# Mobile Radio Networks Project

## Planning Optimization for Wireless Network Deployment

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**Summer 2025**

## Introduction

This project applies Mixed Integer Linear Programming (MILP) to optimize cellular network deployment. Three deployment scenarios were analyzed for a 1500m × 1500m area with 50 candidate sites and 100 test points.

The radio engineering model employs the Okumura-Hata path loss model for signal propagation prediction, link budget analysis for coverage determination, and Shannon capacity theorem for throughput calculations. Technical parameters are configured with macro base stations operating at 40 dBm transmit power with 20 MHz bandwidth, micro base stations at 30 dBm with 10 MHz bandwidth, and a system sensitivity threshold of -75 dBm.

# Mathematical Model Formulation

## Sets and Indices

The optimization model defines the following mathematical sets:

| Set | Mathematical Notation | Description |
|---|---|---|
| $\boldsymbol{CS}$ | $C = \{1, 2, \ldots, \|C\|\}$ | Candidate sites for base station installation |
| $\boldsymbol{TP}$ | $T = \{1, 2, \ldots, \|T\|\}$ | Test points requiring coverage |
| $\boldsymbol{BS\_TYPE}$ | $B = \{macro, micro\}$ | Base station technology types |

## Parameters

The model incorporates physical and economic parameters:

| Parameter | Mathematical Definition | Physical Meaning |
|---|---|---|
| $\boldsymbol{cost}[\boldsymbol{c}, \boldsymbol{b}]$ | $c_{\{c,b\}} \in \mathbb{R}^{+}$ | Installation cost for BS type b at site c |
| $\boldsymbol{coverage}[\boldsymbol{c}, \boldsymbol{t}, \boldsymbol{b}]$ | $a_{\{c,t,b\}} \in \{0,1\}$ | Binary coverage indicator |
| $\boldsymbol{throughput}[\boldsymbol{c}, \boldsymbol{t}, \boldsymbol{b}]$ | $\theta_{\{c,t,b\}} \in \mathbb{R}^{+}$ | Achievable throughput $(Mbps)$ |
| $\boldsymbol{min\_thr}$ | $\theta_{min} = 7$ | Minimum throughput requirement |

## Decision Variables

Binary decision variables represent deployment choices:

| Variable | Domain | Mathematical Interpretation |
|---|---|---|
| $\boldsymbol{install}[\boldsymbol{c}, \boldsymbol{b}]$ | $x_{\{c,b\}} \in \{0,1\}$ | Type-specific installation decision |
| $\boldsymbol{serve}[\boldsymbol{c}, \boldsymbol{t}, \boldsymbol{b}]$ | $y_{\{c,t,b\}} \in \{0,1\}$ | Type-specific service assignment |

## Objective Function

The optimization seeks to minimize total network deployment cost:

**Mixed Deployment Formulation:**

$$\text{minimize} \quad Z = \sum_{c \in C} \sum_{b \in B} \text{cost}_{c,b} \times \text{install}_{c,b}$$

**Single-Type Formulation (Macro-only/Micro-only):**

$$\text{minimize } Z = \sum_{c \in C} \text{cost}[c] \times \text{install}[c]$$

## Constraint Set

The feasible solution space is defined by the following mathematical constraints:

**1. Coverage Constraint (Demand Satisfaction):**

$$\sum_{c \in C} \sum_{b \in B} \text{serve}[c, t, b] \geq 1, \quad \forall t \in T$$

Ensures every test point receives service from at least one base station.

**2. Logical Linking Constraint:**

$$\text{serve}[c, t, b] \leq \text{install}[c, b], \quad \forall c \in C,\ t \in T,\ b \in B$$

Prevents service assignment without base station installation.

**3. Technical Feasibility Constraint:**

$$\text{serve}[c, t, b] \leq \text{coverage}[c, t, b], \quad \forall c \in C,\ t \in T,\ b \in B$$

Restricts service to technically feasible coverage areas.

**4. Quality of Service Constraint:**

$$\sum_{c \in C} \sum_{b \in B} \text{throughput}[c, t, b] \times \text{serve}[c, t, b] \geq \text{min\_thr}, \quad \forall t \in T$$

Guarantees minimum throughput requirements based on Shannon capacity.

