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(54) **MIXED METADATA UPDATE WITHOUT TRANSACTIONAL JOURNAL IN STORAGE SYSTEM WITH METADATA DELTA LOG AND LOG STRUCTURED METADATA**

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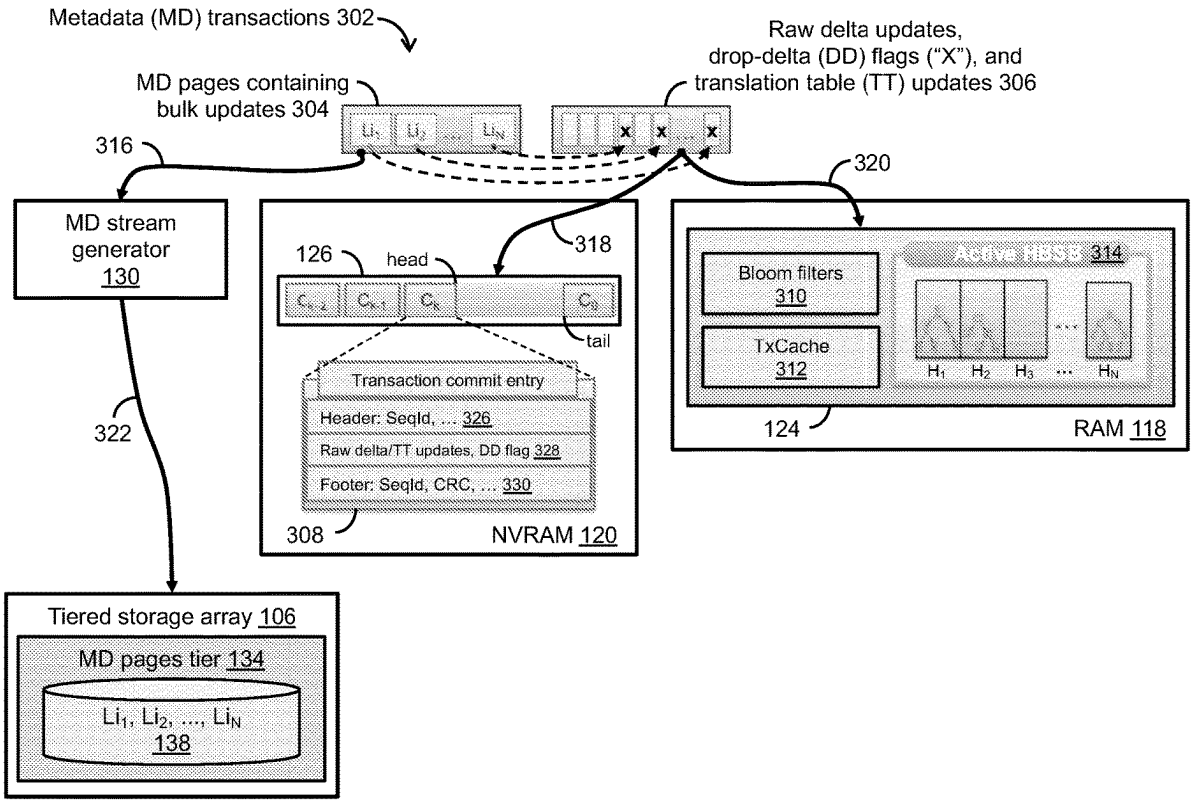
(57) **ABSTRACT**

Techniques for handling mixed metadata (MD) updates using an MD delta log and log structured MD. The techniques include, while performing a transaction commit operation, writing, to an MD delta log, raw delta updates to MD pages, logical-to-physical address translation table (TT) updates for MD pages containing bulk updates, and specialized flags for the MD pages containing bulk updates. For each MD page containing bulk updates, raw delta updates, a TT update, and a specialized flag are written to the MD delta log in association with a transaction identifier. The techniques include generating an MD stream for the MD pages containing bulk updates, and passing the MD stream to an MD pages tier of a storage array. The techniques include, in response to a predetermined event, replaying the MD delta log to apply valid delta updates to at least one MD page containing bulk updates in the MD pages tier.



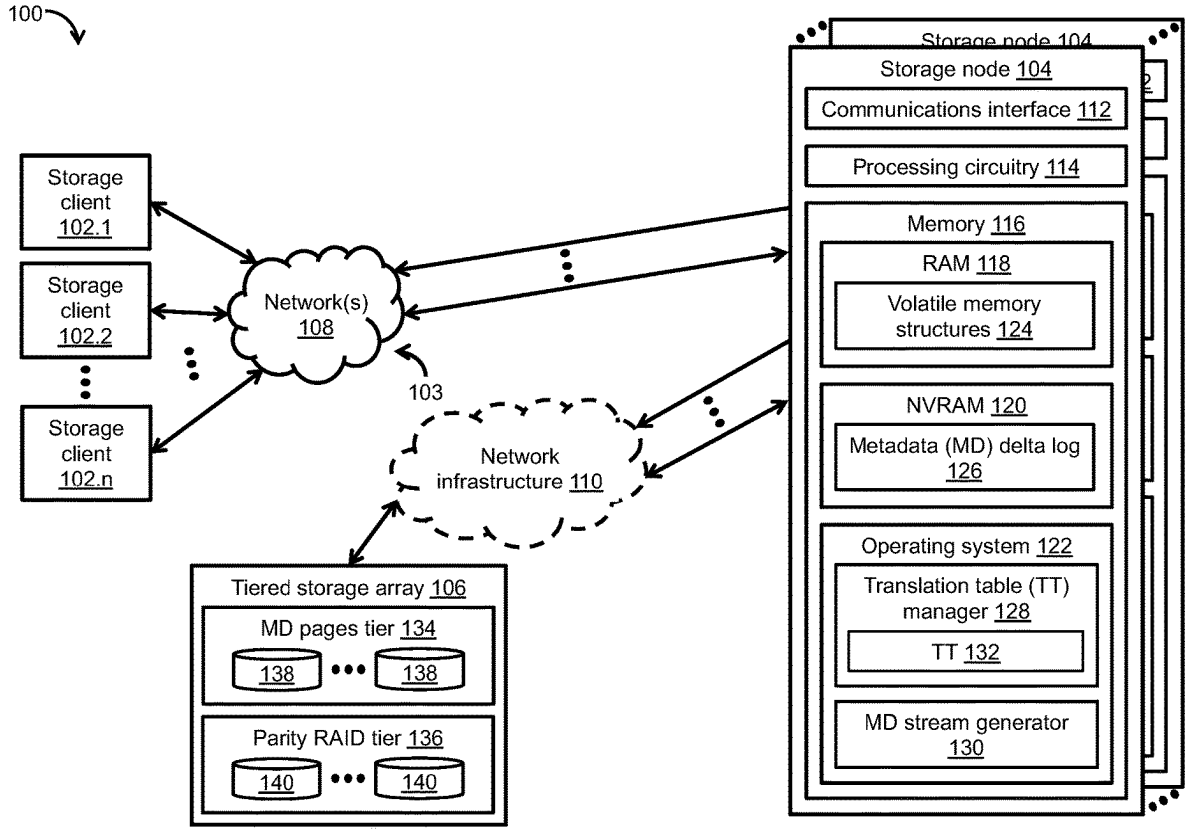

100
Storage client 102.1
Storage client 102.2
Storage client 102.n
Network(s) 108
103
Network infrastructure 110
Tiered storage array 106
MD pages tier 134
138
138
Parity RAID tier 136
140
140
Storage node 104
Storage node 104
Communications interface 112
Processing circuitry 114
Memory 116
RAM 118
Volatile memory structures 124
NVRAM 120
Metadata (MD) delta log 126
Operating system 122
Translation table (TT) manager 128
TT 132
MD stream generator 130

