

DIT and Beyond: Interdomain Routing With Intradomain Awareness for IIoT

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Abstract—Along with the ever-increasing amount of data generated from industrial devices, the cross domain [also known as autonomous systems (ASs)] data transmission problem has attracted more and more attention in the Industrial Internet of Things (IIoT). As mature and widely used interdomain routing protocols, border gateway protocol-based solutions often take the number of domains (i.e., AS hops) of each path as a criterion to make routing decisions, which is simple and effective. However, such protocols can only meet the reachability requirements while ignoring the performance requirements. That is, the path with the minimum AS hops will be selected to carry flows, even if the actual performance of this path does not meet the transmission requirements due to the unawareness of intradomain information on that path. But it is not impractical to directly access intradomain information for making better routing decisions given data privacy concerns. In this article, we propose M-DIT, which can make interdomain routing decisions with the assistance of desensitized intradomain information for multiple-requirement transmissions. To do so, we design a homomorphic encrypted-based private number comparison scheme to export intradomain information securely and, thus, assist in routing decisions. The results of some experiments based on five real topologies (*ATMnet*, *Claranet*, *Compuserve*, *NSFnet*, and *Peer1*) with thousands of interdomain flows demonstrate that M-DIT reduced flow completion time by about 60% or selected high bandwidth paths flexibly for interdomain routing for IIoT scenarios.

Index Terms—Interdomain routing, private number comparison, transmission protocol.

I. INTRODUCTION

THE Industrial Internet of Things (IIoT), as a vital infrastructure, facilitates the development and implementation

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of industrial technologies. In various fields, such as manufacturing, transportation, agriculture, energy, power grid, massive data, and messages generated from IIoT [1]. For example, as shown in Fig. 1, in the intelligent manufacturing scenario, the monitoring cameras upload recording files to the remote cloud server for analyzing and storing, and the industrial robots receive remote control signals from the remote cloud server [2], [3]. Generally, different services have different transmission requirements in terms of delay, bandwidth, forwarding hops, packet loss rate, etc., such as file transfer services prefer high-bandwidth routing path, while control signal transmission services require short latency. Moreover, with the decoupling of data storing and computation, such large-scale interdomain transmission services are becoming more and more common and important [4].

As the most commonly employed interdomain routing protocol, the border gateway protocol (BGP) takes the length of *AS_Path* as the routing priority metric by default [5], [6]. That is, the path with the minimum number of ASes has the highest priority [7], [8], [9]. Such a strategy regards all domains as indiscriminate blackbox and, thus, cannot make performance guaranteed interdomain routing decisions for industrial data transmission due to the lack of intradomain information. As depicted in Fig. 1, without loss of generality, assuming that an industrial terminal in an autonomous system (AS) *s* uploads data to a remote cloud server that belongs to AS *dl*, and there are three interdomain paths between *s* and *dl*: path \mathbb{A} with AS length of 4 ($s \rightarrow a1 \rightarrow a2 \rightarrow a3 \rightarrow dl$), path \mathbb{B} with AS length of 2 ($s \rightarrow b1 \rightarrow dl$), and path \mathbb{C} with AS length of 3 ($s \rightarrow c1 \rightarrow c2 \rightarrow dl$). Assuming the value shown in each AS represents the cost (e.g., delay) generated by crossing it, then \mathbb{A} (with cost 7) is with lower accumulated cost than \mathbb{B} (with cost 8) and \mathbb{C} (with cost 19). However, in line with the BGP routing principle (regardless of manually specified routing rules), \mathbb{B} , which has the fewest AS-hops, will be selected as the forwarding path. However, \mathbb{A} that outperforms \mathbb{B} under the given metric will be omitted from the routing table. Therefore, it can be observed that some intradomain information which can be leveraged to optimize interdomain routing policies should not be ignored.

Several studies are proposed to enhance the interdomain transmission performance by optimizing routing policies [10], [11], [12]. Lakshminarayanan et al. [13], Xiang et al. [14], Asharov et al. [15], and Pouryoucef et al. [16] employed software-defined networks architecture or assign reliable

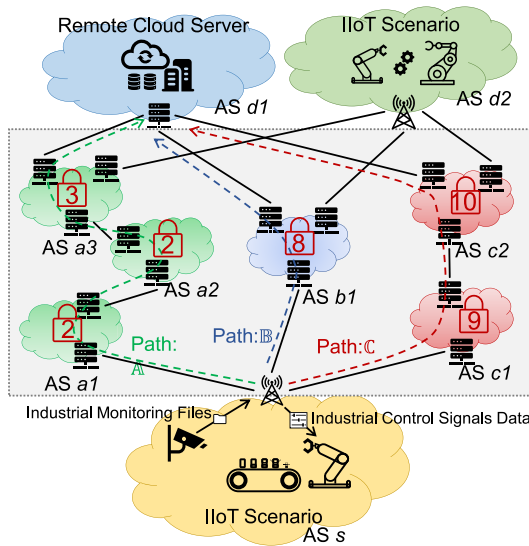


Fig. 1. BGP-based interdomain routing of IIoT scenario.

service systems to compute and distribute routing policies in centralized fashions. However, the centralized fashion has two downsides: 1) it relies on specific intradomain information to generate routing policies, which limits the deployment scope, e.g., such approaches are only suitable for the case where all domains are affiliated with trusted organizations and 2) it also suffers from unsatisfactory scalability. These downsides prevent the centralized fashion from utilizing the intradomain information for interdomain routing, and, hence, the BGP-based distributed protocol remains a practical approach. Given this, would it be practical to directly embed specific intradomain information into the header of BGP notification message packet and diffuse it to other ASes? Such a strawman way is not practicable as ASes affiliated with different organizations may refuse to provide the required intradomain information on account of privacy issues. Hence, bridging the gap between data sharing and privacy protecting remains a challenge.

To this end, we propose a BGP-based intradomain state-aware multirequirement interdomain routing policy for IIoT (M-DIT), which can be either implemented as a complement to the BGP internal functions or as a control plane function. M-DIT enables the accessibility of intradomain information while protecting the privacy of specific data (e.g., intradomain topology, links' status) at the same time, thus bridging the gap between data sharing and privacy protection. More specifically, M-DIT aims to represent the performance evaluation (forwarding hops, latency, bandwidth, etc.) of interdomain routing paths; however, as stated above, it is not secure to directly share the intradomain information by the BGP notification messages. Hence, for each metric of routing path evaluations, M-DIT basically adopts three schemes (*abstraction*, *confusion*, and *comparison*) to guarantee data privacy when notifying and diffusing intradomain information which can facilitate interdomain routing decision making. M-DIT only maintains the border routers (nodes) while ignoring the specific intradomain network topology, and builds weighted virtual connections (edges) between each pair of nodes (*Topology Abstraction*). By doing this, it not only

can mask the topology and employed protocol of intradomain but also preserve the required intradomain information for interdomain routing (Section IV-A1). To prevent intradomain information (the state of links between pairs of nodes of the domain) from being leaked during route notification and diffusion, M-DIT adds a random number to each route before notifying it to neighboring domains from the source domain (*Random Number Confusion*). It protects the state privacy of the intradomain path from the border router to the destination and does not affect the result of the routes priorities calculation (Section IV-A2). Moreover, avoid leakage of intradomain information during route diffusing, we designed a homomorphic encryption (HE)-based algorithm that can compare priorities of paths without exposing specific values (*Private Number Comparison*, Section IV-C). Further to this, M-DIT is extended to multirequirement transmission scenarios which can provide flexible interdomain routing decisions for different types of flows with multiple specified metrics.

We exhibit the advantages of M-DIT by embedding it in the worldwide implemented BGP using five real-world topologies and thousands of simulated flows. The results show that, for the selected representative metrics (flow completion time (FCT), path bandwidth), M-DIT can enable BGP to reduce about 60% FCT on average or select high-bandwidth path preferentially for routing in multiple requirements transmission scenario. In summary, the following outlines our contributions in this article.

- 1) We expose that a series of BGP-based protocols unable to provide optimal interdomain forwarding path for the multiple requirements transmission owing to the unawareness of intradomain state.
- 2) We propose M-DIT, which can select the optimal interdomain path for IIoT and beyond by leveraging HE algorithms to sense intradomain information without leaking it.
- 3) We exhibit the promotions of M-DIT in contrast to traditional BGP-based protocols, by deploying some experiments on different scales in five real network topologies with multiple routing requirements.

This article is structured as follows. We review background and related works in Section II. In Section III, we specify the motivation and design principle of M-DIT. In Section IV, we describe M-DIT in detail. We demonstrate experimental results in Section V. Finally, we summarize this work in Section VI.

