Lancaster University

School of Computing and Communications

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)

On Optimization of Network-coded Scalable Multimedia Service Multicasting

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Starting Point and Goals

- Delivery of multimedia broadcast/multicast services over 4G/5G networks is a challenging task. This has propelled research into delivery schemes.

- **Multi-rate Transmission (MrT) 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* - **Reduce the total amount of radio resources** needed to deliver a layered service.

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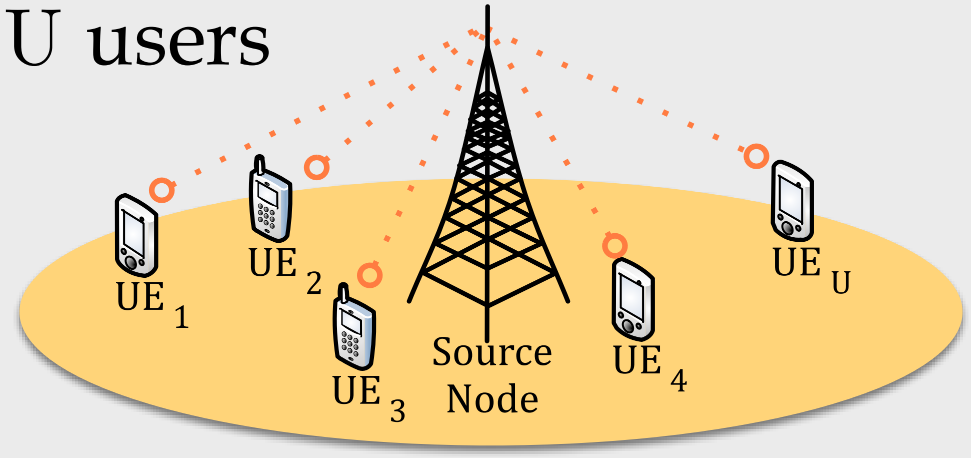
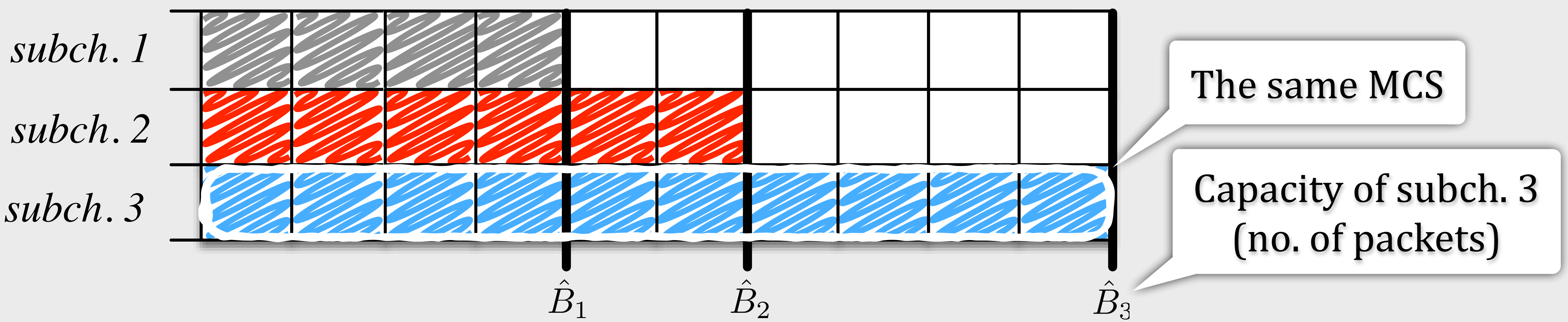
1. System Parameters and Performance Analysis

System Model

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



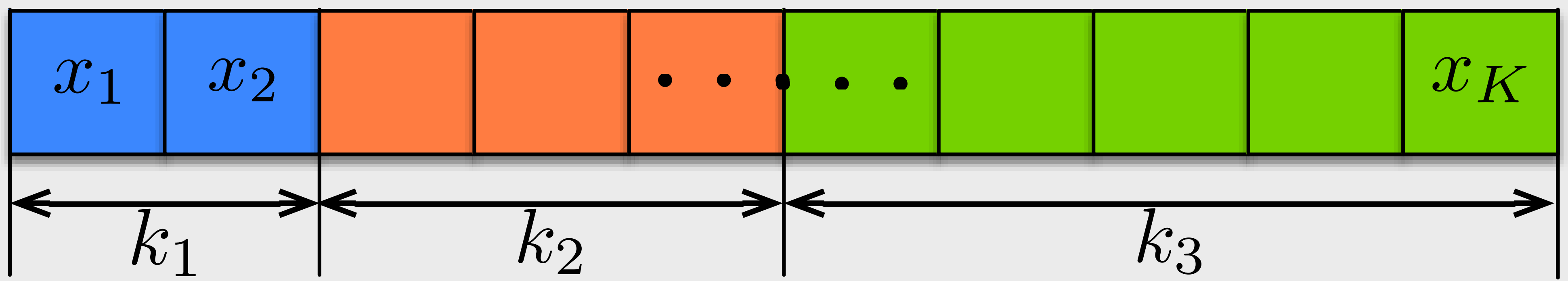
- Each PtM layered service is delivered through C orthogonal broadcast erasure subchannels



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

Non-Overlapping Layered RNC

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



- 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

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

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

PEP

Prob. of decoding layer l

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

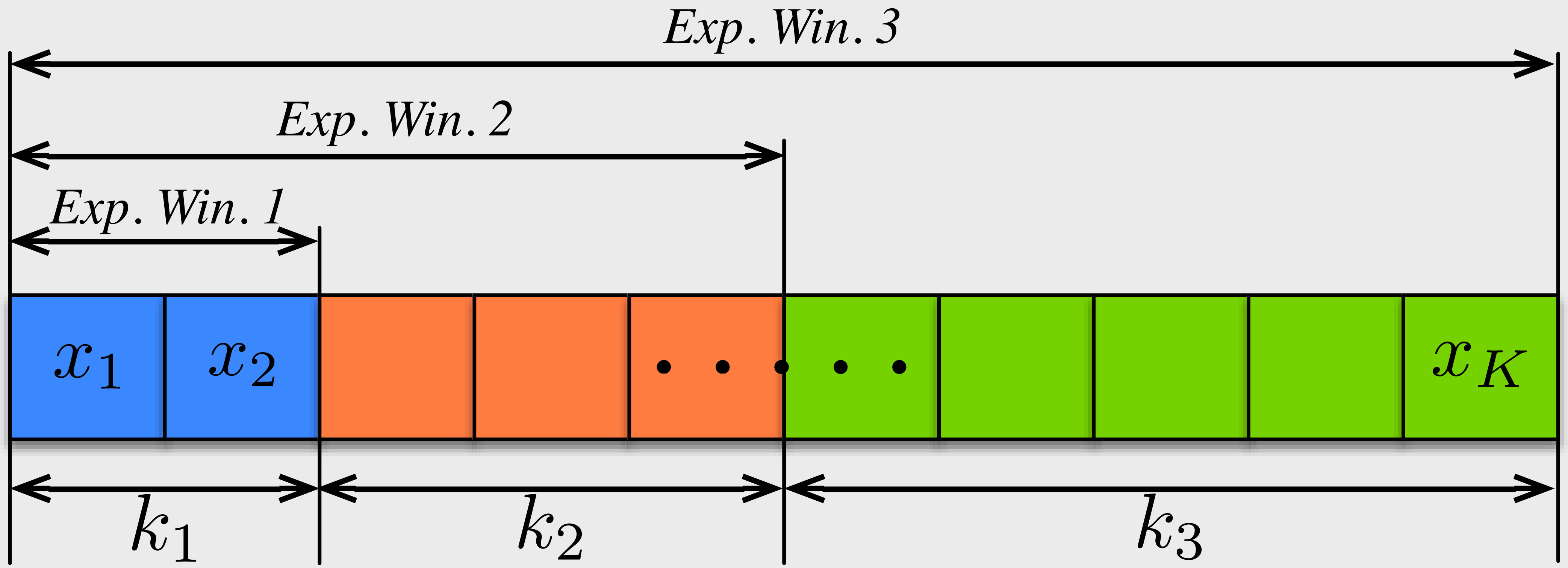
$$= \sum_{r=k_l}^{n_{l,u}} \binom{n_{l,u}}{r} p^{n_{l,u}-r} (1-p)^r \underbrace{\prod_{i=0}^{k_l-1} \left[1 - \frac{1}{q^{r-i}}\right]}_{h(r)}$$

