Title
System and method for routing packets in a content centric network using anonymous datagrams

Author
Garcia-Luna-Aceves, J.J.

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(54) **SYSTEM AND METHOD FOR ROUTING PACKETS IN A CONTENT CENTRIC NETWORK USING ANONYMOUS DATAGRAMS**

(71) Applicant: **CISCO TECHNOLOGY, INC.**, San Jose, CA (US)

(72) Inventor: **Jose J. Garcia-Luna-Aceves**, San Mateo, CA (US)

(73) Assignee: **Cisco Technology, Inc.**, San Jose, CA (US)

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CPC ***H04L 45/745*** (2013.01); ***H04L 45/021*** (2013.01); ***H04L 65/4076*** (2013.01)

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CPC .. H04L 45/745; H04L 65/4076; H04L 45/021
See application file for complete search history.

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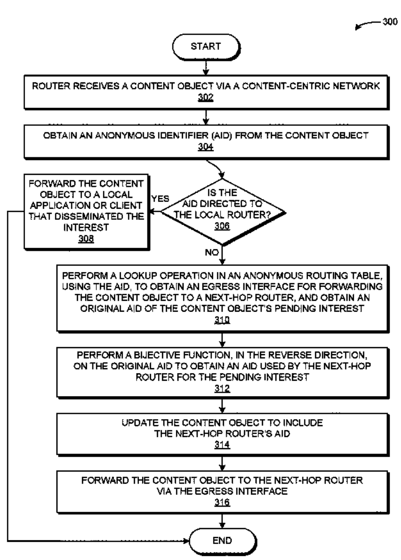
Primary Examiner — Andrew Lai
Assistant Examiner — Harry H Kim

(57) **ABSTRACT**

A router of a content centric network (CCN) can forward messages using anonymous identifiers. The router can receive an Interest via a first interface, and determines a first anonymous identifier (AID) that identifies a name-independent path to the Interest's source via the router. The router can identify a second interface for forwarding the Interest to a next-hop neighbor via CCN, and performs a bijective function on the first AID to obtain a second AID that is to be used by the next-hop neighbor to return a corresponding data packet to the router. The router updates the Interest to include the second AID, and forwards the Interest via the second interface toward the next-hop neighbor. When the router receives the data packet, the router performs a lookup operation in an anonymous routing table (ART), based on the AID, to determine an interface for forwarding the data packet toward the Interest's source.

23 Claims, 8 Drawing Sheets



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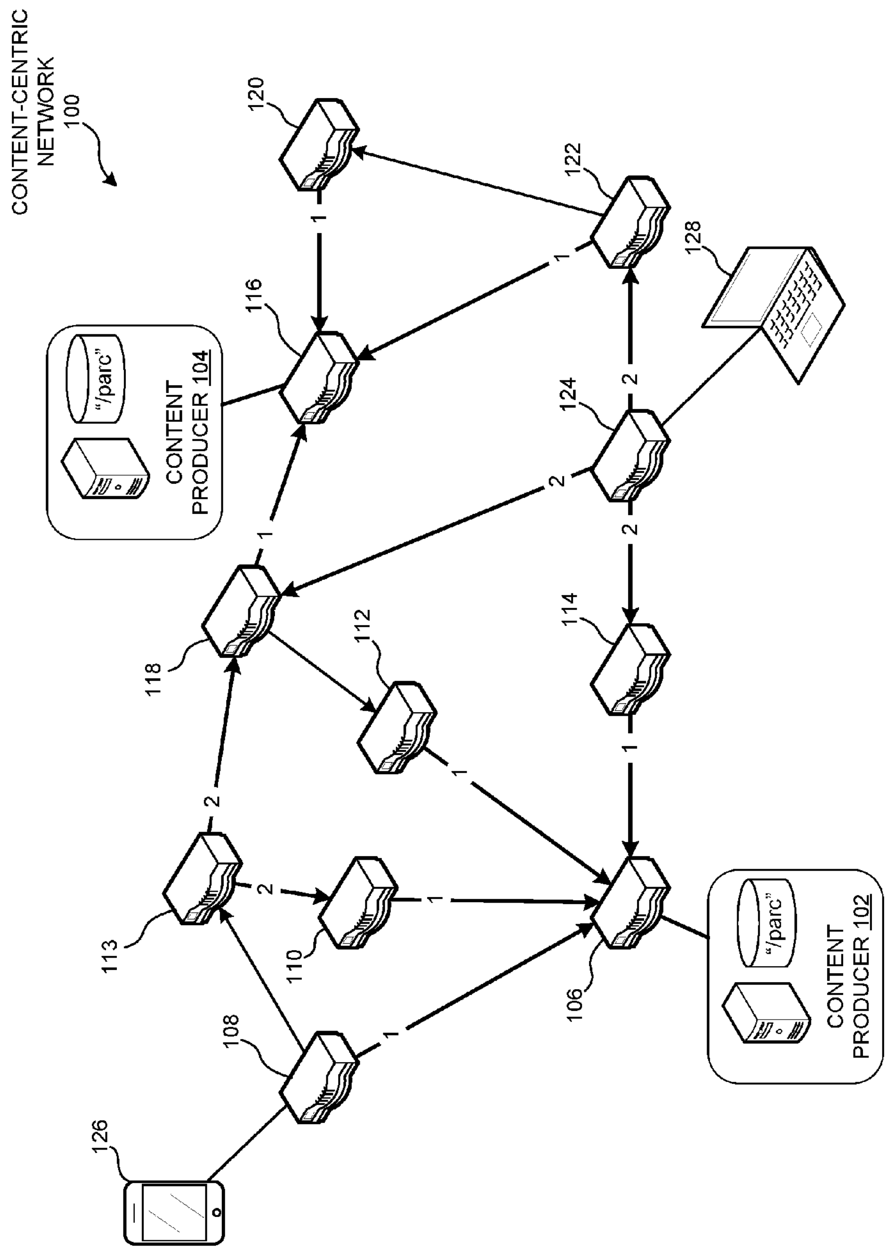
CONTENT-CENTRIC NETWORK 100
CONTENT PRODUCER 104
"/parc"
CONTENT PRODUCER 102
"/parc"
120
122
116
128
124
118
112
114
113
110
106
108
126
1
2

FIG. 1

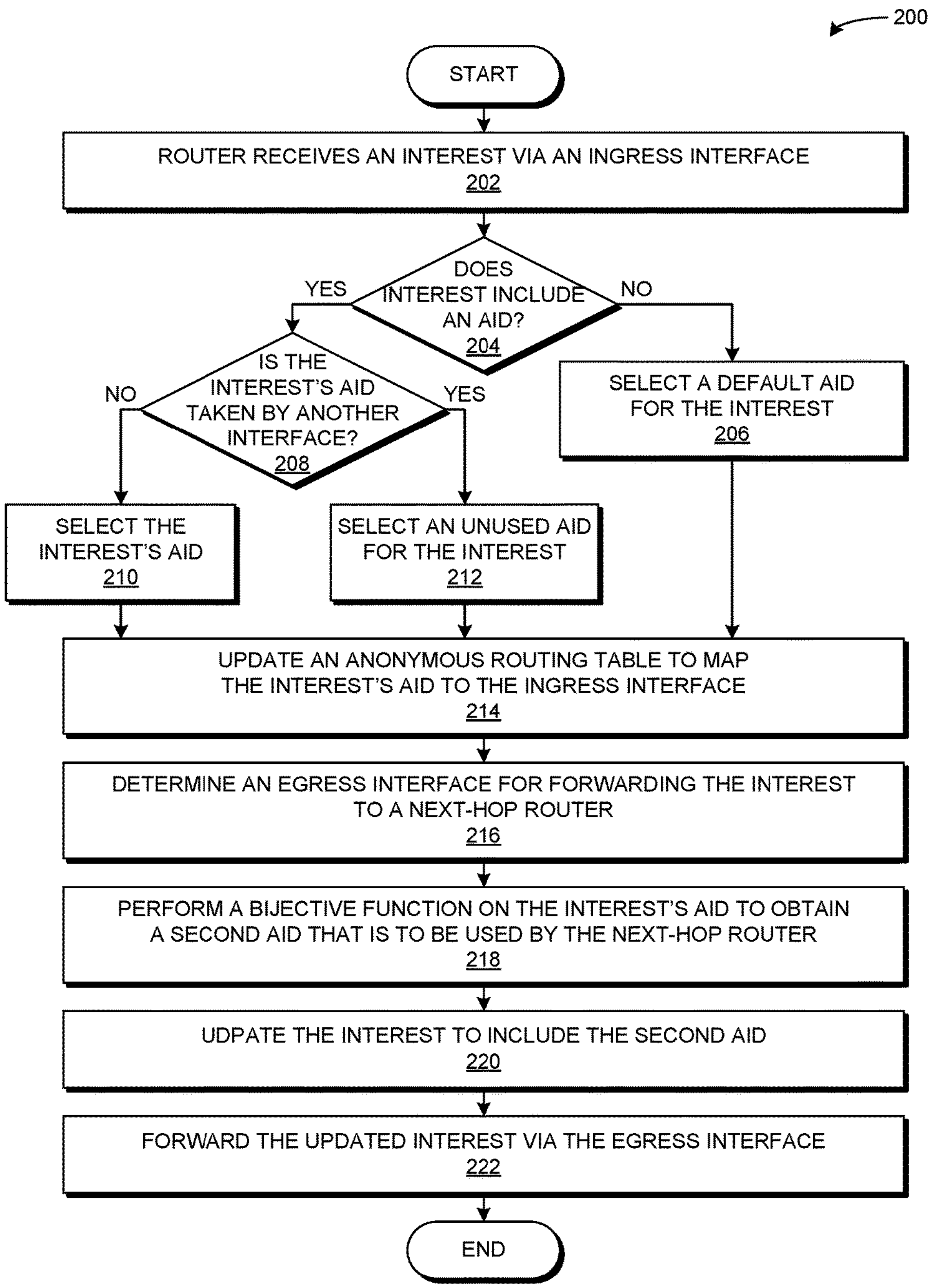
200
START
ROUTER RECEIVES AN INTEREST VIA AN INGRESS INTERFACE
202
DOES INTEREST INCLUDE AN AID?
204
YES
NO
IS THE INTEREST'S AID TAKEN BY ANOTHER INTERFACE?
208
NO
YES
SELECT A DEFAULT AID FOR THE INTEREST
206
SELECT THE INTEREST'S AID
210
SELECT AN UNUSED AID FOR THE INTEREST
212
UPDATE AN ANONYMOUS ROUTING TABLE TO MAP THE INTEREST'S AID TO THE INGRESS INTERFACE
214
DETERMINE AN EGRESS INTERFACE FOR FORWARDING THE INTEREST TO A NEXT-HOP ROUTER
216
PERFORM A BIJECTIVE FUNCTION ON THE INTEREST'S AID TO OBTAIN A SECOND AID THAT IS TO BE USED BY THE NEXT-HOP ROUTER
218
UDPATE THE INTEREST TO INCLUDE THE SECOND AID
220
FORWARD THE UPDATED INTEREST VIA THE EGRESS INTERFACE
222
END

