", GLOBECOM 2023,

[5] Jia Cao, "Design of Random Access Protocols with Neural Networks for the Internet of Things", ENSTA Internship Report, Aug. 2023

IRSA + DRL (Deep-RC-IRSA)

Deep-“Random Codeword”-IRSA (Deep-RC-IRSA)

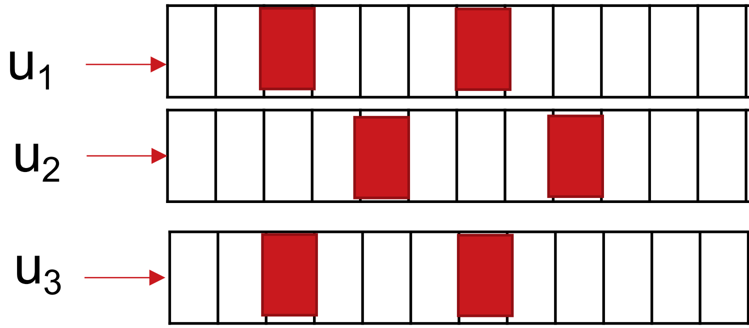
- Model: output the selected slots. Same model for everyone



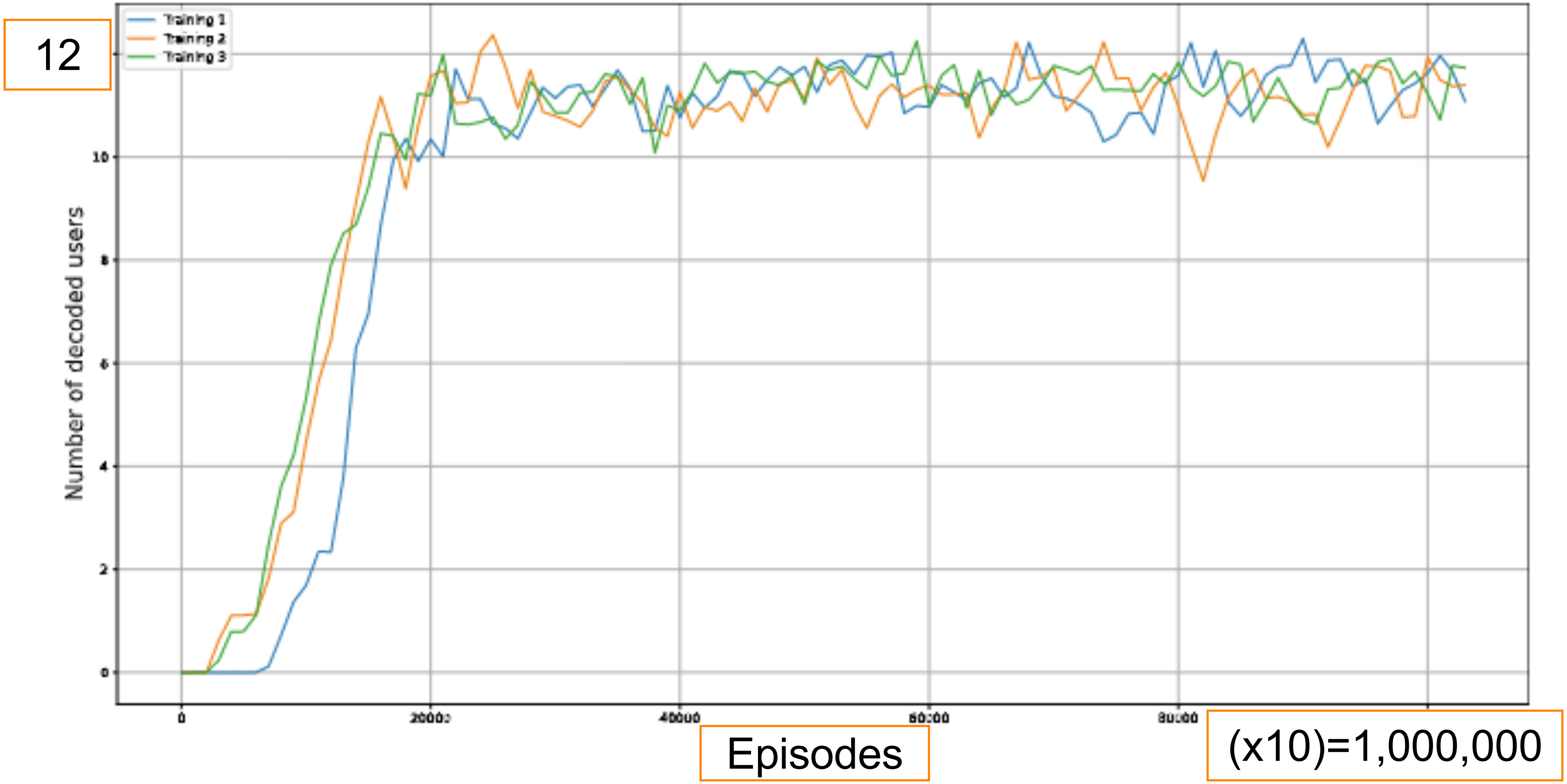
(actually: for each slot the probability that it is selected)

- Deep Reinforcement Learning (DRL)
  - Neural Network with weights θ (policy)
  - Optimize objective function J(θ) = E(decoded users)
  - Policy Gradient Method: $\nabla_\theta J(\theta) = E_\pi[\nabla_\theta(log\pi(\tau|\theta))R(\tau)]$

    Policy function — Score function
  - Proximal Policy Optimization (PPO, impl. “stable baselines”)
- Short-episode DRL



