Optimisation of cellular network structure by graph partitioning techniques

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1 Introduction
2 The problem of assigning PCUs in GERAN
3 Other hierarchical structuring problems in cellular networks
4 Conclusions
1 Introduction

- The network management problem
- The network structuring problem

2 The problem of assigning PCUs in GERAN

3 Other clustering problems in cellular networks

4 Conclusions
The network management problem

Services

- CS-Voice
- Gaming
- VoIP
- Streaming
- Web
- PTT

Features

- FH
- HR
- DTX
- DR
- POC

RATs

- P-GSM
- E-GSM
- UTRAN
- WIFI

Operators

- RAN parameters
- KPIs

Subscribers
The network structuring problem

GERAN architecture
The assignment of PCUs in GERAN

1. Introduction

2. The problem of assigning PCUs in GERAN
   - Problem formulation
   - Solution method
   - Analysis over measurement-based network model

3. Other clustering problems in cellular networks

4. Conclusions
The cell re-selection process in GERAN

- **Purpose**: Terminals in idle/packet-transfer mode camp on the strongest cell
- **Algorithm**: \[ C_{1i} = \text{RLA}_i - \text{RxLevAccessMin}_i \]
  \[ C_{2i} = C_{1i} - \text{CellReselectOffset}_i \]
- **Problem**: CRS delay severely affects performance of RT packet-data services
- **Solution**: 1) Network features (P-BCCH, Network Assisted Cell Change, Packet-data HO)
  2) Optimisation of the assignment base stations to PCUs in each BSC
     a) Connect adjacent cells to the same PCU
     b) Keep the load of all PCUs within given limits
Problem formulation

The assignment of PCUs as a graph partitioning problem

- Classical model

Diagram:

\[
\text{(CPAP) Minimise } \|\delta(V_1, \ldots, V_k)\| = \sum_{(i,j) \in \delta(V_1, \ldots, V_k)} \gamma_{ij} \\
\text{subject to } \|V_n\| = \sum_{i \in V_n} \omega_i \leq B_{aw} \\
\max(\|V_1\|, \ldots, \|V_k\|) \leq B_{rw}
\]
Solution method

The assignment of PCUs as a graph partitioning problem

- Adaptation to the cellular environment

1) Spatially consistent solutions ⇒ Connectedness/site constraints
   [no fragmentation/no overlap]

2) Minimum number of network changes ⇒ Re-labelling subdomains
   [maximum service availability]

Disconnected solution

Connected solution

Cell resolution

Site resolution
The assignment of PCUs as a graph partitioning problem

Minimise $\|\delta(V_1, ..., V_k)\| = \sum_{(i,j) \in \delta(V_1, ..., V_k)} \gamma_{ij}$

subject to $\|V_n\| = \sum_{i \in V_n} \omega_i \leq B_{aw}$

$\frac{\max(\|V_1\|, ..., \|V_k\|)}{\min(\|V_1\|, ..., \|V_k\|)} \leq B_{rw}$

$V_1, V_2, ..., V_k$ are connected

$i, j = 1:N_{sites}$

- # users changing PCU
- PCU capacity
- Load imbalance between PCUS
- Connectivity
- Site resolution

$\left\{ \begin{array}{c} \text{Spatial consistency} \end{array} \right.$
Solution method

Classical graph partitioning methods

a) Exact methods
   - Pure brute-force \[ T = O(k|V|) \]
   - Goldschmidt and Hochbaum \[ T = O(|V|^k) \]
   - Branch-and-cut algorithm over ILP model \[ T = O(2^{|V|} + |E|) \]

b) Heuristic methods
   - Geometric methods \[ T = O(|V|) \text{ or } O(|E|) \]
   - Structural methods \[ T = O(|V|) \text{ or } O(|E|) \]

