118th edition
AEIT International
2026 Annual Conference

Roma ◆ Italy ◆ 8/10 September 2026
Sapienza ◆ University of Rome

Interference-Driven Clustered Optimisation for FM Spectrum Coordination

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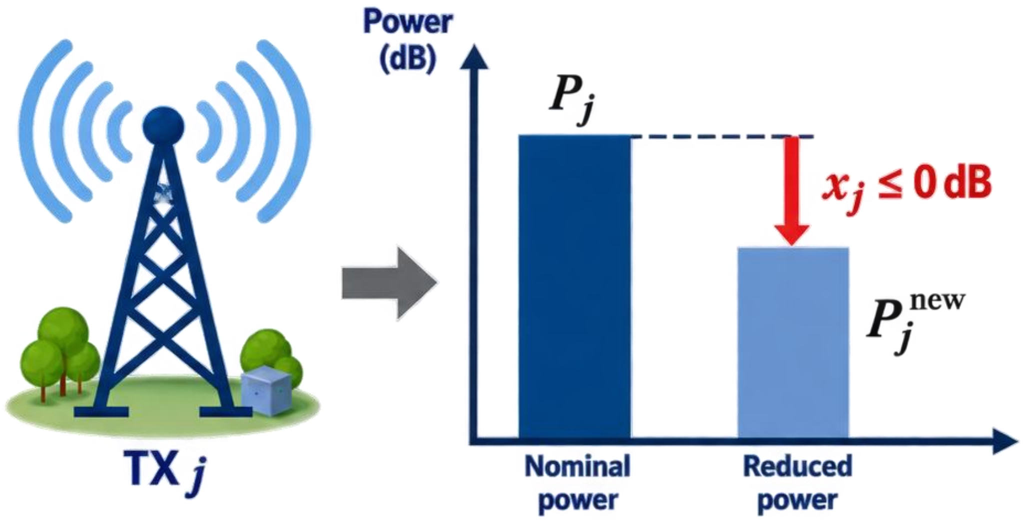
Research, Innovation, Strategy

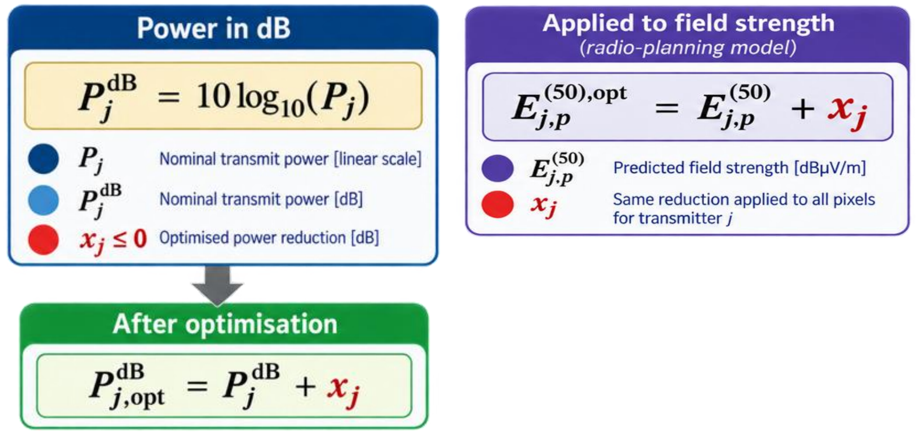
The Cross-Border Coordination Problem

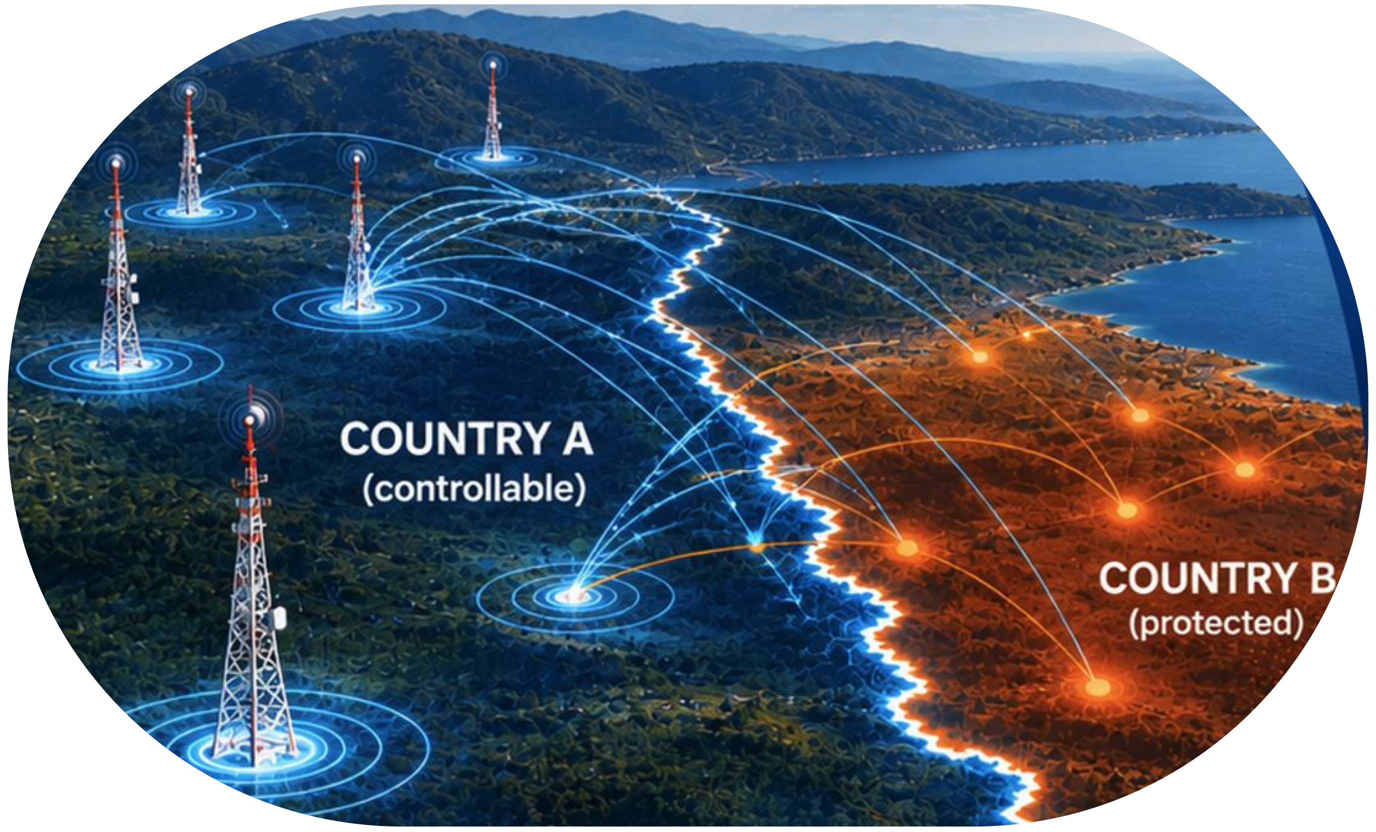
FM transmitters in **Country A** may generate co-channel and adjacent-channel interference towards protected FM services in **Country B**

Objective

Mitigate harmful cross-border interference while preserving national FM service availability through transmit-power optimisation in Country A.