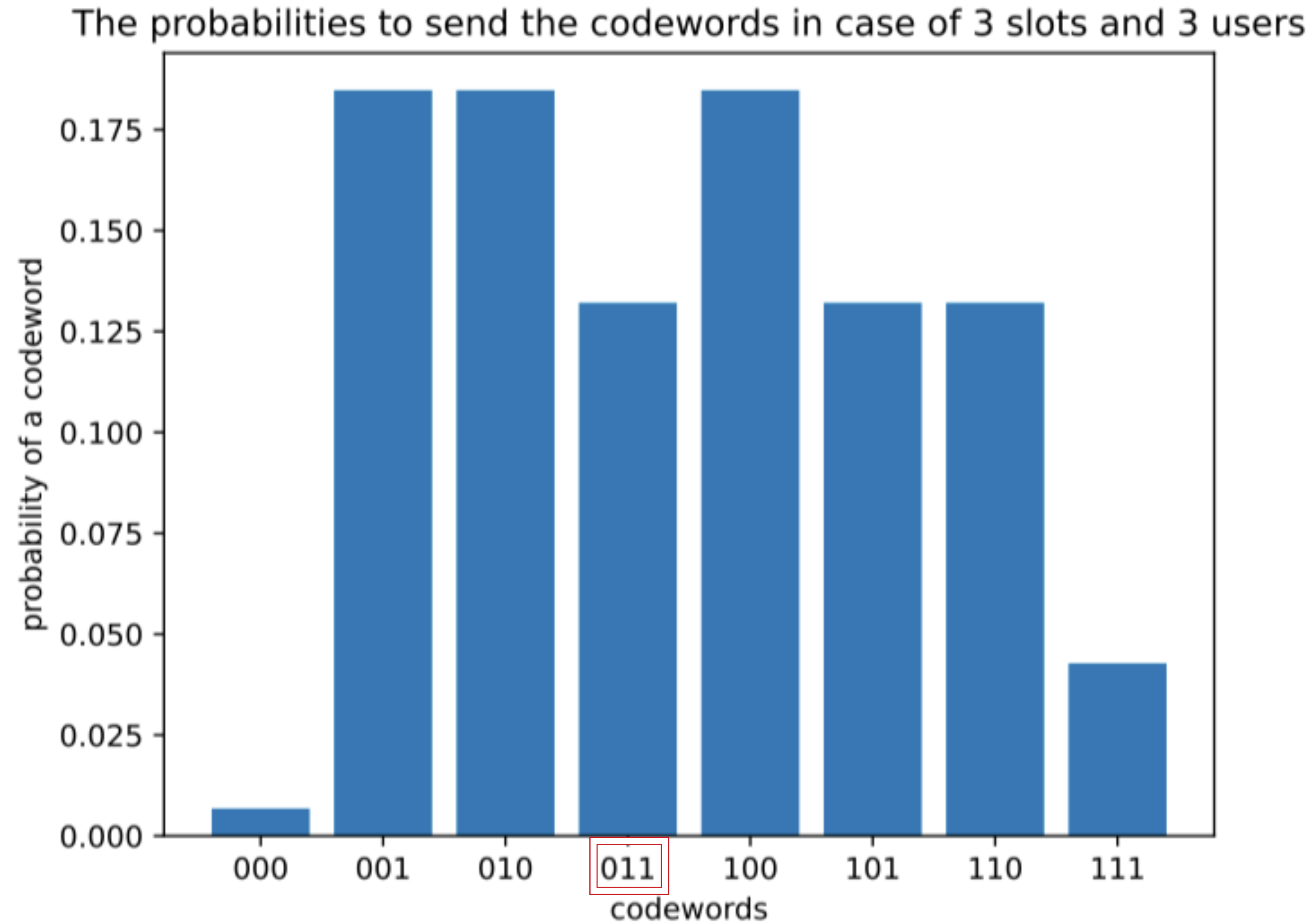
IRSA + DRL (Deep-RC-IRSA)



(c) 25 users and 25 slots

[1] I. Hmedoush, C. Adjih, P. Mühlethaler "Deep learning, sensing-based IRSA (DS-IRSA): Learning a sensing protocol with deep reinforcement learning", Inria Research Report RR9479, sept 2022

IRSA + DRL (Deep-RC-IRSA)



Ex: prob of transmission on the last 2 slots [0, 1, 1]

IRSA + DRL (Deep-RC-IRSA)

Optimal + Codewords

users \ slots	2	3	4	5	6
2	1.333332	1.714285	1.866634	1.935483	1.968247
3	0.969525	1.673334	2.288013	2.615522	2.791376
4	0.899124	1.440759	2.082369	2.789802	3.278239
5	0.864823	1.367171	1.922436	2.546374	–

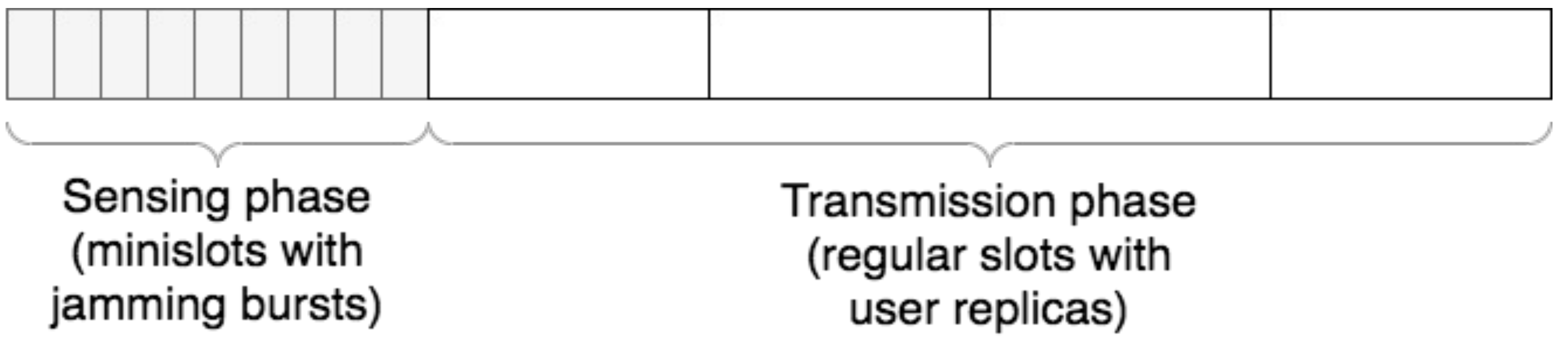
Deep RC IRSA

users \ slots	2	3	4	5	6
2	1.333117	1.701885	1.853383	1.927235	1.959373
3	0.967106	1.658842	2.271073	2.581683	2.754746
4	0.897425	1.436308	2.065276	2.724494	3.208501
5	0.857731	1.361922	1.908074	2.536552	3.160870

IRSA with Sensing + DRL (DS-IRSA)

DS-IRSA: adding a sensing phase before IRSA transmission.

Affordable to synchronize the nodes / avoid collisions?

