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Network coding for content-centric network

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Garcia-Luna-Aceves, J.J.

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(54) **NETWORK CODING FOR
CONTENT-CENTRIC NETWORK**

(71) Applicant: **Palo Alto Research Center
Incorporated**, Palo Alto, CA (US)

(72) Inventors: **Jun Kurihara**, Mountain View, CA
(US); **Ersin Uzun**, Campbell, CA (US);
Jose J. Garcia-Luna-Aceves, San
Mateo, CA (US)

(73) Assignee: **PALO ALTO RESEARCH CENTER
INCORPORATED**, Palo Alto, CA
(US)

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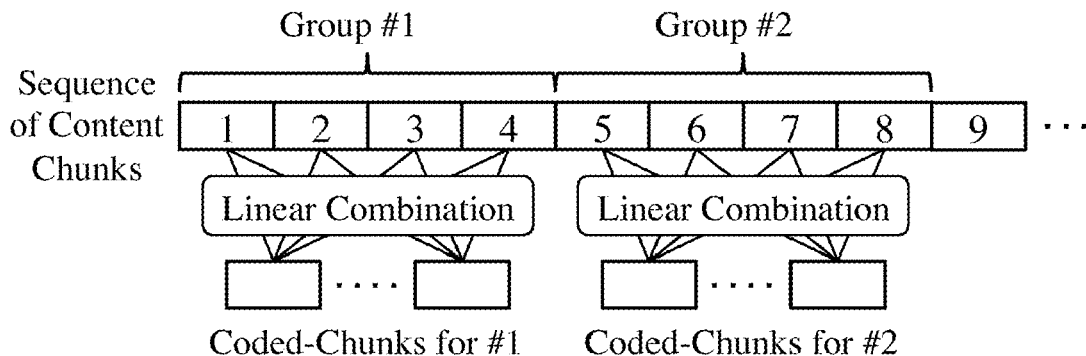
Primary Examiner — Esaw Abraham

(74) *Attorney, Agent, or Firm* — Shun Yao; Park,
Vaughan, Fleming & Dowler LLP

(57) **ABSTRACT**

One embodiment of the present invention provides a system
for facilitating network coding in an information centric
network. During operation, the system sends, from a content
consumer node, one or more interests for a plurality of
chunks associated with a content object. A respective inter-
est indicates the corresponding chunk using a hierarchically
structured variable length identifier which comprises con-
tiguous name components ordered from a most general level
to a most specific level. In response, the system then receives
a number of network-coded data packets, wherein a respec-
tive data packet corresponds to an independent linear com-
bination of all the chunks for the content object. The system
subsequently re-constructs the content object based on the
received data packets.

10 Claims, 7 Drawing Sheets



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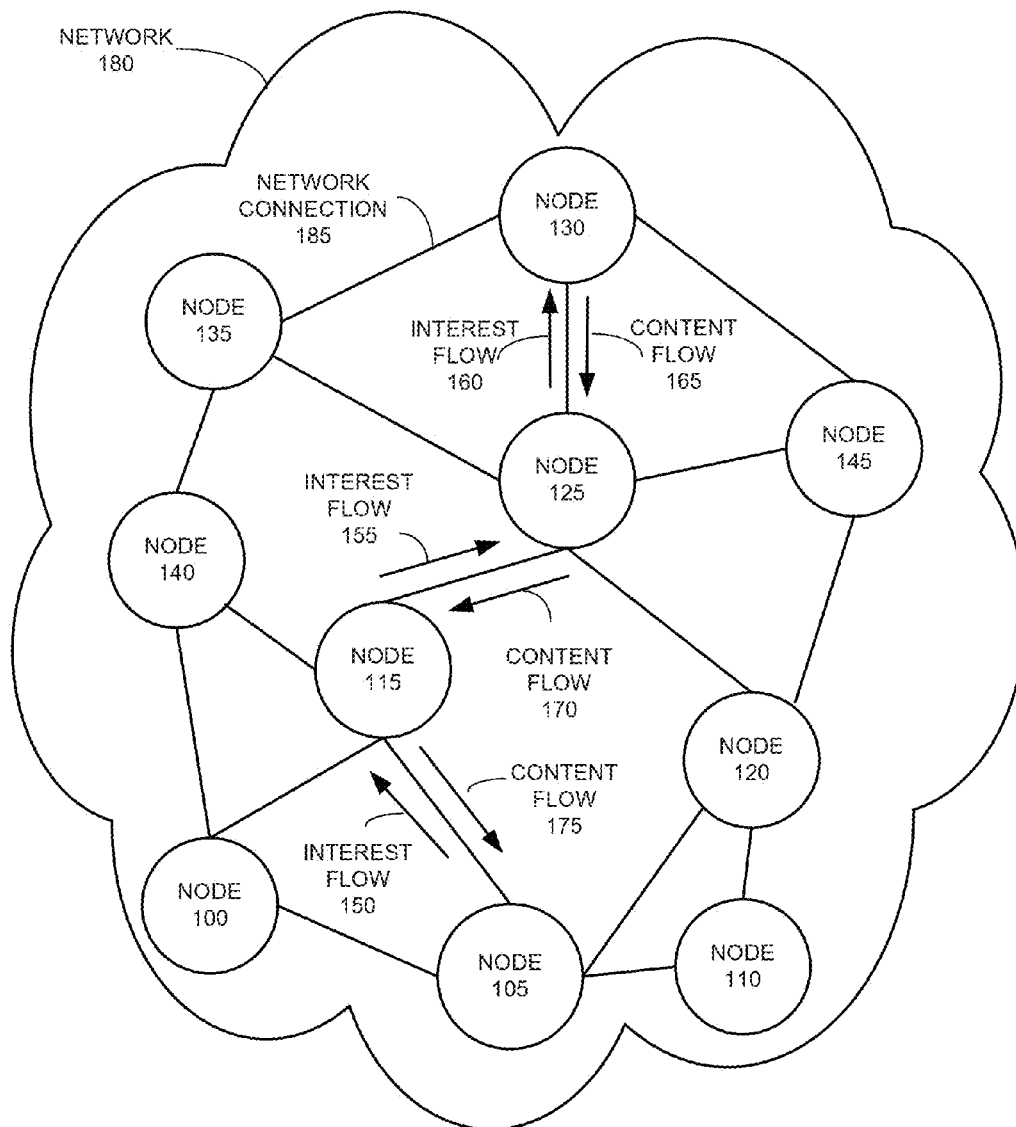