- 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

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

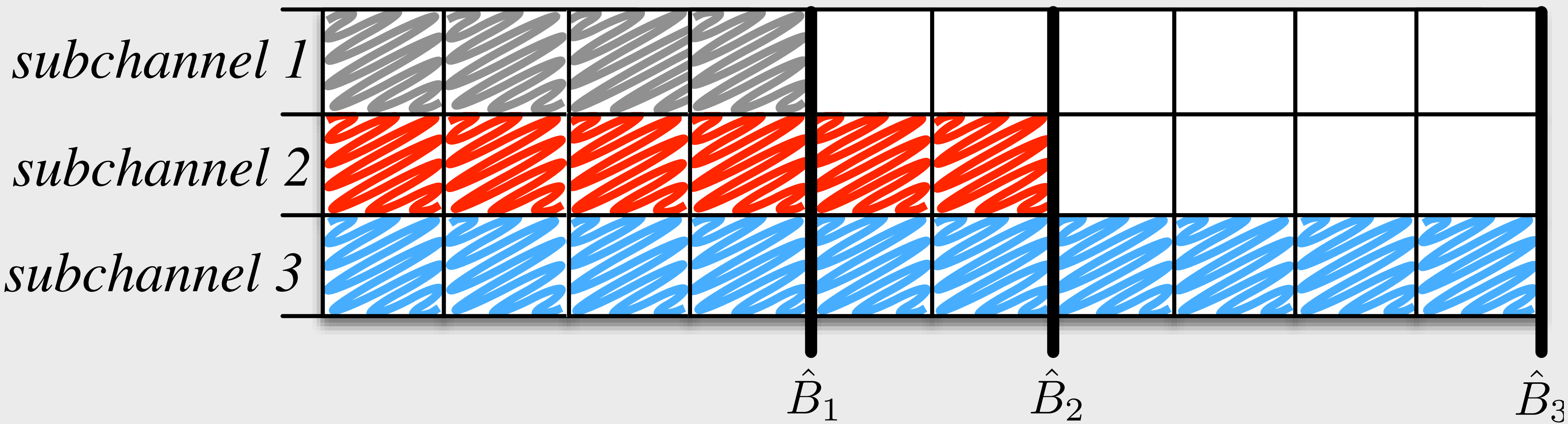
Prob. of receiving $\mathbf{r} = \{r_1, \ldots, r_l\}$ out of $\mathbf{N}_u$ coded symbols

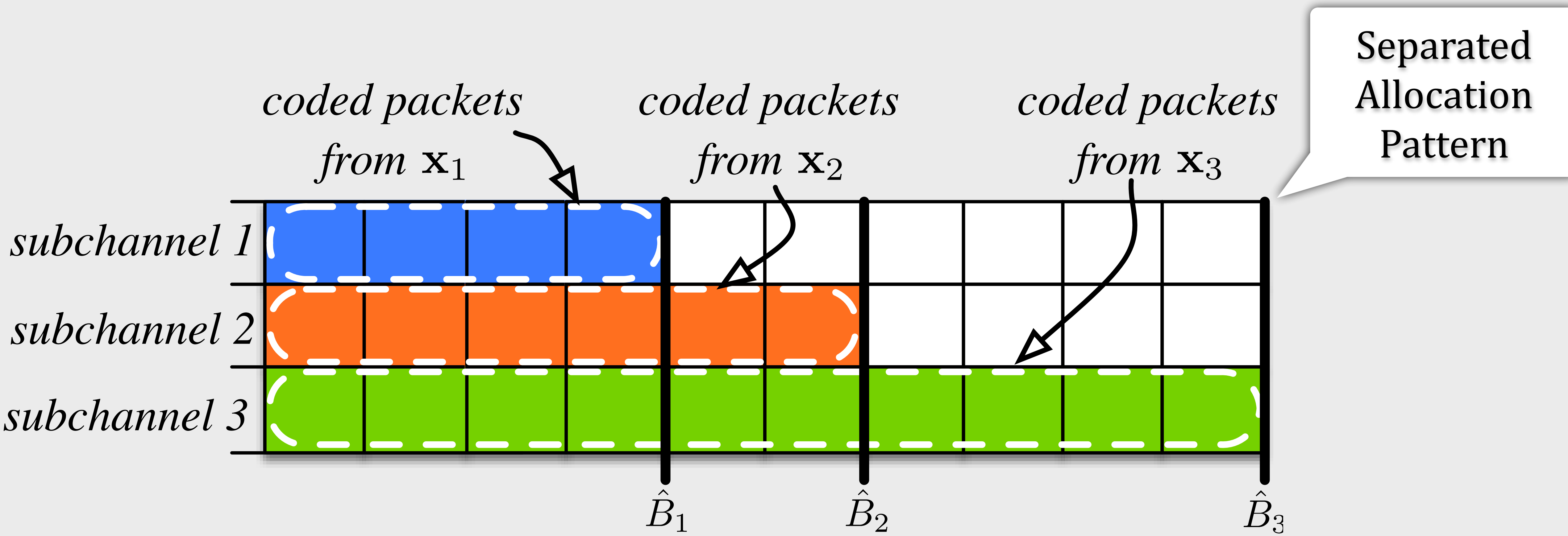
Prob. of decoding window l

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

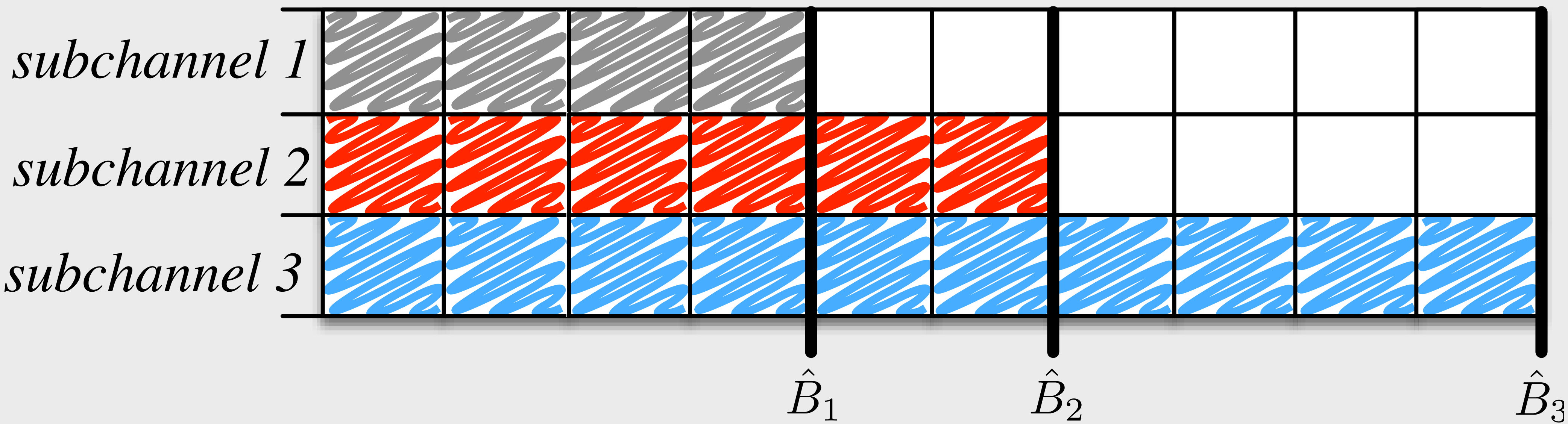
2. Multi-Channel Resource Allocation Models

