Title
System and method for performing key resolution over a content centric network

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(54) **SYSTEM AND METHOD FOR PERFORMING KEY RESOLUTION OVER A CONTENT CENTRIC NETWORK**

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CPC ***H04L 9/321*** (2013.01); ***G06F 21/602*** (2013.01); ***H04L 9/30*** (2013.01); ***H04L 9/3263*** (2013.01); ***H04L 63/06*** (2013.01); ***H04L 63/0823*** (2013.01)

(58) **Field of Classification Search**

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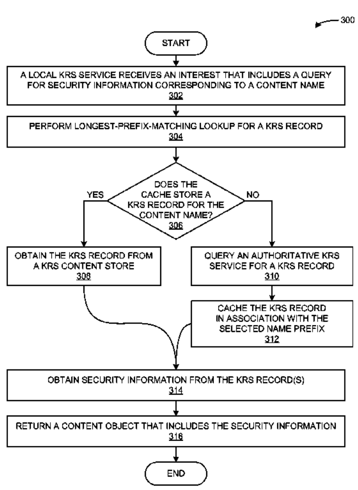
(57) **ABSTRACT**

A key-resolution service (KRS) can facilitate a client device in verifying that Content Objects are signed by a trusted entity. During operation, the KRS service can receive an Interest that includes a KRS query for a content name that is to be resolved. The KRS service obtains the content name from the Interest, and obtains a KRS record that includes security information for the content name or a prefix of the content name. The KRS service then returns a Content Object whose payload includes the KRS record to satisfy the first Interest. The client device can query the KRS service to obtain a trusted key associated with at least a name prefix of the Content Object, and if necessary, can disseminate Interests to obtain keys that complete a chain of trust between the trusted key and a key that is used to authenticate the Content Object.

20 Claims, 12 Drawing Sheets



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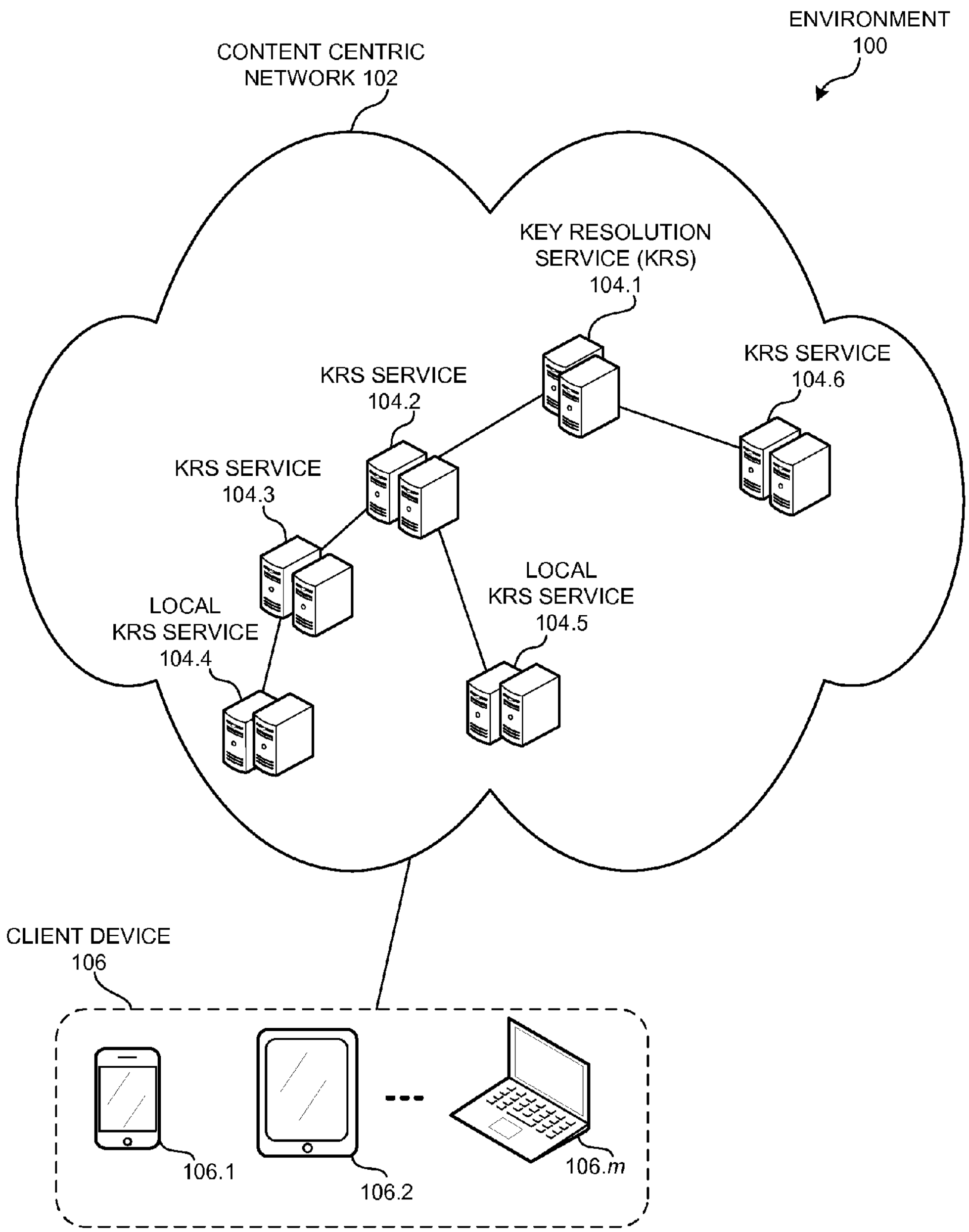
ENVIRONMENT
100
CONTENT CENTRIC
NETWORK 102
KEY RESOLUTION
SERVICE (KRS)
104.1
KRS SERVICE
104.2
KRS SERVICE
104.6
KRS SERVICE
104.3
LOCAL
KRS SERVICE
104.4
LOCAL
KRS SERVICE
104.5
CLIENT DEVICE
106
106.1
106.2
106.m

FIG. 1A

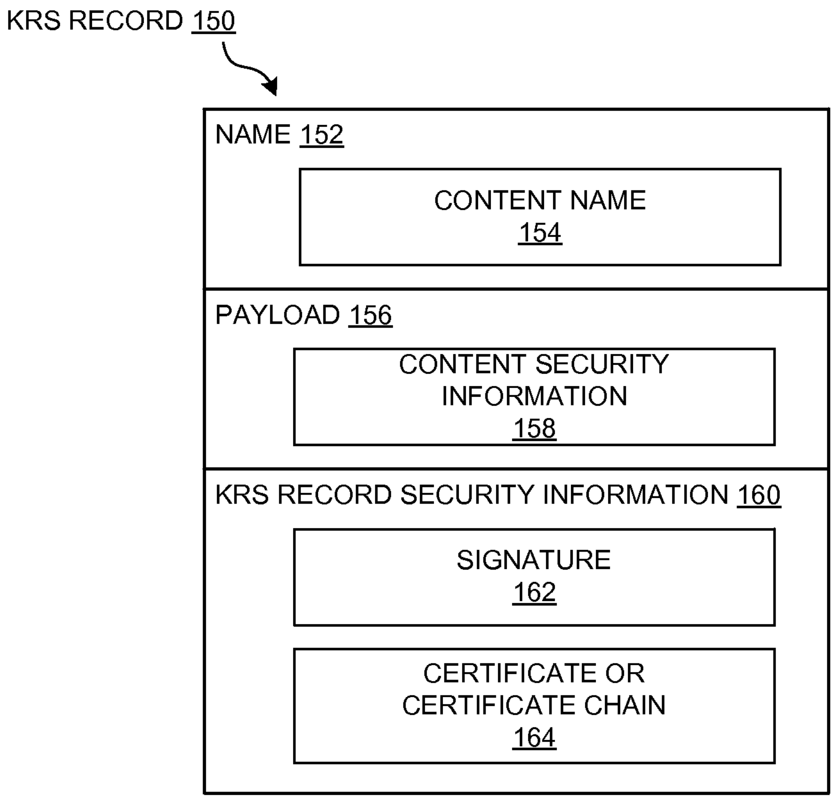
KRS RECORD 150
NAME 152
CONTENT NAME
154
PAYLOAD 156
CONTENT SECURITY
INFORMATION
158
KRS RECORD SECURITY INFORMATION 160
SIGNATURE
162
CERTIFICATE OR
CERTIFICATE CHAIN
164

FIG. 1B

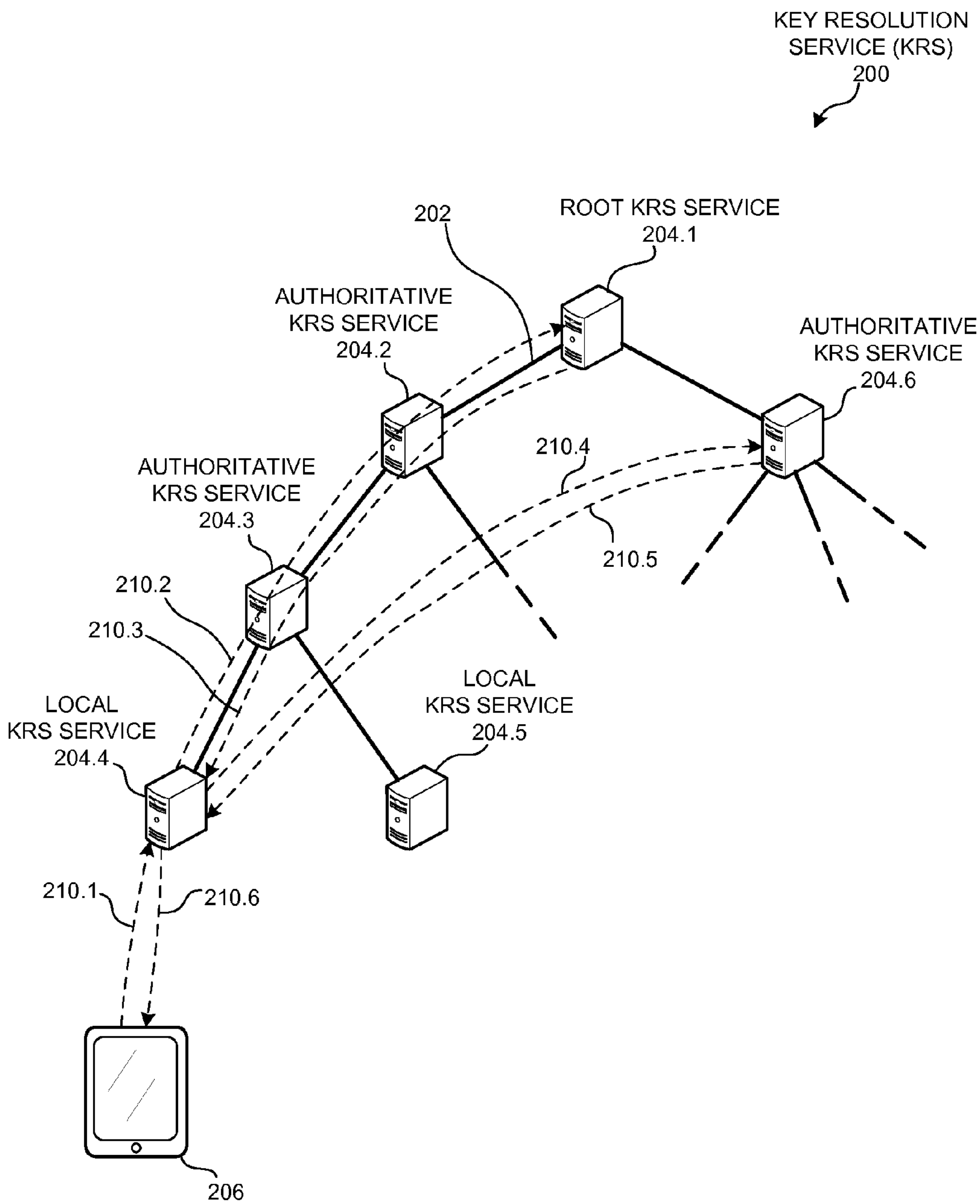
KEY RESOLUTION SERVICE (KRS)
200
202
ROOT KRS SERVICE
204.1
AUTHORITATIVE KRS SERVICE
204.2
AUTHORITATIVE KRS SERVICE
204.6
210.4
AUTHORITATIVE KRS SERVICE
204.3
210.5
210.2
210.3
LOCAL KRS SERVICE
204.5
LOCAL KRS SERVICE
204.4
210.1
210.6
206

