MIRO: MULTI-PATH INTERDOMAIN ROUTING

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Abstract

The Internet consists of thousands of independent domains with different, and sometimes competing, business interests. However, the current interdomain routing protocol (BGP) limits each router to using a single route for each destination prefix, which may not satisfy the diverse requirements of end users. Recent proposals for source routing offer an alternative where end hosts or edge routers select the end-to-end paths. However, source routing leaves transit domains with very little control and introduces difficult scalability and security challenges. In this dissertation, a multi-path interdomain routing protocol called MIRO is presented, it offers substantial flexibility while giving transit domains control over the flow of traffic through their infrastructure and avoiding state explosion in disseminating reachability information. In MIRO, routers learn default routes through the existing BGP protocol, and arbitrary pairs of domains can negotiate the use of additional paths (bound to tunnels in the data plane) tailored to their special needs. It retains the simplicity of the BGP protocol for most traffic, and remains backward compatible with BGP to allow for incremental deployability. Experiments with Internet topology and routing data illustrate that MIRO offers tremendous flexibility for path selection with reasonable overhead.

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Chapter 1

Introduction

As of January 2009, the Internet Systems Consortium estimates that there are around 625 million individual hosts in the Internet [19]. It would be extremely difficult for a single authority to effectively manage the communications among such a gigantic body of independent hosts; therefore, the current Internet is structured more like a loose federation of Autonomous Systems (AS). Each AS is independently administered by a single authority, such as a university, a company, or a government agency. Accordingly, the routing in the Internet can be divided into two parts: intradomain routing, which deals with the routing inside one AS; and interdomain routing, which deals with the routing among different ASes.

Each AS is assigned a unique AS number ranging from 0 to 65535. Then an AS path is described using a sequence of AS numbers. Each AS also owns a range of IP addresses; it could decide to further split its IP addresses into smaller groups with each group containing some contiguous IP addresses called an IP prefix. Interdomain routing paths are calculated for each IP prefix; therefore, different IP prefixes originating from the same AS can take different AS paths simultaneously. Many ASes advertise more than one IP prefix, either because the IP addresses they own are not contiguous or because the ASes want more flexible route selections. In fact, because of the prevalence of multi-homing, in which an AS is connected to more than one neighbor, the number of prefixes grows more rapidly than AS numbers in today's Internet.

Interdomain routing is an important component of Internet routing, as a great deal of traffic traverses more than one AS. Moreover, the fact that each AS is managed by a different authority makes the situation more complicated compared to intradomain routing. In intradomain routing, all resources are administered by the same authority. This authority can use all the resources inside the AS, and its ultimate goal is routing packets in the most effective way. But in interdomain routing, different authorities may have different and sometimes competing business interests, which have a profound impact on interdomain routing practices. For example, ASes generally are not willing to reveal their internal network topologies or routing policies, and they usually choose the routing policies which benefit themselves the most. As a result, interdomain routing is complicated, because it should have the following characteristics:

- Each AS should be able to express local policies that reflect its business interests.
- The protocol needs to be scalable. In terms of scalability, the protocol should consider the large number of ASes, IP prefixes, and potential paths present in the Internet. First, the number of unique ASes advertised in the Internet is around 31,000 and it is still growing. Second, each AS may advertise multiple prefixes, and the number of prefixes recently has been growing more rapidly than the number of ASes. Lastly, each AS may learn more than one path to each prefix, so the number of paths in the Internet grows even larger.
- The privacy of each AS should be respected. In the current Internet, the routing is

	IP Prefix	Next Hop	AS Path
*	128.112.0.0/16	198.32.8.196	11537 10466 88
*		144.228.241.81	1239 7018 88 88 88
*>		205.189.32.44	6509 11537 10466 88
*>	128.113.11.0/24	205.189.32.44	6509 3754 91

Table 1.1: Part of a BGP table

divided into intradomain and interdomain routing, so that an AS can avoid sharing internal details with outsiders. This separation not only improves security, but also helps to confine the effect of internal failures.

In the following sections, this dissertation will briefly introduce how today's interdomain routing protocol works, then motivate the design of a new interdomain routing protocol called MIRO (Multi-path Interdomain ROuting).

1.1 Interdomain Routing in Today's Internet

In today's Internet, a unique 16-bit or 32-bit AS number is assigned to each AS. In April 2009, around 31,000 active ASes were detected by RouteView's observation points [30]. Border Gateway Protocol (BGP) is the current interdomain routing protocol used in the Internet [29]. Section 2.2.2 will describe the BGP protocol in more detail, only a brief overview is presented here.

BGP is a path-vector protocol, in which each router only advertises its own paths to its immediate neighbors. Table 1.1 shows part of a real BGP table in a router. Each BGP entry is associated with a certain IP prefix that is a range of IP addresses. For example, 128.112.0.0/16 means matching the first 16 bits of 128.112.0.0, which stands for IP address range 128.112.0.0 to 128.112.255.255. There may be more than one candidate entry associated with each IP prefix, the table shows three candidate entries for IP prefix

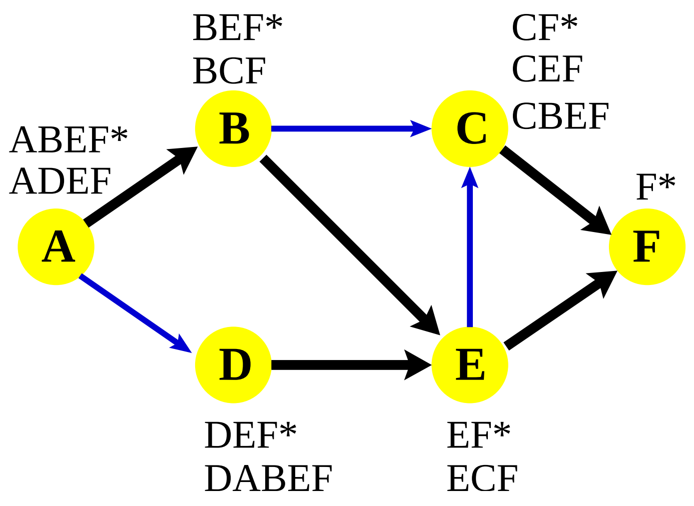


Figure 1.1: Single-path Routing to AS F

128.112.0.0/16. Each candidate entry carries with it a Next Hop IP address and an AS path. Taking the first entry as an example, to reach the IP addresses in 128.112.0.0/16, this router can send packets to the router interface with IP address 198.32.8.196. When the packets reach that router, they will go through AS 11537, then traverse AS 10466, and finally reach the destination in AS 88.

In many cases, there will be more than one candidate entry to choose from. The BGP limits that only a single "best" route be selected for each router. In Table 1.1, the entries selected are represented by the ">" symbol. In the table, the router chose the AS path "6509 11537 10466 88" at 205.189.32.44 for prefix 128.112.0.0/16, and it picked the AS path "6509 3754 91" also at 205.189.32.44 for prefix 128.113.11.0/24. After picking a single route for each prefix, this route will be used in transmitting all traffic destined to this prefix, and all other candidate routes will not be used.

Figure 1.1 shows a simple AS topology. Each AS is represented by a single node, and the connections between ASes are represented by the edges. The candidate routes are shown for each AS, and the route with a * represents the single chosen route. The thick lines represent the links in use by one of the chosen routes destined to AS F. The routes available to one AS are listed in decreasing preference order, for example, AS A prefers route ABEF over ADEF. In this graph, each AS selected its most preferred path, because the most preferred path is among available candidates. In reality, this may not always be the case.

From the graph, it can be seen that the single path restriction has a profound impact on the available flexibility. Many ASes have very little control over the paths their traffic takes through the Internet. For example, an AS might want to avoid paths traversing an AS known to have bad performance or filter data packets based on their contents. This is the situation in Figure 1.1, where AS A does not want AS E to carry its traffic, but it has no choice because both B and D have selected paths through E. Simply asking B to switch to the route BCF is not an attractive solution, because this would force B and all of its neighbors to use BCF. Instead, this dissertation argues that the Internet's interdomain routing protocol should support multiple paths.

1.2 Our Proposal for Multi-path Interdomain Routing

Recent research has considered several alternatives to today's single-path routing protocol, including source routing and overlay networks [17]. In source routing, an end user or edge AS picks the entire path the packets traverse [4, 22, 28, 42, 44]. In overlay networks, packets can travel through intermediate hosts to avoid performance or reliability problems on the direct path [3]. However, these techniques do not give transit ASes, such as Internet Service Providers (ISPs), much control over the traffic traversing their networks. This control is important for ASes to engineer their networks to run efficiently, and to maximize revenue based on business relationships with other ASes. The lack of control for ISPs is a significant impediment to the eventual adoption of source routing. In addition, source routing and overlay networks may not scale effectively enough to drive path selection for a network as big as the Internet. Instead, this dissertation explores an alternative, in which the interdomain routing protocol supports multi-path routing, while providing flexible control for transit ASes and avoiding state explosion in disseminating routing information.

Our solution is motivated by several observations about today's interdomain-routing:

- Having each router select and advertise a single route for each prefix is not flexible enough to satisfy diverse performance and security requirements. In Figure 1.1, today's routing system does not enable AS A to circumvent AS E in sending traffic to AS F.

- The existing routes chosen by today's BGP-speaking routers are sufficient for a large portion of the traffic. In Figure 1.1, AS B and its other customers may be perfectly happy with the path BEF.

- End users need control over the properties of the end-to-end path, rather than complete control over which path is taken. In Figure 1.1, AS A only wants to avoid AS E and does not care about the rest of the path.

- The existing BGP protocol already provides many candidate routes, although the alternate routes are not disseminated. In Figure 1.1, AS B has learned the route BCF but simply has not announced it to AS A.

- An AS selects routes based on business relationships with neighboring domains, but it may be willing to direct a portion of the traffic to other paths for additional cost. In Figure 1.1, AS B prefers BEF for financial reasons, but it may be willing to send AS A's traffic over BCF.

- Today's Internet provides limited methods for one AS to influence another AS's choice. For example, if AS F is a multi-homed stub AS which wants to control how much incoming traffic traverses link CF and EF respectively, it can only advertise a smaller prefix or manipulate the AS paths [27]. However those methods may be easily nullified by other ASes' local policy, so AS F may not be able to achieve its desired goals.

Inspired by these observations, this dissertation proposes a new multi-path interdomain routing protocol, MIRO, with the following features:

- **AS-level path selection:** An AS represents an institution, such as a university or company, and business relationships are easily defined at the AS level. Selecting path at the AS level is simpler and more scalable than giving each end user fine-grain control over path selection.

- **Negotiation for alternate routes:** An AS learns a single route from each neighbor and negotiates to learn alternate routes as needed. This leads to a scalable solution that is backward compatible with BGP, and it also allows policy interaction between two arbitrary ASes that may not be adjacent.

- **Policy-driven export of alternate routes:** The responding AS in the negotiation has control over which alternate paths, if any, it announces in each step of the negotiation. This gives transit ASes control over the traffic entering their networks.

- **Tunnels to direct traffic on alternate paths:** After a successful negotiation, the two ASes establish the state needed to forward data traffic on the alternate route.

The remaining traffic traverses the default route installed in the forwarding tables.

With the additional flexibility, ASes can choose paths that satisfy their special needs, for example:

- *Avoiding a specific AS on the path for security or performance reasons:* An AS can avoid sending sensitive data through a hostile country or avoid an AS that often drops packets [39].

- *Achieving higher performance:* An AS can send traffic through more expensive inter-AS links that are normally not available, to achieve lower latency or higher bandwidth.

- *Load balancing for incoming traffic:* A multi-homed AS trying to balance load over multiple incoming links can request that some upstream ASes use special AS paths to direct traffic over a different incoming link[1].

In designing MIRO, policy and mechanism are separated wherever possible, to support a wide range of policies for interdomain routing. Still, this dissertation presents example policies and useful policy guidelines to illustrate the benefits of adopting this protocol. In the next section, background material and related work is presented. Then, Chapter 3 gives an overview of the main design decisions. This dissertation describes MIRO in greater detail in Chapter 4 and demonstrate the effectiveness and efficiency of MIRO in Chapter 5 using measurement data from RouteViews [30]. Chapter 6 discusses how ASes can configure flexible routing policies. Then, Chapter 7 proves that MIRO will not lead to system oscillation when adopted routing policies satisfy certain constraints. Chapter 8 discusses additional technical issues and concludes the dissertation.

[1]Analysis of RouteView's data [30] shows that 60% of the 31,000 ASes are multi-homed and more than 4900 are announcing smaller subnets into BGP to exert control over incoming traffic. However, announcing small subnets increases routing-table size without providing precise control.

Chapter 2

Background and Related Work

Throughout this dissertation, MIRO will be compared to two other routing architectures: BGP and source routing. BGP is the current interdomain protocol, and uses path-vector routing to limit the amount of information propagated. At the other extreme, source routing propagates a huge amount of information by revealing the entire Internet topology to each source entity. Therefore, it is interesting to compare these protocols to MIRO. Also, many approaches used are currently adopted in virtual routing networks called overlay networks, so this dissertation will also discuss the difference between MIRO and overlay networks.

This chapter starts with a brief comparison of BGP, source routing, and overlay networks. After that, there are more details about today's Internet and the current BGP protocol. Finally, there is a discussion of related literatures.

2.1 The Three Routing Architectures

BGP limits the amount of information propagated by hiding the internal topology of each AS, advertising incremental results only to immediate neighbors, and limiting that a single path be selected for each prefix. However, these restrictions also limit the number of available paths to each AS. In recent interdomain routing proposals, source routing is the most radically different approach in terms of the amount of information distributed. The entire router-level or AS-level Internet topology is disclosed to each end host, and then the packet sources dictate the entire path each packet will traverse. The end hosts in source routing can pick any routes they want while the intermediate routers have to blindly obey the selections. It is also questionable whether source routing protocols are scalable when numerous end hosts are simultaneously picking routes. Overlay networks are not used in interdomain routing, but their member hosts can affect routing by redirecting packets upon request.

2.1.1 BGP

Without getting into the details of BGP protocol, this section illustrates how it works by showing the formation of the routing tables in Figure 2.1. Interested readers should refer to Section 2.2.2 for details. In step 1, AS F knows that prefix 12.34.0.0/16 belongs to F, therefore F adds the NULL AS path F to its routing table, and advertises that to its immediate neighbors C and E. In step 2, C and E accept CF and EF, respectively, as the path to reach 12.34.0.0/16, and then they advertise the path to their immediate neighbors. Even though F might also receive CF and EF, it will find that itself is already included in the path, and accordingly discard those updates to prevent routing loops. In step 3, AS B gets two candidate routes BCF and BEF, and it selects one of the paths, BEF, as the

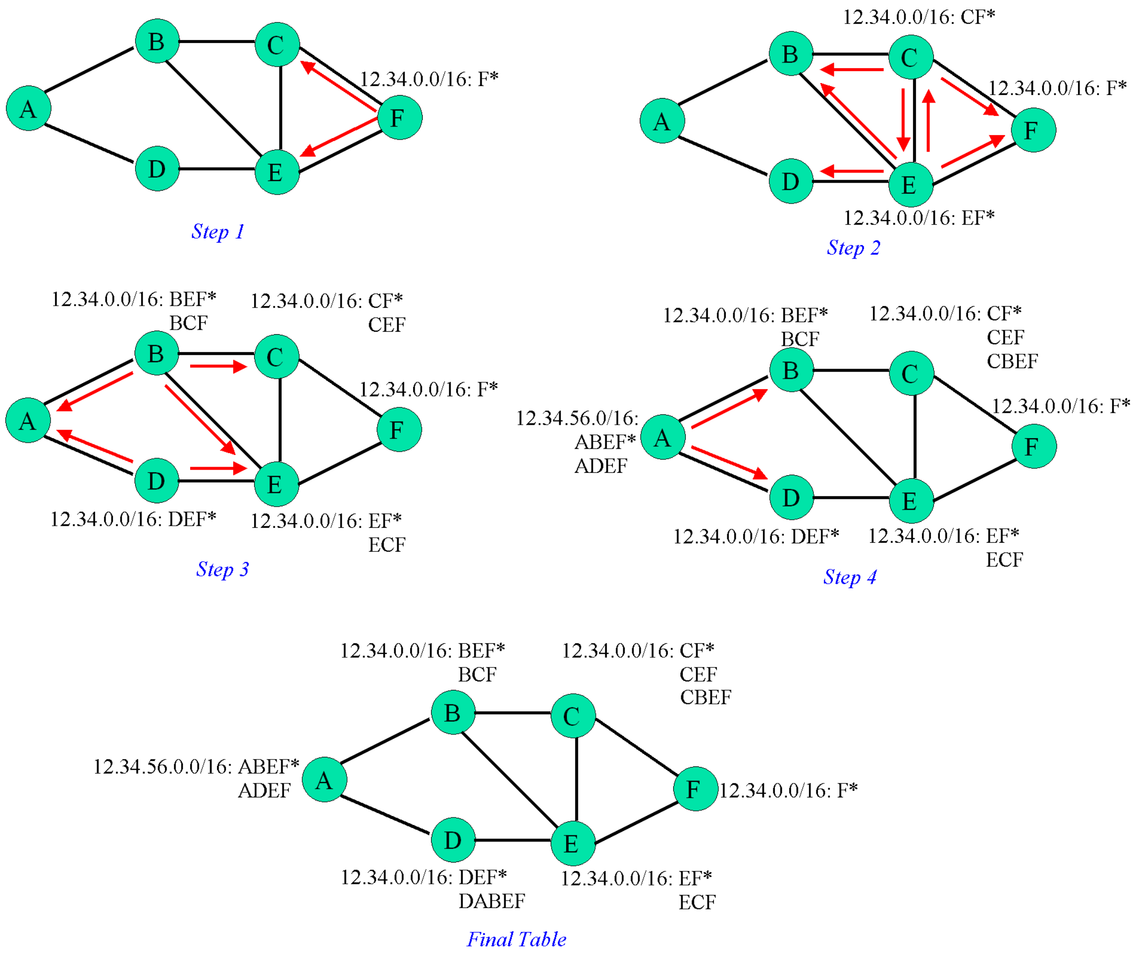


Figure 2.1: The Formation of BGP Routing Table
* represents chosen route.

best route, and only advertises BEF to all its immediate neighbors. Finally in step 4, AS A receives both ABEF and ADEF, picks ABEF as the best path, and advertises that to immediate neighbors B and D. After that, D adds the new path to its routing table, but because the best path at D is still DEF, AS D will keep the candidate route DABEF, but will not send new BGP updates.

From the above description, it can be seen that BGP has several salient features that limit flexibility in path selection:

- *Destination-based forwarding*: BGP distributes reachability information about IP prefixes, and each IP router forwards a packet by performing a longest-prefix match on the destination IP address. For example, 12.34.0.0/16 is associated with all paths in Figure 2.1. If a packet with destination IP 12.34.56.78 has no better matches (e.g., another entry 12.34.56.0/24 which can match the first 24 bits of 12.34.56.78), it will go through the best AS path designated in the 12.34.0.0/16 entry. Because the next hop is determined solely based on the IP destination address, all packets with the same IP destination will follow the same downstream path if they arrive at the same router.

- *Single-path routing*: For each prefix, a router learns at most one route from each neighbor, and it can only select or advertise a single “best” route. In Figure 2.1, only the paths with a “*” are selected and advertised to neighbors. This limits the number of paths advertised, and imposes severe restrictions on flexibility.

- *Path-vector protocol*: The BGP is a path-vector protocol where routers learn only the AS paths advertised by their neighbors. There is another family of routing protocols, which are called link-state protocols. In link-state protocols, every node floods the status of its links to every other node in the network. If a link-state protocol is applied to the topology in Figure 2.1, F will advertise the link CF and EF to all other nodes; while C will advertise BC, CE, and CF to all others, etc. Therefore, all nodes have the complete topology and they can compute the shortest paths simultaneously. Compared to link-state protocols, a path-vector protocol improves scalability at the expense of visibility into the possible paths.

- *Local-policy based*: The BGP gives each AS significant flexibility in deciding which routes to select and export. As in Figure 2.1, each node independently decides which path should be selected as the best path, and because only best path is advertised, the local decision of each node will impact the final choices. As a result, the available routes in BGP depend on the composition of the local policies in the downstream ASes, limiting the control each AS has over path selection.

Another problem in current BGP is that it is hard for one AS to influence another AS's local policy effectively. Inside each AS, paths are selected based on local parameters; sometimes one AS can make local decisions based on parameters attached to announce BGP paths from another AS. However, compared to a bidirectional negotiation, this kind of one-way request does not give the requesting AS any feedback. Moreover, these methods are often used only between adjacent ASes that unconditionally trust each other, e.g., an AS belonging to end-customers and its ISP.

2.1.2 Source Routing

In the past few years, several researchers have proposed source routing as a way to provide greater flexibility in path selection [4, 14, 22, 25, 28, 42, 44]. In contrast to a path-vector protocol like BGP, source routing is more like a link-state protocol, all links inside the network are advertised via flooding to each end AS or end host. Then the end hosts or

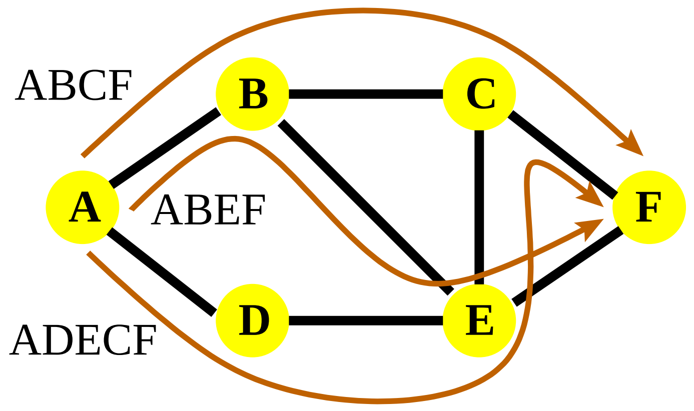


Figure 2.2: Source Routing

edge routers can select the hop-by-hop path from the source to the destinations for each of their packets. The entire hop-by-hop path or a flow identifier that corresponds to the path is encoded in each data packet. As in Figure 2.2, AS A can choose any loop-free path, including ABCF, ABEF, and ADECF. Although source routing maximizes flexibility, several difficult challenges remain:

- *Limited control for intermediate ASes:* Under source routing, intermediate ASes have very little control over how traffic enters or leaves their networks. In Figure 2.2, ASes B, C, D, and E have to unconditionally obey the path selections made by A. This makes it difficult for intermediate ASes to engineer their networks based on their own business goals, which is a barrier to the deployment of source-routing schemes.

- *Scalability:* The sources need to know the entire network topology, at some level of detail, to compute the paths. The volume of topology data and the overhead of path computation would be high, unless the data are aggregated; including load or performance metrics, if necessary, would further increase the overhead. In addition, the sources must receive new topology information quickly when link or router failures make the old paths invalid.

- *Efficiency and stability:* In source routing, end hosts or edge routers adapt path selection based on application requirements and feedback about the state of the network. Although source routing can generate good solutions in certain cases [26], a large number of selfish sources selecting paths at the same time may lead to suboptimal outcomes, or even instability.

