US 20220129162A1

(19) United States
(12) Patent Application Publication
Faibish et al.
(10) Pub. No.: US 2022/0129162 A1
(43) Pub. Date: Apr. 28, 2022

(54) ADAPTIVE INLINE COMPRESSION

(71) Applicant: **EMC IP Holding Company LLC**, Hopkinton, MA (US)

(72) Inventors: **Sorin Faibish**, Newton, MA (US); **Ivan Bassov**, Brookline, MA (US); **Istvan Gonczi**, Berkley, MA (US); **Philippe Armangau**, Acton, MA (US); **Vamsi K. Vankamamidi**, Hopkinton, MA (US)

(21) Appl. No.: **17/082,800**

(22) Filed: **Oct. 28, 2020**

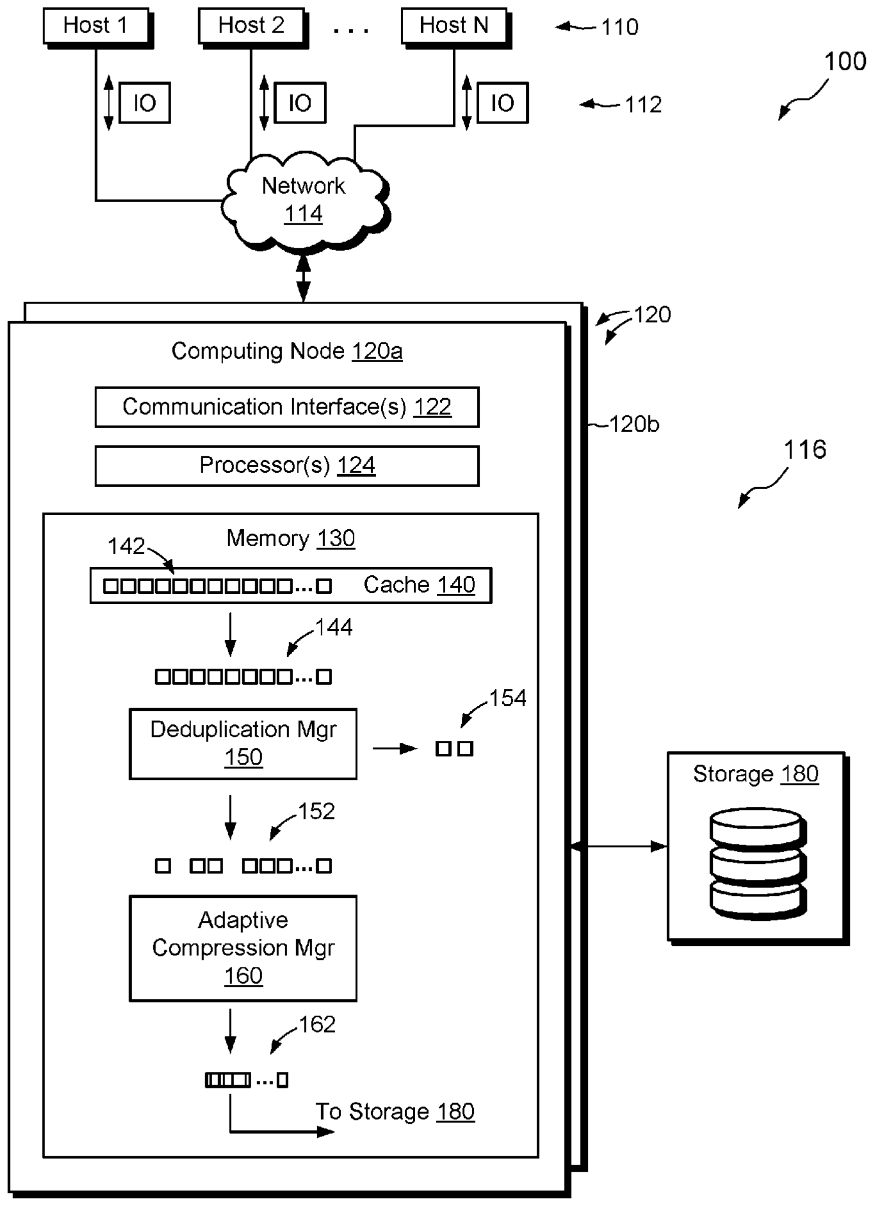
Publication Classification

(51) **Int. Cl.**
G06F 3/06 (2006.01)

(52) **U.S. Cl.**
CPC *G06F 3/0608* (2013.01); *G06F 3/067* (2013.01); *G06F 3/0653* (2013.01); *G06F 3/064* (2013.01)

(57) **ABSTRACT**

A technique for managing data storage includes generating entropy of blocks on a per-block basis and selectively performing inline compression on blocks based at least in part on their entropy. Entropy of a block provides a rough measure of the block's compressibility. Thus, using per-block entropy enables a storage system to steer compression decisions, e.g., whether to compress and/or how much to compress, flexibly and with high granularity, striking a balance between throughput and storage efficiency.



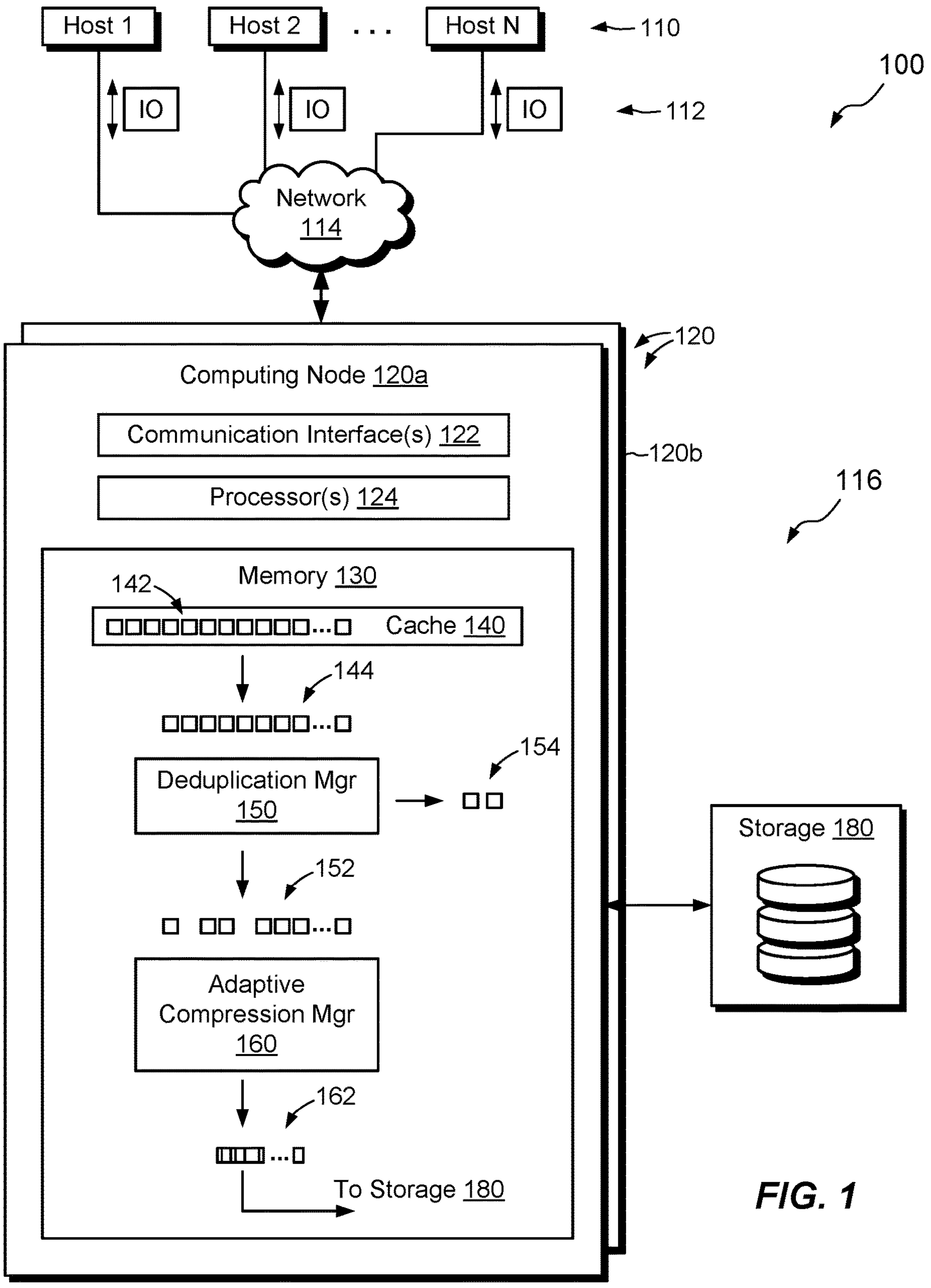

Host 1
Host 2
. . .
Host N
110
IO
IO
IO
112
100
Network 114
120
Computing Node 120a
Communication Interface(s) 122
Processor(s) 124
120b
116
Memory 130
142
Cache 140
144
154
Deduplication Mgr 150
152
Storage 180
Adaptive Compression Mgr 160
162
To Storage 180

