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(12) **United States Patent**
**Rodriguez et al.**

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(45) **Date of Patent: Jul. 19, 2011**

(54) **EFFICIENT POINT-TO-MULTIPOINT DATA RECONCILIATION**

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(73) Assignee: **Microsoft Corporation**, Redmond, WA (US)

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(22) Filed: **Apr. 18, 2005**

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(51) **Int. Cl.**
***G06F 7/00*** (2006.01)
***G06F 17/00*** (2006.01)

(52) **U.S. Cl.** ..... **707/625**; 707/624; 707/634; 711/216

(58) **Field of Classification Search** ..... 711/216
See application file for complete search history.

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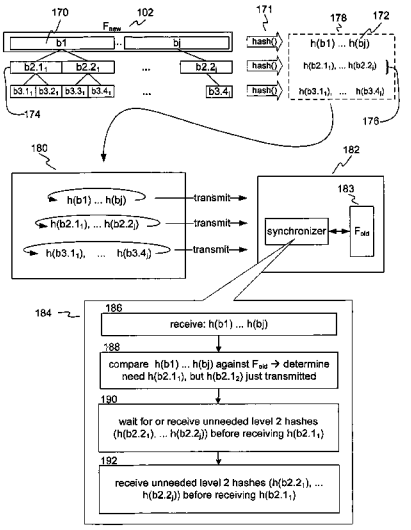
(57) **ABSTRACT**

Efficient reconciliation of different versions of a target file or dataset can be facilitated using a hash hierarchy of a master version of the dataset. Each level of the hash hierarchy has hashes of blocks of the master version that may be sub-blocks of the hashes in the level above. The top level of the hash hierarchy, having the hashes of the largest blocks of the master, may be transmitted on a first communication channel, possibly a one-way or broadcast communication channel. Streams of encodings of each lower level of the hash hierarchy may be transmitted on respective communication channels. The encodings for a level of the hierarchy may be combinations, such as random linear combinations, of the hashes of that level. A receiver with a target dataset can receive the top level hashes from the first channel and use them to determine which lower hashes are needed to identify parts of the master missing from the target. The encodings can be used to help obtain needed lower level hashes that can be used to more finely identify missing parts. Different receivers may not have to wait for a particular piece of information about the master. Rather, any received information (e.g. encoding) about the master will most likely allow any receiver to advance its understanding of the master dataset. Receivers will usually not have to wait for delivery of a particular hash in the hierarchy.

**20 Claims, 14 Drawing Sheets**



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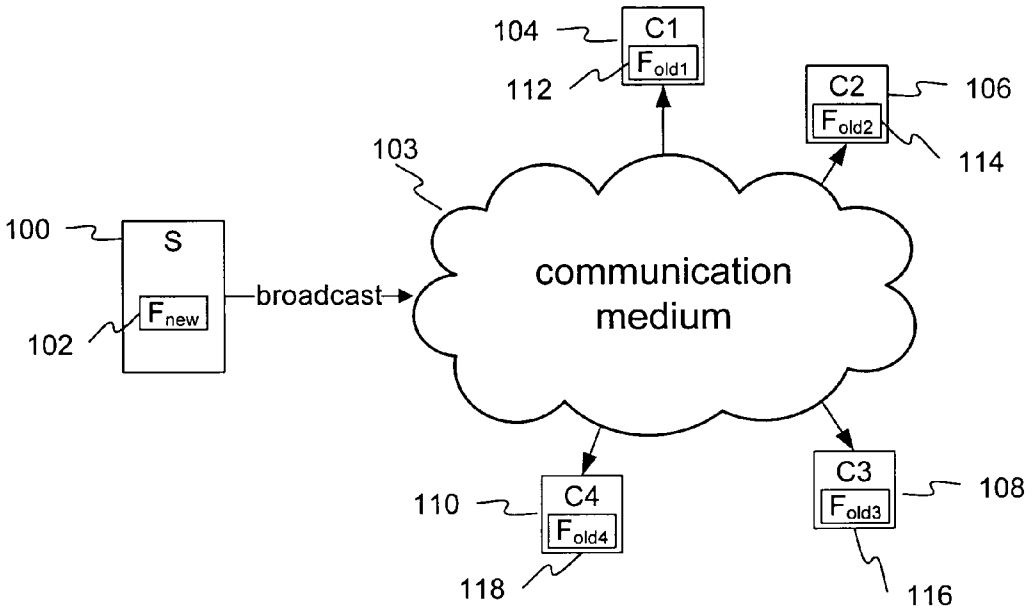
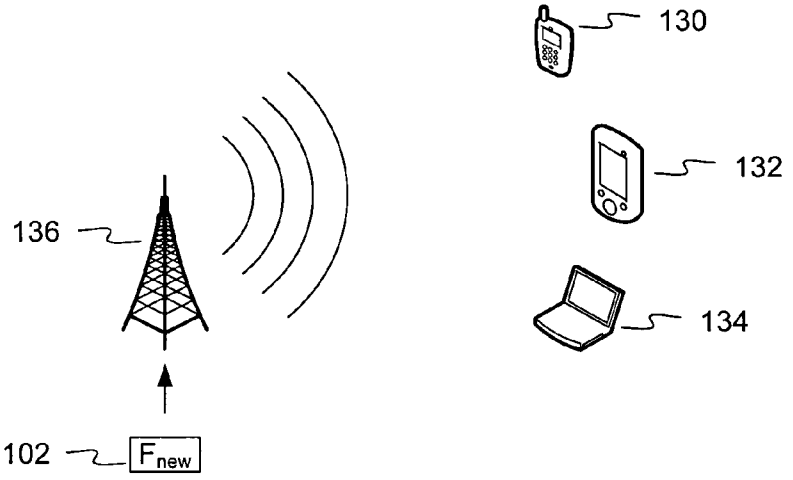