Optimisation goal

Find the appropriate power reduction for each Country A transmitter

$$\mathbf{x} = [x_1, x_2, \ldots, x_{N_T}]^T, \qquad x_j \leq 0$$

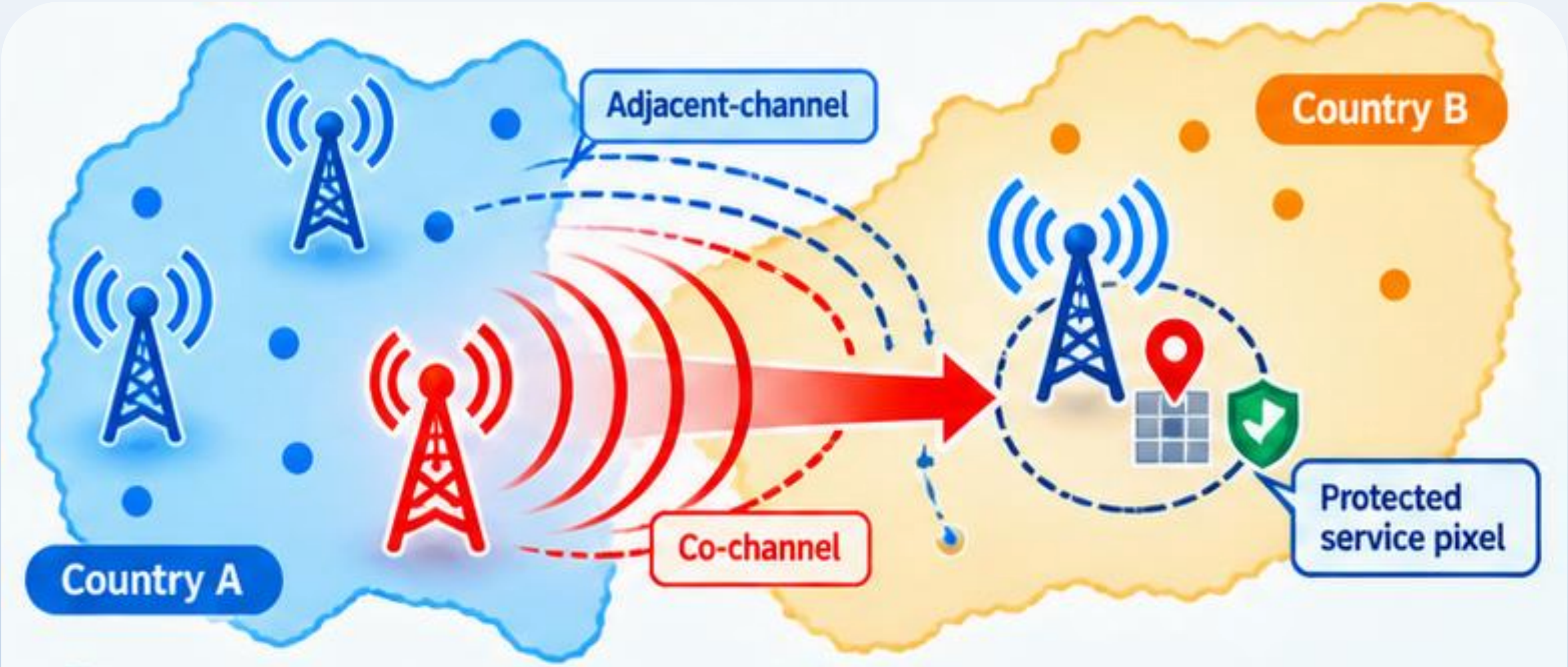
while balancing:

Foreign-service protection ↔ National-service availability ↔ Limited power reductions

Cross-Border Protection and National Service Evaluation

Foreign Service Protection Model

Protect foreign services in Country B



Key equations

1. $C_{m,p} = 10^{E^{(50)}_{m,p}/10} \quad m \in \mathcal{T}_B$
2. $\mathcal{K} = \{0, 100, 200\}$
3. $I_{m,p}(\mathbf{x}) = \sum_{k\in\mathcal{K}} \alpha_k I^{(k)}_{m,p}(\mathbf{x})$
4. $I^{(k)}_{m,p}(\mathbf{x}) = \sum_{j\in\mathcal{I}_k(m,p)} w_{j,p}(\mathbf{x}), \quad k\in\mathcal{K}$
5. $\alpha_k = 10^{M_k/10}$

$w_{j,p} = 10^{E^{(50)}_{j,p}/10} \cdot y_j$

Protection condition

$$C_{m,p} \geq \Gamma_{\mathrm{EXT}} I_{m,p}(\mathbf{x})$$

$\Gamma_{\mathrm{EXT}} = 1$ (0 dB)

Residual violation

$$\xi_{m,p} = \max\left(\Gamma_{\mathrm{EXT}} I_{m,p}(\mathbf{x}) - C_{m,p}, 0\right)$$

● $\xi_{m,p}$=0: protected | ● $\xi_{m,p}$>0: violation severity

National FM Service Evaluation Model

Preserve domestic service via dynamic best-server assignment

Key equations

1. $\mathcal{T}^A(p,f) = \{j : f_j = f \text{ and } w_{j,p}(\mathbf{x}) > 0\}$
2. $b(p,f) = \arg\max_{j\in\mathcal{T}^A(p,f)} w_{j,p}(\mathbf{x})$
3. $C_{p,f}(\mathbf{x}) = w_{b(p,f),p}(\mathbf{x})$
4. $I_{p,f}(\mathbf{x}) = \sum_{k\in\mathcal{K}} \alpha_k I^{(k)}_{p,f}(\mathbf{x})$
5. $I^{(k)}_{p,f}(\mathbf{x}) = \sum_{j\in\mathcal{I}_k(p,f)} w_{j,p}(\mathbf{x}), \quad k\in\mathcal{K}$

$w_{j,p} = 10^{E^{(50)}_{j,p}/10} \cdot y_j$

Coverage conditions

$$C_{p,f}(\mathbf{x}) \geq \Gamma_{\mathrm{A}} I_{p,f}(\mathbf{x})$$

$$E^{(50)}_{b(p,f),p} \geq E^{A}_{\min}$$

$\Gamma_{\mathrm{A}} = 1$ (0 dB)

