

R2D2: Network error control for  
**Rapid and Reliable Data Delivery**  
*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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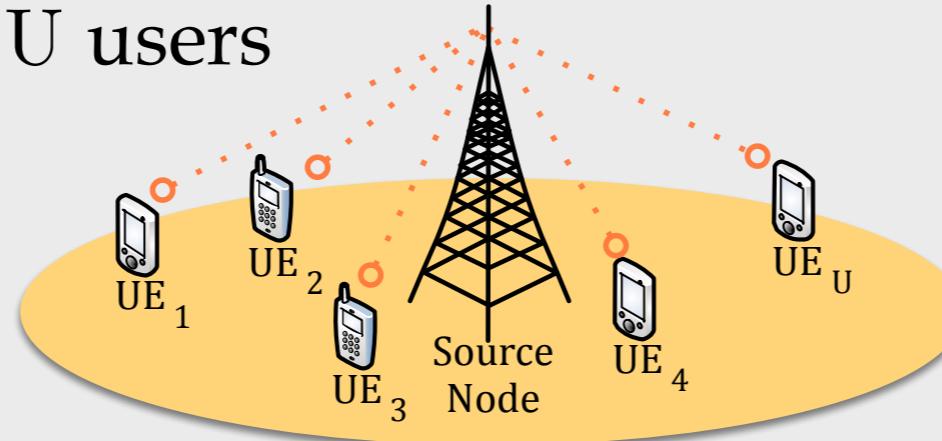
1. System Parameters and Performance Analysis
2. Multi-Channel Resource Allocation Models and Heuristic Strategies
3. Analytical Results
4. Concluding Remarks

# 1. System Parameters and Performance Analysis

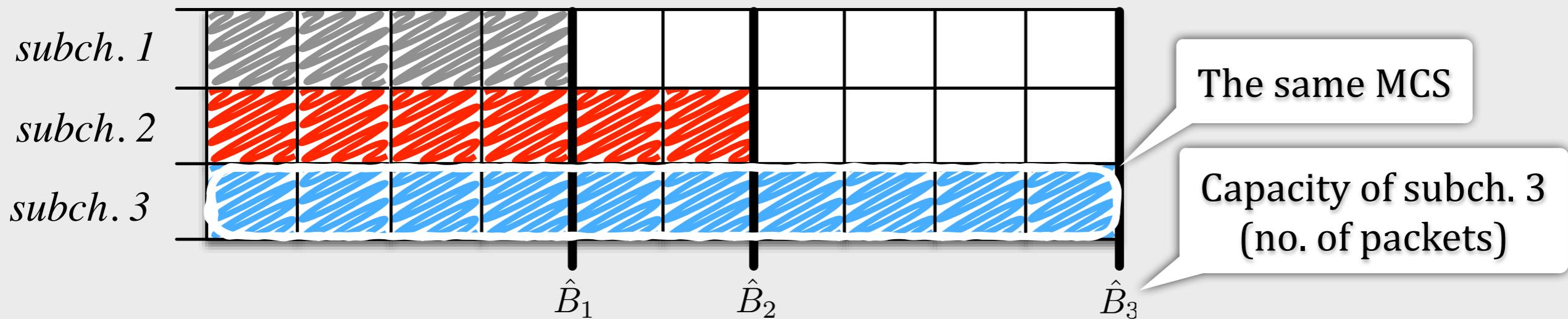


# System Model

- 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

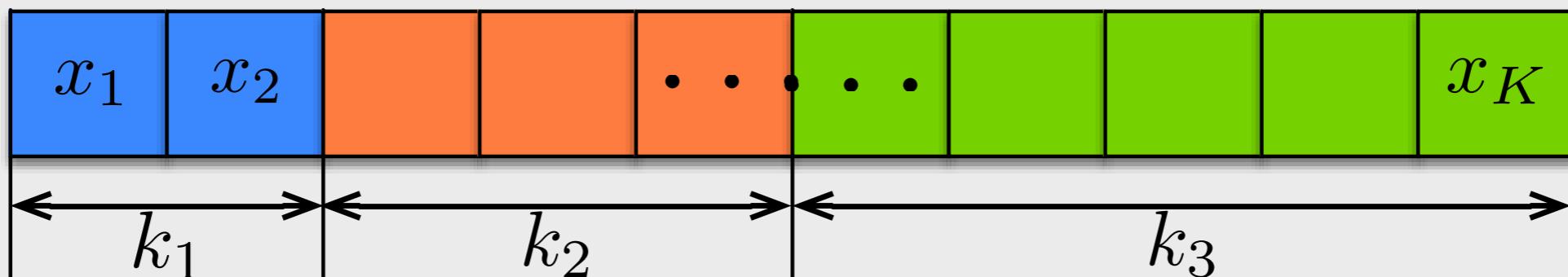


- Each subchannel delivers streams of (en)coded packets (according to the RLNC principle).



# 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

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

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

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

PEP

Prob. of decoding layer  $l$

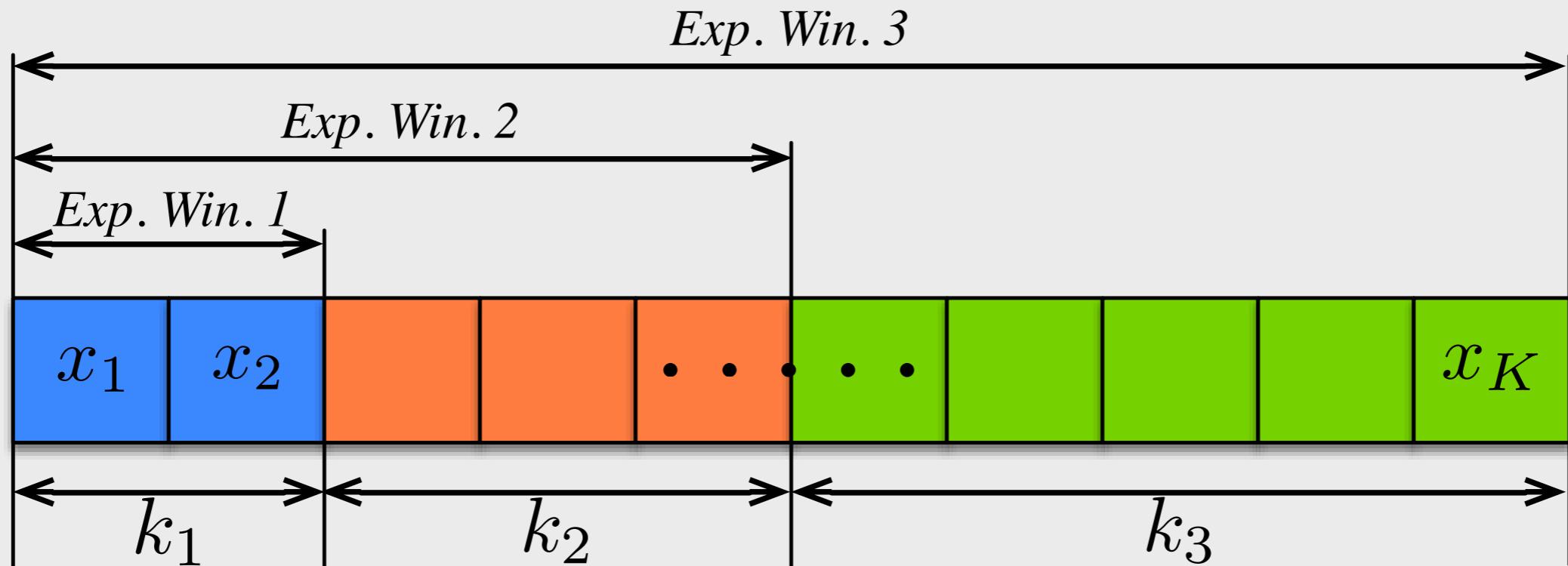
- The probability that user  $u$  recover the first  $l$  service layers is

$$D_{NO,l}(n_{1,u}, \dots, n_{L,u}) = D_{NO,l}(\mathbf{n}_u) = \prod_{i=1}^l P_i(n_{i,u})$$