RELATED ART

FIGURE 1




RELATED ART

FIGURE 2

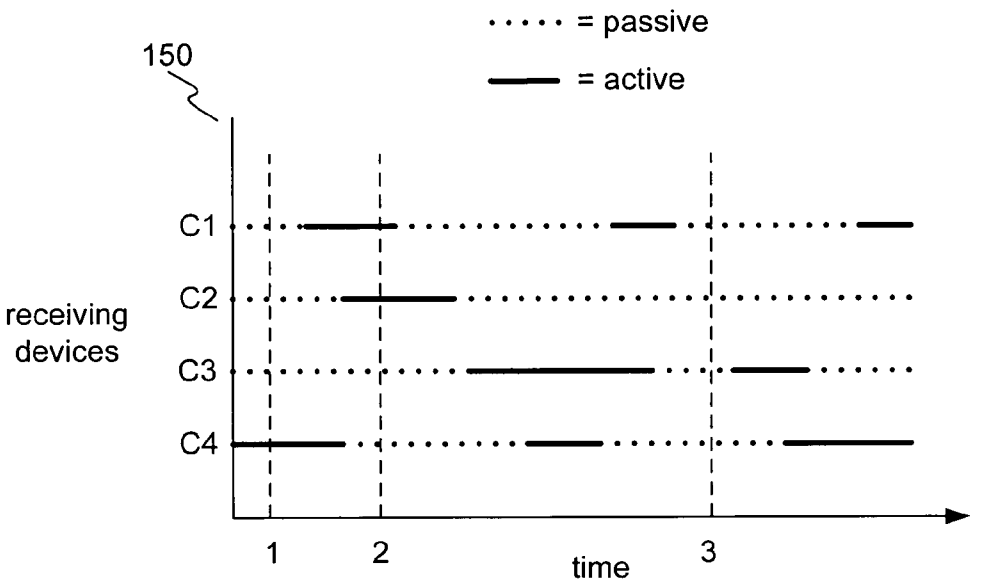



FIGURE 3

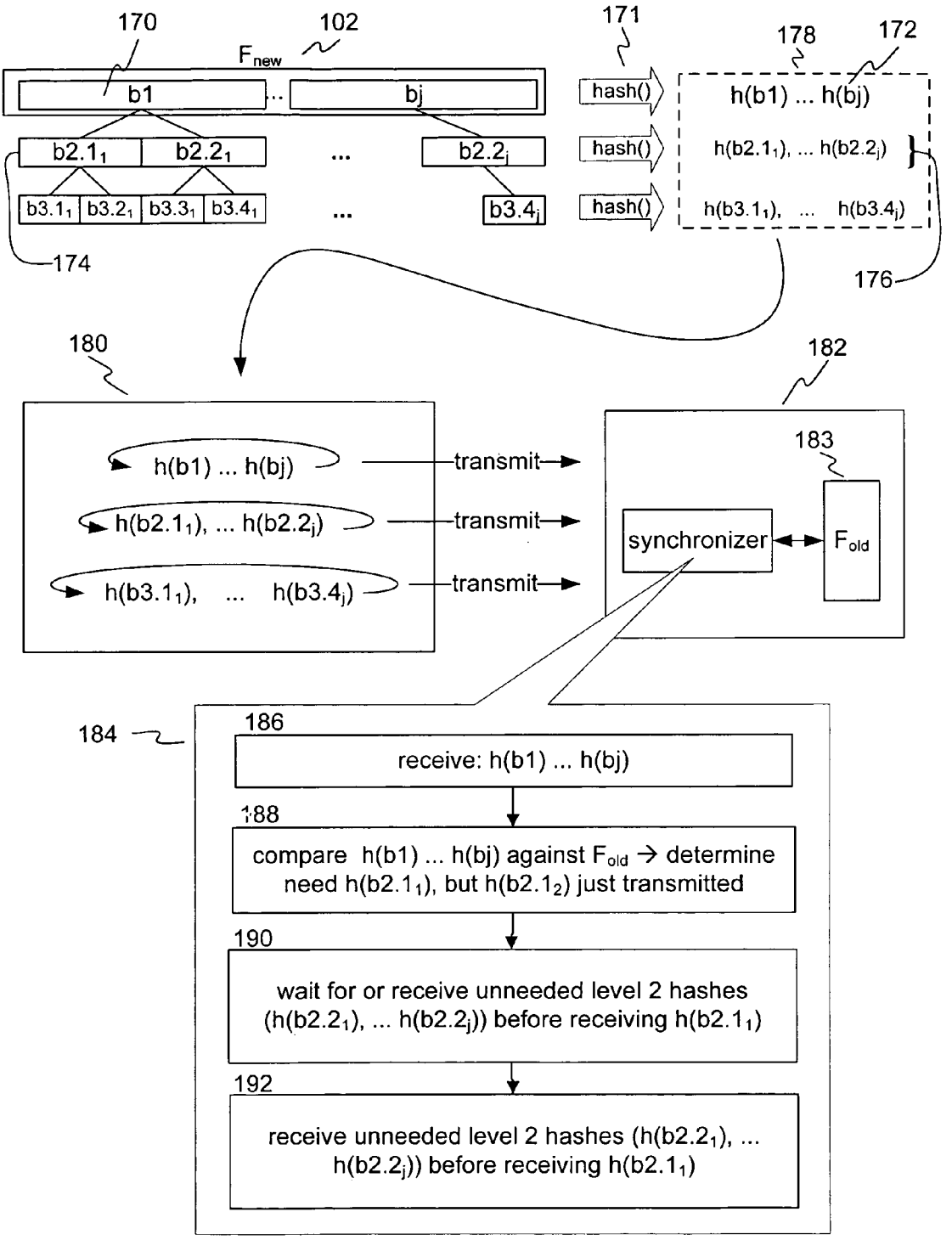

170
102
$F_{new}$
b1
bj
$b2.1_1$
$b2.2_1$
$b2.2_j$
$b3.1_1$
$b3.2_1$
$b3.3_1$
$b3.4_1$
$b3.4_j$
174
171
hash()
hash()
hash()
178
172
h(b1) ... h(bj)
$h(b2.1_1)$, ... $h(b2.2_j)$
$h(b3.1_1)$, ... $h(b3.4_j)$
176
180
182
h(b1) ... h(bj)
$h(b2.1_1)$, ... $h(b2.2_j)$
$h(b3.1_1)$, ... $h(b3.4_j)$
transmit
transmit
transmit
183
synchronizer
$F_{old}$
184
186
receive: h(b1) ... h(bj)
188
compare h(b1) ... h(bj) against $F_{old}$ → determine need $h(b2.1_1)$, but $h(b2.1_2)$ just transmitted
190
wait for or receive unneeded level 2 hashes ($h(b2.2_1)$, ... $h(b2.2_j)$) before receiving $h(b2.1_1)$
192
receive unneeded level 2 hashes ($h(b2.2_1)$, ... $h(b2.2_j)$) before receiving $h(b2.1_1)$

FIGURE 4

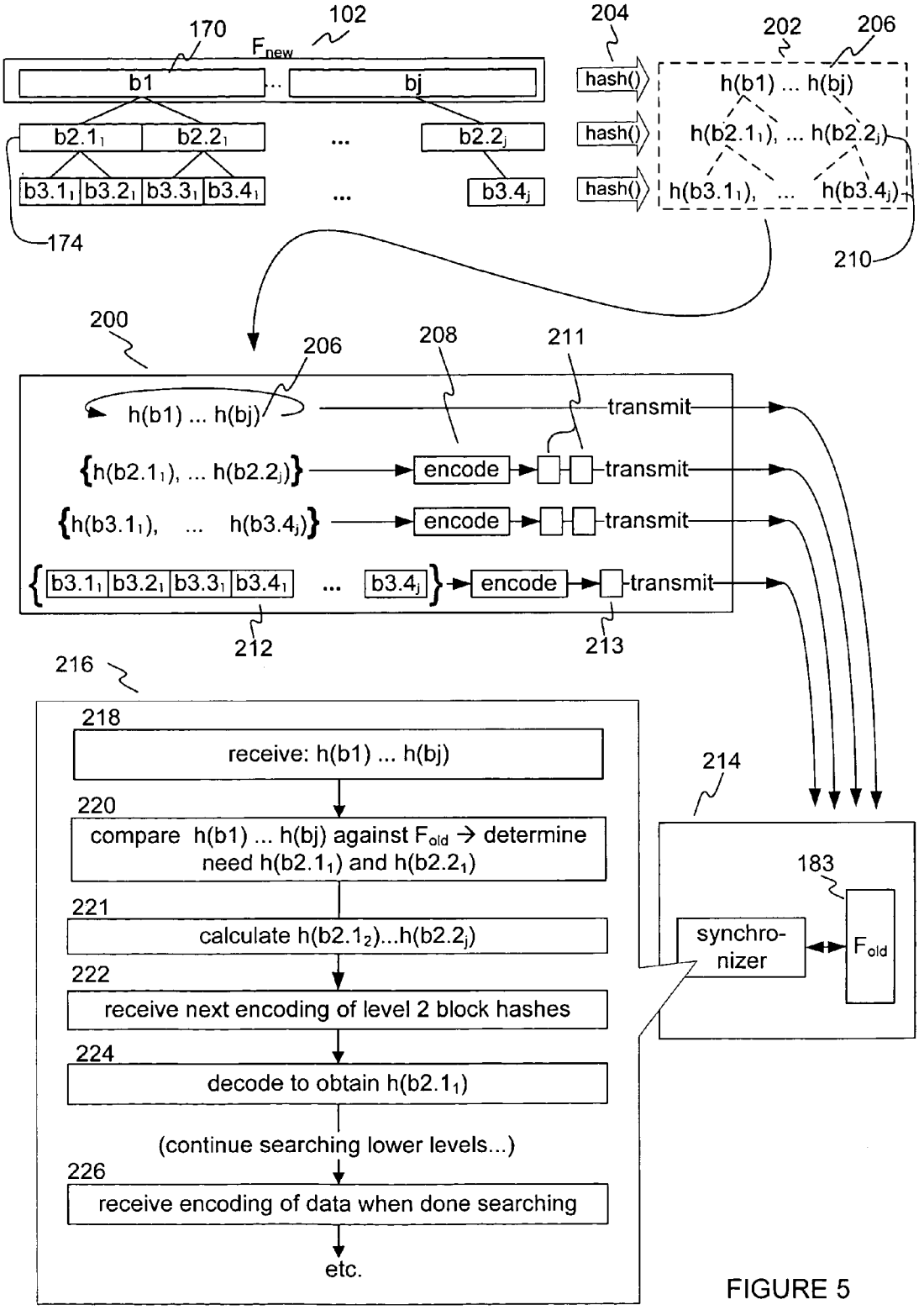

170
102
$F_{new}$
b1
bj
204
202
206
hash()
h(b1) ... h(bj)
$b2.1_1$
$b2.2_1$
$b2.2_j$
$h(b2.1_1)$, ... $h(b2.2_j)$
$b3.1_1$ $b3.2_1$ $b3.3_1$ $b3.4_1$
$b3.4_j$
$h(b3.1_1)$, ... $h(b3.4_j)$
174
210
200
206
208
211
transmit
encode
212
213
216
218
receive: h(b1) ... h(bj)
220
compare h(b1) ... h(bj) against $F_{old}$ → determine need $h(b2.1_1)$ and $h(b2.2_1)$
221
calculate $h(b2.1_2)$...$h(b2.2_j)$
222
receive next encoding of level 2 block hashes
224
decode to obtain $h(b2.1_1)$
(continue searching lower levels...)
226
receive encoding of data when done searching
etc.
214
183
synchro-nizer
$F_{old}$

FIGURE 5

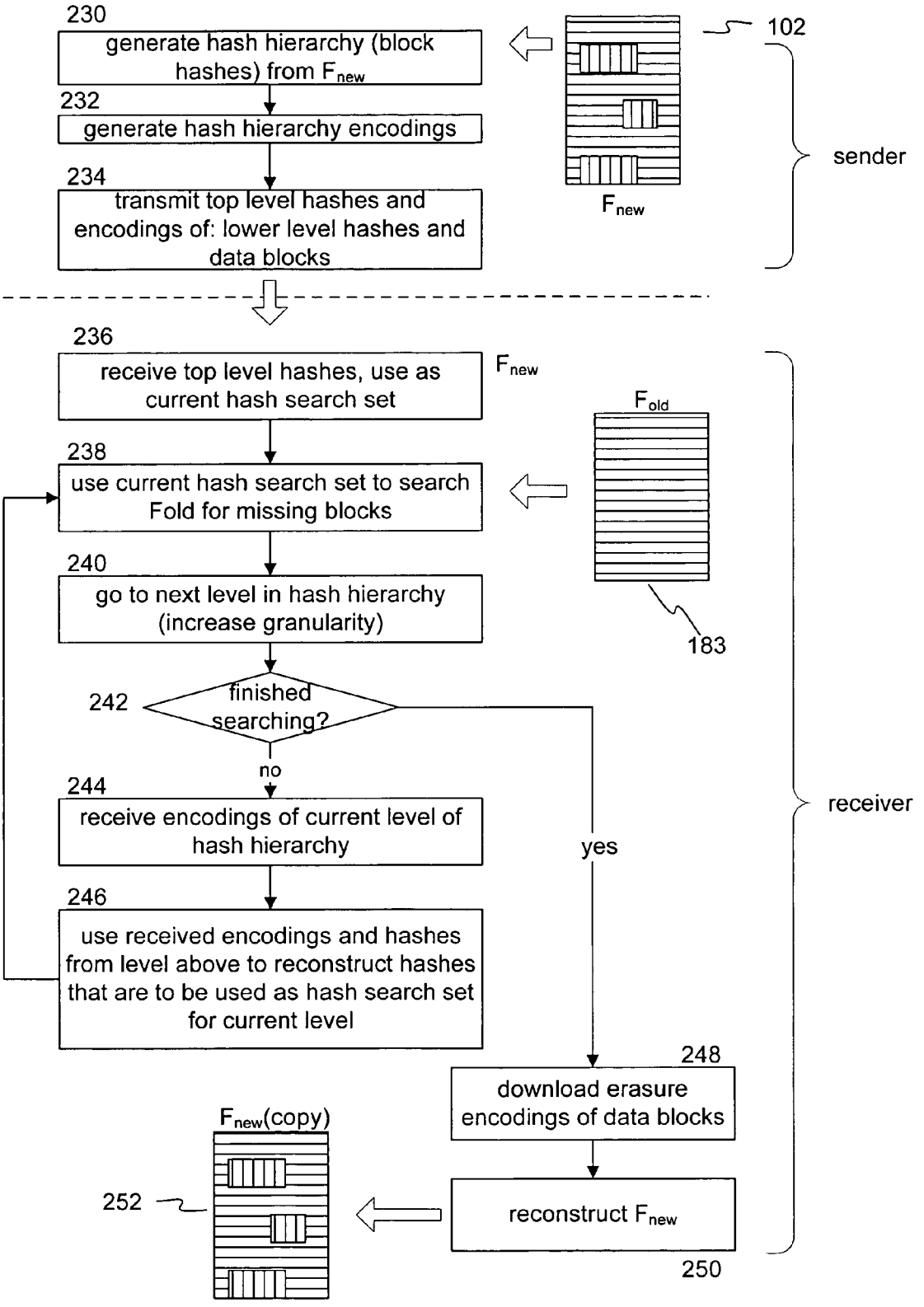

230
generate hash hierarchy (block hashes) from $F_{new}$
232
generate hash hierarchy encodings
234
transmit top level hashes and encodings of: lower level hashes and data blocks
102
$F_{new}$
sender
236
receive top level hashes, use as current hash search set
$F_{new}$
238
use current hash search set to search Fold for missing blocks
$F_{old}$
183
240
go to next level in hash hierarchy (increase granularity)
242
finished searching?
no
yes
244
receive encodings of current level of hash hierarchy
246
use received encodings and hashes from level above to reconstruct hashes that are to be used as hash search set for current level
248
download erasure encodings of data blocks
reconstruct $F_{new}$
250
receiver
$F_{new}$(copy)
252