FIG. 2

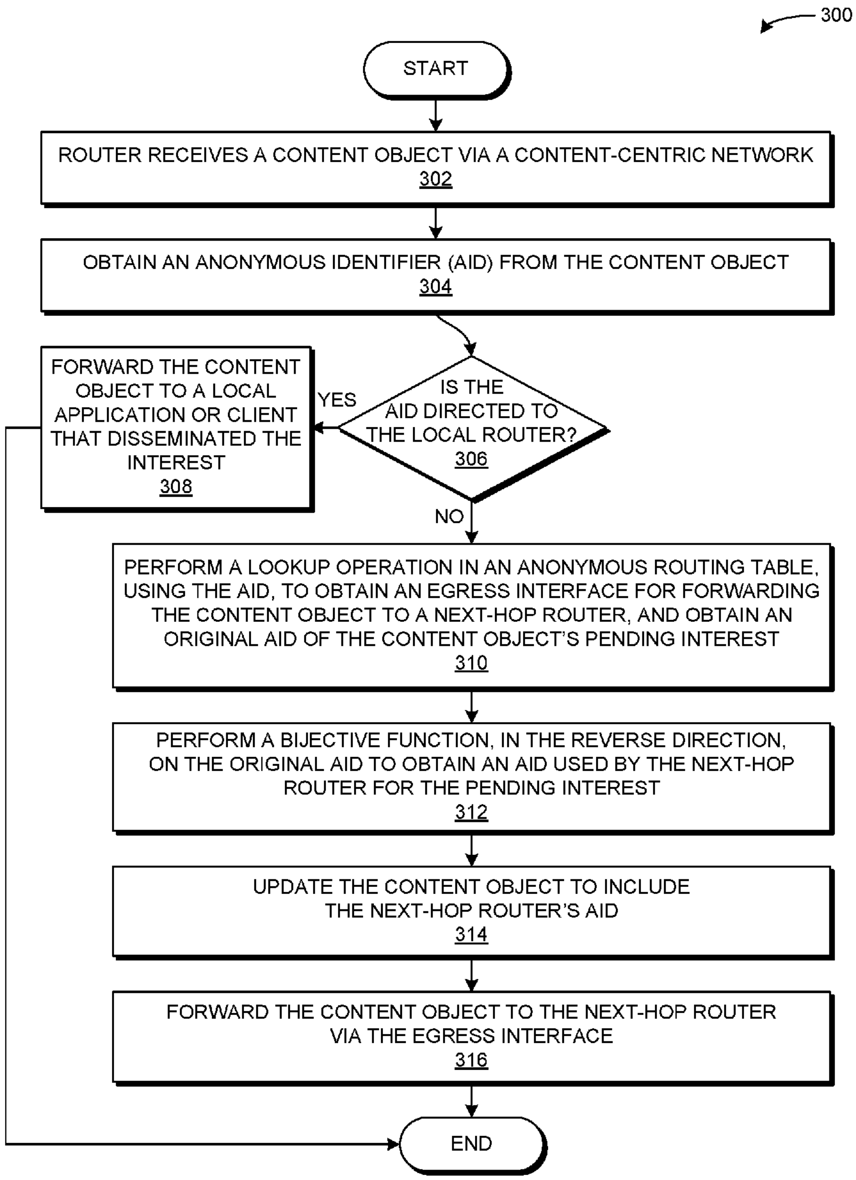
300
START
ROUTER RECEIVES A CONTENT OBJECT VIA A CONTENT-CENTRIC NETWORK 302
OBTAIN AN ANONYMOUS IDENTIFIER (AID) FROM THE CONTENT OBJECT 304
IS THE AID DIRECTED TO THE LOCAL ROUTER? 306
YES
FORWARD THE CONTENT OBJECT TO A LOCAL APPLICATION OR CLIENT THAT DISSEMINATED THE INTEREST 308
NO
PERFORM A LOOKUP OPERATION IN AN ANONYMOUS ROUTING TABLE, USING THE AID, TO OBTAIN AN EGRESS INTERFACE FOR FORWARDING THE CONTENT OBJECT TO A NEXT-HOP ROUTER, AND OBTAIN AN ORIGINAL AID OF THE CONTENT OBJECT'S PENDING INTEREST 310
PERFORM A BIJECTIVE FUNCTION, IN THE REVERSE DIRECTION, ON THE ORIGINAL AID TO OBTAIN AN AID USED BY THE NEXT-HOP ROUTER FOR THE PENDING INTEREST 312
UPDATE THE CONTENT OBJECT TO INCLUDE THE NEXT-HOP ROUTER'S AID 314
FORWARD THE CONTENT OBJECT TO THE NEXT-HOP ROUTER VIA THE EGRESS INTERFACE 316
END

FIG. 3

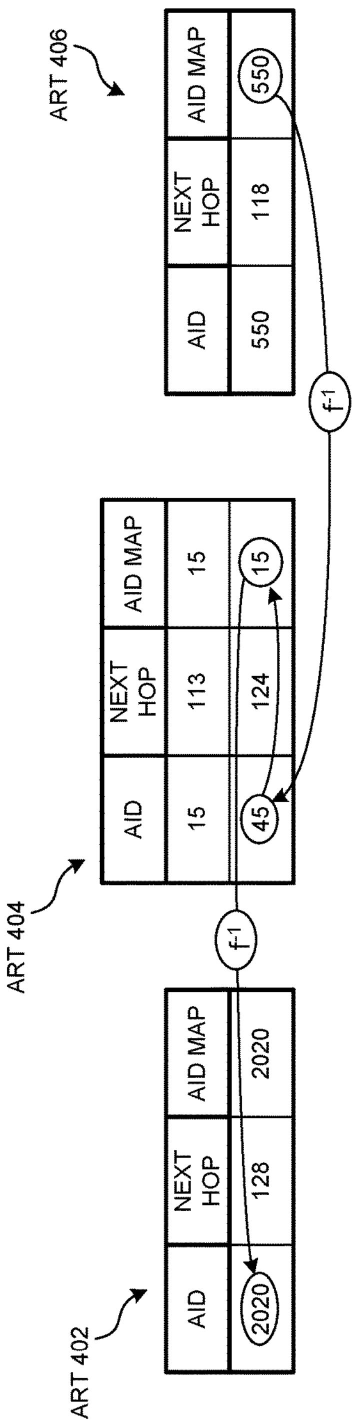

FIG. 4A

MART 450

GROUP NAME	AID	mc	NEXT HOPS
"/parc"	5	3	113, 124
"/parc"	5	2	112
"/parc"	8	2	124

FIG. 4B

NP-FIB 502

NAME PREFIX	ANCHOR	DISTANCE	NEXT HOP
"/parc"	106	2	114
"/alpha"	106	2	114
"/parc"	116	2	118
"/beta"	116	2	118
"/parc"	116	2	122
"/beta"	116	2	122

FIG. 5A

A-FIB 552

ANCHOR	NEXT HOP	DISTANCE
106	114	2
116	118	2
116	122	2

A-FIB 554

ANCHOR	NEXT HOP	DISTANCE
106	112	2
116	116	1

A-FIB 556

ANCHOR	NEXT HOP	DISTANCE
106	118	3

FIG. 5B

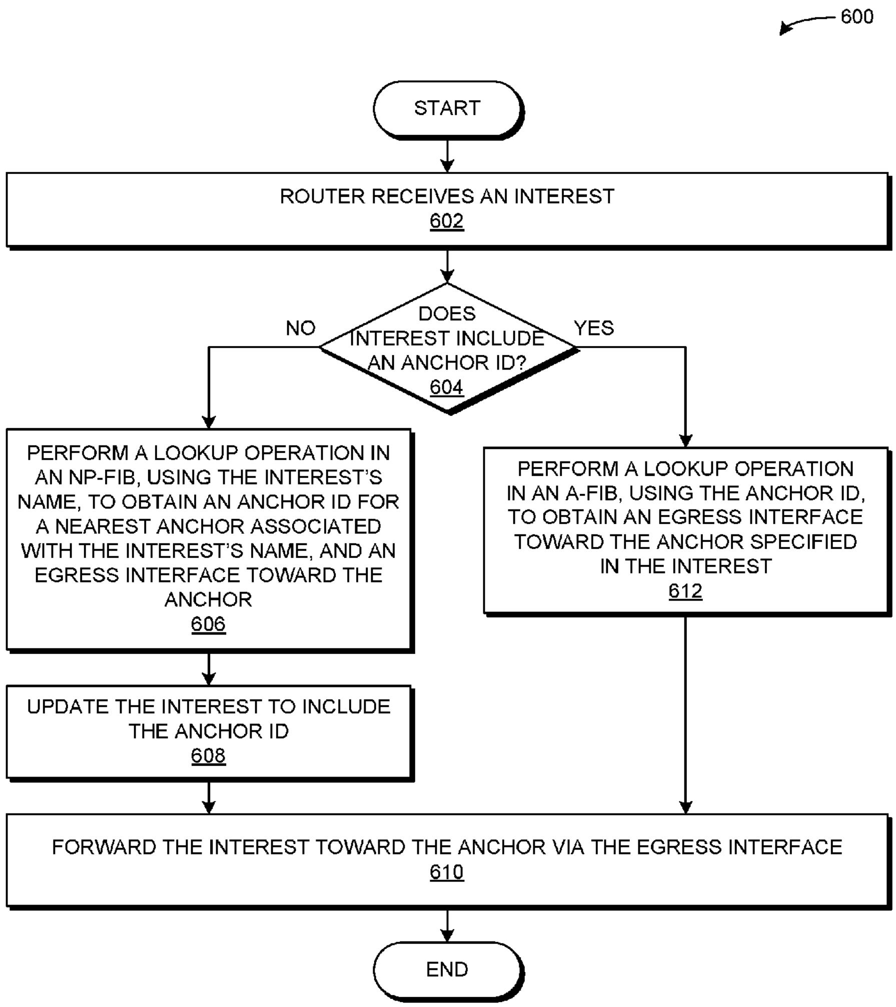
600
START
ROUTER RECEIVES AN INTEREST
602
DOES INTEREST INCLUDE AN ANCHOR ID?
604
NO
YES
PERFORM A LOOKUP OPERATION IN AN NP-FIB, USING THE INTEREST'S NAME, TO OBTAIN AN ANCHOR ID FOR A NEAREST ANCHOR ASSOCIATED WITH THE INTEREST'S NAME, AND AN EGRESS INTERFACE TOWARD THE ANCHOR
606
PERFORM A LOOKUP OPERATION IN AN A-FIB, USING THE ANCHOR ID, TO OBTAIN AN EGRESS INTERFACE TOWARD THE ANCHOR SPECIFIED IN THE INTEREST
612
UPDATE THE INTEREST TO INCLUDE THE ANCHOR ID
608
FORWARD THE INTEREST TOWARD THE ANCHOR VIA THE EGRESS INTERFACE
610
END