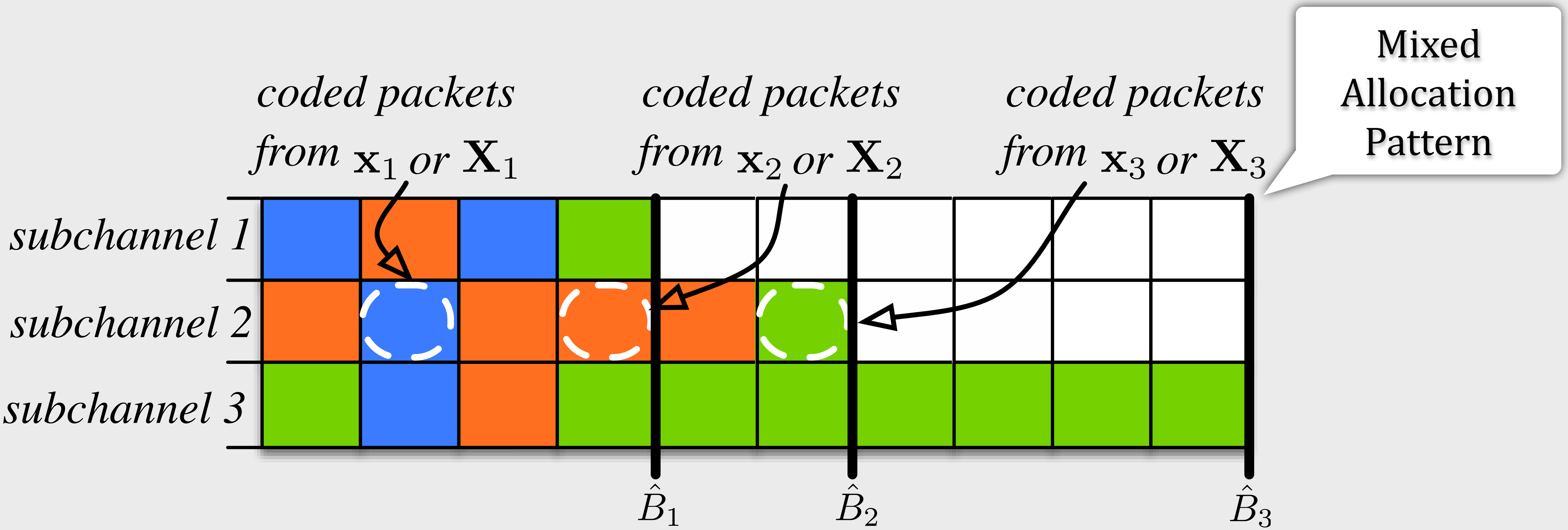
Allocation Patterns

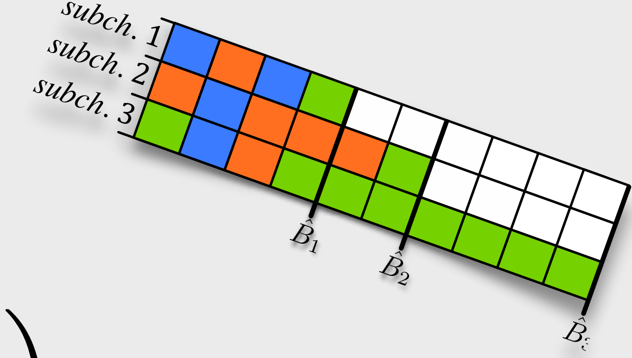




Allocation Patterns







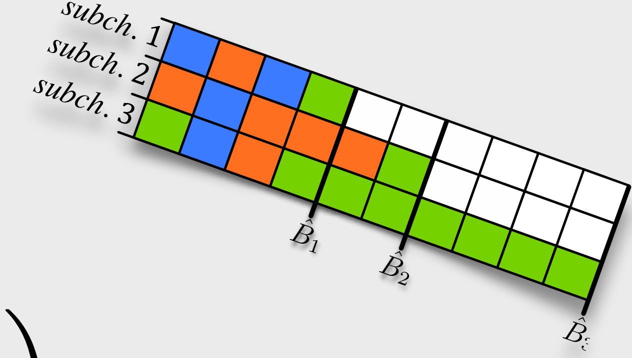
NO-MA Model

- 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 probabili… …ise it is 0.

Minimization of resource footprint

No. of packets of layer l delivered over c

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



NO-MA 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.

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

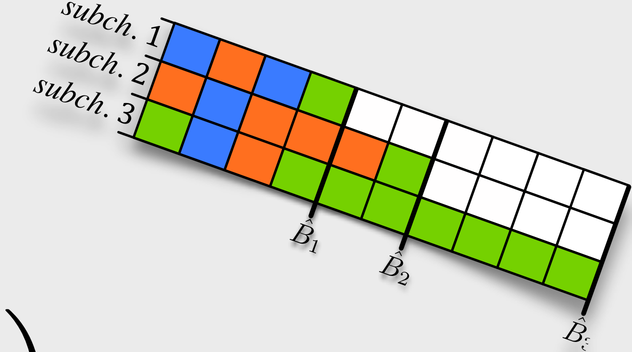
$$\text{subject to} \quad \sum_{u=1}^{U} \lambda_{u,l} \geq U\,\hat{t}_l \qquad l = 1,\ldots,L \qquad (2)$$

Target fraction of users

No. of users

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

NO-MA 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.

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

Dynamic- and system-related constraints

NO-MA Heuristic

- The NO-MA 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 ($n^{(1,c)}, \ldots, n^{(L,c)}$)