FIG. 1

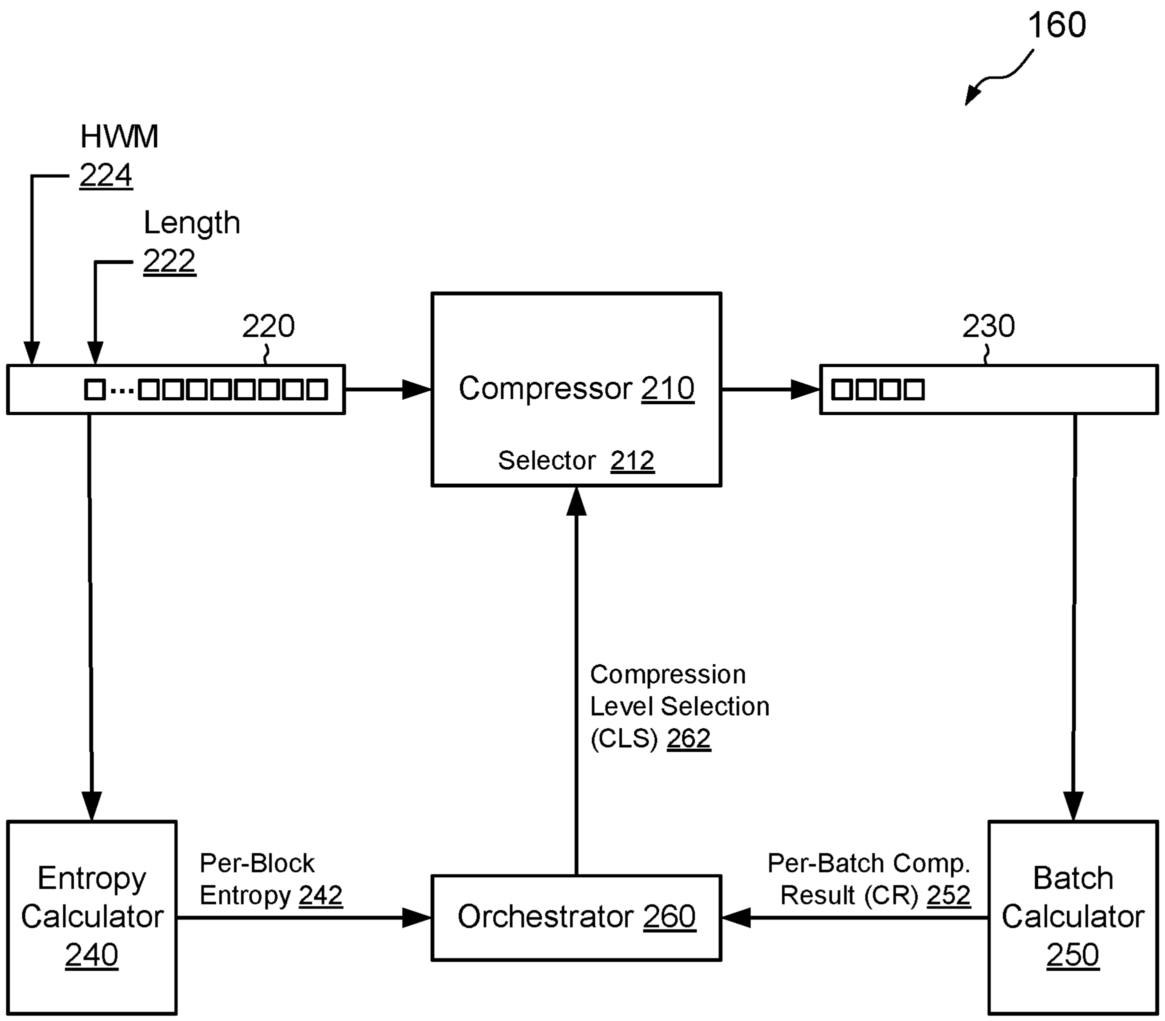

160
HWM 224
Length 222
220
Compressor 210
Selector 212
230
Compression Level Selection (CLS) 262
Entropy Calculator 240
Per-Block Entropy 242
Orchestrator 260
Per-Batch Comp. Result (CR) 252
Batch Calculator 250

FIG. 2

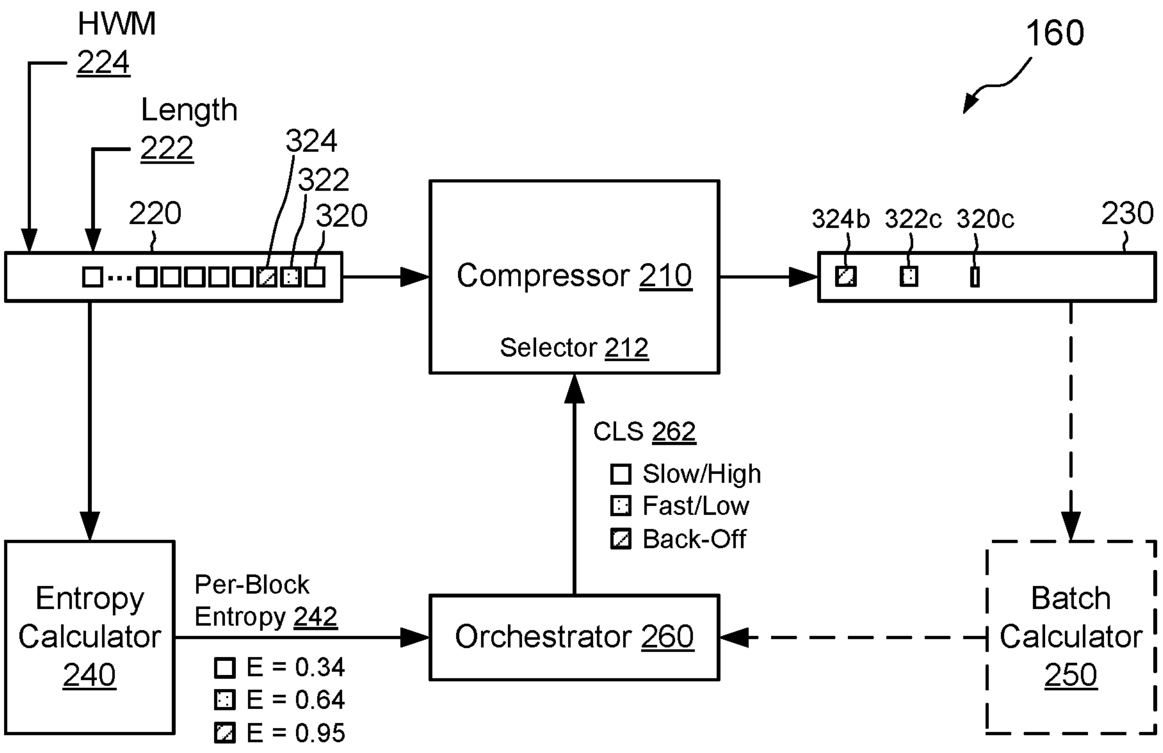

HWM 224
Length 222
220
324
322
320
Compressor 210
Selector 212
324b
322c
320c
230
160
CLS 262
Slow/High
Fast/Low
Back-Off
Entropy Calculator 240
Per-Block Entropy 242
E = 0.34
E = 0.64
E = 0.95
Orchestrator 260
Batch Calculator 250

