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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 Frameworks for Network-coded Layered Multimedia Multicast Services

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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** achieve 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.

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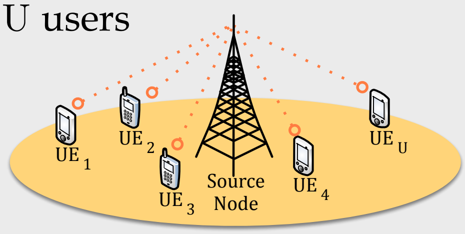
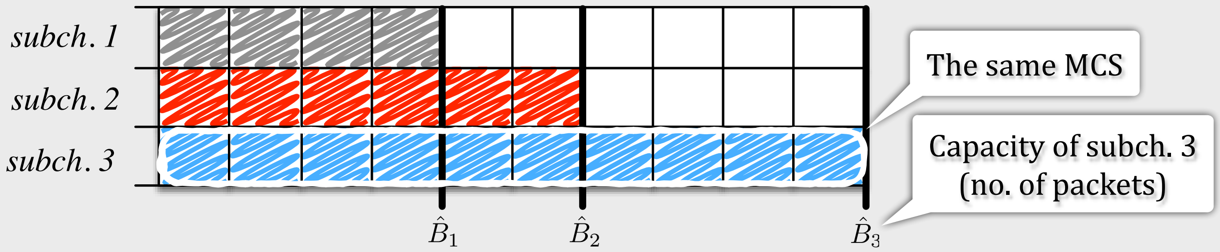
1. System Parameters and Performance Analysis

System Model

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



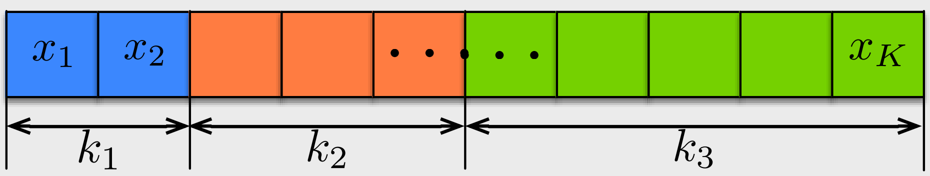
- Each PtM layered service is delivered through C orthogonal broadcast erasure subchannels



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

Non-Overlapping Layered RNC

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



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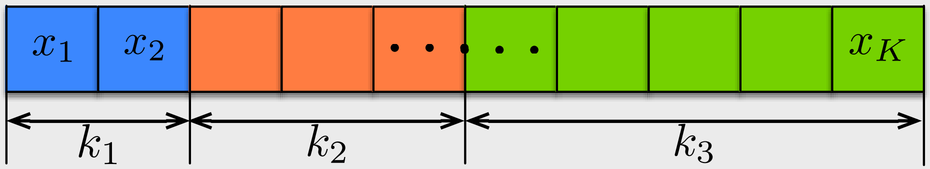


- Encoding performed over each service layer independently from the others.

- 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

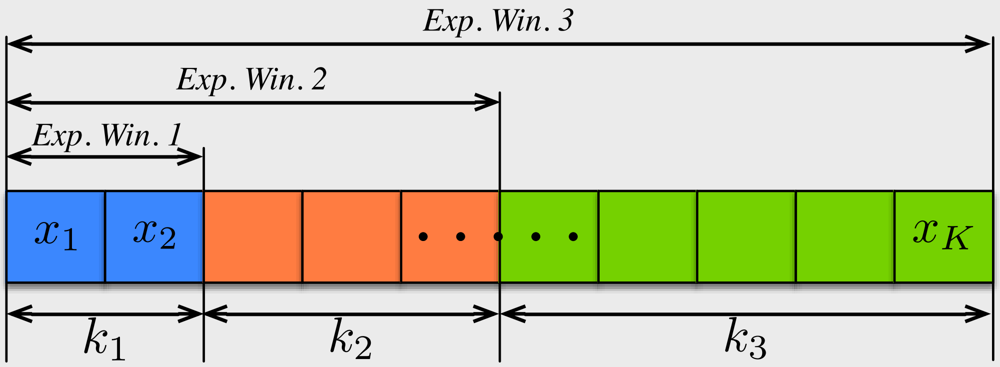
$$= \sum_{r=k_l}^{n_{l,u}} \binom{n_{l,u}}{r} p^{n_{l,u}-r} (1-p)^r \underbrace{\prod_{i=0}^{k_l-1} \left[1 - \frac{1}{q^{r-i}}\right]}_{h(r)}$$