**5. Mutual Exclusivity Constraint (Mixed deployment only):**

$$\sum_{b \in B} \text{install}[c, b] \leq 1, \quad \forall c \in C$$

Prevents multiple base station types at the same candidate site.

# Results of the simulation

## Network Topology and Coverage Feasibility

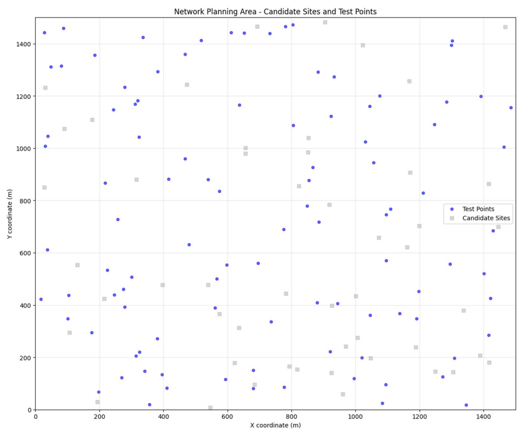



Figure 1 Network Planning Area

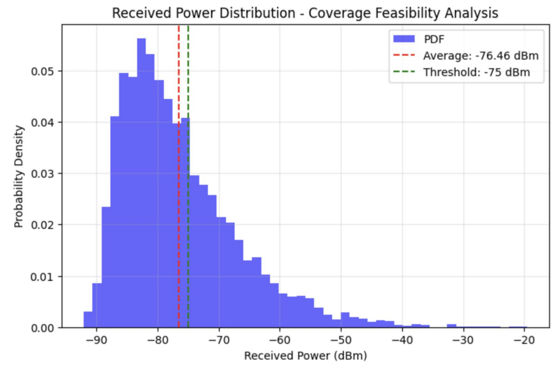



Figure 2 Coverage Feasibility Analysis

## Radio Network Performance Metrics

**Coverage Analysis:** All scenarios achieve 100% area coverage, satisfying:

$$\sum_{c\in C}\sum_{t\in T}\sum_{b\in B}\text{coverage}[c,t,b]\times\text{serve}[c,t,b]\geq|T|$$

**Capacity Analysis:** Minimum throughput constraint satisfaction:

$$\min_{t\in T}\left\{\sum_{c\in C}\sum_{b\in B}\text{throughput}[c,t,b]\times\text{serve}[c,t,b]\right\}\geq 7\text{ Mbps}$$

**Signal Quality Assessment:** All connections exceed sensitivity threshold:

$$P_R[c,t,b]\geq\gamma=-75\text{ dBm},\quad\forall(c,t,b)\text{ such that serve}[c,t,b]=1$$

## Deployment Solutions:

| Scenario | Total Cost | Base Stations | Macro Count | Micro Count | Deployed Sites |
|---|---|---|---|---|---|
| **Macro-only** | $9.24 | 4 | 4 | 0 | [24, 26, 39, 42] |
| **Micro-only** | $7.32 | 12 | 0 | 12 | [4, 6, 10, 16, 20, 23, 26, 31, 39, 46, 47, 48] |
| **Mixed** | $6.77 | 8 | 1 | 7 | *Macro*: [26], *Micro*: [1, 13, 16, 18, 33, 38, 39, 42, 48] |

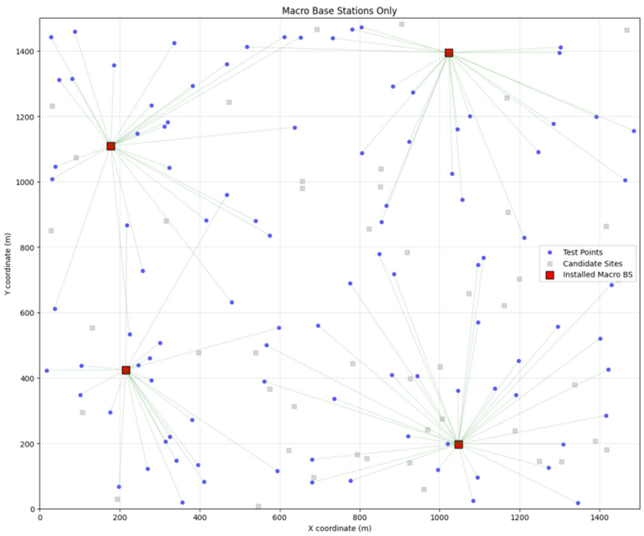



Figure 3 Macro-Only Deployment (4 stations, $9.24)

