          Core Based Trees (CBT) Multicast Routing Architecture

Status of this Memo

Abstract

   CBT is a multicast routing architecture that builds a single delivery
   tree per group which is shared by all of the group's senders and
   receivers. Most multicast algorithms build one multicast tree per
   sender (subnetwork), the tree being rooted at the sender's
   subnetwork. The primary advantage of the shared tree approach is
   that it typically offers more favourable scaling characteristics than
   all other multicast algorithms.

   The CBT protocol [1] is a network layer multicast routing protocol
   that builds and maintains a shared delivery tree for a multicast
   group. The sending and receiving of multicast data by hosts on a
   subnetwork conforms to the traditional IP multicast service model
   [2].

   CBT is progressing through the IDMR working group of the IETF. The
   CBT protocol is described in an accompanying document [1]. For this,
   and all IDMR-related documents, see http://www.cs.ucl.ac.uk/ietf/idmr

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1. Background

   Shared trees were first described by Wall in his investigation into
   low-delay approaches to broadcast and selective broadcast [3]. Wall
   concluded that delay will not be minimal, as with shortest-path
   trees, but the delay can be kept within bounds that may be
   acceptable. Back then, the benefits and uses of multicast were not
   fully understood, and it wasn't until much later that the IP
   multicast address space was defined (class D space [4]). Deering's
   work [2] in the late 1980's was pioneering in that he defined the IP
   multicast service model, and invented algorithms which allow hosts to
   arbitrarily join and leave a multicast group. All of Deering's
   multicast algorithms build source-rooted delivery trees, with one
   delivery tree per sender subnetwork. These algorithms are documented
   in [2].

   After several years practical experience with multicast, we see a
   diversity of multicast applications and correspondingly, a wide
   variety of multicast application requirements. For example,
   distributed interactive simulation (DIS) applications have strict
   requirements in terms of join latency, group membership dynamics,
   group sender populations, far exceeding the requirements of many
   other multicast applications.

   The multicast-capable part of the Internet, the MBONE, continues to
   expand rapidly. The obvious popularity and growth of multicast means
   that the scaling aspects of wide-area multicasting cannot be
   overlooked; some predictions talk of thousands of groups being
   present at any one time in the Internet.

   We evaluate scalability in terms of network state maintenance,
   bandwidth efficiency, and protocol overhead. Other factors that can
   affect these parameters include sender set size, and wide-area
   distribution of group members.

2. Introduction

   Multicasting on the local subnetwork does not require either the
   presence of a multicast router or the implementation of a multicast
   routing algorithm; on most shared media (e.g. Ethernet), a host,

which need not necessarily be a group member, simply sends a
multicast data packet, which is received by any member hosts
connected to the same medium.

For multicasts to extend beyond the scope of the local subnetwork,
the subnet must have a multicast-capable router attached, which
itself is attached (possibly "virtually") to another multicast-
capable router, and so on. The collection of these (virtually)
connected multicast routers forms the Internet's MBONE.

All multicast routing protocols make use of IGMP [5], a protocol that
operates between hosts and multicast router(s) belonging to the same
subnetwork. IGMP enables the subnet's multicast router(s) to monitor
group membership presence on its directly attached links, so that if
multicast data arrives, it knows over which of its links to send a
copy of the packet.

In our description of the MBONE so far, we have assumed that all
multicast routers on the MBONE are running the same multicast routing
protocol. In reality, this is not the case; the MBONE is a collection
of autonomously administered multicast regions, each region defined
by one or more multicast-capable border routers. Each region
independently chooses to run whichever multicast routing protocol
best suits its needs, and the regions interconnect via the "backbone
region", which currently runs the Distance Vector Multicast Routing
Protocol (DVMRP) [6]. Therefore, it follows that a region's border
router(s) must interoperate with DVMRP.

Different algorithms use different techniques for establishing a
distribution tree. If we classify these algorithms into source-based
tree algorithms and shared tree algorithms, we'll see that the
different classes have considerably different scaling
characteristics, and the characteristics of the resulting trees
differ too, for example, average delay. Let's look at source-based
tree algorithms first.