- 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

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

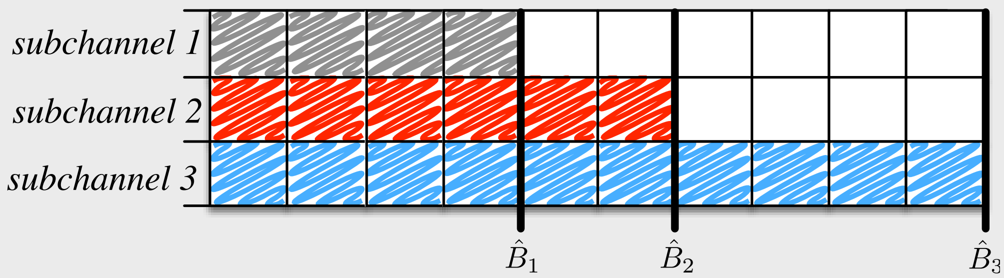
Prob. of receiving $\mathbf{r} = \{r_1,\ldots,r_l\}$ out of $\mathbf{N}_u$ coded symbols

Prob. of decoding window l

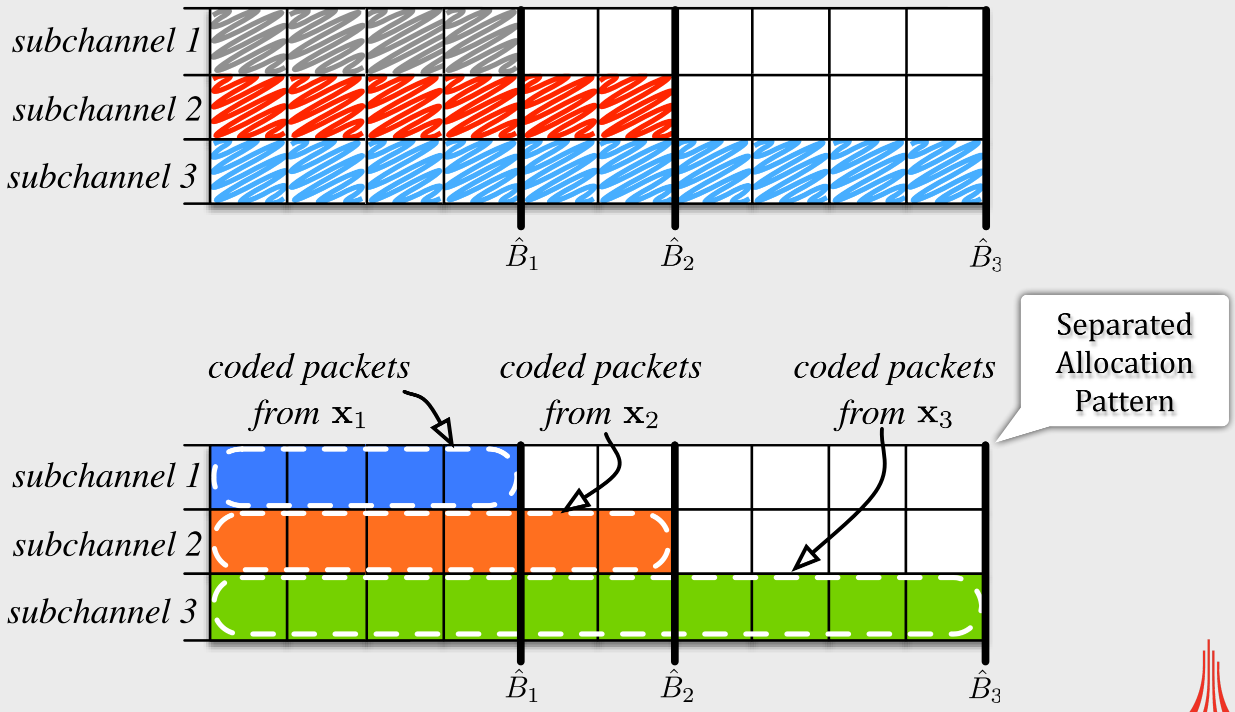
- Sums allow us to consider all the possible combinations of received coded packets