FIG. 3A

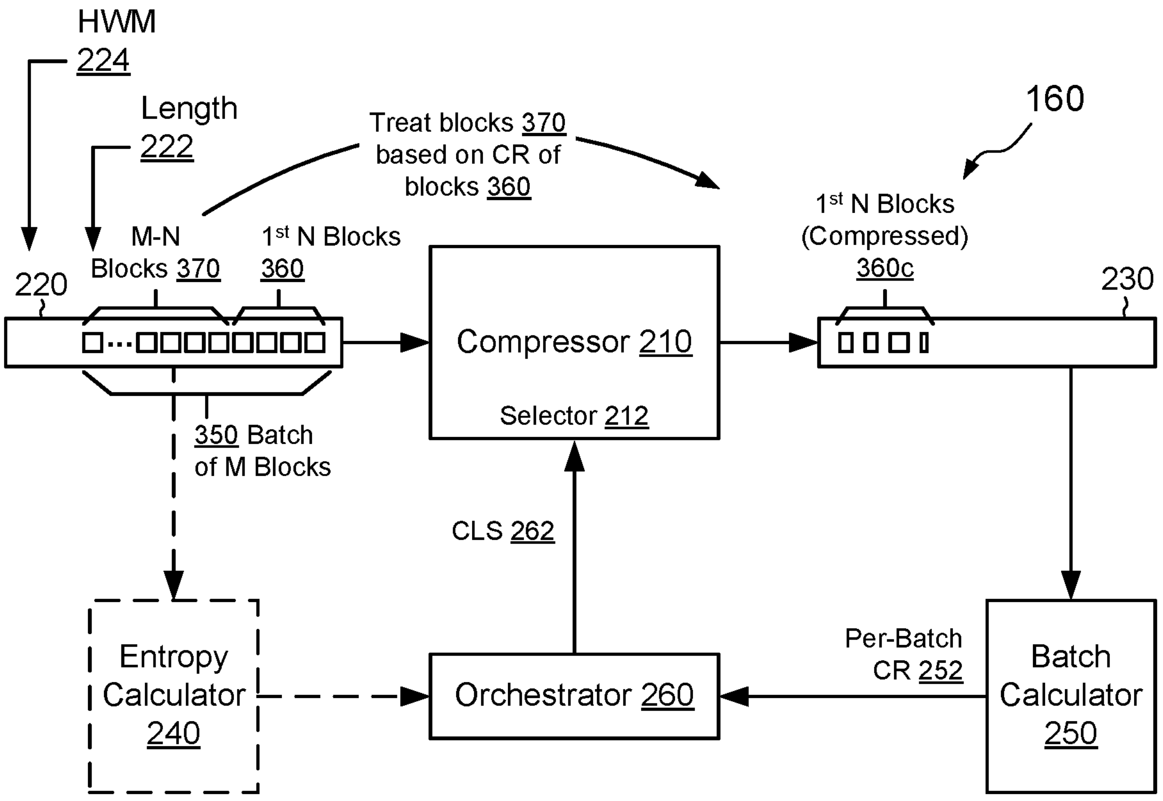

HWM 224
Length 222
Treat blocks 370 based on CR of blocks 360
160
M-N Blocks 370
1st N Blocks 360
220
1st N Blocks (Compressed) 360c
230
Compressor 210
Selector 212
350 Batch of M Blocks
CLS 262
Entropy Calculator 240
Orchestrator 260
Per-Batch CR 252
Batch Calculator 250

FIG. 3B

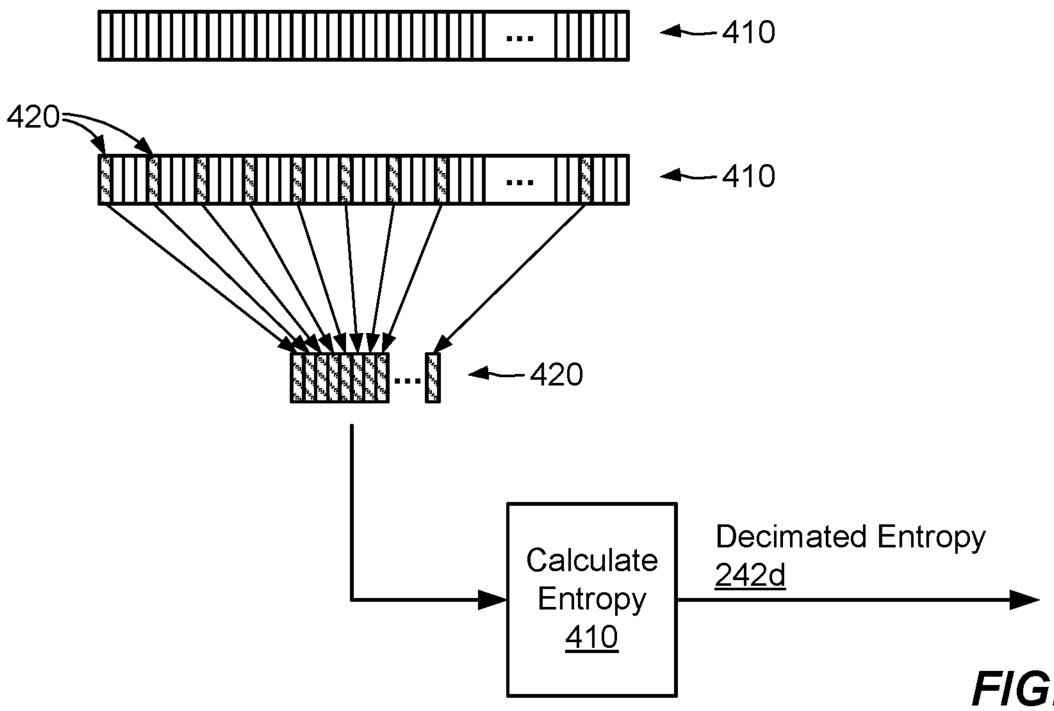

410
420
410
420
Calculate Entropy 410
Decimated Entropy 242d

FIG. 4

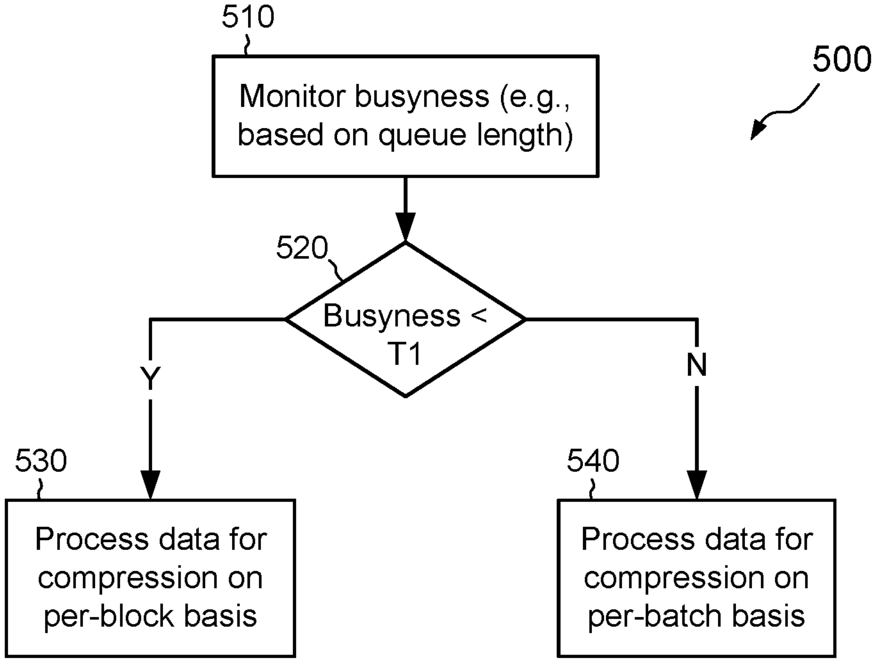

500
510
Monitor busyness (e.g., based on queue length)
520
Busyness < T1
Y
N
530
Process data for compression on per-block basis
540
Process data for compression on per-batch basis

FIG. 5

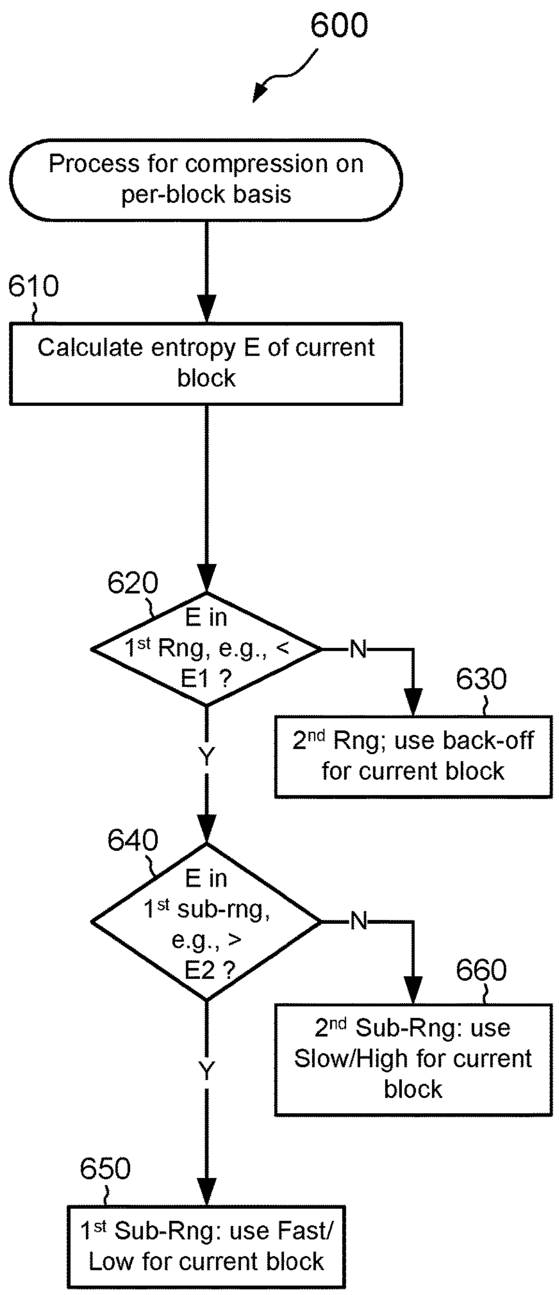

600
Process for compression on per-block basis
610
Calculate entropy E of current block
620
E in 1st Rng, e.g., < E1 ?
N
630
2nd Rng; use back-off for current block
Y
640
E in 1st sub-rng, e.g., > E2 ?
N
660
2nd Sub-Rng: use Slow/High for current block
Y
650
1st Sub-Rng: use Fast/ Low for current block