FIG. 6

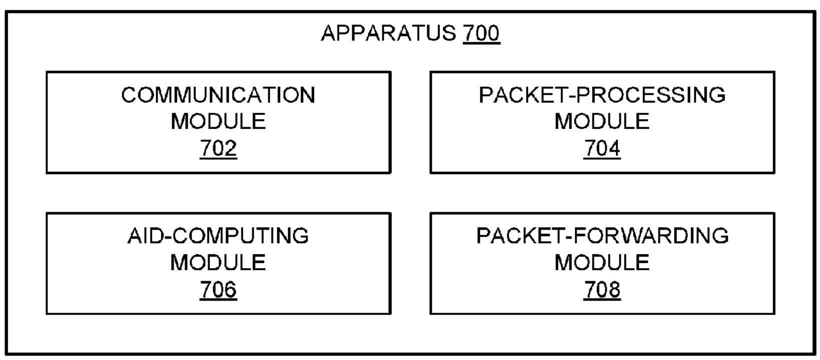
APPARATUS 700
COMMUNICATION MODULE 702
PACKET-PROCESSING MODULE 704
AID-COMPUTING MODULE 706
PACKET-FORWARDING MODULE 708

FIG. 7

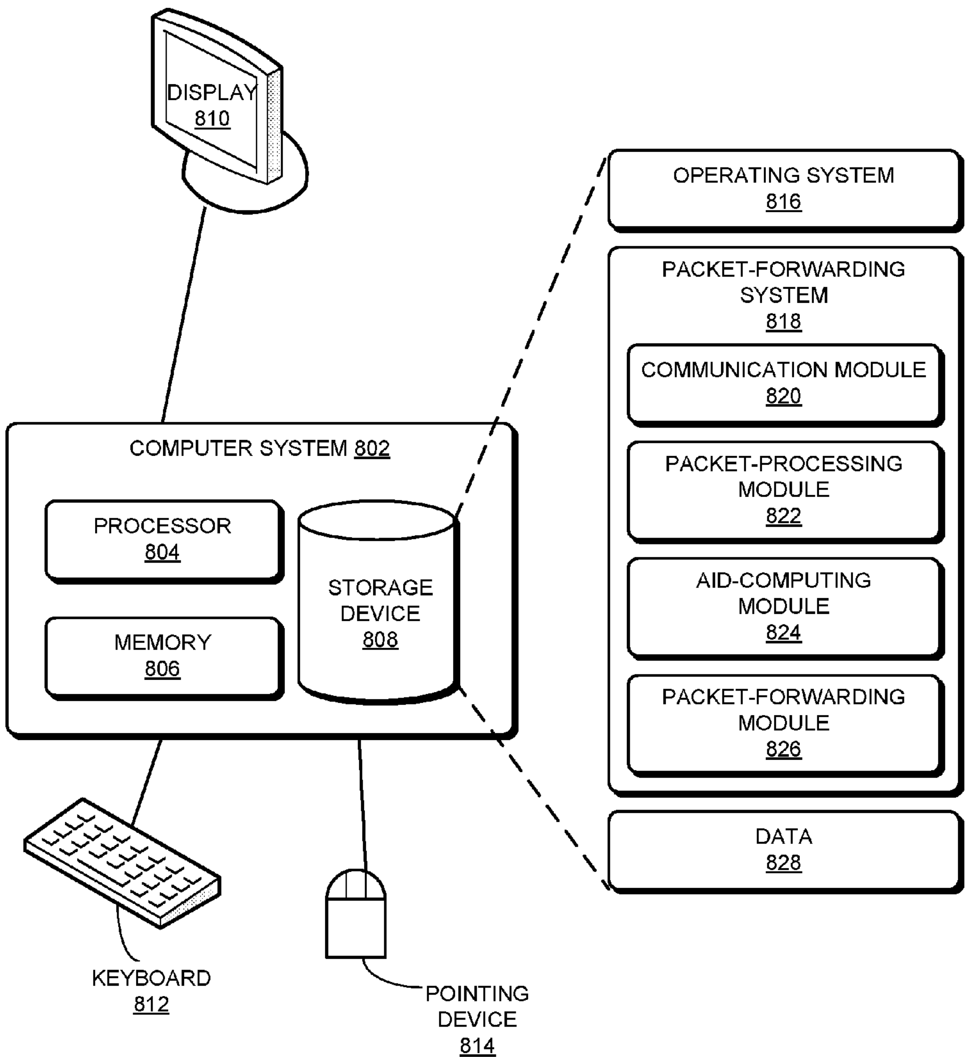
DISPLAY
810
OPERATING SYSTEM
816
PACKET-FORWARDING SYSTEM
818
COMMUNICATION MODULE
820
PACKET-PROCESSING MODULE
822
AID-COMPUTING MODULE
824
PACKET-FORWARDING MODULE
826
COMPUTER SYSTEM 802
PROCESSOR
804
MEMORY
806
STORAGE DEVICE
808
DATA
828
KEYBOARD
812
POINTING DEVICE
814

FIG. 8

SYSTEM AND METHOD FOR ROUTING PACKETS IN A CONTENT CENTRIC NETWORK USING ANONYMOUS DATAGRAMS

BACKGROUND

Field

This disclosure is generally related to a content centric network (CCN). More specifically, this disclosure is related to using anonymous datagrams for routing CCN packets.

Related Art

The proliferation of the Internet and e-commerce continues to fuel revolutionary changes in the network industry. Today, a significant number of information exchanges, from online movie streaming to daily news delivery, retail sales, and instant messaging, are conducted online. An increasing number of Internet applications are also becoming mobile. However, the current Internet operates on a largely location-based addressing scheme. The most ubiquitous protocol, the Internet Protocol (IP), is based on location-based address. That is, a consumer of content can only receive the content by explicitly requesting the content from an address (e.g., IP address) closely associated with a physical object or location. A request that has a URL with an IP address for a specific organization causes the request to go to that organization's servers and not to those of another organization.

Recently, content centric networking (CCN) architectures have been proposed in the industry. CCN brings a new approach to content transport. Instead of having network traffic viewed at the application level as end-to-end connections over which content travels, content is requested or returned based on its unique location-independent name, and the network is responsible for routing content from the provider to the consumer.

With content centric networks, there are generally two types of CCN messages: Interests and Content Objects. An Interest message includes a name for a Content Object, and a client can disseminate the Interest over CCN to obtain the Content Object from any CCN node that hosts the Content Object. The Interest is forwarded toward a CCN node that advertises at least a prefix of the Interest's name. If this CCN node can provide the Content Object, this node can return the Content Object (along the Interest's reverse path) to satisfy the Interest.

The CCN nodes generally use a forwarding information base (FIB) and a pending interest table (PIT) to map name prefixes to a neighbor via which the named content can be obtained. However, the FIB can become substantially large as the number of content producers grows across CCN, which may slow the lookup times at each node along a path between a content consumer and a content producer.

To make matters worse, the size of a node's PIT can increase in proportion to the number of pending Interests at the node. This may allow malicious entities to perform an Interest-flooding attack that virtually disables CCN forwarder nodes by flooding their PITs with erroneous Interests.

SUMMARY

One embodiment provides a packet-forwarding system that facilitates routing information centric networking (ICN) Interests using anonymous identifiers. During operation, a router can receive an Interest via a first interface of the router, and determines, for the Interest, a first anonymous identifier (AID) that identifies a name-independent path to the Interest's source via the router. The router can identify a second interface for forwarding the Interest to a next-hop neighbor via ICN, and performs a bijective function on the first AID to obtain a second AID that is to be used by the next-hop neighbor to establish a name-independent return path to the router. The router may then update the Interest to include the second AID, and may forward the Interest via the second interface toward the next-hop neighbor.

In information centric networks (ICN), each piece of content is individually named, and each piece of data is bound to a unique name that distinguishes the data from any other piece of data, such as other versions of the same data or data from other sources. This unique name allows a network device to request the data by disseminating a request or an Interest that indicates the unique name, and can obtain the data independent from the data's storage location, network location, application, and means of transportation. Named-data network (NDN) or a content-centric network (CCN) are examples of ICN architecture; the following terms describe elements of an NDN or CCN architecture:

Content Object:

A single piece of named data, which is bound to a unique name. Content Objects are "persistent," which means that a Content Object can move around within a computing device, or across different computing devices, but does not change. If any component of the Content Object changes, the entity that made the change creates a new Content Object that includes the updated content, and binds the new Content Object to a new unique name.

