De la coordination optimale d’interférence sur le lien montant

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Context of Satellite Uplink scheduling

Figure: System Architecture

- Multi-beam GEO satellite and its **centralized** gateway
- **DVB-RCS2** Access Method: **MF-TDMA + Demand Assigned Multiple Access (DAMA)**
- **2 polarizations**
Satellite Networks Specificities

- Path-loss (distance) quasi identical for all sat-users.
- Inter-beam/cell isolation:
  1. Cellular: distance from antenna (fading)
  2. Satellite: Angular separation (Highly directive antenna)

Cellular Uplink

Cell a Rx:
\[ P_{1Ga}(d_1) + P_{2Ga}(d_2) + P_{3Ga}(d_3) \]

Satellite Return Link

Beam a Rx:
\[ P_{1Ga}(\alpha_{1,a}) + P_{2Ga}(\alpha_{2,a}) + P_{3Ga}(\alpha_{3,a}) \]
Challenges

Interference Management

- Current systems: Interference Isolation + Estimation.
  \[\Rightarrow 4\text{-}\text{colors} \text{ scheme on 2 polarizations}\]

- 2-colors? Fractional Frequency Reuse?
  \[\rightarrow \text{Interferences are too high.}\]

- Individual Interference coordination needed
Objectives and Obstacles

▶ Question:
  ▶ What is the capacity upper bound with a 2-colors scheme?

⇒ Optimization problem

▶ Difficulties:
  1. Non-linear constraints (SNIR)
  2. Large data sets:
     ▶ ~100 beams
     ▶ ~20 carriers
     ▶ hundreds of users per beam
Principles of our approach

Principles:

- An empty slot may be profitable
- Value the throughput, not the SNIR (i.e. the highest usable MCS)
  - Discretized utility values
  - High (and often useless) SNIR margins are not encouraged
Problem formulation

\[ \text{Maximize} \quad \sum_{k,i_k} \sum_{t,c,m} x_{i_k,m}^{t,c} r_m \]

\[ \forall k, t, c \quad \sum_{i_k,m} x_{i_k,m}^{t,c} \leq 1 \]

\[ \forall k, i_k, t \quad \sum_{c,m} x_{i_k,m}^{t,c} \leq 1 \]

\[ \forall k, i_k, m, t, c \quad x_{i_k,m}^{t,c} \cdot \frac{P_{i_k} G_k(i_k)}{\Gamma_{\text{thresh}}^m} \geq (x_{i_k,m}^{t,c} - 1) \cdot B + N + \sum_{k' \neq k} \sum_{j_{k'}, m'} x_{j_{k'}, m'}^{t,c} \cdot P_{j_{k'}} G_k(j_{k'}) \]

\[ \forall k, i_k, m, t, c \quad x_{i_k,m}^{t,c} \in \{0, 1\} \quad \text{Decision variable for user } i_k \text{ of beam } k \text{ MCS } m, \text{ for RB } (t,c) \]
Problem formulation

Maximize \[ \sum_{k, i_k} \sum_{t, c, m} x_{i_k, m}^{t, c} r_m \]

\[ \forall k, t, c \sum_{i_k, m} x_{i_k, m}^{t, c} \leq 1 \]

\[ \forall k, i_k, t \sum_{c, m} x_{i_k, m}^{t, c} \leq 1 \]

\[ \forall k, i_k, m, t, c \quad x_{i_k, m}^{t, c} \cdot \frac{P_{i_k} G_k(i_k)}{\Gamma_{thresh}^m} \geq (x_{i_k, m}^{t, c} - 1) \cdot B + N + \sum_{k' \neq k} \sum_{j_{k'}, m'} x_{j_{k'}, m'}^{t, c} P_{j_{k'}} G_{k'}(j_{k'}) \]

\[ \forall k, i_k, m, t, c \quad x_{i_k, m}^{t, c} \in \{0, 1\} \] Decision variable for user \( i_k \) of beam \( k \) MCS \( m \), for RB \((t,c)\)

Sum-rate Maximization Objective

Possibility to leave slot empty

1 user per Resource Block

Users are limited to 1 carrier for each timeslot

Discretized SNIR Constraint

Decision variable for user \( i_k \) of beam \( k \) MCS \( m \), for RB \((t,c)\)
Problem formulation