FIG. 6

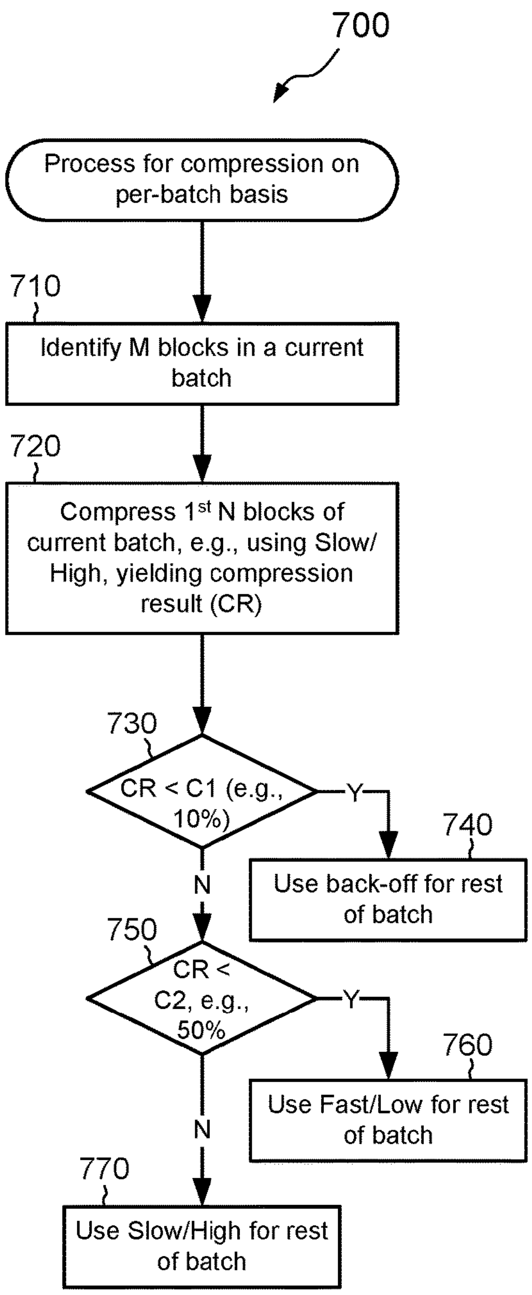

700
Process for compression on per-batch basis
710
Identify M blocks in a current batch
720
Compress 1st N blocks of current batch, e.g., using Slow/ High, yielding compression result (CR)
730
CR < C1 (e.g., 10%)
Y
740
Use back-off for rest of batch
N
750
CR < C2, e.g., 50%
Y
760
Use Fast/Low for rest of batch
N
770
Use Slow/High for rest of batch

FIG. 7

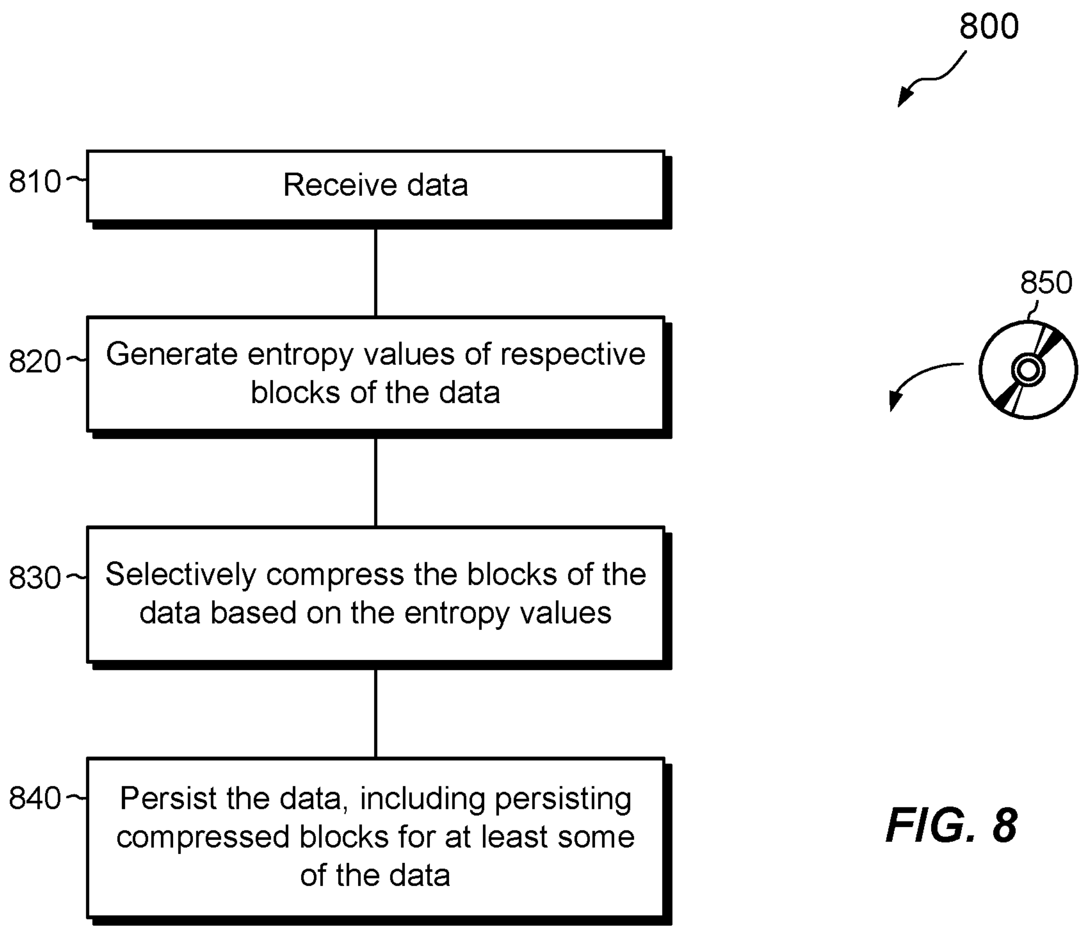

800
810
Receive data
820
Generate entropy values of respective blocks of the data
830
Selectively compress the blocks of the data based on the entropy values
840
Persist the data, including persisting compressed blocks for at least some of the data
850

FIG. 8

ADAPTIVE INLINE COMPRESSION

BACKGROUND

[0001] Data storage systems are arrangements of hardware and software in which storage processors are coupled to arrays of non-volatile storage devices, such as magnetic disk drives, electronic flash drives, and/or optical drives. The storage processors service storage requests, arriving from host machines ("hosts"), which specify blocks, files, and/or other data elements to be written, read, created, deleted, and so forth. Software running on the storage processors manages incoming storage requests and performs various data processing tasks to organize and secure the data elements on the non-volatile storage devices.

[0002] Some storage systems improve efficiency by compressing data inline with write requests. For example, a storage system receives a write request specifying data to be written. The storage system arranges the data into blocks and compresses the blocks prior to flushing them to disk. The first storage to disk of the newly-arriving data is thus in the form of compressed blocks. Later, when the system receives a read request to access the same data, the system reads the compressed blocks from disk, decompresses them, and returns the decompressed data to the requestor.

[0003] Some storage systems that support inline compression implement a back-off feature. Back-off temporarily shuts down inline compression when the systems get too busy. Inline compression can add greatly to the processing load of a storage system and can thus prevent the system from achieving desired throughput. Throughput is typically measured as latency (response time to input/output (I/O) requests) and/or IOPs (I/O's per second). A storage system may detect or predict a drop in throughput and invoke the back-off feature to correct or prevent the reduction in service. Back-off effectively shuts down inline compression, such that the storage system no longer compresses blocks and simply writes them to disk without compressing them.

SUMMARY

[0004] Unfortunately, known back-off features tend to operate in an all-or-none manner. Either no incoming blocks are compressed, when a system is too busy, or all of them are, when the system is not too busy. This all-or-none operation can result in many highly-compressible blocks remaining uncompressed. Although back-off helps to preserve throughput by stopping compression when systems get busy, it typically does so at the expense of storage efficiency, as many opportunities to compress data are lost. Customers increasingly demand both high throughput and high storage efficiency. Thus, a more flexible approach is needed.

[0005] In contrast with the above-described arrangement, in which back-off is implemented as an all-or-none feature, an improved technique for managing data storage includes generating entropy of blocks on a per-block basis and selectively performing inline compression on blocks based at least in part on their entropy. Entropy of a block can be computed inexpensively and provides a rough measure of the block's compressibility. Thus, using per-block entropy enables a storage system to steer compression decisions, e.g., whether to compress and/or how much to compress, flexibly and with high granularity, striking a balance between throughput and storage efficiency.

[0006] Certain embodiments are directed to a method of managing data storage. The method includes receiving data, generating entropy values of respective blocks of the data, selectively compressing the blocks of the data based on the entropy values, and persisting the data, including persisting compressed blocks for at least some of the data.

[0007] Other embodiments are directed to a computerized apparatus constructed and arranged to perform a method of managing data storage, such as the method described above. Still other embodiments are directed to a computer program product. The computer program product stores instructions which, when executed on control circuitry of a computerized apparatus, cause the computerized apparatus to perform a method of managing data storage, such as the method described above.