- *Security:* Currently, authentication of a host is based on its IP address. Source routing will break this kind of authentication, because both the forward and the reverse default paths are overridden, and an attacker can easily inject packets with a false source address without being caught. For that reason, many organizations disable source routing at their border routers [5].

Even if these challenges prove to be surmountable in practice, it is valuable to consider other approaches that make different trade-offs between flexibility for the sources, control for the intermediate ASes, and scalability of the overall system.

2.1.3 Overlay Networks

In overlay networks, several end hosts form a virtual topology on top of the existing Internet [3]. When the direct path through the underlying network has performance or reliability problems, the sending node can direct traffic through an intermediate overlay node. Then, the traffic travels on the path from the source to the intermediate node, followed by the path from the intermediate node to the destination. Overlay nodes are normally placed on end hosts rather than intermediate routers, so they can use more CPU-intensive and flexible high-level routing algorithms. The packets in overlay networks are normally forwarded via encapsulation, wrapping a new IP header outside the original packet, so over-

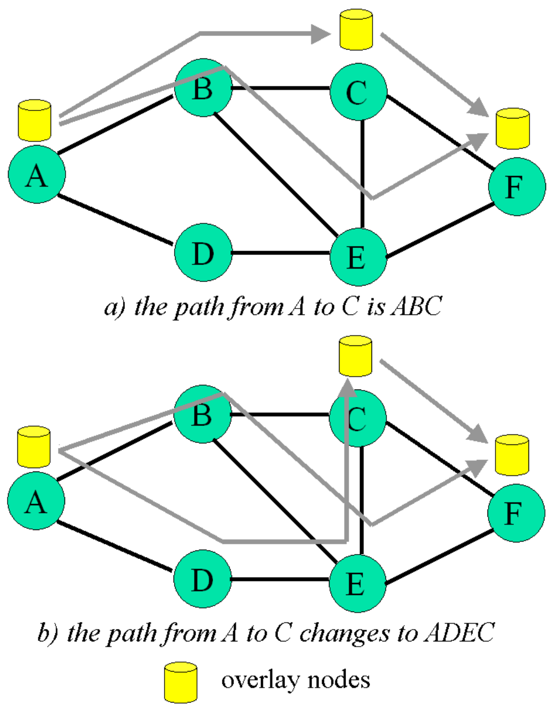

A
B
C
D
E
F
a) the path from A to C is ABC
A
B
C
D
E
F
b) the path from A to C changes to ADEC
overlay nodes

Figure 2.3: Overlay Networks

lay networks require no cooperation from underlying networks while forwarding packets, and different overlay networks can use different routing protocols simultaneously.

In Figure 2.3, there are three overlay nodes, placed at ASes A, C, and F respectively. If the current BGP path from A to C is ABC as in case a), AS A can route its packets through the path ABCF by sending packets to C, and asking C to forward them to F. However, an overlay network is a virtual network built on top of the physical network. Therefore, the overlay network has no control over the physical routes, and can only adapt to physical route changes by forwarding packets through another overlay node. Suppose that the BGP path from A to C suddenly changes from ABC to ADEC as in case b), then AS A has no way to circumvent AS E in this overlay.

Although overlay networks are useful for circumventing problems on the direct path, they are not a panacea for supporting flexible path selection at scale, for several reasons:

- *Data-plane overhead:* Sending traffic through intermediate hosts requires tunneling, which adds overhead for encapsulating and decapsulating the data packets. The packets must traverse the intermediate host's edge link twice, incurring both delay and cost.

- *Limited control:* Overlay networks have no control over the paths between the nodes, and they have limited visibility into the properties of the paths. The paths depend on the underlying network topology, as well as the policies of the various ASes in the network.

- *Probing overhead:* To compensate for poor visibility into the underlying network, overlay networks normally rely on aggressive probing to infer properties of the paths between nodes. Probing has inherent inaccuracies and does not scale well to large deployments.

In contrast to source routing, overlay networks do not require support from the routers or consent from the ASes in the underlying network. Although overlays undoubtedly have an important role to play in enabling new services and adapting to application requirements, the underlying network should have native support for more flexible path selection to support diverse performance and security requirements efficiently, and at scale.

2.2 Interdomain Routing in Today's Internet

Having seen the advantages and disadvantages of the three routing architectures, this dissertation proposes the design of a new interdomain routing protocol that can address most of the concerns. Interdomain routing policies are driven by various business relationships between different ASes. This section will first look at several prevalent business relationships in today's Internet, and then describe the BGP protocol in more detail.

2.2.1 The Prevalent Interdomain Business Relationships

Today's Internet is a loose federation of ASes, and each AS employs local BGP policies that fit its own business interests the best. Therefore, understanding these business relationships can help us understand the policies the ASes are likely to apply. Although it is theoretically possible to sign any kind of business contracts between two ASes, in today's Internet there are several prevalent business relationships, all of them established between neighboring ASes.

The most common relationships are: customer-provider, peer, and sibling [12, 18, 32]. The routes learned from a customer AS are called *customer routes*, similarly those from a peer, sibling, or provider are called *peer routes, sibling routes,* or *provider routes*, respectively.

In a customer-provider relationship, the customer normally pays the provider for transit service; as such, the provider announces the routes learned from any customer to all neighboring ASes, but the customer normally only advertises the routes learned from its provider to its own customers. In a peer-peer relationship, two ASes find it mutually beneficial to carry traffic between each other's customers, often free of charge. Peering agreements normally indicate that the routes learned from a peer can only be advertised to customers. Sibling ASes typically belong to the same institution, such as a large ISP, and siblings provide transit service to each other. Upon learning routes for a destination prefix from multiple neighbors, an AS typically prefers to use customer-learned routes, then siblings, then peers, and finally providers, to maximize revenue. At times, though, providers deviate from these policy conventions upon customer request, e.g., to provide backup connectivity for customers. This dissertation's author believes that business incentives can also motivate an AS to make alternate routes available to neighbors who have special performance or security requirements.

In summary, the interdomain routing policies can be placed into two groups: the export rules and the preference rules. The export rules dictate whether a locally selected path should be advertised to an immediate neighbor, and the preference rules arbitrate whether certain routes should be preferred over others in a local best-path selection process. The interdomain routing policies described above can be summarized as:

- Export Rules
  - Customer routes are advertised to every neighbor
  - Provider or peer routes are advertised to customers only
- Preference Rules: customer routes are preferred the most, followed by peer routes, then by provider routes.

The routing policies between siblings are more complicated. In our experiment, the sibling policies are approximated like this: first, the sibling routes are examined to find the first non-sibling link, then the sibling routes are categorized accordingly (e.g., if the sibling route has several sibling links followed by a peering link, it is treated as a peer route). When such a link can not be found, the route is treated as a customer route. Then the normal export and preference rules above are followed, while adding an entry in export rules which says that all routes are advertised to siblings.

2.2.2 The BGP Protocol

The current BGP protocol used in today's Internet is BGPv4 [29]. The BGP protocol is normally implemented on routers, and the BGP messages are exchanged through a

1	Favor the route with higher local preference
2	Favor the route with lower AS length
3	Favor the route with lower origin type
4	Favor the route with lower Multiple-Exit Discriminator within same next-hop AS
5	Favor the route learned through eBGP session over that from iBGP session
6	Favor the route with lower IGP distance to egress point
7	Favor the route advertised by a router with lower router-id
8	Favor the route advertised by an interface with smaller IP address

Table 2.1: The BGP selection process

persistent TCP connection between two routers. If the two routers belong to different ASes, the session is called an external BGP (eBGP) session, otherwise it is called an internal BGP (iBGP) session. The eBGP sessions exchange routing information between neighboring ASes, while the iBGP sessions distribute those routing information from neighboring ASes to other routers inside the same AS.

The BGP is an incremental protocol. When a router first connects to a neighbor, the entire BGP routing table is transmitted. After that route updates and withdrawals are sent only when the route changes. No regular routing updates are sent; therefore, each router must remember all received routes.

Within each router, the processing on AS paths can be divided into three parts: import processing, path selection, and export processing. When a new update is received via a BGP session, the router first goes through the import processing process which blocks certain routes and sets certain parameters (e.g., local preference value). Then, the resulting candidate paths are fed into the path selection process to pick a single best route for each prefix. Finally, the selected routes are passed to export processing, which will filter and modify those routes and forward the results to other routers that established BGP sessions with this router.

The path selection process picks just one best candidate as the forwarding path, and does this by comparing the attributes of candidate paths step by step, until only one path is left. The process is illustrated in Table 2.1. In certain implementations, limited multipath support can be provided in this process. For example, in some Cisco routers [6], if certain routes are nearly identical to the selected best path (e.g., they are equal up to step 6 and the AS path is identical), then they are used with the best path simultaneously to forward traffic. Still, only the best path is advertised to the neighboring routers.

The AS relationships described in Section 2.2.1 are usually expressed using the local preference value, e.g., all customer routes are assigned a local preference value higher than that of any peer or provider routes. During import processing, different local preference values are assigned to incoming paths based on the different business relationships. For example, all paths from customer ASes may be assigned a local preference value of 400 to 500, all paths from peer ASes may be assigned a local preference of 200 to 300, and all paths from provider ASes may be assigned a local preference of 50 to 100. Then, the export processing filters certain routes, depending on to whom the routes are advertised. For example, only paths with a local preference of 400 to 500 (customer routes) are advertised to the providers of this AS. If the best path for a certain prefix happens to be a peer route, then no paths associated with this prefix will be advertised to the peers or providers of this AS.

Although BGP is an interdomain routing protocol, intradomain considerations will also affect BGP's route selection process. Big networks usually contain more than one BGP-speaking router. The edge routers normally establish eBGP sessions with adjacent routers in other ASes, and then distribute the routes from external sources to others in this AS using iBGP sessions. Different routers may select different AS paths for the same IP prefix. For example, in step 5 of the BGP selection process, routes learned from eBGP sessions are preferred to those from iBGP sessions. If two edge routers connected to different next-hop ASes can reach the same IP prefix, and the two routes are equal in the first four steps, step 5 dictates that they will each prefer going through the immediately connected next-hop AS, so they will select different AS paths simultaneously. When this happens, each AS can no longer be modeled using only one node. In Section 4.1, these issues are addressed.

2.2.3 Routing Convergence

BGP is simultaneously executed on the routers deployed in different ASes, in other words, the route selection process in the Internet is completed in a distributed fashion. The result of a distributed algorithm may depend on the initial state of the system and the execution order during the process. In some cases, a distributed algorithm may not reach a stable state, although stable states are reachable if another initial state or execution order has been picked. When a router switches its best route, temporary loops may be formed, and packets may be lost. If the route selection process in BGP does not converge, certain routers may keep switching best routes forever, which can have a disastrous impact on the Internet traffic. Therefore, protocol convergence is an important concern in designing interdomain routing protocols.

Tim Griffin and others proved that the BGP protocol itself does not guarantee convergence [15]. However, Lixin Gao and Jennifer Rexford later proved that the BGP protocol will converge if certain policy guidelines are obeyed and the Internet topology exhibits certain characteristics [13], and they found that those assumptions are generally true in today's Internet.

In MIRO, each router can select more than one path. With more routes and more complicated routing policies, the original convergence proof for BGP needs to be re-examined. Some policies which can guarantee the convergence of MIRO are described in Chapter 7.

Recent work [38] proved that when using route selection policy specific to each edge, the previous policy guidelines can actually be relaxed, while still guaranteeing convergence. The more flexible default path selection provided by NS-BGP can definitely benefit MIRO.

2.3 Related Work

Section 2.1 compared BGP, source routing, and overlay networks. This section is a brief summary of individual work in source routing [4, 14, 22, 25, 28, 42, 44] and overlay networks [3]. Most source-routing proposals [4,14,22,28,42,44] can provide multiple routes for every source-destination pair, and several of them [42, 44] explicitly suggest routing at the AS level rather than at the router level, as done in MIRO.

The Feedback Based Routing work [44] suggests separating the discovery of links in Internet from inferring availability of these links. Each router on the edge maintains a full topology of the Internet and selects routes for all packets originated from end hosts in the local edge AS, while each router in the core announces the existence of its attached links and forwards the packets as instructed. The availability of links is not announced in the system; instead, edge routers try to avoid failed links by pre-calculating multiple independent routes and sending probes to determine the availability of pre-calculated routes. The dissertation argues that the amount of routing messages in Feedback Based Routing is reduced significantly compared with BGP, since routers only propagate structural information. However, it remains to be seen whether Feedback Based Routing is functionally equivalent to BGP on achieving all traffic engineering goals. Also, Feedback Based Routing assumes packets using the same AS path see similar latency, which may not be true in reality.

The Platypus work [28] points out that there is no way to guarantee that the routes selected by end hosts satisfy traffic policies set by intermediate ASes in previous source routing works. The authors propose using network capabilities to achieve authenticated source routing, and to satisfy traffic policies set by other ASes. Network capabilities are cryptical tokens issued by ASes, only packets with the appropriate network capabilities are allowed to use the routers. In the platypus system, each packet contains a list of waypoints and accompanying network capabilities issued by those waypoints. When one packet reaches a waypoint, the corresponding capability is verified, and then the packet is forwarded to the next waypoint denoted in the packet. Platypus presents an interesting way for end hosts to select routes while respecting the traffic policies set by intermediate ASes, but it is not clear whether all traffic policies can be expressed using pre-assigned capabilities. Platypus is different from other source routing systems in that an intermediate AS may or may not pass on the capabilities it obtained from another AS, therefore not all links are available to an end-host. The decisions made by intermediate ASes on capabilities may have unexpected interactions with the feedback mechanisms used by end-hosts to select routes.

The Loose Source Routing work [4] proposes using Wide-Area Relay Addressing Protocol(WARP) over IP, and the header in the WARP protocol contains hop-by-hop forward path and reverse path. The source calculates and specifies the entire paths in the header, and then routers just forward them as instructed. The paper suggests that the path encoded in the packet can be used to implement both transmit policies and receive polices. When used to enforce receive policies, the receiving host can inspect the path in the packet and ask routers near the source to filter certain malicious traffic. However, the type of receive policies this system can enforce is limited, because the receiving host can not really change the path selected by the sending host.

The Nira work [42] argues that every user or user application should be able to select routes based on the contracts signed by the user and any provider. Since every user may sign multiple service contracts with remote providers, it is impossible for edge routers to make route selections, as this is too much state to keep. On the other hand, end users must keep track of the Internet topology, since they need to select the entire route. To solve these problems, Nira proposes encoding the Internet topology and AS relationships in the source and destination addresses. It assumes that most routes are “valley-free” as defined by Lixin Gao and Jennifer Rexford in [12]; therefore, a hierarchical addressing scheme is proposed where any address of an AS contains a prefix representing the provider of that AS. When an AS is connected to more than one provider, it advertises multiple addresses to its customers. In this system, an address uniquely identifies a provider-customer AS chain. End users pick their routes by putting a specific source and destination address in the packet header, and then the intermediate routers inspect both addresses to infer the next AS on the path. One problem of Nira is that its infrastructure is tightly coupled with “valley-free” routes, and representing other types of routes or exposing other types of AS relationships is not entirely impossible but very complicated. Another problem is its route availability discovery; generally speaking, a user is only notified of the changes on the path to his tier-1 provider, and it is very possible that the user chooses a destination address that uses an unavailable path, and the packets get dropped.

The BANANAS work [22] argues that previous source routing work specifying hop-by-hop path in packets is hard to incrementally deploy in today’s Internet, and it proposes the use of PathID to solve this problem. The PathID is a short hash of a sequence of globally known identifiers describing the path. When an upgraded node in BANANAS calculates a path, it knows not only the topology, but also which other nodes are upgraded in the graph. Also, every upgraded node knows the path calculation algorithm adopted by every other node, so it can compute the complete forwarding table used by every node, if needed. At an upgraded source node, the PathID, which represents the entire path, is put in each packet; at the next upgraded node, the PathID is replaced with a new PathID, which represents the part of path that has not been traveled. One problem of BANANAS is that each upgraded node needs to know the route selection algorithm used by every other node, because it needs to validate the feasibility of the path it selected. As a result, it is hard to use more advanced or dynamic route selection algorithms and to keep the computation cost low at upgraded nodes. Also, it is questionable how much flexibility can be gained in BANANAS if intermediate ASes are only willing to advertise a subset of paths.

Recent work on Pathlet [14] suggests achieving scalability and flexibility by exporting routes at the level of virtual nodes. A virtual node can be a router, a subnet inside one AS, or an entire AS. This method can be used to achieve a middle ground between AS-level path vector routing and router-level link state routing. However, the Pathlet system still assumes that path selection is done by the end hosts. For an intermediate AS, once a pathlet is advertised to its neighbor, the pathlet can be used by any downstream end host. The intermediate AS has little control over how much traffic will be directed to its pathlets.

The Path Splicing work [25] suggests constructing source routes by combining multiple routing trees built on top of the physical network. Given the links in the physical network, a set of path slices are generated, and each path slice is a routing tree towards the given destination. The paper gives an algorithm which can calculate slices with very few overlapping links without significantly increasing path length. When a link fails, packets can be forwarded from one slice to another to guarantee reliability. In the inter-

AS domain, each AS can select more than one candidate path, create multiple forwarding tables, then use the splice number encoded in the packet to select the appropriate forwarding table. The concept of path splicing can be applied in MIRO as well; instead of creating multiple forwarding tables, the additional routes introduced by MIRO can be used to build path splices.

Generally speaking, all of the previous source routing work suggests giving control to end hosts or the edge routers; therefore, they do not give intermediate ASes much control over path selection, as discussed earlier in Section 2.1.2.

Some work considers how receivers can control the paths taken by incoming packets [4], but the purpose there is mainly the filtering of malicious traffic. In contrast, MIRO suggests new methods which can be used to control how incoming packets are routed.

Bearing some similarities to overlay networks, MIRO establishes tunnels that encapsulate and decapsulate packets. However, MIRO selects paths on the underlay with the cooperation of the routers in intermediate ASes, rather than directing packets over virtual links to intermediate hosts.

Several papers propose new routing architectures that refactor how reachability information is disseminated. Nimrod [9] uses clusters to hide the internal topology of a network, revealing additional details only upon request. However, the members of a Nimrod cluster must be contiguous, while the negotiations in MIRO can happen between arbitrary pairs of ASes. Also, the Nimrod work does not present the technical details of how clusters and the request-response protocol should be implemented. The HLP [33] work uses a hybrid of link-state and path-vector protocol. It divides ASes into groups, and each group contains multiple ASes with provider-customer relationships. Within a group, a link-state protocol is used to compute paths; between different groups, a path-vector protocol is used. Compared to HLP, MIRO does not require that a different protocol be used when the AS relationship is different; therefore, MIRO can support more flexible routing policies.

Other routing architectures consider the role of cost and incentives in making interdomain routing decisions. Nexit [23] enables cooperation between neighboring ASes in selecting egress points. Nexit uses negotiation to avoid the inherent inefficiency of hot-potato routing and conventional traffic engineering practices [20]. Compared to MIRO, the negotiation in Nexit focuses specifically on selecting among the existing BGP-learned routes at multiple egress points rather than discovering new interdomain routes. In that sense, the two proposals are complementary and could conceivably be part of a larger framework for using negotiation to improve interdomain routing. Another recent study [1] proposes a routing system that advertises multiple AS paths, with pricing information attached to each announcement. However, the paper does not present a concrete design and evaluation of the protocol, making it difficult to compare to MIRO directly. Some other work [31,34] shows how the economic framework can be established to allow more flexible path selection while rewarding participated parties economically. Similar economic frameworks can be used in MIRO to stimulate the need of routing tunnels.

Multi-path routing has been explored in the context of intradomain routing. Equal Cost Multi-Path (ECMP) allows routers to split traffic over multiple shortest paths in intradomain routing protocols, such as OSPF and IS-IS. Some proposals have considered ways to relax the requirement in ECMP that all candidate paths must have the same cost [10]. Recent work on TeXCP [21] has also explored how to split traffic over multiple intradomain paths for more effective traffic engineering. In TeXCP, ingress nodes dynamically adapt the splitting of traffic over multiple pre-computed paths. It appears TeXCP and MIRO are complementary, in that MIRO focuses on identifying and selecting paths, whereas TeXCP focuses on how to adjust the proportion of traffic on each path.

Techniques for selecting multiple paths within an AS do not extend directly to interdomain routing. The routers within an AS can share topology information, and they are controlled by the same authority. In contrast, in interdomain routing, ASes have limited information about the network topology and may have different (or even conflicting) path-selection goals. Some recent work has proposed extensions to BGP to propagate QoS metrics [40]. However, this approach is problematic in practice, because it requires extensive deployment and cooperation among ASes, and it may introduce scalability challenges if the QoS information changes frequently.

Chapter 3

MIRO Protocol Design

In designing a new interdomain protocol, the aim is to achieve the following goals:

- *Flexibility:* The protocol should not be restricted to single-path routing. Packets going through the same router or the same AS should be able to follow different paths.

- *Scalability:* The new protocol should keep the distributed information to a minimum, preferably close to the amount transferred in current BGP protocol.

- *Control for intermediate ASes:* Both the intermediate ASes and the end hosts should be able to affect the selected paths. Because conflicting business interests exist, it is not always possible for every AS to get its most desired path simultaneously. The goal is to allow selecting better paths if all involved parties will be rewarded for using the new paths. Originally, those paths could not be selected because of the single-path restriction.

- *Backward compatibility:* Even if some ASes are still using the current BGP protocol, MIRO should work.

- *Early adoption benefits:* If the ASes who have adopted MIRO can gain greater benefit than those who have not, it will be a nice incentive for every AS to adopt MIRO eventually.

To achieve these goals, this dissertation proposes using the current BGP protocol to construct *default paths,* while adding multiple *supplemental paths* to the default path through interdomain negotiations. This section presents the key features of MIRO: AS-level path-vector routing for scalability, pull-based route retrieval for backward compatibility and scalability, bilateral negotiation between ASes to contain complexity, selective export of extra routes for scalability and to give control to intermediate ASes, and tunneling in the data plane to direct packets along the chosen routes. For simplicity, each AS is treated like a single node for now, and the implementation details inside an AS are deferred until Chapter 4.

3.1 AS-Level Path-Vector Protocol

At the AS level, MIRO represents both the default paths and the supplemental paths as a sequence of AS numbers. It also employs a path-vector protocol for distributing default paths. As in today's BGP, each AS adds its own AS number to the AS-path attribute before propagating the route announcement to a neighboring AS.

Although AS-level path selection seems natural for an interdomain routing protocol, other options exist. Some protocols propose finer-grained path selection. For example, some source-routing proposals suggest that all links in the Internet be exposed to allow link-level path selection. However, this dissertation argues that link-level path selection exposes too much internal information of intermediate ASes, and also limits the control intermediate ASes can have over the flow of traffic. In addition, supporting link-level path selection requires the protocol to propagate a large amount of state, and updates to this state when internal topology changes. In contrast, some other protocols [33, 44] divide ASes into AS groups, and the routing protocol used between AS groups is different from the protocol used inside each group. The general concern with this kind of protocol is that AS relationships are directly built into the routing protocol, because ASes inside a group and those in different groups exchange different kinds of messages. In these systems, adjusting AS relationships would require reconfiguration at all related sites, and the types of relationship that are not built into the protocol would be hard to implement.