## Macro-Only Deployment

**Mathematical Result:**

$$x_c = 1 \; for \; c \in \{24, 26, 39, 42\}$$

- **Coverage Pattern:** Wide-area coverage with minimal overlap
- **Technical Analysis:** Each macro cell covers ~25 test points
- **Link Budget:** High transmit power compensates for path loss

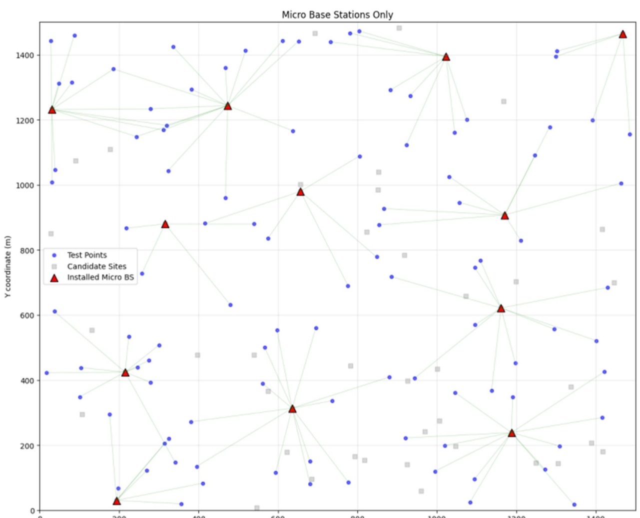



Figure 4 Micro-Only Deployment (12 stations, $7.32)

## Micro-Only Deployment

**Mathematical Result:** $x_c = 1$

$$for \; c \in \{4, 6, 10, 16, 20, 23, 26, 31, 39, 46, 47, 48\}$$

- **Coverage Pattern:** Dense cellular layout with smaller coverage areas
- **Technical Analysis:** Average 8-9 test points per micro cell
- **Network Topology:** The design follows the idea of adding more small cells to improve coverage and capacity.

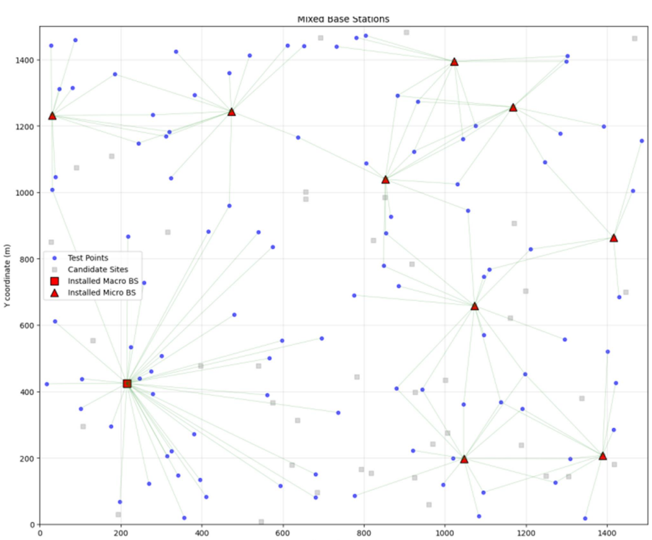



Figure 5 Mixed Deployment (1 macro + 9 micro, $6.77)

## Mixed Deployment

**Mathematical Result:**

- Macro: $x_{\{26,macro\}} = 1$
- Micro:

$x_{\{c,micro\}} = 1 \; for \; c \in \{1, 13, 16, 18, 33, 38, 39, 42, 48\}$

**Technical Analysis:**

- Macro cell cover large areas, acting as a base layer.
- Micro cells handle busy spots, helping reduce congestion.
- Spacing between cells helps avoid signal interference.