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

$$D_{EW,l}(N_{1,u}, \dots, N_{L,u}) = \\ = D_{EW,l}(\mathbf{N}_u)$$

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

$$= \sum_{r_1=0}^{N_{1,u}} \dots \sum_{r_{l-1}=0}^{N_{l-1,u}} \sum_{r_l=r_{\min,l}}^{N_{l,u}} \underbrace{\binom{N_{1,u}}{r_1} \dots \binom{N_{l,u}}{r_l}}_{\text{Prob. of receiving } \mathbf{r} \text{ out of } \mathbf{N}_u \text{ coded symbols}} p^{\sum_{i=1}^l (N_{i,u} - r_i)} (1-p)^{\sum_{i=1}^l r_i} g_l(\mathbf{r})$$

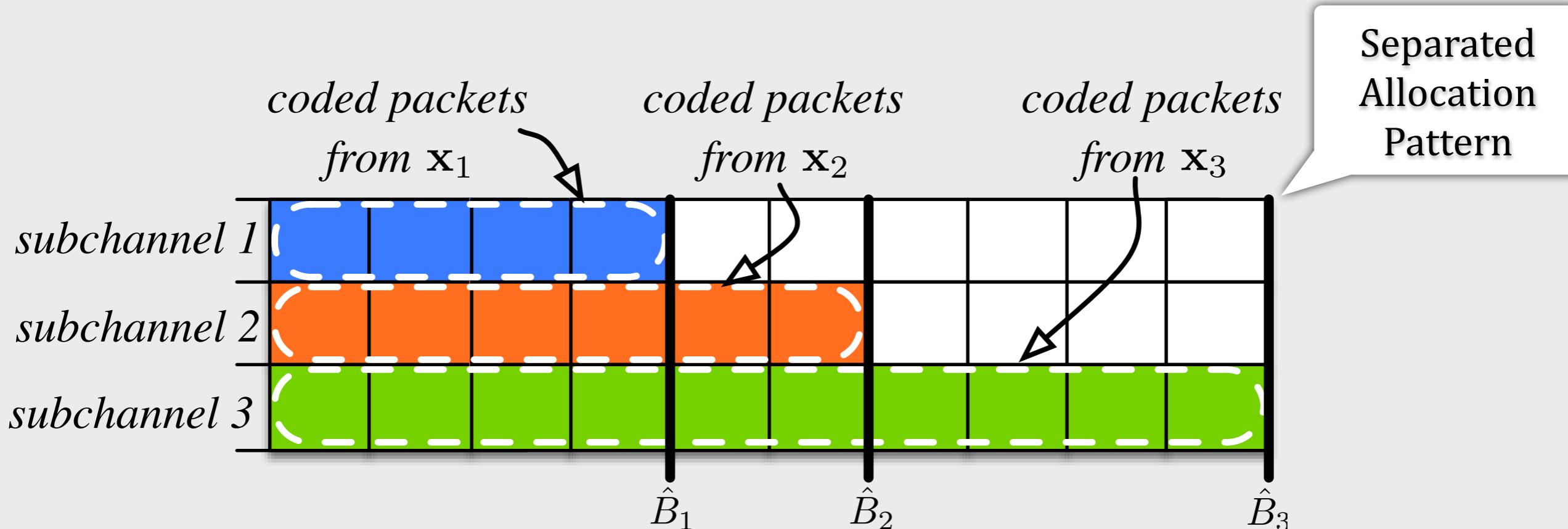
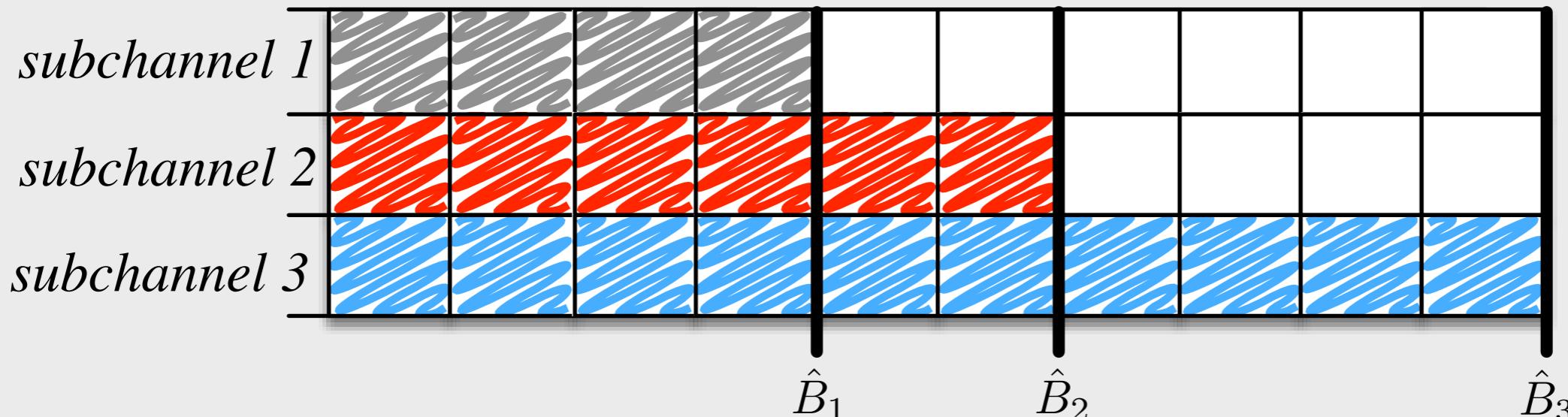
Prob. of decoding  
window  $l$

