Improving **Synchronous Random Access** schemes for SatCom

Ph.D. Candidate

Karine **ZIDANE**, ISAE-SUPAERO

25/11/2016

isae
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

cnes

ThalesAlenia
A Thales / Finmeccanica Company Space

TéSA
Telecommunications for Space and Aeronautics

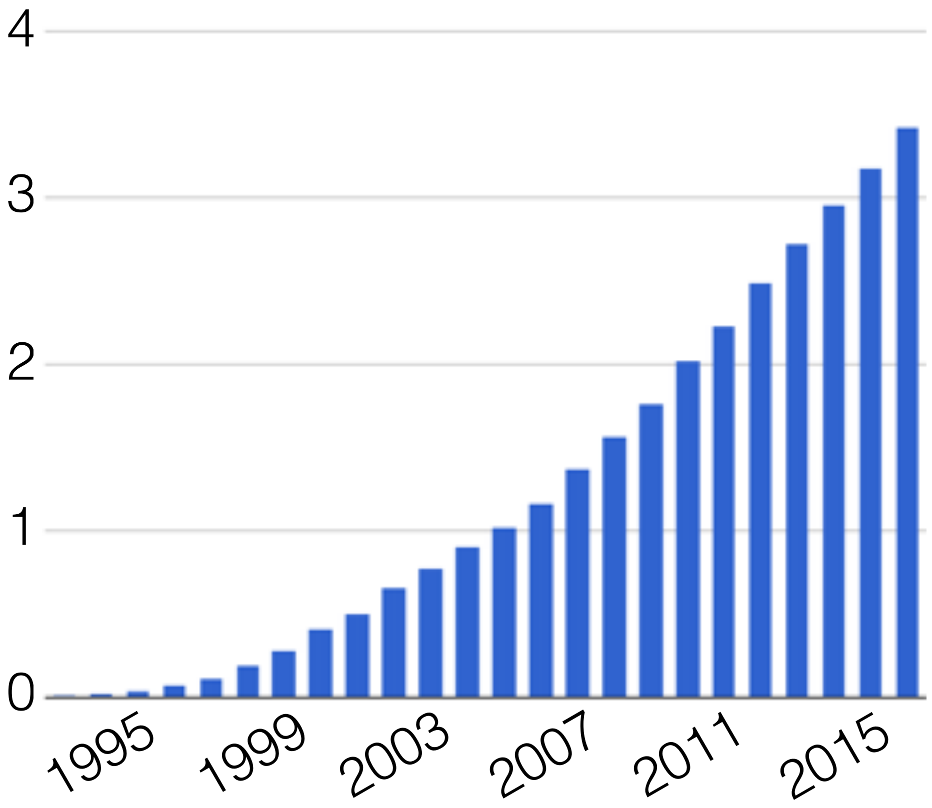
Supervisors

Jérôme **LACAN**, ISAE-SUPAERO & TéSA
Mathieu **GINESTE**, Thales Alenia Space
Caroline **BES**, CNES

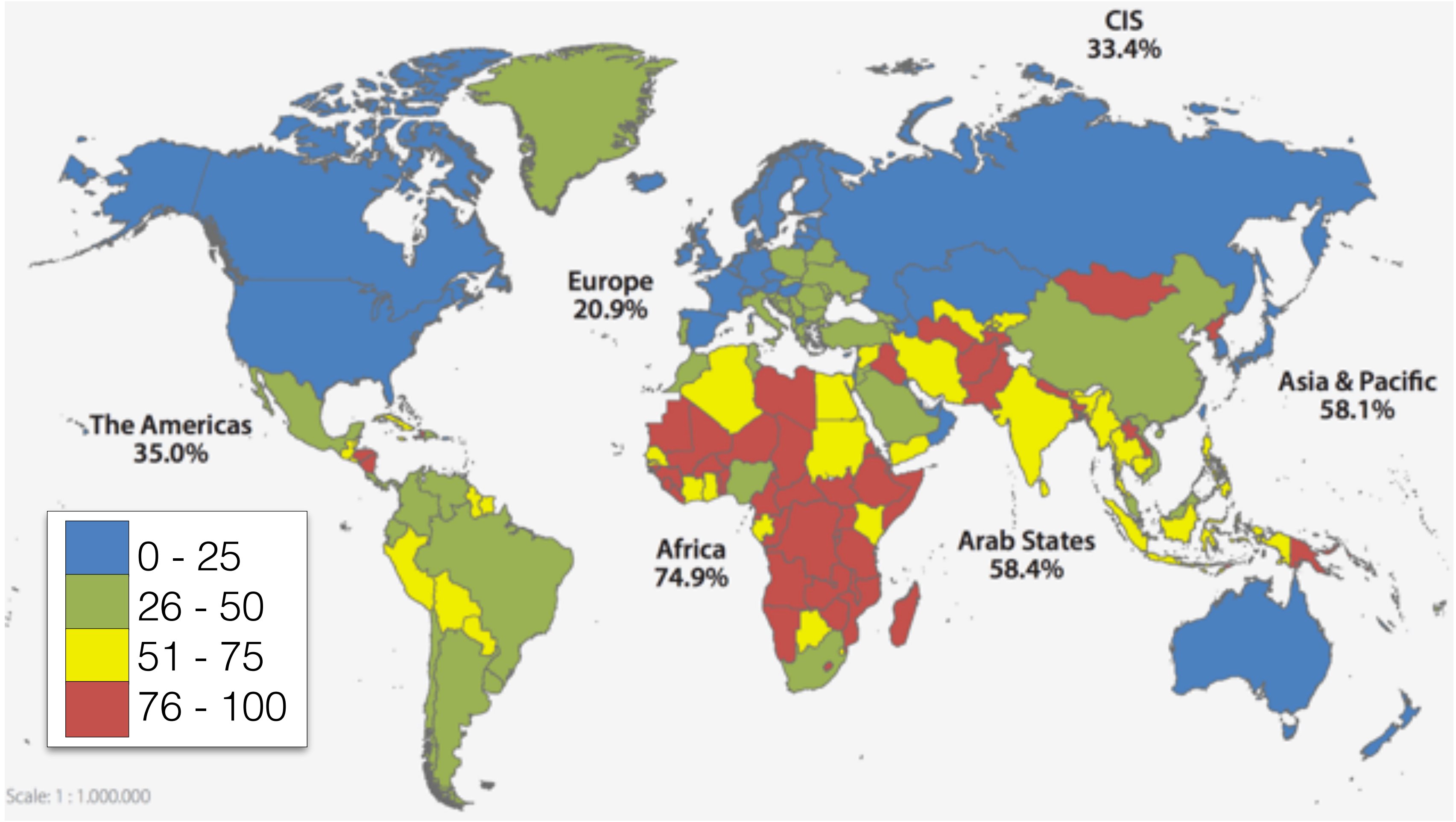
Ph.D. with the collaboration of

Thales Alenia Space, Toulouse
Centre National d'Etudes Spatiales, Toulouse
TéSA, Toulouse

Some facts…



Internet Users in the World
(in billions)

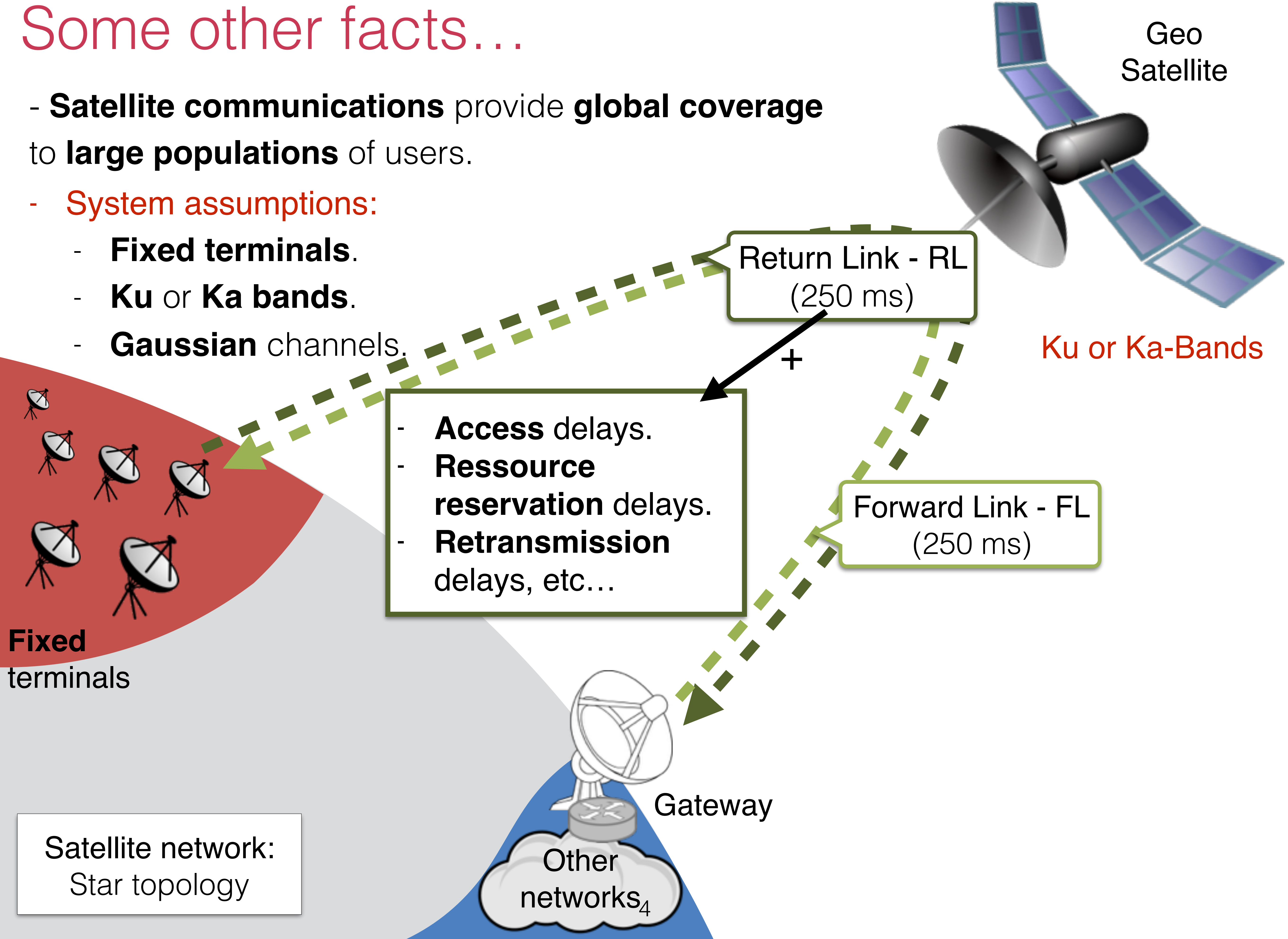


Percentage of individuals not using the Internet

50% of the World's population
still **does not use** the Internet!

Some other facts…

- **Satellite communications** provide **global coverage** to **large populations** of users.
- System assumptions:
  - **Fixed terminals**.
  - **Ku** or **Ka bands**.
  - **Gaussian** channels.



Geo Satellite

Ku or Ka-Bands

Return Link - RL (250 ms)

\+

- **Access** delays.
- **Ressource reservation** delays.
- **Retransmission** delays, etc…

Forward Link - FL (250 ms)

Fixed terminals

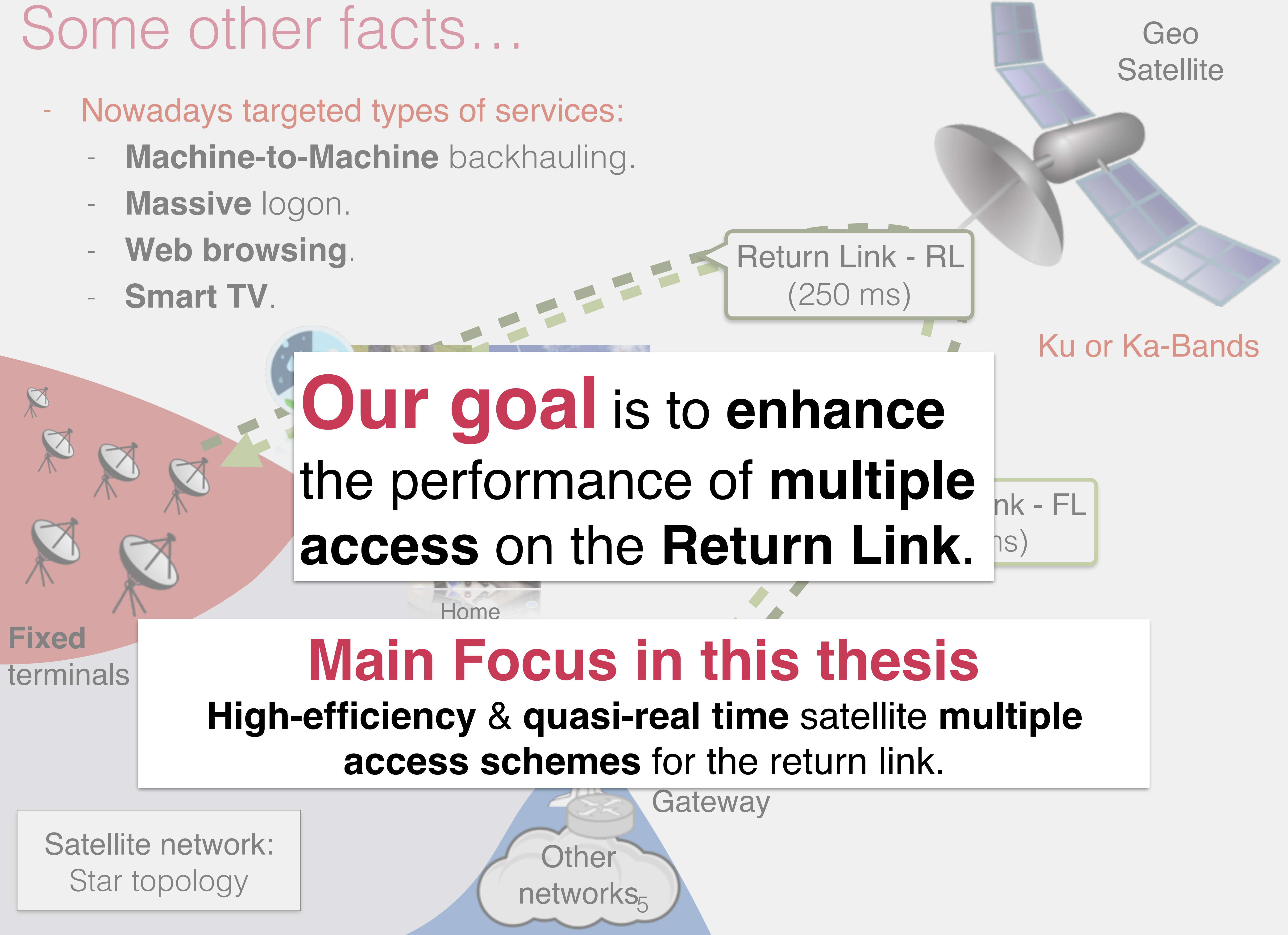
Gateway

Other networks[4]

Satellite network: Star topology

Some other facts…

- Nowadays targeted types of services:
    - **Machine-to-Machine** backhauling.
    - **Massive** logon.
    - **Web browsing**.
    - **Smart TV**.



Satellite network:
Star topology

Our goal is to **enhance** the performance of **multiple access** on the **Return Link.**

Main Focus in this thesis

High-efficiency & **quasi-real time** satellite **multiple access schemes** for the return link.