Fig. 1

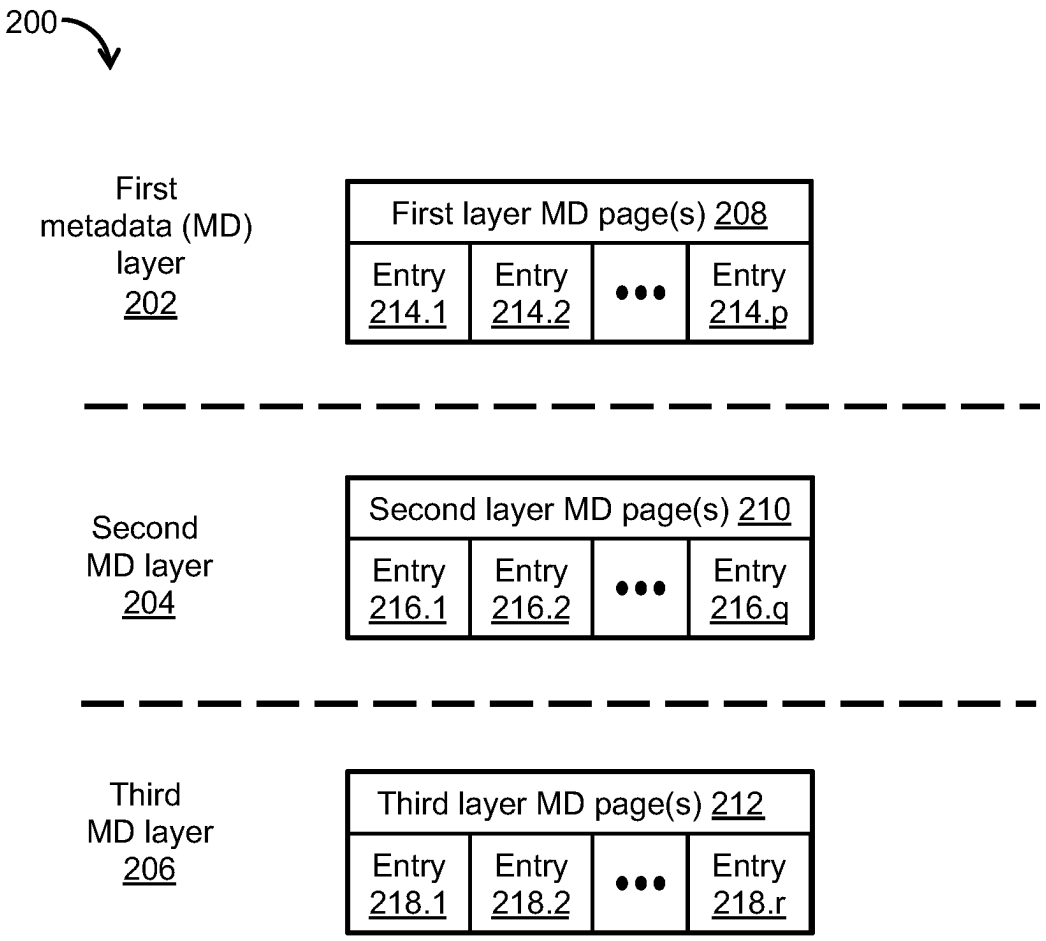

200
First metadata (MD) layer 202
First layer MD page(s) 208
Entry 214.1
Entry 214.2
•••
Entry 214.p
Second MD layer 204
Second layer MD page(s) 210
Entry 216.1
Entry 216.2
•••
Entry 216.g
Third MD layer 206
Third layer MD page(s) 212
Entry 218.1
Entry 218.2
•••
Entry 218.r

Fig. 2

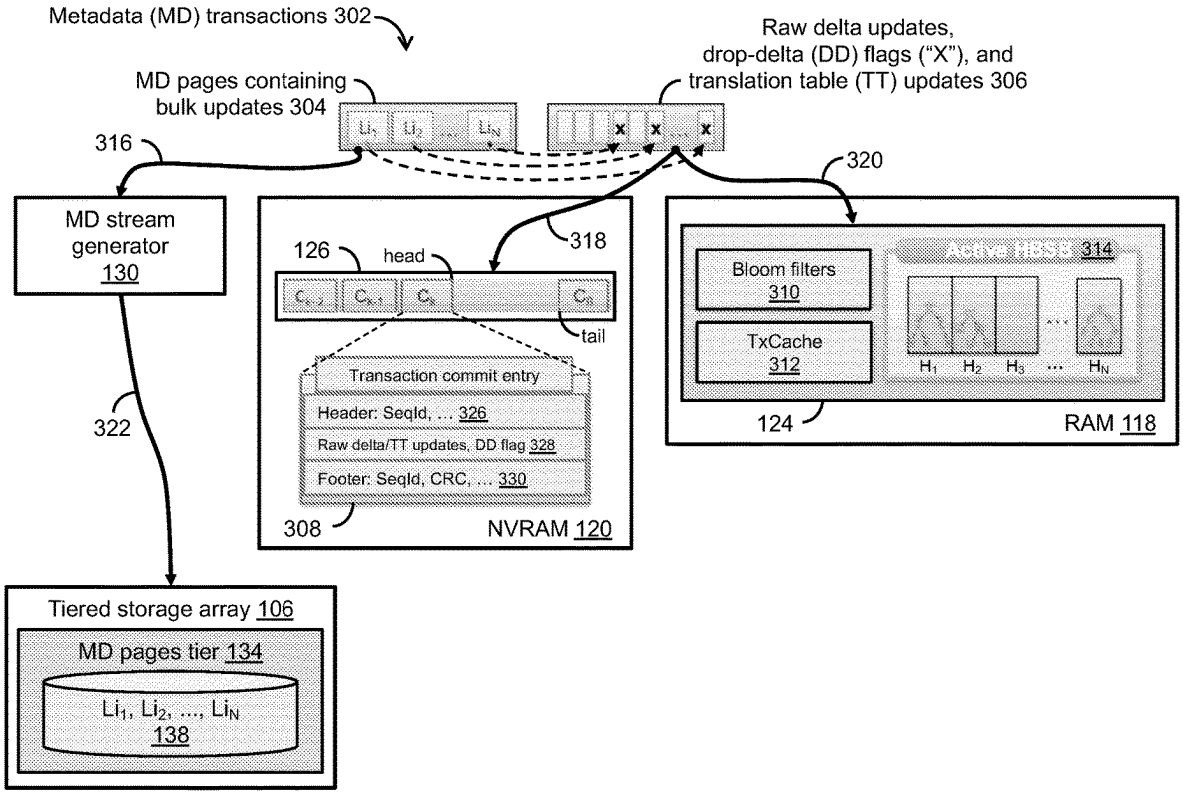

Metadata (MD) transactions 302
MD pages containing bulk updates 304
Raw delta updates, drop-delta (DD) flags ("X"), and translation table (TT) updates 306
316
320
MD stream generator 130
126
head
318
tail
Transaction commit entry
Header: SeqId, ... 326
Raw delta/TT updates, DD flag 328
Footer: SeqId, CRC, ... 330
308
NVRAM 120
Bloom filters 310
TxCache 312
Active HBSTs 314
124
RAM 118
322
Tiered storage array 106
MD pages tier 134
Li1, Li2, ..., LiN 138

