Wide Area Cartesian Routing

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Abstract

Cartesian routing is a fast packet routing mechanism intended for geographic addresses and can effectively accelerate the packet routing process within a local or metropolitan environment.

The wide area Cartesian routing described in this paper is an extension of the Cartesian routing algorithms designed to make the exchange of internetwork packets between geographical regions possible. It also introduces a new hierarchical structure for the entire Internet. The proposed Internet is viewed as a hierarchy of networks consisting of routers. At the highest level of this hierarchy, major routers exchange packets between large geopolitical areas such as countries, states, or provinces. At the lowest level of the structure, packets are routed between local routers in small geographical regions ranging from an office to a small town. There are only four layers in this structure and at each layer Cartesian routing is employed to send packets from the source router to the destination.

Keywords: IPv6, Geographic addresses, Cartesian routing.

1 Introduction

Recently, a number of applications for Global Positioning System (GPS) and geographic addresses have been introduced and investigated [2]. Although the purpose of most such applications has been to target a geographic area or region for receiving broadcast or multicast messages, the use of geographic addresses for unicast routing has been overlooked. In [3], the authors introduced Cartesian networks and discussed how they can accelerate the process of exchanging packets between a set of routers bound to geographic addresses in a metropolitan environment by relieving routers from the maintanance of routing tables. This is achieved by imposing some topological dependencies among the nodes of a network. In this work, the authors introduce wide area Cartesian networks as an extension of Cartesian networks. Since wide area Cartesian networks rely extensively on Cartesian networks, the following section will give a brief introduction to the Cartesian routing and may encourage the reader to consult [3] from which this explanation is taken. In the rest of this paper the terms "Cartesian network" and "network" are used interchangeably.

2 Cartesian Networks

A Cartesian network consists of a set of *collectors* and one or more *arterials*. Each collector is a chain of *collector routers* running east-west and sharing a common latitude. Collector routers have two side ports (east and west) to exchange packets 'horizontally'. Each collector router also has a *bottom* port which allows it to connect to a set of local hosts. Arterials exchange packets between collectors. Each arterial router, except the most northerly and the most southerly has, at least, four ports (north, south, east and west). Arterials need not share a common longitude. In a Cartesian network, the imposed topological structure relieves each router from maintaining routing tables. Each router is bound to a unique pair of addresses, the state information is minimal, and each router maintains the accessibility of arterials to its west and east.

2.1 Cartesian Network Initialization

In Cartesian routing, each arterial issues *Arterial This Way* (ATW) control packets during its initialization process. An ATW tells the receiving collector router if an arterial is accessible through the incoming port. An ATW also specifies what kind of connection is accessible via the incoming port: north, south, north and south or neither. Upon receiving an ATW, each collector router updates its *Arterial Direction Indicator* (ADI) and forwards the ATW to the opposite port. ATWs are also used to establish *Virtual Arterials*, constructed in situations where it is physically impossible for an arterial to span two collectors. The ADI points in the direction of the arterial router (i.e., east or west) and indicates whether the arterial router has a connection to the north, the south, or both. Figure 1 illustrates a Cartesian network.

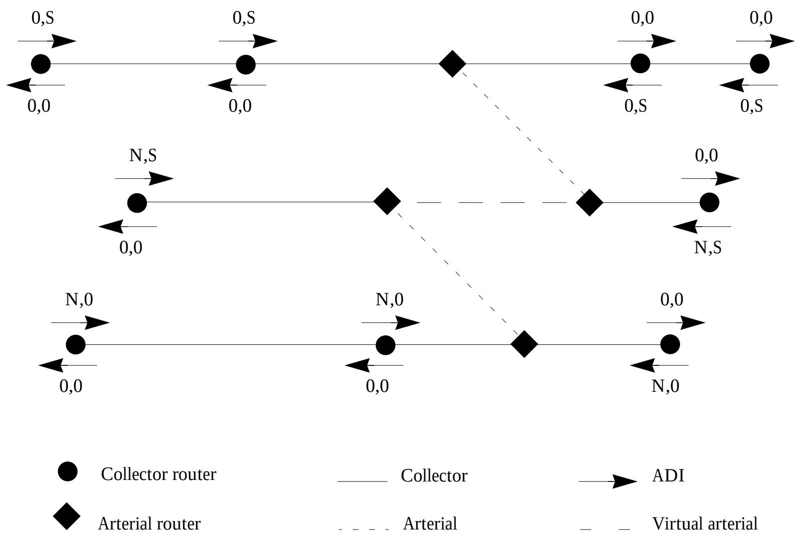

Figure 1: Collectors, collector routers, arterials, arterial routers and virtual arterial

2.2 Cartesian Routing

Packets can arrive on either a west or east port of a collector router. Packets intended for a different latitude are forwarded out the opposite port from which they are received. The ADI determines the packet's initial direction on the collector router when a packet arrives on the bottom port of a collector router. In deciding a packet's initial direction, the router first compares the packet's destination address with its own address. The packet will be forwarded in the direction of the destination if the destination latitude is the same as the collector's. The packet is forwarded in the direction of the ADI if the destination is on a different latitude.