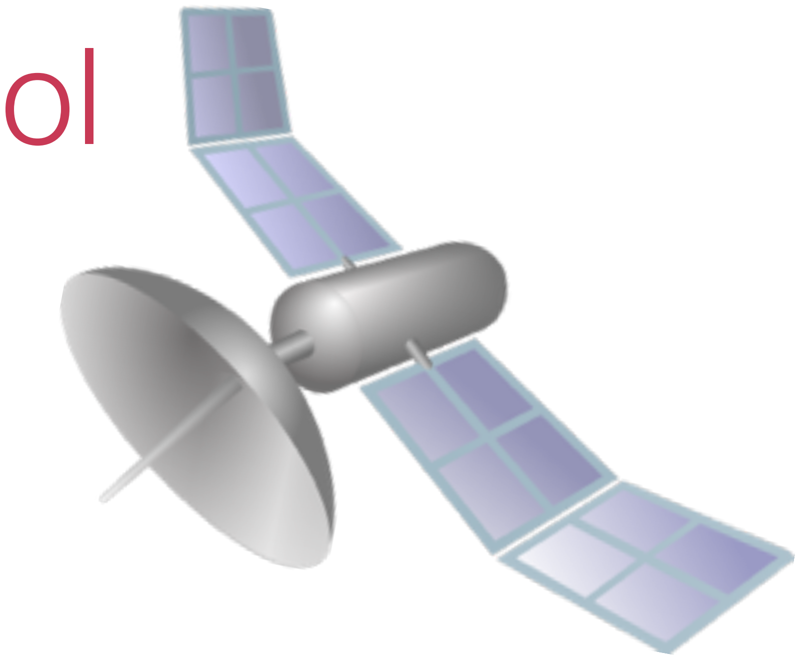
Outline

1. **Background & related work**
2. **Thesis contributions**
    2.1. Channel estimation for recent RA protocols
    2.2. MARSALA
3. **Conclusions & future work**

1

Background & related work

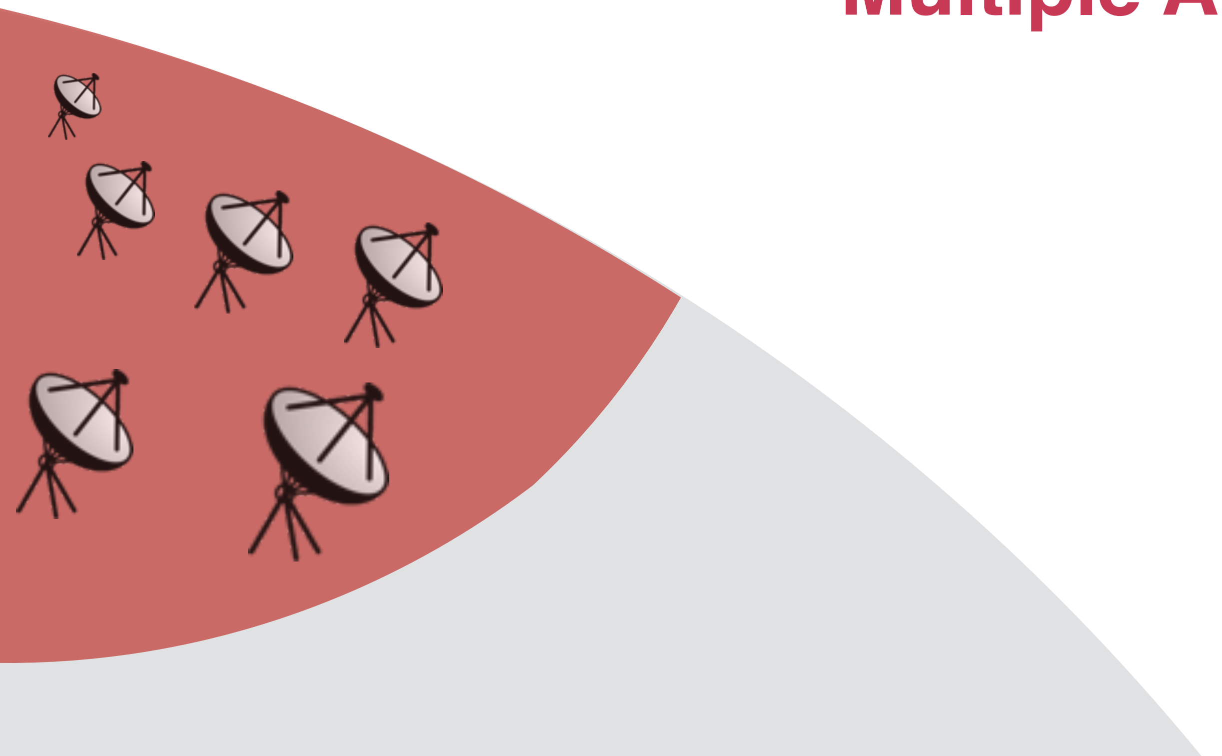
1.1. RL Medium Access Control



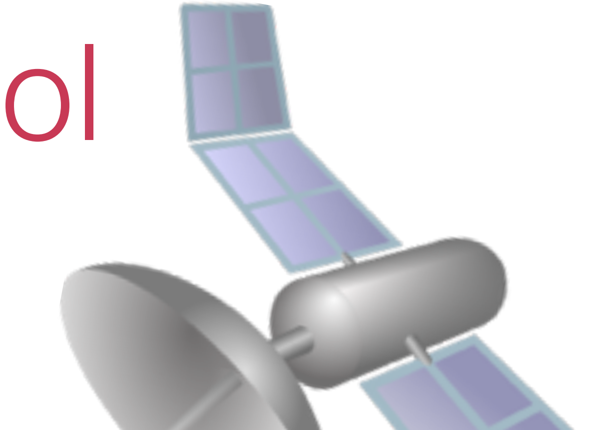
Random Access → usually used to send logon and capacity requests.

Demand Assignment Multiple Access (DAMA) → for data transmissions.

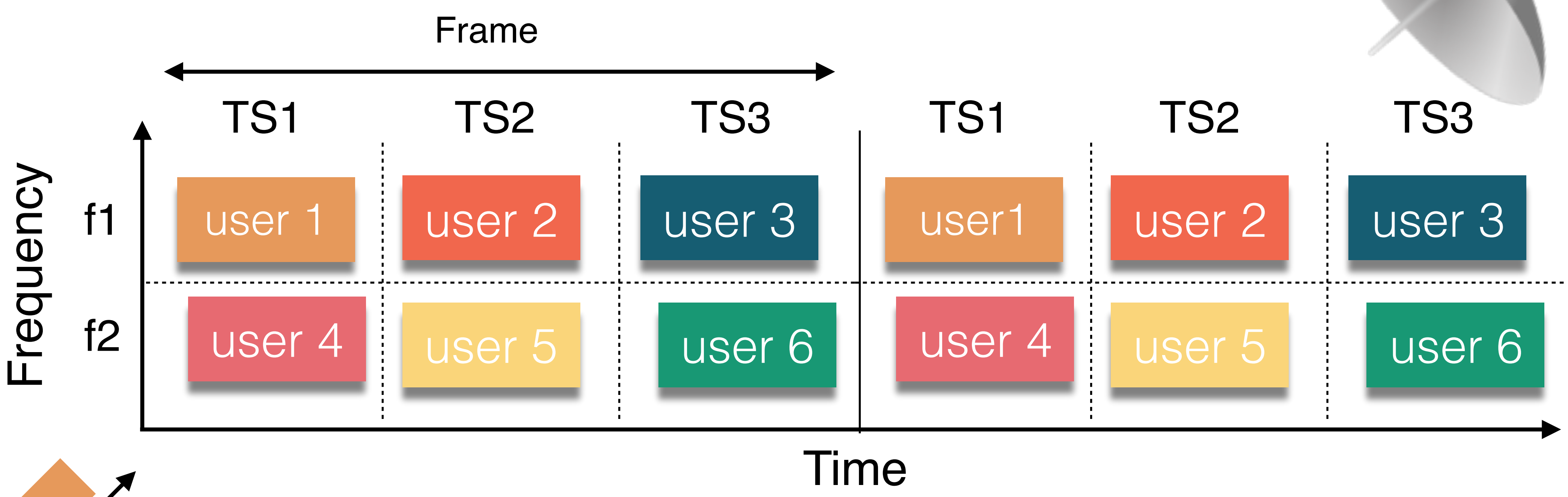
The RL structure is organised with **Multi-Frequency Time Division Multiple Access (MF-TDMA)**



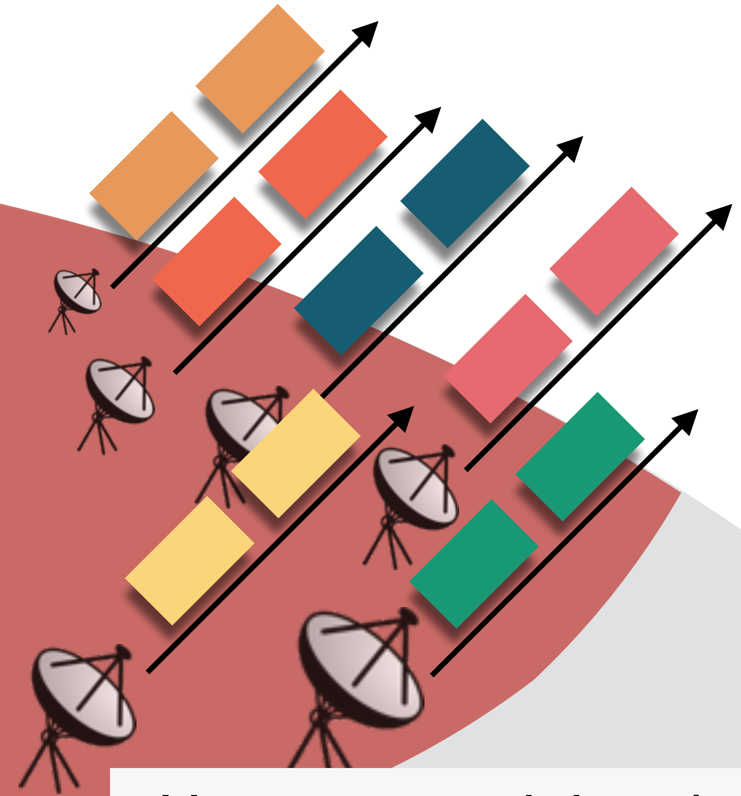
1.1. RL Medium Access Control



Case of Constant rate traffic



	TS1	TS2	TS3	TS1	TS2	TS3
f1	user 1	user 2	user 3	user1	user 2	user 3
f2	user 4	user 5	user 6	user 4	user 5	user 6

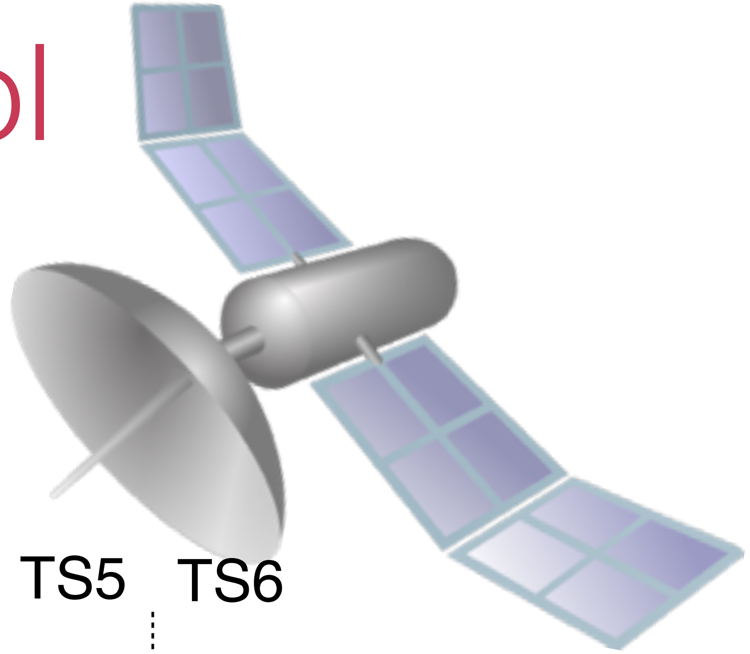


Users transmitting data packets at **constant rate.**

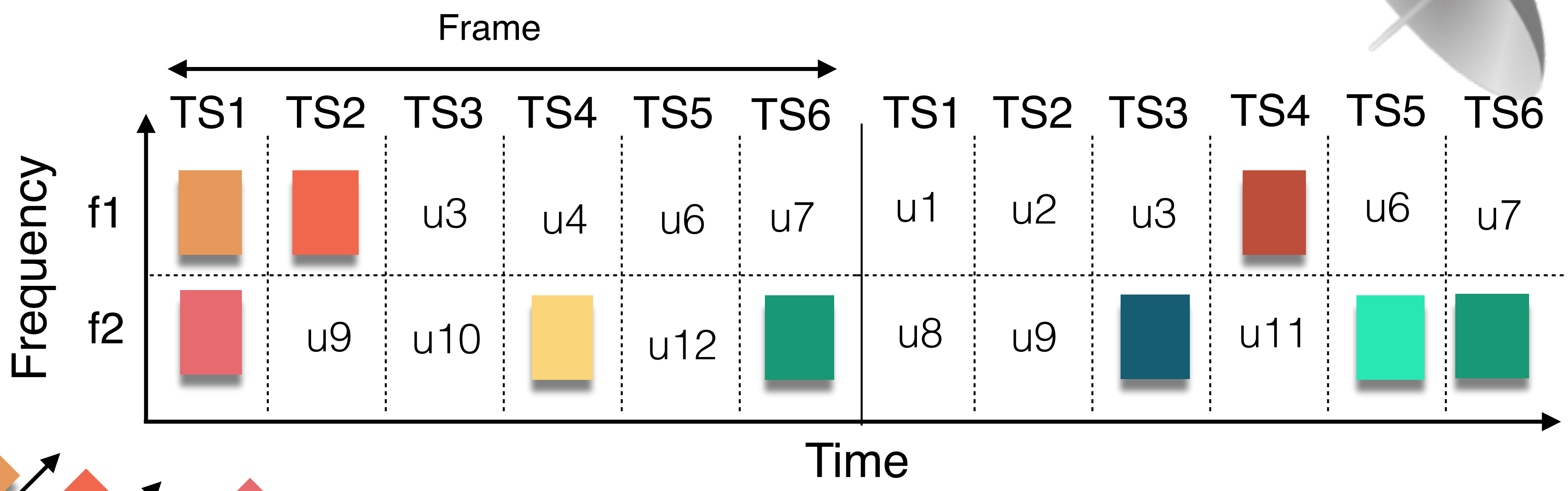
Demand Assignment Multiple Access (DAMA)

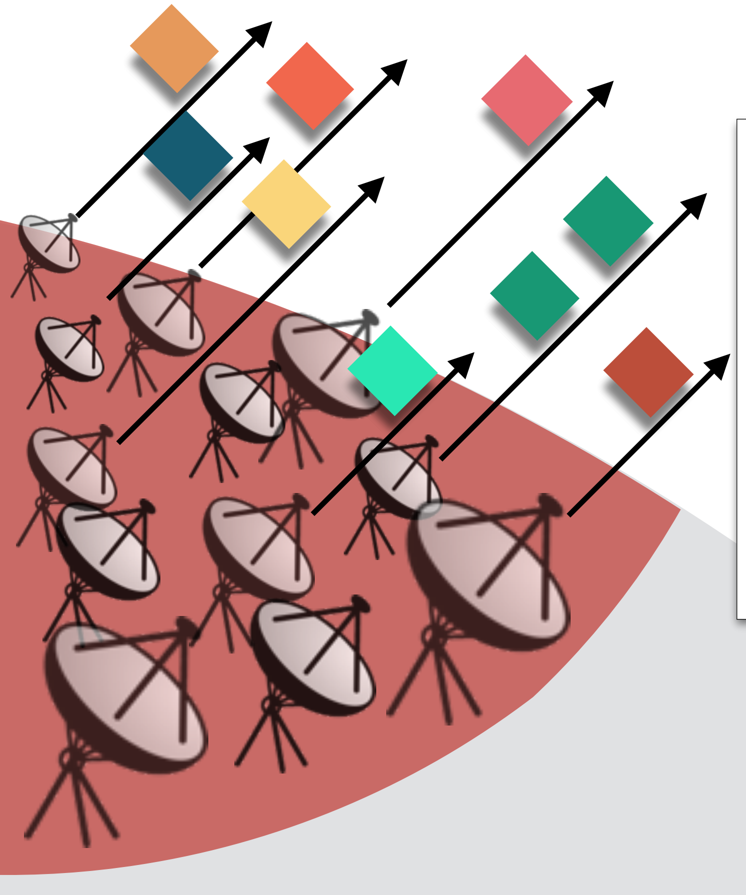
- Provides ressources assignments.
- Better suited for **predictable** and **bulky** internet traffic.
- Generally requires capacity requests.
- For example: **File upload**

1.1. RL Medium Access Control



Case of sporadic traffic with short packets



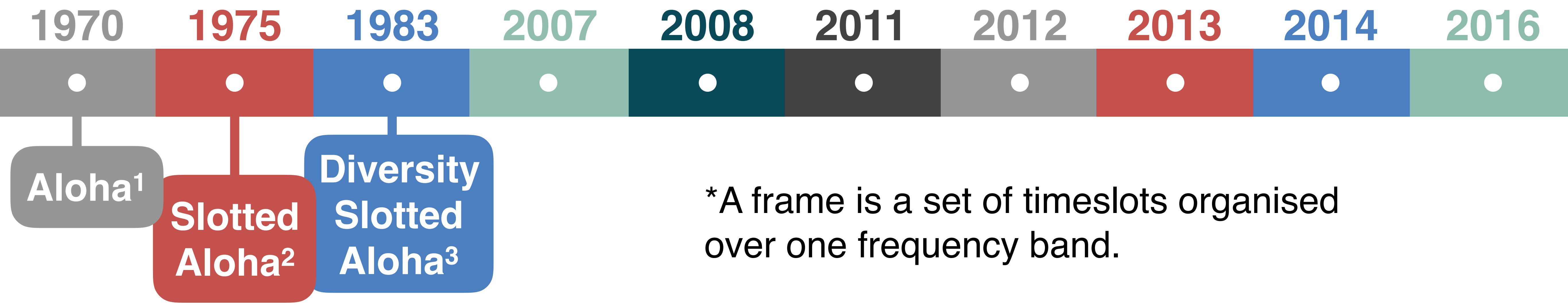


DAMA disadvantages:

- Fixed rate assignment → Inefficient usage of network ressources.
- Demand based assignment → Capacity requests overhead.
  → Long ressource allocation delays.

Random Access

1.2. Legacy Random Access schemes



*A frame is a set of timeslots organised over one frequency band.