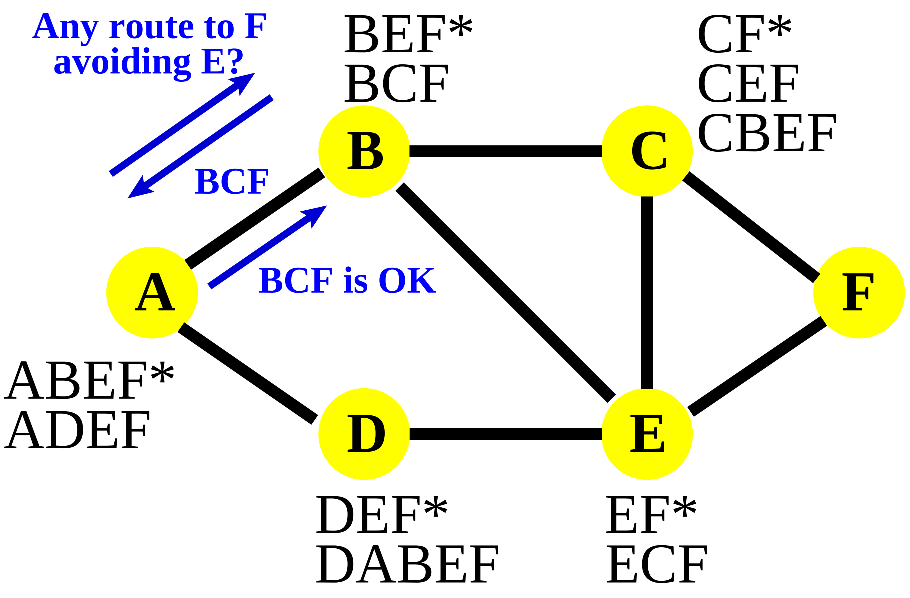
This dissertation argues that routing at the AS level is the right choice. First, each AS is owned and managed by a single authority, making the AS a natural entity of trust and policy specification. Second, routing at the AS level is more scalable than at the link level; each AS can keep its internal structure to itself, and traffic flow inside an AS can be adjusted without affecting the AS path. Third, because business contracts are often signed by authorities, rather than individual users, it is easier to verify that the performance and reliability of a route conforms to an AS-level contract. In MIRO, groups of related ASes can cooperate by exporting extra paths for more flexible path selection. In other words, the ASes in MIRO implement AS-group relationships by adopting more benign policies toward ASes inside the same group, rather than by speaking different routing protocols inside group members. As a result, ASes in MIRO can belong to more than one group simultaneously, but speak only one routing protocol, and non-traditional AS-group relationships can be implemented simply by configuring new routing policies.

3.2 Pull-based Supplemental Route Retrieval

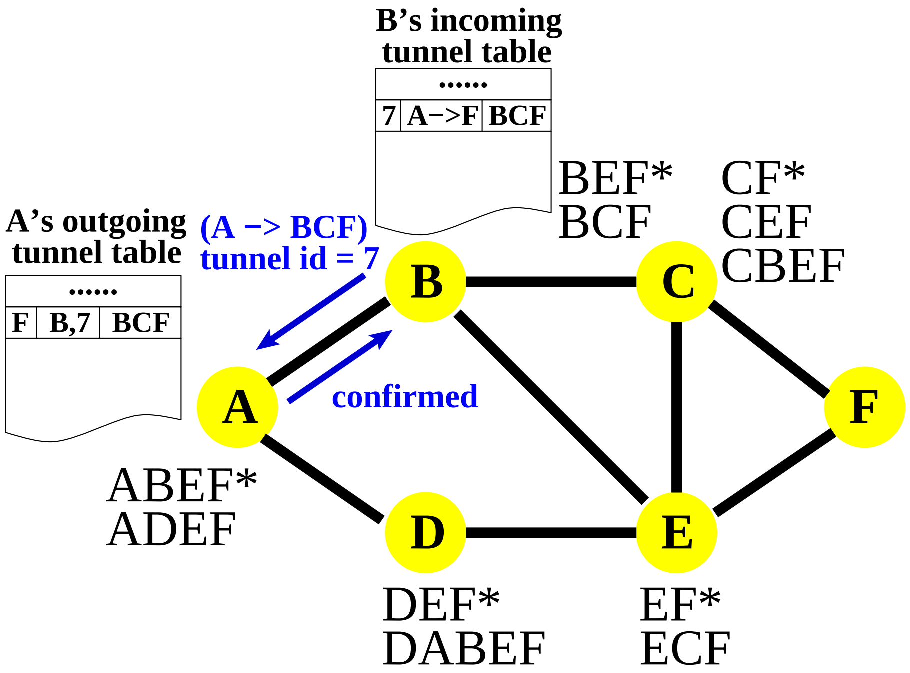
Routing protocols are designed to direct the packets in the correct directions so that the packets can reach desired destinations. To do that, routing protocols need to propagate available links or routes in the system. Both BGP and source routing use push-based route advertisement: the receiver of a candidate route or a candidate link does not explicitly ask for any routes, it just accepts whatever the neighbors send.

In MIRO, the traditional push-based route advertisement is still used for default paths, but pull-based route retrieval is used for supplement route advertisements, instead. The propagation of unnecessary information is avoided, by providing candidate routes passively, and only when someone asks for them. Because it has been observed that most ASes and end users are satisfied with the default routes provided by BGP in the Internet, this dissertation believes only a few ASes need the extra routes propagated. If more people prefer a certain route than the default route, the underlying default routes protocol should switch to the new route instead. The expectation is that the default paths should satisfy most of the ASes, while the rest of the ASes can be satisfied without leading to significant information propagation cost. For example, in Figure 3.1, AS A is the only AS that is unsatisfied with its default route (ABEF). As a result, AS A asks AS B to advertise alternative routes, possibly including a routing policy (e.g., “avoid routes traversing AS E”) in the request. All other ASes simply use their default routes and incur no additional overhead.

Another benefit with pull-based route retrieval is backward compatibility: the ASes that have not deployed our multi-path extensions to BGP can continue to use today’s push-based BGP protocol. For example, even if ASes C and F do not use the enhanced protocol, AS A can still contact AS B for extra route candidates. Each AS can decide



(a) route negotiation



(b) routing tunnel establishment

Figure 3.1: Multi-path Routing Example

on its own whether to deploy the enhanced protocol and to offer a value-added service to others. The evaluation section shows that even a modest deployment of MIRO by a few tier-1 and tier-2 ISPs is sufficient to expose much of the underlying path diversity in today's AS-level topology, making it possible for early adopters to enjoy significant gains. This can encourage other ISPs to deploy the protocol in order to compete effectively with the early adopters in providing value-added services to their customers.

3.3 Bilateral Negotiation Between ASes

When referring to supplemental paths that are constructed "as needed", the next natural question is, how does one define the need of individual ASes? Some of the early routing protocol proposals include a few common path attributes, such as latency or bandwidth in path advertisements. The author of this dissertation believes that different ASes have different definitions of "need," and using several common path attributes may not be enough for everyone. Also, adding new path attributes in path announcements means that the protocol implementation on every related router needs to be updated. In MIRO, it is proposed that ASes use private negotiations to express their needs and path attributes, instead of including standard measures in the public announcements.

Moreover, MIRO uses bilateral negotiation between ASes, where one AS asks another to advertise alternate routes. Bilateral negotiation simplifies the protocol, and it reflects the fact that AS business relationships are often bilateral anyway. In Figure 3.1, negotiating with AS B is sufficient for AS A to learn a path to AS F that circumvents AS E. In bilateral negotiations, the AS initiating the negotiation is referred to as the *requesting AS*, and the other AS as the *responding AS*. The AS closer to the packet source is the *upstream AS*, and the one closer to packet destination is the *downstream AS*. In

Figure 3.1, AS A is the requesting AS and the upstream AS, and AS B is the responding AS and the downstream AS.

Although this focuses on bilateral negotiations, an AS can easily approximate multi-party negotiation by making requests to two ASes. In Figure 3.1, AS A may ask both B and D to advertise additional paths, with the goal of discovering paths that avoid traversing AS E. In responding to a request, an AS may also contact one or more downstream ASes to provide additional paths. For example, AS B may ask AS C to advertise alternate paths as part of satisfying the request from AS A, if C is not already announcing a path that avoids AS E. Still, it is not envisioned that multi-hop negotiation needs to happen very often, because most paths in today's Internet are short, typically traversing four AS hops or less.

In the simplest case, an AS negotiates with an immediate neighbor, as in Figure 3.1, where AS A negotiates with AS B or AS D. Allowing negotiation with non-adjacent ASes provides greater flexibility, especially when the adjacent ASes have not deployed the new multi-path routing protocol. For example, suppose ASes B and D have not deployed the new protocol; AS A could conceivably negotiate with AS C to learn the path CF, using the path ABC through AS B to direct packets to AS C, which then directs the packets onward toward AS F. In directing traffic through an intermediate AS, MIRO is similar to overlay networks, though it is envisioned that the routers in the intermediate ASes can support this functionality directly, rather than requiring data packets to go through intermediate hosts.

Although Figure 3.1 shows an example where the requesting AS is the upstream AS, downstream ASes may also initiate requests. For example, suppose the link EF in Figure 3.1(a) is overloaded with traffic sent by ASes A, B, D, and E to AS F. To reduce the load on link EF, AS F can request one of more of the source ASes to divert traffic to the link CF. For example, AS F can negotiate with AS B to switch to an alternate path that traverses CF. Then, AS B can respond by agreeing to select the path BCF instead of BEF, and AS B will advertise the path BCF to its customers.

3.4 Selective Export of Extra Routes

Both the requesting AS and the responding AS can affect the result in the negotiation. The requesting AS controls the result by selecting who it negotiates with, and which path it picks among the choices; while the responding AS controls the result by selecting which paths are shown to each requesting AS.

Upon receiving a request, the responding AS could conceivably propagate all known alternate routes to the requesting AS. However, announcing all of the routes may incur significant overhead. In addition, the responding AS may not view all routes as equally appealing. As such, it is envisioned that the responding AS can apply routing policies that control which alternate routes are announced, and potentially tag these routes with preference or pricing information to influence the routing decisions of the requesting AS. For example, suppose AS C has a customer (not shown) that wants to avoid the link CF. Rather than offering both CEF and CBEF as alternate routes, AS C may announce only CEF, if sending traffic via AS B incurs a significant financial cost; if AS C wants to announce both, it can also tag the CBEF route with a higher price.

It is envisioned that the policies for exporting alternate routes will depend on the business relationships between the two ASes. For example, suppose an AS has selected a route learned from one customer AS, but it has also learned another route from a different customer AS; the AS may be willing to advertise all customer-learned routes but not routes learned from peers or providers. Alternatively, the AS may be willing to advertise all routes with the same (highest) local-preference value, or advertise other (less preferred) routes only to neighbors that subscribe to a premium service. These kinds of policies are readily expressed using the same kinds of "route map" constructs commonly used in BGP import and export policies today [7], and discussed in more detail in Chapter 6.

3.5 Tunnels for Forwarding Data Packets

Under multi-path routing, the routers cannot forward packets based on the destination IP address alone. Instead, routers must be able to forward the packets along the paths chosen by the upstream ASes. In MIRO, the two negotiating ASes establish a *tunnel* to carry the data packets. The downstream AS provides a tunnel identifier to the upstream AS; this identifier does not need to be globally unique, it only has to be unique in the downstream AS. In Figure 3.1(b), when AS A and AS B agree on the alternate route BCF, AS B assigns a tunnel id of 7 and sends the id to AS A. In the data plane, AS A directs the packets into the tunnel, and AS B removes the packets from the tunnel and forwards them across the link BC. Then, AS C forwards the packets based on the destination IP address along the default path to AS F. Section 4.2 shows several ways to encapsulate the data packets as they enter the tunnel.

The upstream AS does not need to direct all packets into tunnels. Rather, the AS may apply local policies to direct some traffic along tunnels, and send the remaining packets via the default path. In Figure 3.1, suppose BCF has lower latency then BEF; then AS A may want to direct its real-time traffic via BCF, while sending best-effort traffic along BEF, especially if AS B charges for using alternate routes. The upstream AS can implement these traffic-splitting policies by installing classifiers that match packets based on header fields (e.g., IP addresses, port numbers, and type-of-service bits). The upstream AS can also split the traffic to balance load across multiple paths; it can direct a fraction of the traffic along each of the paths by applying a hash function that maps a traffic flow (e.g., packets with the same addresses and port numbers) to a path, as in prior work on multi-path forwarding within an AS [21].

3.6 Summary of MIRO Protocol

In this chapter, the design of MIRO was introduced. It tries to achieve flexibility and scalability by adapting the current AS-level path-vector protocol. The interdomain routing is divided into two levels, single-path path protocol (BGP) for default path propagation, and pull-based route retrievals for additional paths when necessary. When ASes decide that the default paths propagated via the single-path protocol do not suffice, they use bilateral negotiations to discover alternatives. Using negotiations, each party can control the outcome by filtering the paths it is willing to provide or accept. After negotiations, they establish tunnels in the data plane to utilize the new paths they just negotiated. The next chapter illustrates the implementation details of the MIRO protocol.

Chapter 4

MIRO Implementation

The previous chapter gives the high level design of MIRO, and this chapter will describe some implementation details for MIRO to be practical. For example, up to now the simplification was made that interdomain and intradomain routing can be cleanly separated; therefore each AS can be treated like a single node in interdomain routing protocols, ignoring its internal topology. However, in reality ASes often have multiple routers that participate in the interdomain routing protocol, and the choices made in intra-domain routing may affect the paths advertised in the inter-domain routing protocol. Therefore, intra-AS architecture needs to be included in the implementation of MIRO.

In addition, MIRO uses negotiations to discover additional routes and tunnels. Therefore, it is important to clarify how negotiations in the control plane and tunnels in the data plane will be achieved.

This chapter first describes how to implement MIRO across a collection of routers inside an AS. Then, several practical methods are presented for encapsulating packets and identifying the end-points of tunnels in the data plane. Finally, the control plane design is presented.

4.1 Intra-AS Architecture

A large AS typically has multiple routers. Some of those routers are connected with routers in neighboring domains, they are called edge routers. Other routers are called internal routers, and they are only connected to the routers inside the same domain. Routers inside a domain typically exchange routing information via the iBGP protocol, and each router independently picks the best route and propagates the results to other routers. As the decision process is independent, different routers may pick and advertise different AS paths simultaneously for the same destination prefix. In this case, modeling each AS like one node is obviously not enough.

For example, as illustrated in Figure 4.1, routers R1, R2, and R3 are edge routers. Router R2 gets AS path VU from AS V, and AS path WU from AS W, while R3 gets WU from AS W. Assume that the path VU and WU have equal local preference and MED value on all routers, when the best path is being picked in the BGP selection process as illustrated in Table 2.1, VU and WU are equally preferable in steps 1 to 6. Assume that R2 picks VU over WU in step 7, it will then label itself as the egress point for path BD, and announce (VU, R2) to all other routers inside the domain. Although R3 gets (VU, R2), it prefers path WU learned via AS W in step 5 and picks WU instead, then it announces (WU, R3) to other routers. Even if R2 gets (WU, R3), it will decide (VU, R2) is more preferable in step 5 and stick to its choice. Therefore, R1 will get both (VU, R2) and (WU, R3) in the steady state, they are equally preferable to R1 in steps 1 to 5, so the IGP distance could decide which path R1 chooses in step 6. If R2 is closer, R1 will choose (VU, R2) instead of (WU, R3).

From the above example, it can be seen that different routers inside one AS may choose different AS paths for the same prefix. The BGP is a single-path protocol, in that each router picks only one path for each prefix, though it does allow different routers inside one AS to pick different paths. However, the path diversity achieved under this situation is still too restrictive, it assumes that many attributes of the paths are equal, and the final choices depend heavily on the internal network topology. In MIRO, a higher level of flexibility may be achieved by allowing multi-path selections, even on the same router, and by allowing routers like R1 to select paths based on criteria other than IGP distances.

In MIRO, an AS is allowed to advertise any valid AS paths on any of its edge routers (note that including internal routers will not introduce additional valid AS paths). For example, in Figure 4.1, R2 will announce both (VU, R2) and (WU, R2) to all other routers although it will only label (VU, R2) as the default route. Also, R1 may announce both VU and WU as candidate paths although it will mark VU as the default route. In MIRO, AS X can provide WU as an extra route even if neither AS V nor AS W runs MIRO.

To achieve that goal, two issues in MIRO need to be addressed: how do the routers calculate and advertise these additional paths, and how are the packets transmitted inside the domain to traverse the non-default paths? This dissertation will look at the second question next, and return to the first question after that.

In MIRO, the upstream AS forwards packets into a tunnel. The downstream AS takes packets out of the tunnel and continues forwarding them. When the downstream AS is also the responding AS, packets will be forwarded alone negotiated paths; otherwise, they are sent using the default paths.

If each AS is abstracted to be one node, then “continue forwarding packets” means forwarding the packets to the corresponding exit link. However, when different routers in one AS are linked with different neighboring domains and they pick different AS paths,

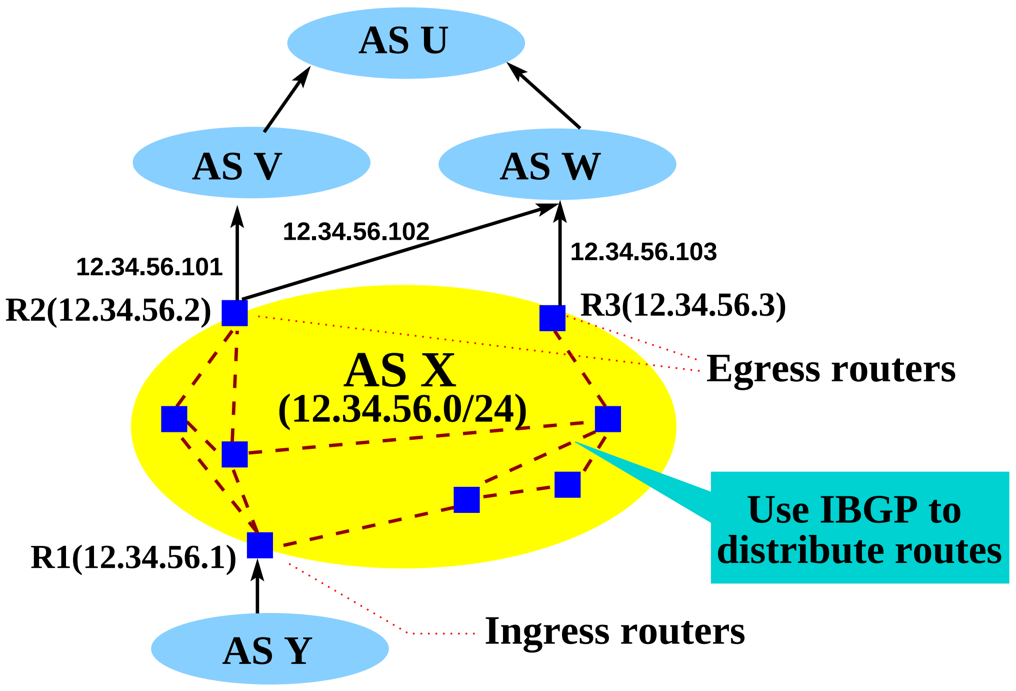


Figure 4.1: Intra-AS Routing Architecture

the packets must be sent to the correct edge router first, then that edge router should also pick the correct exit link. For example, assume that both R2 and R3 choose WU as default routes, and that AS X agrees to provide path VU to AS Y. Then the tunnel between AS X and AS Y should end at router R2, and R2 should know that the packets in that particular tunnel should be forwarded via link XV, rather than the default link XW. That is, R2 needs to decapsulate the packet and to forward the packet based on the tunnel identifier[1]. Then AS Y, in turn, must install the necessary state to ensure that packets entering the network are diverted to the appropriate tunnels. This may require AS Y to install data-plane state at multiple ingress routers where the data packets may arrive.

Providing alternate routes to the customer requires coordination amongst the routers in AS X. Assume again that both R2 and R3 choose WU as the default path. By default,

[1]This functionality, known as "directed forwarding," is already implemented in some routers.

R2 does not announce the alternate route (learned from AS V) to R1 via iBGP. There could be two main ways to implement the control protocol. First, the customer may request alternate routes from R1, which in turn requests alternate routes from its iBGP neighbors R2 and R3. If the client selects the alternate route, R1 propagates the tunnel identifier and instructs R2 to install the necessary data-plane state for decapsulating and forwarding the packets as they leave the tunnel on their way to AS V. Second, a separate service, such as the Routing Control Platform (RCP) [8], the Morpheus platform [36], or the VROOM architecture [37], can manage the interdomain routing information on behalf of the routers. In this approach, the routing platform exchanges interdomain routing information with neighboring domains, and computes BGP paths on behalf of the routers. The routing control platform in AS X handles the requests from the customer's routing control platform for alternate routes to reach the destination. The routing control platform can also install the data-plane state, such as tunneling tables or packet classifiers, in the routers to direct traffic along the chosen paths. The recently proposed BGP ADD-PATH capability can also be used to expose the additional paths to another BGP speaker [35].

4.2 Data Plane Packet Encapsulation

The tunnels and the tunnel identifiers described in Section 3.5 are abstract concepts, any technique that can forward packets on existing networks according to attached tunnel identifiers will work. In today's Internet, people often use IP-in-IP encapsulation for tunneling, so the following discussion will focus on on this specific tunneling technique. In this approach, the original data packet is wrapped in a new IP header when it enters a tunnel, after which the intermediate routers forward the new packet according to the new IP address, and finally, the new IP header is stripped away at the other end of the tunnel to reveal the original data packet. A data packet can be encapsulated in several layers of IP headers, resulting in a "tunnel inside another tunnel."

If this approach is used in MIRO, the response from the downstream AS will include an IP address corresponding to the egress point of the tunnel. To divert a packet into the tunnel, the upstream AS encapsulates the original packet using this IP address. Therefore, MIRO must ensure that the upstream AS knows how to reach this IP address, even if the downstream AS is several AS hops away. In addition, it will need to be determined which IP address MIRO should use, and ensured that the egress router is equipped to decapsulate the packets and to direct them to the next AS in the path. There are two main options for which IP address the downstream AS should provide, with different advantages and disadvantages:

IP Address of the Egress Routers or Exit Links: When IP address of the exit links are used, the downstream AS first labels each exit link with a different reserved IP address, then advertises those addresses to the upstream AS. For example, in Figure 4.1, link R2→AS V, R2→AS W, and R3→AS W are given IP addresses 12.34.56.101, 12.34.56.102, and 12.34.56.103 respectively, then 12.34.56.102 and 12.34.56.103 are advertised to the upstream AS if AS W is the selected next hop AS. This way the exit link is directly encoded in IP destination. Alternatively, the downstream AS can advertise the IP address of egress routers. Because there are fewer egress routers than exit links, this will consume fewer IP addresses, but the tunnel id needs to be encoded so that the egress router knows which exit link to pick. For example, AS X in Figure 4.1 can advertise 12.34.56.2 and 12.34.56.3 if AS W is the next hop AS, and advertise 12.34.56.3 if AS V is selected instead. R2 checks the tunnel id to see if link to AS V or that to AS W should be picked.

