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Experience with the BGP-4 Protocol

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Abstract

The purpose of this memo is to document how the requirements for publication of a routing protocol as an Internet Draft Standard have been satisfied by Border Gateway Protocol version 4 (BGP-4).

This report satisfies the requirement for "the second report", as described in Section 6.0 of RFC 1264. In order to fulfill the requirement, this report augments RFC 1773 and describes additional knowledge and understanding gained in the time between when the protocol was made a Draft Standard and when it was submitted for Standard.

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1. Introduction

The purpose of this memo is to document how the requirements for publication of a routing protocol as an Internet Draft Standard have been satisfied by Border Gateway Protocol version 4 (BGP-4).

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2. BGP-4 Overview

BGP is an inter-autonomous system routing protocol designed for TCP/IP internets. The primary function of a BGP speaking system is to exchange network reachability information with other BGP systems. This network reachability information includes information on the list of Autonomous Systems (ASes) that reachability information traverses. This information is sufficient to construct a graph of AS connectivity for this reachability, from which routing loops may be pruned and some policy decisions, at the AS level, may be enforced.

The initial version of the BGP protocol was published in [RFC1105]. Since then, BGP Versions 2, 3, and 4 have been developed and are specified in [RFC1163], [RFC1267], and [RFC1771], respectively. Changes to BGP-4 after it went to Draft Standard [RFC1771] are listed in Appendix N of [RFC4271].

2.1. A Border Gateway Protocol

The initial version of the BGP protocol was published in [RFC1105]. BGP version 2 is defined in [RFC1163]. BGP version 3 is defined in [RFC1267]. BGP version 4 is defined in [RFC1771] and [RFC4271]. Appendices A, B, C, and D of [RFC4271] provide summaries of the changes between each iteration of the BGP specification.

3. Management Information Base (MIB)

The BGP-4 Management Information Base (MIB) has been published [BGP-MIB]. The MIB was updated from previous versions, which are documented in [RFC1657] and [RFC1269], respectively.

Apart from a few system variables, the BGP MIB is broken into two tables: the BGP Peer Table and the BGP Received Path Attribute Table.

The Peer Table reflects information about BGP peer connections, such as their state and current activity. The Received Path Attribute Table contains all attributes received from all peers before local routing policy has been applied. The actual attributes used in determining a route are a subset of the received attribute table.

4. Implementation Information

There are numerous independent interoperable implementations of BGP currently available. Although the previous version of this report provided an overview of the implementations currently used in the operational Internet, at that time it has been suggested that a separate BGP Implementation Report [RFC4276] be generated.

It should be noted that implementation experience with Cisco's BGP-4 implementation was documented as part of [RFC1656].

For all additional implementation information please reference [RFC4276].

5. Operational Experience

This section discusses operational experience with BGP and BGP-4.

BGP has been used in the production environment since 1989; BGP-4 has been used since 1993. Production use of BGP includes utilization of all significant features of the protocol. The present production environment, where BGP is used as the inter-autonomous system routing protocol, is highly heterogeneous. In terms of link bandwidth, it varies from 56 Kbps to 10 Gbps. In terms of the actual routers that run BGP, they range from relatively slow performance, general purpose CPUs to very high performance RISC network processors, and include both special purpose routers and the general purpose workstations that run various UNIX derivatives and other operating systems.

In terms of the actual topologies, it varies from very sparse to quite dense. The requirement for full-mesh IBGP topologies has been largely remedied by BGP Route Reflection, Autonomous System Confederations for BGP, and often some mix of the two. BGP Route Reflection was initially defined in [RFC1966] and was updated in [RFC2796]. Autonomous System Confederations for BGP were initially defined in [RFC1965] and were updated in [RFC3065].

At the time of this writing, BGP-4 is used as an inter-autonomous system routing protocol between all Internet-attached autonomous systems, with nearly 21k active autonomous systems in the global Internet routing table.

BGP is used both for the exchange of routing information between a transit and a stub autonomous system, and for the exchange of routing information between multiple transit autonomous systems. There is no protocol distinction between sites historically considered "backbones" versus "regional" or "edge" networks.