Fig. 3

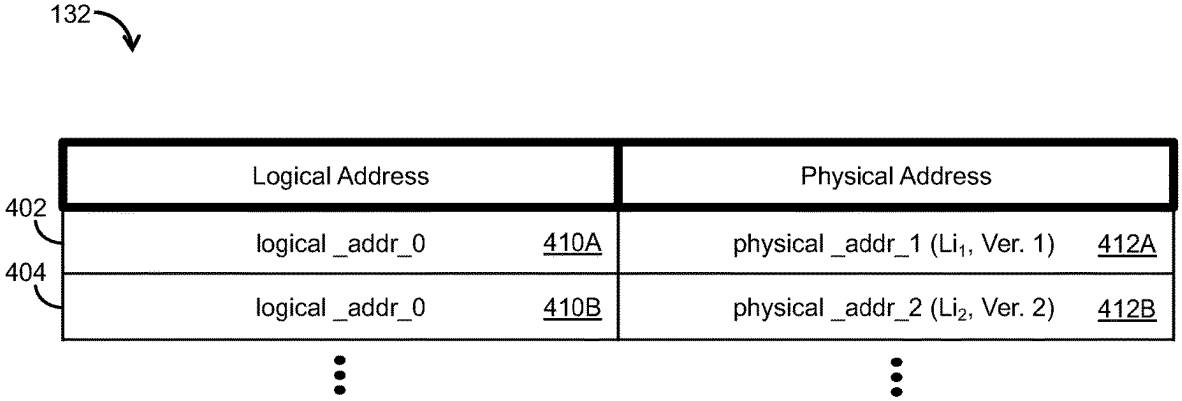

132
Logical Address
Physical Address
402
404
logical _addr_0
410A
physical _addr_1 (Li1, Ver. 1)
412A
logical _addr_0
410B
physical _addr_2 (Li2, Ver. 2)
412B

Fig. 4

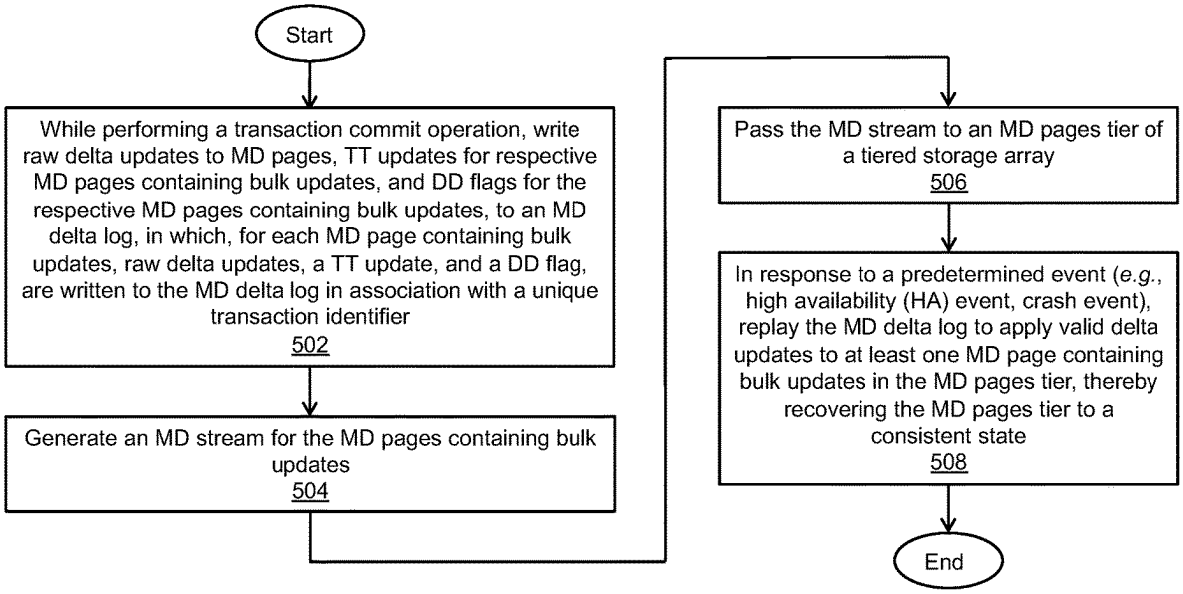

Start
While performing a transaction commit operation, write raw delta updates to MD pages, TT updates for respective MD pages containing bulk updates, and DD flags for the respective MD pages containing bulk updates, to an MD delta log, in which, for each MD page containing bulk updates, raw delta updates, a TT update, and a DD flag, are written to the MD delta log in association with a unique transaction identifier
502
Generate an MD stream for the MD pages containing bulk updates
504
Pass the MD stream to an MD pages tier of a tiered storage array
506
In response to a predetermined event (e.g., high availability (HA) event, crash event), replay the MD delta log to apply valid delta updates to at least one MD page containing bulk updates in the MD pages tier, thereby recovering the MD pages tier to a consistent state
508
End

Fig. 5

MIXED METADATA UPDATE WITHOUT TRANSACTIONAL JOURNAL IN STORAGE SYSTEM WITH METADATA DELTA LOG AND LOG STRUCTURED METADATA

BACKGROUND

[0001] Clustered storage systems employ various techniques and methodologies to protect and/or distribute electronic data, such as user data and metadata (MD). In response to receipt of a write input/output (IO) request ("write request") from a storage client computer ("storage client"), a storage processor ("storage node") of a clustered storage system logs pending changes to MD of a storage element (e.g., MD page) in a journal ("MD delta log") implemented in local memory. Once the pending changes to MD of the MD page have been logged in the MD delta log, the storage node sends an acknowledgement to the storage client that issued the write request. The storage node then stores the pending changes to MD of the MD page in a storage object (e.g., volume (VOL)) on a storage device (e.g., solid state drive (SSD)) of a storage array.

SUMMARY

[0002] In a clustered storage system, a storage node can write pending changes to MD ("delta updates") of a MD page to memory structures in volatile memory, and log the delta updates to the MD page in an MD delta log in persistent memory. The volatile memory structures and the MD delta log can be referred to collectively as the "delta log infrastructure." Upon determination that the delta log infrastructure is full or at any other suitable time, the storage node can perform a transaction commit operation to store the delta updates to the MD page in a VOL on an SSD of a storage array. To that end, the storage node can aggregate any delta updates that correspond to the same MD pages ("small updates"), and store them in the VOL in an amortized fashion. The storage node can also store entire MD pages containing delta updates ("bulk updates"), which themselves may be highly or completely amortized. Unfortunately, however, writing both small updates and bulk updates to the volatile memory structures and/or the MD delta log can overload the delta log infrastructure, significantly reducing the delta log infrastructure's efficiency.

[0003] Improved techniques are disclosed herein for handling mixed MD updates (e.g., small updates, bulk updates) in a storage node using a metadata (MD) delta log and log structured MD. The storage node can include a volatile memory, a persistent memory, and a logical-to-physical address translation table (TT), as well as a tiered storage array that includes an MD pages tier. The volatile memory can include volatile memory structures for storing and/or aggregating delta updates to MD pages. The TT can map a logical address space of the storage node to a physical address space of the MD pages tier, and can be used to track, within the MD pages tier, physical address locations of one or more MD pages containing bulk updates. The persistent memory can include an MD delta log for logging (i) all "raw" delta updates to MD pages, (ii) logical-to-physical address updates to the TT ("TT updates"), and (iii) a specialized "drop-delta" (DD) flag for each MD page containing bulk updates. The DD flag for each MD page containing bulk updates can provide an indication that all delta updates to the MD page that occurred before it was stored in the MD pages tier are no longer valid and should be dropped or discarded. For each MD page containing bulk updates, the MD delta log can maintain raw delta updates, a TT update, and a DD flag, atomically within the scope of a transaction.