2. Multi-Channel Resource Allocation Models and Heuristic Strategies

Allocation Patterns



Allocation Patterns



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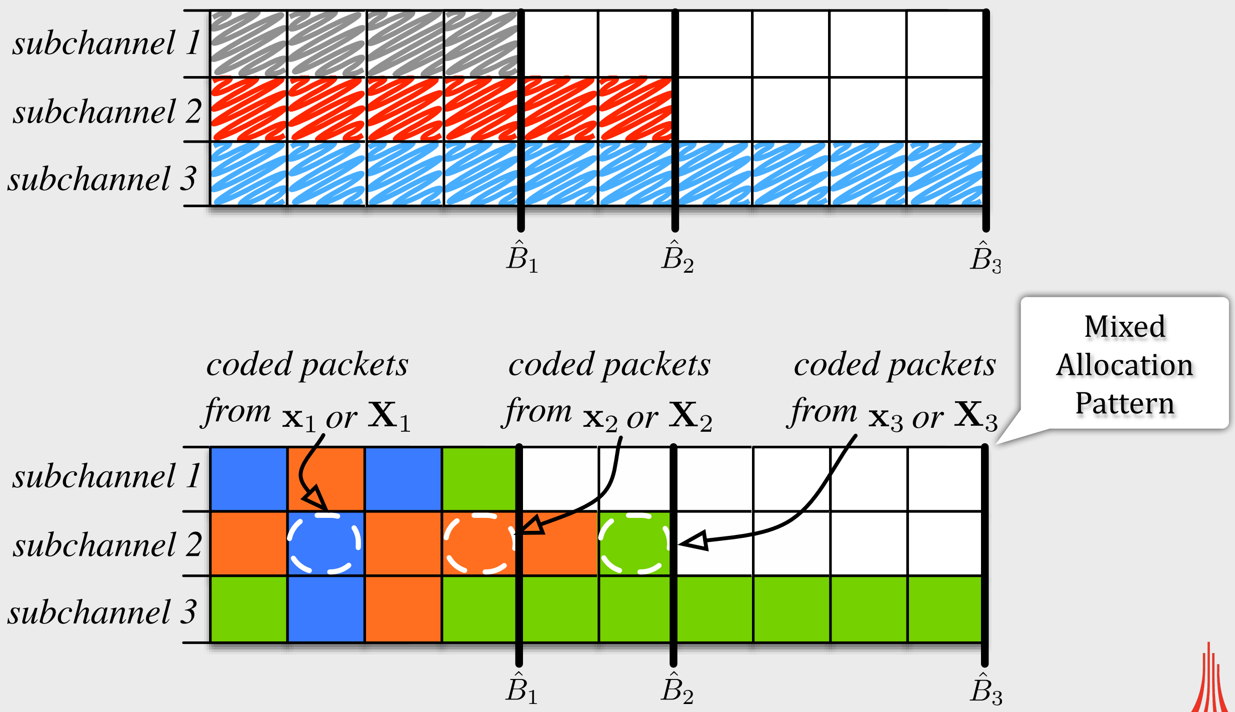

NO-SA Model

- 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.

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- The RA problem for the NO-SA case is

No. of packets of layer l delivered over c

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

Minimization of resource footprint

12

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

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

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

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

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

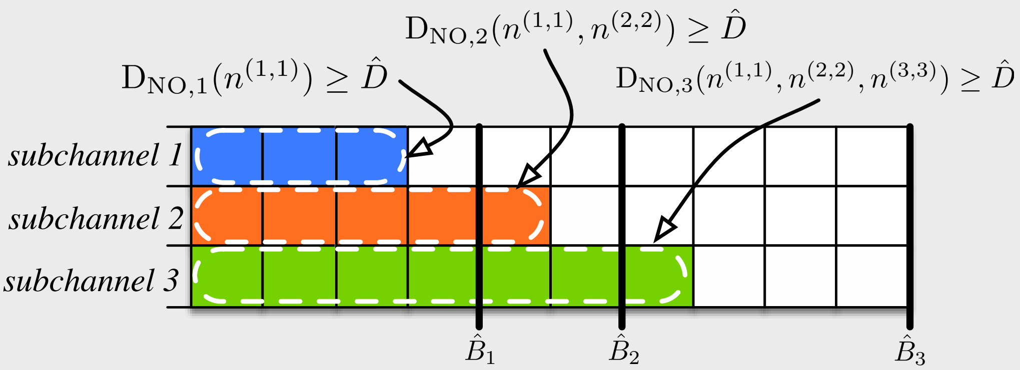
- The **first step** selects the value of m_c such that packets delivered through it are received at least with a target prob. by $U \cdot \hat{t}_c$ users.

Step 1 Subchannel MCSs optimization.

$c \leftarrow C$
$v \leftarrow m_{\text{MAX}}$ 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 $n^{(1,c)}, \dots, n^{(L,c)}$ and can be summarised as follows



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

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

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

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)} && \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} && \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)\\
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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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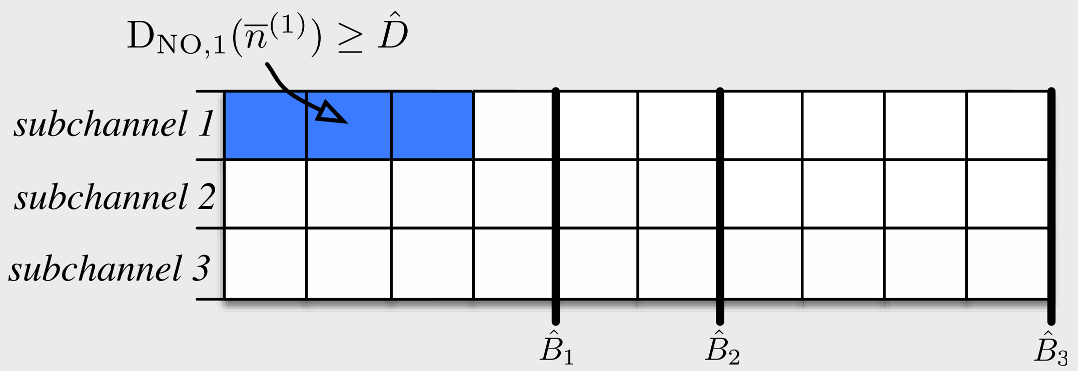