FIG. 1

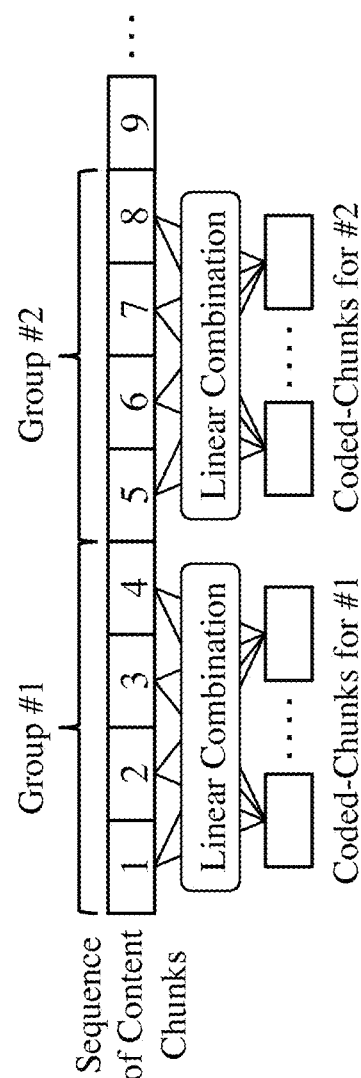


FIG. 2

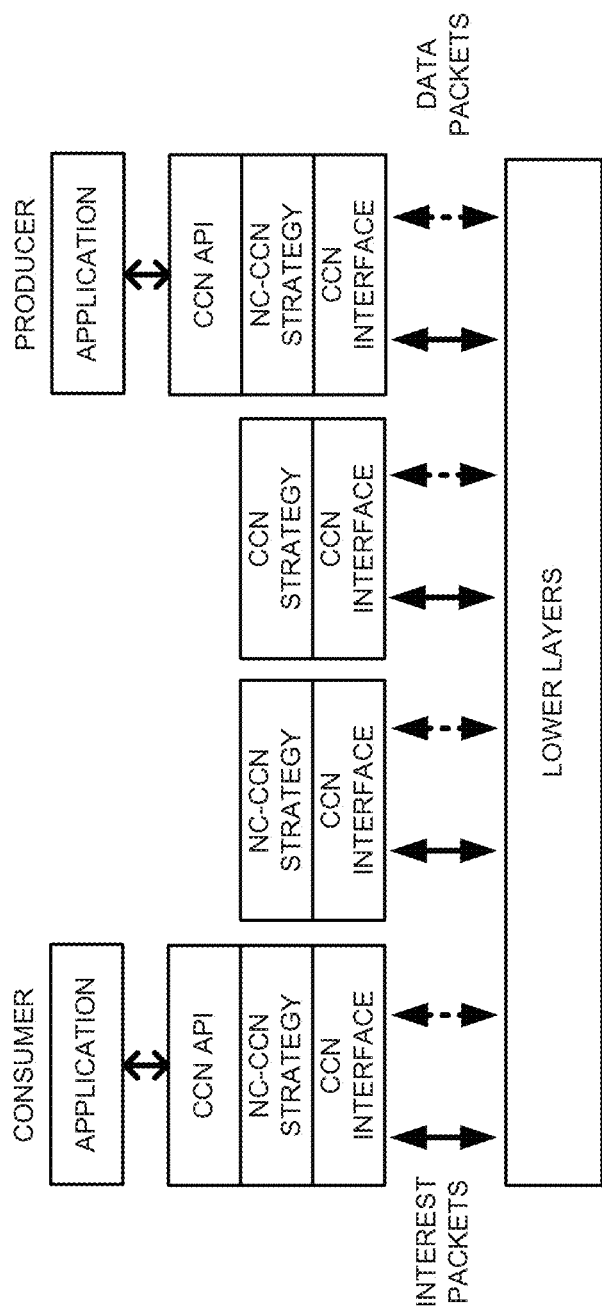


FIG. 3A

NAME IN CCN: / parc.com / jun.jpg / %00%01
 PREFIX SEQ. NUM.

NAME IN NC-CCN: / parc.com / jun.jpg / %A0%10 / %00%03 / %A1%00 / %A2%03
 PREFIX NC FLAG SEQ. RETRY SEEN
 WITH GROUP NUM. FLAG INFO
 SIZE