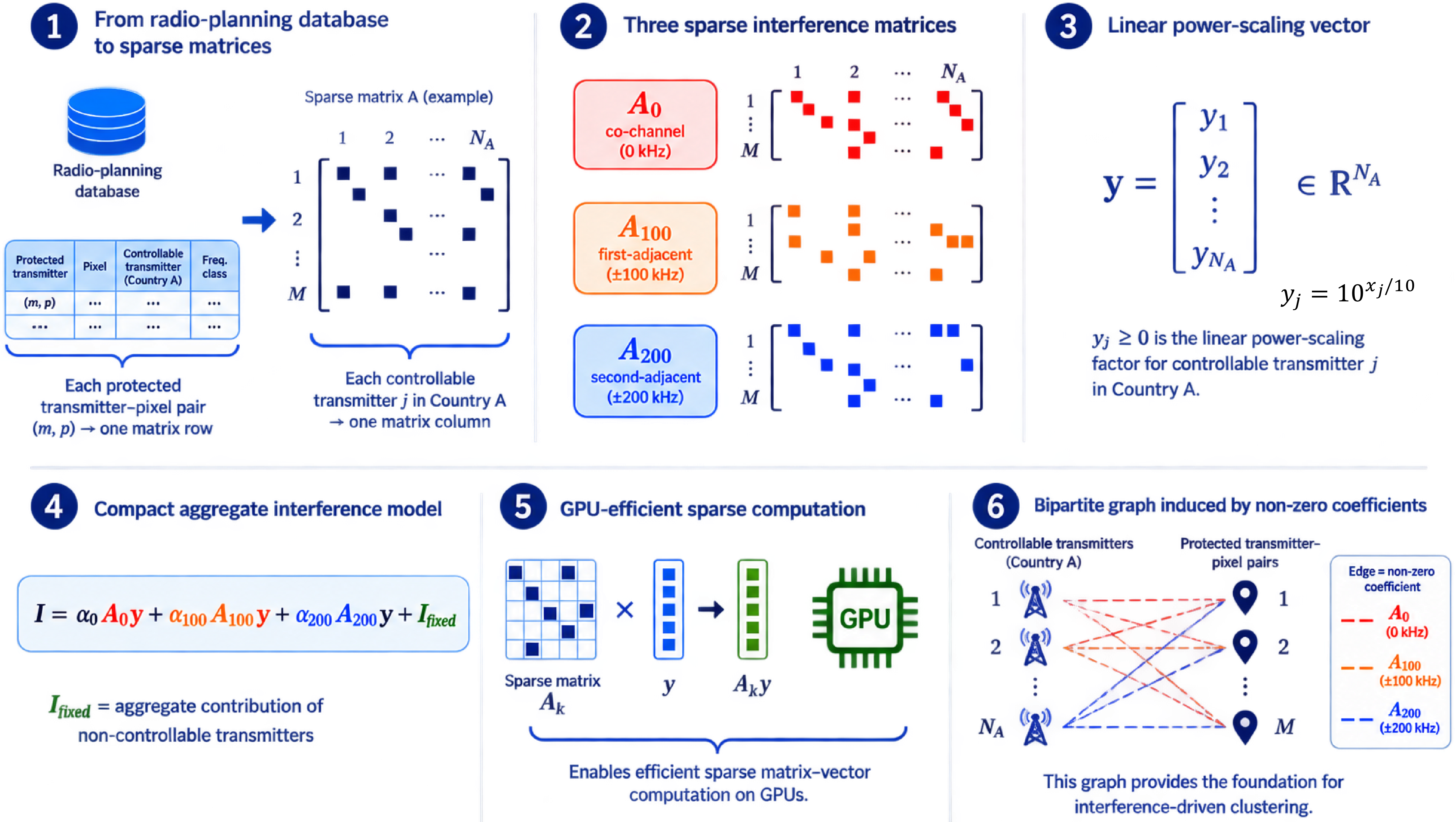
Residual violation

$$z_{p,f}(\mathbf{x}) = \max\left(\Gamma_{\mathrm{A}} I_{p,f}(\mathbf{x}) - C_{p,f}(\mathbf{x}), 0\right)$$

● $z_{p,f}$=0: covered | ● $z_{p,f}$>0: violation severity

Sparse Interference Representation

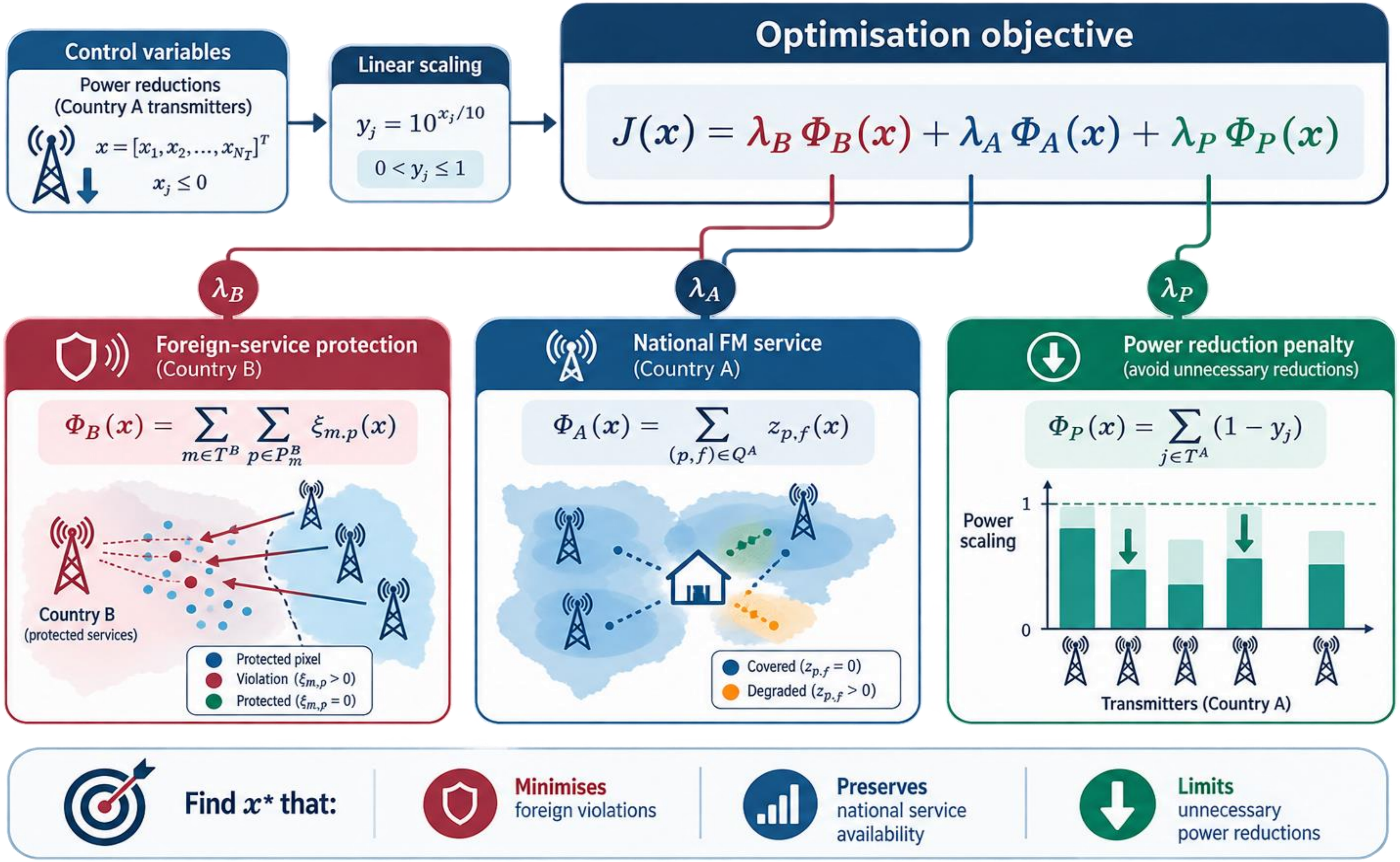
Each **row** represents a **protected transmitter–pixel pair**. Each **column** represents a **controllable transmitter**.