FIG. 2

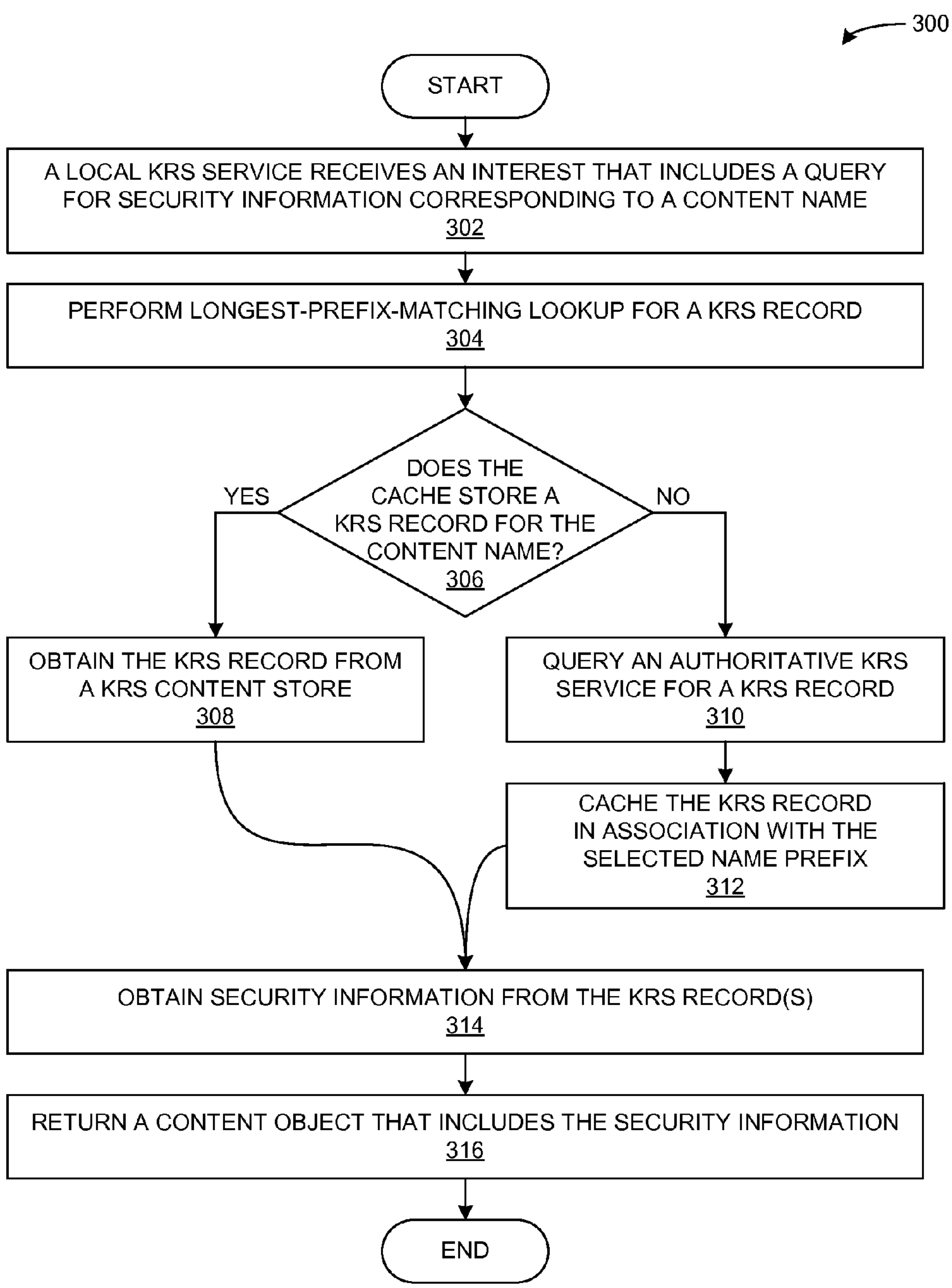
300
START
A LOCAL KRS SERVICE RECEIVES AN INTEREST THAT INCLUDES A QUERY FOR SECURITY INFORMATION CORRESPONDING TO A CONTENT NAME
302
PERFORM LONGEST-PREFIX-MATCHING LOOKUP FOR A KRS RECORD
304
DOES THE CACHE STORE A KRS RECORD FOR THE CONTENT NAME?
306
YES
NO
OBTAIN THE KRS RECORD FROM A KRS CONTENT STORE
308
QUERY AN AUTHORITATIVE KRS SERVICE FOR A KRS RECORD
310
CACHE THE KRS RECORD IN ASSOCIATION WITH THE SELECTED NAME PREFIX
312
OBTAIN SECURITY INFORMATION FROM THE KRS RECORD(S)
314
RETURN A CONTENT OBJECT THAT INCLUDES THE SECURITY INFORMATION
316
END

FIG. 3

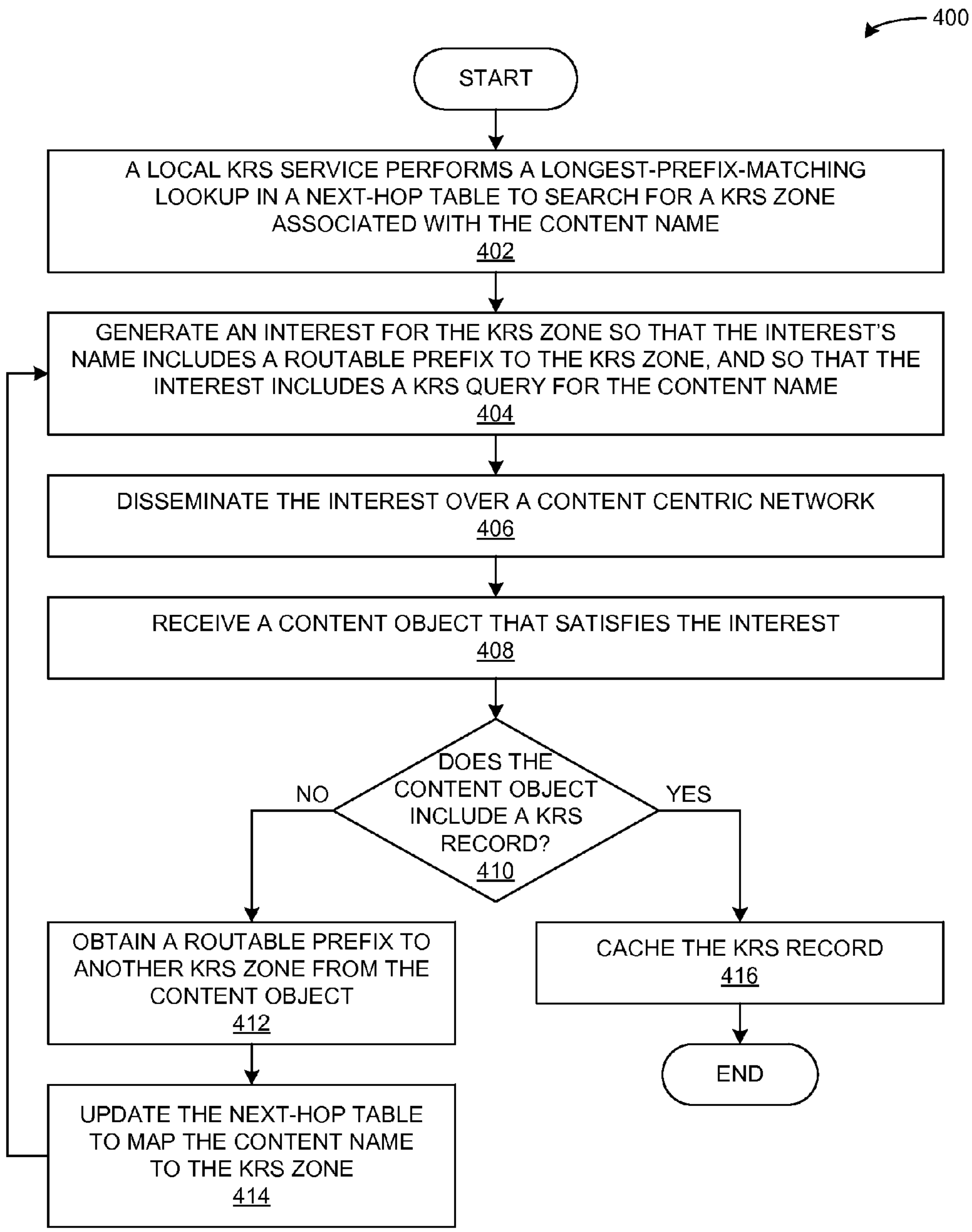
400
START
A LOCAL KRS SERVICE PERFORMS A LONGEST-PREFIX-MATCHING LOOKUP IN A NEXT-HOP TABLE TO SEARCH FOR A KRS ZONE ASSOCIATED WITH THE CONTENT NAME
402
GENERATE AN INTEREST FOR THE KRS ZONE SO THAT THE INTEREST'S NAME INCLUDES A ROUTABLE PREFIX TO THE KRS ZONE, AND SO THAT THE INTEREST INCLUDES A KRS QUERY FOR THE CONTENT NAME
404
DISSEMINATE THE INTEREST OVER A CONTENT CENTRIC NETWORK
406
RECEIVE A CONTENT OBJECT THAT SATISFIES THE INTEREST
408
DOES THE CONTENT OBJECT INCLUDE A KRS RECORD?
410
NO
YES
OBTAIN A ROUTABLE PREFIX TO ANOTHER KRS ZONE FROM THE CONTENT OBJECT
412
CACHE THE KRS RECORD
416
END
UPDATE THE NEXT-HOP TABLE TO MAP THE CONTENT NAME TO THE KRS ZONE
414

FIG. 4

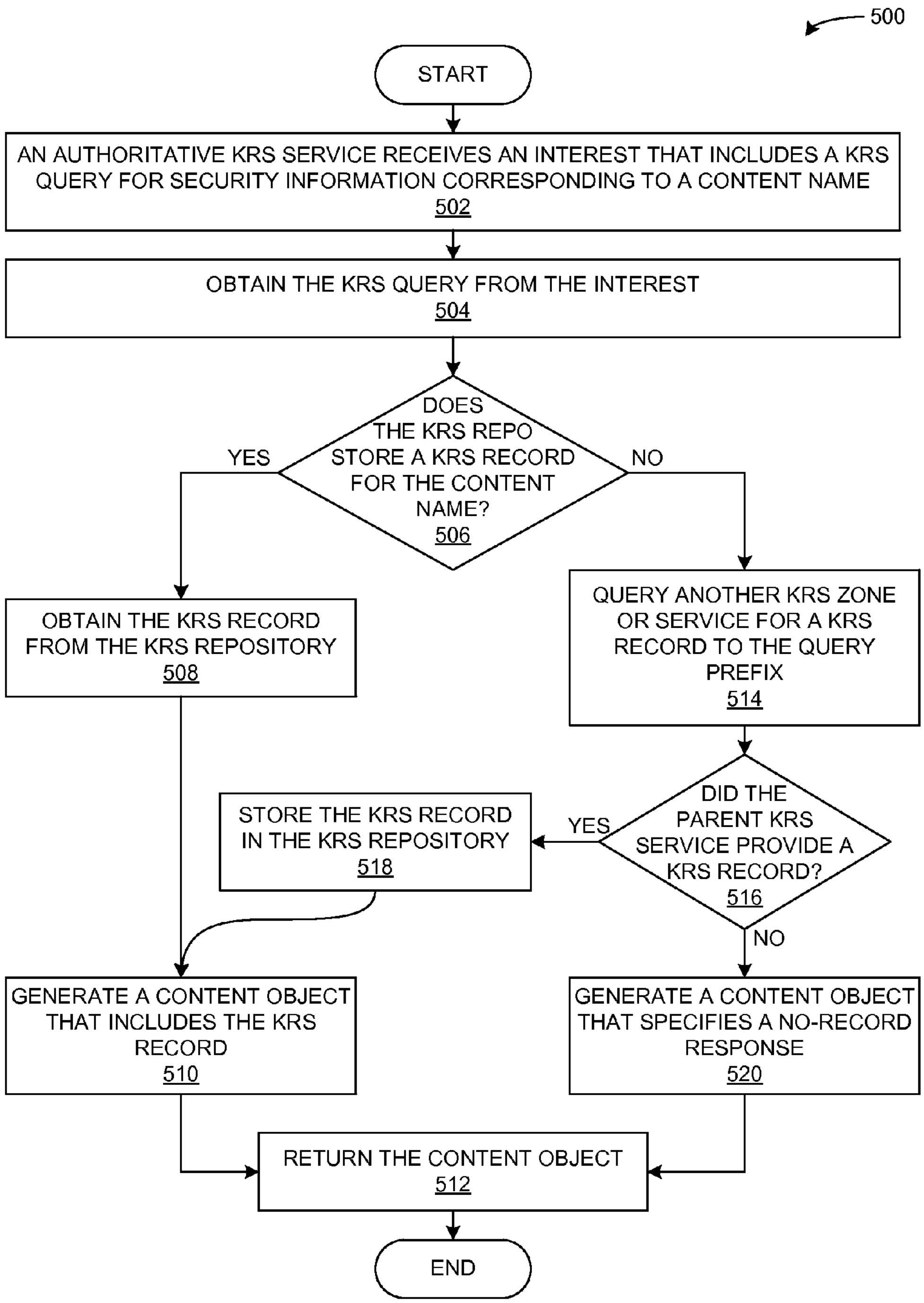
500
START
AN AUTHORITATIVE KRS SERVICE RECEIVES AN INTEREST THAT INCLUDES A KRS QUERY FOR SECURITY INFORMATION CORRESPONDING TO A CONTENT NAME 502
OBTAIN THE KRS QUERY FROM THE INTEREST 504
DOES THE KRS REPO STORE A KRS RECORD FOR THE CONTENT NAME? 506
YES
NO
OBTAIN THE KRS RECORD FROM THE KRS REPOSITORY 508
QUERY ANOTHER KRS ZONE OR SERVICE FOR A KRS RECORD TO THE QUERY PREFIX 514
DID THE PARENT KRS SERVICE PROVIDE A KRS RECORD? 516
YES
STORE THE KRS RECORD IN THE KRS REPOSITORY 518
NO
GENERATE A CONTENT OBJECT THAT INCLUDES THE KRS RECORD 510
GENERATE A CONTENT OBJECT THAT SPECIFIES A NO-RECORD RESPONSE 520
RETURN THE CONTENT OBJECT 512
END

