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Algorithms for computing Maximally Redundant Trees for IP/LDP Fast-Reroute
draft-enyedi-rtgwg-mrt-frr-algorithm-01

Abstract

A complete solution for IP and LDP Fast-Reroute using Maximally Redundant Trees is presented in [I-D.ietf-rtgwg-mrt-frr-architecture]. This document describes an algorithm that can be used to compute the necessary Maximally Redundant Trees and the associated next-hops.

Status of this Memo

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1. Introduction

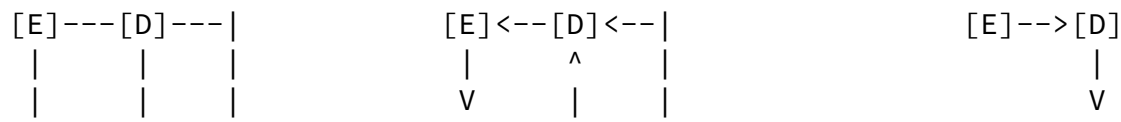
MRT Fast-Reroute requires that packets can be forwarded not only on the shortest-path tree, but also on two Maximally Redundant Trees (MRTs), referred to as the Blue MRT and the Red MRT. A router which experiences a local failure must also have pre-determined which alternate to use. This document describes how to compute these three things and the algorithm design decisions and rationale. The algorithms are based on those presented in [MRTLinear] and expanded in [EnyediThesis].

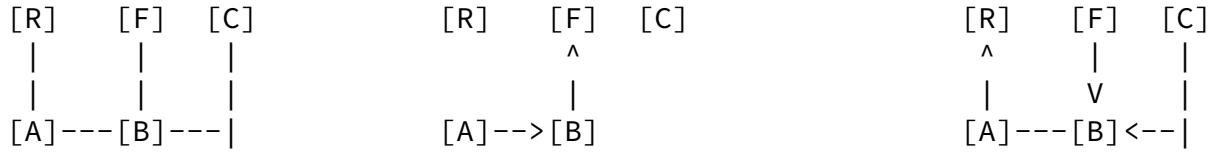
Just as packets routed on a hop-by-hop basis require that each router compute a shortest-path tree which is consistent, it is necessary for each router to compute the Blue MRT and Red MRT in a consistent fashion. This is the motivation for the detail in this document.

As now, a router's FIB will contain primary next-hops for the current shortest-path tree for forwarding traffic. In addition, a router's FIB will contain primary next-hops for the Blue MRT for forwarding received traffic on the Blue MRT and primary next-hops for the Red MRT for forwarding received traffic on the Red MRT.

What alternate next-hops a point-of-local-repair (PLR) selects need not be consistent - but loops must be prevented. To reduce congestion, it is possible for multiple alternate next-hops to be selected; in the context of MRT alternates, each of those alternate next-hops would be equal-cost paths.

This document provides an algorithm for selecting an appropriate MRT alternate for consideration. Other alternates, e.g. LFAs that are downstream paths, may be prefered when available and that decision-making is not captured in this document.





(a) a 2-connected graph

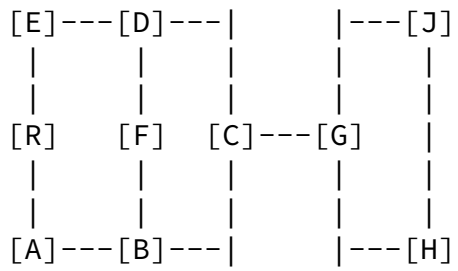
(b) Blue MRT towards R

(c) Red MRT towards R

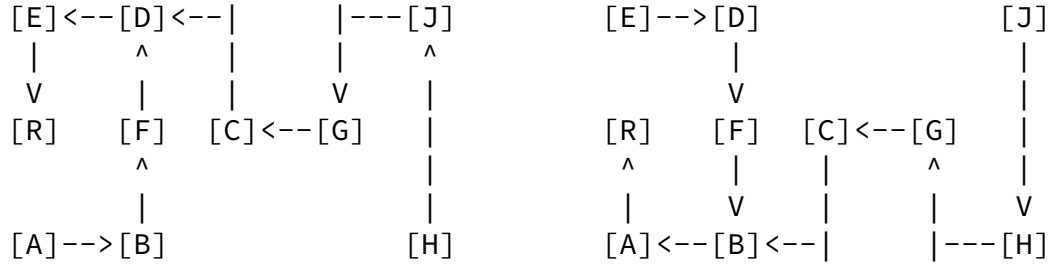
Figure 1

Algorithms for computing MRTs can handle arbitrary network topologies where the whole network graph is not 2-connected, as in Figure 2, as

well as the easier case where the network graph is 2-connected (Figure 1). Each MRT is a spanning tree. The pair of MRTs provide two paths from every node X to the root of the MRTs. Those paths share the minimum number of nodes and the minimum number of links. Each such shared node is a cut-vertex. Any shared links are cut-links.



(a) a graph that isn't 2-connected



(b) Blue MRT towards R

(c) Red MRT towards R

Figure 2

2. Terminology and Definitions

Redundant Trees (RT): A pair of trees where the path from any node X to the root R on the first tree is node-disjoint with the path from the same node X to the root along the second tree. These can be computed in 2-connected graphs.

Maximally Redundant Trees (MRT): A pair of trees where the path from any node X to the root R along the first tree and the path from the same node X to the root along the second tree share the minimum number of nodes and the minimum number of links. Each such shared node is a cut-vertex. Any shared links are cut-links. Any RT is an MRT but many MRTs are not RTs.

network graph: A graph that reflects the network topology where all links connect exactly two nodes and broadcast links have been transformed into the standard pseudo-node representation.

cut-vertex: A vertex whose removal partitions the network.

cut-link: A link whose removal partitions the network. A cut-link by definition must be connected between two cut-vertices. If there are multiple parallel links, then they are referred to as cut-links in this document if removing the set of parallel links would partition the network.

2-connected: A graph that has no cut-vertices. This is a graph that requires two nodes to be removed before the network is partitioned.

spanning tree: A tree containing links that connects all nodes in the network graph.

back-edge: In the context of a spanning tree computed via a depth-first search, a back-edge is a link that connects a descendant of a node x with an ancestor of x.

2-connected cluster: A maximal set of nodes that are 2-connected. In a network graph with at least one cut-vertex, there will be multiple 2-connected clusters.

block: Either a 2-connected cluster, a cut-edge, or an isolated vertex.

DAG: Directed Acyclic Graph - a digraph containing no directed cycle.

ADAG: Almost Directed Acyclic Graph - a digraph that can be transformed into a DAG whith removing a single node (the root node).

GADAG: Generalized ADAG - a digraph, which has only ADAGs as all of its blocks. The root of such a block is the node closest to the global root (e.g. with uniform link costs).

DFS: Depth-First Search

DFS ancestor: A node n is a DFS ancestor of x if n is on the DFS-tree path from the DFS root to x.

DFS descendant: A node n is a DFS descendant of x if x is on the DFS-tree path from the DFS root to n.

ear: A path along not-yet-included-in-the-GADAG nodes that starts at a node that is already-included-in-the-GADAG and that ends at a node that is already-included-in-the-GADAG. The starting and ending nodes may be the same node if it is a cut-vertex.

X >> Y or Y << X: Indicates the relationship between X and Y in a partial order, such as found in a GADAG. X >> Y means that X is higher in the partial order than Y. Y << X means that Y is lower in the partial order than X.

X > Y or Y < X: Indicates the relationship between X and Y in the total order, such as found via a topological sort. X > Y means that X is higher in the total order than Y. Y < X means that Y is lower in the total order than X.

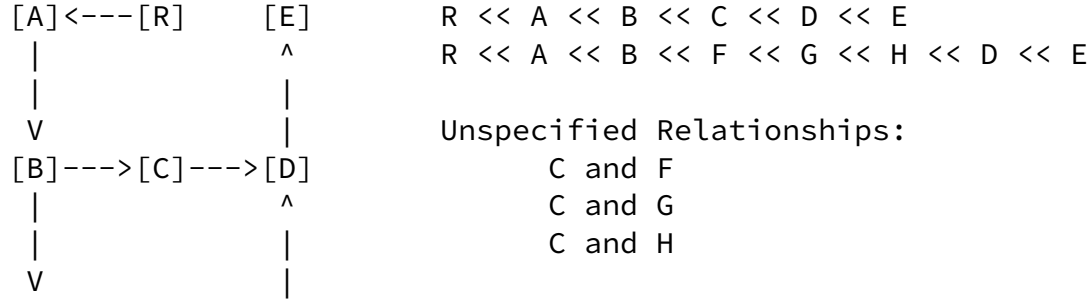
proxy-node: A node added to the network graph to represent a multi-homed prefix or routers outside the local MRT-fast-reroute-supporting island of routers. The key property of proxy-nodes is that traffic cannot transit them.

3. Algorithm Key Concepts

There are five key concepts that are critical for understanding the algorithms for computing MRTs. The first is the idea of partially ordering the nodes in a network graph with regard to each other and to the GADAG root. The second is the idea of finding an ear of nodes and adding them in the correct direction. The third is the idea of a Low-Point value and how it can be used to identify cut-vertices and to find a second path towards the root. The fourth is the idea that a non-2-connected graph is made up of blocks, where a block is a 2-connected cluster, a cut-edge or an isolated node. The fifth is the idea of a local-root for each node; this is used to compute ADAGs in each block.

3.1. Partial Ordering for Disjoint Paths

Given any two nodes X and Y in a graph, a particular total order means that either X < Y or X > Y in that total order. An example would be a graph where the nodes are ranked based upon their IP loopback addresses. In a partial order, there may be some nodes for which it can't be determined whether X << Y or X >> Y. A partial order can be captured in a directed graph, as shown in Figure 3. In a graphical representation, a link directed from X to Y indicates that X is a neighbor of Y in the network graph and X << Y.