FIGURE 6

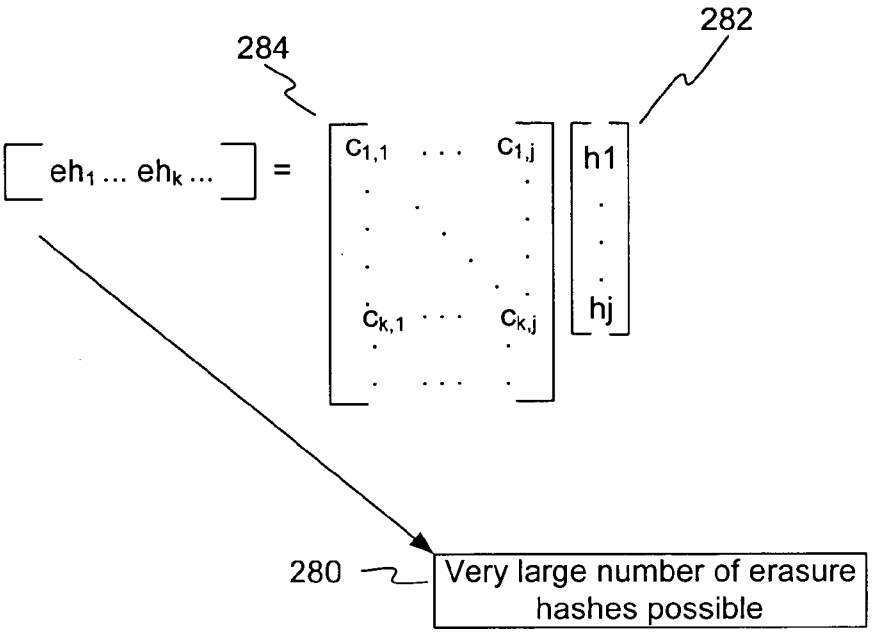

284
282
eh1 ... ehk ...
=
c1,1 . . . c1,j
ck,1 . . . ck,j
h1
hj
280
Very large number of erasure hashes possible

FIGURE 7

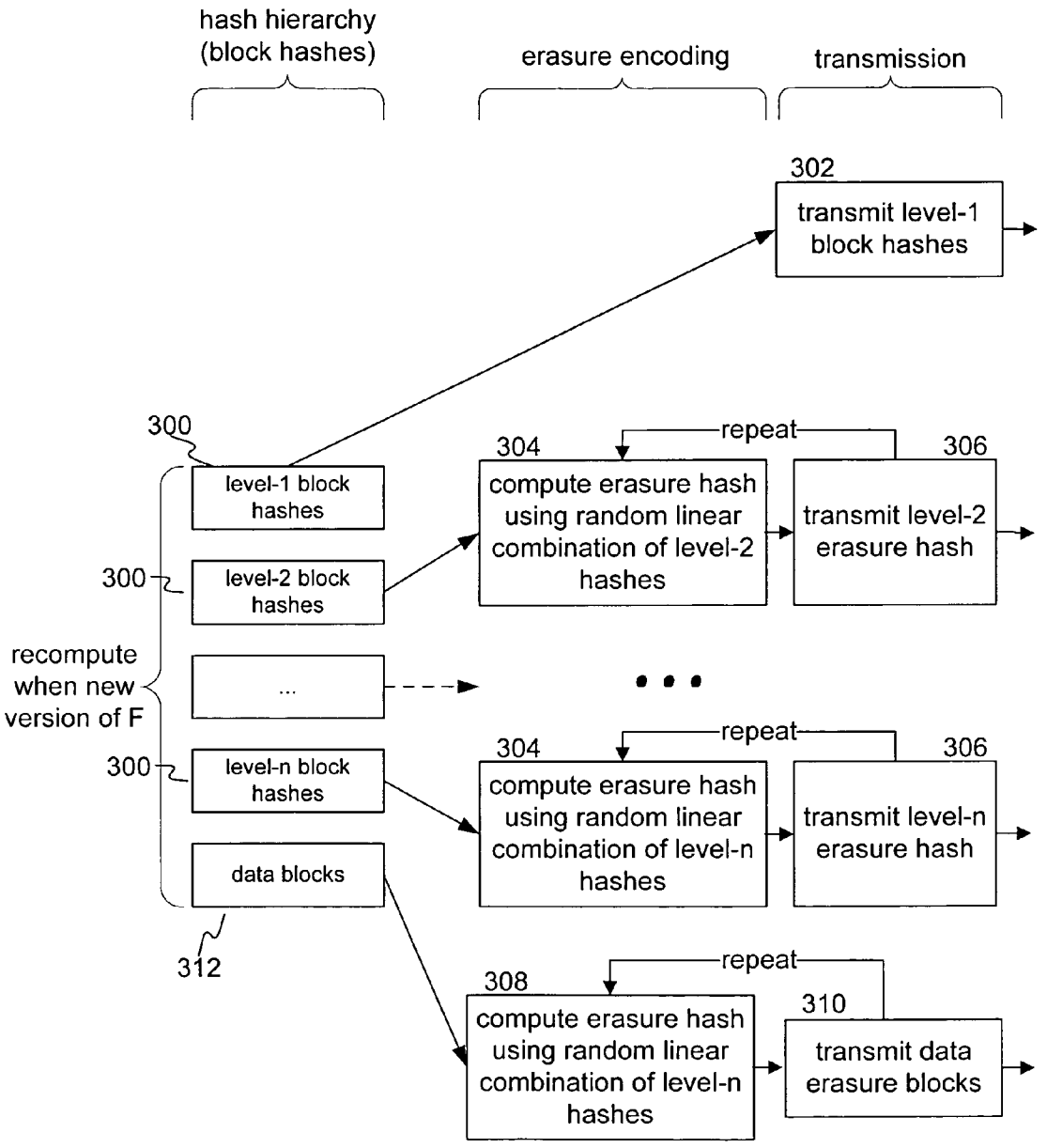

hash hierarchy
(block hashes)
erasure encoding
transmission
302
transmit level-1 block hashes
300
level-1 block hashes
300
level-2 block hashes
recompute when new version of F
...
300
level-n block hashes
data blocks
312
304
repeat
compute erasure hash using random linear combination of level-2 hashes
306
transmit level-2 erasure hash
304
repeat
compute erasure hash using random linear combination of level-n hashes
306
transmit level-n erasure hash
308
repeat
compute erasure hash using random linear combination of level-n hashes
310
transmit data erasure blocks

FIGURE 8

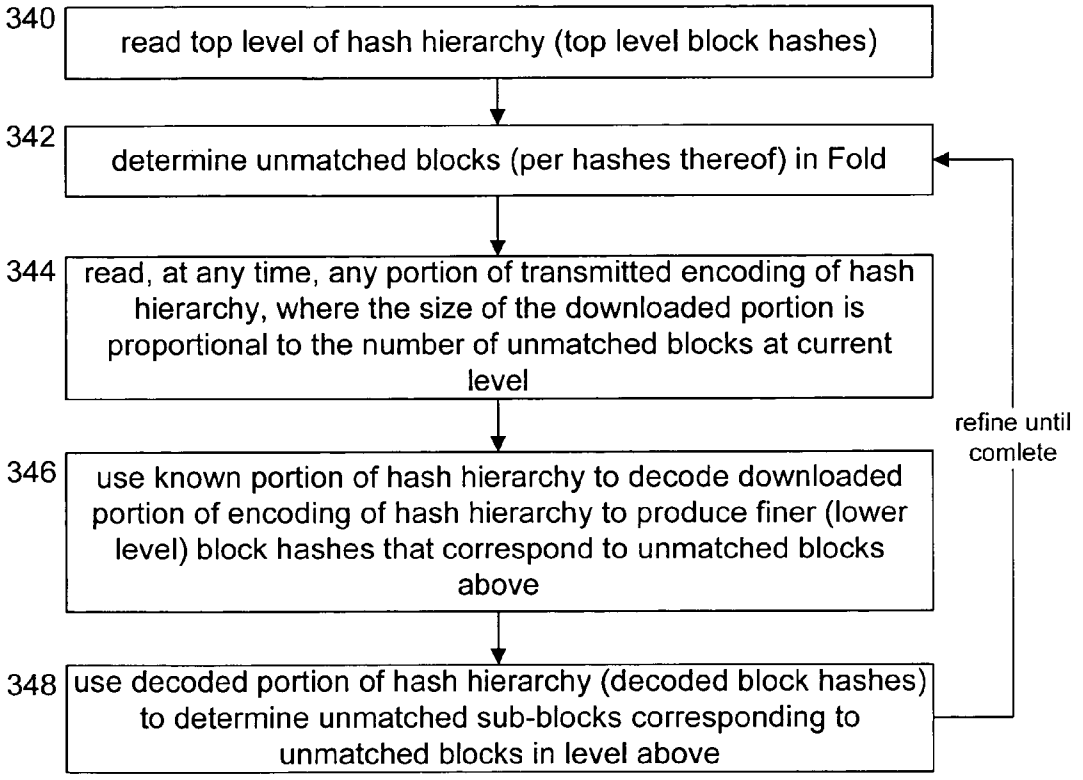

340
read top level of hash hierarchy (top level block hashes)
342
determine unmatched blocks (per hashes thereof) in Fold
344
read, at any time, any portion of transmitted encoding of hash hierarchy, where the size of the downloaded portion is proportional to the number of unmatched blocks at current level
346
use known portion of hash hierarchy to decode downloaded portion of encoding of hash hierarchy to produce finer (lower level) block hashes that correspond to unmatched blocks above
348
use decoded portion of hash hierarchy (decoded block hashes) to determine unmatched sub-blocks corresponding to unmatched blocks in level above
refine until comlete