3. Source-Based Tree Algorithms

The strategy we'll use for motivating (CBT) shared tree multicast is
based, in part, in explaining the characteristics of source-based
tree multicast, in particular its scalability.

Most source-based tree multicast algorithms are often referred to as
"dense-mode" algorithms; they assume that the receiver population
densely populates the domain of operation, and therefore the
accompanying overhead (in terms of state, bandwidth usage, and/or
processing costs) is justified. Whilst this might be the case in a
local environment, wide-area group membership tends to be sparsely

distributed throughout the Internet. There may be "pockets" of
denseness, but if one views the global picture, wide-area groups tend
to be sparsely distributed.

Source-based multicast trees are either built by a distance-vector
style algorithm, which may be implemented separately from the unicast
routing algorithm (as is the case with DVMRP), or the multicast tree
may be built using the information present in the underlying unicast
routing table (as is the case with PIM-DM [7]). The other algorithm
used for building source-based trees is the link-state algorithm (a
protocol instance being M-OSPF [8]).

3.1. Distance-Vector Multicast Algorithm

The distance-vector multicast algorithm builds a multicast delivery
tree using a variant of the Reverse-Path Forwarding technique [9].
The technique basically is as follows: when a multicast router
receives a multicast data packet, if the packet arrives on the
interface used to reach the source of the packet, the packet is
forwarded over all outgoing interfaces, except leaf subnets with no
members attached. A "leaf" subnet is one which no router would use
to reach the souce of a multicast packet. If the data packet does not
arrive over the link that would be used to reach the source, the
packet is discarded.

This constitutes a "broadcast & prune" approach to multicast tree
construction; when a data packet reaches a leaf router, if that
router has no membership registered on any of its directly attached
subnetworks, the router sends a prune message one hop back towards
the source. The receiving router then checks its leaf subnets for
group membership, and checks whether it has received a prune from all
of its downstream routers (downstream with respect to the source).
If so, the router itself can send a prune upstream over the interface
leading to the source.

The sender and receiver of a prune message must cache the <source,
group> pair being reported, for a "lifetime" which is at the
granularity of minutes. Unless a router's prune information is
refreshed by the receipt of a new prune for <source, group> before
its "lifetime" expires, that information is removed, allowing data to
flow over the branch again. State that expires in this way is
referred to as "soft state".

Interestingly, routers that do not lead to group members are incurred
the state overhead incurred by prune messages. For wide-area
multicasting, which potentially has to support many thousands of
active groups, each of which may be sparsely distributed, this
technique clearly does not scale.

3.2. Link-State Multicast Algorithm

Routers implementing a link state algorithm periodically collect
reachability information to their directly attached neighbours, then
flood this throughout the routing domain in so-called link state
update packets. Deering extended the link state algorithm for
multicasting by having a router additionally detect group membership
changes on its incident links before flooding this information in
link state packets.

Each router then, has a complete, up-to-date image of a domain's
topology and group membership. On receiving a multicast data packet,
each router uses its membership and topology information to calculate
a shortest-path tree rooted at the sender subnetwork. Provided the
calculating router falls within the computed tree, it forwards the
data packet over the interfaces defined by its calculation. Hence,
multicast data packets only ever traverse routers leading to members,
either directly attached, or further downstream. That is, the
delivery tree is a true multicast tree right from the start.

However, the flooding (reliable broadcasting) of group membership
information is the predominant factor preventing the link state
multicast algorithm being applicable over the wide-area. The other
limiting factor is the processing cost of the Dijkstra calculation to
compute the shortest-path tree for each active source.

3.3. The Motivation for Shared Trees

The algorithms described in the previous sections clearly motivate
the need for a multicast algorithm(s) that is more scalable. CBT was
designed primarily to address the topic of scalability; a shared tree
architecture offers an improvement in scalability over source tree
architectures by a factor of the number of active sources (where
source is usually a subnetwork aggregate). Source trees scale $O(S *
G)$, since a distinct delivery tree is built per active source. Shared
trees eliminate the source (S) scaling factor; all sources use the
same shared tree, and hence a shared tree scales $O(G)$. The
implication of this is that applications with many active senders,
such as distributed interactive simulation applications, and
distributed video-gaming (where most receivers are also senders),
have a significantly lesser impact on underlying multicast routing if
shared trees are used.

