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INTERCONNECTION LINK ADDITIONS TOWARDS COMMUNICATION NETWORK CONSOLIDATION

Farabi Iqbal*, Muhammad Yusof Mohd Noor, Arnidza Ramli, Mohd Rashidi Salim

Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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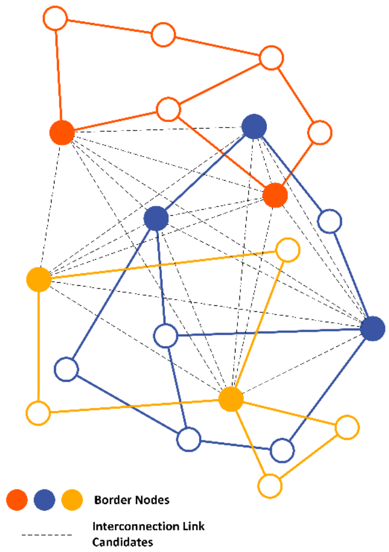
*Corresponding author
alfarabi@utm.my

Graphical abstract



Abstract

The ever-increasing demand for modern communication services and the rising cost of capital and operating expenditures have led to interest in multi-operator network collaborations. These network operators manage different network domains and infrastructures, such that their topologies may be disjointed from each other, and require the addition of intermediate interconnection links for the domains to communicate with each other. The main contribution of this paper is the proposal of an integer linear program for finding the optimum set of interconnection links to be added to the multi-domain networks such that the multi-domain networks become a connected graph, while minimizing either (1) the total length of added interconnection links, (2) the total shortest path length between all the border nodes of the multi-domain networks, or (3) the total number of shortest hop counts between all the border nodes of the multi-domain networks. The proposed integer linear program is shown to find the optimum solution under various properties for the multi-domain networks, albeit with increased computation time as the size of the problem increases. Simulation results using randomly generated multi-domain networks show a trade-off in terms of length of added links, shortest path length and shortest path hop count for each specific objective function.

Keywords: Communication networks, random topology, network collaboration

Abstrak

Permintaan yang sentiasa meningkat bagi perkhidmatan komunikasi moden dan kenaikan kos modal dan perbelanjaan operasi telah menarik minat ke arah kerjasama antara operator rangkaian. Operator rangkaian menguruskan domain dan infrastruktur yang berbeza, dengan topologi yang mungkin terpisah antara satu sama lain, dan memerlukan penambahan pautan perhubungan untuk berkomunikasi. Sumbangan utama kertas ini adalah cadangan program linear integer untuk mencari set pautan perhubungan optimum yang perlu ditambah kepada rangkaian domain agar menjadi graf terhubung, sambil meminimumkan sama ada (1) jumlah panjang keseluruhan pautan perhubungan yang ditambah, (2) jumlah panjang jalan terpendek antara semua nod sempadan, atau (3) jumlah lompatan terpendek antara semua nod sempadan. Formulasi program linear integer yang dicadangkan dapat mencari penyelesaian optimum di bawah pelbagai sifat rangkaian domain, walaupun dengan tempoh pengiraan yang meningkat apabila saiz masalah meningkat. Simulasi menggunakan rangkaian domain yang dijana secara rawak menunjukkan perubahan panjang keseluruhan pautan yang ditambah, panjang jalan terpendek, dan lompatan terpendek, bagi setiap fungsi objektif yang tertentu.

Kata kunci: Rangkaian komunikasi, topologi rawak, kerjasama rangkaian

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1.0 INTRODUCTION

As part of the modernization of telecommunication networks, network operators may find it necessary to consolidate via network cooperation, merger or sharing to adapt to evolving client needs, ever-increasing data consumption, evolving technologies [1], high infrastructure investments [2], high operating expenses, and meeting scalability requirements. Partnerships and joint ventures among network operators are possible via bilateral agreements, e.g., China Tower is formed by three mobile network operators in China, and MTN partnering with American Tower Company in Ghana and Uganda [3]. Network consolidations also help network operator to overcome spectrum deficits, increase profitability, improve service quality, improve cost efficiency, gaining new markets, reducing competition, and acquiring modern technology [4].