FIG. 5

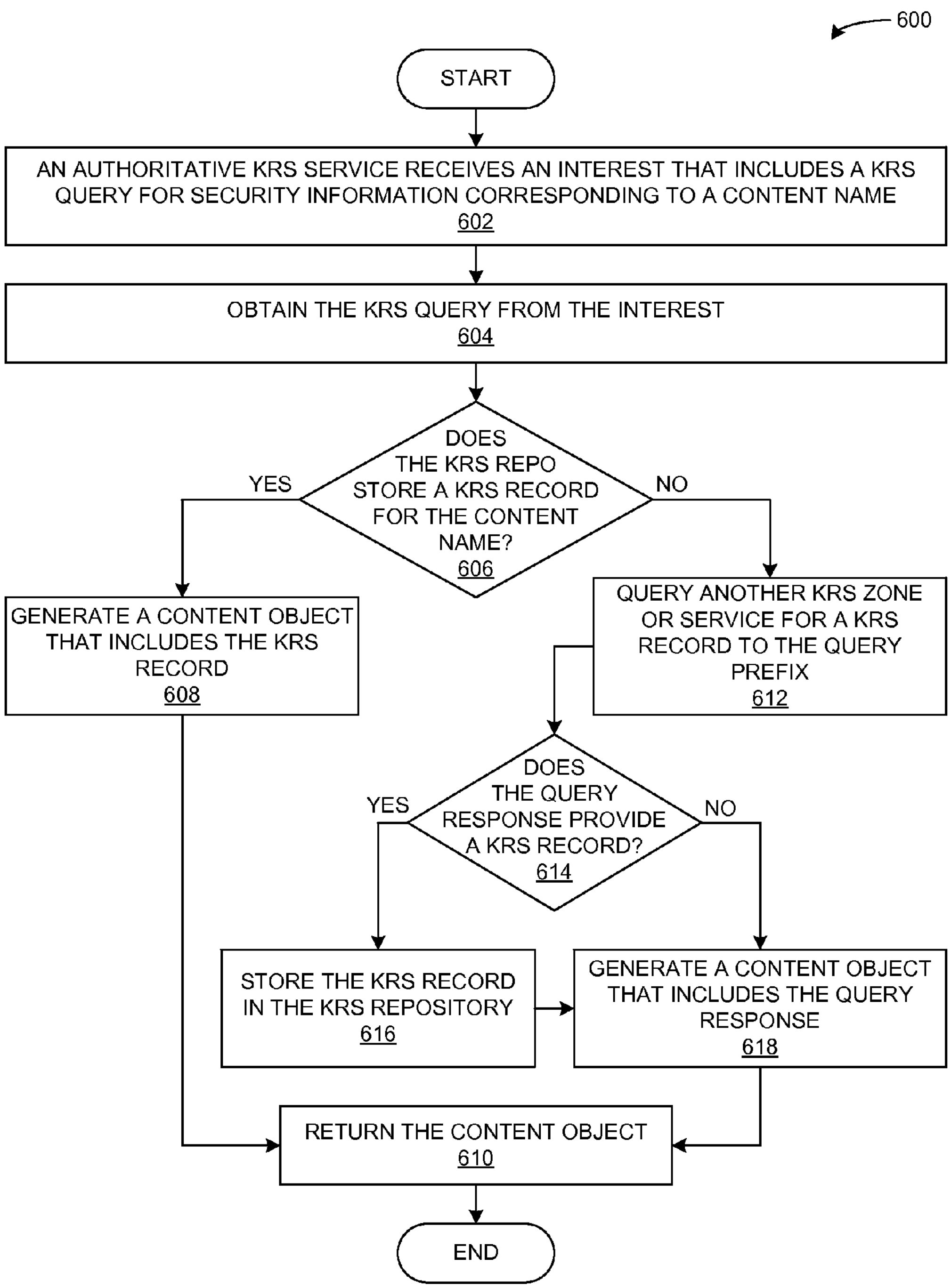
600
START
AN AUTHORITATIVE KRS SERVICE RECEIVES AN INTEREST THAT INCLUDES A KRS QUERY FOR SECURITY INFORMATION CORRESPONDING TO A CONTENT NAME
602
OBTAIN THE KRS QUERY FROM THE INTEREST
604
DOES THE KRS REPO STORE A KRS RECORD FOR THE CONTENT NAME?
606
YES
NO
GENERATE A CONTENT OBJECT THAT INCLUDES THE KRS RECORD
608
QUERY ANOTHER KRS ZONE OR SERVICE FOR A KRS RECORD TO THE QUERY PREFIX
612
DOES THE QUERY RESPONSE PROVIDE A KRS RECORD?
614
YES
NO
STORE THE KRS RECORD IN THE KRS REPOSITORY
616
GENERATE A CONTENT OBJECT THAT INCLUDES THE QUERY RESPONSE
618
RETURN THE CONTENT OBJECT
610
END

FIG. 6

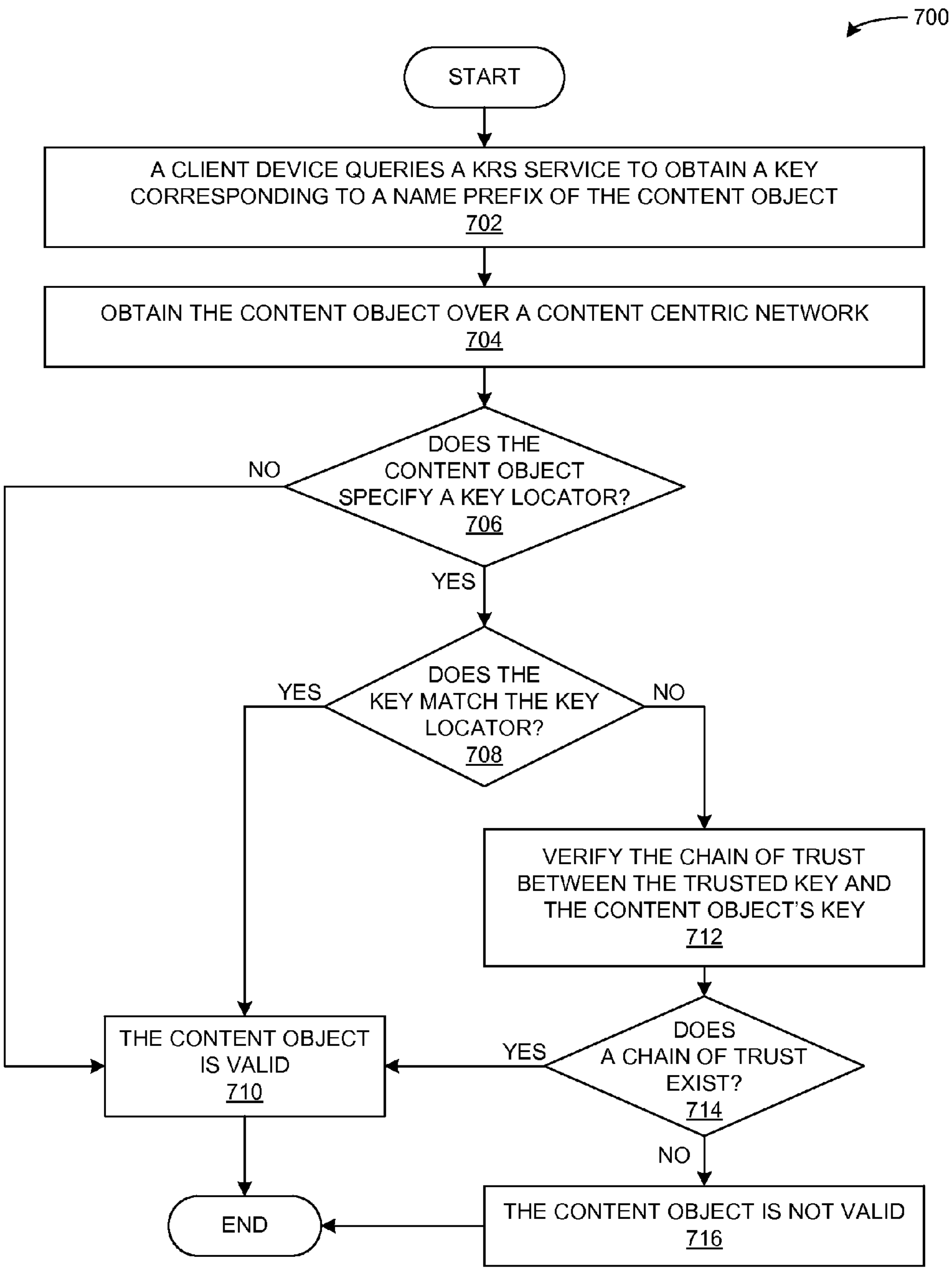
700
START
A CLIENT DEVICE QUERIES A KRS SERVICE TO OBTAIN A KEY CORRESPONDING TO A NAME PREFIX OF THE CONTENT OBJECT 702
OBTAIN THE CONTENT OBJECT OVER A CONTENT CENTRIC NETWORK 704
DOES THE CONTENT OBJECT SPECIFY A KEY LOCATOR? 706
NO
YES
DOES THE KEY MATCH THE KEY LOCATOR? 708
YES
NO
VERIFY THE CHAIN OF TRUST BETWEEN THE TRUSTED KEY AND THE CONTENT OBJECT'S KEY 712
THE CONTENT OBJECT IS VALID 710
YES
DOES A CHAIN OF TRUST EXIST? 714
NO
END
THE CONTENT OBJECT IS NOT VALID 716