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

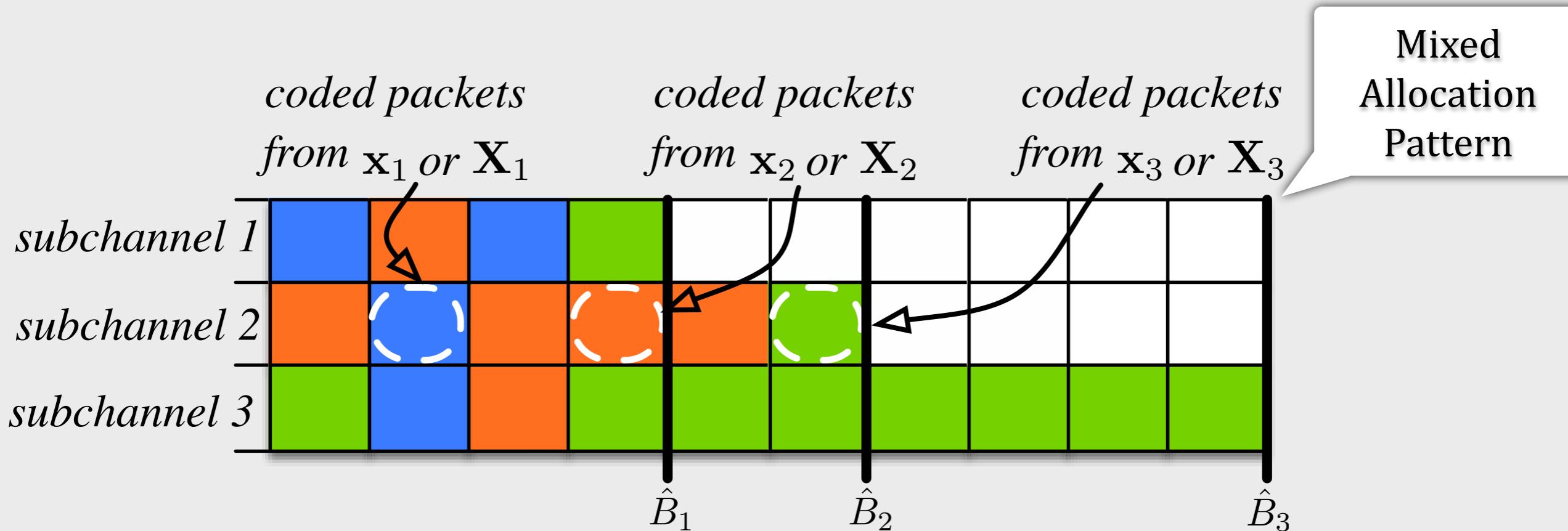
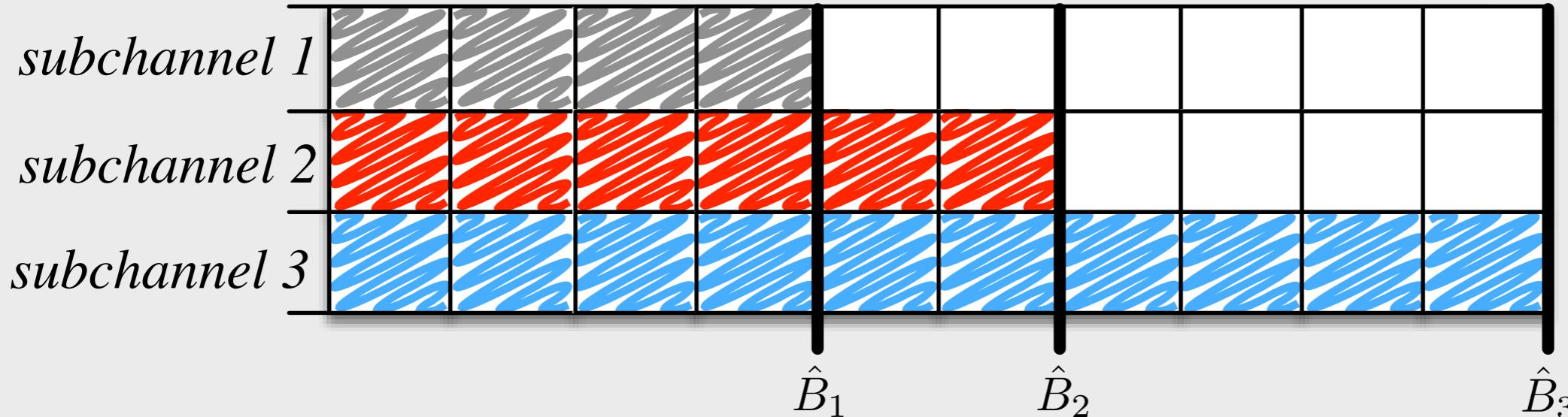


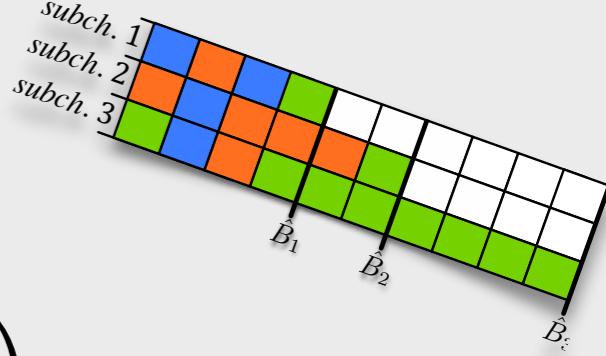
## 2. Multi-Channel Resource Allocation Models

# Allocation Patterns



# Allocation Patterns





# NO-MA Model

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

Minimization of  
resource footprint

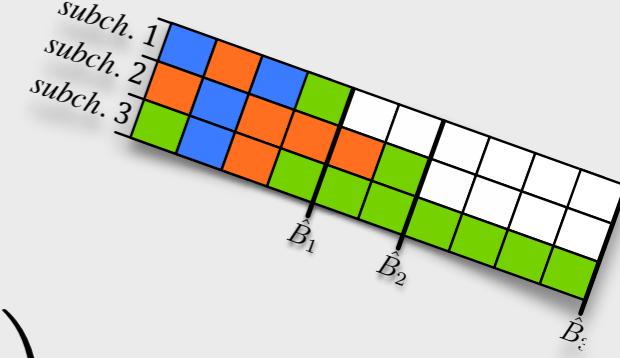
otherwise it is 0.

No. of packets of layer l  
delivered over c

(NO-MA)

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

# NO-MA Model



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

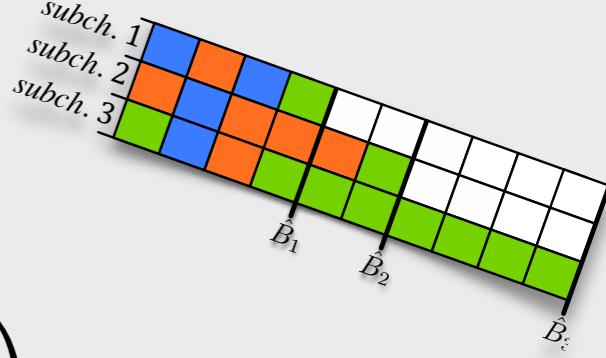
subject to 
$$\sum_{u=1}^U \lambda_{u,l} \geq U \hat{t}_l \quad l = 1, \dots, L \quad (2)$$

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

Target fraction of users

No. of users





# NO-MA Model

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

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

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

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

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

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 (  $m_1, \dots, m_C$  )
  - ii. No. of coded packet per-subchannel optimization (  $n^{(1,c)}, \dots, n^{(L,c)}$  )

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## Step 1 Subchannel MCSs optimization.