One Reserved IP Address for All Tunnels: The downstream AS reserves one special IP address for all tunnels. At each ingress router, the packet destined to this special

IP address is replaced with the correct egress router IP address. For example, AS X in Figure 4.1 chooses 12.34.56.100 as the special IP address, and that IP address is the destination for any packets belonging to any tunnel in X. Also, each ingress router grabs a mapping table of (tunnel_id, set of egress router IP addresses), for example, (tunnel 7, $\{$12.34.56.2, 12.34.56.3$\}$) will be installed on R1 if tunnel 7 uses the AS X$\rightarrow$AS W $\rightarrow$AS U route. Then, R1 learns from intra-domain routing protocol that R2 is the closest one in the set, therefore R1 sets 12.34.56.2 as the chosen IP address. When R1 sees a packet destined to 12.34.56.100, it checks the tunnel id in the packet, finds that the id is 7, and then retrieves 12.34.56.2 from its lookup table. Finally R1 replaces 12.34.56.100 with 12.34.56.2 and forwards the packet to R2.

By using one IP address for all tunnels, the downstream AS does not reveal any internal topology to the upstream AS. Therefore, the downstream AS can freely adjust which exit router and exit link to pick at its ingress routers. However, this method requires packet rewriting, and therefore data-plane modifications at all ingress routers. On the contrary, by exposing IP addresses corresponding to egress routers or exit links, the internal topology is partially exposed to the upstream AS, so changes in internal topology may lead to tunnel destruction or packets traveling longer distance. Moreover, it poses security challenges as anyone can send packets to these addresses and issue a DoS attack. Advanced packet filters or network capabilities [43] can be used to prevent this problem.

4.3 Control Plane Tunnel Management

The control plane manages the creation and destruction of tunnels, based on negotiations between pairs of ASes. Section 4.1 described how routers can coordinate inside one AS. This section discusses how two ASes interact to establish and tear down tunnels.

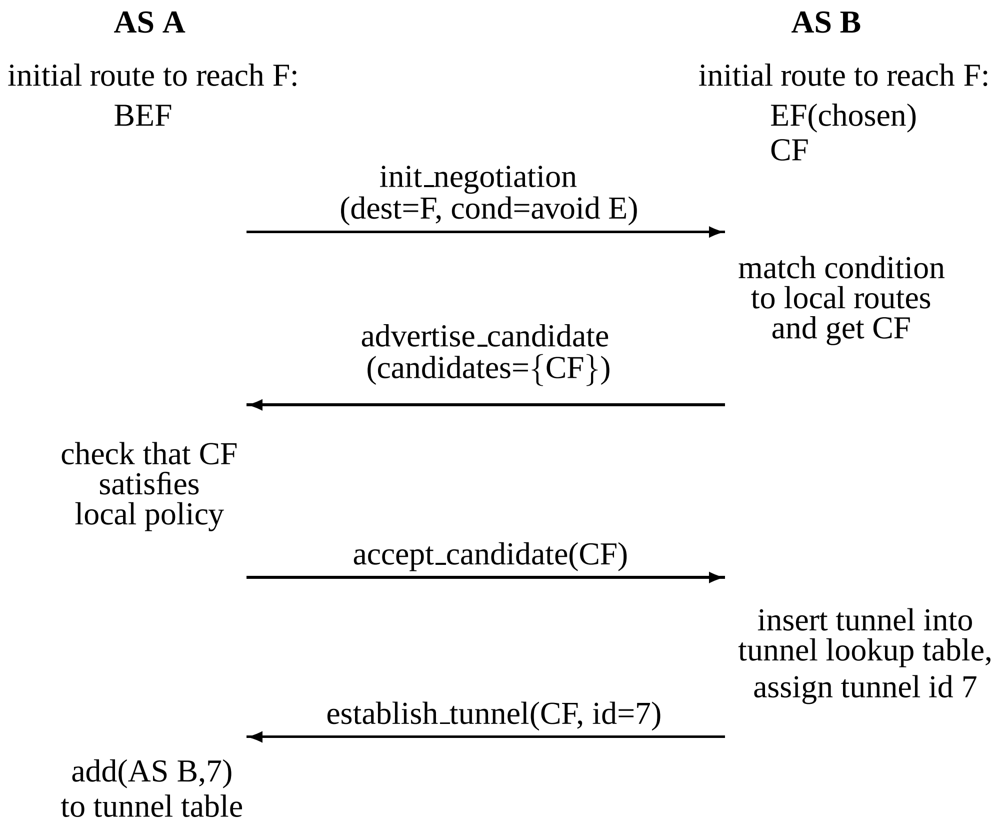


Figure 4.2: Control Plane Negotiation Example

Imagined that each AS defines a set of local policies regarding tunnel management, and then some software on the routers or end hosts can automatically monitor current routing situations and conduct the negotiations. This is similar to the current BGP protocol, where BGP policies are defined by human operators and actual path selections are performed by programs on routers.

Figure 4.2 presents an example in which AS A launches a request to AS B, specifying the destination prefix and (optionally) the desired properties of the alternate routes. Upon receiving the request, AS B advertises the subset of candidate routes that are consistent with its own local policy. Then, AS A selects one candidate route and performs a handshake with AS B to trigger creation of the tunnel. Then, AS B replies with a tunnel identifier (represented by the number “7” in the figure), or the IP address of the tunnel end-point, and the ASes update tunnel tables accordingly.

A tunnel remains active until one AS tears it down, either actively or passively. For example, AS A will tear down the tunnel if the path AB changes (e.g., if the path to B now traverses through E) or fails, and AS B will tear down the tunnel if the path BCF to the destination prefix fails. The ASes can observe these changes in the BGP update messages or session failures. However, when A can no longer reach B, the “active tunnel tear-down” message itself may not be able to reach AS B. To avoid leaving idle tunnels in the downstream ASes, AS A and B should adopt a soft-state protocol, where they exchange “keep-alive” messages in the MIRO control plane, and destroy tunnels when the heartbeat timer expires. These “keep-alive” messages can be directed to a specialized central server (such as the RCP) in each AS; that server will monitor the health for all tunnels and actively tear down unused ones.

4.4 Summary

This chapter addressed several implementation issues of MIRO. First, the intra-AS implementation was described. Different routers in each AS may be connected to different neighboring ASes and they pick default BGP routes independently; MIRO tries to achieve flexibility by allowing an AS to advertise any valid AS paths on any of its edge routers. To do that, MIRO assumes that routers inside the domain exchange non-default paths with each other or that a separate service like RCP exists to manage that information. Tunnels inside MIRO end at the edge routers, therefore intermediate routers can just forward the packets inside a tunnel along the default path, and then the edge routers use “directed forwarding” to send them to the correct exit links.

After that, the data-plane implementation was described. The discussion focused on IP-in-IP encapsulation; the upstream AS will use the IP address it obtained from the downstream AS to encapsulate packets. The downstream AS has several choices in calculating that IP address, each with its own advantages and disadvantages.

Finally, this dissertation presented a brief description of how tunnels can be managed in the control plane. The tunnels in MIRO are established through dynamic negotiations, which are controlled by predefined policies. Then, each AS monitors the changes in the BGP protocol and tears down tunnels if needed.

Other than the issues already addressed, it is imagined that more details will be needed when MIRO is deployed in practice. However, that is outside the scope of this dissertation. This dissertation just illustrates the high level design and show the benefit of MIRO. In the next chapter, MIRO will be evaluated using an AS-level topology and some sample applications.

Chapter 5

Performance Evaluation

In this section, the effectiveness of MIRO is evaluated based on an AS-level topology which is annotated with the business relationships between neighboring ASes. After describing the evaluation methodology, this dissertation shows that MIRO can expose much of the path diversity on this AS-level topology. Demonstrating whether MIRO provides *enough* flexibility requires evaluating the protocol with a particular policy objective in mind. Most of the evaluation focuses on the scenario in which the source AS wishes to avoid a particular intermediate AS for security or performance reasons. These experiments are used to demonstrate that MIRO is flexible and efficient, and that it offers substantial benefits to early adopters. A second application is also briefly considered, in which a multi-homed stub AS needs to negotiate with upstream ASes to balance load across multiple incoming links.

Name	Date	# of Nodes	# of Edges	P/C links	Peering links	Sibling links
Gao 2000	10/1/2000	8829	17793	16531	1031	231
Gao 2003	10/8/2003	16130	34231	30649	3062	520
Gao 2005	10/8/2005	20930	44998	40558	3753	687
Agarwal 2004	2/10/2004	16921	38282	34552	3553	177

Table 5.1: Attributes of the data sets

5.1 Evaluation Methodology

Ideally, MIRO should be evaluated by deploying the new protocol in the Internet and measuring the results. As this is not possible, MIRO is evaluated in an environment as close to the current Internet as possible. Evaluating on streams of BGP update messages is not sufficient, both because of the limited number of data feeds available and of the need to know what routing policies to model. Instead, MIRO is evaluated on the AS-level topology, assuming that each AS selects and exports routes based on the business relationships with its neighbors [13]. This dissertation draws on the results of previous work on inferring AS relationships [12, 32], applied to the BGP tables provided by RouteViews [30]. Invariably, RouteViews does not provide a complete view of the AS-level topology, and even the best inference algorithms are imperfect, but it is believed that this is the most appropriate way to evaluate the effectiveness of MIRO under realistic configurations. The main results depend primarily on the typical AS-path lengths and the small number of high-degree nodes, which are viewed as fundamental properties of the AS-level topology. As such, it is believed our main conclusions still hold, despite the imperfections in the measurement data.

To infer the relationships between ASes, the algorithms presented by Gao [12] and Agarwal [32] are applied. The results using those two algorithms are different, but the main conclusion still holds. A previous study suggested that the Gao algorithm produces

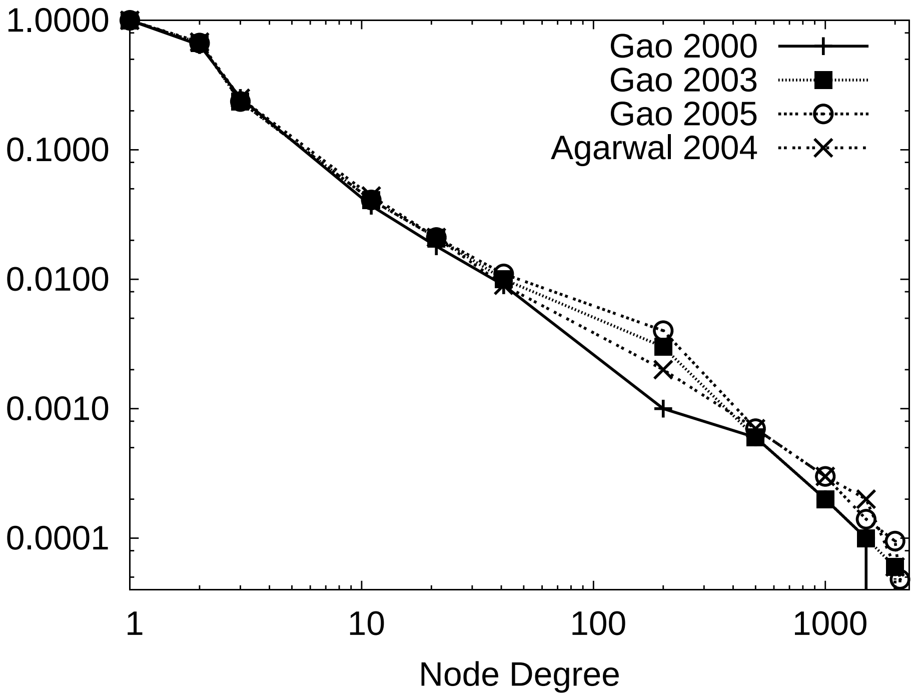


Figure 5.1: Node Distribution

more accurate inference results [24], so this evaluation concentrates on the topology obtained using the Gao algorithm and uses that inferred via the Agarwal algorithm just as a reference. Using the Gao algorithm, MIRO is evaluated under three instances of the AS-level topology, from 2000, 2003, and 2005, to study the effects of the increasing size and connectivity of the Internet on multi-path routing. The result using the Agarwal algorithm on 2004 data are provided as a reference. The key characteristics of the AS topology and business relationships are summarized in Table 5.1. Figure 5.1 plots the distribution of node degrees for the topology data evaluated in the dissertation. The graph is consistent with previous studies that show a wide variance in node degrees, where a small number of nodes have a large number of neighbors; these nodes correspond to the tier-1 ASes that form the core of the Internet.

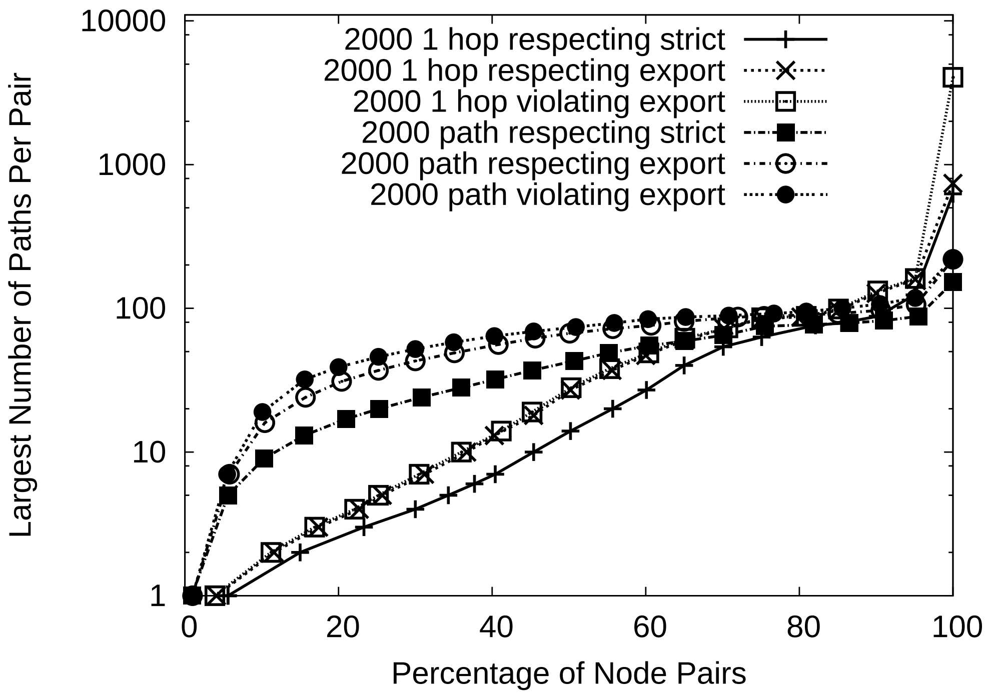
After inferring AS relationships, conventional policies are applied for selecting and exporting routes to construct routing tables, where each AS originates a single destination prefix. This represents the base scenario of single-path routing based on the existing BGP protocol. To evaluate MIRO, this dissertation considers three variations on how a responding AS decides which alternate routes to announce upon request:

- *Strict Policy (/s)*: The responding AS only announces alternate routes with the same local preference as the original default route. For example, if an AS originally advertises a peer-learned route to its neighbors, the AS does not announce any alternate routes learned from a provider. It is assumed that the ASes follow conventional export policies. For example, an AS does not announce a route learned from one peer to another peer.
- *Respect Export Policy (/e)*: The responding AS announces all alternate routes that are consistent with the export policy. For example, an AS announces all alternate routes to its customers, and all customer-learned routes to its peers and providers. This is more relaxed than the Strict Policy, since an AS originally announcing customer routes to its customers can now announce peer or provider routes as well.
- *Most Flexible Policy (/a)*: The responding AS announces all alternate routes to any neighbor, independent of the business relationships.

The last scenario, though arguably unreasonable in practice, provides a basis for evaluating how well MIRO can expose the underlying path diversity in the Internet.

5.2 Exposing the Underlying Path Diversity

The first experiment measures the path diversity under the three policies, and compares MIRO with conventional BGP and source routing. First, the numbers of candidate routes



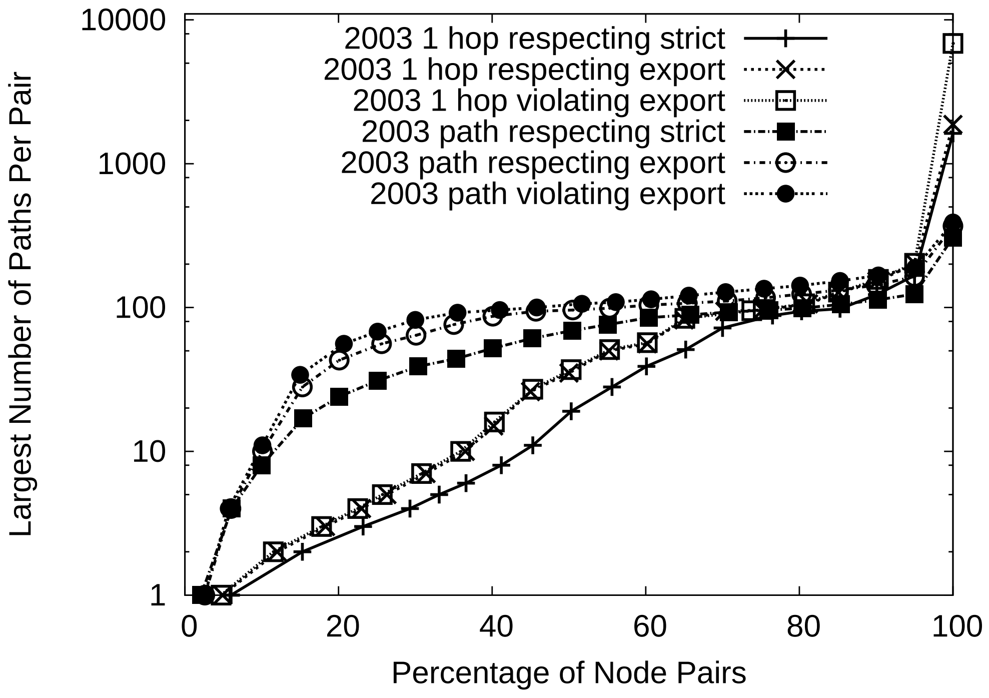
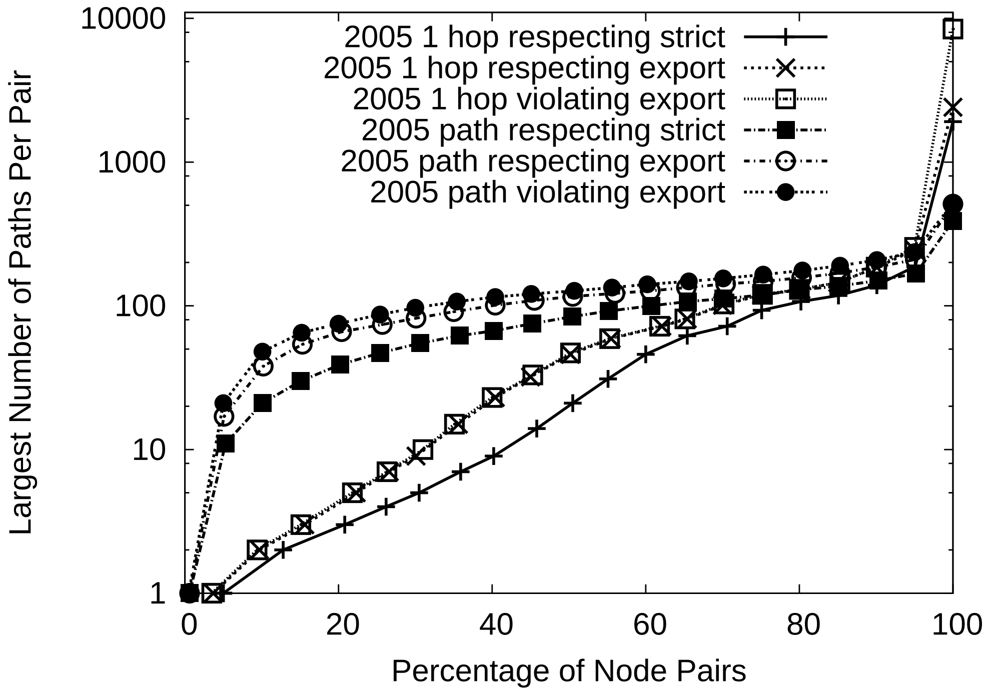


Figure 5.2: Number of Available Routes



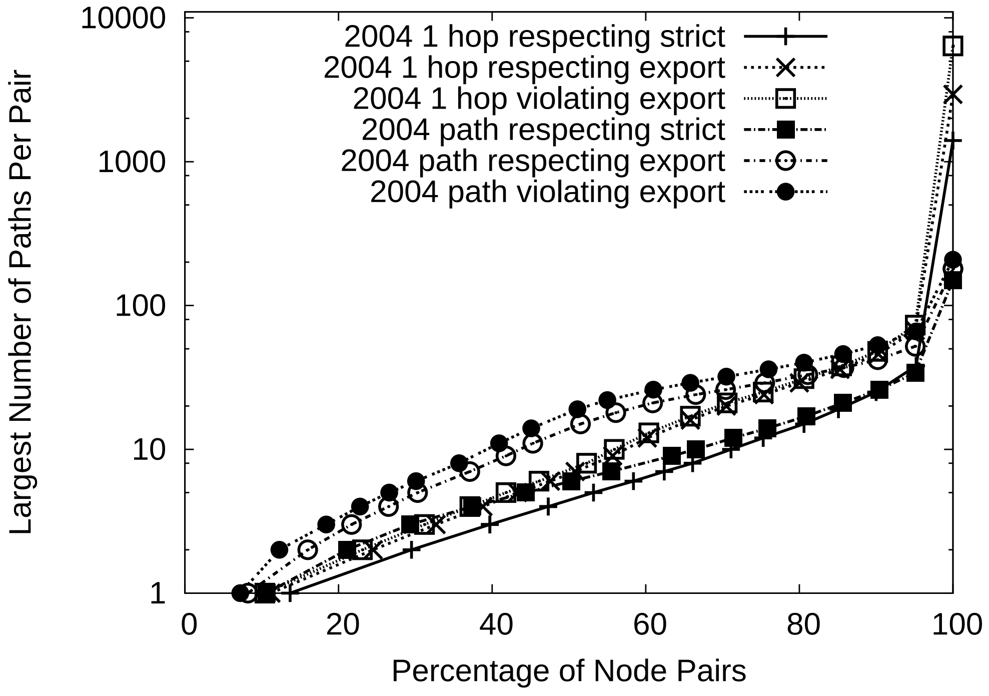


Figure 5.3: Number of Available Routes (Cont.)

between each (source, destination) AS pair are compared, and then the totals are sorted and the distribution is plotted in Figure 5.2 and Figure 5.3. The graph shows the results for two scenarios: (i) each source AS negotiates with any of its immediate neighbors (labeled with “1-hop”) and (ii) each source AS negotiates with any ASes on the default BGP path to destination (labeled with “path”).