The full set of exterior routes carried by BGP is well over 170,000 aggregate entries, representing several times that number of connected networks. The number of active paths in some service provider core routers exceeds 2.5 million. Native AS path lengths are as long as 10 for some routes, and "padded" path lengths of 25 or more autonomous systems exist.

6. TCP Awareness

BGP employs TCP [RFC793] as it's Transport Layer protocol. As such, all characteristics inherent to TCP are inherited by BGP.

For example, due to TCP's behavior, bandwidth capabilities may not be realized because of TCP's slow start algorithms and slow-start restarts of connections, etc.

7. Metrics

This section discusses different metrics used within the BGP protocol. BGP has a separate metric parameter for IBGP and EBGP. This allows policy-based metrics to overwrite the distance-based metrics; this allows each autonomous system to define its independent policies in Intra-AS, as well as Inter-AS. BGP Multi Exit Discriminator (MED) is used as a metric by EBGP peers (i.e., inter-domain), while Local Preference (LOCAL_PREF) is used by IBGP peers (i.e., intra-domain).

7.1. MULTI_EXIT_DISC (MED)

BGP version 4 re-defined the old INTER-AS metric as a MULTI_EXIT_DISC (MED). This value may be used in the tie-breaking process when selecting a preferred path to a given address space, and provides BGP speakers with the capability of conveying the optimal entry point into the local AS to a peer AS.

Although the MED was meant to only be used when comparing paths received from different external peers in the same AS, many implementations provide the capability to compare MEDs between different autonomous systems.

Though this may seem a fine idea for some configurations, care must be taken when comparing MEDs of different autonomous systems. BGP

speakers often derive MED values by obtaining the IGP metric associated with reaching a given BGP NEXT_HOP within the local AS. This allows MEDs to reasonably reflect IGP topologies when advertising routes to peers. While this is fine when comparing MEDs of multiple paths learned from a single adjacent AS, it can result in potentially bad decisions when comparing MEDs of different autonomous systems. This is most typically the case when the autonomous systems use different mechanisms to derive IGP metrics, BGP MEDs, or perhaps even use different IGP protocols with vastly contrasting metric spaces.

Another MED deployment consideration involves the impact of the aggregation of BGP routing information on MEDs. Aggregates are often generated from multiple locations in an AS to accommodate stability, redundancy, and other network design goals. When MEDs are derived from IGP metrics associated with said aggregates, the MED value advertised to peers can result in very suboptimal routing.

The MED was purposely designed to be a "weak" metric that would only be used late in the best-path decision process. The BGP working group was concerned that any metric specified by a remote operator would only affect routing in a local AS if no other preference was specified. A paramount goal of the design of the MED was to ensure that peers could not "shed" or "absorb" traffic for networks they advertise.

7.1.1. MEDs and Potatoes

Where traffic flows between a pair of destinations, each is connected to two transit networks, each of the transit networks has the choice of sending the traffic to the peering closest to another transit provider or passing traffic to the peering that advertises the least cost through the other provider. The former method is called "hot potato routing" because, like a hot potato held in bare hands, whoever has it tries to get rid of it quickly. Hot potato routing is accomplished by not passing the EBGP-learned MED into the IBGP. This minimizes transit traffic for the provider routing the traffic. Far less common is "cold potato routing", where the transit provider uses its own transit capacity to get the traffic to the point in the adjacent transit provider advertised as being closest to the destination. Cold potato routing is accomplished by passing the EBGP-learned MED into IBGP.

If one transit provider uses hot potato routing and another uses cold potato routing, traffic between the two tends to be symmetric. Depending on the business relationships, if one provider has more capacity or a significantly less congested transit network, then that provider may use cold potato routing. The NSF-funded NSFNET backbone

and NSF-funded regional networks are examples of widespread use of cold potato routing in the mid 1990s.

In some cases, a provider may use hot potato routing for some destinations for a given peer AS, and cold potato routing for others. The different treatment of commercial and research traffic in the NSFNET in the mid 1990s is an example of this. However, this might best be described as 'mashed potato routing', a term that reflects the complexity of router configurations in use at the time.

Seemingly more intuitive references, which fall outside the vegetable kingdom, refer to cold potato routing as "best exit routing", and hot potato routing as "closest exit routing".