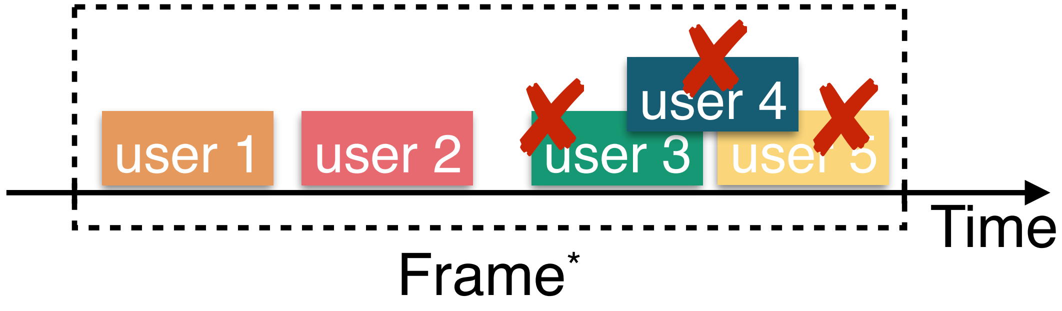


Fig.1- Aloha

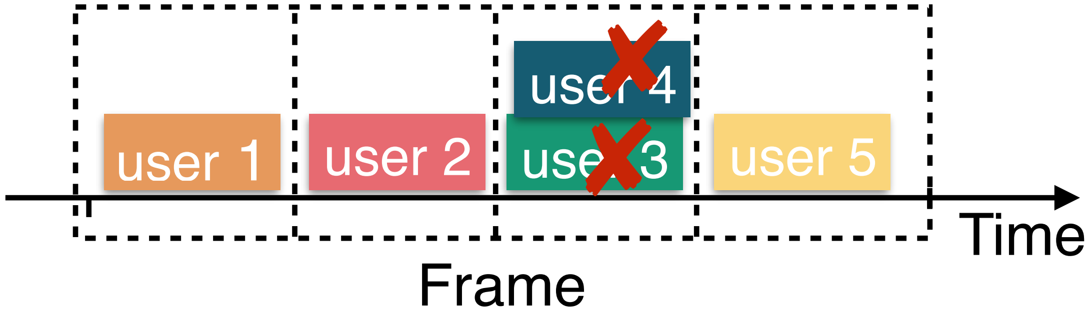


Fig.2- Slotted Aloha (SA)

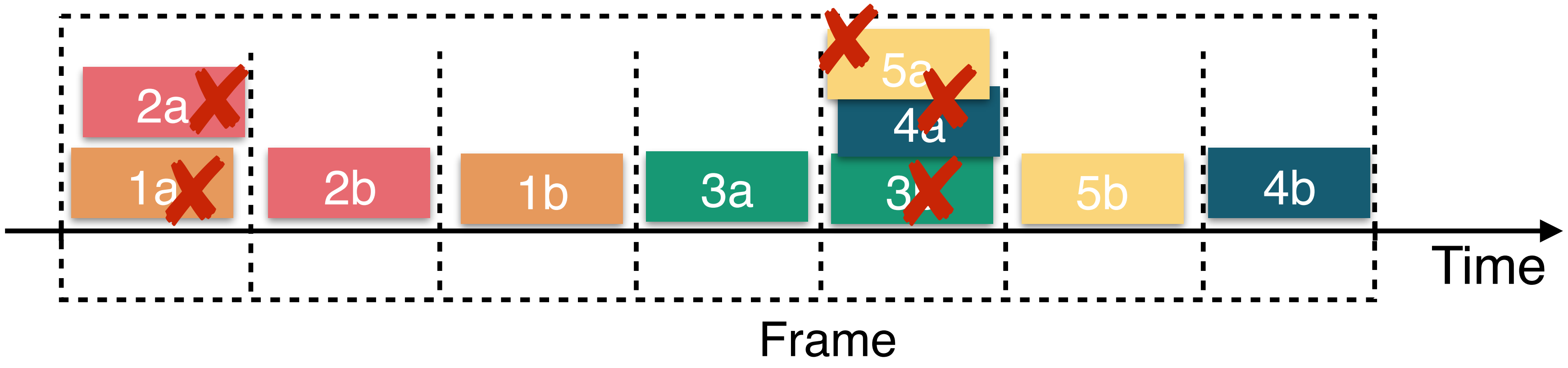


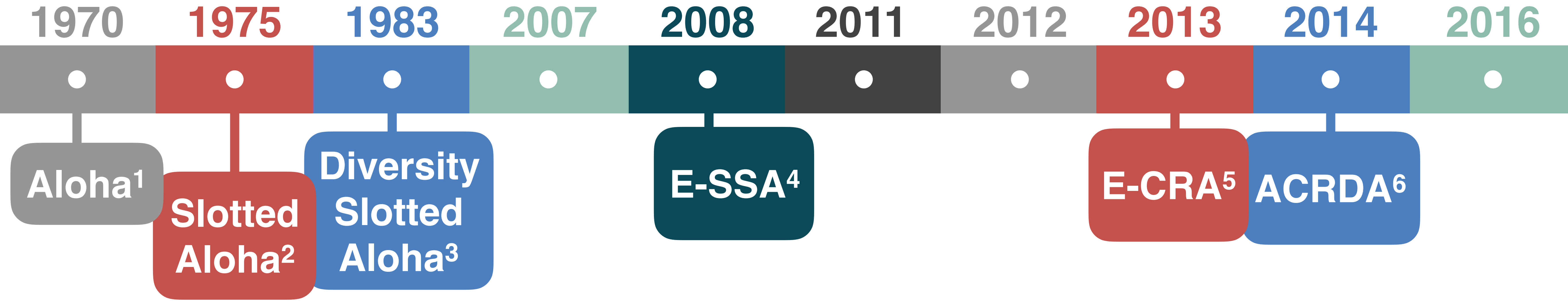
Fig.3- Diversity Slotted Aloha (DSA)

[1] N. Abramson. “The aloha system: Another alternative for computer communications”. In Proceedings of the Fall Joint Computer Conference, pages 281–285, November 17-19, 1970. ACM.

[2] L.G.Roberts. “ALOHA packet system with and without slots and capture”. ACM,SIGCOMM Computer Communication Review, 1975.

[3] L. C. Gagan and S. R. Stephen. “Diversity aloha–a random access scheme for satellite communications”. IEEE Transactions on Communications, 31(3):450–457, March 1983.

1.3. Recent RA protocols


1970 1975 1983 2007 2008 2011 2012 2013 2014 2016

Aloha[1]

Slotted Aloha[2]

Diversity Slotted Aloha[3]

E-SSA[4]

E-CRA[5]

ACRDA[6]

Recent RA protocols use:

- **Successive Interference Cancellation** (SIC).
- Information redundancy or spectrum spreading techniques.

Two major families of RA protocols:

- **Asynchronous** (non slotted):
  - Enhanced Spread Spectrum Aloha (E-SSA).
  - Enhanced Contention Resolution Aloha (E-CRA).
  - Asynchronous Contention Resolution Diversity Aloha (ACRDA).
- **Synchronous** (slotted).

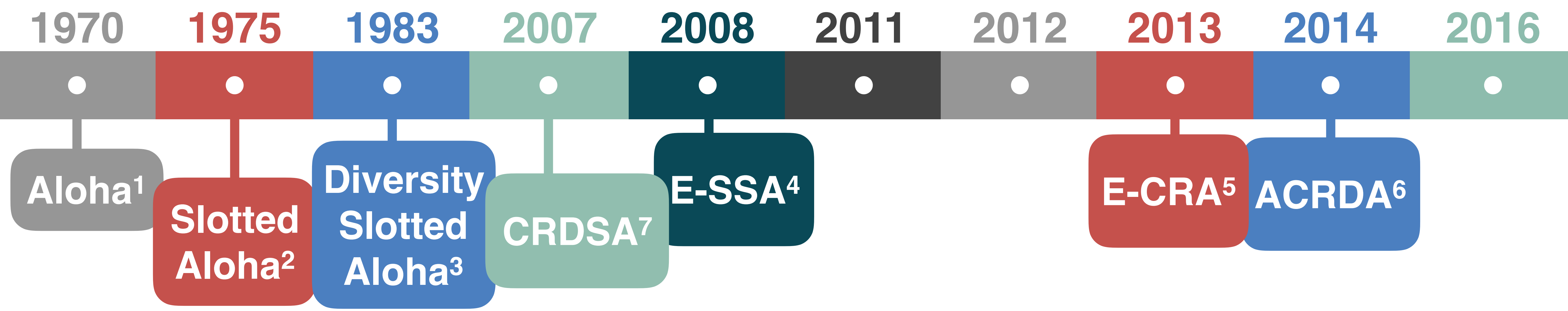
Main focus in this thesis

[4] O. del Rio Herrero and R. De Gaudenzi. “A high efficiency scheme for quasi-real-time satellite mobile messaging systems”. In10th International Workshop on Signal Processing for Space Communications, pages 1–9, Oct 2008.

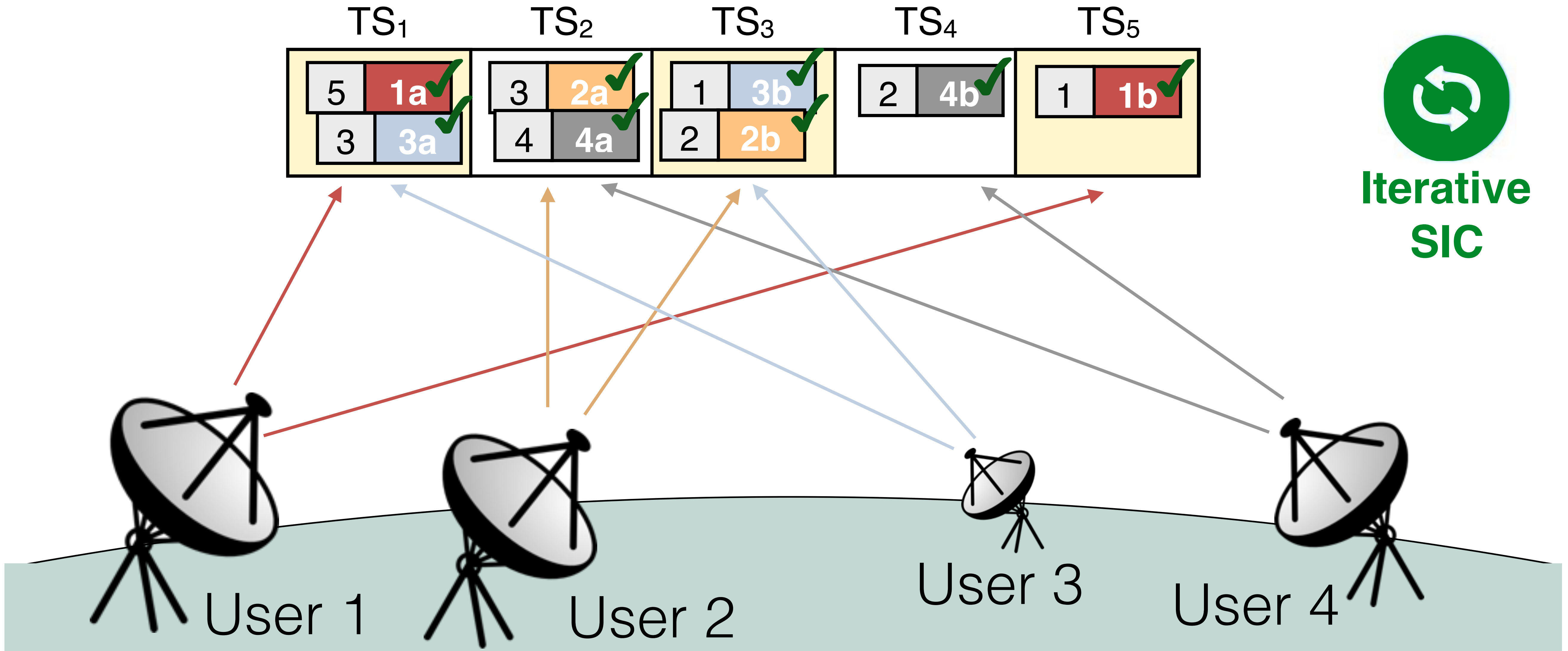
[5] F. Clazzer and C. Kissling. “Enhanced Contention Resolution Aloha - ECRA”. In Proceedings of 2013 9th International ITG Conference on Systems, Communication and Coding (SCC), pages 1–6, Jan 2013.

[6] R. De Gaudenzi, O. del Río Herrero, G. Acar and E. G. Barrabés. “Asynchronous Contention Resolution Diversity ALOHA: Making CRDSA Truly Asynchronous”. IEEE Transactions on Wireless Communications, Nov 2014.

1.3.1 Recent synchronous RA protocols



Contention Resolution Diversity Slotted Aloha (CRDSA)



[7] E. Casini, R. De Gaudenzi, and O. del Rio Herrero, “Contention resolution diversity slotted Aloha (CRDSA): an enhanced random access scheme for satellite access packet networks,” IEEE Trans. Wireless Commun. Apr 2007.

Metrics to measure RA performance

MAC Layer normalised load G - the average number of users per timeslot, normalised with the modulation and coding rate. **Unit:** bits/symbol.

$$G = \frac{\overset{\text{300 users}}{\text{Number of users}}}{\underset{\text{100 slots}}{\text{Number of timeslots}}} \times \overset{1/3}{\text{Code rate}} \times log_2(\overset{\text{4 (QPSK)}}{\text{Modulation order}})$$

Example: G = 2 bits/symbol

MAC Layer normalised throughput T - the average number of users per timeslot getting successful detection of their packets (normalised with the modulation and coding rate). **Unit:** bits/symbol.

$$T = G \times (1 - \text{PLR}(G))$$

Packet Loss Ratio PLR - the ratio of packets lost on a frame for a given G and E_s/N_0.

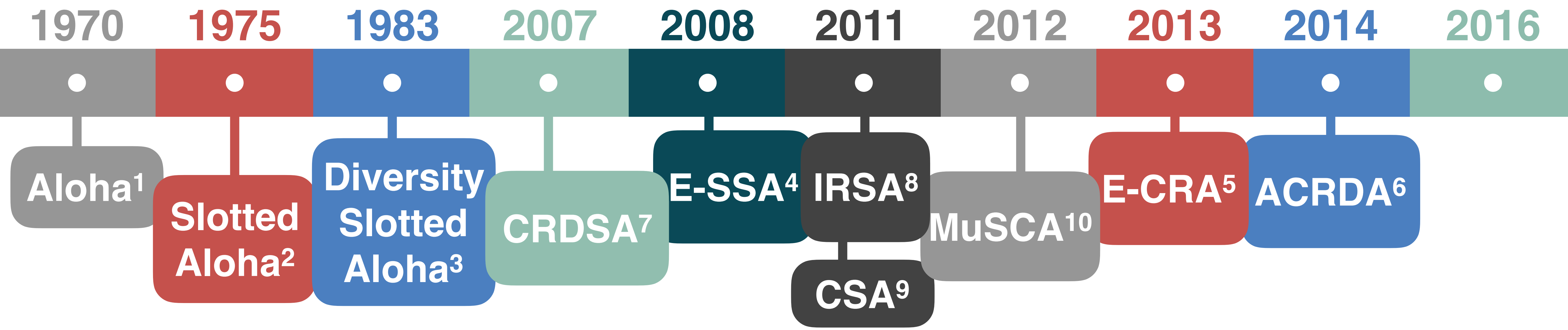
Performance of CRDSA

T = 0.8 bits/symbol with equi-powered packets and target ***PLR = 10^{-4}***

N_b = 3 replicas per packet.

E_s/N_0 = 10 dB, QPSK modulation.

3GPP turbo code, code rate R = 1/3, L_{Packet} = 150 bits.



Other synchronous RA protocols based on SIC

- Irregular Repetition Slotted Aloha (IRSA)
  - Number of replicas varying among users.
  - Calculation of the optimal distribution for the number of replicas.
- Coded Slotted Aloha (CSA)
  - Packet segmentation and erasure coding.
- Multi-slot Coded Aloha (MuSCA)
  - Robust Forward Error Correction (FEC) coding (headers & data).
  - Codeword fragmentation.

👍 Higher throughput. 👎 More complexity & system modifications.

[8] G.Liva. “Graph-based analysis and optimisation of Contention Resolution Diversity Slotted Aloha”, IEEE Transactions on Communications, February 2011.

[9] Paolini, G. Liva and M. Chiani. “High Throughput Random Access via Codes on Graphs: Coded Slotted ALOHA”. In IEEE International Conference on Communications (ICC) 2011, pages 1–6, June 2011.

[10] H.C. Bui, J. Lacan, and M.L. Boucheret. “An enhanced multiple random access scheme for satellite communications”. In Wireless Telecommunications Symposium (WTS), 2012, pages 1–6, April 2012.

2 Thesis Contributions

What are the practical issues related to real channel conditions?

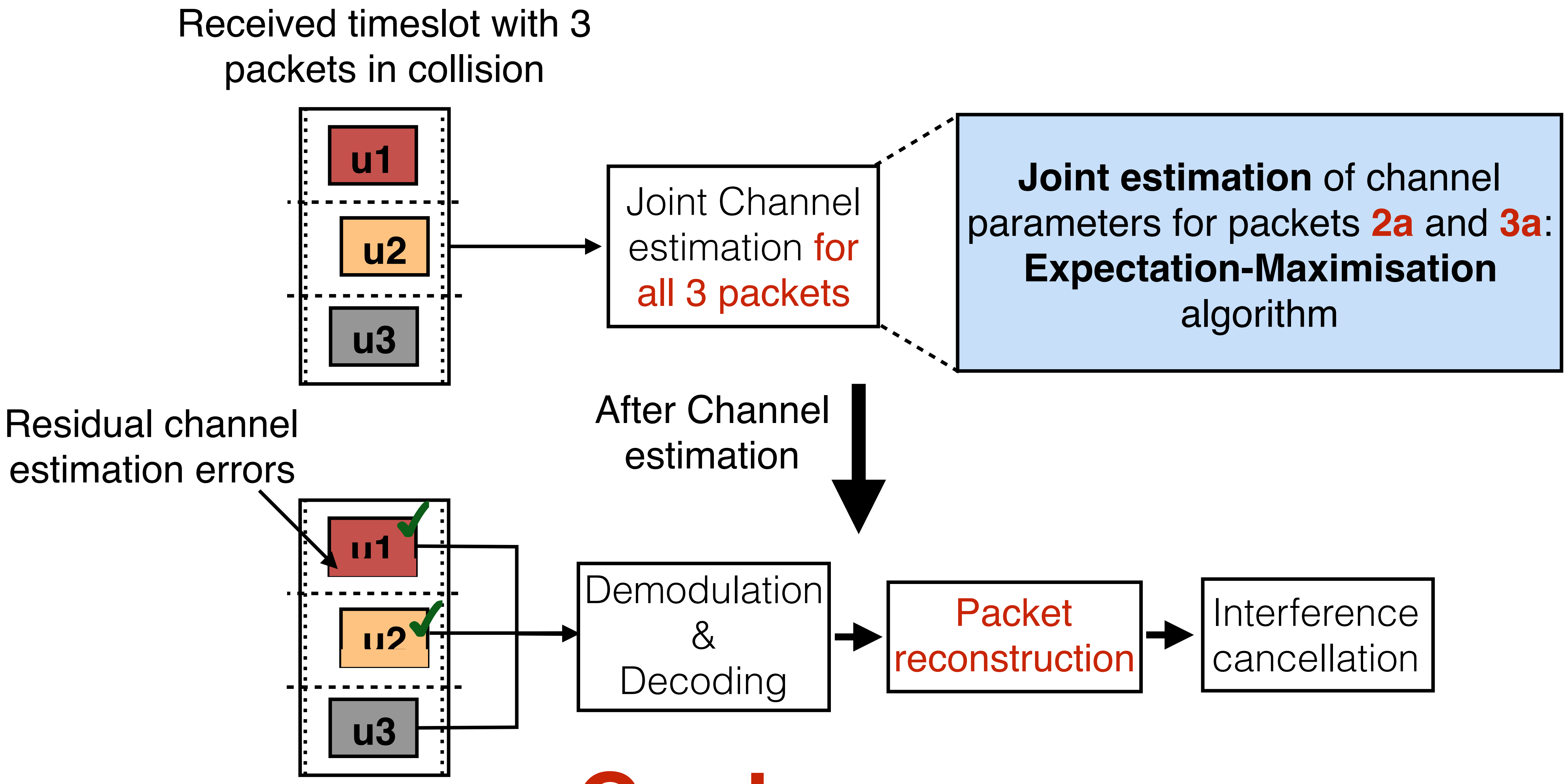
What is the channel estimation algorithm to be used?