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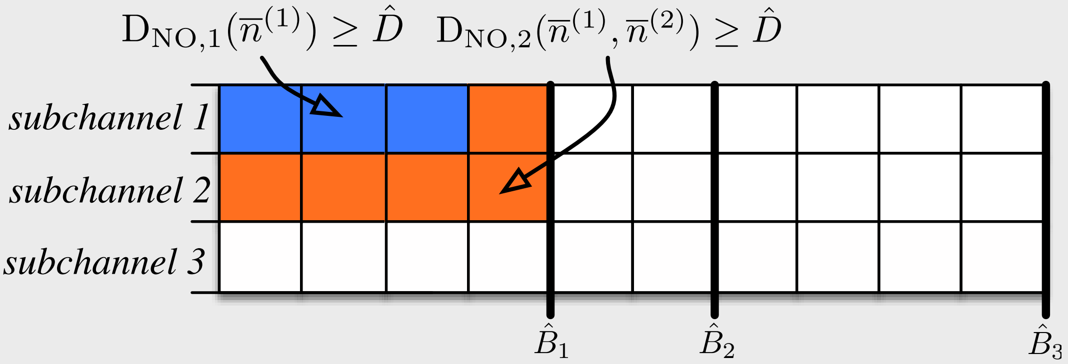

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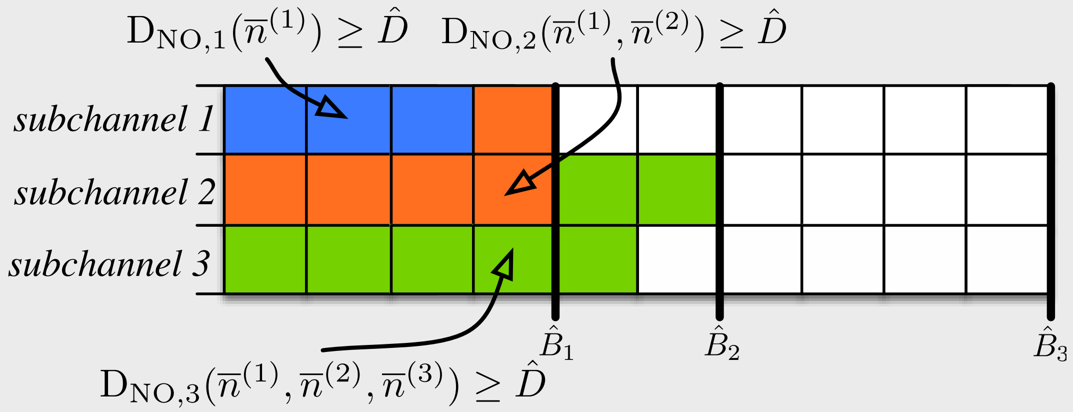

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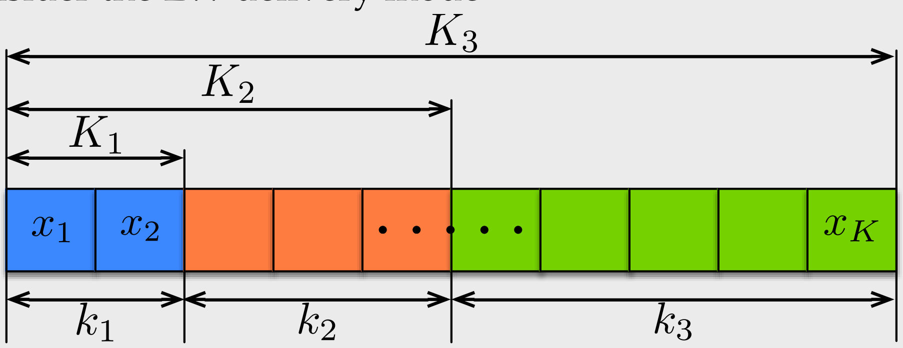
Step 2 Coded packet allocation for a the NO-MA case.