In the "back of the envelope" table below we compare the amount of
state required by CBT and DVMRP for different group sizes with
different numbers of active sources:

Number of groups	10			100			1000		
Group size (# members)	20			40			60		
No. of srcs per group	10%	50%	100%	10%	50%	100%	10%	50%	100%
No. of DVMRP router entries	20	100	200	400	2K	4K	6K	30K	60K
No. of CBT router entries	10			100			1000		

Figure 1: Comparison of DVMRP and CBT Router State

Shared trees also incur significant bandwidth and state savings
compared with source trees; firstly, the tree only spans a group's
receivers (including links/routers leading to receivers) -- there is
no cost to routers/links in other parts of the network. Secondly,
routers between a non-member sender and the delivery tree are not
incurred any cost pertaining to multicast, and indeed, these routers
need not even be multicast-capable -- packets from non-member senders
are encapsulated and unicast to a core on the tree.
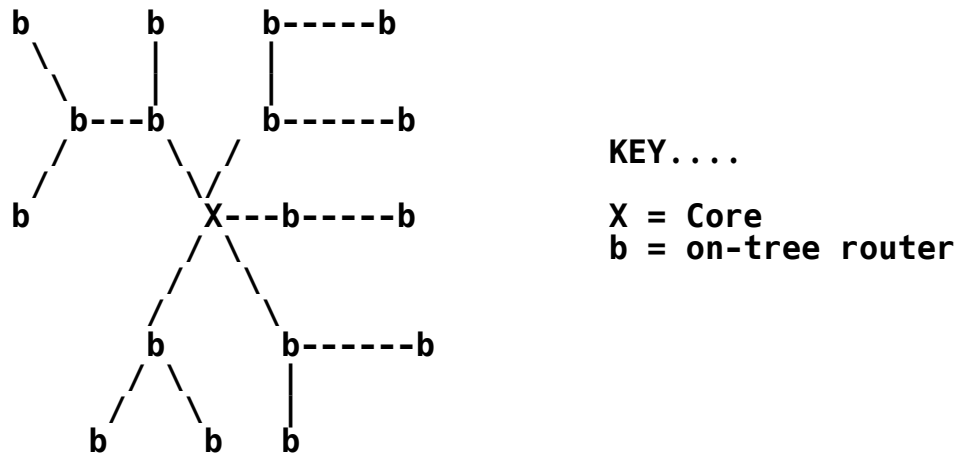
The figure below illustrates a core based tree.

```
        b       b     b-----b
         \      |     |
          \     |     |
           b---b     b------b
          /   \  /
         /     \/
        b      X---b-----b           KEY....
              / \
             /   \                   X = Core
            /     \                  b = on-tree router
           b       b------b
          / \      |
         /   \     |
        b     b    b
```

                    Figure 2: CBT Tree

4. CBT - The New Architecture

4.1. Design Requirements

The CBT shared tree design was geared towards several design
objectives:

o   scalability - the CBT designers decided not to sacrifice CBT's
       O(G) scaling characteric to optimize delay using SPTs, as does
       PIM. This was an important design decision, and one, we think,
       was taken with foresight; once multicasting becomes ubiquitous,
       router state maintenance will be a predominant scaling factor.
       It is possible in some circumstances to improve/optimize the
       delay of shared trees by other means. For example, a broadcast-
       type lecture with a single sender (or limited set of
       infrequently changing senders) could have its core placed in the
       locality of the sender, allowing the CBT to emulate a shortest-
       path tree (SPT) whilst still maintaining its O(G) scaling
       characteristic. More generally, because CBT does not incur
       source-specific state, it is particularly suited to many sender
       applications.

o   robustness - source-based tree algorithms are clearly robust; a
       sender simply sends its data, and intervening routers "conspire"
       to get the data where it needs to, creating state along the way.
       This is the so-called "data driven" approach -- there is no
       set-up protocol involved.