3 Wide Area Cartesian Networks

A Cartesian network provides a straightforward topological structure that relieves collector routers from the need to maintain routing tables. However, it would be unrealistic to implement a single worldwide Cartesian network. Such a widespread Cartesian network, for example, requires every packet destined for a router with the same latitude identifier as the source router's latitude identifier to visit all the collector routers in between. It is also necessary for such a network to have one collector for every possible latitude. These limitations suggest that implementing a single worldwide Cartesian network would be impractical.

An alternative to a worldwide Cartesian network is to create a set of smaller Cartesian networks and implement a mechanism for interchanging packets between them.

One approach to interchanging packets between Cartesian networks is to forward packets towards their destinations. When a packet reaches the boundary of a network it “falls off” the edge and is delivered to a special router to be forwarded towards the destination address. The process of routing a packet from one network to another using this approach becomes problematic when networks are *interleaved* or *overlapped*.

Two networks are considered interleaved if there is at least one collector router on one of the networks where its longitude identifier lies between the longitude identifiers of two collectors from the other network and its latitude identifier lies between the latitude identifiers of two collectors from the other network. Figure 2 illustrates two interleaved networks.

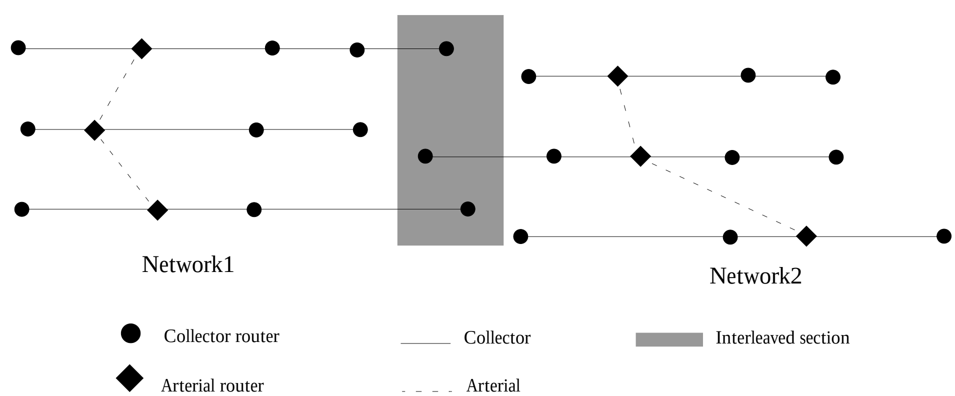

Figure 2: Two interleaved networks: Network1 and Network2 are interleaved at the shaded area

Two networks are said to be overlapped if there is at least one collector router on one of the networks where its longitude identifier lies between the longitude identifiers of two collectors from the other network and all three of them share the same latitude identifier. Figure 3 illustrates two overlapped networks.