[0004] The disclosed techniques can include, while performing a transaction commit operation, writing, to an MD delta log, raw delta updates to MD pages, TT updates for respective MD pages containing bulk updates, and DD flags for the respective MD pages containing bulk updates. For each MD page containing bulk updates, raw delta updates, a TT update, and a DD flag are written to the MD delta log in association with a unique transaction identifier. The disclosed techniques can include generating an MD stream for the MD pages containing bulk updates, and passing the MD stream to an MD pages tier of a tiered storage array. The disclosed techniques can include, in response to a predetermined event (e.g., high availability (HA) event, crash event), replaying the MD delta log to apply valid delta updates to at least one MD page containing bulk updates in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0005] In certain embodiments, a method includes, during performance of a first transaction commit operation by a storage node, writing raw delta updates to MD pages to a metadata (MD) delta log. At least some of the raw delta updates can correspond to bulk updates to a first MD page. The method includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID). The method includes generating an MD stream for at least the first MD page containing bulk updates, and passing the MD stream including at least the first MD page to an MD pages tier of a storage array. The first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page. The method includes, in response to a predetermined event (e.g., high availability event (HA), crash event), replaying the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0006] In certain arrangements, the method includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, the logical-to-physical address TT update for the first MD page, and a first specialized flag for the first MD page, in association with the first unique transaction ID. The first specialized flag provides an indication that all delta updates to the first MD page that occurred prior to the first MD page being stored in the MD pages tier are to be dropped or discarded.

[0007] In certain arrangements, the method includes, during the performance of the first transaction commit operation by the storage node, acquiring a first exclusive lock for the first MD page containing bulk updates.

[0008] In certain arrangements, the method includes synchronizing at least the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in association with the first unique transaction ID, in a volatile memory structure, and, in response to the synchronizing of the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page,

in the volatile memory structure, releasing the first exclusive lock for the first MD page containing bulk updates.

[0009] In certain arrangements, the method includes, during performance of a second transaction commit operation by the storage node, writing raw delta updates to MD pages to the MD delta log. At least some of the raw delta updates correspond to bulk updates to a second MD page. The method includes, for the second MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the second MD page, and a logical-to-physical address TT update for the second MD page, in association with a second unique transaction ID.

[0010] In certain arrangements, the method includes, during the performance of the second transaction commit operation by the storage node, acquiring a second exclusive lock for the second MD page containing bulk updates.

[0011] In certain arrangements, the method includes synchronizing at least the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in association with the second unique transaction ID, in a volatile memory structure, and, in response to the synchronizing of the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in the volatile memory structure, releasing the second exclusive lock for the second MD page containing bulk updates.

[0012] In certain arrangements, the method includes generating the MD stream for the first MD page and the second MD page, and passing the MD stream including the first MD page and the second MD page to the MD pages tier. The first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page, and the second MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the second MD page.

[0013] In certain arrangements, the method includes, for the second MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the second MD page, the logical-to-physical address TT update for the second MD page, and a second specialized flag for the second MD page, in association with the second unique transaction ID. The second specialized flag provides an indication that all delta updates to the second MD page that occurred prior to the second MD page being stored in the MD pages tier are to be dropped or discarded.

[0014] In certain arrangements, the first MD page corresponds to a first version of a respective MD page containing bulk updates, and the second MD page corresponds to a second version of the respective MD page containing bulk updates. The method includes replaying the MD delta log to apply the valid delta updates written thereto to at least the first version of the respective MD page stored in the MD pages tier.

[0015] In certain embodiments, a system includes a memory, and processing circuitry configured to execute program instructions out of the memory, during performance of a first transaction commit operation, to write raw delta updates to MD pages to a metadata (MD) delta log. At least some of the raw delta updates correspond to bulk updates to a first MD page. The processing circuitry is configured to execute the program instructions out of the memory, for the first MD page containing bulk updates, to write, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID), to generate an MD stream for at least the first MD page containing bulk updates, and to pass the MD stream including at least the first MD page to an MD pages tier of a storage array. The first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page. The processing circuitry is configured to execute the program instructions out of the memory, in response to a predetermined event (e.g., high availability (HA) event, crash event), to replay the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0016] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory, for the first MD page containing bulk updates, to write, to the MD delta log, the bulk updates to the first MD page, the logical-to-physical address TT update for the first MD page, and a first specialized flag for the first MD page, in association with the first unique transaction ID. The first specialized flag provides an indication that all delta updates to the first MD page that occurred prior to the first MD page being stored in the MD pages tier are to be dropped or discarded.

[0017] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory, during the performance of the first transaction commit operation, to acquire a first exclusive lock for the first MD page containing bulk updates.

[0018] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory to synchronize at least the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in association with the first unique transaction ID, in a volatile memory structure, and, in response to synchronizing the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in the volatile memory structure, release the first exclusive lock for the first MD page containing bulk updates.

[0019] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory, during performance of a second transaction commit operation, to write raw delta updates to MD pages to the MD delta log. At least some of the raw delta updates correspond to bulk updates to a second MD page. The processing circuitry is configured to execute the program instructions out of the memory, for the second MD page containing bulk updates, to write, to the MD delta log, the bulk updates to the second MD page, and a logical-to-physical address TT update for the second MD page, in association with a second unique transaction ID.

[0020] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory, during the performance of the second transaction commit operation, to acquire a second exclusive lock for the second MD page containing bulk updates.

[0021] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory to synchronize at least the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in association with the second unique transaction ID, in a volatile memory structure, and, in response to synchronizing the bulk updates to

the second MD page, and the logical-to-physical address TT update for the second MD page, in the volatile memory structure, release the second exclusive lock for the second MD page containing bulk updates.

[0022] In certain arrangements, the processing circuitry is configured to execute the program instructions out of the memory to generate the MD stream for the first MD page and the second MD page, and to pass the MD stream including the first MD page and the second MD page to the MD pages tier. The first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page, and the second MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the second MD page.

[0023] In certain arrangements, the first MD page corresponds to a first version of a respective MD page containing bulk updates, and the second MD page corresponds to a second version of the respective MD page containing bulk updates. The processing circuitry is configured to execute the program instructions out of the memory to replay the MD delta log to apply the valid delta updates written thereto to at least the first version of the respective MD page stored in the MD pages tier.

[0024] In certain embodiments, a computer program product includes a set of non-transitory, computer-readable media having instructions that, when executed by processing circuitry of a storage node in a clustered system, cause the processing circuitry to perform a method including, during performance of a first transaction commit operation by the storage node, writing raw delta updates to MD pages to a metadata (MD) delta log. At least some of the raw delta updates correspond to bulk updates to a first MD page. The method includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID), generating an MD stream for at least the first MD page containing bulk updates, and passing the MD stream including at least the first MD page to an MD pages tier of a storage array. The first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page. The method includes, in response to a predetermined event (e.g., high availability (HA) event, crash event), replaying the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0025] Other features, functions, and aspects of the present disclosure will be evident from the Detailed Description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The foregoing and other objects, features, and advantages will be apparent from the following description of particular embodiments of the present disclosure, as illustrated in the accompanying drawings, in which like reference characters refer to the same parts throughout the different views.

[0027] FIG. **1** is a block diagram of an exemplary storage environment, in which techniques can be practiced for handling mixed metadata (MD) updates (e.g., small updates, bulk updates) in a storage node using an MD delta log and log structured MD;

[0028] FIG. **2** is a block diagram of exemplary logical layers of MD pages, which can be maintained by a storage node in the storage environment of FIG. **1**;

[0029] FIG. **3** is a block diagram of volatile memory components, persistent memory components, and MD storage components of the storage node of FIG. **2**;

[0030] FIG. **4** is an exemplary logical-to-physical address translation table (TT) containing TT updates for several versions of MD pages containing bulk updates; and

[0031] FIG. **4** is a flow diagram of an exemplary method of handling mixed MD updates in a storage node using an MD delta log and log structured MD.