$c \leftarrow 1$
$\overline{n}^{(l,c)} \leftarrow 1$ 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-SA case is

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

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

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

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

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

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

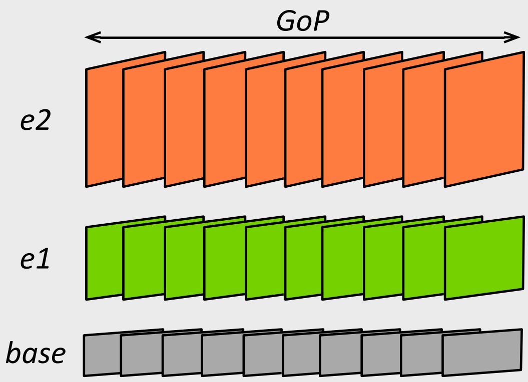
3. H.264/SVC Service Delivery over eMBMS Networks

Layered Video Streams

Video streams formed by multiple video layers:

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

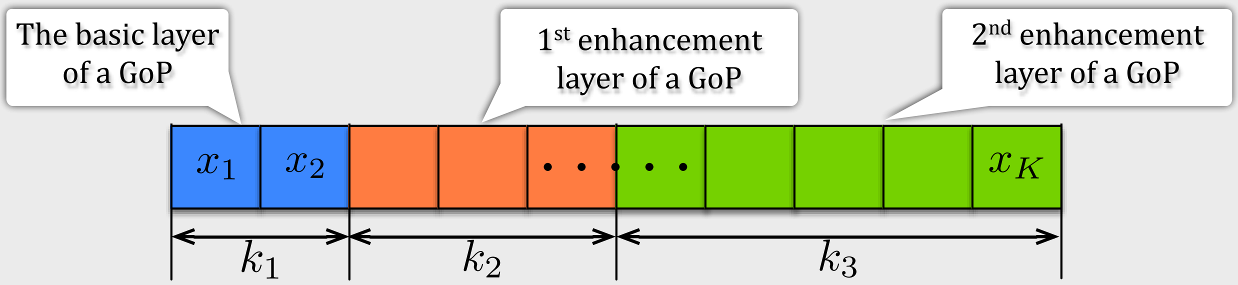
Considering a H.264/SVC video stream



- it is a GoP stream
- a GoP has fixed number of frames
- it is characterised 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

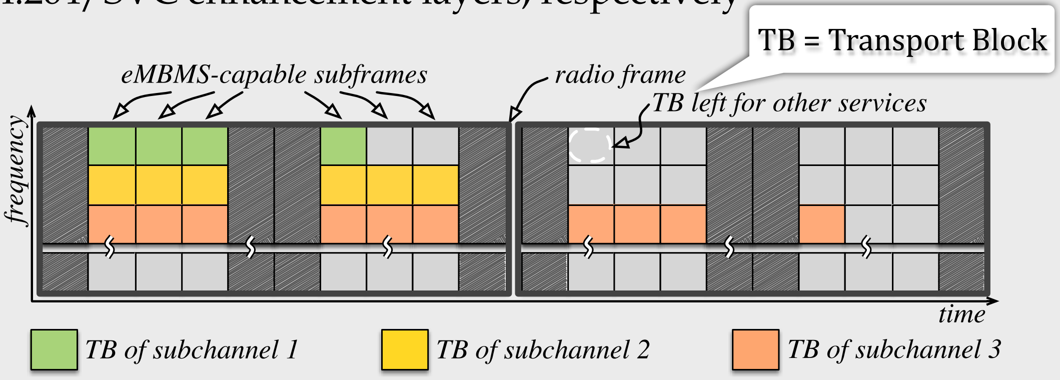
Time duration of a GoP

$$k_l = \left\lceil \frac{R_l \, d_{\text{GoP}}}{H} \right\rceil$$

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 formed by L different layers to the target MG
- The first and the L-th layers represents the basic and L-1 H.264/SVC enhancement layers, respectively



3. Analytical Results

Analytical Results

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

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

It is a maximisation of the sum of the user QoS

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

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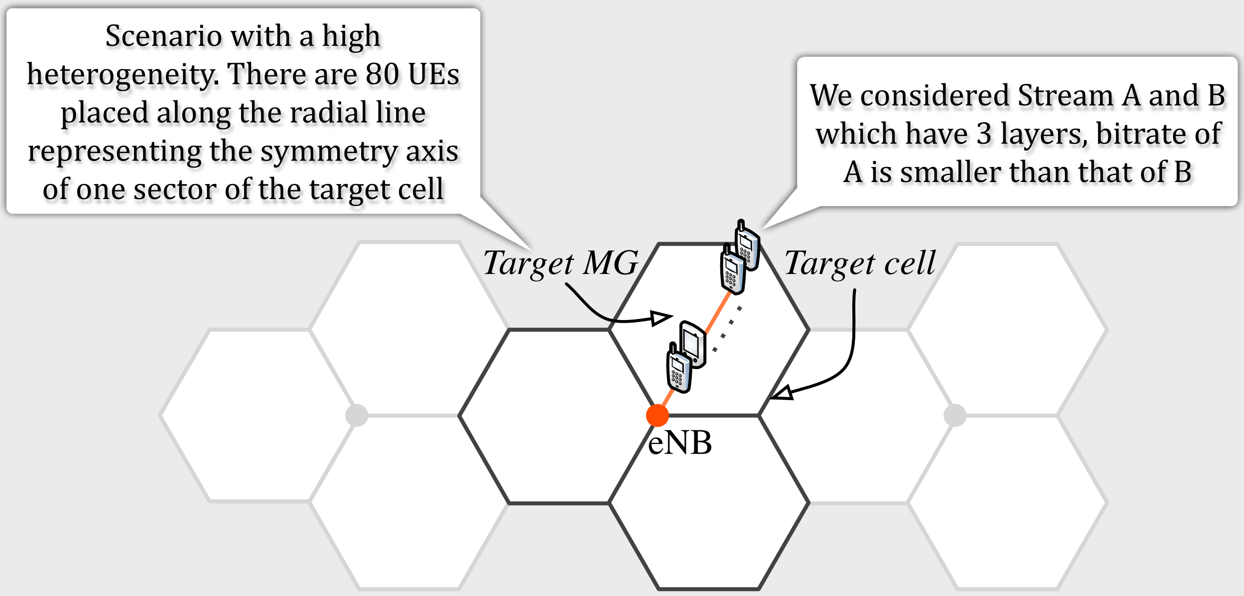
PSNR after recovery of the basic and the first l enhancement layers