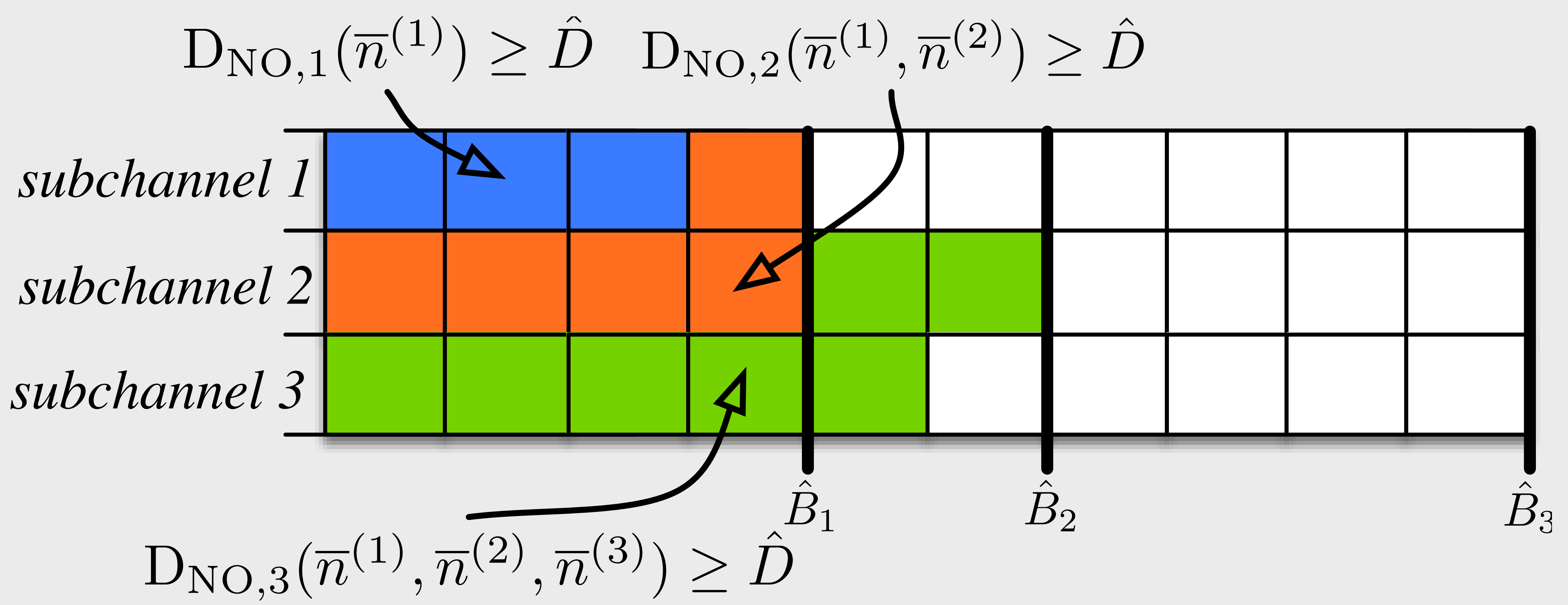
- The **first step** selects the value of m_c such that packets delivered through subch. c are received (at least with a target prob.) by $U \cdot \hat{t}_c$ users.