II. BACKGROUND AND RELATED WORK

In this part, we first present the background of this work from three aspects, i.e., BGP, multiple requirements routing, and HE. And, correspondingly, we exhibit developments and research status of them.

A. Background

1) *Border Gateway Protocol*: Currently, as one of the most widely employed routing protocols among domains, BGP enables to glue a vast volume of ASes distributed all around the world together. Each domain takes its border gateway/router which implemented the external BGP as the egress

and ingress for exchanging route entries to peers, the others inside routers execute the internal BGP. The content of the *AS_PATH* field of each route entry indicates the length of the forwarding path in AS granularity, but it exclusively ignores the varying internal transmission capabilities of each AS.

BGP mainly includes four type messages: 1) OPEN; 2) UPDATE; 3) NOTIFICATION; and 4) KEEPALIVE. The UPDATE is utilized to notify and withdraw route entries, which mainly includes three features for route selecting: 1) *AS_PATH*; 2) *MULTI_EXIT_DISC (MED)*; and 3) *LOCAL_PREF*. *AS_PATH* is used to keep track of which ASes a route has crossed during transmission. The router will reject all route entries that contain its own AS number, which can be used for loop-proof and also for path selection, i.e., the shorter the *AS_PATH* the better. *MED* is announced by neighbor AS to discriminate its multiple export ports. By default, for the same neighbor AS, the lower *MED*, the higher the priority of the export port. *LOCAL_PREF* is usually configured manually by the local administrator. When an AS has multiple egress routers, the router with the largest *LOCAL_PREF* value will be set as the egress.

Manually configuring on the basis of experience is a preferred manner of interdomain routing in the current network. However, it still has limitations in inflexibility or incorrect configuration, for example, the global service disruption at Meta due to careless configurations by engineers [17]. Auto-configuration for the evolving network is becoming a developing trend. The inability of sensing the interdomain state, the current BGP can only provide a connectivity guarantee that selects the forwarding path according to *AS_PATH* by default. However, with the ever-increasing volume of network traffic and the multiple requirements of services, the disadvantages introduced by ignoring intradomain capabilities will be increasingly visible.

2) *Multiple Requirements Routing*: Multiple requirements transmission, also referred to as multiple optimality criteria routing and multiple objective routing in some work, is a routing strategy to support the development of diverse network services. There are different priorities for different services regarding latency, bandwidth, packet loss, forwarding hops, and other metrics. Routing strategies-based only on reliability or a single metric are overstretched for modern networks, which makes the research of multiple requirements transmission more valuable.

Typically, the metrics can be divided into two categories: 1) accumulative type and 2) bottleneck type. For accumulative-type metrics, the final routing path performance is impacted by cumulative qualities of every traversed link, which is commonly calculated by addition or multiplication, such as delay, forwarding hops, and packet loss rate. The final path quality corresponding to the bottleneck-type metrics is determined by the extreme values of all the links traversed, which can be calculated by $\min()$ or $\max()$, e.g., the link bandwidth.

3) *Homomorphic Encryption*: HE is a cryptographic method, which can perform arithmetic calculations on ciphertext and get an equal result with encrypted form to performing specified calculations on plaintext of these ciphertext [18]. Hence, it may provide a potential solution to bridging the

gap between information sharing and privacy protecting. Concretely, HE can be demonstrated as follows:

$$De(En(a) \odot En(b)) = a \oplus b \quad (1)$$

where $En()$ is the encryption operation, $De()$ is the decryption operation, and \odot and \oplus correspond to the operations on the plaintext and cyphertext domains, respectively. When \oplus represents addition, this encryption is an additive HE, and when \odot represents multiplication, this encryption is a multiplicative HE. The encryption function that satisfies both additive and multiplicative homomorphism properties and can perform any times of additive or multiplicative operations is called fully HE.

HE algorithms, especially, complete ones, suffer from high computational complexity. Nevertheless, it is merely necessary to calculate little numbers on the condition of additive HE in this work. Then, it will avoid the potential issues introduced by the complex calculation of HE algorithms. Inspired by the feature of HE algorithms, we exploit an additive HE-assisted intradomain state sensing scheme without data leaking, whose details will be introduced in Section IV.

B. Related Work

1) *Enhancement of BGP*: BGP is the most widely deployed interdomain routing protocols on the Internet. There are several works dedicated to optimizing it in terms of convergence, security, etc. [6], [19], [20]. Milani et al. [21] aim to accelerate the BGP convergence process by decreasing the route notification time according to the domain-level topology and validate this scheme through a series of experiments. Brenes et al. [8] relieved the traffic losing during the reconverging process of BGP by ordering the prefixes based on the unbalanced traffic distribution. García-Martínez and Bagnulo [22] designed a route collector&beacon-based scheme to facilitate the time synchronizing between source and destination device systems of BGP route. Given the achievements of blockchain in information security areas, many studies have used it to enhance the security of BGP [23], [24], [25]. He et al. [26] proposed a decentralized architecture based on blockchain technology, ROA chain, which specifies every AS enable to verify the route source and prevent prefix hijacking based on a globally consistent and tamper-resistant database. There are some works attempting to dedicate deep learning to address BGP issues regarding security, configuration, and more [27], [28], [29].

2) *Interdomain Routing Schemes*: There are several works that focus on the optimization of interdomain routing policies, which are commonly categorized into two types [5], [30], [31], [32], [33], [34]. The first type is built on the architecture with a dedicated third party (e.g., a controller) [13], [15], [16], [35], [36], [37], [38]. Xiang et al. [14] based on the idea of the software defined network to design a new software defined interconnections-based network architecture for the cross-domain scenario, which enables senders to define interdomain forwarding path via a programmable interface. Straightforwardly, Pouryousef et al. [16] exploited the strong performance of the Cloud server in terms of bandwidth and computing power to accelerate the computation and convergence of interdomain protocols.

With the development of machine learning, many researches have applied it to network system. Reinforcement learning has recently been employed in traffic engineering decision-making scenarios. Zhao et al. [38] presented a extensible RL-based framework with multiple layers to facilitate cross domain transmission performance. Nevertheless, the same precondition of above schemes is employing dedicated managers to guarantee the effectiveness and impenetrability of corresponding data. The practical feasibility of such a idealized architecture is pending further discussion. Tunnel-based overlay architectures are concluded as the second type [39], [40], [41], [42], [43], whose essential approach is making it feasible to select a specified forwarding path by allowing ASes to establish tunnels between each other. In this circumstance, the overhead of each tunnel, i.e., the forwarding path, can be captured directly. However, the feature that tunnel information is not exposed to other ASes may lead to security issues, which makes it difficult to be accepted by network organizations. Furthermore, such tunnels are only notified within related domains for converging purpose of interdomain routing, which may lead to undetectable traffic agreements to ISP. Given that, the deployment of these schemes may not be acceptable by ISPs.

3) *Multiple Requirements Routing*: As a classical problem, the multiple requirements routing research mainly involves intradomain routing scenarios, which can be divided into two main categories [44], [45].

- 1) The first is machine learning-based architecture. Liu et al. [46] leveraged reinforcement learning in intradomain routing scenarios with multiple types of services to improve network transmission performance and utilization, etc. Cong et al. [47] extended the single-metric routing problem to multimetric scenarios by using model fusion fashion.
- 2) The second is algebra-based strategies. Sobrinho and Ferreira [44] designed a network routing model with multimetric and associated protocol, which tried to solve the interdomain routing problem with multiple optimization criteria via a fully distributed approach. Moreover, to address the delayed convergence problem present in this work, Garcia-Luna-Aceves et al. [48] introduced DRIP, which is loop-free at every instant and can guarantee the convergence of feasible or optimal routing paths.

These works are hardly migrated to tackle interdomain multiple requirements routing directly. Although Sobrinho’s work has been extended to interdomain routing [49], it is still premised on requiring the necessary intradomain information, which is not in line with the purpose of this work.

4) *Homomorphic Encryption*: The widely used partial HE schemes include Benaloh [50] and Paillier [18] algorithms for additive homomorphism, Rivest et al. [51], and ElGamal [52] algorithms for multiplicative homomorphism, and Goldwasser and Micali [53] algorithm for bitwise homomorphism. These classical partial HE schemes are highly secure and computationally efficient and can guarantee data security and meet the computational efficiency requirements for eligible application scenarios. Gentry [54] proposed the first fully

Path	AS-path	BGP Priority	State	Evaluation
$\mathbb{B}:[d1, b1, s]$	3	↑↑↑	selected	$\ominus = \delta(\ominus)$
$\mathbb{C}:[d1, c1, c2, s]$	4	↑↑	ignored	$\ominus = \delta(\ominus, \ominus)$
$\mathbb{A}:[d1, a1, a2, a3, s]$	5	↑	ignored	$\ominus = \delta(\ominus, \ominus, \ominus)$

Fig. 2. Routing table of AS s .