α_k incorporates the frequency-dependent **ITU-R BS.412 protection ratio**

Optimisation Problem

Cross-border interference mitigation is formulated as a constrained optimisation problem that minimises residual protection violations ξ and unnecessary transmitter power reductions, while preserving national FM service availability.



Optimisation Challenges

Simultaneous full FM networks optimisation is computationally intensive

Thousands of controllable transmitters.

Millions of transmitter-to-pixel relationships.

3x Channel evaluations per relationship (Co-channel, ±100kHz, ±200kHZ).

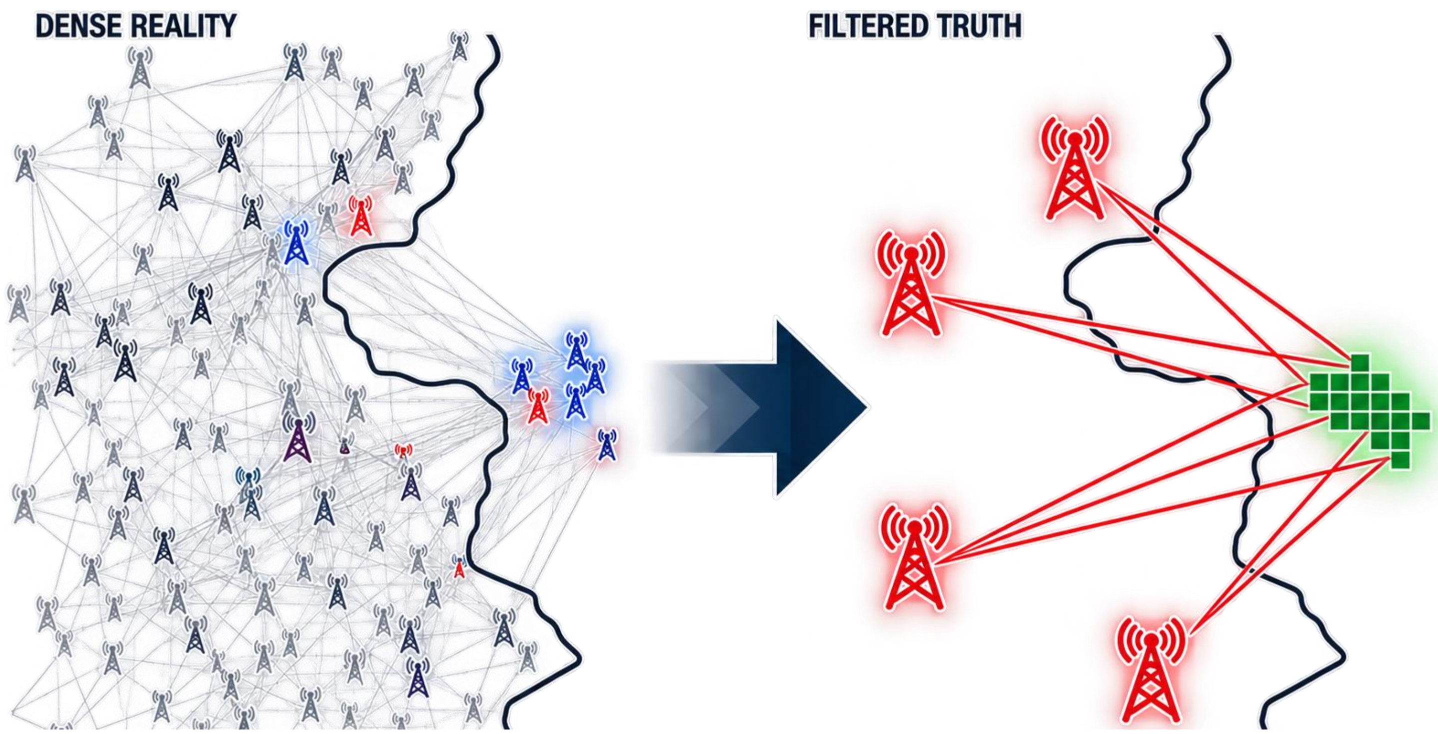
Protecting foreign services while preserving national service availability leads to a **high-dimensional optimisation problem,** characterized by:

- high computational cost
- limited suitability for rapid operational deployment

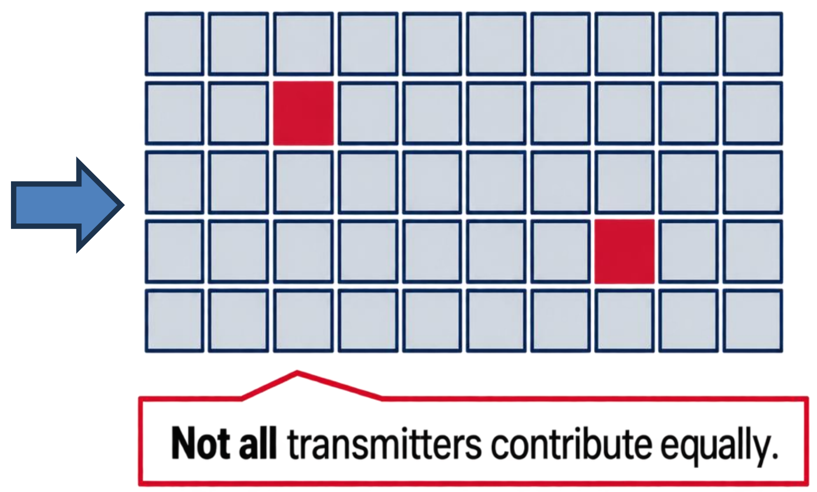
Key observation

Cross-border protection violations are typically dominated by a limited subset of interfering transmitters.