FIGURE 9

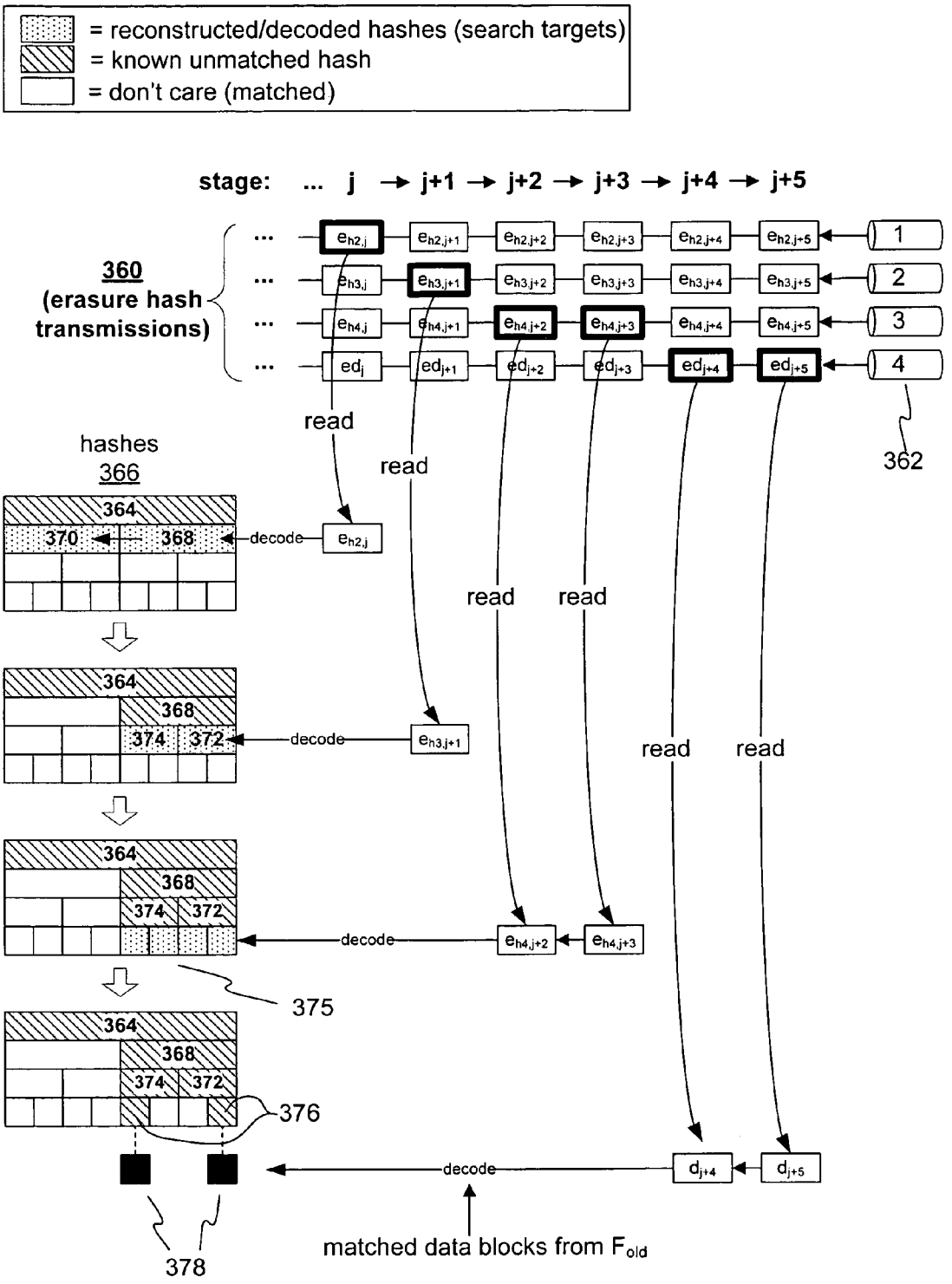

= reconstructed/decoded hashes (search targets)
= known unmatched hash
= don't care (matched)
stage: ... j → j+1 → j+2 → j+3 → j+4 → j+5
360
(erasure hash transmissions)
1
2
3
4
362
read
hashes
366
364
370
368
decode
374
372
375
376
matched data blocks from $F_{old}$
378

FIGURE 10

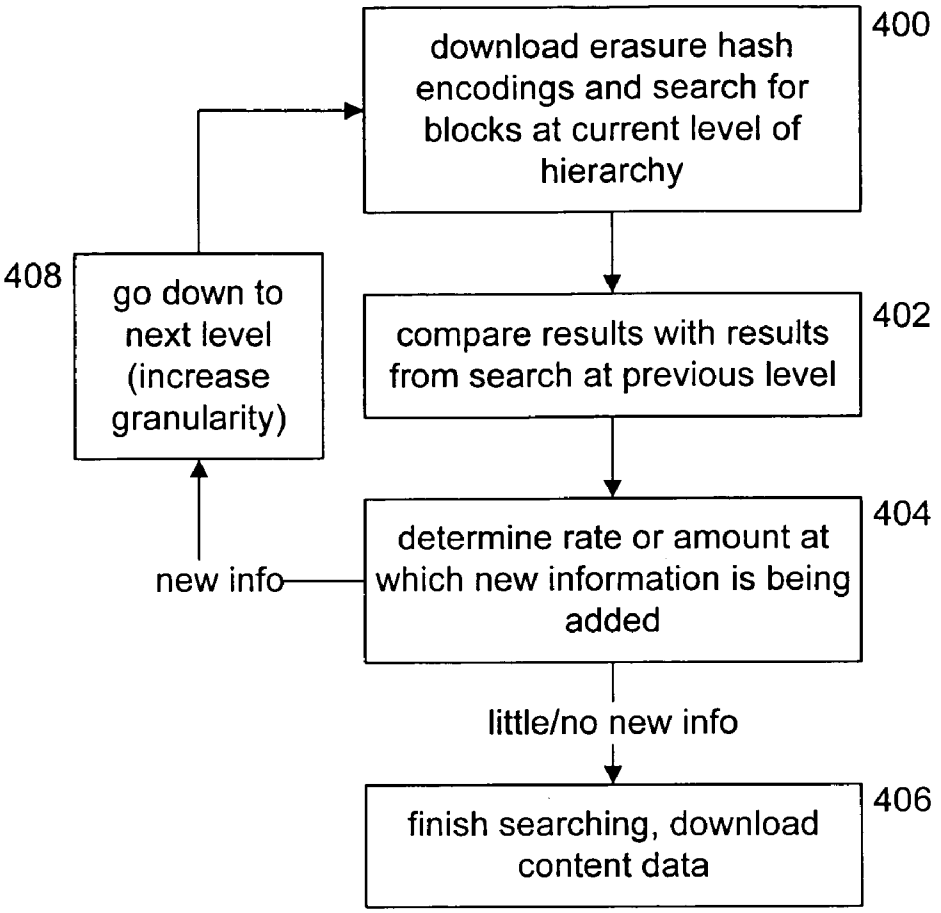

download erasure hash encodings and search for blocks at current level of hierarchy
400
compare results with results from search at previous level
402
determine rate or amount at which new information is being added
404
new info
go down to next level (increase granularity)
408
little/no new info
finish searching, download content data
406

FIGURE 11

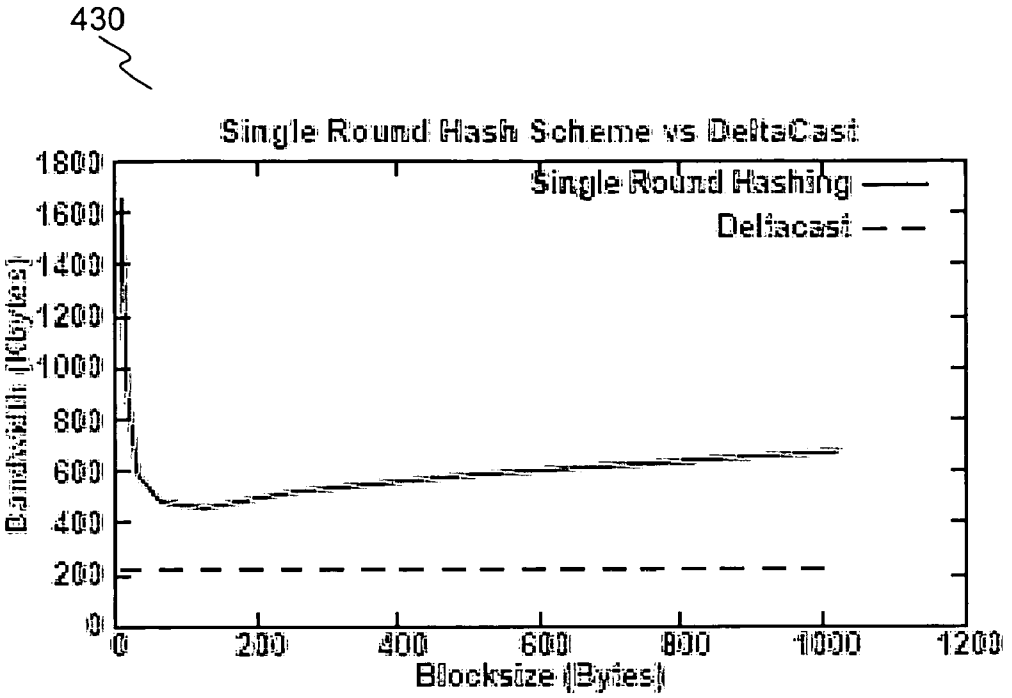
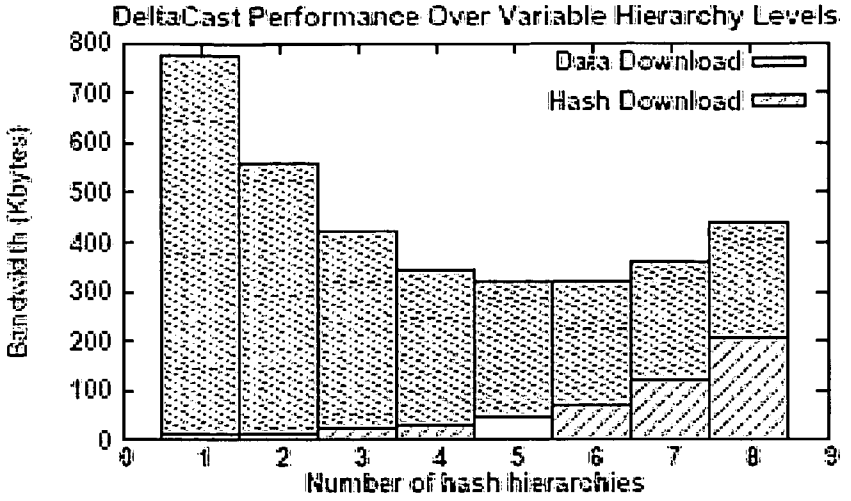

430
Single Round Hash Scheme vs DeltaCast
Single Round Hashing
Deltacast
Bandwidth (Kbytes)
Blocksize (Bytes)
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200