What is the impact of residual channel estimation errors on SIC?

2.1. Channel estimation for recent RA protocols

Problem statement

Residual channel estimation errors after SIC



Received timeslot with 3 packets in collision

Joint Channel estimation for all 3 packets

Joint estimation of channel parameters for packets 2a and 3a: **Expectation-Maximisation** algorithm

After Channel estimation

Residual channel estimation errors

Demodulation & Decoding

Packet reconstruction

Interference cancellation

Goal To **minimise** the impact of the **residual channel estimation errors**.

System assumptions

Received signal

$$y = \underbrace{A_1 e^{j(\Delta f_1 t+\phi_1)}}_{h_1} \times \boxed{\text{u1}} + \underbrace{A_2 e^{j(\Delta f_2 t+\phi_2)}}_{h_2} \times \boxed{\text{u2}} + \underbrace{A_3 e^{j(\Delta f_3 t+\phi_3)}}_{h_3} \times \boxed{\text{u3}} + \text{AWGN}$$

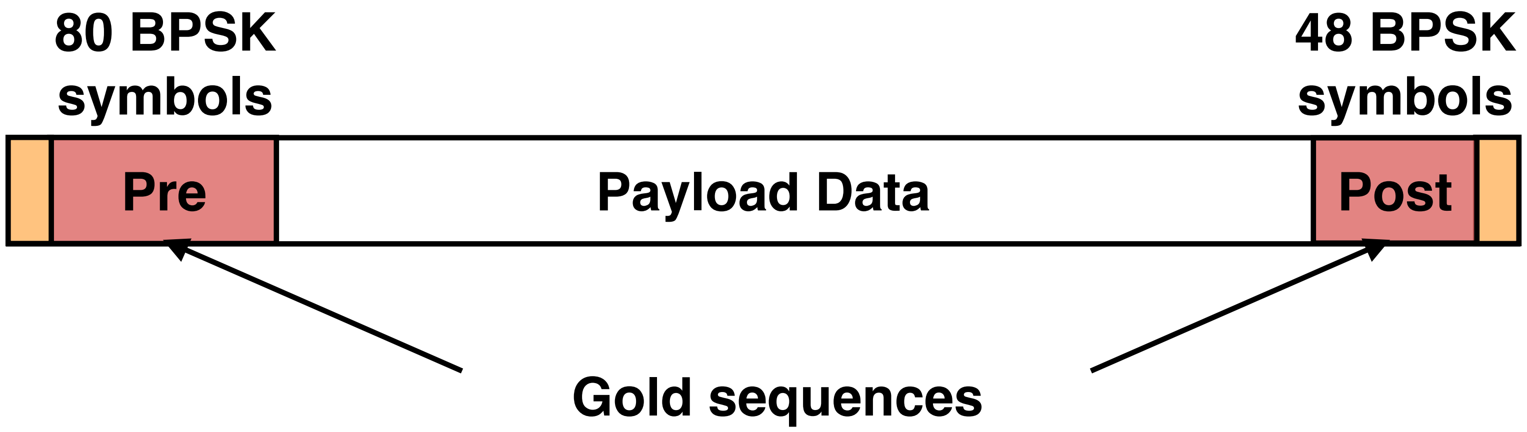
Based on [8]

Amplitude A_k - supposed constant over the frame duration.

Frequency offset Δf_k - supposed constant over the frame duration.

Phase shift Φ_k - supposed to vary randomly from one slot to another.

Packet structure with a preamble and a postamble, i.e. training symbols



80 BPSK symbols

48 BPSK symbols

Pre

Payload Data

Post

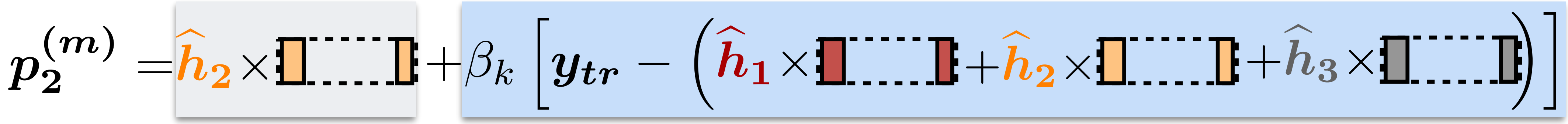
Gold sequences

[11] Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Guidelines for Implementation and Use of LLS: EN 301 545-2, 2012.

Expectation-Maximisation algorithm

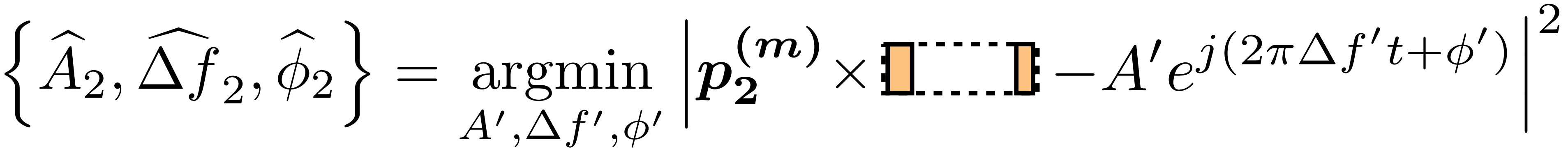
- The **Expectation-Maximisation** (EM) algorithm is a **two-step** iterative estimation method.
- EM is applied **for each packet in collision** on the **same timeslot**.
- For example, for **user 2**, and for each **iteration m**:

E-step: Find an estimation vector **p₂** for the signal of user 2.



$$\boldsymbol{p_2}^{(m)} = \widehat{\boldsymbol{h_2}} \times \square + \beta_k \left[\boldsymbol{y_{tr}} - \left(\widehat{\boldsymbol{h_1}} \times \square + \widehat{\boldsymbol{h_2}} \times \square + \widehat{\boldsymbol{h_3}} \times \square \right) \right]$$

M-step: Minimise the difference between the **reconstructed estimated** signal and the **actual** received symbols.

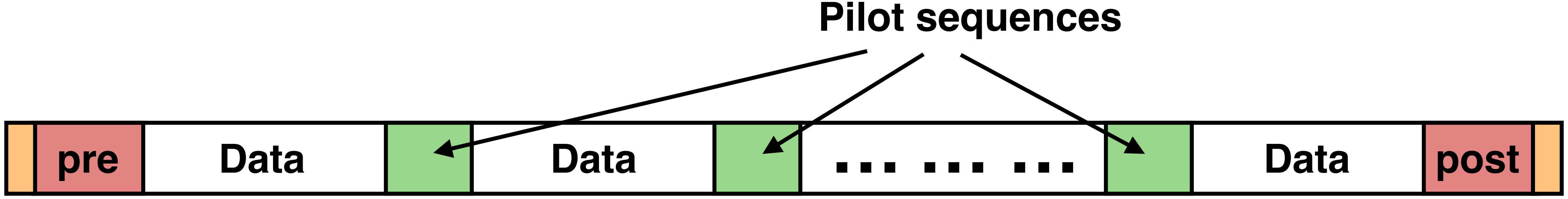


$$\left\{ \widehat{A}_2, \widehat{\Delta f}_2, \widehat{\phi}_2 \right\} = \underset{A', \Delta f', \phi'}{\operatorname{argmin}} \left| \boldsymbol{p_2}^{(m)} \times \square - A' e^{j(2\pi \Delta f' t + \phi')} \right|^2$$

- Same steps are performed **iteratively** for the packets of users **1** and **3**.

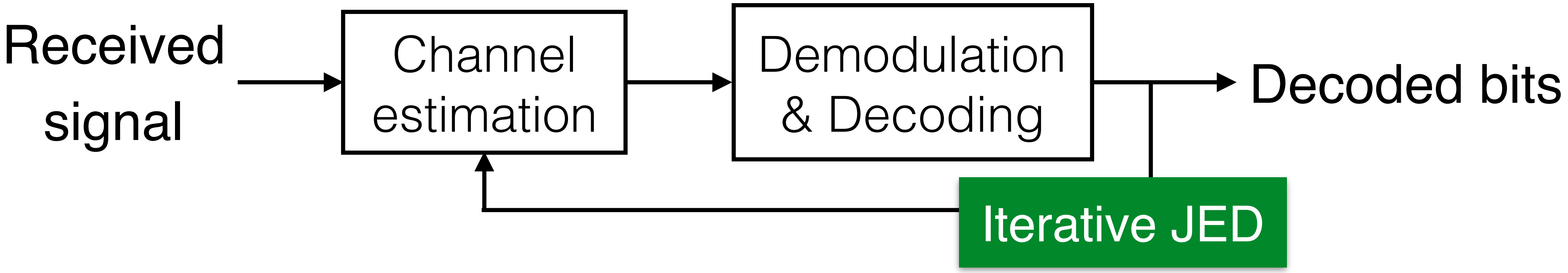
Contributions related to channel estimation with EM

1. Apply the EM algorithm on the **preamble** and the **postamble** parts.
2. Use **auto-correlation initialisation** for **faster** and more **accurate** results.
3. Apply the EM algorithm on **Pilot-Symbol Assisted Modulation** (PSAM), for **finer frequency offset estimation.**

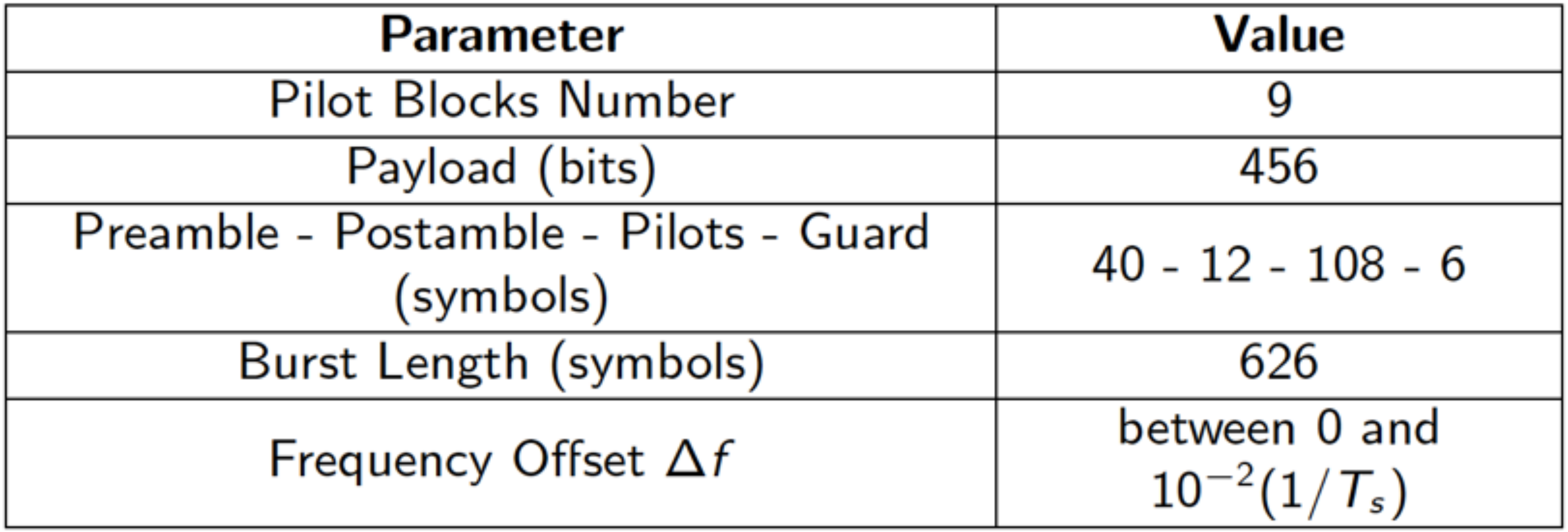


4.Consideration of **Timing offsets**.

5. **Joint Estimation & Decoding** (JED).



Simulation parameters



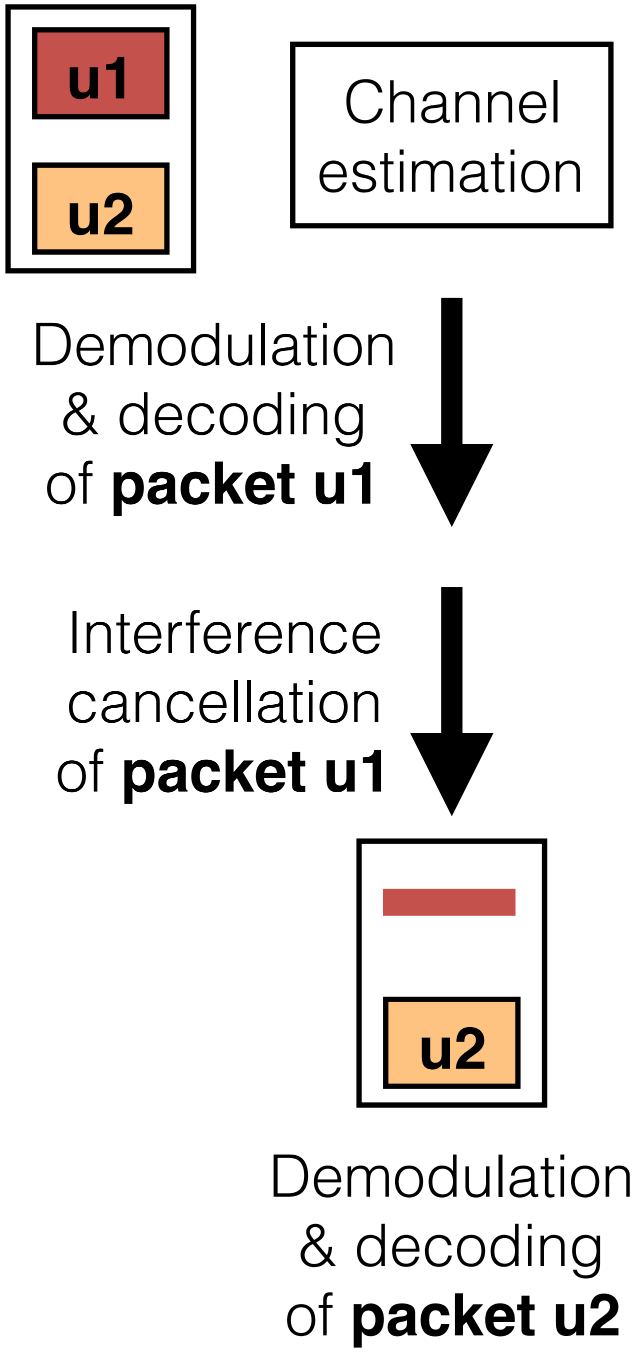
Parameter	Value
Pilot Blocks Number	9
Payload (bits)	456
Preamble - Postamble - Pilots - Guard (symbols)	40 - 12 - 108 - 6
Burst Length (symbols)	626
Frequency Offset Δf	between 0 and $10^{-2}(1/T_s)$

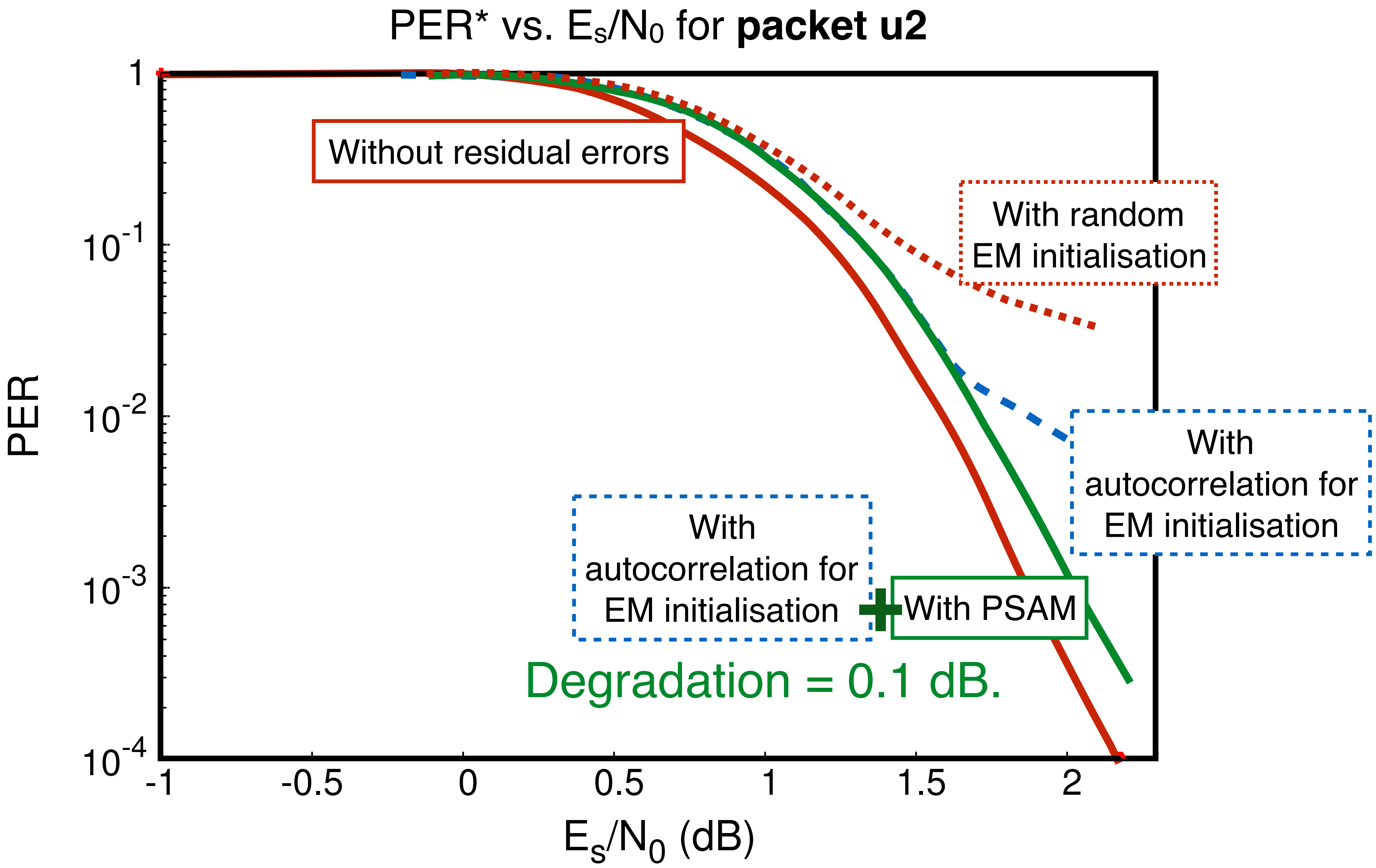
- We consider a frame of **100** time slots, and an oversampling factor **Q = 5**.
- With PSAM, the additional overhead compared to without PSAM is **7%**.
- The EM algorithm is iterated **4 times**, and the JED is repeated **3 times**.