Unique Names:

A name in an CCN is typically location independent and uniquely identifies a Content Object. A data-forwarding device can use the name or name prefix to forward a packet toward a network node that generates or stores the Content Object, regardless of a network address or physical location for the Content Object. In some embodiments, the name may be a hierarchically structured variable-length identifier (HSVLI). The HSVLI can be divided into several hierarchical components, which can be structured in various ways. For example, the individual name components parc, home, ndn, and test.txt can be structured in a left-oriented prefix-major fashion to form the name "/parc/home/ndn/test.txt." Thus, the name "/parc/home/ndn" can be a "parent" or "prefix" of "/parc/home/ndn/test.txt." Additional components can be used to distinguish between different versions of the content item, such as a collaborative document.

In some embodiments, the name can include an identifier, such as a hash value that is derived from the Content Object's data (e.g., a checksum value) and/or from elements of the Content Object's name. A description of a hash-based name is described in U.S. patent application Ser. No. 13/847,814 (entitled "ORDERED-ELEMENT NAMING FOR NAME-BASED PACKET FORWARDING," by inventor Ignacio Solis, filed 20 Mar. 2013), which is hereby incorporated by reference. A name can also be a flat label. Hereinafter, "name" is used to refer to any name for a piece of data in a name-data network, such as a hierarchical name or name prefix, a flat name, a fixed-length name, an arbitrary-length name, or a label (e.g., a Multiprotocol Label Switching (MPLS) label).

Interest:

A packet that indicates a request for a piece of data, and includes a name (or a name prefix) for the piece of data. A data consumer can disseminate a request or Interest across an information-centric network, which CCN/NDN routers can propagate toward a storage device (e.g., a cache server) or a data producer that can provide the requested data to satisfy the request or Interest.

In some embodiments, the ICN system can include a content-centric networking (CCN) architecture. However, the methods disclosed herein are also applicable to other ICN architectures as well. A description of a CCN architecture is described in U.S. patent application Ser. No. 12/338,175 (entitled "CONTROLLING THE SPREAD OF INTERESTS AND CONTENT IN A CONTENT CENTRIC NETWORK," by inventors Van L. Jacobson and Diana K. Smetters, filed 18 Dec. 2008), which is hereby incorporated by reference.

In some embodiments, while determining the first AID, the router may select a default AID associated with the router as the first AID in response to determining that the Interest does not include an AID.

In some embodiments, while determining the first AID, the router may obtain an AID from the Interest.

In some variations on these embodiments, while determining the first AID, the router may select for the Interest, an AID that the router has not assigned to an interface different than the first interface, in response to determining that the router has mapped the Interest's AID to a third interface different than the first interface, selecting.

In some embodiments, the router may update an anonymous routing table (ART) to include an ART entry that maps the first AID to the first interface, if the ART entry does not exist in the ART.

In some variations on these embodiments, while updating the ART, the router may create the ART entry so that the ART entry maps the first AID to an AID specified in the original Interest.

In some embodiments, if the router determines that the Interest corresponds to a multicast stream, the router may update a multicast anonymous routing table (MART) to include a MART entry that maps a group identifier and the AID to at least the first interface, if the mapping does not exist in the MART.

In some variations on these embodiments, the Interest can include a multicast counter which identifies a starting sequence number for the multicast stream. Also, while updating the MART, the router may store the multicast counter in the MART entry.

In some embodiments, while performing the bijective function, the router may determine, from an ordered AID list corresponding to the next-hop neighbor, the second AID that corresponds to the first AID in a local ordered AID list for the router.

One embodiment provides a packet-forwarding system that facilitates routing ICN data packets using anonymous identifiers. During operation, a router may receive an ICN data packet that includes a response to a pending Interest. The router may obtain, from the ICN data packet, an anonymous identifier (AID) that identifies a name-independent path to the Interest's source via the router. The router may then perform a lookup operation in an anonymous routing table (ART), based on the AID, to determine an interface of the router for forwarding the ICN data packet toward the pending Interest's source. The router may update the ICN data packet to include an AID used by the next-hop neighbor for the pending Interest, and may forward the ICN data packet via the interface.

In some embodiments, while updating the ICN data packet, the router may obtain, from the ART, an ART entry that maps the ICN data packet's AID to an original AID of the pending Interest.

In some variations on these embodiments, while updating the ICN data packet, the router may perform a bijective function on the original AID to determine the AID used by the next-hop neighbor for the pending Interest.

In some embodiments, the ART may be a multicast anonymous routing table (MART), with a MART entry that maps the AID and a multicast group identifier of the ICN data packet to one or more next-hop neighbors of a multicast tree that are to receive the ICN data packet.

In some variations on these embodiments, the MART entry may include a multicast counter which identifies a sequence number for a next ICN data packet that the next-hop neighbors are to receive via the multicast tree. Moreover, the router may increment the multicast counter in the MART in response to forwarding the ICN data packet.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates an exemplary content-centric network in accordance with an embodiment.

FIG. **2** presents a flow chart illustrating a method for selecting an anonymous identifier for an Interest while forwarding the Interest in a content-centric network in accordance with an embodiment.

FIG. **3** presents a flow chart illustrating a method for forwarding a Content Object based on an AID associated with one or more pending Interests in accordance with an embodiment.

FIG. **4**A illustrates exemplary anonymous routing tables (ARTs) in accordance with an embodiment.

FIG. **4**B illustrates exemplary multicast anonymous routing tables (MARTs) in accordance with an embodiment.

FIG. **5**A illustrates exemplary name-prefix forwarding information base (NP-FIB) tables in accordance with an embodiment.

FIG. **5**B illustrates exemplary anchor forwarding information base (A-FIB) tables in accordance with an embodiment.

FIG. **6** presents a flow chart illustrating a method for determining an egress interface for forwarding an Interest based on an anchor's identifier in accordance with an embodiment.

FIG. **7** illustrates an exemplary apparatus that facilitates forwarding Interests and Content Objects based on anonymous datagrams in accordance with an embodiment.

FIG. **8** illustrates an exemplary computer system that facilitates forwarding Interests and Content Objects based on anonymous datagrams in accordance with an embodiment.

In the figures, like reference numerals refer to the same figure elements.

DETAILED DESCRIPTION

The following description is presented to enable any person skilled in the art to make and use the embodiments, and is provided in the context of a particular application and its requirements. Various modifications to the disclosed embodiments will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the present disclosure. Thus, the present invention is not limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed herein.

Overview

Embodiments of the present invention provide a packet-forwarding system that can use anonymous datagrams to establish name-independent unicast and multicast routes in an information-centric network (ICN), such as a content-centric network (CCN). CCN routers can use anonymous identifiers to establish a path to a content consumer, without having to store a per-Interest forwarding state to the consumer, and without having to store a global identifier for the consumer.

In some embodiments, a CCN Interest can specify a name for content, an anonymous identifier (AID), and a distance to a nearest content provider associated with a name prefix. Routers can use the AID to establish a path to the requester that disseminated the Interest, and can use the distance value to avoid establishing forwarding loops. The router can determine the distance based on a routing protocol in the control plane that populates the node's forwarding information base (FIB), and in some embodiments, may include the distance value in the FIB along with the name prefix.

Routers use can establish anonymous return paths without storing a per-Interest forwarding state by having each router along a path give its neighbors an AID to use when responding with a Content Object. This AID does not need to be globally unique across the network, and can vary between neighboring nodes along the return path. The AID only needs to be unique between the two neighbors (locally unique) for a path, and does not reveal information about the network clients from where the Interest originated. For example, if a router sees an AID value of 15, the router will not know whether the previous hop was the origin of the Interest or a relay for the Interest. However, the router can use the AID for performing a lookup operation in a local anonymous routing table (ART) to determine which neighbor has requested the Content Object.

Hence, the AID is only used for the purposes of forwarding a matching Content Object to the previous hop from where the Interest originated, but does not have a fixed association with a source of the Interest. The caching sites, relays, or the content producers will not know who asked for the content. Using the AID to establish a path to a consumer allows the forwarding operations to remain localized at each router along the path. If multiple consumers disseminate Interests to request the same content, each router only needs to keep track of the local neighbors that can be used to forward a Content Object with a given AID value; the local router does not need to keep track of all entities that have requested the content, and does not need to keep track of the Interests that have been received from these entities.

System Architecture

FIG. **1** illustrates an exemplary content-centric network **100** in accordance with an embodiment. CCN **100** can include content producers **102** and **104** for a name prefix "/parc." Content producer **102** can be accessed via a CCN router **106**, and content producer **104** can be accessed via router **116**. Routers **106** and **116** are hereinafter referred to as "anchors" for name prefix "/parc," as they are next-hop neighbors to content producers for the name prefix "/parc."

Routers across CCN **100** can populate a name-prefix FIB (NP-FIB) that maps a name prefix to an anchor identifier for a nearest anchor for the name prefix, and an interface toward the nearest anchor. The routers can also populate an anchor FIB (A-FIB) that maps each anchor identifier to a next-hop neighbor toward the anchor. For example, routers **106**, **108**, **110**, **112**, and **114** may create an NP-FIB entry which designates node **106** as the nearest anchor for the name prefix "/parc." Also, routers **118**, **120**, and **122** may create an NP-FIB entry which designates router **116** as the nearest anchor for the name prefix "/parc."

In some embodiments, some routers may include multiple NP-FIB entries for a given name prefix. For example, router **124** may include an NP-FIB entry that designates router **114** as the next-hop neighbor for anchor **106**, and may include another NP-FIB entry that designates anchor **118** as a next-hop neighbor toward anchor **116**.

CCN Interests typically do not include a name or identifier of a client that created and disseminated the Interest. Hence, when a gateway router receives an Interest from a client device, the gateway router can assign a local default AID value to any new Interest that the gateway router receives from a client device. For example, a client **128** can be coupled to gateway router **124**. Gateway router **124** can assign a default AID value of 2020 to any Interest received from client **128** (or from any other client), and can perform a lookup operation in the NP-FIB (e.g., based on the Interest's name) to identify an interface to a next-hop neighbor that can forward the Interest.

Gateway router **124** may then update a local ART to create an entry that maps the AID to the next-hop interface. Also, gateway router **124** can determine which Content Objects are directed to itself when gateway router **124** receives a Content Object with its default AID value (e.g., default AID value **2020** for router **124**), and proceeds to return the Content Object to client **128** instead of routing the Content Object to another router.