FIG. 3B

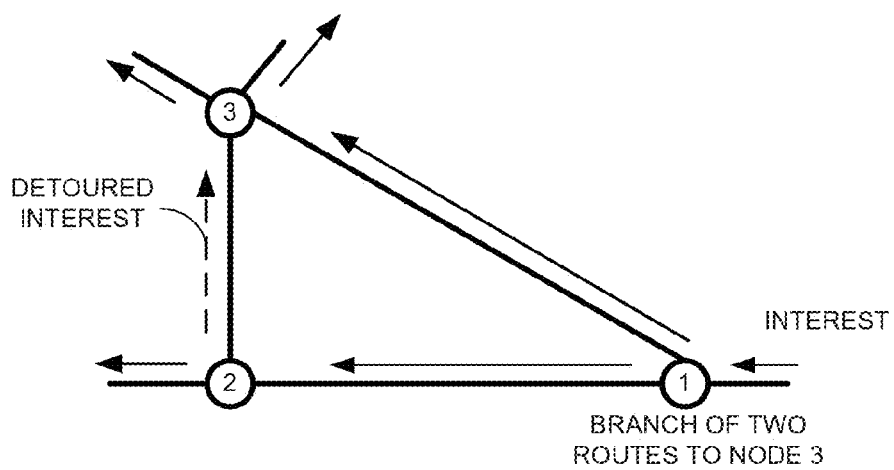
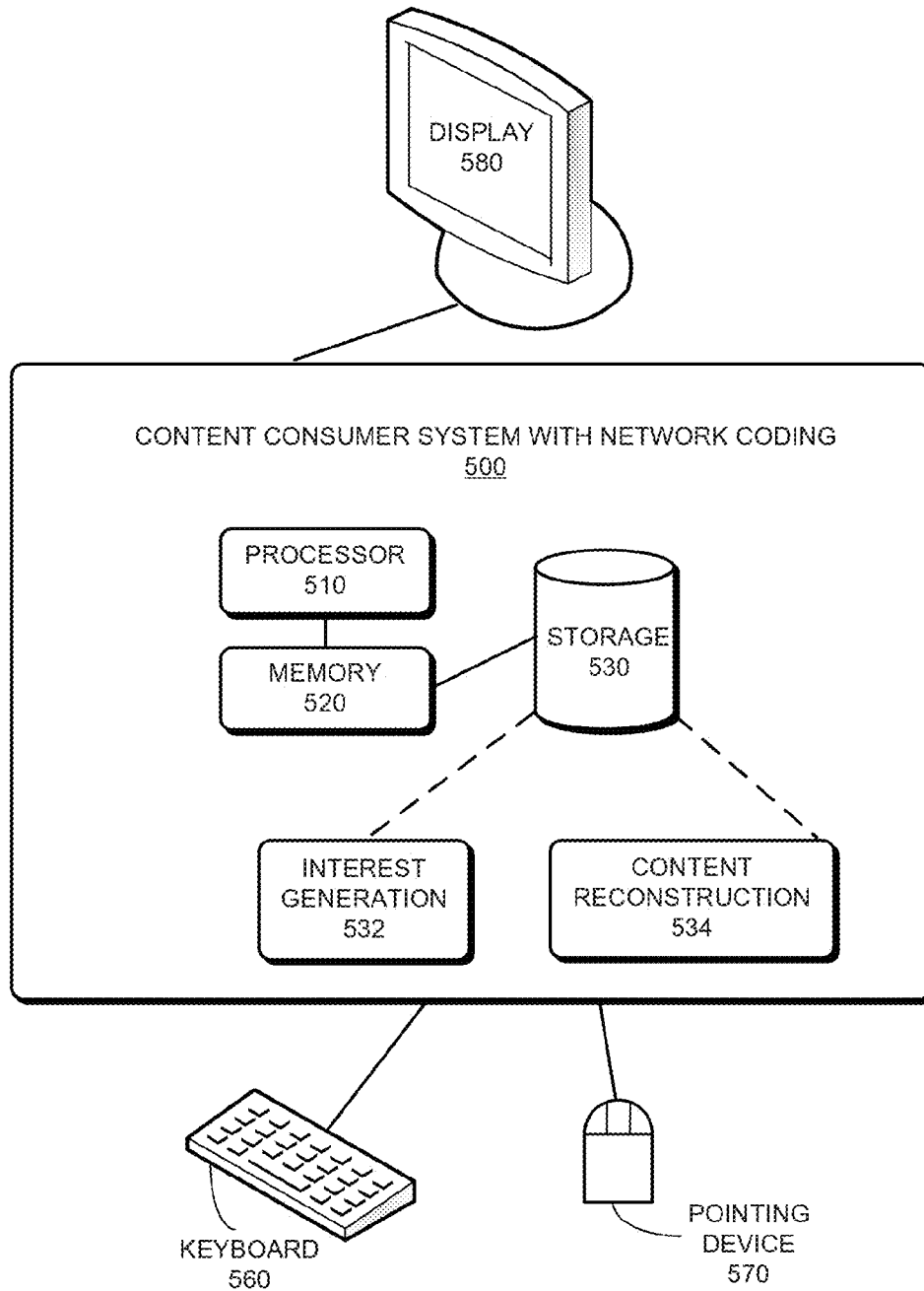


FIG. 4

**FIG. 5**

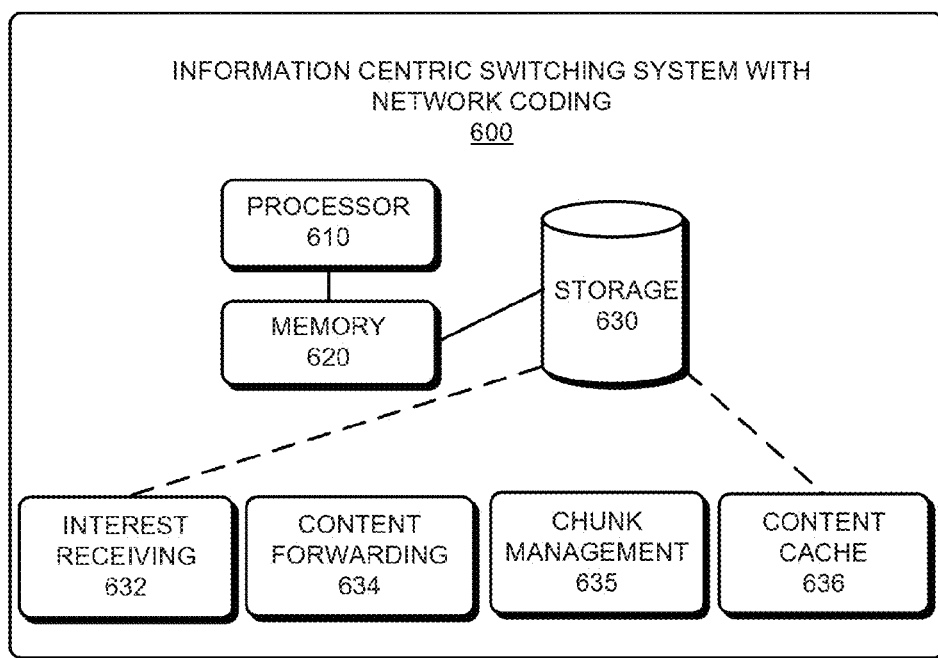


FIG. 6

1

NETWORK CODING FOR CONTENT-CENTRIC NETWORK

RELATED APPLICATIONS

The subject matter of this application is related to the subject matter in the following U.S. Pat. No. 8,243,735, entitled "SYSTEM FOR FORWARDING PACKETS WITH HIERARCHICALLY STRUCTURED VARIABLE-LENGTH IDENTIFIERS USING AN EXACT-MATCH LOOKUP ENGINE," by inventors Van L. Jacobson and James D. Thornton, filed on 15 Dec. 2009; U.S. Pat. No. 8,160,069, entitled "SYSTEM FOR FORWARDING A PACKET WITH A HIERARCHICALLY STRUCTURED VARIABLE-LENGTH IDENTIFIER," by inventors Van L. Jacobson and James D. Thornton, filed 23 Sep. 2009; and U.S. Pat. No. 8,204,060, entitled "METHOD AND SYSTEM FOR FACILITATING FORWARDING A PACKET IN A CONTENT-CENTRIC NETWORK", by inventors Van L. Jacobson and James D. Thornton, filed on 17 Dec. 2009; the disclosures of which herein are incorporated by reference in their entirety.