Simulation results (1)

*PER: Packet Error Rate

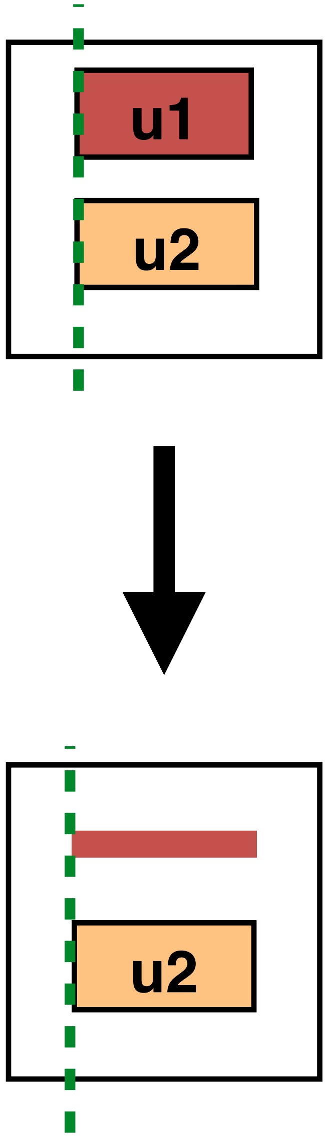
Simulations scenario with 2 synchronous packets without JED

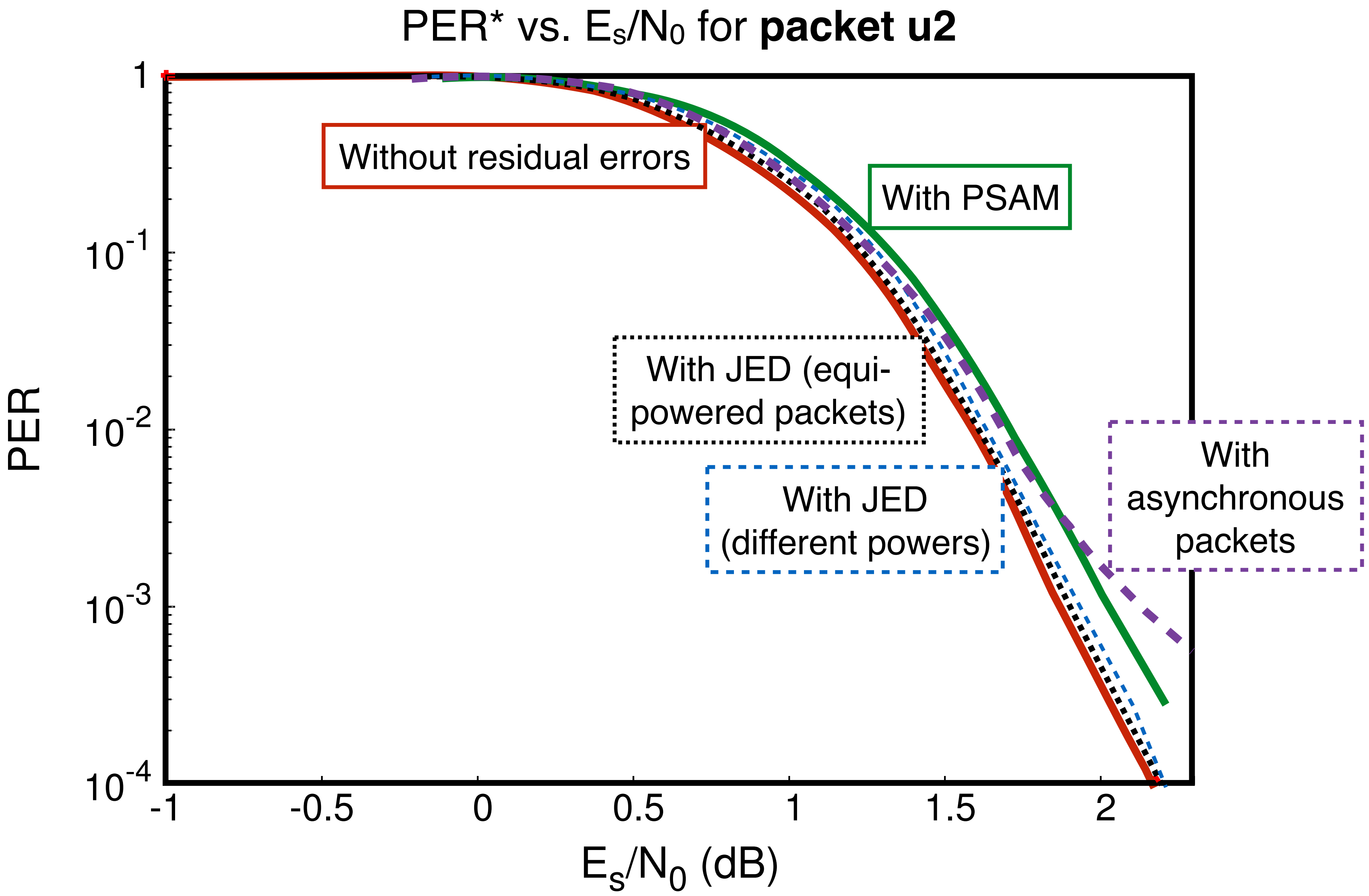




Simulation results (2)

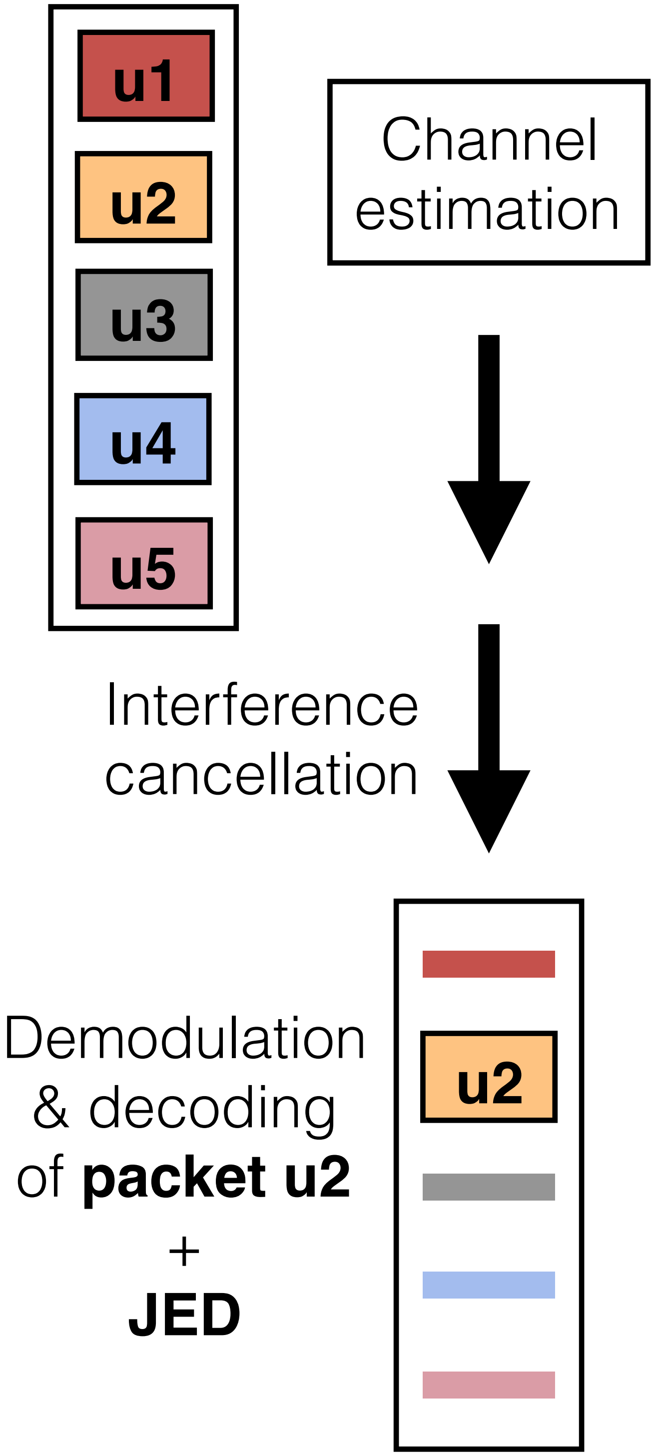
Simulations scenario with 2 packets and JED (3 JED iterations)





Simulation results (3)

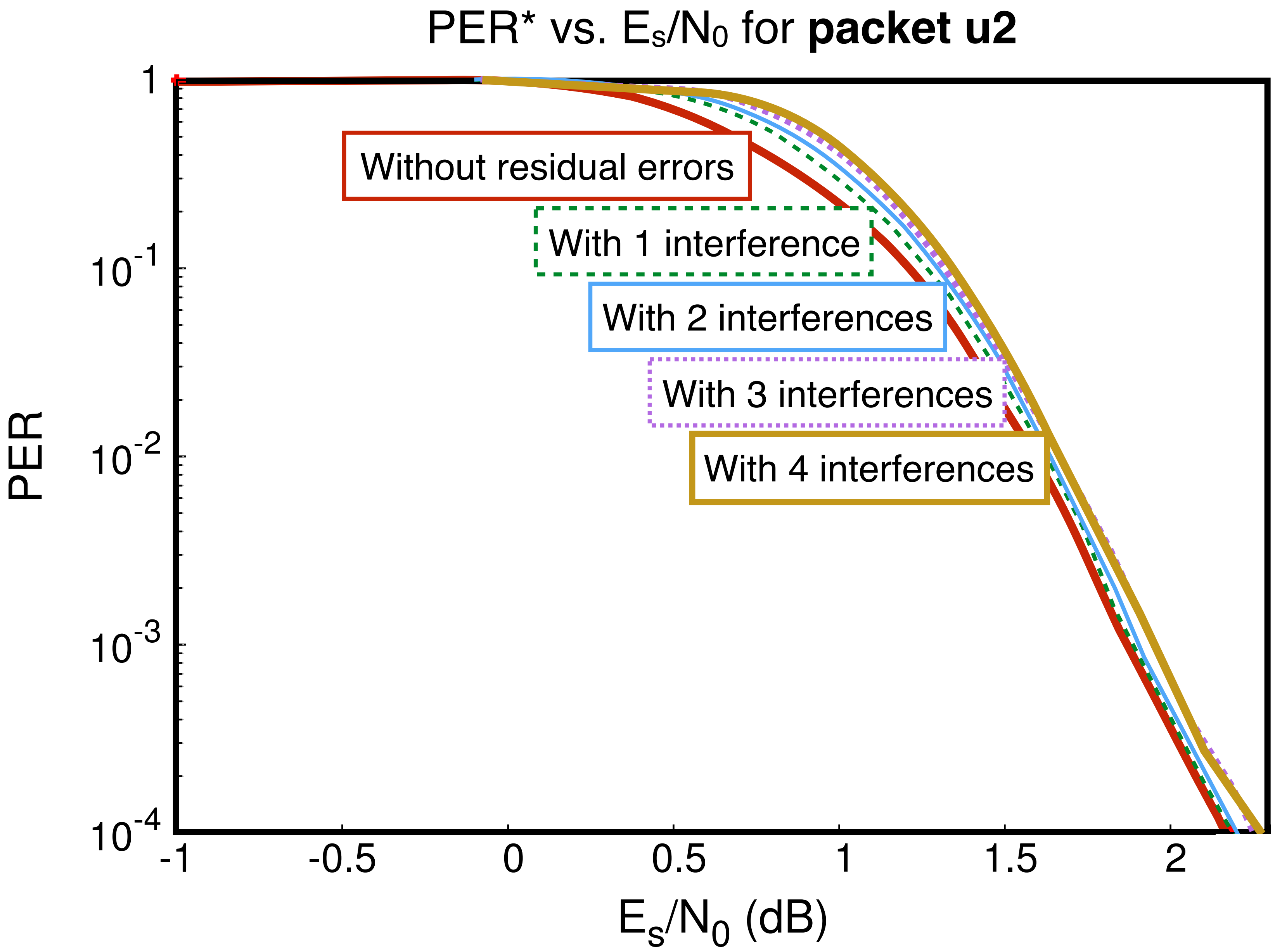
Simulations scenario with several synchronous packets



Channel estimation

Interference cancellation

Demodulation & decoding of **packet u2** + **JED**



Summary & conclusion of **1st contribution**

- **Problem presented:**
  Impact of **residual channel estimation** errors on the performance of **SIC**.

  Proposed solution:
  Evaluation of the **EM estimation** algorithm with autocorrelation initialisation, PSAM and JED.

- **Conclusions:**
  - **Enhancement of the PER** in presence of channel estimation residual errors.

  - The proposed algorithm requires the **knowledge of users** on one timeslot before channel estimation, which is **not very practical** in all RA schemes.

- **Remaining challenges:**
  - More **accurate timing offset estimation**.
  - **Less complex** algorithms.

- **Another remaining challenge:**
  Enhancing the throughput and the PLR of existing synchronous RA protocols?

  Proposed solution:
  Multi-replicA decoding using coRrelation baSed locALisAtion (MARSALA).

2.2. MARSALA

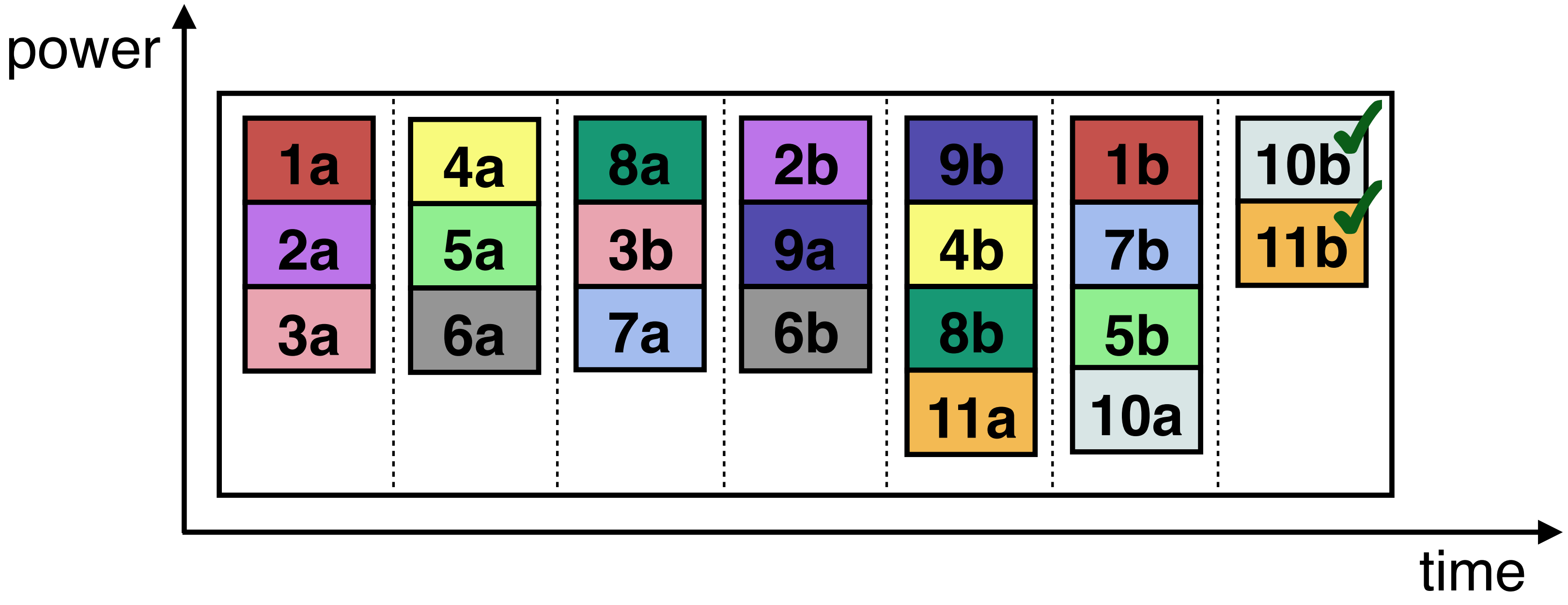
Photo source: **Wikipedia**

MARSALA RA scheme

Definition

MARSALA is a new decoding technique for CRDSA in case additional packets cannot be recovered due to strong collisions.