DETAILED DESCRIPTION

[0032] Improved techniques are disclosed herein for handling mixed metadata (MD) updates (e.g., small updates, bulk updates) in a storage node using an MD delta log and log structured MD. The disclosed techniques can include, while performing a transaction commit operation, writing, to an MD delta log, raw delta updates to MD pages, logical-to-physical address translation table (TT) updates for respective MD pages containing bulk updates, and specialized "drop-delta" (DD) flags for the respective MD pages containing bulk updates. For each MD page containing bulk updates, raw delta updates, a TT update, and a DD flag are written to the MD delta log in association with a unique transaction identifier. The disclosed techniques can include generating an MD stream for the MD pages containing bulk updates, and passing the MD stream to an MD pages tier of a tiered storage array. The disclosed techniques can include, in response to a predetermined event (e.g., high availability (HA) event, crash event), replaying the MD delta log to apply valid delta updates to at least one MD page containing bulk updates in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0033] FIG. **1** depicts an illustrative embodiment of an exemplary storage environment **100**, in which techniques can be practiced for handling mixed MD updates (e.g., small updates, bulk updates) in a storage node using an MD delta log and log structured MD. As shown in FIG. **1**, the storage environment **100** can include a plurality of storage client computers ("storage clients") **102.1**, **102.2**, . . . , **102.***n*, a plurality of storage processors ("storage nodes") **104**, and a tiered storage array **106**, as well as a communications medium **103** that includes at least one network **108**. Each storage client **102.1**, . . . , **102.***n* can be configured to provide, over the network(s) **108**, storage input/output (IO) requests (e.g., small computer system interface (SCSI) commands, network file system (NFS) commands) to a storage node **104**. Such storage IO requests (e.g., write requests, read requests) can direct the storage node **104** to write and/or read user data and/or MD pages, blocks, files, or any other suitable storage elements to/from volumes (VOLs), virtual volumes (VVOLs) (e.g., VMware® VVOLs), logical units (LUs), filesystems, directories, or any other suitable storage objects maintained on storage devices (e.g., hard disk drives (HDDs), solid state drives (SSDs), flash drives) in the tiered storage array **106**.

[0034] The communications medium **103** can be configured to interconnect the plurality of storage clients **102.1**, . . . , **102.***n* with the storage node **104** to enable them to communicate and exchange user data, MD, and/or control signaling. As shown in FIG. **1**, the communications medium **103** can be illustrated as a "cloud" to represent different

network topologies, such as a storage area network (SAN) topology, a network attached storage (NAS) topology, a local area network (LAN) topology, a metropolitan area network (MAN) topology, a wide area network (WAN) topology, and so on. As such, the communications medium **103** can include copper-based communications devices and cabling, fiber optic devices and cabling, wireless devices, and so on, or any suitable combination thereof.

[0035] The storage node **104** can be communicably connected directly to the tiered storage array **106**, or through an optional network infrastructure **110**, which can include an Ethernet (e.g., layer **2** or layer **3**) network, an InfiniBand network, a fiber channel network, and/or any other suitable network. As shown in FIG. **1**, the storage node **104** can include a communications interface **112**, processing circuitry **114**, and a memory **116**. The communications interface **112** can include an Ethernet interface, an InfiniBand interface, a fiber channel interface, or any other suitable communications interface. The communications interface **112** can further include SCSI target adapters, network interface adapters, or any other suitable adapters for converting electronic, optical, or wireless signals received over the network(s) **108** to a form suitable for use by the processing circuitry **114**. The processing circuitry **114** (e.g., central processing unit (CPU)) can include a set of processing cores (e.g., CPU cores) configured to execute specialized code and data as program instructions out of the memory **116**, process storage IO requests (e.g., write requests, read requests) issued by the storage clients **102.1**, . . . , **102.***n*, and store user data and/or MD to the storage devices in the tiered storage array **106** within the storage environment **100**, which can be a redundant array of independent disks (RAID) environment. In one embodiment, the tiered storage array **106** can include an MD pages tier **134** (e.g., a "fast" tier) containing a plurality of SSDs **138**, and a parity RAID tier **136** (e.g., a "slow" tier) containing a plurality of HDDs **140**.

[0036] The memory **116** can include volatile memory **118**, such as a random access memory (RAM) or any other suitable volatile memory, and nonvolatile memory **120**, such as a nonvolatile RAM (NVRAM), nonvolatile dual in-line memory module (NVDIMM), SSD, or any other suitable nonvolatile memory. As shown in FIG. **1**, the RAM **118** can include volatile memory structures **124**, and the NVRAM **120** can include an MD delta log **126**. In one embodiment, the volatile memory structures **124** can store, at least temporarily, transaction records of MD specified by write requests issued by the storage clients **102.1**, . . . , **102.***n*. Further, the MD delta log **126** can store and persist, at least temporarily, MD specified by such write requests, which can be de-staged, flushed, passed, or otherwise transferred (e.g., in the background) to storage objects (e.g., VOLs) maintained on storage devices (e.g., SSDs) of the MD pages tier **134**, as well as maintained on storage devices (e.g., HDDs) of the parity RAID tier **136**. The memory **116** can accommodate an operating system (OS) **122**, such as a Linux OS, Unix OS, Windows OS, or any other suitable OS, as well as specialized software modules including a logical-to-physical address translation table (TT) manager **128** for managing updates to a TT **132** ("TT updates"), and an MD stream generator **130** for generating MD streams of MD pages containing bulk updates.

[0037] In the context of the processing circuitry **114** being implemented by a set of CPU cores executing specialized code and data as program instructions out of the memory **116**, a computer program product can be configured to deliver all or a portion of the specialized code and data to the respective CPU cores. Such a computer program product can include one or more non-transient computer-readable storage media, such as a magnetic disk, magnetic tape, compact disk (CD), digital versatile disk (DVD), optical disk, flash drive, SSD, secure digital (SD) chip or device, application specific integrated circuit (ASIC), field programmable gate array (FPGA), and so on. Further, the non-transient computer-readable storage media can be encoded with sets of program instructions for performing, when executed by the respective CPU cores, the various techniques and/or methods disclosed herein.

[0038] FIG. **2** depicts exemplary logical layers **200** of MD pages, which can be maintained by the storage node **104** in the storage environment **100** of FIG. **1**. It is noted that any other suitable logical layer structure can be maintained by the storage node **104**, using the techniques and/or methods disclosed herein. As shown in FIG. **2**, the logical layers **200** can include a first MD layer **202**, a second MD layer **204**, and a third MD layer **206**. The first MD layer **202** can include at least one first layer MD page **208**. Further, the second MD layer **204** can include at least one second layer MD page **210**, and the third MD layer **206** can include at least one third layer MD page **212**. It is noted that the first MD layer **202**, the second MD layer **204**, and the third MD layer **206** are depicted in FIG. **2** as containing MD "pages" for purposes of illustration, and that any other suitable storage elements may be employed.

[0039] As shown in FIG. **2**, the first layer MD page **208** can include a plurality of entries **214.1**, **214.2**, . . . , **214.***p*. Further, the second layer MD page **210** can include a plurality of entries **216.1**, **216.2**, . . . , **216.***q*, and the third layer MD page **212** can include a plurality of entries **218.1**, **218.2**, . . . , **218.***r*. The plurality of entries **214.1**, **214.2**, . . . , **214.***p* included in the first layer MD page **208** can map and/or point to at least some of the plurality of entries **216.1**, **216.2**, . . . , **216.***q* of the second layer MD page **210**. For example, the first MD layer **202** may represent various ranges of logical block addresses (LBAs), and each of the plurality of entries **214.1**, **214.2**, . . . , **214.***p* of the first layer MD page **208** may be associated with a particular LBA range. In one embodiment, the first MD layer **202** can be organized as a "tree" data structure (e.g., b-tree), in which each "leaf" of the tree corresponds to a particular LBA range. As a result, the first layer MD page **208** can maintain a particular LBA mapping to the second layer MD page **210**.

