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(54) **DISTRIBUTED DATABASE CONFIGURATION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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(63) Continuation of application No. 18/090,453, filed on Dec. 28, 2022, now Pat. No. 11,907,258, which is a (Continued)

(51) **Int. Cl.**

G06F 16/27	(2019.01)
G06F 16/25	(2019.01)
G06F 16/955	(2019.01)
H04L 67/1023	(2022.01)
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(58) **Field of Classification Search**

None

See application file for complete search history.

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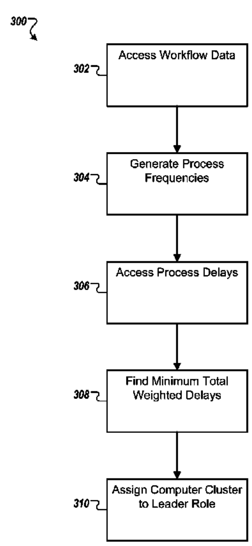
(57) **ABSTRACT**

Replicas are selected in a large distributed network, and the roles for these replicas are identified. In one example, a leader is selected from among candidate computing clusters. To make this selection, an activity monitor predicts or monitors the workload of one or more clients. Different activities of the workload are given corresponding weights. The delay in performing requested activities, modified by these weights is found, and the candidate leader with the lowest weighted delay is selected as the leader.

20 Claims, 16 Drawing Sheets



Related U.S. Application Data

continuation of application No. 17/074,578, filed on Oct. 19, 2020, now Pat. No. 11,556,561, which is a continuation of application No. 15/200,939, filed on Jul. 1, 2016, now Pat. No. 10,831,777.

(60) Provisional application No. 62/188,076, filed on Jul. 2, 2015.

(51) **Int. Cl.**
H04L 67/1097 (2022.01)
H04L 67/52 (2022.01)

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Prosecution History from U.S. Appl. No. 17/074,578, now issued U.S. Pat. No. 11,556,561, dated Nov. 9, 2021, through Sep. 20, 2022, 67 pp.
Prosecution History from U.S. Appl. No. 18/090,453, now issued U.S. Pat. No. 11,907,258, dated May 22, 2023, through Oct. 12, 2023, 39 pp.

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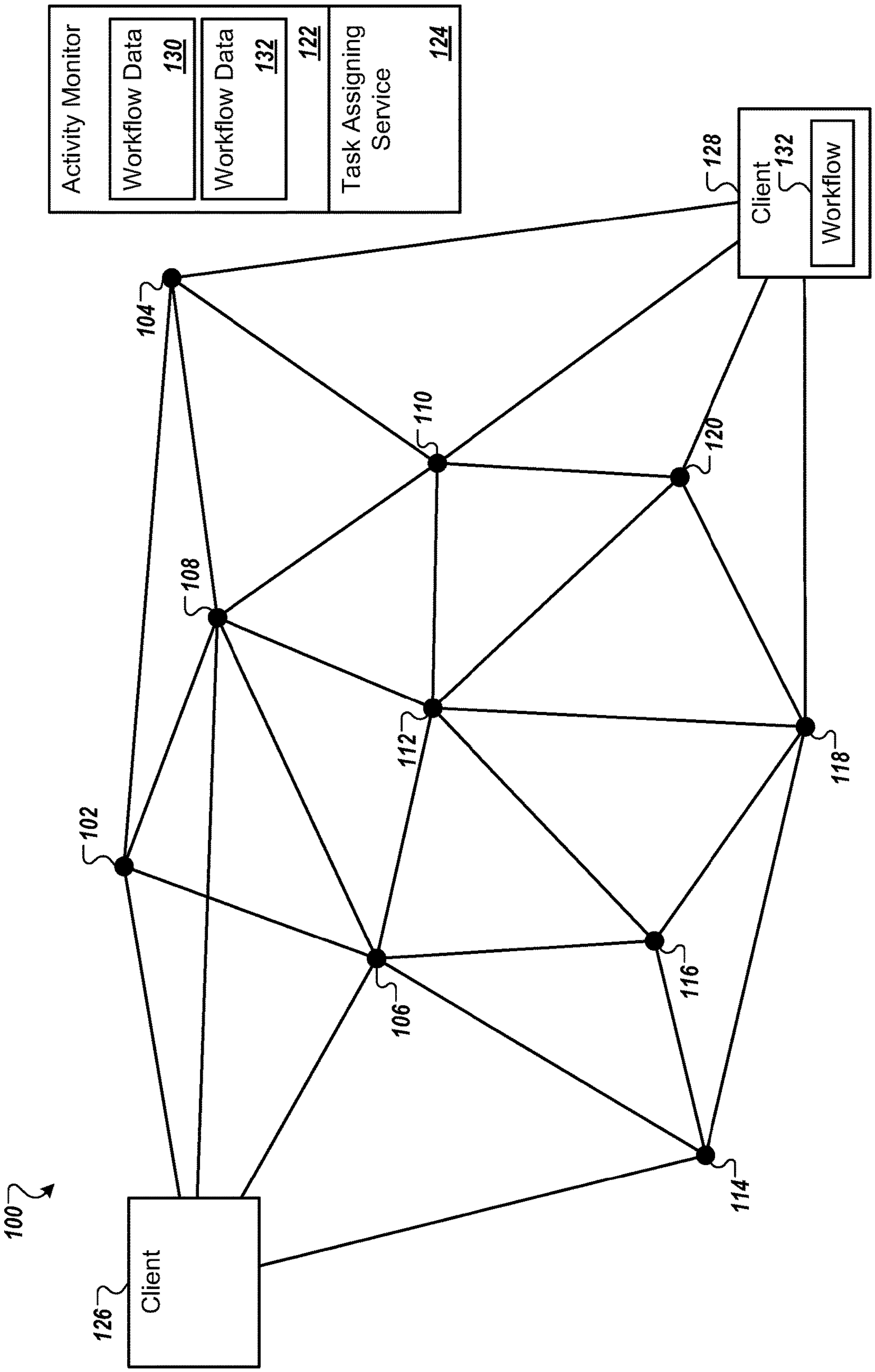


100
Activity Monitor
Workflow Data
130
Workflow Data
132
122
Task Assigning Service
124
Client
128
132
Workflow
104
110
120
108
112
118
102
116
106
114
Client
126

FIG. 1

200

206

202

	Process 1	Process 2	Process 3	Process 4	Weight1	Weight2	Weight3
$Node_{106}$	28	68	78	62	236.0	241.8	276.81
$Node_{102}$	87	13	49	45	194.0	184.4	82.2
$Node_{112}$	41	27	29	19	101.0	**75.4**	74.1
$Node_{118}$	54	77	23	36	190.0	145.3	133.4
$Node_{108}$	46	19	10	20	95.0	75.6	**63.3**
$Node_{116}$	41	37	93	13	184.0	177.0	214.0
$Node_{114}$	11	01	36	21	**69.0**	86.3	105.5
$Node_{110}$	66	11	76	59	212.0	230.6	254.6
Sample1	1	1	1	1			
Sample2	0.5	0.4	1.3	1.6			
Sample3	0.1	0.3	1.9	1.7			

204

FIG. 2

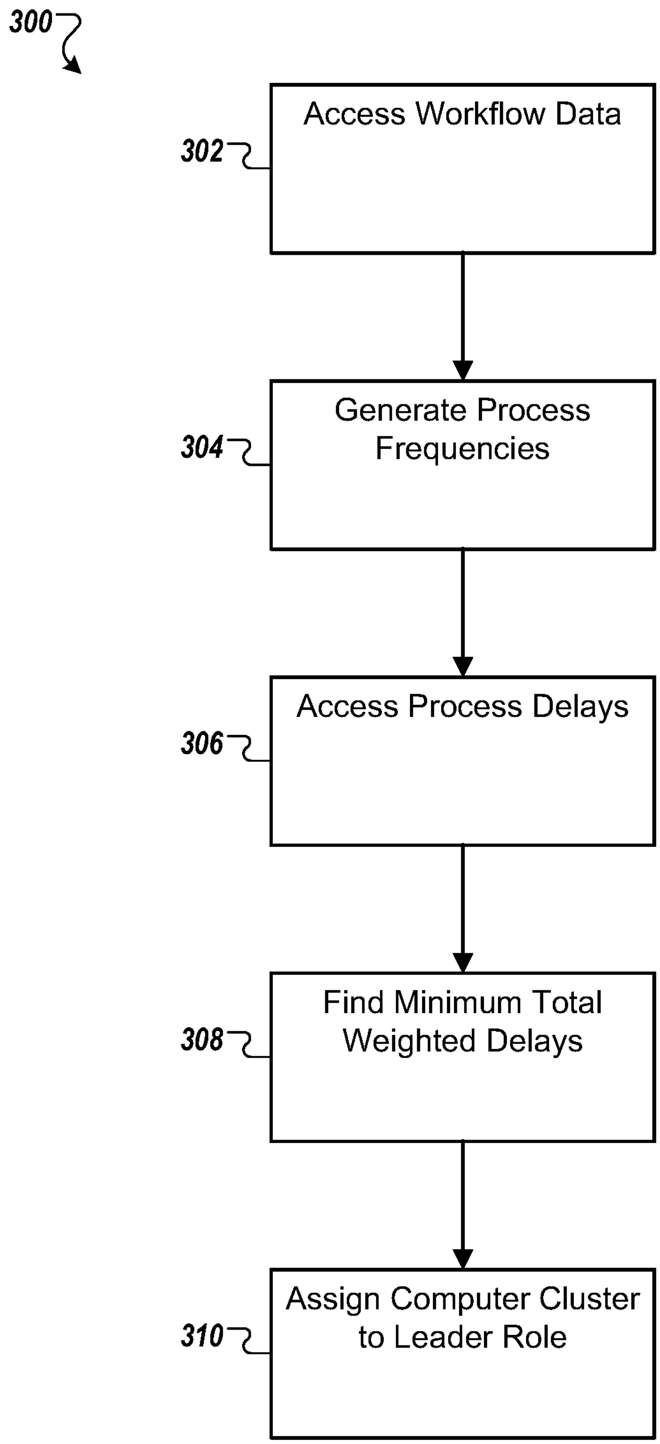

300
302
Access Workflow Data
304
Generate Process Frequencies
306
Access Process Delays
308
Find Minimum Total Weighted Delays
310
Assign Computer Cluster to Leader Role