Step 1 Subchannel MCSs optimization.

```
c ← 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-MA Heuristic

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



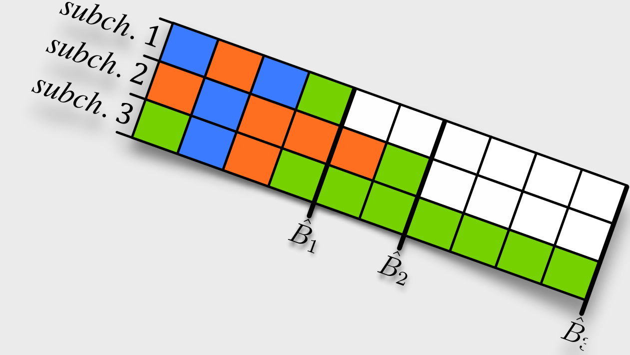
NO-MA Heuristic

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

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

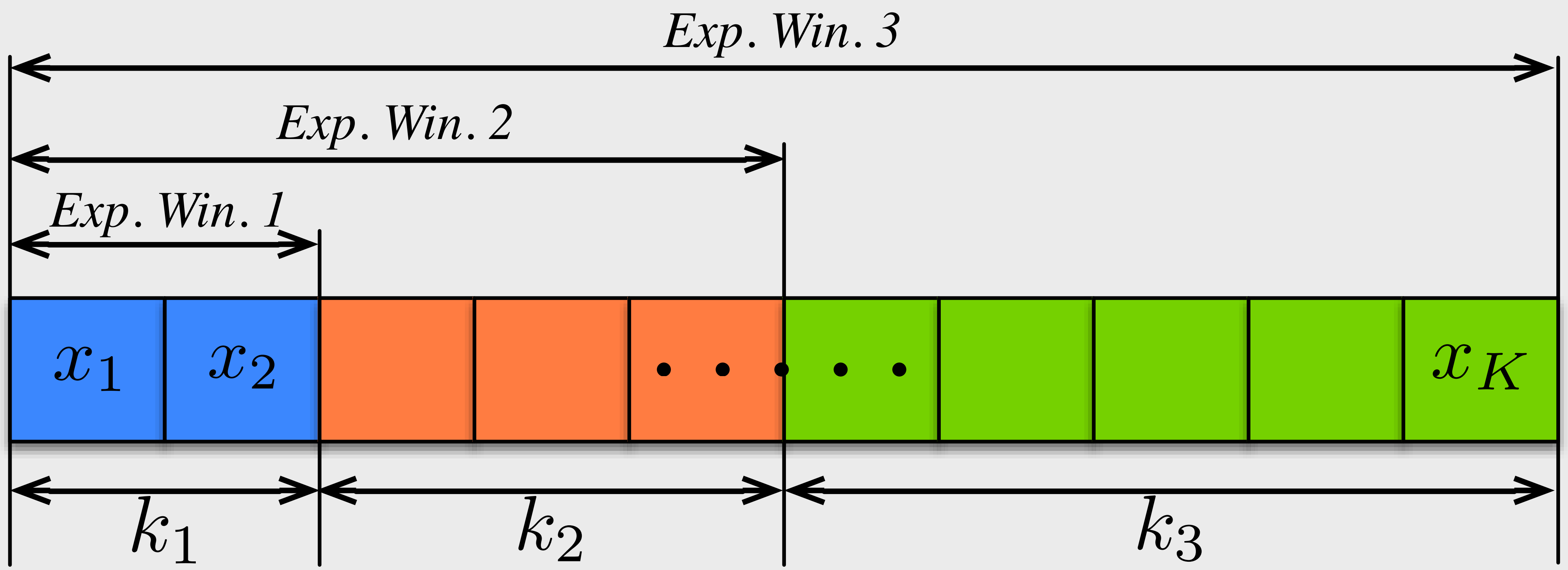
$c \leftarrow 1$
$\overline{n}^{(l,c)} \leftarrow 1$ for any $l = 1, \ldots, L$ and $c = 1, \ldots, C$
$\overline{\mathbf{n}} = \{\overline{n}^{(l)}\}_{l=1}^{L}$, where $\overline{n}^{(l)} \leftarrow 1$ for any $l = 1, \ldots, L$
for $l \leftarrow 1, \ldots, L$ **do**
    while $\mathrm{D}_{\mathrm{NO},l}(\overline{\mathbf{n}}) < \hat{D}$ 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

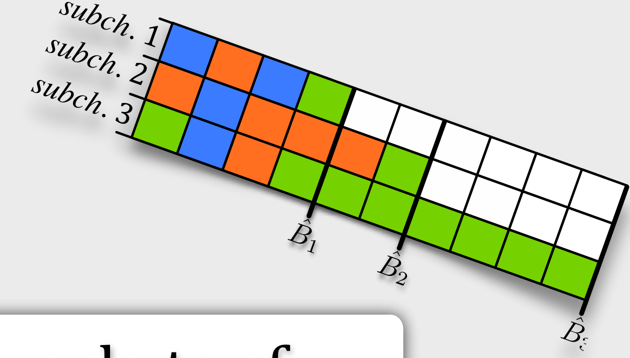


- We define the indicator variable

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

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



- The RA problem for the EW-MA case is

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

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

