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R2D2: Network error control for
Rapid and **R**eliable **D**ata **D**elivery
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Resource Allocation Schemes for Layered Video Broadcasting

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Starting Point and Goals

- Delivery of multimedia broadcast/multicast services over 4G networks is a challenging task. This has propelled research into delivery schemes.
- **Multi-rate transmission strategies** have been proposed as a means of delivering layered services to users experiencing different downlink channel conditions.
- Layered service consists of a **basic layer** and **multiple enhancement layers**.

Goals

- *Error control* - Ensure that a **predetermined fraction of users** achieves a certain service level **with at least a given probability**
- *Resource optimisation* - **Minimise the total amount of radio resources** needed to deliver a layered service.

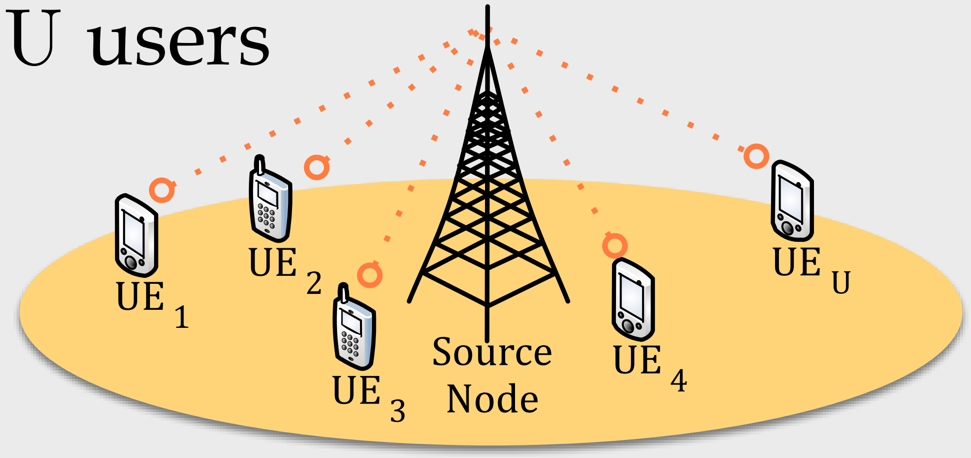
Index

1. System Parameters and Performance Analysis
2. Multi-Channel Resource Allocation Models and Heuristic Strategies
3. H.264/SVC Service Delivery over LTE-A eMBMS Networks
4. Analytical Results
5. Concluding Remarks

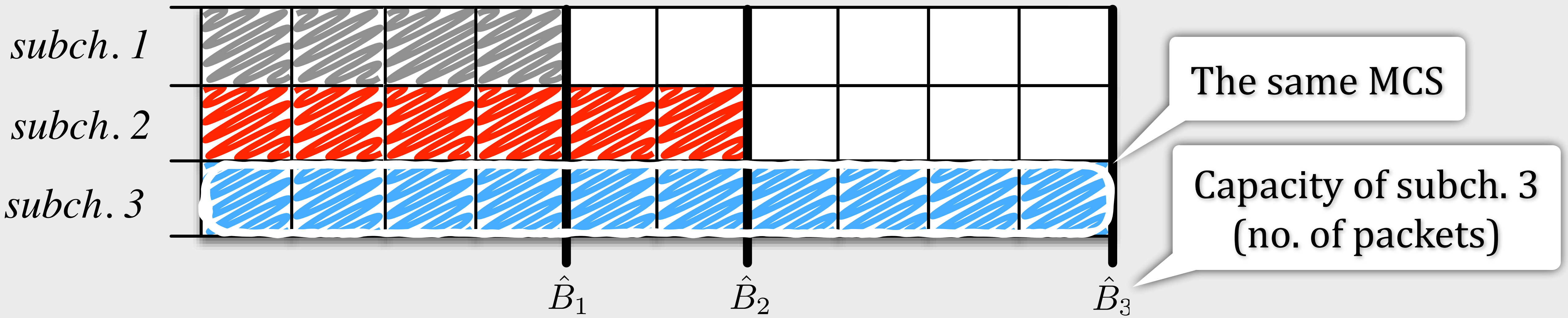
1. System Parameters and Performance Analysis

System Model

- One-hop wireless communication system composed of one source node and U users



- Each PtM layered service is delivered through C orthogonal broadcast erasure subchannels



- Each subchannel delivers streams of (en)coded packets (according to the RLNC principle).

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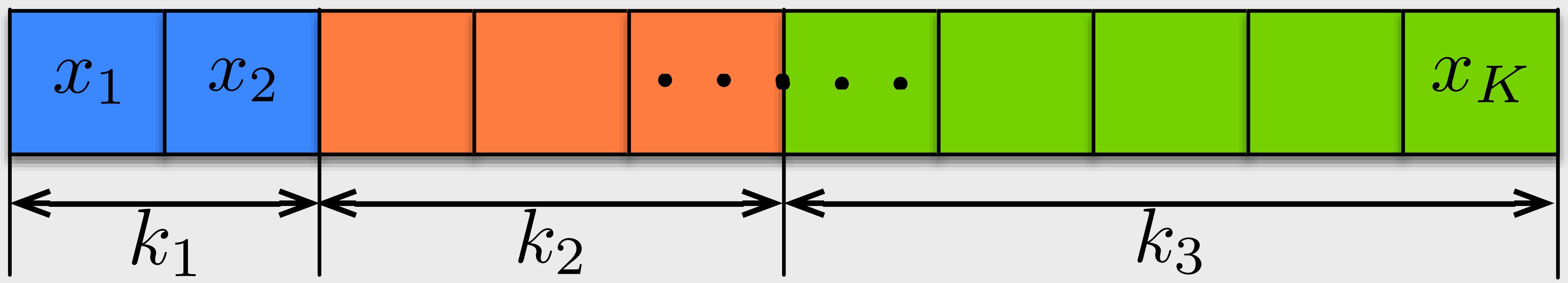
Non-Overlapping Layered RNC

- $\mathbf{x} = \{x_1, \ldots, x_K\}$ is a layered source message of K source packets, classified into L service layers



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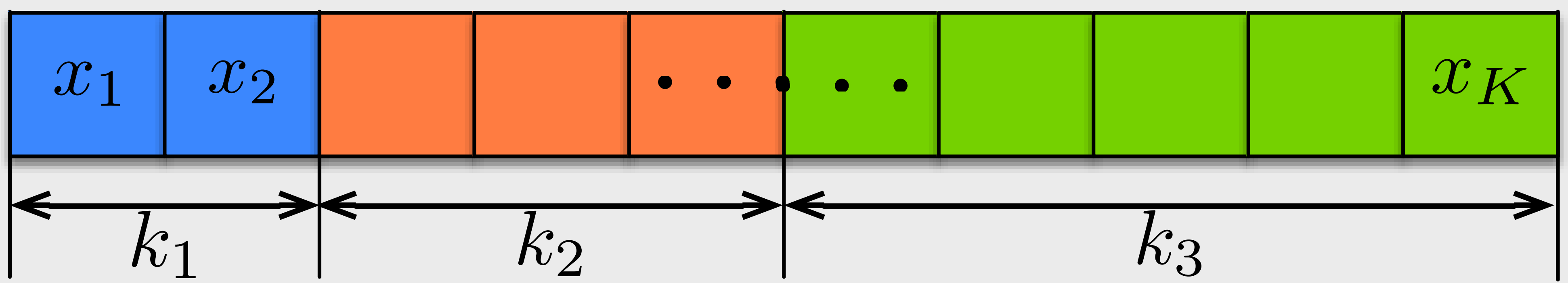


- Encoding performed over each service layer independently from the others.

- The source node will linearly combine the k_l data packets composing the l-th layer $\mathbf{x}_l = \{x_i\}_{i=1}^{k_l}$ and will generate a stream of $n_l \geq k_l$ coded packets $\mathbf{y} = \{y_j\}_{j=1}^{n_l}$, where

$$y_j = \sum_{i=1}^{k_l} g_{j,i} x_i$$

Coefficients of the linear combination are selected over a finite field of size q

Non-Overlapping Layered RNC

- User u recovers layer l if it will collect k_l linearly independent coded packets. The prob. of this event is

Prob. of receiving r out of $n_{l,u}$ coded symbols

$$\mathrm{P}_l(n_{l,u}) = \sum_{r=k_l}^{n_{l,u}} \binom{n_{l,u}}{r} p^{n_{l,u}-r} (1-p)^r \, h(r)$$

PEP

Prob. of decoding layer l

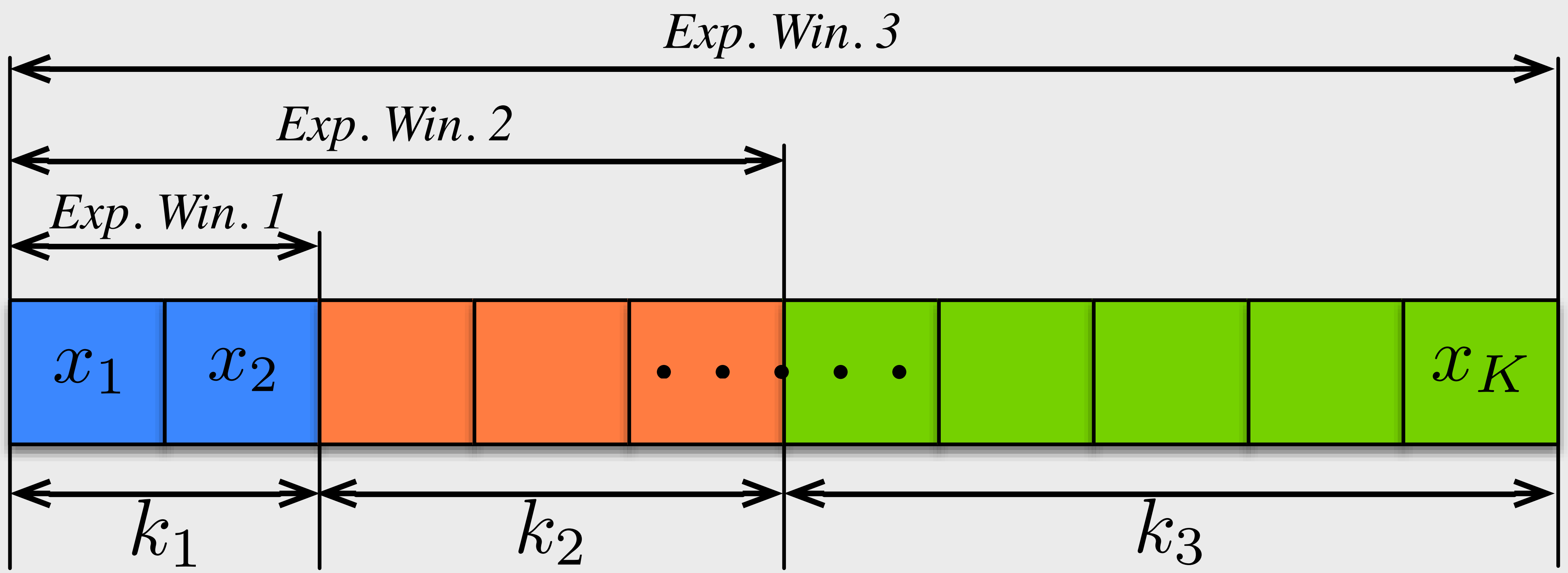
$$= \sum_{r=k_l}^{n_{l,u}} \binom{n_{l,u}}{r} p^{n_{l,u}-r} (1-p)^r \underbrace{\prod_{i=0}^{k_l-1} \left[1 - \frac{1}{q^{r-i}}\right]}_{h(r)}$$

- The probability that user u recover the first l service layers is

$$\mathrm{D}_{\mathrm{NO},l}(n_{1,u}, \ldots, n_{L,u}) = \mathrm{D}_{\mathrm{NO},l}(\mathbf{n}_u) = \prod_{i=1}^{l} \mathrm{P}_i(n_{i,u})$$

Expanding Window Layered RNC

- We define the l-th window $\mathbf{X}_l$ as the set of source packets belonging to the first l service layers. Namely, $\mathbf{X}_l = \{x_j\}_{j=1}^{K_l}$ where $K_l = \sum_{i=1}^{l} k_i$



- The source node (i) linearly combines data packets belonging to the same window, (ii) repeats this process for all windows, and (iii) broadcasts each stream of coded packets over one or more subchannels

Expanding Window Layered RNC

- The probability $\mathrm{D}_{\mathrm{EW},l}$ of user u recovering the first l layers (namely, the l-th window) can be written as

$$\mathrm{D}_{\mathrm{EW},l}(N_{1,u},\ldots,N_{L,u}) = \\ =\mathrm{D}_{\mathrm{EW},l}(\mathbf{N}_u) \\ = \sum_{r_1=0}^{N_{1,u}} \cdots \sum_{r_{l-1}=0}^{N_{l-1,u}} \sum_{r_l=r_{\min,l}}^{N_{l,u}} \binom{N_{1,u}}{r_1} \cdots \binom{N_{l,u}}{r_l} p^{\sum_{i=1}^{l}(N_{i,u}-r_i)} (1-p)^{\sum_{i=1}^{l} r_i} g_l(\mathbf{r})$$

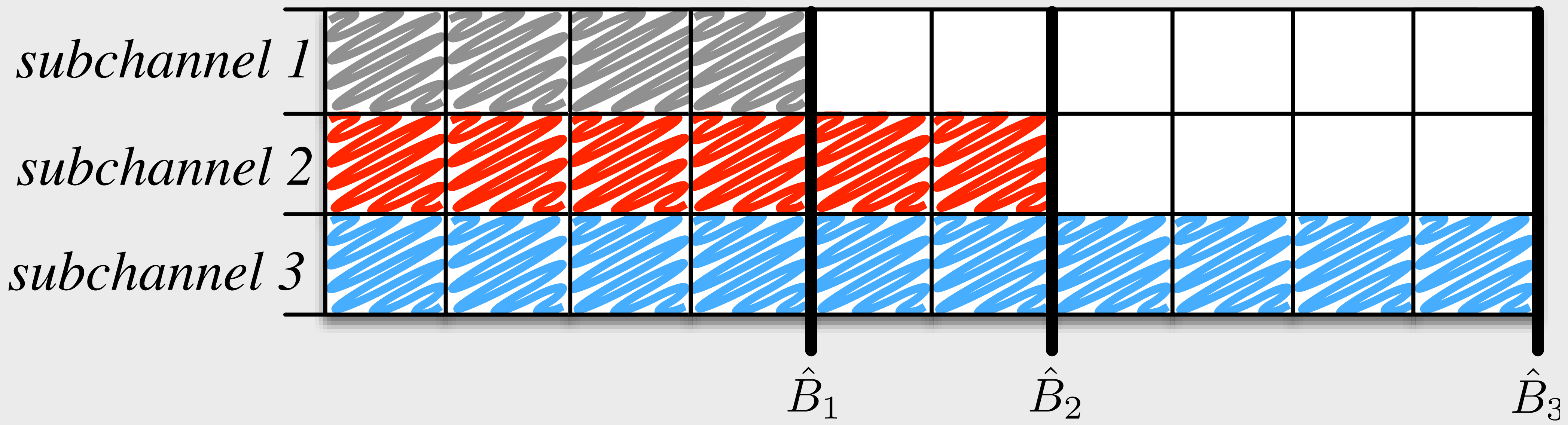
Prob. of receiving $\mathbf{r} = \{r_1, \ldots, r_l\}$ out of $\mathbf{N}_u$ coded symbols

Prob. of decoding window l

- Sums allow us to consider all the possible combinations of received coded packets

2. Multi-Channel Resource Allocation Models and Heuristic Strategies

Allocation Patterns



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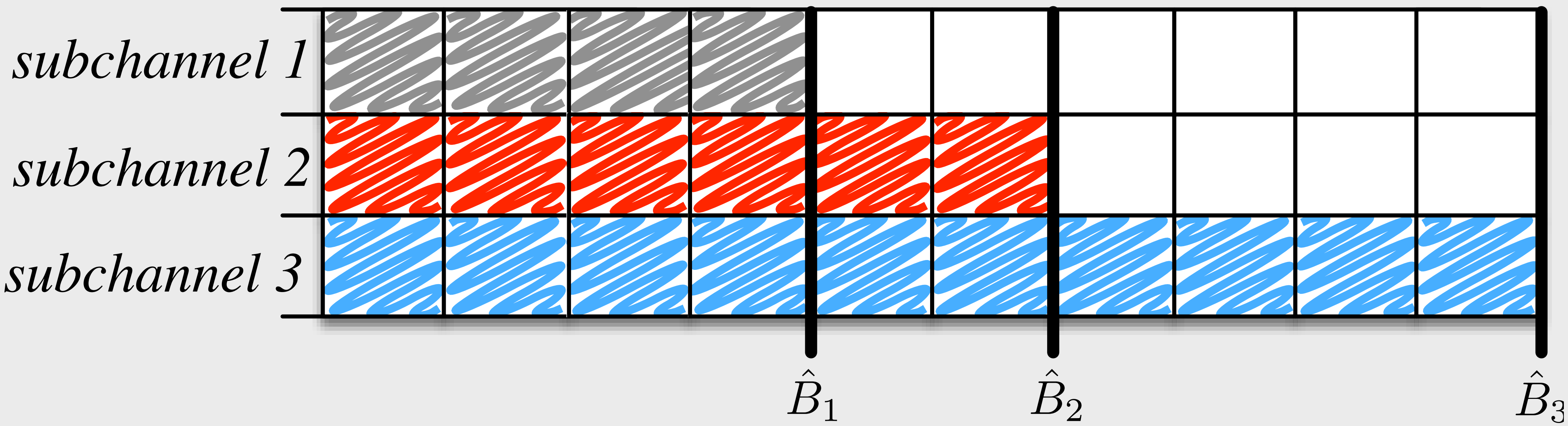