Example of a deadlock for CRDSA at the receiver

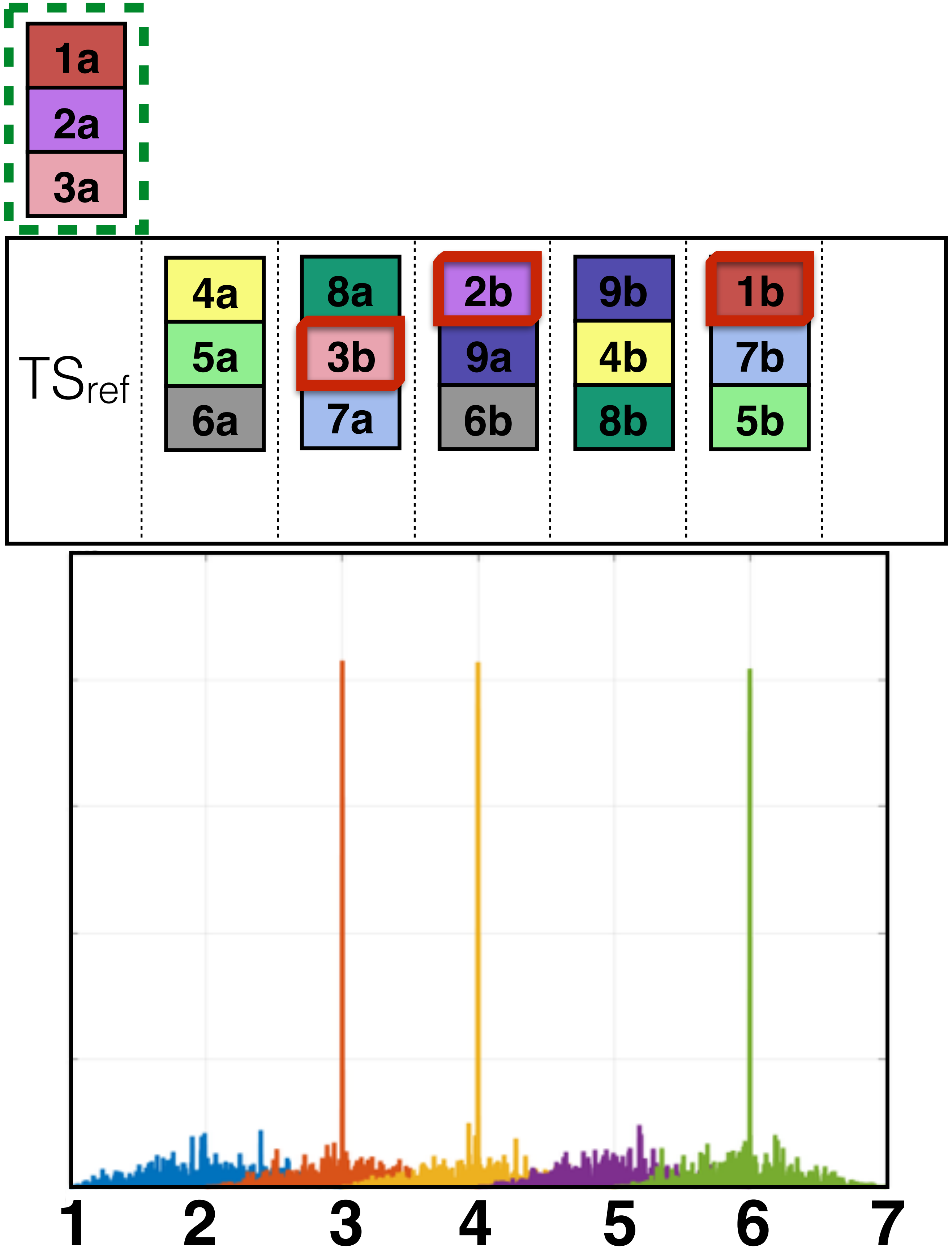


Replicas localisation

1. Select a reference timeslot TS_{ref}.
2. Cross-Correlation of the signal of TS_{ref} with the signals on the other timeslots.
3. Identify the timeslots showing a **correlation peak.**

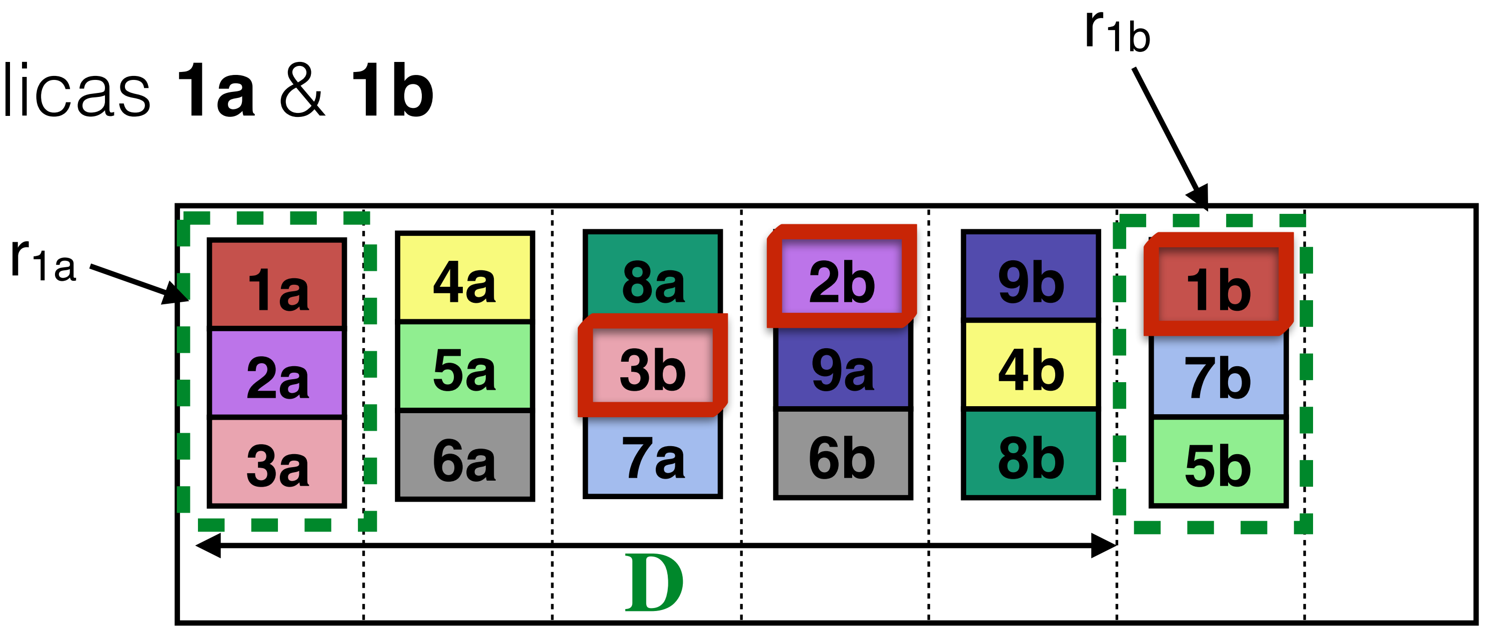
System assumptions

- The frequency offset **is constant for the same user** on the frame duration.
- The timing and phase shifts **vary from one timeslot to another** but have **constant** values over one timeslot.



Replicas synchronisation

Example: replicas **1a** & **1b**



$$r_{1a} = \boldsymbol{s_1}(t - \boldsymbol{\tau_{1a}})e^{j(2\pi\boldsymbol{\Delta f_{1a}}t+\boldsymbol{\phi_{1a}})} + s_{2}$$ se

Cross-correlation peak position

$$r_{1b} = \boldsymbol{s_1}(t - \boldsymbol{\tau_{1b}})e^{j(2\pi\boldsymbol{\Delta f_{1a}}(t+\mathbf{D})+\boldsymbol{\phi_{1b}})} + s_{7b} + s_{5b} + \text{noise}$$

Estimation of $(\boldsymbol{\tau_{1a}} - \boldsymbol{\tau_{1b}})$

and $(\boldsymbol{\phi_{1a}} - \phi 1b - \boldsymbol{\Delta f_{1a}}\mathbf{D})$

r1b after timing and phase compensation

$$\widehat{r}_{1b} = \boldsymbol{s_1}(t - \boldsymbol{\tau_{1a}} + \boldsymbol{\tau_{err}})e^{j(2\pi\boldsymbol{\Delta f_{1a}}t+\boldsymbol{\phi_{1a}}+\boldsymbol{\phi_{err}})} + s_{7b} + s_{5b} + \text{noise}$$

residual timing error

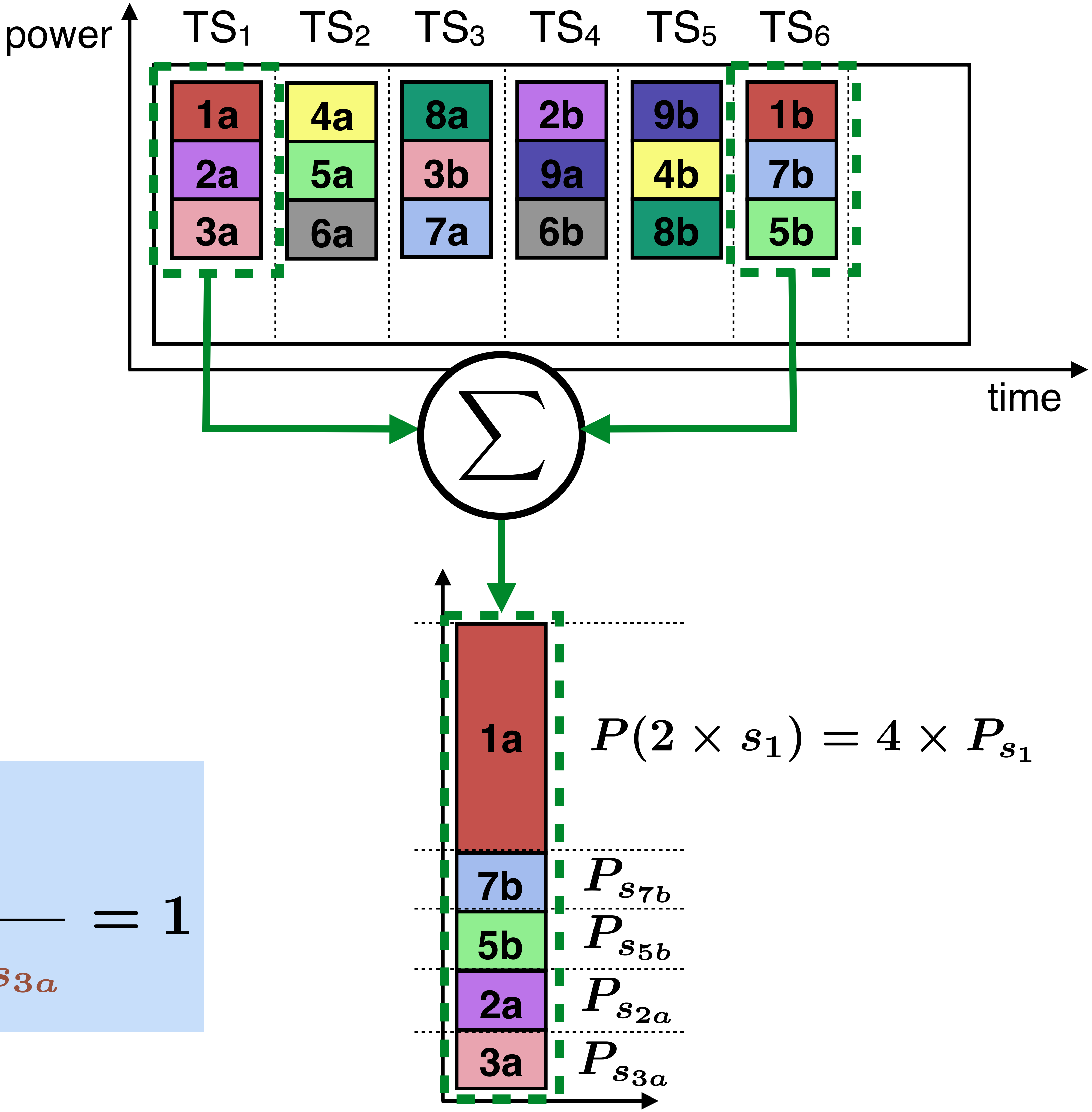
Cross-correlation peak angle

Replicas combination

***SIR: Signal to Interference Ratio**

For example on **TS**₁,
With **equi-powered** packets,
SIR* for **packet 1a:**

$$\frac{P_{s_1}}{P_{s_{2a}}+P_{s_{3a}}} = \frac{1}{2}$$



After combining the signals on
TS₁ and TS₆ in MARSALA,
SIR* for **packet 1a:**

$$\frac{4 \times P_{s_1}}{P_{s_{7b}}+P_{s_{5b}} + P_{s_{2a}} + P_{s_{3a}}} = 1$$

2.2.1. Evaluation of MARSALA in real channel conditions

Analytical model for combined replicas

$$\widehat{r}_{1b} = \boldsymbol{s_1}(t - \boldsymbol{\tau_{1a}} + \boldsymbol{\tau_{err}})e^{j(2\pi \boldsymbol{\Delta f_{1a}} t + \boldsymbol{\phi_{1a}} + \boldsymbol{\phi_{err}})} + s_{7b} + s_{5b} + \text{noise}$$

residual timing error

residual phase error

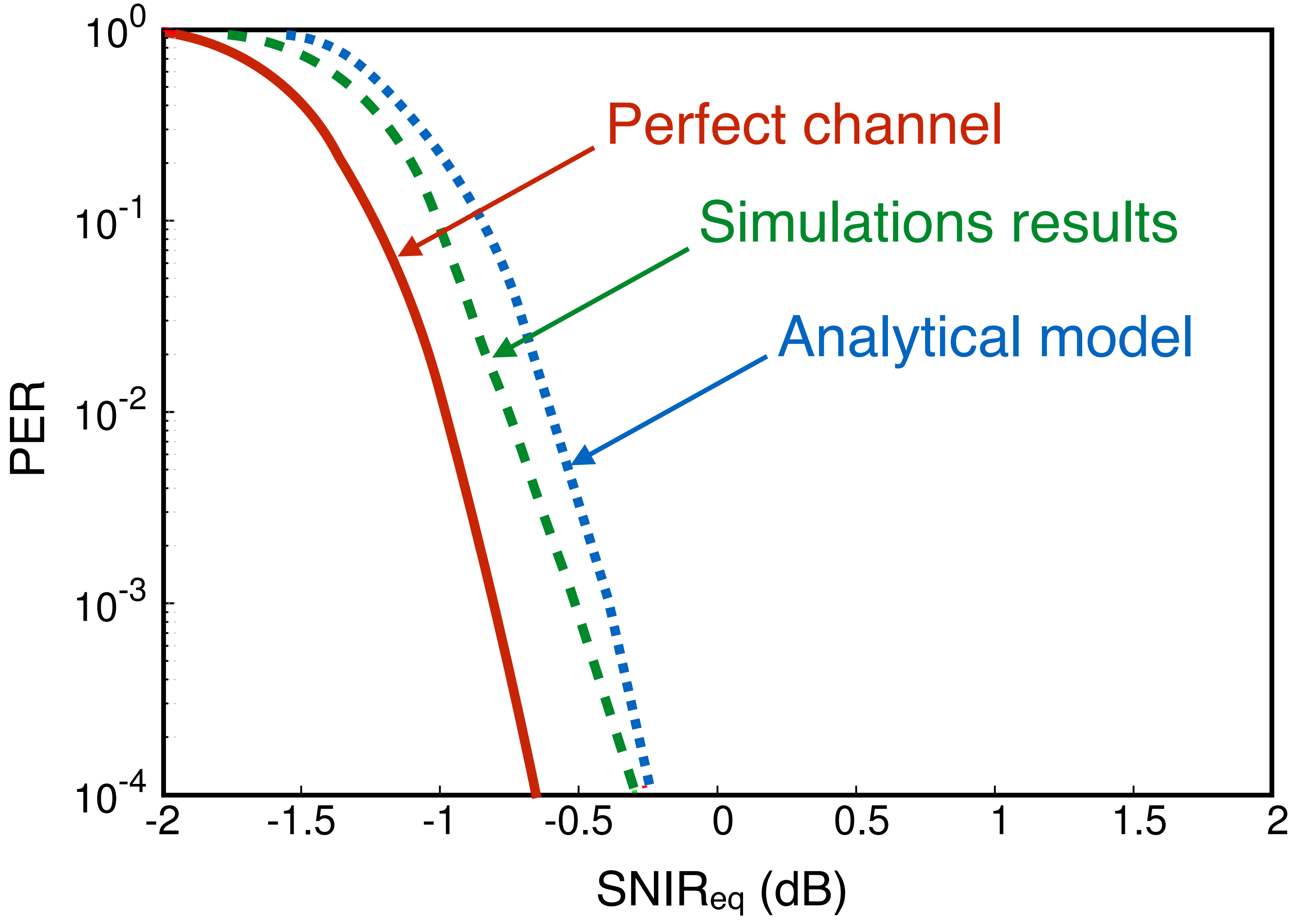
- Define a **model** to calculate **the equivalent SNIR*** after replicas combining **in real channel conditions**.
- Provide this SNIR calculation as an **input to the turbo decoder**.
- **Average equivalent SNIR in real channel conditions**

$$SNIR_{eq} = \frac{\text{Power of } \textbf{combined useful} \text{ signal}}{P_{\boldsymbol{ISI}} + \text{Power of } \textbf{interference \& Noise}}$$

*SNIR: Signal to Noise plus Interference Ratio.
*ISI: Inter-Symbol Interference.