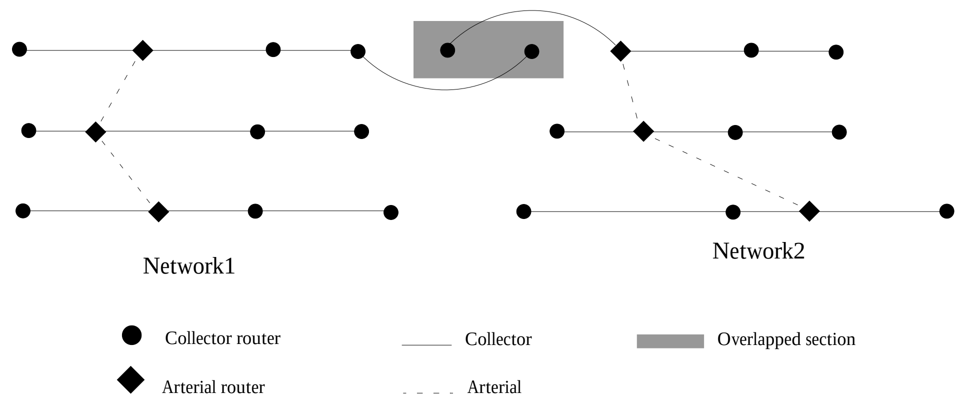

Figure 3: Two overlapped networks

An alternative method for delivering a packet to its destination is to find the destination network address and then to route the packet to the destination network by using Cartesian routing algorithms. This implies that each network must be identifiable using the packet's destination address. If we assume that each network has a rectangular shape, recognizing the destination network is a matter of comparing the packet's destination address with the network's boundaries. However, there are a number of reasons to assume that it would be unrealistic to expect networks to have rectangular borders: geographical barriers and political jurisdictions, for example.

Since Cartesian routing uses latitude and longitude pairs to identify the source and the destination addresses of packets, this information is not sufficient to determine to which network a collector/arterial belongs in the case of interleaved and overlapped networks. This, in turn, suggests that an additional set of information is required to identify to which network a collector or arterial is connected. To achieve this, the authors propose a hierarchical structure for Cartesian networks. In the next section the possibility of multiple-layer Cartesian networks as a solution for interchanging packets between arbitrary shaped interleaved and overlapped Cartesian networks is explained. In the remainder of this paper, the terms "wide area Cartesian networks" and "multiple-layer Cartesian networks" are used interchangeably.

4 Multiple-Layer Cartesian Networks

Multiple-layer Cartesian networks impose a new set of topological dependencies among a set of Cartesian networks, such that interchanging packets between networks is feasible without creating and maintaining routing tables. Generally, in multiple layer Cartesian networks, the idea of Cartesian networks is expanded in a larger scale using a hierarchical structure.

4.1 Topology

Multiple-layer Cartesian networks have a hierarchical structure. The highest layer of the hierarchy is a single Cartesian network. Each underlying layer consists of a set of mutually disjoint Cartesian networks (i.e., they are physically disjoint and share no collector or arterial router); however, networks in the same layer can be interleaved or overlapped. A layer of the hierarchy is referred to as layer-n, where n can be replaced by a constant or an equation. The lowest layer of the hierarchy is layer-1 and the highest layer is layer-m, where m is the maximum number of layers. A multiple-layer Cartesian network with a maximum of m layers is defined as an *m-layer Cartesian network*. Collector routers in layer-1 are connected to local hosts through their bottom port. Each Collector router at layer-n represents a single Cartesian network at layer-(n-1), where $1 < n \leq m$. When a collector router R in network A at layer-n represents a Cartesian network B at layer-(n-1), it is said that network A and collector router R "encompass" network B. Network A also encompasses all the networks encompassed by network B.

In an m-layer Cartesian network, each network at layer-n, $1 \leq n < m$, is connected to another network at layer-(n+1) via a single *internetwork router* (IR). An IR is a bridge, interchanging packets between a Cartesian network and its "immediate" encompassing network. Each IR is an arterial router with an additional port, the *top* port, that connects a network at layer-n to its encompassing network at layer-(n+1). Figure 4 illustrates an encompassing network (A) and two encompassed networks (B and C) along with two IRs.