HE method according to the ideal lattice from a theoretical perspective, which caused a surge of research on fully HE in academia. Subsequent work has been based on Gentry’s work and is aimed at reducing computational overhead, improving computational efficiency, and taking into account security. Theoretically, the fully HE scheme is the best choice to protect data confidentiality without losing data availability, but the high overhead of the scheme, the computational model, and the high security make it impossible to be applied in practice. The high overhead of the fully HE scheme make it impossible to be applied in practice. However, scholars have since proposed somewhat HE [55], which is only applicable to low-order polynomial operations and allows only a limited number of homomorphic additions and multiplications on the encrypted data.

III. MOTIVATION AND DESIGN PRINCIPLE

In this section, we first introduce the motivation of this work. Then, on basis of the motivation, we further clarify the design principle of M-DIT.

A. Motivation

The routing table of AS s in the above example is shown in Fig. 2. Path \mathbb{B} will be selected as the forwarding path due to the smallest AS_PATH value than that of path \mathbb{A} and \mathbb{C} . When considering the cost or link quality of the ASes as described previously, i.e., evaluating the performance of end-to-end interdomain transmission, however, \mathbb{B} is actually not the optimal path. For example, when the value shown in each AS indicates the delay, then $\mathbb{A} > \mathbb{B} > \mathbb{C}$ ($\text{sum}(2, 2, 3) < \text{sum}(8) < \text{sum}(9, 10)$); while, if the value indicates the bandwidth, then $\mathbb{C} > \mathbb{B} > \mathbb{A}$ ($\text{min}(9, 10) > \text{min}(8) > \text{min}(2, 2, 3)$), where $>$ means *better than*.

How to simultaneously satisfy the requirements of exporting intradomain information, privacy protection, and ensuring the correctness of routing calculation is the key to addressing this issue. Then, on top of this, it is possible to leverage the accumulated intradomain data as an additional attribute of the local routing information base to aid in routing decisions. Although the motivated example is explanatory, it can be seen that the influence of intradomain status on interdomain transmission is nonnegligible. In other words, intradomain information awareness will be beneficial when making interdomain routing.

B. Design Principle

To eliminate the conflict of information sharing versus data leakage, a scheme that is aware of but does not leak intradomain data is necessary. Therefore, we specify these two requirements in detail.

- 1) *Exporting Information*: The performances of interdomain paths are corporately affected by abilities of all links that contained by traversed ASes, so it is necessary to notify such beneficial information along the path with a specified form to facilitate interdomain routing. Such information mainly includes the performance evaluation of an intradomain path regarding delay, bandwidth, packet loss, hops, and more.
- 2) *Protecting Privacy*: For security reasons (e.g., it is possible to infer the detailed network topology of the domain by forwarding hops) or business reasons, the exported data by each AS should not be captured or inferred by others. This security guarantee is also a prerequisite for each AS to provide such relevant information.

Detailed schemes of how M-DIT satisfies the design principles are exhibited in Section IV.

IV. M-DIT METHODOLOGY

In this section, without loss of generality, M-DIT is illustrated by using the accumulated forwarding hops as an evaluation metric. On this basis, we explain the differences in the computation of bottleneck-type metric and extend M-DIT to multiple requirements interdomain routing. Finally, the incremental deployability, as well as the flexibility of M-DIT, are discussed.

A. M-DIT Overview

The field used to assist in routing path selection in the BGP header is *AS_Path* by default [5], which is also used for free-loop guarantee, then we introduce a new header field (*Attr*) to carry performance evaluation of the interdomain path for M-DIT. Alternatively, the existing fields of BGP header (such as *MED*) can also be redefined and reused to simplify implementation.

1) *Topology Abstraction*: In the current network architecture, on the one hand, the intradomain routing policy is independent of the interdomain routing protocol, that is, each domain forwards incoming traffic to the egress border router along a specified path determined by the employed intradomain protocol; on the other hand, the interdomain paths of BGP are granularized by border routers, which means that the next hop specified by the forwarding path is the border router of a domain [7]. Then, the performance evaluation of the path from ingress to egress of a domain is sufficient to be the intradomain information which can be utilized to promote the generating of interdomain routing polices.

It is reasonable to abstract each detail intradomain topo into a graph which only contains all border routers. Given the connectivity within a domain, there are direct links or indirect connections between all border router (node) pairs, and these links and connections are recognized as edges in the graph. The *Abstraction* example is depicted in Fig. 3. It is acceptable to maintain these paths' performance of a domain. First, some protocols operating in domains or controllers of software-defined network architectures commonly maintain such information, e.g., the OSPF routing protocol maintains

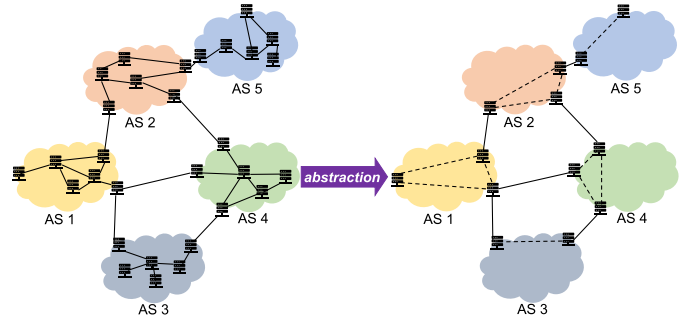


Fig. 3. Topology abstraction.

the forwarding hops of intradomain paths. Alternatively, the complexity of additional maintenance of the required peer-to-peer path information is $O(N^2)$, where N is the number of border routers of a domain and is generally a small number. By doing so, it is possible to mask some intradomain details while preserving essential information.

2) *Random Number Confusion*: When path information (which can be assumed as the forwarding hops from the ingress to the egress router for ease of understanding) is embedded into the BGP header directly and notified to neighboring domains, the accumulated computation (addition for forwarding hops) of multiple domains during route diffusion can inherently protect the information privacy. It can be directly explained from mathematical perspective that specific values of the two elements cannot be inferred from their sum, i.e., $c \rightarrow a$ and $c \rightarrow b$, where $a \in \mathbb{R}$, $b \in \mathbb{R}$, and $c = a + b$. Moreover, such mathematical characteristic is one of the basic principles for privacy guarantee in M-DIT design. In the case of Fig. 3, assuming that AS5 receives a route to a destination belonging to AS1 via AS2, it cannot infer the specific intradomain information corresponding to AS2 and AS1 from the cumulative path information carried in this route.

However, the inherent information protection of the aforementioned accumulated computations is only valid when such computations have been performed at least one time. For example, AS2 can obtain some intradomain information about AS1 from the routes notified by AS1 that the destination belongs to it. Consequently, when notifying the route from its destination belonged domain to directly connected neighboring domains, the protection of accumulated computation will fail, which is named the *Direct Connection* (\leftrightarrow) leakage in this article.

To this end, we design the *Random Number Confusion* to fix such leakage. The performance evaluation values of different paths to the same destination are only used to compare relative magnitudes, therefore, the absolute values of these data do not affect the routing results as long as the relative relations remain constant. Mathematically explaining, according to the inequality principle, adding or subtracting the same value on both sides of an inequality simultaneously will not affect the comparing result. That is, if $\exists a, \exists b \in \mathbb{R}^+ \rightarrow a < b$, then $\forall c \in \mathbb{R} \rightarrow a + c < b + c$. Alternatively, it can also be understood as assigning a fixed random offset to all nodes of a coordinate system will not shift their relative positions.