7.1.2. Sending MEDs to BGP Peers

[RFC4271] allows MEDs received from any EBGP peers by a BGP speaker to be passed to its IBGP peers. Although advertising MEDs to IBGP peers is not a required behavior, it is a common default. MEDs received from EBGP peers by a BGP speaker SHOULD NOT be sent to other EBGP peers.

Note that many implementations provide a mechanism to derive MED values from IGP metrics to allow BGP MED information to reflect the IGP topologies and metrics of the network when propagating information to adjacent autonomous systems.

7.1.3. MED of Zero Versus No MED

[RFC4271] requires an implementation to provide a mechanism that allows MED to be removed. Previously, implementations did not consider a missing MED value the same as a MED of zero. [RFC4271] now requires that no MED value be equal to zero.

Note that many implementations provide a mechanism to explicitly define a missing MED value as "worst", or less preferable than zero or larger values.

7.1.4. MEDs and Temporal Route Selection

Some implementations have hooks to apply temporal behavior in MED-based best path selection. That is, all things being equal up to MED consideration, preference would be applied to the "oldest" path, without preference for the lower MED value. The reasoning for this is that "older" paths are presumably more stable, and thus preferable. However, temporal behavior in route selection results in non-deterministic behavior, and as such, may often be undesirable.

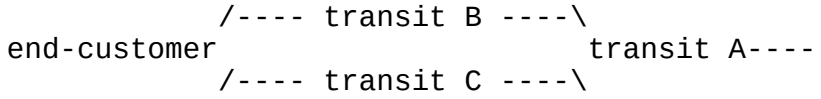
8. Local Preference

The LOCAL_PREF attribute was added to enable a network operator to easily configure a policy that overrides the standard best path determination mechanism without independently configuring local preference policy on each router.

One shortcoming in the BGP-4 specification was the suggestion that a default value of LOCAL_PREF be assumed if none was provided. Defaults of zero or the maximum value each have range limitations, so a common default would aid in the interoperation of multi-vendor routers in the same AS (since LOCAL_PREF is a local administration attribute, there is no interoperability drawback across AS boundaries).

[RFC4271] requires that LOCAL_PREF be sent to IBGP Peers and not to EBGP Peers. Although no default value for LOCAL_PREF is defined, the common default value is 100.

Another area where exploration is required is a method whereby an originating AS may influence the best path selection process. For example, a dual-connected site may select one AS as a primary transit service provider and have one as a backup.



In a topology where the two transit service providers connect to a third provider, the real decision is performed by the third provider. There is no mechanism to indicate a preference should the third provider wish to respect that preference.

A general purpose suggestion has been the possibility of carrying an optional vector, corresponding to the AS_PATH, where each transit AS may indicate a preference value for a given route. Cooperating autonomous systems may then choose traffic based upon comparison of "interesting" portions of this vector, according to routing policy.

While protecting a given autonomous systems routing policy is of paramount concern, avoiding extensive hand configuration of routing policies needs to be examined more carefully in future BGP-like protocols.

9. Internal BGP In Large Autonomous Systems

While not strictly a protocol issue, another concern has been raised by network operators who need to maintain autonomous systems with a large number of peers. Each speaker peering with an external router is responsible for propagating reachability and path information to all other transit and border routers within that AS. This is typically done by establishing internal BGP connections to all transit and border routers in the local AS.

Note that the number of BGP peers that can be fully meshed depends on a number of factors, including the number of prefixes in the routing system, the number of unique paths, stability of the system, and, perhaps most importantly, implementation efficiency. As a result, although it’s difficult to define "a large number of peers", there is always some practical limit.

In a large AS, this leads to a full mesh of TCP connections (n * (n-1)) and some method of configuring and maintaining those connections. BGP does not specify how this information is to be propagated. Therefore, alternatives, such as injecting BGP routing information into the local IGP, have been attempted, but turned out to be non-practical alternatives (to say the least).

To alleviate the need for "full mesh" IBGP, several alternatives have been defined, including BGP Route Reflection [RFC2796] and AS Confederations for BGP [RFC3065].