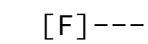


Figure 3: Directed Graph showing a Partial Order

To compute MRTs, it is very useful to have the root of the MRTs be at the very bottom and the very top of the partial ordering. This means that from any node X, one can pick nodes higher in the order until the root is reached. Similarly, from any node X, one can pick nodes lower in the order until the root is reached. For instance, in Figure 4, from G the higher nodes picked can be traced by following the directed links and are H, D, E and R. Similarly, from G the lower nodes picked can be traced by reversing the directed links and are F, B, A, and R. A graph that represents this modified partial order is no longer a DAG; it is termed an Almost DAG (ADAG) because if the links directed to the root were removed, it would be a DAG.

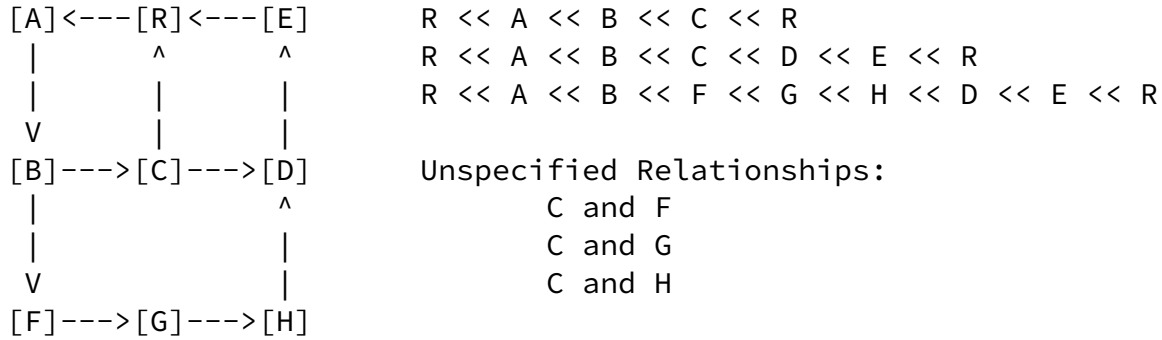


Figure 4: ADAG showing a Partial Order with R lowest and highest

Most importantly, if a node Y >> X, then Y can only appear on the increasing path from X to the root and never on the decreasing path. Similarly, if a node Z << X, then Z can only appear on the decreasing path from X to the root and never on the inceasing path.

Additionally, when following the increasing paths, it is possible to pick multiple higher nodes and still have the certainty that those paths will be disjoint from the decreasing paths. E.g. in the previous example node B has multiple possibilities to forward packets

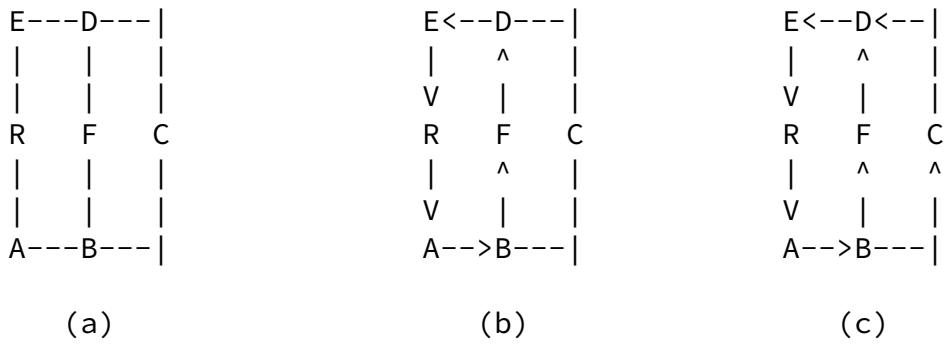
along an increasing path: it can either forward packets to C or F.

3.2. Finding an Ear and the Correct Direction

For simplicity, the basic idea of creating a GADAG by adding ears is described assuming that the network graph is a single 2-connected cluster so that an ADAG is sufficient. Generalizing to multiple blocks is done by considering the block-roots instead of the GADAG root - and the actual algorithms given in Section 4.3 and Section 4.4.

In order to understand the basic idea of finding an ADAG, first suppose that we have already a partial ADAG, which doesn't contain all the nodes in the block yet, and we want to extend it to cover all the nodes. Suppose that we find a path from a node X to Y such that X and Y are already contained by our partial ADAG, but all the remaining nodes along the path are not added to the ADAG yet. We refer to such a path as an ear.

Recall that our ADAG is closely related to a partial order, more precisely, if we remove root R, the remaining DAG describes a partial order of the nodes. If we suppose that neither X nor Y is the root, we may be able to compare them. If one of them is definitely lesser with respect to our partial order (say X<<Y), we can add the new path to the ADAG in a direction from X to Y. As an example consider Figure 5.



(a) A 2-connected graph
(b) Partial ADAG (C is not included)
(c) Resulting ADAG after adding path (or ear) B-C-D

Figure 5

In this partial ADAG, node C is not yet included. However, we can find path B-C-D, where both endpoints are contained by this partial ADAG (we say those nodes are *ready* in the sequel), and the remaining node (node C) is not contained yet. If we remove R, the remaining DAG defines a partial order, and with respect to this

partial order we can say that B<<D, so we can add the path to the ADAG in the direction from B to D (arcs B->C and C->D are added). If B were strictly greater than D, we would add the same path in reverse direction.

If in the partial order where an ear's two ends are X and Y, X << Y, then there must already be a directed path from X to Y already in the ADAG. The ear must be added in a direction such that it doesn't create a cycle; therefore the ear must go from X to Y.

In the case, when X and Y are not ordered with each other, we can select either direction for the ear. We have no restriction since neither of the directions can result in a cycle. In the corner case when one of the endpoints of an ear, say X, is the root (recall that the two endpoints must be different), we could use both directions again for the ear because the root can be considered both as smaller and as greater than Y. However, we strictly pick that direction in which the root is lower than Y. The logic for this decision is explained in Section 4.6

A partial ADAG is started by finding a cycle from the root R back to itself. This can be done by selecting a non-ready neighbor N of R and then finding a path from N to R that doesn't use any links between R and N. The direction of the cycle can be assigned either way since it is starting the ordering.

Once a partial ADAG is already present, we can always add ears to it: just select a non-ready neighbor N of a ready node Q, such that Q is not the root, find a path from N to the root in the graph with Q removed. This path is an ear where the first node of the ear is Q, the next is N, then the path until the first ready node the path reached (that second ready node is the other endpoint of the path). Since the graph is 2-connected, there must be a path from N to R without Q.

It is always possible to select a non-ready neighbor N of a ready node Q so that Q is not the root R. Because the network is 2-connected, N must be connected to two different nodes and only one can be R. Because the initial cycle has already been added to the ADAG, there are ready nodes that are not R. Since the graph is 2-connected, while there are non-ready nodes, there must be a non-ready neighbor N of a ready node that is not R.

```
Generic_Find_Ears_ADAG(root)
   Create an empty ADAG.  Add root to the ADAG.
   Mark root as IN_GADAG.
   Select the shortest cycle containing root.
   Add the shortest cycle to the ADAG.
   Mark cycle's nodes as IN_GADAG.
   Add cycle's non-root nodes to process_list.
   while there exists connected nodes in graph that are not IN_GADAG
      Select a new ear.  Let its endpoints be X and Y.
      if Y is root or (Y << X)
         add the ear towards X to the ADAG
      else // (a) X is root or (b)X << Y or (c) X, Y not ordered
         Add the ear towards Y to the ADAG
```

Figure 6: Generic Algorithm to find ears and their direction in 2-connected graph

Algorithm Figure 6 merely requires that a cycle or ear be selected without specifying how. Regardless of the way of selecting the path, we will get an ADAG. The method used for finding and selecting the ears is important; shorter ears result in shorter paths along the MRTs. There are two options being considered. The Low-Point Inheritance option is described in Section 4.3. The SPF-based option is described in Section 4.4.

As an example, consider Figure 5 again. First, we select the shortest cycle containing R, which can be R-A-B-F-D-E (uniform link costs were assumed), so we get to the situation depicted in Figure 5 (b). Finally, we find a node next to a ready node; that must be node C and assume we reached it from ready node B. We search a path from C to R without B in the original graph. The first ready node along this is node D, so the open ear is B-C-D. Since B<<D, we add arc B->C and C->D to the ADAG. Since all the nodes are ready, we stop at this point.

3.3. Low-Point Values and Their Uses

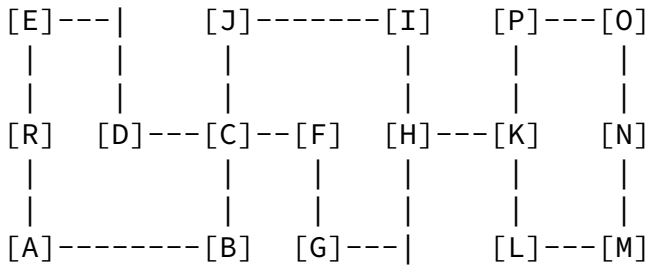
A basic way of computing a spanning tree on a network graph is to run a depth-first-search, such as given in Figure 7. This tree has the

important property that if there is a link (x, n), then either n is a DFS ancestor of x or n is a DFS descendant of x. In other words, either n is on the path from the root to x or x is on the path from the root to n.