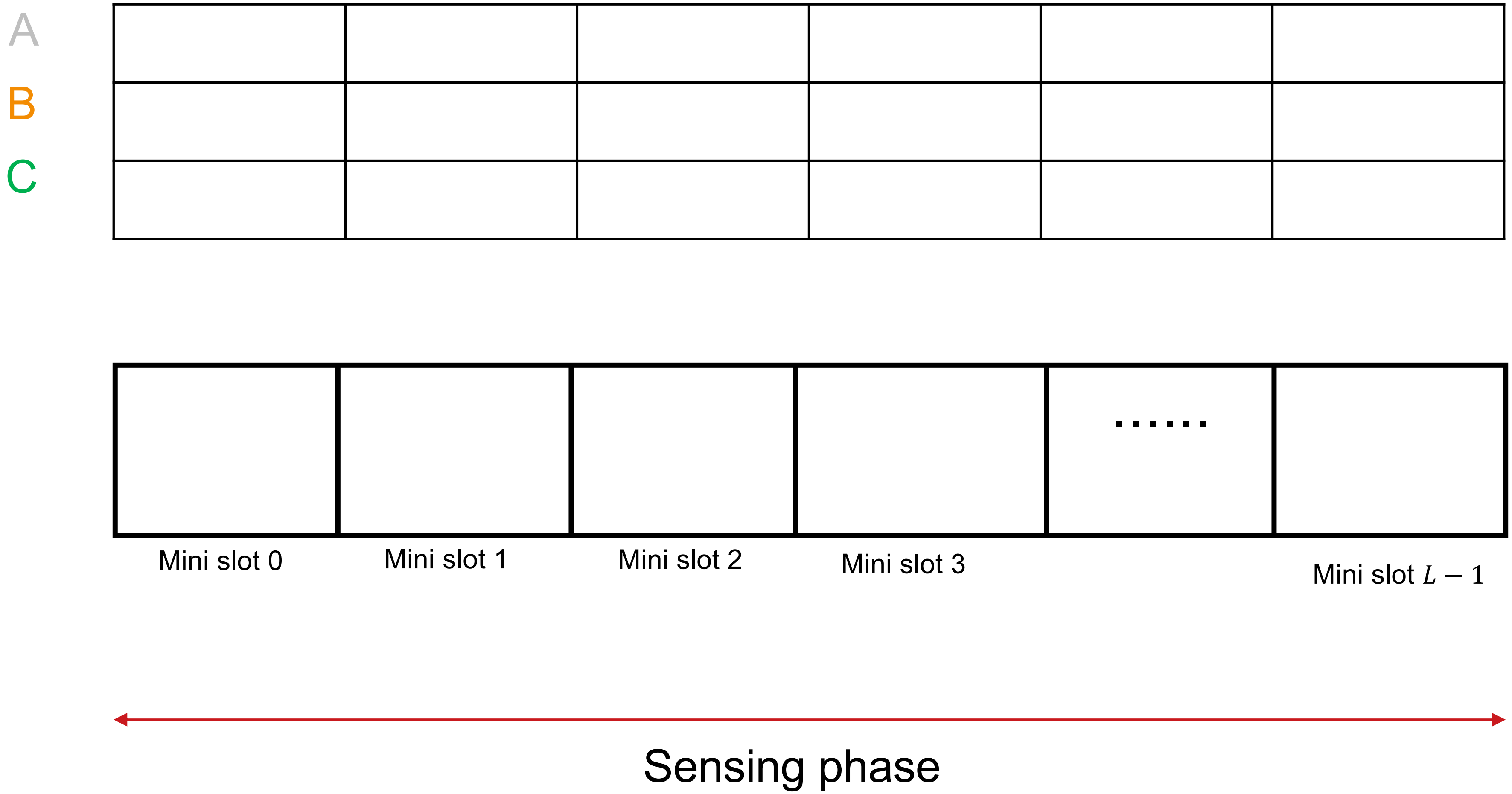


IRSA with Sensing, Sensing-based IRSA, S-IRSA

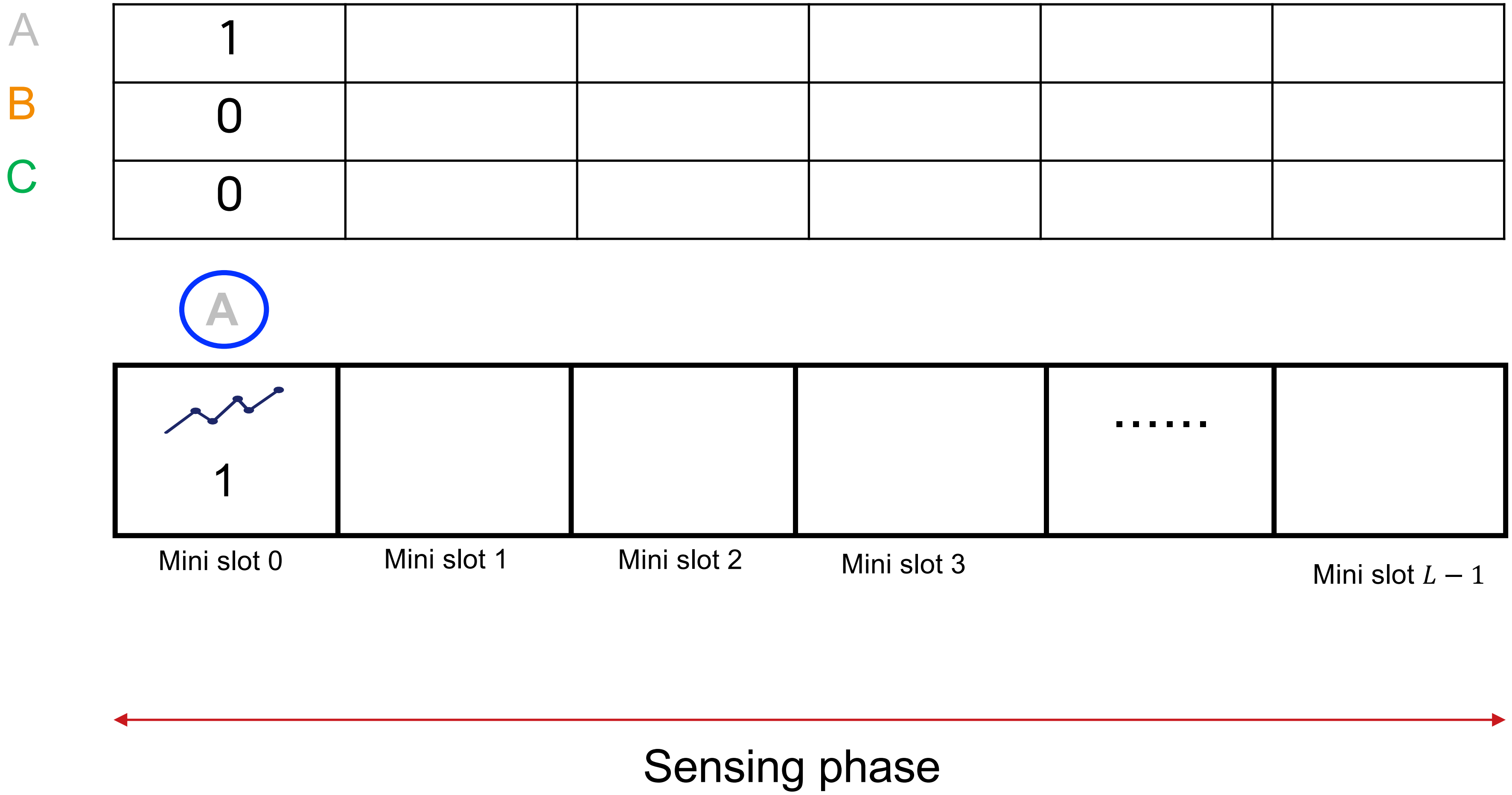
- Sensing Phase: Similar to Carrier Sense Multiple Access (CSMA)
  - Send jamming « burst » or not

- Transmission Phase: as before

IRSA with Sensing + DRL (DS-IRSA)