- System performance was evaluated in terms of

QoS

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

Analytical Results



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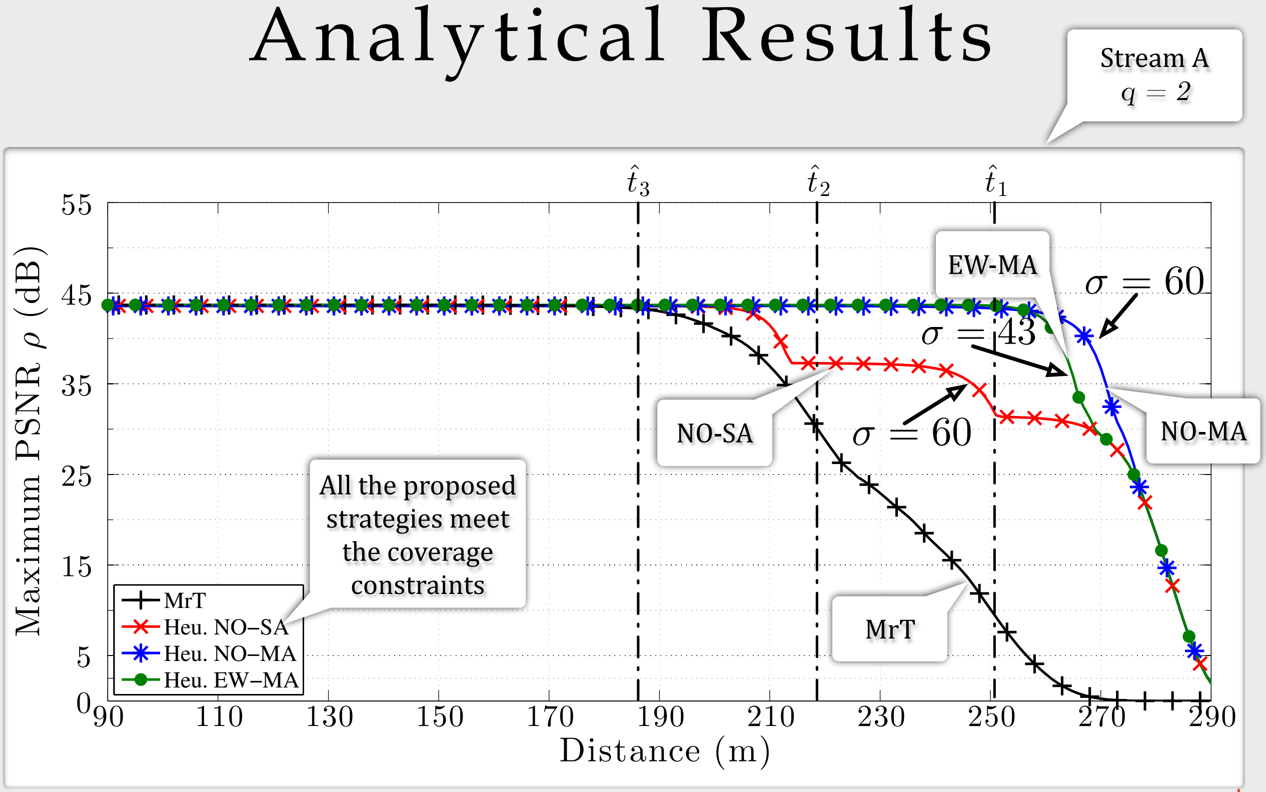