Geometrical method

Structural method
**a) Exact method**

- **General Integer Linear Programming Model (GM)**

\[
\text{(GM)} \quad \text{Min} \quad \sum_{i=1}^{V-1} \sum_{j=i+1}^{V} \gamma_{ij}(1 - \sum_{n=1}^{k} Z_{ijn})
\]

s.t. \[
\sum_{n=1}^{k} X_{in} = 1, \quad \forall i \in V,
\]

\[
\sum_{i=1}^{V} \omega_i X_{in} \leq B_{aw}, \quad \forall n \in N,
\]

\[
\sum_{i=1}^{V} \omega_i X_{im} - B_{rw} \sum_{i=1}^{V} \omega_i X_{in} \leq 0, \quad \forall m, n \in N, m \neq n,
\]

\[
Z_{ijn} \leq X_{in}, \quad \forall (i, j) \in U, n \in N,
\]

\[
Z_{ijn} \leq X_{jn}, \quad \forall (i, j) \in U, n \in N,
\]

\[
Z_{ijn} \geq X_{in} + X_{jn} - 1, \quad \forall (i, j) \in U, n \in N,
\]

\[
X_{in} \in \{0, 1\}, \quad \forall i \in V, n \in N,
\]

\[
Z_{ijn} \in \{0, 1\}, \quad \forall (i, j) \in U, n \in N.
\]
a) **Exact method**

- Compact Integer Linear Programming Model (CM)

\[
(CM) \quad \text{Min} \quad \sum_{(i,j) \in E} \gamma_{ij}(1 - \sum_{n \in N} Z_{ijn})
\]

subject to:

\[
\sum_{n \in N} X_{in} = 1, \quad \forall i \in V,
\]

\[
\sum_{i \in V} \omega_i X_{in} \leq B_{aw}, \quad \forall n \in N,
\]

\[
\sum_{i \in V} \omega_i X_{im} - B_{rw} \sum_{i=1}^{\lfloor V \rfloor} \omega_i X_{in} \leq 0, \quad \forall m, n \in N, m \neq n,
\]

\[
Z_{ijn} \leq X_{in}, \quad \forall (i, j) \in E, n \in N,
\]

\[
Z_{ijn} \leq X_{jn}, \quad \forall (i, j) \in E, n \in N,
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\[
Z_{ijn} \geq X_{in} + X_{jn} - 1, \quad \forall (i, j) \in E, n \in N,
\]

\[
X_{in} \in \{0, 1\}, \quad \forall i \in V, n \in N,
\]

\[
Z_{ijn} \in \{0, 1\}, \quad \forall (i, j) \in E, n \in N.
\]
a) Exact method

- Compact Integer Linear Programming Model with Less Symmetry (CMS)

\[(CMS) \text{ Min } \sum_{(i,j)\in E} \gamma_{ij} - \left( \sum_{j\in V(v)} \gamma_{v,j} X_{j,1} + \sum_{(i,j)\in E-E(v)} \gamma_{ij} \sum_{n=1}^{k} Z_{ijn} \right)\]

s.t. \[\sum_{n=1}^{k} X_{in} = 1, \quad \forall i \in V, i \neq v,\]
\[\sum_{i\in V,i\neq v} \omega_i X_{i,1} \leq B_{aw} - \omega(v),\]
\[\sum_{i\in V} \omega_i X_{in} \leq B_{aw}, \quad \forall n \in N, n \neq 1,\]
\[\sum_{i\in V,i\neq v} \omega_i X_{i,1} + \omega_v - B_{rw} \sum_{i\in V,i\neq v} \omega_i X_{in} \leq 0, \quad \forall n \in N, n \neq 1,\]
\[\sum_{i\in V,i\neq v} \omega_i X_{in} - B_{rw} \left( \sum_{i\in V,i\neq v} \omega_i X_{i,1} + \omega_v \right) \leq 0, \quad \forall n \in N, n \neq 1,\]
\[\sum_{i\in V,i\neq v} \omega_i X_{im} - B_{rw} \sum_{i\in V,i\neq v} \omega_i X_{in} \leq 0, \quad \forall m,n \in N, m,n \neq 1, m \neq n,\]
\[Z_{ijn} \leq X_{in}, \quad \forall (i,j) \in E-E(v), n \in N,\]
\[Z_{ijn} \leq X_{jn}, \quad \forall (i,j) \in E-E(v), n \in N,\]
\[Z_{ijn} \geq X_{in} + X_{jn} - 1, \quad \forall (i,j) \in E-E(v), n \in N,\]
\[X_{in} \in \{0,1\}, \quad \forall i \in V, i \neq v, n \in N,\]
\[Z_{ijn} \in \{0,1\}, \quad \forall (i,j) \in E-E(v), n \in N,\]
a) Exact method