In some embodiments, gateway router **124** can also insert a distance value to the Interest along with the AID. For example, when router **124** receives the Interest from client **128**, router **124** can obtain the expected distance to anchor router **116** from the FIB (along with the local interface toward anchor router **116**). Then, other routers that forward the Interest can decrement the distance value in the Interest prior to forwarding the Interest toward an anchor router.

Recall that the AID values are local to neighboring nodes. In some embodiments, it may be possible for collisions to occur between AID identifiers when a router receives Interests with the same AID from two different neighboring routers. For example, router **118** may receive Interests with the same AID from routers **113** and **124**. To handle these collisions, router **118** can choose an unused AID value for the Interest, and can map the new AID value to the Interest's original AID value in the ART. Router **118** can create an ART entry that specifies an "AID" field for the Interest's original AID value, and an "AID-map" field for the new AID value.

Once router **118** creates the ART entry (if the ART entry doesn't exist), router **118** can perform a bijective function (e.g., a two-way function) on the Interest's local AID value before forwarding the Interest to the next-hop router. For example, each router may have a set of AID values that it can accept, such that neighboring nodes may or may not have overlapping AID values. The bijective function may map an AID value from one router's set to a corresponding AID value in the next-hop router's set. Router **118** can replace an Interest's AID value with the next-hop router's AID value before forwarding the Interest to next-hop router **116**, which happens to be an anchor for the CCN collection "/parc."

In some embodiments, the routers across CCN **100** can implement a loop-free forwarding rule (LFR) to avoid forwarding Interests in loops. For example, a router i may accept an Interest I[n(j), $AID^I(k)$, $D^I(k)$] from router k if:

$$\exists v \in S^{i}_{n(j)}{}^{*}(D^I(k) > D(i, n(j)^{*}, v)) \tag{1}$$

Equation (1) provides an exemplary LFR that may be used by router i at runtime. In equation (1), $S^i_{n(j)}$ denotes a set of next-hop neighbors of router i for a name prefix n(j)*, $D^I(k)$ denotes the distance specified in an Interest from router k, and D(i, n(j)*, v) denotes a distance stored by a neighbor v of router i for the name prefix n(j)*.

Once anchor router **116** receives the Content Object, the router can obtain the ART entry using the Content Object's AID, and can perform the bijective function on the ART entry's AID-map value. Router **116** then inserts the resulting AID value from the reverse-bijective function into the Content Object before returning the Content Object to router **118**. Router **118** also performs the lookup operation in the local ART, and updates the Content Object's AID (by performing the reverse-bijective function) before forwarding the Content Object to gateway router **124**.

In some embodiments, replacing the CCN pending Interest table (PIT) with the ART provides storage and runtime improvements when establishing return paths. The ART can have an expected size that is in the order of the number of routes that traverse the router, regardless of the number of Interests that may be pending along those routes. So for example, when router **124** sends any Interest along the path to router **118**, these Interests will have the same AID (e.g., **2020**). In contrast, the PIT would need to store a number of entries in the order of the number of the Interests that traverse the router, given that the PIT would need to store an entry for each pending Interest that has not timed out (a per-Interest state).

Moreover, performing a lookup operation in the ART can be faster than performing a lookup operation in a CCN PIT, given that the ART is substantially smaller than the PIT, and because searching the ART may not need a longest-prefix matching lookup operation. The ART does not store a name or name prefix, which allows a router to find an entry based on a single value (e.g., the AID) without having to perform a longest-matching prefix lookup operation.

Forwarding Interests

FIG. **2** presents a flow chart illustrating a method **200** for selecting an anonymous identifier for an Interest while forwarding the Interest in a content-centric network in accordance with an embodiment. During operation, the router can receive an Interest via an ingress interface (operation **202**), and determines whether the Interest includes an AID (operation **204**). If the Interest does not include an AID, the router can select a default AID for the Interest (operation **206**).

Otherwise, if the Interest does specify an AID, the router determines whether the Interest's AID is already associated with a local interface different than the Interest's ingress interface (operation **208**). If the AID is not taken, the router selects the AID specified in the Interest (operation **210**); otherwise, the router can select an unused AID for the Interest (operation **212**). Once the router selects an AID for the incoming Interest, the router may then update an anonymous routing table (ART) to include an ART entry that maps the selected AID to the ingress interface, if the ART entry does not already exist (operation **214**).

The router may then select an egress interface for forwarding the Interest to a next-hop router, such as by performing a lookup operation in a FIB, an NP-FIB, or an A-FIB (operation **216**). The router may perform a bijective function on the Interest's AID to obtain a second AID that is to be used by the next-hop router (operation **218**), and updates the Interest to include the second AID (operation **220**). The router may then forward the Interest to the next-hop router via the egress interface (operation **222**).

Bijection Function

When a local router selects a next-hop router for forwarding the Interest, the router can select an anonymous identifier (AID) that the next-hop router is to use for the Interest. In some embodiments, the local router can use a bijective function to map a local AID for the Interest to the next-hop AID that is to be used by the next-hop router. One possible implementation of this bijective function can be realized by having each router provide a Local interval of Identifiers (LI) list to its neighbors, which specifies the AIDs accepted by the router. Then, to perform the bijection, a local router can determine an index to the local AID in the local router's LI, and uses the index to perform a lookup operation in its neighbor's LI to obtain the neighbor's AID for the Interest. Hence, the LI lists provides an effective way of controlling which AIDs can be used locally by each router, and provide a one-to-one AID mapping between neighboring routers.

If each LI list has a set of sequential numbers, the bijection numbers can be computed by a router s using the equation:

$$AID_B=\alpha+(AID_A-LI_A(s))+(LI_B(s)\bmod|LI|) \quad (2)$$

Equation (2) includes simple mathematical operations that can be computed quickly by a processor's arithmetic unit. The value AID_A corresponds to the Interest's AID (which is a member of the local node's LI list). The value $(AID_A-LI_A(s))$ provides the index of AID_A in LI_A (e.g., the offset from the starting value $LI_A(s)$ in LI_A), and the value ($LI_B(s)$ mod $|LI|$) provides the starting value of $LI_B(s)$.

Hereinafter, the notation $f_i(n)$ denotes the bijective mapping performed by router i, using an LI list from neighbor n $LI^i(n)$, in the forward direction from $LI^i(i)$ to $LI^i(n)$. Also, the notation $f_i^{-1}(n)$ denotes the bijective function performed by router i in the reverse direction using the LI list from neighbor n. The bijective functions and reverse bijective functions are two-way functions, which allows: $f_i^{-1}(n)[f(n)[a]]=a$. Also, in some embodiments, neighboring nodes can reverse a bijective function when returning a data packet: $f_n(i)[f_i(n)[a]]=a$.

In some embodiments, neighboring routers can exchange LI lists with their neighbors in the data plane using Interests and data packets, or in the control plane as part of the routing protocol. For example, the neighboring routers can exchange LI lists in HELLO messages, link-state advertisements, or distance updates.

Table 1 provides an exemplary algorithm for processing an Interest from a consumer c at a router i, and Table 2 provides an exemplary algorithm for processing an Interest from a router p at a router i. In Tables 1 and 2, and hereinafter, the notation n(j) represents a name prefix, and $D^I(p)$ represents a distance specified in the Interest from router p. $AID^I(p)$ represents an AID for an Interest from router p (which router p computed using the bijection function $f_p(s)$ for neighbor s), and $AID^R(i)$ represents an AID for a return packet from router i (which router i computed using the reverse-direction bijection function $f_i^{-1}(s)$ for neighbor s).

Based on these notations, the notation I[n(j), $AID^I(p)$, $D^I(p)$] represents an Interest from router p, such that the Interest specifies a name prefix n(j), an Interest AID with value $AID^I(p)$, and a distance $D^I(p)$. Similarly, the notation DP[n(j), $AID^R(i)$, sp(j)] represents a data packet being returned by router p (e.g., a Content Object), such that the data packet specifies a name prefix n(j) (or a CCN name that includes prefix n(j)), a response AID with value $AID^R(i)$, and a payload sp(j) that corresponds to name prefix n(j).

In some embodiments, the router may need to return a negative acknowledgement (NACK) when the router may not be able to forward the Interest, or may not be able to receive a response data packet. The notation NA[n(j), $AID^R(i)$, CODE] represents NACK from router i, such that the NACK specifies a name prefix n(j), a response AID with value $AID^R(i)$, and a NACK code or message that states a reason for the NACK response. For example, a router may return a NACK response when the router detects an Interest loop, when a route to a name prefix n(j) or a corresponding anchor is not found, or when the requested content is not found by the content producer.

The CCN routers may maintain a set of data structures that facilitate forwarding Interests and/or Content Objects based on AID values. Specifically, router i may include at least a $LIGHT^i$, a LISTi, a FIB^i, and an ART^i data structure.

The notation $LIGHT^i$ stands for Local Interests Gathered Table, and denotes a set of names of the Content Objects (COs) that router i has requested (e.g., pending Interests), or has stored (e.g., cached COs). $LIGHT^i$ may take a name prefix n(j) as input (e.g., as the index), and each $LIGHT^i$ entry can include a CO name n(j), a pointer to the content of the CO (p[n(j)]), and a local consumer list lc[n(j)]. The notation lc[n(j)] denotes a list of local consumers with pending Interests for the name prefix n(j).

The notation $LIST^i$ stands for Local Interval Set Table, and denotes a set (e.g., a sequential interval) of anonymous identifiers (AIDs) used by router i. For each neighbor k, $LIST^i$ states the local interval of identifiers accepted by router k ($LI^i(k)$), and the local interval of identifiers accepted by router i ($LI^i(i)$). Given that neighboring routers exchange LI lists with each other, $LI^i(k)=LI^k(k)$. In some embodiments, all local intervals have the same length, |LI|. The notation map(ART^i) denotes an AID mapping in the ART of router i, which router i may use to identify potential AID collisions.

FIB^i denotes a forwarding information base at router i (e.g., a CCN FIB, an NP-FIB, and/or an A-FIB), and ART^i denotes an anonymous routing table at router i (e.g., a unicast ART, or a multicast ART). The FIB^i entries specify a distance reported by each next-hop neighbor for a given name prefix. The notation D(i, n(j)*, s) denotes a distance stored by a neighbor s of router i for the name prefix n(j)*. In some embodiments, router i stores each entry in the FIB^i for at most a time duration determined by a lifetime of the corresponding entry in the routing table of router i. ART^i may take an anonymous identifier as input (e.g., as the index), which is a member of $LI^i(i)$. Each ART^i entry ART^i[AID, s, map] may specify an AID(ART^i)∈$LI^i(i)$, an interface to a next hop neighbor s toward the destination, and an identifier mapping map(ART^i)∈$LI^i(i)$ which router i may use to handle identifier collisions.