FIG. 7

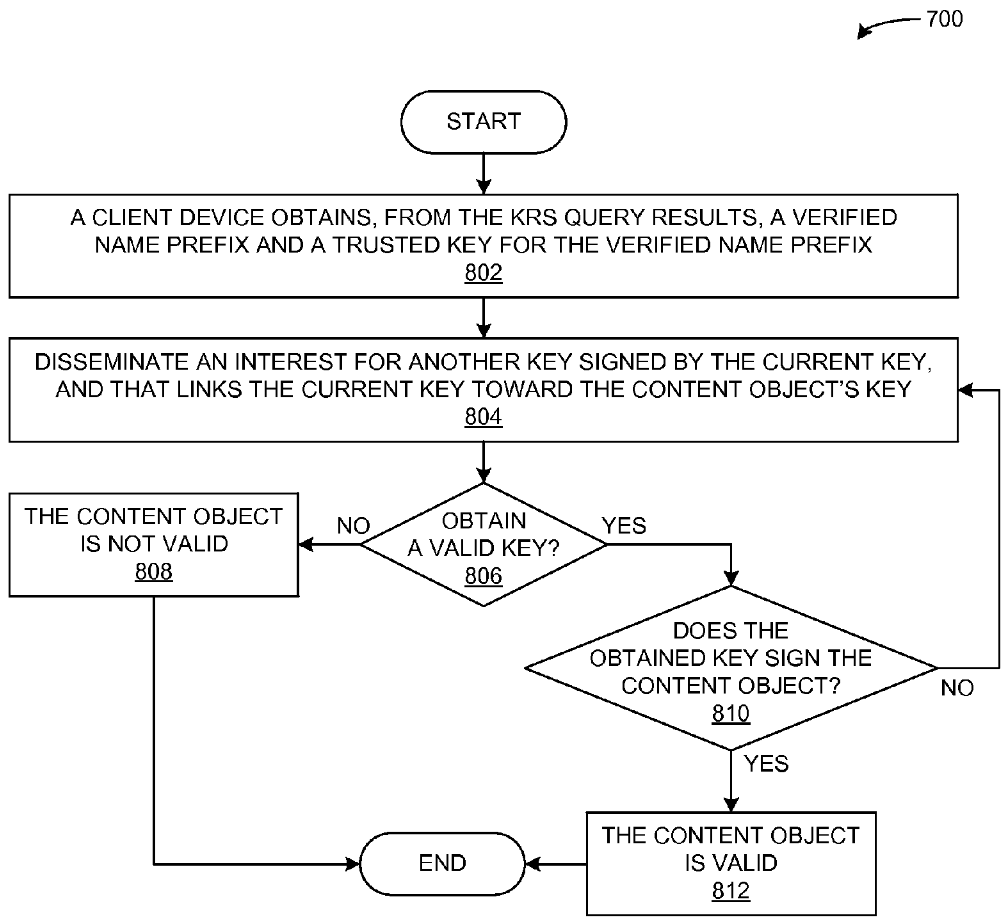
700
START
A CLIENT DEVICE OBTAINS, FROM THE KRS QUERY RESULTS, A VERIFIED NAME PREFIX AND A TRUSTED KEY FOR THE VERIFIED NAME PREFIX
802
DISSEMINATE AN INTEREST FOR ANOTHER KEY SIGNED BY THE CURRENT KEY, AND THAT LINKS THE CURRENT KEY TOWARD THE CONTENT OBJECT'S KEY
804
THE CONTENT OBJECT IS NOT VALID
808
NO
OBTAIN A VALID KEY?
806
YES
DOES THE OBTAINED KEY SIGN THE CONTENT OBJECT?
810
NO
YES
END
THE CONTENT OBJECT IS VALID
812

FIG. 8A

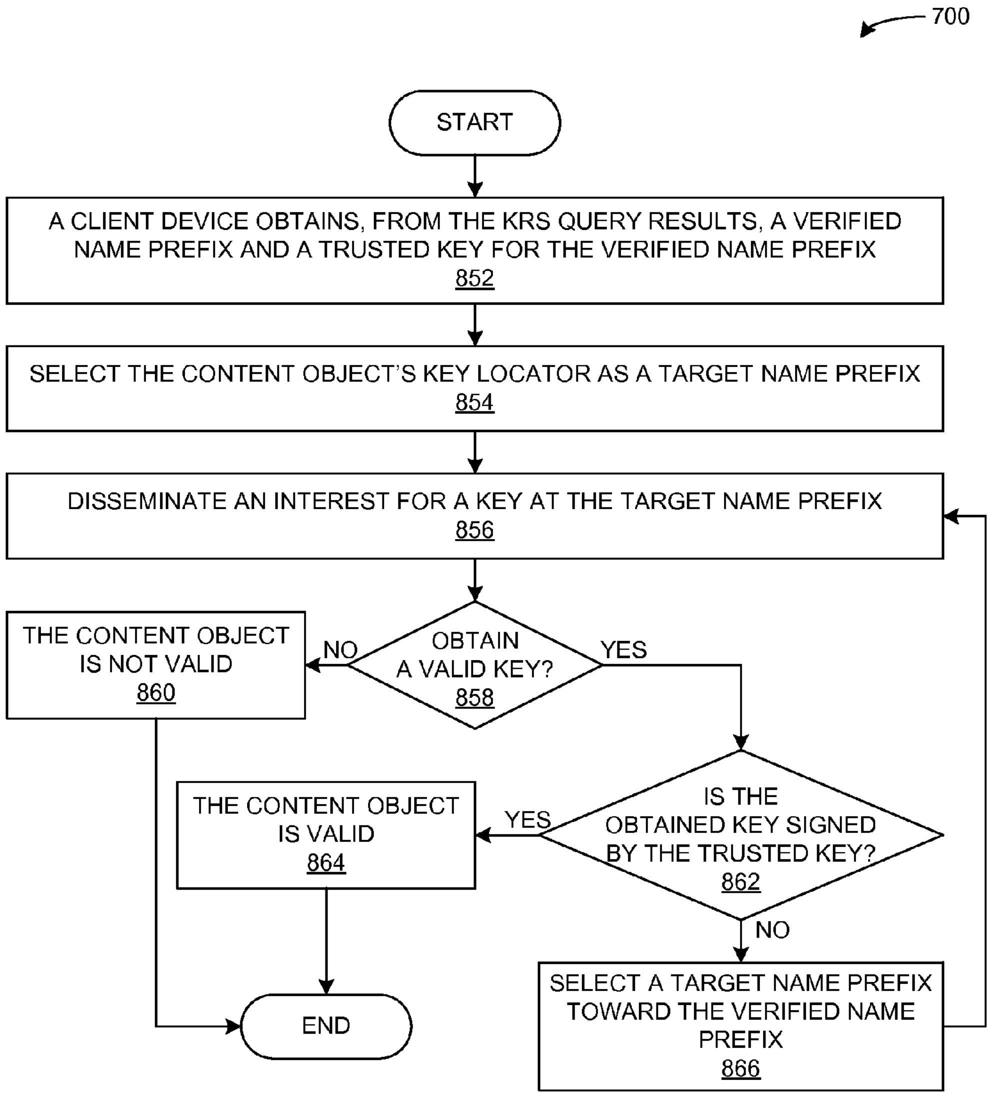
700
START
A CLIENT DEVICE OBTAINS, FROM THE KRS QUERY RESULTS, A VERIFIED NAME PREFIX AND A TRUSTED KEY FOR THE VERIFIED NAME PREFIX 852
SELECT THE CONTENT OBJECT'S KEY LOCATOR AS A TARGET NAME PREFIX 854
DISSEMINATE AN INTEREST FOR A KEY AT THE TARGET NAME PREFIX 856
OBTAIN A VALID KEY? 858
NO
YES
THE CONTENT OBJECT IS NOT VALID 860
IS THE OBTAINED KEY SIGNED BY THE TRUSTED KEY? 862
YES
NO
THE CONTENT OBJECT IS VALID 864
SELECT A TARGET NAME PREFIX TOWARD THE VERIFIED NAME PREFIX 866
END

FIG. 8B

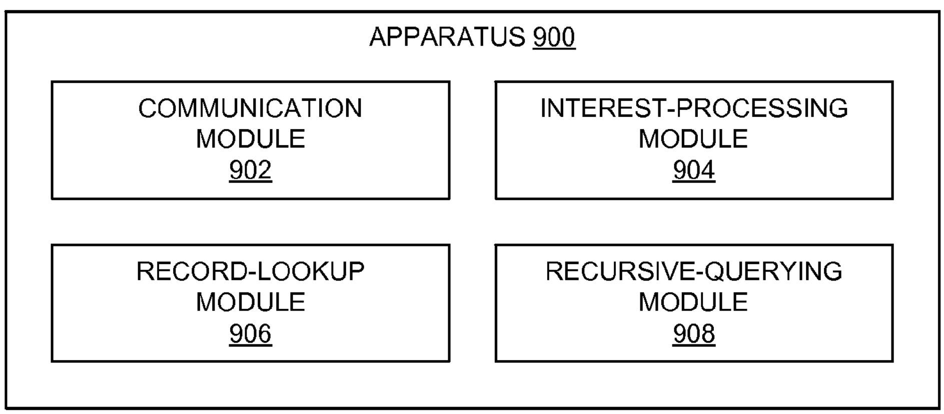
APPARATUS 900
COMMUNICATION MODULE 902
INTEREST-PROCESSING MODULE 904
RECORD-LOOKUP MODULE 906
RECURSIVE-QUERYING MODULE 908

FIG. 9

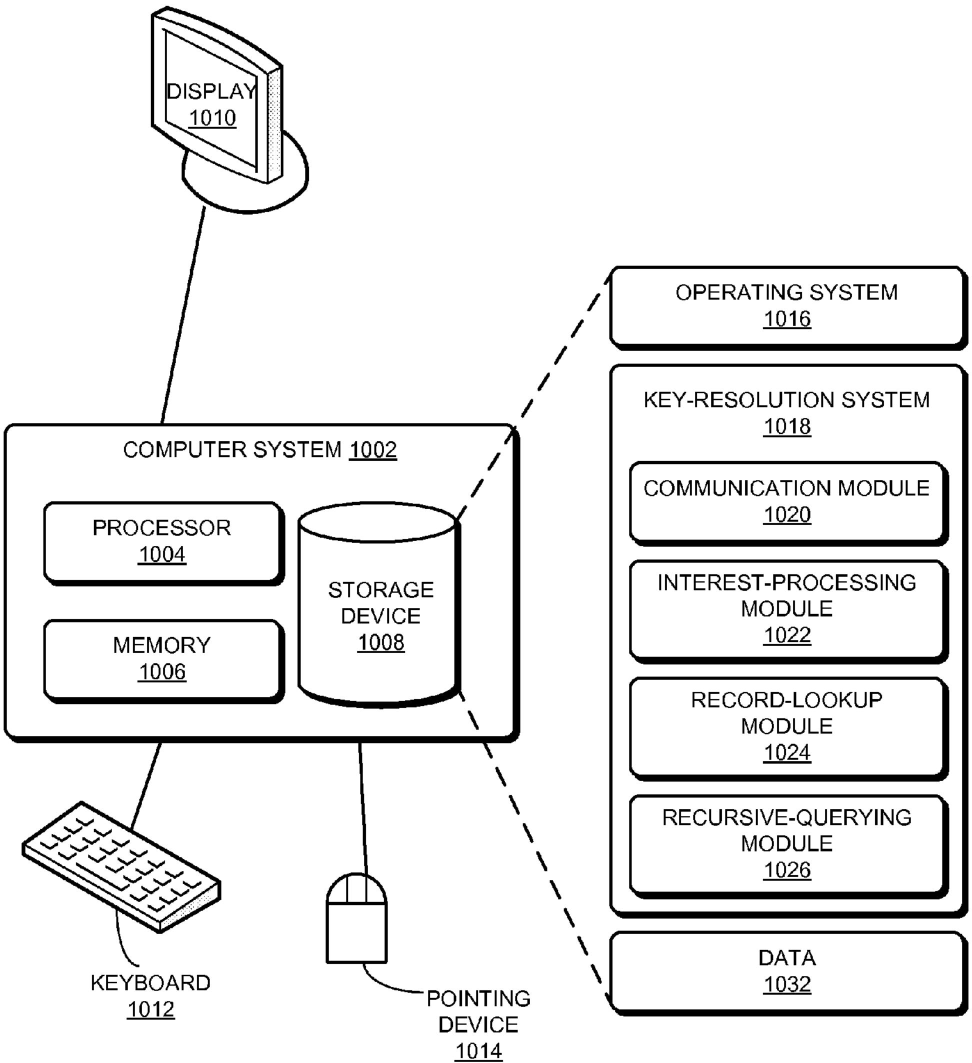
DISPLAY
1010
COMPUTER SYSTEM 1002
PROCESSOR
1004
MEMORY
1006
STORAGE
DEVICE
1008
KEYBOARD
1012
POINTING
DEVICE
1014
OPERATING SYSTEM
1016
KEY-RESOLUTION SYSTEM
1018
COMMUNICATION MODULE
1020
INTEREST-PROCESSING
MODULE
1022
RECORD-LOOKUP
MODULE
1024
RECURSIVE-QUERYING
MODULE
1026
DATA
1032

FIG. 10

SYSTEM AND METHOD FOR PERFORMING KEY RESOLUTION OVER A CONTENT CENTRIC NETWORK

STATEMENT OF GOVERNMENT-FUNDED RESEARCH

This invention was made with U.S. Government support under Contract No. G015.3707, awarded by the National Science Foundation (NSF) Future Internet Architectures (FIA) program, Named Data Networking (NDN) project. The U.S. Government has certain rights in this invention.