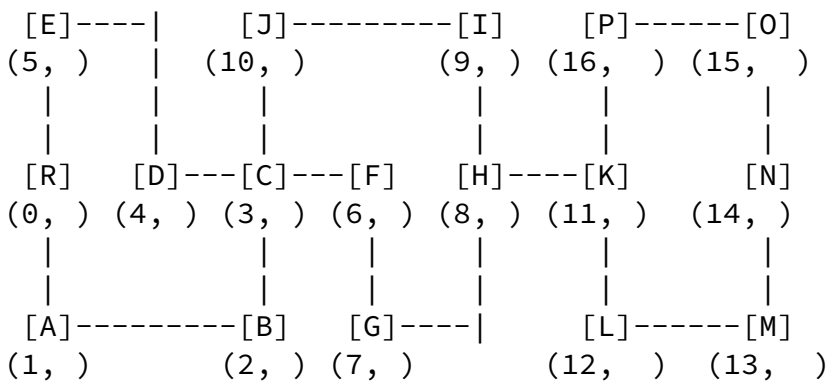

```
global_variable: dfs_number

DFS_Visit(node x, node parent)
   D(x) = dfs_number
   dfs_number += 1
   x.dfs_parent = parent
   for each link (x, w)
     if D(w) is not set
       DFS_Visit(w, x)

Run_DFS(node root)
   dfs_number = 0
   DFS_Visit(root, NONE)
```

Figure 7: Basic Depth-First Search algorithm

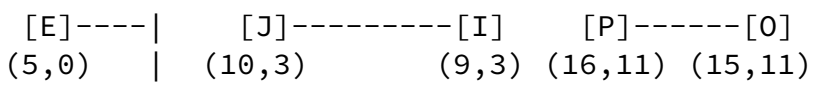
Given a node x, one can compute the minimal DFS number of the neighbours of x, i.e. min(D(w) if (x,w) is a link). This gives the highest attachment point neighbouring x. What is interesting, though, is what is the highest attachment point from x and x's descendants. This is what is determined by computing the Low-Point value, as given in Algorithm Figure 9 and illustrated on a graph in Figure 8.

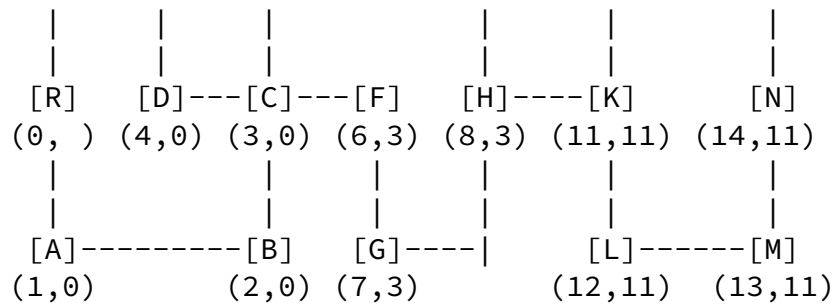


(a) a non-2-connected graph



(b) with DFS values assigned (D(x), L(x))





(c) with low-point values assigned (D(x), L(x))

Figure 8


```
global_variable: dfs_number

Lowpoint_Visit(node x, node parent, interface p_to_x)
   D(x) = dfs_number
   L(x) = D(x)
   dfs_number += 1
   x.dfs_parent = parent
   x.dfs_parent_intf = p_to_x
   x.lowpoint_parent = NONE
   for each interface intf of x:
     if D(intf.remote_node) is not set
       Lowpoint_Visit(intf.remote_node, x, intf)
       if L(intf.remote_node) < L(x)
          L(x) = L(intf.remote_node)
          x.lowpoint_parent = intf.remote_node
          x.lowpoint_parent_intf = intf
     else if intf.remote_node is not parent
       if D(intf.remote_node) < L(x)
```

```
                    L(x) = D(intf.remote)
                    x.lowpoint_parent = intf.remote_node
                    x.lowpoint_parent_intf = intf

            Run_Lowpoint(node root)
               dfs_number = 0
               Lowpoint_Visit(root, NONE, NONE)
```

Figure 9: Computing Low-Point value

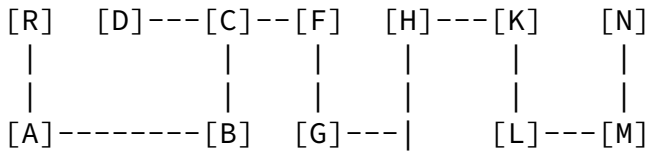
From the low-point value and lowpoint parent, there are two very useful things which motivate our computation.

First, if there is a child c of x such that L(c) >= D(x), then there are no paths in the network graph that go from c or its descendants to an ancestor of x - and therefore x is a cut-vertex. This is useful because it allows identification of the cut-vertices and thus the blocks. As seen in Figure 8, even if L(x) < D(x), there may be a block that contains both the root and a DFS-child of a node while other DFS-children might be in different blocks. In this example, C's child D is in the same block as R while F is not.

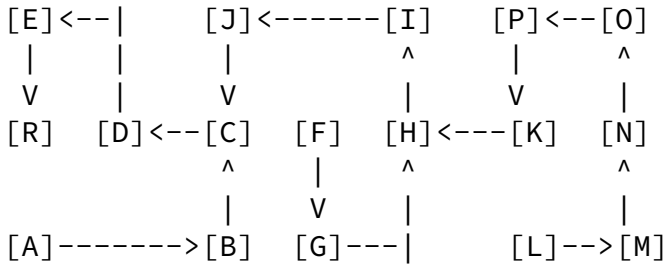
Second, by repeatedly following the path given by lowpoint_parent, there is a path from x back to an ancestor of x that does not use the link [x, x.dfs_parent] in either direction. The full path need not be taken, but this gives a way of finding an initial cycle and then ears.

3.4. Blocks in a Graph

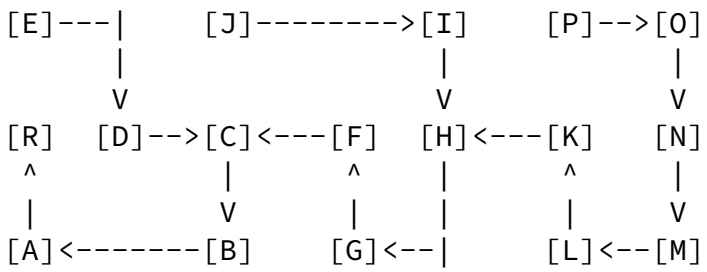
A key idea for the MRT algorithm is that any non-2-connected graph is made up by blocks (e.g. 2-connected clusters, cut-links, and/or isolated nodes). To compute GADAGs and thus MRTs, computation is done in each block to compute ADAGs or Redundant Trees and then those ADAGs or Redundant Trees are combined into a GADAG or MRT.



(a) A graph with four blocks that are:
3 2-connected clusters and a cut-link



(b) Blue MRT



(c) Red MRT

Figure 10

Consider the example depicted in Figure 10 (a). In this figure, a special graph is presented, showing us all the ways 2-connected clusters can be connected. It has four blocks: block 1 contains R, A, B, C, D, E, block 2 contains C, F, G, H, I, J, block 3 contains K,

L, M, N, O, P, and block 4 is a cut-edge containing H and K. As can be observed, the first two blocks have one common node (node C) and blocks 2 and 3 do not have any common node, but they are connected through a cut-edge that is block 4. No two blocks can have more than

one common node, since two blocks with at least 2 common nodes would qualify as a single 2-connected cluster.

Moreover, observe that if we want to get from one block to another, we must use a cut-vertex (the cut-vertices in this graph are C, H, K), regardless of the path selected, so we can say that all the paths from block 3 along the MRTs rooted at R will cross K first. This observation means that if we want to find a pair of MRTs rooted at R, then we need to build up a pair of RTs in block 3 with K as a root. Similarly, we need to find another one in block 2 with C as a root, and finally, we need the last one in block 1 with R as a root. When all the trees are selected, we can simply combine them; when a block is a cut-edge (as in block 4), that cut-edge is added in the same direction to both of the trees. The resulting trees are depicted in Figure 10 (b) and (c).

Similarly, to create a GADAG it is sufficient to compute ADAGs in each block and connect them.

It is necessary, therefore, to identify the cut-vertices, the blocks and identify the appropriate local-root to use for each block.

3.5. Determining Local-Root

Each node in a network graph has a local-root, which is the cut-vertex (or root) in the same block that is closest to the root. The local-root is used to determine whether two nodes share a common block.

```
Compute_Localroot(node x, node localroot)
    x.localroot = localroot
    for each DFS child c
        if L(c) < D(x)   //x is not a cut-vertex
            Compute_Localroot(c, x.localroot)
        else
            mark x as cut-vertex
            Compute_Localroot(c, x)

Compute_Localroot(root, root)
```

Figure 11: A method for computing local-roots

There are two different ways of computing the local-root for each node. The stand-alone method is given in Figure 11 and better

illustrates the concept. It is used in the second option for computing a GADAG using SPFs. The other method is used in the first option for computing a GADAG using Low-Point inheritance and the essence of it is given in Figure 12.

```
            Get the current node, s.
            Compute an ear from s to a child c
               and then via lowpoint inheritance, e.g.
                 ( n = c
                   while n is not ready:
                      n = n.lowpoint_parent
                   e = n
                  )
                 to a ready node e.
            if s is e
               s is a cut-vertex
               x.localroot = s
            else
               for each node x in the ear that is not s or e
                   x.localroot = s.localroot
```

Figure 12: Ear-based method for computing local-roots

Once the local-roots are known, two nodes X and Y are in a common block if and only if one of the following three conditions apply.

- Y's local-root is X's local-root : They are in the same block and neither is the cut-vertex closest to the root.
- Y's local-root is X: X is the cut-vertex closest to the root for Y's block
- Y is X's local-root: Y is the cut-vertex closest to the root for X's block

4. Algorithm Sections

This algorithm computes one GADAG that is then used by a router to determine its blue MRT and red MRT next-hops to all destinations. Finally, based upon that information, alternates are selected for each next-hop to each destination. The different parts of this algorithm are described below. These work on a network graph after, for instance, its interfaces are ordered as per Figure 13.