Optimisation should target only the sources of harmful interference.



Interference Sparcity Principle



From Sparse Interference to Graph

Cross-border interference is dominated by a limited subset of controllable transmitters

1. From Violations to Dominant Interferers

Identify violated protected service points

$$\xi_{m,p} > 0$$

$$\downarrow$$

2. For each protected service m:

Rank interfering transmitters by their contribution

$$\downarrow$$

$$\boxed{\mathcal{I}_m^{TopK} = \{i_1, i_2, \dots, i_K\}}$$

Keep only the Top-K dominant interferers

3. Construct Interference Graph
   - **Nodes** → country A transmitters
   - **Edges** → transmitters i and j are connected if they both appear among **interferers** of at least one fore

$$i \sim j \iff \exists m : \; i, j \in \mathcal{I}_m^{TopK}$$

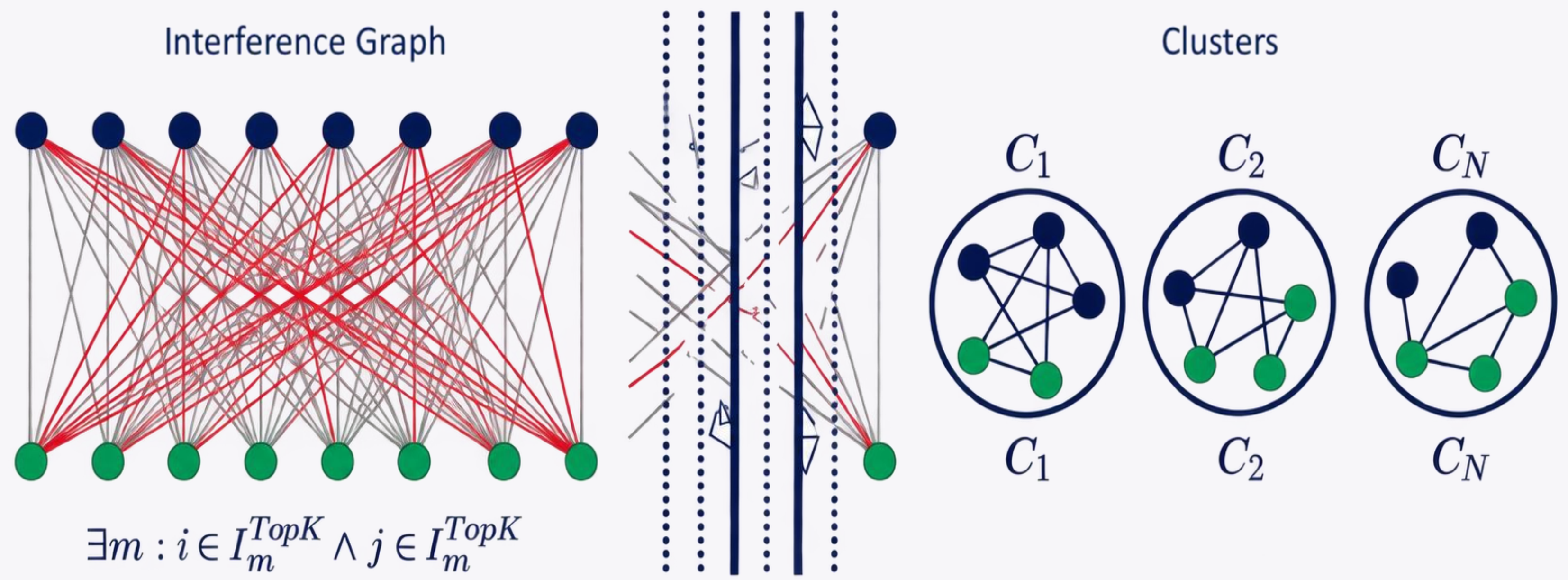
Evaluate 7 million links. Red dots indicate ITU-R protection violations.

Retain only the Top-K dominant interferers for each protected service.

Edges connect transmitters that jointly appear in a Top-K list.

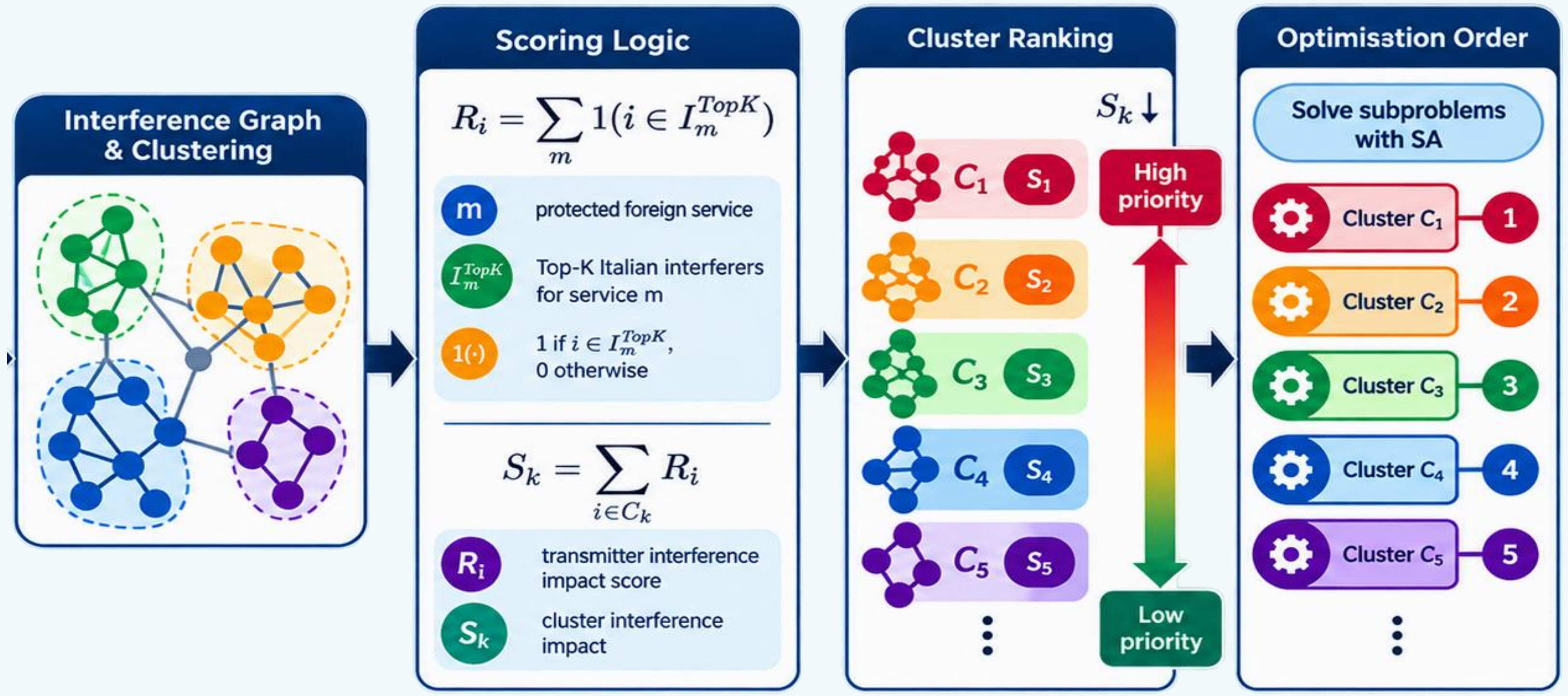
Interference Graph to Independent Optimisation Subproblems

