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.
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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

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

\[ x_1 \quad x_2 \quad \cdots \quad \cdots \quad x_K \]

\[ k_1 \quad k_2 \quad k_3 \]

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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.

- 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

\[
P_l(n_{l,u}) = \sum_{r=k_l}^{n_{l,u}} \binom{n_{l,u}}{r} p^{n_{l,u}-r} (1 - p)^r h(r)
\]

The probability that user \( u \) recover the first \( l \) service layers is

\[
D_{NO,l}(n_{1,u}, \ldots, n_{L,u}) = D_{NO,l}(n_u) = \prod_{i=1}^{l} P_i(n_{i,u})
\]
Expanding Window Layered RNC

- We define the $l$-th window $X_l$ as the set of source packets belonging to the first $l$ service layers. Namely, $X_l = \{x_j\}_{j=1}^{K_l}$, 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:

$$D_{EW,l}(N_1,u, \ldots, N_L,u) = D_{EW,l}(N_u) = \sum_{r_1=0}^{N_1,u} \cdots \sum_{r_{l-1}=0}^{N_{l-1},u} \sum_{r_l=r_{\min,l}}^{N_{l,u}} \binom{N_1,u}{r_1} \cdots \binom{N_l,u}{r_l} p \sum_{i=1}^{l} (N_i,u - r_i) (1 - p) \sum_{i=1}^{l} r_i \quad gl(r)$$

Prob. of decoding window $l$

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

Sums allow us to consider all the possible combinations of received coded packets.
2. Multi-Channel Resource Allocation Models and Heuristic Strategies
Allocation Patterns

subchannel 1
subchannel 2
subchannel 3

\( B_1 \) \( B_2 \) \( B_3 \)
Allocation Patterns

subchannel 1
subchannel 2
subchannel 3

\[ \hat{B}_1 \quad \hat{B}_2 \quad \hat{B}_3 \]

*Separated Allocation Pattern*

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Mixed Allocation Pattern

Allocation Patterns

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Consider the variable $\lambda_{u,l} = I\left(D_{NO,l}(n_u) \geq \hat{D}\right)$. 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

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

The RA problem for the NO-SA case is

\[
\text{(NO-SA)} \quad \min_{m_1, \ldots, m_C} \sum_{l=1}^{L} \sum_{c=1}^{C} n^{(l,c)} \sum_{n(1,c), \ldots, n(L,c)}^{m_1, \ldots, m_C} \text{subject to } \sum_{l=1}^{L} \sum_{c=1}^{C} n^{(l,c)} \leq \hat{D} \]

Minimization of resource footprint

No. of packets of layer \( l \) delivered over \( c \)
NO-SA Model

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

The RA problem for the NO-SA case is

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

subject to

\[
\sum_{u=1}^{U} \lambda_{u,l} \geq U \hat{t}_l \quad l = 1, \ldots, L
\]
NO-SA Model

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

- The RA problem for the NO-SA case is

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

subject to

$$\sum_{u=1}^{U} \lambda_{u,l} \geq U \, \hat{t}_l \quad l = 1, \ldots, L$$

$$m_{c-1} < m_c \quad c = 2, \ldots, L$$

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

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

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:
  1. MCSs optimisation \((m_1, \ldots, m_C)\)
  2. 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.

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 \(|U^{(m_c)}| \geq U \cdot \hat{t}_c\) or \(v < m_{\text{min}}\)
8: \(c \leftarrow c - 1\)
9: end while

---
NO-SA Heuristic

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

\[
\begin{align*}
D_{\text{NO},1}(n^{(1,1)}) &\geq \hat{D} \\
D_{\text{NO},2}(n^{(1,1)}, n^{(2,2)}) &\geq \hat{D} \\
D_{\text{NO},3}(n^{(1,1)}, n^{(2,2)}, n^{(3,3)}) &\geq \hat{D}
\end{align*}
\]

**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 \( D_{\text{NO},l}(n^{(1,1)}, \ldots, n^{(l,l)}) < \hat{D} \) do
4: \( n^{(l,l)} \leftarrow n^{(l,l)} + 1 \)
5: end while
6: end for

Requires a no. of steps
\[
\leq \sum_{t=1}^{L} (\hat{B}_t - k_t + 1)
\]
NO-MA Model

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

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

subject to

\[
\sum_{u=1}^{U} \lambda_{u,l} \geq U \hat{t}_l \quad l = 1, \ldots, L \quad (2)
\]

\[
m_{c-1} < m_c \quad c = 2, \ldots, L \quad (3)
\]