[0008] The foregoing summary is presented for illustrative purposes to assist the reader in readily grasping example features presented herein; however, this summary is not intended to set forth required elements or to limit embodiments hereof in any way. One should appreciate that the above-described features can be combined in any manner that makes technological sense, and that all such combinations are intended to be disclosed herein, regardless of whether such combinations are identified explicitly or not.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0009] The foregoing and other features and advantages will be apparent from the following description of particular embodiments, as illustrated in the accompanying drawings, in which like reference characters refer to the same or similar parts throughout the different views.

[0010] FIG. **1** is a block diagram of an example environment in which embodiments of the improved technique can be practiced.

[0011] FIG. **2** is a block diagram of an example adaptive compression manager of FIG. **1**.

[0012] FIGS. **3**A and **3**B are respective block diagrams showing the adaptive compression manager of FIG. **2** arranged for processing compression on a per-block basis (FIG. **3**A) and on a per-batch basis (FIG. **3**B).

[0013] FIG. **4** is a block diagram showing an example arrangement for calculating entropy using byte-based decimation.

[0014] FIG. **5** is a flowchart showing an example method of selectively performing data compression in the environment of FIG. **1**.

[0015] FIG. **6** is a flowchart showing an example method of performing compression on a per-block basis.

[0016] FIG. **7** is a flowchart showing an example method of performing compression on a per-batch basis.

[0017] FIG. **8** is a flowchart showing an example method of managing data storage in the environment of FIG. **1**.

DETAILED DESCRIPTION

[0018] Embodiments of the improved technique will now be described. One should appreciate that such embodiments are provided by way of example to illustrate certain features and principles of the disclosure but are not intended to be limiting.

[0019] An improved technique for managing data storage includes generating entropy of blocks on a per-block basis and selectively performing inline compression on blocks based at least in part on their entropy. Unlike prior back-off solutions, which can sacrifice data reduction to maintain high throughput, the improved technique can achieve a better balance between both. For example, highly compressible blocks can be compressed, promoting storage efficiency, while uncompressible blocks can be skipped, preserving high throughput. In some examples, a storage system supports multiple levels of compression, e.g., with a first level providing lower compression but executing faster, and a second level providing higher compression but executing more slowly. In some examples, entropy values steer not only decisions on whether to compress but also which level of compression to use. Such examples provide an even finer degree of granular control over the tradeoff between throughput and storage efficiency.

[0020] FIG. **1** shows an example environment **100** in which embodiments of the improved technique can be practiced. As shown, multiple hosts **110** are arranged to access a data storage appliance **116** over a network **114**. The data storage appliance **116** includes a computing node **120***a* (also referred to as a "node," "storage processor," or "SP") and storage **180**, such as magnetic disk drives, electronic flash drives, and/or the like. The data storage appliance **116** may include multiple nodes **120** (e.g., a second node **120***b*). Multiple nodes **120** may be provided as circuit board assemblies or blades, which plug into a chassis that encloses and cools the nodes **120**. The chassis has a backplane for interconnecting the nodes **120**, and additional connections may be made among nodes **120** using cables. In some examples, the appliance **116** is part of a storage cluster, such as one that contains any number of storage appliances **116**, where each appliance includes a pair of nodes **120** coupled to shared storage devices. In some arrangements, a host application runs directly on a node (or nodes), such that separate host machines **110** need not be present. No particular hardware configuration is required, and any number of nodes **120** may be provided, including a single node **120**, in any arrangement, and the node or nodes **120** can be any type of computing device capable of running software and processing host I/O's.

[0021] The network **114** may be any type of network or combination of networks, such as a storage area network (SAN), a local area network (LAN), a wide area network (WAN), the Internet, and/or some other type of network or combination of networks, for example. In cases where hosts **110** are provided, such hosts **110** may connect to the SP **120***a* using various technologies, such as Fibre Channel, iSCSI (Internet small computer system interface), NFS (network file system), and CIFS (common Internet file system), for example. As is known, Fibre Channel and iSCSI are block-based protocols, whereas NFS and CIFS are file-based protocols. Each node **120** is configured to receive I/O requests **112** according to block-based and/or file-based protocols and to respond to such I/O requests **112** by reading or writing the storage **180**.

[0022] As shown, the node **120***a* includes one or more communication interfaces **122**, a set of processors **124**, and memory **130**. The communication interfaces **122** include, for example, SCSI target adapters and/or network interface adapters for converting electronic and/or optical signals received over the network **114** to electronic form for use by the node **120***a*. The processor(s) **124** include one or more processing chips and/or assemblies, such as numerous multi-core CPUs (central processing units). The processor(s) **124** may further include one or more coprocessors, one example being the QAT (Quick Assist Technology) Adapter, available from Intel® Corporation of Santa Clara, Calif. The QAT provides hardware acceleration for data compression and decompression.

[0023] The memory **130** includes both volatile memory, e.g., RAM (Random Access Memory), and non-volatile memory, such as one or more ROMs (Read-Only Memories), disk drives, solid state drives, and the like. The processor(s) **124** and memory **130** together form control circuitry, which is constructed and arranged to carry out various methods and functions as described herein. Also, the memory **130** includes a variety of software constructs realized in the form of executable instructions. When the executable instructions are run by the processor(s) **124**, the processor(s) **124** carry out the operations of the software constructs. Although certain software constructs are specifically shown and described, it is understood that the memory **130** typically includes many other software components, which are not shown, such as an operating system, various applications, processes, and daemons.

[0024] As further shown in FIG. **1**, the memory **130** "includes," i.e., realizes by execution of software instructions, a cache **140**, a deduplication manager **150**, and an adaptive compression manager **160**. The cache **140** is configured to receive incoming data from hosts **110**, e.g., in response to write requests issued by applications running thereon, and to arrange the data in blocks **142**. A "block" is a storage extent that usually corresponds to a smallest addressable unit of storage space. Block sizes are typically uniform for any given storage system and can vary between storage systems, with typical block sizes being 4 kB (kilobytes) or 8 kB, for example. In some examples, the cache **140** is further configured to arrange blocks **142** based on LUN (Logical UNit) and/or based on logical address, such that logically contiguous blocks may be arranged in order.

[0025] The deduplication manager **150** is configured to perform inline deduplication. Such deduplication may proceed by computing digests (e.g., hash values) of blocks **142** and attempting to match the digests to those stored in a digest cache (not shown). A match of the digest of a new block to an entry in the digest cache identifies a block that has already been stored, and the deduplication manager **150** can effect storage of the new block by arranging pointers but without having to redundantly store of the matched block.

[0026] The adaptive compression manager **160** is configured to perform compression on blocks **142** selectively based on generated values of entropy. As is known, the "entropy" of a block provides a measure of the block's information content. Entropy may be expressed, for example, as a percentage that varies between 0% and 100%. A block with low entropy has low information content and high internal redundancy, whereas a block with high entropy has high information content and low internal redundancy. Given that data compression generally works by removing redundancy, the entropy of a block provides a good prediction of that block's compressibility. For instance, a low-entropy block tends to be highly compressible and a high-entropy block tends to be uncompressible, or nearly so. Computations of entropy are known in the art, but they typically involve floating-point arithmetic, which can be burdensome to processors and difficult to use in high-throughput applications.

[0027] Fortunately, an efficient technique has been developed for computing entropy without requiring floating-point arithmetic. An example of such a technique is disclosed in copending U.S. application Ser. No. 16/669,160, filed Oct. 30, 2019, the contents and teachings of which are incorporated herein by reference. In some examples, the adaptive compression manager **160** applies the efficient technique of the incorporated application for computing the entropy of blocks at low computational cost. The incorporated technique is not required, however, as it is still possible for embodiments to use less efficient techniques for computing entropy to great advantage.

[0028] In example operation, the hosts **110** issue I/O requests **112** to the data storage appliance **116**. Node **120***a* receives the I/O requests **112** at the communication interface(s) **122** and initiates further processing. In the case of write I/O requests, node **120***s* receives data specified by such requests into cache **140**. The data may arrive from hosts **110** in various size increments, which typically range, for example, from 512 B (0.5 kB) to 256 kB. Cache **140** may arrange the incoming data in blocks **142**, e.g., 4-kB blocks. Cache **140** may further arrange blocks **142** based on LUN, based on logical address, and/or based on other factors.

[0029] At some point, cache **140** may perform a flush operation to flush certain blocks to lower-level structures (e.g., a mapping subsystem, RAID subsystem, etc.; not shown), which place the blocks into persistent structures in the storage **180**. The flush operation may work on one batch of blocks at a time, such as batch **144**. Each batch typically includes at least several blocks, and up to thousands of blocks. In various examples, flushing is repeated at regular intervals and may be conducted in parallel by multiple threads running on node **120***a*.

[0030] Upon the cache **140** initiating a flush of batch **144**, the deduplication manager **150** checks the blocks in the batch **144** for matches to blocks recorded in the digest cache. In the example shown, blocks **154** are found to match blocks that are already stored in the storage appliance **116**. Such blocks **154** may be pulled out of the batch **144** and deduplicated, e.g., by associating logical addresses of the blocks **154** with respective locations of matching blocks in storage **180**. The remaining blocks **152** may be processed for adaptive compression.