TABLE 1

```
function Interest_Source
INPUT: LIGHT^i, LIST^i, FIB^i, ART^i, AID^i, I[n(j), c, nil];
if n(j) ∈ LIGHT^i then
  if p[(n(j)] ≠ nil then
    retrieve CO n(j);
    send DP[n(j), c, sp(j)] to consumer c;
  else
    p[n(j)] = nil;
    lc[n(j)] = lc[n(j)] ∪ c;              (Interest is aggregated)
  end if
else
  if n(j)* ∈ LIGHT^i then
    send NA[n(j), c, no content];         (n(j) does not exist)
  else
```


TABLE 1-continued

```
    if n(j)* ∉ FIB^i then
      send NA[n(j), no route, c] to c; (No route to n(j)* exists)
    else
      create entry for n(j) in LIGHT^i; (Interest from c is recorded);
      lc[n(j)] = lc[n(j)] ∪ c;
      p[n(j)] = nil;
      for each v ∈ N^i by rank in FIB^i do
        if AID^i = nil then
          SET = Ø;
          for each entry ART^i[AID, v, map] do
            SET = SET ∪ {AID};
          end for
          select a ∈ LI^i(i) − SET;
          AID^i = a;
          create entry ART^i[AID^i, i AID^i]
        end if
        AID^i(i) = f_i(v)[AID^i];
        D^I(i) =D(i, n(j)*, v);
        send I[n(j), AID^I(i), D^I(i)] to v;
        return;
      end for
    end if
  end if
end if
```

TABLE 2

```
function forwarding
INPUT: LIGHT^i, LIST^i, FIB^i, ART^i, I[n(j), AID^I(p), D^I(p)];
AID^R(i) = AID^I(p);
if n(j) ∈ LIGHT^i then
  if p[(n(j)] ≠ nil then
    retrieve CO n(j); send DP[n(j), AID^R(i), sp(j)] to router p;
  end if
else
  if n(j)* ∈ LIGHT then
    send NA[n(j), AID^R(i), no content] to p;    (n(j) does not exist)
  else
    if n(j)* ∉ FIB^i then
      send NA[n(j), AIDR(i), no route] to p;    (No route to n(j)* exists)
    else
      for each s ∈ N^i by rank in FIB^i do
        if D^I(p) > D(i, n(j)*, s) then              (LFR is satisfied)
          SET = Ø; AID^I(i) = nil; collision = 0;
          for each entry ART^i[AID, s, map] do
            SET = SET ∪ {AID};
            if AID(ART^i) = AID^I(p) then
              if s(ART^i) = p then
                AID^I(i) = f(s)[AID(ART^i)];
              else
                collision = 1;
              end if
            end if
            if map(ART^i) = AID^I(p) and s(ART^i) = p then
              AID^I(i) = f(s)[AID(ART^i)];
            end if
          end for
          if collision = 0 and AID^I(i) = nil then
            create entry ART^i[AID^I(p), p, AID^I(p)]; AID^I(f_i(s)[AID^I(p)];
          end if
          if collision = 1 and AID^I(i) = nil then
            select a ∈ LI^i(i) − SET;
            create entry ART^i[a, p, AID^i(p)]; AID^I(i) = f_i(v)[a];
          end if
          D^I(i)=D(i, n(j)*, s); send I[n(j), AID^I(i), D^I(i)] to s;
          return;
        end if
      end for     (LFR is not satisfied; Interest may be traversing a loop)
      send NA[n(j), AID^R(i), loop] to p;
    end if
  end if
end if
```

Forwarding Content Objects

FIG. **3** presents a flow chart illustrating a method for forwarding a Content Object based on an AID associated with one or more pending Interests in accordance with an embodiment. During operation, the router can receive a Content Object via CCN (operation **302**), and obtains an AID from the Content Object (operation **304**). The router may then determine if the AID is directed to the local router, such as by determining whether the AID matches the local router's default AID value (operation **306**). If so, the router is a gateway for a local application or a client device from where the Interest originated, and can proceed to forward the Content Object to the local application or client device (operation **308**).

However, if the AID is not directed to the local router, the router can perform a lookup operation in an ART, using the AID as input, to obtain an egress interface for forwarding the Content Object to a next-hop router, and to obtain an original AID of the Content Object's pending Interest (operation **310**). The router may then perform a bijective function, in the reverse direction, on the original AID to obtain the AID which the next-hop router used for its pending Interest (operation **312**). The router then updates the Content Object to include the next-hop router's AID (operation **314**), and forwards the Content Object to the next-hop router via the egress interface (operation **316**).

FIG. **4**A illustrates exemplary anonymous routing tables (ARTs) in accordance with an embodiment. ART **402** can correspond to router **124** of CCN **100** (FIG. **1**), ART **404** can correspond to router **118** of CCN **100**, and ART **406** can correspond to router **116** of CCN **100**. When router **124** receives an Interest from client **128**, router **124** can assign the default AID **2020** to the Interest, and creates an ART entry that maps AID **2020** to client **128**.

Router **124** then performs a bijective function on AID **2020** to obtain AID **15** for router **118**, and sends the Interest to router **118** using AID **15**. However, if router **118** already has an entry with the AID value **15**, router **118** may create a new entry in ART **404** that maps a new AID value **45** to router **124** and to AID **15**. Router **118** then performs the bijective function on AID **45** to obtain an AID value **550** for router **116**, and forwards the Interest to router **116** using AID value **550**. Router **116** creates a new entry in ART **406** that maps AID **550** to router **118**.

Once router **116** receives a Content Object for the Interest, router performs the bijective function on AID **550** (from the "AID MAP" field), in the reverse direction, to return the Content Object using AID value **45**. Then, router **118** performs a lookup operation in ART **404** using AID **45** to identify router **124** as the next-hop router, and to obtain AID value **15**. Router **118** also performs the bijective function, in the reverse direction, on AID value **15** to forward the Content Object to router **124** using the AID value **2020**.

Table 3 presents an algorithm implemented by a router to return a data packet, and Table 4 presents an algorithm implemented by the router to return a NACK.

TABLE 3

```
function Data Packet
INPUT: LIGHT^i, LIST^i, ART^i,DP[n(j), AID^R(p), sp(j)];
verify sp(j);
if verification of sp(j) fails then
   discard DP[n(j), AID^R(s), sp(j)];
end if
a =f_i^-1(s)[AID^R(s)];
retrieve entry ART^i[a, p, m];
if ART^i[a, p, m] does not exist then
   drop DP[n(j), AIDR(s), sp(j)];
end if
if p=i then
   for each c ∈ lc[n(j)] do
      send DP[n(j), c, sp(j)] to c;
```

TABLE 3-continued

```
      lc[n(j)] = lc[n(j)] − {c};
   end for
else
   if p ∈ N^i then
      AID^R(i) = m;
      send DP[n(j), AID^R(i), sp(j)] to p;
   end if
end if
if no entry for n(j) exists in LIGHT^i then
   create LIGHT^i entry for n(j): lc[n(j)] = Ø;
end if
store CO in local storage;
p[n(j)] = address of CO in local storage;
```

TABLE 4

```
function NACK
INPUT: LIGHT^i, LIST^i, ART^i, NA[n(j), AID^R(s), CODE];
a =f_i^-1(s)[AID^R(s)];
retrieve entry ART^i[a, p, m];
if ART^i[a, p, m] does not exist then
   drop NA[n(j), AID^R(s), CODE];
end if
if p=i then
   for each c ∈ lc[n(j)] do
      send NA[n(j), c, CODE] to c;
   end for
   delete entry for n(j) in LIGHT^i;
else
   if p ∈ N^i then
      AID^R(i) = m;
      send NA[n(j), AID^R(i), CODE] to p;
   end if
end if
```

Multicast Anonymous Routing Table

In CCN, when clients disseminate Interests for a multicast stream, these Interests create return paths by creating entries in the PITs along CCN routers toward the multicast source. These return paths form a multicast tree traversed by the multicast packets. However, because ARTs keep track of paths to clients and don't keep track of Interests, a basic ART may not be able to keep track of the recipients in a multicast tree.

In some embodiments, routers can use a multicast anonymous routing table (MART) to provide support for multicast packets, without having to store per-Interest forwarding state along the routers in a multicast tree. The MART maintains a per-group forwarding state, unlike the ART which maintains a per-path forwarding state, and unlike a PIT that maintains a per-Interest forwarding state. When a neighbor forwards an Interest associated with a multicast group to a router, the router can add the neighbor to the list of next-hop neighbors that have joined the multicast group. If two neighbors use the same multicast AID, the router can aggregate these neighbors in the next-hop list of the same multicast group in the MART.

For example, in some embodiments, the MART may not need to store state information for the content being transmitted along the multicast tree. Also, similar to the ART, the MART does not need to store a per-Interest forwarding state. If a neighbor forwards another Interest directed to the same multicast group to the same router, the router may not need to create a new entry for the multicast group, even if the name associated with the Interest is directed to different content (e.g., even if the name has a different name prefix).

On the other hand, if two neighbors use a different multicast AID for the multicast group, the router may create a separate MART entry for each new multicast AID and multicast-group name combination. These MART entries across CCN routers create a multicast forwarding tree (MFT) for a given multicast-group's name along the CCN routers. Because of this, the size of the MART can grow proportionally to the number of gateway routers that join the multicast group, and not based on the number of Interests that have been disseminated for a name prefix associated with the multicast group.

In some embodiments, the identity function used to obtain a multicast AID for a multicast group is a type of bijective function (e.g., has a one-to-one mapping). For example, a router can forward multicast Interests using a process similar to how unicast Interests are forwarded. However, when performing the bijective function on a multicast AID, the router can use a multicast identifier (MI) list instead of the LI list. Also, multicast routing allows collisions to occur between multicast AIDs for the same multicast group, so the MART may not need to map an Interest's AID to a different locally-unique AID.