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

\[
n^{(l,c)} = 0 \quad \text{for } l \neq c \quad (5)
\]
The NO-SA problem can be easily extended to the MA pattern by removing the last constraint

\[
\begin{align*}
\text{(NO-MA)} & \quad \min_{m_1, \ldots, m_C} \sum_{l=1}^L \sum_{c=1}^C n(l,c) \\
\text{(NO-SA)} & \quad \text{subject to } \sum_{u=1}^U \lambda_{u,l} \geq U \hat{t}_l \quad l = 1, \ldots, L \\
& \quad m_{c-1} < m_c \quad c = 2, \ldots, L \\
& \quad 0 \leq \sum_{l=1}^L n(l,c) \leq \hat{B}_c \quad c = 1, \ldots, C \\
& \quad n(l,c) = 0 \quad \text{for } l \neq c
\end{align*}
\]
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.
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.

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

\[
D_{NO,1}(\bar{m}^{(1)}) \geq \hat{D}
\]

\[
\begin{array}{c}
\text{subchannel 1} \\
\text{subchannel 2} \\
\text{subchannel 3}
\end{array}
\]

\[
\begin{array}{c}
\hat{B}_1 \\
\hat{B}_2 \\
\hat{B}_3
\end{array}
\]
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

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

\[
D_{NO,1}(\bar{n}^{(1)}) \geq \hat{D} \quad D_{NO,2}(\bar{n}^{(1)}, \bar{n}^{(2)}) \geq \hat{D}
\]
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

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

\[
D_{\text{NO,1}}(n^{(1)}) \geq \hat{D} \quad D_{\text{NO,2}}(n^{(1)}, n^{(2)}) \geq \hat{D}
\]

- For subchannel 1:
  \[
  D_{\text{NO,1}}(n^{(1)}) \geq \hat{D}
  \]

- For subchannel 2:
  \[
  D_{\text{NO,2}}(n^{(1)}, n^{(2)}) \geq \hat{D}
  \]

- For subchannel 3:
  \[
  D_{\text{NO,3}}(n^{(1)}, n^{(2)}, n^{(3)}) \geq \hat{D}
  \]
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
- The idea behind the second step can be summarised as follows

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

\[
\begin{align*}
1: & \quad c \leftarrow 1 \\
2: & \quad \overline{n}^{(l,c)} \leftarrow 1 \text{ for any } l = 1, \ldots, L \text{ and } c = 1, \ldots, C \\
3: & \quad \overline{n} = \{\overline{n}^{(l)}\}_{l=1}^{L}, \text{ where } \overline{n}^{(l)} \leftarrow 1 \text{ for any } l = 1, \ldots, L \\
4: & \quad \textbf{for } l \leftarrow 1, \ldots, L \textbf{ do} \\
5: & \quad \quad \textbf{while } D_{NO,l}(\overline{n}) < \hat{D} \text{ and } c \leq C \textbf{ do} \\
6: & \quad \quad \quad \overline{n}^{(l,c)} \leftarrow \overline{n}^{(l,c)} + 1 \\
7: & \quad \quad \quad \overline{n}^{(l)} \leftarrow \sum_{t=1}^{C} \overline{n}^{(l,t)} \text{ for any } l = 1, \ldots, L \\
8: & \quad \quad \quad \textbf{if } \sum_{t=1}^{L} \overline{n}^{(t,c)} = \hat{B}_c \textbf{ then} \\
9: & \quad \quad \quad \quad c \leftarrow c + 1 \\
10: & \quad \quad \textbf{end if} \\
11: & \quad \textbf{end while} \\
12: & \quad \textbf{if } D_{NO,l}(\overline{n}) < \hat{D} \text{ and } c > C \textbf{ then} \\
13: & \quad \quad \text{no solution can be found.} \\
14: & \quad \textbf{end if} \\
15: & \quad \textbf{end for}
\]

Requires a no. of steps 
\[
\leq \sum_{t=1}^{C} \hat{B}_t
\]
Consider the EW delivery mode

We define the indicator variable

\[ \mu_{u,l} = I \left( \bigvee_{t=l}^{L} \{ D_{EW,t}(N_u) \geq \hat{D} \} \right) \]

User \( u \) will recover the first \( l \) service layers (at least) with probability \( \hat{D} \) if any of the windows \( l, l+1, \ldots, L \) are recovered (at least) with probability \( \hat{D} \)
The RA problem for the EW-MA case is