1. Select the root to use for the GADAG. [See Section 4.1.]

2. Initialize all interfaces to UNDIRECTED. [See Section 4.2.]

3. Compute the DFS value,e.g. D(x), and lowpoint value, L(x). [See Figure 9.]

4. Construct the GADAG. [See Section 4.3 for Option 1 using Lowpoint Inheritance and Section 4.4 for Option 2 using SPFs.]

5. Assign directions to all interfaces that are still UNDIRECTED. [See Section 4.5.]

6. From the computing router x, compute the next-hops for the blue MRT and red MRT. [See Section 4.6.]

7. Identify alternates for each next-hop to each destination by determining which one of the blue MRT and the red MRT the computing router x should select. [See Section 4.7.]

To ensure consistency in computation, it is necessary that all routers order interfaces identically. This is necessary for the DFS, where the selection order of the interfaces to explore results in different trees, and for computing the GADAG, where the selection order of the interfaces to use to form ears can result in different GADAGs. The recommended ordering between two interfaces from the same router x is given in Figure 13.

```
 Interface_Compare(interface a, interface b)
   if a.metric < b.metric
      return A_LESS_THAN_B
   if b.metric < a.metric
      return B_LESS_THAN_A
   if a.neighbor.loopback_addr < b.neighbor.loopback_addr
      return A_LESS_THAN_B
   if b.neighbor.loopback_addr < a.neighbor.loopback_addr
      return B_LESS_THAN_A
   // Same metric to same node, so the order doesn't matter anymore.
   // To have a unique, consistent total order,
   // tie-break based on ifindex.
   if a.ifindex < b.ifindex
      return A_LESS_THAN_B
```

```
   return B_LESS_THAN_A
```

Figure 13: Rules for ranking multiple interfaces. Order is from low to high.

4.1. Root Selection

The precise mechanism by which routers advertise a priority for the GADAG root is not described in this document. Nor is the algorithm for selecting routers based upon priority described in this document.

A network may be partitioned or there may be islands of routers that support MRT fast-reroute. Therefore, the root selected for use in a GADAG must be consistent only across each connected island of MRT fast-reroute support. Before beginning computation, the network graph is reduced to contain only the set of routers that support a compatible MRT fast-reroute.

The selection of a GADAG root is done among only those routers in the same MRT fast-reroute island as the computing router x. Additionally, only routers that are not marked as unusable or overloaded (e.g. ISIS overload or [RFC3137]) are eligible for selection as root.

4.2. Initialization

Before running the algorithm, there is the standard type of initialization to be done, such as clearing any computed DFS-values, lowpoint-values, DFS-parents, lowpoint-parents, any MRT-computed next-hops, and flags associated with algorithm.

It is assumed that a regular SPF computation has been run so that the primary next-hops from the computing router to each destination are known. This is required for determining alternates at the last step.

Initially, all interfaces must be initialized to UNDIRECTED. Whether they are OUTGOING, INCOMING or both is determined when the GADAG is constructed and augmented.

It is possible that some links and nodes will be marked as unusable, whether because of configuration, overload, or due to a transient cause such as [RFC3137]. In the algorithm description, it is assumed that such links and nodes will not be explored or used and no more disussion is given of this restriction.

4.3. Option 1: Computing GADAG using lowpoint inheritance

The basic idea of this is to find ears from a node x that is already in the GADAG (known as IN_GADAG). There are two methods to find ears; both are required. The first is by going to a not IN_GADAG DFS-child and then following the chain of low-point parents until an IN_GADAG node is found. The second is by going to a not IN_GADAG neighbor and then following the chain of DFS parents until an

IN_GADAG node is found. As an ear is found, the associated interfaces are marked based on the direction taken. The nodes in the ear are marked as IN_GADAG. In the algorithm, first the ears via DFS-children are found and then the ears via DFS-neighbors are found.

By adding both types of ears when an IN_GADAG node is processed, all ears that connect to that node are found. The order in which the IN_GADAG nodes is processed is, of course, key to the algorithm. The order is a stack of ears so the most recent ear is found at the top of the stack. Of course, the stack stores nodes and not ears, so an ordered list of nodes, from the first node in the ear to the last node in the ear, is created as the ear is explored and then that list is pushed onto the stack.

Each ear represents a partial order (see Figure 4) and processing the nodes in order along each ear ensures that all ears connecting to a node are found before a node higher in the partial order has its ears explored. This means that the direction of the links in the ear is always from the node x being processed towards the other end of the ear. Additionally, by using a stack of ears, this means that any unprocessed nodes in previous ears can only be ordered higher than nodes in the ears below it on the stack.

In this algorithm that depends upon Low-Point inheritance, it is necessary that every node have a low-point parent that is not itself. If a node is a cut-vertex, that will not yet be the case. Therefore,

any nodes without a low-point parent will have their low-point parent set to their DFS parent and their low-point value set to the DFS-value of their parent. This assignment also properly allows an ear to a cut-vertex to start and end at the same node.

Finally, the algorithm simultaneously computes each node's local-root, as described in Figure 12. The local-root can be inherited from the node x being processed to the nodes in the ear unless the child of x is a cut-vertex in which case the rest of the nodes in the ear are in a different block than x and have the child of x as their local-root.


```
            Construct_GADAG_via_Lowpoint(topology, root)
              root.IN_GADAG = true
              Initialize Stack to empty
              push root onto Stack
              while (Stack is not empty)
                 x = pop(Stack)
                 foreach interface intf of x
                    if ((intf.remote_node.IN_GADAG == false) and
                        (intf.remote_node.dfs_parent is x))
                        Construct_Ear(x, Stack, intf, CHILD)
                 foreach interface intf of x
                    if ((intf.remote_node.IN_GADAG == false) and
                        (intf.remote_node.dfs_parent is not x))
                        Construct_Ear(x, Stack, intf, NEIGHBOR)

            Construct_Ear(x, Stack, intf, type)
               ear_list = empty
               cur_node = intf.remote_node
               cur_intf = intf
```

```
            not_done = true

            while not_done
               cur_intf.UNDIRECTED = false
               cur_intf.OUTGOING = true
               cur_intf.remote_intf.UNDIRECTED = false
               cur_intf.remote_intf.INCOMING = true

               if cur_node.IN_GADAG is false
                  cur_node.IN_GADAG = true
                  add_to_list_end(ear_list, cur_node)
                  if type is CHILD
                     cur_intf = cur_node.lowpoint_parent_intf
                  else type must be NEIGHBOR
                     cur_intf = cur_node.dfs_parent_intf
                  cur_node = cur_intf.remote_node
               else
                  not_done = false

            if (type is CHILD) and (cur_node is x)
               localroot = x
            else
               localroot = x.localroot
            while ear_list is not empty
               y = remove_end_item_from_list(ear_list)
               push(Stack, y)

         Construct_GADAG_via_Lowpoint(topology, root)
```


Figure 14: Low-point Inheritance GADAG algorithm

4.4. Option 2: Computing GADAG using SPFs

The basic idea in this option is to use slightly-modified SPF computations to find ADAGs in each block. In each block, an SPF computation is first done to find a cycle from the local root and then SPF computations find ears until there are no more interfaces to be explored. The used result from the SPF computation is the path of interfaces indicated by following the previous hops from the mininized IN_GADAG node back to the SPF root.

To do this, first all cut-vertices must be identified and local-roots assigned as specified in Figure 11

The slight modifications to the SPF are as follows. The root of the block is referred to as the block-root; it is either the GADAG root or a cut-vertex.

a. The SPF is rooted at a neighbor x of an IN_GADAG node y. All links between y and x are marked as TEMP_UNUSABLE. They should not be used during the SPF computation.

b. If y is not the block-root, then it is marked TEMP_UNUSABLE. It should not be used during the SPF computation. This prevents ears from starting and ending at the same node and avoids cycles; the exception is because cycles to/from the block-root are acceptable and expected.

c. Do not explore links to nodes whose local-root is not the block-root. This keeps the SPF confined to the particular block.

d. Terminate when the first IN_GADAG node z is minimized.

e. Respect the existing directions (e.g. INCOMING, OUTGOING, UNDIRECTED) already specified for each interface.


```
Mod_SPF(spf_root, block_root)
   Initialize spf_heap to empty
   Initialize nodes' spf_metric to infinity
   spf_root.spf_metric = 0
   insert(spf_heap, spf_root)
```

```
        found_in_gadag = false
        while (spf_heap is not empty) and (found_in_gadag is false)
            min_node = remove_lowest(spf_heap)
            if min_node.IN_GADAG is true
               found_in_gadag = true
            else
               foreach interface intf of min_node
                  if ((intf.OUTGOING or intf.UNDIRECTED) and
                      ((intf.remote_node.localroot is block_root) or
                       (intf.remote_node is block_root)) and
                      (intf.remote_node is not TEMP_UNUSABLE) and
                      (intf is not TEMP_UNUSABLE))
                     path_metric = min_node.spf_metric + intf.metric
                     if path_metric < intf.remote_node.spf_metric
                        intf.remote_node.spf_metric = path_metric
                        intf.remote_node.spf_prev_intf = intf
                        insert_or_update(spf_heap, intf.remote_node)
        return min_node

     SPF_for_Ear(spf_root, block_root, ear_list, cut_vertex_list)
        end_ear = Mod_SPF(spf_root, block_root)
        y = end_ear.spf_prev_hop
        while y.local_node is not spf_root
          add_to_list_start(ear_list, y)
          if y.local_node is a cut-vertex
             add_to_list_end(cut_vertex_list, y.local_node)
          y = y.local_node.spf_prev_intf
```

Figure 15: Modified SPF for GADAG computation

In Figure 15, while the path is determined, any non-end node in the path that is a cut-vertex is added to the list of cut-vertices. This ensures that there is a path from the GADAG root to that cut-vertex before adding it to the list of nodes. All such cut-vertices will be treated as the root of a block and the ADAG in that block will be computed.