Network consolidation empowers network operators to construct more agile, scalable, and cost-effective networks capable of better supporting their ever-expanding customer base. Mobile network operators may have previously deployed their own network infrastructure and compete for end-users [3] before the needs for network consolidation arises, and as such having disconnected network topologies and technologies that require interconnection for initiating the network consolidation process. Network consolidation involves the process of merging multiple individual networks (network domains [5]) into a unified structure. New links may be added as interconnections of networks at strategic locations [6]. Strategically placed interconnection links enable the initially disconnected network domains to efficiently communicate for using resources located in different network domains. Then, the number of operational links can be lowered by suspending less important links and restored when bandwidth demand increases [6]. Link addition is also important for infrastructural maintenance in improving the robustness of the network [7], without destructing existing structures [8].

In this paper, the problem of establishing new interconnection links between multiple disconnected network domains is addressed, as illustrated in Figure 1. Ensuring connectivity is vital in communication networks for seamless data transmission, where a connected graph guarantees the existence of a route [9] between any two network nodes. Instead of considering all nodes within the multi-domain networks as potential candidates for interconnection link addition, several candidate nodes from each network were considered in this paper, for reducing the computational complexity of the problem. Such an approach is feasible in networks where nodes vary in importance and function, with some nodes possessing higher functionality than others. For example, in wireless sensor networks [10, 11], gateway nodes function as intermediaries between sensor nodes and the external world, serving as entry or exit points for the network by facilitating communication (e.g., protocol translation) between them. Cluster head nodes [10] manage data collection, data aggregation, and data transmission, and therefore possess more processing power and energy resources compared to sensor nodes. Similarly, in telecommunication networks [12], border nodes positioned at the network edge are responsible for exchanging routing information with nodes from other network domains. Border nodes play a crucial role in interconnecting network domains and determining optimal paths for routing traffic between them. Border nodes with a direct interconnection link between them can communicate directly, while those without need to communicate via other intermediate border nodes to communicate indirectly. There are also ongoing trends on facilitating sharing of access networks [13] in telecommunication networks, such as via the Multi Operator Core Network [14] architecture.

The positioning of interconnection links to be added to the multi-domain networks plays a vital role in the communication performance between the domains. Strategically placing interconnection links may lead to changes in network traffic characteristics and flow, optimizing traffic routing, and enhancing overall network performance. For example, by establishing an interconnection link between two border nodes with high betweenness centrality, the efficiency and resiliency of information exchange can be enhanced. This facilitates the flow of information between various parts of the multi-domain networks by reducing communication bottlenecks and delays.

This paper proposes an Integer Linear Program (ILP) in Section 2 for establishing interconnection links between disconnected network domains, where the ILP is flexible to be used with three different objectives functions, catering to specific needs of network interconnections. As such, this paper highlights the complexity in deciding appropriate objective function in establishing interconnection links (in Section 3), for ensuring high-performance data transmission and reducing deployment costs.

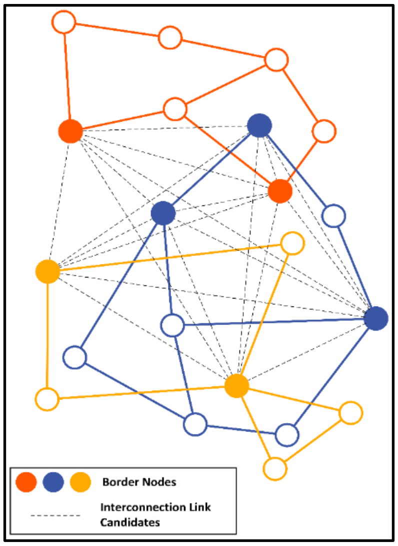


Figure 1 Example of three network domains with interconnection link candidates

Table 1 Comparison with existing work

Paper	Link Addition	Aim	Network Metric	Link Weight	Node Weight	Multi-Domain/ Network	Approach
Leung *et al.* [6]	*k*	resource optimization	number of network links	yes	no	Yes	ILP
Chujyo and Hayashi [8]	*k*	robustness and efficiency	node degree/ path length	yes	no	No	link addition strategies
Xie and Chen [15]	two	resource optimization	number of network links	yes	no	Yes	cut-based algorithm
Gudmundsson and Sha [16]	*k*	minimize radius	radius	yes	no	No	3-approximation algorithm
Adriaens and Gionis [17]	*k*	minimize diameter	diameter	no	no	No	approximation algorithm and heuristic
Du *et al.* [18]	*k*	minimize path length	path length	no	no	No	memetic algorithm
Gozzard *et al.* [19]	one	minimize path length	path length/ hop count	yes	no	No	exact algorithms
Corò *et al.* [20]	*k*	connectivity	weighted number of reachable nodes	no	yes	No	dynamic programming and greedy algorithms
This paper	*k*	connectivity	link length / path length/ hop count	yes	no	Yes	topology aggregation + ILP