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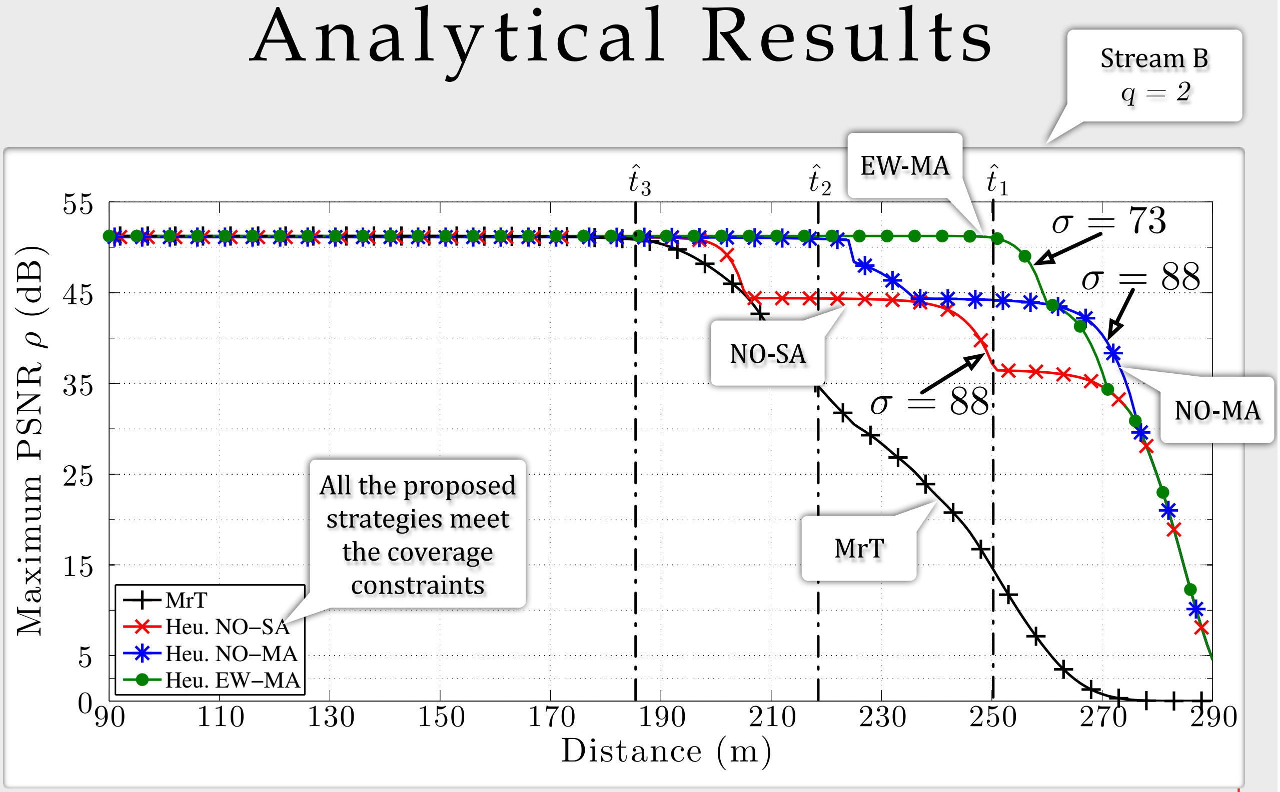

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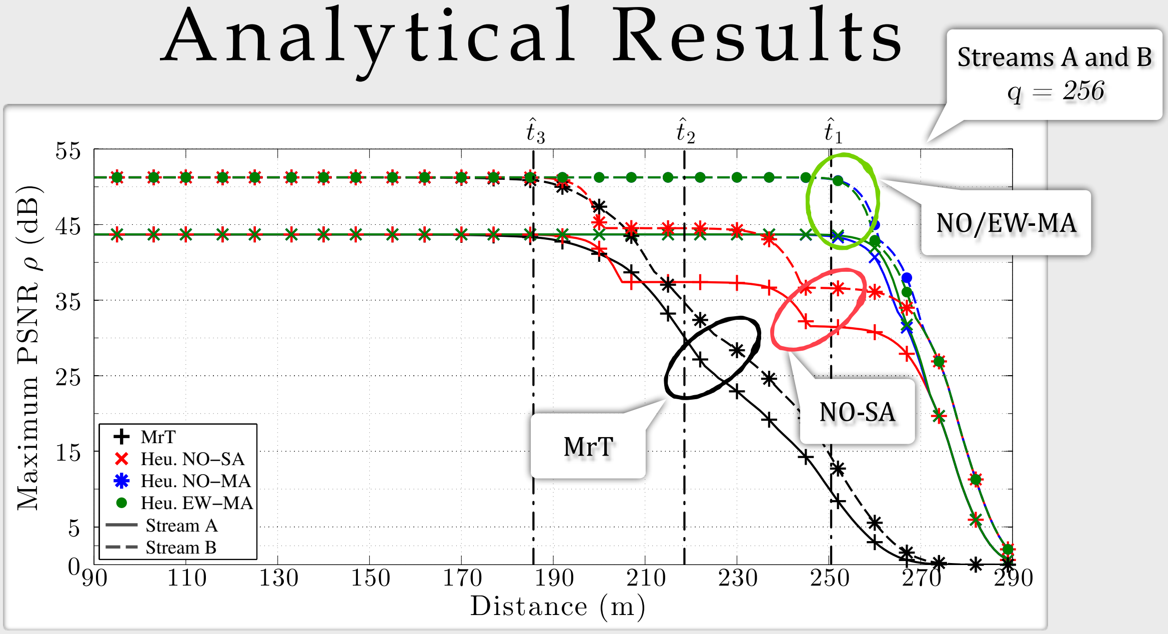