[0031] The adaptive compression manager **160** processes the batch **152** by computing entropy values of at least some of the blocks in batch **152** and steering compression decisions based on the computed entropy values. In one example, the compression manager **160** computes the entropy of each of the blocks in the batch **152** and uses the respective entropy values in deciding how to compress the respective blocks. For instance, the compression manager **160** may decide, based on a first block having moderate entropy, to compress the first block with a first compression procedure. Likewise, the compression manager **160** may decide, based on a second block having lower entropy, to compress the second block with a second compression procedure. The first compression procedure may execute faster than the second compression procedure but may yield a lesser degree of data compression than the second compression procedure. For convenience, the first compression procedure is referred to herein as "fast/low" and the second compression procedure is referred to herein as "slow/high," where "fast" and "slow" are used in a comparative sense, as are "high" and "low." Further, the compression manager **160** may decide, based on a third block having high entropy, not to compress the third block at all. The decision not to compress may be based on a prediction that the third block is not compressible, or that it is not compressible enough to justify the cost in throughput that compressing the third block would entail. Uncompressible blocks may include, for example, blocks that already contain compressed data, such as data of MPEG files, JPEG files, or the like. Although first and second compression procedures are described, one should appreciate that embodiments may provide any number of compression procedures, e.g., those covering a range of execution speeds and compression levels. Some embodiments may provide only a single compression level, however.

[0032] In another example, embodiments may use a sampling approach in generating the entropy of blocks, rather than computing the entropy of each and every block. Entropy may be computed, for example, on every other block, on every fourth block, on every hundredth block, and so on. Sampling may be especially attractive when blocks contain similar data, such as email data or video data. When using sampling, the adaptive compression manager **160** may use the entropy of sampled blocks as representatives of blocks that follow, and/or of other blocks in the same batch. Based on the entropy of a sampled block (or of multiple sampled blocks), a compression decision may be made, e.g., to use the first compression procedure, the second compression procedure, or no compression (also called "back-off"), and that decision can be applied to unsampled blocks as well as to sampled blocks.

[0033] FIG. **2** shows an example arrangement of the adaptive compression manager **160** of FIG. **1**. Here, the adaptive compression manager **160** includes a compressor **210**, an input queue **220**, and an output queue **230**. An entropy calculator **240** is operatively coupled to the input queue **220**, and a batch calculator **250** is operatively coupled to the output queue **230**. An orchestrator **260** is provided to control operations.

[0034] The compressor **210** may be implemented using hardware, software, firmware, or any combination thereof. In a particular example, the compressor **210** includes the above-described Intel QAT adapter, which provides hardware acceleration for data compression and decompression. The QAT adapter implements four levels of compression, referred to as L1-L4. In a particular embodiment, the above-described first (fast/low) compression level corresponds to QAT Adapter level L1, which roughly corresponds to Lempel-Ziv compression level LZ1. Also, the above-described second (slow/high) compression level corresponds to QAT Adapter level L4, which roughly corresponds to Lempel-Ziv compression level LZ9. QAT Adapter levels L2 and L3 may be used in some embodiments but are not illustrated in those which are depicted. For implementing no compression (e.g., back-off), it may be necessary to bypass the QAT adapter (e.g., if the QAT Adapter does not natively support a bypass function). Compressor **210** may implement a copy feature (not shown) for this purpose, e.g., one that identifies blocks in the input queue **220** for which no compression is specified and copies the identified blocks to the output queue **230**.

[0035] As shown, the compressor **210** has a selector input **212**, which is configured to receive a compression level selection (CLS) **262**. The CLS **262** may specify, for example, the first (fast/low) compression procedure, the second (slow/high) compression procedure, some other compression procedure (if supported), or no compression (back-off). The compressor **210** is configured to respond to the CLS **262** on a per-block basis, for compressing blocks in the input queue **220** based on respective settings of the CLS **262**. In an example, the compressor **210** is configured for pipelined operation, and the CLS **262** provides a pipelined sequence of settings, e.g., one setting for each of multiple blocks in the input queue **220**.

[0036] In an example, the input queue **220** and output queue **230** are implemented in memory **130** of the computing node **120***a* (FIG. **1**), as are the entropy calculator **240**, batch calculator **250**, and orchestrator **260**. Although one input queue **220** and one output queue **230** are shown, any number of such queues may be provided. For example, the QAT Adaptor is known to include three endpoints that support three-way parallel compression. For implementations that employ the QAT Adaptor, the adaptive compression manager **160** may include three input queues **220** and three output queues **230**, with the orchestrator **260** configured to load balance among them.

[0037] As further shown, the input queue **220** has a length **222** and a high-water mark (HWM) **224**. The length **222** indicates a number of blocks waiting to be processed in the input queue **220**, and the high-water mark **224** indicates a queue length at which the input queue **230** is close to being full. In an example, the high-water mark **224** is set to 90% of the maximum length of the input queue **220**; however, other values may be used. Also, the high-water mark **224** may be adjustable.

[0038] The entropy calculator **240** is configured to generate values of per-block entropy **242**, e.g., one entropy value for each block. In some examples, the entropy calculator **240** may operate on a sampling basis, such that entropy values need not be generated for each and every block. Per-block operation is described more fully in connection with FIG. **3**A.

[0039] The batch calculator **250** is configured to select a desired per-batch compression result (CR) **252**, e.g., for cases in which entropy or compressibility of certain blocks in a batch is used to steer compression decisions for other blocks in the same batch. Per-batch operation is described more fully in connection with FIG. **3**B.

[0040] In some examples, the orchestrator **260** is configured to monitor the length **222** of the input queue **220** and respond to changes by modifying how compression is performed. For instance, the orchestrator **260** may temporarily disable the slow/high compression option when the length **222** exceeds the high-water mark **224** or some other threshold. Also, the orchestrator **260** may switch from per-block operation to per-batch operation depending on the length **222** of input queue **220**.

[0041] FIG. **3**A shows an example of the adaptive compression manager **160** of FIG. **2** configured for per-block operation. Here, blocks in cache **140**, such as blocks **320**, **322**, and **324**, are arranged in the input queue **220**. Entropy calculator **240** may generate the entropy of blocks in the input queue **220** on a first-in-first-out (FIFO) basis. For instance, entropy calculator **240** calculates an entropy E=0. 34 for block **320**, then calculates an entropy E=0.64 for block **322**, then calculates an entropy E=0.95 for block **324**, and so on. These entropy values may be input to orchestrator **260**, which produces respective compression level settings (CLS) **262** for the respective entropy values. For example, orchestrator **260** selects slow/high compression for block **320**, fast/low compression for block **322**, and no compression (back-off) for block **324**. Each selection is made based on the computed entropy of the respective block. The compressor **210** receives these settings **262** at selector input **212** and proceeds to implement the corresponding compression procedures (or no compression) for the corresponding blocks.

[0042] The output queue **230** shows example results of operation. As shown, compressed block **320***c* appears as a highly compressed version of block **320**. Compressed block **322***c* appears as a somewhat less-highly compressed version of block **322**. Also, block **324***b* appears as a back-off block, which is identical to block **324** as it appeared in the input queue **220**.

[0043] In some examples, orchestrator **260** may base its per-block compression decisions on additional factors besides entropy. For example, some embodiments may store compression headers appended to compressed blocks but may not store such headers for uncompressed blocks. The header for a compressed block may include metadata, such as compressed size, compression procedure used in compressing the block, a checksum, and so forth. Where compression headers are used, the total size of a compressed block includes not only the size of the compressed data but also the size of the header. If the sum of compressed data plus header would approach or exceed the block size (e.g., 4 kB), the orchestrator **260** may opt for back-off, even if the data itself would compress to something smaller than the block size.

[0044] Processing with entropy sampling works the same way as per-block processing without sampling, except that entropy may be calculated on every N*th* block in the input queue **220**, rather than on each and every block. In an example, the orchestrator **260** produces a CLS value **262** for every N*th* block and maintains that value until the next N*th* block is processed, at which point the CLS value **262** is changed to reflect the new entropy value.

[0045] Given that sampling does not separately consider the entropy of each block that gets compressed, sampling raises the risk that some compressed blocks may end up being larger than the block size, particularly when they include headers. To avoid this result, orchestrator **260** may check the sizes of blocks in the output queue **230** and replace any compressed blocks larger than the block size with their uncompressed counterparts. Such counterparts may still reside in cache **140**.

[0046] FIG. **3**B shows an example of the adaptive compression manager **160** of FIG. **2** configured for per-batch operation. In some examples, the adaptive compression manager **160** switches from per-block processing to per-batch processing when its gets busy. Busyness may be estimated, for example, based on queue length **222**. When queue length **222** exceeds the high-water mark **224**, the adaptive compression manager **160** may switch from per-block processing to per-batch processing. It may later switch back to per-block processing when the queue length **222** falls below the high-water mark **224** (or when it falls below some lower threshold, to prevent chattering). In other examples, the adaptive compression manager **160** uses per-batch processing under other circumstances, which may be independent of busyness.

