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.
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 and Future Extensions
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
Non-Overlapping Layered RNC

- \( x = \{x_1, \ldots, x_K\} \) 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 \( x_l = \{x_i\}_{i=1}^{k_l} \) and will generate a stream of \( n_l \geq k_l \) coded packets \( y = \{y_j\}_{j=1}^{n_l} \), 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 \( q \).

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

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

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

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

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

$$D_{EW,l}(N_{1,u}, \ldots, N_{L,u}) = D_{EW,l}(N_u) = \sum_{r_1=0}^{N_{1,u}} \sum_{r_{l-1}=0}^{N_{l-1,u}} \sum_{r_l=r_{\min,l}}^{N_{l,u}} \frac{N_{1,u}}{r_1} \cdot \frac{N_{l,u}}{r_l} p \sum_{i=1}^{l} (N_{i,u} - r_i) (1-p)^{\sum_{i=1}^{l} r_i} g_l(r)$$

- 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

$\hat{B}_1$ $\hat{B}_2$ $\hat{B}_3$
Allocation Patterns

Subchannel 1
Subchannel 2
Subchannel 3

B_1  B_2  B_3

Coded packets from x_1
Coded packets from x_2
Coded packets from x_3

Separated Allocation Pattern

Allocation Patterns

Subchannel 1
Subchannel 2
Subchannel 3

B_1  B_2  B_3

Coded packets from x_1 or X_1
Coded packets from x_2 or X_2
Coded packets from x_3 or X_3

Mixed Allocation Pattern
**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

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

**Minimization of resource footprint**

No. of packets of layer $l$ delivered over $c$
NO-SA Model

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

\[
\begin{align*}
\text{(NO-SA)} & \quad \min_{m_1, \ldots, m_C} \sum_{l=1}^{L} \sum_{c=1}^{C} n^{(l,c)} \\
\text{subject to} & \quad \sum_{u=1}^{U} \lambda_{u,l} \geq U \hat{t}_l & l = 1, \ldots, L
\end{align*}
\]

In the context of the NO-SA model, the variables $n^{(l,c)}$ represent the target fraction of users, and $U$ is the number of users. Each service level shall be achieved by a predetermined fraction of users.

Dynamic- and system-related constraints

Because of the SA pattern

Because of the SA pattern

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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 optimisation** \((n^{1,c}, \ldots, n^{L,c})\)

- 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.

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**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. \(c \leftarrow c - 1\)
4. **end while**

---

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

1. **for** \(l \leftarrow 1, \ldots, L\) **do**
2. \(n^{(l,t)} \leftarrow k_l\)
3. **while** \(D_{\text{NO},1}(n^{(1,1)}, \ldots, n^{(l,t)}) < \hat{D}\) **do**
4. \(n^{(l,t)} \leftarrow n^{(l,t)} + 1\)
5. **end while**
6. **end for**

\[\sum_{t=1}^{L} (\hat{B}_t - k_t + 1)\]
The NO-SA problem can be easily extended to the MA pattern by removing the last constraint.

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

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-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:

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

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

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

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

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

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EW-MA Model

- Consider the EW delivery mode

![Diagram of EW-MA Model]

- We define the indicator variable

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

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 \( \hat{D} \)

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The RA problem for the EW-SA case is

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

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 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

![Diagram of GoP stream with layers](image)

- 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

![Diagram of GoP stream with layers](image)

- Hence, the $k_l$ can be defined as

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

- 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 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

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

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

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

Resource footprint

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 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

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

Scenario with a high heterogeneity. There are 80 UEs 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
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We considered Stream A and B which have 3 layers, bitrate of A is smaller than that of B.

Analytical Results
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Stream A
q = 2

All the proposed strategies meet the coverage constraints.

Maximum PSNR ρ (dB)
Distance (m)

0 5 10 15 20 25 30 35 40 45 50 55
90 110 130 150 170 190 210 230 250 270 290

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

EW-MA
σ = 60

NO-SA
σ = 43

NO-MA
σ = 60

MrT
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.

![Diagram of Single Frequency Network](image)

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.
Thank you for your attention

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

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