By considering the Top-K interferers of each foreign service, the global interference graph is decomposed into independent connected subgraphs, **each defining a local optimisation problem**.



Clusters naturally emerge as the connected components of the Top-K interference graph.

Clusters are ranked by interference impact S_k to prioritise those with the highest mitigation potential in optimisation process



R_i **:** number of protected foreign services for which transmitter i appears among the **Top-K dominant interferers**

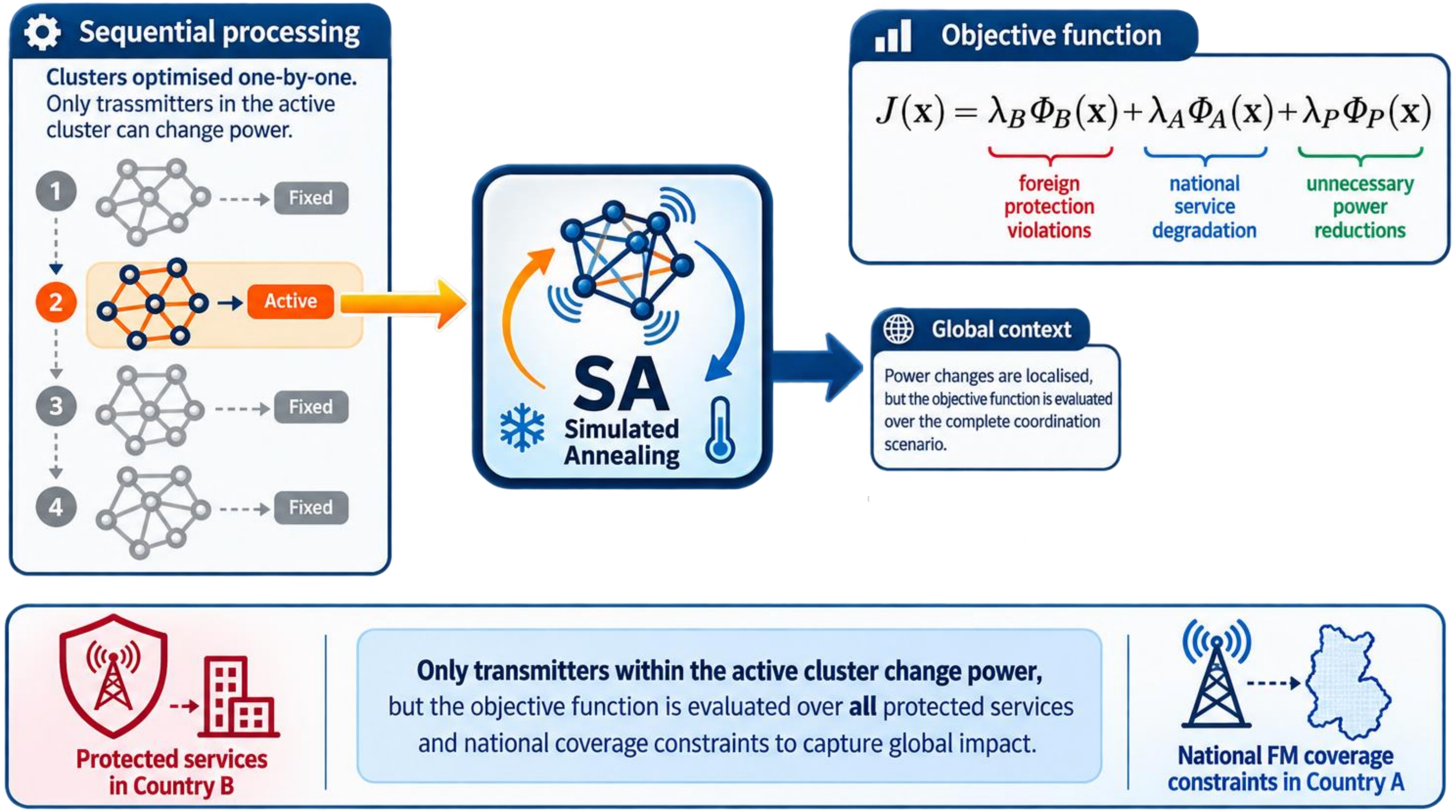
S_k : Interference relevance of cluster C_k

