Optimal Gateway Selection in Multi-domain Wireless Networks: A Potential Game Perspective

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Overview

Coalition Networks with Multiple Domains

Scenario:

- Coalition networks with **heterogenous** groups.
- Inter-connected via wireless links, e.g., IEEE 802.11, WiMAX, UAV, satellite, 3G/4G etc.

Example:

- Joint military missions, US-UK
- Disaster rescue teams, fire-fighters and police officers
- Wireless sensor networks of different organizations, e.g., Internet of Things (IoT), Smart Planet Solutions

Interoperability Issue

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Problems:

- Inter-domain communication is non-trivial for heterogenous domains
- Different network protocol, security schemes, policies
- Security and policy enforcement, traffic analysis

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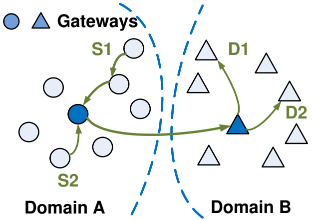
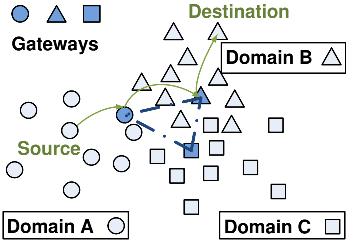
Solution:

Designate **gateway** nodes



Cost Efficient Gateway Selection



Each pair of nodes has a **cost**, e.g., routing metric cost, such as

- hop count, RIP, AODV etc.
- Euclidean distance
- ETX, ETT, RTT
- Energy consumption etc.

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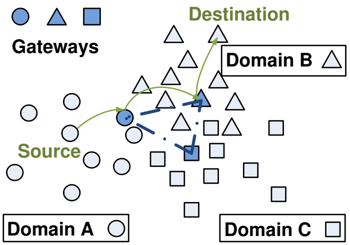

For a single domain

Intra-domain cost

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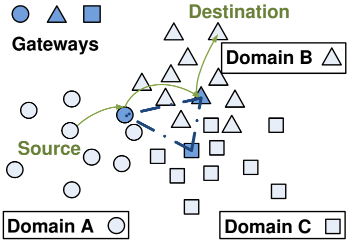

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For a single domain

Intra-domain cost

For the network

Inter-domain backbone cost

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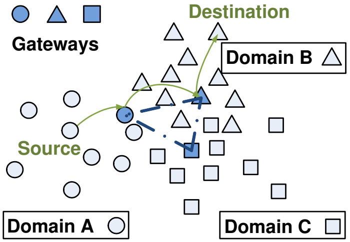

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For a single domain

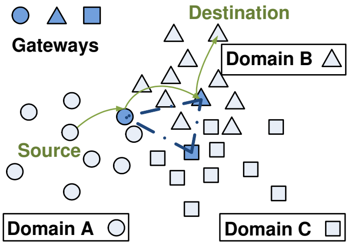
For the network

Intra-domain cost + **Inter-domain backbone cost**

Question:

How to select the set of gateways s.t. the **overall** cost is minimized?

Challenges



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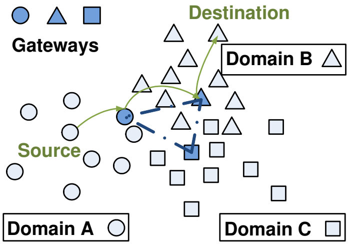
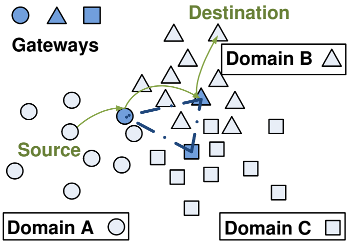


- Combinatorial nature of solution space

Challenges



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Distributed solution

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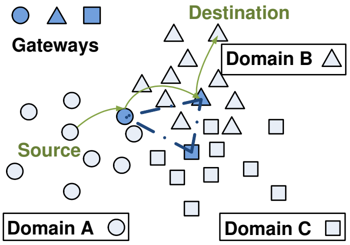

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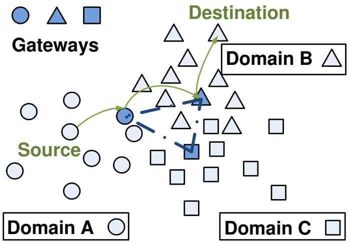