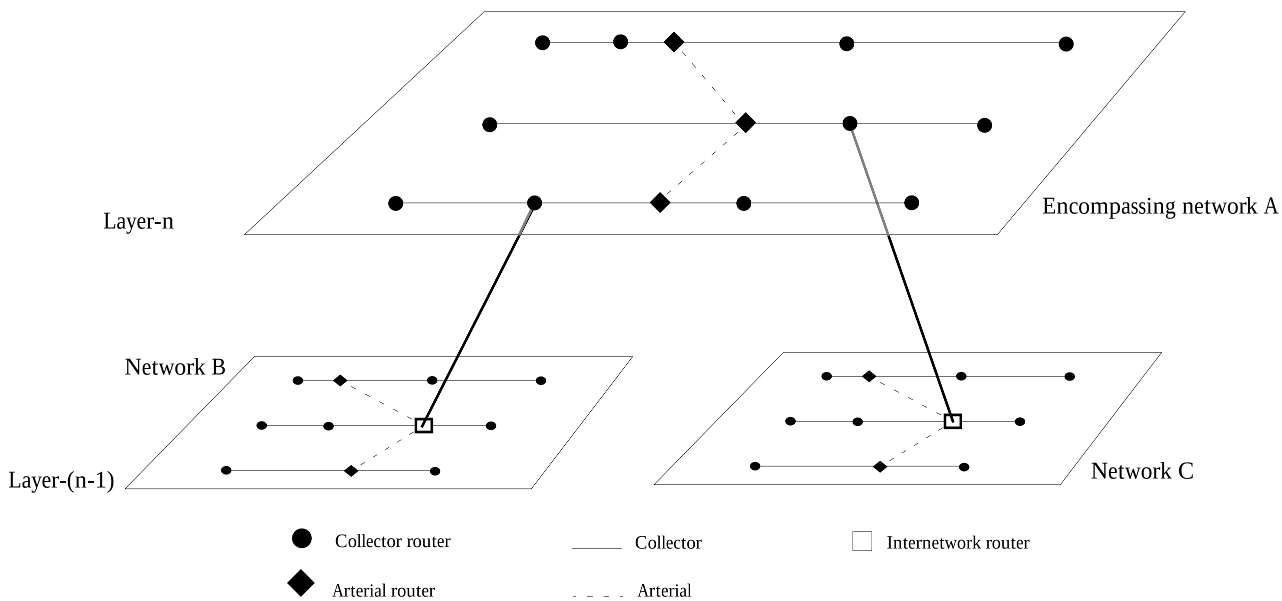

Figure 4: An encompassing network (A) and two encompassed networks (B and C).

4.2 Router Identification

In a Cartesian network, each router is bound to a Cartesian address [3]. Whereas, in a multiple-layer Cartesian network, each router is bound to an *identifier*. The identifier of a router at layer-m of an m-layer Cartesian network is the same as its Cartesian address. An identifier of a router at lower layers is the identifier of its immediate encompassing router, followed by the Cartesian address of the router itself, meaning that an identifier is an ordered list of Cartesian addresses. For example, routers at layer-(m-1) maintain the Cartesian address of the router that represents the network to which they belong, followed by their own Cartesian address. In general, in an m-layer Cartesian network, each router at layer-n maintains a list of (m-n+1) ordered Cartesian addresses, where $1 \leq n \leq m$. For example, routers at the lowest layer of the hierarchy, layer-1, which are connected to local hosts through their bottom ports, are bound to m ordered Cartesian addresses: m-1 correspond to the identifier of the encompassing router at layer-2, and one, the Cartesian address of the router itself. Figure 5 illustrates the hierarchical addressing structure of an identifier for a router at layer-n of an m-layer Cartesian network.

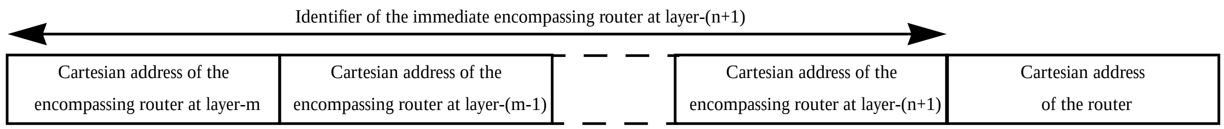

Figure 5: Hierarchical addressing structure of an identifier for a collector router at layer-n.

The hierarchical addressing structure overcomes the problems with both interleaved and overlapped networks since every router in the hierarchy has a unique address. It also enables a router in a network at layer-n to determine if a packet is local to the network or not. A packet is said to be *local* to a network if the network encompasses the destination address of the packet. A router can determine this by comparing the most significant m-n Cartesian addresses of the packet's destination address with the first m-n Cartesian addresses of its own identifier.

4.3 Packet Routing

In an m-layer Cartesian network, each collector router at layer-n is bound to an identifier which is a list of m-n+1 Cartesian addresses. A packet can enter a network at layer-n through the bottom port of a collector router or the top port of the network's IR. Packets received on the bottom port of a collector router are either local or non-local to the network, as described above. When a packet is found to be local, that is, the network encompasses the destination address, the router "tags" the packet as a local packet by setting a single bit of the packet's address called the *local bit*. When a packet is local to a network at layer-n, the $(m\text{-}n\text{+}1)^{th}$ Cartesian address of the packet's destination address is used to route the packet in the network using Cartesian routing algorithm. For example, at layer-m, the first Cartesian address is used for Cartesian routing, while at layer-1 the m^{th} address is used. When a packet is received by a router on its bottom port, the address is inspected. Non-local packets must be sent towards the network's IR in order to be delivered to the encompassing network. The router clears the local bit and forwards the packet towards the IR. Forwarding a packet to the IR requires that each collector router and arterial maintains an *Internetwork Router Direction Indicator* or IRDI. The IRDI determines if the internetwork router is accessible through the west port, east port or neither, in the case of collector routers; or whether it is accessible through the north port, south port or neither, in the case of arterials. If the packet is determined to be non-local, it is forwarded in the direction specified by the IRDI. When the IRDI indicates that IR is not accessible, the packet is dropped and a message is returned to the source notifying that the destination address is not reachable.