- Classical method

⇒ Branch-and-Cut = Branch-and-Bound + Cutting planes

\[ (IP) \quad \min \ f(X) \]
\[ \text{st.} \quad g_j(X) \leq 0 \]
\[ c_e(X) \leq 0 \]
\[ x_i \in \{0,1\} \quad \forall i \neq 1 \]

Branching

\[ (LP) \quad \min \ f(X) \]
\[ \text{st.} \quad g_j(X) \leq 0 \]
\[ c_e(X) \leq 0 \]

Bounding

\[ (IP) \quad \min \ f(X) \]
\[ \text{st.} \quad g_j(X) \leq 0 \]
\[ c_e(X) \leq 0 \]
\[ x_i = 1 \]
\[ x_i \in \{0,1\} \quad \forall i \neq 1 \]

Branching

\[ (LP) \quad \min \ f(X) \]
\[ \text{st.} \quad g_j(X) \leq 0 \]
\[ c_e(X) \leq 0 \]

Bounding

\[ (IP) \quad \min \ f(X) \]
\[ \text{st.} \quad g_j(X) \leq 0 \]
\[ c_e(X) \leq 0 \]
\[ x_i = 0 \]
\[ x_i \in \{0,1\} \quad \forall i \neq 1 \]
Solution method

a) Exact method

- Refinements to classical method

  1) Initialization with a heuristic solution (i.e., multi-level refinement)

  2) Use of exact method over a set of problem instances with loose runtime constraints

Runtime sharing strategies among problem instances

\[
\begin{align*}
\text{a) Size-based} & \quad T_{ssj} = \frac{|E_j| k_j}{N_p} \cdot T_{ov} \quad \forall j = 1 : N_p, \\
\text{b) Edge-cut based} & \quad T_{esj} = \frac{Q_j}{N_p} \cdot T_{ov} \quad \forall j = 1 : N_p,
\end{align*}
\]
b) Heuristic method

- Classical method \Rightarrow Multi-Level Clustered Adaptive Multi-Start (ML-CAMS)

\[ \begin{align*}
G^{(0)} & \quad \text{Initial partitioning} \\
G^{(1)} & \quad \text{Coarsening} \\
G^{(2)} & \quad \text{Uncoarsening and refinement} \\
G^{(m)} & \quad \text{Kernighan-Lin refinement}
\end{align*} \]

- Sorted Heavy Edge Matching
- Clustered Adaptive Multi-Start
b) Heuristic method

- Classical method $\Rightarrow$ Multi-Level Clustered Adaptive Multi-Start (ML-CAMS)

Stage 2) Initial partitioning by Clustered Adaptive Multi-Start (CAMS)

- Greedy Graph Growing Partitioning
- Random Greedy Graph Growing Partitioning
- Floyd-Warshal Greedy Graph Growing Partitioning
- Single attempt
- Naive Multi-Start
- Adaptive Multi-Start

Distance from global optimum

![Graphs and charts showing different partitioning methods and their edge-cut and optimal values](image-url)
Solution method

b) Heuristic method

- Classical method \(\Rightarrow\) Multi-Level Clustered Adaptive Multi-Start (ML-CAMS)

Stage 2) Initial partitioning by Clustered Adaptive Multi-Start (CAMS)

**Step 0**

Solution set:

\[[1, 2, 2, 3, 1, 3, 3, 4, 4, 4, 5, 4, 4, 1, 5],
[1, 1, 2, 2, 1, 1, 3, 3, 4, 4, 4, 5, 5, 4],
[1, 2, 2, 3, 1, 1, 3, 4, 4, 5, 4, 4, 5, 5],
[1, 2, 2, 3, 1, 3, 3, 4, 4, 5, 4, 4, 5, 5]\]