BACKGROUND

Field

The present disclosure relates generally to facilitating data processing in network. More specifically, the present disclosure relates to a system and method for facilitating network coding in content-centric networks.

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 viewing 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 two most ubiquitous protocols, the Internet Protocol (IP) and Ethernet protocol, are both based on location-based addresses. That is, a consumer of content can only receive the content by explicitly requesting the content from an address (e.g., IP address or Ethernet media access control (MAC) address) closely associated with a physical object or location. This restrictive addressing scheme is becoming progressively more inadequate for meeting the ever-changing network demands.

Recently, content-centric network (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 conversations over which content travels, content is requested or returned based on its unique name, and the network is responsible for routing content from the provider to the consumer. Note that content includes data that can be transported in the communication system, including any form of data such as text, images, video, and/or audio. A consumer and a provider can be a person at a computer or an automated process inside or outside the CCN. A piece of content can refer to the entire content or a respective portion of the content. For example, a newspaper article might be represented by multiple pieces of content embodied as data packets. A piece of content can also be associated with metadata describing or augmenting the piece of content with information such as authentication data, creation date, content owner, etc.

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In CCN, content objects and interests are identified by their names, which is typically a hierarchically structured variable-length identifier (HSVLI). When an interest in a piece of content is received at a CCN node, a local content cache is checked to see if the content being requested exists. In certain situations, however, transporting data through a number of CCN nodes and links can be inefficient when multiple copies of an interest are sent out.

SUMMARY

One embodiment of the present invention provides a system for facilitating network coding in an information centric network. During operation, the system sends, from a content consumer node, one or more interests for a plurality of chunks associated with a content object. A respective interest indicates the corresponding chunk using a hierarchically structured variable length identifier which comprises contiguous name components ordered from a most general level to a most specific level. In response, the system then receives a number of network-coded data packets, wherein a respective data packet corresponds to an independent linear combination of all the chunks for the content object. The system subsequently re-constructs the content object based on the received data packets.

In a variation on this embodiment, re-constructing the content object based on the received data packets involves determining that at least one more data packet is needed for re-constructing a missing chunk and sending a retry interest which indicates the missing chunk.

In a variation on this embodiment, the hierarchically structured variable length identifier includes a component which indicates use of network coding and a number of chunks for the content object.

In a variation on this embodiment, the hierarchically structured variable length identifier includes a component which indicates whether the corresponding interest is a retry interest.

In a variation on this embodiment, the hierarchically structured variable length identifier includes a component which indicates one or more chunks that have already been re-constructed.

One embodiment of the present invention provides a system for facilitating network coding at a switching node in an information centric network. During operation, the system receives an interest generated by a content consumer node for a chunk associated with a content object. In response to the chunk being locally available and not having been sent previously to a node from which the interest is received, the system sends an independent linear combination of the chunk and one or more other chunks associated with the content object to the node from which the interest is received. In response to the chunk not being locally available, the system forwards the interest and subsequently caching an independent linear combination of the chunk and other chunks for the content object when such combination is received in response of the forwarded interest.

In a variation on this embodiment, the system receives a linear combination of a plurality of chunks for the content object from another node. The system then determines that the received linear combination of chunks is not independent from a locally cached linear combination of chunks and discards the received linear combination of chunks.

In a variation on this embodiment, subsequent to sending the independent linear combination of the chunks, the system indicates that the chunk has been sent to the node from which the interest is received.

In a variation on this embodiment, the system determines a received interest is a detour interest and, in response, discards the detour interest

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 illustrates an exemplary architecture of a network, in accordance with an embodiment of the present invention.

FIG. 2 shows an exemplary chunking for a Content Object, in accordance with an embodiment of the present invention.

FIG. 3A presents a block diagram illustrating an exemplary network protocol stack, in accordance with an embodiment of the present invention.

FIG. 3B illustrates exemplary name components in accordance with an embodiment of the present invention.

FIG. 4 presents a diagram illustrating an exemplary detour Interest, in accordance with an embodiment of the present invention.

FIG. 5 illustrates an exemplary content-consumer system with network coding, in accordance with an embodiment of the present invention.

FIG. 6 illustrates an exemplary switching system with network coding, in accordance with an embodiment of the present invention.

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

DETAILED DESCRIPTION

Several information centric networking (ICN) architectures have been proposed to date as alternatives to the existing Internet architecture to enable efficient access to content and services by name, independently of their locations. Meanwhile, network coding (NC) has been shown to improve the throughput of information dissemination in networks subject to multi-point communication or connectivity disruption. This is attained by encoding data packets in a way that sources and relays can transmit (component-wise) linear combinations of the data packets, rather than the individual data packets themselves, such that any relay or intended receiver is able to decode the data packets as long as it receives sufficient independent linear combinations of the data packets.

NC can increase the overall performance of ICN in terms of information dissemination. Few proposals, however, have been advanced to date on the integration of NC and ICN. Furthermore, it is usually assumed that all routers support NC.

Embodiments of the present invention facilitate network-coded content centric networking (NCCN) as an example of how NC can be integrated with ICN approaches seamlessly in order to improve the performance of an ICN without requiring all routers to implement NC. NCCN allows Interests and data packets to be processed by normal CCN or named data networking (NDN) nodes without NC capability as normal CCN or NDN packets. To realize this compatibility, NCCN introduces new Name components that represent information required for the use of NC, without any change to the structures of Interest and Data packets. The protocol stack of NCCN is designed with minimal changes to normal CCN or NDN stack. NCCN only adds additional steps prior to the basic forwarding and caching strategies of CCN or NDN to enable the use of NC. This implies that existing forwarding strategies and caching strategies designed for CCN or NDN can be used without modification in NCCN.