Table 1 compares this paper's contribution to existing work. Leung *et al.* [6] and Xie and Chen [15] examine the consolidation of two optical networks by adding interconnection links strategically to reduce operational costs, enabling links between co-located nodes. Leung *et al.* [6] devised an ILP model, while Xie and Chen [15] proposed a cut-based algorithm. Xie and Chen [15] accounted for overlapping network domains in certain geographic areas, whereas Leung *et al.* [6] assumed identical geographic coverage. This paper extends this by considering multiple network domains (not limited to two network domains) generated within the same area, potentially overlapping geographically. While both Xie and Chen [15] and Leung *et al.* [6] consider that interconnection links are added only between co-located nodes, this paper considers that the selection of border nodes is to be assigned by network operators based on their network operation requirements.

While this paper focuses on establishing connectivity between disconnected network domains, other researchers have different objectives while studying problem similar to ours, albeit with different approaches. Gudmundsson and Sha [16] proposed a 3-approximation augmentation algorithm for minimizing the network radius by adding *k* number of network links. Predari *et al.* [7] proposed adding k new network links such that the resulting graph topology has minimal total effective resistance. Adriaens and Gionis [17] proposed three algorithms for adding a fixed number of new network links to a graph for minimizing the graph diameter under the constraint that the number of added links for each node is bounded. Chujyo and Hayashi [8] proposed on adding links based on minimum degree and longest distance strategies for improving network robustness (based on node removal attacks) and efficiency (based on shortest path hop counts).

Achieving a lower average network path length is highly desirable, as it facilitates and amplifies dynamic processes within the network, e.g., information dissemination [18], and improving the communication delay [19]. Gozzard *et al.* [19] proposed simple and efficient exact algorithms for adding a single network link for minimizing the average shortest path length of the network. Du *et al.* [18] proposed a memetic algorithm for minimizing the network's average path length by adding network links. However, they consider adding a fixed number of network link(s) for improving their corresponding network metrics, while the proposed approach of this paper sets a bound to the number of link addition for making the multi-domain networks connected. It is desirable that network paths consist of as few intermediate hops as possible [19]. Corò *et al.* [20] focused on improving the reachability of a graph, by proposing a dynamic programming algorithm on trees with a single source and greedy algorithms that guarantee (1/e)-approximation ratio on directed acyclic graphs with a single source, a single sink or two sources.

This paper mainly deals with the problem of establishing *k* number of interconnection links between multiple disconnected and potentially overlapping multi-domain networks with weighted links. In order to reduce the computation complexity, topology aggregation is utilized where border nodes are assigned as candidate interconnection points while minimizing either the interconnection link length, path length or path hop count using the proposed ILP.

2.0 METHODOLOGY

Multi-Domain Networks Connectivity Problem

Consider an undirected multi-domain networks topology $G = \{B, L\}$ of $|B|$ nodes and $|L|$ links, which is derived from a union of a set D of $|D|$ network domains. Each domain $d \in D$ is itself characterized by a set N of $|N|$ network nodes, and a set E of $|E|$ intra-domain links. Each intra-domain link $(u, v) \in E$ connects nodes $u \in N$ and $v \in N$. Find the optimum set of interconnection links $l \notin L$ to be added to topology G such that G becomes a connected graph.

A multi-objective Integer Linear Program (ILP) is proposed for solving the problem, with the disconnected multi-domain graph G as the input. The ILP seeks solutions (e.g., by utilizing Python API of IBM ILOG CPLEX Optimization Studio 20.1.0) that satisfy the constraints while optimizing the objective function for the ILP constants and variables defined in Table 2.