Assume that an ear is found by going from y to x and then running an SPF that terminates by minimizing z (e.g. y<->x...q<->z). Now it is necessary to determine the direction of the ear; if y << z, then the path should be y->x...q->z but if y >> z, then the path should be y<-x...q<-z. In Section 4.3, the same problem was handled by finding

all ears that started at a node before looking at ears starting at nodes higher in the partial order. In this algorithm, using that approach could mean that new ears aren't added in order of their total cost since all ears connected to a node would need to be found before additional nodes could be found.

The alternative is to track the order relationship of each node with respect to every other node. This can be accomplished by maintaining two sets of nodes at each node. The first set, Higher_Nodes, contains all nodes that are known to be ordered above the node. The second set, Lower_Nodes, contains all nodes that are known to be ordered below the node. This is the approach used in this algorithm.

```
      Set_Ear_Direction(ear_list, end_a, end_b, block_root)
        // Default of A_TO_B for the following cases:
        //  (a) end_a and end_b are the same (root)
        // or (b) end_a is in end_b's Lower Nodes
        // or (c) end_a and end_b were unordered with respect to each
        //        other
        direction = A_TO_B
        if (end_b is block_root) and (end_a is not end_b)
           direction = B_TO_A
        else if end_a is in end_b.Higher_Nodes
           direction = B_TO_A
        if direction is B_TO_A
           foreach interface i in ear_list
               i.UNDIRECTED = false
               i.INCOMING = true
               i.remote_intf.UNDIRECTED = false
               i.remote_intf.OUTGOING = true
        else
           foreach interface i in ear_list
               i.UNDIRECTED = false
               i.OUTGOING = true
               i.remote_intf.UNDIRECTED = false
               i.remote_intf.INCOMING = true
         if end_a is end_b
            return
         // Next, update all nodes' Lower_Nodes and Higher_Nodes
         if (end_a is in end_b.Higher_Nodes)
            foreach node x where x.localroot is block_root
                if end_a is in x.Lower_Nodes
                   foreach interface i in ear_list
                      add i.remote_node to x.Lower_Nodes
                if end_b is in x.Higher_Nodes
                   foreach interface i in ear_list
                      add i.local_node to x.Higher_Nodes
          else
            foreach node x where x.localroot is block_root
                if end_b is in x.Lower_Nodes
                   foreach interface i in ear_list
                      add i.local_node to x.Lower_Nodes
                if end_a is in x.Higher_Nodes
                   foreach interface i in ear_list
                      add i.remote_node to x.Higher_Nodes
```

Figure 16: Algorithm to assign links of an ear direction

A goal of the algorithm is to find the shortest cycles and ears. An ear is started by going to a neighbor x of an IN_GADAG node y. The path from x to an IN_GADAG node is minimal, since it is computed via

SPF. Since a shortest path is made of shortest paths, to find the shortest ears requires reaching from the set of IN_GADAG nodes to the closest node that isn't IN_GADAG. Therefore, an ordered tree is maintained of interfaces that could be explored from the IN_GADAG nodes. The interfaces are ordered by their characteristics of metric, local loopback address, remote loopback address, and ifindex, as in the algorithm previously described in Figure 13.

Finally, cut-edges are a special case because there is no point in doing an SPF on a block of 2 nodes. The algorithm identifies cut-edges simply as links where both ends of the link are cut-vertices. Cut-edges can simply be added to the GADAG with both OUTGOING and INCOMING specified on their interfaces.

```
    Construct_GADAG_via_SPF(topology, root)
       Compute_Localroot(root, root)
       if root has multiple DFS-children
          mark root as a cut-vertex
       Initialize cut_vertex_list to empty
       Initialize ordered_intfs_tree to empty
       add_to_list_end(cut_vertex_list, root)
       while cut_vertex_list is not empty
          v = remove_start_item_from_list(cut_vertex_list)
          foreach interface intf of v
             if L(intf.remote_node) == D(intf.remote_node)
                // Special case for cut-edges
                intf.UNDIRECTED = false
                intf.remote_intf.UNDIRECTED = false
                intf.OUTGOING = true
                intf.INCOMING = true
                intf.remote_intf.OUTGOING = true
                intf.remote_intf.INCOMING = true
                if intf.remote_node.IN_GADAG == false
                   if intf.remote_node is a cut-vertex
                     add_to_list_end(cut_vertex_list, intf.remote_node)
                   intf.remote_node.IN_GADAG = true
             else if intf.remote_node.localroot is v
                insert(ordered_intfs_tree, intf)
          v.IN_GADAG = true
          while ordered_intfs_trees is not empty
            cand_intf = remove_lowest(ordered_intfs_tree)
            if cand_intf.remote_node.IN_GADAG is false
```

```
Mark all interfaces between cand_intf.remote_node
   and cand_intf.local_node as TEMP_UNUSABLE
if cand_intf.local_node is not v
   Mark cand_intf.local_node as TEMP_UNUSABLE
Initialize ear_list to empty
ear_end = SPF_for_Ear(cand_intf.remote_node, v, ear_list,
          cut_vertex_list)
add_to_list_start(ear_list, cand_intf)
Set_Ear_Direction(ear_list, cand_intf.remote, ear_end, v)
Clear TEMP_UNUSABLE from all interfaces between
   cand_intf.remote_node and cand_intf.local_node
Clear TEMP_UNUSABLE from cand_intf.local_node
```

Figure 17: SPF-based GADAG algorithm

4.5. Augmenting the GADAG by directing all links

The GADAG, whether constructed via Low-Point Inheritance or with SPFs, at this point could be used to find MRTs but the topology does not include all links in the network graph. That has two impacts. First, there might be shorter paths that respect the GADAG partial ordering and so the alternate paths would not be as short as possible. Second, there may be additional paths between a router x and the root that are not included in the GADAG. Including those provides potentially more bandwidth to traffic flowing on the alternates and may reduce congestion compared to just using the GADAG as currently constructed.

The goal is thus to assign direction to every remaining link marked as UNDIRECTED to improve the paths and number of paths found when the MRTs are computed.

To do this, we need to establish a total order that respects the partial order described by the GADAG. This can be done using Kahn's topological sort[Kahn_1962_topo_sort] which essentially assigns a number to a node x only after all nodes before it (e.g. with a link

incoming to x) have had their numbers assigned. The only issue with the topological sort is that it works on DAGs and not ADAGs or GADAGs.

To convert a GADAG to a DAG, it is necessary to remove all links that point to a root of block from within that block. That provides the necessary conversion to a DAG and then a topological sort can be done. Finally, all UNDIRECTED links are assigned a direction based upon the partial ordering. Any UNDIRECTED links that connect to a root of a block from within that block are assigned a direction INCOMING to that root. The exact details of this whole process are captured in Figure 18

```
Set_Block_Root_Incoming_Links(topo, root, mark_or_clear)
   foreach node x in topo
      if node x is a cut-vertex or root
         foreach interface i of x
            if (i.remote_node.localroot is x)
               if i.UNDIRECTED
                  i.OUTGOING = true
                  i.remote_intf.INCOMING = true
                  i.UNDIRECTED = false
                  i.remote_intf.UNDIRECTED = false
               if i.INCOMING
                  if mark_or_clear is mark
                     if i.OUTGOING  // a cut-edge
```



```
                        i.STORE_INCOMING = true
                        i.INCOMING = false
                        i.remote_intf.STORE_OUTGOING = true
                        i.remote_intf.OUTGOING = false
                     i.TEMP_UNUSABLE = true
                     i.remote_intf.TEMP_UNUSABLE = true
                  else
                     i.TEMP_UNUSABLE = false
                     i.remote_intf.TEMP_UNUSABLE = false
               if i.STORE_INCOMING and (mark_or_clear is clear)
                  i.INCOMING = true
                  i.STORE_INCOMING = false
                  i.remote_intf.OUTGOING = true
                  i.remote_intf.STORE_OUTGOING = false
```

```
Run_Topological_Sort_GADAG(topo, root)
   Set_Block_Root_Incoming_Links(topo, root, MARK)
   foreach node x
     set x.unvisited to the count of x's incoming interfaces
        that aren't marked TEMP_UNUSABLE
   Initialize working_list to empty
   Initialize topo_order_list to empty
   add_to_list_end(working_list, root)
   while working_list is not empty
      y = remove_start_item_from_list(working_list)
      add_to_list_end(topo_order_list, y)
      foreach interface i of y
          if (i.OUTGOING) and (not i.TEMP_UNUSABLE)
             i.remote_node.unvisited -= 1
             if i.remote_node.unvisited is 0
                 add_to_list_end(working_list, i.remote_node)
    next_topo_order = 1
    while topo_order_list is not empty
        y = remove_start_item_from_list(topo_order_list)
        y.topo_order = next_topo_order
        next_topo_order += 1
    Set_Block_Root_Incoming_Links(topo, root, CLEAR)

Add_Undirected_Links(topo, root)
    Run_Topological_Sort_GADAG(topo, root)
    foreach node x in topo
      foreach interface i of x
         if i.UNDIRECTED
           if x.topo_order < i.remote_node.topo_order
              i.OUTGOING = true
              i.UNDIRECTED = false
              i.remote_intf.INCOMING = true
              i.remote_intf.UNDIRECTED = false
```



```
              else
                 i.INCOMING = true
                 i.UNDIRECTED = false
                 i.remote_intf.OUTGOING = true
                 i.remote_intf.UNDIRECTED = false

Add_Undirected_Links(topo, root)
```

Figure 18: Assigning direction to UNDIRECTED links

Proxy-nodes are used to represent multi-homed prefixes and routers that do not support MRT Fast-Reroute. Until now, the network graph has not included proxy-nodes because the computation for a GADAG assumes that the nodes can be transited.