[0040] The plurality of entries **216.1**, **216.2**, . . . , **216.***q* included in the second layer MD page **210** can map and/or point to at least some of the plurality of entries **218.1**, **218.2**, . . . , **218.***r* of the third layer MD page(s) **212**. In one embodiment, the second MD layer **204** can be configured to isolate logical address locations of MD pages in the first MD layer **202** from actual physical address locations of the MD pages. As such, the second layer MD page **210** can encapsulate a physical address location of an MD page to allow for its relocation without having to update the first layer MD page **208**. In this way, the second MD layer **204** can decouple the LBA space from the physical address space.

[0041] The plurality of entries **218.1**, **218.2**, . . . , **218.***q* included in the third layer MD page **212** can store MD pages. For example, the third MD layer **206** may describe actual physical address locations of the MD pages in the tiered storage array **106**. In one embodiment, each third layer MD

page (e.g., the third layer MD page **212**) can correspond to an MD page having a specified amount of storage capacity (e.g., 4 kilobytes (KB), 8 KB), such as an MD page containing bulk updates. Such MD pages, which may be highly or completely amortized, can be stored in the MD pages tier **134** in the tiered storage array **106**, using the techniques and/or methods described herein.

[0042] During operation, the storage node **104** can use the volatile memory structures **124** to store and/or aggregate delta updates to MD pages. Further, the storage node **104** can use the TT **132** to map a logical address space to the physical address space of the MD pages tier **134**, and to track, within the MD pages tier **134**, physical address locations of one or more MD pages containing bulk updates. In addition, the storage node **104** can use the MD delta log **126** to log (i) all "raw" delta updates to MD pages, (ii) logical-to-physical address updates to the TT **132** ("TT updates"), and (iii) a specialized "drop-delta" (DD) flag for each MD page containing bulk updates. The DD flag for each MD page containing bulk updates can provide an indication that all delta updates to the MD page that occurred before it was stored in the MD pages tier **134** are no longer valid and should be dropped or discarded. For each MD page containing bulk updates, the MD delta log **126** can maintain raw delta updates, a TT update, and a DD flag, atomically within the scope of a transaction.

[0043] While performing a transaction commit operation, the storage node **104** can write, to the MD delta log **126**, raw delta updates to MD pages, TT updates for respective versions of MD pages containing bulk updates, and DD flags for the respective versions of MD pages containing bulk updates. For each MD page containing bulk updates, raw delta updates, a TT update, and a DD flag can be written to the MD delta log **126** in association with a unique transaction identifier (e.g., sequence identifier or "SeqId"). The storage node **104** can generate an MD stream for the MD pages containing bulk updates, and pass the MD stream to the MD pages tier **134** in the tiered storage array **106**. The storage node **104**, in response to a predetermined event (e.g., high availability (HA) event, crash event), can replay the MD delta log **126** to apply valid delta updates to at least one of the MD pages containing bulk updates in the MD pages tier **134**, thereby recovering the MD pages tier **134** to a consistent state.

[0044] The disclosed techniques for handling mixed MD updates (e.g., small updates, bulk updates) in a storage node using an MD delta log and log structured MD will be further understood with reference to the following illustrative example and FIG. **3**. FIG. **3** depicts several exemplary components of the storage node **104**, namely, the RAM **118**, the NVRAM **120**, and the MD stream generator **130**, as well as the tiered storage array **106** including the MD pages tier **134**. As shown in FIG. **3**, the RAM **118** can include the volatile memory structures **124**, which can include a bloom filter **310**, a transaction cache ("TxCache") **312**, and a set of active hash-based sorted buckets (HBSBs) **314**. The HBSBs **314** can include a set of data containers H_1, H_2, H_3, . . . , H_N for storing delta updates to MD pages. In one embodiment, each of the data containers H_1, . . . , H_N can be configured as a tree data structure (e.g., b-tree). The storage node **104** can use the bloom filter **310** to quickly determine whether or not delta updates for particular MD pages are contained in any of the data containers H_1, . . . , H_N of the HBSBs **314**.

[0045] As shown in FIG. **3**, the NVRAM **120** can include the MD delta log **126**, which can store a plurality of transaction commit entries, C_{k-2}, C_{k-1}, C_k, C_0, each of which can include one or more raw delta updates, a TT update, and a DD flag (generally illustrated at reference numeral **328**) within the scope of a transaction. In one embodiment, the MD delta log **126** can be configured as a ring buffer, in which transaction commit entries (e.g., C_{k-2}, C_{k-1}, C_k) can be added to the "head" of the ring buffer, and transaction commit entries (e.g., C_0) can be released from the "tail" of the ring buffer. Each of the transaction commit entries, C_{k-2}, C_{k-1}, C_k, C_0 (such as the transaction commit entry, C_k), can include a header **326** containing at least a transaction ID ("SeqId"), and a footer **330** containing at least the SeqId and a cyclic redundancy code or checksum ("CRC") value.

[0046] In this example, the storage node **104** performs transaction commit operations to commit, in respective MD transactions **302**, MD pages **304** (e.g., Li_1, Li_2, . . . , Li_N) containing bulk updates to storage in the MD pages tier **134**. In this example, the MD pages, Li_1, Li_2, correspond to two versions, Ver. 1, Ver. 2, respectively, of the same MD page containing bulk updates. In a first transaction commit operation, the storage node **104** executes a first transaction commit thread to acquire an exclusive lock for the first version, Li_1 (Ver. 1), of the MD page, and to write or persist the transaction commit entry, C_{k-2}, to the MD delta log **126** (as illustrated by an arrow **318**). In this example, the transaction commit entry, C_{k-2}, includes, for the first version, Li_1 (Ver. 1), of the MD page, one or more raw delta updates, a DD flag, X, and a TT update (generally illustrated at reference numeral **306**). The storage node **104** further executes the first transaction commit thread to update the header of the transaction commit entry, C_{k-2}, to include a corresponding SeqId, and to update the footer of the transaction commit entry, C_{k-2}, to include the corresponding SeqId as well as a CRC value. It is noted that, while building an up-to-date MD page, e.g., during a cache miss or de-stage operation, the DD flag, X, can provide an indication that all delta updates that occurred before the writing of the MD page are no longer valid and should be dropped or discarded.

[0047] FIG. **4** depicts the logical-to-physical address translation table (TT) **132**, which contains TT updates for at least the two versions, Li_1 (Ver. 1), Li_2 (Ver. 2), of the MD page containing bulk updates. As described herein, the storage node **104** can use the TT **132** to map a logical address space to the physical address space of the MD pages tier **134**. As a result, MD pages in the physical address space of the MD pages tier **134** can be moved without having to update any logical address references associated with the MD pages. In this example, the storage node **104** uses the TT **132** to map a logical address, logical_addr_0 **410**A, to a physical address, physical_addr_1 **412**A, of the first version, Li_1 (Ver. 1), of the MD page containing bulk updates.

[0048] Having written or persisted the transaction commit entry, C_{k-2}, to the MD delta log **126**, the storage node **104** executes the first transaction commit thread to update or synchronize, in the volatile memory structures **124** (as illustrated by an arrow **320**), the raw delta updates, the TT update, and the DD flag, X, included in the transaction commit entry, C_{k-2}. In one embodiment, such updates can be converted into an MD update "tuple" including multiple tuple entries, such as (i) a logical index, Li, of a corresponding MD page, (ii) an offset, Ei, within the MD page, (iii) a record or delta type, T, defining the size of the update, and

(iv) a payload or value, V, of the update. Further, the designations, H_1, H_2, and so on, of the data containers of the active HBSBs **314** can correspond to hash values, which can be obtained by applying a hash function to the logical indices, Li_1, Li_2, and so on, of the MD pages. In this way, the data container, H_1, of the HBSBs **314** can be associated with the first version, Li_1 (Ver. 1), of the MD page, based on the hash of the logical index, Li_1, of the MD page. Once the raw delta updates, the TT update, and the DD flag, X, included in the transaction commit entry, C_{k-2}, are updated or synchronized in the volatile memory structures **124**, the exclusive lock for the first version, Li_1 (Ver. 1), of the MD page is released.