Table 2 ILP Constants and Variables

Parameters	Values
B	set of border nodes
R	number of all possible border nodes pairs
Z	maximum number of link addition allowed
$C_{r(s,t)}$	set of all possible source(s)-destination(t) border node pairs
A_{uv}	is 1 if a path exists from u to v in G; else 0
D_{uv}	is the shortest path length from node u and v if the path exists in G; else is the Euclidean distance from node u to v
Z_{uv}	is 1 if link (u, v) is to be added; else 0
P_{ruv}	is 1 if the shortest path of connection r uses link (u, v); else 0

ILP Objective(s):

Choose one:

$$\text{Minimize} \sum_{u\in B, v\in B} D_{uv} \times Z_{uv} \tag{1}$$

$$\text{Minimize} \sum_{r\in R, u\in B, v\in B} P_{ruv} \times D_{uv} \tag{2}$$

$$\text{Minimize} \sum_{r\in R, u\in B, v\in B} P_{ruv} \tag{3}$$

ILP Constraints:

$$\sum_{u\in B} P_{ruj} = \sum_{v\in B} P_{rjv} \qquad \forall\, r \in \mathrm{R}, j \in B, j \neq C[r][0], j \neq C[r][1] \tag{4}$$

$$\sum_{u\in B} P_{ruC[r][1]} = \sum_{v\in B} P_{rC[r][0]v} = 1 \qquad \forall\, r \in \mathrm{R} \tag{5}$$

$$\sum_{u\in B} P_{rC[r][1]u} = \sum_{v\in B} P_{rvC[r][0]} = 0 \qquad \forall\, r \in \mathrm{R} \tag{6}$$

$$P_{ruv} \leq A_{uv} + Z_{uv} + Z_{vu} \qquad \forall\, r \in \mathrm{R}, u \in B, v \in \mathrm{B} \tag{7}$$

$$\sum_{v\in B} P_{ruv} \leq 1 \qquad \forall\, r \in \mathrm{R}, u \in B \tag{8}$$

The goal is to find the best possible value for the objective while adhering to the given constraints. The ILP outputs a set of interconnection links Z for achieving graph connectivity. Each objective addresses a minimization problem based on the optimization requirements, utilizing identical constraints and variables.

Equation 1 aims to minimize the total length of added links. Links are assumed to be added in a straight-line deployment, and that the distance between them is the length of the line segment between them. This conserves physical resources and reduces the complexity involved (e.g., deployment permit and local municipality permission) for deployment while ensuring network connectivity.

Equation 2 aims to minimize the total shortest path length between all the border nodes of the multi-domain networks. Path length is one factor that can influence latency, especially in networks where the transmission speed is a limiting factor, where delays can significantly impact real-time user experience. Border nodes manage the communication from the domain to external domains. Since information on internal domain communication is often not shared with external parties, a full mesh topology aggregation is used to mask the internal domain information and use only the information of the shortest path length between the border nodes as variable L_{uv}.

Equation 3 aims to minimize the total shortest path hop counts between the border nodes of the multi-domain networks. Minimum hop paths often result in lower energy consumption for data transmission since fewer intermediate nodes participate in the communication. Compared to Equation 2, minimum hop paths tend to be more resilient to node failures or environmental interference since they rely on fewer intermediate nodes for data forwarding. In contrast, minimum length paths may traverse longer distances and are more susceptible to signal attenuation or packet loss. Since minimum hop paths also usually involve fewer intermediate nodes, data can reach the destination node quickly, reducing latency.

Equation 4 ensures that any connection entering an intermediate node must exit it. Equations 5 and 6 ensure that each inter-domain link starts from border node s and ends at border node t. It is assumed that intra-domain connections are managed by each domain, respectively. Equation 7 ensures that paths are routed through viable links from the adjacency list A_{uv} or added in Z_{uv}, while ensuring that the interconnection link is undirected. Equation 8 ensures that the shortest path is a simple path. The optimum interconnection link addition candidate will be returned by the variable Z_{uv} at the end of the ILP execution.