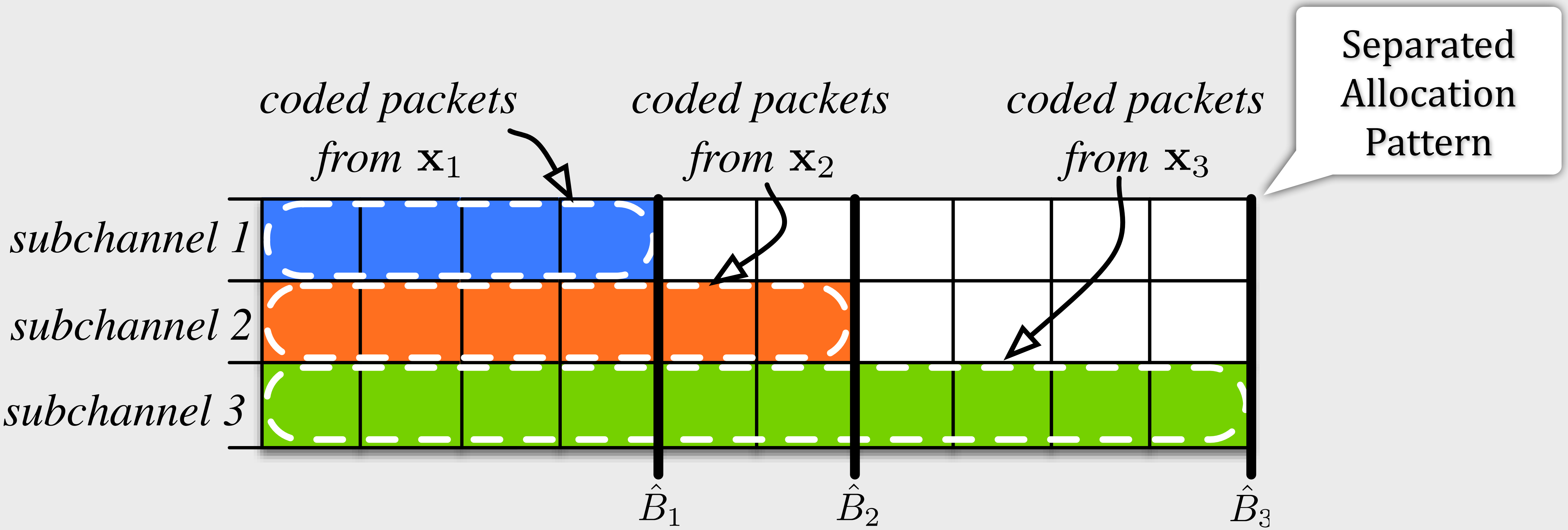

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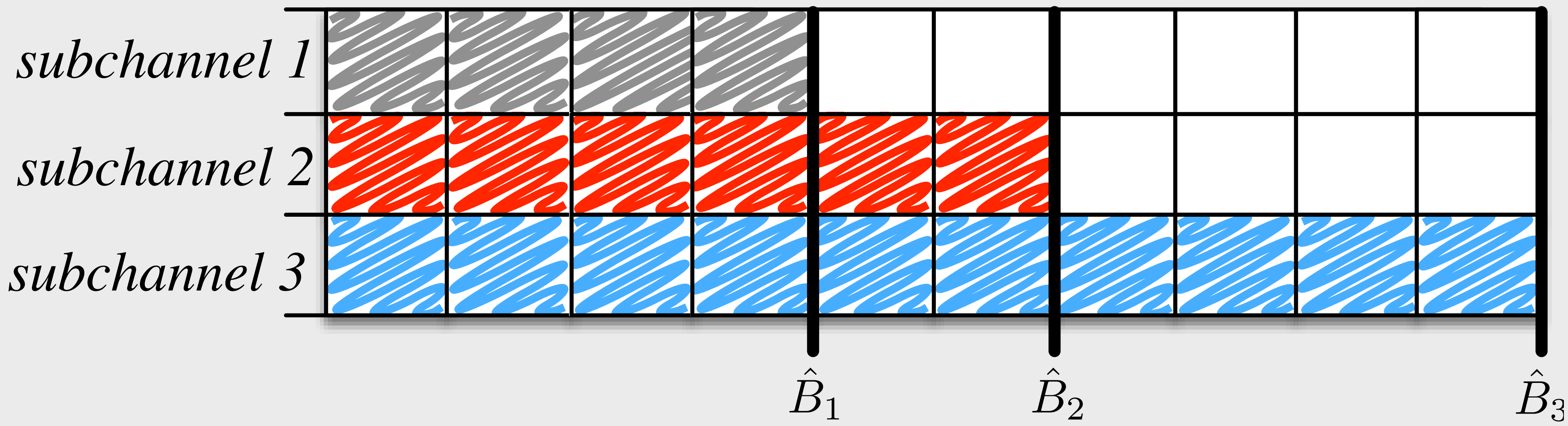
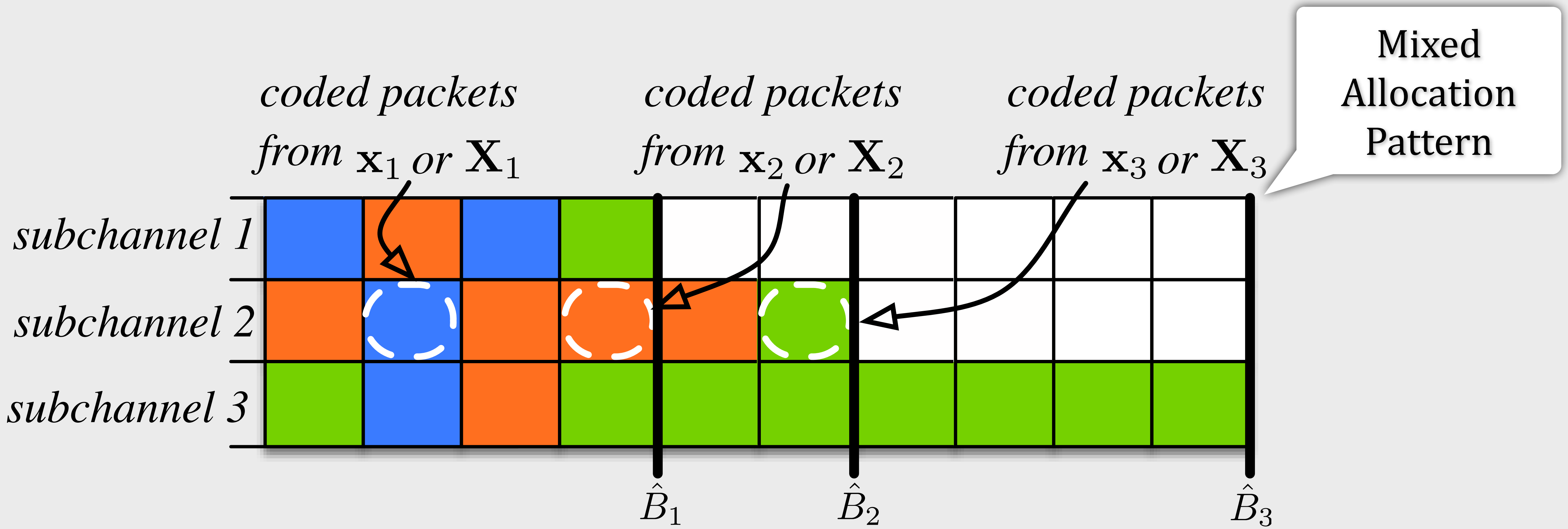
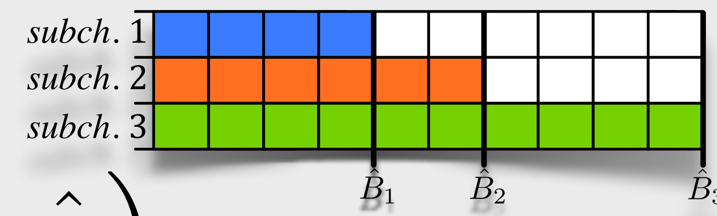


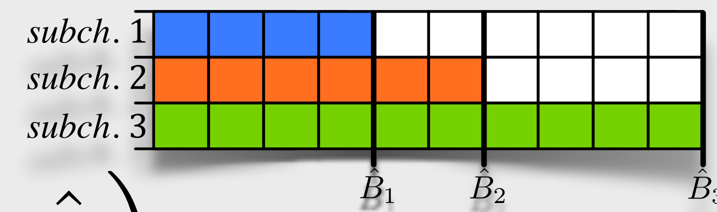


NO-SA Model



- Consider the variable $\lambda_{u,l} = I\left(\mathrm{D}_{\mathrm{NO},l}(\mathbf{n}_u) \geq \hat{D}\right)$. It is 1, if u can recover the first l layers with a probability value $\geq \hat{D}$, otherwise it is 0.

NO-SA Model



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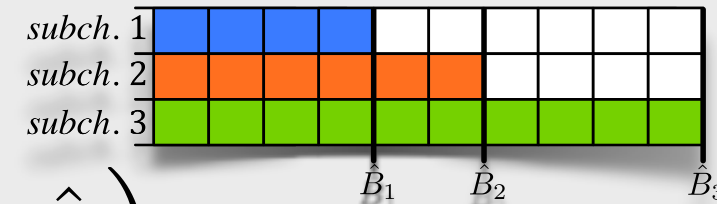
- The RA problem for the NO-SA case is

No. of packets of layer l delivered over c

$$\text{(NO-SA)} \qquad \min_{\substack{m_1,\ldots,m_C \\ n^{(1,c)},\ldots,n^{(L,c)}}} \sum_{l=1}^{L} \sum_{c=1}^{C} n^{(l,c)} \qquad (1)$$

Minimization of resource footprint

NO-SA Model



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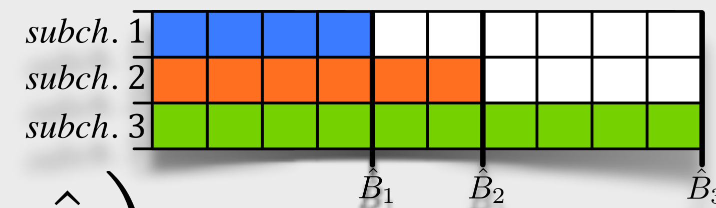
$$\text{subject to} \quad \sum_{u=1}^{U} \lambda_{u,l} \geq U\,\hat{t}_l \qquad l = 1,\ldots,L \qquad (2)$$

Target fraction of users

No. of users

Each service level shall be achieved by a predetermined fraction of users

NO-SA Model



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$$\text{subject to} \quad \sum_{u=1}^{U} \lambda_{u,l} \geq U\,\hat{t}_l \qquad l = 1, \ldots, L \tag{2}$$

$$m_{c-1} < m_c \qquad c = 2, \ldots, L \tag{3}$$

$$0 \leq \sum_{l=1}^{L} n^{(l,c)} \leq \hat{B}_c \qquad c = 1, \ldots, C \tag{4}$$

$$n^{(l,c)} = 0 \qquad \text{for } l \neq c \tag{5}$$

Dynamic- and system-related constraints

Because of the SA pattern

NO-SA Heuristic

- The NO-SA is an **hard integer optimisation problem** because of the coupling constraints among variables

- We propose a two-step heuristic strategy
  i. MCSs optimisation ($m_1, \ldots, m_C$)
  ii. No. of coded packet per-subchannel optimization ($n^{(1,c)}, \ldots, n^{(L,c)}$)

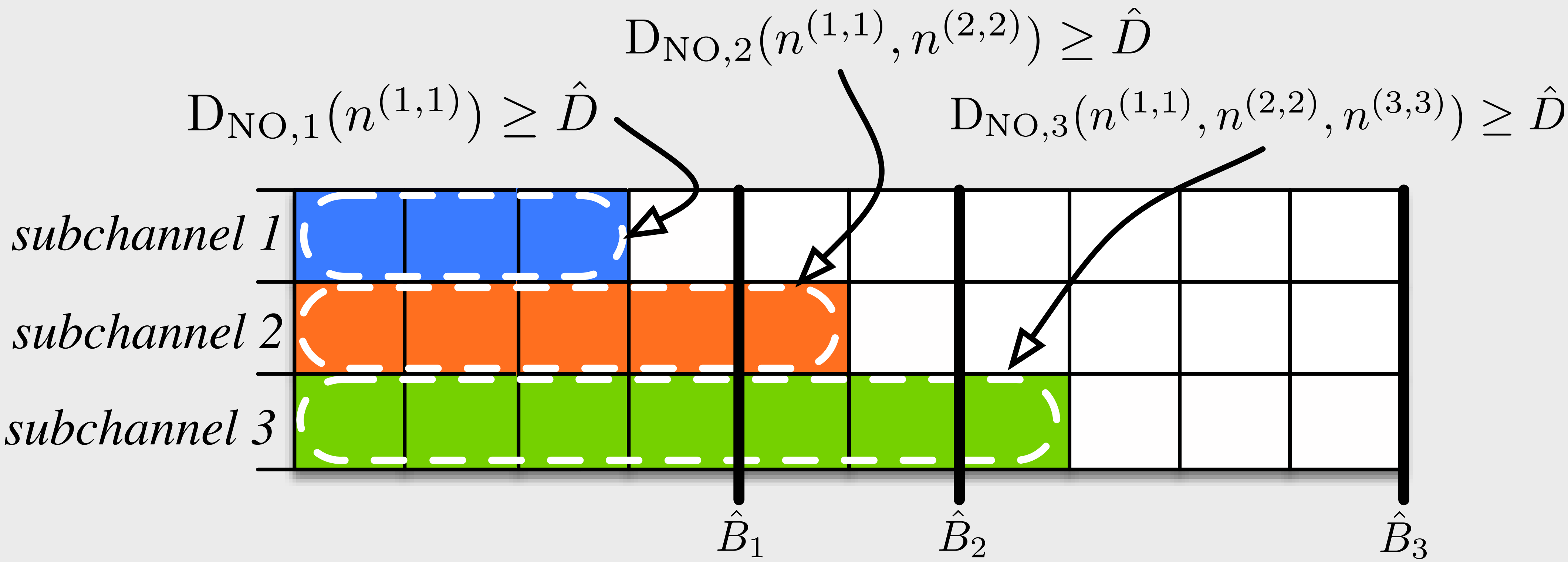
- The **first step** selects the value of m_c such that packets delivered through subch. c are received (at least with a target prob.) by $U \cdot \hat{t}_c$ users.

Step 1 Subchannel MCSs optimization.

$c \leftarrow C$
$v \leftarrow m_{\mathrm{MAX}}$ and
while $c \geq 1$ **do**
  repeat
    $m_c \leftarrow v$
    $v \leftarrow v - 1$
  until $|\mathcal{U}^{(m_c)}| \geq U \cdot \hat{t}_c$ **or** $v < m_{\min}$
  $c \leftarrow c - 1$
end while

NO-SA Heuristic

- The second step aims at optimising $n^{(1,c)}, \ldots, n^{(L,c)}$ and can be summarised as follows

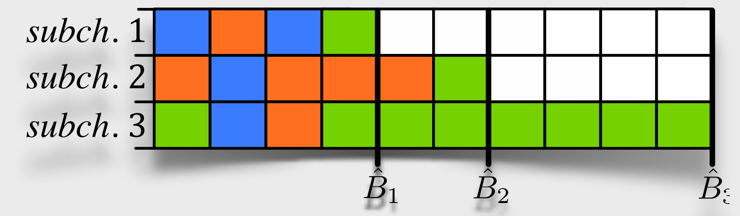


Step 2 Coded packet allocation for the NO-SA case.

1: **for** $l \leftarrow 1, \ldots, L$ **do**
2: $n^{(l,l)} \leftarrow k_l$
3: **while** $\mathrm{D}_{\mathrm{NO},l}(n^{(1,1)}, \ldots, n^{(l,l)}) < \hat{D}$ **do**
4: $n^{(l,l)} \leftarrow n^{(l,l)} + 1$
5: **end while**
6: **end for**

Requires a no. of steps $\leq \sum_{t=1}^{L} \left(\hat{B}_t - k_t + 1\right)$

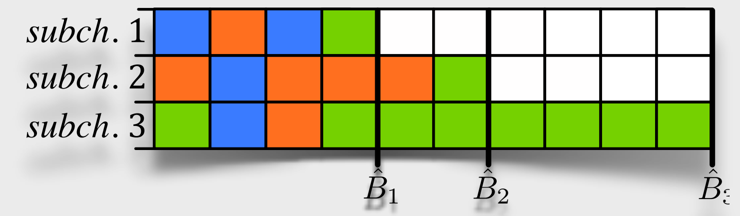
NO-MA Model



- The NO-SA problem can be easily extended to the MA pattern by removing the last constraint

$$
\begin{aligned}
\text{(NO-SA)} \quad & \min_{\substack{m_1,\dots,m_C \\ n^{(1,c)},\dots,n^{(L,c)}}} \sum_{l=1}^{L} \sum_{c=1}^{C} n^{(l,c)} && && (1) \\
\text{subject to} \quad & \sum_{u=1}^{U} \lambda_{u,l} \geq U\,\hat{t}_l && l = 1, \dots, L && (2) \\
& m_{c-1} < m_c && c = 2, \dots, L && (3) \\
& 0 \leq \sum_{l=1}^{L} n^{(l,c)} \leq \hat{B}_c && c = 1, \dots, C && (4) \\
& n^{(l,c)} = 0 && \text{for } l \neq c && (5)
\end{aligned}
$$

NO-MA Model



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(NO-MA)

~~(NO-SA)~~

$$\min_{\substack{m_1,\dots,m_C \\ n^{(1,c)},\dots,n^{(L,c)}}} \sum_{l=1}^{L}\sum_{c=1}^{C} n^{(l,c)} \quad (1)$$

subject to

$$\sum_{u=1}^{U} \lambda_{u,l} \geq U\,\hat{t}_l \qquad l = 1,\dots,L \quad (2)$$

$$m_{c-1} < m_c \qquad c = 2,\dots,L \quad (3)$$

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NO-MA Heuristic

- The NO-MA is still an **hard integer optimisation problem**. We adopt the same two-step heuristic strategy.
- For the first step we resort to the ‘Step 1’ procedure

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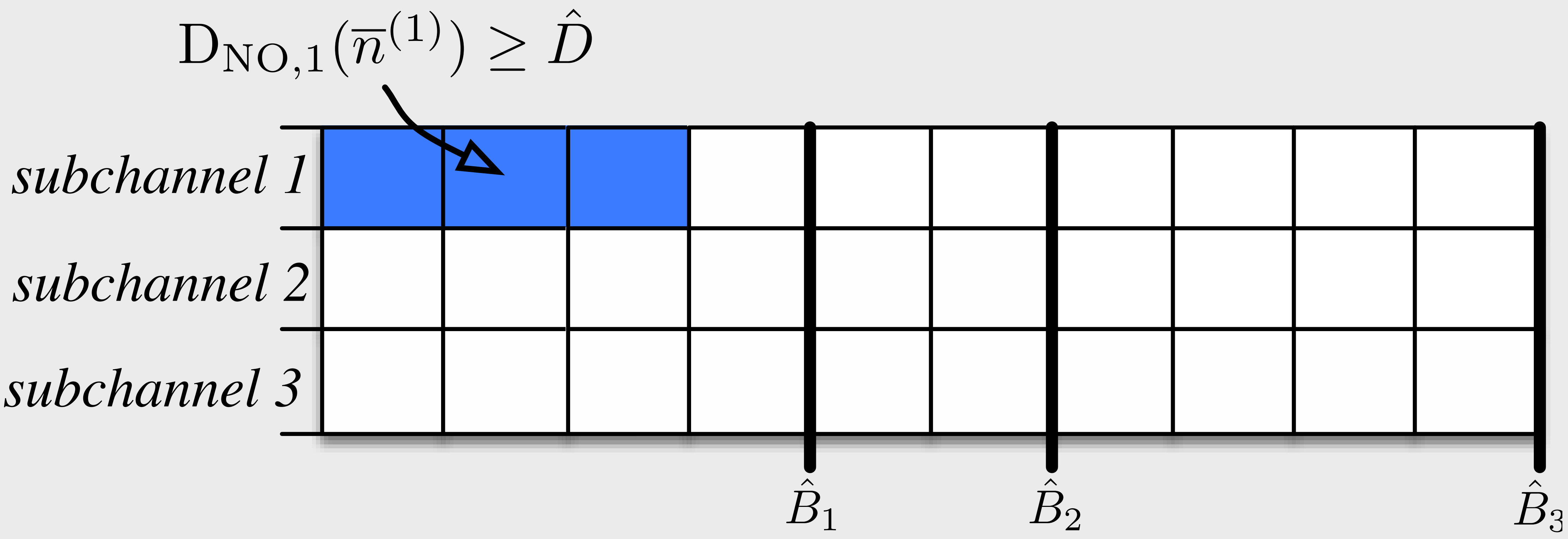
- The idea behind the second step can be summarised as follows



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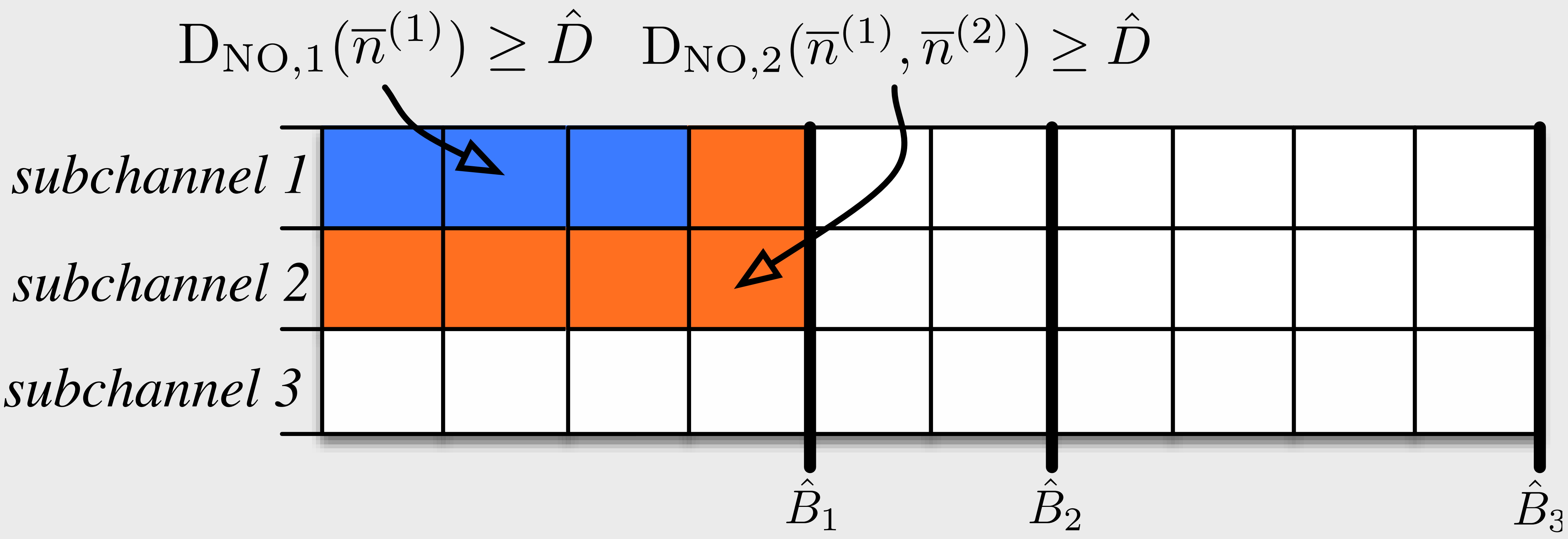

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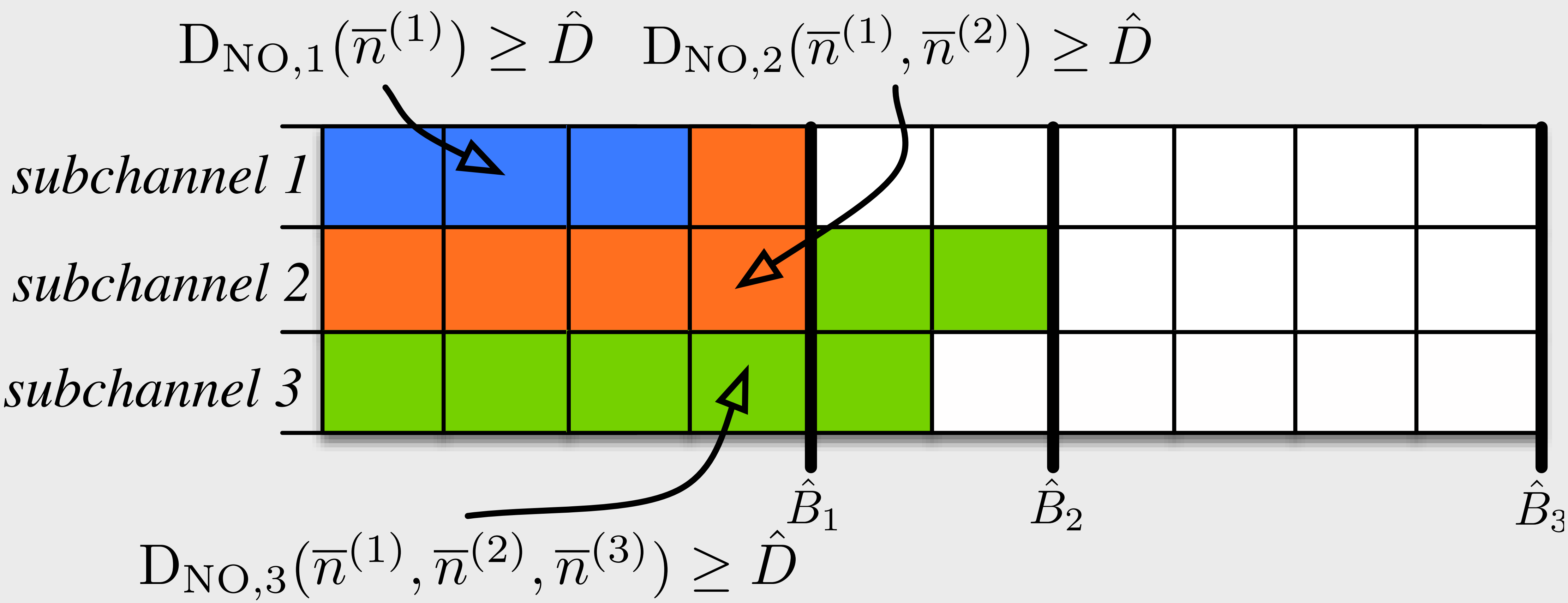

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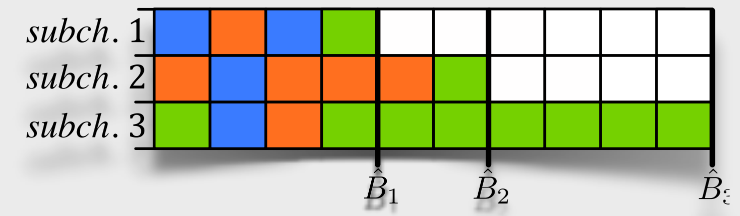
- For the first step we resort to the 'Step 1' procedure
- The idea behind the second step can be summarised as follows

Step 2 Coded packet allocation for a the NO-MA case.