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Equilibrium efficiency

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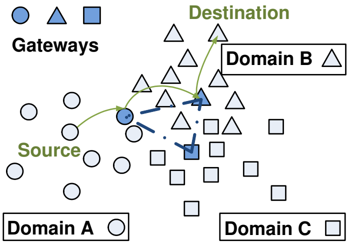

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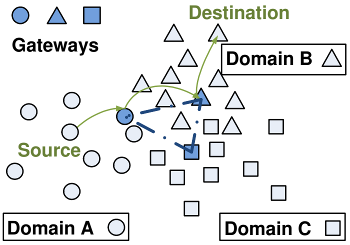

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Local information only

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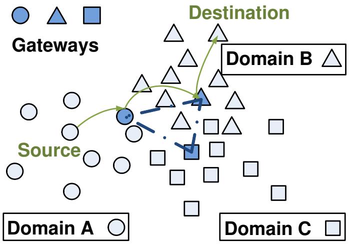

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Distributed solution | Equilibrium efficiency | Local information only

potential game theory & equilibrium selective learning

Network Model

- $\mathcal{M}$: the set of domains in the coalition network
- $\mathcal{N}_m$: the set of nodes in the domain
- $g_m^i = 1$: node i is selected as the gateway node and $g_m^i = 0$ o.w. and $\widehat{i_m} = \text{argmax}_{i \in \mathcal{N}_m} g_m^i$ be the selected gateway node
- $\mathbf{g}_m = \{g_m^1, g_m^2, \cdots, g_m^{|\mathcal{N}_m|}\}$: the **gateway selection strategy** of domain m
- $\mathbf{s} = \{\mathbf{g}_1, \mathbf{g}_2, \cdots, \mathbf{g}_{|\mathcal{M}|}\}$: the joint **gateway selection profile** of the network
- Satellite/UAV/3G/4G link: cost η (expensive), to enforce always-on connectivity
- A pair of node i and j: $c(i,j) \geq 0$ is the associated symmetric link cost, $c(i,j) = \eta$ if out of range
- $c'(i,j) \triangleq \min\left(c(i,j), \eta\right)$

Gateway Selection Game

For each single domain

Minimize (**Local** information and observation only)

$$\mathcal{U}_m(\mathbf{g}_m, \mathbf{g}_{-m}) = \sum_{i \neq \widehat{i_m}, i \in \mathcal{N}_m} c\left(i, \widehat{i_m}\right) + \sum_{n \neq m, n \in \mathcal{M}} c'\left(\widehat{i_m}, \widehat{i_n}\right) \tag{1}$$

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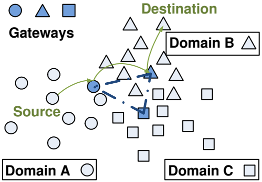

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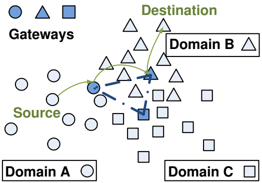

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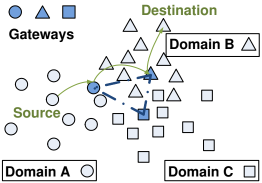

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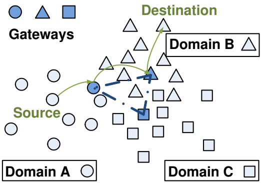

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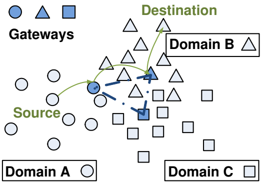

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For overall network

Minimize (**intra-domain cost** + **cost of backbone communication links**)

$$\mathcal{R}(\mathbf{s}) = \sum_m \sum_{i \neq \widehat{i_m}, i \in \mathcal{N}_m} c\left(i, \widehat{i_m}\right) + \sum_{\left(\widehat{i_m}, \widehat{i_n}\right) \in \mathrm{MCG}(\mathbf{s})} c'\left(\widehat{i_m}, \widehat{i_n}\right). \quad (2)$$