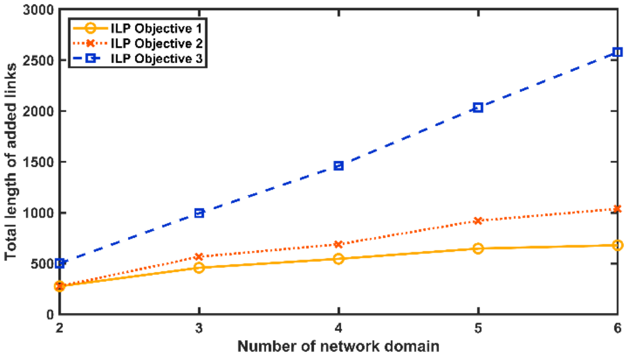
3.0 RESULTS AND DISCUSSION

The performance of the proposed ILP formulation was analysed in terms of total length of added links, average shortest path length, average shortest path hop count and computation time using randomly generated multi-domain networks. A random topology was generated for each domain using the Waxman graph model. The Waxman graph is chosen due to its unique property of decaying link existence over distance. Network physical locations are assumed to be mapped to a planar coordinate system. For each operator, |*N*| = 50 nodes are placed uniformly at random coordinates in the network area. Intra-domain link existence is reflected by $ie^{-l_{uv}/ja}$, where l_{uv} is the Euclidean distance between nodes *u* and *v*, and *a* is the maximum Euclidean distance between nodes. Higher *i* leads to higher link densities, and higher *j* increases the number of long links relative to short links, where *i* and *j* are set to 0.3 while ensuring that each generated topology is a connected graph. Link weight corresponds to the Euclidean distance between the nodes. All simulation results were averaged over a hundred runs on an 12th Gen Intel Core i5-1240P 1.70 GHz machine of 8GB RAM memory.

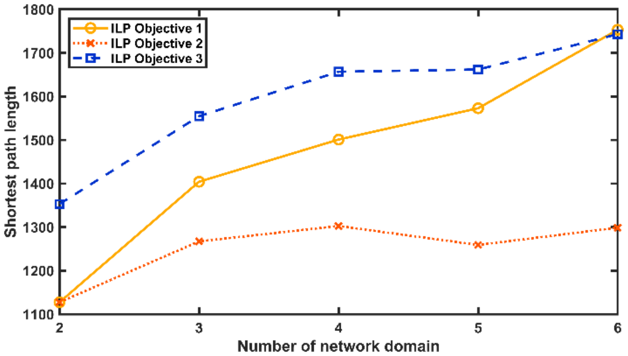
Figure 2a illustrates the correlation between the number of domains and the total length of added links for the three ILP objectives. The number of nodes per domain is set as |*N*| = 50, number of border nodes as |*B*| = 2 × |*D*|, and maximum permissible link additions |*Z*| are capped at |*D*-1|. If |*B*| = |*N*|, all the intra-domain nodes will be considered as border nodes, leading to very high computation time when the number of domains or nodes are high. As the number of domains increases, the total length of added links increases due to the necessity of incorporating additional interconnection links to establish connectivity among the disconnected domains, ensuring the existence of at least one path between all border nodes. ILP Objective 1, aim at minimizing the length of added links, results in the lowest total length of added links, up to 34.57% lower than ILP Objective 2 and up to 73.66% lower than ILP Objective 3 for the simulated scenarios. ILP Objective 2 and ILP Objective 3 often require longer interconnection links between border nodes to effectively decrease the overall shortest path length/hop counts across the network.

Figure 2b depicts the influence of the number of network domains on the average shortest path length. Since all domains are generated within the same network plane, there exists the potential for domain overlap contingent upon the spatial arrangement of individual intra-domain nodes. Consequently, the average shortest path length between border nodes generally increases with the increase in the number of network domains. Among the considered optimization objectives, ILP Objective 2 emerges as the most effective in minimizing the average shortest path length, up to 25.91% lower than ILP Objective 1 and up to 25.48% lower than ILP Objective 3 for the simulated scenarios.

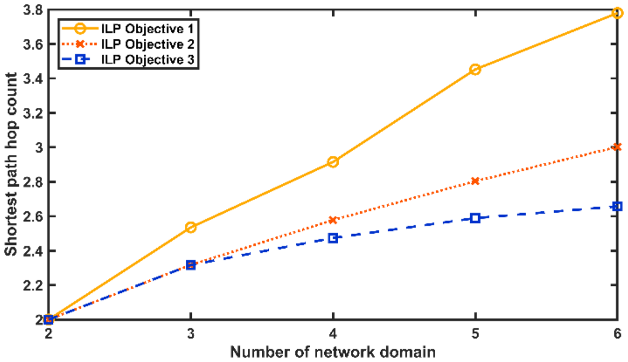
Figure 2c shows the effect of the number of network domains on the average shortest path hop count. As the number of domains increases, there is a consistent rise in the average shortest path hop count between border nodes since the inter-domain paths may need to traverse more domains before reaching their destination. ILP Objective 3 achieves the lowest average shortest path hop count, up to 29.68% lower than ILP Objective 1 and up to 11.50% lower than ILP Objective 2 for the simulated scenarios. While ILP Objective 2 is not as optimal as Objective 3, it still demonstrates a notable minimization of the number of hops as a by-product of minimizing the shortest path length. ILP Objective 1 comes last since it aims only to optimize the physical properties (length) of the interconnection links and does not consider the internal dynamics of the network.