(EW-MA) \[ \min_{m_1, \ldots, m_C} \sum_{l=1}^{L} \sum_{c=1}^{C} N^{(l,c)} \] subject to \[ \sum_{u=1}^{U} \mu_{u,l} \geq U \hat{t}_l \quad l = 1, \ldots, L \] \[ m_{c-1} < m_c \quad c = 2, \ldots, L \] \[ 0 \leq \sum_{l=1}^{L} N^{(l,c)} \leq \hat{B}_c \quad c = 1, \ldots, C \]

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

The basic layer of a GoP

1st enhancement layer of a GoP

2nd enhancement layer of a GoP

- Hence, the $k_l$ can be defined as

$$k_l = \left[ \frac{R_l}{H} \frac{d_{GoP}}{H} \right]$$

Bitrate of the video layer

Time duration of a GoP

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

![Diagram showing eMBMS-capable subframes, radio frame, TB left for other services, TB of subchannel 1, TB of subchannel 2, TB of subchannel 3]
3. Analytical Results
Analytical Results

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

\[ \max_{m_1, \ldots, m_L} \sum_{u=1}^{U} \text{PSNR}_u \]

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

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

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

\[ \max_{m_1, \ldots, m_L} \sum_{u=1}^{U} \text{PSNR}_u \]

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

\[ \rho(u) = \begin{cases} 
\max_{l=1, \ldots, L} \{ \text{PSNR}_l \ D_{\text{NO},l}^{(u)} \}, & \text{for NO-RNC} \\
\max_{l=1, \ldots, L} \{ \text{PSNR}_l \ D_{\text{EW},l}^{(u)} \}, & \text{for EW-RNC} 
\end{cases} \]

PSNR after recovery of the basic and the first \( l \) enhancement layers.
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.
Analytical Results

Maximum PSNR $\rho$ (dB)

Distance (m)

- MrT
- Heu. NO-SA
- Heu. NO-MA
- Heu. EW-MA

PSNR layers 1+2+3
PSNR layers 1+2
PSNR layers 1

All the proposed strategies meet the coverage constraints

Stream A
$q = 2$

$\hat{t}_1$
$\hat{t}_2$
$\hat{t}_3$

$\tau = 60$
$\tau = 43$

NO-SA
NO-MA
EW-MA
MrT
Analytical Results

Stream B $q = 2$

All the proposed strategies meet the coverage constraints.
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

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

Thank you for your attention
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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.
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
System Model

๏ We adopted this convention

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

๏ Reception of a coded packet is \textbf{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

Minimize the total amount of radio resources

Finite field size $q$

Total TB transmissions $\sigma$
Results at a Glance

Minimize the total amount of radio resources

A predetermined fraction of users achieves a certain service level
Expanding Window Layered RNC

Owing to the lack of an accurate expression for \( g_\ell(r) \), we approximate it as

\[
g_\ell(r) \approx h \left( \sum_{i=1}^{l} r_i \right) = \prod_{i=0}^{l-1} \left[ 1 - \frac{1}{q(\sum_{i=1}^{l} r_i)^{-i}} \right]
\]

In other words, we say that

The prob. of recovering the \( \ell \)-th window given
\( r = \{r_1, r_2, \ldots, r_l\} \)

\( \equiv \)

The prob. of recovering the \( \ell \)-th window given
\( r = \{0, 0, \ldots, \sum_{i=1}^{l} r_i\} \)
Expanding Window Layered RNC
Expanding Window Layered RNC

\[ K_3 \]

\[ K_2 \]

\[ K_1 \]

\[ x_1 \]

\[ x_2 \]

\[ \ldots \]

\[ \ldots \]

\[ x_K \]

\[ k_1 \]

\[ k_2 \]

\[ k_3 \]

\[ r_1 \]

\[ r_{\text{min},2} \]
Expanding Window Layered RNC

\[ x_1 \quad x_2 \quad \ldots \quad \ldots \quad \ldots \quad x_K \]

\[ k_1 \quad k_2 \quad k_3 \]

\[ r_1 \quad r_2 \quad r_3 \]

\[ r_{\text{min,3}} \]
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

$$D_{EW,l}(N_1,u, \ldots, N_L,u) = D_{EW,l}(N_u)$$

$$= \sum_{r_1=0}^{N_1,u} \cdots \sum_{r_{l-1}=0}^{N_{l-1},u} \sum_{r_l=r_{\min,l}}^{N_l,u} \binom{N_1,u}{r_1} \cdots \binom{N_l,u}{r_l} p \sum_{i=1}^{l} (N_i,u - r_i) (1 - p)^{\sum_{i=1}^{l} r_i} g_l(r)$$