In general, CCN uses two types of messages: Interests and Content Objects. An Interest carries the hierarchically structured variable-length identifier (HSVLI), also called the “name,” of a Content Object and serves as a request for that object. If a network element (e.g., router) receives multiple interests for the same name, it may aggregate those interests. A network element along the path of the Interest with a matching Content Object may cache and return that object, satisfying the Interest. The Content Object follows the reverse path of the Interest to the origin(s) of the Interest. A Content Object contains, among other information, the same HSVLI, the object’s payload, and cryptographic information used to bind the HSVLI to the payload.

The terms used in the present disclosure are generally defined as follows (but their interpretation is not limited to such):

“HSVLI:” Hierarchically structured variable-length identifier, also called a Name. It is an ordered list of Name Components, which may be variable length octet strings. In human-readable form, it can be represented in a format such as `ccnx:/path/part`. There is not a host or query string. As mentioned above, HSVLIs refer to content, and it is desirable that they be able to represent organizational structures for content and be at least partially meaningful to humans. An individual component of an HSVLI may have an arbitrary length. Furthermore, HSVLIs can have explicitly delimited components, can include any sequence of bytes, and are not limited to human-readable characters. A longest-prefix-match lookup is important in forwarding packets with HSVLIs. For example, an HSVLI indicating an interest in `“/parc/home/bob”` will match both `“/parc/home/bob/test.txt”` and `“/parc/home/bob/bar.txt.”` The longest match, in terms of the number of name components, is considered the best because it is the most specific.

“Interest:” A request for a Content Object. The Interest specifies an HSVLI name prefix and other optional selectors that can be used to choose among multiple objects with the same name prefix. Any Content Object whose name matches the Interest name prefix and selectors satisfies the Interest.

“Content Object:” A data object sent in response to an Interest. It has an HSVLI name and a Contents payload that are bound together via a cryptographic signature. Optionally, all Content Objects have an implicit terminal name component made up of the SHA-256 digest of the Content Object. In one embodiment, the implicit digest is not transferred on the wire, but is computed at each hop, if needed.

As mentioned before, an HSVLI indicates a piece of content, is hierarchically structured, and includes contiguous components ordered from a most general level to a most specific level. The length of a respective HSVLI is not fixed. In content-centric networks, unlike a conventional IP network, a packet may be identified by an HSVLI. For example, `“abcd/bob/papers/ccn/news”` could be the name of the content and identifies the corresponding packet(s), i.e., the “news” article from the “ccn” collection of papers for a user named “Bob” at the organization named “ABCD.” To request a piece of content, a node expresses (e.g., broadcasts) an interest in that content by the content’s name. An interest in a piece of content can be a query for the content according to the content’s name or identifier. The content, if available in the network, is routed back to it from any node that stores the content. The routing infrastructure intelligently propagates the interest to the prospective nodes that

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are likely to have the information and then carries available content back along the path which the interest traversed.

FIG. 1 illustrates an exemplary architecture of a network, in accordance with an embodiment of the present invention. In this example, a network **180** comprises nodes **100-145**. Each node in the network is coupled to one or more other nodes. Network connection **185** is an example of such a connection. The network connection is shown as a solid line, but each line could also represent sub-networks or super-networks, which can couple one node to another node. Network **180** can be content-centric, a local network, a super-network, or a sub-network. Each of these networks can be interconnected so that a node in one network can reach a node in other networks. The network connection can be broadband, wireless, telephonic, satellite, or any type of network connection. A node can be a computer system, an end-point representing users, and/or a device that can generate interest or originate content.

In accordance with an embodiment of the present invention, a consumer can generate an Interest in a piece of content and then send that Interest to a node in network **180**. The piece of content can be stored at a node in network **180** by a publisher or content provider, who can be located inside or outside the network. For example, in FIG. 1, the Interest in a piece of content originates at node **105**. If the content is not available at the node, the Interest flows to one or more nodes coupled to the first node. For example, in FIG. 1, the Interest flows (interest flow **150**) to node **115**, which does not have the content available. Next, the Interest flows (interest flow **155**) from node **115** to node **125**, which again does not have the content. The Interest then flows (interest flow **160**) to node **130**, which does have the content available. The flow of the content then retraces its path in reverse (content flows **165**, **170**, and **175**) until it reaches node **105**, where the content is delivered. Other processes such as authentication can be involved in the flow of content.

In network **180**, any number of intermediate nodes (nodes **100-145**) in the path between a content holder (node **130**) and the Interest generation node (node **105**) can participate in caching local copies of the content as it travels across the network. Caching reduces the network load for a second subscriber located in proximity to other subscribers by implicitly sharing access to the locally cached content.

We first introduce definitions and notation that will be used in the description of NCCN. Let F_q be a finite field of order q and F_q^m ($m>0$) be an m -dimensional vector space over F_q . Consider that a Content Object is split into multiple chunks $k_1, k_2, \dots$, of equal size. We treat each chunk as an element of a finite field F_q , or a vector in F_q^m ($m>0$). For instance, each chunk is regarded as a 1024-dimensional vector over F_2 when the size of each chunk is 1024 bytes. We assume the use of groups of content chunks with fixed size n , and assume that intersections between any two groups are empty. We also assume that each group has a unique identifier or number.

FIG. 2 shows an exemplary chunking for a Content Object, where $n=4$. Each group in the figure has the number #1, #2, $\dots$. For each group we define coded-chunks as linear combinations of content chunks in that group. Suppose that a network node has t coded-chunks $y_1, \dots, y_t \in F_q^m$ of a group $(k_1, \dots, k_n)$ in its cache, and that they are represented as $[y_1, \dots, y_t]^T = A[k_1, \dots, k_n]^T$, where $A = [\alpha_{i,j}]_{i=1, j=1}^{t,n} \in F_q^{t \times n}$ and $\bullet^T$ denotes the transpose. Since

$$y_i = \sum_{j=1}^n \alpha_{i,j} k_j$$

holds, the vector $[\alpha_{i,1}, \dots, \alpha_{i,n}] \in F_q^n$ is called the coefficient vector of y_i . We say that a coded-chunk is linearly indepen-

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dent from another coded-chunk if their coefficient vectors are linearly independent. Let $V_A \subseteq F_q^n$ be a linear subspace spanned by row vectors, i.e., coefficient vectors, of A . We then introduce the definition of seen and unseen chunks: A chunk k_i is said to be seen if a vector of the form $[0, \dots, 0, 1, \beta_{i+1}, \beta_{i+2}, \dots, \beta_n] \in F_q^n$ belongs to V_A . Otherwise, it is said to be unseen.