Matching

\[\{\{1,5\},2,3,4,6,7,8,\{9,10,11,13\},11,12,14,15,16\}\]

**Step 1**

- **Solution set:**

\[[1, 2, 2, 3, 1, 3, 3, 4, 4, 4, 5, 4, 4, 4, 5],
[1, 1, 2, 2, 1, 1, 3, 3, 4, 4, 4, 5, 5, 4],
[1, 2, 2, 3, 1, 1, 3, 4, 4, 5, 4, 4, 5, 5],
[1, 2, 2, 3, 1, 3, 3, 4, 4, 5, 4, 4, 5, 5]\]

Matching

\[\{\{1,5\},2,3,4,6,7,8,\{9,10,11,13\},11,12,14,15,16\}\]

**Step 2**

- **Solution set:**

\[[1, 2, 2, 3, 1, 3, 3, 4, 4, 4, 5, 4, 4, 1, 5],
[1, 1, 2, 2, 1, 1, 3, 3, 4, 4, 4, 5, 5, 4],
[1, 2, 2, 3, 1, 1, 3, 4, 4, 5, 4, 4, 5, 5],
[1, 2, 2, 3, 1, 3, 3, 4, 4, 5, 4, 4, 5, 5]\]

Matching

\[\{\{1,5\},2,3,4,6,7,8,\{9,10,11,12,13,16\},11,\{14,15\}\}\]

**Step N**
b) Heuristic method

- Adaptation to the cellular environment
  1) Control of weight imbalance between subdomains
  2) Enforcement of connected subdomains
  3) Control of the granularity of the assignment
  4) Reduction of the number of changes in the network

\[
\max(\|V_1\|, \ldots, \|V_k\|) \leq B_{rw} \leq \min(\|V_1\|, \ldots, \|V_k\|)
\]

- Connected FM refinement
- Graphs of site resolution
- Re-labelling of subdomains

\[
\text{# articulation vertices} = 4
\]
Analysis over measurement-based network model

Analysis setup

- **Purpose**: Evaluate more sophisticated methods in a wider set of real graphs
- **Scenario**: 61 BSCs (61 CPAP instances)
- **Methodology**: Graph partitioning analysis based on HO stats in NMS

1) **Build problem instances**
   - HO statistics \( \gamma \), GPRS config. (nºPCUs/BSC, #GPRS TSLs/cell) \( k, \omega \)
   - Operator’s constraints \( B_{aw} = 256, B_{rw} = 2 \)

2) **Evaluate CPAP optimisation surface by R-GGGP in isolated instances**
   - Build a distributional model for the local minima values
   - Prove the correlation between the best local minima

3) **Compare proposed and classical methods over the entire instance set**
   - Branch-and-cut in CPLEX, heuristic methods built from scratch

- **Criteria**
  - Total edge-cut \( \Rightarrow \) Total nbr. of inter-PCUs CRs
  - Avg. weight imbalance ratio \( \Rightarrow \) Avg. load imbalance ratio between PCUs
  - Total execution time
## Analysis setup

**Example of BSC Graph**

<table>
<thead>
<tr>
<th></th>
<th>BTS-level</th>
<th>Site-level</th>
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<tbody>
<tr>
<td>$</td>
<td>V</td>
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<tr>
<td>$</td>
<td>E</td>
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<tr>
<td>$k$</td>
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<tr>
<td>$\max(</td>
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<tr>
<td>$\min(</td>
<td>E(i)</td>
<td>)$</td>
</tr>
<tr>
<td>$\max(\omega)$</td>
<td>23.2</td>
<td>9.3</td>
</tr>
<tr>
<td>$\min(\omega)$</td>
<td></td>
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</table>
Analysis over measurement-based network model

Analysis results

1) Optimisation surface

![Optimisation surface graph]

- Gumbel distribution
  - $a = 6.12 \times 10^5$
  - $b = 1.08 \times 10^5$

![Distance from global optimum graph]

- Edge-cut
- Prob
- Avg. distance to other local minima
- Nbr. of attempts
- Distance from global optimum
Analysis over measurement-based network model