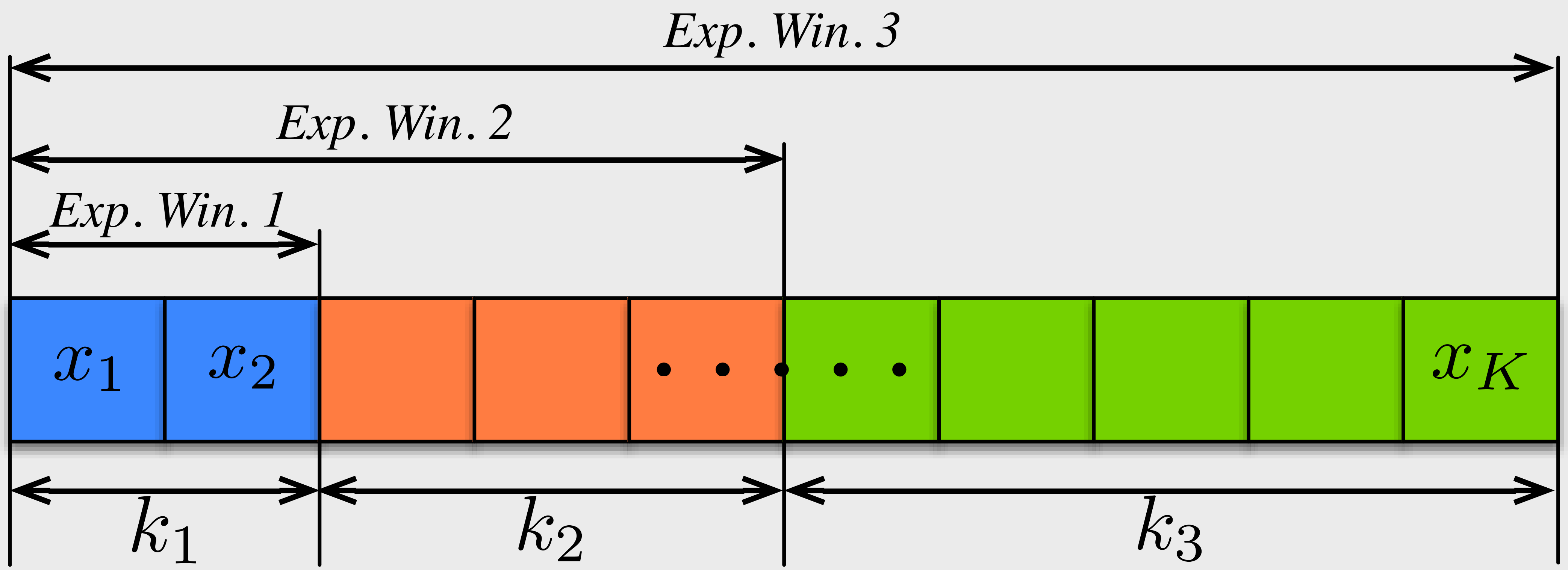
$c \leftarrow 1$
$\overline{n}^{(l,c)} \leftarrow 1$ for any $l = 1, \ldots, L$ and $c = 1, \ldots, C$
$\overline{\mathbf{n}} = \{\overline{n}^{(l)}\}_{l=1}^{L}$, where $\overline{n}^{(l)} \leftarrow 1$ for any $l = 1, \ldots, L$
for $l \leftarrow 1, \ldots, L$ **do**
  while $\mathrm{D}_{\mathrm{NO},l}(\overline{\mathbf{n}}) < \hat{D}$ and $c \leq C$ **do**
    $\overline{n}^{(l,c)} \leftarrow \overline{n}^{(l,c)} + 1$
    $\overline{n}^{(l)} \leftarrow \sum_{t=1}^{C} \overline{n}^{(l,t)}$ for any $l = 1, \ldots, L$
    if $\sum_{t=1}^{L} \overline{n}^{(t,c)} = \hat{B}_c$ **then**
      $c \leftarrow c + 1$
    end if
  end while
  if $\mathrm{D}_{\mathrm{NO},l}(\overline{\mathbf{n}}) < \hat{D}$ and $c > C$ **then**
    no solution can be found.
  end if
end for

Requires a no. of steps $\leq \sum_{t=1}^{C} \hat{B}_t$

EW-MA Model



- Consider the EW delivery mode

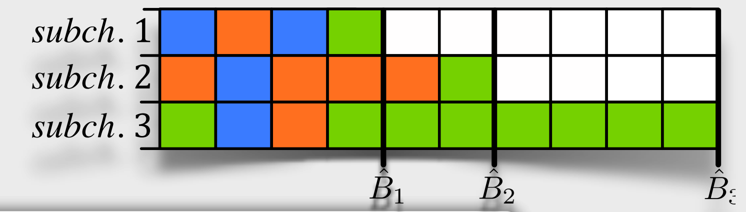


- We define the indicator variable

$$\mu_{u,l} = I\left(\bigvee_{t=l}^{L}\left\{\mathrm{D}_{\mathrm{EW},t}(\mathbf{N}_u) \geq \hat{D}\right\}\right)$$

User u will recover the first l service layers (at least) with probability $\hat{D}$ if any of the windows l, $l+1$, …, L are recovered (at least) with probability $\hat{D}$

EW-MA Model



No. of packets of **window** l delivered over c

- The RA problem for the EW-MA case is

$$\text{(EW-MA)} \quad \min_{\substack{m_1,\ldots,m_C \\ N^{(1,c)},\ldots,N^{(L,c)}}} \sum_{l=1}^{L} \sum_{c=1}^{C} N^{(l,c)} \tag{1}$$

$$\text{subject to} \quad \sum_{u=1}^{U} \mu_{u,l} \geq U \ \hat{t}_l \qquad l = 1, \ldots, L \tag{2}$$

$$m_{c-1} < m_c \qquad c = 2, \ldots, L \tag{3}$$

$$0 \leq \sum_{l=1}^{L} N^{(l,c)} \leq \hat{B}_c \quad c = 1, \ldots, C \tag{4}$$

- It is still an **hard integer optimisation problem but the previously proposed heuristic strategy can be still applied.**

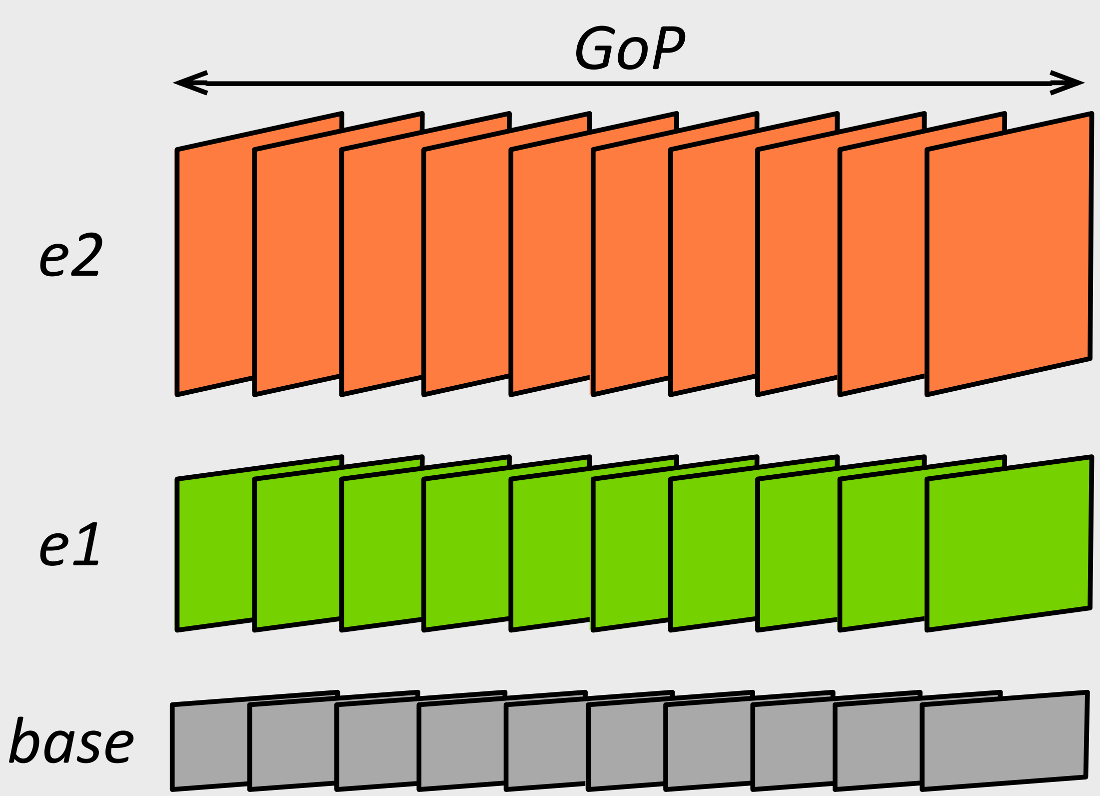
3. H.264/SVC Service Delivery over eMBMS Networks

Layered Video Streams

H.264/SVC video stream formed by multiple video layers:

- **the base layer** - provides basic reconstruction quality
- **multiple enhancement layers** - which gradually improve the quality of the base layer

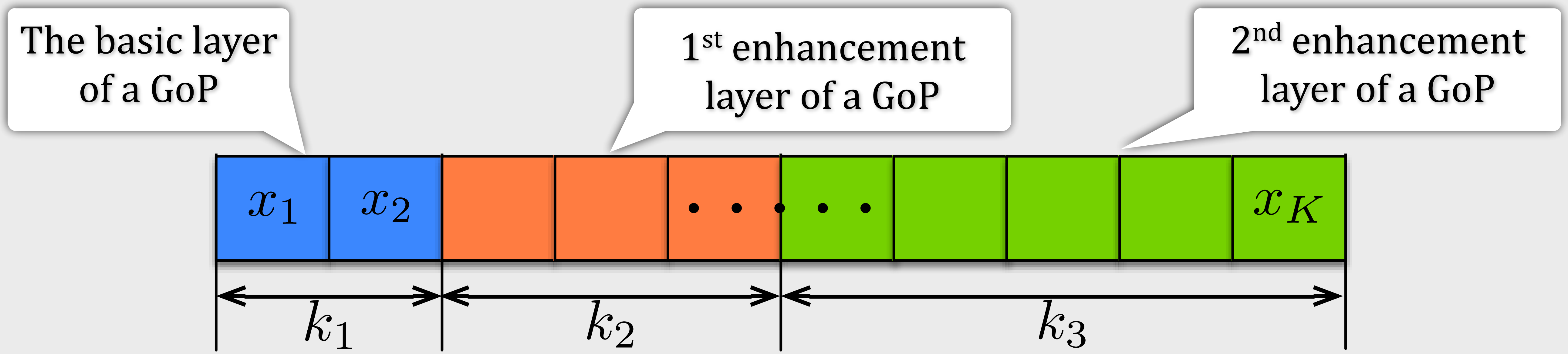
Considering a H.264/SVC video stream



- it is a GoP stream
- a GoP has fixed number of frames
- it is characterized by a time duration (to be watched)
- it has a layered nature

H.264/SVC and NC

- The decoding process of a H.264/SVC service is performed on a GoP-basis



- Hence, the k_l can be defined as

Bitrate of the video layer

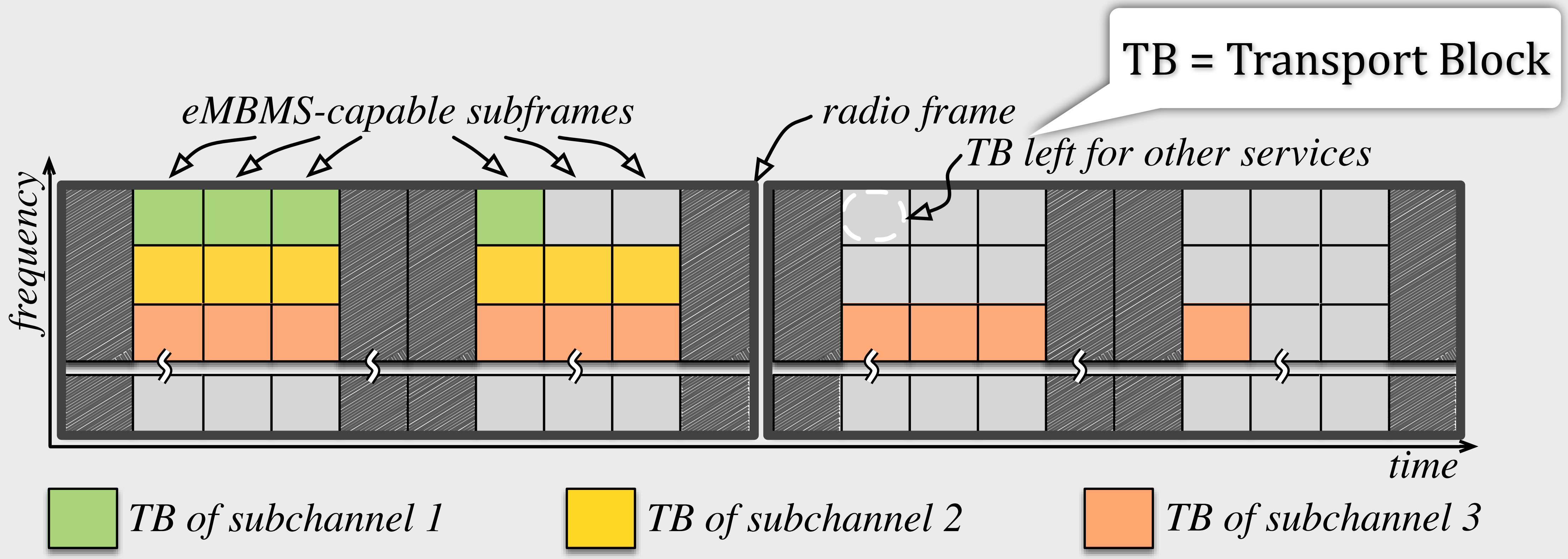
Time duration of a GoP

$$k_l = \left\lceil \frac{R_l \; d_{\mathrm{GoP}}}{H} \right\rceil$$

Source/Coded packet bit size

LTE-A System Model

- PtM communications managed by the eMBMS framework
- We refer to a **SC-eMBMS** system where a eNB delivers a **H.264/SVC** video service a target MG
- The DL phase of LTE-A adopts the OFDMA and has a framed nature



3. Analytical Results

Analytical Results

- We compared the proposed strategies with a classic Multi-rate Transmission strategy

It is a maximization of the sum of the user QoS

$$\max_{m_1,\ldots,m_L} \sum_{u=1}^{U} \mathrm{PSNR}_u$$

No error control strategies are allowed (ARQ, RLNC, etc.)

- System performance was evaluated in terms of

Resource footprint

$$\sigma = \begin{cases} \sum_{l=1}^{L}\sum_{c=1}^{C} n^{(l,c)}, & \text{for NO-RNC} \\ \sum_{l=1}^{L}\sum_{c=1}^{C} N^{(l,c)}, & \text{for EW-RNC} \end{cases}$$

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It is a maximization of the sum of the user QoS

No error control strategies are allowed (ARQ, RLNC, etc.)

- System performance was evaluated in terms of

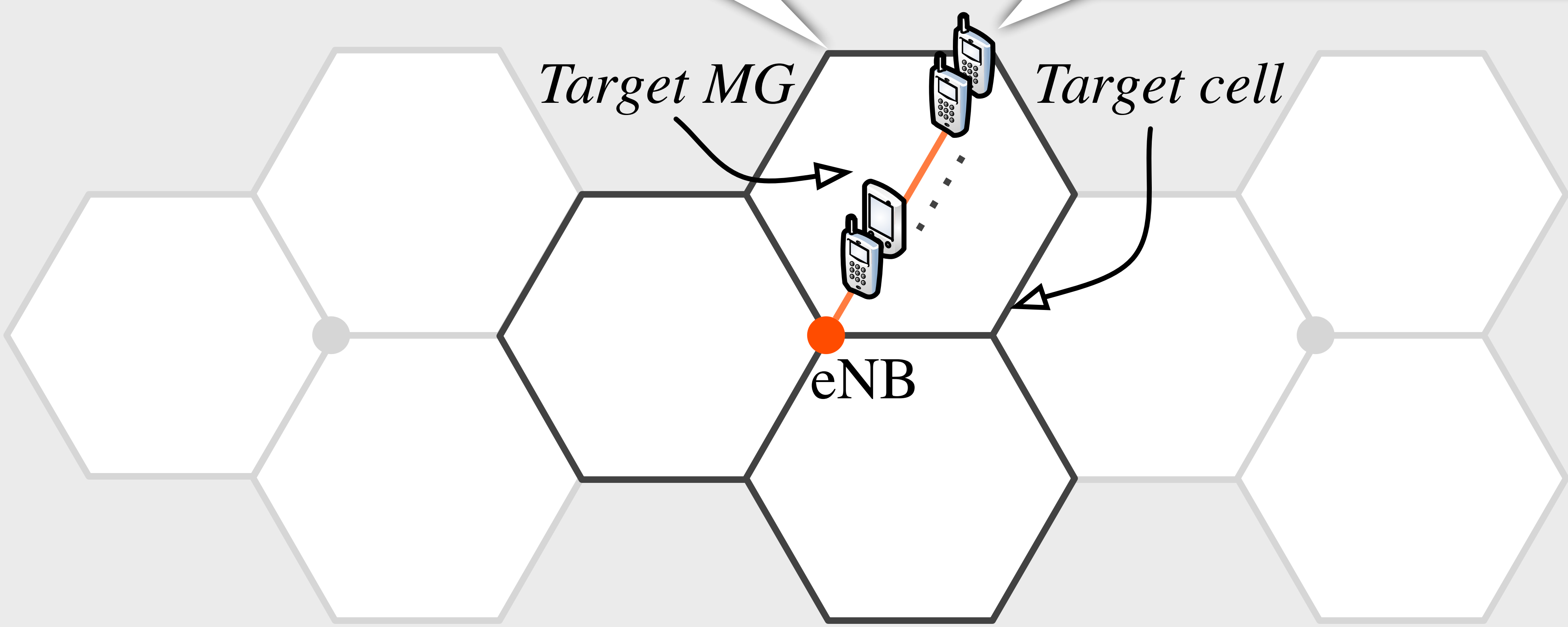
PSNR after recovery of the basic and the first l enhancement layers

$$\rho(u) = \begin{cases} \max_{l=1,\dots,L} \left\{ \mathrm{PSNR}_l \ \mathrm{D}_{\mathrm{NO},l}^{(u)} \right\}, & \text{for NO-RNC} \\ \max_{l=1,\dots,L} \left\{ \mathrm{PSNR}_l \ \mathrm{D}_{\mathrm{EW},l}^{(u)} \right\}, & \text{for EW-RNC} \end{cases}$$

Analytical Results

Scenario with a high heterogeneity. 80 UEs equally spaced and placed along the radial line representing the symmetry axis of one sector of the target cell

We considered Stream A and B which have 3 layers, bitrate of A is smaller than that of B