We note that the number of seen chunks at the node equals $\dim V_A$. The information of chunks from a given group that are seen at a node is represented by an n -dimensional binary vector. For example, in the case where $n=4$ and the first and second chunks in a group are seen, the information of the seen or unseen chunks in the group is given by $[1, 1, 0, 0] \in F_2^4$.

A key design goal in NCCN is to attain compatibility with the normal CCN or NDN architecture in such a way that incremental deployment from CCN or NDN to NCCN is possible. This means that, even if some intermediate nodes in the network are normal CCN or NDN nodes that do not support NCCN, they can process NCCN Interest and data packets as normal CCN or NDN packets, but the producer and consumer can still communicate using network coding. Conversely, NCCN nodes can serve Interest and data packets of normal CCN or NDN traffic with producers and consumers communicating without using network coding.

FIG. 3A illustrates the intended compatibility between NCCN and CCN or NDN. The NCCN protocol stack has the same interfaces to lower layers and the same application programming interfaces (API) as normal CCN or NDN nodes. In addition, the NCCN strategy layer must be able to forward and cache packets in such a way that minimal changes are needed from that of the normal CCN or NDN protocol stack. On the other hand, whenever network coding is used, encoded content must be decoded to guarantee the availability of the original (non-encoded) content. In CCN or NDN, data packets are cached opportunistically by forwarding nodes and used repeatedly to answer Interests referring to the same content. The second key design goal in NCCN is for it to allow the dissemination of encoded content chunks over the network by having the consumers of content decode the original content.

The design of NCCN involves the way in which content is named, forwarded, and cached in order to take full advantage of network coding (NC) in the context of CCN and NDN.

To attain maximum compatibility between CCN, NDN, and NCCN, new name components are defined in NCCN that allow NCCN routers to process Interest packets and data packets taking advantage of NC, while CCN or NDN routers can process such packets without NC. The packet formats of Interest and data packets in NCCN are the same as those in CCN.

The approach adopted in NCCN for the dissemination and caching of encoded content chunks implements a table of sent-flags at each NCCN node. The table of sent-flags at a node shows that each content chunk is regarded as 'seen' or 'unseen' to its downstream nodes. By referring to the sent-flags, each NCCN node controls how to forward or cache incoming packets prior to executing the basic strategy of CCN or NDN. Using this control method based on sent-flags, NCCN nodes can disseminate encoded content chunks over the network while maintaining the decodability at the consumers.

FIG. 3B illustrates the three new name components introduced in NCCN to enable the use of NC, in accordance with one embodiment of the present invention. In this FIG. 3B, 'Name in CCN/NDN' represents an example of the name for a chunk with sequence number 0x03 in CCN/NDN, and

'Name in NCCN' represents the same chunk encoded with other chunks in the group using the NC operations. As shown in this example, we introduce three name components:

Network coding flag (NC flag) with the group size.

Retry flag.

"Seen" information at the consumer.

The markers, e.g., the prefix %00 of the sequence number in FIG. 3B, are control characters in the CCN or NDN architecture. Generally, control characters in a Name indicate additional information of the content chunks, such as version number or sequence number. We introduce three new markers to add three new Name components.

The NC flag is indicated by the marker %A0 in FIG. 3B, and the value following the marker represents the group size. For example, when an Interest has the Name of NCCN in FIG. 3B, it is a request for a coded-chunk in a group of size $0 \times 10 = 16$, where the group includes the chunk with sequence number 0×03 . The group can be uniquely determined by the sequence number that originally exists and the group size. Note that by virtue of the NC flag, incoming Interest/data packets to the intermediate node can be recognized as the NCCN packets or as the CCN/NDN packets.

The retry flag is indicated by the marker %A1 in FIG. 3B. The value following the marker is 0×00 (false) or 0×01 (true). If an Interest has a Name including %A1%01, it is a special Interest called a retry-Interest for a particular chunk. Otherwise, it is just a normal Interest for a coded-chunk.

When a consumer transmits an Interest for a coded chunk, the information of chunks in the group that have been seen by the consumer is appended to the name. The information of chunks in a given group G seen by the consumer is called the "seen information" of G and is represented by an n -dimensional binary vector, $v_{seen,G} \in F_2^n$. In FIG. 3B, the seen information is indicated by the marker %A2. The value following the marker is the hexadecimal value representing $v_{seen,G}$. For example, when $n=4$ and $v_{seen,G}=[1,1,0,0]$, the seen information value is $(0011)_2 = 0 \times 03$.

These new naming components are used to control the behavior of intermediate NCCN nodes and to maintain compatibility with normal CCN or NDN nodes. Although NCCN adds three new name components, it does not change the rest of the CCN or NDN Interest packet format. Coded chunks and the information needed to execute network coding operations are included in the payload field of the CCN or NDN data packet format. Given that the name components introduced in NCCN are regarded just as parts of the name in CCN and NDN, the interfaces of NCCN nodes remain unchanged from those of CCN or NDN nodes, and normal CCN or NDN nodes can serve Interest and data packets of NCCN packets as normal CCN or NDN packets.

The handling of Interest packets in NCCN is similar to that of normal CCN or NDN. When a node receives an Interest for a coded-chunk, the node generates a data packet including a new coded-chunk from cached data packets (if available) and sends it as the response to the Interest if some conditions are satisfied. Otherwise, as normal CCN or NDN, the node adds the Interest to the pending Interest table (PIT), and if the Interest has not been forwarded within a fixed time period, the node also forwards the Interest over some faces by referring to the PIT and the forwarding information base (FIB) according to the basic forwarding strategy.

In NCCN, every data packet includes a coded-chunk and its coefficient vector in the payload field of the data packet format of CCN or NDN.

Algorithm 1 below describes the caching algorithm of NCCN, which essentially works over the basic caching strategy of normal CCN or NDN. As shown in Algorithm 1, the additional step with respect to CCN and NDN is that, when the coded-chunk of received data Y in group G does

not increase the degree of freedom (i.e., it does not expand the subspace spanned by coefficient vectors of cached coded-chunks for G), the node does not cache the data packet and discards it.