Existence of Nash Equilibrium

Theorem

The gateway selection game has a Nash equilibrium, which minimizes, either locally or globally, the following function

$$\mathcal{F}(\mathbf{s}) = \sum_{m} \sum_{i \neq \widehat{i_m}, i \in \mathcal{N}_m} c\left(i, \widehat{i_m}\right) + \sum_{\left(\widehat{i_m}, \widehat{i_n}\right) \in \mathrm{CCG}(\mathbf{s})} c'\left(\widehat{i_m}, \widehat{i_n}\right). \quad (3)$$

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- Nash equilibrium may not be unique
- Multiple Nash equilibria have different performance
- To capture the (in)efficiency of Nash equilibrium, **Price of Anarchy** and **Price of Stability** are introduced

  $$\text{Price of Stability} = \frac{\text{value of best equilibrium}}{\text{value of optimal solution}}$$

Efficiency of Nash Equilibria

For $|\mathcal{M}| = 2$

For two player gateway selection games, the best Nash Equilibrium is the global network optimum solution, i.e., the price of stability is 1.

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For $|\mathcal{M}| \geq 3$, if the link cost metric $c(a, b)$ satisfies the triangle inequality, the price of stability is always 1.

All else

If the triangle inequality does not hold, the price of stability of an $|\mathcal{M}|$-player gateway selection game is at most $(1 + \delta)$, where

$$\delta = \frac{\eta \left(\frac{|\mathcal{M}|}{2} + \frac{1}{|\mathcal{M}|} - \frac{3}{2} \right)}{\min_{m \in \mathcal{M}} \min_{\mathbf{g}_m} \sum_{i \neq \widehat{i_m}(\mathbf{g}_m), i \in \mathcal{N}_m} c\left(i, \widehat{i_m}(\mathbf{g}_m)\right)}. \tag{4}$$

B-logit: Binary Logit Algorithm

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and

$$\Pr\left(\mathbf{g}_m(t+1) = \mathbf{g}_m(t)\right) = 1 - \Pr\left(\mathbf{g}_m(t+1) = \widetilde{\mathbf{g}_m}\right) \quad (6)$$

where τ is a small positive constant, a.k.a., the **smoothing factor** of the algorithm.

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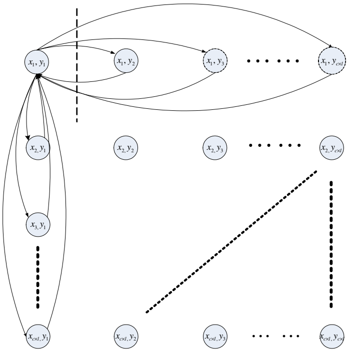
    where τ is a small positive constant, a.k.a., the **smoothing factor** of the algorithm.
- It is known that as $\tau \to 0$, `B-logit` converges to the best Nash equilibrium with arbitrarily high probability.

Proof (sketch)



- Note $\Pr(\mathbf{s}' \to \mathbf{s}'')$

$$\frac{1}{|\mathcal{M}|}\frac{1}{|\mathcal{N}_m|}\frac{\exp^{-\mathcal{U}(\mathbf{s}'')/\tau}}{\exp^{-\mathcal{U}_m\left(\widetilde{\mathbf{g}_m},\mathbf{g}_{-m}(t)\right)/\tau}+\exp^{-\mathcal{U}_m\left(\mathbf{g}_m(t),\mathbf{g}_{-m}(t)\right)/\tau}}$$

- Verify

$$\pi(\mathbf{s}') = \frac{\exp^{-\mathcal{F}(\mathbf{s}')/\tau}}{\sum_{\mathbf{s}\in\mathcal{S}}\exp^{-\mathcal{F}(\mathbf{s})/\tau}}$$

  satisfies the **detailed balance equation**, i.e., $\pi(\mathbf{s}')\Pr(\mathbf{s}' \to \mathbf{s}'') = \pi(\mathbf{s}'')\Pr(\mathbf{s}'' \to \mathbf{s}')$

- `B-logit` algorithm induces a reversible, irreducible, and aperiodic Markov chain and it is the **unique** steady state distribution.