To handle destinations that can only be reached via proxy-nodes, each proxy-node should be added into the network graph after Add_Directed_Links() has beeen run once. A proxy-node P is connected to two routers, X and Y, which have been found to offer the best cost. If X.topo_order < Y.topo_order, then the proxy-node P is added along with a link X->P and a link P->Y. Once all the proxy-nodes have been added in this fashion, Run_Topological_Sort_GADAG() should be rerun so that the topological order includes the proxy-nodes as well. This is needed for determining which MRT can offer alternates, as is explained in Section 4.7.

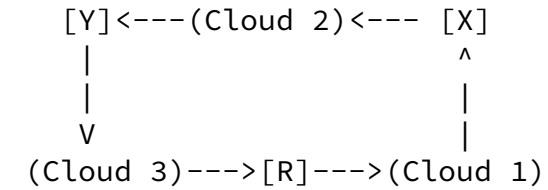
4.6. Compute MRT next-hops

As was discussed in Section 3.1, once a ADAG is found, it is straightforward to find the next-hops from any node X to the ADAG root. However, in this algorithm, we want to reuse the common GADAG and find not only one pair of redundant trees with it, but a pair rooted at each node. This is ideal, since it is faster and it results packet forwarding easier to trace and/or debug. The method for doing that is based on two basic ideas. First, if two nodes X and Y are ordered with respect to each other in the partial order, then the same SPF and reverse-SPF can be used to find the increasing and decreasing paths. Second, if two nodes X and Y aren't ordered with respect to each other in the partial order, then intermediary nodes can be used to create the paths by increasing/decreasing to the intermediary and then decreasing/increasing to reach Y.

As usual, the two basic ideas will be discussed assuming the network is two-connected. The generalization to multiple blocks is discussed in Section 4.6.4. The full algorithm is given in Section 4.6.5.

4.6.1. MRT next-hops to all nodes partially ordered with respect to the computing node

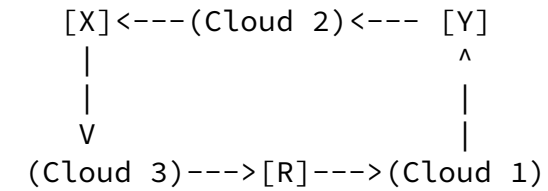
To find two node-disjoint paths from the computing router X to any node Y, depends upon whether Y >> X or Y << X. As shown in Figure 19, if Y >> X, then there is an increasing path that goes from X to Y without crossing R; this contains nodes in the interval [X,Y]. There is also a decreasing path that decreases towards R and then decreases from R to Y; this contains nodes in the interval [X,R-small] or [R-great,Y]. The two paths cannot have common nodes other than X and Y.



Blue MRT path: X->Cloud 2->Y
Red MRT path: X->Cloud 1->R->Cloud 3->Y

Figure 19: Y >> X

Similar logic applies if Y << X, as shown in Figure 20. In this case, the increasing path from X increases to R and then increases from R to Y to use nodes in the intervals [X,R-great] and [R-small, Y]. The decreasing path from X reaches Y without crossing R and uses nodes in the interval [Y,X].



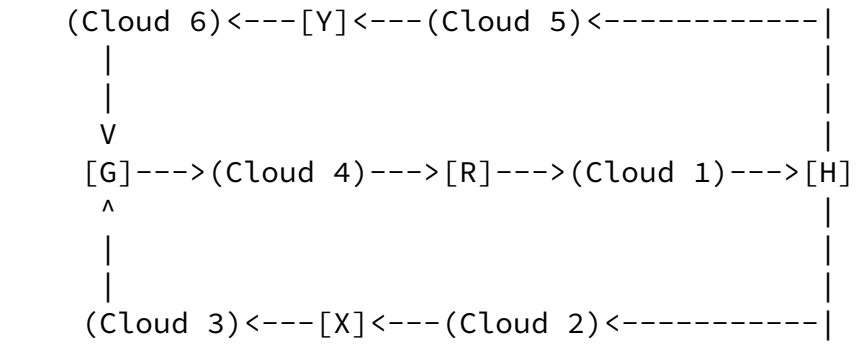
Blue MRT path: X->Cloud 3->R->Cloud 1->Y
Red MRT path: X->Cloud 2->Y

Figure 20: Y << X

4.6.2. MRT next-hops to all nodes not partially ordered with respect to the computing node

When X and Y are not ordered, the first path should increase until we get to a node G, where G >> Y. At G, we need to decrease to Y. The other path should be just the opposite: we must decrease until we get

to a node H, where H << Y, and then increase. Since R is smaller and greater than Y, such G and H must exist. It is also easy to see that these two paths must be node disjoint: the first path contains nodes in interval [X,G] and [Y,G], while the second path contains nodes in interval [H,X] and [H,Y]. This is illustrated in Figure 21. It is necessary to decrease and then increase for the Blue MRT and increase and then decrease for the Red MRT; if one simply increased for one and decreased for the other, then both paths would go through the root R.



Blue MRT path: decrease to H and increase to Y
X->Cloud 2->H->Cloud 5->Y
Red MRT path: increase to G and decrease to Y
X->Cloud 3->G->Cloud 6->Y

Figure 21: X and Y unordered

This gives disjoint paths as long as G and H are not the same node. Since G >> Y and H << Y, if G and H could be the same node, that would have to be the root R. This is not possible because there is only one incoming interface to the root R which is created when the initial cycle is found. Recall from Figure 6 that whenever an ear was found to have an end that was the root R, the ear was directed from R so that the associated interface on R is outgoing and not incoming. Therefore, there must be exactly one node M which is the largest one before R, so the Red MRT path will never reach R; it will turn at M and decrease to Y.

4.6.3. Computing Redundant Tree next-hops in a 2-connected Graph

The basic ideas for computing RT next-hops in a 2-connected graph were given in Section 4.6.1 and Section 4.6.2. Given these two

ideas, how can we find the trees?

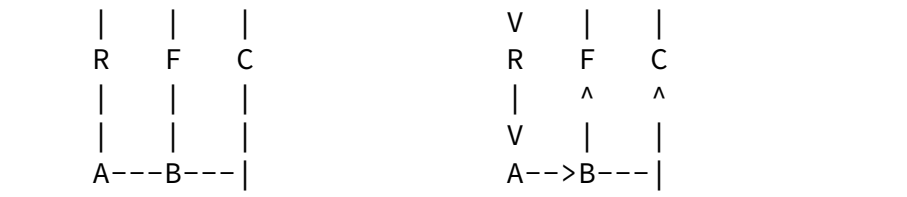
If some node X only wants to find the next-hops (which is usually the case for IP networks), it is enough to find which nodes are greater and less than X, and which are not ordered; this can be done by

running an SPF and a reverse-SPF rooted at X and not exploring any links from the ADAG root. (Other traversal algorithms could safely be used instead where one traversal takes the links in their given directions and the other reverses the links' directions.)

An SPF rooted at X and not exploring links from the root will find the increasing next-hops to all Y >> X. Those increasing next-hops are X's next-hops on the Blue MRT to reach Y. A reverse-SPF rooted at X and not exploring links from the root will find the decreasing next-hops to all Z << X. Those decreasing next-hops are X's next-hops on the Red MRT to reach Z. Since the root R is both greater than and less than X, after this SPF and reverse-SPF, X's next-hops on the Blue MRT and on the Red MRT to reach R are known. For every node Y >> X, X's next-hops on the Red MRT to reach Y are set to those on the Red MRT to reach R. For every node Z << X, X's next-hops on the Blue MRT to reach Z are set to those on the Blue MRT to reach R.

For those nodes, which were not reached, we have the next-hops as well. The increasing Blue MRT next-hop for a node, which is not ordered, is the next-hop along the decreasing Red MRT towards R and the decreasing Red MRT next-hop is the next-hop along the increasing Blue MRT towards R. Naturally, since R is ordered with respect to all the nodes, there will always be an increasing and a decreasing path towards it. This algorithm does not provide the specific path taken but only the appropriate next-hops to use. The identity of G and H is not determined.

The final case to considered is when the root R computes its own next-hops. Since the root R is << all other nodes, running an SPF rooted at R will reach all other nodes; the Blue MRT next-hops are those found with this SPF. Similarly, since the root R is >> all other nodes, running a reverse-SPF rooted at R will reach all other nodes; the Red MRT next-hops are those found with this reverse-SPF.



(a) A 2-connected graph (b) A spanning ADAG rooted at R

Figure 22

As an example consider the situation depicted in Figure 22. There

node C runs an SPF and a reverse-SPF The SPF reaches D, E and R and the reverse SPF reaches B, A and R. So we immediately get that e.g. towards E the increasing next-hop is D (it was reached though D), and the decreasing next-hop is B (since R was reached though B). Since both D and B, A and R will compute the next hops similarly, the packets will reach E.

We have the next-hops towards F as well: since F is not ordered with respect to C, the increasing next-hop is the decreasing one towards R (which is B) and the decreasing next-hop is the increasing one towards R (which is D). Since B is ordered with F, it will find a real increasing next-hop, so packet forwarded to B will get to F on path C-B-F. Similarly, D will have a real decreasing next-hop, and packet will use path C-D-F.

4.6.4. Generalizing for graph that isn't 2-connected

If a graph isn't 2-connected, then the basic approach given in Section 4.6.3 needs some extensions to determine the appropriate MRT next-hops to use for destinations outside the computing router X's blocks. In order to find a pair of maximally redundant trees in that graph we need to find a pair of RTs in each of the blocks (the root of these trees will be discussed later), and combine them.