Sum-rate Maximization Objective

\[ \max_x \sum_{k,i_k, t,c,m} x_{i_k,m}^{t,c} r_m \]

Possibility to leave slot empty

\[ \forall k, t, c \quad \sum_{i_k,m} x_{i_k,m}^{t,c} \leq 1 \]

1 user per Resource Block

Users are limited to 1 carrier for each timeslot

\[ \forall k, i_k, t \quad \sum_{c,m} x_{i_k,m}^{t,c} \leq 1 \]

Discretized SNIR Constraint

\[ \forall k, i_k, m, t, c \quad x_{i_k,m}^{t,c} \cdot \frac{P_{i_k}G_k(i_k)}{\Gamma_{\text{thresh}}^m} \geq (x_{i_k,m}^{t,c} - 1) \cdot B + N + \sum_{k' \neq k} \sum_{j_k',m'} x_{j_k',m'}^{t,c} P_{j_k'} G_k(j_k') \]

Decision variable for user \( i_k \) of beam \( k \) MCS \( m \), for RB \( (t,c) \)

From Non-Linear to Integer Linear Program

Problem too large to be solved even for small scenarios

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Decompositions and Simplifications: 3 propositions

1. **Time symmetry**: Capacity maximization will produce $N_{tti}$ identical solutions (independant subproblems)
   $\Rightarrow$ **TSO**: Time-Slot Optimization

2. **Carrier quasi-symmetry**: Sequentially optimize each carrier, with an iterative control on the carrier constraint
   $\Rightarrow$ **seqC-TSO**: sequential Carrier and Time-Slot Optimization

3. **Importance of Neighbors**: No need for global coordination
   $\Rightarrow$ Different ranges of coordination
**Simplification 3: Importance of Neighbors**

- **Rationale:** All neighbors don't contribute at the same level to a beam’s interference.

- **4 coordination ranges:** direct neighbors, 4 most interfering beams, 2nd order beams, and global.

<table>
<thead>
<tr>
<th>Range $s$</th>
<th>Set $\Omega_s(k)$</th>
<th>$I_{est}(s)/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>global</strong></td>
<td>all</td>
<td>$-\infty$ dB</td>
</tr>
<tr>
<td><strong>order $\leq 2$</strong></td>
<td>${a, b, c, d, e, f, g, h, i, j}$</td>
<td>$-15$ dB</td>
</tr>
<tr>
<td><strong>order $\leq 1.5$</strong></td>
<td>${a, b, c, d}$</td>
<td>$-12$ dB</td>
</tr>
<tr>
<td><strong>order 1</strong></td>
<td>${a, b}$</td>
<td>$-7.5$ dB</td>
</tr>
</tbody>
</table>

- **When a beam is not in coordination range,** other beams’ contribution to interference is estimated.
For 18 beams per polarization, 8 carriers, 5 MCS, varying number of users with $\rho = \frac{N_{\text{users}}}{N_{\text{carriers}}}$ per beam.

System throughput loss:
- $\rho = 0.5$: -13%
- $\rho = 1.0$: -4%
- $\rho = 2.0$: -2%

Normalized throughput (%)

User to Sub-carrier Ratio

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Results - Scalability

For 18 beams per polarization, 8 carriers, 5 MCS, constant user to carrier ratio

![Graph showing scalability results.]

**Time-wise decomposition**

**Time-wise + Carrier-wise decomposition**

Carrier count at $\rho = 2.0$
Conclusions

- Using a **2-colors base** scheme with interference coordination can provide up to **60% Capacity gain** compared to the uncoordinated 4-colors scheme.
- Our simplified heuristics can provide high quality solutions for **real scale scenarios**, with a relatively low optimality loss (≈ 6%).
- Next steps:
  - Use various fairness metrics.
  - Design fast algorithms to perform interference-aware scheduling (centralized or decentralized).
  - Combine with advanced interference cancellation techniques (e.g. SIC).
Questions ?
2C vs 4C

Frequency

2 colors

RHCP LHCP

4 colors

Frequency
Model: Uplink SNIR constraint

- **Indexes:**
  - $k$: beam ID
  - $i_k$ or $j_{k'}$: user ID in beam $k$ (resp. $k'$)
  - $t, c$: Resource block ID in the frame, on TTI $t$ and carrier $c$