(a)Total length of added links



(b)Average shortest path length



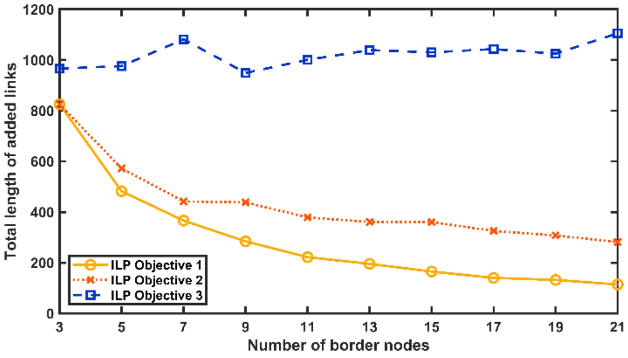
(c)Average shortest path hop count

Figure 2 Effect of number of domains (*N*=50, *B*=2×D, *Z*=*D*-1)

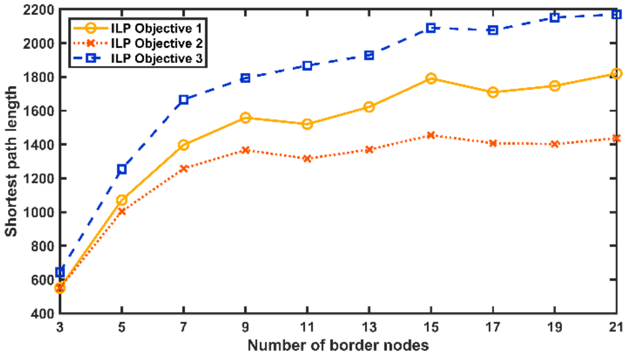
Figure 3a illustrates the correlation between the number of border nodes and the total length of added links. The number of nodes per domain is set as |*N*|= 50, number of domains as |*D*| = 3, and maximum permissible link additions |*Z*| are capped at |*D*-1|. Adding links to a network requires physical resources and monetary investment from network operators, altering the network's performance and dynamics. Managing a network with too many links can be complicated, administratively burdensome, and potentially lead to additional network risks. Selected border nodes are chosen from each network domain as fair as possible. As the number of border nodes increases, while the number of domains and the number of interconnection links are kept constant, the total length of added links decreases for ILP Objective 1 and ILP Objective 2 since the multi-domain networks are generated within the same network plane, such that the increase of border nodes per network domain decreases the average Euclidean distance between them. On the other hand, no apparent trend is discernible for ILP Objective 3, with up to 9.68 times higher than ILP Objective 1, since it aims to minimize the average shortest path hop count, which is not based on Euclidean distance and does not consider the length of interconnection links as in its optimization process.

Figure 3b and Figure 3c depict the influence of the number of border nodes on the shortest path length/hop count. Shortest path length/hop count between border nodes tends to increase with the increase of border nodes due to the densification of network connections. Increase in number of possible paths between pairs leads to a higher likelihood of longer paths between nodes. ILP Objective 2 emerges as the most effective in minimizing the average shortest path length, up to 21.02% lower than ILP Objective 1 and 33.73% lower than ILP Objective 3 for the simulated scenarios, while ILP Objective 3 emerges as the most effective in minimizing the average shortest path hop count, up to 9.31% lower than ILP Objective 1 and 9.93% lower than ILP Objective 2 for the simulated scenarios. Since ILP Objective 1 aims to optimize the physical properties (length) of the interconnection links, it fares better than ILP Objective 3 in reducing the shortest path length, which is also influenced by the interconnection link length, but worse for reducing the shortest path hop count, which does not depend on interconnection link length.