FIGURE 12

FIGURE 13

440

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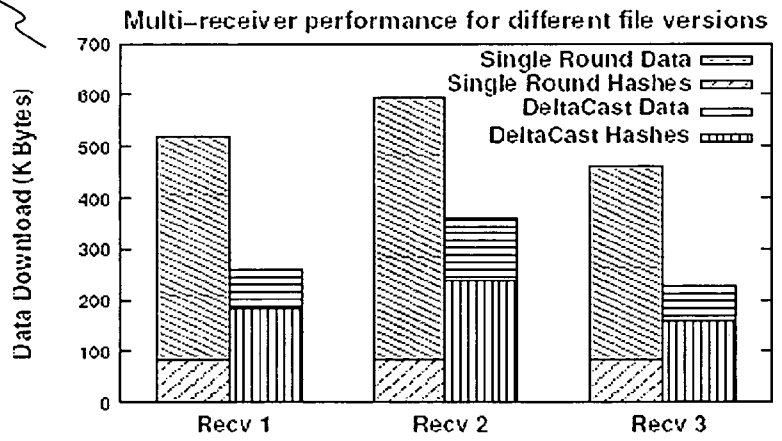
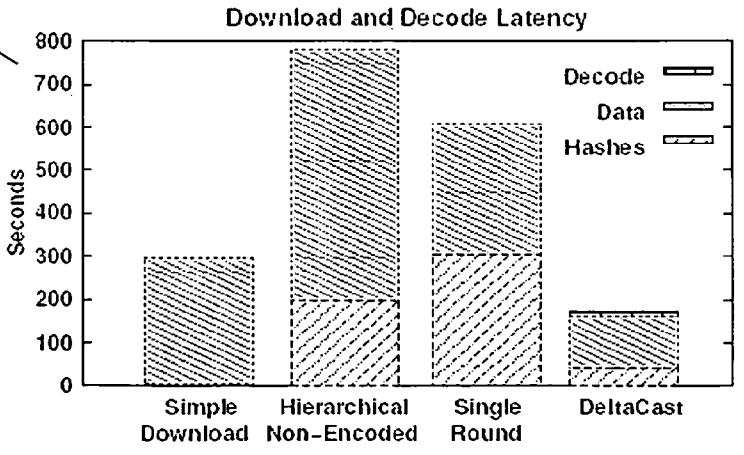



444



470

| | DeltaCast | | | Hierarchical | | | Single Layer | | | Simple Download | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. Latency | 41.6 | 120.1 | 173.4 | 204.9 | 583.03 | 797.93 | 303.79 | 305.21 | 609 | 0 | 291.6 | 291.6 |
| Active Time | 41.6 | 120.1 | 173.4 | 41.6 | 120.1 | 161.7 | 303.79 | 62.9 | 366.69 | 0 | 291.6 | 291.6 |
| Data Download | 31.7 | 366.8 | 398.5 | 31.7 | 366.8 | 398.5 | 83.4 | 366.8 | 450.2 | 0 | 1780 | 1780 |
| Decoding Time | 0.4 | 11.6 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

FIGURE 14

# EFFICIENT POINT-TO-MULTIPOINT DATA RECONCILIATION

## TECHNICAL FIELD

This description relates generally to enabling efficient data reconciliation and more specifically to enabling efficient reconciliation of an outdated or modified version or copy of a master file or dataset.

## BACKGROUND

There are many scenarios where data is mirrored, replicated, synchronized, etc. For example, different web servers may each serve an identical copy of a set of web pages. When a master of the set changes, the copies of the set need to be updated to match the master set. When a software package is revised, the latest revision may need to be propagated to a number of systems that distribute duplicate copies of the package. A news bulletin that changes frequently over time may need to be quickly updated on a number of clients, each of which may have a different outdated version of the news bulletin. Storage devices may also be synchronized. A network router may need to update other routers with a latest routing table. Any system providing a source or master dataset will be referred to as a sender and any system receiving difference or update information from a sender will be referred to as a receiver. A dataset can be any arbitrary type of data, such as a file, a file system directory, a set of one or more web pages, a BLOB, a data structure, etc.

In some cases, a receiver with a dataset that needs to be updated may send feedback to a sender indicating the differences between the receiver's dataset and the sender will use that feedback to provide the receiver with individually tailored update information that the receiver can use to update its version of the dataset to match the sender's master version of the dataset. However, in some situations it may be impractical or impossible for a receiver to provide a sender with clues or feedback about the particular data that the receiver needs to update its copy of the dataset. For example, if the sender is a server on a data network such as the Internet, the sender may not be able to handle the overhead needed to form individual bi-directional connections with a large number of clients (receivers); one-way broadcasting may be the only means of propagating update information to clients. If a one-way communication medium is being used, for example broadcast radio, then feedback will not be possible. Whether feedback is possible or not, and regardless of the application, there is a general need to minimize the amount of information that a receiver or client needs to receive in order to be able to compare or update its version of a corresponding file, dataset, table, data store, etc. There is also a need to minimize the bandwidth used to update multiple receivers. Minimizing the amount of delta or update information can conserve network bandwidth, reduce the active listening time of a wireless device, conserve battery energy, and reduce the time that it takes to bring a receiver's version up to date.

## SUMMARY

The following summary is included only to introduce some concepts discussed in the Detailed Description below. This summary is not comprehensive and is not intended to delineate the scope of protectable subject matter.

One source, a sender, may enable updating at multiple receivers by sending each receiver the same update information. Any receiver can use the same update information to increase its knowledge about how its target dataset differs from the master dataset, even though its target dataset may uniquely differ from the master dataset. The master dataset may be divided into divisions and subdivisions, which may be hashed to form a hash hierarchy. The update information sent by the sender may include a top level of hashes of the hash hierarchy as well as encodings of the lower levels of the hash hierarchy and encodings of blocks of the content of the master dataset. The encodings may be erasure hashes, for example. An erasure hash may be computed, for example, as a random linear combination of the hashes of a given level of the hierarchy.

Any receiver is highly likely to be able to use any hash encoding to improve its understanding about how its target dataset differs from the master dataset. More specifically, parts of the master that a receiver knows it already has may be hashed and those hashes may be used, based on a received encoding or erasure hash (and possibly based also on information about how the encoding was encoded) to reproduce a needed hash. A receiver can use received, computed, and/or reproduced hashes to determine which parts of the master it might need. A receiver may use encodings of the blocks of the master to obtain blocks of the master, which may be applied to the receiver's target to construct a local copy of the master.

Many of the attendant features will be more readily appreciated as the same become better understood by reference to the following detailed description considered in connection with the accompanying drawings.



## DESCRIPTION OF THE DRAWINGS

The present description will be better understood from the following detailed description read in light of the accompanying drawings, wherein:

FIG. **1** shows a generic distribution arrangement.

FIG. **2** shows an example of a wireless file distribution arrangement.

FIG. **3** shows a timeline of receivers.

FIG. **4** shows a hierarchical hash scheme.

FIG. **5** shows an efficient hash hierarchy encoding scheme.

FIG. **6** shows a process of a sender providing update information to a receiver and a receiver performing an update.

FIG. **7** shows an erasure hash encoding scheme.

FIG. **8** summarizes a hashing, encoding, and transmission process for a sender.

FIG. **9** shows an overview of how a receiver can find unmatched blocks in its target dataset.

FIG. **10** shows a reconstruction process performed by a receiver when the sender uses a decomposable erasure scheme.

FIG. **11** shows a process a receiver may use to determine when to stop downloading erasure hashes.

FIG. **12** shows a graph.

FIG. **13** shows three performance graphs.

FIG. **14** shows a table of empirical results for different download methods.

Like reference numerals are used to designate like parts in the accompanying drawings.

## DETAILED DESCRIPTION

### Overview of Data Synchronization

FIG. **1** shows a generic distribution arrangement. A sender **100** has a master dataset **102**. A communication medium **103** allows at least one-way communication from the sender **100** to receivers **104**, **106**, **108**, and **110**, each with its own target dataset, **112**, **114**, **116**, and **118**, respectively. The communi-

cation medium **103** could be a data network, a mobile wireless network, a radio broadcast, a system bus in a computer, or even physically distributed storage mediums such as diskettes. The target datasets **112**, **114**, **116**, and **118** are various outdated versions of the master dataset **102**. The target datasets **112**, **114**, **116**, and **118** may differ from the master dataset **102** by varying degrees. Target datasets **112**, **114**, **116**, and **118** are to be updated or synchronized to match the master dataset **102**. A target dataset may be empty or may not have any parts of the master dataset.

Because data synchronization is such a common task, it would be difficult to list all possible applications for an efficient data synchronization scheme. For example, data synchronization can occur between devices sharing a bus, between file systems, between applications, between systems, and so on. FIG. **2** shows an example of a wireless file distribution arrangement. In FIG. **2**, various wireless mobile devices such as cell phone **130**, PDA **132**, and laptop **134** receive radio signals from broadcast system **136**. Mobile devices, **130**, **132**, and **134** may each have their own outdated versions of master dataset **102**. The radio signals convey information about the master dataset **102** that receivers can use to bring their respective versions of the dataset up to date. As mentioned above, wireless systems can particularly benefit from an efficient data synchronization scheme that minimizes listening time, minimizes latency, and minimizes battery consumption by minimizing CPU usage.

If each receiver had the same version of a dataset and listened to the sender at the same time, then updating would not be a difficult problem; the sender would send the particular differences between the master dataset **102** and the receiver's version, the receivers would receive the same difference information at the same time and apply the differences to reconstruct the master dataset **102**. However, in reality receivers may have different versions of the master dataset **102**, and some receivers may listen to the sender at different times.

FIG. **3** shows a timeline **150** of receivers. Four different receivers C**1**, C**2**, C**3**, and C**4** are active at different times. At time **1**, only C**4** is active. At time **2**, C**1** and C**2** are active. At time **3**, no receivers are active or receiving information from the sender. Not only may receivers read or receive at different times, as noted above, the receivers may have different versions of the master dataset **102**. To accommodate ranges of receiving times and target versions, the sender may take a one-size-fits-all approach. That is, the sender may send or broadcast one set of differential information that each receiver can apply to its version to identify differences or reconstruct a local copy of the master dataset **102**. One approach for providing differential information is to use a hierarchical hash scheme.