The router can maintain a local MI list, and may share the MI list with its neighbors. When the router or its neighbors perform the bijective function to determine the multicast AID for the next-hop router, they may select a multicast AID associated with the multicast group in the MI list. This way, if multiple nodes are forwarding an Interest for the same multicast group to the same router, these neighbors can use the router's MI list to select the same multicast AID to assign to the multicast Interest before forwarding the Interest to the router.

CCN traditionally implements a pull technique, where clients need to disseminate an Interest for each Content Object they receive, both for unicast and multicast streams. However, push content dissemination can provide advantages for multicast streams. In some embodiments, the MART can include a field for a multicast counter (mc) that routers can use to support both push and pull content dissemination.

Routers can use the mc field to implement push dissemination by increasing the value of the mc counter after they forward each Content Object in a stream's sequence across the MFT. For example, a gateway router can support push-based multicast routing by forwarding a multicast Interest that includes an initial mc value to establish a path to a multicast content producer. Then, the content producer can push a sequence of NDN messages along the multicast tree, without the client having to disseminate additional Interests. In some embodiments, a router in the MFT can remove the MART entry if the MFT times out (e.g., if a message is not forwarded across the multicast tree for a predetermined time interval).

It's far easier to keep an mc counter than it is to keep per-Interest entries in the MART. The mc counter indicates a sequence identifier of the next message that the clients are to receive, and routers may not need to remove the corresponding MART entry after a message is forwarded across the MFT. The content producer can return each Content Object, one at a time, with the corresponding mc counter in the Content Object. As each router in the MFT receives the next message, the router can perform a lookup in the MART based on the group name, the multicast AID, and the mc counter to obtain the list of next-hop routers. The router can then increment the mc counter in the MART entry when the router forwards the Content Object to the next-hop routers along the MFT. For example, the multicast data packet (e.g., a Content Object) can have the following data structure: $DP[g(j), AID^R(i), sp(j), mc^R(i), payload]$, where g(j) states a name of a multicast group, $AID^R(i) \in MIi(i)$, sp(j) represents a security payload for the multicast group, and $mc^R(i)$ represents the multicast counter for the return data packet (e.g., a Content Object payload, or a NACK code).

CCN clients and routers can also specify an mc field in multicast Interests to implement pull-based dissemination by allowing clients to use the mc counter to implement a source-pacing algorithm. Different clients can start a stream at different times, or can request stream packets at different rates, by specifying an mc counter in the multicast Interest for each Content Object in the multicast stream. The clients can increase the value of the mc counter for each additional multicast Interest that they disseminate over CCN, and the CCN routers may then create a new MART entry for each unique mc counter value that is pending for the multicast group. For example, if clients are disseminating their multicast Interests for the same multicast group at varying rates, the CCN routers may group the paths directed to the same mc value in a single MART entry, and may create an additional MART entry for each other mc counter value pending for the multicast group.

FIG. **4**B illustrates an exemplary multicast anonymous routing table (MART) **450** in accordance with an embodiment. MART **450** includes three entries for a multicast group "/parc." MART **450** may correspond to router **118** of CCN **100** (FIG. **1**), which may have an MFT established with routers **112**, **113**, and **124** for a first multicast stream (with AID value **5**) from anchor **116** (e.g., for the name prefix "/pare"), and may have another MFT established with router **124** for a second multicast stream (with AID value **8**) from anchor **116**.

The first MART entry corresponds to a third packet in the multicast stream with AID value **5**, and the second MART entry corresponds to a second packet in the multicast stream. For example, the first MART entry may correspond to the multicast stream being pushed to routers **113** and **124**, such that router **118** may increment the mc counter from **3** to **4** after receiving and forwarding the third Content Object of the multicast stream. The second MART, on the other hand, may correspond to a pull request, which may have occurred if a client disseminated a multicast Interest with the mc value **2** to request the second Content Object in the multicast stream.

The third MART entry in MART **450** may correspond to a second packet in the second multicast stream with ID value **5**, which includes router **124** in the MFT.

Name-Prefix FIB and Anchor FIB

Recall that the CCN routers can use a forwarding information base (FIB) to determine an egress interface via which to forward an Interest. In a typical content centric network, the router would need to perform a longest-prefix matching lookup in the FIB, using the Interest's name, to determine an interface associated with the longest matching prefix. However, the FIBs are undesirably large, and performing a lookup in a typical FIB can be undesirably slow.

For example, an Internet protocol (IP) FIB can have a size in the order of millions of FIB entries ($O(10^6)$), and a typical CCN FIB can have a size in the order of billions of FIB entries ($O(10^9)$). A relatively small table can easily be made faster by implementing the table using a parallel-search architecture, such as in an application-specific integrated circuit (ASIC) or in a general purpose graphics processing unit (GPGPU). However, a larger table with billions of entries may require an optimization trade-off between (money, size, energy) vs. speed.

Embodiments of the present invention avoid having to optimize a conventional CCN FIB by replacing the CCN FIB with two smaller FIBs: a name-prefix FIB (NP-FIB) for mapping a CCN name prefix to a nearest anchor node, and an anchor FIB (A-FIB) for mapping an anchor's identifier to a local interface or next-hop neighbor via which the anchor can be reached. The NP-FIB and A-FIB can provide optimizations across CCN nodes that perform most of the Interest forwarding.

The gateway routers that receive Interests from client devices can perform a longest-prefix matching lookup on the NP-FIB to determine the nearest anchor associated with an Interest's name prefix, and insert the anchor's identifier in the Interest. The other routers across CCN can perform a faster exact-match lookup in the smaller A-FIB to forward the Interest toward a specific anchor, regardless of the data collection being requested from the anchor. The routers can perform the exact-match lookup in the A-FIB, using the Interest's anchor identifier, to determine the local interface (to a next-hop router) via which the router can forward the Interest toward the anchor.

In some embodiments, the A-FIB is sufficiently small to store in a small memory, and to implement a parallel lookup operation in a hardware (e.g., ASIC) implementation of the lookup table. In some embodiments, the A-FIB lookup table is sufficiently small to be searched quickly by a single CPU core, and can be further improved by dividing the lookup process across multiple cores of a CPU or GPU.

The routers can dynamically bind a CCN name to an interface toward an anchor, regardless of the routing protocol used in name-based routing. For example, each router can maintain a routing table with entries that specify an anchor identifier, a distance, a next-hop interface, and a sequence number. Each router can use the anchor identifier and sequence number in the routing table to establish loop freedom in the control plane. The router may then populate the NP-FIB and A-FIB based on the routing table, and can use the distance value in the NP-FIB entries and the A-FIB entries to maintain loop freedom in the data plane.

In some embodiments, an NP-FIB entry can include a name prefix field, an anchor identifier field, a distance field that specifies a distance to the anchor, and a next-hop field that specifies an interface to a next-hop router toward the anchor. The anchor identifier in the NP-FIB can be any unique identifier for the router that announced or advertised the presence of the name prefix. Moreover, an A-FIB entry can include an anchor identifier, a next-hop field that indicates an interface to a next-hop router toward the anchor, and a distance field that specifies a distance to the anchor.

Given that the locations of data collections are oftentimes static, the binding decisions made by the routers may typically be stable. Also, the bindings at network nodes that route packets to one replica of a collection (e.g., to anchor **106** of CCN **100** in FIG. **1**) are typically independent of the bindings at network nodes that route packets to another replica of the same collection (e.g., to anchor **116**). For example, the binding decisions at nodes between router **124** and **116** are made with respect to how to forward Interests associated with the name prefix "/pare" to anchor **116**, even though anchor **106** or another anchors for the same name prefix may exist throughout CCN **100**.

FIG. **5**A illustrates exemplary name-prefix forwarding information base (NP-FIB) table **502** in accordance with an embodiment. NP-FIB **502** can correspond to gateway router **124** of CCN **100** (FIG. **1**), and can include a name prefix field, an anchor field that specifies an anchor's identifier, a distance field that specifies a distance to the anchor, and a next-hop field which specifies an interface via which the anchor can be reached. Specifically, NP-FIB **502** can include six entries, which specify next-hop routers to anchor **106** for the name prefixes "/parc" and "/alpha", and specify next-hop routers to anchor **116** for the name prefixes "/parc" and "/beta."

FIG. **5**B illustrates exemplary anchor forwarding information base (A-FIB) tables **552**, **554**, and **556** in accordance with an embodiment. A-FIBs **552**, **554**, and **556** may correspond to routers along a path between gateway router **124** and anchor **116** of CCN **100**, and each can include entries with an anchor field, a next-hop field, and a distance field. Specifically, the A-FIB **552** may correspond to gateway router **124**, A-FIB **554** may correspond to router **118**, and A-FIB **554** may correspond to anchor **116**. The number of entries in A-FIBs **552**, **554**, and **556** are smaller than those of an NP-FIB, given that the A-FIBs map anchors to a next-hop neighbor, regardless of the content (name prefix) being requested from the anchor.

FIG. **6** presents a flow chart illustrating a method **600** for determining an egress interface for forwarding an Interest based on an anchor's identifier in accordance with an embodiment. During operation, the router can receive an Interest (operation **602**), and can determine whether the Interest includes an anchor identifier (operation **604**). If so, the router can perform a lookup operation in an A-FIB (e.g., an exact-match lookup), using the anchor identifier, to obtain an egress interface toward the anchor specified in the Interest (operation **612**). The router then forwards the Interest toward the anchor via the egress interface (operation **610**).

However, if the Interest does not include an anchor identifier, the router can perform a lookup operation in an NP-FIB (e.g., a longest-matching prefix lookup), using the Interest's name, to obtain an anchor identifier associated with the Interest's name, and to obtain an egress interface toward the anchor (operation **606**). The router also updates the Interest to include the anchor identifier (operation **608**), and proceeds to operation **610** to forward the updated Interest toward the anchor via the egress interface.

FIG. **7** illustrates an exemplary apparatus **700** that facilitates forwarding Interests and Content Objects based on anonymous datagrams in accordance with an embodiment. Apparatus **700** can comprise a plurality of modules which may communicate with one another via a wired or wireless communication channel. Apparatus **700** may be realized using one or more integrated circuits, and may include fewer or more modules than those shown in FIG. **7**. Further, apparatus **700** may be integrated in a computer system, or realized as a separate device which is capable of communicating with other computer systems and/or devices. Specifically, apparatus **700** can comprise a communication module **702**, a packet-processing module **704**, an AID-computing module **706**, and a packet-forwarding module **708**.