FIG. 3

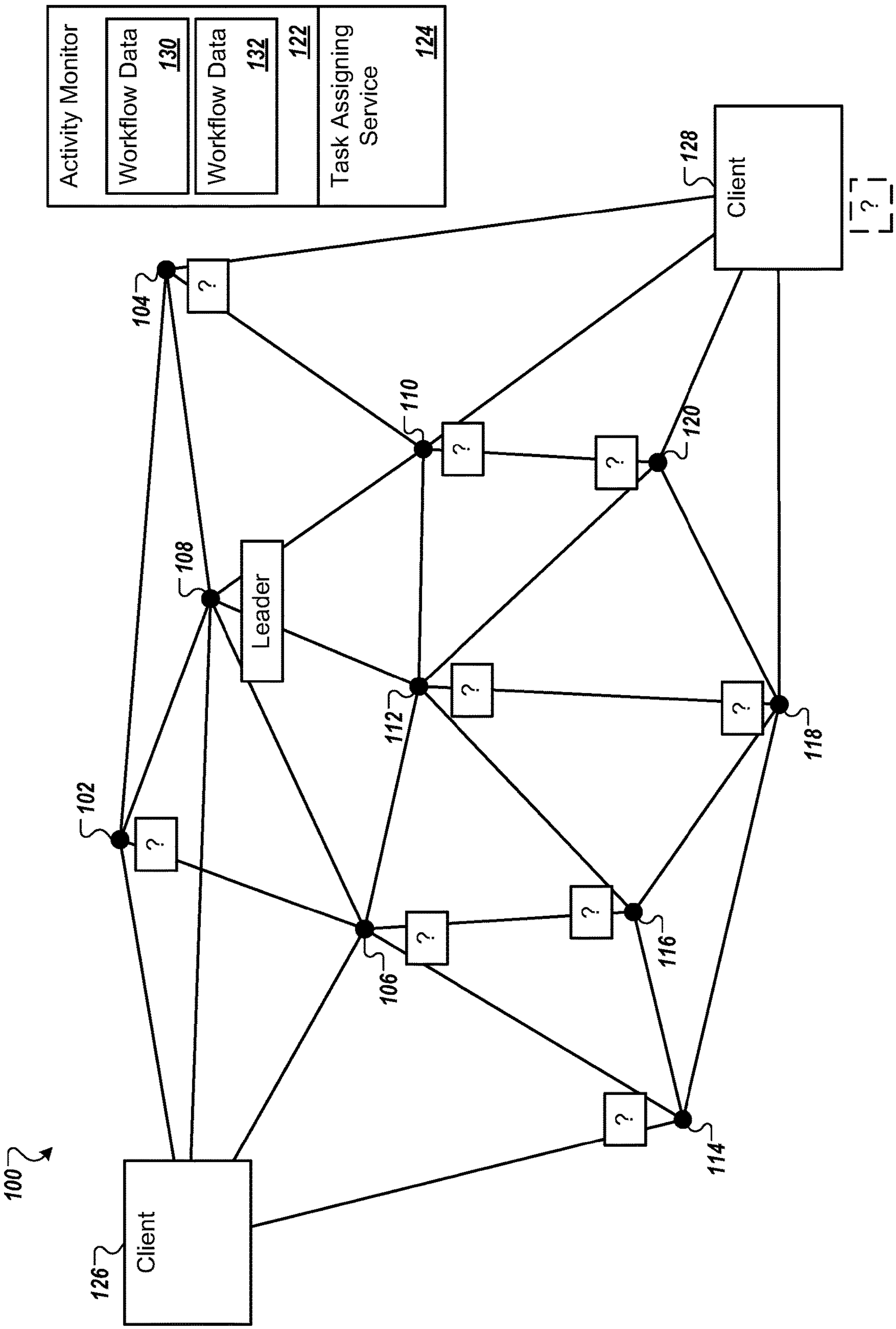

Activity Monitor
Workflow Data
130
Workflow Data
132
122
Task Assigning Service
124
Client
128
?
104
110
120
108
Leader
112
118
102
106
116
114
100
Client
126

FIG. 4

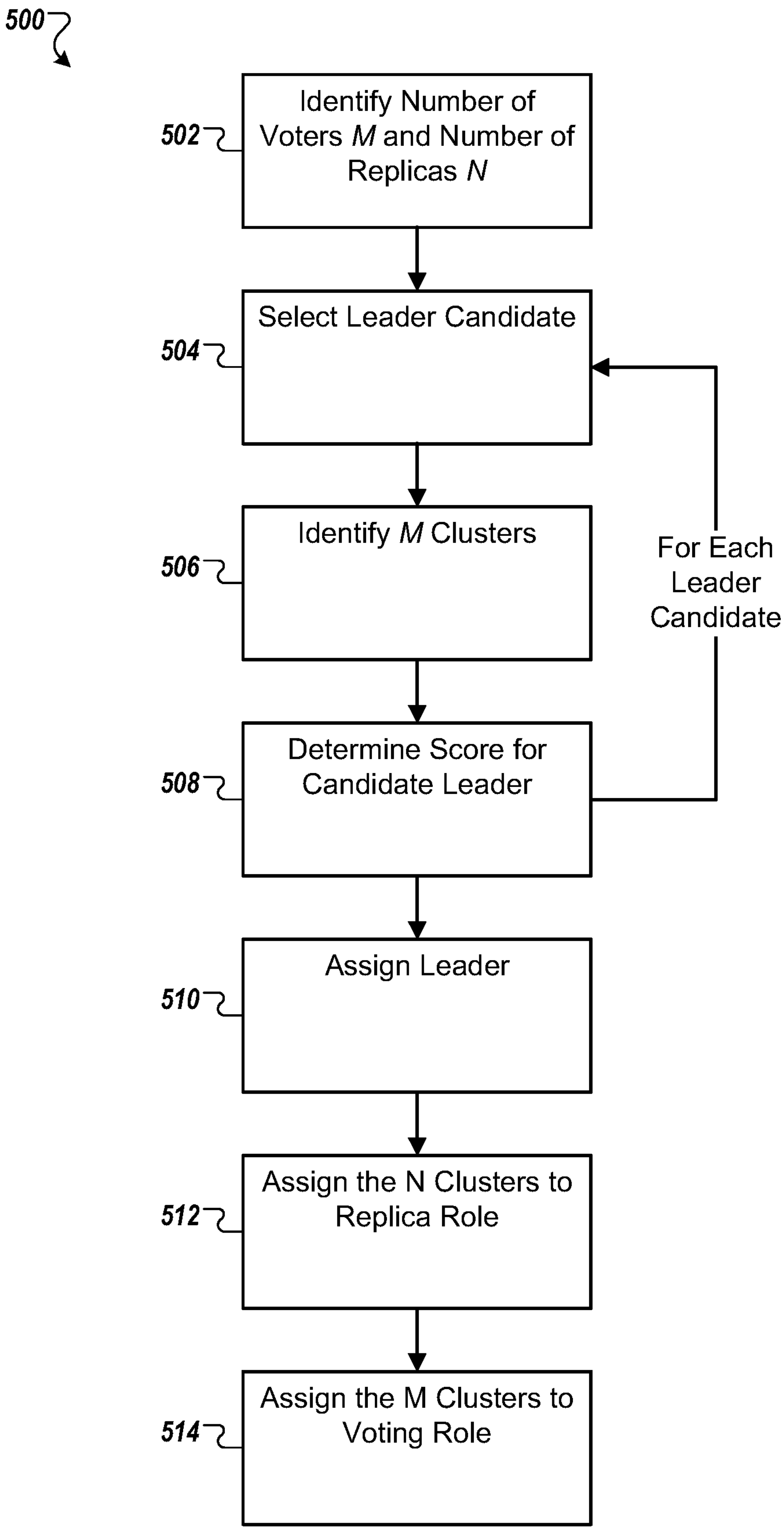

500
502
Identify Number of Voters M and Number of Replicas N
504
Select Leader Candidate
506
Identify M Clusters
508
Determine Score for Candidate Leader
For Each Leader Candidate
510
Assign Leader
512
Assign the N Clusters to Replica Role
514
Assign the M Clusters to Voting Role

FIG. 5A

550

$$\lambda_{db}^{(i)} = \arg\min_{\ell \in V(db)} \{score^{(i)}(\ell)\},$$

551

$$: \sum_{\alpha,c} \mathbf{t}_{\alpha,c}^{(i)}(\ell) \cdot \mathbf{n}_{\alpha,c}^{(i)}.$$

552

$$\begin{aligned}
&Pr(\mathbf{t}_{bounded\ read,c}^{(i)}(\ell) = x) = \\
&Pr(\mathbf{rtt}_{c,nearest(c,\mathcal{R})} + \mathbf{rtt}_{nearest(c,\mathcal{R}),\ell} = x) = \\
&\sum_{k=m}^{x} Pr(\mathbf{rtt}_{c,nearest(c,\mathcal{R})} = k, \mathbf{rtt}_{nearest(c,\mathcal{R}),\ell} = x - k) = \\
&\sum_{k=m}^{x} Pr(\mathbf{rtt}_{c,nearest(c,\mathcal{R})} = k) \cdot Pr(\mathbf{rtt}_{nearest(c,\mathcal{R}),\ell} = x - k),
\end{aligned}$$

554

$$\begin{aligned}
Pr(\max(\mathbf{rtt}_{\ell,v}, \mathbf{rtt}_{\ell,w}) \leq x) &= Pr(\mathbf{rtt}_{\ell,v} \leq x, \mathbf{rtt}_{\ell,w} \leq x) \\
&= Pr(\mathbf{rtt}_{\ell,v} \leq x) \cdot Pr(\mathbf{rtt}_{\ell,w} \leq x)
\end{aligned}$$

556

$$\begin{aligned}
Pr(q_\ell^{(i)} < x) = Pr(\mathbf{rtt}_{\ell,v} \leq x) + Pr(\mathbf{rtt}_{\ell,w} \leq x) \\
- Pr(\max(\mathbf{rtt}_{\ell,v}, \mathbf{rtt}_{\ell,w}) \leq x)
\end{aligned}$$