Algorithm 1:

Caching arrived data Y including a coded-chunk y in group G with coefficient vector v at the node that has t coded-chunks $y_1, \dots, y_t \in F_q^m$ with coefficient vectors $v_1, \dots, v_t \in F_q^n$ for G in its cache:

```

 $V \subseteq F_q^n \leftarrow$  subspace spanned by  $v_1, \dots, v_t$ 
if  $v \in V$  then
    Discard  $Y$ 
    return
end if

```

Cache Y According to the Basic Strategy

Every NCCN node has a table of sent-flags for each group G that is represented by an n -dimensional binary vector $v_{sent,G} \in F_2^n$, where the initial value of the vector is 0. The purposes of sent-flags are to manage which chunks are seen or unseen by downstream nodes, and to decide if the node should respond to an Interest by using coded-chunks in its cache. If the sent-flag corresponding to a chunk k in G (an element of $v_{sent,G}$) is 1, it indicates that the node has already generated a coded-chunk and has sent out a Data with the Name of k . Then, we assume k as the one that is already seen by downstream nodes. Also, if the number of cached coded-chunks in group G is smaller than the Hamming weight of $v_{sent,G}$, we assume that there exist some chunks in G that can newly become seen by downstream nodes by generating and sending out coded-chunks from the node.

Algorithm 2 describes the procedure used to respond to an Interest received by an NCCN node or the one pending in its PIT. When a Data packet in a group G arrives and it can be cached by Algorithm 1, the node checks all Interests for coded-chunks in G stored in its PIT by Algorithm 2, and tries to respond to one of them.

Algorithm 2:

Responding to an Interest for a chunk k in group G at a node that has t coded-chunks in G with sent-flags $v_{sent,G} \in F_2^n$ in its cache:

```

flag  $\leftarrow$  the component of  $v_{sent,G}$  that corresponds to  $k$ 
wt( $v_{sent,G}$ )  $\leftarrow$  the Hamming weight of  $v_{sent,G}$ 
if flag  $\neq 1$  then
    if wt( $v_{sent,G}$ )  $< t$  and  $k$  is unseen in the cache then
        return
    end if
    1  $\rightarrow$  the component of  $v_{sent,G}$  that corresponds to  $k$ 
end if

```

Generate a Data Packet Y by Algorithm 3

Respond to the Interest

Algorithm 3:

Generating a data packet Y as a response to a (pending) Interest X in group G at the node that has t coded-chunks $y_1, \dots, y_t \in F_q^m$ for G :

```

repeat
    Randomly choose  $a_1, \dots, a_t \in F_q$ 
until  $(a_1, \dots, a_t) \neq 0$ 

```

$$v \leftarrow \sum_{i=1}^t a_i v_i$$

-continued

$$y \leftarrow \sum_{i=1}^t a_i y_i$$

Generate Y Including y and v with the Name of X

As shown in Algorithm 2, each NCCN node responds to an Interest for a chunk only if the chunk ‘is already seen’ or ‘can be seen’ by downstream nodes. This avoids the unnecessary transmission of coded-chunks that do not expand the subspace spanned by coefficient vectors of coded-chunks cached in each downstream node.

When a node decides to respond to an Interest and generate a data packet, it employs random network coding following the process described in Algorithm 3.

According to Algorithm 3, a node generates a random linear combination of cached coded-chunks for G, and sends it as the response to the (pending) Interest. Then, if the PIT entry has multiple outgoing faces, the coded-chunk sent through each outgoing face should be different and hence Algorithm 3 needs to be executed for each face.

When an NCCN node receives an Interest for a coded-chunk in group G, the node first updates $v_{sent,G}$ before executing Algorithm 2. Let $\dim_G$ denote the number of cached coded-chunks for G. $\dim_G$ equals the dimension of the subspace spanned by the coefficient vectors of the cached coded-chunks, and $wt(v_{sent,G}) \leq \dim_G$ always holds in our construction, where wt is the Hamming weight. By $v_{seen,G}$ obtained from the name of the arrived Interest, let u_G be

$$u_G = \min\{\dim_G - wt(v_{sent,G}), wt(v_{seen,G} \oplus v_{sent,G} \& v_{seen,G})\},$$

where “ $\oplus$ ” and “ $\&$ ” are the component-wise exclusive-or operation and the ‘and’ operation, respectively. Then, u_G elements of zeros in $v_{sent,G}$ are turned to 1’s. For example, if $\dim_G=3$, $v_{sent,G}=[1,1,0,0]$ and $v_{seen,G}=[1,0,1,0]$, $v_{sent,G}$ is updated to $[1,1,1,0]$. By updating the sent-flags, NCCN nodes can manage the status of data packets received by consumers. The ability of decode content chunks is ensured by executing this update algorithm prior to Algorithm 2.

Using random network coding in NCCN, a consumer of content is able to reconstruct it as long as enough coded-chunks are delivered to reconstruct each group, i.e., n linearly independent coded-chunks for each group with high probability if the size of F_q is large.

The dissemination techniques based on sent-flags support the dissemination of linearly independent coded-chunks over the network. However, the consumer might obtain fewer than n linearly independent coded-chunks needed to decode a piece of content, and coefficient vectors of all coded-chunks cached in all the nodes other than the producer might not span the space of dimension n . Then, some chunks in a group cannot be seen within a fixed time period and the requests for such chunks time out. To address this case and allow the content chunks to be decoded, NCCN uses a special Interest called the retry-Interest. The retry-Interest is indicated by the marker in the Name as explained previously. The consumer is allowed to transmit a retry-Interest for a chunk when the chunk has not been seen and the previous pending interest timed out.

When an NCCN node receives the retry-Interest for a chunk in group G, it processes the retry-Interest as a normal Interest if the node has n coded-chunks for G in its cache. In the case where the node has fewer than n coded-chunks, the node changes the sent-flag for the chunk to 0 and forwards the retry-Interest to upstream nodes according to the basic CCN or NDN forwarding strategy. The role of the retry-

Interest for a chunk is to restart the encoding and transmission for the chunk over the network.