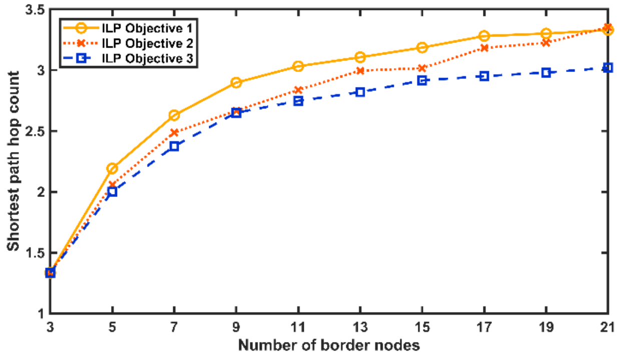
Figure 4a illustrates the correlation between the number of domains and the computation time. When the maximum number of link additions is restricted to *Z*=*D*-1, the ILP consumes more time to find the optimum link additions as the number of interconnection links increases. ILP Objective 1 consumes minimal time, up to 95.29% lower than ILP Objective 2 and up to 97.36% lower than ILP Objective 3 for the simulated scenarios, since it only considers the length of the interconnection links to be added as the optimization criterion. ILP Objectives 2 and 3 consume more time since they consider shortest path characteristics of the network as well, which can vary depending on the selection of interconnection links. ILP Objective 3 computes slower than ILP Objective 2 since finding the minimum hop path is often harder than finding the minimum length path, as it tries to minimize the number of links traversed regardless of their weights. Finding minimum hop path may involve exploring a larger portion of the graph compared to the minimum length path, making it computationally more demanding in certain cases. Hence, while an optimal solution might exist, finding the optimal solution in very large multi-domain network can be impractical to obtain within a reasonable timeframe using our ILP approach. However, utilizing topology aggregation has greatly reduce the computation time since its intra-domain nodes and links have been aggregated before the optimization.



(a)Total length of added links



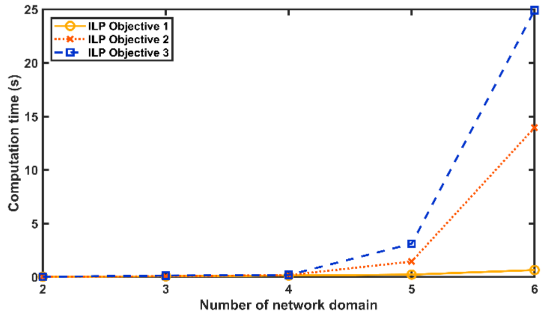
(b)Average shortest path length



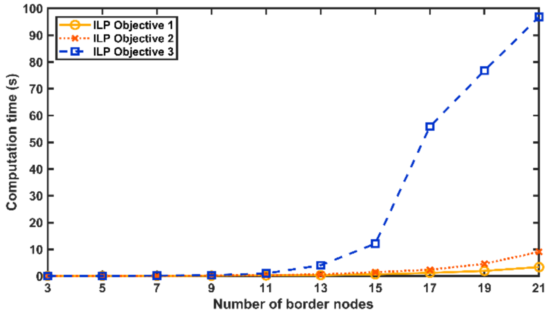
(c)Average shortest path hop count

Figure 3 Effect of number of border nodes per domain (*N*=50, *D*=3, *Z*=*D*-1)

Figure 4b illustrates the correlation between the number of border nodes and the average computation time for the three considered objectives. When the number of domains is kept constant, but the number of border nodes is increased, the computation time of the ILP also increases. However, considering only border nodes for link addition reduces the computational complexity compared to considering all the intra-domain nodes as well, which can be intractable in terms of computation time. In practical applications, candidate nodes for establishing communications to other domains are already predetermined since not all nodes carry the same importance or purpose within a network.



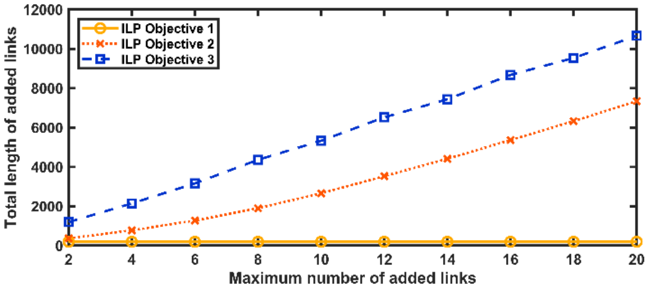
(a) Varying number of domains (N=50, B=2×D, Z=D-1)



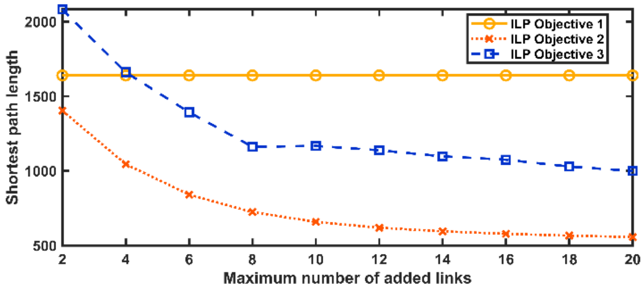
(b) Varying number of border nodes per domain (N=50, D=3, Z=D-1)