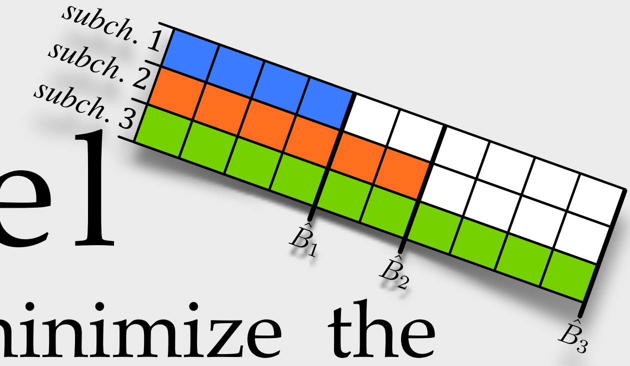
$$\text{subject to} \quad \sum_{u=1}^{U} \mu_{u,l} \geq U\ \hat{t}_l \qquad l = 1, \ldots, L \qquad (2)$$

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

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

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

"Egalitarian" Model



- Previous strategies ensure minimum SLA and minimize the resource footprint. **Point of view of the ISP…**
- **Best practice for burglars** - To still object with the maximum value and the minimum weight. The profit-cost ratio is maximized.

del for a SA pattern as:

Profit - No. of video layers recovered by any of the users

Cost - No. of transmissions needed

SLA-related constraint

$$\text{(E-SA)} \quad \underset{\substack{m_1,\dots,m_L \\ N^{(1)},\dots,N^{(L)}}}{\text{maximize}} \quad \boxed{\sum_{u=1}^{U}\sum_{l=1}^{L} Q_{u,l}} \Big/ \boxed{\sum_{l=1}^{L} N^{(l)}} \tag{1}$$

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

$$0 \leq N^{(l)} \leq \hat{B}_l \qquad l = 1,\dots,L. \tag{3}$$

- We can refer to the previous heuristics.