[0047] Per-batch processing may proceed by identifying a batch **350** of M blocks in the input queue **222**, where M may be several tens, hundreds, or thousands, for example. Compressor **210** may proceed to compress a first N blocks **360** of the M blocks (N<M), e.g., using the slow/high compression procedure, thus producing N compressed blocks **360***c*. The batch calculator **250** computes a compression result (CR) **252** of the first N blocks, e.g., by comparing a total size of the N compressed blocks **360***c* with the size of the N blocks **360** prior to compression.

[0048] The compression result **252** may be expressed as a total compressed size of compressed blocks **360***c* (e.g., across all N blocks), as a mean compressed size of compressed blocks **360***c*, as a ratio of total compressed size to total uncompressed size, or in any other suitable manner. In the example shown, compression result **252** is expressed as a reduction ratio, such as

$$CR = \frac{\text{Uncompressed Size} - \text{Compressed Size}}{\text{Uncompressed Size}}.$$

[0049] The batch calculator **250** outputs the compression result **252** of the first N blocks **360** to the orchestrator **260**. In response, the orchestrator **260** establishes a CLS value **262** for the rest of the batch **350**, e.g., for the remaining M-N blocks **370**, based on the compression result **252** for the first N blocks **360**. For example, if the first N blocks **360** were only 5% compressible, the orchestrator **260** would set the CLS value **262** to back-off, indicating no compression. The compressor **210** would then perform no compression on the remaining M-N blocks **370** of the batch **350**. If the first N blocks were 40% compressible, however, the orchestrator **260** would set the CLS value **262** to the first compression level, causing the compressor **210** to perform fast/low compression on the remaining N-M blocks **370**. But if the first N blocks were 75% compressible, the orchestrator **260** would set the CLS value **262** to the second compression level, causing the compressor **210** to perform slow/high compression on the remaining N-M blocks **370**.

[0050] Although the depicted example bases compression of remaining blocks in a batch on actual compression results obtained by compressing the first N blocks **360**, the decision could alternatively be based on average entropy of the first N blocks **360**. As before, if any compressed blocks (including headers) turn out to be larger than the system block size (e.g., 4 kB), such compressed blocks may be replaced with their uncompressed counterparts, e.g., from cache **140**.

[0051] FIG. **4** shows an example arrangement for further optimizing entropy calculations. The activities described may be performed, for example, by the entropy calculator **240** of FIG. **2**. As shown, a decimation (undersampling) process reduces the number of bytes **420** in a block **410** from which entropy is computed.

[0052] For example, the entropy calculator **240** may receive a block **410** and sample particular bytes of the block, such as every fourth, eighth, sixteenth, etc., byte in block **410**. The resulting data set **420** is smaller than the original block **410**, enabling an entropy calculation to proceed much more quickly. It is noted that the efficient entropy calculation described in incorporated U.S. application Ser. No. 16/669, 160 works with variable numbers of bytes and is thus compatible with decimation.

[0053] The resulting decimated entropy values **242***d* may be used for steering compression decisions in the same way that entropy values **242** are used above. The accuracy of decimated entropy values **242***d* depends on the distribution of information content among bytes in a block. The more even the distribution, the better the accuracy, and the more closely decimated entropy values **242***d* match with undecimated entropy values.

[0054] In some examples, the adaptive compression manager **160** may initially be configured to operate the entropy calculator **240** without decimation. It may further be configured to switch operation of the entropy calculator **240** to a decimation mode when the system gets busy and/or when it is compressing certain types of data, e.g., that known to have uniform information content, such as text.

[0055] FIGS. **5**-**8** show example methods that may be carried out in connection with the environment **100**. Such methods are typically performed, for example, by the software constructs described in connection with FIG. **1**, which reside in the memory **130** of the computing node **120***a* and are run by the processor(s) **124**. The various acts of the depicted methods may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in orders different from those illustrated, which may include performing some acts simultaneously.

[0056] FIG. **5** shows an example method **500** for managing data compression in the environment of FIG. **1**. Method **500** may be carried out by the adaptive compression manager **160**, for example.

[0057] At **510**, the adaptive compression manager **160** monitors system busyness, e.g., by monitoring the length **222** of the input queue **220** to compressor **210** (FIG. **2**). Additional factors may be considered in evaluating busyness, such as memory usage, CPU utilization, and the like.

[0058] At **520**, the adaptive compression manager **160** determines whether the monitored busyness falls below a predetermined threshold T**1**. If so, operation proceeds to **530**, whereupon the adaptive compression manager **160** processes data for compression on a per-block basis, such as described above in connection with FIG. **3**A. If not, operation proceeds to **540**, whereupon the adaptive compression manager **160** processes data for compression on a per-batch basis, such as described above in connection with FIG. **3**B.

[0059] In an example, threshold T**1** corresponds to the high-water mark **224** of the input queue **220** (FIG. **2**). Busyness below threshold T**1** thus corresponds to length **222** of the input queue **220** being below the high-water mark **224**. Likewise, busyness exceeding threshold T**1** corresponds to length **222** of the input queue **220** exceeding the high-water mark **224**.

[0060] FIG. **6** shows an example method **600** of processing data for compression on a per-block basis. FIG. **6** thus presents a more expanded view of act **530** of FIG. **5**.

[0061] At **610**, entropy calculator **240** calculates the entropy of a current block. The calculation may be based on the entire block or a decimated version thereof. Orchestrator **260** compares the calculated entropy "E" with one or more thresholds to determine how to treat the current block for compression.

[0062] For example, at **620**, orchestrator **260** determines whether the entropy E of the current block falls within a first range or within a second range. Entropy values within the first range are processed for compression, whereas entropy values within the second range are not. A threshold E**1** distinguishes the first range from the second range and may be set to a high value, such as 90%. Blocks with entropy values that fall within the second range are thus uncompressible or compressible to such as small extent that there is little or no benefit to compressing them. If the entropy of the current block falls outside the first range, operation proceeds to **630**, whereupon the orchestrator **260** selects back-off for the current block, indicating that no compression is to be performed. Otherwise, operation proceeds to **640**.

[0063] Given that the illustrated embodiments support two levels of compression, an additional comparison may be performed (at **640**) to determine whether the entropy of the current block falls within a first sub-range or a second sub-range of the first range. Here, threshold E**2** distinguishes the two subranges and may assume an intermediate entropy value, such as 50%. If the current block has an entropy value less than E**2**, operation proceeds to **650**, whereupon the current block may be processed using the first compression procedure (e.g., fast/low). Otherwise, operation may proceed to **660**, whereupon the current block may be processed using the second compression procedure (e.g., slow/high). The current block is then processed, and a next block in the input queue **220** may be identified as a new current block, at which point the method **600** is repeated.

[0064] One should appreciate that the particular operation as shown in method **600** may be varied while achieving similar results. For example, the particular thresholds can be varied. Also, additional sub-ranges may be added, for supporting additional compression levels. Thus, FIG. **6** is intended to be illustrative rather than limiting.

[0065] FIG. **7** shows an example method **700** of processing data for compression on a per-batch basis. FIG. **7** thus presents a more expanded view of act **540** of FIG. **5**.

[0066] At **710**, a current batch **350** is identified. For example, the batch is identified as M blocks **350** within the input queue **220** of the adaptive compression manager **160**. In an example, the batch corresponds to a set of blocks being processed as part of a flush transaction from cache **140**.

[0067] At **720**, the adaptive compression manager **160** compresses a first N blocks **360** of the current batch, e.g., as shown in FIG. **3**B, thus yielding compressed blocks **360***c*. In an example, blocks **360** are compressed using the slow/high compression procedure. Batch calculator **250** then computes a compression result **252** of the N-block compression. In the example shown, compression result **252** is expressed as a reduction ratio, such as that described in connection with FIG. **3**B. The acts that follow then have the effect of steering compression of the remaining M-N blocks **370** of the current batch based on the results obtained by compressing the first N blocks **350**.

[0068] For example, at **730** the orchestrator **260** determines whether the compression result (CR) falls below a first threshold C**1**, which may represent a minimal reduction in size, such as 10%. If the compression result falls below C**1** (indicating less than 10% reduction), operation proceeds to **740**, whereupon the orchestrator **260** applies back-off (no compression) to the remaining M-N blocks **370** of the current batch.

[0069] At **750**, the orchestrator **260** determines whether CR falls below a second threshold C**2**, which may represent a good reduction in size, such as 50%. If CR for the first N blocks **350** falls below C**2**, indicating only fair data reduction, operation proceeds to **760**, whereupon the orchestrator **260** applies the fast/low compression procedure to the remaining M-N blocks **370** in the current batch.

[0070] Otherwise, if the orchestrator **260** determines that CR exceeds C**2** (indicating good-to-excellent compression), operation proceeds to **770**, whereupon the orchestrator **260** applies the slow/high compression procedure to the remaining M-N blocks **370** in the current batch. In this manner, slow/high compression is performed on blocks that are expected to be highly compressible, whereas fast/low compression is performed on blocks that are expected to be somewhat less compressible. The method **700** may then be repeated for a next batch of blocks.

[0071] The particular operation as shown in method **700** may be varied while achieving similar results. Also, one can readily see that the particular thresholds can be varied. Thus, FIG. **7** is intended to be illustrative rather than limiting.

[0072] FIG. **8** shows a method **800** that may be carried out in the environment **100** and provides a high-level review of some of the features described above.