A collector router that receives a packet on its west or east port checks the local bit; if set, the Cartesian routing algorithm is employed to route the packet, otherwise the packet is forwarded to the opposite port.

When a packet enters a network through the top port of the network's IR, the packet is guaranteed to be local, since this has already been verified by the encompassing network. Upon receiving the packet, the IR sets the local bit and then applies the Cartesian routing algorithm on the $(m\text{-}n\text{+}1)^{th}$ Cartesian address of the packet's destination address.

5 Cartesian Networks for Terrestrial Applications

The general description of wide area Cartesian networks discussed in the previous sections imposes no limits on the number of layers, and subsequently, the size of the address structure. Clearly, any implementation of a wide area Cartesian network will have limits imposed, either by the number of layers or by the size of the available address structure. As an example of a possible implementation of a wide area Cartesian network, the authors now consider a network for the Earth.

5.1 Terrestrial Layering

The Earth is nearly spherical, with an equatorial circumference of 40,075 km and a polar circumference of 39,940 km.The first step in developing the network is to project the Earth onto a two-dimensional surface, 40,075 km by 39,940 km.This is the *world* layer.

Since Cartesian routing is to take place at the world-layer, it is necessary to divide this layer into a grid of horizontal lines (the latitudes) and vertical lines (the longitudes). For simplicity, by using two bytes to represent the address of a layer (i.e., one byte for the latitude and the other for longitude), a layer can be divided into 2^{16} grid elements (subsequently referred to as *cantons*). Each canton is associated with its own IR.

At the world layer, each canton measures approximately 156 km by 156 km. These cantons, referred to as *areas*, can also be subdivided. If two bytes are used to identify cantons within an area, each canton (a *region*) measures about 611 metres by 611 metres. Subdividing a region into its cantons, results in a canton about 2.4 metres by 2.4 metres (a *subregion*). (A further division of a subregion would reduce the size of a canton to about 9.4 mm by 9.4 mm; this subdivision is not considered at this time.)

A four-layer model, with byte-pairs addressing cantons within each layer, allows a subregion to be identified on the Earth by using only six bytes. Table 1illustrates the different layers, their sizes, and possible examples.

Layer	Name	Size	Example
4	World	40,075 by 39,940 Km	The entire planet
3	Area	156 by 156 Km	Small country, state, or province
2	Region	611 by 611 metres	Village or several city blocks
1	Subregion	2.4 by 2.4 metres	Small room

Table 1: A four-layer mode for terrestrial addressing

5.2 Geopolitical Considerations

The layers proposed in the previous section for a terrestrial Cartesian network imply that a uniform, grid-like structure can be applied to the planet. Clearly, both geography and politics make such a structure impossible to achieve; however, despite this limitation, by allowing the size of a canton to vary, the four-layer model described above permits the handling of geopolitical boundaries.

In Figure 5, a boundary passes through canton B. Since it is not possible to associate the canton with more than one IR, it is necessary to allocate all or part of the canton to adjacent cantons. For example, the smaller portion of canton B could be allocated to canton C, increasing the size of C. The remainder of B could be assigned its own IR or even be allocated to canton A.

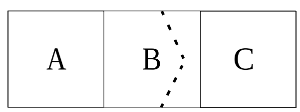

Figure 5: A boundary passing through a canton

When the size of a canton increases, the size of its encompassed cantons also increase. Similarly, if a canton decreases in size, its encompassed cantons also decrease in size.

5.3 Address Structures

The terrestrial four-layer model discussed above requires three address pairs (two-bytes each), as well as the local bit, required by Cartesian routers. If further addressing is expected to take place within a subregion, additional address space is required, over and above the three address pairs. For example, if eight byte EUI [1] addresses identify entities within a subregion, the address structure requires 113 bits and can be accommodated as a 128-bit IPv6 address.

5.4 Example

The following is an example of the rapid convergence of traversing from one layer to its encompassed layers. Figure 6 shows a possible division of the world layer over New York City and its environs; each of the squares is an area, 156 km by 156 km. If the area immediately over New York City is divided into regions, the nine regions in the centre of the area are represented in Figure 7; each of these squares is a region, 611 metres by 611 metres. Finally, Figure 8 shows the size of a subregion(the solid box in the centre of the map) within the region of New York City; the subregion is 2.4 metres by 2.4 metres.