Simple Hierarchical Hashing

FIG. **4** shows a hierarchical hash scheme. The master dataset **102** is implicitly or explicitly divided into coarse top level blocks **170** (b**1**, . . . , bj). A hash function **171** is applied to the top level blocks **170**, creating top level block hashes **172**. The top level blocks **170** are subdivided into two or more smaller blocks **174** ($b2.1_1, \ldots, b2.2_j$). The hash function **171** is applied to the smaller blocks **174** to create second level hashes **176**, and so on. In the example in FIG. **4**, hash hierarchy **178** has three levels but two or more may be used. Any receiver possessing a complete hash hierarchy **178** can determine its differences over the sender's master dataset **102**. The sender **180** may broadcast or send each level of the hash hierarchy **178** on a different communication channel (not shown). The hashes of each level are repeatedly sent as though on a data carousel. The receiver **182** receives the transmitted hashes and also data blocks of the master dataset (not shown) and performs a reconstruction process **184** using it target dataset **183** (an outdated version of master dataset **102**).

Regarding the reconstruction process **184**, receiver **182** initially reads or receives **186** the top level block hashes **172**. The receiver **182** compares **188** the top level block hashes **172** against the target dataset **183** ($F_{old}$). More specifically, the receiver **182** moves a sliding window (the size of a top level block **170**) across the target dataset **183**, applying the hash function **171** to windowed blocks in the target dataset **183**. The matching process can also be done through hierarchical fingerprints as described elsewhere and as discussed further below. If the hash of a windowed block in the target dataset **183** matches a top level block hash **172**, then the block in the target dataset **183** is marked as a match and the sliding window moves to the next unmatched block in the target dataset **183**. To aid eventual reconstruction of the master dataset **102**, matched blocks from target dataset **183** may be accumulated into a temporary file. Furthermore, by identifying top level signatures or hashes **172** that do not map to a top level block in target dataset **183**, the receiver **182** in effect identifies top level blocks **170** in the master dataset **102** that are not found in the target dataset **183** (although the receiver **182** does not yet know the contents of these missing blocks, it does know that they are not in its target dataset **183**). In other words, the receiver **182** can identify any top level hashes **172** of the master dataset **102** that are not mapped-to by any part of the target dataset **102**.

Referring again to the reconstruction process **184**, if the receiver **182** compares **188** the top level hashes **172** and determines that top level block b**1** is not in the target dataset **183**, then the receiver will need second level hashes h($b2.1_1$) and h($b2.2_1$) to identify the portion of block b**1** (e.g. $b2.1_1$ or $b2.2_1$) that is not in the target dataset **183**. However, if h($b2.1_1$) has just passed on the second level data carousel, then the receiver **182** will have to wait **190** for all of the other level two hashes **176** to transmit on the data carousel before actually receiving **192** the level two hash that it needs. This unproductive waiting time increases the time that it takes for the receiver **182** to synchronize its target dataset **183**. If the receiver **182** is a wireless device, then power may be consumed receiving unneeded hashes. On average, a receiver will wait for half the number of hashes of a hierarchy level before receiving a needed hash, and the cost will increase with the number of levels in the hash hierarchy.

Erasure Encodings of Hash Hierarchy, or "Erasure Hashes"

FIG. **5** shows an efficient hash hierarchy encoding scheme. In FIG. **5**, sender **200** generates a' hash hierarchy **202** preferably using a special hash function **204**. The dashed lines in hash hierarchy **202** indicate a mathematical relationship between the hashes in neighboring levels. This relationship results from the choice of hash function **204** and will be explained further below. Sender **200** carousels the top level block hashes **206**. However, rather than carousel or transmit the lower level hashes **210** themselves, the sender **200** first encodes **208** the lower level block hashes **210** and transmits encodings **211** of the lower level hashes **210**. The sender **200** also encodes **208** data blocks **212** (b**3.1 1**, b**3.2 1**, . . . b**3.4***j*), which contain the actual content of the master dataset **102**. The encodings **213** of the data blocks **212** are also transmitted. The encoding **208** is discussed below with reference to FIG. **7**.

Receiver **214** receives transmissions from the sender **200** and performs a synchronization or reconstruction process **216**. The receiver **214** receives **218** the top level block hashes **206**. Similar to step **188** in FIG. **4**, the receiver **214** compares **220** the top level hashes **206** against the target dataset **183**

($F_{old}$) to determine which second level hashes will be needed to identify unmatched parts of unmatched level one blocks **170**. For example, the receiver **214** may determine that block b**1** is not found in the target dataset **183** and level two hashes—h(b**2.1**$_1$) and h(b**2.2**$_1$)—will be needed to determine whether target dataset **183** has either block b**2.1**$_1$, or block b**2.2**$_1$, or neither. However, rather than having to wait for a data carousel to come around with the block hashes for those particular blocks, the receiver **214** first calculates **221** determinable hashes h(b**2.1**$_2$) . . . h(b**2.2**$_j$), which it can calculate by applying the known hash function **204** to copies of blocks b**2.1**$_2$ . . . b**2.2**$_j$ (from its target dataset **183**) which it knows from step **220** match the master dataset **102**. The receiver then receives **222** the next (or any) encodings **211** of the level 2 hashes and, using the calculated **221** hashes at the same level, decodes **224** them to produce the needed block hashes, in this example h(b**2.1**$_1$) and h(b**2.2**$_1$). Note steps **221** and **222** can occur in any order. Given sufficient block hashes the receiver **214** is easily able to determine which data blocks (e.g. b**3.2**$_1$ and b**3.4**$_1$) need to be applied to the target dataset **183** to reproduce the master dataset **102**. However, as with the block hashes, the receiver **214** does not need to wait for a particular data block to arrive. Instead, the receiver **214** receives **226** any encodings **213**, preferably the next transmitted encodings **213**, and uses the received **226** encodings **213** to reproduce the needed data blocks.

Notably, with a well-chosen encoding scheme such as an erasure encoding, the receiver **214** is likely to be able to use any encodings **211**/**213** to help reconstruct the needed block hashes (e.g. h(b**2.1** and h(b**2.2**)) or data blocks **212**. In other words, each encoding **211** received by receiver **214** is likely to contribute to the reconstruction of a needed block hash and the subsequent identification of portions of the master dataset **102** that are missing from the target dataset **183**. Each encoding **213** of the data blocks **212** is likely to contribute to the reconstruction of a needed data block. However, the decoding process may not be able to commence until all needed encodings are received, although progressive decoding is sometimes possible.

FIG. **6** shows a process of a sender providing update information to a receiver and a receiver performing an update. The sender generates **230** a hash hierarchy as discussed above. Namely, the sender generates **230** block hashes of divisions and subdivisions of the master dataset **102** ($F_{old}$). The sender generates **232** encodings of the hash hierarchy. The sender then: transmits **234** the top level block hashes of the hash hierarchy (the hashes of the largest divisions of the master dataset **102**); transmits **234** encodings of the lower level hashes; and transmits **234** encodings of blocks of the actual content of the master dataset **102**. Level one hashes can also be encoded, however, most of the time this will not provide a significant benefit.

To identify blocks of data (via their hashes/signatures) that it will need to reconstruct the master dataset **102**, the receiver iteratively downloads transmissions from the sender and reconstructs, level by level with increasing fineness, hashes of the hash hierarchy that it determines it needs. The receiver obtains the top level of the hash hierarchy by receiving **236** the top level hashes, which it uses as a current hash search set. The receiver uses **238** the current hash search set to search the target dataset **183** ($F_{old}$) for hashes in the current search set that do not have a matching block in target dataset **183**. The receiver then goes **240** down to the next level of the hash hierarchy. If the searching is not finished **242** then the receiver receives **244** the encodings of the new level of the hash hierarchy. The receiver uses **246** the encodings and the subhashes for the matched blocks at the current level to reconstruct block hashes at the new/current level that will be used as the hash search set, again performing a search **238**. Subhashes for matched blocks can be easily calculated by the receiver since the receiver is also aware of the hashing algorithm used by the server and the receiver has the same content of the matched blocks in its target dataset.

The searching **238**, receiving **244**, and reconstruction **246** are repeated at lower finer levels until there is a determination that the overall searching process is finished **242**. This determination can be as simple as reaching a predetermined or lowest level of the hash hierarchy, or it could be a dynamic determination based, for example, on whether new searches **238** are improving the receiver's knowledge of the master dataset **102**. If the receiver realizes that it did not match anything at the first level, then it will not need to download the second level. If the receiver realizes that it has many matches on the first level, but on the second level and third levels it keeps matching the same things, then it realizes it cannot get any more information than it got on the third level, and it may stop. In other words, the receiver can measure the benefit at a given level and stop if there is no benefit. This adaptive search approach allows the receiver to search with fine granularity when there are only small differences between the master dataset **102** and the target dataset **183**. The receiver may search with coarse granularity when there are large differences between the datasets **102**, **183**. Put another way, the receiver can dynamically adjust how much of the hash hierarch it will need to download.

Returning to FIG. **6**, when the receiver has finished searching **242**, arbitrary erasure encodings of the data blocks may be downloaded **248** in a quantity proportional to the number of unmatched hashes at the lowest level of the hash hierarchy. The encodings of the data blocks may be decoded and used to reconstruct **250** a copy **252** of the target dataset **102**.

It may be surprising that, at a given level, any commonly transmitted encoding is highly likely to allow any receiver to make a determination at that level about what part of the master dataset is not missing from a receiver's particular master dataset. Following is an explanation of how the same encoding can be used to help different receivers reconstruct different particular portions of the hash hierarchy that the different receivers need. Consider the following conceptual illustration. Two receivers, Receiver**1** and Receiver**2**, both need to learn two numbers, "1" and "2", and the receivers are listening from a server that has to provide these two numbers. If Receiver**1** already knows "1", and Receiver**2** already knows "2", the server can tell Receiver**1**:"2" and can tell Receiver**2**:"1". Then Receiver**1** and Receiver**2** will know both numbers. However, it will have cost the server two numbers/operations (inform Receiver**1**, inform Receiver**2**). If, instead, the server sends both receivers "3", and sends information instructing the receivers to "subtract the number that I'm sending you from the number that you have" (i.e. the server says, "3 and subtract"), then Receiver**1** will subtract 1 from 3 to obtain 2; its missing number. Similarly, Receiver**2** will subtract 2 from 3 to obtain its missing number; 1. With the same transmitted information each receiver can generate the number it needs. The server saved time and bandwidth by providing a number that is really a combination of the numbers that the receivers already have and by providing an operation that can reconstruct the number a receiver is missing. As discussed below, block hashes can be encoded with a similar concept.