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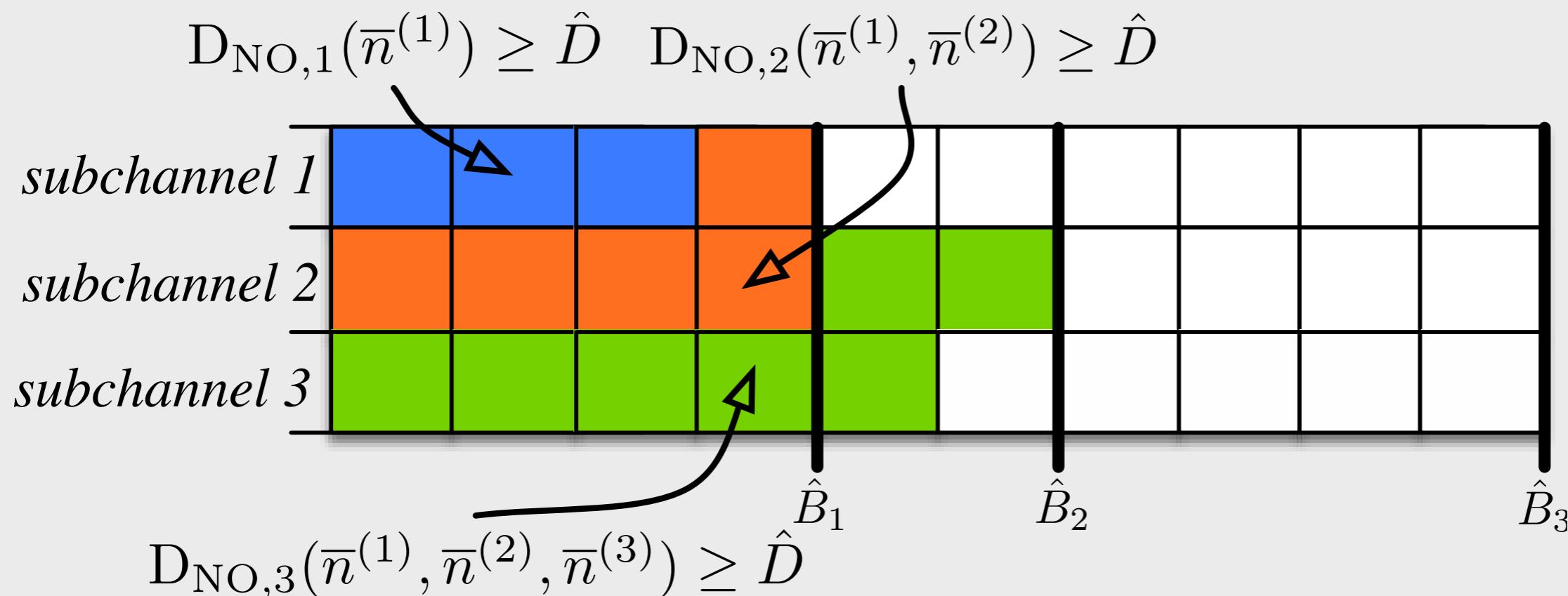
- The **first step** selects the value of  $m_c$  such that packets delivered through subch. c are received (at least with a target prob.) by  $U \cdot \hat{t}_c$  users.

```
1:  $c \leftarrow C$ 
2:  $v \leftarrow m_{\text{MAX}}$  and
3: while  $c \geq 1$  do
4:   repeat
5:      $m_c \leftarrow v$ 
6:      $v \leftarrow v - 1$ 
7:   until  $|\mathcal{U}^{(m_c)}| \geq U \cdot \hat{t}_c$  or  $v < m_{\text{min}}$ 
8:    $c \leftarrow c - 1$ 
9: end while
```