- By taking $\tau \to 0$, we have

$$\pi(\mathbf{s}^*) \to 1, \text{ where } \mathbf{s}^* = \operatorname{argmin}_{\mathbf{s}\in\mathcal{S}} \mathcal{F}(\mathbf{s})$$

Generalization of B-logit

Generalization of B-logit

γ-logit algorithm family (Γ):

- γ-logit shares the same structure as B-logit except in (5), where the probability is calculated as

$$\Pr\left(\mathbf{g}_m(t+1) = \widetilde{\mathbf{g}_m}\right) = \frac{\exp^{-\mathcal{U}_m\left(\widetilde{\mathbf{g}_m}, \mathbf{g}_{-m}(t)\right)/\tau}}{\gamma\left(\mathbf{s}', \mathbf{s}''\right)} \tag{7}$$

where $\mathbf{s}' = \{\mathbf{g}_m(t), \mathbf{g}_{-m}(t)\}$ and $\mathbf{s}'' = \{\widetilde{\mathbf{g}_m}, \mathbf{g}_{-m}(t)\}$ are two gateway selection profiles in $\mathcal{S}$, and γ satisfies

1. **Symmetry**
   $\gamma(\mathbf{s}', \mathbf{s}'') = \gamma(\mathbf{s}'', \mathbf{s}'), \forall \mathbf{s}' \in \mathcal{S}, \mathbf{s}'' \in \mathcal{S}$,
2. **Feasibility**
   $\gamma(\mathbf{s}', \mathbf{s}'') \geq \max\left(\exp^{-\mathcal{U}_m(\mathbf{s}')/\tau}, \exp^{-\mathcal{U}_m(\mathbf{s}'')/\tau}\right)$.

- B-logit is a **special case** of γ-logit algorithm with

$$\gamma\left(\mathbf{s}', \mathbf{s}''\right) = \gamma\left(\mathbf{s}'', \mathbf{s}'\right) = \exp^{-\mathcal{U}_m\left(\mathbf{s}'\right)/\tau} + \exp^{-\mathcal{U}_m\left(\mathbf{s}''\right)/\tau}.$$

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Every γ-`logit` algorithm in Γ is equilibrium selective, i.e., converging to the global minimizer of the potential function asymptotically.

- Which is **better**?
- Each γ-`logit` algorithm induces a Markov chain with different transition probability matrix, where

$$P_{i,j}(\gamma) \triangleq \Pr\left(\mathbf{s}^i \to \mathbf{s}^j\right) = \frac{1}{|\mathcal{M}|}\frac{1}{|\mathcal{N}_m|}\frac{\exp^{-\mathcal{U}(\mathbf{s}^j)/\tau}}{\gamma(\mathbf{s}^i, \mathbf{s}^j)}$$

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- The mixing rate of a Markov chain is determined by the **second largest eigenvalue modulus (SLEM)**, i.e.,

$$\mu\left(P(\gamma)\right) = \max\left(\left|\lambda_2\left(P(\gamma)\right)\right|, \left|\lambda_{|\mathcal{S}|}\left(P(\gamma)\right)\right|\right).$$

- The **smaller** $\mu\left(P(\gamma)\right)$ is, the **faster**.

Solution: MAX-logit Algorithm

MAX-logit:

For every time slot t:

- Randomly select one of the players, say m, to update its gateway selection while other domains remain unchanged.
- Denote the current gateway selection of domain m as $\mathbf{g}_m(t)$. Domain m randomly selects a node in its domain as the gateway candidate. Denote the candidate gateway selection strategy by $\widetilde{\mathbf{g}_m}$. Domain m updates as

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Denote μ^{MAX} as the second largest eigenvalue modulus associated with `MAX-logit` algorithm.

Theorem

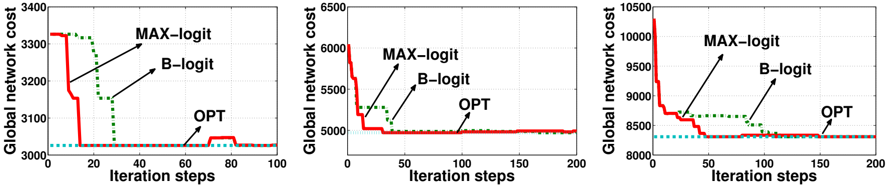
Denote $\mu\left(P(\gamma)\right)$ as the second largest eigenvalue modulus induced by an arbitrary γ-`logit` algorithm in Γ. We have $\mu^{MAX} \leq \mu\left(P(\gamma)\right)$.