FIG. **7** shows an erasure hash encoding scheme. In general, a sender can encode block hashes into erasure hashes (encodings of block hashes) by taking the block hashes at a given level and combining them. A random linear combination of

block hashes is an efficient way to combine block hashes. In FIG. **7**, an erasure hash **280** is produced by crossing a vector **282** of preferably random coefficients with a matrix **284** of block hashes. Each erasure hash **280** is produced by its own corresponding vector of random coefficients. Operations happen in a finite field, e.g. Galois Field ($2^{16}$). If the receiver knows the coefficients **282** and the erasure hash (encoding) **280**, and if the receiver knows sufficient hashes in the matrix **284**, then the receiver can use known linear algebra techniques to solve for a missing hash. The receiver can hash blocks in its target dataset that are known to match the master dataset to locally obtain some or most of the hash vectors in the matrix **284**. Unknown hashes can then be solved using the known vectors in the matrix **284**, using the known coefficients **282**, and using one or more erasure hashes **280**. Generally, the number of erasure hashes needed by the receiver will be proportional to the number of known blocks (or, conversely, the number of unknown hashes). To further explain, if a receiver has an original block it really has a vector of all zeroes and a one, which is like knowing a variable in a system of equations for variables, e.g. X1 . . . X5. Knowing X1 . . . X4 (from the local original/matched blocks), the final variable X5 can be found because the final equation, the erasure hash, may have something like X1+3X2+ . . . +5X5=c. From this, and the known values for X1 . . . X4 it is possible to solve for the last variable X5.

FIG. **8** summarizes a hashing, encoding, and transmission process for a sender. As mentioned above, the sender can generate or otherwise obtain block hashes **300** for increasingly smaller blocks of subdivisions of a target dataset. The sender transmits **302** the level-1 block hashes, preferably on their own communication channel. For each level of block hashes **300** below level-1 the sender computes **304** an erasure hash as a random linear combination of the block hashes **300** at that level. The erasure hash is transmitted **306**. The computing **304** and transmitting **306** is repeated to produce a stream of substantially unique erasure hashes for each level. The sender also encodes **308** the data blocks **312** into an erasure block and transmits **310** the erasure block. The encoding **308** and transmitting **310** is repeated to provide a steady stream of erasure blocks of the content of the master dataset **102**. Preferably, the stream of erasure blocks has its own communication channel. Each stream of erasure hashes preferably has its own communication channel, which allows different receivers to pull an erasure hash from any level at any time without having to wait. Parallel transmission **302**, **306**, **310** of top level block hashes, erasure hashes, and erasure blocks is preferred but not necessary.

Although not shown in FIG. **8**, the sender may also transmit with each erasure hash the vector of coefficients that were used to produce the erasure hash. An efficient alternative is to have the sender transmit a seed for a random number generator. Each receiver can use the seed and generator to reproduce the same sequence of coefficients used by the sender to linearly combine hashes to produce erasure hashes. A large book of predetermined coefficients could be stored in advance at the sender and each receiver. Any coefficient sharing mechanism may be used.

Many hash algorithms can be used for block hashing. Preferably the block hash is a weak rolling block hash, as used with the well known rsync algorithm. With a rolling block hash, if a block is hashed (producing a first hash) and then the block is extended by a small amount, the first hash can be used to cheaply hash the extended block.

A rateless erasure algorithm has been described above. If, in terms of network layers, the erasure algorithm is implemented at the application layer, then error correction can be presumed to be handled at a lower layer such as the link or transport layer. However, if error correction or redundancy is desired, a rated erasure may be used to provide error correction.

In one embodiment an erasure hash may be a random linear combination of all the block hashes at the level of that erasure hash. However, for efficiency a linear combination of a subset of block hashes can be used, which makes the encoding matrix sparser. If all block hashes are used then the encoding matrix will not be sparse. A non-sparse matrix may require a lot of time to decode at the receiver side because more equations need to be solved. For the block hashes this is not much of a concern because the hashes are small, but the actual downloaded content data blocks may be relatively large and solving a full matrix can be expensive. It is possible to probabilistically produce some linear combinations that are just a combination of one data block. If only some blocks (not all of them) are encoded there is a chance that a receiver will receive a block that it already has. However, to avoid downloading redundant data a receiver can skip a data block if it already has the coefficients for that block. That is, if the receiver knows the coefficients of a forthcoming block, for example by receiving it before receiving a block or by using the shared-seed scheme discussed above, then the receiver can use the coefficients for the data block that is going to be distributed next to determine whether that upcoming data block will provide information new to the receiver.

This determination may be made by calculating the rank of the matrix of coefficient vectors; the receiver already has a set of blocks and it knows the coefficients of those blocks, so it can start building the matrix. A receiver can download the seed, calculate the coefficients that are going to be used for the next/new block, add those coefficients to those that it already has stored locally. The receiver can then calculate the rank of the combined matrix. If the rank increases by one that indicates that whatever is being broadcast through the air is new to the receiver. Otherwise, the receiver won't need it. Calculating the rank is a way to make sure that the new coefficient vector is linearly independent of the coefficient vectors for blocks already received or known by the receiver. If the rank does not increase that indicates that the new coefficient vector is linearly dependent on what the receiver already has, i.e. no new information will be obtained. If, for example, a data block is one megabyte, it might take 5 minutes for it to be downloaded by the receiver. But, if the receiver only has to download the relatively small coefficients (e.g. 16 bytes) produced by the seed to determine whether or not to download the next data block, the receiver can skip the block and wait for next coefficients/block, etc.

Whether to use block prediction as discussed above may be decided by weighing the overhead against the fairly low probability that a receiver will receive information that it will not need. Most of the time data blocks are linear combinations of all of the blocks and will be useful to a receiver.

Decomposable Erasure Hashes

For the following discussion, u(i) is a shorthand expression for the number of unmatched blocks at level i.

In a simple embodiment, assuming that each block is divided into two sub-blocks, for each level i>1 of hash values, the receiver downloads u(i−1)*2 erasure hashes in order to reconstruct the correct set of hashes at level i. However, the number of erasure hashes downloaded at level i can be halved by using decomposable homomorphic hashes. Such hashing functions hold the property that h(a)=h(b)+h(c) where a is the top level block, and b and c are the sub-level blocks corresponding to the top-level block a. This property enables a

receiver to reconstruct all hashes at level i by downloading only half as many erasure hashes, that is, by downloading u(i−1) erasure hashes.

Following is an explanation of a decomposable hash function. Assume that a top-level block is created out of bytes [l, r], and the corresponding children blocks are [l,m] and [m, r]. A hash function is decomposable if h(f[m+1, r]) can be computed from the values h(f[l, r]), h(f[l,m]), r−l, and r−m−1, and also h(f[l,m]) from h(f[l, r]), h(f[m+1, r]), r−l, and m−l. Use of a decomposable hash function can save on the cost of delivering block hashes used to identify matching data. Since receivers already have a hash for the parent block, they can receive one additional hash per pair of sibling child blocks, the hash for the other sibling can then be computed from these two.

In general, decomposable hashes can be implemented using homomorphic hashing functions, which are known and described elsewhere. Where h(a+b)=h(a)+h(b) or h(a*b)=h(a)*h(b), a and b being two different blocks, h( ) may be said to be homomorphic. Preferably, a decomposable function h(f[l, r]) for a block at a given level is equal to h(f[l,m])+h(f[m, r]), where h(f[l,m]) and h(f[m, r]) are the hashes for the corresponding sibling blocks at the next hierarchy level. To this extent, h may be defined such that

$$h(b_1, \ldots, b_n) = \sum_{v=1}^{v=n} g^v \cdot b_n,$$

where $b_i$ is an individual block, $(b_1, \ldots, b_n)$ is the parent block made of the concatenation of blocks **1**, . . . , n, and g is a generator number of a given Galois field. Or,

$$h(b_1, \ldots, b_n) = \sum_{v=1}^{v=n} c_v \cdot b_n$$

where $c_v$ are random coefficients.

It was not previously known that decomposable hashes can be efficiently used in combination with erasure hashes. Decomposable hashes at a given level can be used as input to the erasure decoding algorithm at the next level of hierarchy where, given the parent hash and an additional erasure block, any of the siblings can be reconstructed. In fact, decomposable parent hashes can be interpreted as simple linear combinations of the two child block hashes when the erasure hash is created as the addition of two hashes.

To explain further, consider a receiver that downloaded an erasure hash from level 1. That hash failed, and the receiver goes to level 2. At level 2 the receiver needs 2 master block hashes to determine if it is the first or second half of that block that is missing. The receiver only needs to download one erasure hash. This has not been possible with previous block hashing methods. However, by producing erasure hashes as linear combinations of block hashes, it is possible to preserve the homomorphic decomposability of the block hashing function. With homomorphic decomposability, if each erasure hash is thought of as an equation, and each block is thought of as a variable, and there are 1,000 variables, only one equation that is linearly independent with the known equations will be needed to solve the unknown variable if 999 variables are known. To reproduce the newly needed block hash the receiver only needs the 999 downloaded/known block hashes, the 1 erasure hash, and the corresponding vector (coefficients) that was used to generate that erasure hash.

FIG. **9** shows an overview of how a receiver can find unmatched blocks in its target dataset. The receiver reads **340** the top level of the hash hierarchy which it uses to determine **342** hashes—and therefore blocks—of the master dataset that do not have a top-level equivalent in the target dataset. For convenience, the hashes can be stored in a dictionary. Each top-level block in the target dataset (moving one byte or symbol at a time) is hashed and its hash is searched for in the dictionary. The receiver then reads **344**, at any time, any portion of the transmitted encoding of the hash hierarchy, where the size of the downloaded portion is proportional to the number of unmatched blocks at the current level. The portion of the hash hierarchy that is known to the receiver is used **346** to decode the portion of the hash hierarchy needed by the receiver. These decoded block hashes are hashes of finer sub-blocks of the unmatched blocks in the level above. The decoded portions of the hash hierarchy (the decoded block hashes) are used **348** to determine unmatched sub-blocks corresponding to the determined **342** unmatched blocks in the level above. The process may be repeated downward as necessary and then the necessary data blocks may be obtained by the receiver.