Analytical model results

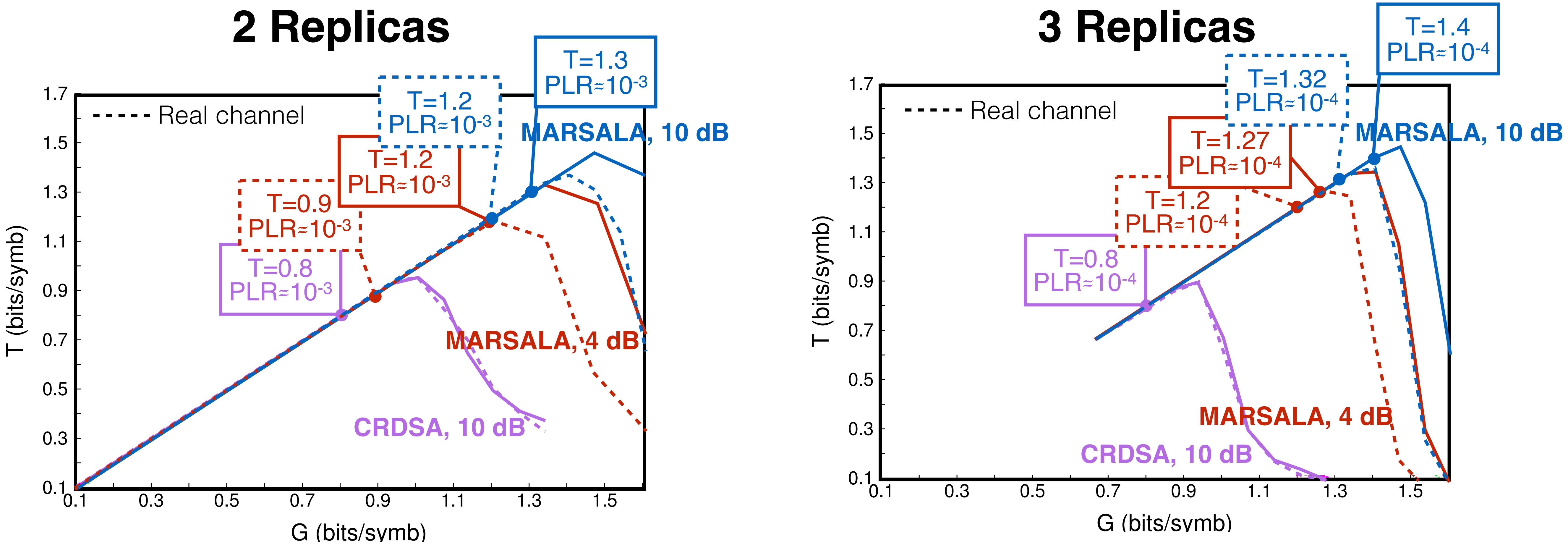
- **According to the analytical model**, the **degradation of SNIR$_{eq}$** in real channel conditions compared to perfect CSI* is between **0.2 dB** and **0.3 dB**.
- The residual phase error has **negligible impact** on the SNIR degradation.
- **Validation with simulations**



Simulation parameters

- **2 interference packets** on each timeslot.
- **N$_b$ = 2** replicas.
- Residual timing error is $0.5\frac{T}{Q}$ (worst ISI case).
- **QPSK** modulation.
- **DVB-RCS2** turbo code of **rate 1/3**.

Throughput of MARSALA



2 Replicas

3 Replicas

Throughput obtained with **CRDSA alone** and **CRDSA combined with MARSALA** with QPSK modulation and DVB-RCS2 turbo code of rate 1/3 (waveform id 3).

Conclusion for MARSALA in real channel conditions

- **MARSALA-3 is more robust** to real channel conditions than MARSALA-2.
- Even in presence of **residual synchronisation errors** among replicas, MARSALA shows **significant performance gains**.

2.2.2. Enhancement schemes for MARSALA

MARSALA with Maximum Ratio Combining

- **Optimal** Maximum Ratio Combining (**MRC**) for **packet 1:**

$$\alpha_{TS_1} = \mathrm{SNIR}_{1a}$$

$$\alpha_{TS_6} = \mathrm{SNIR}_{1b}$$

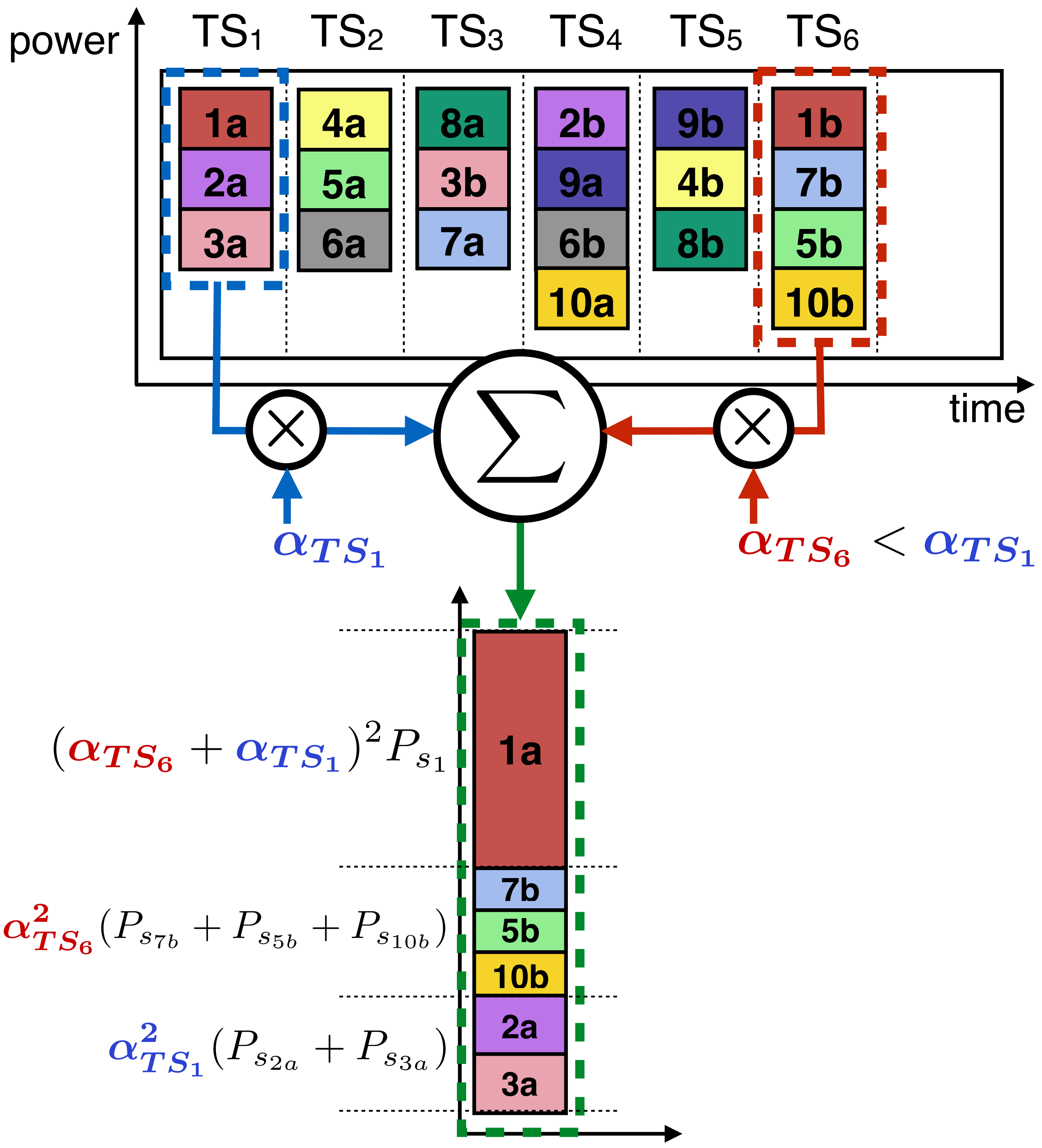
👎 **Less precise**

- **MRC** by normalising with **the total received power** on **TS₁** and **TS₆:**

$$\alpha_{TS_1} = \frac{1}{P_{TS_1}}$$

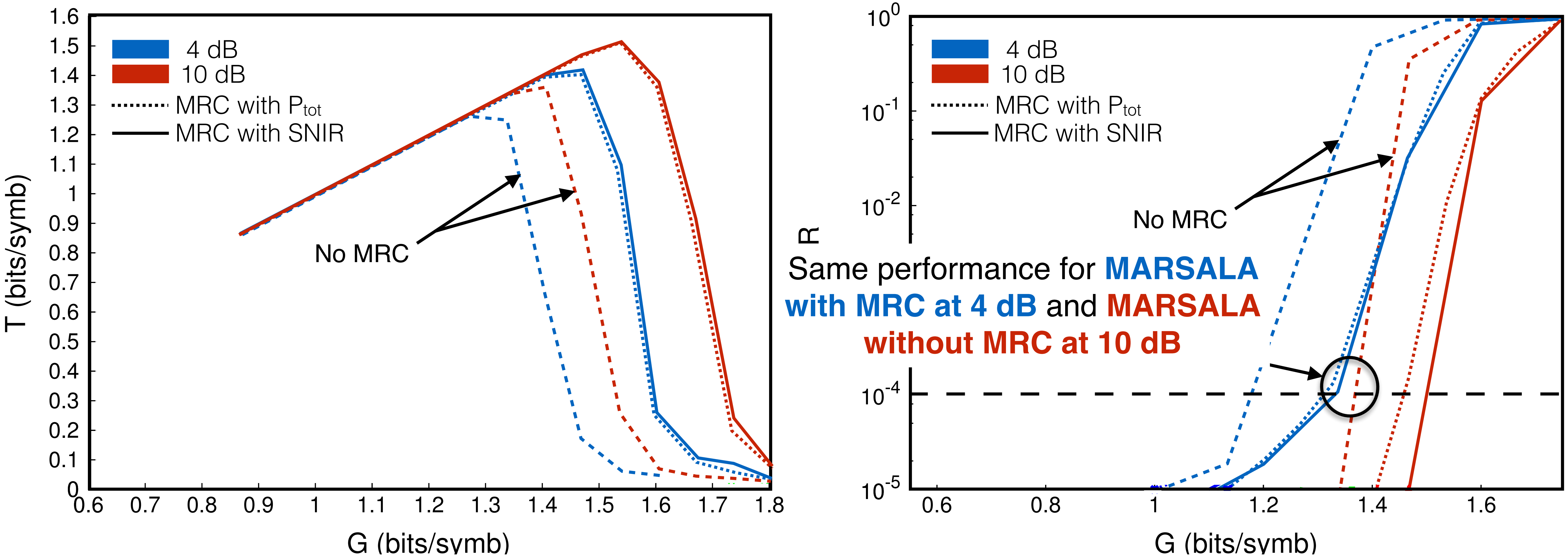
$$\alpha_{TS_6} = \frac{1}{P_{TS_6}}$$

👍 **Less complex to compute**



Throughput & PLR with MRC

MARSALA with 3 Replicas

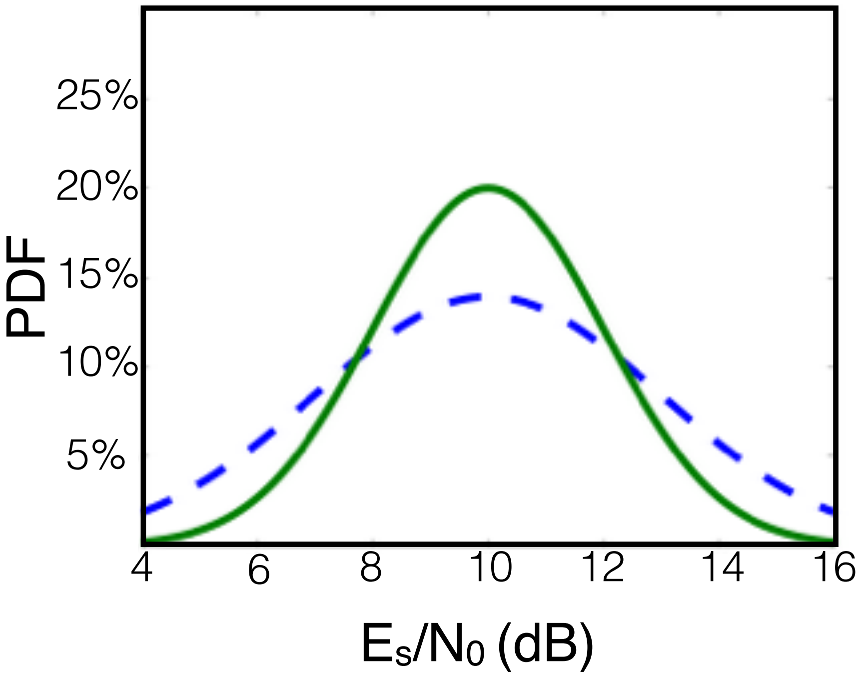


Same performance for **MARSALA with MRC at 4 dB** and **MARSALA without MRC at 10 dB**

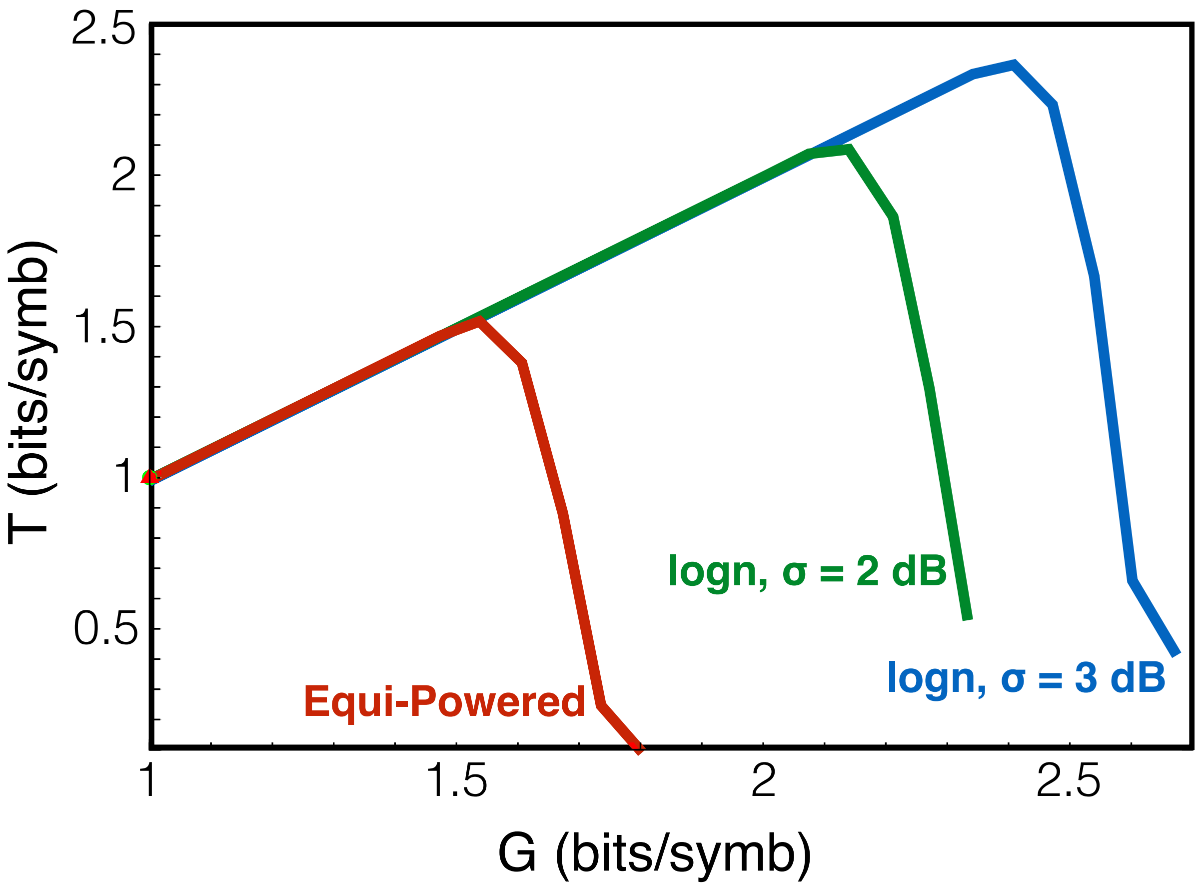
Throughput and PLR obtained with MARSALA with QPSK modulation and DVB-RCS2 turbo code of rate 1/3 (waveform id 3).