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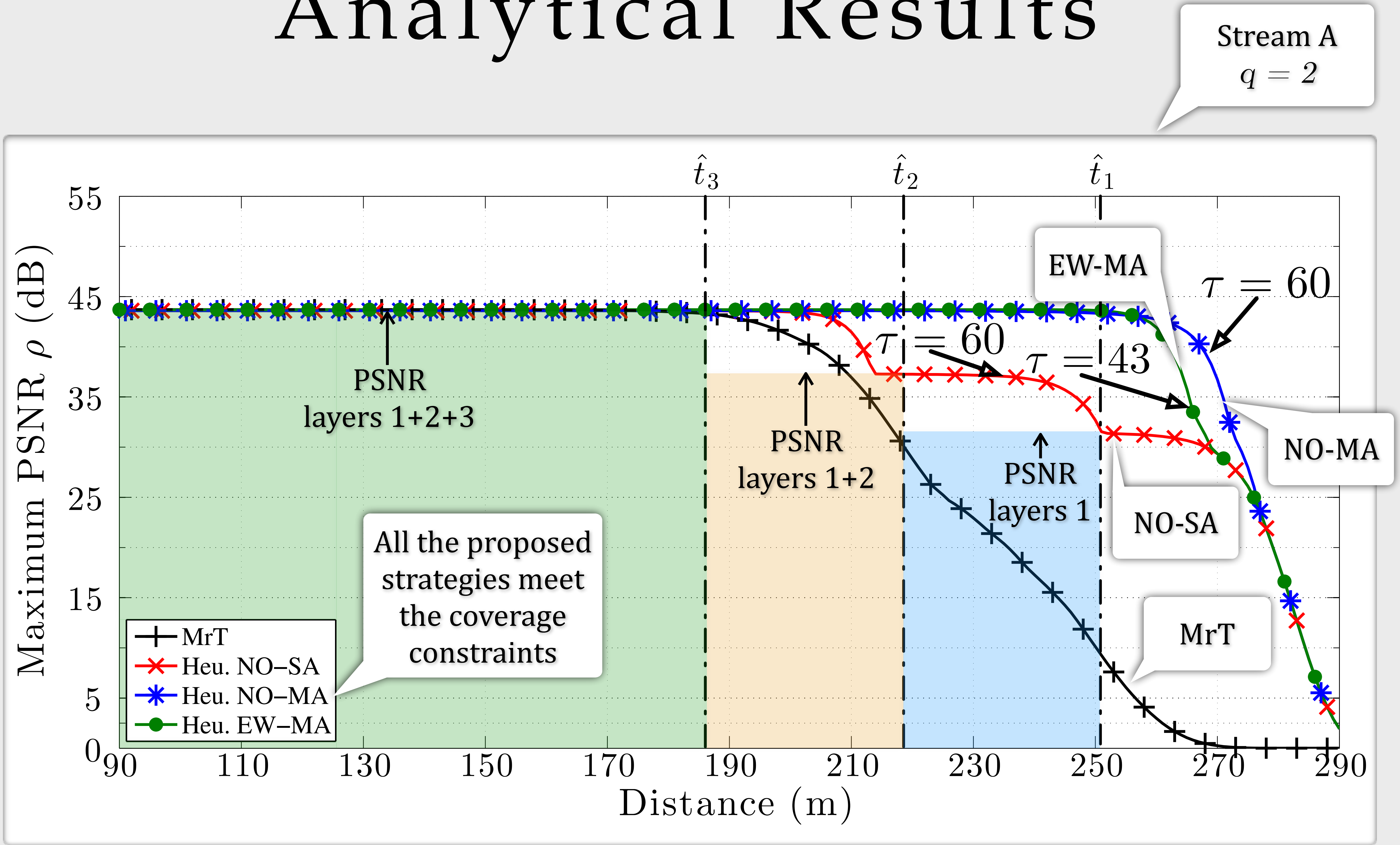

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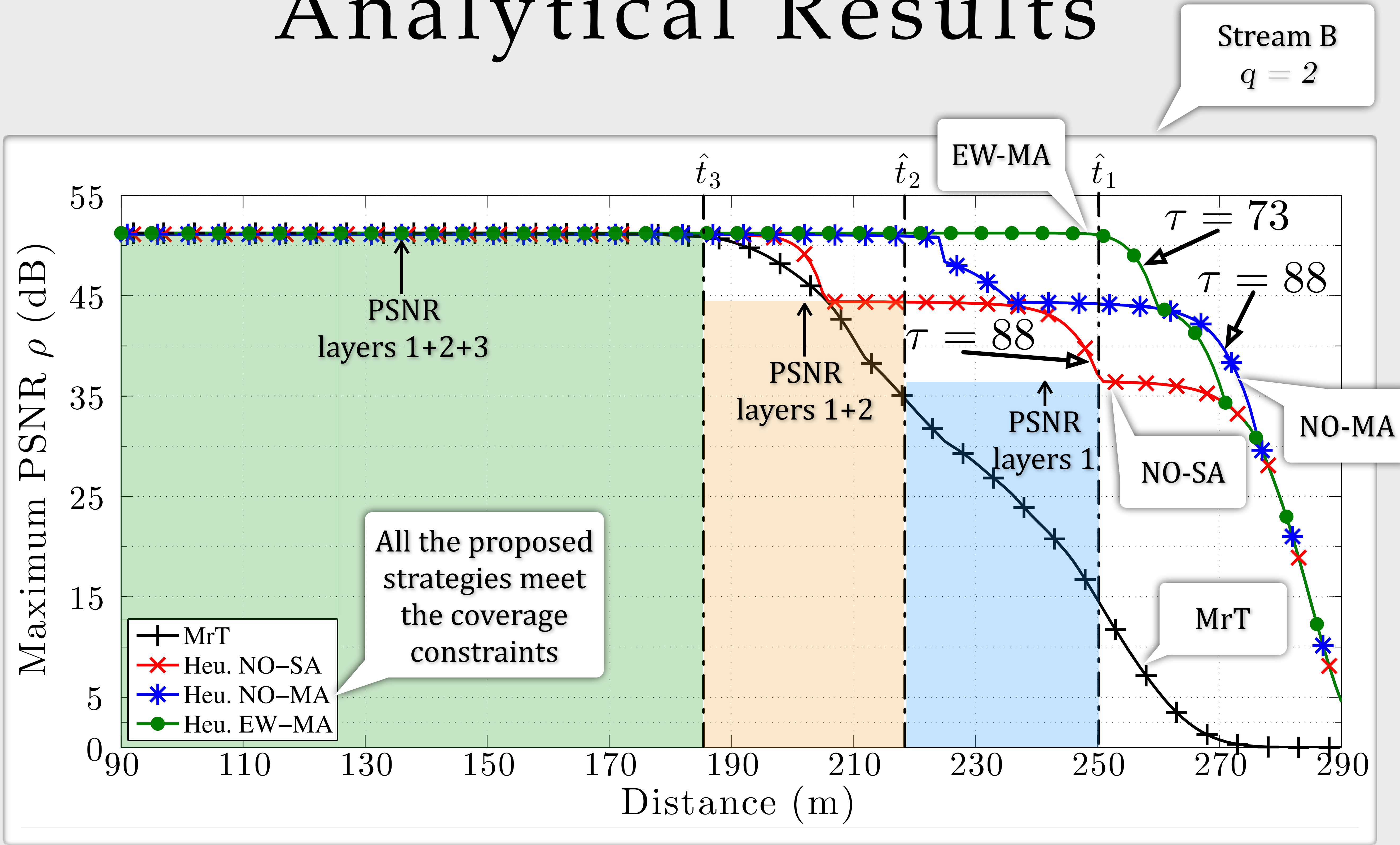
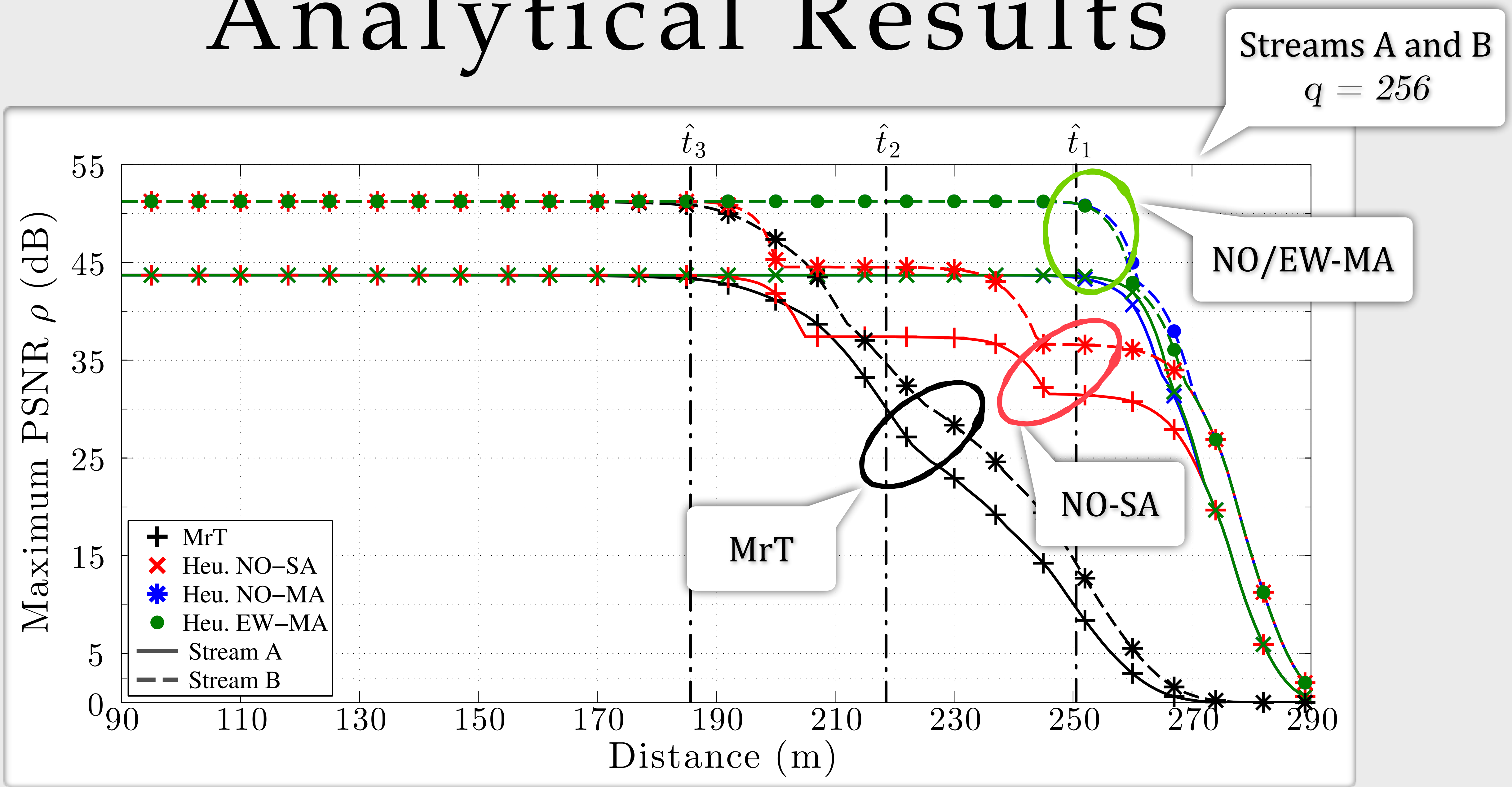


Analytical Results



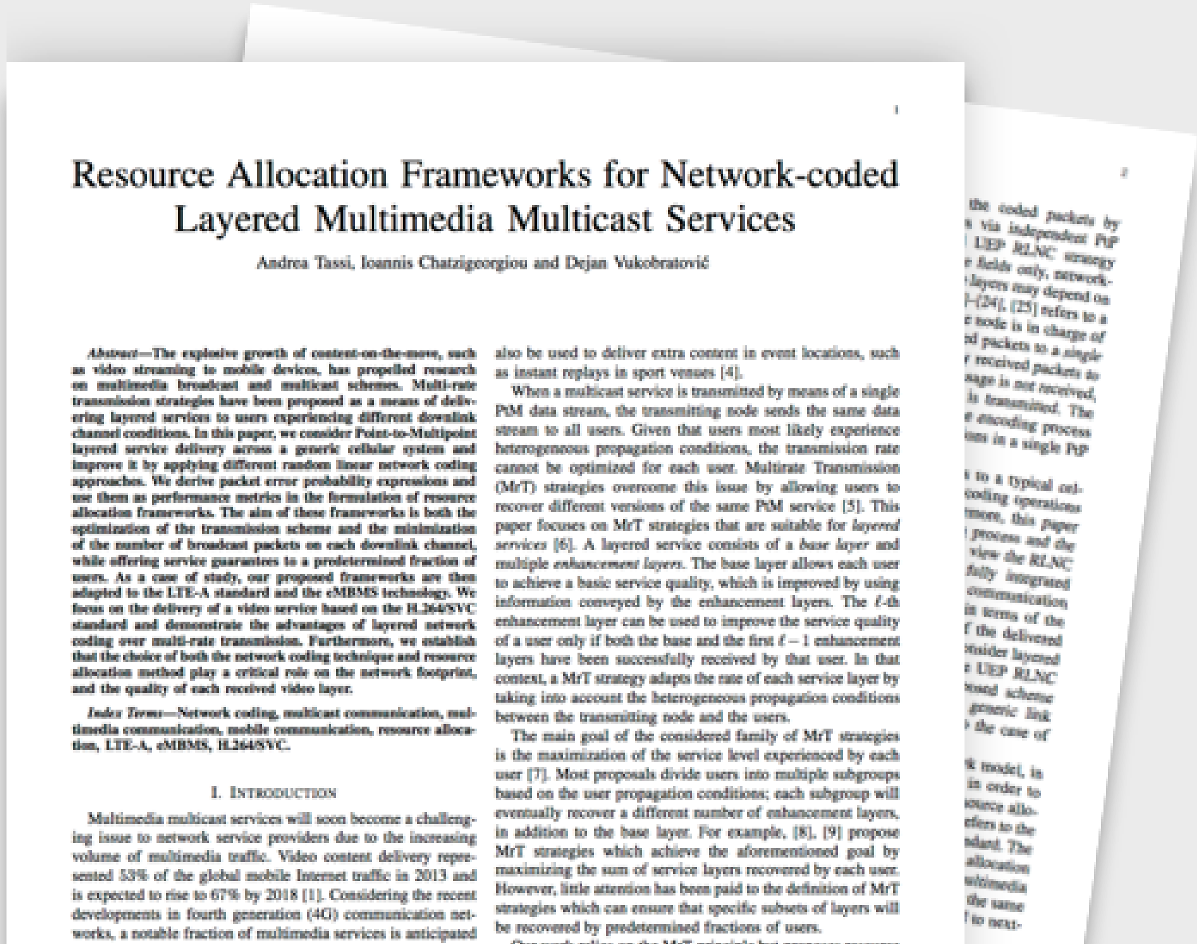
- The **NO-MA** and **EW-MA strategies are equivalent** both in terms of resource footprint and service coverage
- The service coverage of NO-SA still diverges from that of NO-MA and EW-MA.

4. Concluding Remarks

Concluding Remarks

- Definition of a **generic system model** that can be easily adapted to practical scenarios
- Derivation of the **theoretical framework to assess user QoS**
- **Definition of efficient resource allocation frameworks**, that can jointly optimise both system parameters and the error control strategy in use
- Development of **efficient heuristic strategies that can derive good quality solutions in a finite number of steps.**

Concluding Remarks



1

Resource Allocation Frameworks for Network-coded Layered Multimedia Multicast Services

Andrea Tassi, Ioannis Chatzigeorgiou and Dejan Vukobratović

Abstract—The explosive growth of content-on-the-move, such as video streaming to mobile devices, has propelled research on multimedia broadcast and multicast schemes. Multi-rate transmission strategies have been proposed as a means of delivering layered services to users experiencing different downlink channel conditions. In this paper, we consider Point-to-Multipoint layered service delivery across a generic cellular system and improve it by applying different random linear network coding approaches. We derive packet error probability expressions and use them as performance metrics in the formulation of resource allocation frameworks. The aim of these frameworks is both the optimization of the transmission scheme and the minimization of the number of broadcast packets on each downlink channel, while offering service guarantees to a predetermined fraction of users. As a case of study, our proposed frameworks are then adapted to the LTE-A standard and the eMBMS technology. We focus on the delivery of a video service based on the H.264/SVC standard and demonstrate the advantages of layered network coding over multi-rate transmission. Furthermore, we establish that the choice of both the network coding technique and resource allocation method play a critical role on the network footprint, and the quality of each received video layer.

Index Terms—Network coding, multicast communication, multimedia communication, mobile communication, resource allocation, LTE-A, eMBMS, H.264/SVC.

I. Introduction

Multimedia multicast services will soon become a challenging issue to network service providers due to the increasing volume of multimedia traffic. Video content delivery represented 53% of the global mobile Internet traffic in 2013 and is expected to rise to 67% by 2018 [1]. Considering the recent developments in fourth generation (4G) communication networks, a notable fraction of multimedia services is anticipated also be used to deliver extra content in event locations, such as instant replays in sport venues [4].

When a multicast service is transmitted by means of a single PtM data stream, the transmitting node sends the same data stream to all users. Given that users most likely experience heterogeneous propagation conditions, the transmission rate cannot be optimized for each user. Multirate Transmission (MrT) strategies overcome this issue by allowing users to recover different versions of the same PtM service [5]. This paper focuses on MrT strategies that are suitable for *layered services* [6]. A layered service consists of a *base layer* and multiple *enhancement layers*. The base layer allows each user to achieve a basic service quality, which is improved by using information conveyed by the enhancement layers. The ℓ-th enhancement layer can be used to improve the service quality of a user only if both the base and the first $\ell - 1$ enhancement layers have been successfully received by that user. In that context, a MrT strategy adapts the rate of each service layer by taking into account the heterogeneous propagation conditions between the transmitting node and the users.

The main goal of the considered family of MrT strategies is the maximization of the service level experienced by each user [7]. Most proposals divide users into multiple subgroups based on the user propagation conditions; each subgroup will eventually recover a different number of enhancement layers, in addition to the base layer. For example, [8], [9] propose MrT strategies which achieve the aforementioned goal by maximizing the sum of service layers recovered by each user. However, little attention has been paid to the definition of MrT strategies which can ensure that specific subsets of layers will be recovered by predetermined fractions of users.

For more information

http://arxiv.org/abs/1411.5547

or

http://goo.gl/Z4Y9YF

A. Tassi, I. Chatzigeorgiou, and D. Vukobratović, "**Resource Allocation Frameworks for Network-coded Layered Multimedia Multicast Services**",

IEEE Journal on Selected Areas in Communications, Special Issue on "Fundamental Approaches to Network Coding in Wireless Communication Systems", *in press*.

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R2D2: Network error control for **R**apid and **R**eliable **D**ata **D**elivery
Project supported by EPSRC under the First Grant scheme (EP/L006251/1)

Resource Allocation Schemes for Layered Video Broadcasting

Andrea Tassi and Ioannis Chatzigeorgiou

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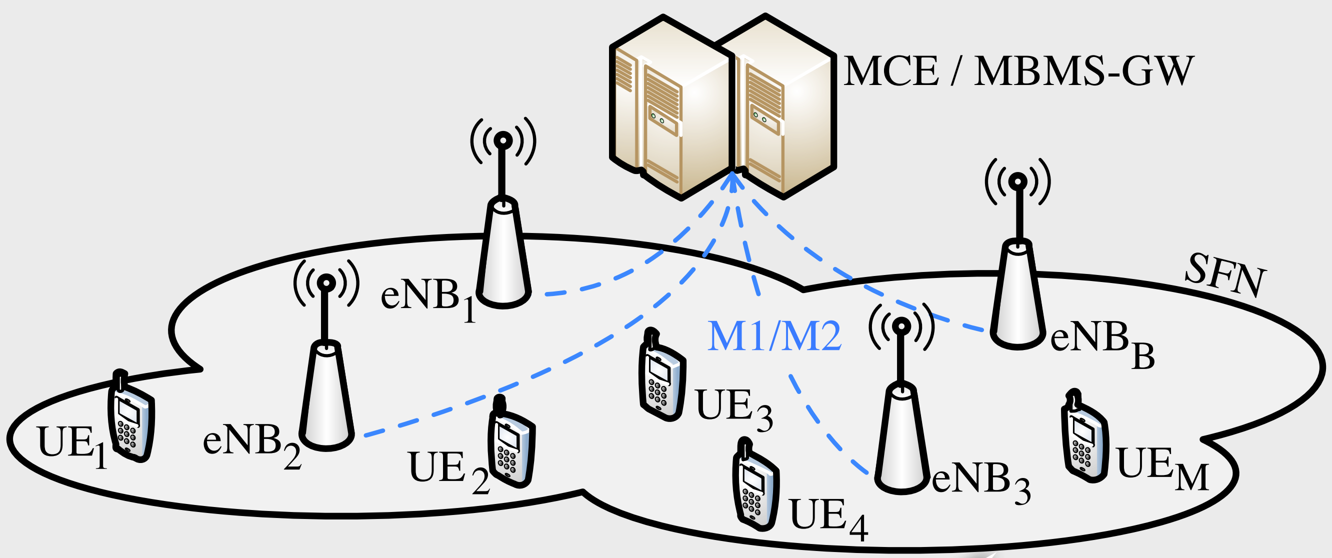
University of Edinburgh

Edinburgh, 28th November 2014

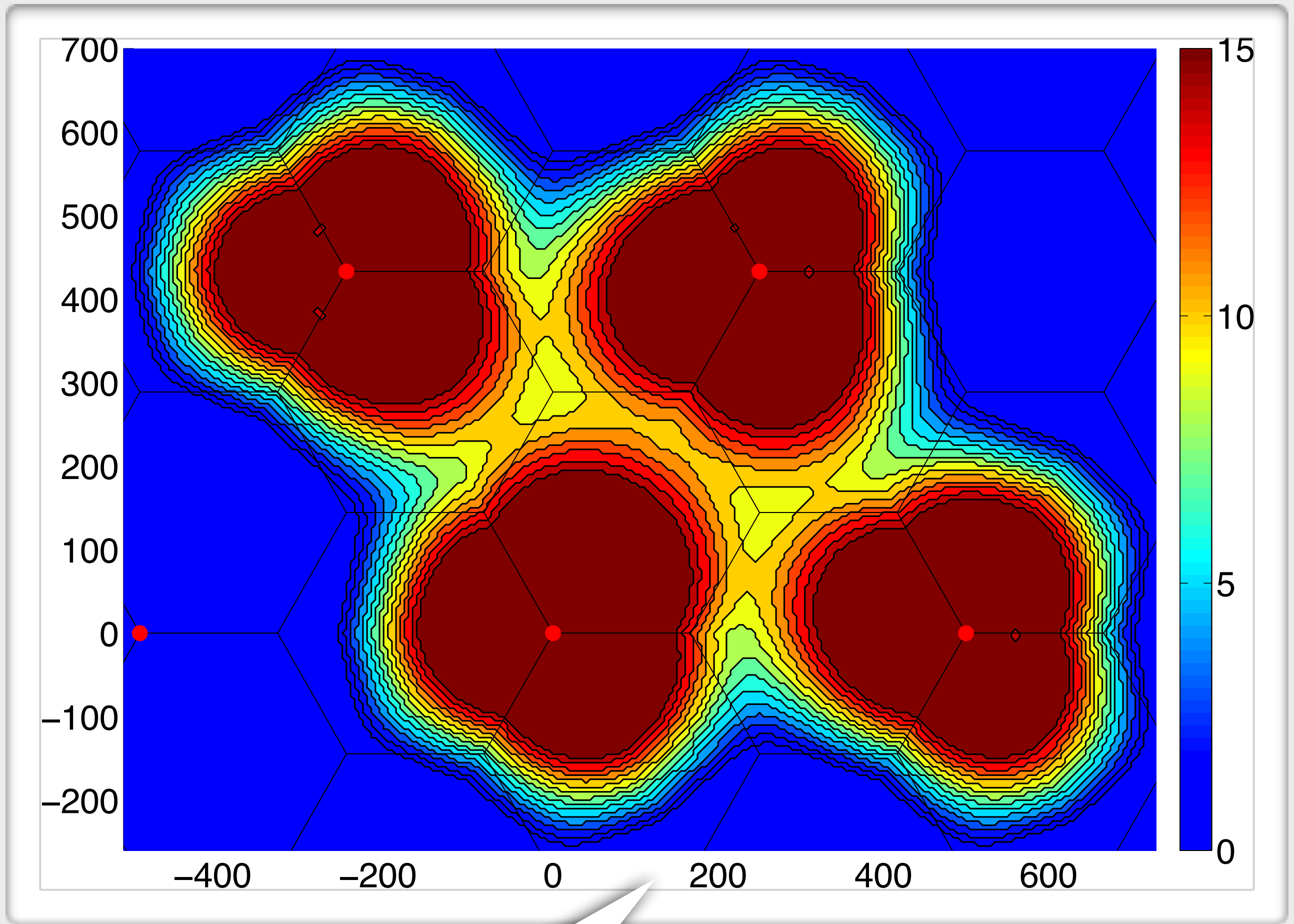
Backup Slides

Future Extensions

- LTE-A allows multiple contiguous BS to deliver (in a synchronous fashion) the same services by means of the same signals
- Users can combine multiple transmissions and do not need of HO procedures.