FIG. 5B

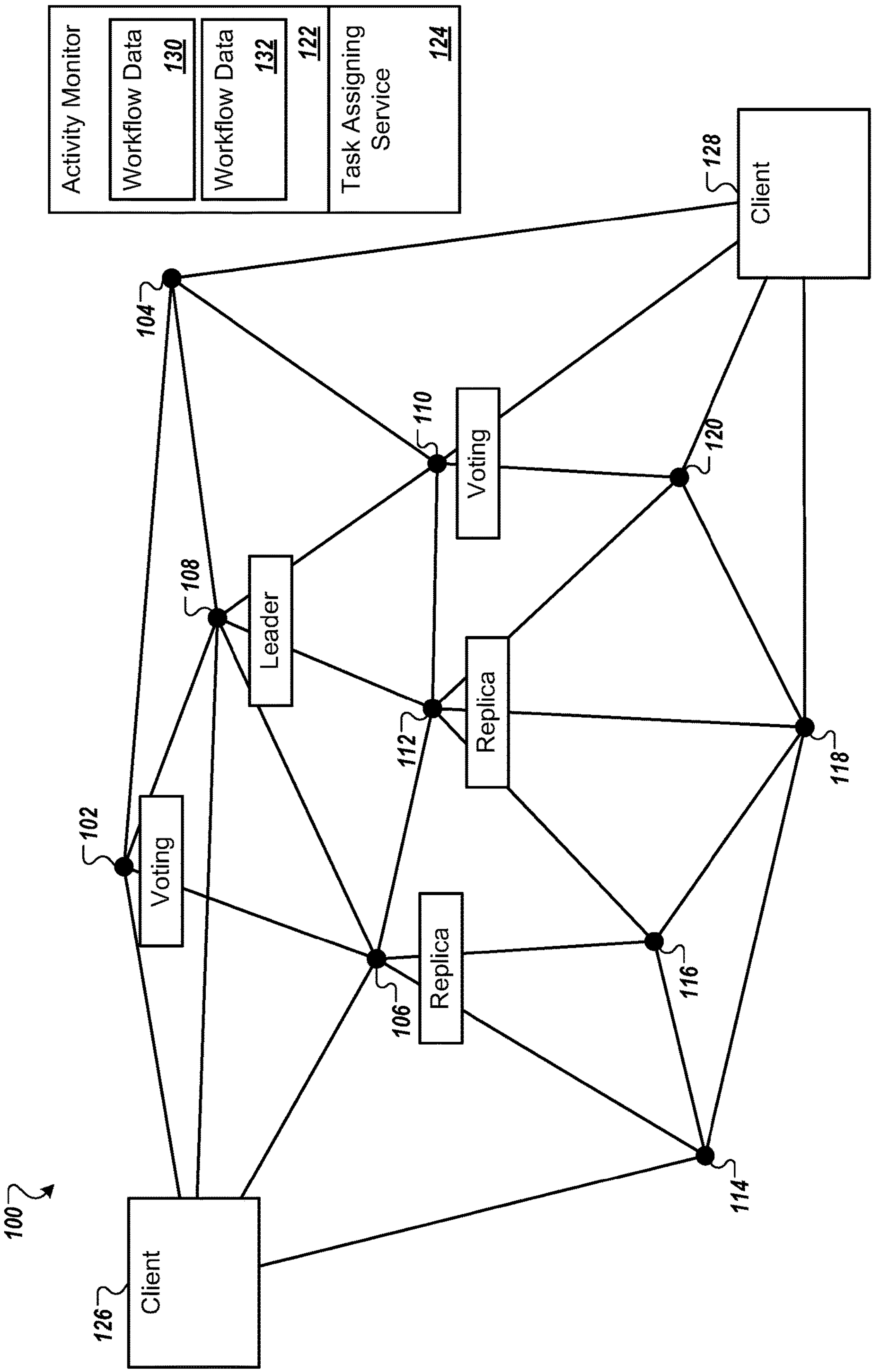

100
Activity Monitor
Workflow Data
130
Workflow Data
132
122
Task Assigning Service
124
Client
128
104
110
Voting
120
108
Leader
Replica
112
118
102
Voting
Replica
116
106
114
Client
126

FIG. 6

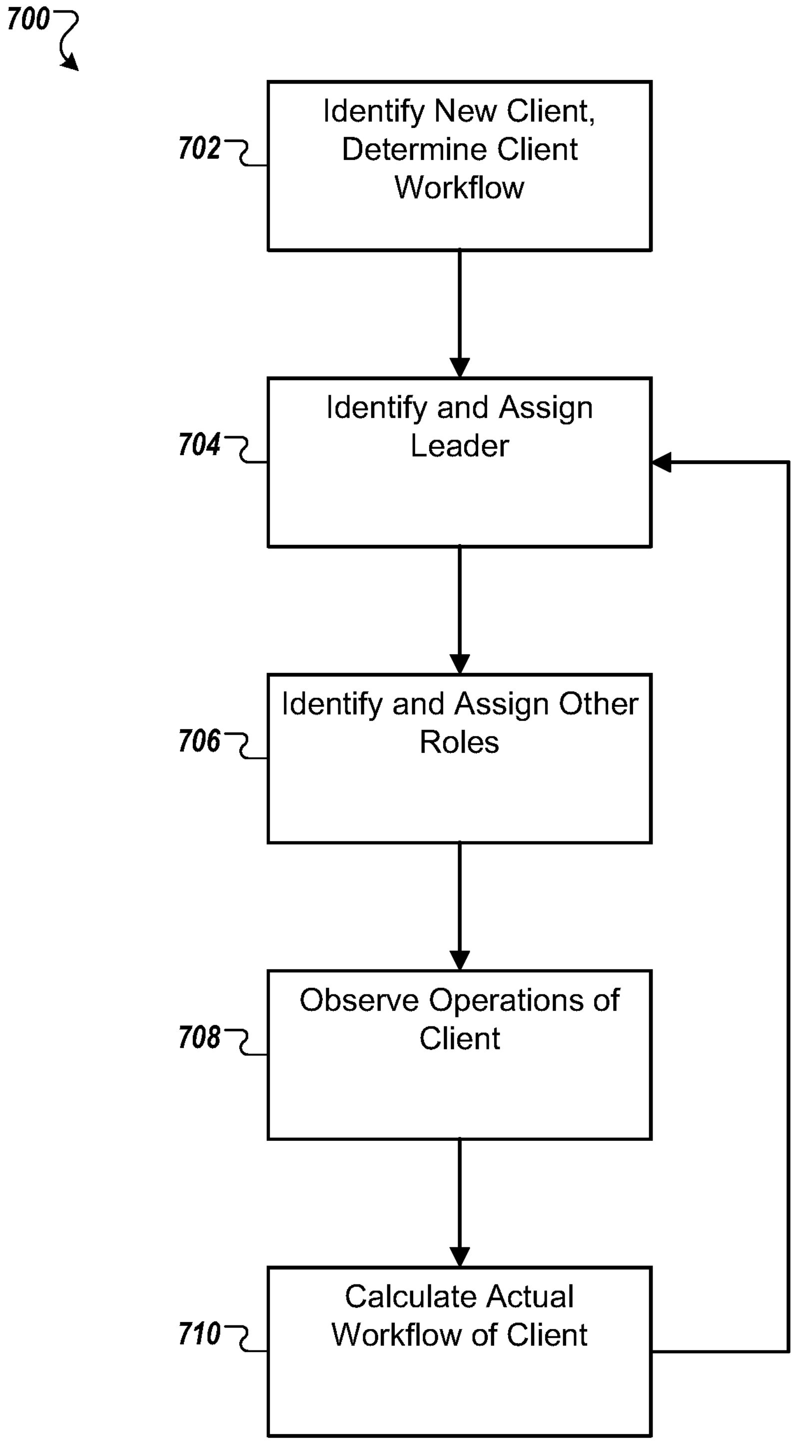

700
702
Identify New Client, Determine Client Workflow
704
Identify and Assign Leader
706
Identify and Assign Other Roles
708
Observe Operations of Client
710
Calculate Actual Workflow of Client

FIG. 7

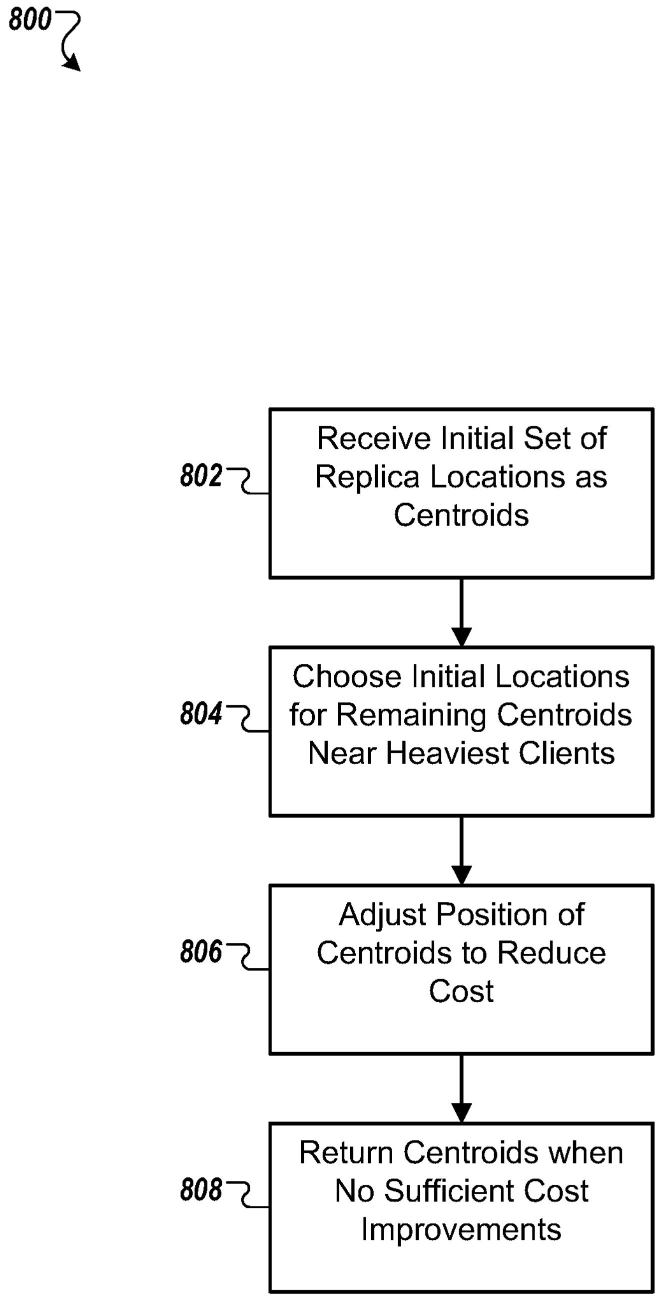

800
802
Receive Initial Set of Replica Locations as Centroids
804
Choose Initial Locations for Remaining Centroids Near Heaviest Clients
806
Adjust Position of Centroids to Reduce Cost
808
Return Centroids when No Sufficient Cost Improvements