10. Internet Dynamics

As discussed in [RFC4274], the driving force in CPU and bandwidth utilization is the dynamic nature of routing in the Internet. As the Internet has grown, the frequency of route changes per second has increased.

We automatically get some level of damping when more specific NLRI is aggregated into larger blocks; however, this is not sufficient. In Appendix F of [RFC4271], there are descriptions of damping techniques that should be applied to advertisements. In future specifications of BGP-like protocols, damping methods should be considered for mandatory inclusion in compliant implementations.

BGP Route Flap Damping is defined in [RFC2439]. BGP Route Flap Damping defines a mechanism to help reduce the amount of routing information passed between BGP peers, which reduces the load on these peers without adversely affecting route convergence time for relatively stable routes.

None of the current implementations of BGP Route Flap Damping store route history by unique NRLI or AS Path, although RFC 2439 lists this as mandatory. A potential result of failure to consider each AS Path separately is an overly aggressive suppression of destinations in a densely meshed network, with the most severe consequence being suppression of a destination after a single failure. Because the top tier autonomous systems in the Internet are densely meshed, these adverse consequences are observed.

Route changes are announced using BGP UPDATE messages. The greatest overhead in advertising UPDATE messages happens whenever route changes to be announced are inefficiently packed. Announcing routing changes that share common attributes in a single BGP UPDATE message helps save considerable bandwidth and reduces processing overhead, as discussed in Section 12, Update Packing.

Persistent BGP errors may cause BGP peers to flap persistently if peer dampening is not implemented, resulting in significant CPU utilization. Implementors may find it useful to implement peer dampening to avoid such persistent peer flapping [RFC4271].

11. BGP Routing Information Bases (RIBs)

[RFC4271] states "Any local policy which results in routes being added to an Adj-RIB-Out without also being added to the local BGP speaker’s forwarding table, is outside the scope of this document".

However, several well-known implementations do not confirm that Loc-RIB entries were used to populate the forwarding table before installing them in the Adj-RIB-Out. The most common occurrence of this is when routes for a given prefix are presented by more than one protocol, and the preferences for the BGP-learned route is lower than that of another protocol. As such, the route learned via the other protocol is used to populate the forwarding table.

It may be desirable for an implementation to provide a knob that permits advertisement of "inactive" BGP routes.

It may be also desirable for an implementation to provide a knob that allows a BGP speaker to advertise BGP routes that were not selected in the decision process.

12. Update Packing

Multiple unfeasible routes can be advertised in a single BGP Update message. In addition, one or more feasible routes can be advertised in a single Update message, as long as all prefixes share a common attribute set.

The BGP4 protocol permits advertisement of multiple prefixes with a common set of path attributes in a single update message, which is commonly referred to as "update packing". When possible, update packing is recommended, as it provides a mechanism for more efficient behavior in a number of areas, including:

- o Reduction in system overhead due to generation or receipt of fewer Update messages.
- o Reduction in network overhead as a result of less packets and lower bandwidth consumption.
- o Reduction in frequency of processing path attributes and looking for matching sets in the AS_PATH database (if you have one). Consistent ordering of the path attributes allows for ease of matching in the database, as different representations of the same data do not exist.

The BGP protocol suggests that withdrawal information should be packed in the beginning of an Update message, followed by information about reachable routes in a single UPDATE message. This helps alleviate excessive route flapping in BGP.

13. Limit Rate Updates

The BGP protocol defines different mechanisms to rate limit Update advertisement. The BGP protocol defines a MinRouteAdvertisementInterval parameter that determines the minimum time that must elapse between the advertisement of routes to a particular destination from a single BGP speaker. This value is set on a per-BGP-peer basis.

Because BGP relies on TCP as the Transport protocol, TCP can prevent transmission of data due to empty windows. As a result, multiple updates may be spaced closer together than was originally queued. Although it is not common, implementations should be aware of this occurrence.

13.1. Consideration of TCP Characteristics

If either a TCP receiver is processing input more slowly than the sender, or if the TCP connection rate is the limiting factor, a form of backpressure is observed by the TCP sending application. When the TCP buffer fills, the sending application will either block on the write or receive an error on the write. In early implementations or naive new implementations, setting options to block on the write or setting options for non-blocking writes are common errors. Such implementations treat full buffer related errors as fatal.