Single Frequency Network



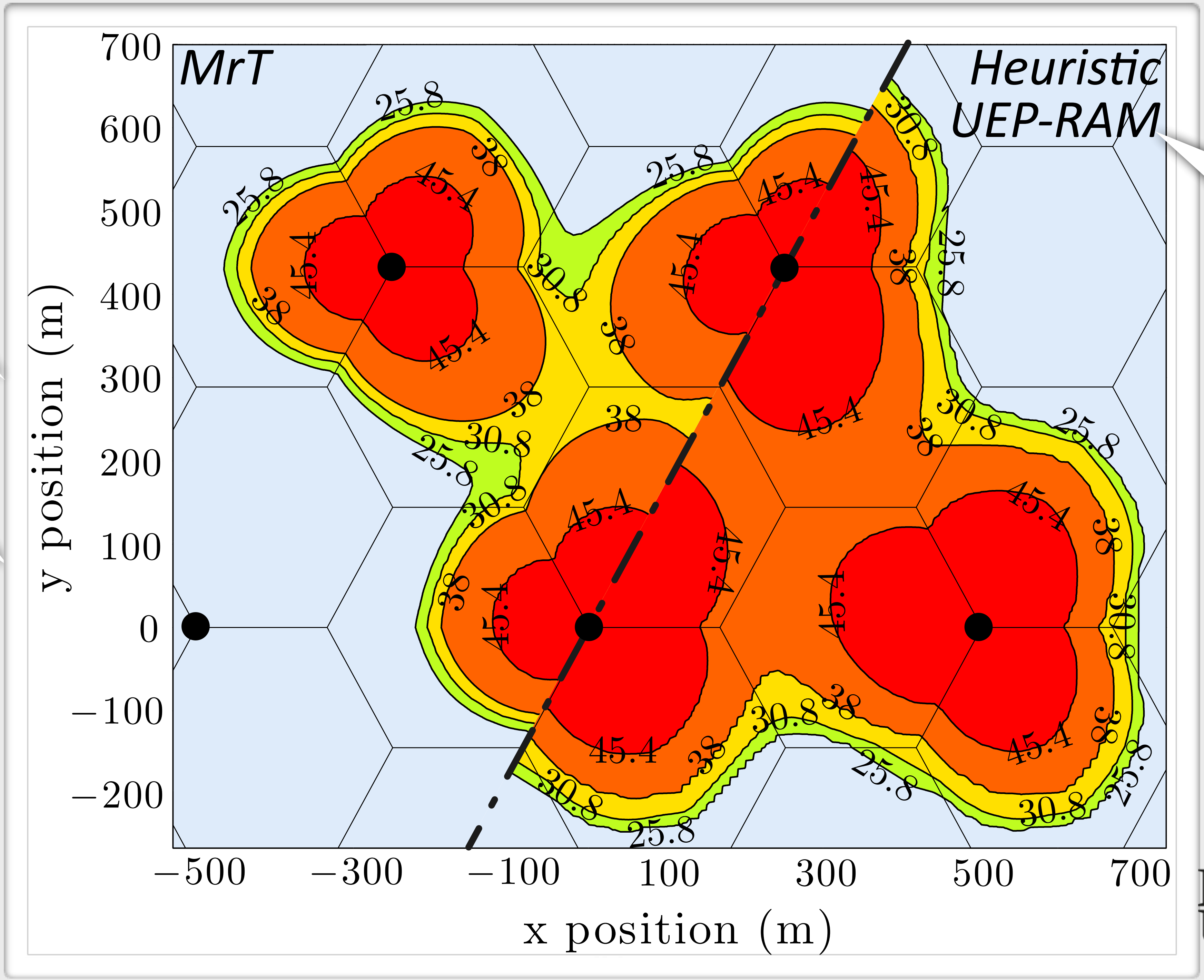
Distribution of the maximum acceptable user MCSs

Future Extensions

- We are extending the theoretical framework.
- These are some preliminary results for a grid of users placed on the SFN.

Each color represents the number of recovered video layers

4 video layers



EW-based strategy

System Model

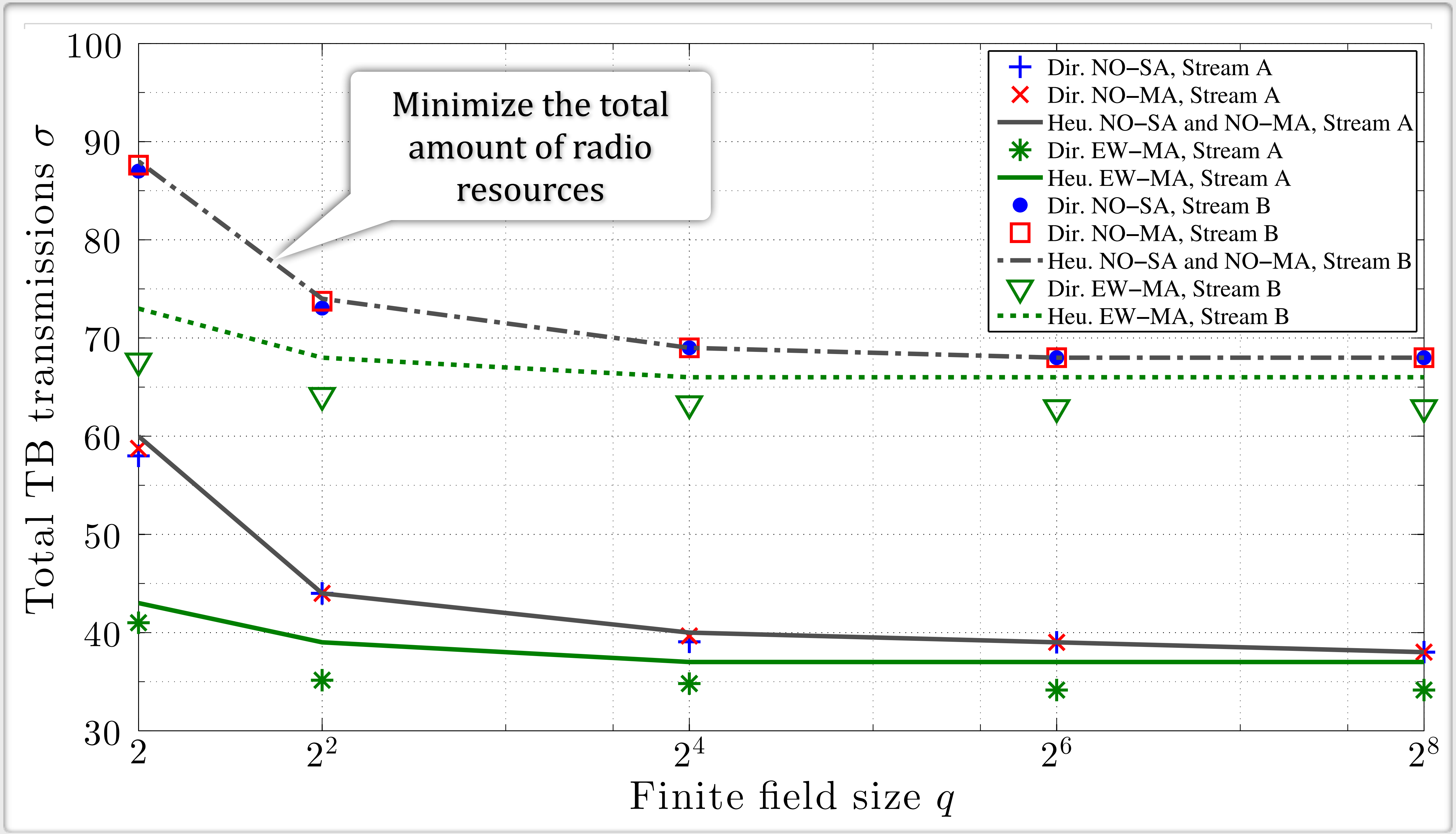
- We adopted this convention

$$p_u(m_a) \leq p_u(m_b) \text{ if } m_a < m_b$$

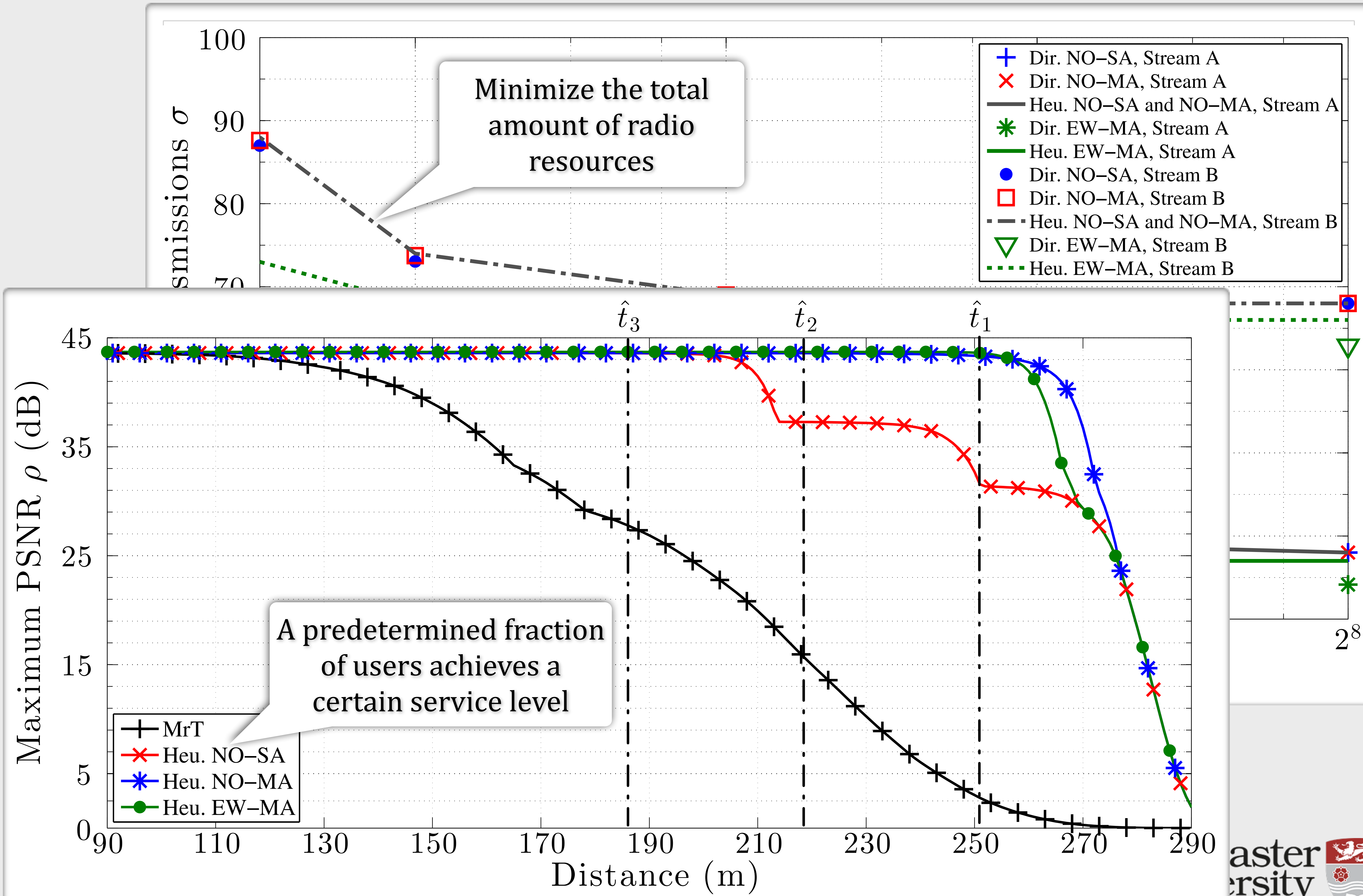
PEP experienced by an user *u* when the MCS m_a is adopted

- Reception of a coded packet is **acceptable** if $p_u(m) \leq \hat{p}$ holds
- Each subchannel delivers streams of (en)coded packets (according to the RLNC principle).

Results at a Glance



Results at a Glance



Expanding Window Layered RNC

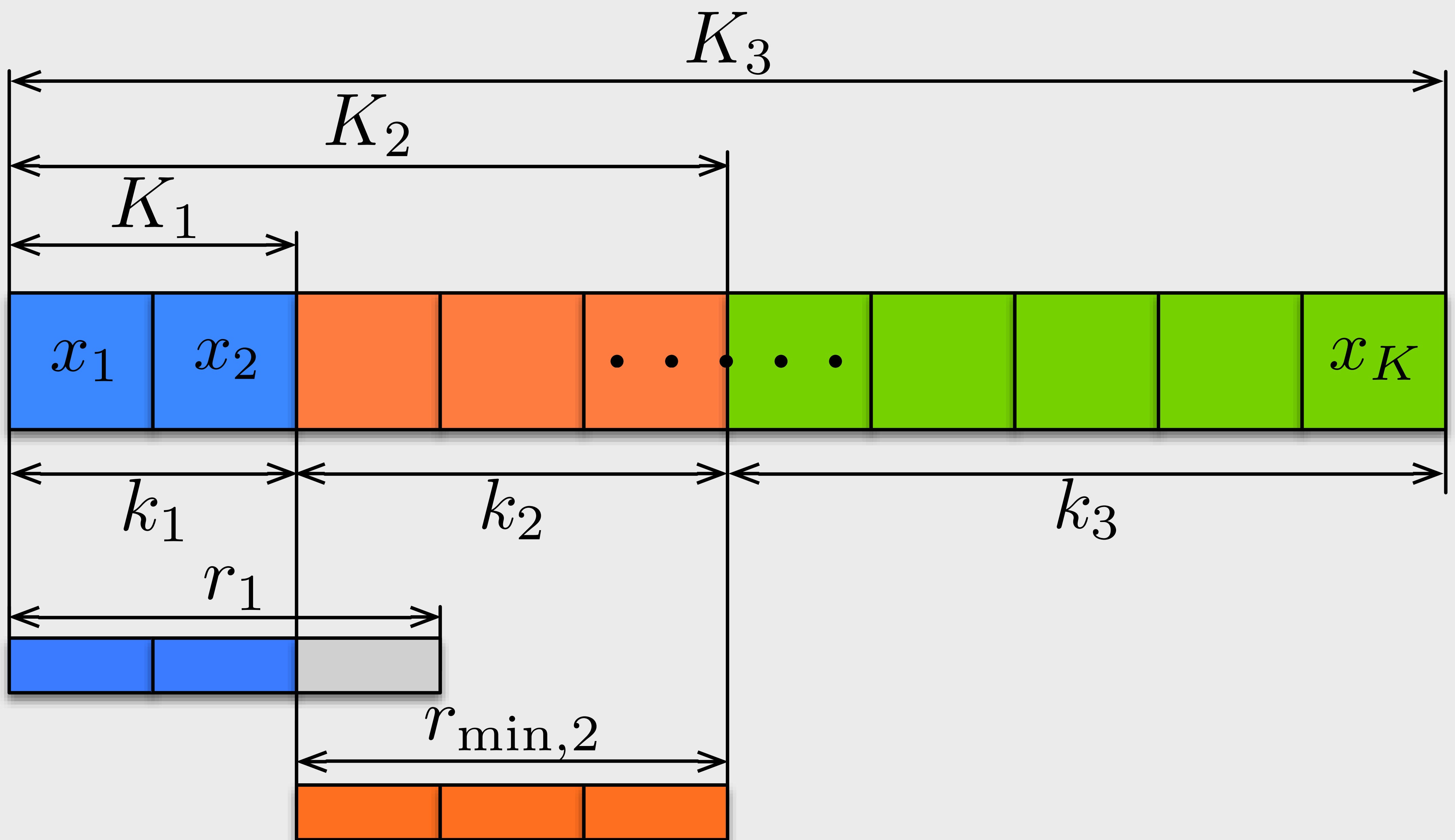
- Owing to the lack of an accurate expression for $g_l(\mathbf{r})$, we approximate it as

$$g_l(\mathbf{r}) \cong h\left(\underbrace{\sum_{i=1}^{l} r_i}_{x}\right) = \prod_{i=0}^{K_l-1}\left[1 - \frac{1}{q^{\left(\sum_{i=1}^{l} r_i\right)-i}}\right]$$

In other words, we say that

The prob. of recovering the l-th window given $r = \{r_1, r_2, \ldots, r_l\}$	$\cong$	The prob. of recovering the l-th window given $r = \{0, 0, \ldots, \sum_{i=1}^{l} r_i\}$