FIG. 8A

850

```
// L_fixed: set of fixed replica locations, which can't be moved
// num_replicas: total number of replicas to be placed
procedure weighted-k-means(L_fixed, num_replicas)
    // pick initial centroids
    G ← L_fixed
    sort all client clusters c ∈ C by descending w_c
    while |G| < num_replicas and more client clusters remain
        c ← next client cluster in C
        if nearest(c, S) ∉ G then
            add nearest(c, S) to G
    new_cost ← cost(G)
    repeat
        prev_cost ← new_cost
        // cluster clients according to nearest centroid
        ∀g ∈ G let C_g ← {c | g = nearest(c, G)}
        // attempt to adjust centroids
        for each g ∈ G \ L_fixed
            g' ← v ∈ S s.t. Σ_{c∈C_g} w_c · rtt^{(i)}_{c,v} is minimized
            update centroid g to g'
        new_cost ← cost(G)
    until new_cost − prev_cost < threshold
    return G
```

FIG. 8B

900

$$w_c = \sum_{\alpha} \mathsf{n}_{\alpha,c}^{(i)} = \mathsf{n}_{weak\ read,c}^{(i)} + \mathsf{n}_{bounded\ read,c}^{(i)} + \mathsf{n}_{strong\ read,c}^{(i)} + \mathsf{n}_{single\text{-}group\ transaction,c}^{(i)} + \mathsf{n}_{multi\text{-}group\ transaction,c}^{(i)}$$

902

$$\mathtt{cost}(G) = \sum_{c \in C} w_c \cdot \mathtt{rtt}_{c,nearest(c,G)}^{(i)}$$

FIG. 9

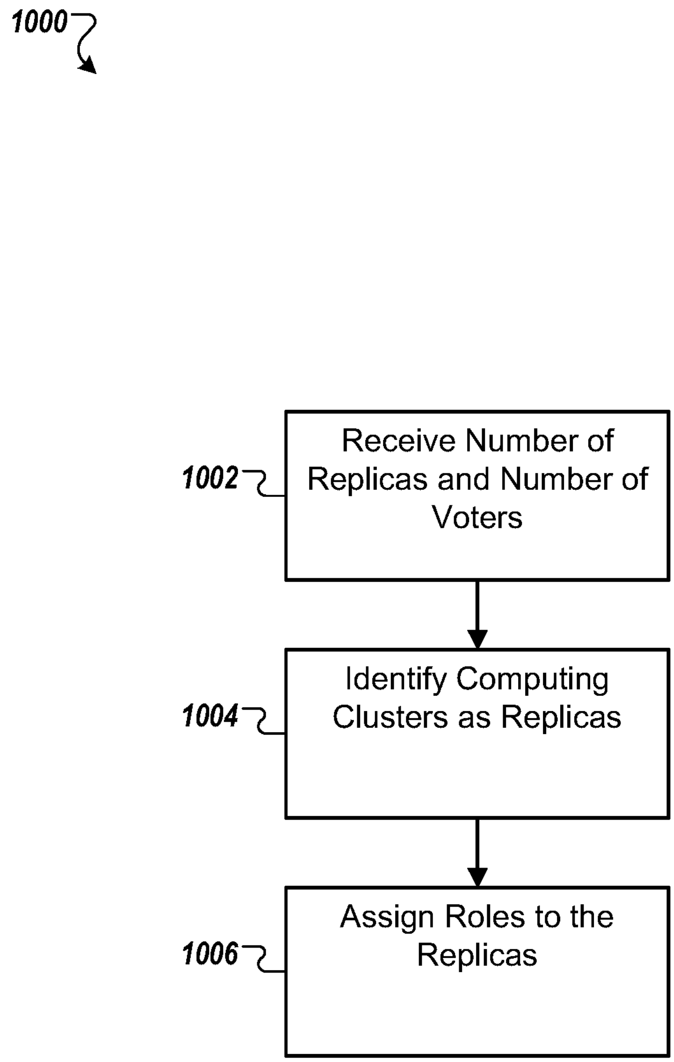

1000
1002
Receive Number of Replicas and Number of Voters
1004
Identify Computing Clusters as Replicas
1006
Assign Roles to the Replicas

FIG. 10A

1050

```
procedure KMeans-Quorum(num_replicas, num_voters)
    G ← weighted-k-means(∅, num_replicas) 800
    (λ, V) ← tier-2-efficient(G, num_voters) 500
    // Return the leader, set of voters and set of replicas
    return (λ, V, G)
```

FIG. 10B

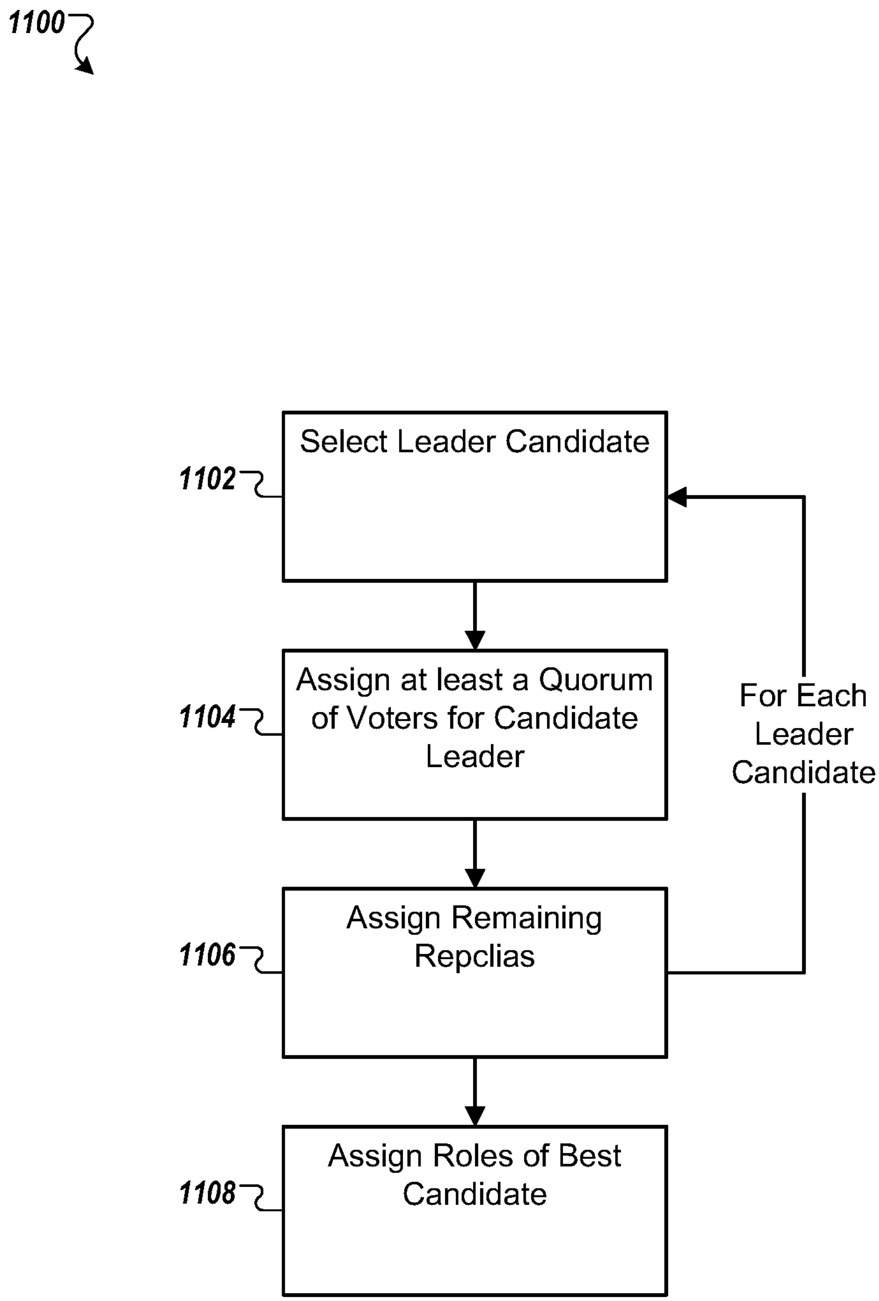

1100
1102
Select Leader Candidate
1104
Assign at least a Quorum of Voters for Candidate Leader
For Each Leader Candidate
1106
Assign Remaining Repclias
1108
Assign Roles of Best Candidate

FIG. 11A

1150

procedure *Quorum-KMeans*(*num_replicas*, *num_voters*)

$majority \leftarrow \lceil \frac{num\_voters+1}{2} \rceil$

$minority \leftarrow num\_voters - majority$

for each replica $\ell \in S$

$q_\ell^{(i)} \leftarrow majority$-th smallest $\mathtt{rtt}_{\ell,s}^{(i)}, s \in S$

$Q_\ell \leftarrow k\text{-}closest(\ell, majority, q_\ell^{(i)}, S)$

$G_\ell \leftarrow weighted\text{-}k\text{-}means(Q_\ell, num\_replicas)$

$score_\ell \leftarrow \mathbf{agg\_score}^{(i)}(\ell, G_\ell, q_\ell^{(i)})$ (Equation 2)