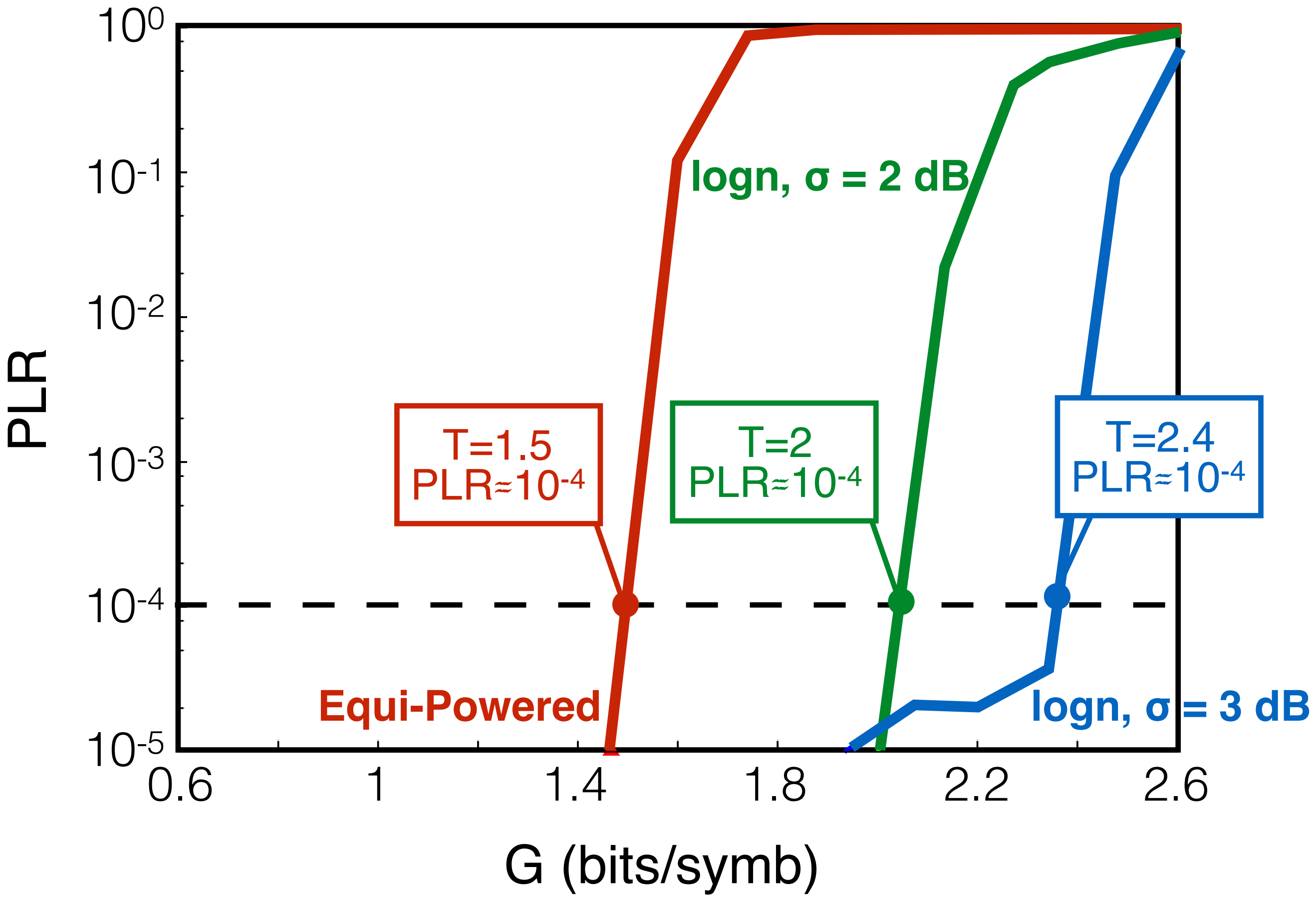
MARSALA with packets power unbalance

Log-normal packets power distribution



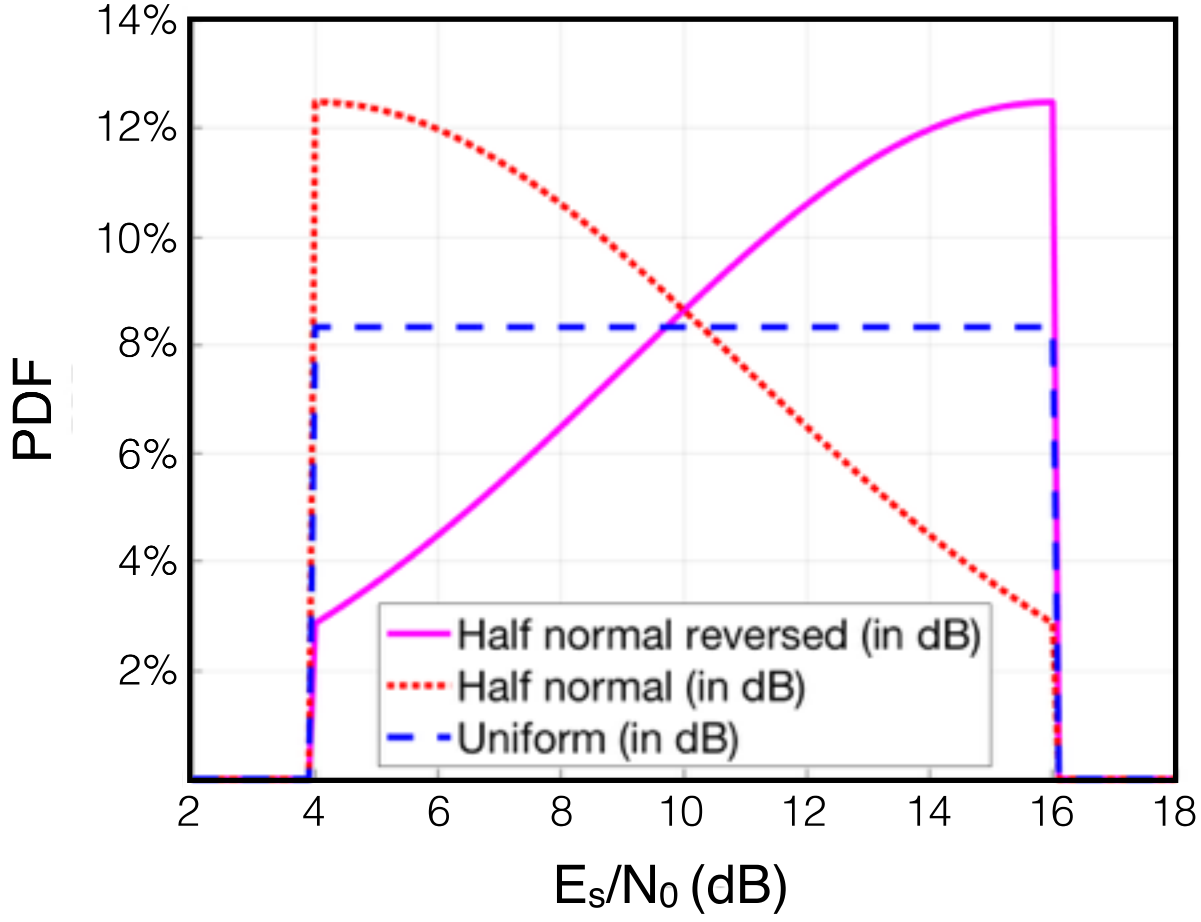
MARSALA with 3 Replicas and MRC

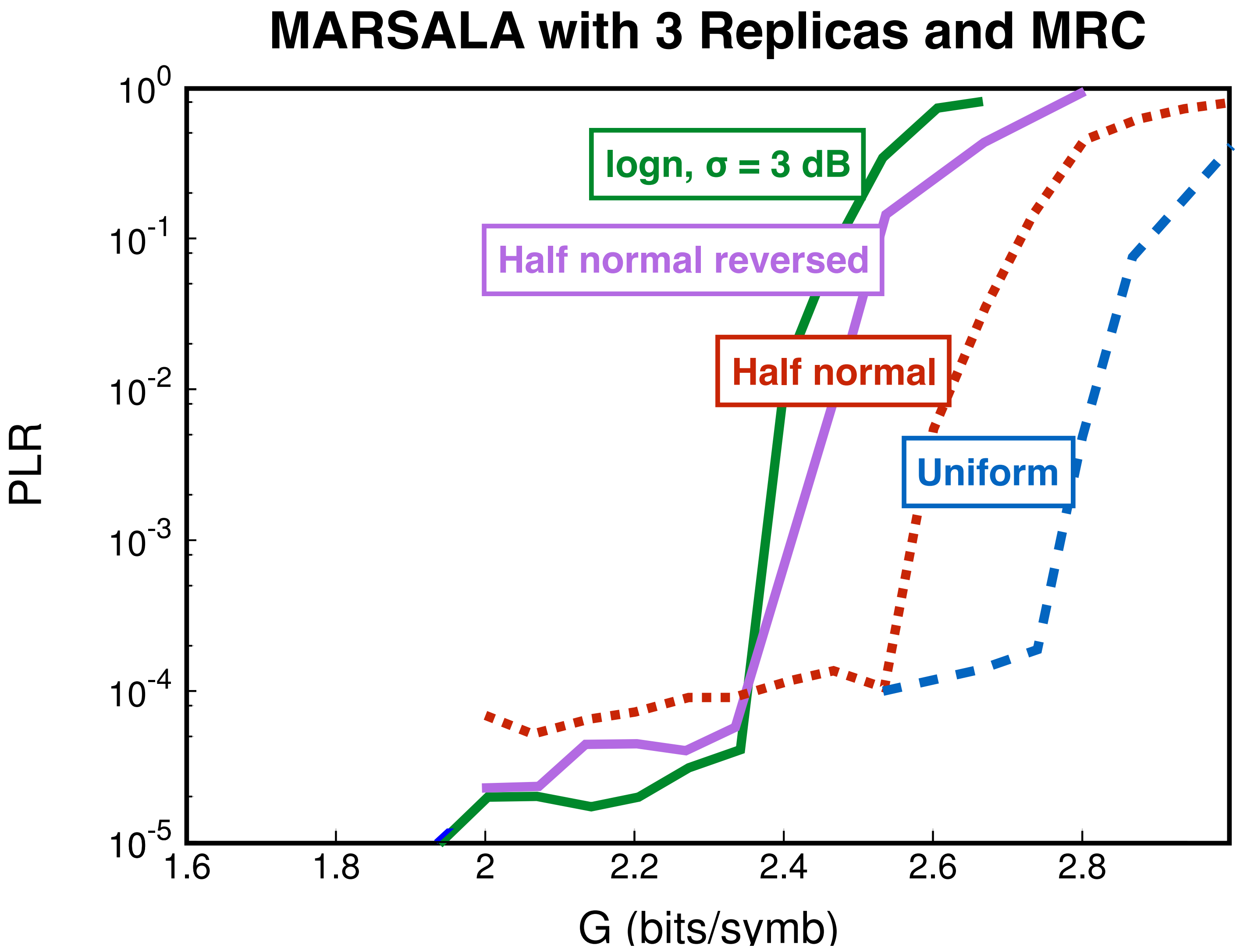




MARSALA with packets power unbalance

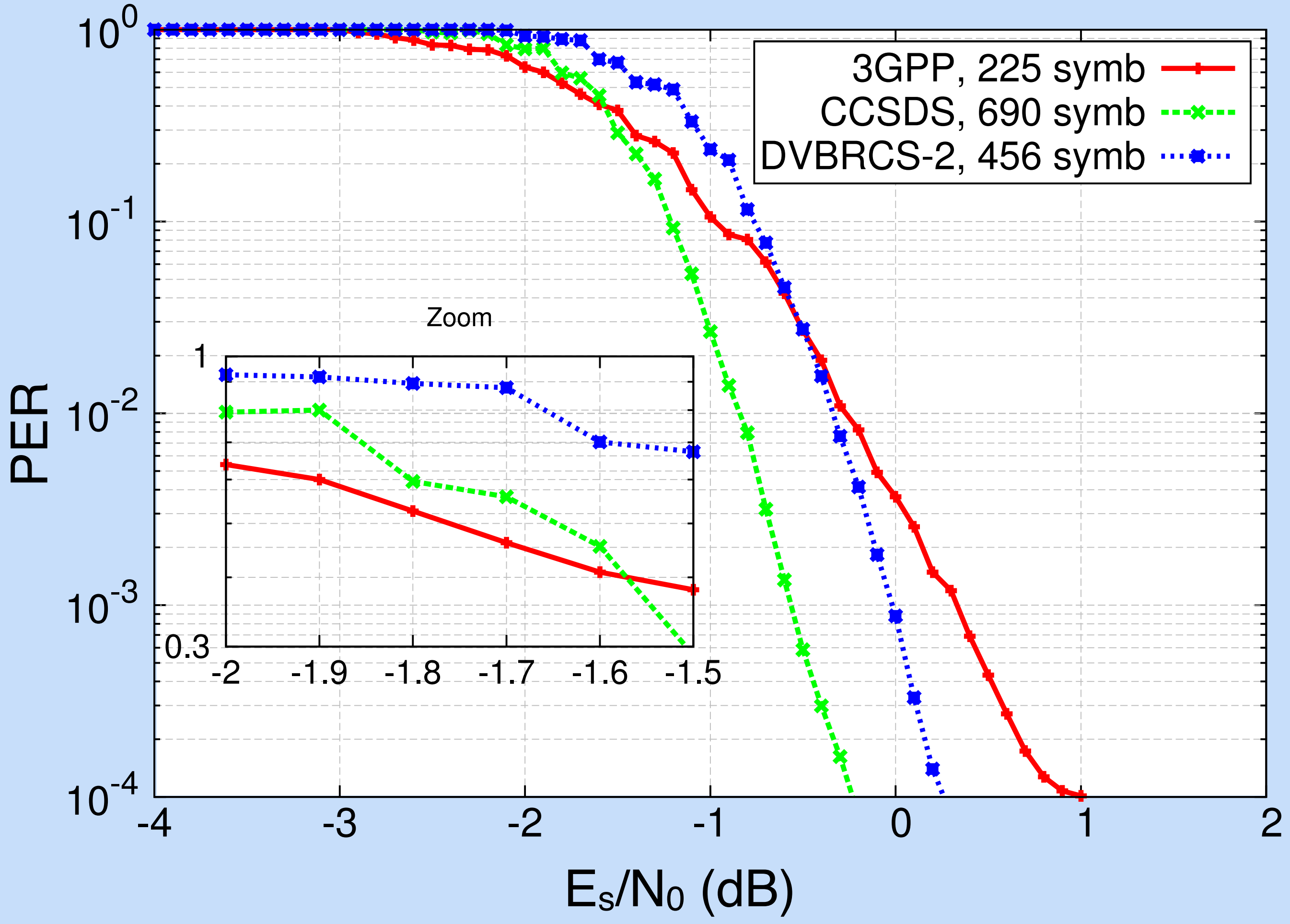
Proposed packets power distributions



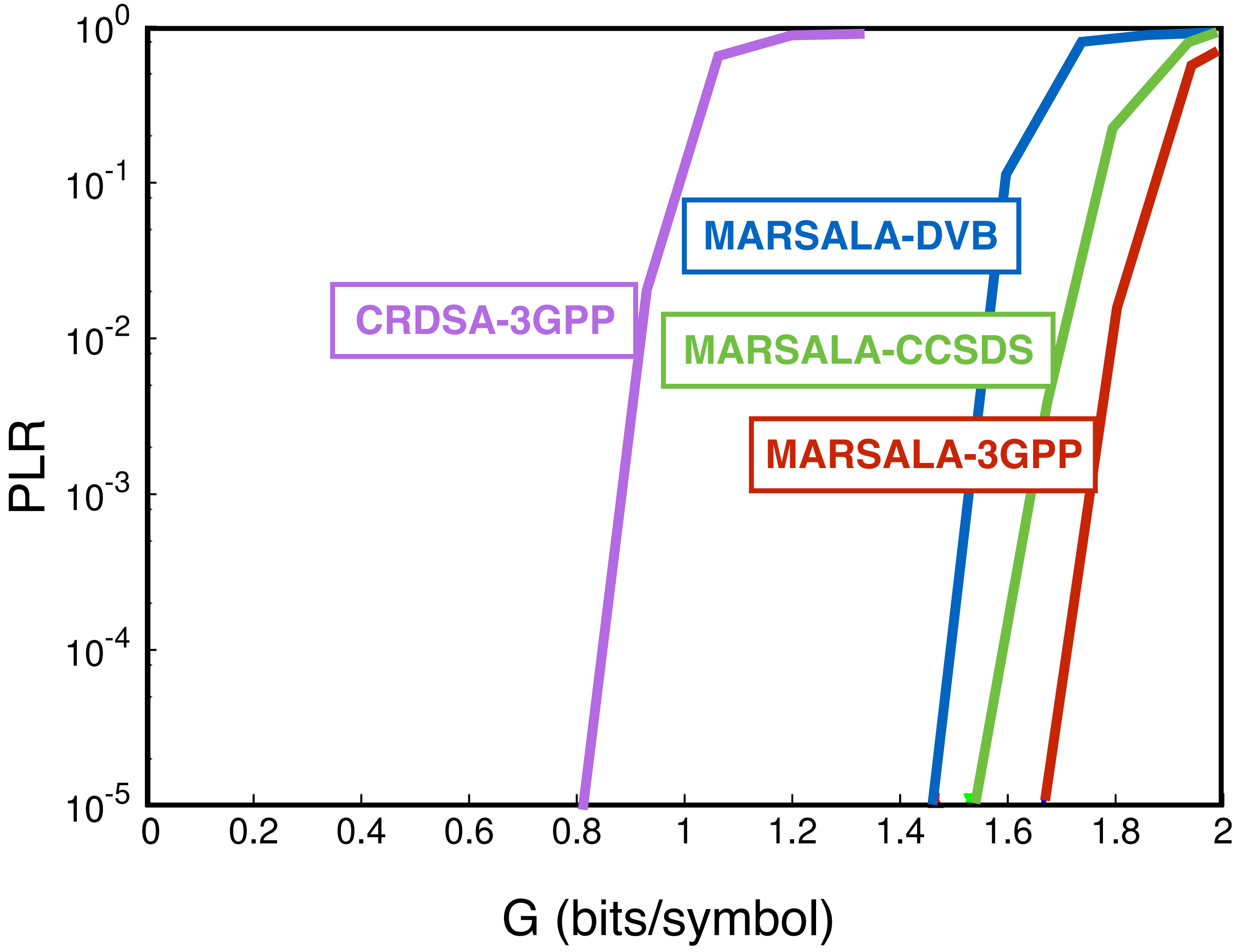


MARSALA with various coding schemes

Turbo-code performances with rate **R=1/3**



MARSALA with 3 replicas and **MRC**
Equi-Powered Packets



Summary of **2^{nd} thesis contribution**

Target PLR=10^{-4}	DVB-RCS2 mod cod	3GPP mod cod
No MRC	**1.3**	-
MRC	1.5	1.7
MRC + logn, σ = 3 dB	2.35	2.75
MRC + half normal	2.5	3
MRC + uniform	2.77	**3.25**

Throughput of MARSALA-3 in bits/symb with E_s/N_0 = 10 dB and a target PLR of 10^{-4}. QPSK modulation.

- **Significantly higher throughputs** for low targeted PLRs.
- However, **higher throughputs** induce **higher complexity**.

Conclusions & remaining challenges

Main conclusions

- MARSALA is able to achieve higher throughput and low PLR **with Es/N0 values as low as 4 dB**.

- With **packets power unbalance**, the performance is further enhanced.

On-going & future work

- The challenge to maintain **synchronisation** among users at the frame level → high signalling overhead.

- The challenge to detect packets in presence of **phase noise**.

- The challenge to lower the **complexity** at the receiver side.

Further Ideas

- **Irregular MARSALA** with a varying number of packet replicas per user.
- **Multi-coded MARSALA** with a varying code rate per user.
- Evaluation of MARSALA in an **asynchronous transmission scheme**.
- Define **optimal coding schemes** for an optimal PLR performance with SIC.

Thank you for your attention.