## Cost-Benefit Analysis

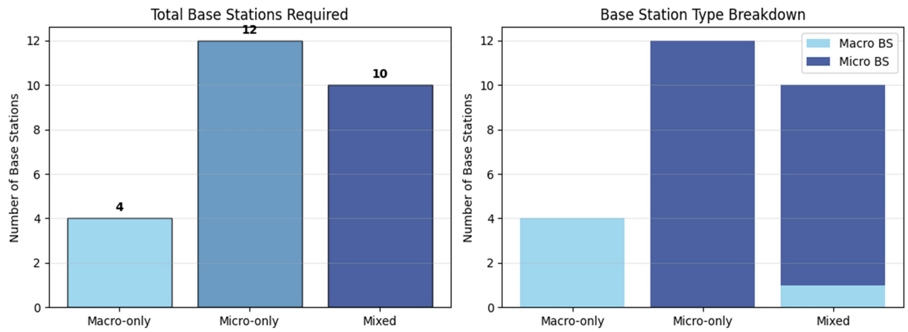
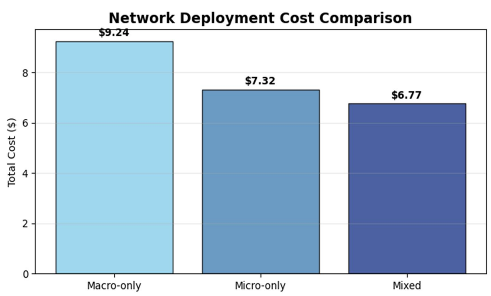



Figure 6 Numbers of Base Stations



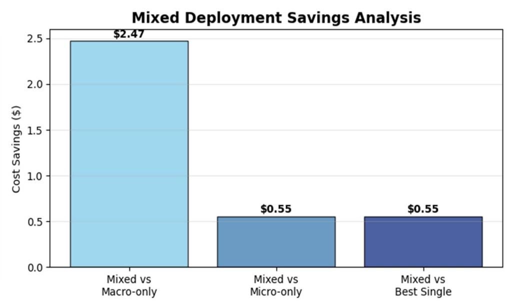




Figure 7 Cost Comparison

Figure 8 Savings Analysis

| Scenario | Total Cost ($) | Total Base Stations | Macro Stations | Micro Stations | Cost vs Best (%) |
|---|---|---|---|---|---|
| Macro-only | 9.24 | 4 | 4 | 0 | +36.6% |
| Micro-only | 7.32 | 12 | 0 | 12 | +8.2% |
| Mixed | 6.77 | 10 | 1 | 9 | +0.0% |

Figure 9 Detailed Cost and Deployment Comparisons

# Analysis and Recommendations

## Answers to the Big Telco Questions

1. **Which is more effective: macro or micro base stations?**
   Micro base stations are more cost-efficient, especially in dense urban environments. With a 5:1 cost advantage over macro base stations, they provide flexible, localized coverage. In contrast, macro base stations are better suited for wide-area coverage with fewer installations, making them ideal for rural or low-density regions.

2. **What is the total cost when deploying only one base station type?**

    - **Macro-only**: \$9.24 (4 base stations)
    - **Micro-only**: \$7.32 (12 base stations)
      The micro-only approach is approximately 21% more cost-effective than macro-only, while still fulfilling all coverage and performance requirements.

3. **Can further savings be achieved by combining both types?**
   Yes. A mixed deployment of 1 macro and 9 micro base stations results in the lowest cost of \$6.77, offering:

    - **26.7% savings** over macro-only
    - **7.6% savings** over micro-only
      This approach achieves full coverage and required throughput while balancing cost, capacity, and performance. However, it introduces minor operational complexity due to managing two infrastructure types.

### Recommendation

Use a mixed deployment with one macro base station (at site 26) and nine micro base stations placed in key locations. This setup offers the best balance between cost and performance**,** covering the entire area and meeting all service requirements.

If keeping the system simple is more important, a micro-only deployment with 12 micro stations is also a strong option. However it costs more than mixed strategy, it avoids the extra effort of managing two types of base stations.

## Conclusion

The MILP optimization successfully identified cost-optimal network configurations for all scenarios while maintaining 100% coverage and 7 Mbps minimum throughput. The micro base station technology emerges as the clear winner for single-type deployments, with mixed deployments offering marginal additional savings.

### Google Colab Notebook:

https://colab.research.google.com/drive/12T0WBu_Vr4ub91-DC5ij-ran_-aIZMRD#scrollTo=UM9yRCNScmTL