BACKGROUND

1. Field

This disclosure is generally related to securing digital content. More specifically, this disclosure is related to a Key Resolution Service that resolves keys for Content Objects.

2. Related Art

Advancements in computing and networking technologies have made it possible for people to incorporate electronics into their daily lives. People typically use computers to perform online banking, to interact with others, and to search for and consume information published by others. More recently, advancements in machine-to-machine communications has made it possible for people's appliances to automate tasks for their users. For example, some digital thermostats can interact with a central controller that can generate an optimized schedule for the thermostat, and which configures the thermostat to use this schedule to control a heating, ventilation, and air conditioning (HVAC) unit.

The convenience provided by these advancements is built upon the underlying networking protocols used to exchange communication packets between user's devices and with application servers. In many cases, these communication packets can include sensitive information about the users and their daily habits; information that the users may not intend to share with the general public. Hence, in the Web today, application developers typically use Hypertext Transfer Protocol Secure (HTTPS) as the primary protocol to provide secure content delivery.

However, HTTPS requires the content server to provide to a client a certificate signed by a trusted Certificate Authority (CA). The client verifies the certificate through a Public Key Infrastructure (PKI), and uses the certificate to generate a symmetric key. The client then uses this key to encrypt and decrypt all information for the duration of the communication session with the content server. Unfortunately, there exists many CAs that can sign digital certificates, and it's up to the user to decide which CAs are trustworthy. Typically, a user needs to specify which CAs are trustworthy, and uses these CAs as "root" CAs. Other CAs function as intermediate CAs when they are trusted by the root CA directly, or indirectly via a chain of trust.

Recent developments in computer networking include Content Centric Networking (CCN), which allows clients to obtain data by disseminating an "Interest" that specifies a unique name for the data. Any peer CCN device that is storing this data can provide the data to the client, regardless of where this peer CCN device is located. However, allowing any peer network device to satisfy an Interest for a piece of data from a trusted publisher makes it difficult to ensure the data has actually originated from the trusted publisher. For example, HTTPS uses digital certificates to map a server to a person or organization that publishes data from this server. The client device uses HTTPS and the CAs to verify that they received the data from the organization they expect the data to arrive from. Unfortunately, a CCN client device cannot use HTTPS to verify that a piece of data originated from a given publisher when the client obtains this data from a different source, such as from a peer CCN device that has obtained and cached the same data in the past.

SUMMARY

One embodiment provides a key-resolution service (KRS) that facilitates a client device in verifying that Content Objects are signed by a trusted entity. The KRS service can include a set of local KRS services that receive Interest messages from clients, a set of authoritative KRS services that each maintain security information (using KRS records) for one or more KRS zones (e.g., name prefixes), and a root KRS service that maintains security information for root name prefixes. During operation, a local KRS service can receive, over a Content Centric Network (CCN), an Interest message with a name that includes a routable prefix associated with the local KRS service, and that includes a KRS query for a content name that is to be resolved. The Interest can include the KRS query appended to the routable prefix in the Interest's name, or can include the KRS query in a payload. The KRS service processes the Interest message to obtain a KRS record for the content name. The KRS record includes security information for the content name or a prefix of the content name. The KRS service generates and returns a Content Object whose payload includes the KRS record to satisfy the Interest message.

In some embodiments, the KRS record includes a name or name prefix for which the KRS record resolves security information, a payload comprising security information for the name or name prefix, and/or security information that is used to authenticate the KRS record.

In some embodiments, the underlying CCN nodes forward the client device's Interest message to a local KRS service associated with the Interest message's routable prefix. The local KRS service can obtain the KRS record by performing a longest-prefix-matching lookup in a next-hop table, using the content name as input, to obtain another routable prefix for a key-resolution zone associated with the content name or a prefix of the content name. The local KRS service then generates another Interest message whose name includes the routable prefix to the KRS zone, and includes the query for the content name in the name or a payload of the second Interest. The local KRS service disseminates this Interest message over the CCN network to query an authoritative KRS server for a KRS record.

In some embodiments, a respective entry of the next-hop table includes a name or name prefix, a routable prefix for a key-resolution zone mapped to the name or name prefix, and/or a public key for a key-resolution service associated with the key-resolution zone.

In some embodiments, a KRS service (e.g., a local KRS service or an authoritative KRS service) can disseminate an Interest to query a target key-resolution zone. If a service at the target key-resolution zone does not include a KRS record for the query, the KRS service can receive a Content Object that includes a routable prefix for another key-resolution zone. The KRS service can query the new key-resolution zone by generating another Interest message whose name includes the routable prefix for the new key-resolution zone, and that includes the query for the content name in the name or a payload of the Interest. The KRS service can disseminate this Interest to receive a Content Object that includes the KRS record.

In some variations to this embodiment, the KRS service can update the next-hop table to include an entry that maps the content name to the routable prefix for the second key-resolution zone.

In some variations to this embodiment, the KRS service can receive a Content Object that includes the KRS record, and caches the KRS record in a KRS record repository.

In some embodiments, the authoritative KRS service can obtain the KRS record by performing a longest-prefix-matching lookup in a KRS record repository, using the content name as input. This KRS record includes the security information associated with at least a prefix of the content name.

In some embodiments, the security information for the content name or a prefix of the content name in the KRS record can include a public key, a public key certificate, a certificate chain, a cryptographic digest of a Content Object, and/or a cryptographic digest of a content object, signed by the Content Object's producer or a trusted entity.

One embodiment provides a client device that uses a key from the KRS service to verify that a Content Object is signed by a trusted entity. During operation, the client device can query the KRS service to obtain a trusted key for a Content Object. The client device can also obtain the Content Object itself over CCN, and analyzes the Content Object to obtain a key locator for a key that is used to authenticate the Content Object. The client device then determines whether a chain of trust exists between the trusted key and a key associated with the Content Object's key locator. The client device determines that the Content Object is valid if the chain of trust exists.

In some embodiments, while determining that the chain of trust exists, the client device verifies that the key locator references the trusted key from the key-resolution server.

In some embodiments, while determining that the chain of trust exists, the client device can disseminate an Interest for an intermediate key signed by the trusted key, and that links the trusted key toward the Content Object's key.

In some variations to these embodiments, when the client device determines that the key locator does not reference a current intermediate key at the end of a current chain of trust from the trusted key, the client device can extend the chain of trust toward the Content Object's key by disseminating an Interest for another intermediate key signed by the current intermediate key, and that links the current intermediate key toward the Content Object's key.

In some embodiments, the client device can determine that the chain of trust exists by obtaining a target key over CCN, for example, by disseminating an Interest whose name includes the key locator.

In some variations to these embodiments, when the client device determines that the trusted key does not sign a current intermediate key at the start of a current chain of trust to the Content Object's key, the client device can extend the chain of trust toward the trusted key by iteratively disseminating an Interest for another intermediate key that is used to authenticate the current intermediate key at the start of the current chain of trust.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A illustrates an exemplary computing environment that facilitates resolving keys for Content Objects in accordance with an embodiment.

FIG. **1**B illustrates an exemplary KRS record in accordance with an embodiment.

FIG. **2** illustrates an exemplary client device querying the Key Resolution Service in accordance with an embodiment.

FIG. **3** presents a flow chart illustrating a method for processing a key-resolution query by a local KRS service in accordance with an embodiment.

FIG. **4** presents a flow chart illustrating a method for obtaining a KRS record from an authoritative KRS service in accordance with an embodiment.

FIG. **5** presents a flow chart illustrating a method for responding to an Interest iteratively by an authoritative KRS service in accordance with an embodiment.

FIG. **6** presents a flow chart illustrating a method for responding to an Interest recursively by an authoritative KRS service in accordance with an embodiment.

FIG. **7** presents a flow chart illustrating a method for validating a Content Object in accordance with an embodiment.

FIG. **8**A presents a flow chart illustrating a method for analyzing a chain of trust between a trusted key from the KRS system and the Content Object's key in accordance with an embodiment.

FIG. **8**B presents a flow chart illustrating a method for analyzing a chain of trust between a Content Object's key and a trusted key from the KRS system in accordance with an embodiment.

FIG. **9** illustrates an exemplary apparatus that facilitates resolving keys for Content Objects in accordance with an embodiment.

FIG. **10** illustrates an exemplary computer system that facilitates resolving keys for Content Objects 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 Key Resolution Service (KRS) that solves the problem of providing a client device with security information that can be used to verify a given data object. This KRS service is deployed and executed across a multitude of computing devices (e.g., servers) organized into various KRS "zones," such that a KRS service can exist for each zone. Each KRS service can store security information for a collection of CCN names, and can use a next-hop table to map a content name to another KRS service that may store security information for the content name.

For example, Content Centric Networks (CCN) are designed around the concept that users are interested in content itself, not where the data comes from. This allows a client to obtain content from any source, such as the publisher, a nearby cache, or other users that previously requested a particular Content Object. Because of this architectural characteristic, security in CCN is designed to secure the Content Object itself, rather than the end-to-end channel over which the Content Object is transmitted.

In some embodiments, a client can disseminate an Interest that queries the KRS service for security information associated with the Content Object's name or name prefix, and can use this security information to verify the Content Object. Securing a Content Object can be performed using self-certifying names, where the name of the Content Object is bound to its security information. Securing a Content Object can also be performed by including security information with the Content Object, which the client can use to verify that the Content Object's data is correct and has not been tampered with. This security information itself can take several forms, such as a public key, a public key certificate, a signed certificate chain, a cryptographic digest of a Content Object, a cryptographic digest of a content object that is signed by the Content Object's producer or a trusted entity, and/or a simple hash of the Content Object's payload.

Hence, the KRS service maps a CCN name or name prefix (e.g., "/parc/jj/paper1.pdf") to security information for the name. A client can query the KRS service for the security information before issuing an Interest for the Content Object, which allows the client to verify the authenticity of the Content Object when it is received. In some embodiments, the KRS service is designed as a distributed service that runs on top of CCN using Interest and Content Objects, and does not require changes to the CCN architecture or the CCN protocol.

The KRS service implements a hierarchical trust model that enables clients to verify both the integrity of the security information received with a Content Object, as well as the integrity of the security information returned by the KRS service. The KRS service can store and transport the security information using KRS records are themselves secure to prevent attackers from providing false KRS records along with malicious Content Objects. This way, when a client queries the KRS service and receives a response, the client can independently verify the received KRS record. Moreover, the KRS service is flexible enough to support a wide range of security models, since different publishers and organizations may employ dramatically different security techniques.

FIG. **1** illustrates an exemplary computing environment **100** that facilitates resolving keys for Content Objects in accordance with an embodiment. Specifically, environment **100** includes a Key Resolution Service (KRS) **104** that is organized into a set of KRS zones, such that each zone manages security information records (KRS records) for various name prefixes. KRS service **104** includes a root zone (e.g., root KRS service **104.1**), a local KRS service that processes requests from clients (e.g., one or more servers for KRS services **104.4** and **104.5**), and a set of authoritative KRS services that maintain KRS records for various name prefixes. In some embodiments, a respective authoritative KRS service is deployed across a collection of computers (e.g., a set of distributed servers) associated with a KRS zone.

In some embodiments, the root KRS service can maintain a next-hop table that maps a content name to a globally routable name for a KRS zone associated with the content name. Each entry of the next-hop table stores the name and public key of the KRS service that either stores the KRS record for that content name, or that knows the name of the next-hop server or next-hop KRS zone to whom the KRS request can be forwarded.

A local or authoritative KRS service can also maintain a next-hop table, which maps a content name to a name and public key of another KRS service that can be used to forward a KRS query. This way, a KRS service that does not store a KRS record for a content name can search through the next-hop table for another KRS service that stores the KRS record, or that knows the name of yet another KRS service to which the KRS request can be forwarded. If the KRS service does not know of another KRS service for the content name (e.g., if the next-hop table does not include an entry for the content name), the KRS service can forward the KRS query to the root KRS service. The root KRS service can return a globally routable name of a KRS zone for the content name.