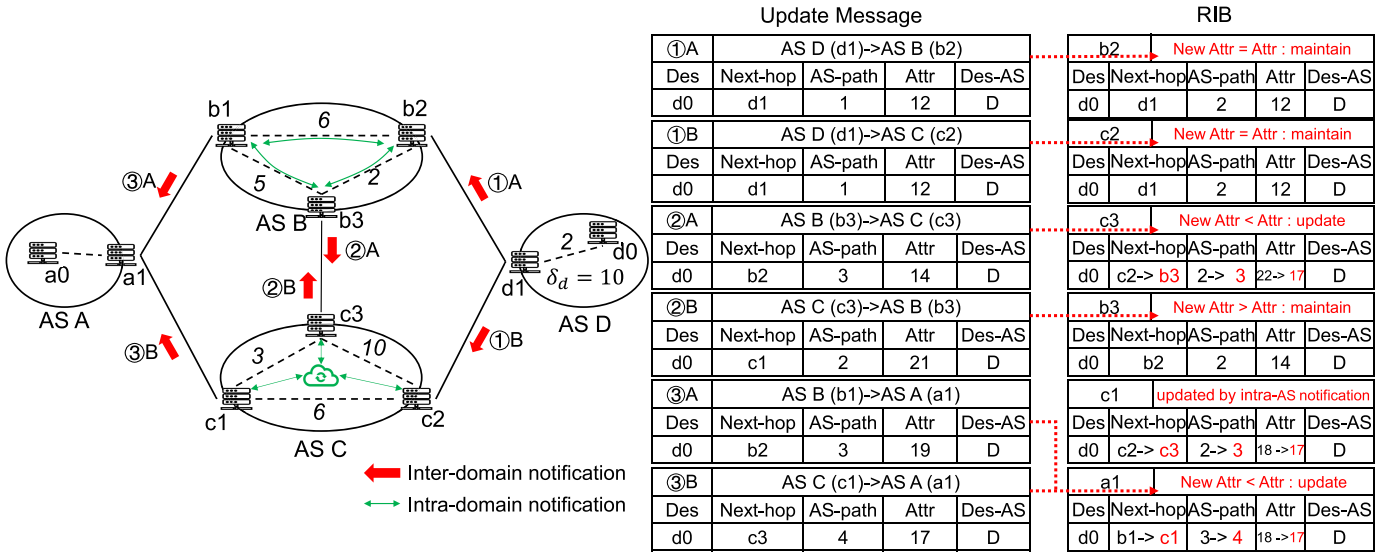


Fig. 4. Diffusion illustration: MSGs diffusion and RIB updates of M-DIT triggered by new routes.

M-DIT stipulates that the destination's domain adds a specified random value to the initial intradomain information before notifying the route to neighbor domains. This process can be defined as

$$d_{\text{Notified}} = d_{\text{initial}} + \delta_d \quad (2)$$

where d_{Notified} , d_{initial} , and δ_d are the notified value, the initial value, and the corresponding specified random value of the routes with destination d , respectively. The indeterminate δ_d makes it impossible for neighboring domains to obtain the corresponding intradomain information, which can also remain the correctness of the route computation result during subsequent route diffusion.

As a result, M-DIT is able to address the *Direct Connection* (\leftrightarrow) leakage by employing accumulated computation coupled with *Random Number Confusion* without shifting the routing selection.

3) *Information Diffusion*: In this work, we define and add a new field *Attr* for the BGP header to carry the mentioned data. However, this solution is optional and it is feasible to redefine and reuse existing fields, such as *MED*. Then, the quantified evaluation of the routing path performance will be written in *Attr* of the BGP update message (MSG).

Whether the domain is running traditional protocols (AS_B of Fig. 4) or based on the software-defined architecture (AS_C), it is permitted as long as the *Attr* field can be processed accurately according to M-DIT. Assuming that the route of $d0$ is updated, AS_D ($d1$) will send this update to AS_B ($b2$) and AS_C ($c2$). The *Attr* of update MSG is 12 ($\delta_d + 2$). $b2/c2$ determines whether updates local route or not by comparing the *Attr* value of received MSG with the local route. The corresponding route will be refreshed if its *Attr* is greater than the newly received *Attr*. And vice versa. In the interior of AS_B/AS_C , this route update will be exchanged by intradomain protocol/controller. After the internal exchange, AS_B diffuses the update MSG to AS_C , where *Attr* is summed by two components: 1) the

performance of intradomain forwarding path ($b3, b2$) (the qualified value is 2) and 2) the *Attr* value received from $b2$ (12). That is, the value of *Attr* in this MSG is 14 ($2 + 12$). Similarly, AS_C ($c3$) sends an update MSG with *Attr* = 21 ($3 + 6 + 12$) to AS_B ($b3$). $c3$ will update the corresponding local route due to the received *Attr* from $b3$ is smaller than the local value. On the contrary, $b3$ will do not modify local RIB. Then, AS_B ($b1$)/ AS_C ($c1$) send update MSG to AS_A ($a1$) with *Attr* is 19 ($b1, b3, b2, d1$)/17 ($c1, c3, b3, b2, d1$). Finally, $a1$ updates the forwarding path to destination $d0$ for AS_A according to these received messages. Then, $a1$ will assign $c1$ as the next hop for traffic with destination $d0$ based on the new route entries.

B. Delta Trap

The proposed schemes so far appear to guarantee data privacy, but there is still a potential risk of information leakage during routing diffusion. Then, this leakage risk will be introduced for convenience from the description of a simple mathematical problem. Given b_1 and b_2 are known, where b_1 equals $a_1 + a_2 + a_3$ and b_2 equals $a_1 + a_2$. It is possible to obtain a_3 from the difference (*Delta Trap*, Δ) between b_1 and b_2 , even if both a_1 and a_2 are unknown ($a_3 = b_1 - b_2$). This problem is mapped to the information leakage problem in route diffusion as follows: in Fig. 4, after receiving the routes about $d0$ from AS_D and AS_C successively, due to the information of *AS_Path*, AS_B ($b3$) can obtain intradomain information about AS_C based on the difference between the two routes' *Attr* (the intradomain routing policy of $c2$ to $c3$ and corresponding path state, $[c2 \rightarrow c1 \rightarrow c3]$), which is a potential risk for AS_C . However, adding a random value to *Attr* is not applicable for routes with destinations outside local domains. The proposed *Random Number Confusion* would shift the result of subsequent route computation, which can be described as " $x_1 > x_2 \rightarrow x_1 > x_2 + \delta \mid x_1, x_2, \delta \in \mathbb{R}$ " from a mathematical perspective.

To address the aforementioned issues, we further propose *Private Number Comparison* for M-DIT.

C. Enhanced M-DIT

Delta Trap (Δ) is caused by receiving two routes destined for the same destination, where one traverses one additional domain than the other. Topologically describing, the domains in a triangular connection suffer from such information leakage risk during route diffusion. This risk can be eliminated by breaking the triangular connection in the topology provided keeping the forwarding path unaffected, i.e., logically masking links between connected domains that are not on the optimal routing path.

To this end, we propose *Private Number Comparison*, which can complete the comparison calculations without disclosing the specific values of all three parties. Then, the comparison results can assist in masking nonoptimal links from the topology during route diffusion. In the following, the adopted HE algorithm and the specific workflows of *Private Number Comparison* will be presented in detail.

1) *Homomorphic Encryption*: The cryptosystem generally uses public/private keys to encrypt/decrypt the plaintext/ciphertext. Paillier, a classical HE method [18], is employed in this work, whose processes of keys generation, encryption, and decryption and homomorphism of addition are as follows.

- 1) *Key Generation*: Randomly selecting two large prime numbers p and q that satisfy $\gcd(pq, (p-1)(q-1)) = 1$, and calculating $n = pq$ and $\lambda = \text{lcm}(p-1, q-1)$. And randomly selecting integer $g \in \mathbb{Z}_{n^2}^*$, and calculating $\mu = (L(g^\lambda \bmod n^2))^{-1} \bmod n$, where $L(u) = (u-1)/u$, for $\forall u \in \{u < n^2 \mid u = 1 \bmod n\}$. Then, the public key is (n, g) and private key is (λ, μ) .
- 2) *Encryption*: For plaintext $m \in \mathbb{Z}_n^*$, its encrypted ciphertext is $c = g^m \cdot r^n \bmod n^2$.
- 3) *Decryption*: For ciphertext $c \in \mathbb{Z}_{n^2}^*$, its decrypted plaintext is $m = L(c^\lambda \bmod n^2 \cdot \mu) \bmod n$.

Assuming that $r_1, r_2 \in \mathbb{Z}_{n^2}^*$ are two random integers, for the plaintext m_1 and m_2 , their ciphertext are $En(m_1) \equiv g^{m_1} \cdot r_1^n \bmod n^2$ and $En(m_2) \equiv g^{m_2} \cdot r_2^n \bmod n^2$, respectively. Then

$$\begin{aligned} En(m_1) \cdot En(m_2) &\equiv g^{m_1} \cdot r_1^n \cdot g^{m_2} \cdot r_2^n \bmod n^2 \\ &\equiv g^{m_1+m_2} \cdot (r_1 \cdot r_2)^n \bmod n^2 \\ &\equiv En(m_1 + m_2). \end{aligned}$$

As $r_1, r_2 \in \mathbb{Z}_{n^2}^*$, then $r_1 \cdot r_2 \in \mathbb{Z}_{n^2}^*$, so the Paillier cryptosystem is additive homomorphic. Hence, in this work, Paillier is subtly applied during the number comparison process to prevent specific values from being disclosed.