It is not as easy to achieve the same degree of robustness in
shared tree algorithms; a shared tree's core router maintains
connectivity between all group members, and is thus a single
point of failure. Protocol mechanisms must be present that
ensure a core failure is detected quickly, and the tree
reconnected quickly using a replacement core router.

o   simplicity - the CBT protocol is relatively simple compared to
     most other multicast routing protocols. This simplicity can lead
     to enhanced performance compared to other protocols.

o   interoperability - from a multicast perspective, the Internet is
     a collection of heterogeneous multicast regions. The protocol
     interconnecting these multicast regions is currently DVMRP [6];
     any regions not running DVMRP connect to the DVMRP "backbone" as
     stub regions. CBT has well-defined interoperability mechanisms
     with DVMRP [15].

4.2. CBT Components & Functions

The CBT protocol is designed to build and maintain a shared multicast
distribution tree that spans only those networks and links leading to
interested receivers.

To achieve this, a host first expresses its interest in joining a
group by multicasting an IGMP host membership report [5] across its
attached link. On receiving this report, a local CBT aware router
invokes the tree joining process (unless it has already) by
generating a JOIN_REQUEST message, which is sent to the next hop on
the path towards the group's core router (how the local router
discovers which core to join is discussed in section 6). This join
message must be explicitly acknowledged (JOIN_ACK) either by the core
router itself, or by another router that is on the unicast path
between the sending router and the core, which itself has already
successfully joined the tree.

The join message sets up transient join state in the routers it
traverses, and this state consists of <group, incoming interface,
outgoing interface>. "Incoming interface" and "outgoing interface"
may be "previous hop" and "next hop", respectively, if the
corresponding links do not support multicast transmission. "Previous
hop" is taken from the incoming control packet's IP source address,
and "next hop" is gleaned from the routing table - the next hop to
the specified core address. This transient state eventually times out
unless it is "confirmed" with a join acknowledgement (JOIN_ACK) from
upstream. The JOIN_ACK traverses the reverse path of the
corresponding join message, which is possible due to the presence of
the transient join state. Once the acknowledgement reaches the

router that originated the join message, the new receiver can receive
traffic sent to the group.

Loops cannot be created in a CBT tree because a) there is only one
active core per group, and b) tree building/maintenance scenarios
which may lead to the creation of tree loops are avoided. For
example, if a router's upstream neighbour becomes unreachable, the
router immediately "flushes" all of its downstream branches, allowing
them to individually rejoin if necessary. Transient unicast loops do
not pose a threat because a new join message that loops back on
itself will never get acknowledged, and thus eventually times out.

The state created in routers by the sending or receiving of a
JOIN_ACK is bi-directional - data can flow either way along a tree
"branch", and the state is group specific - it consists of the group
address and a list of local interfaces over which join messages for
the group have previously been acknowledged. There is no concept of
"incoming" or "outgoing" interfaces, though it is necessary to be
able to distinguish the upstream interface from any downstream
interfaces. In CBT, these interfaces are known as the "parent" and
"child" interfaces, respectively.

With regards to the information contained in the multicast forwarding
cache, on link types not supporting native multicast transmission an
on-tree router must store the address of a parent and any children.
On links supporting multicast however, parent and any child
information is represented with local interface addresses (or similar
identifying information, such as an interface "index") over which the
parent or child is reachable.

When a multicast data packet arrives at a router, the router uses the
group address as an index into the multicast forwarding cache. A copy
of the incoming multicast data packet is forwarded over each
interface (or to each address) listed in the entry except the
incoming interface.