Clustered Simulating Annealing

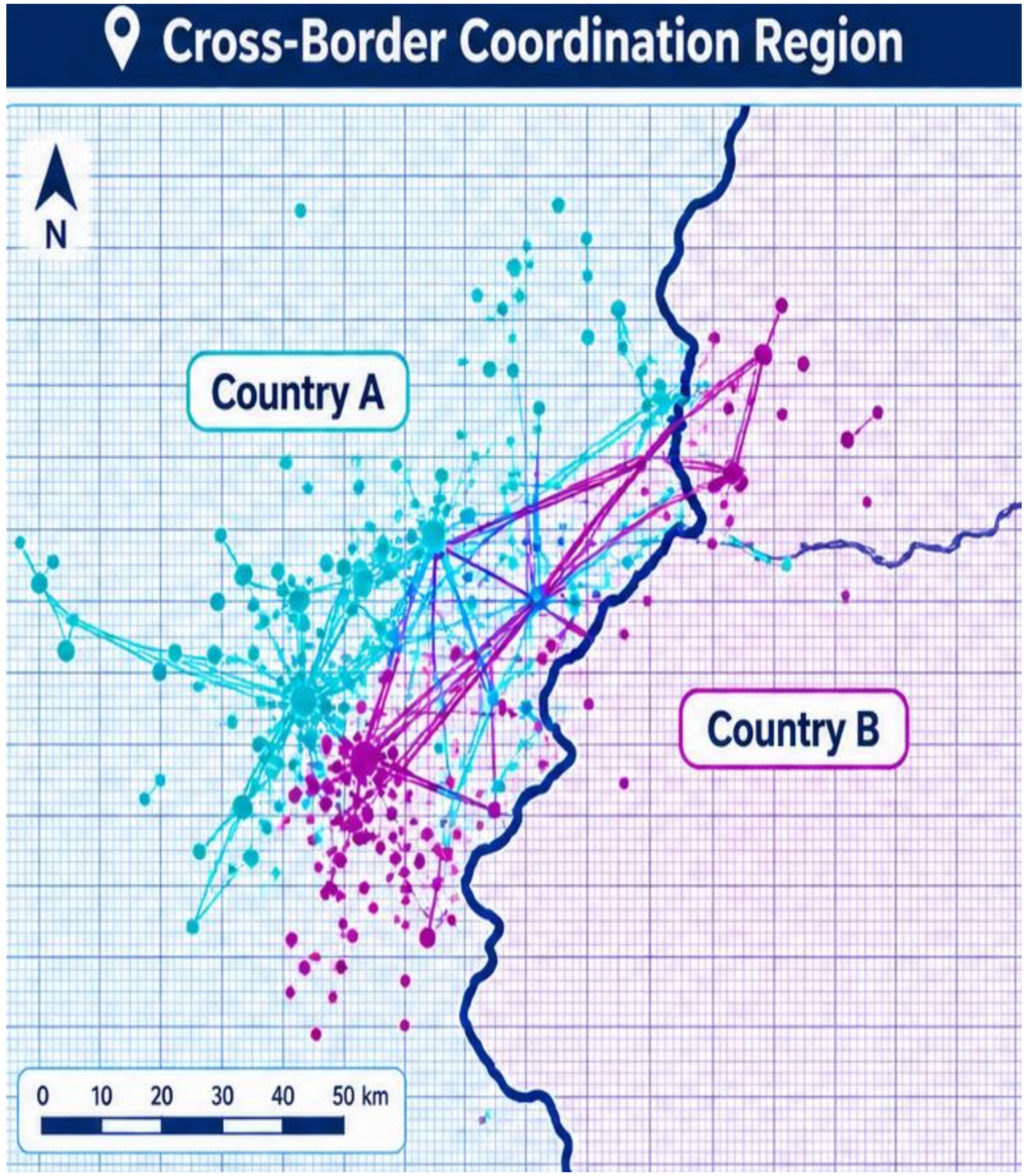
The large-scale, coupled and non-convex nature of the power-control problem makes **exact optimisation computationally prohibitive** at operational scale, motivating the use of heuristic methods.

Simulated Annealing is adopted because it can explore complex, non-convex search spaces and escape poor local minima.

Clustered SA: solves the complex power-control problem through smaller sequential cluster-level subproblems, while evaluating each solution over the complete coordination scenario.



Validation in an Operational Cross-Border Scenario



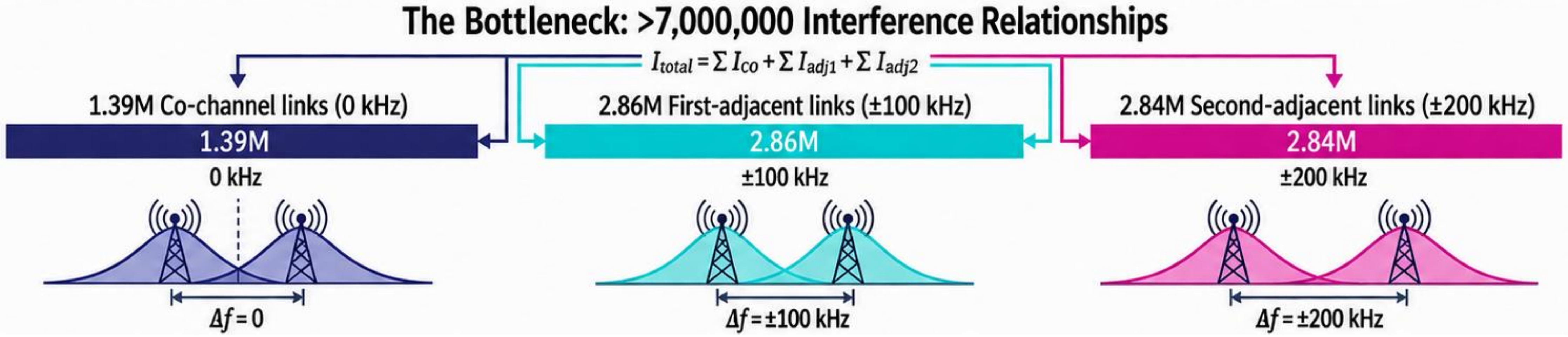
15,766 km² coordination area

~2 km² spatial resolution grid

3,247 Transmitters (Country A)

630 Protected Services (Country B)

~94,000 Candidate Service Points



The massive dimensionality is managed using **GPU acceleration** *(Dual* **NVIDIA A100 40GB***)* *and* **sparse matrix representations** *(A_0, A_{100}, A_{200}) to isolate co-channel and adjacent-channel contributions.*