- The **NO-MA** and **EW-MA strategies are equivalent** both in terms of resource footprint and service coverage
- The service coverage of NO-SA still diverges from that of NO-MA and EW-MA.

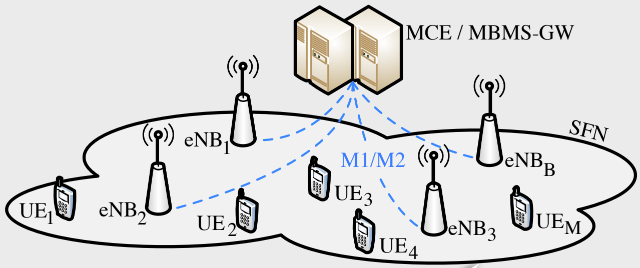
4. Concluding Remarks and Future Extensions

Concluding Remarks

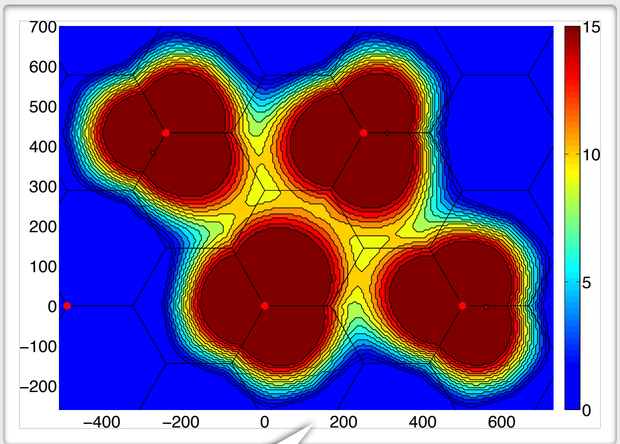
- **Generic system model** that can be easily adapted to practical scenarios has been presented
- Derivation of the **theoretical framework to assess user QoS**
- **Definition of efficient resource allocation frameworks**, that can jointly optimise both system parameters and the error control strategy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

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 does not need of HO procedures.



Single Frequency Network



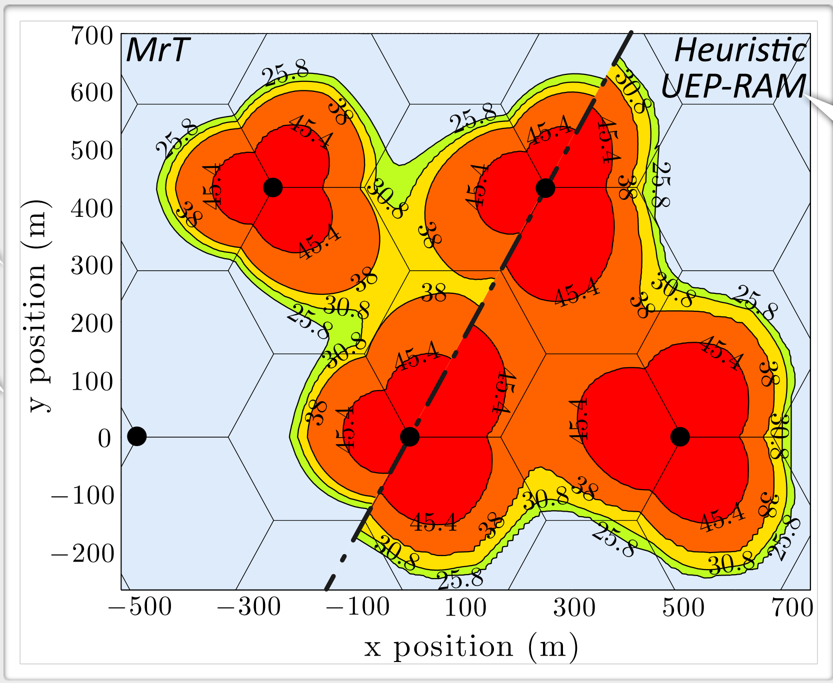
Distribution of the maximum acceptable user MCSs

Future Extensions

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

Each colour represents the number of recovered video layers

4 video layers



EW-based strategy

Thank you for
your attention

These slides are available at
http://lancs.ac.uk/~tassi/talks/ucl.pdf

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