2) *Private Number Comparison*:

Traps Detection: It is necessary to detect triangular connections from the domain topology. The first step is adjacent domains exchange locally maintained neighboring domains list. The second step is that each domain calculates the corresponding triangle connection according to Algorithm 1. This process can be operated by specific applications or existing BGP messages.

Although this algorithm is designed for the case of directed links between domains, it can still be adapted to the undirected link scenario by simply removing duplicated triangle elements.

Algorithm 1: Δ Detection

```

1 get_neighbors(AS): get AS's neighbor list
Input: neighboring domains lists
Output: the triangular connections list of AS
2 for  $i$  in get_neighbors(AS) do
3   for  $j$  in get_neighbors( $i$ ) do
4      $res.append([AS, i, j])$ 
5 return  $res$ 

```

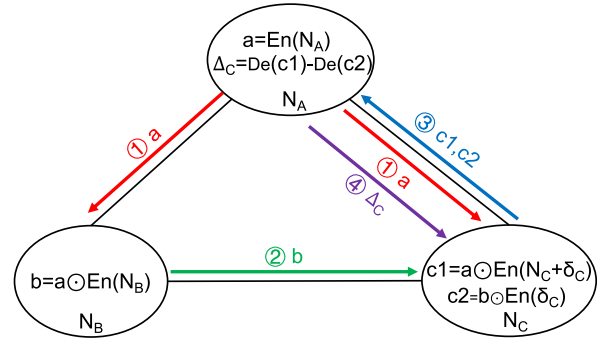


Fig. 5. Workflows of *Private Number Comparison*.

Moreover, the triangle connection remains stable provided that links between domains remain unchanged.

Comparing Paths: In the generic triangular topology, as shown in Fig. 5, path comparison and selection would be accomplished by communicating with each other, which is described as pseudo code Algorithm 2.

Suppose A , B , and C , each of which is responsible for local values, N_A , N_B , and N_C , respectively. First, A sends encrypted N_A by private key of A , $En^A(N_A)$, to B and C . After receiving the MSG from A , B sends $En^A(N_A) \odot En^A(N_B)$ to C , where \odot represents homomorphic addition calculation, which means $En(x) \odot En(y) \equiv En(x+y)$. After receiving the MSG from A and B , C sends $En^A(N_A + N_B) \odot En^A(\delta_C)$ and $En^A(N_A) \odot En^A(N_C + \delta_C)$ to A in the specified order. After receiving the MSG from C , A decrypts and subtracts the two values, $De^A(En^A(N_A + N_B + \delta_C)) - De^A(En^A(N_A + N_C + \delta_C))$, and get the signed delta value Δ_C , which will be sent back to C . Finally, according to Δ_C , C and A can determine the priority of the two paths, $Path_{(C \rightarrow A)}$ and $Path_{(C \rightarrow B \rightarrow A)}$.

The reason why A has to send N_A to B and C is that the cost of C or B through A to the same border router of A during interdomain transmission may be different, i.e., the N_A sent by A to B and C is the respective corresponding cost, and this comparison algorithm is still feasible.

The confidentiality of the entire comparison process is explained here. The value sent by A to B and C is encrypted and cannot be decrypted by B and C with public keys, and likewise, the value sent by B to C cannot be deciphered. The malicious case of forcing to break the encryption algorithm is not considered here. The two values sent by C to A use the confusion strategy by adding a random value, which makes A only can get Δ_C after decryption.

Constraining Diffusion: In the case of Fig. 4, if the AS_C does not receive the route update from AS_D , it would not

Algorithm 2: Comparison

```

1 En( $x$ ): encrypt  $x$ 
2 De( $x$ ): decrypt  $x$ 
3 Send( $[x_1, x_2]$ ,  $[D_1, D_2]$ ): send  $[x]$  to  $[D]$ 
4 Rec( $MSG$ ): receive message  $MSG$ 
   Input: the connection of  $(A, B, C)$ 
   Output: comparing result
5 AS A:
6    $ena = \text{En}(N_A, key_A)$ 
7    $A.\text{Send}(ena, [B, C])$  // marked  $MSG_1$ 
8 AS B:
9    $na = B.\text{Rec}(MSG_1)$ 
10   $enb = na \odot \text{En}(N_B, key_A)$ 
11   $B.\text{Send}(enb, C)$  // marked  $MSG_2$ 
12 AS C:
13   $na = C.\text{Rec}(MSG_1)$ 
14   $nb = C.\text{Rec}(MSG_2)$ 
15   $enc = na \odot \text{En}(N_C + \delta_C, key_A)$ 
16   $enb = nb \odot \text{En}(\delta_C, key_A)$ 
17   $C.\text{Send}([enc, enb], A)$  // marked  $MSG_3$ 
18 AS A:
19   $nc, nb = A.\text{Rec}(MSG_3)$ 
20   $nb = \text{De}(nb, KEY_A)$ 
21   $nc = \text{De}(nc, KEY_A)$ 
22   $\Delta_C = nc - nb$ 
23   $A.\text{Send}(\Delta_C, C)$  // marked  $MSG_4$ 
24 AS C:
25   $\Delta_C = C.\text{Rec}(MSG_4)$ 

```

cause intradomain information leakage and will also properly update the local RIB based on the route received from AS_B . Therefore, M-DIT constrains the route diffusion for the triangle-connected domains on the basis of the comparison results. As shown in Fig. 6, the constraint can be divided into two cases: 1) if B and C forward traffic with the same destination via A as the corresponding optimal path, then A will set a flag “ $TAG_\Delta = 1$ ” when notified of the related route to declares that B and C are forbidden to notify this route to each other and 2) it is assumed without loss of generality that path $[C \rightarrow B \rightarrow A]$ is better than $[C \rightarrow A]$, then A only notifies the corresponding route to B with flag “ $TAG_\Delta = 0$,” which means B can notify this route to C . And C will inherently avoid notifying this route back to A according to the loop-free property of BGP.

D. Completeness Analysis of Privacy

The enhancement of interdomain routing by leveraging intradomain information requires protecting the data of each domain from being obtained by others, which can be modeled as an equation solving problem. During the convergence of a route, domain S accumulates maintained local transmission performance $cost_S$ (e.g., forwarding hops) on the $Attr$ coming

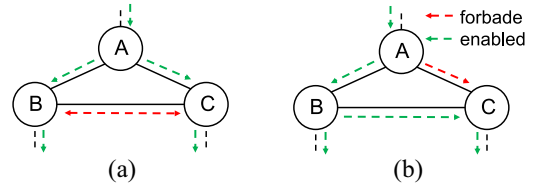


Fig. 6. Constraint illustration. (a) Constraint type 1. (b) Constraint type 2.

upstream and spreads downstream. Thus, each domain can obtain an equation $Attr_i = \sum_J^{AS_PATH_i} cost_J$ based on the $Attr$ and AS_PATH of route i . Privacy protection aims to prevent any domain from inferring any $cost_J$ from a series of equations generated by different routes of local RIB. In the following, we first mathematically model the problem and then prove the privacy completeness of the M-DIT.

1) *Formulation:* We define the cumulative cost for domain S of being forwarded by its border router j to domain D is

$$COST_S^{j \rightarrow D}. \quad (3)$$

Then, based on different n border routers, S can obtain the set of equations \mathbb{C}

$$COST_S^{i \rightarrow D} = y_i, i \in n \quad (4)$$

where y_i is the value of $Attr$ of each related route i . Each $COST_S^{j \rightarrow D}$ can be expressed in the form of a cumulative sum of the $cost$ of route i . So the set \mathbb{C} can be converted as

$$cost_{AS_0}^D + cost_{AS_1}^D + \dots + cost^D = y_i, i \in n \quad (5)$$

where $cost_{AS_j}^D$ represents the cost of the j th domain of the path forwarded by the border router i to domain D . Intradomain data leakage occurs when any $cost$ can be inferred from \mathbb{C} .

2) *Mathematical Analysis:* For the first case, if there exists $i \in [0, n - 1]$ that makes $\sum_{j=1}^D cost_j^D \in \mathbb{C}$, i.e., the aforementioned *Direct Connection* (\leftrightarrow), it is straightforward to obtain that $cost_{j_0}^D = y_0$. This situation is solved by random number confusion.

For the second case, if there is no intersection of the paths, i.e., there are no identical domains on the paths except for the end domain. At this point of \mathbb{C} , the number of unknowns is greater than the number of equations, so no unique solution can be derived.

For the third case, there are intersections in multiple paths, we have the following theorem.