Analysis results

2) Exact methods

![Graph showing edge-cut ratio vs. runtime for different methods: BC-SS, BC-ES, R-GGGP (non-conn.), and IO. The graph plots runtime [h] on the x-axis and edge-cut ratio [%] on the y-axis.](image)
Analysis results

3) Heuristic methods

a) Edgecut-runtime tradeoff

Analysis over measurement-based network model
Analysis results

3) Heuristic methods

b) Influence of optimisation constraints ⇒ Network performance
Analysis over measurement-based network model

Analysis results

3) Heuristic methods

b) Influence of optimisation constraints

⇒ Network performance

- Connectedness
- Site granularity

<table>
<thead>
<tr>
<th></th>
<th>Connected</th>
<th>Non-connected</th>
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<tbody>
<tr>
<td>ML</td>
<td></td>
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<tr>
<td>ML-CAMS</td>
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<tr>
<td>R-GGGP</td>
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<td>BC-ES</td>
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<td></td>
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<tr>
<td>R-GGGP</td>
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</tbody>
</table>

Nbr. of disconnected subdomains

Total edge-cut
Analysis results

3) Heuristic methods

  b) Influence of optimisation constraints ⇒ Ease of management
Other clustering problems in cellular networks

3 Other clustering problems in cellular networks

- Site re-parenting problem
- Location area planning problem

4 Conclusions
Site re-parenting problem

Problem formulation
Site re-parenting problem

Problem formulation

Minimise \[ \|\delta(V_1, ..., V_k)\| = \sum_{(i,j) \in \delta(V_1, ..., V_k)} \gamma_{ij} \]

subject to \[ \|V_n\| = \sum_{i \in V_n} \omega_i \leq B_{aw} \]

\[ \max(\|V_1\|, ..., \|V_k\|) \leq B_{rw} \]

\[ \min(\|V_1\|, ..., \|V_k\|) \leq B_{rw} \]

\[ V_1, V_2, ..., V_k \] are connected

\[ i, j = 1: N_{\text{sites}} \]

\[ d(\Pi^*, \Pi_0) \leq B_{ch} \]

\[ \# \text{ users changing BSC} \]

\[ BSC \text{ capacity} \]

\[ \# \text{ site re-allocations} \]

Spatial consistency

Connectivity

Site resolution

\[ \# \text{ load imbalance between BSCs} \]
Site re-parenting problem

Problem formulation

☐ ILP model

\[
\begin{align*}
(M) \quad & \text{Min} \quad \sum_{(i,j) \in E} \gamma_{ij}(1 - \sum_{n \in N} Z_{ijn}) \\
\text{s.t.} \quad & \sum_{n \in N} X_{in} = 1, \quad \forall i \in V, \\
& \sum_{i \in V} \omega_i X_{in} \leq B_{aw}, \quad \forall n \in N, \\
& \sum_{i \in V} \omega_i X_{im} - B_{rw} \sum_{i \in V} \omega_i X_{in} \leq 0, \\
& \sum_{i \in V} \sum_{n \in N, n \neq \Pi_0(i)} \omega_i X_{in} \leq B_{ch}, \\
& Z_{ijn} \leq X_{in}, \quad \forall (i, j) \in E, n \in N, \\
& Z_{ijn} \leq X_{jn}, \quad \forall (i, j) \in E, n \in N, \\
& Z_{ijn} \geq X_{in} + X_{jn} - 1, \quad \forall (i, j) \in E, n \in N, \\
& X_{in} \in \{0, 1\}, \quad \forall i \in V, n \in N, \\
& Z_{ijn} \in \{0, 1\}, \quad \forall (i, j) \in E, n \in N.
\end{align*}
\]
Problem formulation
LA planning problem

Problem formulation

Minimise  \[ \| \delta(V_1, \ldots, V_k) \| = \sum_{(i,j) \in \delta(V_1, \ldots, V_k)} \gamma_{ij} \]
subject to  \[ \| V_n \| = \sum_{i \in V_n} \omega_i \leq B_{aw} \]
\[ k \in \{1, \ldots, |V| \} \]

\[ \rightarrow \quad \# \text{ users changing LA} \]
\[ \rightarrow \quad \text{LA paging capacity} \]
LA planning problem