Expanding Window Layered RNC



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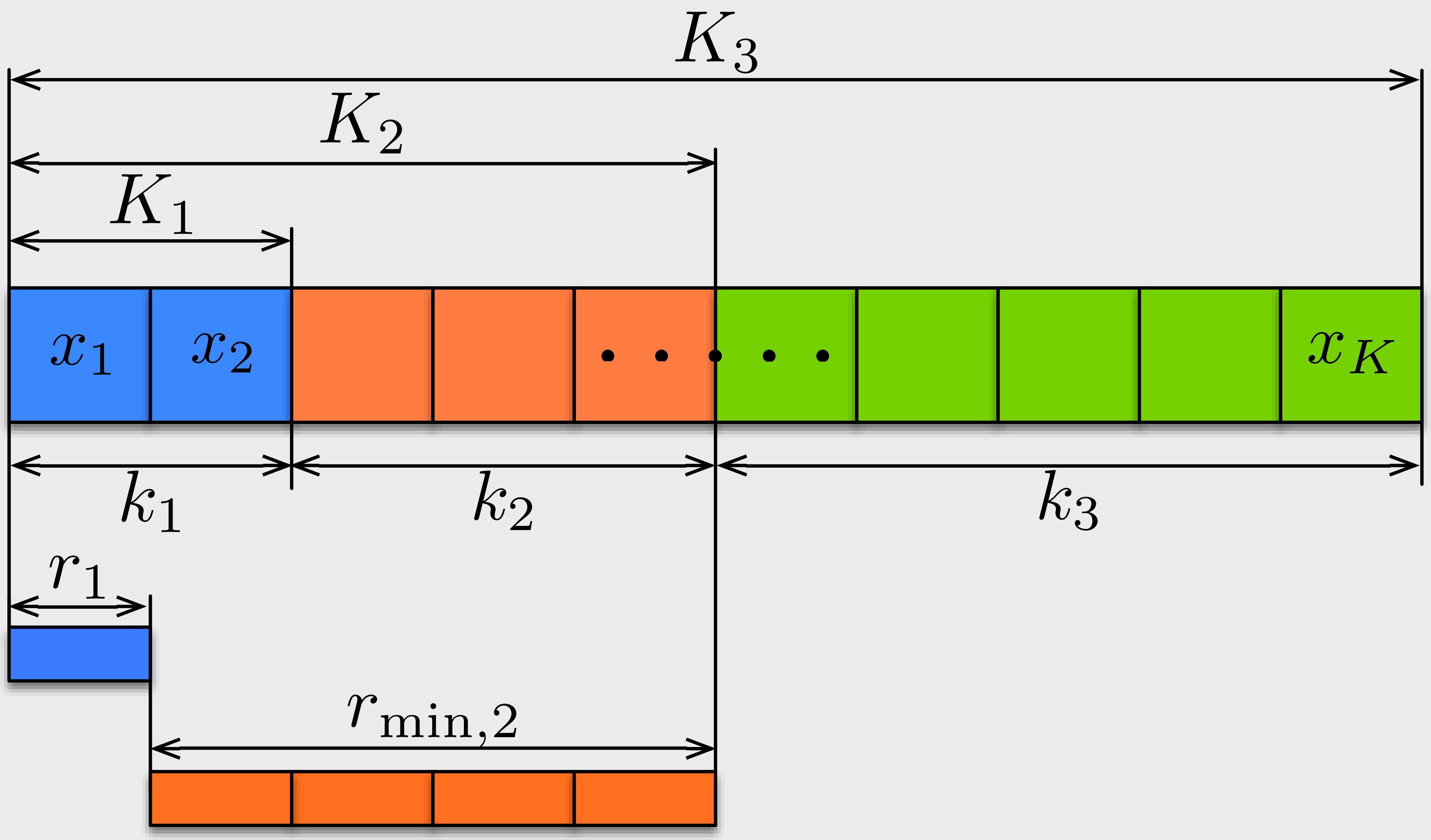
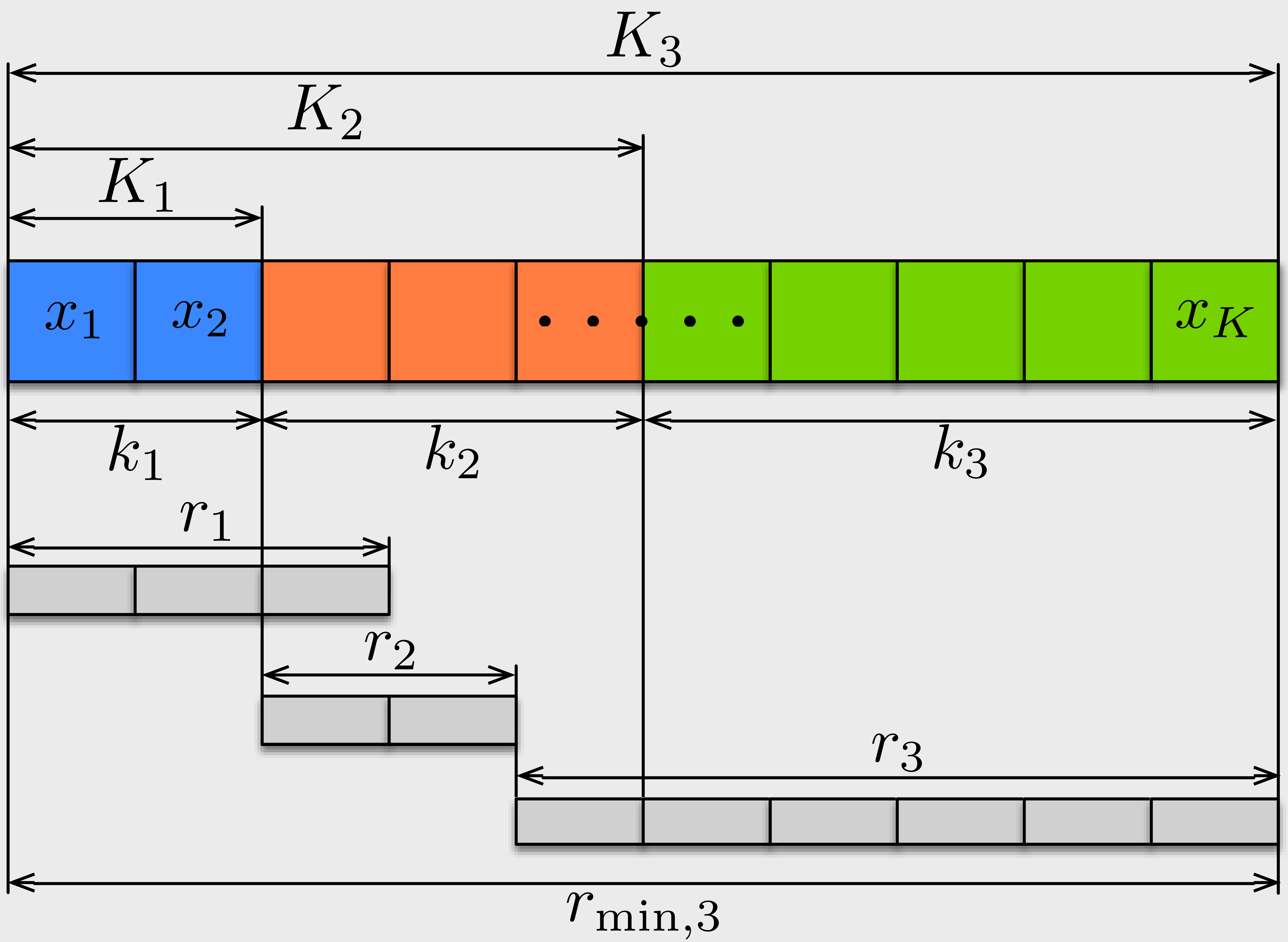


Expanding Window Layered RNC



Expanding Window Layered RNC

- The probability $D_{EW,l}$ of user u recovering the first l layers (namely, the l-th window) can be written as

$$D_{EW,l}(N_{1,u},\dots,N_{L,u}) = $$
$$= D_{EW,l}(\mathbf{N}_u)$$
$$= \sum_{r_1=0}^{N_{1,u}} \cdots \sum_{r_{l-1}=0}^{N_{l-1,u}} \sum_{r_l=r_{\min,l}}^{N_{l,u}} \binom{N_{1,u}}{r_1} \cdots \binom{N_{l,u}}{r_l} p^{\sum_{i=1}^{l}(N_{i,u}-r_i)} (1-p)^{\sum_{i=1}^{l} r_i} g_l(\mathbf{r})$$

Prob. of receiving $\mathbf{r} = \{r_1, \dots, r_l\}$ out of $\mathbf{N}_u$ coded symbols

Prob. of decoding window l

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Prob. of receiving $\mathbf{r}=\{r_1,\dots,r_l\}$ out of $\mathbf{N}_u$ coded symbols

Prob. of decoding window l

- $r_{\min,l}$ is the minimum value of r_l such that $D_{EW,l}(\mathbf{N}_u)$ is not zero. We can prove that

$$r_{\min,l}=\begin{cases}K_1 & \text{for } l=1\\ K_l-K_{l-1}+\max\left(r_{\min,l-1}-r_{l-1},\ 0\right) & \text{for } l\geq 2\end{cases}$$

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Expanding Window Layered RNC

- Owing to the lack of an accurate expression for $g_l(\mathbf{r})$, we approximate it.

- We inspected the quality of the considered approximation, for
  - p $=$ *0.1* and *0.3*
  - q $=$ *2* and *256*
  - $K_1 = 5$, $K_2 = 10$ and $K_3 = 15$

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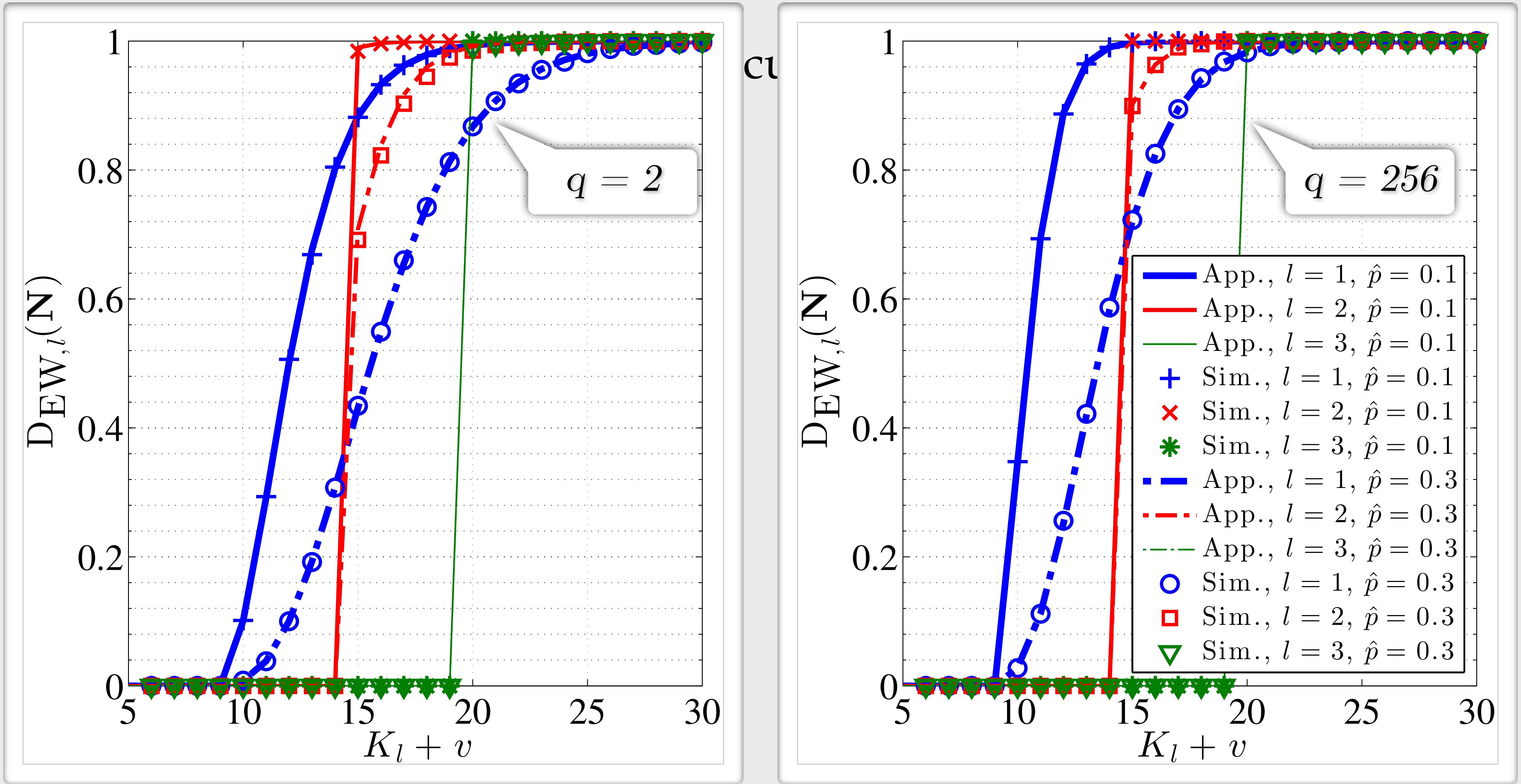
Expanding Window Layered RNC



- The maximum performance gap is smaller than *0.017* for q=*2*. **The gap becomes negligible for larger values of** q

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NO-SA Heuristic

- The NO-SA is an **hard integer optimisation problem** because of the coupling constraints among variables
- We propose a two-step heuristic strategy

  i. MCSs optimisation ($m_1, \ldots, m_C$)

  ii. No. of coded packet per-subchannel optimization ($n^{(1,c)}, \ldots, n^{(L,c)}$)

- The **first step** selects the value of m_c such that $|\mathcal{U}^{(m_c)}| \geq U \cdot \hat{t}_c$

$u \in \mathcal{U}^{(m_c)}$ if

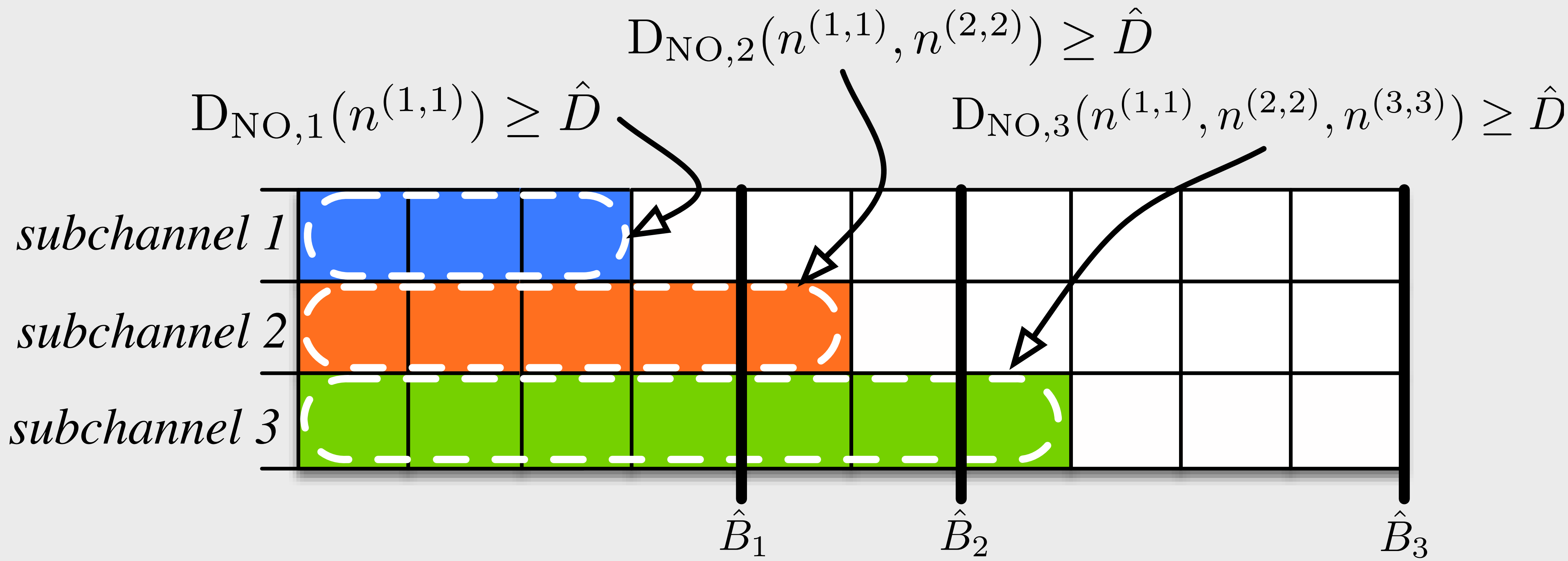
$M(u) \geq m_c$

Step 1 Subchannel MCSs optimization.

```
c ← C
v ← m_MAX and
while c ≥ 1 do
    repeat
        m_c ← v
        v ← v − 1
    until |U^(m_c)| ≥ U · t̂_c or v < m_min
    c ← c − 1
end while
```

NO-SA Heuristic

- The second step aims at optimising $n^{(1,c)}, \ldots, n^{(L,c)}$ and can be summarised as follows



Step 2 Coded packet allocation for the NO-SA case.

for $l \leftarrow 1, \ldots, L$ **do**
    $n^{(l,l)} \leftarrow k_l$
    while $\mathrm{D}_{\mathrm{NO},l}(n^{(1,1)}, \ldots, n^{(l,l)}) < \hat{D}$ **do**
        $n^{(l,l)} \leftarrow n^{(l,l)} + 1$
    end while
end for

Requires a no. of steps $\leq \sum_{t=1}^{L} \left(\hat{B}_t - k_t + 1 \right)$

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NO-MA Heuristic

- The NO-MA is still an **hard integer optimisation problem**. We adopt the same two-step heuristic strategy.
- For the first step we resort to the 'Step 1' procedure

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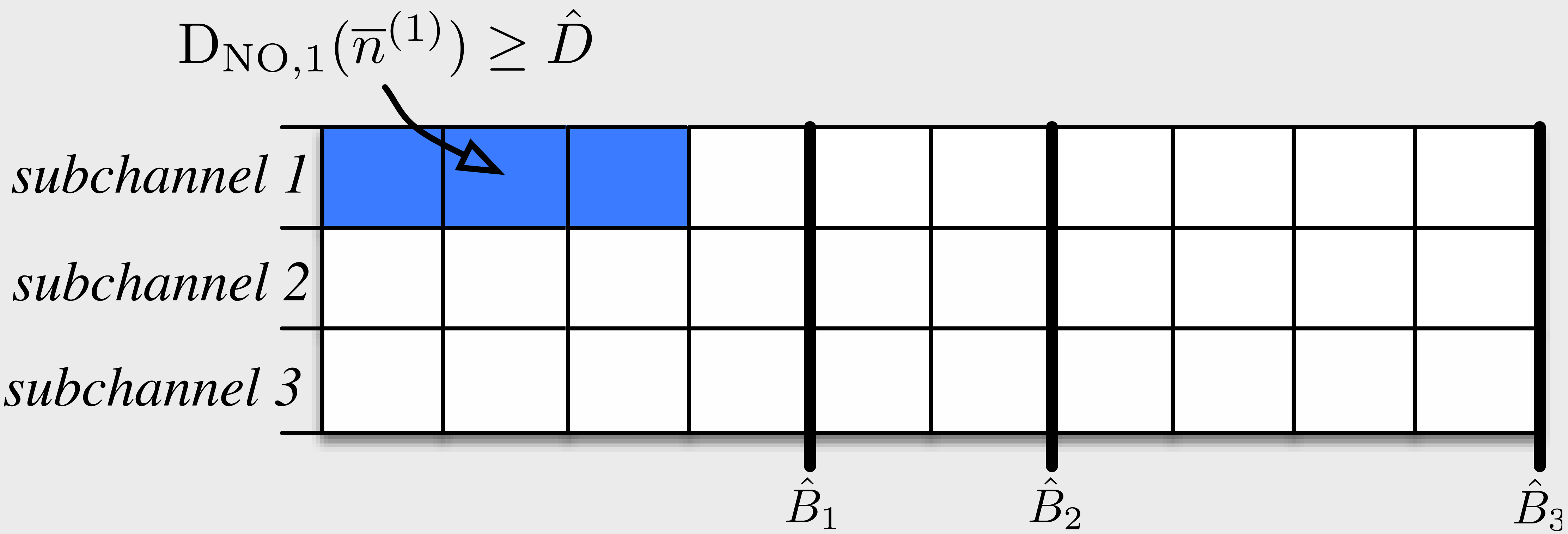

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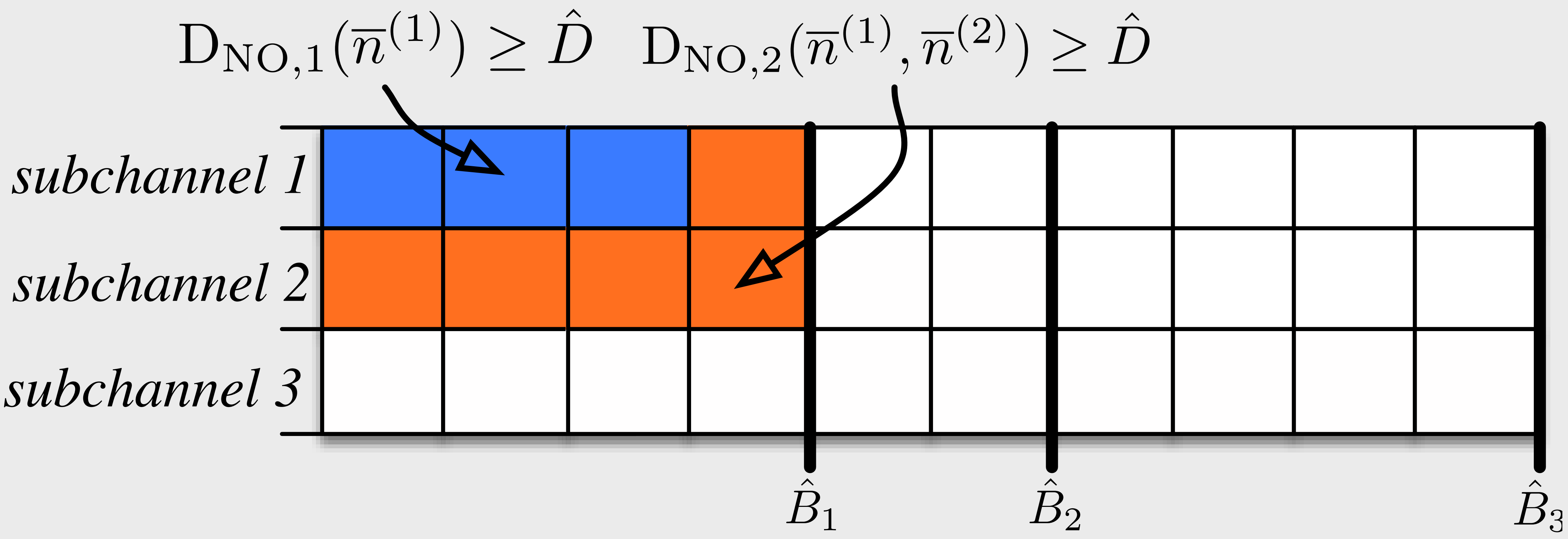

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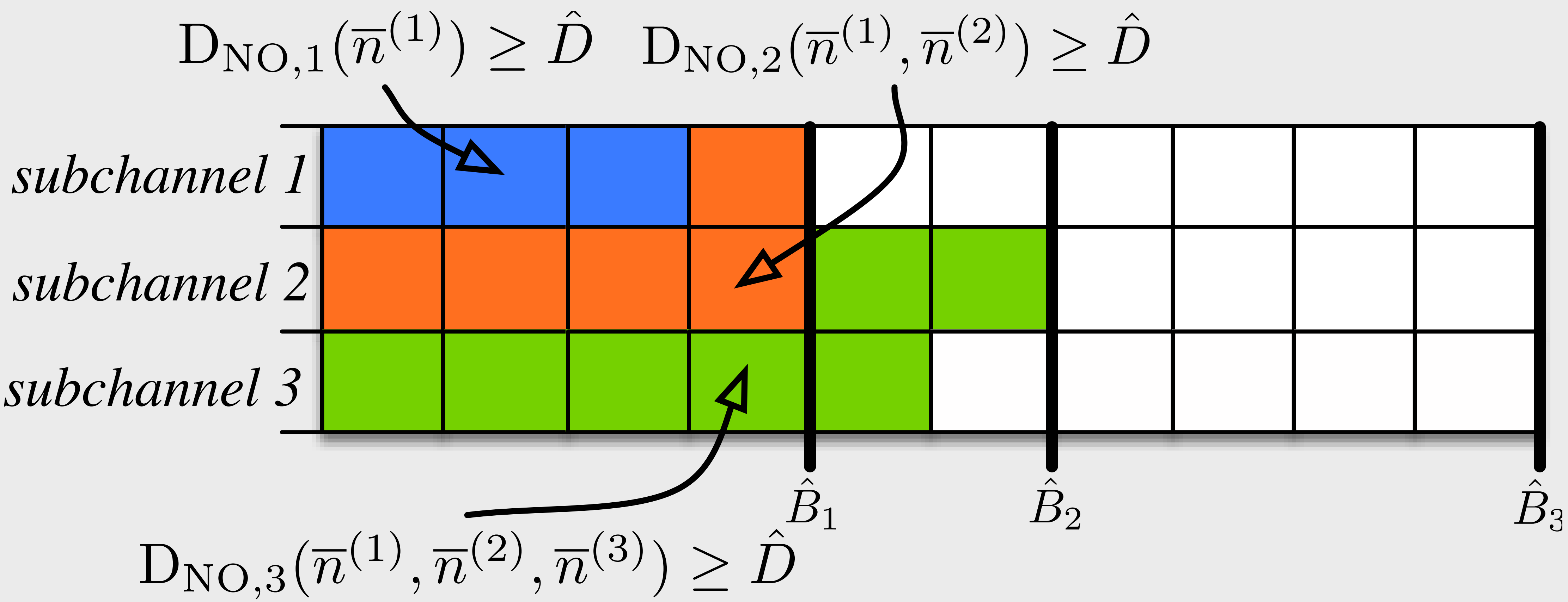