---

# NO-MA Heuristic

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



# NO-MA Heuristic

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

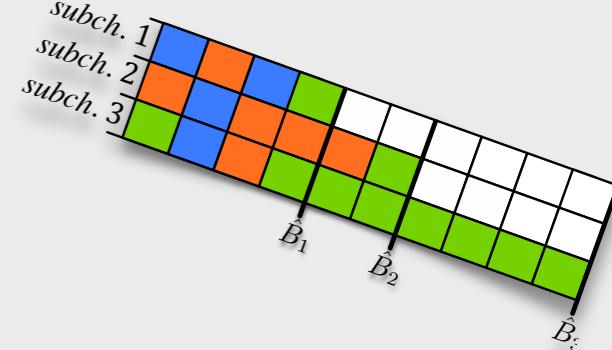
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```
1:  $c \leftarrow 1$ 
2:  $\bar{n}^{(l,c)} \leftarrow 1$  for any  $l = 1, \dots, L$  and  $c = 1, \dots, C$ 
3:  $\bar{\mathbf{n}} = \{\bar{n}^{(l)}\}_{l=1}^L$ , where  $\bar{n}^{(l)} \leftarrow 1$  for any  $l = 1, \dots, L$ 
4: for  $l \leftarrow 1, \dots, L$  do
5:   while  $D_{NO,l}(\bar{\mathbf{n}}) < \hat{D}$  and  $c \leq C$  do
6:      $\bar{n}^{(l,c)} \leftarrow \bar{n}^{(l,c)} + 1$ 
7:      $\bar{n}^{(l)} \leftarrow \sum_{t=1}^C \bar{n}^{(l,t)}$  for any  $l = 1, \dots, L$ 
8:     if  $\sum_{t=1}^L \bar{n}^{(t,c)} = \hat{B}_c$  then
9:        $c \leftarrow c + 1$ 
10:      end if
11:    end while
12:    if  $D_{NO,l}(\bar{\mathbf{n}}) < \hat{D}$  and  $c > C$  then
13:      no solution can be found.
14:    end if
15:  end for
```

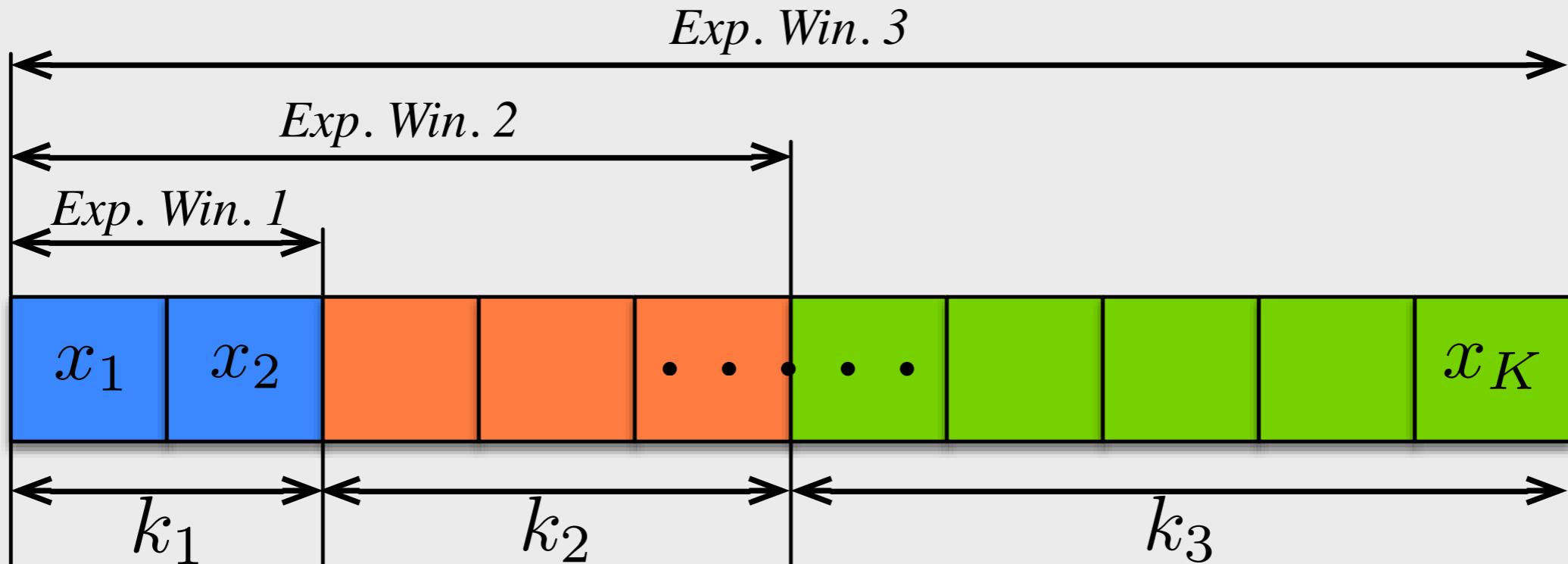
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Requires a no. of steps  
 $\leq \sum_{t=1}^C \hat{B}_t$

# EW-MA Model



- Consider the EW delivery mode

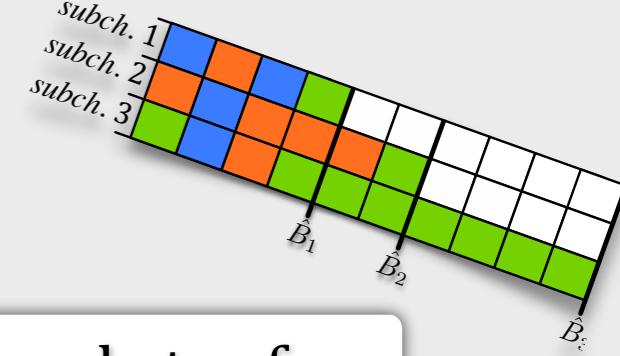


- We define the indicator variable