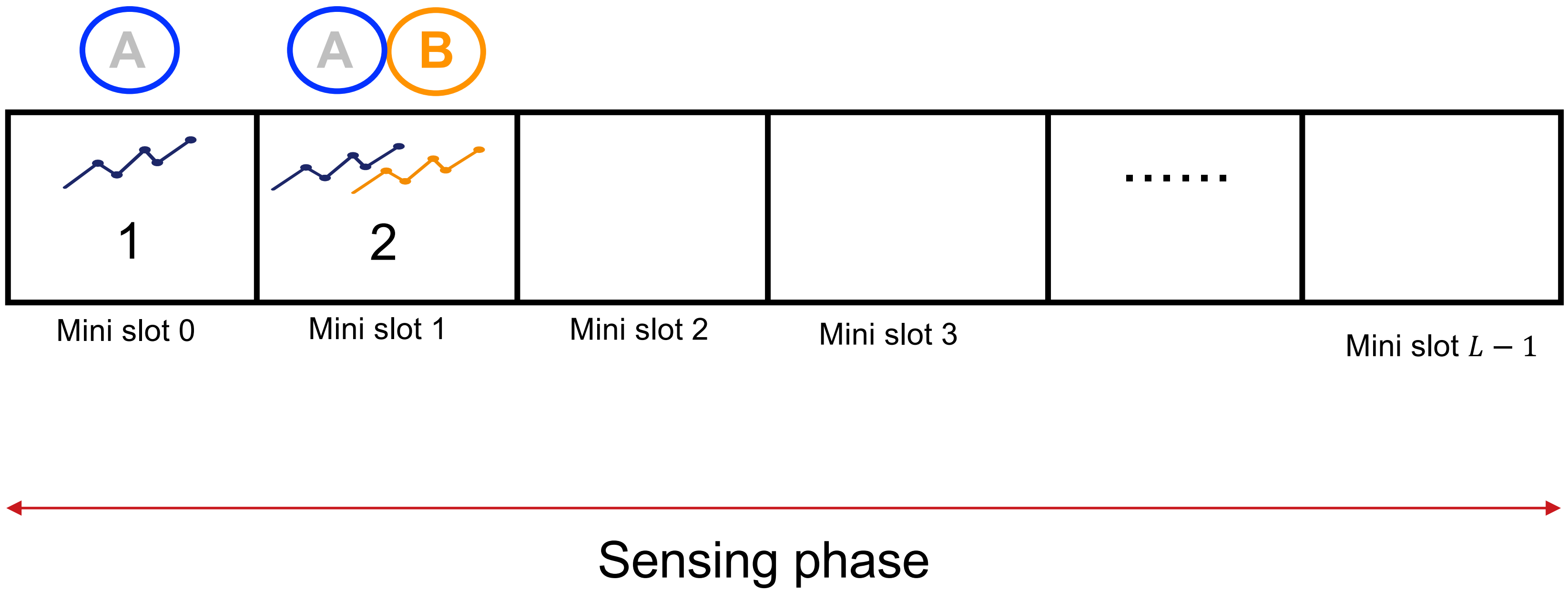


IRSA with Sensing + DRL (DS-IRSA)



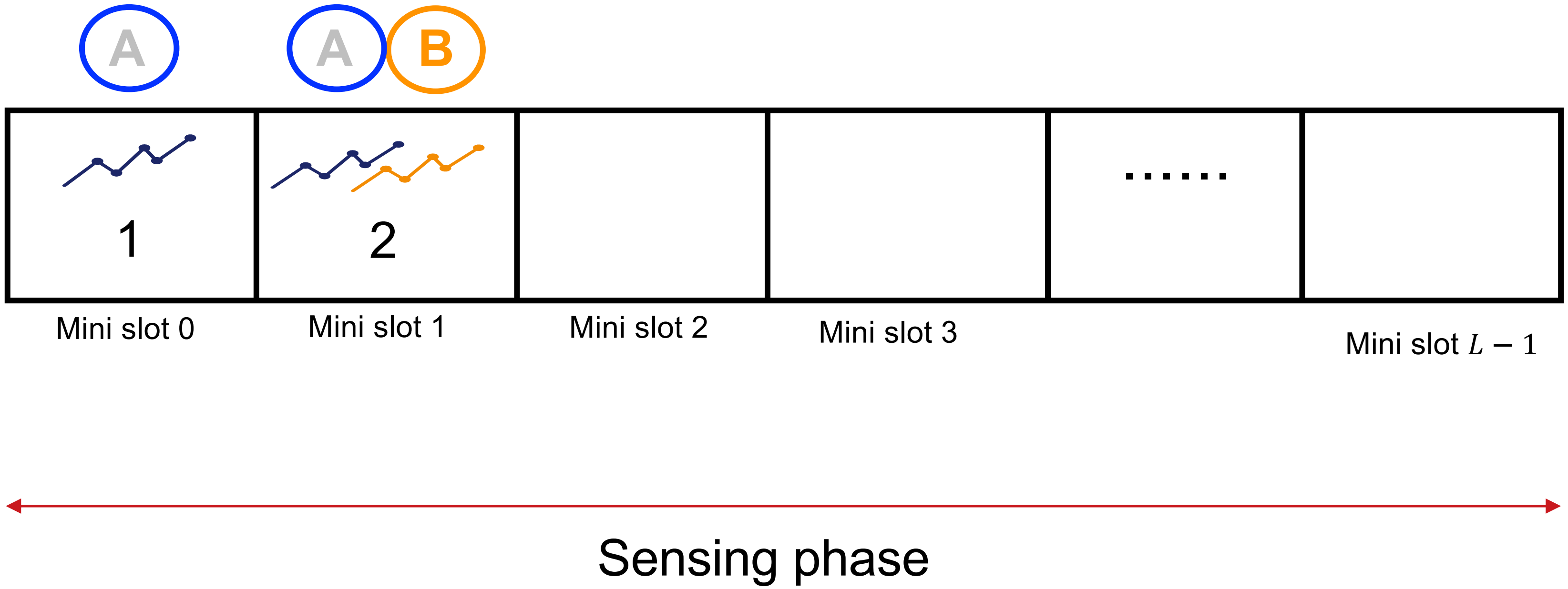
IRSA with Sensing + DRL (DS-IRSA)

A	1	1				
B	0	1				
C	0	0				



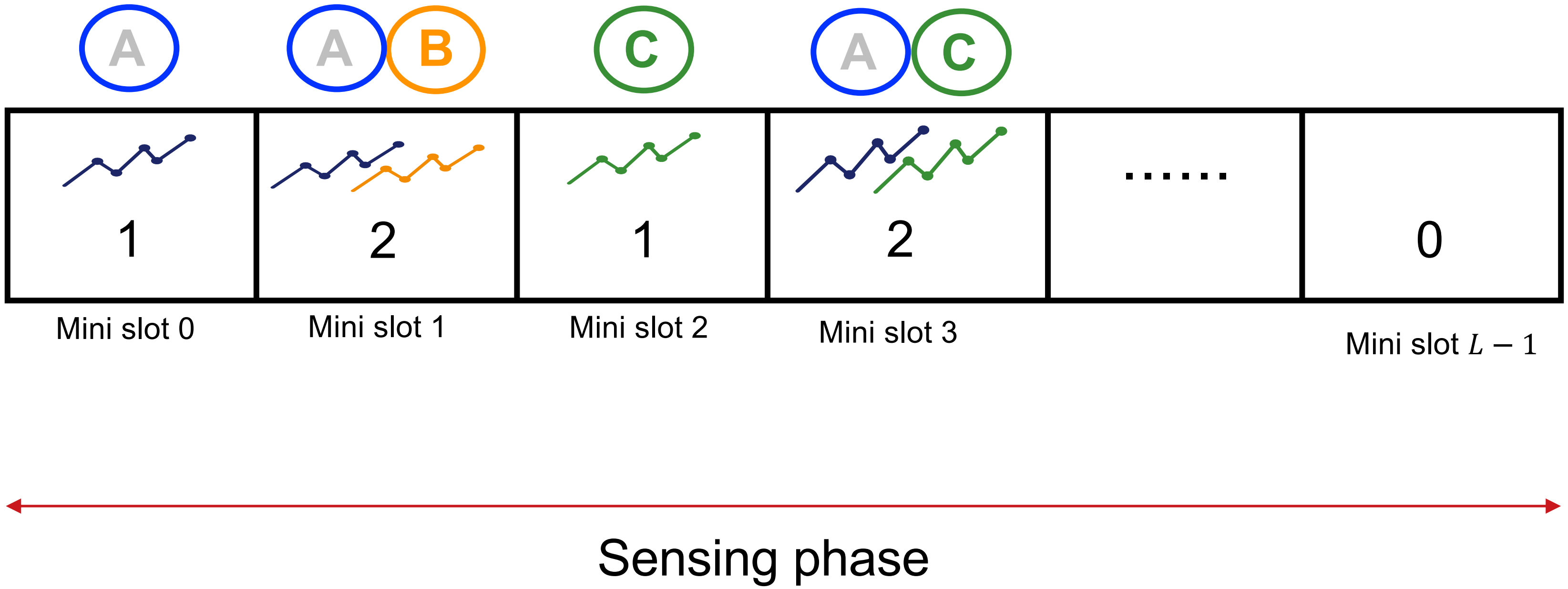
IRSA with Sensing + DRL (DS-IRSA)