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NO-MA Heuristic

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- For the first step we resort to the 'Step 1' procedure
- The idea behind the second step can be summarised as follows

Step 2 Coded packet allocation for a the NO-MA case.

```
c ← 1
n̄^(l,c) ← 1 for any l = 1,...,L and c = 1,...,C
n̄ = {n̄^(l)}_{l=1}^L, where n̄^(l) ← 1 for any l = 1,...,L
for l ← 1,...,L do
    while D_{NO,l}(n̄) < D̂ and c ≤ C do
        n̄^(l,c) ← n̄^(l,c) + 1
        n̄^(l) ← Σ_{t=1}^C n̄^(l,t) for any l = 1,...,L
        if Σ_{t=1}^L n̄^(t,c) = B̂_c then
            c ← c + 1
        end if
    end while
    if D_{NO,l}(n̄) < D̂ and c > C then
        no solution can be found.
    end if
end for
```

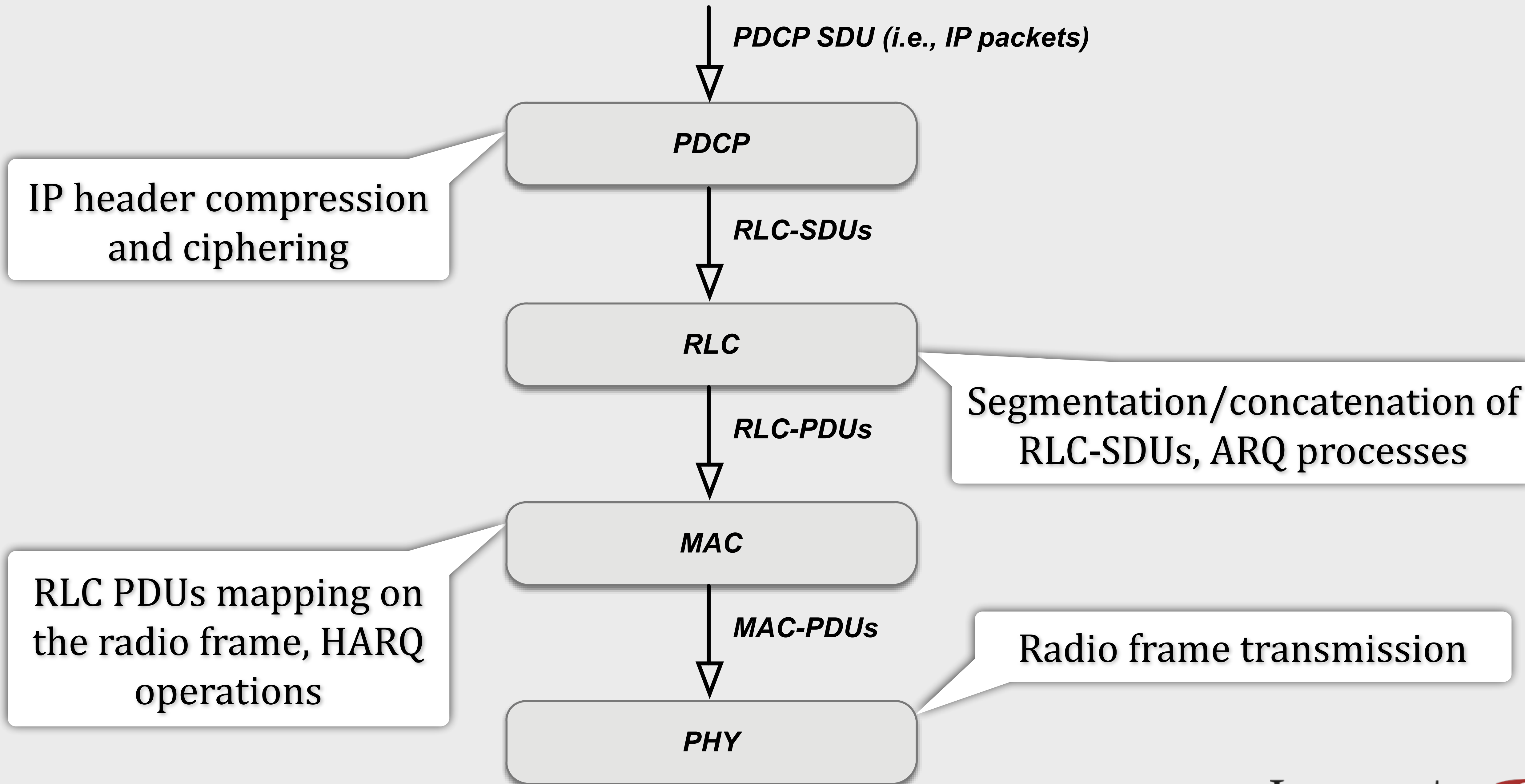
Requires a no. of steps $\leq \sum_{t=1}^{C} \hat{B}_t$

EW-MA Heuristic

- The EW-MA is still an **hard integer optimisation problem** but the same two-step heuristic principle still holds
- The **first step** follows the 'Step 1' procedure
- The **second step** relies on the same idea we considered for the NO-MA case
- The **second step** requires a no. of steps $\leq \sum_{t=1}^{C} \hat{B}_t$.

LTE/LTE-A Stack

3GPP's LTE is one of the most promising 4G standard for mobile networks. It promises to practically manage PtM service delivery.



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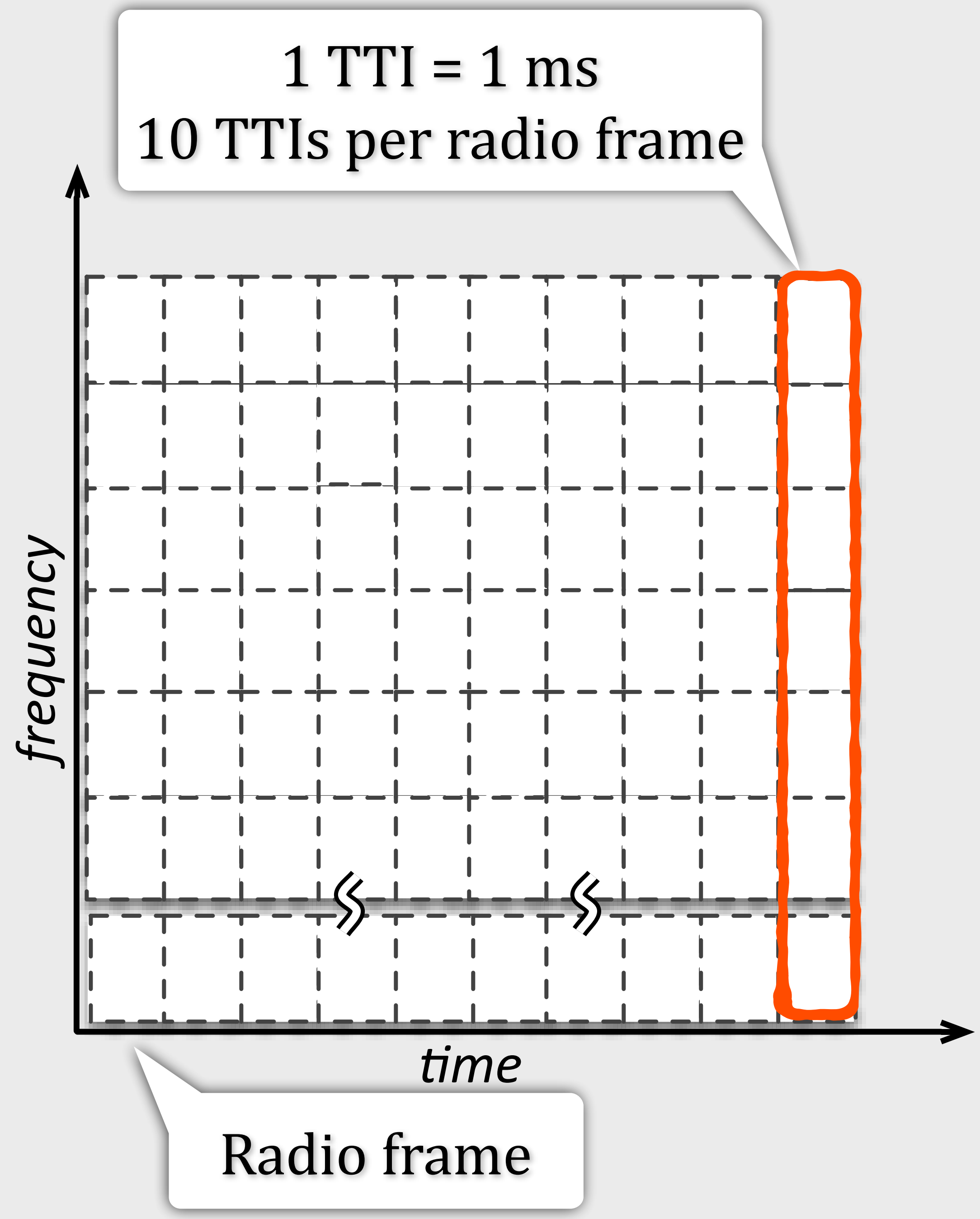
LTE/LTE-A Radio Resources

It Relies on OFDMA. Resources are organised in a time/frequency structure called **radio frame**.



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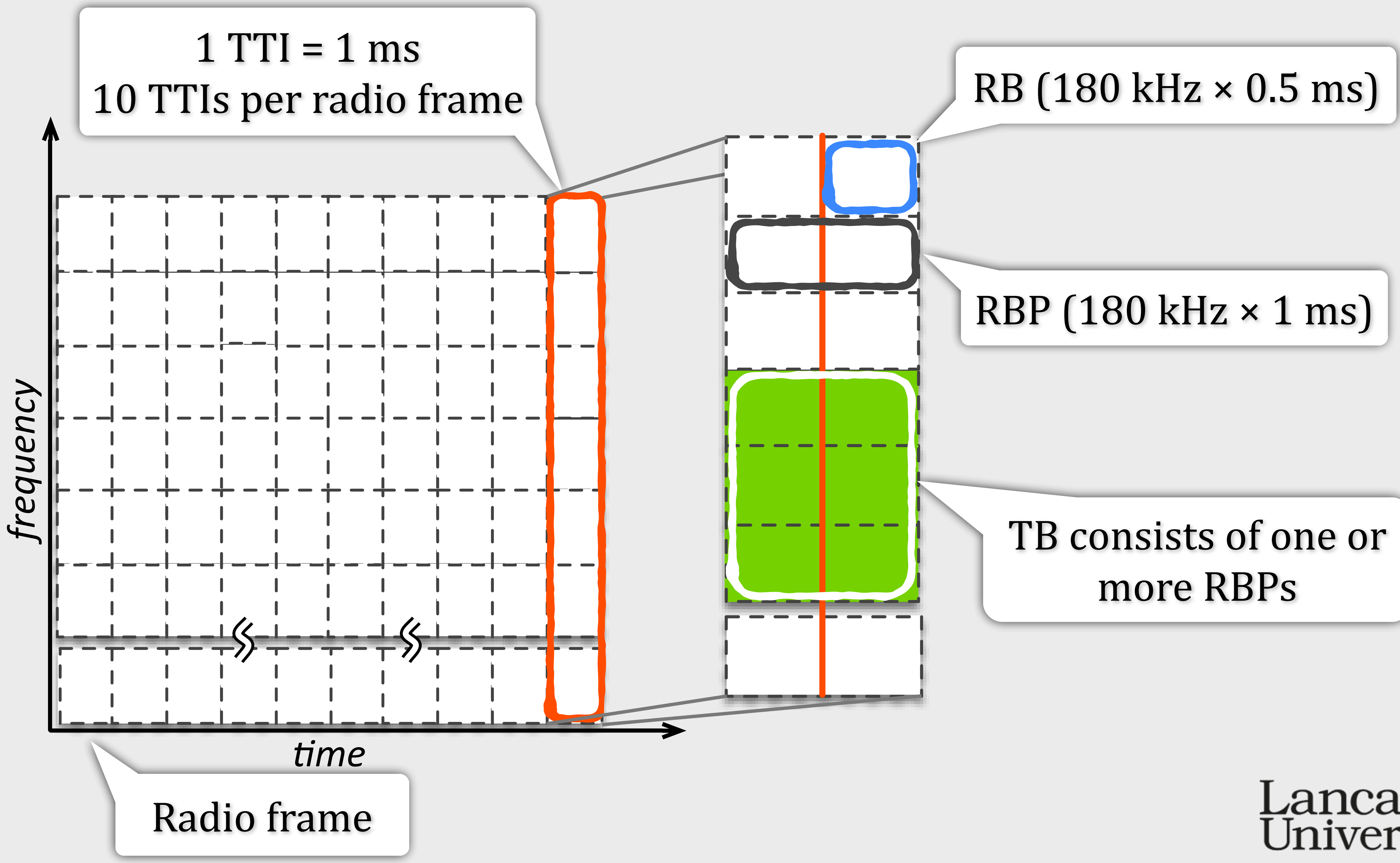
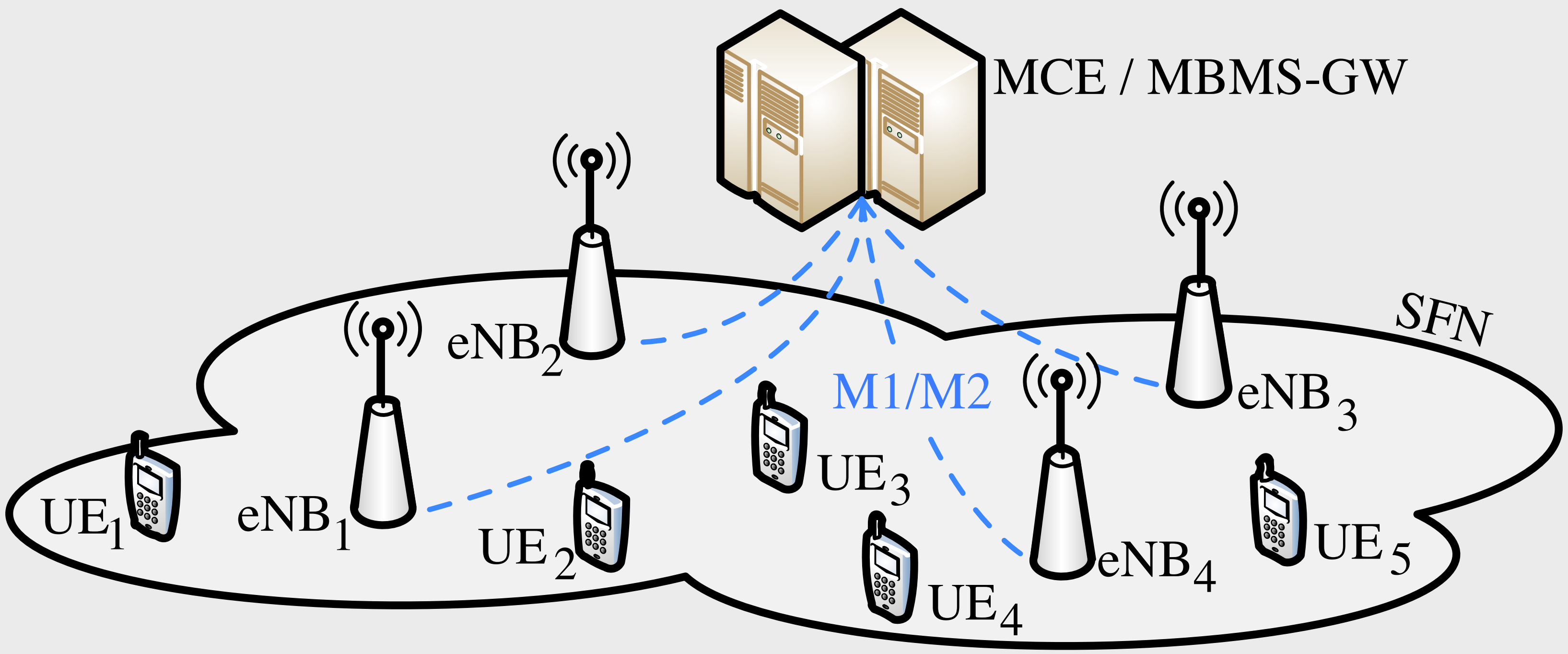


LTE-A Radio Resources

PtM communications managed by the eMBMS framework.
Two transmission modes have been defined:

- **SC-eMBMS** - Service delivered on each cell independently
  - ✓ Pros: Each eNB can independently optimise the delivered services
  - ✓ Cons: Neighbouring cells may interfere with each other
- **SFN-eMBMS** - Service delivered on a group of cells
  - ✓ Pros: No interfering cells in the SFN
  - ✓ Cons: Services optimised in a centralised fashion



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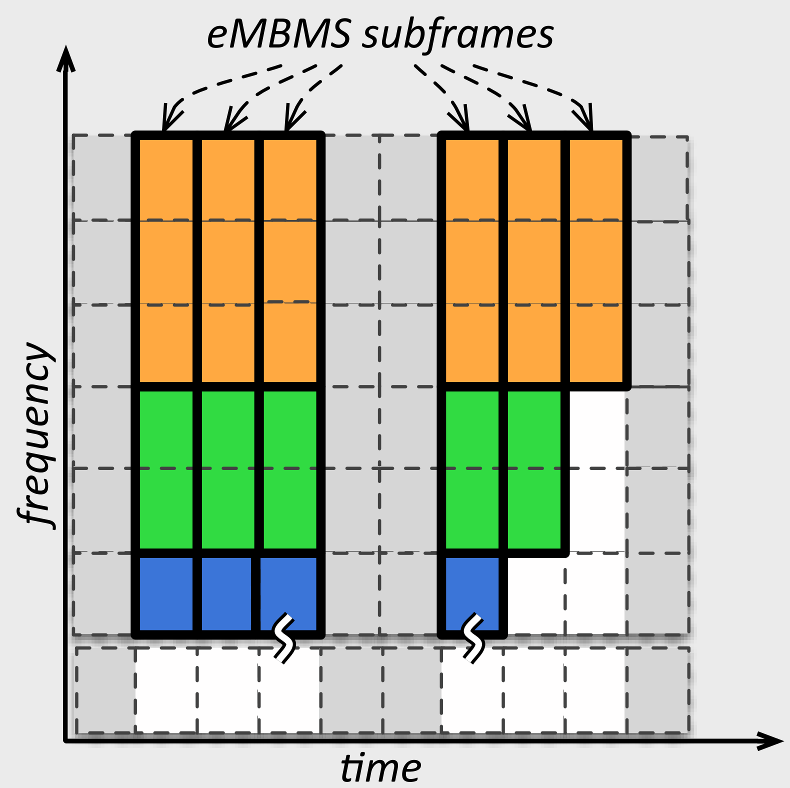

- ✓ At most 6 out of 10 TTIs can convey eMBMS data
- ✓ Fixed allocation pattern

Peak Signal-to-Noise Ratio

- It is defined on a frame-basis
- It can be defined by means of the Mean Squared Error (MSE)