3. Analytical Results

Analytical Results *(part 1)*

- LTE-A eMBMS scenarios
- We compared the proposed strategies wit
  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

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

Analytical Results *(part 1)*

- LTE-A eMBMS scenarios
- We compared the proposed strategies wit 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

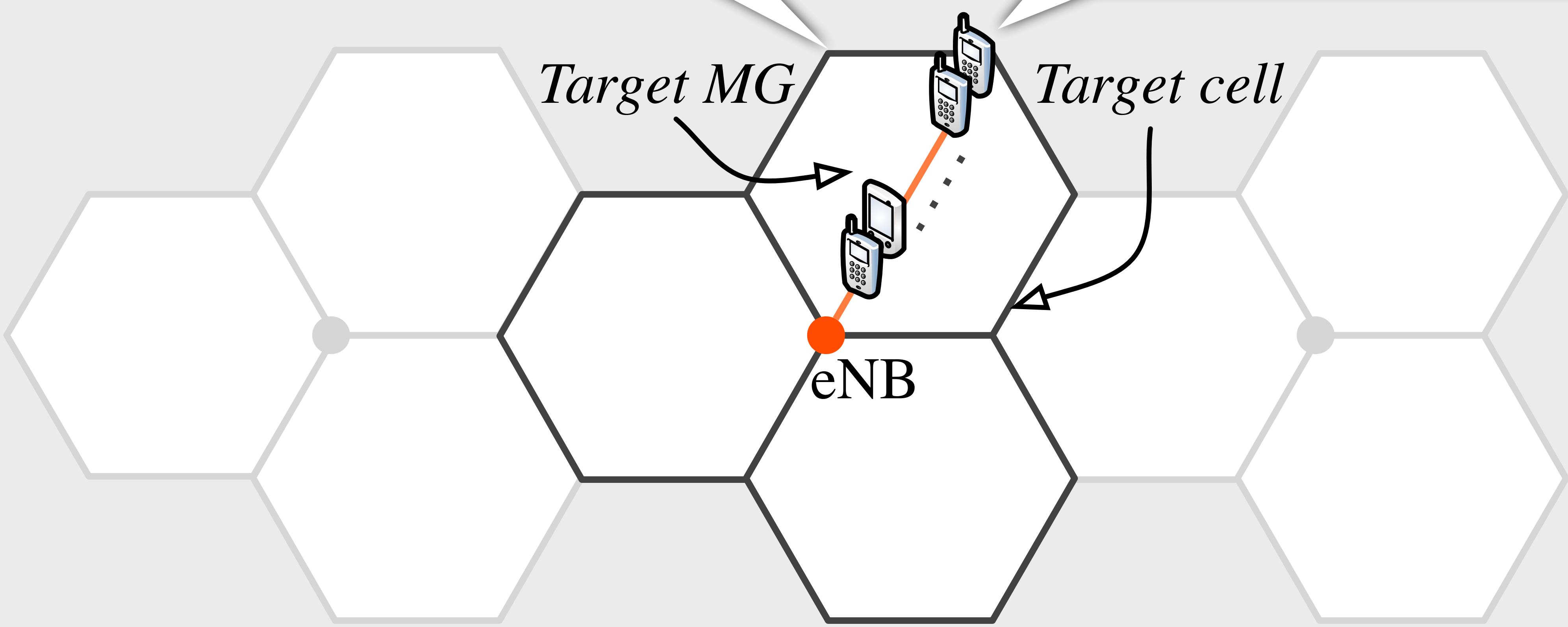
PSNR after recovery of the basic and the first l enhancement layers

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

Analytical Results *(part 1)*

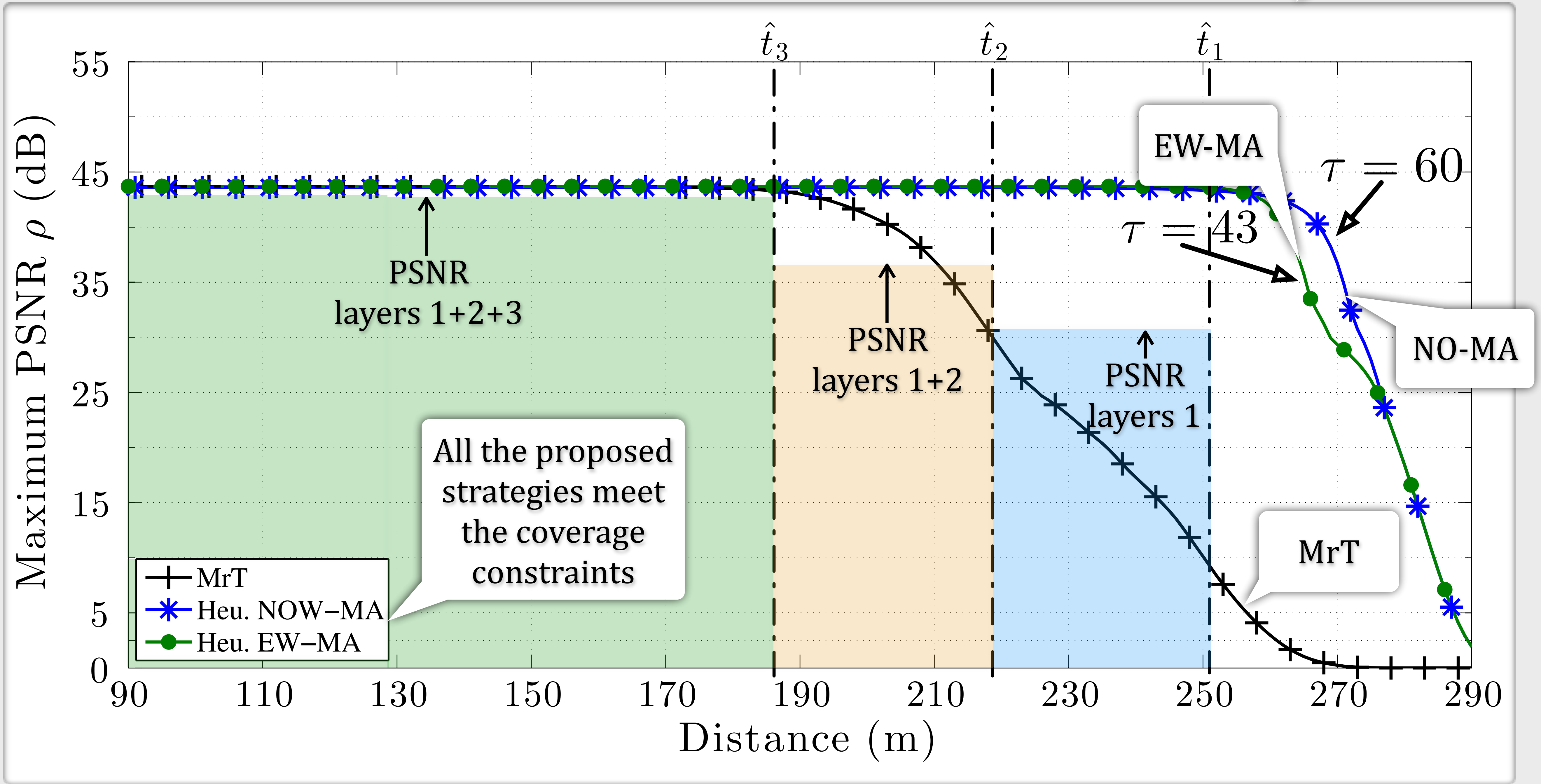
Scenario with a high heterogeneity. 80 UEs equally spaced and placed along the radial line representing the symmetry axis of one sector of the target cell

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

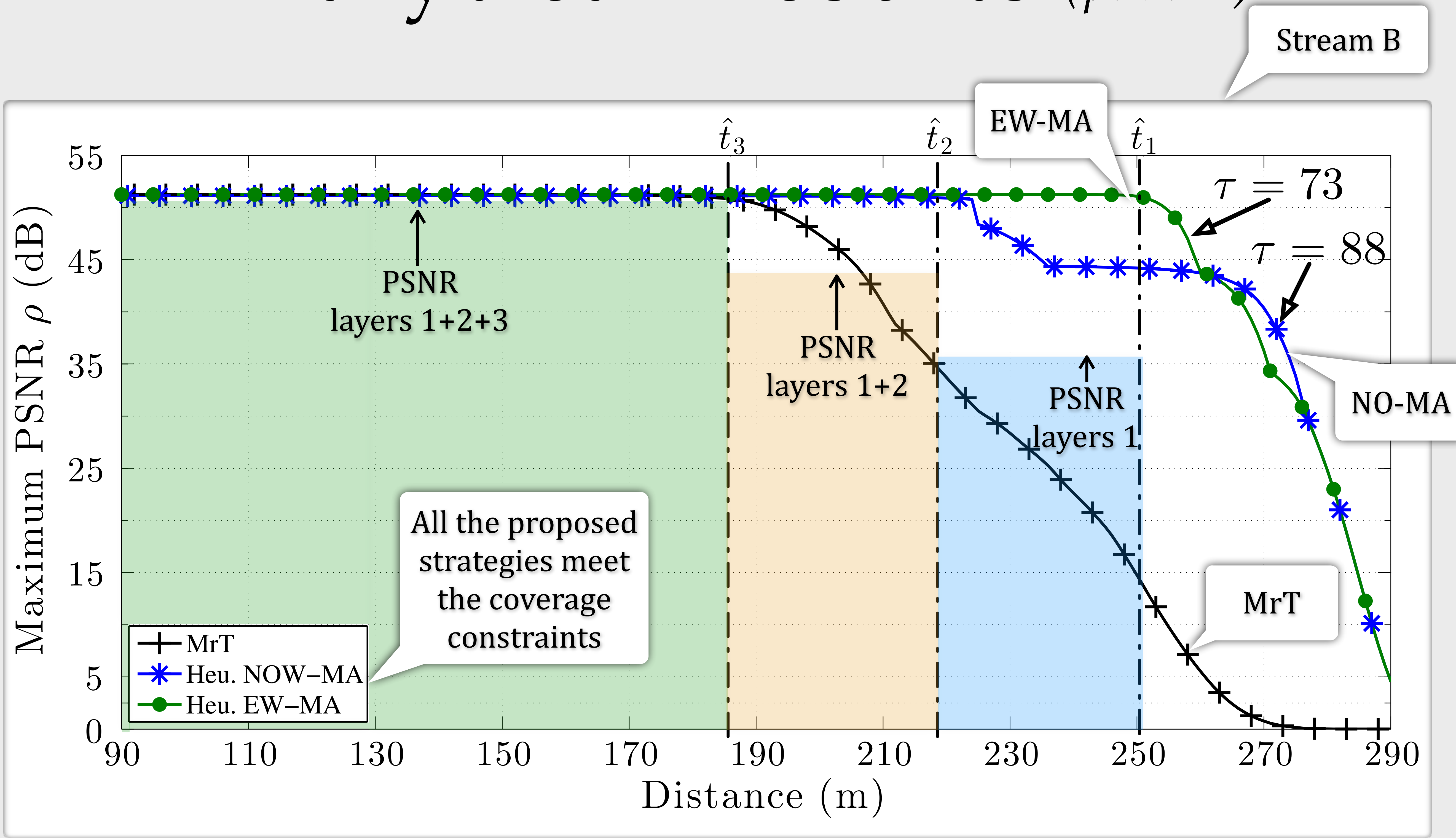


Analytical Results *(part 1)*

Stream A



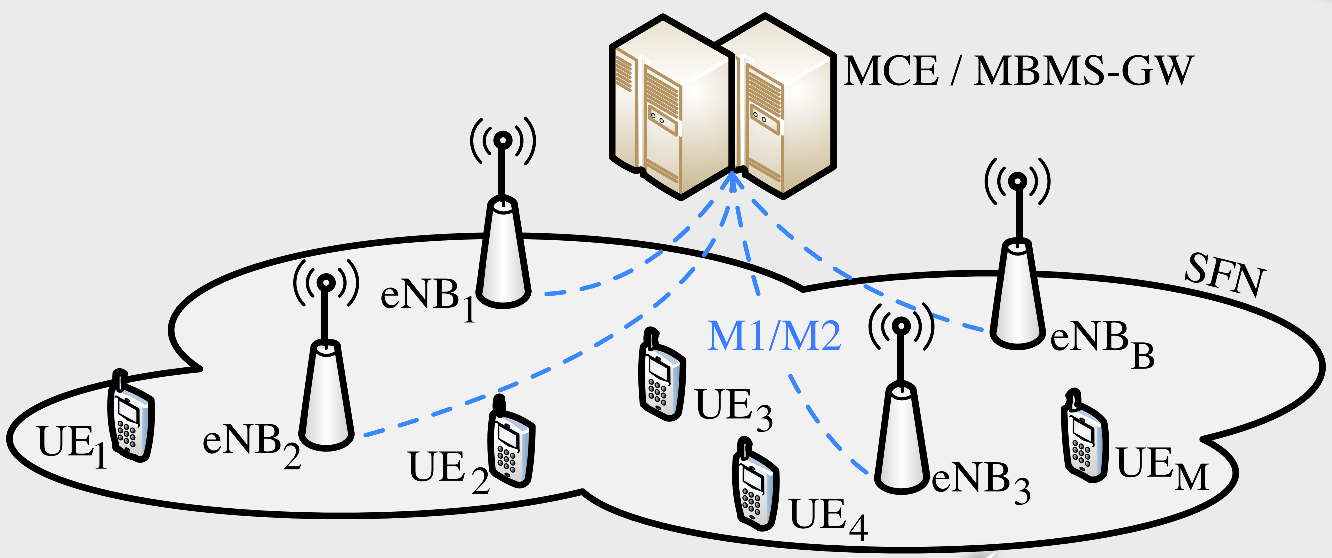
Analytical Results *(part 1)*



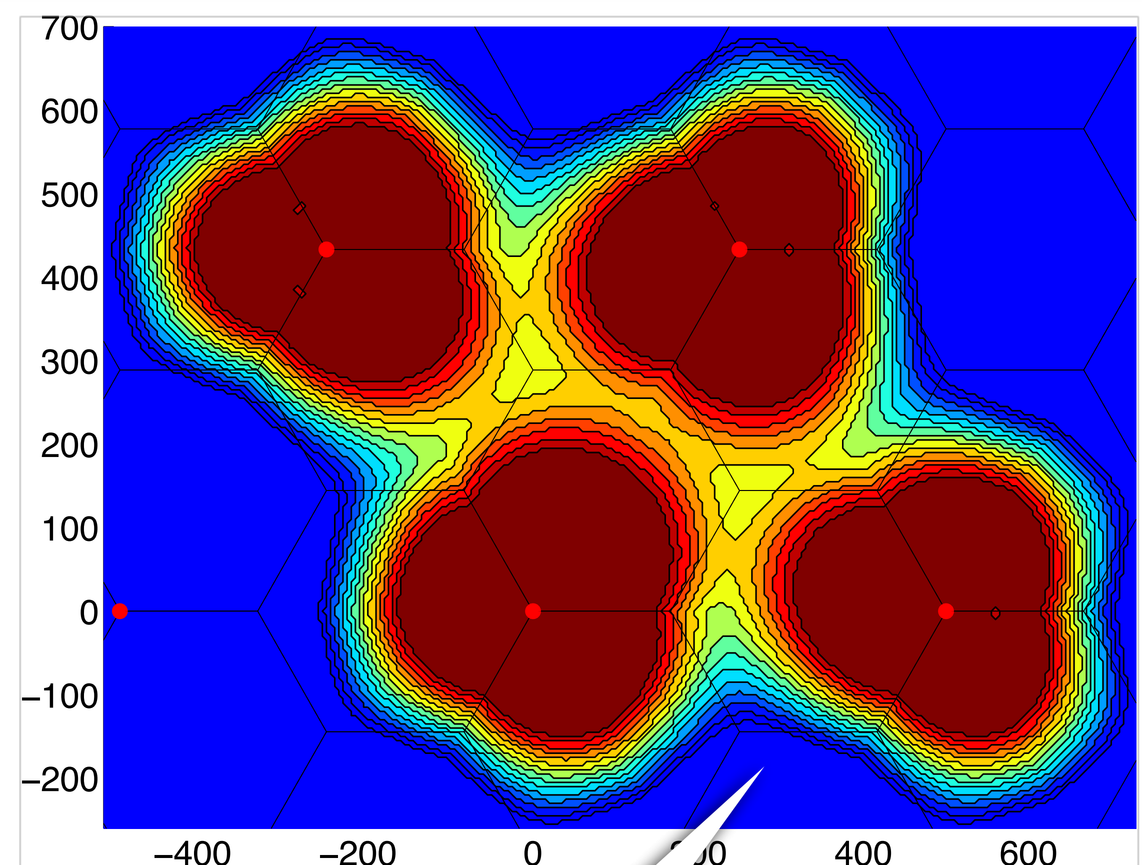
Analytical Results *(part 2)*