Evaluation setup

- $|\mathcal{M}|$ domains where each domain has $|\mathcal{N}|$ nodes
- For each domain, nodes are randomly deployed in a round area with radius $125m$, centered at a random point within the square field of $1000 \times 1000m^2$
- **Link cost:**
  1. Euclidean distance: Network optimum solution is the best Nash (γ-`logit` algorithms converge to the network optimum solution)
  2. Random cost: γ-`logit` algorithm converges to the approximate $1 + \delta$ solution (Nash equilibrium)
  3. Randomly select p% of the links in the network and add random cost offset which is uniformly distributed between 0 and 5% of the original cost
- Global link cost $\eta = 500$, $|\mathcal{M}| = 2, 3, 4$
- $\tau = 0.0001$

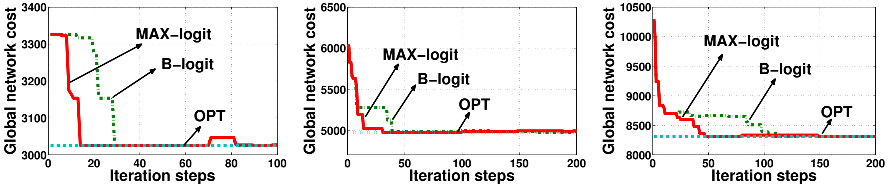
Euclidean Distance Scenarios

- $p\% = 0\%$
- 2, 3, 4 domains where each domain has 20 nodes



Euclidean Distance Scenarios

- $p\% = 0\%$
- 2, 3, 4 domains where each domain has 20 nodes

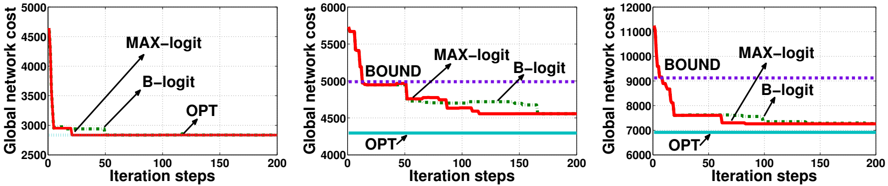


Nodes per domain	2 domains	3 domains	4 domains
5 nodes	16.06%	24.52%	33.85%
10 nodes	25.00%	29.81%	28.55%
20 nodes	11.96%	20.19%	20.36%
30 nodes	5.87%	16.46%	17.60%

- Average over 5000 sample runs
- Performance improvement declines when no. of nodes increases

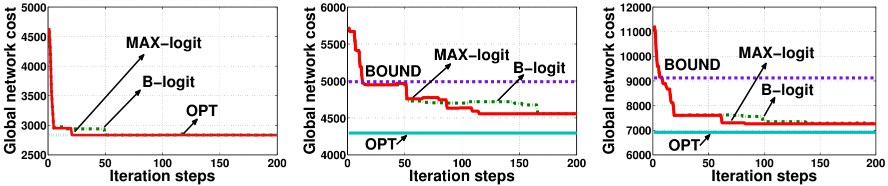
Random Cost Scenarios

- $p = 50$, i.e., 50% of the links in the network are associated with random link cost
- 2, 3, 4 domains where each domain has 20 nodes



Random Cost Scenarios

- $p = 50$, i.e., 50% of the links in the network are associated with random link cost
- 2, 3, 4 domains where each domain has 20 nodes



Nodes per domain	2 domains	3 domains	4 domains
5 nodes	21.84%	24.46%	27.38%
10 nodes	21.00%	21.44%	21.56%
20 nodes	9.54%	9.13%	5.47%
30 nodes	1.90%	1.93%	2.24%

Table: Convergence rate improvement by `MAX-logit` when $p = 50$.

Conclusions

- Interactive gateway selection by multiple domains in coalition networks
- In a potential game framework, the existence and inefficiency of Nash equilibria are characterized (two domains, multi-domains)
- Equilibrium selective learning: generalized `B-logit` into γ-`logit`, or Γ
- Propose `MAX-logit` which converges to the best Nash equilibrium at the fastest speed in Γ
- Other applications of potential games in power control, channel allocation, spectrum sharing content distribution etc.