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

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

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

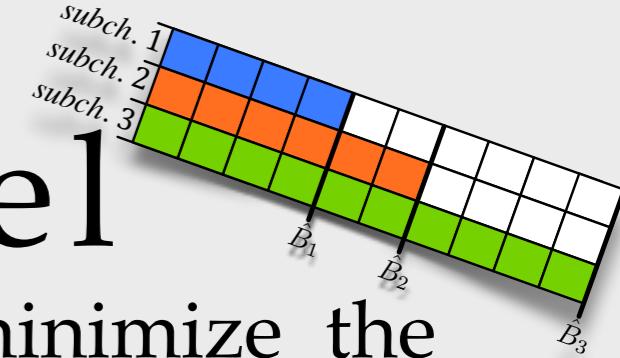
subject to  $\sum_{u=1}^U \mu_{u,l} \geq U \hat{t}_l \quad l = 1, \dots, L \quad (2)$

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

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

- 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.

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

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

Model for a SA pattern as:

**Cost** - No. of transmissions needed

$$\left/ \sum_{l=1}^L N^{(l)} \right. \quad (1)$$

subject to

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

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

- We can refer to the previous heuristics.

## 3. Analytical Results



# Analytical Results (*part 1*)

- LTE-A eMBMS scenarios
- We compared the proposed strategies with the Maximum Likelihood Rate Transmission strategy

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

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

It is a maximization of the sum of the user QoS

- 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
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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