Considering a frame of $m \times n$ pixels

$$\text{MSE} = \frac{1}{m\,n} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(I_{i,j} - K_{i,j} \right)^2$$

i,j-th pixel of the compressed frame

i,j-th pixel of the original frame

- Hence, the PSNR can be defined as follows

$$\text{PSNR} = 10 \log_{10} \left(\frac{I^2_{\text{MAX}}}{\text{MSE}} \right)$$

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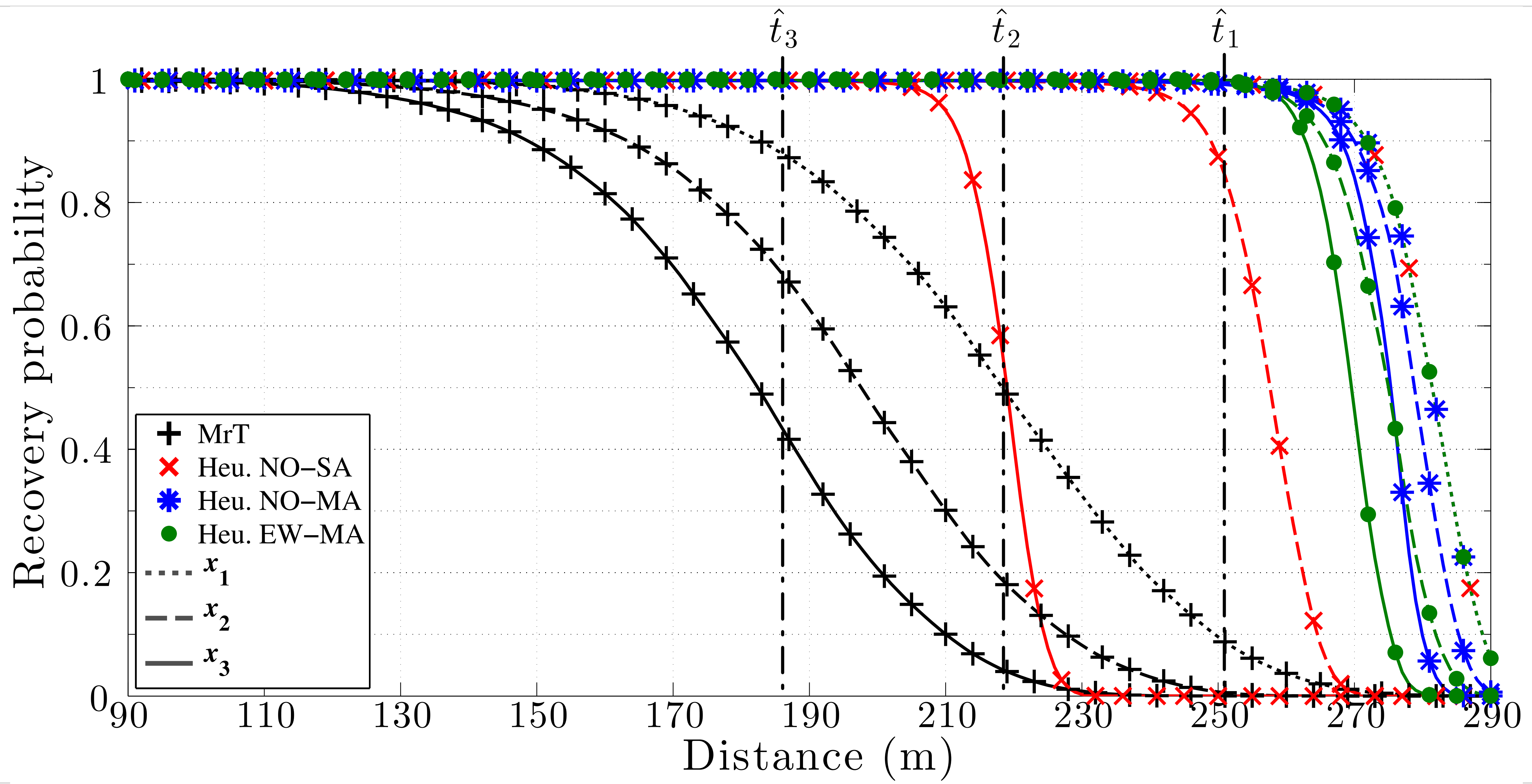
Analytical Results

Stream A
$q = 2$



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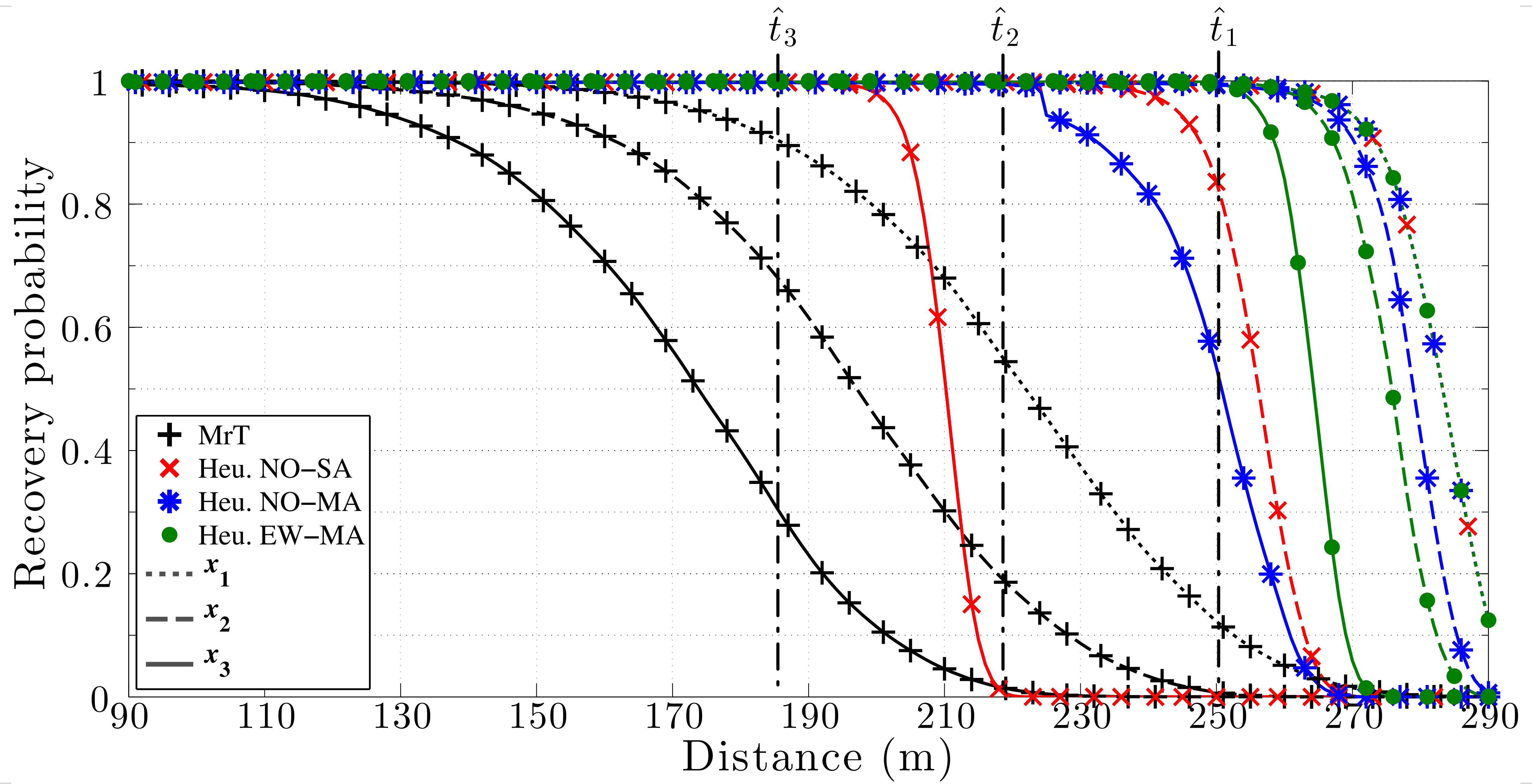
Analytical Results

Stream B
$q = 2$



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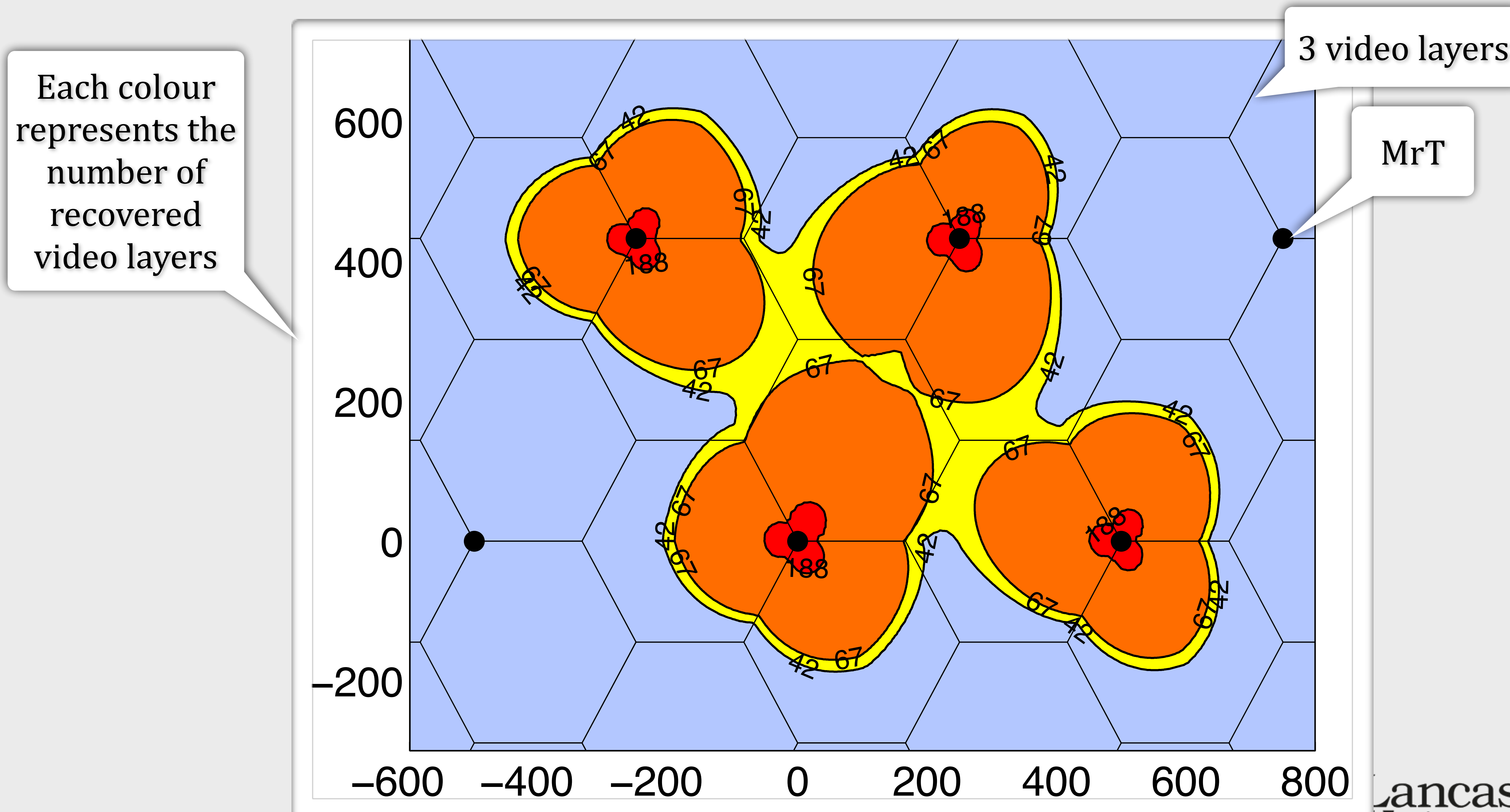
- We are extending the theoretical framework.
- These are some preliminary results for a grid of users placed on the SFN.



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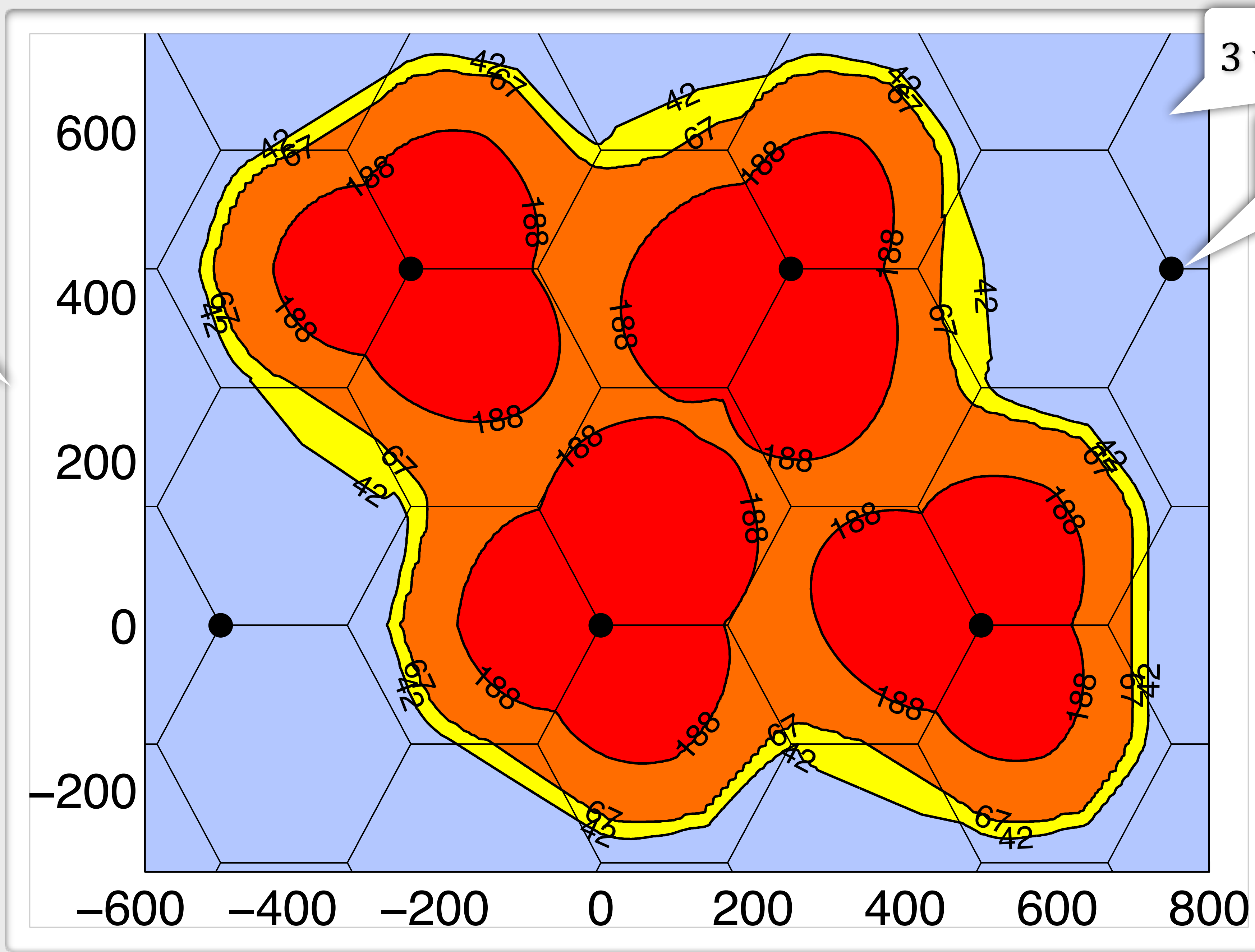

Each colour represents the number of recovered video layers

3 video layers

EW r.a.

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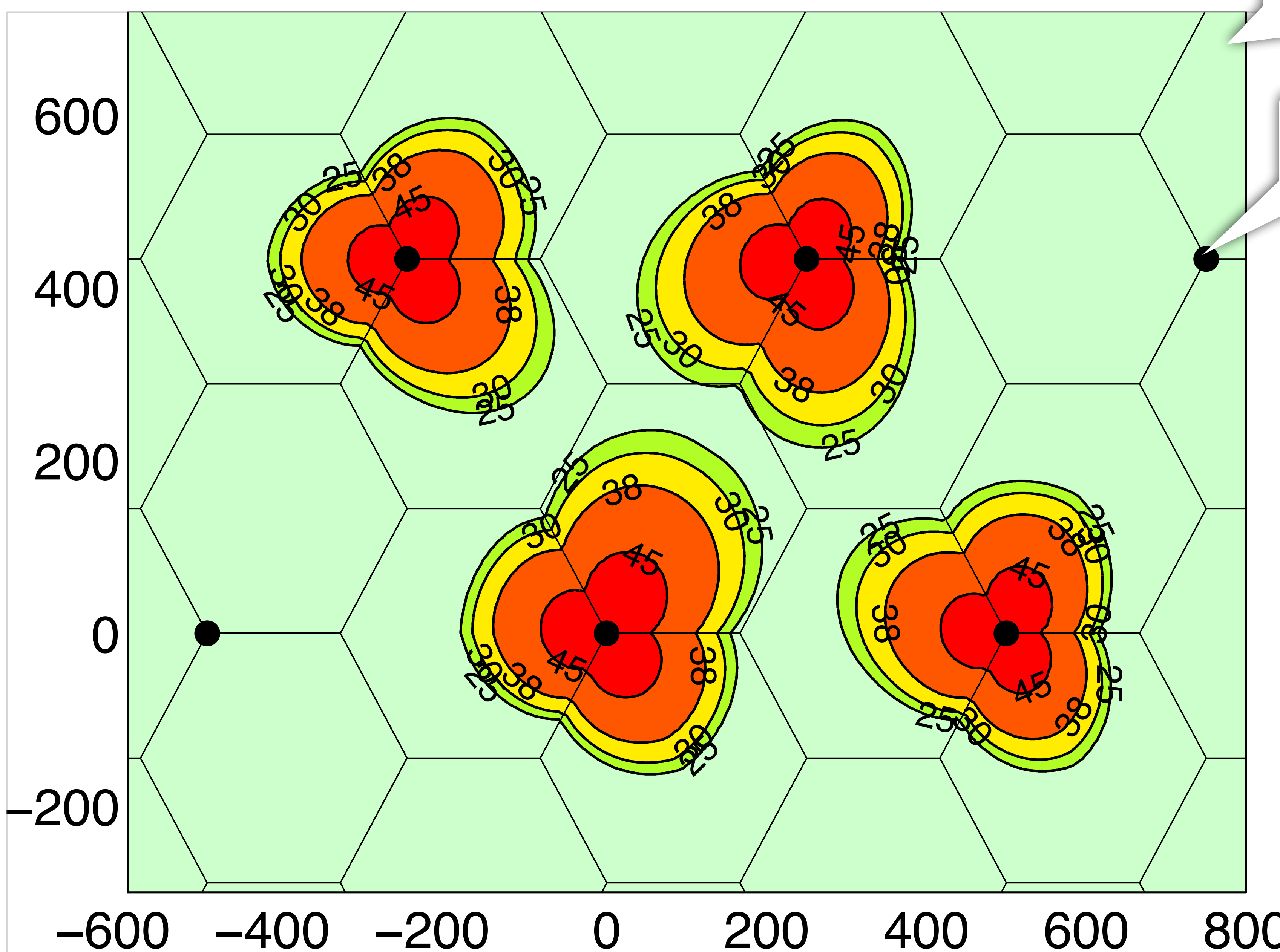

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4 video layers

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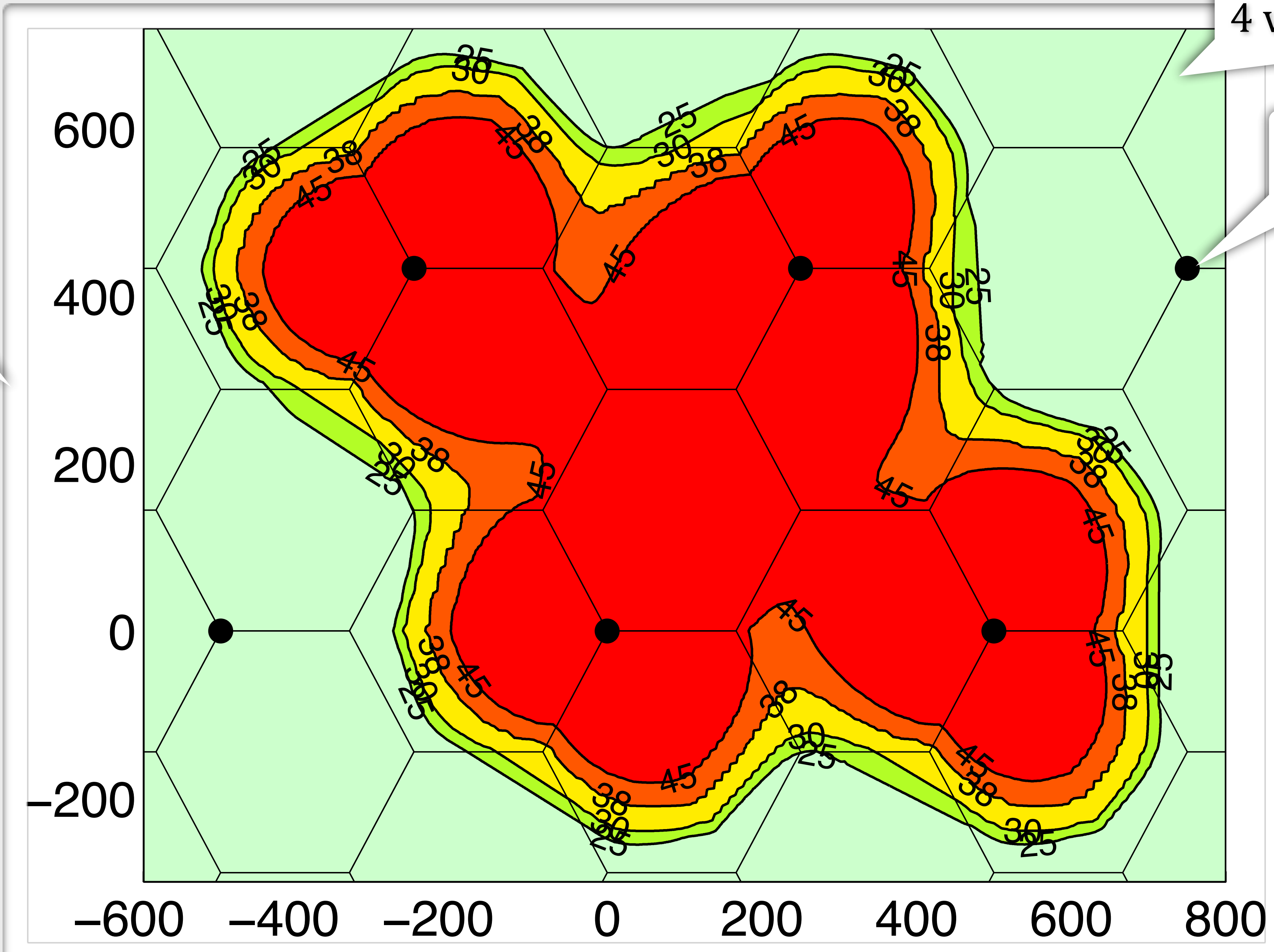

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