Theorem 1: If there are overlapped ASes on any two routing paths to the same destination, then the subpaths of these two paths from the overlapped AS to the destination are the same.

Proof: Assuming that the two subpaths from the overlapped domain to the destination are different, i.e., there are more than one optimal paths to the destination from the overlapped AS, which contradicts the principle that each domain will only choose one optimal path to the destination. That is, the assumption is not valid. ■

Based on Theorem 1, we represent the domains before the overlapped domain as $\sum_{j=1}^D cost_j^D$. Then, the equation corresponding to the paths with overlapped domain, \mathbb{K} , can be

converted as

$$\text{cost}_l^D + \text{cost}_{l_1}^D + \dots + \sum_{j=1}^D \text{cost}_{j_l}^D = y_l, \quad l \in \mathbb{K}. \quad (6)$$

According to the property of a system of nonhomogeneous linear equations, the necessary and sufficient condition for the equation system $Ax = b$ to have a solution is that the rank of the coefficient matrix is equal to the rank of the augmented matrix, i.e., $\text{rank}(A) = \text{rank}(A, b)$, and the necessary and sufficient condition for having a unique solution is $\text{rank}(A) = n$. For (6), **iff** $\exists a \in \mathbb{K} \rightarrow \sum_{j=1}^D \text{cost}_{j_l}^D = y_l$, and $\exists b \in \mathbb{K} \rightarrow \text{cost}_b^D + \sum_{j=1}^D \text{cost}_{j_l}^D = y_l$, it can uniquely infer the value of an unknown quantity. That is, $\text{cost}_b^D = y_l - y_b$. This situation corresponding to the aforementioned *Delta Trap* (Δ), which can be solved by private number comparison. Hence, it is capable to guarantee M-DIT's privacy.

E. Multiple Requirements Routing

Before extending the single metric interdomain routing scheme to multiple metrics, we describe the difference between the desensitization procedure for bottleneck type and the aforementioned desensitization procedure for cumulative type. First, the abstraction process remains consistent, i.e., masking specific topologies and states inside the domain and preserving connections between border routers. Second, in the random number confusion process, when the source domain notifies a route entry, it is required to assign an initial value to the metric evaluation. For example, for bandwidth, a relatively large value or desired bandwidth will be set so that the subsequent $\min()$ calculation would not be biased. Conversely, if a smaller evaluation value for a metric is preferred, the initial value should be zero to ensure the correctness of the subsequent $\max()$ calculation. Finally, since the target of the private number comparison process is to compare the priority of two paths, the process remains fundamentally consistent. The only difference is whether the path with a larger or smaller value should be specified according to the characteristics of the corresponding metric.

Based on the above, the interdomain routing scheme can be extended to multiple requirements scenarios in two implementation ways. The key concerns of transmission are mainly concentrated on a few metrics, e.g., latency, bandwidth, packet loss, etc. Then, the first implementation employs a straightforward and efficient way of notifying routes independently for different metrics. Such a fashion not only ensures the convergence independence of each metric, i.e., only the corresponding route should be converged when a metric of paths changes, but also enables flexible adjustment of the weights of concerned metrics in routing decisions according to requirements. It decouples the various requirements of transmission services and route entries, thus maximizing the flexibility of routing decisions. The second implementation is embedding values of multiple metrics into specified several sequenced *Attr* fields the packet header. In route notification messages, the *Attr* field associated with the metric that is forbidden to diffuse or do not need to be reconverged will be filled with

0, which indicates that this *Attr* field is unavailable. The calculation of each field is executed independently following the aforementioned operations.

Assuming that each *Attr* is f bits, the notification message excluding the *Attr* field is N bits, n metrics need to be maintained in the network, and the number of messages generated by once convergence of metric $_i$ is P_i . Then the overhead generated by once convergence of the first implementation is $(N + f) * \sum_{i=1}^n P_i$, and that of the second implementation is $(N + nf) * \max(P_i | i \in [1, n])$. It is possible to choose a more efficient way depending on the network demand following the calculation. For convenience, we employ the first implementation scheme in this work.

F. Discussion of Incremental Deployment and Flexibility

Given the scale of the existing Internet, it is impossible to deploy M-DIT all at once, although it can enhance interdomain transmission performance. Therefore, incremental deployability is necessary. The nature of M-DIT is to desensitize intradomain data to assist in interdomain routing, thus, such information can be carried by protocols other layers to pass through the domains that do not support M-DIT. That is, M-DIT can be converged in incremental deployment scenarios. In this case, assuming that several paths have the same length of *AS_Path*, it is possible to: 1) specify that paths with a higher proportion of non-M-DIT have lower priority; 2) specify the evaluation of the non-M-DIT domain path as the average performance of all M-DIT domains; and 3) discard paths that will cross domains with poor performance directly. The above strategy may reduce the traffic crossed the non-M-DIT domain, which in turn may affect their revenue [56]. Therefore, M-DIT motivates each domain to deploy it from business and performance enhancement perspectives.

In addition, M-DIT does not interfere with each domain's behavior regarding cross-domain traffic. First, M-DIT does not force each domain to specifically provide the optimal links for interdomain traffic, instead only requires sharing the performance evaluation of links that it would provide; second, M-DIT allows domains to egress traffic based on existing routing algorithms, such as *hot potato* routing algorithms, or to assign an ingress for traffic by setting the best evaluation to the path from the destination to the ingress border router.

V. EVALUATION

In this part, we first describe the experiment settings. Then, we comprehensively analyze M-DIT's improvements over BGP demonstrated by a series of experiments.

A. Experiment Setup

The network simulated by NS3 (dce-ns3-dev) on the Ubuntu 16.04.7-LTS operating system. The server is equipped with 8G of RAM, dual core Intel Core i5-6300HQ 2.30-GHz CPU, and 128-GB HDD. We use five real network topologies, *ATMnet*, *Claranet*, *Compuserve*, *NSFnet*, and *Peer1*, selected from *Topology Zoo* [57] for evaluation. As shown in Fig. 7, each node of the topology represents an AS that implicitly contains a number of border routers and internal routers set in

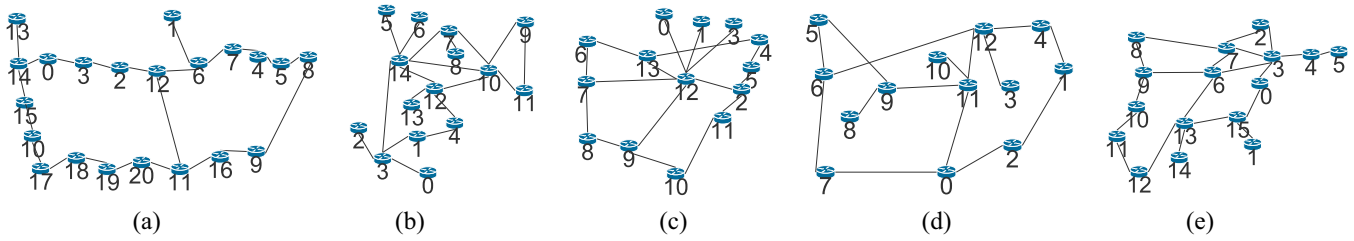


Fig. 7. Topology sketches of experiments. (a) ATMnet. (b) Claranet. (c) Compuserve. (d) NSFnet. (e) Peer1.

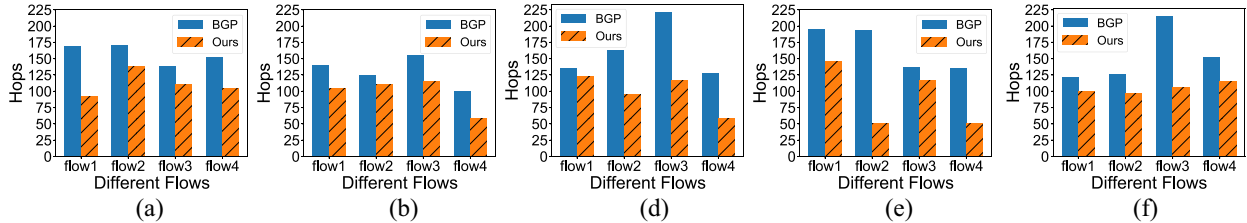


Fig. 8. Hops improvements. (a) ATMnet. (b) Claranet. (c) Compuserve. (d) NSFnet. (e) Peer1.