A	1	1				
B	0	1				
C	0	0				



IRSA with Sensing + DRL (DS-IRSA)

A	1	1	0	1	......	0
B	0	1	0	0	......	0
C	0	0	1	1	......	0

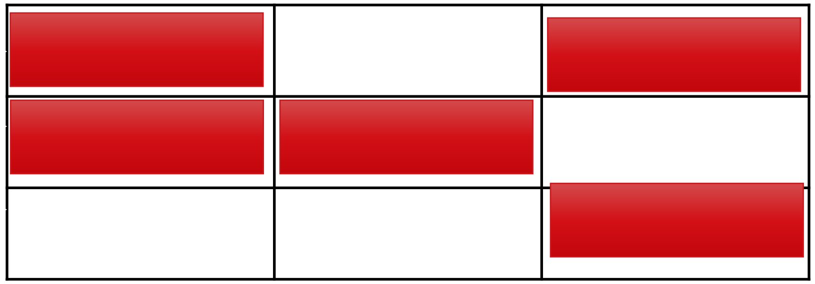


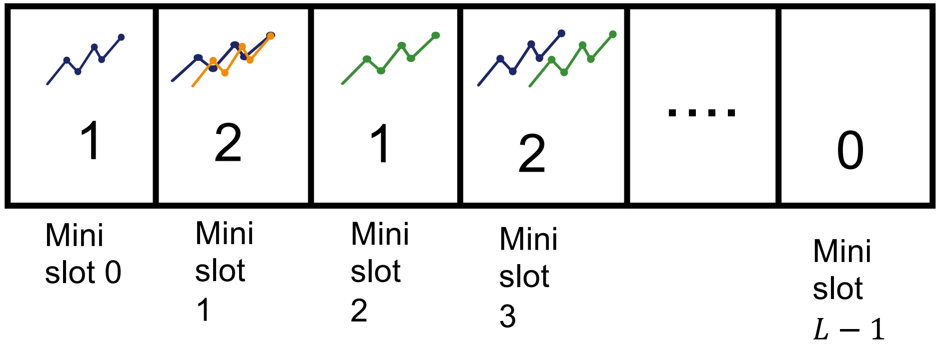
IRSA with Sensing + DRL (DS-IRSA)

Jamming bursts

A	1	1	0	1	......	0
B	0	1	0	0	......	0
C	0	0	1	1	......	0

Slots (copies)





IRSA

Sensing phase

Transmission phase

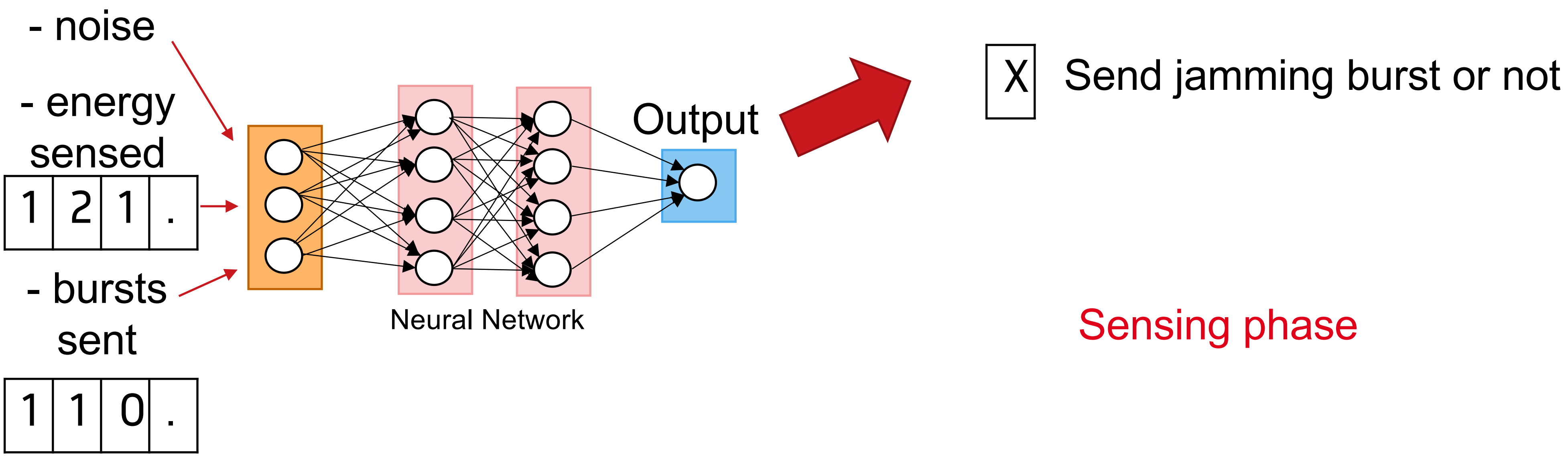
IRSA with Sensing + DRL (DS-IRSA)

Sensing Phase

- Action: jamming burst or not
- Sensing completed on one minislot before the next decision (full duplex, energy)

More state:

- History: energy on the previous minislots
- History: burst sent by the users on the previous minislots



IRSA with Sensing + DRL (DS-IRSA)

Sensing Phase

- Action: jamming burst or not
- Sensing completed on one minislot before the next decision (full duplex, energy)

More state:

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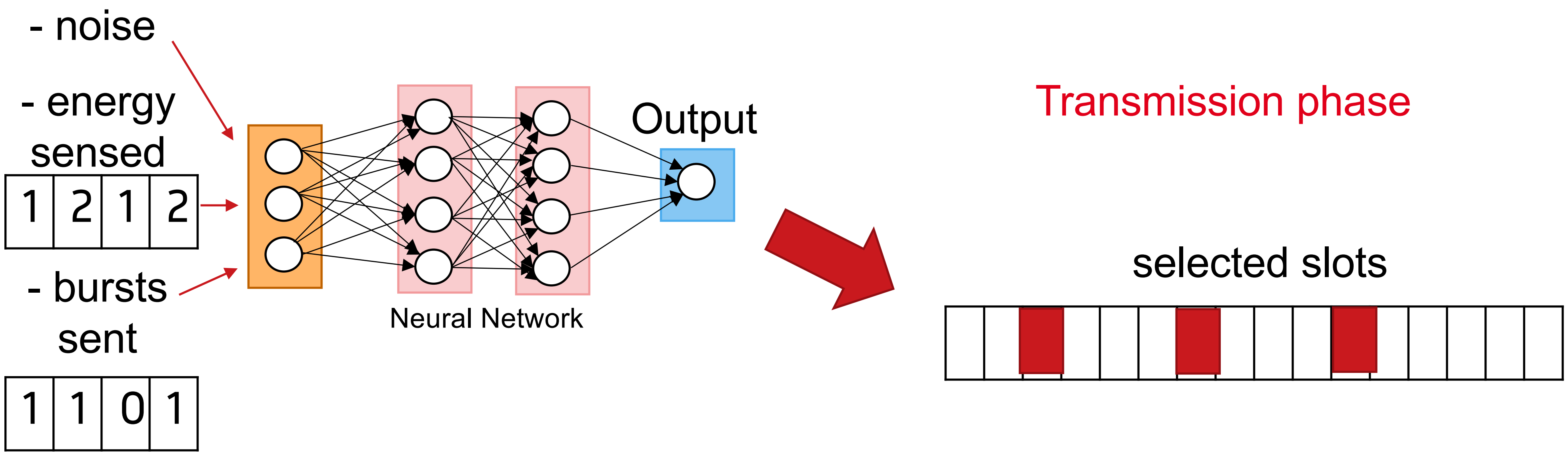
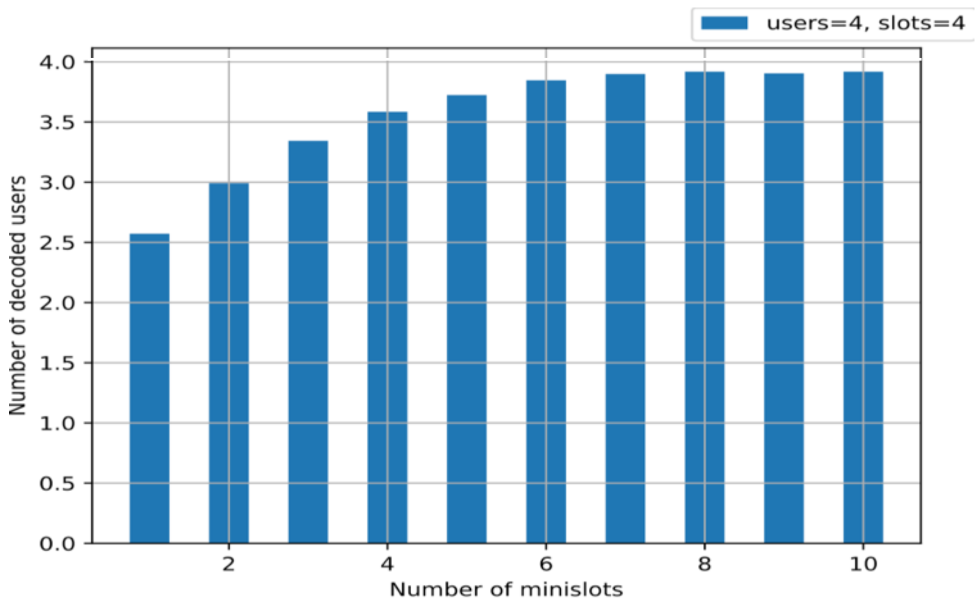
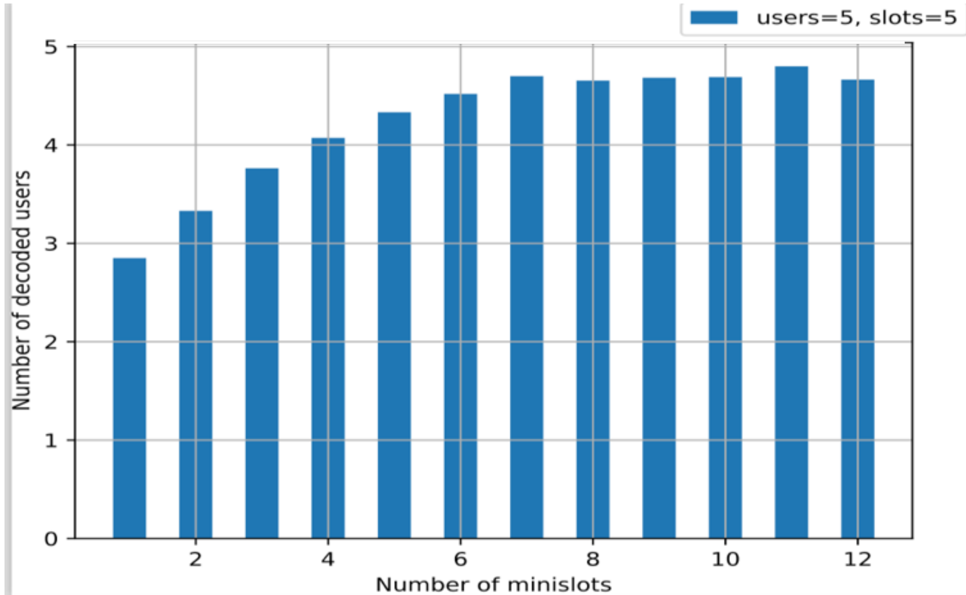


IRSA with Sensing + DRL (DS-IRSA)

Impact of the number of minislots on the throughput



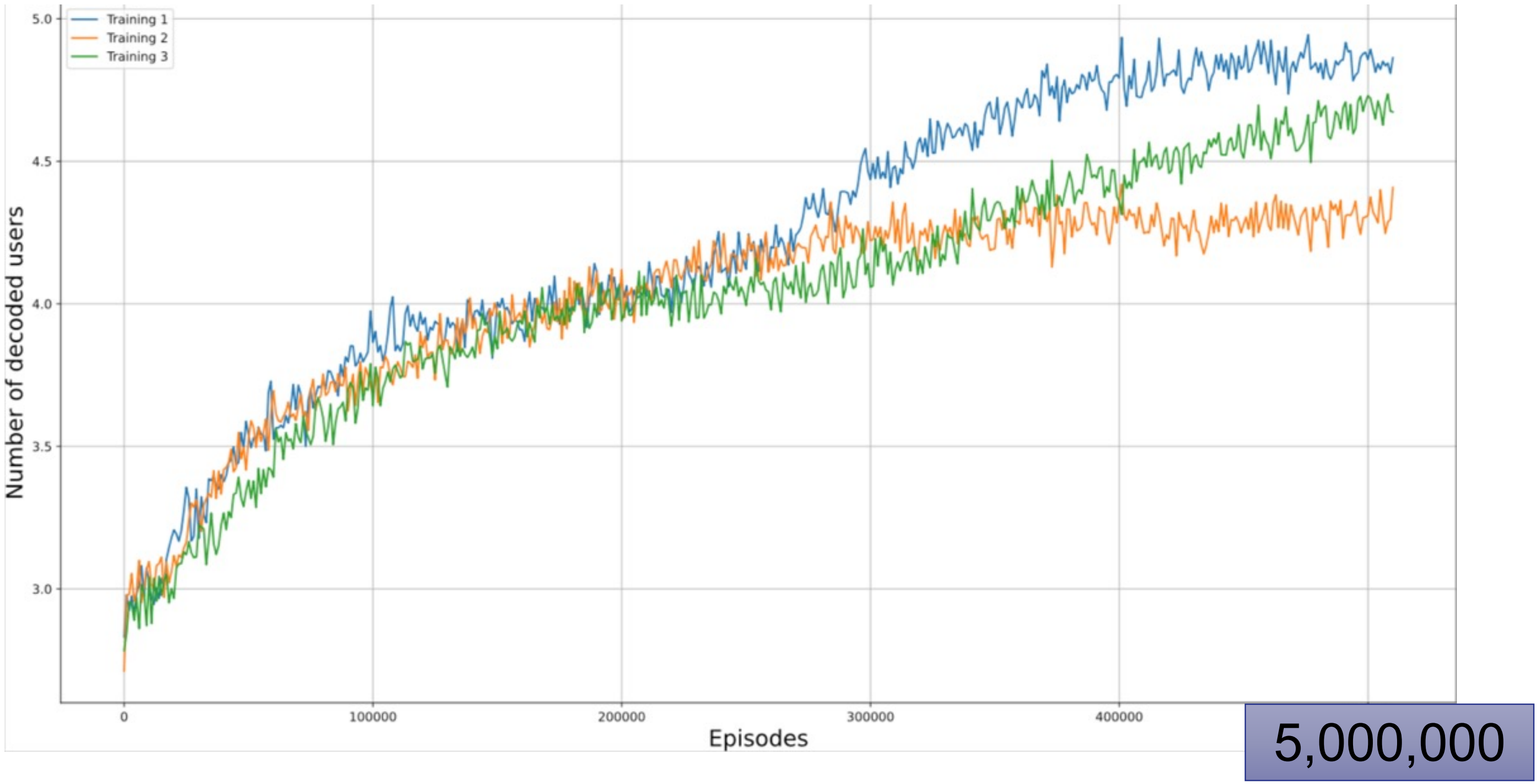
DS-IRSA with **4 users and 4 slots**



DS-IRSA with **5 users and 5 slots**

IRSA with Sensing + DRL (DS-IRSA)