In the Gao 2005 data, of the 300 million (source, destination) AS pairs analyzed, only 5% have no alternate paths in the worst case (i.e., the (5%, 1) plot on the “1-hop strict policy” line). The number of paths grows exponentially in the “path” curves, while it increases pretty quickly and stays relatively flat in the “1-hop” curves. For both sets of data, more than half of the AS pairs can find at least tens of alternate paths, and a quarter of the AS pairs have at least one hundred alternate paths. Moreover, the “respect export policy” and the “most flexible policy” curves are similar for both sets of data, meaning that most of the benefits of multipath routing can be reaped without violating the export policy. The “strict policy” line is a bit more restrictive, but still performs quite well. Interestingly, the shapes of the curves are pretty similar over different years of data, although the absolute numbers grow over time. For comparison, in the Agarwal data, around 13% have no alternate paths in the worst case, and there is little difference between the “1-hop”curve and the “path”curve. Therefore, different topology inference algorithms have some impact on the degree of flexibility, but in all cases, MIRO can expose a lot of underlying paths even under the strictest policy.

5.3 Avoiding an AS in Default Path

Counting the number of paths is not sufficient to evaluate the effectiveness of MIRO, as many of the paths may share some nodes or edges in common. Next, it is evaluated

Name	Single	Multi/s	Multi/e	Multi/a	Source
Gao 2000	27.8%	65.4%	72.9%	75.3%	89.5%
Gao 2003	31.2%	67.0%	74.6%	76.6%	90.4%
Gao 2005	29.5%	67.8%	73.7%	76.0%	91.1%
Sharad 2004	34.6%	56.7%	62.0%	68.1%	86.3%

Table 5.2: Comparing the routing policies

how well MIRO can satisfy a specific policy objective: avoiding an intermediate AS known to have security or performance problems. The success rate is calculated for every (source AS, destination AS, and AS-to-avoid) triple. Cases where the AS-to-avoid is an immediate neighbor of the source AS are deliberately excluded. In these cases, avoiding the AS requires the source to select a path from another immediate AS anyway. In addition, an AS is not likely to distrust one of its own immediate neighbors.

5.3.1 Success Rate of Different Policies

Table 5.2 presents the cumulative percentage of the success rate for each policy. As expected, the table shows that single-path, multi-path, and source routing policies provide increasing degrees of flexibility. In the single-path case, the source AS can only satisfy its policy objective by selecting a route announced by another immediate neighbor. In the multi-path case, the source AS is allowed to use the routes announced by BGP, or establish a routing tunnel with another AS. Although source routing can select any path, the source AS cannot always find a path that avoids the offending AS. If the AS-to-avoid lies on every path to the destination, then no policy can successfully circumvent the AS. A depth-first search algorithm is run on the graph to identify those nodes.

Multi-path routing performs very well for this application. In the Gao data, using the strictest multi-path policy, the success rate increases from around 30% in the single-path routing case to around 65%. Relaxing the policy boosts that number further to around 72%. If the tunnels are allowed to traverse paths that violate conventional export policies, the success rate can be increased to around 76%. This is not all that far from the source-routing policy's success rate of 90%. Source routing achieves most of this gain by selecting paths that conflict with the business objectives for intermediate ASes. For example, source routing allows two ISPs to communicate by directing traffic through a stub AS, which is not desirable. In the Agarwal data, the difference between different policies are smaller, and multi-path policy has smaller gain, but still, MIRO increases the success rate from around 34% to 68%.

5.3.2 Avoiding State Explosions

The next experiment quantifies the amount of state that MIRO must handle to negotiate a routing tunnel. This analysis was conducted by counting the number of ASes the source must contact, as well as the number of candidate paths received before a successful alternative is identified. For this test, the cases where today's single-path routing can succeed were eliminated, because MIRO does not need to establish tunnels on alternate paths in these cases. Table 5.3 lists the success rate of multi-path routing, the average number of AS queries per (source, avoid, target) tuple, and the average number of paths obtained in each case.

For the 2005 data, when the flexible policy is used instead of the strict policy, the average number of ASes contacted decreases to 2.43 from 3.30, which seems to suggest that the source AS initiates fewer negotiations. However, by switching to flexible policy from the strict one, the average number of paths increases from 43.1 to 164, so there is a need to check more paths, although there are fewer negotiations. Similar trends can be seen in other years, because the more flexible policy tends to allow more candidate

Policy	Success Rate	AS#/tuple	Path#/tuple
strict/s	65.4%	2.55	15.9
export/e	72.9%	2.18	27.3
flexible/a	75.3%	2.00	71.5

a) Gao 2000 data

Policy	Success Rate	AS#/tuple	Path#/tuple
strict/s	67.0%	2.83	28.7
export/e	74.6%	2.38	44.3
flexible/a	76.6%	2.22	106.8

b) Gao 2003 data

Policy	Success Rate	AS#/tuple	Path#/tuple
strict/s	67.8%	2.80	36.6
export/e	73.7%	2.53	58.9
flexible/a	76.0%	2.38	139.0

c) Gao 2005 data

Policy	Success Rate	AS#/tuple	Path#/tuple
strict/s	56.7%	1.99	4.62
export/e	62.0%	1.90	8.30
flexible/a	68.1%	1.66	71.1

d) Sharad 2004 data

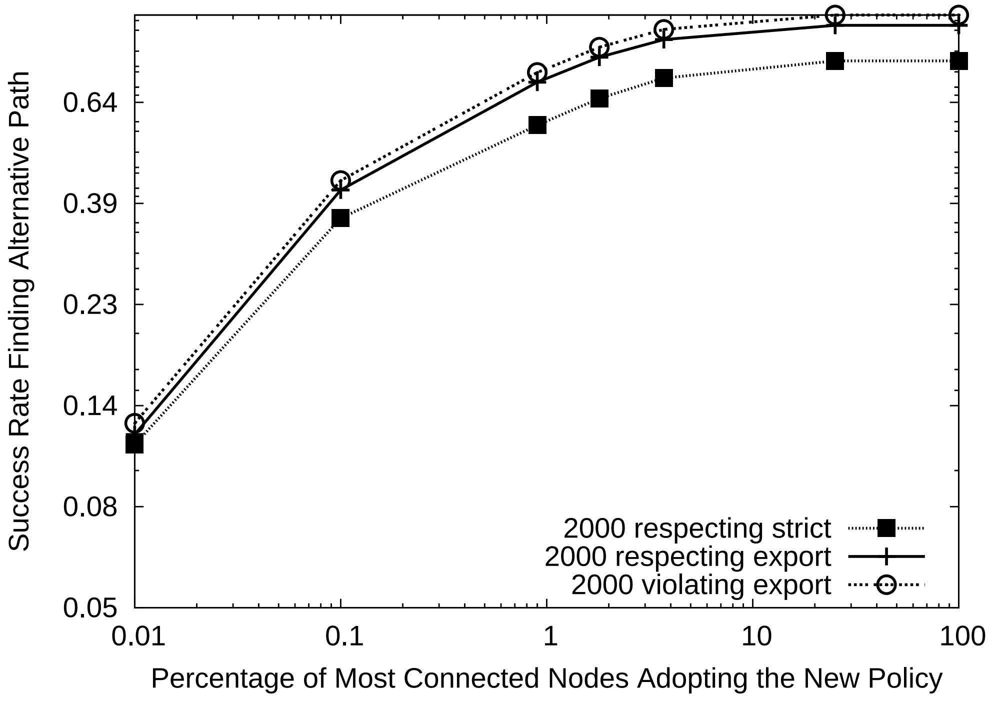
Table 5.3: Comparing the intermediate states

routes in the responding AS. Comparing across the years, the number of paths per tuple increases with time because the AS topology becomes better connected. As expected, the higher path diversity increases the success rate as well. In Sharad data, fewer ASes and paths are explored, but the success rate is also a little bit lower.

5.3.3 Incremental Deployment

The next experiment shows that MIRO is effective even when only a few ASes adopt the enhanced protocol. The tests show that a handful of highly connected tier-1 ASes contribute to most of the path alternatives, if export policies are respected. Referring back to Figure 5.1, only 0.2% of the ASes has more than 200 neighbors, and less than 1% has more than 40. However, these ASes play an important role in MIRO. In Figure 5.4 and Figure 5.5, the x-axis is the percentage of nodes that have adopted MIRO, plotted on a logarithmic scale. It is assumed that the source AS can only establish tunnels with one of these nodes, in order of decreasing node degree to capture the likely scenario where the nodes with higher degree adopt MIRO first. The y-axis plots the ratio of success in finding a path that avoids the offending AS, using as base the numbers for ubiquitous deployment and the most flexible policy.

The curves in Figure 5.4 and Figure 5.5 confirm that the most connected nodes contribute most of the benefit. In the 2005 data, if only the 0.2% most-connected nodes (i.e., nodes with more than 200 neighbors) adopt MIRO, the system can already have around 40% to 50% of the total gain. If the 1% most-connected nodes (i.e., with degree greater than 40) adopt MIRO, the system can get around 50% to 75% of the benefit; these nodes include many of the tier-1 and tier-2 ISPs. Inspecting the result on other years, the numbers in Sharad data are a bit lower, and can only achieve 25% to 46% of the total gain when the top 0.2% nodes adopt MIRO, and can only get 40% to 68% gain with top



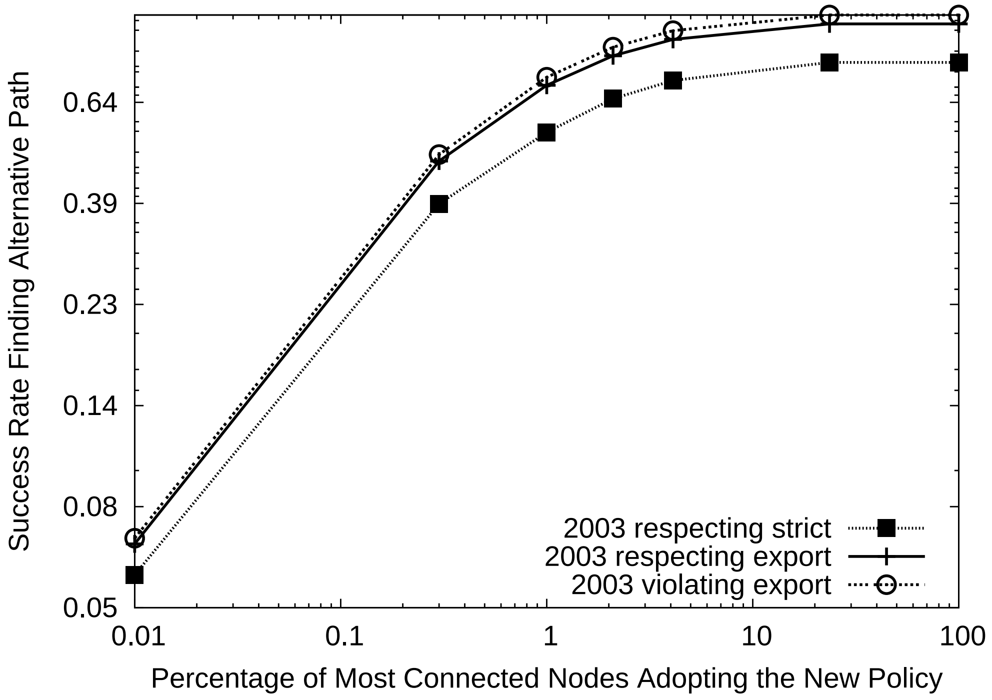
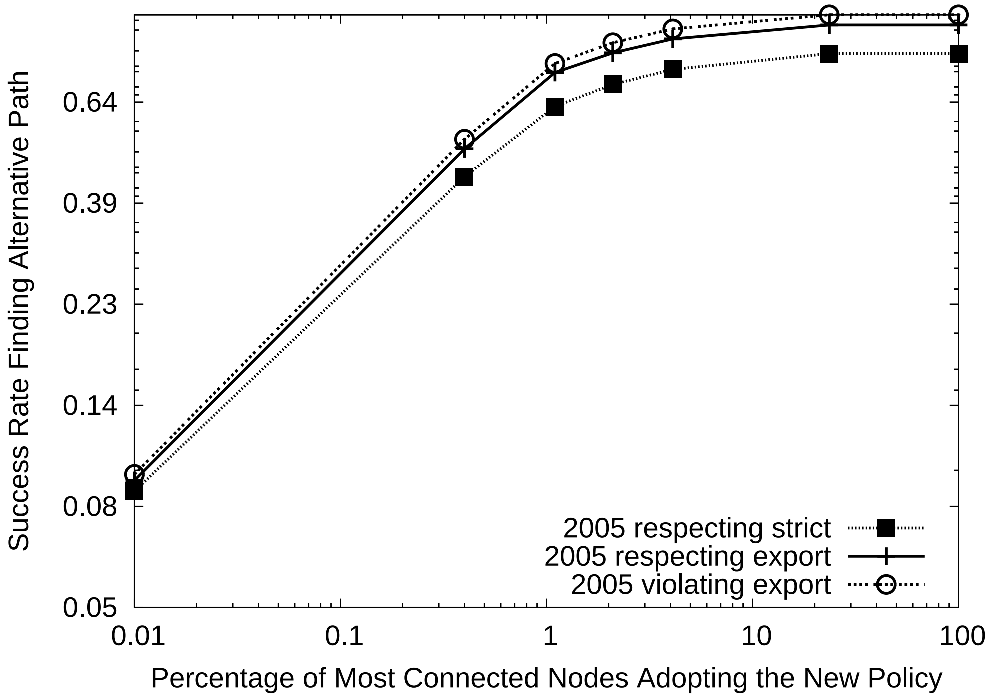


Figure 5.4: Incremental Deployment



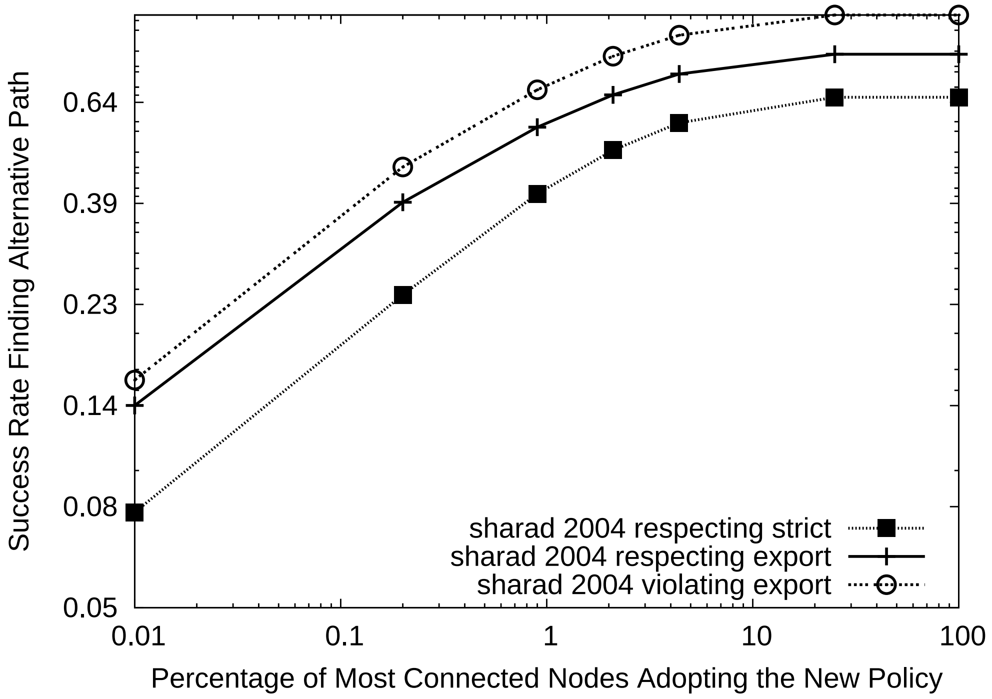


Figure 5.5: Incremental Deployment(Cont.)

1% nodes converted to MIRO. Still, the data in different years show similar trends, and the numbers are quite impressive. For the sake of comparison, the effects of low-degree nodes adopting the protocol first are also evaluated. Analyzing the 2005 data, success rates were less than 10% until 95% of the nodes adopted MIRO. Therefore, it is not very effective to deploy the new protocol at the edge first. Fortunately, it is much more likely that a small number of large ASes will adopt MIRO than a large number of small ASes.

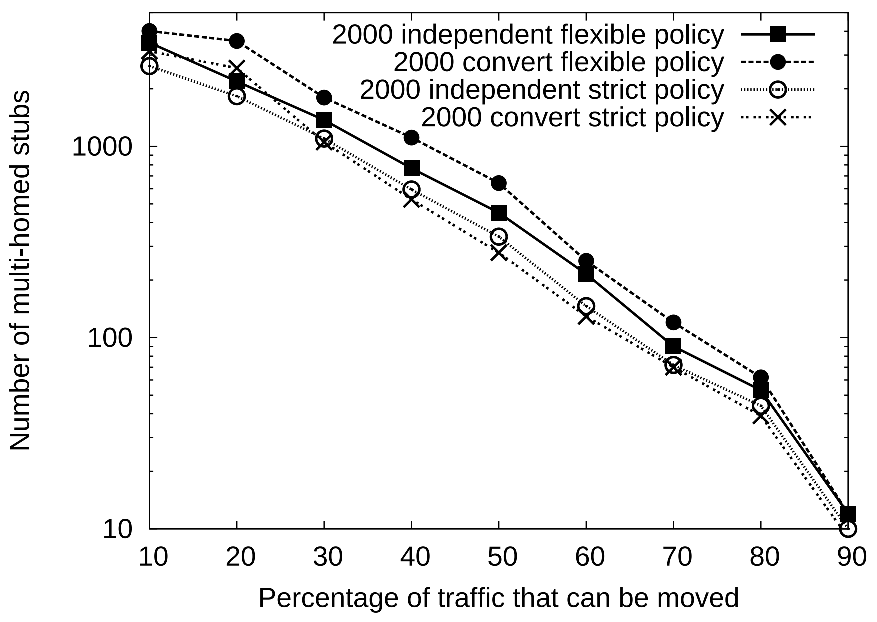
5.4 Controlling Incoming Traffic

Next, brief evaluation is presented of a second application of multi-path routing. This example focuses on multi-homed stub ASes that want to exert control over inbound traffic to balance load over multiple incoming links. Evaluating a traffic-engineering application is difficult without a global view of the offered traffic, so the results should be viewed as a back-of-the-envelope analysis to demonstrate the role that MIRO can play in this application. In the absence of traffic measurements, it is assumed that each source AS generates equal amounts of traffic. This allows an estimation of the total traffic on each incoming link simply by counting the number of source ASes using this link.

Another question that needs an answer is what will happen when the default path changes. In the original evaluation of MIRO [41], it was assumed that all the ASes that transit through an intermediate AS always use this intermediate AS to send traffic. It was also assumed the ASes originally using other paths would not be affected to simplify the calculation. This dissertation also evaluates the case where each AS independently reselects its own path when an intermediate AS changes its selection; therefore, some ASes may not select the incoming link as expected. In reality, it is possible the intermediate AS forces its clients to prefer a longer path over a shorter path using BGP community values. Therefore, the former method gives the upper bound, while the latter gives the lower bound, and this dissertation calls the two methods "convert_all" and "independent_selection", and label them "convert" and "independent" respectively in the graph.

This dissertation calls a node a "power node" if it lies on the AS path to the destination AS for many source ASes, and evaluates the benefits of the destination AS requesting the power node to switch to an alternate path that traverses a different incoming link. If that power node advertises the new default path to all its neighbors, hopefully many neighbors will also switch to the new path. This application is evaluated by showing how many stub ASes can find at least one "power node" that can potentially move designated amount of traffic using this method.