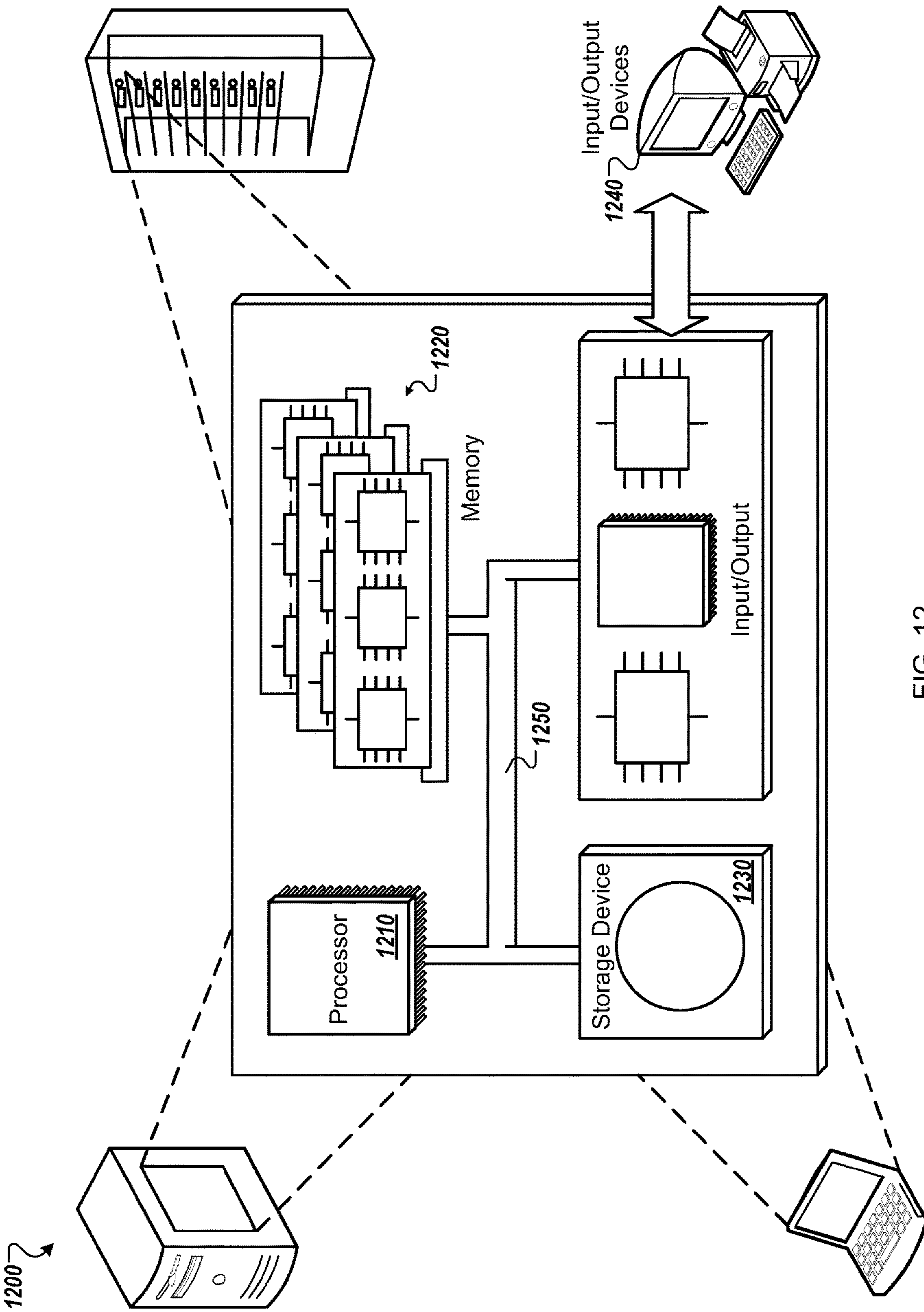
$\lambda = \arg\min_{\ell \in S}\{score_\ell\}$

$O \leftarrow$ any *minority* locations from $G_\lambda \setminus Q_\lambda$

// Return the leader, set of voters and set of replicas

return $(\lambda, Q_\lambda \cup O, G_\lambda)$

FIG. 11B



1200
1220
Memory
Processor
1210
Storage Device
1230
Input/Output
1250
1240
Input/Output Devices

FIG. 12

DISTRIBUTED DATABASE CONFIGURATION

CROSS-REFERENCE TO RELATED APPLICATION

This U.S. patent application is a continuation of, and claims priority under 35 U.S.C. § 120 from, U.S. patent application Ser. No. 18/090,453, filed on Dec. 28, 2022, which is a continuation of U.S. patent application Ser. No. 17/074,578, now U.S. Pat. No. 11,556,561, filed on Oct. 19, 2020, which is a continuation of, U.S. patent application Ser. No. 15/200,939, now U.S. Pat. No. 10,831,777, filed on Jul. 1, 2016, which claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 62/188,076, filed on Jul. 2, 2015. The disclosures of these prior applications are considered part of the disclosure of this application and are hereby incorporated by reference in their entireties.

TECHNICAL FIELD

The present document relates to configuration of distributed computer databases.

BACKGROUND

A computer network is a collection of computers and other hardware interconnected by communication channels that allow sharing of resources and information. Communication protocols define the rules and data formats for exchanging information in a computer network.

A distributed database is a computing entity that holds data across a number of computers. These computers can be interlinked with computer networking links, allowing the computers to communicate with each other and coordinate the tasks associated with the database. In some distributed databases, the constituent computers can be organized into computing clusters and assigned to respective roles in the distributed database. These roles may, for example, describe some of the permissions and activities of the cluster in the distributed database.

SUMMARY

The systems and processes described here may be used to optionally provide a number of potential advantages. By monitoring the activity of clients and the computing environment, roles for a distributed database can be efficiently assigned. This efficiency may be greater than alternative methods such as user selection and heuristics using only information local to a particular node of the system. By selecting a leader first, and then selecting other roles based on the leader selection, the number of combinations of role assignments can be drastically reduced compared to other processes that do not select the leader first. This results in an improvement in the technological field of distributed databases.

In general, one innovative aspect of the subject matter described in this specification can be embodied in systems that include a plurality of computing clusters each including computer memory and a computer processor; a distributed database running on at least a subset of the plurality of the computing clusters and that interacts with a client application running on a client computer, the distributed database configured to: store data of the distributed database in shards distributed among computing clusters of the distributed database; and use each computing cluster of the computing

clusters of the distributed database according to a respective role assigned to the computing cluster that identifies functions of the computing cluster; an activity monitor service configured to: monitor interactions between the client application and the distributed database; and generate, from the monitoring of the interactions between the client application and the distributed database, workload data describing the interactions between the client application and the distributed database; and a task assigning service configured to: assign, based on the workload data, a particular computing cluster to a leader role in the distributed database. Other embodiments of this aspect include corresponding methods, apparatus, and computer programs, configured to perform the action of the methods, encoded on computer storage devices.

These and other embodiments can each optionally include one or more of the following features. To assign, based on the workload data, a particular computing cluster to a leader role in the distributed database, the task assigning service is configured to: find the cluster having a lowest latency for completing processes identified in the workload data.

To find the cluster having the lowest latency for completing processes identified in the workload data, the task assigning service is configured to: identify a frequency for each process; identify a latency value for each process for each computing cluster; and find, for each computing cluster, a weighted latency value that incorporates a aggregation of the latency values for the cluster, wherein the latency values in the aggregation of the latency values have been weighted according to the frequency of the corresponding processes.

The activity monitor is configured to repeat the monitoring and the generating and wherein the task assigning service is configured to repeat the assigning.

To repeating the assigning, the task assigning service is configured to assign, based on the workload data, a different particular computing cluster to the leader role in the distributed database.

The activity monitor is configured to repeat the monitoring and the generating and wherein the task assigning service is configured to repeat the assigning on a schedule that is based on cyclical changes in usage of the computing clusters.

The activity monitor service and the task assigning service are running on one or more of the computing clusters.

The client computer is one of the computing clusters.

Other features, aspects and potential advantages will be apparent from the accompanying description and figures.

DESCRIPTION OF DRAWINGS

FIG. **1** is block diagram of an example distributed computing environment that can be used to support distributed databases.

FIG. **2** is spreadsheet of example calculations used to determine communication delays.

FIG. **3** is a flow chart of an example flow for selecting a leader for a distributed database.

FIG. **4** is block diagram of an example distributed computing environment in which some computing clusters are candidates for replica and voting roles within a distributed database.

FIG. **5A** is a flow chart of an example flow for selecting computing clusters for replica and voting roles within a distributed database.

FIG. 5B shows equations that can be used in selecting computing clusters for replica and voting roles within a distributed database.

FIG. 6 is a block diagram of an example distributed computing environment in which some computing clusters are selected for replica and voting roles within a distributed database.

FIG. 7 is a flow chart of an example flow for periodically selecting computing clusters for roles in a distributed database.

FIG. 8A is a flowchart of example flow that may be used to identify replica locations and roles.

FIG. 8B is an example of pseudocode that may be used to implement the operations shown in FIG. 8A.

FIG. 9 are example formulas in the process shown in FIG. 8B.

FIG. 10A is a flowchart of example flow that may be used to identify replica locations and roles.

FIG. 10B is an example of pseudocode that may be used to implement the operations shown in FIG. 10A.

FIG. 11A is a flowchart of example flow that may be used to identify replica locations and roles.

FIG. 11B is an example of pseudocode that may be used to implement the operations shown in FIG. 11A.

FIG. 12 is a schematic diagram that shows an example of a computing system.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Distributed storage systems are widely used in the cloud, both within data centers as well as for replication across data centers. Many distributed databases assign roles to the computers that constitute the database. On such example is the Paxos protocol, in which the distributed database uses nodes in the system as "replicas" which replicate some or all of the distributed database. Additionally, the distributed database can use some or all of the nodes according to respective roles defined by the Paxos protocol that identify functions of the nodes. These roles include "client," "proposer," "voter," "learner," and "leader" roles. Clients can interact with the distributed database by issuing requests to a proposer of the distributed database. Proposers can propose an action in the distributed database, for example an update or query of the stored data. The voters (sometimes called acceptors) can accept or deny the proposed actions from the proposers. If a quorum of voters accept a proposal, the distributed database should complete the proposed action. Quorums may be a simple majority of voters or may require a different number of voters, depending on the configuration of the distributed database. Learners act on actions that have been approved by a quorum of the voters. The leader is a proposer, and in many cases, the only proposer that is able to successfully propose actions that will be accepted by a quorum of voters.

This document discusses the selection of replicas in a large distributed network, and the selection of roles for these replicas. In one example, a leader is selected from among candidate computing clusters (or servers, datacenters, etc.). To make this selection, an activity monitor predicts or monitors the workload of one or more clients. Different activities of the workload are given corresponding weights. The delay in performing requested activities, modified by these weights is found, and the candidate leader with the lowest weighted delay is selected as the leader. In another example, each candidate leader is examined, and a list of candidate replicas is identified in the network. To select a leader and replicas from the candidates, the candidate leader having replicas with the lowest communication delay with the leader are identified. Of those replicas, M can be assigned as voting replicas. In yet another example, two heuristics using global information about the computing environment are used, and the best result from the heuristics is selected.