[0073] At **810**, data is received. As shown in FIG. **1**, for example, computing node **120***a* may receive data arriving in write I/O requests issued by hosts **110**. The computing node **120***a* may receive such data into cache **140**, which organizes the data into blocks **142**.

[0074] At **820**, entropy values are generated from respective blocks of the data received. For example, entropy calculator **240** (FIG. **2**), running within adaptive compression manager **160**, generates per-block entropy values **242** of blocks **152**, e.g., blocks received into cache **140** but not deduplicated. The entropy calculator **240** may generate entropy values on all such blocks or any subset of them. For example, entropy calculator **240** may operate on a sampling basis. Also, entropy calculator **240** may operate with byte-based decimation or without.

[0075] At **830**, the blocks of the data are selectively compressed based on the entropy values. For example, orchestrator **260** (FIG. **2**) may direct compressor **210** to compress blocks in the input queue **220** based on the entropy values **242** calculated for the respective blocks, such as by using back-off for high-entropy blocks, fast/low compression for moderate entropy blocks, and slow/high compression for low-entropy blocks. If sampling is used, the entropy calculated on sampled blocks may be used in steering compression decisions for nearby, unsampled blocks.

[0076] At **840**, the data is persisted, which includes persisting compressed blocks for at least some of the data. For example, blocks **162** processed by the adaptive compression manager **160** may be persisted to storage **180**. Such blocks **162** may include both compressed blocks and uncompressed blocks.

[0077] An improved technique has been described for managing data storage. The technique includes generating entropy of blocks on a per-block basis and selectively performing inline compression on blocks based at least in part on their entropy. Entropy of a block can be computed inexpensively and provides a rough measure of the block's compressibility. Thus, using per-block entropy enables a storage system to steer compression decisions, e.g., whether to compress and/or how much to compress, flexibly and with high granularity, striking a balance between throughput and storage efficiency.

[0078] Having described certain embodiments, numerous alternative embodiments or variations can be made. For instance, a certain efficient entropy calculation is described. But this is merely one suitable example. Also, a particular hardware accelerator is described. But this is also merely one example. Neither example is intended to be limiting.

[0079] Further, although features have been shown and described with reference to particular embodiments hereof, such features may be included and hereby are included in any of the disclosed embodiments and their variants. Thus, it is understood that features disclosed in connection with any embodiment are included in any other embodiment.

[0080] Further still, the improvement or portions thereof may be embodied as a computer program product including one or more non-transient, computer-readable storage media, such as a magnetic disk, magnetic tape, compact disk, DVD, optical disk, flash drive, solid state drive, SD (Secure Digital) chip or device, Application Specific Integrated Circuit (ASIC), Field Programmable Gate Array (FPGA), and/or the like (shown by way of example as medium **850** in FIG. **8**). Any number of computer-readable media may be used. The media may be encoded with instructions which, when executed on one or more computers or other processors, perform the process or processes described herein. Such media may be considered articles of manufacture or machines, and may be transportable from one machine to another.

[0081] As used throughout this document, the words "comprising," "including," "containing," and "having" are intended to set forth certain items, steps, elements, or aspects of something in an open-ended fashion. Also, as used herein and unless a specific statement is made to the contrary, the word "set" means one or more of something. This is the case regardless of whether the phrase "set of" is followed by a singular or plural object and regardless of whether it is conjugated with a singular or plural verb. Also, a "set of" elements can describe fewer than all elements present. Thus, there may be additional elements of the same kind that are not part of the set. Further, ordinal expressions, such as "first," "second," "third," and so on, may be used as adjectives herein for identification purposes. Unless specifically indicated, these ordinal expressions are not intended to imply any ordering or sequence. Thus, for example, a "second" event may take place before or after a "first event," or even if no first event ever occurs. In addition, an identification herein of a particular element, feature, or act as being a "first" such element, feature, or act should not be construed as requiring that there must also be a "second" or other such element, feature or act. Rather, the "first" item may be the only one. Also, and unless specifically stated to the contrary, "based on" is intended to be nonexclusive. Thus, "based on" should not be interpreted as meaning "based exclusively on" but rather "based at least in part on" unless specifically indicated otherwise. Although certain embodiments are disclosed herein, it is understood that these are provided by way of example only and should not be construed as limiting.

[0082] Those skilled in the art will therefore understand that various changes in form and detail may be made to the embodiments disclosed herein without departing from the scope of the following claims.

What is claimed is:

1. A method of managing data storage, comprising:
receiving data;
generating entropy values of respective blocks of the data;
selectively compressing the blocks of the data based on the entropy values; and
persisting the data, including persisting compressed blocks for at least some of the data.

2. The method of claim **1**, wherein selectively compressing the blocks of the data includes:
compressing a first set of blocks having entropy values within a first range; and
skipping compression of a second set of blocks having entropy values outside the first range.

3. The method of claim **2**, wherein compressing the first set of blocks includes:
compressing a first subset of blocks having entropy values within a first sub-range of the first range using a first compression procedure; and
compressing a second subset of blocks having entropy values within a second sub-range of the first range using a second compression procedure.

4. The method of claim **3**, wherein the first compression procedure executes faster than the second compression procedure and yields a lesser degree of data compression than the second compression procedure.

5. The method of claim **3**,
wherein blocks of the data are arranged in a queue,
wherein generating entropy values of respective blocks of the data is performed by sampling fewer than all blocks in the queue, and
wherein the method further comprises selectively compressing un-sampled blocks in the queue based on entropy values generated from one or more sampled blocks in the queue.

6. The method of claim **3**, wherein generating entropy values of respective blocks includes, for at least one block, generating an entropy value based on sampling bytes within the respective block, the entropy value thus reflecting sampled bytes but not un-sampled bytes within the respective block.

7. The method of claim **3**, wherein blocks of the data are arranged in a queue, and wherein the method further comprises disabling the second compression procedure in response to a length of the queue exceeding a predetermined high water mark.

8. The method of claim **3**, further comprising:
providing an ordered set of M blocks of data;
determining a compressibility level of a first N blocks of the M blocks of data (N<M);
based on the compressibility level of the first N blocks, selecting a processing procedure as one of (i) no compression, (ii) the first compression procedure, or (iii) the second compression procedure; and
processing a remaining M-N blocks of the M blocks using the selected processing procedure.

9. The method of claim **8**, wherein the ordered set of M blocks of data are blocks contained within a flush transaction for flushing the M blocks of data from a cache.

10. The method of claim **3**, wherein persisting the data includes:
storing a compressed block with a compression header that includes metadata describing a compression procedure used to compress the compressed block; and
storing an uncompressed block without a compression header.

11. A computerized apparatus, comprising control circuitry that includes a set of processing units coupled to memory, the control circuitry constructed and arranged to:
receive data;
generate entropy values of respective blocks of the data;

selectively compress the blocks of the data based on the entropy values; and

persist the data, including compressed blocks for at least some of the data.

12. A computer program product including a set of non-transitory, computer-readable media having instructions which, when executed by control circuitry of a computerized apparatus, cause the computerized apparatus to perform a method of managing data storage, the method comprising:

receiving data;

generating entropy values of respective blocks of the data;

selectively compressing the blocks of the data based on the entropy values; and

persisting the data, including persisting compressed blocks for at least some of the data.

13. The computer program product of claim **12**, wherein selectively compressing the blocks of the data includes:

compressing a first set of blocks having entropy values within a first range; and

skipping compression of a second set of blocks having entropy values outside the first range.

14. The computer program product of claim **12**, wherein compressing the first set of blocks includes:

compressing a first subset of blocks having entropy values within a first sub-range of the first range using a first compression procedure; and

compressing a second subset of blocks having entropy values within a second sub-range of the first range using a second compression procedure.

15. The computer program product of claim **14**, wherein the first compression procedure executes faster than the second compression procedure and yields a lesser degree of data compression than the second compression procedure.

16. The computer program product of claim **14**,

wherein blocks of the data are arranged in a queue,

wherein generating entropy values of respective blocks of the data is performed by sampling fewer than all blocks in the queue, and

wherein the method further comprises selectively compressing un-sampled blocks in the queue based on entropy values generated from one or more sampled blocks in the queue.

17. The computer program product of claim **14**, wherein generating entropy values of respective blocks includes, for at least one block, generating an entropy value based on sampling bytes within the respective block, the entropy value thus reflecting sampled bytes but not un-sampled bytes within the respective block.

18. The computer program product of claim **14**, wherein blocks of the data are arranged in a queue, and wherein the method further comprises disabling the second compression procedure in response to a length of the queue exceeding a predetermined high water mark.

19. The computer program product of claim **14**, further comprising:

providing an ordered set of M blocks of data;

determining a compressibility level of a first N blocks of the M blocks of data (N<M);

based on the compressibility level of the first N blocks, selecting a processing procedure as one of (i) no compression, (ii) the first compression procedure, or (iii) the second compression procedure; and

processing a remaining M-N blocks of the M blocks using the selected processing procedure.

20. The computer program product of claim **19**, wherein the ordered set of M blocks of data are blocks contained within a flush transaction for flushing the M blocks of data from a cache.

* * * * *