In Figure 5.6 and 5.7, both the flexible policy and the strict policy are examined on the data. For example, in the 2005 data, 10,383 multi-homed stub ASes were tested, in total. The figure shows that under strict policy and "convert_all" model, around 83% of the stubs have at least one power node that can move more than 10% of the incoming traffic, and around half of them have one power node that can move at least 25% of traffic. If flexible policy is used in the "convert_all" model, 98% of the stubs have at least one power node that can move more than 10% of the traffic, and around half have one power node that can move 35% of traffic. Under strict policy and the "independent_selection" model, around 64% of the stubs can find at least one power node which can move more than 10% of the traffic, half of them have one power node that can move at least 15% of traffic; under flexible policy in this model, 77% of the stubs have at least one power node that can move more than 10% of the traffic, and half of them have one power node that can move at least 20% of traffic. There is a gap between the two models, but a big portion of traffic can be moved even under the "independent_selection" model. Interestingly, in some cases, more power nodes can be found under the "convert_all" model. The reason



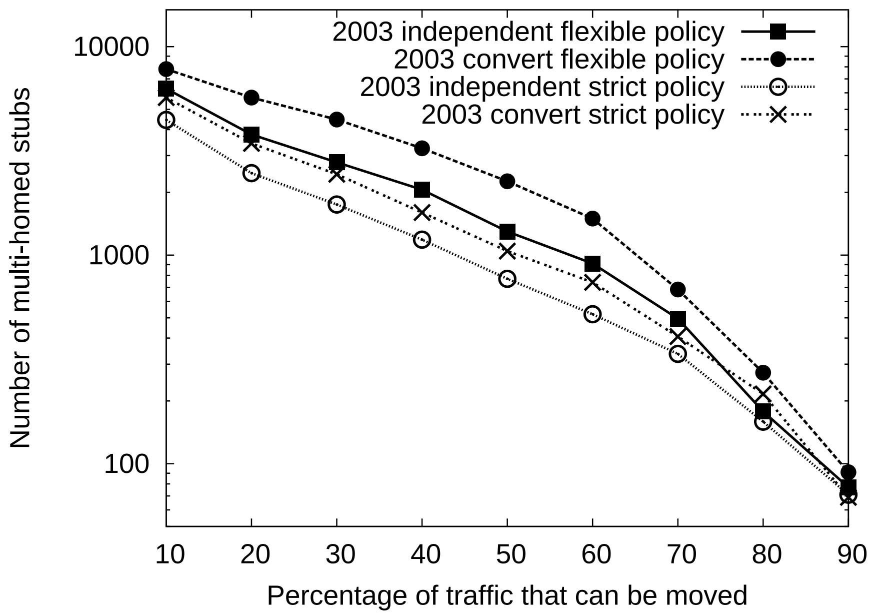
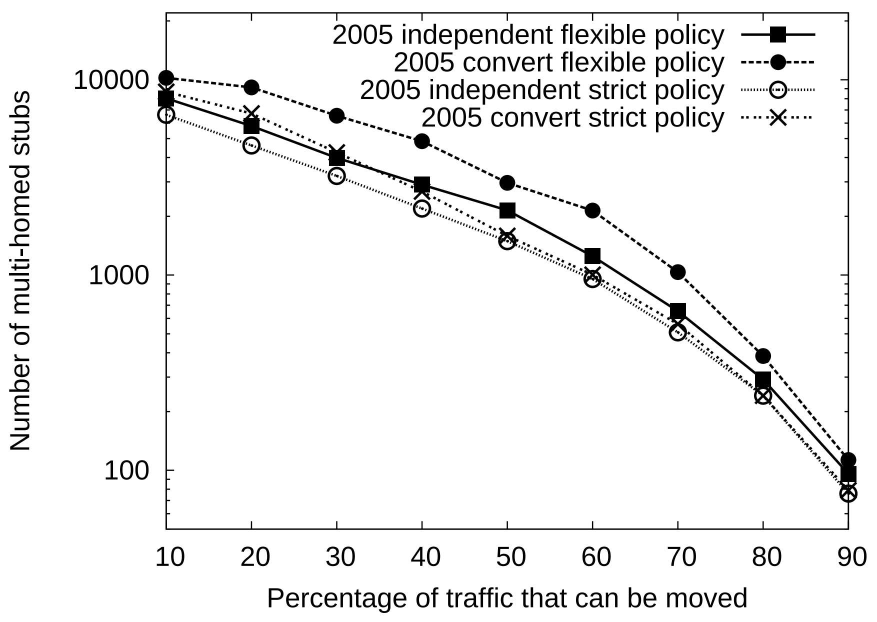


Figure 5.6: Multi-homed Stub ASes with Power Nodes



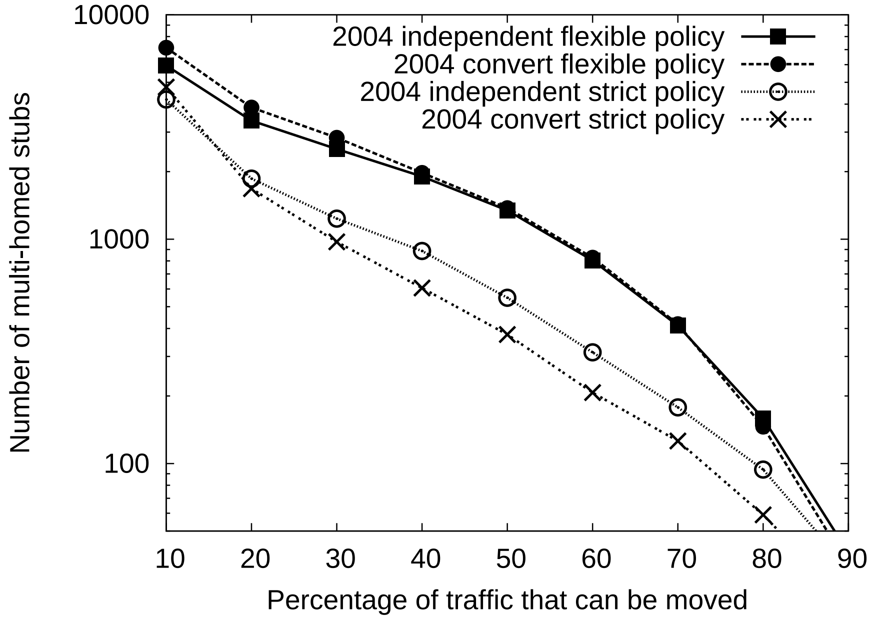


Figure 5.7: Multi-homed Stub ASes with Power Nodes(Cont.)

is that some stub ASes originally not using the converting transit AS prefer the new path and switch over.

Further analysis on the power nodes in the 2005 data and finds that more than 90% are nodes with more than 200 neighbors—most likely tier-1 ISPs. Immediate neighbors of the destination AS constitute only 9% of the power nodes; around 68% of the power nodes are two hops away from the destination AS. Therefore, MIRO's ability to send requests to non-immediate neighbors offers a significant gain, and being able to negotiate with tier-1 ISPs, in particular, is especially useful.

5.5 Summary

The experiments show that MIRO is very effective in helping ASes achieve their policy objectives. In the avoid-an-AS application, MIRO helps increase the success rate from 30% to 76% by establishing only one tunnel for a (source, destination) pair. Although source routing can push the success rate to 90%, it requires huge changes to the routing framework, and must exploit unusual paths that traverse stub ASes. In the incoming-traffic-control application, more than 64% of the stub ASes can move around 10% of traffic, and half of them can move at least 15% of the traffic by negotiating with a single intermediate AS.

This also shows that most of the alternate routes are provided by the most-connected nodes. This conclusion may lead people to conclude that MIRO benefits the big ISPs most. Yet, MIRO is designed to expose the existing candidate paths in the Internet, so it is not surprising that the participation of the well-connected ASes provide the most benefit. Yet, these results are quite dramatic, suggesting that even early adopters can achieve a significant gain, especially if ASes can negotiate with the non-adjacent ASes.

Chapter 6

Routing Policies

The policy specification language is intentionally excluded in this design, because the underlying mechanisms should give users maximum flexibility in picking and expressing their own policies. However, to give the readers a concrete picture, this dissertation will present some sample policies and describe how they can be configured. This chapter first describes how policy configuration is done in current Internet, then compares that to the multi-path case.

6.1 Policy Configuration in Current Internet

The current BGP specification (RFC 4271) describes how two BGP neighbors exchange information and the decision process, without defining routing policy specification [29]. Various vendors have come up with their own policy specification language and tools, and this dissertation will describe how MIRO can be configured by extending one current policy specification language. Similar extensions to the Routing Policy Specification Language (RPSL) [2] should be easy to make.

The BGP policies can be divided into import policies and export policies. Import policies define which unwanted paths should be filtered, and how various attributes (e.g., local preference value) should be set on the received paths. Export policies filter the paths advertised to each neighbor, and adjust various attributes of the paths. The BGP route decision process tries to pick the route with the highest local preference. If several routes are equal on local preference, a set of steps are applied to break ties, like comparing path length, path origin, MED value, internal path cost, and next hop router id, in that order.

Cisco designed route-map command which can be used to configure policy routing. The user can specify the actions to be taken when the matching condition is satisfied. The syntax is as follows:

```
route-map map-tag [permit | deny] [sequence-number]
```

Where *map-tag* is a name for this rule, *permit* or *deny* gives the action to be taken, and *sequence-number* gives the position of the rule in all route maps.

For example, the following route-map command specifies that any route received from 12.34.56.1 that matches the filter parameters set in AS access list 200 (routes that never go through AS 312) will have its local preference set to 250 and will be accepted.

Cisco route-map example

```
 router bgp 100
!
  neighbor 12.34.56.1 route-map FIX-LOCALPREF in
  neighbor 12.34.56.1 remote-as 1
!
route-map FIX-LOCALPREF permit
  match as-path 200
  set local-preference 250
!
  ip as-path access-list 200 deny _312_
```

6.2 Multi-path Routing Policies

In the multi-path case, aside from defining which route updates to match and then what actions to take, it is necessary to define how negotiations should be conducted. The policies are divided into two parts: negotiation related rules and route selection rules. The negotiation rules specify how to establish and manage negotiations, while the route selection rules filter the available candidates.

6.2.1 Negotiation Related Rules

In the requesting AS, the rules should specify when to trigger negotiation and with whom to negotiate. In the responding AS, the rules should describe when and from whom new negotiations will be allowed.

- *Requesting AS–when to trigger negotiation:* Negotiations should only be triggered if none of the current routes satisfy the desired property. Whenever the routes or the policies change, the router should check the triggering conditions, then initiate a negotiation when the conditions are satisfied.

- *Requesting AS–whom to negotiate with:* The requesting AS has to guess which ASes may have appropriate candidate routes, good guesses can greatly shorten the negotiation process. For security policy like "avoiding AS 312", some possible candidates are the ASes on the default path between the requesting AS and the

AS 312 that understand the new protocol. This can be done via regular expression matching on the default route.

- *Responding AS–whether to allow negotiations:* The responding AS can specify a limit for the total number of tunnels, a rate limit for establishing new tunnels, or a firewall where only negotiation requests from trusted peers are accepted.

6.2.2 Route Selection Rules

The responding AS can specify filter rules to selectively export its candidate routes. The requesting AS should also set evaluation rules to determine which candidates to pick. Those rules may evaluate several factors in the decision process, like the cost or the quality of different routes.

- *Route filtering:* Many existing metrics can be utilized in specifying filtering rules, e.g., only advertise routes with a local preference value of more than 100. In practice, it is often the case that all customer routes are assigned the same preference value, all peer routes with a lower value, and all provider routes with the smallest local preference value. Therefore, the selective export rules described in Section 3.4 can be easily specified by reasoning with specific local preference values.

  Optionally, the requesting ASes can specify simple requirements to avoid getting useless candidate routes. For example, the requesting AS can explicitly request "only give me paths without AS 312." The responding AS adds the requirement to candidate filtering before responding with final answers.

- *Route preference and cost:* The routes preferred by the requesting AS may be those less desired to the responding AS. For example, the requesting AS wants to select a low latency route in the responding AS which goes through an expensive provider link. In this case, a price system can be introduced so that the responding AS gets compensated accordingly. Any notion of price would work as long as both parties agree on it. With a price tag attached to each route, innovative business models can be enabled. For example, the responding AS can sell all customer routes for a lower price and all peer routes for a higher price. The requesting AS then picks a candidate based on both local preference and cost.

How to build the economic framework is an interesting topic in itself, but it is outside the scope of this dissertation. In the following examples, it is assumed that ASes use integers to specify a fixed price for a route in each negotiation. When a negotiation succeeds, the requesting AS agrees to pay the price for the route, and the responding AS agrees to provide transit service. Whenever one of the parties is no longer satisfied with the price, the tunnel will be terminated, then the requesting AS will re-negotiate a new tunnel using a new price if needed.

6.3 Multi-path Policy Specification Example

Next, this dissertation shows how to specify the policies described above using a simple example. In this example, the administrator specifies a simple security policy "always try to avoid AS 312," similar to what was done in the route-map example. However, previously that AS is stuck if all of its candidate routes go through AS 312. With MIRO, negotiations can be initiated to explore other options.

The following specification is written in this dissertation's imaginary "extended" route-map command. It says that the requesting AS (AS 100) will initiate a negotiation if the "deny AS 312" rule results in an empty candidate set. It will try to initiate negotiations with each AS that sits between itself and AS 312 on any of the current candidate paths. The maximum price to pay for this tunnel is 250. The responding AS (AS 150) specifies that it will accept negotiations from anybody as long as the number of active tunnels is less than 1000. It is willing to provide all customer routes (local_pref $>$ 200) with a cost of 120 and sell all peer routes (local_pref $>$ 100) with a higher cost of 180.

Imaginary extended route-map example

The Requesting AS

```
router bgp 100
!
route-map AVOID_AS permit 10
 match empty path 200
 try negotiation NEG-312
!
ip as-path access-list 200 deny _312_
!
negotiation NEG-312
 match all path #1312_
 start negotiation #1 with maximum cost 250
```

The Responding AS

```
router bgp 150
!
accept negotiation from any
 when tunnel_number < 1000
```

```
!
negotiation filter FILTER-1
 filter permit local_pref > 200
 set tunnel_cost 120
 filter permit local_pref > 100
 set tunnel_cost 180
```

Chapter 7

Convergence Proof

As described in Section 2.2.3, in a distributed route selection algorithm, it is very important to guarantee that the algorithm converges to a stable state. For the current BGP protocol, previous work [13, 15] showed that routing instability may happen in BGP; however, if certain policy guidelines are obeyed, and the Internet topology exhibits certain characteristics, the algorithm is guaranteed to converge.

Under MIRO, ASes can establish new tunnels through negotiations, therefore the proof in [13] cannot be trivially applied here. This dissertation will show that, in addition to the assumptions made in [13], if ASes follow some additional guidelines in route negotiations, the algorithm used by MIRO is still guaranteed to converge.

This chapter will first introduce an abstract model on which the whole convergence proof is based, then briefly summarize the convergence proof in [13]. After that, this chapter shows why the previous convergence proof cannot be trivially applied in MIRO, and gives out three new guidelines which can guarantee convergence. Finally, the effect of mixing and matching the three guidelines in practice is discussed.

7.1 Abstract Models

This section first presents an abstract model for MIRO. The model and proof are an extension to the work in [13], therefore, the original notations are kept whenever possible.

7.1.1 BGP with Routing Tunnels

As in [13], the topology of the BGP system is modeled as a clustered graph. But in MIRO, there are two kinds of paths, rather than just one kind in the original model: the default paths provided by the BGP system, and the special routing tunnels established between AS pairs. The routers speaking MIRO are a subset of BGP speakers. Therefore, the topology of MIRO is modeled as a clustered graph $G = (N, V, E, E')$, where the set N consists of ASes, the vertex set V consists of all routers speaking BGP protocol, the default edge set E consists of all eBGP peering sessions, and the tunnel edge set E' consists of all routing tunnel sessions. In MIRO, E' reflects all pairs of BGP speakers that can possibly establish a tunnel, there can be an edge between two BGP speakers even though the tunnel is not eventually established. Each router belongs to only one AS, but each AS may have more than one router. This dissertation uses $a(i) \in N$ to denote the AS to which a BGP speaker i belongs.

A BGP route update r includes destination prefix (*r.prefix*), next-hop interface address (*r.next_hop*), AS path (*r.as_path*), and local preference(*r.local_pref*). As in [15], it is assumed that each AS uses its own ranking function *f(r.next_hop, r.local_pref, r.as_path)* to pick the best path among all available candidates. Each BGP speaker advertises updates for one or more prefixes, and the updates can be selectively sent to adjacent routers via an iBGP or eBGP session.

Although MIRO uses a pull model instead of a push one, its convergence can still be proved by calculating routing updates. In MIRO, the requesting AS first sends out a request asking for suitable candidates. Upon request, a responding AS selects a subset from its available paths, and returns them back to the requesting AS. Finally the requesting AS picks the most preferred candidate and establishes the tunnel, or gives up if no routes are suitable. When convergence is proven in MIRO, there is the assumption that when the requesting AS first asks for candidates, it does not attach any restrictions in the request. Instead, it filters all inappropriate paths after the responding AS sends back the candidates. While the responding AS will send more candidates than necessary in this model, it does not change the result of route negotiations if the filtering function of the responding AS does not depend on the restrictions the requesting AS sent out. In this model, it is assumed that every responding AS has a filtering function to prune its available paths, and every requesting AS has a separate ranking function which returns the best route for the tunnel or empty set if no paths qualify. The candidate paths returned by the responding AS are called a tunnel update.

This dissertation uses R to denote BGP route updates, T for tunnel updates, and U for the union of two sets. That is, $U = R \cup T$. The symbol u denotes a MIRO update, which can either be a BGP update or a tunnel update, each MIRO update contains at least the destination prefix ($u.prefix$), and the AS path selected ($u.as\_path$).

In modifying BGP routes, each router applies an implicit import policy defined by the protocol specification and an explicit import policy configured by the network operator. Let $b\_im\_import(l, v)[U]$ denote the set of updates after applying the implicit import policy of v on edge l. The implicit import policy b_im_import says that a loop can never be introduced in the AS path: if $a(v) \in r.as\_path$, then $b\_im\_import(l, v)[\{r\}] = \{\}$ removes the path, otherwise $b\_im\_import(l, v)[\{r\}] = \{r\}$ keeps the path. The explicit import policy b_ex_import then applies further updates to the incoming path set. Therefore, the import policy transforms the set of updates *U* as *b_import(l,v)*[*U*] = *b_ex_import(l,v)*[*b_im_import(l, v)*[*U*]].

After applying the import policies, each BGP speaker follows a route selection process *BSelect(S)* to pick the best route for each prefix. Also, each BGP speaker uses export policies to determine which updates it should broadcast further to its neighbors and how to modify those updates in advertisements. During the selection process, the BGP speaker picks the route with the highest $r.local\_pref$, then breaks ties by considering the length of $r.as\_path$ and other metrics.

As explained above, in the convergence proof, this dissertation assumes that each requesting AS has a ranking function to evaluate routes and each responding AS has a filtering function to prune possible candidates; this dissertation calls the former select policy of the requesting AS, and the latter export policy of the responding AS. In MIRO, it is unnecessary for either the requesting AS or the reporting AS to explicitly check for cycles in AS paths, as packets in tunnels are transferred using special methods. For example, if IP-in-IP encapsulation is used, packets in tunnels will have their destination IP addresses temporarily rewritten, so paths like ABC(BD) where A and C establish tunnel ABC to reach D is perfectly legal. Although in practice, paths with too many redundant ASes are unlikely to be selected by the requesting AS because of latency.

Therefore, in MIRO, there are no import rules. The effective filtering rule is the intersection of all export policies. The tunnel route finally selected by requesting AS *w* and responding AS *v* can be represented as *TSelect*(*w*, *v*)*t_export*(*w*, *v*)[*U*]

7.1.2 The Distributed Path Selection

As in the BGP protocol, MIRO route selection process is done in a distributed and asynchronous fashion, triggered by advertisements and withdrawals of routes and tunnels. In proving the convergence property of the protocol, the exact timing of message transmissions can be ignored, and the model can just contain the order in which events occur. In the BGP protocol, route aggregation does not affect convergence, so this proof can just concentrate on a single destination prefix *d* that originates from AS_d. In MIRO, depending on how routing policy is set up, the convergence of routes to one prefix may or may not be affected by the convergence of other prefixes. This will show how convergence of one prefix may be affected that of another in Section 7.3.

The system state is defined as a vector $s = (s_1, s_2, ..., s_n)$, in which s_i denotes (*R*, *T*, *T'*) chosen by speaker $i(1 \leq i \leq n)$, *R* is the chosen BGP route or empty set if no path is chosen, *T* is a set of routing tunnels, and *T'* is a set of candidate paths for tunnels still in negotiation. *Activating* a BGP speaker *i* means that *i* will first apply export policies to the advertised routes, then it will apply the import policies and selection process to pick the best routes if available. When a MIRO speaker *i* is activated, for each incoming tunnel request, in addition to the above actions, it will apply export policy to its own routes and send back candidate routes; for each response from its own tunnel request, *i* will use selection process to pick a candidate and establish the tunnel. In the BGP protocol, selected routes in an AS are only advertised to its neighbors.

For the BGP speaker in AS_d, the BGP route to *d* is the null AS path denoted as r_0, and the MIRO tunnels to *d* is the empty set assuming intra AS paths will be preferred over inter-AS tunnels. For any BGP speaker *i* not in AS_d, the selection of BGP routes in s_i may be affected by the choice of any speaker *j* that has a BGP session with $k \in a(i)$, where *j* may or may not be in the same AS as *i*. The path chosen by *i* depends on the route s_j, the export policies of *j*, and the import policies of *k*. If *i* is a MIRO speaker, it can use negotiated tunnels in addition to the BGP routes, it can also redistribute negotiated tunnels and BGP routes to other neighbors. Specific export and selection policies control the establishment of these tunnels. Therefore, the candidate routes of *i* in MIRO can be expressed as follows:

$$Candidates(i,s) = \begin{cases} (r_0, r_0), & if\ a(i) = (AS_d, \{\}) \\ (Candidates_b(i,s), Candidates_t(i,s)), & otherwise \end{cases}$$

where

$Candidates_b(i,s) = \bigcup_{l=(k,j)\in E \wedge k\in a(i)} b\_import(l,k)[b\_export(l,j)(s_j)]$

$Candidates_t(i,s) = \bigcup_{l=(k,j)\in E' \wedge k\in a(i)} [t\_export(l,j)(s_j)]$

After that *i* selects the best routes:

BestRoute(*i, s*) = *Select*(*Candidates*(*i, s*)).

As in the original model, the routers speaking BGP or MIRO protocol operate independently, therefore only a subset *A*⊆*V* of speakers are activated at a time, the remaining speakers do not use the path-selection process and therefore do not change their BGP paths or routing tunnels. Thus the next state *s'* = ($s'_1, s'_2, ..., s'_n$) has s'_i = *BestRoute(i, s)* for *i*∈*A*, and s'_i = s_i for *i*∉*A*. As in [13], $s \xrightarrow{A} s'$ is used to denote the transition from state *s* to *s'* given the activation set *A*. A state *s* is *stable* if and only if $s \xrightarrow{A} s$ for any activation set *A*. For the convergence proof, an *activation sequence* is defined as a (possibly infinite) sequence of activations. As in the original model, σ is used to denote the activation sequence and $\sigma(j) \subseteq V$ to denote the *j* th activation in σ. A *fair* activation sequence σ is an infinite sequence that has an infinite sub-sequence of *i* for each BGP speaker *i*∈*V*. A system *converges* for a particular activation sequence and initial state if it is stable after the activation sequence.

7.1.3 Hierarchical AS Graph

The convergence proof in [13] depends on the fact that the Internet topology forms a hierarchical graph; the proof in this dissertation also depends on this. Therefore, this section will briefly reiterate the AS relationship assumptions in [13].

AS relationships are defined by the contracts that describe their cost and traffic policies. In *customer-provider* relationship, the customer pays for its traffic sent from and to the provider. In *peer-peer* or *sibling-sibling* relationship, both parties act as transit for free. Two siblings usually belong to the same organization, while two peers are normally managed by different organizations. As in [13], *first(r.as_path)* denotes the next-hop AS in *r.as_path*, and *crop_first(r.as_path)* denotes the remaining AS path after taking out the next-hop AS in *r.as_path*. A route *r* is called a customer route if $first(r.as\_path) \in customer(a)$, a peer route if $first(r.as\_path) \in peer(a)$, or a provider route if
$first(r.as\_path) \in provider(a)$. The relationships typically lead to the following BGP export policies:

- An AS exports any route to its customer.
- An AS normally exports its customer routes only to its peers or providers.

It is assumed here that there is a hierarchical customer-provider relationship among ASes, as in [13]. In practice the provider is often larger in size than its customers; therefore, the topology considering only customer-provider relationships is a directed acyclic graph.

7.2 BGP Policy Guidelines that Guarantees Convergence

The convergence proof for MIRO is built upon the proof in [13], so this section will briefly reiterate the original proof for completeness. In [13], it is shown that certain policy configuration guidelines can provably guarantee the convergence of the BGP protocol. The guidelines cover the scenarios where ASes may establish *backup links*, which normally carry no traffic unless there is a link failure in the system; the backup links are given the lowest local preference to indicate they should only be used under emergency. The guidelines are:

1. BGP systems with no backup links

   It assumes that any customer route is preferred over any peer or provider route.

2. BGP systems with no backup links and constrained peer-to-peer agreements

   In the previous guideline, it is assumed that any customer route is more preferable than any peer or provider routes. In practice, it is possible to have more relaxed peering agreements. This guideline assumes that it is possible that peer routes sometimes are equally preferable as customer routes.

3. BGP Systems with backup links

Three guidelines are given in [13], but this dissertation will only summarize and extend the first guideline. For the other two guidelines, the proof is similar, so the full proof is omitted for brevity.