[0049] In this example, in a second transaction commit operation, the storage node **104** executes a second transaction commit thread to acquire an exclusive lock for the second (or subsequent) version, Li_2 (Ver. 2), of the MD page, and to write or persist the transaction commit entry, C_{k-1}, to the MD delta log **126** (as illustrated by an arrow **318**). The transaction commit entry, C_{k-1}, includes, for the second version, Li_2 (Ver. 2), of the MD page, one or more raw delta updates, a DD flag, X, and a TT update (generally illustrated at reference numeral **306**). The storage node **104** executes the second transaction commit thread to update the header of the transaction commit entry, C_{k-1}, to include a corresponding SeqId, and to update the footer of the transaction commit entry, C_{k-1}, to include the corresponding SeqId as well as a CRC value. Further, the storage node **104** uses the TT **132** to map a logical address, logical_addr_0 **410**B (see FIG. **4**), to a physical address, physical_addr_1 **412**B (see FIG. **4**), of the second version, Li_2 (Ver. 2), of the MD page containing bulk updates.

[0050] Having written or persisted the transaction commit entry, C_{k-1}, to the MD delta log **126**, the storage node **104** executes the second transaction commit thread to update or synchronize, in the volatile memory structures **124** (as illustrated by an arrow **320**), the raw delta updates, the TT update, and the DD flag, X, included in the transaction commit entry, C_{k-1}. As described herein with reference to the first transaction commit thread, such updates performed while executing the second transaction commit thread can be converted into an MD update "tuple" including multiple tuple entries (e.g., Li, Ei, T, V). Further, the designations, H_1, H_2, and so on, of the data containers of the HBSBs **314** can correspond to hash values, which can be obtained by applying a hash function to the logical indices, Li_1, Li_2, and so on, of the MD pages. In this way, the data container, H_2, of the HBSBs **314** can be associated with the second version, Li_2 (Ver. 2), of the MD page, based on the hash of the logical index, Li_2, of the MD page. Once the raw delta updates, the TT update, and the DD flag, X, included in the transaction commit entry, C_{k-1}, are updated or synchronized in the volatile memory structures **124**, the exclusive lock for the second version, Li_2 (Ver. 2), of the MD page is released. It is noted that the storage node **104** can perform additional transaction commit operations, like the first and second transaction commit operations described herein, for each of the MD pages **304** (e.g., Li_1, Li_2, . . . , Li_N) containing bulk updates.

[0051] Having written or persisted the transaction commit entries, C_{k-2}, C_{k-1}, to the MD delta log **126**, and updated or synchronized the raw delta updates, TT updates, and DD flags, X, included in the transaction commit entries, C_{k-2}, C_{k-1}, in the volatile memory structures **124**, the storage node **104** uses the MD stream generator **130** to generate an MD stream containing at least the first version, Li_1 (Ver. 1), of the MD page, and the second version, Li_2 (Ver. 2), of the MD page. In one embodiment, the MD stream generator **130** stores multiple versions of MD pages containing bulk updates (e.g., Li_1 (Ver. 1), Li_2 (Ver. 2), and so on) in a contiguous chunk of MD (e.g., 2 megabyte (MB)), which is referred to herein as a "stripe" (e.g., RAID stripe) or "physical large block" (PLB). Once the PLB (e.g., 2 MB chunk) is full, the MD stream generator **130** passes it in the MD stream to the MD pages tier **134** (as illustrated by an arrow **322**) for storage on the SSD **138** (see FIG. **3**), in accordance with the TT updates. Because the MD stream containing at least the first and second versions, Li_1 (Ver. 1), Li_2 (Ver. 2), of the MD page is passed in the MD stream to the MD pages tier **134**, while bypassing the volatile memory structures **124** and the MD delta log **126**, unwanted overloading of the delta log infrastructure can be avoided, thereby increasing the delta log infrastructure's efficiency.

[0052] It is noted that a version history of the MD pages (e.g., Li_1 (Ver. 1), Li_2 (Ver. 2)) can be stored to the MD pages tier **134**, and/or one or more of the MD pages (e.g., Li_1 (Ver. 1), Li_2 (Ver. 2)) can be stored ("de-staged") to the parity RAID tier **136**. It is further noted that the storage node **104**, in response to a predetermined event (e.g., high availability (HA) event, crash event), can replay the MD delta log **126** to apply valid delta updates to at least the first version, Li_1 (Ver. 1), of the MD page stored to the MD pages tier **134**, thereby recovering at least the most recent second version, Li_2 (Ver. 2), of the MD page.

[0053] An exemplary method of handling mixed MD updates in a storage node using an MD delta log and log structured MD is described below with reference to FIG. **5**. As depicted in block **502**, while performing a transaction commit operation, raw delta updates to MD pages, TT updates for respective MD pages containing bulk updates, and DD flags for the respective MD pages containing bulk updates, are written to an MD delta log, in which, for each MD page containing bulk updates, raw delta updates, a TT update, and a DD flag, are written to the MD delta log in association with a unique transaction identifier. As depicted in block **504**, an MD stream for the MD pages containing bulk updates is generated. As depicted in block **506**, the MD stream is passed to an MD pages tier of a tiered storage array. As depicted in block **508**, in response to a predetermined event (e.g., high availability (HA) event, crash event), the MD delta log is replayed to apply valid delta updates to at least one MD page containing bulk updates in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

[0054] Several definitions of terms are provided below for the purpose of aiding the understanding of the foregoing description, as well as the claims set forth herein.

[0055] As employed herein, the term "storage system" is intended to be broadly construed to encompass, for example, private or public cloud computing systems for storing data, as well as systems for storing data comprising virtual infrastructure and those not comprising virtual infrastructure.

[0056] As employed herein, the terms "client," "host," and "user" refer, interchangeably, to any person, system, or other entity that uses a storage system to read/write data.

[0057] As employed herein, the term "storage device" may refer to a storage array including multiple storage

devices. Such a storage device may refer to any non-volatile memory (NVM) device, including hard disk drives (HDDs), solid state drives (SSDs), flash devices (e.g., NAND flash devices, NOR flash devices), and/or similar devices that may be accessed locally and/or remotely, such as via a storage area network (SAN).

[0058] As employed herein, the term "storage array" may refer to a storage system used for block-based, file-based, or other object-based storage. Such a storage array may include, for example, dedicated storage hardware containing HDDs, SSDs, and/or all-flash drives.

[0059] As employed herein, the term "storage entity" may refer to a filesystem, an object storage, a virtualized device, a logical unit (LUN), a logical volume (LV), a logical device, a physical device, and/or a storage medium.

[0060] As employed herein, the term "LUN" may refer to a logical entity provided by a storage system for accessing data from the storage system and may be used interchangeably with a logical volume (LV). The term "LUN" may also refer to a logical unit number for identifying a logical unit, a virtual disk, or a virtual LUN.

[0061] As employed herein, the term "physical storage unit" may refer to a physical entity such as a storage drive or disk or an array of storage drives or disks for storing data in storage locations accessible at addresses. The term "physical storage unit" may be used interchangeably with the term "physical volume."

[0062] As employed herein, the term "storage medium" may refer to a hard drive or flash storage, a combination of hard drives and flash storage, a combination of hard drives, flash storage, and other storage drives or devices, or any other suitable types and/or combinations of computer readable storage media. Such a storage medium may include physical and logical storage media, multiple levels of virtual-to-physical mappings, and/or disk images. The term "storage medium" may also refer to a computer-readable program medium.

[0063] As employed herein, the term "IO request" or "IO" may refer to a data input or output request such as a read request or a write request.