- LTE-A allows multiple contiguous BS to deliver (in a synchronous fashion) the same services by means of the same signals

4-BS SFN, 1700 users placed at the vertices of a regular square grid placed on the playground.

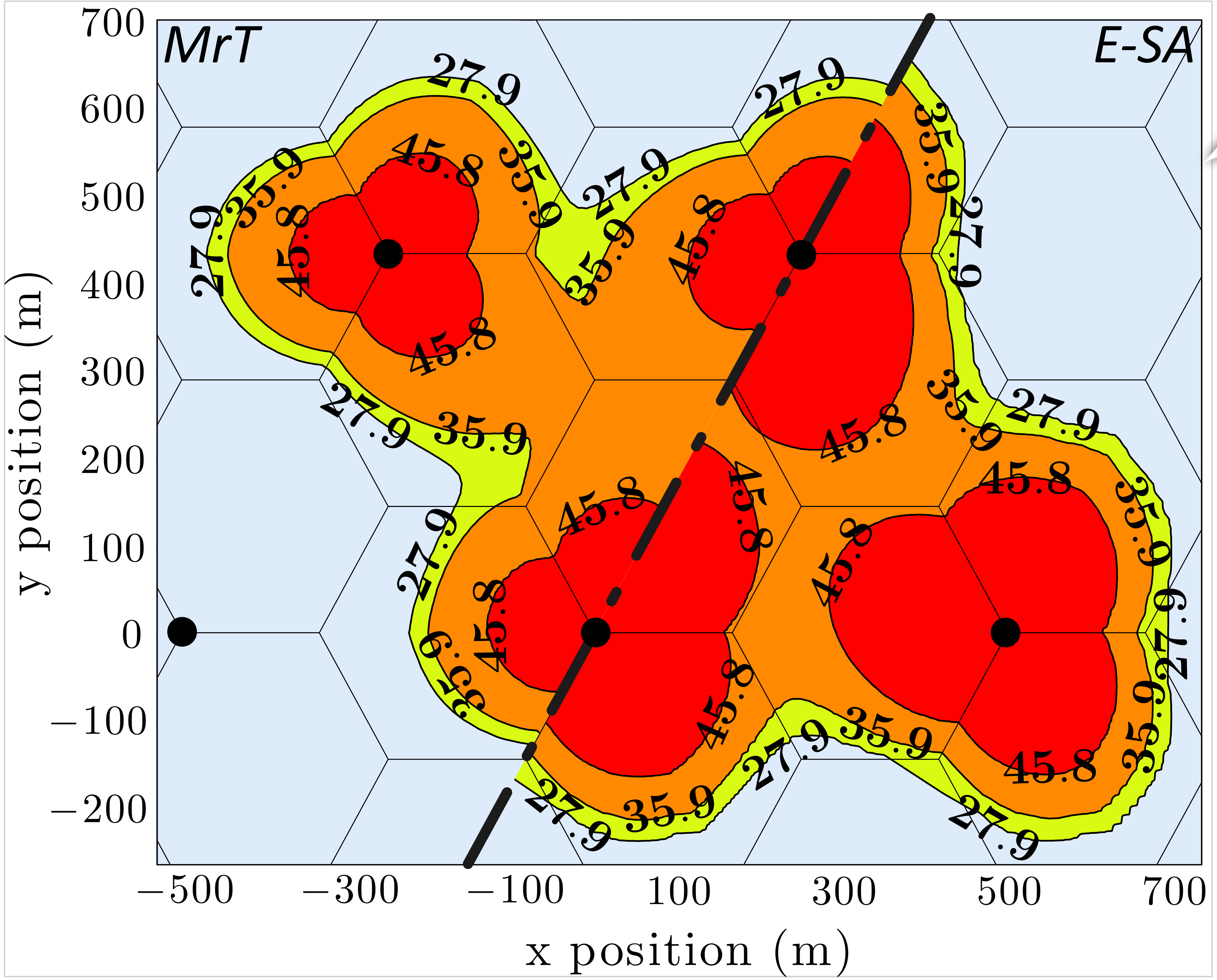


Single Frequency Network



Spacial SINR distribution

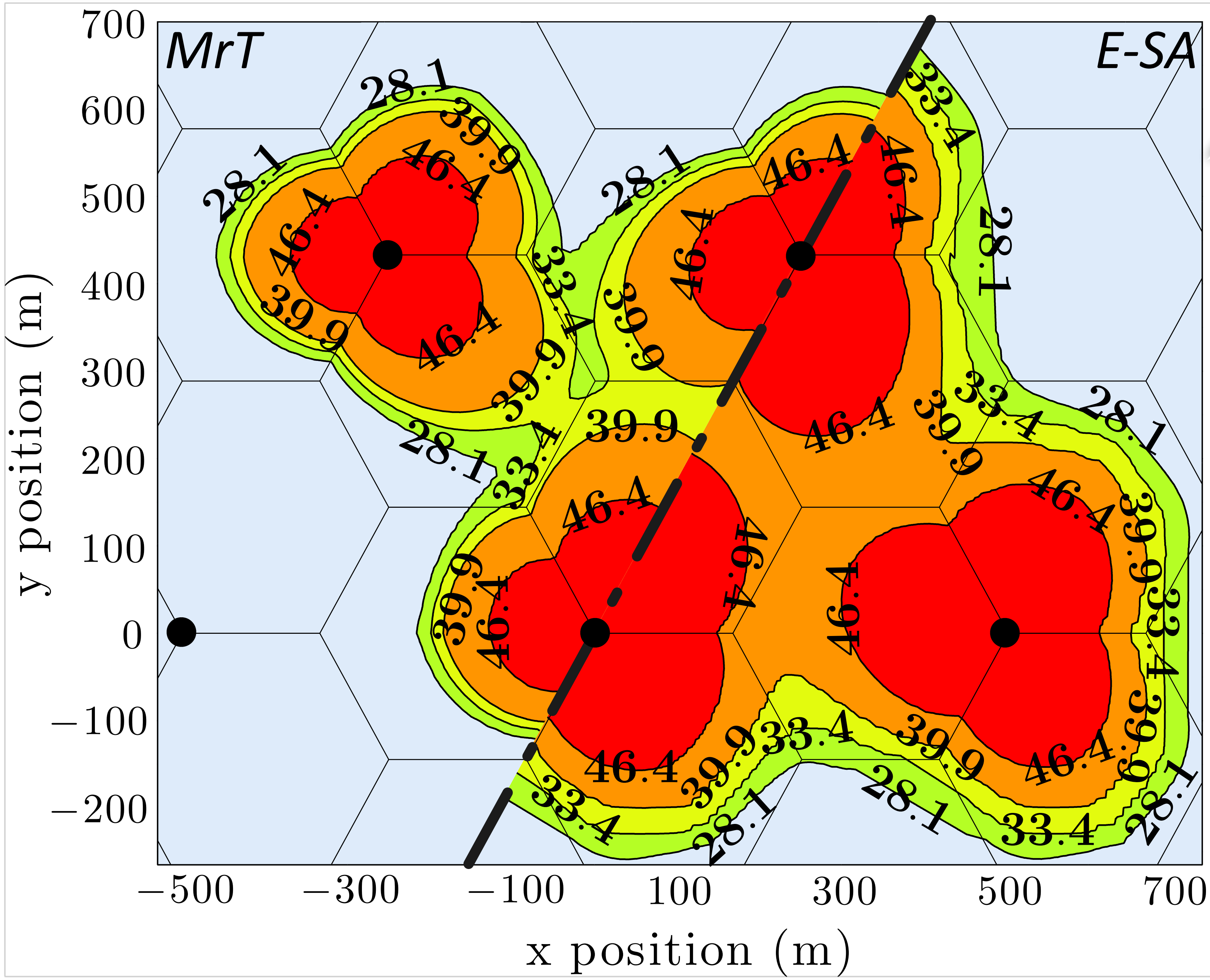
Analytical Results *(part 2)*



3-layer stream

- Also in this case MrT cannot ensure the desired coverage!

Analytical Results *(part 2)*



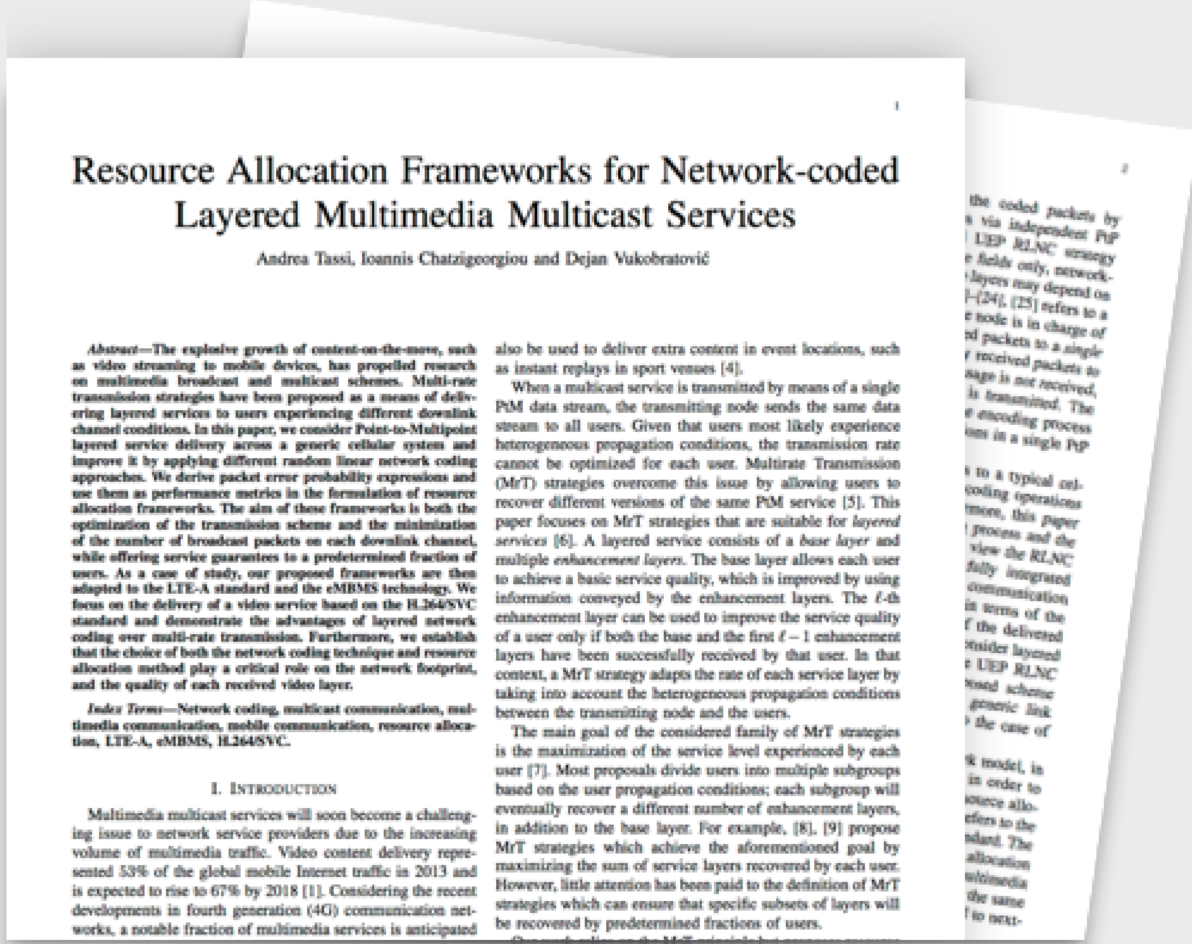
4-layer stream

- Also in this case MrT cannot ensure the desired coverage!

4. Concluding Remarks

Concluding Remarks

- Definition of a **generic system model** that can be easily adapted to practical scenarios and different viewpoints (ISP vs users).
- 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.**


Resource Allocation Frameworks for Network-coded Layered Multimedia Multicast Services

Andrea Tassi, Ioannis Chatzigeorgiou and Dejan Vukobratović

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*.

Thank you for your attention

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