When computing the MRT next-hops from a router X, there are three basic differences:

1. Only nodes in a common block with X should be explored in the SPF and reverse-SPF.

2. Instead of using the GADAG root, X's local-root should be used. This has the following implications:

   A. The links from X's local-root should not be explored.

   B. If a node is explored in the increasing SPF so Y >> X, then X's Red MRT next-hops to reach Y uses X's Red MRT next-hops to reach X's local-root and if Z <<, then X's Blue MRT next-hops to reach Z uses X's Blue MRT next-hops to reach X's local-root.

   C. If a node W in a common block with X was not reached in the SPF or reverse-SPF, then W is unordered with respect to X. X's Blue MRT next-hops to W are X's decreasing aka Red MRT next-hops to X's local-root. X's Red MRT next-hops to W are X's increasing aka Blue MRT next-hops to X's local-root.

3. For nodes in different blocks, the next-hops must be inherited via the relevant cut-vertex.

These are all captured in the detailed algorithm given in Section 4.6.5.

4.6.5. Complete Algorithm to Compute MRT Next-Hops

The complete algorithm to compute MRT Next-Hops for a particular router X is given in Figure 23. In addition to computing the Blue MRT next-hops and Red MRT next-hops used by X to reach each node Y, the algorithm also stores an "order_proxy", which is the proper cut-vertex to reach Y if it is outside the block, and which is used later in deciding whether the Blue MRT or the Red MRT can provide an acceptable alternate for a particular primary next-hop.

```
 global_var: max_block_id

 Assign_Block_ID(x, cur_block_id)
   x.block_id = cur_block_id
   foreach DFS child c of x
      if (c.local_root is x)
```

```
            max_block_id += 1
            Assign_Block_ID(c, max_block_id)
          else
            Assign_Block_ID(c, cur_block_id)

    In_Common_Block(x, y)
      if ((x.localroot is y.localroot) or (x is y.localroot) or
          (y is x.localroot))
        return true
      return false

    Store_Results(y, direction, spf_root, store_nhs)
       if direction is FORWARD
          y.higher = true
          if store_nhs
             y.blue_next_hops = y.next_hops
       if direction is REVERSE
          y.lower = true
          if store_nhs
             y.red_next_hops = y.next_hops

    SPF_No_Traverse_Root(spf_root, block_root, direction, store_nhs)
       Initialize spf_heap to empty
       Initialize nodes' spf_metric to infinity and next_hops to empty
       spf_root.spf_metric = 0
       insert(spf_heap, spf_root)
```



```
       while (spf_heap is not empty)
           min_node = remove_lowest(spf_heap)
           Store_Results(min_node, direction, spf_root, store_nhs)
           if ((min_node is spf_root) or
               ((min_node is not block_root) and
                (min_node is not a proxy_node)))
              foreach interface intf of min_node
                 if (((direction is FORWARD) and intf.OUTGOING) or
                     ((direction is REVERSE) and intf.INCOMING)  and
                     In_Common_Block(spf_root, intf.remote_node))
                    if direction is FORWARD
                       path_metric = min_node.spf_metric + intf.metric
                    else
                       path_metric = min_node.spf_metric +
                                     intf.remote_intf.metric
```

```
                    if path_metric < intf.remote_node.spf_metric
                       intf.remote_node.spf_metric = path_metric
                       if min_node is spf_root
                         intf.remote_node.next_hops = make_list(intf)
                       else
                         intf.remote_node.next_hops = min_node.next_hops
                       insert_or_update(spf_heap, intf.remote_node)
                    else if path_metric is intf.remote_node.spf_metric
                       if min_node is spf_root
                          add_to_list(intf.remote_node.next_hops, intf)
                       else
                          add_list_to_list(intf.remote_node.next_hops,
                                           min_node.next_hops)

    SetEdge(y)
      if y.blue_next_hops is empty and y.red_next_hops is empty
        SetEdge(y.localroot)
        y.blue_next_hops = y.localroot.blue_next_hops
        y.red_next_hops = y.localroot.red_next_hops
        y.order_proxy = y.localroot.order_proxy

    Compute_MRT_NextHops(x, root)
       foreach node y
         y.higher = y.lower = false
         clear y.red_next_hops and y.blue_next_hops
         y.order_proxy = y
       SPF_No_Traverse_Root(x, x.localroot, FORWARD, TRUE)
       SPF_No_Traverse_Root(x, x.localroot, REVERSE, TRUE)

       // red and blue next-hops are stored to x.localroot as different
       // paths are found via the SPF and reverse-SPF.
       // Similarly any nodes whose local-root is x will have their
       // red_next_hops and blue_next_hops already set.
```



```
       // Handle nodes in the same block that aren't the local-root
       foreach node y
         if ((y is not x) and (y.localroot is x.localroot) and
             ((y is x.localroot) or (y.block_id is x.block_id))
           if y.higher
              y.red_next_hops = x.localroot.red_next_hops
           else if y.lower
              y.blue_next_hops = x.localroot.blue_next_hops
```

```
            else
               y.blue_next_hops = x.localroot.red_next_hops
               y.red_next_hops = x.localroot.blue_next_hops

        // Inherit next-hops and order_proxies to other components
        if x is not root
           root.blue_next_hops = x.localroot.blue_next_hops
           root.red_next_hops = x.localroot.red_next_hops
           root.order_proxy = x.localroot
        foreach node y
           if (y is not root) and (y is not x)
             SetEdge(y)

    max_block_id = 0
    Assign_Block_ID(root, max_block_id)
    Compute_MRT_NextHops(x, root)
```

Figure 23

4.7. Identify MRT alternates

At this point, we have that a computing router S knows its Blue MRT next-hops and Red MRT next-hops for each destination. However, we usually needed to find out which one among these two should be used in order to avoid a potentially failed node. Usually, the node needs only to avoid the default next-hop (which has just failed), which is a neighbor. However, there is a much complex use case for multicast forwarding, when an alternate area border router must be avoided. Thus, first we provide a simple algorithm for finding the correct trees to avoid a given neighbor, and later this algorithm is modified for a node far away.

For each primary next-hop node F to each destination D, S can call Select_Alternates(S, D, F) to determine whether to use the Blue MRT next-hops as the alternate next-hops for that primary next-hop or to use the Red MRT next-hops. The algorithm is given in Figure 24 and discussed afterwards. Note that we suppose that each link was already added to the GADAG in some direction, thus S and F must be ordered, and there must be a block of the GADAG, which contains both S and F. Moreover, we also suppose that if there are parallel links

between S and F, and only one of them fails, the connection with F is

not lost, and IPFRR is not activated (instead this event is handled by some other protection). Finally, if F is the primary next-hop along a shortest path towards D, D (or D.order_proxy) must be in the same block. If this final assumption were not true, we would have to put an extra condition into the algorithm for checking if F and D.order_proxy are not in the same block, and if they were in different blocks, both trees could be used.

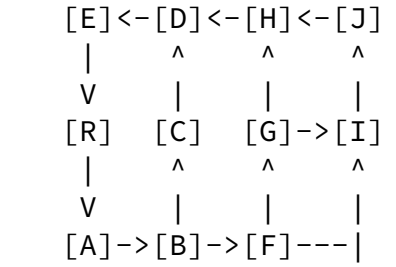
```
 Select_Alternates_For_NH(S, D, F)
     if D.order_proxy is not D
         D_lower = D.order_proxy.lower
         D_higher = D.order_proxy.higher
         D_topo_order = D.order_proxy.topo_order
     else
         D_lower = D.lower
         D_higher = D.higher
         D_topo_order = D.topo_order

     ///When D==F, we can do only link protection
     if ((D == F) or (D.order_proxy == F))
         if (D_lower)
             return USE_BLUE
         else
             return USE_RED

     //There are three corner cases when S, F or D is the local root
     if (S == F.local_root && S == D.local_root)
         if (F.topo_order < D.topo_order)
             return USE_RED
         else
             return USE_BLUE

     if (F == S.local_root && F == D.local_root)
         if (D_lower)
             return USE_RED
         else
             return USE_BLUE

     if (D == S.local_root && D == F.local_root)
         if (F.lower)
             return USE_BLUE
         else
             return USE_RED

     //This is the main part. Recall that S and F must be ordered
     if (D_lower)
         if (F.lower && F.topo_order > D_topo_order)
```

```
            return USE_BLUE
        else
            return USE_RED
    else if (D_higher)
        if (F.higher && F.topo_order < D_topo_order)
            return USE_RED
        else
            return USE_BLUE
    else    //S and D are not ordered
       if (F.lower)
          return USE_RED
       else
          return USE_BLUE
```

Figure 24

The algorithm first handles some corner cases, when either of S, D and F is the local root. When D is in a different block, the cut-vertex leading to D's block is used instead as D's order-proxy. If that is not true, there must be a block, which contains all the three of them. If S>>D.order_proxy, we can use the red path (decreasing path), unless F is in interval [D.order_proxy,S] - that is checked in the second if branch. Similarly, when S<<D.order_proxy, we can use the blue path unless F can be in interval [S,D.order_proxy]. When S and D.order_proxy are not ordered, and F<<S, we know that the first increasing than decreasing (red) path must not contain F. Trivially, when F>>S, we need to use the blue path.

As an example, consider the ADAG depicted in Figure 25 and first suppose that G is the source, D is the destination and H is the failed next-hop. Since D>>G, we need to check if H can be in interval [G,D]. Since H>>G and D.topo_order>H.topo_order, this may be possible (actually, in this example that is not only possible but true), so we select the decreasing path towards the root (red path). Observe, that we are not sure that H is really in [G,D], but we are sure that it is not in interval [R, G] and not in interval [R, D] (R is the smallest and the greatest node), so the decreasing path will always be usable. If, however, the destination was instead J, we would find that H.topo_order>J.topo_order, so we can be sure that H is not in [G, J], so using the increasing (blue) path is safe.