As previously explained, NCCN assumes the use of multi-face forwarding strategies supported in the native CCN or NDN architecture. Considering multi-face forwarding strategies, we can introduce an additional step prior to the procedure to add the received Interest to the PIT of a node. When NCCN or normal CCN or NDN nodes in the network uses a strategy of forwarding to multiple faces, there could exist a ‘detour’ of Interests to a node as illustrated in FIG. 4. In order to benefit from network coding, although distinct multiple paths from the consumer to producer should be provided, the detour of Interests illustrated in FIG. 4 is unnecessary. In this example, the Interest coming from node 2 to node 3 is regarded as the detoured one. In fact, responses to such detoured Interests consume unnecessary network bandwidth and computational resources in NCCN. Thus, such unnecessary detoured Interests should not be added to PITs.

Algorithm 4 presents the additional step used to discard detoured Interests. Intermediate nodes omit and discard detoured Interests based on the arrival time or hop counts of received Interests. In particular, if the difference between the hop count from the (unique) consumer node or the arrival time of a detoured Interest and that of the same Interest stored in PIT is greater than threshold t_{detour} , the detoured Interest is discarded. The hop count is usually included in Interest packets, and the arrived time is obvious from the life time of PIT entries.

Algorithm 4:

Discarding detoured Interests X_d that has the nonce at nodes with multi-face forwarding:

```

35   $h_d \leftarrow$  hop count (arrival time) of  $X_d$ 
    Check if  $\exists$  Interest  $X_p$  with nonce in PIT
    if  $X_p \neq \text{NULL}$  then
36       $h_p \leftarrow$  hop count (arrival time) of  $X_p$ 
      if  $h_d - h_p > t_{detour}$  then
37          Discard  $X_d$ 
          return
      end if
    end if
    end if

```

Process X_d According to the Basic Strategy

FIG. 5 illustrates an exemplary content-consumer system that facilitates network coding, in accordance with an embodiment. A content-consumer system 500 with network coding capabilities comprises a processor 510, a memory 520, and a storage 530. Storage 530 typically stores instructions which can be loaded into memory 520 and executed by processor 510 to perform the methods mentioned above. In one embodiment, the instructions in storage 530 can implement an interest generation module 532 and a content reconstruction module 534, which can be in communication with each other through various means. In one embodiment, content consumer system 500 is coupled to a display 580, a keyboard 560, and a pointing device 570.

During operation, interest generation module 532 generates interests corresponding to the chunks of a content object. Content reconstruction module 534 re-constructs the content object using received linear combinations of the chunks, as described above.

FIG. 6 illustrates an exemplary switching system that facilitates network coding, in accordance with one embodiment of the present invention. In this example, an information centric switching system 600 with network coding capabilities comprises a processor 610, a memory 620, and

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a storage 630. Storage 630 typically stores instructions which can be loaded into memory 620 and executed by processor 610 to perform the methods mentioned above. In one embodiment, the instructions in storage 630 can implement an interest receiving module 632, a network coded content forwarding module 634, a chunk management module 635, and a content cache 636.

During operation, interest receiving module 632 receive interests corresponding to the chunks of a content object. Content forwarding module 634 then constructs independent linear combinations of chunks stored in content cache 536 in response to received interests. Chunk management module 635 maintains records on which linear combinations have been previously sent to requesting nodes, and also manages which linear combinations are to be cached locally.

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, methods and processes described herein can be included in hardware modules or apparatus. These modules or apparatus may include, but are not limited to, an application-specific integrated circuit (ASIC) chip, a field-programmable gate array (FPGA), a dedicated or shared processor that executes a particular software module or a piece of code at a particular time, and/or other programmable-logic devices now known or later developed. When the hardware modules or apparatus are activated, they perform the methods and processes included within them.

The above 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.

What is claimed is:

1. A computer-executable method for facilitating network coding in an information centric network, the method comprising:

sending, from a content consumer node, one or more interests for a plurality of chunks associated with a content object, wherein a respective interest indicates the corresponding chunk using a hierarchically structured variable length identifier which comprises contiguous name components ordered from a most general level to a most specific level,

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wherein the identifier includes a name component which indicates whether the corresponding interest is a retry interest;

in response, receiving a number of network-coded data packets, wherein a respective data packet corresponds to an independent linear combination of all the chunks for the content object; and

re-constructing the content object based on the received data packets, which involves:

determining that at least one more data packet is needed for re-constructing a missing chunk; and
sending a first retry interest which indicates the missing chunk.

2. The method of claim 1, wherein sending the first retry interest is in response to determining that the corresponding missing chunk has not been seen by the content consumer node and that a previous pending interest for the corresponding missing chunk has timed out.

3. The method of claim 1, wherein the hierarchically structured variable length identifier includes a component which indicates use of network coding and a number of chunks for the content object.

4. The method of claim 1, wherein a name for the first retry interest includes a name component which indicates that the corresponding interest is a retry interest.

5. The method of claim 1, wherein the hierarchically structured variable length identifier includes a component which indicates one or more chunks that have already been re-constructed.

6. A computer system for facilitating network coding in an information centric network, the computer system comprising:

a processor; and

a storage device storing instructions that when executed by the processor cause the processor to perform a method, the method comprising:

sending, from a content consumer node, one or more interests for a plurality of chunks associated with a content object, wherein a respective interest indicates the corresponding chunk using a hierarchically structured variable length identifier which comprises contiguous name components ordered from a most general level to a most specific level,

wherein the identifier includes a name component which indicates whether the corresponding interest is a retry interest; and

in response, receiving a number of network-coded data packets, wherein a respective data packet corresponds to an independent linear combination of all the chunks for the content object; and

re-constructing the content object based on the received data packets, which involves:

determining that at least one more data packet is needed for re-constructing a missing chunk; and
sending a first retry interest which indicates the missing chunk.

7. The computer system of claim 6, wherein sending the first retry interest is in response to determining that the corresponding missing chunk has not been seen by the content consumer node and that a previous pending interest for the corresponding missing chunk has timed out.

8. The computer system of claim 6, wherein the hierarchically structured variable length identifier includes a component which indicates use of network coding and a number of chunks for the content object.

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9. The computer system of claim 6, wherein a name for the first retry interest includes a name component which indicates that the corresponding interest is a retry interest.

10. The computer system of claim 6, wherein the hierarchically structured variable length identifier includes a component which indicates one or more chunks that have already been re-constructed. 5

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