Problem formulation

- **ILP model**

\[(CMS) \quad \text{Min} \quad \sum_{(i,j) \in E} \gamma_{ij} (1 - \sum_{n \in N} Z_{ijn})\]

\[\text{s.t.} \quad \sum_{n \in N} n \in N, \quad \forall i \in V,\]

\[\sum_{i \in V} \omega_i X_{in} \leq B_{aw}, \quad \forall n \in N,\]

\[\sum_{i \in V} \omega_i (X_{in} - X_{i,n+1}) \geq 0, \quad \forall n = 1, \ldots, k - 1, \quad \forall k = 1, \ldots, |V|\]

\[Z_{ijn} \leq X_{in}, \quad \forall (i, j) \in E, n \in N,\]

\[Z_{ijn} \leq X_{jn}, \quad \forall (i, j) \in E, n \in N,\]

\[Z_{ijn} \geq X_{in} + X_{jn} - 1, \quad \forall (i, j) \in E, n \in N,\]

\[X_{in} \in \{0, 1\}, \quad \forall i \in V, n \in N,\]

\[Z_{ijn} \in \{0, 1\}, \quad \forall (i, j) \in E, n \in N.\]
### Instance size comparison

#### Instance statistics

<table>
<thead>
<tr>
<th></th>
<th>PCU planning</th>
<th>Site re-parenting</th>
<th>LA planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V</td>
<td>$</td>
<td>110</td>
</tr>
<tr>
<td>$</td>
<td>E</td>
<td>$</td>
<td>541</td>
</tr>
<tr>
<td>$k$</td>
<td>4</td>
<td>6</td>
<td>11-58</td>
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<tr>
<td># ILP var.</td>
<td>2472</td>
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<td>196-11368</td>
</tr>
<tr>
<td># ILP const.</td>
<td>8705</td>
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<td>671-35612</td>
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<tr>
<td># ILP non-zeros</td>
<td>19808</td>
<td>74399</td>
<td>1278-80736</td>
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<tr>
<td></td>
<td>207 [SCIP/Cplex]</td>
<td>-</td>
<td>- [LPSOLVE]</td>
</tr>
<tr>
<td></td>
<td>3486 [LPSOLVE*]</td>
<td>-</td>
<td>- [GLPK]</td>
</tr>
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<td></td>
<td>- [GLPK]</td>
<td>-</td>
<td>- [GLPK]</td>
</tr>
</tbody>
</table>
Conclusiones

1. Introduction

2. Optimisation of the assignment of PCUs in GERAN

3. Other clustering problems in cellular networks

4. Conclusions
   - Main results
   - Open issues
Main results

- Hierarchical network structuring of a cellular network gives rise to different clustering problems that can be solved by graph partitioning techniques.

- Resulting graphs are smaller but more irregular and dense than in other applications domains, which suggests the use of more sophisticated methods.

- Most graph partitioning packages in the public domain do not consider peculiarities of the cellular environment.

- Even the simplest heuristic achieves a significant gain in network performance and operational efficiency due to the current manual approach followed by operators.

- When formulated as an ILP model, state-of-the-art solvers find difficulties to prove optimality in some instances of the PCU planning, site re-parenting and LA planning problems.
Open issues

Formulation

- Include connectedness constraint in ILP model
- Find new constraints to tighten the ILP model

Solution technique

- Find best LP/ILP solver in the public domain
- Find best default settings for standard solvers (or systematic methodology)
  - Dual-Primal/Primal-Dual, Ceiling/Floor, 1st/PseudoNonInt/Pseudocost, basis crash, …
- Estimate time to prove optimality (or find a solution of reasonable quality)
- Design solution method from scratch
  - Branch-and-price, branch-and-cut based on cover inequalities, rounding heuristic

Dissemination of results

- Find journals in computer science/applied OR
- Find network operator/partners
Optimisation of cellular network structure by graph partitioning techniques

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