(a)
a 2-connected graph

Figure 25

For ADAGs, the previous algorithm can easily be extended to compute the right next-hops for a failed node F. One needs only to find out what to do, when S is ordered with neither F nor D. In that situation, the first part of the path (the decreasing part for the blue path or the increasing part of the red path) is ordered with S, so that do not contain F. Thus, we can use the blue path if F>D and the red path if F<D, since the second part of these paths are not containing F. This extended algorithm is described below (the differing part is at the end); keep in mind that this algorithm is applicable only for ADAGs, so the initial part for finding D.order_proxy is excluded.

```
 Select_Alternates_For_ADAG(S, D, F)
     //When D==F, we can do only link protection
     if (D == F)
       if Blue next-hops do not include primary next-hop
          return USE_BLUE
       else if Red next-hops do not include primary next-hop
          return USE_RED
       else if Blue next-hops minus primary next-hop is not empty
          return USE_BLUE_MINUS_LINK
       else if Red next-hops minus primary next-hop is not empty
          return USE_BLUE_MINUS_LINK

     //There are three corner cases when S, F or D is the local root
     if (S == F.local_root && S == D.local_root)
```

```
            if (F.topo_order < D.topo_order)
                return USE_RED
            else
                return USE_BLUE

        if (F == S.local_root && F == D.local_root)
            if (D.lower)
                return USE_RED
            else
```



```
                return USE_BLUE

        if (D == S.local_root && D == F.local_root)
            if (F.lower)
                return USE_BLUE
            else
                return USE_RED

        //This is the main part. Recall that S and D must be ordered
        if (D.lower)
            if (F.lower && F.topo_order > D_topo_order)
                return USE_BLUE
            else
                return USE_RED
        else if (D.higher)
            if (F.higher && F.topo_order < D_topo_order)
                return USE_RED
            else
                return USE_BLUE
        else    //S and D are not ordered
            if (F.lower)
               return USE_RED
            else
               return USE_BLUE
            else //THIS IS DIFFERENT: S is not ordered with both F and D
               if (F.topo_order > D_topo_order)
                  return USE_BLUE
               else
                  return USE_RED
```

Figure 26

Select_Alternates_For_ADAG is valid, only when S, F, and D are in the same block; if this is not the case, we do not even have order between the nodes. Therefore, if we have a GADAG, where S and F are not in the same block, we need to convert it into an ADAG.

The transformation is straightforward. Suppose that there is a node X along the path from S to D. We need to split that into two nodes, let them be X1 and X2, and add an X1->X2 arc between them. For that block where X was not the local root, all the arcs going into X must be added to X1 and all the arcs going out from X must be added to X2. Moreover, for all the blocks, where X was the local root, do the opposite, i.e. add arcs going out from X to X1, and those going into X should be added to X2. It can be seen that the blue and the red paths will be the same after the transformation, except that where previously they both crossed X, the red now crosses X1 and the blue now crosses X2. It is straightforward to see that in this way the

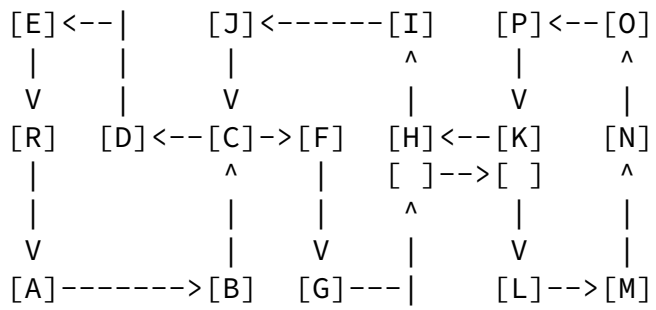
blocks separated by X are opened up into a single block. Naturally, if the blue or the red path could avoid using a given node F in the resulting ADAG, path with the same color will avoid F in the original GADAG. Below is the pseudo code of the generalized algorithm.

```
 Convert_GADAG_to_ADAG(GADAG, ADAG)
     ADAG = GADAG
     for_each local_root X in GADAG
         remove X from ADAG
         add X1 to ADAG
         add X2 to ADAG
         add X1->X2 to ADAG
         for_each arc Y->X in GADAG {
             if (Y.local_root != X)
                 add Y->X1 to ADAG
             else
                 add Y->X2 to ADAG
         }
         for_each arc X->Y in GADAG {
             if (Y.local_root != X)
                add X2->Y to ADAG
             else
                add X1->Y to ADAG
         }
```

```
Select_Alternates_For_GADAG(S, D, F)
    if (ADAG == NULL)   //Need this once, not once for each F and D
        Convert_GADAG_to_ADAG(GADAG, ADAG)
        // Now determine the orderings via an SPF and rSPF on ADAG
        SPF_No_Traverse_Root(S, S.localroot, FORWARD, FALSE)
        SPF_No_Traverse_Root(S, S.localroot, REVERSE, FALSE)

    return Select_Alternates_For_ADAG(S, D, F)
```

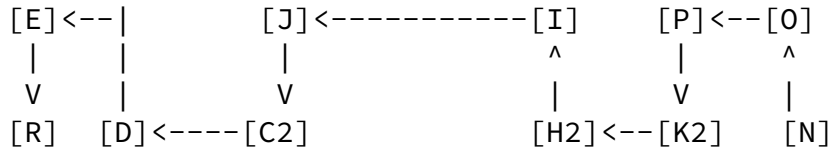
Figure 27

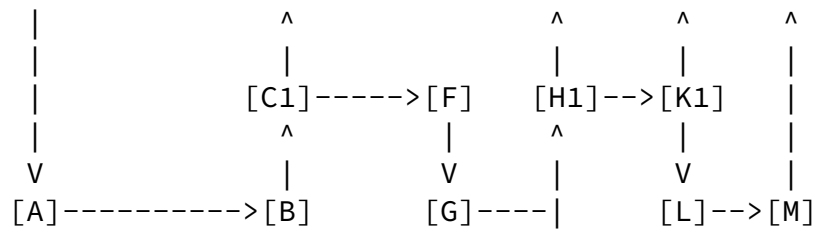
As an example consider the GADAG depicted in Figure 28. In that GADAG, three cut-vertices can be found: C, H and K; we need to split them all. First, split C, now we have C1 and C2 and a C1->C2 arc between them. We have arcs B->C and J->C going into C. Since B does not have C as local root, we add B->C1 to ADAG. However, J.local_root is C, so J->C2 is added. Similarly we add C2->D and C1->F. The resulting ADAG is depicted in Figure 29. Now that the GADAG is converted to an ADAG, it is straightforward to use Select_Alternates_For_ADAG for this ADAG.



A GADAG with multiple blocks

Figure 28





The ADAG after conversion

Figure 29

5. Algorithm Alternatives and Evaluation

This description of the algorithm assumes a particular approach that is believed to be a reasonable compromise between complexity and computation. There are two options given for constructing the GADAG as both are reasonable and promising.

SPF-based GADAG Compute the common GADAG using Option 2 of SPF-based inheritance. This considers metrics when constructing the GADAG, which is important for path length and operational control. It has higher computational complexity than the Low-Point Inheritance GADAG.

Low-Point Inheritance GADAG Compute the common GADAG using Option 1 of Low-Point Inheritance. This ignores metrics when constructing the GADAG, but its computational complexity is O(links) which is attractive. It is possible that augmenting the GADAG by assigning directions to all links in the network graph and adding them to

the GADAG will make the difference between this and the SPF-based GADAG minimal.

In addition, it is possible to calculate Destination-Rooted GADAG, where for each destination, a GADAG rooted at that destination is computed. The GADAG can be computed using either Low-Point Inheritance or SPF-based. Then a router would need to compute the blue MRT and red MRT next-hops to that destination. Building GADAGs per destination is computationally more expensive, but may give somewhat shorter alternate paths. It may be useful for live-live multicast along MRTs.

5.1. Algorithm Evaluation

When evaluating different algorithms and methods for IP Fast Reroute [RFC5714], there are three critical points to consider.

- Coverage: For every Point of Local Repair (PLR) and local failure, is there an alternate to reach every destination? Those destinations include not only routers in the IGP area, but also prefixes outside the IGP area.

- Alternate Length: What is the length of the alternate path offered compared to the optimal alternate route in the network? This is computed as the total length of the alternate path divided by the length of an optimal alternate path. The optimal alternate path is computed by removing the failed node and running an SPF to find the shortest path from the PLR to the destination.

- Alternate Bandwidth: What percentage of the traffic sent to the failed point can be sent on the alternates? This is computed as the sum of the bandwidths along the alternate paths divided by the bandwidth of the primary paths that go through the failure point.

Simulation and modeling to evalute the MRT algorithms is underway. The algorithms being compared are:

- SPF-based GADAG

- Low-Point Inheritance GADAG

- Destination-Rooted SPF-based GADAG

- Destination-Rooted Low-Point Inheritance GADAG

- Not-Via to Next-Next Hop[I-D.ietf-rtgwg-ipfrr-notvia-addresses]

- Loop-Free Alternates[RFC5286]

- Remote LFAs[I-D.shand-remote-lfa]

6. Algorithm Work to Be Done

Broadcast Interfaces: The algorithm assumes that broadcast interfaces are already represented as pseudo-nodes in the network graph. The exact rules for extending the set of next-hops and ensuring that the neighboring node is avoided need to be fully specified.

Local SRLG Protection: The algorithmic extensions to handle local SRLGs, where each member of the SRLG shares a common router end, need to be fully specified.

General SRLG Protection: Creating MRTs that consider general SRLGs is still a challenging open research problem.

7. IANA Considerations

This doument includes no request to IANA.

8. Security Considerations

This architecture is not currently believed to introduce new security concerns.

9. References

9.1. Normative References

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