In some configurations, these processes can use an activity monitor that is capable of collecting measurements of the distributed computing system and provide metrics for use in the configuration and execution of applications running on the system. For example, in order to identify the leader as described above, the activity monitor can monitor and/or predict the activity of a client application. Based on this activity measure, an accurate or likely weighting can be used to correctly select a leader. The use of such an activity monitor can provide a more accurate result than, for example, local heuristic tests, the human intuition of network administrators, or random chance. In some cases, an administrator can adjust the weights of the workload in order to achieve a desired property or configuration. For example, the administrator may know that commit latency is of particular importance, the weighting can be adjusted to more heavily consider commits, for example.

FIG. 1 is block diagram of an example distributed computing environment 100 that can be used to support distributed databases. In general, distributed databases can store data in shards distributed among the computing clusters of the distributed computing environment 100 that are included in the distributed database. The distributed computing environment 100 is shown schematically with nodes representing computing clusters 102-120 and edges representing communication links between the computing clusters 102-120. An activity monitor 122 can monitor the distributed computing environment 100 (e.g., interactions between clients and the distributed database, communication delays between elements of the distributed computing environment) and provide metrics for use in the configuration and execution of applications running on the distributed computing environment 100. A task assigning service 124 can, possibly using information from the activity monitor 122, assign the computing clusters to various roles within a distributed database running on the distributed computing environment 100. In some configurations, the activity monitor 122 and/or the task assigning service 124 are software services that run on one or more of the computer clusters 102-120.

The computer cluster 102-120 represent computing clusters, network servers, datacenters, one or more computers, or other appropriate computing systems able to work together to generate the distributed computing environment 100 and to execute computing tasks such as running software applications, creating virtual machines, etc. The computing clusters 102-120 may be made of heterogeneous or homogenous computing hardware that includes computer readable memory, processors, and network infrastructure to facilitate communication within a cluster and between clusters 102-120.

The distributed computing environment 100 can also include and/or interact with any number of clients, with clients 126 and 128 shown here. The clients 126 and 128 may be computing systems that are communicably coupled to the distributed computing environment 100 and/or may be computing clusters of the distributed computing environment 100. In any case, the clients 126 and 128 may interact with distributed computing environment 100 to perform distributed computing operations. In this example, the clients **126** and **128** are two clients that are associated with the same distributed database operating on the distributed computing system **100**. More or fewer clients can be associated with a distributed database, including a single client for a particular database. Further, the number and location of clients may change over time, with clients being added, moved, or removed.

The clients **126** and/or **128** may be elements of other computing system or application, and in some of those cases, the clients **126** and/or **128** may perform other, non-client related activities. For example, a web server (not shown) may serve webpages to many browsers (not shown) over the internet. To manage the content of this webpage, the web server may use a distributed database running on the computing environment **100**. To access the distributed database, the web server may communicate with or serve as, for example, the client **126**.

The client **126** and **128** perform workloads of requests to their associated distributed database. This workload include any technologically appropriate processes for interacting with a distributed database, including but not limited to reading, writing and deleting data; interpreting queries; etc. The activity monitor **122** can be configured to monitor the clients **126** and **128** in order to generate the workload data **130** and **132**, which describes the interactions with the distributed database by the clients **126** and **128**, respectively. The workload data **130** and **132** may take the form of, for example, logs of interactions with the distributed database, summary information such as counts of the types of interactions, classifications of the workload according to set of defined types of workloads, etc.

For each of the clients of distributed databases (e.g., one for client **126** and **128**, and for other distributed databases not shown), the task assigning service can assign some of the computing clusters **102-120** to be replicas, voters, or a leader. These distributed databases need not include all of the computing clusters **102-120**, and in some configurations may be associated with any technologically appropriate number of clients. For clarity, going forward, this document will discuss the selection and assignment of one distributed database associated with the clients **126** and **128**. However, it should be understood that these sorts of selections and assignments can be done for many distributed databases, possibly contemporaneously.

As will be described below, one computer cluster **102-120** is selected and assigned to the leader role. After this, N other computer clusters **102-120** are selected and assigned to be replicas, and M computer clusters are selected and assigned to be voters.

In order to select the leader, the activity monitor **122** can access and/or generate the workload **130** and **132**. The activity monitor **122** can then determine or predict the frequency of each process called by the clients **126** and **128**. The task assigning service **124** may then use these frequencies to weight the delay of each computer cluster **102-120** in performing the operations for the clients **126** and **128** and select the computer cluster **102-120** with the lowest weighted delay as the leader.

In addition to the calculations discussed below, additional constraints may be placed on replica and role allocations. For example, a constraint defining a minimum of central processing unit (CPU) resources may be set so that a leader is able to handle the requirements of leading. In some cases, it may be desirable to consider latency for only a subset of operations (e.g., just writes). To do so, some operations may be excluded from consideration; additional weightings can be used for different operations or types of operations, etc.

FIG. **2** is spreadsheet **200** of example calculations used to determine communication delays. For example, the spreadsheet **200** may be calculated by, or may represent internal calculations performed by, the task assigning service **124** as it selects a computer cluster **102-120** to be a leader of a distributed database. For clarity, the data is shown for a single client **126** of the distributed database, but this data may be extended to more clients, including all clients of a distributed database.

Cells **202** show the delay associated with processes that can be called by the clients **126** and **128** to the computer clusters **102-120** (some rows are excluded for clarity). The processes 1-4 may represent any appropriate process such as a data read, write, copy, etc. In this example, if the client **126** calls Process 1 to computer cluster **106**, the associated delay is shown as 28 milliseconds (ms). This 28 ms delay may be the delay between when the client **126** calls the process and when the process is completed, between call and receipt of confirmation by the client **126**, or any other technologically appropriate measure. That is, the delay can include time for processing the process, time for network delay (including routing through other computer clusters) and other delays.

Cells **204** show a measured or predicted frequency of the processes that the client **126** will call or has called. In this example, the number represents the number of times per second that a process is called as measured or predicted for a sample window of one minutes. For example, in sample 2, the client **126** calls the Process 2 0.4 times per second. However, any technologically appropriate scheme to show relative frequencies may be used. For example, the frequencies may be normalized to add to a particular value (e.g., 1 or 100). In this example, Sample1 is made as a naïve default that can be used when, for example, nothing is known about the client **126**. In the Sample1, each process is given the same value of 1, representing a default assumption that each process will be called the same number of times. In some configurations, different defaults may be used. For example, clients of a similar class to the client **126** may be examined and a probability distribution based on those similar client's recorded activity may be used. Sample2 and Sample3, in this example, represent measured process calls made by the client **126**.

Cells **206** show the total delay of all processes, weighted according to a sample. To find this total, for each computing cluster **102-120**, the delay for each process is weighted according to the corresponding weight in the sample, and the aggregation of the weighted delays is found. The calculations for computing cluster **110** under the weighting of Sample 2 will be shown below, as way of an example:

Total delay=(Process 1 delay*Sample 2 Process 1 frequency)+(Process 2 delay*Sample 2 Process 2 frequency)+(Process 3 delay*Sample 2 Process 3 frequency)+(Process 4 delay*Sample 2 Process 4 frequency)

Total delay=(66*0.5)+(11*0.4)+(76*1.3)+(59*1.6)

Total delay=230.6

Other types of aggregations are possible. Other examples include a median, a maximum, or any type of aggregation operating for a subset of operations. Such a subset may be only stat-altering operations or only reads, for example.

As previously described, the calculations shown in the spreadsheet **200** can be used for identifying the computing cluster **102-120** that, for a given workload **130**, would result in the minimum total delay. As such, the minimum total delays under Weight **1**, **2**, and **3** are shown in bold in the cells **206**. As shown, the computer cluster **102-120** with the minimum total delays for Weight **1**, **2**, and **3** are computer clusters **114**, **112**, and **108**, respectively. For purposes of clarity, the leader selection that follows will be described with respect to Sample 3, in which computer cluster **108** has the lowest weighted delay.

FIG. **3** is a flow chart of an example flow **300** for selecting a leader for a distributed database. For clarity, the flow **300** will be described with respect to the distributed computing environment **100** and the data related to Sample 3 in the spreadsheet **200**. However, other systems and other data may be used to perform the flow **300** or a similar process.

The flow **300** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select a computing cluster **102-120** as a leader role of a distributed database used by the client **126**. In general, this leader can be selected based on the expected delay required to perform the interactions identified in the workload **130**. By accessing data about the distributed computing environment **110**, the activity monitor is able to accurately identify the kinds of processes in the workload **130** and perform a leader selection more accurately than, for example, selections based off of incomplete and bias information.

Workload data is accessed **302**. For example, the activity monitor **122** can generate the workload data **130** that describes the historical interactions between the client **126** and the distributed database. This workload data **130** may be analyzed to, for example, understand the kinds of interactions that the client **126** is likely to have with the distributed database based on the recent or past behavior of the client **126**. In some cases, the activity monitor **122** can observe and log process calls made by the client **126** to the distributed database. In case historical records like the logs are not available (e.g., a new client joins or a new distributed database is created), the activity monitor can create predicted workload data. For example, if a client application has been used historically for a particular purpose, and the client **126** instantiates a new copy of the same client for the same purpose, the activity monitor **122** can use the old workload data from the other client and apply it to the client **126** for this purpose.

Process frequencies are generated **304**. For example, the activity monitor **122** can parse the historical data for the workload **130** to identify instances of the client **126** calling a process of the distributed database, along with associated timestamps, parameters used, etc. The activity monitor **122** can then generate data representing the frequency with which the client **126** calls the each process. Example data of this type is shown in the cells **204** of the spreadsheet **200**.

Process delays are accessed **306**. For example, the activity monitor **122** can generate, or access from another service, information about the delay needed for computing clusters **102-120** to complete the processes of the distributed database. This delay may include, for example, network delay caused by the communication between the client **126** and the clusters **102-120** and the processing delay needed by the cluster to perform the requested process. In many cases, irregular network topologies, computing resources, and load differentials can result in each cluster **102-120** having delay values that are different than the delay values of other clusters. Example data of this type is shown in the cells **202** of the spreadsheet **200**.