Each router that comprises a CBT multicast tree, except the core
router, is responsible for maintaining its upstream link, provided it
has interested downstream receivers, i.e. the child interface list is
not NULL. A child interface is one over which a member host is
directly attached, or one over which a downstream on-tree router is
attached. This "tree maintenance" is achieved by each downstream
router periodically sending a "keepalive" message (ECHO_REQUEST) to
its upstream neighbour, i.e. its parent router on the tree. One
keepalive message is sent to represent entries with the same parent,
thereby improving scalability on links which are shared by many
groups. On multicast capable links, a keepalive is multicast to the
"all-cbt-routers" group (IANA assigned as 224.0.0.15); this has a

suppressing effect on any other router for which the link is its
parent link. If a parent link does not support multicast
transmission, keepalives are unicast.

The receipt of a keepalive message over a valid child interface
immediately prompts a response (ECHO_REPLY), which is either unicast
or multicast, as appropriate.

The ECHO_REQUEST does not contain any group information; the
ECHO_REPLY does, but only periodically. To maintain consistent
information between parent and child, the parent periodically
reports, in a ECHO_REPLY, all groups for which it has state, over
each of its child interfaces for those groups. This group-carrying
echo reply is not prompted explicitly by the receipt of an echo
request message. A child is notified of the time to expect the next
echo reply message containing group information in an echo reply
prompted by a child's echo request. The frequency of parent group
reporting is at the granularity of minutes.

It cannot be assumed all of the routers on a multi-access link have a
uniform view of unicast routing; this is particularly the case when a
multi-access link spans two or more unicast routing domains. This
could lead to multiple upstream tree branches being formed (an error
condition) unless steps are taken to ensure all routers on the link
agree which is the upstream router for a particular group. CBT
routers attached to a multi-access link participate in an explicit
election mechanism that elects a single router, the designated router
(DR), as the link's upstream router for all groups. Since the DR
might not be the link's best next-hop for a particular core router,
this may result in join messages being re-directed back across a
multi-access link. If this happens, the re-directed join message is
unicast across the link by the DR to the best next-hop, thereby
preventing a looping scenario. This re-direction only ever applies
to join messages. Whilst this is suboptimal for join messages, which
are generated infrequently, multicast data never traverses a link
more than once (either natively, or encapsulated).

In all but the exception case described above, all CBT control
messages are multicast over multicast supporting links to the "all-
cbt-routers" group, with IP TTL 1. When a CBT control message is sent
over a non-multicast supporting link, it is explicitly addressed to
the appropriate next hop.

4.2.1. CBT Control Message Retransmission Strategy

Certain CBT control messages illicit a response of some sort. Lack of
response may be due to an upstream router crashing, or the loss of
the original message, or its response. To detect these events, CBT

retransmits those control messages for which it expects a response,
if that response is not forthcoming within the retransmission-
interval, which varies depending on the type of message involved.
There is an upper bound (typically 3) on the number of
retransmissions of the original message before an exception condition
is raised.

For example, the exception procedure for lack of response to an
ECHO_REQUEST is to send a QUIT_NOTIFICATION upstream and a FLUSH_TREE
message downstream for the group. If this is router has group members
attached, it restarts the joining process to the group's core.

4.2.2. Non-Member Sending

If a non-member sender's local router is already on-tree for the
group being sent to, the subnet's upstream router simply forwards the
data packet over all outgoing interfaces corresponding to that
group's forwarding cache entry. This is in contrast to PIM-SM [18]
which must encapsulate data from a non-member sender, irrespective of
whether the local router has joined the tree. This is due to PIM's
uni-directional state.

If the sender's subnet is not attached to the group tree, the local
DR must encapsulate the data packet and unicast it to the group's
core router, where it is decapsulated and disseminated over all tree
interfaces, as specified by the core's forwarding cache entry for the
group. The data packet encapsulation method is IP-in-IP [14].

Routers in between a non-member sender and the group's core need not
know anything about the multicast group, and indeed may even be
multicast-unaware. This makes CBT particulary attractive for
applications with non-member senders.

5. Interoperability with Other Multicast Routing Protocols

See "interoperability" in section 4.1.

The interoperability mechanisms for interfacing CBT with DVMRP are
defined in [15].