Having recognized that full write buffers are to be expected, additional implementation pitfalls exist. The application should not attempt to store the TCP stream within the application itself. If the receiver or the TCP connection is persistently slow, then the buffer can grow until memory is exhausted. A BGP implementation is required to send changes to all peers for which the TCP connection is not blocked, and is required to send those changes to the remaining peers when the connection becomes unblocked.

If the preferred route for a given NLRI changes multiple times while writes to one or more peers are blocked, only the most recent best route needs to be sent. In this way, BGP is work conserving [RFC4274]. In cases of extremely high route change, a higher volume of route change is sent to those peers that are able to process it more quickly; a lower volume of route change is sent to those peers that are not able to process the changes as quickly.

For implementations that handle differing peer capacities to absorb route change well, if the majority of route change is contributed by a subset of unstable NRLI, the only impact on relatively stable NRLI that makes an isolated route change is a slower convergence, for which convergence time remains bounded, regardless of the amount of instability.

14. Ordering of Path Attributes

The BGP protocol suggests that BGP speakers sending multiple prefixes per an UPDATE message sort and order path attributes according to Type Codes. This would help their peers quickly identify sets of attributes from different update messages that are semantically different.

Implementers may find it useful to order path attributes according to Type Code, such that sets of attributes with identical semantics can be more quickly identified.

15. AS_SET Sorting

AS_SETs are commonly used in BGP route aggregation. They reduce the size of AS_PATH information by listing AS numbers only once, regardless of the number of times it might appear in the process of aggregation. AS_SETs are usually sorted in increasing order to facilitate efficient lookups of AS numbers within them. This optimization is optional.

16. Control Over Version Negotiation

Because pre-BGP-4 route aggregation can't be supported by earlier versions of BGP, an implementation that supports versions in addition to BGP-4 should provide the version support on a per-peer basis. At the time of this writing, all BGP speakers on the Internet are thought to be running BGP version 4.

17. Security Considerations

BGP provides a flexible and extendable mechanism for authentication and security. The mechanism allows support for schemes with various degrees of complexity. BGP sessions are authenticated based on the IP address of a peer. In addition, all BGP sessions are authenticated based on the autonomous system number advertised by a peer.

Because BGP runs over TCP and IP, BGP's authentication scheme may be augmented by any authentication or security mechanism provided by either TCP or IP.

17.1. TCP MD5 Signature Option

[RFC2385] defines a way in which the TCP MD5 signature option can be used to validate information transmitted between two peers. This method prevents a third party from injecting information (e.g., a TCP Reset) into the datastream, or modifying the routing information carried between two BGP peers.

At the moment, TCP MD5 is not ubiquitously deployed, especially in inter-domain scenarios, largely because of key distribution issues. Most key distribution mechanisms are considered to be too "heavy" at this point.

Many have naively assumed that an attacker must correctly guess the exact TCP sequence number (along with the source and destination ports and IP addresses) to inject a data segment or reset a TCP transport connection between two BGP peers. However, recent observation and open discussion show that the malicious data only needs to fall within the TCP receive window, which may be quite large, thereby significantly lowering the complexity of such an attack.

As such, it is recommended that the MD5 TCP Signature Option be employed to protect BGP from session resets and malicious data injection.

17.2. BGP Over IPsec

BGP can run over IPsec, either in a tunnel or in transport mode, where the TCP portion of the IP packet is encrypted. This not only prevents random insertion of information into the data stream between two BGP peers, but also prevents an attacker from learning the data being exchanged between the peers.

However, IPsec does offer several options for exchanging session keys, which may be useful on inter-domain configurations. These options are being explored in many deployments, although no definitive solution has been reached on the issue of key exchange for BGP in IPsec.

Because BGP runs over TCP and IP, it should be noted that BGP is vulnerable to the same denial of service and authentication attacks that are present in any TCP based protocol.

17.3. Miscellaneous

Another routing protocol issue is providing evidence of the validity and authority of routing information carried within the routing system. This is currently the focus of several efforts, including efforts to define threats that can be used against this routing information in BGP [BGPATTACK], and efforts to develop a means of providing validation and authority for routing information carried within BGP [SBGP] [soBGP].