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

Prob. of decoding window $l$
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

\[
D_{EW,l}(N_1,u, \ldots, N_L,u) =
\]

\[
= D_{EW,l}(N_u)
\]

\[
= \sum_{r_1=0}^{N_1,u} \cdots \sum_{r_{l-1}=0}^{N_{l-1},u} \sum_{r_l=r_{\min,l}}^{N_{l},u} \binom{N_1,u}{r_1} \cdots \binom{N_{l},u}{r_l} \sum_{i=1}^{l} (N_i,u - r_i) \left( 1 - p \right) \sum_{i=1}^{l} r_i g_l(r)
\]

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

\[
r_{\min,l} = \begin{cases} 
K_1 & \text{for } l = 1 \\
K_l - K_{l-1} + \max(r_{\min,l-1} - r_{l-1}, 0) & \text{for } l > 2
\end{cases}
\]
Expanding Window Layered RNC

Owing to the lack of an accurate expression for $g_l(r)$, 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 $K_3 = 15$
The maximum performance gap is smaller than \(0.017\) for \(q=2\). The gap becomes negligible for larger values of \(q\).
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 $|\mathcal{U}(m_c)| \geq U \cdot \hat{t}_c$

  \[ u \in \mathcal{U}(m_c) \text{ if } M(u) \geq m_c \]

**Step 1** Subchannel MCSs optimization.

1: $c \leftarrow C$
2: $v \leftarrow m_{\text{MAX}}$ and
3: **while** $c \geq 1$ **do**
4: \hspace{1em} **repeat**
5: \hspace{2em} $m_c \leftarrow v$
6: \hspace{2em} $v \leftarrow v - 1$
7: \hspace{1em} **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-SA Heuristic

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

\[
D_{NO,1}(n^{(1,1)}) \geq \hat{D} \\
D_{NO,2}(n^{(1,1)}, n^{(2,2)}) \geq \hat{D} \\
D_{NO,3}(n^{(1,1)}, n^{(2,2)}, n^{(3,3)}) \geq \hat{D}
\]

**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** \( D_{NO,l}(n^{(1,1)}, \ldots, n^{(l,l)}) < \hat{D} \) **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 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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\[
D_{NO,1}(n^{(1)}) \geq \hat{D} \quad D_{NO,2}(n^{(1)}, n^{(2)}) \geq \hat{D}
\]

\[
D_{NO,3}(n^{(1)}, n^{(2)}, n^{(3)}) \geq \hat{D}
\]
NO-MA Heuristic

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

1. \( c \leftarrow 1 \)
2. \( \bar{n}^{(l,c)} \leftarrow 1 \) for any \( l = 1, \ldots, L \) and \( c = 1, \ldots, C \)
3. \( \bar{n} = \{ \bar{n}^{(l)} \}_{l=1}^L \), where \( \bar{n}^{(l)} \leftarrow 1 \) for any \( l = 1, \ldots, L \)
4. for \( l \leftarrow 1, \ldots, L \) do
5. \[ \text{while } D_{NO,l}(\bar{n}) < \hat{D} \text{ and } c \leq C \] do
6. \[ \bar{n}^{(l,c)} \leftarrow \bar{n}^{(l,c)} + 1 \]
7. \[ \bar{n}^{(l)} \leftarrow \sum_{t=1}^{C} \bar{n}^{(l,t)} \text{ for any } l = 1, \ldots, L \]
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 \( D_{NO,l}(\bar{n}) < \hat{D} \text{ and } c > C \) then
13. no solution can be found.
14. end if
15. end for

Requires a no. of steps \( \leq \sum_{t=1}^{C} \hat{B}_t \)
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 \( \leq \sum_{t=1}^{C} \hat{B}_t \).
3GPP’s LTE is one of the most promising 4G standard for mobile networks. It promises to practically manage PtM service delivery.
LTE/LTE-A Radio Resources

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

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

1 TTI = 1 ms
10 TTIs per radio frame

- RB (180 kHz × 0.5 ms)
- RBP (180 kHz × 1 ms)
- TB consists of one or more RBPs

Radio frame
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
LTE-A Radio Resources

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![Diagram of eMBMS subframes]

- 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:

\[
\text{MSE} = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} (I_{i,j} - K_{i,j})^2
\]

- Hence, the PSNR can be defined as follows

\[
\text{PSNR} = 10 \log_{10} \left( \frac{I_{\text{MAX}}^2}{\text{MSE}} \right)
\]
Analytical Results

Stream A
\( q = 2 \)
Analytical Results

Stream B
$q = 2$
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.

3 video layers

MrT
- We are extending the theoretical framework.
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3 video layers
EW r.a.
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4 video layers

EW r.a.