Experimental Results

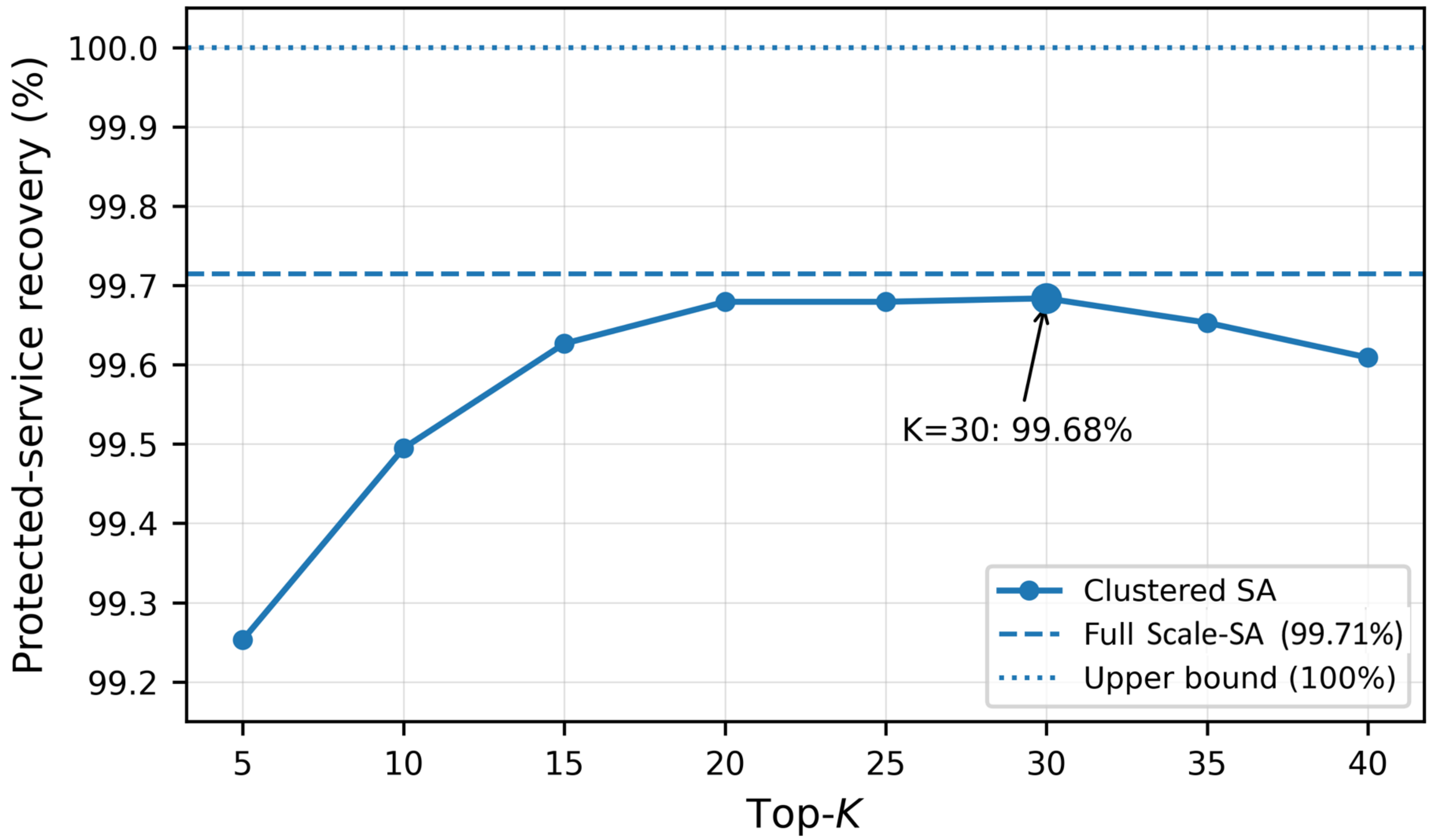
Baseline: the original FM planning configuration, with no optimisation or transmitter power reductions applied, used as the reference for evaluating the improvement achieved by the proposed method.

✓ **Foreign-service protection**
70.7% → 99.68%
of the maximum recoverable service area

✓ **National FM availability**
10,315 → 17,418 covered pixel–frequency pairs
+68.9%

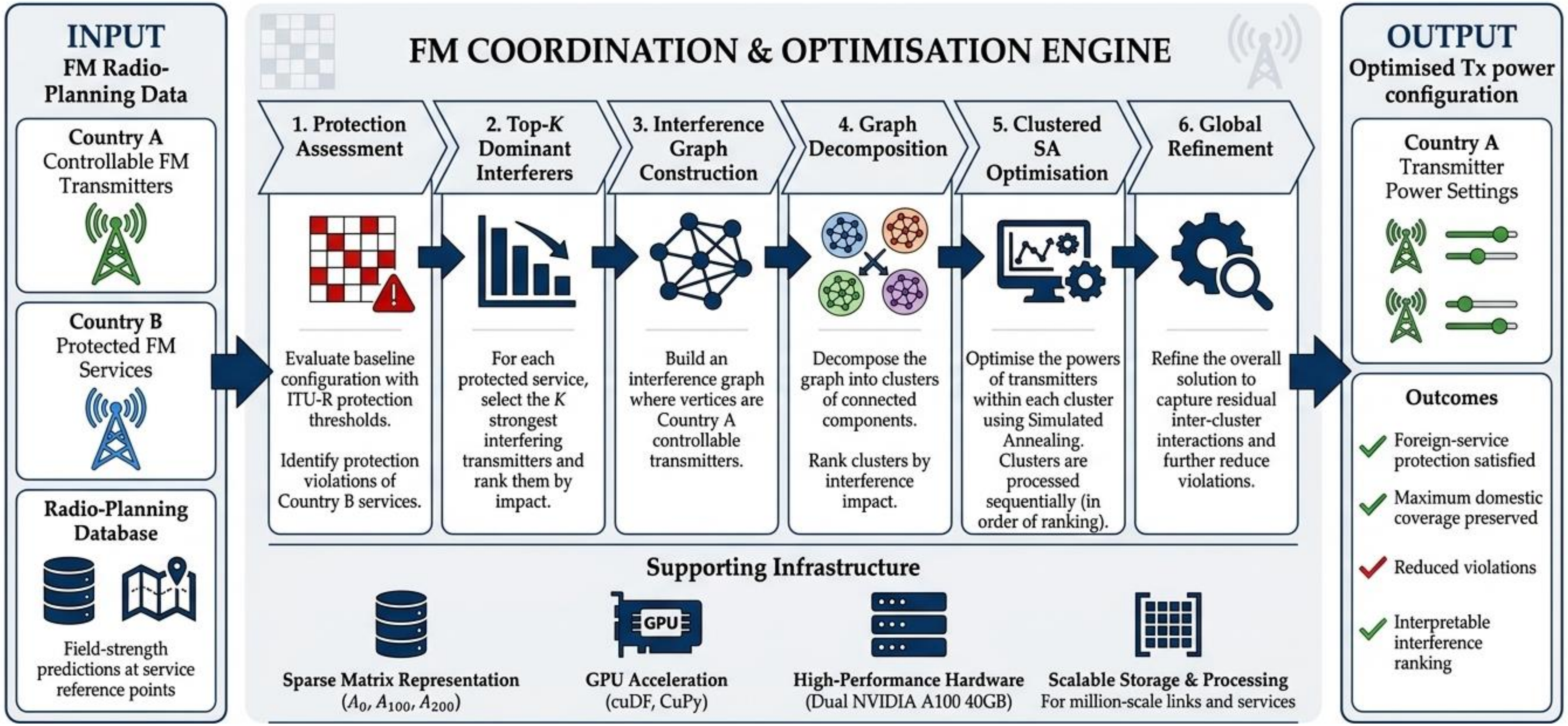
✓ **Computational efficiency**
324 s vs 5,517 s
94% runtime reduction

✓ **Near-monolithic performance**
22,691 vs 22,698 pixels
only **7 pixels** below Full-Scale SA



Clustered SA recovers virtually the same coordination performance as Full-Scale SA while solving much smaller optimisation problems.

Optimisation Framework



Conclusions

- ✓ **Cross-border interference is dominated by a limited set of transmitters**, enabling an effective graph-based decomposition of the coordination problem.
- ✓ **Clustered SA recovers 99.68% of the maximum recoverable foreign-service area**, while preserving national FM service availability.
- ✓ **Near-identical performance to Full-Scale SA at only ~6% of the runtime**.

Exploiting interference structure transforms large-scale coordination from a computationally prohibitive problem into a tractable sequence of cluster-level optimisations.

Thank you for your attention

Questions?