Computing environment **100** can also include a client device **106**, such as a smartphone **106.1**, a tablet computer **106.2**, and/or a personal computing device **106.***m* (e.g., a laptop). Client device **106** can query KRS service **104** to obtain security information for a query prefix. KRS service **104** can implement a key-value store that maps the name or name-prefix to its corresponding security information. KRS service **104** can return a response that specifies the security information, or a response which affirms that no such information exists for the query prefix.

Client device **106** can perform the KRS operations underneath individual CCN applications. When an application running on client device **106** issues a request for a Content Object, client device **106** can query KRS service **104** to resolve whichever security information is appropriate, and can then use this information when constructing the Interest for obtaining the Content Object.

In some embodiments, KRS service **104** can support local client discovery that allows client device **106** to communicate with a nearby server of KRS service **104**. For example, when client device **106** joins a Wi-Fi network at a coffee shop, client device **106** may not have a-priori information regarding the network topology. Local KRS services **104.4** and **104.5** support local client discovery by advertising the CCN prefix "/krs." This enables client device **106** to take advantage of CCN's nearest-replica-routing to route an Interest with a KRS query to the closest local KRS service without a priori knowledge of the local CCN network topology. When client device **106** wishes to use KRS service **104** to resolve the security information for a content name, client device **106** can create a KRS query by creating an Interest that includes a routable prefix to the KRS service (e.g., the prefix "/krs"), and includes the query for the content name. Client device **106** can request for security information for the name "/parc/papers/krs.pdf" by disseminating an Interest "/krs/q=/parc/papers/krs.pdf." Alternatively, client device **106** can create the Interest to include the query within a payload of the Interest.

When a local KRS service receives an Interest from client device **106**, the local KRS service can store the received Interest and obtains the KRS query from the Interest. The local KRS service then performs a longest-prefix-matching lookup through its next-hop table using the KRS query's content name as input to determine a routable prefix for forwarding this request, and creates a recursive Interest for the request. The local KRS service disseminates this recursive Interest over CCN to receive a response from an authoritative KRS service. The local KRS service may receive a Content Object that encapsulates a KRS record that includes the security information for the content name, that includes a routable prefix to another KRS zone for the content name, or that encapsulates a KRS record which specifies that security information does not exist for the content name.

Whenever the local KRS service receives a routable prefix to another KRS zone, the local KRS service generates and disseminates another Interest to the other KRS zone. The local KRS service can generate an Interest that includes the routable prefix to the other KRS service in the Interest's name, and can include the KRS query for the content name in the Interest's name or in a payload of the Interest.

The local KRS service can continue to issue a KRS query each time it receives a routable prefix to another KRS zone until the local KRS service receives a KRS record that includes the security information for the content name, or specifies that security information does not exist for the content name. When the local KRS service receives a Content Object that includes the KRS record, the local KRS service generates a new Content Object that encapsulates the KRS record and whose name matches the name from the initial Interest from the client device. The local KRS service returns this new Content Object over CCN to satisfy the KRS query from the client device.

Similar to the local KRS service, when an authoritative KRS service receives an Interest addressed to its routable prefix, the authoritative KRS service obtains a content name from the Interest's name or payload. The authoritative KRS service then uses this name prefix to search the records in its zone for a KRS record. If the authoritative KRS service has the KRS record, the authoritative KRS service can return a Content Object that includes the KRS record.

On the other hand, if the authoritative KRS service does not store the KRS record for the content name, the authoritative KRS service performs a lookup in a next-hop table to determine a KRS zone for the content name. The authoritative KRS service can implement a recursive forwarding technique or an iterative forwarding technique. In the iterative forwarding technique, the authoritative KRS service generates a Content Object to include the KRS zone in the payload, and to include the same name as the initial Interest, and returns the Content Object to satisfy the initial Interest.

In the recursive forwarding technique, the authoritative KRS service generates a query in the form of an Interest for this KRS zone (with the content name appended to the Interest's name, or in a payload), and disseminates the Interest to obtain a KRS record for the content name from the KRS zone. This KRS record may include security information for the content name, or may include an indication that such security information does not exist. The authoritative KRS service then encapsulates the KRS record in a Content Object that includes the initial Interest's name, and returns this Content Object to satisfy the initial Interest.

In some embodiments, root KRS service **104.1** manages the security information for the top-level prefixes. Unlike other authoritative KRS services, root KRS service **104.1** does not have an organizational responsibility (e.g., a KRS service for the prefix "/parc" is responsible for the name prefix "/parc/csl"). However, the resolution of any top-level prefix depends on the root prefix zone. Because of this, the root prefix zone needs to remain operational and accessible without interruption, which can be achieved, for example, by using a distributed hash table (DHT) or a collection of independently-operated root KRS servers governed by an independent organization.

The local and authoritative KRS services can look up the next destination for a KRS request using a longest-prefix-matching algorithm on the next-hop table. This improves performance and scalability by enabling servers of the KRS service to cache KRS records, and by enabling the use of "default" records to reduce the total number of records stored in the KRS service. For example, a publisher JJ may have a public-private key pair which he uses to sign all content published under the name prefix "/parc/jj." Rather than storing the same key as a separate KRS record for each published Content Object, the KRS service may simply store the key once in the authoritative zone "/parc," with the notation that this record is the final response for any name including the prefix "/parc/jj." In some embodiments, the table used to perform longest-prefix-matching uses a special designation (e.g., an asterisk "*") at a KRS record for a prefix, which indicates that there are no further KRS records below the prefix.

FIG. **1B** illustrates an exemplary KRS record **150** in accordance with an embodiment. KRS record **150** can include a name **152**, a payload **156**, and security information **160** for KRS record **150**. Name **152** can include the content name (or name prefix) that is being resolved, and payload **156** can include the security information **158** associated with name **152**. Security information **158** can include, for example, a public key for the Content Object or a content hash of the Content Object. Also, KRS record **150** is individually secured with a cryptographic signature **162** and carries a public key certificate or certificate chain **164** for the signing key. A consumer receiving KRS record **150** can trust KRS record **150** if signature **162** is valid, and certificate chain **164** for the signing key anchors at a trusted entity (e.g., a global certificate authority). As stated previously, the KRS records are transmitted in a CCN Content Object. These CCN Content Objects also include a signature that can be used to authenticate KRS services, and include a Publisher Public Key Digest (PPKD) field that can be used to validate the Content Object as an acceptable response to an Interest carrying a KRS query to a trusted KRS service instance.

Unlike the Domain Name System (DNS) that implements top-down forwarding, the servers of the KRS service may also employ bottom-up forwarding. In bottom-up forwarding, the local KRS services have a prefix name that assigns to them a place in the prefix hierarchy. When a local KRS service receives a query for which it has no immediate forwarding information, the local KRS service sends the query to its parent (instead of sending the query directly to the root of the prefix tree, as is done in top-down forwarding).

FIG. **2** illustrates an exemplary client device **206** querying the Key Resolution Service **200** in accordance with an embodiment. Specifically, KRS service **204** can be organized into a tree topology **202**, such that a local KRS service **204.4** has a parent KRS service **204.3**. Also, authoritative KRS service **204.3** has a parent KRS service **204.2**, whose parent is a root KRS service **204.1**.

A client device **206** can disseminate an Interest that includes a KRS query, and CCN nodes can forward this Interest to a local KRS service **204.4** (along a path **210.1**). If local KRS service **204.4** does not cache a KRS record for a content name of the KRS query, local KRS service **204.4** can forward the KRS query to a parent KRS service (e.g., authoritative KRS service **204.3**). However, if KRS service **204.3** and its parent KRS service **204.2** do not store a KRS record for the content name, query **210.2** may be forwarded to root KRS service **204.1** (e.g., recursively along a path **210.2**, or iteratively by local KRS service **204.4**).

At this point, root KRS service **204.1** can perform a longest-prefix-matching lookup in a next-hop table to determine a KRS zone for the content name, and returns a Content Object that encapsulates the KRS zone to local KRS service **204.4** (e.g., along path **210.3** if using recursive forwarding, or directly to local KRS service **204.4** if using iterative forwarding). For example, authoritative KRS service **204.6** may be a member of this KRS zone. Local KRS service **204.4** can use the routable prefix for this KRS zone to send the KRS query directly to authoritative KRS service **204.6** (along a path **210.4**). Authoritative KRS service **204.6** processes the KRS query to return a KRS record that specifies the security information for the content name of the KRS query (along a path **210.5**). Local KRS service **204.4** can encapsulate the security information in a Content Object (with the same name as the initial Interest from client device **206**), and returns this Content Object to client device **206** over a path **210.6**.

In some embodiments, KRS services can update their local next-hop table when they receive a Content Object (from a parent KRS service) that includes a KRS zone for given content name or name prefix. This way, if authoritative KRS service **204.3** receives a query Interest for the same query prefix from another local KRS service **204.5**, authoritative KRS service **204.3** can obtain the KRS record directly from KRS service **204.6** without requiring the KRS query to propagate all the way to root KRS service **204.1**.

Also, the KRS records can be cached by the local KRS services, by the authoritative KRS services, and/or they may also be cached by nodes of the underlying CCN network. However, typical CCN nodes perform exact matching when searching for KRS records to satisfy an Interest, unlike the KRS services that can perform longest-prefix matching when searching for a KRS record that can be used to satisfy an Interest.

To highlight the distinction between these two forms of caching, consider the example where a local KRS service receives a request to resolve "/parc/csl/papers/krs.pdf." In the process of iteratively resolving this request, the local KRS service receives and caches the KRS records for "/parc," "/parc/csl," and "/parc/csl/papers." At a later time, the local KRS service may receive another request to resolve the name prefix "/parc/csl/papers/paper2.pdf". Though these two requests share the prefix "/parc/csl/papers," CCN caching does not provide any benefits because CCN caching requires performing exact matching (e.g., requiring two names to include the same components in the same order). However, since servers of the KRS service translate Interest and Content Object packets into query prefixes, these servers may perform longest-prefix matching on these query prefixes to reduce the number of KRS referrals necessary. Continuing the example from above, the local KRS service may satisfy the KRS query for "/parc/csl/papers/paper2.pdf" by taking advantage of the cached entry for "/parc/csl/papers" to resolve the full KRS request with only one referral to the authoritative KSR server for "/parc/csl/papers."

Local KRS Service

FIG. **3** presents a flow chart illustrating a method **300** for processing a KRS query by a local KRS service in accordance with an embodiment. The local KRS service can be deployed across, and executed by, one or more servers of the underlying KRS service. During operation, the local KRS service can receive an Interest that includes a query for security information corresponding to a content name (operation **302**). The Interest can include the KRS query in the Interest's name, or in a payload. For example, the Interest's name can have the form:

$$/krs/q=/\{QUERY\_PREFIX\} \quad (1)$$

In expression (1), the prefix "/krs" includes a routable prefix that routes the Interest to a local KRS service, which is local to the client device that disseminated the Interest. Also, "q=/{QUERY_PREFIX}" specifies the KRS query to obtain security information for a Content Object being validated by the client device. For example, a Content Object for a "Sports Headlines" web page from the New York Times may include a structured name: "/NYTimes/Sports/Headlines/index.html." The KRS service may store security information for the name prefix "/NYTimes/Sports/Headlines," or for any prefix of this name prefix.

In some embodiments, the local KRS service can search for security information corresponding to one or more name prefixes of the Interest's KRS query. The local KRS service can perform a longest-prefix-matching lookup for a KRS record whose name is a longest match to content name in the Interest's KRS query (operation **304**), and determines whether a local cache or Content Store stores a KRS record for the content name (operation **306**).

If the local KRS service is storing the KRS record in the KRS Content Store, the local KRS service obtains the KRS record from the KRS Content Store (operation **308**). Otherwise, the local KRS service obtains the KRS record by querying an authoritative KRS service (operation **310**), and can create an entry in the KRS Content Store to cache the KRS record in association with the content name (operation **312**).

The local KRS service then analyzes the KRS records to obtain security information for the query prefix (operation **314**), and returns a Content Object that includes this security information (operation **316**). Continuing the above example, the local KRS service may analyze the KRS record to obtain security information for the name prefix "/NYTimes/Sports/," and returns a Content Object that includes this security information.