Figure 6:New York area

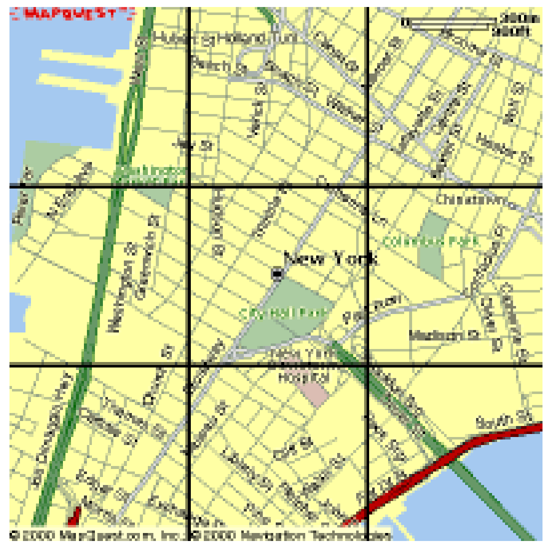

Figure 7:New York regions

Figure 8:A sub-region in New York

6 Limitations

The proposed wide area Cartesian network topology operates as a layered structure, with networks at layer-(n-1) communicating with other networks via internetwork routers (IR) through the encompassing layer-n. Limiting each network to one internetwork router leads to two related problems: the lack of fault tolerance and the distance from routers to the IR.

6.1 Fault Tolerance

The wide area Cartesian network discussed in this paper suffers from the same problem confronting the present generation Internet, notably that when four percent of the most important nodes are destroyed, the Internet loses its integrity, becoming fragmented into small, disconnected domains [5]. In the case of the wide area Cartesian network, communications between two networks via an encompassing network will cease should the internetwork router associated with either of the networks fail.

6.2 Internetwork Router Positioning

The position of an internetwork router, relative to that of other routers, will affect the performance of the network. Since a network has only one internetwork router leading to its encompassing network, all packets with addresses for non-local networks are forwarded to this router. The path taken by the packet to the internetwork router depends upon the location of the internetwork router and where the packet first enters the network, although traffic analysis can place the internetwork router in an optimal position in a network.

6.3 Discussion

By increasing the number of internetwork routers in a network, the fault tolerance of the entire network can improve, while potentially reducing the distance between routers and the internetwork routers.

Although increasing the number of internetwork routers has no impact on the wide area Cartesian routing algorithm, it does introduce a number of new problems; for example,

- each router's internetwork router direction indicator (IRDI) must be able to indicate that there are possibly multiple routes to the network's internetwork routers.
- if the top port of each internetwork router connects to a unique collector router in the encompassing network, the address associated with each of these collectors becomes problematic.

A number of solutions to these problems are currently under investigation and will be the subject of a subsequent paper.

7 Summary

The original Cartesian Routing algorithm, described in [3], has shown how a local or metropolitan network could operate without the use of routing tables. However, extending this algorithm to a larger region or even to an entire planet is problematic for a number of reasons: traversing a single, flat network could be time-consuming, while running disjoint networks leads to the problems of interleaving and overlapping.

The wide-area Cartesian Routing algorithm overcomes these problems by creating a hierarchical network consisting of two or more layers. Each network at a given layer encompasses one or more networks. Each network, regardless of its layer, employes the Cartesian Routing algorithm for packet routing. Two extensions to the original Cartesian Routing algorithm are required:

- each network (except for the highest) requires an internetwork router that can direct packets destined for other networks "up" to the encompassing network.
- the address structure reflects the network structure, with specific fields in the address associated with each layer.

Packet routing is still performed without the use of routing tables. When a packet is found with an address "outside" the current network, it is forwarded to the network's internetwork router which passes the packet out its top port to the encompassing network. This cycle is repeated recursively until a network is found that encompasses the destination network; at this point, the packet is forwarded "down" to its destination.

The use of a single internetwork router in each layer-(n-1) network to connect to the encompassing layer-n network is both a single point of failure and a potential bottleneck. Increasing the number of internetwork routers in each layer can overcome these limitations. The placement of the routers and where they connect in the encompassing network is presently the subject of further study.

The authors have recently complected the implementation of a collector router [4] and are in the process of building a small Cartesian network. A multi-layered demonstration network is presently in the design stage.

8 References

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