The first guideline assumes that there are no backup links in the system, and any customer route is preferred over any peer or provider route. The guideline can be formalized as:

Guideline A:

If $((first(r_1.as\_path) \in customer(a))$ and

$(first(r_2.as\_path) \in peer(a) \cup provider(a)))$

then $r_1.loc\_pref > r_2.loc\_pref$

To prove that guideline A can guarantee convergence, first two lemmas are proved:

Lemma 1 *The BGP system has a stable state.*

proof: The lemma is proved by constructing an activation sequence σ^* that results in a stable state from any initial state. Let *d* be the destination prefix and AS_d be the AS that originates *d*. Because activation order inside an AS does not affect the preference on routes, all BGP speakers inside an AS are activated simultaneously. Later when this dissertation says activating an AS, this means activating all BGP speakers in this AS. The activation sequence σ^* is divided into two phases:

Phase 1: Activate ASes in a linear order that conforms to the partial order in the customer-to-provider DAG.

Phase 2: Activate ASes in a linear order that conforms to the partial order in the provider-to-customer DAG.

The ASes are divided into two classes: AS_d and the ASes that select a customer route in Phase 1 are called *Phase-1 ASes*, their BGP speakers *Phase-1 BGP speakers*; the rest are called *Phase-2 ASes*, their speakers *Phase-2 BGP speakers*. The following claims hold:

Claim 1 *A Phase-1 BGP speaker reaches a stable state after its activation in Phase 1.*

proof: Prove by induction on the activation order. AS_d is the first activated AS and the claim certainly holds for AS_d. When activating Phase-1 BGP speaker *i* belonging to AS_n, suppose all Phase-1 BGP speakers in an AS preceding AS_n are activated and stable, *i* will select the best route among its customer routes. All customers of AS_n precede AS_n in the activation sequence for Phase 1, therefore, each customer either is stable before AS_n in Phase 1, or it does not get a customer route in Phase 1. When the latter holds, that customer will not export its non-customer route to *i* according to the export rule, so that customer's choice will not affect the choice of *i*. Therefore *i* is stable after its activation in Phase 1. $\square$

Claim 2 *Any AS that selects a customer route is a Phase-1 AS.*

proof: This proof is implied in the proof of the two original claims in [13], it is explicitly listed here to help the readers understand the proof. This is proven by contradiction. Suppose there is a group of ASes A' that ultimately select customer routes, but belong to Phase-2 ASes. The symbol AS_1 is used to denote the first activated AS in A' during Phase 1 and r for the route it picks, and AS_2 is used to denote $first(r.as\_path)$, as r is a customer route, AS_2 is a customer of AS_1. If AS_2 is a Phase-1 AS, then it must be stable after its activation in Phase 1. As AS_1 is activated after AS_2 in phase 1, AS_1 must have learned the route r when it is activated in Phase 1. If AS_1 did not pick r in Phase-1, preference rule tells us that it is only possible if a more preferable customer route r' is picked. Following the same argument as above, the customer providing r' is also stable after Phase 1, so r' should also be available thereafter, and always preferable over r, contradicting our assumption that r is picked in the end. If AS_2 is not a Phase-1 AS, it does not belong to A', because it is activated before AS_1. Therefore, AS_2 must have picked a provider or peer route, by export rule the route picked by AS_2 should not be advertised to AS_1, contradicting the assumption that r exists. $\square$

Claim 3 *A Phase-2 BGP speaker reaches a stable state after its activation in Phase 2.*

proof: Again, this claim is proved by induction on the activation order. Let AS_0 be the first Phase-2 AS activated in Phase 2, AS_0 cannot have any Phase-2 providers. Because AS_0 is a Phase-2 AS, its speakers can only get routes from AS_0's peers and providers. AS_0's providers must be Phase-1 ASes, so their routes are already stable. By Claim 2, any of AS_0's peers either (a) gets a customer route so it is a Phase-1 AS and is stable in Phase 1, or (b) does not get a customer route so the provider or peer route it picked will not be advertised to AS_0 and will not affect AS_0's choice. Therefore, all of AS_0's BGP speakers will get stable routes after the activation.

When activating Phase-2 BGP speaker *i* belonging to AS_n, suppose all Phase-2 BGP speakers in an AS preceding AS_n are activated and stable. Because *i* is a Phase-2 speaker, by Claim 2 it can only select a provider or peer route. AS_n's providers are either Phase-1 ASes or activated before AS_n in Phase 2, in either case they are already stable. Similarly, every peer of AS_n should either be a Phase-1 AS or a Phase-2 AS. In the former case it is already stable, in the latter case it selects a provider or peer route according to Claim 2, and the provider or peer route it picked will not be advertised to AS_n so will not affect AS_n's choice. Therefore, *i* already have all its possible candidate paths stable, so it reaches a stable state after being activated. $\square$

With the above claims, the activation sequence σ^* will lead the system to a stable state no matter what the initial state is. $\square$

Lemma 2 *The BGP system converges to the stable state for any initial state and any fair activation sequence.*

proof: Given the activation sequence σ^* constructed above, for any fair activation sequence σ, the lemma is proven by induction on the activation order used in σ^*. Clearly AS_d is stable once activated. Assume that all BGP speakers in the ASes that precede AS_n are stable after activation $\sigma(t)$, and $\sigma(t')$ is the first activation set such that every BGP speaker in AS_n is at least activated once between $\sigma(t)$ and $\sigma(t')$. Similar to how the stability for AS_n is proven above, it can be proved that every speaker in AS_n will be stable after $\sigma(t')$. Also, removing any node or edge from the BGP system does not change the proof of the above lemmas, so the BGP system is inherently safe. □

Theorem 1 *For a BGP system that has only customer-provider and peer-peer relationships, if all ASes follow guideline A, then the BGP system is inherently safe.*

proof: Using the two lemmas above, any initial state and fair activation sequence will lead to a stable state in the BGP system, and removing nodes or edges does not affect the proof, so the BGP system is inherently safe. □

7.3 MIRO Guidelines that Guarantee Convergence

Obviously, as MIRO is built on top of BGP, if the BGP routes do not converge, then the MIRO routes can never converge. In addition, as MIRO routing tunnels introduce additional dependencies, there is a need to introduce additional guidelines and pair them with the above BGP guidelines, to guarantee the convergence of the protocol. To illustrate additional guidelines are needed to guarantee convergence, a simple counter-example is given below. In this counter-example, the MIRO tunnels do not converge, even though BGP routes converge.

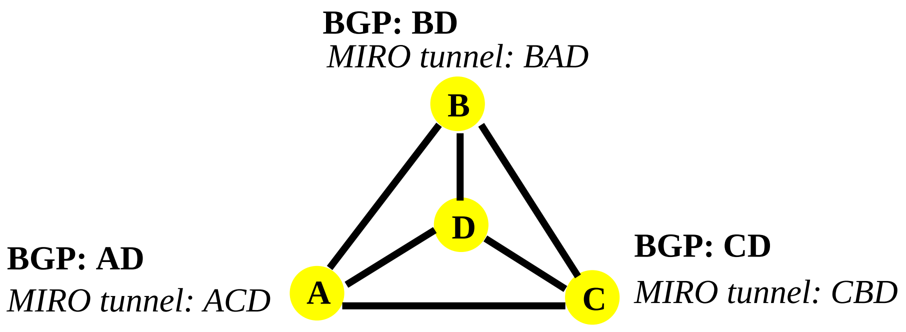


Figure 7.1: An Example where MIRO Does Not Converge

Figure 7.1 shows a case where MIRO tunnels do not converge, and it is similar to the counter-example in [16]. Assume that ASes A, B, and C are all customers of D, and they establish peering links with each other, since customer-provider routes will never be exported to peers, ASes A, B, and C can use only the direct customer-provider routes to reach D, so the BGP routes will converge to the routes shown in bold fonts. However, if there are no restrictions on MIRO tunnels, tunnels can be used to violate the BGP export policy and break the convergence. In the graph, if A, B, and C can each establish the tunnel shown in italic fonts, and they can prefer the tunnel over BGP route, then the situation is exactly the same as in [16], ASes A, B, and C will oscillate between the BGP route and the MIRO tunnel, so the system can never converge.

As shown above, there is a need to use additional guidelines on MIRO tunnels so that the system converges. The following sections will prove that the following guidelines can guarantee convergence when paired with the BGP guidelines.

7.3.1 Adding Tunnels as a Higher Level Layer

In this section, a very simple model is studied that guarantees the convergence of the protocol. In this model, the routing tunnels can be deemed as a separate layer of routes above the BGP paths. The established tunnels are built using only “pure” BGP routes, which do not contain any tunnels, and the resulting tunnels are not advertised as BGP paths. Intuitively, routing tunnels built using this principle will not affect the convergence of BGP protocol, and the tunnels do not depend on each other, so MIRO convergences whenever BGP converges. The proof is shown below, the part identical to the BGP convergence proof is omitted.

In addition to the guidelines above, Guideline B is given:

Guideline B:

$$e_b(l,j)(r,T) = \begin{cases} b\_export(l,j)(r) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$e_t(l,j)(r,T) = \begin{cases} t\_export(l,j)(r) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$export(l,j)(s_j) = (e_b(l,j)(s_j), e_t(l,j)(s_j))$

$$i_b(l,j)(r,T) = \begin{cases} b\_import(l,j)(r) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$i_t(l,j)(r,T) = \begin{cases} t\_import(l,j)(T) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$import(l,j)(r,T) = (i_b(l,j)(r,T), i_t(l,j)(r,T))$

The guideline says that only BGP routes containing no tunnels (r) can be used to construct new routing tunnels (e_t), and that routing tunnels are not used in BGP route advertisement (e_b), while tunnels (t) are not in use at all in export decisions. Therefore, the established MIRO tunnels will never be used to construct another tunnel or a new BGP path. Next, it will be proven that this MIRO system converges when Guideline A and Guideline B are combined.

Lemma 3 *The MIRO system has a stable state.*

proof: The proof is constructed by activating the MIRO system in three phases.

Phase 1: Activate ASes in a linear order that conforms to the partial order in the customer-to-provider DAG.

Phase 2: Activate ASes in a linear order that conforms to the partial order in the provider-to-customer DAG.

Phase 3: Activate ASes in an arbitrary linear order.

Phase 1 and Phase 2 activations are done in the same way as in Lemma 1; note that while the proof is done for one prefix, in reality the routes for all prefixes are updated simultaneously.

As in the proof of Guideline A, this dissertation will prove that any activation sequence leads to this stable state, therefore this is both a stable and unique state.

Claim 4 *A Phase-1 BGP speaker reaches a stable state on BGP routes after its activation in Phase 1.*

Claim 5 *A Phase-2 BGP speaker reaches a stable state on BGP routes after its activation in Phase 2.*

The proof for Claim 4 and Claim 5 are the same as in Claim 1 and Claim 2. Because tunnels can not be used to construct BGP paths, the resulting BGP routes will always be the same as when no routing tunnels are constructed. Therefore the proof in Lemma 1 still holds. Even though a certain BGP speaker might be Phase-1 BGP speaker for one prefix while being Phase-2 speaker for another prefix, it does not hurt the correctness of the original proof. After the two phases, the BGP routes for all prefixes are stable.

Claim 6 *A Phase-3 MIRO speaker reaches a stable state after its activation in Phase 3.*

proof: First, the BGP paths for every BGP speaker are stable after Phase 2. Therefore, for each MIRO speaker i, when it is activated in Phase 3, the candidate paths advertised by all possible responding ASes are already stable. Also, the intermediate path from the upstream AS to the downstream AS is stable because it is a BGP path. Therefore, the routing tunnels formed at i are stable. Considering the fact that i already has a stable BGP path, the state of i is stable after activation. □

With Claim 4, 5, and 6, the activation sequence σ^* leads to a stable state starting from any initial state. □

Lemma 4 *The MIRO system converges to the stable state for any initial state and any fair activation sequence.*

proof: Given the activation sequence σ^* constructed above, for any fair activation sequence σ, the lemma is proven by induction on the activation order used in σ^*. The proof is similar to that in Lemma 2. □

Theorem 2 *For a MIRO system built on top of a BGP system that has only customer-provider and peer-peer relationships, if all ASes follow Guideline A and B, then the MIRO system is inherently safe.*

proof: According to the lemmas above, any initial state and fair activation sequence will lead to a stable state in the MIRO system, and removing nodes or edges does not affect the proof, so the system is inherently safe. □

7.3.2 Advertising Tunnels Only to Leaf Nodes

In some cases, Guideline B may be too restrictive, because it does not allow the routing tunnels to be advertised to other ASes. In Chapter 1, load balancing is used for incoming traffic as one of the motivations. Use Figure 1.1 for example, F may convince B to switch to BCF instead of BEF so that more traffic come in through the link CF. In addition to that, it can convince B to advertise BCF to all its customers, so more traffic will switch away from the EF link, this requires that the tunnel BCF can be advertised as candidate BGP routes. However, the new requirement will complicate the convergence proof of the MIRO protocol.

Luckily, as shown in Figure 5.1, today's Internet is relatively flat, and many of the nodes are actually only connected to one or two other ASes. Further study suggests that most of the ASes are leaf nodes, that is, they only act as customers in any of their inter-AS agreements. This section proves that MIRO is guaranteed to converge, if (i) tunnels can only be advertised to leaf nodes as BGP routes, and (ii) leaf nodes will not advertise routes to anyone else. Because there are so many leaf nodes in today's Internet, this relaxation will probably allow enough flexibility to achieve the load balancing of incoming traffic.

The proof is mostly the same as before: in a leaf node, all its routes are provider routes, and those provider routes will not be advertised to another provider, therefore a leaf node will never advertise any BGP routes to its neighbors. Because of that, using tunnels as BGP routes in a leaf node should have no effect on the convergence of BGP.

Instead of Guideline B, now there is Guideline C.

Guideline C:

$$e_b(l,j)(r,T) = \begin{cases} b\_export(l,j)(r) & if\ l \in E \wedge (l \notin E' \vee l.dst \notin leaf\_nodes) \\ b\_export(l,j)(r \cup T) & if\ l \in E' \wedge l.dst \in leaf\_nodes \\ \{\} & otherwise \end{cases}$$

$$e_t(l,j)(r,T) = \begin{cases} t\_export(l,j)(r) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$export(l,j)(s_j) = (e_b(l,j)(s_j), e_t(l,j)(s_j))$

$$i_b(l,j)(r,T) = \begin{cases} b\_import(l,j)(r) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$i_t(l,j)(r,T) = \begin{cases} t\_import(l,j)(T) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$import(l,j)(r,T) = (i_b(l,j)(r,T), i_t(l,j)(r,T))$

Lemma 5 *The MIRO system conforming to Guideline A and Guideline C has a stable state.*

proof: The MIRO system is activated in four phases:

Phase 1: Activate ASes in a linear order that conforms to the partial order in the customer-to-provider DAG.

Phase 2: Activate ASes in a linear order that conforms to the partial order in the provider-to-customer DAG.

Phase 3: Activate non-leaf ASes in an arbitrary linear order.

Phase 4: Activate leaf ASes in an arbitrary linear order.

Claim 7 *Any non-leaf AS reaches a stable state after its activation in Phase 3.*

Since only leaf nodes can use routing tunnels to construct BGP routes, all other ASes have exactly the same BGP route candidates as before, so they will choose the same BGP path after Phase 1 and 2.

Because any non-leaf AS can never use a BGP route containing any routing tunnel, it should have all tunnel candidates stable after Phase 2, so it will pick a tunnel which is stable after Phase 3.

Claim 8 *Any leaf AS reaches a stable state after its activation in Phase 4.*

Since a leaf AS is a customer to all its neighbors, any of its neighbors must be a non-leaf AS, so that neighbor should have reached a stable state after Phase 3. Therefore, in Phase 4, a leaf AS has all BGP routes and tunnels from all its neighbors, after its activation, and it will stick with the BGP route and tunnels it has chosen. □

Lemma 6 *The MIRO system converges to the stable state for any initial state and any fair activation sequence.*

Given the activation sequence σ^* constructed above, for any fair activation sequence σ, the lemma is proven by induction on the activation order used in σ^*. The proof is similar to that in Lemma 2. □

Theorem 3 *For a MIRO system built on top of a BGP system that has only customer-provider and peer-peer relationships, if all ASes follow Guideline A and C, then the MIRO system is inherently safe.*

proof: According to the lemmas above, any initial state and fair activation sequence will lead to a stable state in the MIRO system, and removing nodes or edges does not affect the proof, so the system is inherently safe. □

7.3.3 Using Same-class Routes for Tunnels

This section studies the convergence of an alternate policy: the requirements that tunnels cannot be used in BGP updates is relaxed; however, the type of advertised candidate routes are more restricted, and now the responding AS can only advertise the routes that both obey export policies and are in the same class as the current advertised BGP routes. For example, if the responding AS is advertising a customer route as the chosen BGP path, it will only advertise its customer routes to the requesting AS, hiding all peer or provider routes. This policy is called “strict policy” in [41].

However, the strict policy alone can not guarantee the convergence of MIRO, as shown in the following counter-example. In Figure 7.2, D is trying to decide which route it should use to reach A, B, and C, respectively. D has direct BGP routes DA, DB, and DC available, but those are all provider routes. D can also establish tunnels with A, B, or C, as those three ASes agree to export all of their BGP routes to D. So to reach AS A, D can either use the provider route DA, or establish a tunnel with B to use the route DBA; to make it obvious DBA uses a tunnel established between D and B, the route is written as D(BA). Assume that AB, BC, and CA are peering links, these tunnels will not violate the strict policy, because B is advertising a peer route to its customer. Similarly, D can also establish D(CB) and D(AC) to reach B and C respectively. Assume that D always pays less using the tunnel route over direct route, therefore, it will prefer D(BA) over DA, D(CB) over DB, and D(AC) over DC. As shown in Figure 7.2, D can never

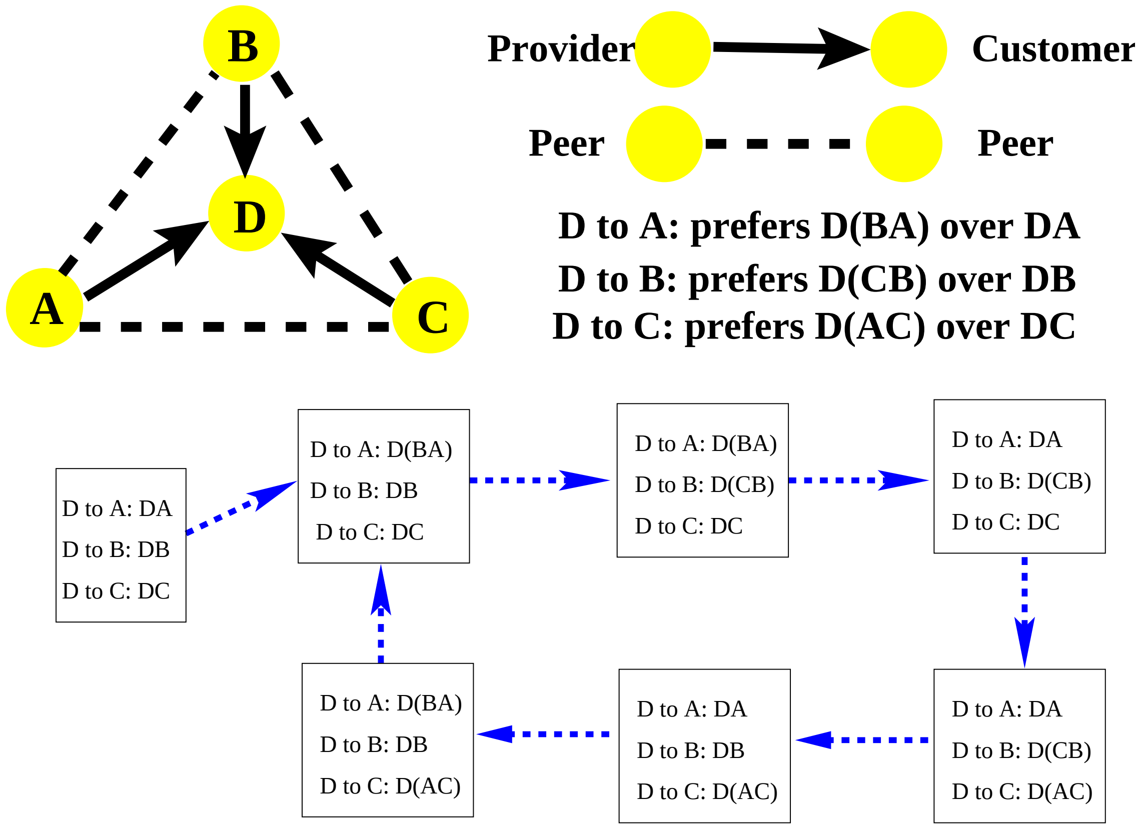


Figure 7.2: An Example where MIRO Does Not Converge under Strict Policy

reach a stable state. It first switches to D(BA) instead of DA to reach A, then replaces the route DB with D(CB) to reach B, at this point D finds out the tunnel D(BA) is no longer available since the BGP route DB has been replaced with D(CB), so it withdraws D(BA) in its routing table and falls back to DA to reach A. Assume that D does the same thing with the routes to B and C, then the routes of D will potentially oscillate as shown in the graph.

This counter example shows that the convergence of MIRO is more complex than that in the BGP world, since a path containing a tunnel now depends on the path to reach the downstream AS. For example, route D(AC) can only exist if D chooses path DA to reach A. If D switches to another route to reach A, this tunnel no longer exists; while in BGP, the routes to different prefixes are independent of each other. Because the convergence of one prefix can now depend on that of another prefix, additional rules are needed to guarantee that each AS chooses routes deterministically.

Intuitively, the oscillation above can be eliminated by introducing some order between the routes to A, B, and C inside D. Some new notations will be introduced as follows: for an AS path r, if the source AS obtained the path through tunnel negotiation with another AS, then $first\_downstream(r)$ denotes the first downstream AS on the path, and $crop\_first\_downstream(r)$ is the path the first downstream AS picked. For example, in Figure 7.2, $first\_downstream(D(BA)) = B$, $crop\_first\_downstream(D(BA)) = A$, $first\_downstream(D(AC)) = A$, and $crop\_first\_downstream(D(AC)) = C$. If the source AS got the path through BGP advertisement, then $first\_downstream(r) = a(r.prefix)$ is the destination AS, and $crop\_first\_downstream(r)$ is the empty path.

Instead of Guideline C, now there is Guideline D. Guideline D says that a tunnel t is exported only when it is in the same class as the advertised BGP route. For example, if the first AS on the advertised AS path is a customer of the current AS, then t can only be advertised if the first AS on t is also a customer of the current AS. If a tunnel satisfies this constraint, then it can either be advertised as a BGP path or a tunnel to other ASes. In addition to that, there must exist a strict partial order $\prec_x$ in each AS X, such that X will only prefer tunnel route t over BGP routes if the first downstream AS Y of t and the destination AS Z of t have the relationship $Y \prec_x Z$. This partial order guarantees that any pair of tunnels within an AS will not indirectly depend on each other and cause divergence.