Training convergence

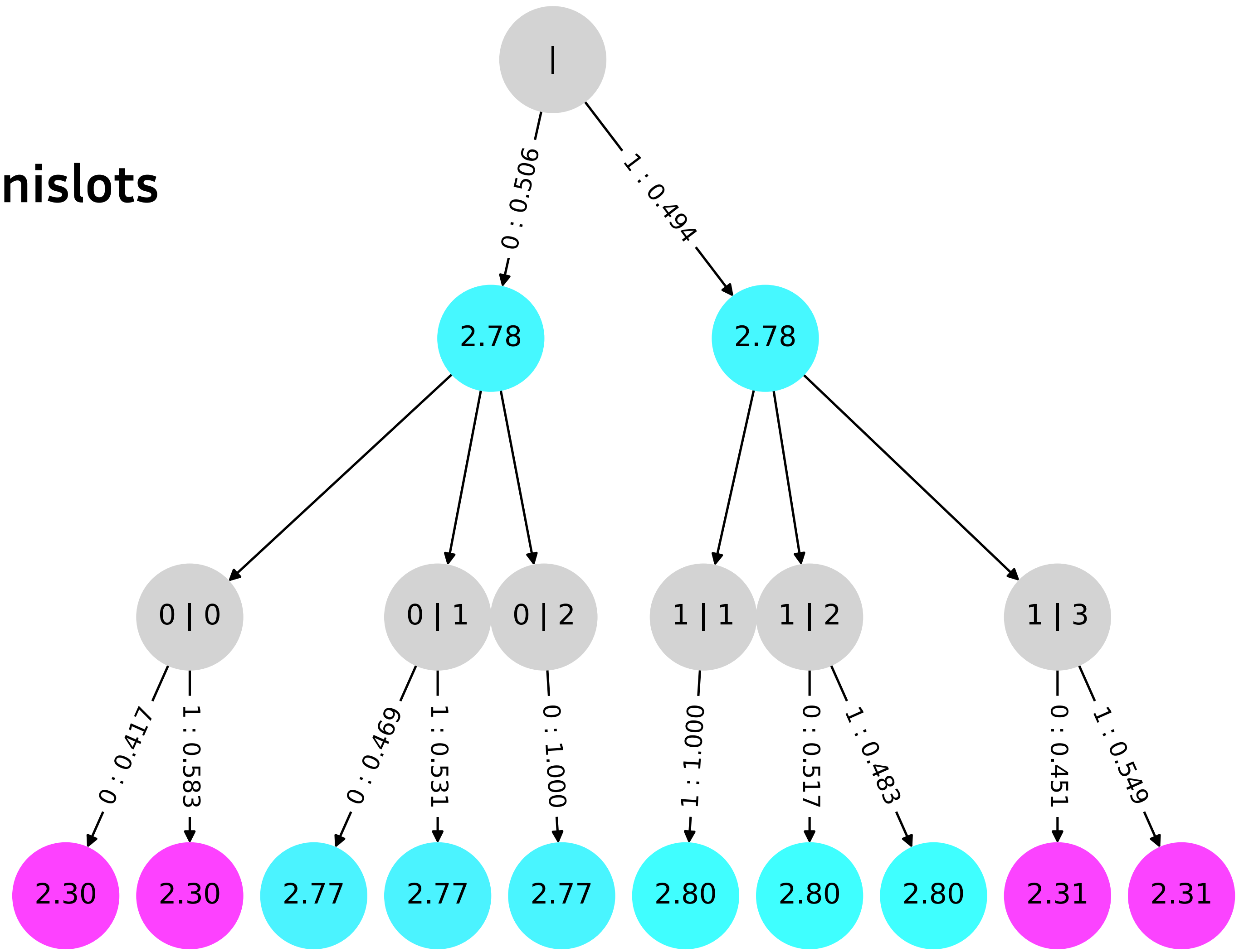


DS-IRSA convergence with 6 users and 6 slots and 7 minislots

IRSA with Sensing + DRL (DS-IRSA)

Learnt Protocol:

3 users, 3 slots, 2 minislots

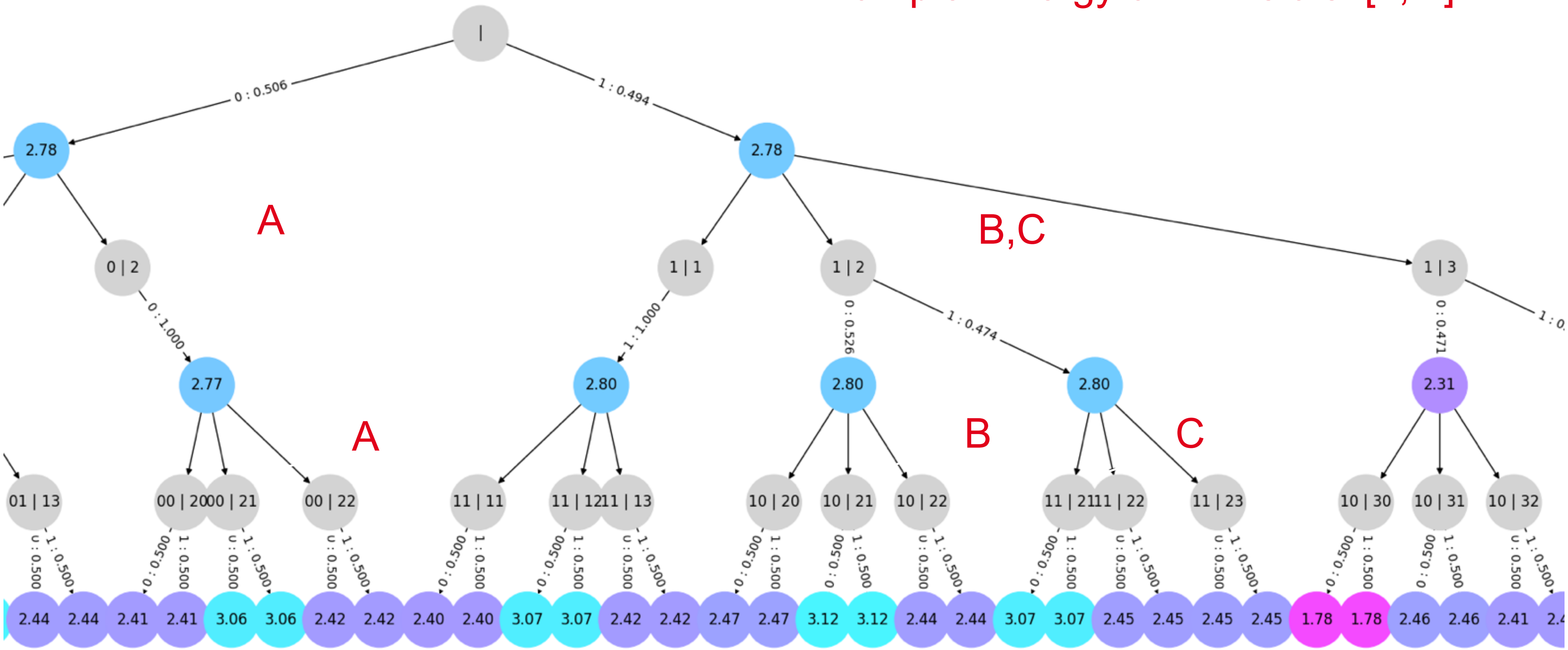


IRSA with Sensing + DRL (DS-IRSA)