Figure 4 Computation time analysis

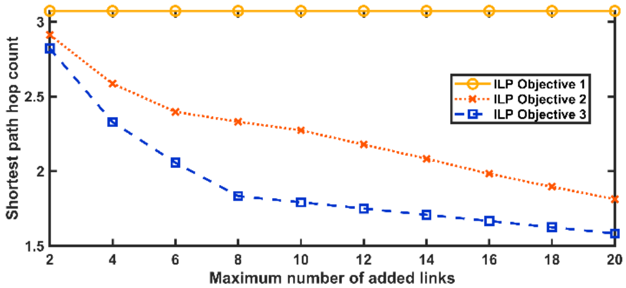
Figure 5a and Figure 5b illustrate the impact of the maximum interconnection link additions for the three ILP objectives. The minimum number of links that need to be added for achieving inter-domain connectivity depends on the number of domains, and not on the intra-domain nodes. Hence, topology aggregation can help in reducing the computation time. When restricted to a value higher than Z=D-1, the ILP consumes less time and improves the shortest path characteristics of Objectives 2 and 3, shown in Figure 5b and Figure 5c, compared to Z=D-1. However, this improvement comes with added interconnection links (the maximum allowed), as shown in Figure 5d. ILP Objective 1 aims to reduce link length by adding the minimum possible links. With a constant number of border nodes, once the maximum additions reach a certain value, computation time drastically decreases as shown in Figure 5e since most candidate link additions are used.



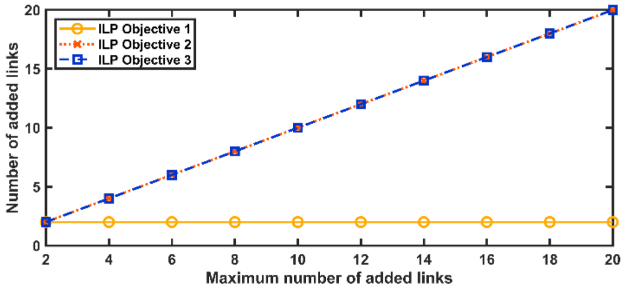
(a) Total length of added links



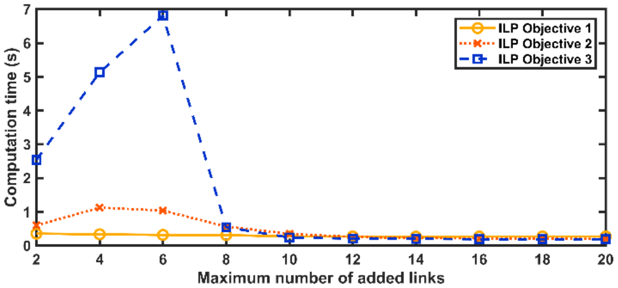
(b) Average shortest path length



(c) Average shortest path hop count



(d) Average number of added links



(e) Computation time

Figure 5 Effect of maximum number of link addition (*N*=50, *D*=3, *B*=12)

4.0 CONCLUSION

In this paper, an integer linear program was proposed for finding the optimum set of interconnection links to be added such that the multi-domain networks become a connected graph, while minimizing either (1) total length of added interconnection links, (2) total shortest path length between border nodes of the multi-domain networks, or (3) total number of shortest hop counts between border nodes of the multi-domain networks. Simulations on randomly generated multi-domain networks showed that the proposed integer linear program is capable of finding the optimum solution under various multi-domain networks properties. Finding the optimum solution while minimizing the shortest path length or hop counts proves to be more time-consuming than minimizing the total added link length, with up to 37.88 times slower computation time, but leads to better overall network performance, with up to 25.91% lower average shortest path length and up to 29.68% lower average shortest path hop count, at the cost of up to 9.68 times higher average added link length for the simulated scenarios. This highlights the importance of considering both physical attributes and internal network dynamics to comprehensively enhance the efficiency of multi-domain networks. For future work, the proposed ILP could be extended for achieving network biconnectivity, considering more complex network metrics as objective functions, eliminating cross-links to ensure non-overlapping inter-domain links, or proposing intelligent and faster exact or approximation algorithms for finding optimum solutions in larger size multi-domain networks.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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