FIG. **4** presents a flow chart illustrating a method **400** for obtaining a KRS record from an authoritative KRS service in accordance with an embodiment. During operation, the local KRS service can perform a longest-prefix-matching lookup in a next-hop table to search for a KRS zone associated with a content name (operation **402**). Continuing the example from above, while querying an authoritative KRS service for the name prefix /NYTimes/Sports/headlines," the local KRS service may not find any KRS records for the name "/NYTimes/Sports/headlines" (or for a prefix thereof). However, the local KRS service may find an entry in the next-hop table for the name prefix "/NYTimes/Sports," as the longest-prefix match to the name prefix "/NYTimes/Sports/headlines."

The local KRS service then generates a recursive Interest for the KRS zone, which can include the KRS query in the Interest's name or payload. If the Interest includes the KRS query in the name, the Interest's name can have the form:

$$\{ROUTABLE\_PREFIX\}/krs/q=/\{QUERY\_PREFIX\} \quad (2)$$

In expression (2), {ROUTABLE_PREFIX} includes the routable prefix to the KRS zone, which the CCN forwarder nodes use to forward the recursive Interest to any authoritative KRS service that belongs to the target KRS zone. The name portion "/krs/q=/" designates the beginning of the KRS query, and {QUERY_PREFIX} specifies the name prefix for which to obtain the security information (e.g., "/NYTimes/Sports/headlines"). The local KRS service then disseminates the recursive Interest over CCN (operation **406**).

After disseminating the recursive Interest, the local KRS service can obtain a Content Object that satisfies the Interest (operation **408**), and determines whether the Content Object includes a KRS record or a routable prefix to another KRS zone (operation **410**). If the KRS record includes a routable prefix to another KRS zone, the local KRS service can obtain the routable prefix from the Content Object (operation **412**), and updates the next-hop table to map the content name to the KRS zone (operation **414**). The local KRS service then returns to operation **404** to generate a recursive Interest to the KRS zone.

On the other hand, if the local KRS service determines at operation **410** that the Content Object includes a KRS record, the local KRS service can cache the KRS record in association with the query's name prefix (operation **416**). The local KRS service can then use the KRS record to return security information to the client device.

Authoritative KRS Service

In some embodiments, an authoritative KRS service can process a recursive Interests either iteratively or recursively. For example, when responding to Interests iteratively, the authoritative KRS service can return a KRS record if it exists, or can return a routable prefix to another KRS zone if one is found. The authoritative KRS service may return the security information by responding to the Interest with a Content Object (CO) having the form:

iterative CO: {ROUTABLE PREFIX}::{ZONE}::{SECURITY} (3)

In expression (3), {ROUTABLE PREFIX} contains the routable prefix of the authoritative server for the next zone, and {ZONE} contains the prefix that this zone is responsible for. Also, {SECURITY} contains the security information necessary for the receiver to verify the integrity of responses coming from this server, such as a certificate chain or public key.

On the other hand, when responding to Interests recursively, the authoritative KRS service can obtain another KRS zone from a next-hop table, and disseminates a recursive Interest to the KRS zone to obtain the security information. Then, similar to a local KRS service, when the authoritative KRS service receives a Content Object, the authoritative KRS service either uses the Content Object's KRS record to respond to the original Interest, or uses the Content Object's KRS zone to construct another Interest.

FIG. **5** presents a flow chart illustrating a method **500** for responding to an Interest iteratively by an authoritative KRS service in accordance with an embodiment. During operation, the authoritative KRS service can receive an Interest that includes a KRS query for security information corresponding to a content name (operation **502**), and analyzes the Interest to obtain the KRS query (operation **504**).

The authoritative KRS service then determines whether the KRS repository stores a KRS record for the content name (operation **506**). If so, the authoritative KRS service obtains the KRS record from the KRS repository (operation **508**), generates a Content Object that includes the KRS record (operation **510**), and returns the Content Object (operation **512**).

If the KRS repository does not store a KRS record for the name prefix, the authoritative KRS service can query another KRS zone or another KRS service (operation **514**). For example, the authoritative KRS service can perform a lookup in the next-hop table for another KRS zone associated with the content name. Recall that the Key Resolution Service includes a set of authoritative KRS services organized into a tree topology. Hence, if the next-hop table does not store an entry for the content name, the authoritative KRS service can query its parent KRS service for a KRS record for the content name.

The authoritative KRS service then determines whether the parent KRS service provided a KRS record (operation **516**). If so, the authoritative KRS service stores the KRS record in the KRS repository (operation **518**), and proceeds to operation **510** to generate and return a Content Object that includes the KRS record. On the other hand, if the parent KRS service does not provide a KRS record, the authoritative KRS service generates a Content Object which includes a no-record response (e.g., a response specifying that a KRS record does not exist for the query prefix) (operation **520**), and proceeds to operation **512** to return the Content Object.

FIG. **6** presents a flow chart illustrating a method **600** for responding to an Interest recursively by an authoritative KRS service in accordance with an embodiment. During operation, the authoritative KRS service can receive an Interest that includes a KRS query for security information corresponding to a content name (operation **602**), and analyzes the Interest to obtain the KRS query (operation **604**).

The authoritative KRS service then determines whether the KRS repository stores a KRS record for the content name (operation **606**). If so, the authoritative KRS service generates a Content Object that includes the KRS record (operation **608**), and returns the Content Object (operation **610**).

On the other hand, if the KRS repository does not store a KRS record for the content name, the authoritative KRS service can query another KRS zone or KRS service for a KRS record (operation **612**). This remote KRS service may correspond to an authoritative KRS service for a zone identified in the next-hop table, or may be a parent KRS service to the authoritative KRS service. The authoritative KRS service analyzes the query response from the other KRS zone or service to determine whether the response includes a KRS record (operation **616**). If not, the KRS service generates a Content Object that includes the query response (operation **618**), and proceeds to operation **610** to return the Content Object. This query response can include a routable prefix to another KRS zone, which a local KRS service can use to forward a query to the KRS zone via the iterative forwarding technique.

On the other hand, if the query response includes a KRS record, the KRS service stores the KRS record in the KRS repository (operation **616**), and proceeds to operation **610** to generate and return a Content Object that includes the query response.

Client Device

FIG. **7** presents a flow chart illustrating a method **700** for validating a Content Object in accordance with an embodiment. During operation, the client device can query the KRS service to obtain a trusted key corresponding to a desired Content Object (operation **702**). The client device can also obtain the Content Object over CCN by disseminating an Interest that includes the Content Object's name (operation **704**).

Some pieces of data are signed using a key from the data's publisher, while other pieces of data may be left unsigned. When the client device receives the Content Object, the client device can analyze the Content Object to determine whether the Content Object specifies a key locator (operation **706**). If the Content Object does not specify a key locator, the client device determines that the Content Object is valid (operation **710**). Otherwise, the client device determines whether the key matches the key locator (operation **708**). Recall that the KRS service is a trusted entity that stores keys for various name prefixes. Hence, if the key obtained from the KRS service matches the Content Object's key locator, the client device determines that the Content Object is valid (operation **710**).

Otherwise, the client device verifies the chain of trust between the trusted key (from the KRS service) and the Content Object's key (operation **712**). If the client device can verify that the chain of trust exists (operation **714**), the client device determines that the Content Object is valid (operation **710**). Otherwise, if the client device cannot verify that the chain of trust exists, the client device determines that the Content Object is not valid (operation **716**).

For example, the Content Object can include a web page with the name "/NYTimes/Sports/headlines/index.html," and can specify a key locator "/NYTimes/Sports/headlines/key" for a key that is used to authenticate content with the name prefix "/NYTimes/Sports/headlines." However, the KRS service may only store a key for the name prefix "/NYTimes" (e.g., a key named "/NYTimes/key"). Hence, the client device would need to obtain a set of keys over CCN that establishes a chain of trust between the trusted key "/NYTimes/key" and the Content Object's key "/NYTimes/Sports/headlines/key."

FIG. **8**A presents a flow chart illustrating a method **800** for analyzing a chain of trust between a trusted key from the KRS service and the Content Object's key in accordance with an embodiment. During operation, the client device can obtain, from the KRS query results (e.g., from a KRS record), a verified name prefix and a trusted key for the verified name prefix (operation **802**). Continuing the example from above, the KRS query results can include the trusted key "/NYTimes/key" for the verified name prefix "/NYTimes."

To establish the chain of trust starting from the trusted key, the client device can disseminate an Interest for a key which is signed by the current key, and that links the current key toward the Content Object's key (operation **804**). For example, in the initial iteration, the current key is the trusted key "/NYTimes/key." The client device disseminates an Interest for the key "/NYTimes/Sports/key," so that this key is signed by the current key "/NYTimes/key." While there may exist multiple keys "/NYTimes/Sports/key" across CCN nodes, the client device is only interested in the key that is signed by the current key in the verified chain (e.g., signed by "/NYTimes/key").

After disseminating the Interest, the client device determines whether it has obtained a valid key (operation **806**). If the next key does not exist, or an invalid key was received (e.g., the next key was not signed by the current trusted key), the client device determines that the Content Object is not valid (operation **808**). Otherwise, the client device determines whether the obtained key authenticates the Content Object (operation **810**). For example, the client device can determine whether the key authenticates the Content Object by determining whether the key's name matches the Content Object's key locator. If so, the client device determines that the Content Object is valid (operation **812**).

However, if the obtained key does not sign the Content Object, the client device can return to operation **804** to disseminate an Interest for the next key that is signed by the last key along the current validated chain of trust. For example, during the second iteration, the client device can return to operation **804** to disseminate an Interest for a key "/NYTimes/Sports/Headlines/key" that is signed by the key "/NYTimes/Sports/key."

In some embodiments, the client device can verify the chain of trust by iteratively searching for keys, starting from the Content Object's key locator, to form a key chain between the trusted key (e.g., a key from a KRS service) and the Content Object's key.

FIG. **8**B presents a flow chart illustrating a method **850** for analyzing a chain of trust between a Content Object's key and a trusted key from the KRS service in accordance with an embodiment. During operation, the client device can obtain, from the KRS query results, a verified name prefix and a trusted key for the verified name prefix (operation **852**). The client device begins verifying the chain of trust by selecting the Content Object's key locator as the target name prefix (operation **854**), and disseminates an Interest for a key at the target name prefix (operation **856**). For example, continuing the example from above, the "target name prefix" may initially correspond to the key locator "/NYTimes/Sports/headlines/key." Then to verify the chain of trust, the client device determines whether it has obtained a valid key (operation **858**). If the client device could not obtain a key, or a valid key, the client device determines that the Content Object is not valid (operation **860**).

On the other hand, if the client device does obtain a valid key, the client device determines whether the obtained key is signed by the trusted key (from the KRS service) (operation **862**). If the obtained key is indeed signed by the trusted key, the client device has successfully validated the chain of trust, and goes on to determine that the Content Object is indeed valid (operation **864**). However, if the obtained key is not signed by the trusted key, the client device selects a target name prefix for a key that may complete the chain of trust toward the trusted key (operation **866**). For example, during the first iteration, the client device may obtain the key "/NYTimes/Sports/headlines/key" which can be used to authenticate the Content Object "/NYTimes/Sports/headlines/index.html." Since this key is not signed by the trusted key "/NYTimes/key," the client device selects the name "/NYTimes/Sports/key" as the next target name prefix, and returns to operation **856** to disseminate an Interest for this target name prefix.

The client device can obtain the key "/NYTimes/Sports/key" over CCN, which can be satisfied by any device operating on the CCN network. Because of this, it is possible that the client device may receive a key that does not sign the key "/NYTimes/Sports/headlines/key." In this case, the client device can disseminate additional Interests (e.g., Interests directed to other segments of the CCN network) to search for an instance of the key which does sign the key "/NYTimes/Sports/headlines/key." If the client device cannot find a valid key after a predetermined number of attempts, the client device can conclude that a valid key does not exist.

Managing KRS Records

A publisher can create a new KRS record to be stored in an authoritative KRS service by first creating the new security information to be stored in the KRS service. This new KRS record can correspond to a name prefix that the publisher will use to publish self-certified content. The publisher can create this security information by producing a pair of keys, a content-signature, a hash digest of the Content Object, or any other security-related information now known or later developed. The publisher can then have the appropriate KRS signing entity (e.g., a CA) sign the new KRS record, and provides the signed KRS record to an authoritative KRS service of the desired KRS zone. The authoritative KRS service stores the KRS record, and uses the KRS record to perform a longest-matching-prefix lookup on the publisher's name prefix.

For example, the publisher can use CCN to create, update, or delete a KRS entry using a communication protocol as follows.