In some embodiments, communication module **702** can receive an Interest or a data packet. Packet-processing module **704** can obtain a name or an AID from the Interest or data packet.

AID-computing module **706** can compute an AID that is to be used by a next-hop neighbor, from the previous AID associated with the Interest or data packet and a bijective function. Packet-forwarding module **708** can update the Interest or data packet to include the new AID before forwarding the Interest or data packet to the next-hop neighbor.

FIG. **8** illustrates an exemplary computer system **802** that facilitates forwarding Interests and Content Objects based on anonymous datagrams in accordance with an embodiment. Computer system **802** includes a processor **804**, a memory **806**, and a storage device **808**. Memory **806** can include a volatile memory (e.g., RAM) that serves as a managed memory, and can be used to store one or more memory pools. Furthermore, computer system **802** can be coupled to a display device **810**, a keyboard **812**, and a pointing device **814**. Storage device **808** can store operating system **816**, packet-forwarding system **818**, and data **828**.

Packet-forwarding system **818** can include instructions, which when executed by computer system **802**, can cause computer system **802** to perform methods and/or processes described in this disclosure. Specifically, packet-forwarding system **818** may include instructions for receiving an Interest or a data packet (communication module **820**), and can include instructions for obtaining a name or an AID from the Interest or data packet (packet-processing module **822**).

Further, packet-forwarding system **818** can include instructions for computing an AID that is to be used by a next-hop neighbor, from the previous AID associated with the Interest or data packet and a bijective function (AID-computing module **824**). Packet-forwarding system **818** can also include instructions for updating the Interest or data packet to include the new AID before forwarding the Interest or data packet to the next-hop neighbor (packet-forwarding module **826**).

Data **828** can include any data that is required as input or that is generated as output by the methods and/or processes described in this disclosure. Specifically, data **828** can store at least a LIGHT data structure, a LIST data structure, a FIB data structure, and an ART data structure.

The data structures and code described in this detailed description are typically stored on a computer-readable storage medium, which may be any device or medium that can store code and/or data for use by a computer system. The computer-readable storage medium includes, but is not limited to, volatile memory, non-volatile memory, magnetic and optical storage devices such as disk drives, magnetic tape, CDs (compact discs), DVDs (digital versatile discs or digital video discs), or other media capable of storing computer-readable media now known or later developed.

The methods and processes described in the detailed description section can be embodied as code and/or data, which can be stored in a computer-readable storage medium as described above. When a computer system reads and executes the code and/or data stored on the computer-readable storage medium, the computer system performs the methods and processes embodied as data structures and code and stored within the computer-readable storage medium.

Furthermore, the methods and processes described above can be included in hardware modules. For example, the hardware modules can include, but are not limited to, application-specific integrated circuit (ASIC) chips, field-programmable gate arrays (FPGAs), and other programmable-logic devices now known or later developed. When the hardware modules are activated, the hardware modules perform the methods and processes included within the hardware modules.

The foregoing descriptions of embodiments of the present invention have been presented for purposes of illustration and description only. They are not intended to be exhaustive or to limit the present invention to the forms disclosed. Accordingly, many modifications and variations will be apparent to practitioners skilled in the art. Additionally, the above disclosure is not intended to limit the present invention. The scope of the present invention is defined by the appended claims.

What is claimed is:

1. A method, comprising: receiving, by a router of an information-centric network, an Interest via a first interface of the router, the Interest including at least a name prefix for a requested piece of data; determining, for the Interest, a first anonymous identifier (AID) that identifies a name-independent path to the Interest's source via the router without revealing information about the source; performing, by the router, a lookup operation for the name prefix of the Interest in a name-prefix forwarding information base that maps name prefixes to interfaces toward a nearest anchor for a given name prefix; identifying a second interface for forwarding the Interest to a next-hop neighbor via the information-centric network, based on matching the name prefix of the Interest to the second interface during the lookup operation; performing a bijective function on the first AID to obtain a second AID that is to be used by the next-hop neighbor to establish a name-independent return path to the router without revealing information about the identity of the router; updating the Interest to include the second AID; and forwarding the Interest via the second interface toward the next-hop neighbor.

2. The method of claim **1**, wherein determining the first AID involves:

responsive to determining that the Interest does not include an AID, selecting a default AID associated with the router as the first AID.

3. The method of claim **1**, wherein determining the first AID involves obtaining an AID from the Interest.

4. The method of claim **3**, wherein determining the first AID further involves:

in response to determining that the router has mapped the Interest's AID to a third interface different than the first interface, selecting, for the Interest, an AID that the router has not assigned to an interface different than the first interface.

5. The method of claim **1**, further comprising:

updating an anonymous routing table (ART) to include an ART entry that maps the first AID to the first interface, if the ART entry does not exist in the ART.

6. The method of claim **4**, wherein updating the ART further involves:

creating the ART entry so that the ART entry maps the first AID to an AID specified in the original Interest.

7. The method of claim **1**, further comprising:

determining that the Interest corresponds to a multicast stream; and

updating a multicast anonymous routing table (MART) to include a MART entry that maps a group identifier and the AID to at least the first interface, if the mapping does not exist in the MART.

8. The method of claim **7**, wherein the Interest includes a multicast counter which identifies a starting sequence number for the multicast stream; and

wherein updating the MART further comprises storing the multicast counter in the MART entry.

9. The method of claim **1**, wherein performing the bijective function involves:

determining, from an ordered AID list corresponding to the next-hop neighbor, the second AID that corresponds to the first AID in a local ordered AID list for the router.

10. A non-transitory computer-readable storage medium storing instructions that when executed by a computer cause the computer to perform a method, the method comprising: receiving an Interest via a first interface of the router, the Interest including at least a name prefix for a requested piece of data; determining, for the Interest, a first anonymous identifier (AID) that identifies a name-independent path to the Interest's source via the router without revealing information about the source; performing, by the router, a lookup operation for the name prefix of the Interest in a name-prefix forwarding information base that maps name prefixes to interfaces toward a nearest anchor for a given name prefix; identifying a second interface for forwarding the Interest to a next-hop neighbor via the information-centric network, based on matching the name prefix of the Interest to the second interface during the lookup operation; performing a bijective function on the first AID to obtain a second AID that is to be used by the next-hop neighbor to establish a name-independent return path to the router without revealing information about the identity of the router; updating the Interest to include the second AID; and forwarding the Interest via the second interface toward the next-hop neighbor.

11. The storage medium of claim **10**, wherein determining the first AID involves obtaining an AID from the Interest.

12. The storage medium of claim **10**, further comprising:

updating an anonymous routing table (ART) to include an ART entry that maps the first AID to the first interface, if the ART entry does not exist in the ART.

13. The storage medium of claim **10**, further comprising:

determining that the Interest corresponds to a multicast stream; and

updating a multicast anonymous routing table (MART) to include a MART entry that maps a group identifier and the AID to at least the first interface, if the mapping does not exist in the MART.

14. The storage medium of claim **10**, wherein performing the bijective function involves:

determining, from an ordered AID list corresponding to the next-hop neighbor, the second AID that corresponds to the first AID in a local ordered AID list for the router.

15. A method, comprising: receiving, by a router of an information-centric network (ICN), an ICN data packet that includes a response to a pending Interest; obtaining a first anonymous identifier (AID) from the ICN data packet, wherein the first AID identifies a name-independent path to the Interest's source via the router without revealing information about the source; performing a lookup operation in an anonymous routing table (ART), based on the first AID, to determine an interface of the router for forwarding the ICN data packet toward the pending Interest's source; performing a reverse bijective function on the first AID to determine a second AID used by a next-hop neighbor for the pending Interest without revealing information about the identity of the router; updating the ICN data packet to include the second AID used by the next-hop neighbor for the pending Interest; and forwarding, by the router, the ICN data packet via the interface.

16. The method of claim **15**, wherein updating the ICN data packet involves obtaining, from the ART, an ART entry that maps the first AID to an original AID of the pending Interest.

17. The method of claim **16**, wherein updating the ICN data packet further involves:

performing a bijective function on the original AID to determine the first AID used by the next-hop neighbor for the pending Interest.

18. The method of claim **15**, wherein the ART is a multicast anonymous routing table (MART) with a MART entry that maps the first AID and a multicast group identifier of the ICN data packet to one or more next-hop neighbors of a multicast tree that are to receive the ICN data packet.

19. The method of claim **18**, wherein the MART entry includes a multicast counter which identifies a sequence number for a next ICN data packet that the next-hop neighbors are to receive via the multicast tree; and

wherein the method further comprises incrementing the multicast counter in the MART in response to forwarding the ICN data packet.

20. An apparatus, comprising: a processor; and a memory storing instructions that when executed by the processor cause the apparatus to implement: a communication circuit to receive an information-centric networking (ICN) data packet that includes a response to an Interest; a packet-processing circuit to obtain a first anonymous identifier (AID) from the ICN data packet, wherein the first AID identifies a name-independent path to the Interest's source via the router without revealing information about the source; and a packet-forwarding circuit to: perform a lookup operation in an anonymous routing table (ART), based on the first AID, to determine an interface of the router for forwarding the ICN data packet toward the Interest's source; perform a reverse bijective function on the first AID to determine a second AID used by a next-hop neighbor for the pending Interest without revealing information about the identity of the router; update the ICN data packet to include the second AID used by the next-hop neighbor for the pending Interest; and configure the communication circuit to forward the ICN data packet via the interface.

21. The apparatus of claim **20**, wherein the packet forwarding circuit is configured to update the ICN data packet by obtaining, from the ART, an ART entry that maps the first AID to an original AID of the pending Interest.

22. The apparatus of claim **20**, wherein the ART is a multicast anonymous routing table (MART) with a MART entry that maps the first AID and a multicast group identifier of the ICN data packet to one or more next-hop neighbors of a multicast tree that are to receive the ICN data packet.

23. The apparatus of claim **22**, wherein the MART entry includes a multicast counter which identifies a sequence number for a next ICN data packet that the next-hop neighbors are to receive via the multicast tree; and

wherein the packet-forwarding circuit is configured to increment the multicast counter in the MART in response to forwarding the ICN data packet.

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