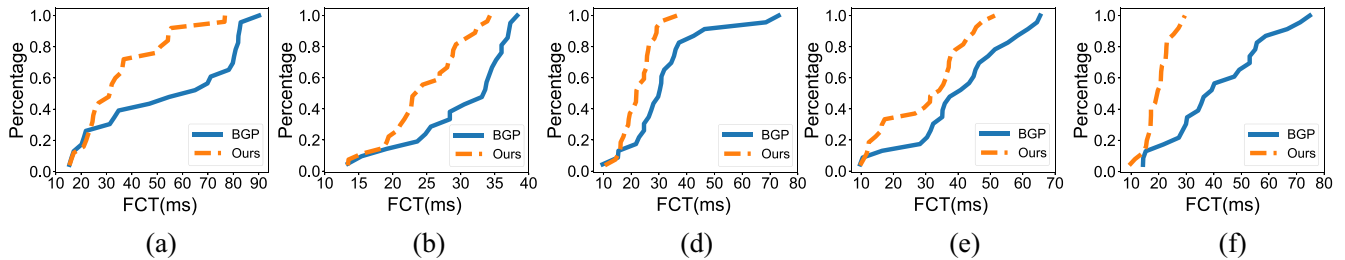


Fig. 9. FCT improvements. (a) ATMnet. (b) Claranet. (c) Compuserve. (d) NSFnet. (e) Peer1.

experiments. We set the latencies for all links with a uniform distribution of $U(0.5 \text{ ms}, 4.0 \text{ ms})$. Moreover, we randomly select a few links and increased their latency with a probability distribution of $U(20.0 \text{ ms}, 50.0 \text{ ms})$ to simulate the uncertain performance of links in practical networks. We generate simulated IIoT flows by referring to existing works [58], [59].

Existing interdomain routing optimization schemes are based on centralized architectures, which derive the global view based on explicit intradomain information. However, the prerequisite of M-DIT is guaranteeing the privacy of intradomain information. Therefore, this section mainly demonstrates the improvement over classical BGP.

B. Experimental Results

In the following, we first evaluated the performance of M-DIT in forwarding hops metric and the corresponding improvement in delay, i.e., FCT. Then, we integrated the bandwidth metric to analyze the performance of multiple requirements routing. Finally, we investigated M-DIT in terms of the effects of large-scale traffic and intradomain scale, convergence performance and the required computational overhead.

1) *Performance of Forwarding Hops*: We randomly generated some flows on the selected topologies, whose source and destination are distant apart, which enables multiple paths to

better demonstrate the enhancement in terms of interdomain routing of M-DIT over BGP.

In this set of experiments, we mainly measured the metric of forwarding hops as described in Section IV. In the five topologies, for flows with the same source and destination, the corresponding point-to-point forwarding hops for M-DIT and BGP are shown in Fig. 8. The experimental results indicate that M-DIT can leverage the additional information to select the routing path more properly than BGP in the case with multiple interdomain paths.

M-DIT and BGP would have the same routing policy for the flow that only has one single forwarding path, which generally exists between adjacent domains. That is, there is no room for optimization in this case for M-DIT. Therefore, it is unnecessary to measure the performance of all flows between all pair nodes, which will be present in Section V-B5 in detail.

2) *Performance of FCT*: Through the experiment above, we found that while taking the forwarding hops as the optimization metric, the corresponding FCT can also be reduced. This is because a reduction of forwarding hops can reduce the total processing delay at switches/routers for a flow. Therefore, it is possible to switch the FCT optimization to the more stable forwarding hops metric.

Then, specifically, we measured the FCT of flows generated in the above experiments under running M-DIT and BGP, respectively, i.e., point-to-point interdomain transmission latency of the flows. The results shown in Fig. 9 indicate that

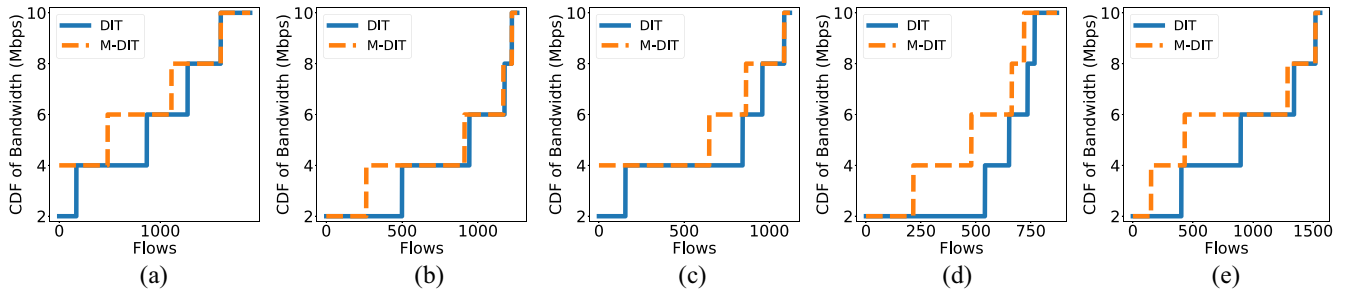


Fig. 10. M-DIT versus DIT on performance of bandwidth-sensitive flows (we added these charts of supplemented experiment analysis, and this explanation will be removed in the formal version). (a) ATMnet. (b) Claranet. (c) Compuserve. (d) NSFnet. (e) Peer1.

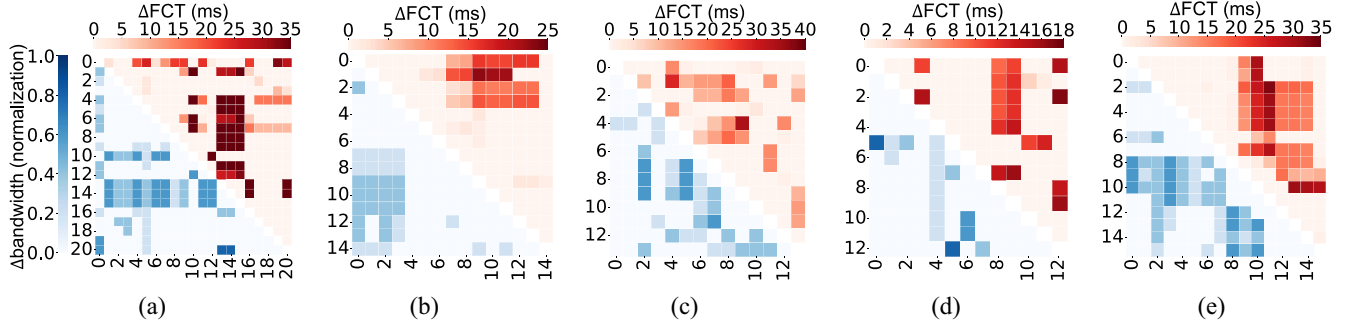


Fig. 11. Multiple requirements routing performances. (a) ATMnet. (b) Claranet. (c) Compuserve. (d) NSFnet. (e) Peer1.

M-DIT can outperform BGP regarding FCT of generated flows on the selected topologies, despite targeting forwarding hops as the optimization metric.

3) *Multiple Requirement Routing*: To illustrate the enhancement of M-DIT in a multiple requirements scenario, we generate, delay-sensitive and bandwidth-sensitive, two typical types of flows between any pair of ASes in these five network topologies, which prefer the routing path with the shortest delay and the routing path with the largest bandwidth, respectively. There is a router inside each AS that is specified to receive and send flows, which is directly connected with the border routers. In addition, to exemplify the impact of intradomain state only, the bandwidth of all links between ASes is set to 10 Mb/s, and the bandwidth of all links inside ASes is randomly set to 10, 8, 6, 4, or 2 Mb/s. The delay of each link is kept consist as above experiments. The M-DIT is implemented in the network with both delay and bandwidth metrics.

a) *Necessity*: We compared M-DIT and single-metric DIT [1], where DIT takes the number of hops as the optimization goal. DIT performs the same routing policy for bandwidth-sensitive and delay-sensitive flows, both of which follow the minimum hops principle. M-DIT can leverage the multiple attributes to appropriately select interdomain paths for both types of flows, which means that M-DIT have comparable average performance with DIT on thousands of delay-sensitive flows, as shown in the Table I.

Therefore, this experiment mainly demonstrates and analyzes the comparisons of bandwidth-sensitive flows performance between M-DIT and DIT. As shown in Fig. 10(a)–(e), the results indicate that M-DIT improves the transmission performance on bandwidth on average 12.94%

TABLE I
AVERAGE FCT OF DELAY-SENSITIVE FLOWS

(# ms) \	ATMnet	Claranet	Compuserve	NSFnet	Peer1
DIT	22.258	12.471	14.137	14.758	10.489
M-DIT	22.260	12.469	14.136	14.757	10.487

(11.24%, 17.49%, 37.42%, and 21.24%) over DIT in *ATMnet* (*Claranet*, *Compuserve*, *NSFnet*, and *Peer1*). Although the improvement in bandwidth metrics is traded with the reduction of FCT, it is reasonable and acceptable for bandwidth-sensitive flows.