Minimum total weighted delays are found **308**. For example, the activity monitor **122** can find, for each of the computing clusters **102-120** of the distributed computing environment **100**, a total weighted delay. To find this delay, the activity monitor **122** can multiply each process' delay by the process' frequency, and sum these weighted delays. Example data of this type is shown in cells **206** of the spreadsheet **200**.

A computing cluster is assigned to a leader role **310**. For example, the activity monitor **122** can find the lowest total weighted delay and the task assigning service **124** can assign the associated computer cluster **102-120** to the leader role for the distrusted database. In the example of Sample 3 of the spreadsheet **200**, this minimum total weighted delay is 63.3 ms, associated with computing cluster **108**. As such, the task assigning service **124** can assign computing cluster **108** to the leader role.

FIG. **4** is block diagram of the example distributed computing environment **100** in which some computing clusters are candidates for replica and voting roles within a distributed database. As shown, the computing cluster **108** has been assigned to the leader role for a distributed database running on the distributed computing environment **100**. In this example, the leader role has been selected according to a process in which a minimum total weighted delay for a given workload is found. However, other processes for finding and assigning a leader could be used. For example, a human administrator could select the leader, a different metric could be created to find a leader, etc. Once some or all of the roles are selected, the distributed database can begin storing data of the distributed database in shards distributed among computing clusters **102-120**.

In addition to having a leader role, the task assigning service **124** can assign other computing clusters **102-106**, **110-120** to other roles in the distributed database. In this example, the distributed database will include five total replicas, with three of the replicas having a voting role. The leader in this example counts as a voting replica. In some cases, some computing clusters may host other clients (e.g., client **128**) of other distributed database, the client of this distributed database may be running on one of the computing clusters, and/or the activity monitor **122** and/or the task assigning service **124** may be running on one or more of the computing clusters of the distributed computing environment **100**.

With the leader selected, and having specified that the distributed database should have five replicas, three of which are voting, the activity monitor **122** and the task assigning service **124** can determine which of the other computing clusters **102-106**; **110-120** are to be assigned to replica and voting roles. In this example, activity monitor **122** can find the communication round-trip time (RTT) between the leader computing cluster **108** and the other computing clusters **102-106**; **110-120**. Based on the RTTs, the task assigning service can assign, to the two computing clusters **102-106**; **110-120** with the lowest RTTs, a voting role in the distributed database. The task assigning service can assign, to the two computing cluster **102-106**; **110-120** with the next two lowest RTTs, a replica role within the distributed database. By doing both, the task assigning service **124** can thus assign a total of five replicas (two replica role, two voting role, one leader role) with three voting replicas (two voting role, one leader role).

FIG. **5**A is a flow chart of an example flow **500** for selecting computing clusters for replica and voting roles within a distributed database. For clarity, the flow **500** will be described with respect to the distributed computing environment **100**. However, other systems may be used to perform the flow **500** or a similar process.

The flow **500** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replica, and to assign leader and voting roles of a distributed database used by the clients **126** and **128**. In general, each computing cluster **102-120** can be considered as a candidate leader. Then, replica and voting roles can be selected based on the expected RTT to communicate with the candidate leader. The candidate leader showing the best performance (e.g., minimum total RTT between the leader and every replica) can then be selected as the actual leader, with the corresponding replica and voting roles assigned. By accessing data about the distributed computing environment **110**, the activity monitor is able to accurately identify the delays in the distributed computing environment **100** and perform role selection more accurately than, for example, selections based off of incomplete and bias information.

The number of voters (M) and number of replicas (N) are identified **502**. For example, the client **126** can request to the distributed computing environment **100** to generate a distributed database. This request may include a request to have five replicas to provide redundancy in case one replica is down for maintenance and another replica fails or in case two replicas fail, three replicas will still be available. The request may further request to have three voting replicas.

With M and N specified, the task assigning service **124** may provisionally assign **504** to a candidate leader role to a computer cluster **102-120** of the distributed computing environment **100**. For clarity, this example will consider computing cluster **108** as a candidate leader. This provisional assignment may be based on, for example, random or ordered selection, the delay associated with completing processes in the workload **130**; based on a heuristic looking at the client **126** and or the distributed computing environment **100**; a user selection; or any other technologically appropriate process.

M clusters are identified **506**. For example, the activity monitor **122** can track activity within the distributed computing environment **100**, including but not limited to tracking the RTTs between the computing clusters **102-120** and other metrics. For example, the activity monitor can identify the leader that minimized operational latency with other replicas using equation **550** of FIG. **5**B. In the equation **550**,$\lambda^{(i)}_{db}$ is the candidate leader, $\text{score}^{(i)}(I)$ is equal to equation **551**. Using these calculations, the activity monitor **122** can then identify the M computing clusters **102-106**; **110-120** associated with the best score using equation **550**. In this example, M is two, and the computing clusters **102** and **110** are the M are identified.

The score for the candidate leader is determined **508**. For example, the activity monitor can score the leader according to a metric used to identify the quality of the candidate leader, compared to other candidate leaders. One example calculation could be the total RTT between the candidate leader and each of the M clusters. Another example calculation could be finding the k-th smallest RTT between the candidate leader and other replicas, where k=[(num_voters+1)/2].

The steps **504-508** are then repeated for each possible candidate leader. This pool of candidate leaders may include all of the computing clusters **102-120**, or some of the computing clusters **102-120** may be excluded. For example, some of the computing clusters **102-120** may be excluded if they do not have sufficient computing resources, are located in an undesirable geographic location, etc. Once completed for each candidate leader, the candidate leader associated with the most preferable overall configuration is selected. For example, the most preferable may be the candidate having the lowest score according to the metric used to identify the quality of the candidate leader previously discussed.

The M clusters are assigned to a voting role **506**. With the M computing clusters **102** and **110** identified, the task assigning service **124** can assign to the M computing clusters **102** and **110** a voting role for the distributed database requested by the client **126**.

N clusters are assigned to a replica role **510**. The activity monitor **122** and/or the assigning service **124** may select N computing clusters to be assigned to a replica role (e.g., a replica that is not a voter) according to any technologically appropriate process. For example, the task assigning service **124** may assign replica roles near clients, to computing clusters **102-120** with low operating costs, to computing clusters **102-120** in preferred jurisdictions, or based on geographic concerns. In this example, the task assigning service **124** can assign the N computing clusters **106** and **112** a replica role for the distributed database requested by the client **126**.

The flow **500** has been described to select for best results on the expected latency. In another example, a selected configuration may be one that reduces tail latency.

When considering tail latency, linear properties may not provide useful metrics. Instead, an alternative score calculation is shown in equations **552** in FIG. **5**B. As input, instead of the average roundtrip-time latencies, the roundtrip-time latency distribution $H_{a,b}$ between each pair of locations a and b is used. In other words, $H_{a,b}$ is based on the round trip time between each communication link between each computing cluster. For clarity, it will be assumed that these distributions are independent and that the latencies are discretized as multiples of 1 ms.

When computing the latency for each operation type, instead of summing averages, the distributions of the sum of the random variables is computed. As an example, consider a simple case of a bounded read, which travels from a client c to the closest replica nearest(c,R), then from nearest(c,R) to the leader/and back all the way to the client. In order to find the latency distribution of this operation, a discrete convolution $H_{c,nearest(c,r)} * H_{nearest(c,R),l}$ is performed, as shown in the equations **552**. In the equation **552**, m denotes the minimum possible value of $t^{(i)}_{bounded\ read,\ c}(I)$ and rtt is the random variable corresponding to the latency (rather than the average latency). Once the distribution of the sum has been computed, the required percentile can be taken from the distribution. This required percentile may be a user selected input, or received from a different source. For example, a database administrator may be interested to minimize the 99% latency, and would thus supply 99% as the required percentile.

In this implementation, a quorum latency is determined as a variable. A quorum latency is the latency for a quorum of voters to approve a vote after the vote is submitted to the quorum. One process of computing a quorum latency is to compute a distribution of quorum latencies. This involves selecting multiple different quorums from a group and computing a latency for each selected quorum. One numeric method to do this is to perform a Monte Carlo simulation, repeatedly sampling the distributions $H_{l,v}$ for $v \in V$ and computing the median latency for each time. For an analytical solution, observe that the leader needs to collect majority-1 responses from the other servers, where majority←[(|V|+1)/2] and assume that the leader's own response arrives faster than any other response. The cumulative distribution function (CDF) of the maximum response time for any set of read-write replicas is simply the product of the CDFs of response time for the individual replicas. For example, for 3 read-write replicas l, v and w where l is the candidate leader, see equation **554**. In other words, the CDF of the maximum is the probability that the maximum is less than x for different values of x. The maximum of events a and b is less than x when both a and b are less than x. If events a and b are independent, then the probability that both a and b are less than x is equal to the probability that a is less than x multiplied by the probability that b is less than x.

Therefore, the CDF of the maximum response time can be calculated for every subset of read-write replicas can be constructed. From these, using the inclusion-exclusion principal, the probability of the event that at least one subset of the read-write replicas, of cardinality majority-1, has maximum response latency less than x can be computed, for each x. This event is equivalent to the event that the quorum's response time is less than x, hence it gives the CDF of the quorum response time. Continuing the example of 3 read-write replicas, the equation **556** is provided. In other words, the equation **556** applies the principal that a union of two sets A and B is A+B-their intersections. The intersection may be removed, for example, to avoid double counting the members of the intersection.

FIG. **6** is a block diagram of the distributed computing environment **100** in which some computing clusters **102**-**120** are selected for replica and voting roles within a distributed database. In this example, the activity monitor **122** and the task assigning service **124** have used the flow **500** to assign the computing cluster **108** to a leader role in the distributed database, the computer clusters **102** and **110** to a voting role in the distributed database and assign the computer clusters **106** and **112** to a replica role in the distributed database.

With these roles assigned to the clusters **102**-**112**, the client **126** may interact with the distributed database, for example, to store, manipulate, and access data. In addition, the client **128** and other clients may use the distributed computing environment **100** to run other distributed databases and to run other software and services. In many cases, the overall usage of the distributed computing environment **100** can change over time. This change may be periodic or cyclical.