Guideline D:

$$e(r)(t) = \begin{cases} \{t\} & \begin{array}{l} (first(t.as\_path) \in customer(a) \\ and\ first(r.as\_path \in customer(a))) \\ or\ \ (first(t.as\_path) \in peer(a) \\ and\ first(r.as\_path \in peer(a))) \\ or\ \ (first(t.as\_path) \in provider(a) \\ and\ first(r.as\_path \in provider(a))) \end{array} \\ \{\} & otherwise \end{cases}$$

$e'(r)(T) = \cup_{t \in T} e(r)(t)$

$$e_b(l,j)(r,T) = \begin{cases} b\_export(l,j)(r \cup e'(r)(T)) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$e_t(l,j)(r,T) = \begin{cases} t\_export(l,j)(r \cup e'(r)(T)) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$export(l,j)(s_j) = (e_b(l,j)(s_j), e_t(l,j)(s_j))$

$$i_b(l,j)(r,T) = \begin{cases} b\_import(l,j)(r) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$i_t(l,j)(r,T) = \begin{cases} t\_import(l,j)(T) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$import(l,j)(r,T) = (i_b(l,j)(r,T), i_t(l,j)(r,T))$

For each AS x, there exists a strict partial order $\prec_x$ such that:

x prefers a tunnel route r over all BGP routes only if $first\_downstream(r) \prec_x a(r.prefix)$.

Lemma 7 *Adding tunnels does not change reachability. That is, an AS S will have a route to another AS T, if and only if S can find a route to reach T in a system where all other elements stay the same but the routing tunnels are not used.*

proof: Assume that there is a route R between AS S and T, if R contains a tunnel, then at the first downstream AS $S' = first\_downstream(R)$, part of R after S' is a valid route for S' to advertise to the AS S'' preceding it in $R.as\_path$. However that route is not selected in BGP, which means that there exists a route R' from S' to T with a higher local preference. Guideline A tells us R' should also be advertised to S'', therefore whatever is reachable in MIRO should originally be reachable if no tunnels are used.

If there exists a route R between S and T if no tunnels are used, in MIRO, tunnels will only replace part of the path with some new path with higher local preference, which should not be blocked according to Guideline A and the export rules. So what was reachable in BGP will still be reachable here. □

Lemma 8 *The MIRO system conforming to Guideline A and D has a stable state.*

proof: The original BGP convergence proof considers one prefix at a time, but with Guideline D the availability of a tunnel depends on the selected path to another prefix, so all prefixes have to be activated in the process, and the order of activating these prefixes has to be considered.

An activation sequence σ is constructed using two phases:

Phase 1: Activate ASes in a linear order that conforms to the partial order in the customer-to-provider DAG. Inside each AS, update prefixes in a linear order that conforms to the partial order in the provider-to-customer DAG, any order can be used while activating prefixes belonging to the same AS.

Phase 2: Activate ASes in a linear order that conforms to the partial order in the provider-to-customer DAG. Inside each AS, prefixes are updated in a linear order that conforms to the partial order required by Guideline D.

The definitions of Phase-1 ASes and Phase-2 ASes must be modified slightly in this proof; now, if an AS selects a customer route to prefix d as its BGP path, this dissertation calls it *d's Phase-1 AS*, its BGP speakers *d's Phase-1 BGP speakers*; the rest of ASes are called *d's Phase-2 ASes*, their BGP speakers *d's Phase-2 BGP speakers*.

In the following proof, this dissertation takes advantage of the fact that the export policies lead to "valley-free" AS paths [12]. That is, each valid path is in a (customer-to-provider)*(peer-peer)?(provider-to-customer)* format, including the paths constructed using routing tunnels. This means that a customer route consists of (provider-to-customer) links only.

Claim 9 *When a BGP speaker i is activated in Phase 1, any BGP route or tunnel route to a prefix picked by i is stable after activation if it is a customer route.*

proof: This claim is proven by induction on the activation order.

For the first BGP speaker i_0 the AS has no customers, the set of customer routes is empty, so it is stable.

Assume that all previously activated BGP speakers have stable customer routes, when BGP speaker i is activated, this dissertation again proves by induction on the activation order of the prefixes.

For the first prefix d_0 that gets a customer route in *i*, the route must be the direct link from *i* to d_0 and it is the only customer route to d_0 in *i*, otherwise the ASes on the path between *i* and d_0 gets a customer route and those prefixes are activated before d_0 in *i*. Because this is the only customer route to d_0, it will stay stable after activation.

Assume that for a prefix d_j, any preceding prefix d' which gets a customer route is stable, this dissertation now proves if d_j will eventually get a customer route, it will pick that route after this activation.

Assume that i eventually selects customer BGP route r' to reach d_j, then $i' = first(r'.as\_path)$ is a customer of i, so it should have been activated before i and $crop\_first(r'.as\_path)$ should be available when d_j is activated in i. If i eventually selects customer tunnel route r' to reach d_j, then $i' = first\_downstream(r')$ is a descendant of i on the provider-to-customer DAG, and it should have been activated already, so the customer routes in i' are all stable upon activation. Also i' is an ancestor of $AS(d_j)$ on the provider-to-customer DAG, so any prefixes to $AS(i')$ should be activated before d_j, their customer routes should also be stable before d_j is activated. Therefore r' should also be available upon activation.

Since the best routes i can pick are available upon activation, it should stick with these routes in future activations.

Therefore, by induction, when i is activated in Phase 1, any route to a prefix selected by i is stable after activation if it is a customer route.□

The above claim also means that if a BGP speaker *i* eventually chooses a customer route r to reach prefix d, it will choose this route in Phase 1, otherwise r is not stable and contradicts the claim.

Claim 10 *The Phase-1 BGP speaker i for a prefix d reaches a stable state on its BGP path to d after its activation in Phase 1.*

proof: Guideline A says *i* prefers any customer route over peer or provider routes, so if *i* has a customer route available, it will only pick customer routes, by claim 9, the customer route *i* picks is stable after activation in Phase 1, so it will stick to this customer route it picked. □

Claim 11 *For any BGP speaker i activated in Phase 2, if all BGP routes in i are stable upon activation, then i is stable after activation.*

proof: This claim is proven by induction on the order of the prefix activated. For the first prefix d_0 updated in i, according to Guideline D, i will prefer a tunnel route r over all BGP routes only if $first\_downstream(r) \prec_x a(r.prefix)$. Because d_0 is the first prefix activated, there can never be any $first\_downstream(r) \prec_x a(r.prefix)$, so a tunnel route will be chosen only if no BGP routes are available. By Lemma 7, if there exists a tunnel route to reach d_0, then there must exist at least one BGP route, therefore i will never choose a tunnel route over a BGP route. Since it is assumed that BGP routes are stable upon activation, the routes to d_0 will also be stable upon activation.

For prefix d, by induction all routes to previous prefixes are stable. If i establishes a tunnel with downstream AS i' for d, since i already has all its BGP routes stable and routing tunnels do not change reachability, this tunnel can only affect the choices of i if it is preferred over all BGP routes. By Guideline D, in that case $i' \prec_x a(d)$. Since the prefixes are activated according to the order, all prefixes in i' must have been activated already and the routes are stable, therefore the tunnel through i' is available upon activation and stable. In summary, i has all BGP routes and the routing tunnels which it may prefer over BGP routes available and stable upon activation, so the routes to d will also be stable after activation.

Therefore, after activation, i is stable. □

Claim 12 *Assume that i_0 is the first activated BGP speaker in Phase 2, then i_0 is stable after activation.*

proof: Because i_0 is the first activated BGP speaker in Phase 2, it does not have any providers, therefore, all its routes are either customer ro utes or peer routes.

By Claim 9 all customer routes are stable, since i_0 only has customer routes or peer routes, i_0 and all its peers should have all customer routes stable at this point, therefore all BGP routes i_0 can choose are stable upon activation, by Claim 11 i_0 is stable after activation. □

Claim 13 *When updating BGP speaker i in Phase 2, assume that all preceding speakers are stable, then i is also stable after activation.*

proof: When any prefix d is activated inside i, if i has a customer route to reach d, by Claim 9 the route is stable. If i has a peer or provider route r to reach d and i did not establish a tunnel with another speaker for this route, then this route is propagated via the normal BGP protocol from a neighboring speaker i'. If i' is a peer of i, $crop\_first(r)$ is a customer route and it should be stable at i' after Phase 1. If i' is a provider of i, it is activated before i in Phase 2 and by assumption all of the routes in i' are stable. Therefore, i has all BGP routes available and stable upon activation, by Claim 11 i is stable after activation. □

Claim 14 *For any prefix d, a BGP speaker i reaches a stable state after Phase 2.*

proof: The claim is proven by induction on the activation order in Phase 2. With Claim 12 the initial condition is proven, and Claim 13 proves the induction step. □

By Claim 10 and Claim 14, the described activation sequence leads to a stable state. □

Lemma 9 *The MIRO system converges to the stable state for any initial state and any fair activation sequence.*

proof: Given the activation sequence σ^* constructed above, for any fair activation sequence σ, this lemma is proven by induction on the activation order of all (AS, prefix) pair used in σ^*. The proof is similar to that in Lemma 2. □

Theorem 4 *For a MIRO system built on top of a BGP system that has only customer-provider and peer-peer relationships, if all ASes follow Guideline A, Guideline C, and Guideline B, then the MIRO system is inherently safe.*

proof: Using the two lemmas above, any initial state and fair activation sequence will lead to a stable state in the MIRO system, and removing nodes or edges does not affect the proof, so the system is inherently safe. □

Guideline D provides one way to break the loop in Figure 7.2, it requires that each BGP speaker imposes an order among all prefixes and uses that order to determine which tunnels are valid. Since it is an order local to each BGP speaker, this should not be too difficult to implement. There is another way to break the loop in the counter example, which is to forbid the use of tunnels to establish tunnel routes inside each BGP speaker, as expressed by Guideline E.

Guideline E:

$$e(r)(t) = \begin{cases} \{t\} & \begin{array}{l} (first(t.as\_path) \in customer(a) \\ and\ first(r.as\_path \in customer(a))) \\ or\ \ (first(t.as\_path) \in peer(a) \\ and\ first(r.as\_path \in peer(a))) \\ or\ \ (first(t.as\_path) \in provider(a) \\ and\ first(r.as\_path \in provider(a))) \end{array} \\ \{\} & otherwise \end{cases}$$

$e'(r)(T) = \cup_{t \in T} e(r)(t)$

$$e_b(l,j)(r,T) = \begin{cases} b\_export(l,j)(r \cup e'(r)(T)) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$e_t(l,j)(r,T) = \begin{cases} t\_export(l,j)(r \cup e'(r)(T)) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$export(l,j)(s_j) = (e_b(l,j)(s_j), e_t(l,j)(s_j))$

$$i_b(l,j)(r,T) = \begin{cases} b\_import(l,j)(r) & if\ l \in E \\ \{\} & otherwise \end{cases}$$

$$i_t(l,j)(r,T) = \begin{cases} t\_import(l,j)(T) & if\ l \in E' \\ \{\} & otherwise \end{cases}$$

$import(l,j)(r,T) = (i_b(l,j)(r,T), i_t(l,j)(r,T))$

In each BGP speaker i, a tunnel route r is allowed only if the path from i to $first\_downstream(r)$ does not contain another tunnel established by i.

As in Guideline D, Guideline E requires that a tunnel t is exported only when it is in the same class as the advertised BGP route. But instead of a strict partial order in each AS, it requires that each BGP speaker i invalidates a tunnel r if r depends on another tunnel established in i. Since i has knowledge of all its tunnels, it can easily use local information to validate each new tunnel.

Lemma 10 *The MIRO system conforming to Guideline A and E has a stable state.*

proof: The MIRO system is activated in two phases:

Phase 1: Activate ASes in a linear order that conforms to the partial order in the customer-to-provider DAG. Within each AS, activate prefix in a linear order that conforms to the partial order in the provider-to-customer DAG.

Phase 2: Activate ASes in a linear order that conforms to the partial order in the provider-to-customer DAG. Within each AS, first activate all prefixes in any order, and then activate all prefixes in any order for another time.

Claim 15 *When a BGP speaker i is activated in Phase 1, any BGP route or tunnel route to a prefix picked by i is stable after activation if it is a customer route.*

proof: This claim is proven by induction on the activation order, and the proof is very similar to that in Lemma 9, except that inside each AS, the tunnel to one prefix will not depend on the tunnel from the same AS to another prefix, so the proof is actually simpler.

For the first BGP speaker i_0, the AS has no customers, the set of customer routes is empty, so it is stable.

Assume that all previously activated BGP speakers have stable customer routes, when the first prefix d_0 in i is activated, if i has a customer route r to reach d_0, then $i' = first(r)$ must be an ancestor of $A(d_0)$ on the provider-to-customer DAG. Since prefixes are activated according to the provider-to-customer DAG order and d_0 is the first activated prefix, there can be no such i', so the set of customer routes from i to d_0 is an empty set, the customer routes from i to d_0 are stable upon activation.

Assume that for a prefix d_j, any preceding prefix d' which gets a customer route is stable, it will be proven that if d_j will eventually get a customer route, it will pick that route after this activation.

If the final customer route picked by i to reach d_j is a BGP route, that means $i' = first(r.as\_path)$ advertised the route $crop\_first(r.as\_path)$ to i. Since i' is a customer of i, it must be activated before i in Phase 1, so all its customer routes are stable. Therefore i has all its BGP customer routes available and stable upon activation.

If the final customer route picked by i to reach d_j is a tunnel, then $i' = first\_downstream(r)$ is a descendant of i on the provider-to-customer DAG, it must be activated before i in Phase 1, by induction assumption the routes of i' are stable if they are customer routes, since only customer routes can be advertised to providers, this means all candidate routes i' can advertise to i are stable when i is activated. Also, i' is an ancestor of $a(d_j)$ on the provider-to-customer DAG, so the prefixes belonging to i' are activated before d_j, by induction assumption the customer routes from i to i' are all stable, therefore all customer routes i can establish through tunneling to reach d_j are available and stable upon activation. Since the BGP routes to reach d_j are also available upon activation, this means the customer routes from i to d_j are stable after activation.

By induction, any customer route picked by *i* is stable after activation. □

Claim 16 *For any prefix d, a BGP speaker i reaches a stable state after Phase 2.*

proof: Again, this is proven by induction.

For the first BGP speaker i_0 activated in Phase 2, it has no providers, so it can only have peer routes or customer routes. According to Claim 15, all customer routes are stable after Phase 1, so upon activation of i_0, the customer routes in i_0 and all its peers are stable, so all BGP routes of i_0 are stable after activation. If i_0 eventually picks a BGP route, then that route should be stable and available after the first round of activation. On the other hand, if i_0 eventually picks a tunnel route r, according to Guideline E, the path from i to $first\_downstream(r)$ must not be a tunnel established by i, so this part of the path must be stable after the first round of activation. Moreover, since all routes of i_0 are either peer routes or customer routes, $crop\_first\_downstream(r)$ must be a customer route, so it is stable after Phase 1. Therefore, r must be available and stable upon the second round of activation in Phase 2, the routes of i_0 are stable after two rounds of activation in Phase 2.

Assume that all previously activated BGP speakers have stable routes, when BGP speaker i is activated, next it will be proven that its routes are also stable after activation.

For any prefix d, if i eventually picks a BGP route r, r is either a customer route, a peer route, or a provider route. After Phase 1, all customer routes are stable, so the customer routes of i and all its peers are stable, r must be available and stable upon first round of activation in Phase 2 if r is a customer route or peer route. If r is a provider route, $first(r.as\_path)$ must be the provider of i, so it should have been activated in Phase 2 already and all of its path should be stable. Therefore, r should also be available and stable upon first round of activation in Phase 2 if it is a provider route.

On the other hand, if i eventually picks a tunnel route r, according to Guideline E, the path from i to $first\_downstream(r)$ must not be a tunnel established by i, so this part of the path must be a BGP route of i and it should be stable after the first round of activation. For $r' = crop\_first\_downstream(r)$, if r' is a customer route, it should already be stable after Phase 1. If r' is a peer or provider route, since any valid AS path is “valley-free”,

$first\_downstream(r)$ must be an ancestor of i in the provider-to-customer DAG, so it must be activated before i in Phase 2 and all of its routes must be stable upon activation of i. Therefore, r should also be stable upon the second round of activation in Phase 2.

By induction, the route to any prefix d in any BGP speaker are stable after Phase 2. □

Lemma 11 *The MIRO system converges to the stable state for any initial state and any fair activation sequence.*

proof: Given the activation sequence σ^* constructed above, for any fair activation sequence σ, the lemma is proven by induction on the activation order of all (AS, prefix) pair used in σ^*. The proof is similar to that in Lemma 2. □

7.4 Mixing and Matching the Above Guidelines

Four guidelines which can guarantee convergence in the MIRO protocol were discussed, and they cover some common use cases that were envisioned. Guideline B models the case where ASes establish routing tunnels to occasionally bypass the BGP routes, but do not expect them to be suitable for traffic originated from all sources. Guideline C models the case where tunnels are used to give leaf nodes more flexible choices. As shown in Figure 5.1, many of the nodes in today's Internet topology are leaf nodes, and they can greatly benefit from the tunnels allowed by Guideline C. Guidelines D and E model the cases where tunnels can be freely utilized to transfer the traffic that originally would go through BGP paths, in these guidelines it is assumed the economics incentive that defined Guideline A is still in effect. Moreover, Guideline D requires that each AS arranges its own tunnels so that it does not introduce a loop between its prefixes, while in Guideline E tunnel routes should not be established using tunnels initiated from the same AS.

Guideline D requires that each AS imposes a strict partial order among all prefixes. It might seem difficult to achieve, but this dissertation argues that it is not impractical. This guideline only requires that some partial order exists if tunnels are favored over direct paths for provider routes, and all those are local policies confined within the same AS. Therefore, it is imagined that an AS can build the partial order on-the-fly when it negotiates tunnels. The only restriction is that if a new negotiation attempt may violate the existing partial order, then the old tunnels should be torn down or the new tunnels should be forbidden. This is actually similar to the Banker's algorithm [11] in deadlock checking, whenever a possible loop is found, corresponding measures are taken. So this dissertation argues it is doable in practice.

In Guideline E, each AS simply labels the routes which do not use a tunnel initiated from itself, and only uses these routes to construct tunnels with downstream ASes. Since each AS only needs information about the tunnels established by itself, this policy should be easy to enforce.

It is also possible to mix and match the above guidelines as follows:

1. This dissertation proves that MIRO converges when it satisfies Guideline A and an additional guideline, the proof is also true for other BGP guidelines presented by Lixin Gao and Jennifer Rexford in [13].

2. It can also be requires that each AS conforms to either Guidelines A and C, or Guidelines A and D, convergence is still guaranteed. Similarly, if each AS conforms to either Guidelines A and C, or Guidelines A and E, convergence is also guaranteed.

For brevity the detailed proof is omitted, and an outline is given here. For any leaf node, if it conforms to Guideline C, it will not export any tunnel routes as BGP paths; if it conforms to Guideline D, all its BGP paths are provider routes. So those tunnels of the leaf node can never be exported to its neighbors; therefore, a leaf node will never export any BGP paths or tunnels to its neighbors in both cases. For any node connected to a leaf node, if it conforms to Guideline C, it can only export tunnels to a leaf node, so those tunnels will never be propagated further. Therefore, the existence of Guideline C nodes will not change the convergence proof for Guideline D. Same goes for Guideline E.

3. Guideline B can be extended so that Guideline-B tunnels can be built on top of either BGP paths, Guideline-C tunnels, Guideline-D tunnels, or Guideline-E tunnels. If these Guideline-B tunnels can not be used to advertise as BGP paths or to build other types of tunnels, convergence is still guaranteed.

   To prove the resulting system converges, an additional round of activation needs to be added at the end. When the previous rounds of activation finish, all BGP paths, Guideline-C, Guideline-D, or Guideline-E tunnels are stable, so the resulting Guideline-B tunnels are also stable.

7.4.1 Practical Implications and Summary

The previous sections prove that four new guidelines can guarantee the convergence of MIRO protocol when paired with the original BGP guidelines. The four guidelines can roughly be described as:

1. Build tunnels on top of BGP paths

2. Only advertise tunnels as BGP paths to leaf nodes

3. Conform to “strict policy” and maintain a partial order inside each AS
4. Conform to “strict policy” and avoid using tunnels inside the same AS to reach the first downstream AS

As explained above, the four guidelines can be mixed and matched together; the first guideline can be extended to build arbitrary tunnels on top of BGP paths or other type of tunnels. In reality, the above guidelines probably cover most use cases, because of the following observations:

First, a requesting AS often needs just one tunnel to satisfy its path-selection goals.

- Most of the ASes are stub ASes. In the April 2009 topology generated by the Gao algorithm, 12,468 out of 31,311 ASes are stubs.
- The observed average AS path length is only 4, therefore tunnel concatenations are likely to be very rare—so rare they can be precluded.
- Negotiations are allowed between non-adjacent ASes, so instead of establishing a chain of tunnels, the source AS can directly contact the other end of the chain.

As such, this dissertation envisions that an end-to-end path typically includes at most one tunnel. The first guideline above says that MIRO is guaranteed to converge in this case.

Second, as shown in Figure 5.1, in today’s Internet, very few ASes have a large number of neighbors, while most ASes are stub ASes. The second guideline guarantees that an AS can freely advertise the tunnels to any stub ASes, which means that many stub ASes can have pretty flexible path choices.

Third, it is expected that economic incentives explained by Lixin Gao and Jennifer Rexford in [13] will still affect routing policies. Therefore, “strict policy” describes a very practical tunnel export strategy. The third and fourth guidelines say that under "strict policy" and some easily implementable intra-AS guideline, MIRO is guaranteed to converge.

As explained above, this dissertation believes the four guidelines proven to guarantee convergence in MIRO are practical and cover most use cases that interest people.

Chapter 8

Conclusions

This dissertation presents a multi-path interdomain routing protocol, called MIRO. It defaults to the single-path routing provided by conventional BGP, but it also allows ASes to negotiate alternate paths as needed. This provides flexibility where needed, while remaining backward compatible with BGP. Compared to source routing, MIRO gives intermediate ASes more control over the flow of traffic in their networks. It does not attempt to define global metrics for price or quality; two negotiating parties can agree to tag route announcements in any meaningful way. Multiple policy specification languages may coexist; new metrics or path-selection methods can be added over time.

The evaluation on realistic AS-level topologies shows that MIRO exposes much of the underlying path diversity in the Internet, even when only the major ISPs have deployed the enhanced protocol. This study also finds that significant path diversity is available, even if ASes adhere to conventional practices for exporting routes based on their business relationships with their neighbors. Guaranteeing convergence is an important part in any routing framework. This dissertation presents a formal model for MIRO and proves that it converges under four guidelines. As explained in the dissertation, it is believed that those guidelines cover most use cases in practice. Flexible support for negotiation of alternate routes opens up many interesting research problems regarding how to incorporate information about pricing, traffic load, and performance directly into the path-selection process. These are exciting areas for future work.

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