User A: [0, 0]
User B: [1, 0]
User C: [1, 1]

Learnt Protocol: 3 users, 3 slots, 2 minislots

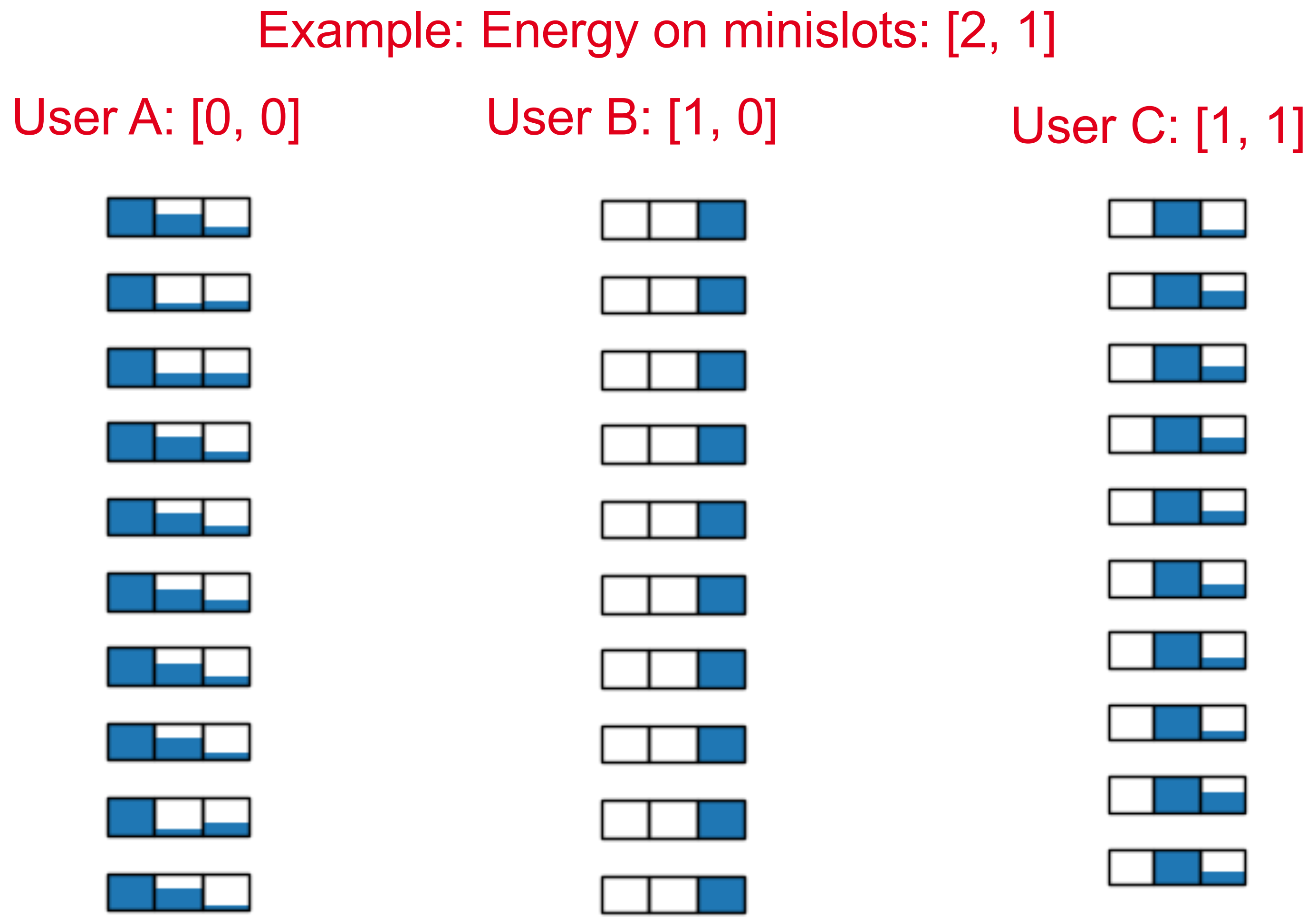
Example: Energy on minislots: [2, 1]



Inria

IRSA with Sensing + DRL (DS-IRSA)

Learnt Protocol: 3 users, 3 slots, 2 minislots



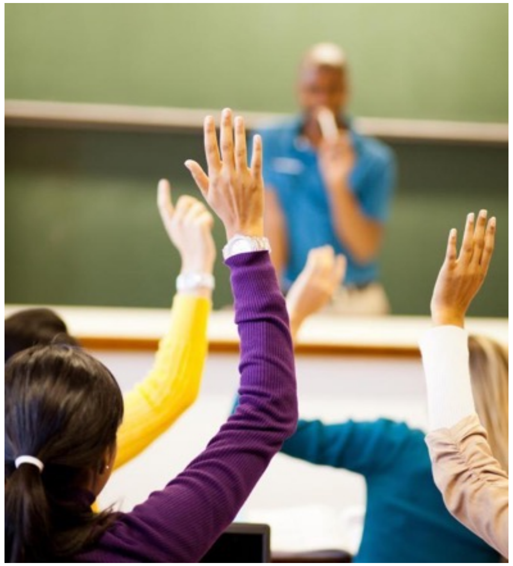
05
Conclusions

- Description of Modern Random Access
  - applicable using many legacy building blocks « receiver-only » IRSA

- Interested in making it practical for grant-free cellular networks:
  - Modelling: Inter-slot SIC modeling and errors
  - Implementation of the basic inter-slot SIC, improvement of inter-slot SIC
  - Experimentation
  - Performance bounds with small frame size
    - Decoding process for short frames (LDPC short-code)

- Explore more AI/ML techniques for optimization

Thank you



Context

- **“Random Access” → “Modern Random Access”**
- **Context:**
  - CEFIPRA Project on “D2D” (-2017): Post-Doc Ehsan E. Khaleghi (with A.Alloum and V.Kumar)
  - Common Lab Inria-Nokia Bell Labs: PhD Thesis, Iman Hmedoush: “Connectionless Transmission in Wireless Networks (IoT) ” 2022
- Ongoing background work, collaboration with:
  - International Team MAGICO: IIT Guwahati (K. Deka), IIT (BHU) Varanasi (S. Sharma)
  - BPI 5G-mMTC Project - PhD Saeed Alsabbagh (advisor N. Ait-Saadi, and with A. Adouane) on 5G RedCap & IoT
  - PEPR-NF PERSEUS