FIG. **10** shows a reconstruction process performed by a receiver when the sender uses a decomposable erasure scheme. Erasure hashes **360** are transmitted via 4 channels **362**. The "h2" erasure hashes are at level-2, the "h3" hashes are at level-3, and the "h4" hashes are at level-4. At stage j the receiver knows that block **364** is the only unmatched level-1 block hash. As an aside, block hashes **366** are shown with different size to emphasize the sizes of the blocks that they represent. In practice, the block hashes **366** are preferably the same size or same order of magnitude. Returning to stage j, the receiver did not match level-1 master hash **364** so the receiver needs to determine whether its target dataset has either of the master sub-blocks of hash **366**'s master block. As discussed above, because only 1 master block/hash is unmatched at stage j, the receiver only needs to download one level-2 erasure hash. Therefore, the receiver reads, from channel 1, erasure block hash $e_{h2,j}$. Because the hash function is decomposable, the receiver uses hash **364**, erasure hash $e_{h2,j}$, and the other hashes for matched blocks at level 2, to produce hash **368** and hash **370**. The receiver then determines whether hashes **368** and **370** have matching blocks in its target dataset. In the example in FIG. **10**, hash **368** is not matched and hash **370** is matched. Moving to stage j+1, the receiver again needs to download only one erasure hash, level-3 erasure hash $e_{h3,j+1}$, which it reads from channel 2. Hash $e_{h3,j+1}$, is used together with hash **368** to compute hash **372** and hash **374**. The receiver then uses these hashes to determine which sub-blocks of hash **368**'s master block are missing from the target dataset. Neither hash matches and at stages j+2 and j+3 the receiver reads the next two level-4 erasure hashes from channel 3; $e_{h4,j+2}$ and $e_{h4,j+3}$. The child hashes **375** of hashes **372** and **374** are computed and used to determine that level-4 hashes **376** do not have a match. At stage j+4 the receiver knows that it only needs two data erasures and reads data erasures $ed_{j+4}$ and $ed_{j+5}$ from channel 4. Using previously matched data blocks from the target dataset ($F_{old}$) and the known coefficients with which data erasures $ed_{j+4}$ and $ed_{j+5}$ were encoded, the receiver decodes the data erasures $ed_{j+4}$ and $ed_{j+5}$ to produce the missing master data blocks **378** that correspond to block hashes **376**.

FIG. **11** shows a process a receiver may use to determine when to stop downloading erasure hashes. The receiver downloads **400** erasure hashes and searches for blocks at the current level of the hierarchy. The results are compared **402** to results from searching at the previous level. The receiver

determines **404** the rate or amount of new information being added. Methods for making determination **404** are discussed above. If the rate is low or if no new information is being added, then the receiver finishes **406** searching and may download content data. Otherwise, the receiver goes **408** to the next level and repeats steps **400**, **402**, and **404**.

Significantly, a receiver can quickly obtain the hashes it needs, by downloading an amount of information proportional to the number of missing hashes/blocks yet without having to provide feedback to the sender.

Settings and Emperical Results

Some empirical results and preferred parameters will now be discussed. According to tests, any random generator will suffice but most processors will be most efficient with 2-byte coefficients. Furthermore, a hash size of 7 bytes was found to be optimal for many types of applications. An MD5 or SHA1 hash can be used as a signature to verify that a reconstructed dataset matches its master dataset. Although the examples above discuss dividing a block into two sub-blocks at each level, the same idea works similarly for an arbitrary number of sub-blocks per block.

FIG. **12** shows a graph **430**. In graph **430**, it can be seen that over a range of different blocksizes hierarchical hashing ("DeltaCast") requires less than half the bandwidth of a single round hashing scheme. Further regarding block size, the blocks of the master dataset do not have to be divided into fixed sizes. Variable sized blocks can be used for greater efficiency. As long the receiver knows the sizes in advance the same techniques may be used. Rather than use a rolling window sized to the size of the blocks at the current search level, the rolling window can be matched to a certain value (fingerprint) that identifies the border of a block. That is, the window keeps rolling until the edge of the window matches another border identifier/value, and so on. This variable block size approach works well when the master file or dataset is updated with arbitrary insertions/deletions. There may be a range of block sizes at one level, and at the next level the range of block sizes will be halved. However, blocks will need to be padded to a multiple of a fixed block size.

FIG. **13** shows three performance graphs. Graph **440** shows how performance can vary with the number of levels in the hash hierarchy. Graph **442** shows how performance can vary when receivers have different outdated versions of the dataset. Graph **444** shows a comparison of average download latencies for four different schemes: (a) simple full file download with no hashes, (b) hierarchical hashing scheme with no encoded data, (c) single-layer hashing, and (d) hierarchical hashing with erasure encoding ("DeltaCast"). The total latency represented in graph **444** includes (i) the time to download the hashes or the erasure hashes, (ii) the time to download the missing data, (iii) the idle time waiting in the different carrousels for the specific hashes and data to arrive, and (iv) the time to decode the encoded hashes and data. Note that not all latency factors are part of every scheme. For instance, the total latency in scheme (a) is determined by the latency factor (i). The latency in schemes (b) and (c), however, is determined by factors (i), (ii), and (iii), while the latency in scheme (d) is determined by factors (i), (ii), and (iv).

FIG. **14** shows a table **470** of empirical results for different download methods. As can be seen in FIG. **14**, the "DeltaCast" approach offers significant performance improvement over other techniques. Three sub-columns represent three different sets of synchronized data. In each case, the "DeltaCast" was superior. These findings also indicate an improvement in power or battery consumption.

SUMMARY

Various embodiments discussed herein may involve reconstructing a master dataset at a receiver. However, there may be some applications where actual reconstruction is not needed or performed and data blocks of the master dataset (or encodings thereof) may not be sent and/or received. For example, there may be cases where it is useful to simply determine where a target dataset differs from a master dataset. Stale data in the target dataset could be deleted from the target dataset to cause the target dataset to become a proper subset of the master dataset. Or, if the master dataset is known to differ only by deletions, then the target dataset could be rendered equivalent to the master dataset by deleting portions determined to be absent from the master dataset. It should also be noted that embodiments discussed herein are highly useful for one-way sender-receiver communication. However, aspects of the embodiments may also be useful for two-way communication systems. For example, a receiver could determine missing parts of a master dataset in ways discussed herein and then use a feedback communication to the sender to request specific missing parts of the master dataset. In sum, techniques discussed herein are useful with but not limited to one-way communication systems.

Those skilled in the art will realize that storage devices utilized to store program instructions can be distributed across a network. For example a remote computer may store an example of the process described as software. A local or terminal computer may access the remote computer and download a part or all of the software to run the program. Alternatively the local computer may download pieces of the software as needed, or distributively process by executing some software instructions at the local terminal and some at the remote computer (or computer network). Those skilled in the art will also realize that by utilizing conventional techniques known to those skilled in the art that all, or a portion of the software instructions may be carried out by a dedicated circuit, such as a DSP, programmable logic array, or the like.

Those skilled in the art will also realize that a variety of well-known types of computing systems, networks, and hardware devices, such as workstations, personal computers, PDAs, mobile devices, and so on, may be used to perform embodiments discussed herein. Such systems and their typical components such as CPUs, memory, storage devices, network interfaces, etc. are well known and detailed description thereof is unnecessary and omitted.

The invention claimed is:

**1**. A method of generating update information for a dataset, the method comprising:

generating, by a processor, a hash hierarchy based on the dataset, wherein the hash hierarchy includes a plurality of levels, and wherein a top level of the hash hierarchy comprises first hashes of first level subdivisions of the dataset, and wherein each subsequent level of the hash hierarchy comprises hashes of subdivisions of next higher level subdivisions of the dataset;

generating, by the processor, erasure hashes based on one of the plurality of levels of the hash hierarchy, wherein each erasure hash is produced by crossing a vector of coefficients with a matrix of a portion of the hashes of the one of the plurality of levels of the hash hierarchy; and

repeatedly broadcasting the erasure hashes to a receiver that is configured to compute a subset of the portion of the hashes that is unknown to the receiver based on the received erasure hash and its corresponding coefficients and another subset of the portion of the hashes that is known to the receiver.

2. A method according to claim 1, wherein the erasure hashes comprise linear combinations of at least a portion of the hashes of the one of the plurality of levels of the hash hierarchy.

3. A method according to claim 1, the method further comprising:

generating encodings of the hashes of the one of the plurality of levels of the hash hierarchy; and

repeatedly broadcasting the encodings.

4. A method according to claim 1, wherein the subdivisions are variable sized blocks.

5. A method according to claim 4, wherein the variable sized blocks have a border identifiable by a fingerprint value.

6. A method according to claim 1, wherein the generating a hash hierarchy is performed using at least a homomorphic hashing function.

7. A method according to claim 1, wherein the generating erasure hashes is performed using at least a homomorphic hashing function.

8. A method according to claim 1, wherein the erasure hashes are decomposable.

9. At least one computer-readable storage storing computer executable instructions that, when executed by a processor of a sending device, cause the sending device to perform a process comprising:

generating a hash hierarchy based on the dataset, wherein the hash hierarchy includes a plurality of levels, and wherein a top level of the hash hierarchy comprises first hashes of first level subdivisions of the dataset, and wherein each subsequent level of the hash hierarchy comprises hashes of subdivisions of next higher level subdivisions of the dataset;

generating erasure hashes based on one of the plurality of levels of the hash hierarchy, wherein each erasure hash is produced by crossing a vector of coefficients with a matrix of a portion of the hashes of the one of the plurality of levels of the hash hierarchy; and

repeatedly broadcasting the erasure hashes, wherein a receiver of a broadcast erasure hash is configured to compute a subset of the portion of the hashes that is unknown to the receiver based on the received erasure hash and its corresponding coefficients and a subset of the portion of the hashes that is known to the receiver.

10. At least one computer-readable storage according to claim 9, wherein the erasure hashes comprise linear combinations of at least a portion of the hashes of the one of the plurality of levels of the hash hierarchy.

11. At least one computer-readable storage according to claim 10, the process further comprising:

generating encodings of the hashes of the one of the plurality of levels of the hash hierarchy; and

repeatedly broadcasting the encodings.

12. At least one computer-readable storage according to claim 10, wherein the erasure hashes are decomposable.

13. At least one computer-readable storage according to claim 9, wherein the generating a hash hierarchy is performed using at least a homomorphic hashing function.

14. At least one computer-readable storage according to claim 9 wherein the generating erasure hashes is performed using at least a homomorphic hashing function.

15. At least one computer-readable storage storing computer-executable instructions that, when executed by a processor of a receiving device, cause the receiving device to perform a process comprising:

receiving first hashes of first level subdivisions of a dataset, wherein a top level of a hash hierarchy comprises the first hashes, and wherein the hash hierarchy includes a plurality of levels, and wherein each subsequent level of the hash hierarchy comprises hashes of subdivisions of next higher level subdivisions of the dataset;

receiving erasure hashes that are based on one of the plurality of levels of the hash hierarchy, wherein each erasure hash is produced by crossing a vector of coefficients with a matrix of a portion of the hashes of the one of the plurality of levels of the hash hierarchy;

computing a subset of the portion of the hashes that is unknown to the receiving device based on the received erasure hash and its corresponding coefficients and a subset of the portion of the hashes that is known to the receiving device.

16. At least one computer-readable storage according to claim 15, wherein all of the hashes are the same size.

17. At least one computer-readable storage according to claim 15, further comprising constructing a copy of the master dataset at the receiving device based at least on the computing.

18. At least one computer-readable storage according to claim 15, wherein the erasure hashes are decomposable.

19. At least one computer-readable storage according to claim 15, wherein the first hashes are received via a first communication channel, and wherein the erasure hashes are received via a second communication channel.

20. At least one computer-readable storage according to claim 15, wherein the subdivisions are of varying length.

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