"create" Interest: {ROUTABLE PREFIX}/*krs*/create/{PREFIX}/{SECURITY} (4)

"create" CO: {PREFIX}::{SECURITY}::{SIGNATURE} (5)

"update" Interest: {ROUTABLE PREFIX}/*krs*/update/{PREFIX}/{SECURITY} (6)

"update" CO: {PREFIX}::{SECURITY}::{SIGNATURE} (7)

"delete" Interest: {ROUTABLE PREFIX}/*krs*/delete/{PREFIX}/ (8)

"delete" CO: {PREFIX}::"NONE"::{SIGNATURE} (9)

The publisher creates and disseminates Interests using an expression (4), (6), or (8), which is forwarded over CCN toward an authoritative KRS service associated with the routable prefix of the Interest. The authoritative KRS service responds to the publisher by generating and returning a corresponding Content Object (CO) using expression (5), (7), or (9). More specifically, in expressions (4)-(9), {ROUTABLE PREFIX} represents the routable prefix to the authoritative KRS service, {PREFIX} represents the full prefix for the

KRS record (e.g., a prefix of the content object), and {SECURITY} represents security information for the prefix. Also, in expressions (5), (7), and (9), {SIGNATURE} represents security provided by the signing entity for the KRS record.

In some embodiments, the publisher can provide an unsigned KRS record to a KRS signing entity, using an off-line data transfer, or through CCN itself. When using CCN to provide the unsigned KRS record, the publisher can use expression (4) to provide the unsigned KRS record to the KRS signing entity, and the KRS signing entity can use expression (5) to return the signature. In expressions (4) and (5), {ROUTABLE PREFIX} represents the routable prefix of the signing entity, {PREFIX} represents the full prefix to be stored in the KRS, {SECURITY} represents the security information for the prefix, and {SIGNATURE} represents the signature provided by the signing entity.

When the signing entity receives an unsigned entry, the signing entity can perform a form of access-control before signing the KRS record and returning the signed KRS record to the publisher. This access-control can involve verifying the publisher's identity, for example, using a name and password, by performing cryptographic verification, etc. However, the selection of an individual access-control policy, as well as the protocol or communication necessary to enact the policy, is outside the scope of the paper. Such a policy may entail several more Interest/Data pairs, but what is important for the sake of the KRS Update Protocol is that the publisher initiates communication with the Interest, and the signing entity responds to this Interest with the corresponding Data packet once the operation has been authorized.

In some embodiments, the KRS service may distribute the routable prefix of the signing entity to the publishers. However, to achieve a higher level of security, an organization may distribute this information through off-line channels. In some other embodiments, a publisher might have a dedicated prefix (e.g., a publisher "JJ" can publish content under the prefix "/parc/users/jj"), in which case the publisher can be its own signing entity.

Once a publisher receives the signed response from the signing entity, the publisher then provides the received security information to an authoritative KRS service of the target KRS zone. The publisher can provide the security information through a push-based communication over CCN, or through an off-line manual configuration.

FIG. **9** illustrates an exemplary apparatus **900** that facilitates resolving keys for Content Objects in accordance with an embodiment. Apparatus **900** can comprise a plurality of modules which may communicate with one another via a wired or wireless communication channel. Apparatus **900** may be realized using one or more integrated circuits, and may include fewer or more modules than those shown in FIG. **9**. Further, apparatus **900** 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 **900** can comprise a communication module **902**, an Interest-processing module **904**, a record-lookup module **906**, and a record-querying module **908**.

In some embodiments, communication module **902** can receive an Interest with a name that includes a routable prefix associated with the key-resolution server, and includes a query prefix for a first Content Object. Interest-processing module **904** can parse the Interest to obtain the query prefix for the Content Object. Record-lookup module **906** can obtaining a cryptographic key associated with at least a prefix from the Content Object's query prefix, for example, by performing a longest-prefix-matching lookup based on the query prefix to obtain a key-resolution record. Record-querying module **908** can also obtain a routable prefix for a key-resolution zone associated with the query prefix, and disseminates an Interest that queries a key-resolution server of the zone to obtain a trusted key for the Content Object.

FIG. **10** illustrates an exemplary computer system **1002** that facilitates resolving keys for Content Objects in accordance with an embodiment. Computer system **1002** includes a processor **1004**, a memory **1006**, and a storage device **1008**. Memory **1006** 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 **1002** can be coupled to a display device **1010**, a keyboard **1012**, and a pointing device **1014**. Storage device **1008** can store operating system **1016**, a key-resolution service **1018**, and data **1026**.

Key-resolution service **1018** can include instructions, which when executed by computer system **1002**, can cause computer system **1002** to perform methods and/or processes described in this disclosure. Specifically, key-resolution service **1018** may include instructions for receiving an Interest with a name that includes a routable prefix associated with the key-resolution server, and includes a query prefix for a first Content Object (communication module **1020**).

Key-resolution service **1018** can also include instructions for parsing the Interest to obtain the query prefix for the Content Object (Interest-processing module **1022**), and for obtaining a cryptographic key associated with at least a prefix from the Content Object's query prefix (record-lookup module **1024**). For example, key-resolution service **1018** can obtain the cryptographic key by performing a longest-prefix-matching lookup based on the query prefix to obtain a key-resolution record. Key-resolution service **1018** can also include instructions that can obtain a routable prefix for a key-resolution zone associated with the query prefix, and disseminates an Interest that queries a key-resolution server of the zone to obtain a trusted key for the Content Object (record-querying module **1026**).

Data **1028** 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 **1028** can store at least a repository for a plurality of final KRS records, and a lookup data structure (e.g., a lookup table) that facilitates performing a longest-prefix-matching lookup using a query prefix as input to select a KRS record that can satisfy a query for security information. Data **1028** can also store a next-hop table that facilitates performing a longest-prefix-matching lookup to determine a KRS zone associated with a given content name or name prefix.

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 computer-implemented method, comprising:
- receiving, by a server computer of the key-resolution service (KRS) over a Content Centric Network, an Interest message with a name that includes a routable prefix associated with the key-resolution service, wherein the Interest includes a query for a content name that is to be resolved in the name or a payload of the Interest;
- obtaining, from the Interest message, the content name that is to be resolved;
- obtaining, by the server computer, a KRS record for the content name, wherein the KRS record includes security information for the content name or security information for a prefix of the content name, wherein obtaining the KRS record involves:
  - performing a longest-prefix-matching lookup in a next-hop table, using the content name as input, to obtain a second routable prefix for a key-resolution zone associated with the content name or a prefix of the content name;
  - disseminating, over the Content Centric Network, a second Interest message that includes the query for the content name, and whose name includes the second routable prefix for the key-resolution zone; and
  - in response to receiving, from the key-resolution zone, a Content Object that includes a routable prefix for a second key-resolution zone, obtaining the KRS record from the second key-resolution zone; and
- returning, by the server computer, a Content Object whose payload includes the security information that satisfies the query, and whose name includes the Interest message's name, to satisfy the Interest message.

2. The method of claim **1**, wherein the Content Object's payload includes the KRS record.

3. The method of claim **1**, wherein the KRS record includes at least one of:
- a name or name prefix for which the KRS record resolves security information;
- a payload comprising security information for the name or name prefix; and
- security information that is used to authenticate the KRS record.

4. The method of claim **1**,
- wherein generating the second Interest message involves including the query for the content name in the name or a payload of the second Interest message.

5. The method of claim **1**, wherein a respective entry of the next-hop table includes at least one of:
- a name or name prefix;
- a routable prefix for a key-resolution zone mapped to the name or name prefix; and
- a public key for a key-resolution service associated with the key-resolution zone.

6. The method of claim **1**, wherein obtaining the KRS record from the second key-resolution zone involves:
- generating a third Interest message whose name includes the routable prefix for the second key-resolution zone, and includes the query for the content name in the name or a payload of the third Interest; and
- responsive to disseminating the third Interest for the second key-resolution zone, receiving a Content Object that includes the KRS record.

7. The method of claim **1**, further comprising updating the next-hop table to include an entry that maps the content name to the routable prefix for the second key-resolution zone.

8. The method of claim **1**, further comprising:
- responsive to disseminating the second Interest for the key-resolution zone, receiving a Content Object that satisfies the second Interest, and includes the KRS record; and
- caching the KRS record in a KRS record repository.

9. The method of claim **1**, wherein obtaining the KRS record involves:
- performing a longest-prefix-matching lookup in a KRS record repository, using the content name as input, to obtain the KRS record that includes the security information associated with at least a prefix of the content name.

10. The method of claim **1**, wherein the security information for the content name or a prefix of the content name in the KRS record includes one or more of:
- a public key;
- a public key certificate;
- a certificate chain;
- a cryptographic digest of a Content Object; and
- a cryptographic digest of a content object, signed by the Content Object's producer or a trusted entity.

11. 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, over a Content Centric Network, an Interest message with a name that includes a routable prefix associated with a key-resolution service, wherein the Interest includes a query for a content name that is to be resolved in the name or a payload of the Interest;
- obtaining, from the Interest message, the content name that is to be resolved;
- obtaining a KRS record for the content name, wherein the KRS record includes security information for the content name or security information for a prefix of the content name, wherein obtaining the KRS record involves:
  - performing a longest-prefix-matching lookup in a next-hop table, using the content name as input, to obtain a second routable prefix for a key-resolution zone associated with the content name or a prefix of the content name;
  - disseminating, over the Content Centric Network, a second Interest message that includes the query for the content name, and whose name includes the second routable prefix for the key-resolution zone; and
  - in response to receiving, from the key-resolution zone, a Content Object that includes a routable prefix for a second key-resolution zone, obtaining the KRS record from the second key-resolution zone; and

returning a Content Object whose payload includes the security information that satisfies the query, and whose name includes the Interest message's name, to satisfy the Interest message.

12. The storage medium of claim **11**, wherein the Content Object's payload includes the KRS record.

13. The storage medium of claim **11**, wherein the KRS record includes at least one of:

a name or name prefix for which the KRS record resolves security information;

a payload comprising security information for the name or name prefix; and

security information that is used to authenticate the KRS record.

14. The storage medium of claim **11**,

wherein generating the second Interest message involves including the query for the content name in the name or a payload of the second Interest message.

15. The storage medium of claim **11**, wherein a respective entry of the next-hop table includes at least one of:

a name or name prefix;

a routable prefix for a key-resolution zone mapped to the name or name prefix; and

a public key for a key-resolution service associated with the key-resolution zone.

16. The storage medium of claim **11**, wherein obtaining the KRS record from the second key-resolution zone involves:

generating a third Interest message whose name includes the routable prefix for the second key-resolution zone, and includes the query for the content name in the name or a payload of the third Interest; and

responsive to disseminating the third Interest for the second key-resolution zone, receiving a Content Object that includes the KRS record.

17. The storage medium of claim **11**, further comprising updating the next-hop table to include an entry that maps the content name to the routable prefix for the second key-resolution zone.

18. The storage medium of claim **11**, further comprising:

responsive to disseminating the second Interest for the key-resolution zone, receiving a Content Object that satisfies the second Interest, and includes the KRS record; and

caching the final key-resolution record.

19. The storage medium of claim **11**, wherein obtaining the KRS record involves:

performing a longest-prefix-matching lookup in a KRS record repository, using the content name as input, to obtain the KRS record that includes the security information associated with at least a prefix of the content name.

20. A server computer of a key-resolution service (KSR), comprising:

a processor; and

a memory storing instructions that when executed by the processor cause the server computer to implement:

a communication module configured to receive, over a Content Centric Network, an Interest message with a name that includes a routable prefix associated with the key-resolution service, wherein the Interest includes a query for a content name that is to be resolved in the name or a payload of the Interest;

an Interest-processing module configured to obtain, from the Interest message, the content name that is to be resolved; and

a record-lookup module configured to obtain a KRS record for the content name, wherein the KRS record includes security information for the content name or security information for a prefix of the content name, wherein obtaining the KRS record involves:

performing a longest-prefix-matching lookup in a next-hop table, using the content name as input, to obtain a second routable prefix for a key-resolution zone associated with the content name or a prefix of the content name;

disseminating, over the Content Centric Network, a second Interest message that includes the query for the content name, and whose name includes the second routable prefix for the key-resolution zone; and

in response to receiving, from the key-resolution zone, a Content Object that includes a routable prefix for a second key-resolution zone, obtaining the KRS record from the second key-resolution zone; and

wherein the communication module is further configured to return a Content Object whose payload includes the security information that satisfies the query, and whose name includes the Interest message's name, to satisfy the Interest message.

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