In addition, the Routing Protocol Security Requirements (RPSEC) working group has been chartered, within the Routing Area of the IETF, to discuss and assist in addressing issues surrounding routing protocol security. Within RPSEC, this work is intended to result in feedback to BGP4 and future protocol enhancements.

18. PTOMAINE and GROW

The Prefix Taxonomy (PTOMAINE) working group, recently replaced by the Global Routing Operations (GROW) working group, is chartered to consider and measure the problem of routing table growth, the effects of the interactions between interior and exterior routing protocols, and the effect of address allocation policies and practices on the global routing system. Finally, where appropriate, GROW will also document the operational aspects of measurement, policy, security, and VPN infrastructures.

GROW is currently studying the effects of route aggregation, and also the inability to aggregate over multiple provider boundaries due to inadequate provider coordination.

Within GROW, this work is intended to result in feedback to BGPv4 and future protocol enhancements.

19. Internet Routing Registries (IRRs)

Many organizations register their routing policy and prefix origination in the various distributed databases of the Internet Routing Registry. These databases provide access to information using the RPSL language, as defined in [RFC2622]. While registered information may be maintained and correct for certain providers, the lack of timely or correct data in the various IRR databases has prevented wide spread use of this resource.

20. Regional Internet Registries (RIRs) and IRRs, A Bit of History

The NSFNET program used EGP, and then BGP, to provide external routing information. It was the NSF policy of offering different prices and providing different levels of support to the Research and Education (RE) and the Commercial (CO) networks that led to BGP's initial policy requirements. In addition to being charged more, CO networks were not able to use the NSFNET backbone to reach other CO networks. The rationale for higher prices was that commercial users of the NSFNET within the business and research entities should subsidize the RE community. Recognition that the Internet was evolving away from a hierarchical network to a mesh of peers led to changes away from EGP and BGP-1 that eliminated any assumptions of hierarchy.

Enforcement of NSF policy was accomplished through maintenance of the NSF Policy Routing Database (PRDB). The PRDB not only contained each networks designation as CO or RE, but also contained a list of the preferred exit points to the NSFNET to reach each network. This was the basis for setting what would later be called BGP LOCAL_PREF on the NSFNET. Tools provided with the PRDB generated complete router configurations for the NSFNET.

Use of the PRDB had the fortunate consequence of greatly improving reliability of the NSFNET, relative to peer networks of the time. PRDB offered more optimal routing for those networks that were sufficiently knowledgeable and willing to keep their entries current.

With the decommission of the NSFNET Backbone Network Service in 1995, it was recognized that the PRDB should be made less single provider centric, and its legacy contents, plus any further updates, should be made available to any provider willing to make use of it. The European networking community had long seen the PRDB as too US-centric. Through Reseaux IP Europeens (RIPE), the Europeans created an open format in RIPE-181 and maintained an open database used for

address and AS registry more than policy. The initial conversion of the PRDB was to RIPE-181 format, and tools were converted to make use of this format. The collection of databases was termed the Internet Routing Registry (IRR), with the RIPE database and US NSF-funded Routing Arbitrator (RA) being the initial components of the IRR.

A need to extend RIPE-181 was recognized and RIPE agreed to allow the extensions to be defined within the IETF in the RPS WG, resulting in the RPSL language. Other work products of the RPS WG provided an authentication framework and a means to widely distribute the database in a controlled manner and synchronize the many repositories. Freely available tools were provided, primarily by RIPE, Merit, and ISI, the most comprehensive set from ISI. The efforts of the IRR participants has been severely hampered by providers unwilling to keep information in the IRR up to date. The larger of these providers have been vocal, claiming that the database entry, simple as it may be, is an administrative burden, and some acknowledge that doing so provides an advantage to competitors that use the IRR. The result has been an erosion of the usefulness of the IRR and an increase in vulnerability of the Internet to routing based attacks or accidental injection of faulty routing information.

There have been a number of cases in which accidental disruption of Internet routing was avoided by providers using the IRR, but this was highly detrimental to non-users. Filters have been forced to provide less complete coverage because of the erosion of the IRR; these types of disruptions continue to occur infrequently, but have an increasingly widespread impact.

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