6. Core Router Discovery

Core router discovery is by far the most controversial and difficult
aspect of shared tree multicast architectures, particularly in the
context of inter-domain multicast routing (IDMR). There have been
many proposals over the past three years or so, including advertising
core addresses in a multicast session directory like "sdr" [11],
manual placement, and the HPIM [12] approach of strictly dividing up

the multicast address space into many "hierarchical scopes" and using
explicit advertising of core routers between scope levels.

There are currently two options for CBTv2 [1] core discovery; the
"bootstrap" mechamism, and manual placement. The bootstrap mechanisms
(as currently specified with the PIM sparse mode protocol [18]) is
applicable only to intra-domain core discovery, and allows for a
"plug & play" type operation with minimal configuration. The
disadvantage of the bootstrap mechanism is that it is much more
difficult to affect the shape, and thus optimality, of the resulting
distribution tree. Also, it must be implemented by all CBT routers
within a domain.

Manual configuration of leaf routers with <core, group> mappings is
the other option (note: leaf routers only); this imposes a degree of
administrative burden - the mapping for a particular group must be
coordinated across all leaf routers to ensure consistency. Hence,
this method does not scale particularly well. However, it is likely
that "better" trees will result from this method, and it is also the
only available option for inter-domain core discovery currently
available.

6.1. Bootstrap Mechanism Overview

It is unlikely at this stage that the bootstrap mechanism will be
appended to a well-known network layer protocol, such as IGMP [5] or
ICMP [13], though this would facilitate its ubiquitous (intra-domain)
deployment. Therefore, each multicast routing protocol requiring the
bootstrap mechanism must implement it as part of the multicast
routing protocol itself.

A summary of the operation of the bootstrap mechanism follows. It is
assumed that all routers within the domain implement the "bootstrap"
protocol, or at least forward bootstrap protocol messages.

A subset of the domain's routers are configured to be CBT candidate
core routers. Each candidate core router periodically (default every
60 secs) advertises itself to the domain's Bootstrap Router (BSR),
using "Core Advertisement" messages. The BSR is itself elected
dynamically from all (or participating) routers in the domain. The
domain's elected BSR collects "Core Advertisement" messages from
candidate core routers and periodically advertises a candidate core
set (CC-set) to each other router in the domain, using traditional
hopby-hop unicast forwarding. The BSR uses "Bootstrap Messages" to
advertise the CC-set. Together, "Core Advertisements" and "Bootstrap
Messages" comprise the "bootstrap" protocol.

When a router receives an IGMP host membership report from one of its
directly attached hosts, the local router uses a hash function on the
reported group address, the result of which is used as an index into
the CC-set. This is how local routers discover which core to use for
a particular group.

Note the hash function is specifically tailored such that a small
number of consecutive groups always hash to the same core.
Furthermore, bootstrap messages can carry a "group mask", potentially
limiting a CC-set to a particular range of groups. This can help
reduce traffic concentration at the core.

If a BSR detects a particular core as being unreachable (it has not
announced its availability within some period), it deletes the
relevant core from the CC-set sent in its next bootstrap message.
This is how a local router discovers a group's core is unreachable;
the router must re-hash for each affected group and join the new core
after removing the old state. The removal of the "old" state follows
the sending of a QUIT_NOTIFICATION upstream, and a FLUSH_TREE message
downstream.

7. Summary

This document presents an architecture for intra- and inter-domain
multicast routing. We motivated this architecture by describing how
an inter-domain multicast routing algorithm must scale to large
numbers of groups present in the internetwork, and discussed why most
other existing algorithms are less suited to inter-domain multicast
routing. We followed by describing the features and components of
the architecture, illustrating its simplicity and scalability.

8. Security Considerations

Security considerations are not addressed in this memo.

Whilst multicast security is a topic of ongoing research, multicast
applications (users) nevertheless have the ability to take advantage
of security services such as encryption or/and authentication
provided such services are supported by the applications.

RFCs 1949 and 2093/2094 discuss different ways of distributing
multicast key material, which can result in the provision of network
layer access control to a multicast distribution tree.

[19] offers a synopsis of multicast security threats and proposes
some possible counter measures.

Beyond these, little published work exists on the topic of multicast security.

Acknowledgements

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