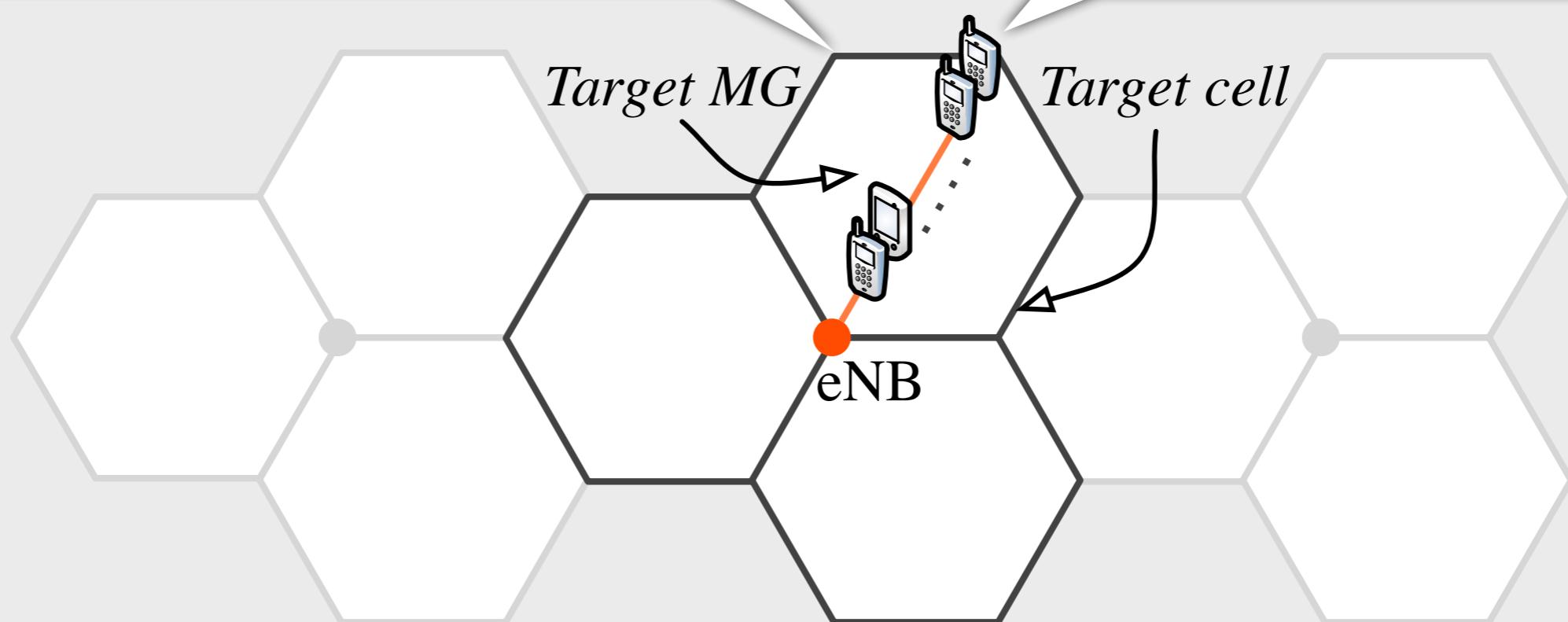
$$\rho(u) = \begin{cases} \max_{l=1, \dots, L} \left\{ \text{PSNR}_l \ D_{\text{NO},l}^{(u)} \right\}, & \text{for NO-RNC} \\ \max_{l=1, \dots, L} \left\{ \text{PSNR}_l \ D_{\text{EW},l}^{(u)} \right\}, & \text{for EW-RNC} \end{cases}$$



# Analytical Results (part 1)

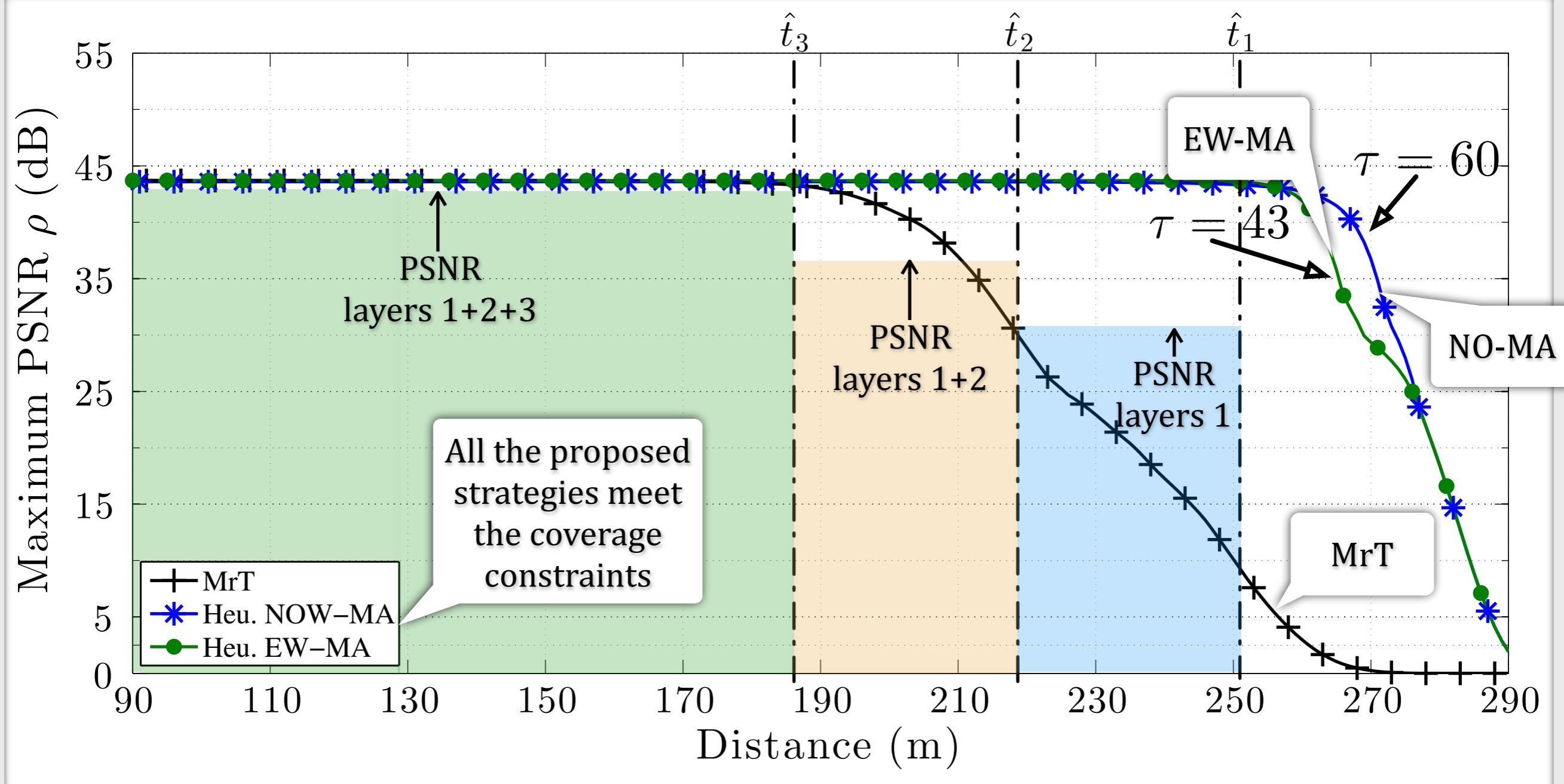
Scenario with a high heterogeneity. 80 UEs equally spaced and placed along the radial line representing the symmetry axis of one sector of the target cell

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

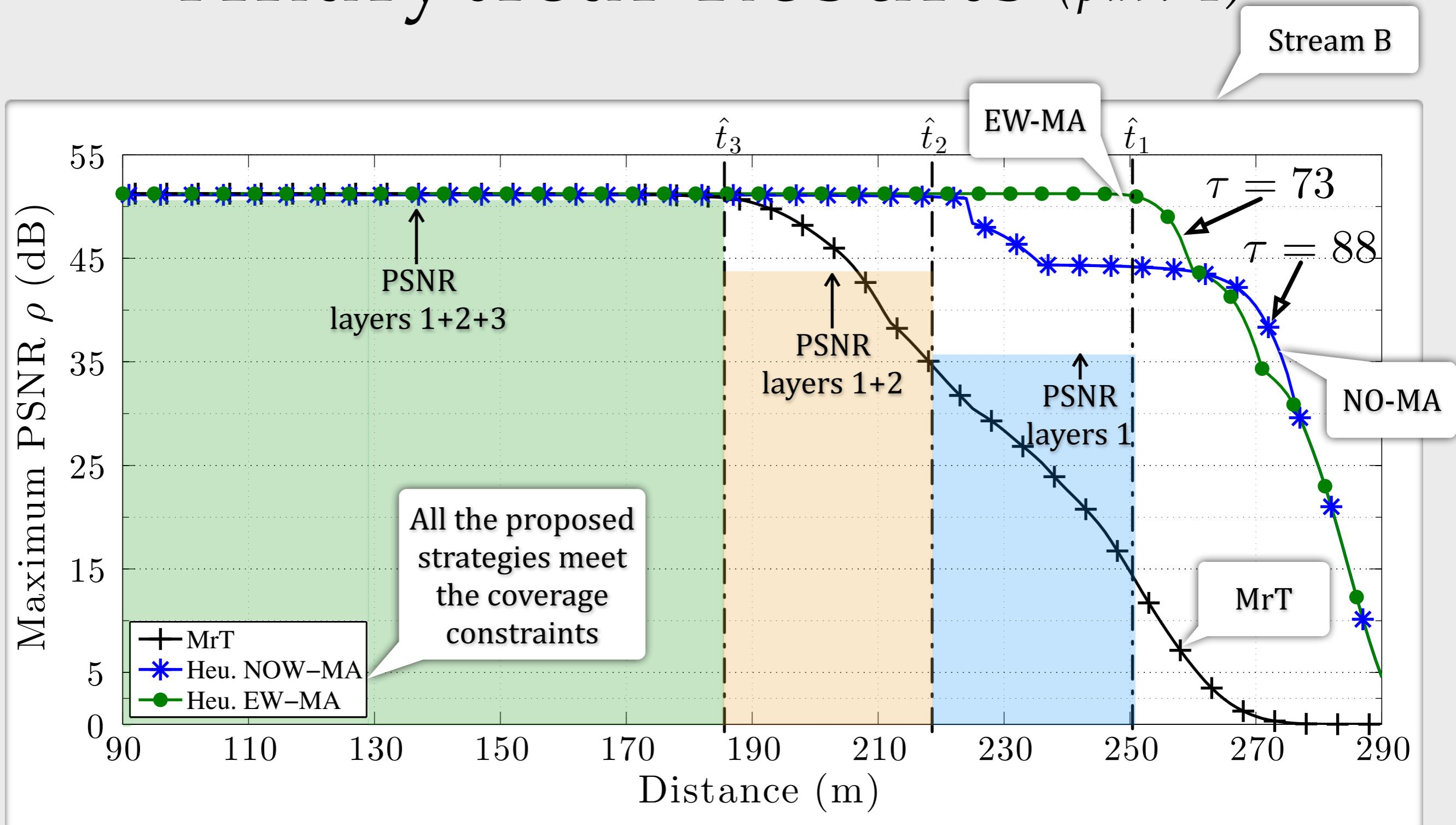


# Analytical Results (part 1)

Stream A



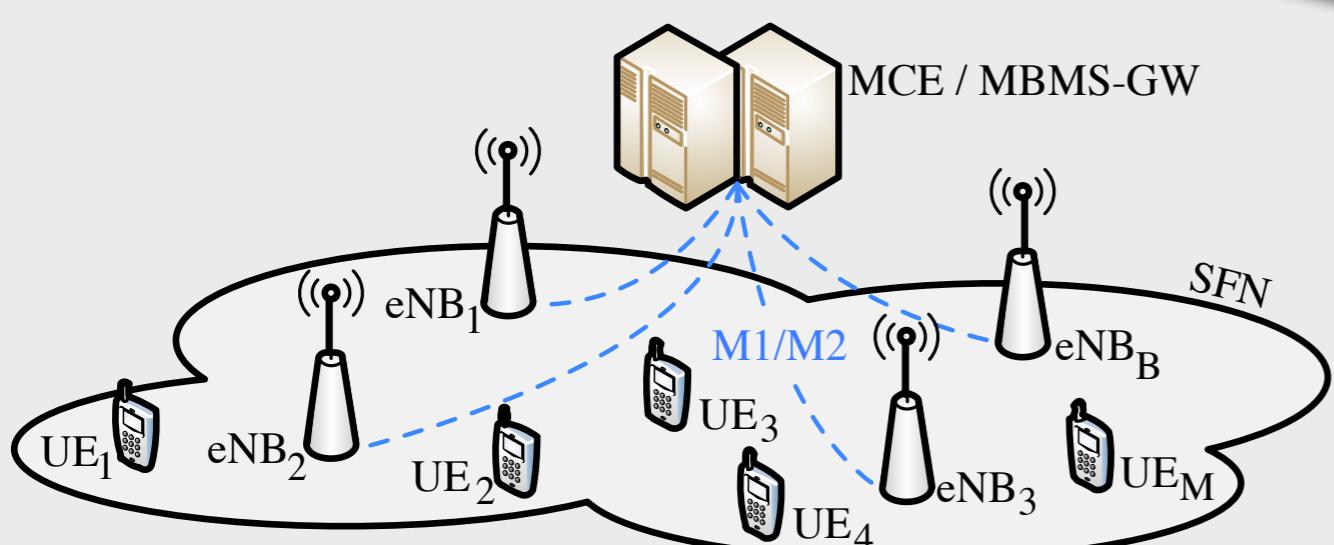
# Analytical Results (part 1)



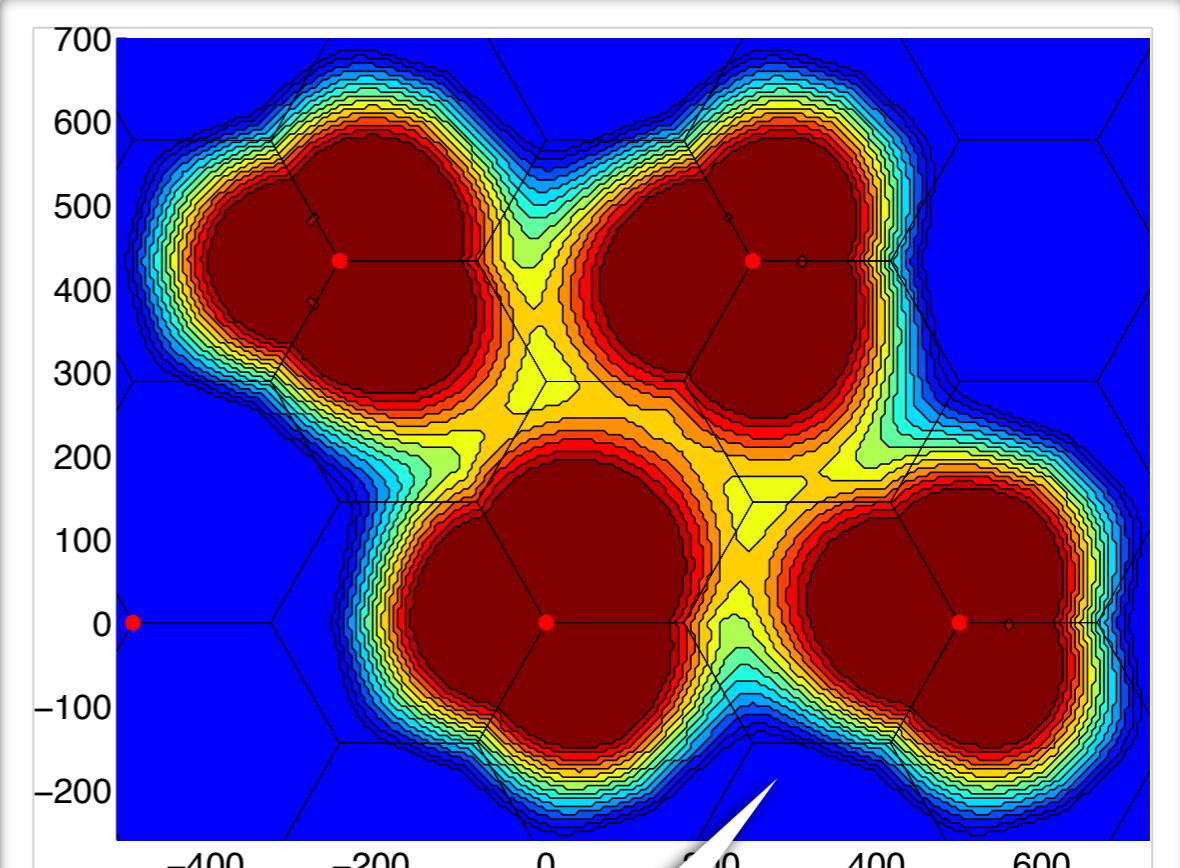
# Analytical Results (*part 2*)

- 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.



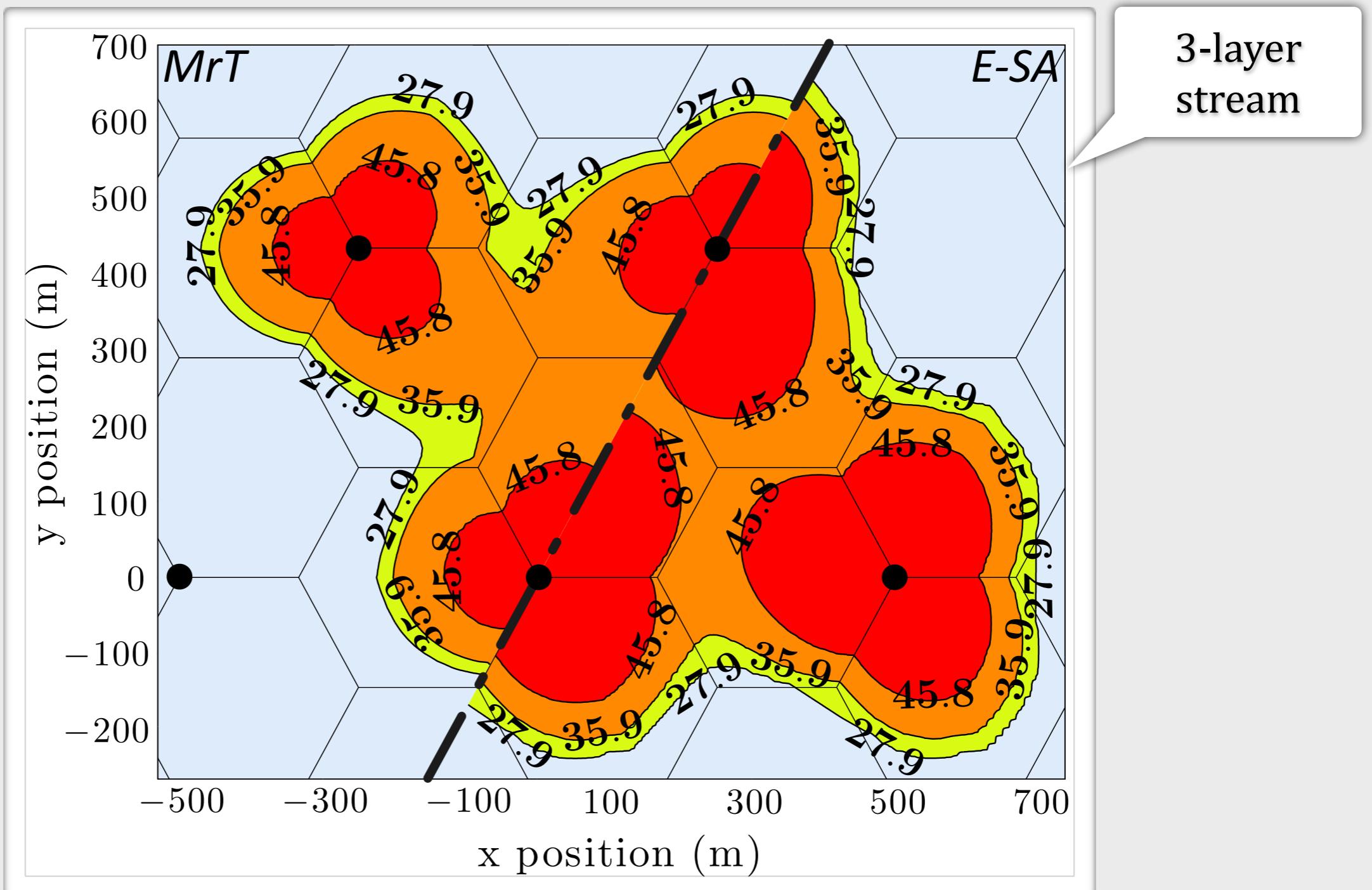
Single Frequency Network



Spacial SINR distribution



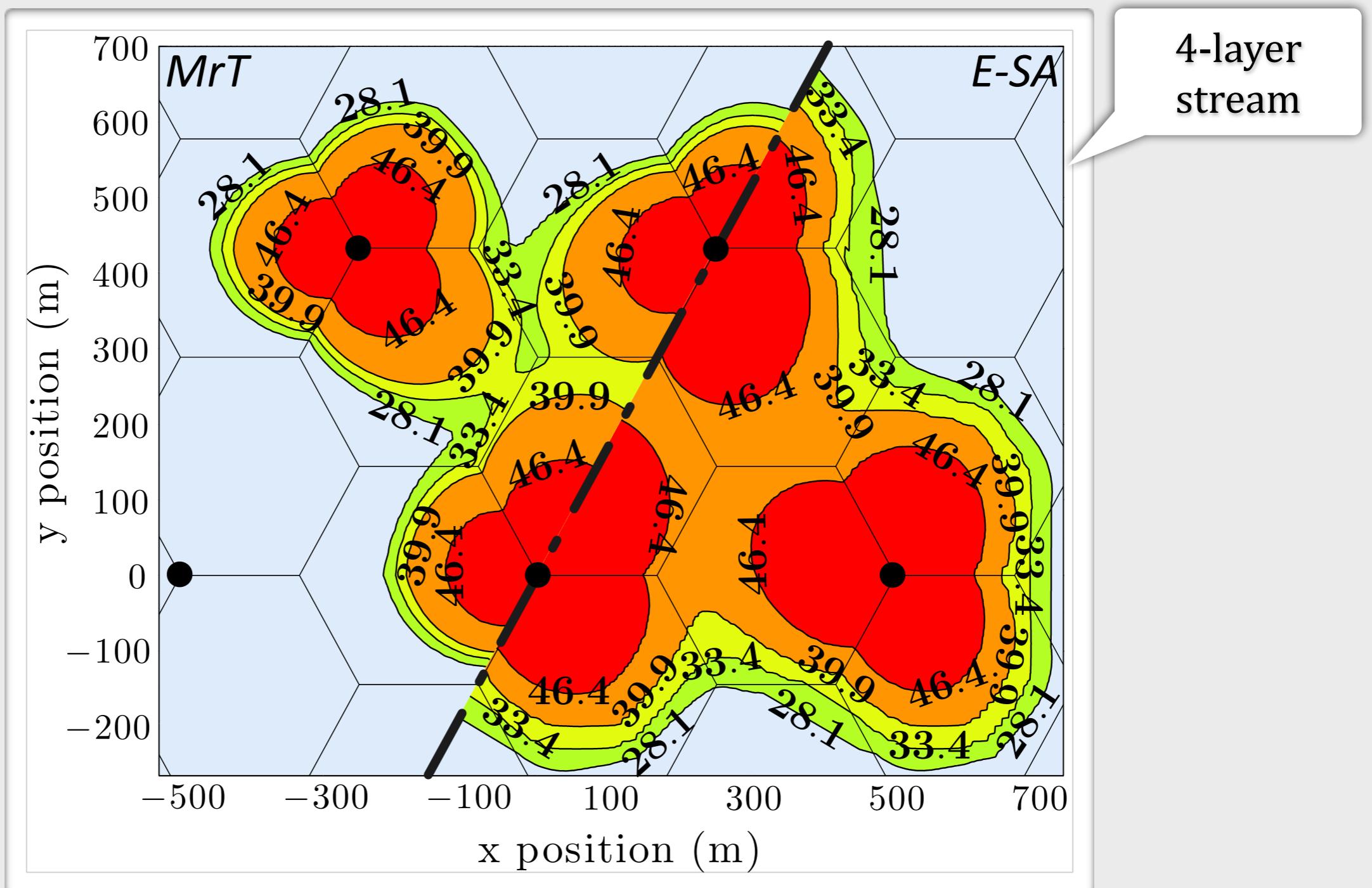
# Analytical Results (part 2)



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



# Analytical Results (part 2)



- 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