Based on the above analyses, it is beneficial and significant to provide different routing policies for different types of flows. The performances of M-DIT versus BGP will be further evaluated in the following.

b) *Outperformance*: Fig. 11(a)–(e) shows the performance improvements of M-DIT over BGP, where the values of axes indicate the source and destination indices. The undirected nature of the link properties set in the experiment makes the transmission performance symmetric for the same pair of ASes. Thus, we integrate the results of these two metrics, i.e., the upper part of the heat map indicates the ΔFCT (BGP minus M-DIT) of the selected routing paths, while the lower part indicates the $\Delta bandwidth$ (normalized value of M-DIT minus BGP). Moreover, the darker color indicates a more significant improvement of M-DIT. The experimental results show that M-DIT can also provide routing policies that better than or at least equal to BGP in multiple requirements transmission scenario.

4) *IIoT Service Emulation*: Referring to existing works, two typical IIoT services are involved in this experiment:

TABLE II
IIoT SERVICE EMULATION PERFORMANCE

Service Type	Protocol	<i>ATMnet</i>	<i>Claranet</i>	<i>Compuserve</i>	<i>NSFnet</i>	<i>Peer1</i>
Signal Transmission Average FCT (#ms)	BGP	34.4 / 35.1 / 79.1	31.4 / 34.4 / 35.3	35.2 / 37.2 / 72.2	58.4 / 64.4 / 45.5	32.3 / 30.5 / 73.2
	M-DIT	22.1 / 11.5 / 32.2	24.0 / 25.2 / 21.2	23.0 / 17.2 / 20.1	40.3 / 11.7 / 38.2	19.2 / 20.0 / 21.2
Files Uploading Path Bandwidth (#Mbps)	BGP	2 / 2 / 6	2 / 2 / 2	2 / 4 / 2	2 / 10 / 10	4 / 2 / 4
	M-DIT	10 / 6 / 6	4 / 6 / 6	6 / 6 / 8	2 / 10 / 10	6 / 6 / 6

1) monitoring files uploading with the size of 2 MB per file, which represent bandwidth-sensitive services [58] and 2) control signal transmission with flows size randomly of 30, 50, or 100 B, which represent a series of delay-sensitive services [59]. Without loss of generality, three pairs of ASes are selected as source and destination ASes for emulated services in five topologies (*ATMnet*: 13 to 1, 13 to 16, 1 to 9; *Claranet*: 0 to 8, 2 to 10, 9 to 2; *Compuserve*: 6 to 2, 8 to 4, 7 to 2; *MSFnet*: 8 to 3, 5 to 11, 10 to 5; and *Peer1*: 14 to 5, 14 to 8, 9 to 1). Since it is only necessary to consider the service characteristics in the end-to-end interdomain transmission, hundreds of aforementioned flows are randomly generated with equal probability at the egress node of the source AS based on [58], [59].

The average FCT of control signal transmission and the bandwidth of forwarding path of the files uploading between three pairs of selected source and destination ASes in each of five topologies are shown in Table II. The smaller the value of the FCT, the better, and vice-versa for the bandwidth. In all AS-pairs selected in this experiment, compared with BGP, M-DIT averagely reduces 49.28% FCT for delay-sensitive flows and selects a $2.03\times$ bandwidth routing path for bandwidth-sensitive flows. The results indicate that M-DIT outperforms the BGP for interdomain transmission for IIoT services and maintains a similar improvement with the above experiments, which further confirms the superiority of M-DIT.

5) *Performance of Full-Set Flows*: To completely analyze the capability of M-DIT, we simultaneously generated almost 900 different flows for all pairs of border nodes (full-set flows) in *NSFnet*. The FCTs of such full-set flows were, respectively, measured under M-DIT and BGP. Since M-DIT is overall superior to BGP in terms of forwarding hops theoretically, we reasonably analyze M-DIT the performance under full-set flows in terms of latency.

With full-set flows, the result of the BGP-based FCT exceeds the M-DIT-based FCT for each flow is exhibited in Fig. 12, where larger values (i.e., redder elements) indicate better performance for M-DIT. The results demonstrate that M-DIT enabled most flows to outperform or at least equalling BGP in terms of FCT in large-scale flows. It is reasonable that the performance of roughly 0.5% of flows forwarded by M-DIT is slightly inferior to BGP (negative values/light blue elements of Fig. 12) due to uncertain fluctuations, e.g., packets queuing or link congestion. Overall, the result objectively indicates that M-DIT shows significant general improvements over BGP.

6) *Influence of Intradomain Scale*: The influence of different intradomain scales (i.e., the number of routers within a domain) on the boost that M-DIT can achieve varies. We

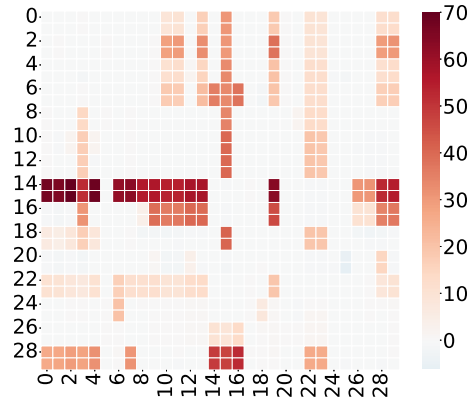


Fig. 12. FCT under full-set flows.

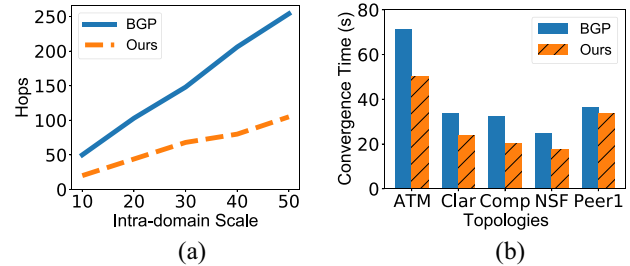


Fig. 13. Protocol convergence and influence of intradomain scale. (a) Intradomain scales. (b) Convergence time.

individually measured the forwarding hops of intradomain scales from 10 to 50, where intradomain links were randomly generated. Moreover, in each experiment setting, the scales of a few domains were extended beyond the assigned scale to simulate some uncertain cases.

Fig. 13(a) displays the average forwarding hops for flows with different intradomain scales under M-DIT and BGP, where the flow setting remains consistent with Section V-B1. The larger the domain scale corresponds to a bigger intradomain performance difference, and as the accumulated effect of interdomain transmission, the final improvement in performance becomes more pronounced. The results indicate that M-DIT reduces the average point-to-point forwarding hops up to 60% for the intradomain scale of 50.

7) *Convergence and Cryptogram Overhead*: Moreover, the convergence of interdomain protocols is an essential metric. Based on the selected five topologies, we compared the convergence times of M-DIT and BGP. The result of Fig. 13(b) indicates that M-DIT outperforms classic BGP in terms of convergence, which is because M-DIT pruned some route diffusion path, thus speeding up the convergence process. Additionally, the M-DIT is an independent process that precedes the route diffusion, so additional computations (e.g.,

HE/decryption/computation, comparison) will not affect the convergence process of the protocol.

In the experiments, we also evaluate the computation overhead associated with HE. We precompute sufficient available primes for selection to promote computational efficiency, and stipulate that the three computations of encrypting, homomorphic addition, and decrypting are specified as an operation. The results show that the *Paillier*, implemented by Python (NTL library of C language [60]), incurs a time overhead of 30 ms (0.1 ms) per operation that averaged over 10^5 computations.

VI. CONCLUSION

In this work, we demonstrate the potential and benefit of intradomain state awareness for multiple requirements interdomain routing. However, it is not well supported by existing interdomain protocols for privacy reasons in IIoT scenarios and beyond. Given all this, we design an intradomain state-aware interdomain routing scheme that can securely leverage intradomain information to enhance interdomain routing decisions. Specifically, we exploit HE algorithms to secure intradomain information, thus, avoiding potential private data leaking induced by information sharing. The experimental results on five real network topologies exhibit that our proposed scheme outperforms the existing BGP-based protocols. M-DIT reduced FCT by about 60% or selected high bandwidth paths flexibly for interdomain routing in IIoT scenarios and beyond.

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This article extends [1] by adding the solution of interdomain multiple requirements routing for IIoT scenario and beyond.

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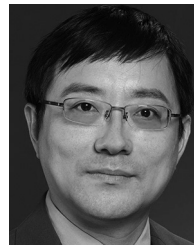


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