[0064] As employed herein, the terms, "such as," "for example," "e.g.," "exemplary," and variants thereof refer to non-limiting embodiments and have meanings of serving as examples, instances, or illustrations. Any embodiments described herein using such phrases and/or variants are not necessarily to be construed as preferred or more advantageous over other embodiments, and/or to exclude incorporation of features from other embodiments.

[0065] As employed herein, the term "optionally" has a meaning that a feature, element, process, etc., may be provided in certain embodiments and may not be provided in certain other embodiments. Any particular embodiment of the present disclosure may include a plurality of optional features unless such features conflict with one another.

[0066] While various embodiments of the present disclosure have been particularly shown and described, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the present disclosure, as defined by the appended claims.

What is claimed is:

1. A method comprising:

during performance of a first transaction commit operation by a storage node:

writing raw delta updates to MD pages to a metadata (MD) delta log,

wherein at least some of the raw delta updates correspond to bulk updates to a first MD page, and

wherein the writing to the MD delta log includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID);

generating an MD stream for at least the first MD page containing bulk updates;

passing the MD stream including at least the first MD page to an MD pages tier of a storage array,

wherein the first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page; and

in response to a predetermined event, replaying the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

2. The method of claim **1** wherein the writing to the MD delta log includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, the logical-to-physical address TT update for the first MD page, and a first specialized flag for the first MD page, in association with the first unique transaction ID,

wherein the first specialized flag provides an indication that all delta updates to the first MD page that occurred prior to the first MD page being stored in the MD pages tier are to be dropped or discarded.

3. The method of claim **1** further comprising:

during the performance of the first transaction commit operation by the storage node:

acquiring a first exclusive lock for the first MD page containing bulk updates.

4. The method of claim **3** further comprising:

synchronizing at least the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in association with the first unique transaction ID, in a volatile memory structure; and

in response to the synchronizing of the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in the volatile memory structure, releasing the first exclusive lock for the first MD page containing bulk updates.

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

during performance of a second transaction commit operation by the storage node:

writing raw delta updates to MD pages to the MD delta log,

wherein at least some of the raw delta updates correspond to bulk updates to a second MD page, and

wherein the writing to the MD delta log includes, for the second MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the second MD page, and a logical-to-physical address TT update for the second MD page, in association with a second unique transaction ID.

6. The method of claim **5** further comprising:

during the performance of the second transaction commit operation by the storage node:

acquiring a second exclusive lock for the second MD page containing bulk updates.

7. The method of claim 6 further comprising:

synchronizing at least the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in association with the second unique transaction ID, in a volatile memory structure; and

in response to the synchronizing of the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in the volatile memory structure, releasing the second exclusive lock for the second MD page containing bulk updates.

8. The method of claim 5 wherein the generating of the MD stream includes generating the MD stream for the first MD page and the second MD page,

wherein the passing of the MD stream to the MD pages tier of the storage array includes passing the MD stream including the first MD page and the second MD page to the MD pages tier, and

wherein the first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page, and the second MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the second MD page.

9. The method of claim 8 wherein the writing to the MD delta log includes, for the second MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the second MD page, the logical-to-physical address TT update for the second MD page, and a second specialized flag for the second MD page, in association with the second unique transaction ID,

wherein the second specialized flag provides an indication that all delta updates to the second MD page that occurred prior to the second MD page being stored in the MD pages tier are to be dropped or discarded.

10. The method of claim 8 wherein the first MD page corresponds to a first version of a respective MD page containing bulk updates, and the second MD page corresponds to a second version of the respective MD page containing bulk updates, and

wherein the replaying of the MD delta log includes replaying the MD delta log to apply the valid delta updates written thereto to at least the first version of the respective MD page stored in the MD pages tier.

11. A system comprising:

a memory; and

processing circuitry configured to execute program instructions out of the memory to:

during performance of a first transaction commit operation:

write raw delta updates to MD pages to a metadata (MD) delta log,

wherein at least some of the raw delta updates correspond to bulk updates to a first MD page, and

wherein writing to the MD delta log includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID);

generate an MD stream for at least the first MD page containing bulk updates;

pass the MD stream including at least the first MD page to an MD pages tier of a storage array,

wherein the first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page; and

in response to a predetermined event, replay the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

12. The system of claim 11 wherein the processing circuitry is configured to execute the program instructions out of the memory, for the first MD page containing bulk updates, to write, to the MD delta log, the bulk updates to the first MD page, the logical-to-physical address TT update for the first MD page, and a first specialized flag for the first MD page, in association with the first unique transaction ID,

wherein the first specialized flag provides an indication that all delta updates to the first MD page that occurred prior to the first MD page being stored in the MD pages tier are to be dropped or discarded.

13. The system of claim 11 wherein the processing circuitry is configured to execute the program instructions out of the memory to:

during the performance of the first transaction commit operation:

acquire a first exclusive lock for the first MD page containing bulk updates.

14. The system of claim 13 wherein the processing circuitry is configured to execute the program instructions out of the memory to:

synchronize at least the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in association with the first unique transaction ID, in a volatile memory structure; and

in response to synchronizing the bulk updates to the first MD page, and the logical-to-physical address TT update for the first MD page, in the volatile memory structure, release the first exclusive lock for the first MD page containing bulk updates.

15. The system of claim 11 wherein the processing circuitry is configured to execute the program instructions out of the memory to:

during performance of a second transaction commit operation:

write raw delta updates to MD pages to the MD delta log,

wherein at least some of the raw delta updates correspond to bulk updates to a second MD page, and

wherein writing to the MD delta log includes, for the second MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the second MD page, and a logical-to-physical address TT update for the second MD page, in association with a second unique transaction ID.

16. The system of claim 15 wherein the processing circuitry is configured to execute the program instructions out of the memory to:

during the performance of the second transaction commit operation:

acquire a second exclusive lock for the second MD page containing bulk updates.

17. The system of claim **16** wherein the processing circuitry is configured to execute the program instructions out of the memory to:

synchronize at least the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in association with the second unique transaction ID, in a volatile memory structure; and

in response to synchronizing the bulk updates to the second MD page, and the logical-to-physical address TT update for the second MD page, in the volatile memory structure, release the second exclusive lock for the second MD page containing bulk updates.

18. The system of claim **15** wherein the processing circuitry is configured to execute the program instructions out of the memory to:

generate the MD stream for the first MD page and the second MD page; and

pass the MD stream including the first MD page and the second MD page to the MD pages tier,

wherein the first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page, and the second MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the second MD page.

19. The system of claim **18** wherein the first MD page corresponds to a first version of a respective MD page containing bulk updates, and the second MD page corresponds to a second version of the respective MD page containing bulk updates, and wherein the processing circuitry is configured to execute the program instructions out of the memory to replay the MD delta log to apply the valid delta updates written thereto to at least the first version of the respective MD page stored in the MD pages tier.

20. A computer program product including a set of non-transitory, computer-readable media having instructions that, when executed by processing circuitry of a storage node in a clustered system, cause the processing circuitry to perform a method comprising:

during performance of a first transaction commit operation by the storage node:

writing raw delta updates to MD pages to a metadata (MD) delta log,

wherein at least some of the raw delta updates correspond to bulk updates to a first MD page, and

wherein the writing to the MD delta log includes, for the first MD page containing bulk updates, writing, to the MD delta log, the bulk updates to the first MD page, and a logical-to-physical address translation table (TT) update for the first MD page, in association with a first unique transaction identifier (ID);

generating an MD stream for at least the first MD page containing bulk updates;

passing the MD stream including at least the first MD page to an MD pages tier of a storage array,

wherein the first MD page is stored in the MD pages tier in accordance with the logical-to-physical address TT update for the first MD page; and

in response to a predetermined event, replaying the MD delta log to apply valid delta updates written thereto to the first MD page stored in the MD pages tier, thereby recovering the MD pages tier to a consistent state.

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