**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  $\ell$ -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.

pe. Inoltre, la disponibilità di trasmettere contenuti in più strati (4G) consentirà di aumentare le prestazioni di rete per i servizi multimediali. Ad esempio, nel 2013 il 53% del traffico mobile mondiale era costituito da contenuti video, mentre nel 2018 si prevede che questo valore raggiunga il 67% [1]. Considerando gli sviluppi recenti delle reti di comunicazione di quarta generazione (4G), una notevole frazione di servizi multimediali è prevista

the coded packets by via independent P2P UEP RLNC strategy fields only, network layers may depend on [24], [25] refers to a node is in charge of packets to a single received packets to page is not received, is transmitted. The encoding process in a single P2P

to a typical coding operations, this paper process and the view the RLNC fully integrated communication in terms of the of the delivered consider layered UEP RLNC based scheme generic link the case of K model, in order to source allocation refers to the island. The allocating multimedia the same to next

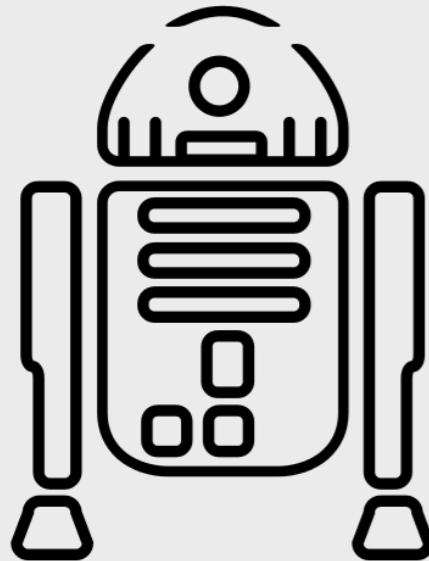
**For more information**  
<http://arxiv.org/abs/1411.5547>  
**or**  
<http://goo.gl/Z4Y9YF>

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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Bristol, 5<sup>th</sup> February 2015