- **SNIR model for uplink $\forall i_k$:**

\[
SNIR(i_k) = \frac{P_i G_k(i_k)}{N + \sum_{k' \neq k} \sum_{j_{k'}} x^{t,c}_{j_{k'}} P_{j_{k'}} G_k(j_{k'})}
\]

- User $i_k$ transmission power
- Reception Gain of the $k$-th beam for user $i_k$
- Noise power (same for each $c$)
- Indicator of user $j_{k'}$ assigned to RB $(t,c)$
Model: SNIR constraints (continued)

- Changed into (largely inspired from Lopez-Perez¹) \( \forall i_k, \forall m: \)

\[
\frac{P_{i_k} G_k(i_k)}{\Gamma_{m}^{thresh}} \geq N + \sum_{k' \neq k} \sum_{j_{k'}, m'} x_{j_{k'}, m'}^{t, c} P_{j_k'} G_k(j_{k'})
\]

SNIR threshold for MCS \( m \)
Indicator of user \( j_{k'} \) assigned to RB \((t, c)\) with MCS \( m'\)

Results - Larger scenario

For 45 beams per polarization, 30 carriers, 5 MCS, 60 users per beam: solved in $\approx 100 \text{ s}$
Beam a Rx:
\[ P_{1Ga}(\alpha_{1,a}) + P_{2Ga}(\alpha_{2,a}) + P_{3Ga}(\alpha_{3,a}) \]

Beam a Rx:
\[ P_{1Ga}(\alpha_{1,a}) + P_{bGb}(\alpha_{1,b}) + P_{cGc}(\alpha_{1,c}) \]
Beam a Rx:

\[ P_1 G_a(\alpha_{1,a}) + P_2 G_a(\alpha_{2,a}) + P_3 G_a(\alpha_{3,a}) \]
Simplification 2: Carrier quasi-symmetry

- **Rationale:** For high user-to-carrier ratio (high loads), every carrier will be filled to maximum capacity.
- **Principle:**
  - Decompose the problem to $N_{\text{carriers}}$ sub-problems
  - Problems are solved sequentially for each timeslot:
    - $c=0$: Formulate and solve problem with all users
    - $c=1$: Formulate problem with all users except those assigned during step $c = 0$, solve it.
    - $c=...$: Repeat.
Complete TSO Problem

Problem TSO\( (s) \) :

Maximize \( \sum_{k, i_k} \sum_{c, m} x^c_{i_k, m} r_m \) \hspace{1cm} (1a)

s.t.:

\( \forall k, c \sum_{i_k, m} x^c_{i_k, m} \leq 1 \) \hspace{1cm} (1b)

\( \forall k, i_k \sum_{c, m} x^c_{i_k, m} \leq 1 \) \hspace{1cm} (1c)

\( \forall k, i_k, m, c x^c_{i_k, m} \frac{P_{i_k} G_k(i_k)}{\Gamma_m^{\text{thresh}}} \geq (x^c_{i_k, m} - 1) \cdot B + N \)

\( + I_{\text{est}} + \sum_{k' \in \Omega_s(k)} x^c_{j_{k'}, m'} P_{j_{k'}} G_k(j_{k'}) \) \hspace{1cm} (1d)

\( \forall k, i_k, m, c x^c_{i_k, m} \in \{0, 1\} \) \hspace{1cm} (1e)

where \( r_m \) is the instant throughput of MocCod \( m \).
seqC-TSO Problem

Sub-problem sub-seqC-TSO(s) :

Maximize

\[
\sum_{k, i_k} \sum_{m} x_{i_k, m} r_m
\]

s.t.:

\[
\forall k \sum_{i_k, m} x_{i_k, m} \leq 1
\]

\[
x_{i_k, m} \frac{P_{i_k} G_k(i_k)}{\Gamma_{\text{thresh}}^m} \geq (x_{i_k, m} - 1) \cdot B + N + I_{\text{est}} + \sum_{k' \in \Omega_{s(k)}} x_{j_{k'}, m'} P_{j_{k'}} G_k(j_{k'})
\]

\[
\forall k, i_k, m \quad x_{i_k, m} \in \{0, 1\}
\]