For example, the distributed computing environment **100** may physically span the Earth. As different population centers around the Earth transition from day to night, their usage of the distributed computing environment **100** can change. For example, many clients are most active during the work day and are less active at night and on weekends. Other cyclical changes can occur on different time frames. For example, e-commerce and accounting system may have heavier usage at year end, which are heavy holiday shopping and account closing times in many countries. Similarly, systemic changes can be made to the distributed computing environment **100**. New clients can come online, old clients removed, resources can be added to or removed from existing computing clusters **102**-**120**, computing clusters can be added and removed, network communication links changed, etc.

All of these changes can result in changing performance by the distributed computing environment **100**. To account for these changes, the processes described here, in which roles of a distributed database are assigned to computing clusters of the distributed computing environment **100**, may be repeated. This may result in some or all of the roles reassigned to different computing clusters.

FIG. **7** is a flow chart of an example flow **700** for periodically selecting computing clusters for roles in a distributed database. For clarity, the flow **700** will be described with respect to the distributed computing environment **100**. However, other systems may be used to perform the flow **700** or a similar process.

The flow **700** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102**-**120** as leader, replica, and voting roles of a distributed database used by the client **126**. Once the roles are selected and the activity monitor **122** can generate accurate workload data for the client **126** and to take advantage of periodic or system changes to the distributed computing environment **100**, portions of the flow **700** can be repeated to reassign the roles of the distributed database.

A new client is identified, and the new client's workload is determined **702**. For example, the client **126** can request a new distributed database be created on the distributed computing environment **100**. The activity monitor **122** can generate data to predict the type of workload **130** that the client **126** will produce. In some cases, the activity monitor may use heuristics. Information about the client **126**, the users of the client **126**, and other data may be used to formulate a predicted workload. In some cases, the activity monitor **122** can identify a client similar to the client **126** and use the similar client's workload in place of the client **126**'s workload **130**. For example, if the client **126** is an off-the-shelf e-commerce application, the activity monitor **122** can use historical workload data from other instances of the same e-commerce application to predict the workload of the client **126**.

A leader is identified and assigned **704**. For example, the activity monitor **122** and/or the task assigning service **124** can use the flow **300**, or any other process, to identify and select one of the computing clusters **102**-**120** as the leader for the distributed database.

Other roles are identified and assigned **706**. For example, the activity monitor **122** and/or the task assigning service **124** can use the flow **500**, or any other process, to identify and select one or more of the computing clusters **102**-**120** as, for example, voters and replicas for the distributed database.

Operations of the client are observed **708** and actual workload for the client is calculated **710**. For example, as the client operates, the activity monitor **122** can track the activity of the client **126**, or receive data from another system tracking the activity of the client **126**. From this, the activity monitor can generate data reflecting the actual workload **130**.

The flow **704**-**710** can be repeated. These may be repeated according to one or more scheduled, and/or for one or more reasons.

One reason for repeating the flow **704**-**710** is to reassign roles that were assigned using predicted, instead of historical, information about the workload **130**. For example, after assigning the roles based on the predicted workload for the client **126**, the task assigning service **124** can later reassign those roles based on the real workload **130** that has been observed.

Another reason for repeating the flow **704**-**710** is to reassign roles after one or more systemic changes to the client **126** and/or the distributed computing network **100**. For example, the client **126** may be part of the back-end of a webpage that receives a large increase is user traffic. This may result in a change to the workload **130**, and thus there may be a configuration of roles that could increase the efficiency of the distributed database. In another example, new network infrastructure may change the communication delay between some of the computer clusters **102-120**, and thus there may be a configuration of roles that could increase the efficiency of the distributed database.

Another reason for repeating the flow **704-710** is to reassign roles to take advantage of periodic changes to the distributed computing system's **100** workload. For example, during the day local to the client, one configuration of roles may be most efficient, but at night local to the client, a different configuration of roles may be more efficient. By timing the repetition properly (e.g., every 12 hours, monthly, quarterly), these changes may be taken advantage of.

In addition to, or in the alternative to, using the previously described processes for selecting replicas and assigning roles to the replicas, there are other processes for selecting replicas and assigning roles to the replicas. As will be described, these processes may be used together, or only one or some of the processes may be used.

Described now will be a process by which two operations are used to select the best set of replicas R from possible locations S, a set of voters V⊆R (that is, the voters are a subset or equal to the set of replicas), and the best leader from V. By use of these operations, large savings in computational time may be realized. For example, some brute force search methods may require hours or days to compute, while this process may compute within minutes or seconds.

FIG. **8**A is a flowchart of example flow **800** that may be used to identify replica locations and roles. For clarity, the flow **800** will be described with respect to the distributed computing environment **100**. However, other systems may be used to perform the flow **800** or a similar process.

The flow **800** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replicas. In general, a few computing clusters **102-120** are assigned as replicas and treated as centroids. Additional centroids are identified near clients with heavy usage, and then the replica locations are refined.

An initial set of replica location are received **802** as centroids. For example, the activity monitor **122** and the task assigning service **124** may select one, two, or three of the computing clusters **102-120** as centroids.

Initial locations for remaining centroids are chosen **804** for the remaining centroids. For example, the activity monitor **122** can identify the clients **126** and **128** with the heaviest workload based on the workload data **130** and **132** and the task assigning service **124** can assign the nearest computing clusters **102-120** as centroids.

The positions of centroids are adjusted **806** to reduce cost. For example, the activity monitor **122** and the task assigning service **124** can change the selected centroids.

The selected centroids are returned **808**. For example, when an end condition is met (e.g. lack of sufficient cost improvements per change), the task assigning service **124** can set the centroids as replicas.

FIG. **8**B is an example of pseudocode **850** that may be used to implement the flow **800**. For clarity, the pseudocode **850** will be described with respect to the distributed environment **100**. However, other systems may be used to perform the pseudocode **850** or a similar process.

The pseudocode **850** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replicas. In general, groups of the computing clusters **102-120** around each client are iteratively identified until a final set of replicas are identified. Then, based on the selection of those replicas, voting and leader roles are assigned.

The flow **500** uses a variant of a weighted K-Means. The flow **500** assigns a weight **14**), to each client c (e.g., clients **126** and **128**) based on the total number of operations performed by c. In some examples, the value for we may be calculated with the formula **900** shown in FIG. **9**. As part of the operation of the pseudocode **850**, the pseudocode **850** can be configured to find a minimum value for cost(G), according to the formula **902**.

The pseudocode **850** received an initial set of replica locations, called centroids L_{fixed}, selected from the computing clusters **102-120**. Additionally, the pseudocode **850** receives a value num_replicas that specifies the number of desired replica location. The task assigning service **124** chooses initial locations for the remaining centroids (lines **6-10**) by placing them close to the "heaviest" client according to we. Each centroid location g defines a set of client clusters C g for which g is the nearest centroid (line **15**). The remainder of the pseudocode **850** adjusts the position of each centroid g in a way that minimizes cost (weighted roundtrip-time) for clients in C g. The centroids L_{fixed} may be set and not moved. The process can complete returning the set of centroids G once there is no sufficient improvement in the total cost (i.e. formula **902**).

FIG. **10**A is a flowchart of example flow **1000** that may be used to identify replica locations and roles. For clarity, the flow **1000** will be described with respect to the distributed computing environment **100**. However, other systems may be used to perform the flow **1000** or a similar process.

The flow **1000** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replicas. In general, replica locations are found, and then roles are assigned.

A number of replicas and a number of voters is received **1002**. For example, a new distributed database may be set up in the computing environment **100**. As part of this set, an administrator may select the number of replicas and number of voters to be included in the distributed database.

Computing clusters are identified **1004** as replicas. For example, the activity monitor **122** and the task assigning service **124** may select the appropriate number of the computing clusters **102-120** as replicas.

Roles are assigned **1006** to replicas. For example, the activity monitor **122** and the task assigning service **124** may assign, to the replicas, roles in the distributed database.

FIG. **10**B is an example of pseudocode **1050** that may be used to implement the flow **1000**. For clarity, the pseudocode **1050** will be described with respect to the distributed environment **100**. However, other systems may be used to perform the pseudocode **1050** or a similar process.

The pseudocode **1050** can be performed by, for example the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replicas and then to assign roles to the selected computing clusters **102-120**. In general, the pseudocode **1050** may be called "KQ" because it first uses a weighted K-Means operations to find replica location, then if finds a Q quorum. By way of comparison, the pseudocode **1150**, described below, may be called "QK" because if first finds a Q quorum then uses K-Means to find replica locations.

The pseudocode **1050** can receive num_replicas and num_voters (e.g., N and M as described above) as input values that specify the number of replicas and voters, respectively, which the distributed database should have. These values may often be configured based on the design goals or usage of the distributed database. For example, a num_voters of 7 and a quorum of 4 may be selected for a computing environment **100** that has never experienced more than 3 computing clusters **102-120** being unavailable at once.

The num_replicas and num_voters received, the activity monitor **122** and the task assigning service **124** can perform the pseudocode **850** in order to identify the G replicas of the computing clusters **102-120**. Next, the activity monitor **122** and the task assigning service **124** can perform the flow **500** to assign roles, to the G computing clusters **102-120**. The pseudocode **1050** can then return the leader, set of voters, and set of replicas.

FIG. **11**A is a flowchart of example flow that may be used to identify replica locations and roles. For clarity, the flow **1100** will be described with respect to the distributed computing environment **100**. However, other systems may be used to perform the flow **1100** or a similar process.

The flow **1100** can be performed by, for example, the activity monitor **122** and the task assigning service **124** in order to select computing clusters **102-120** as replicas. In general, for each leader candidate, a leader and a quorum of voters are placed, then the remaining replicas are placed near clients.

A leader candidate is selected **1102**. For example, a new distributed database may be set up in the computing environment **100**. To find the computing clusters **102-104**, the task assigning service **124** can select a candidate computing cluster **102-120** as a candidate leader.

At least a quorum of voters are assigned **1104**. For example, the task assigning service **124** can select a number of computing clusters **102-120** nearest the leader and assign these computing clusters **102-120** as voters.

The remaining replicas are assigned **1106**. For example, the task assigning service **124** can assign additional computing clusters **102-120** near clients **126** and **128** as voters or replicas.

The flow **1102-1106** are repeated for each candidate leader, and for the best candidate leader, the roles are assigned **1108**. For example, the task assigning service may find the candidate leader with the best overall configuration, and assign the roles associated with that candidate leader.

FIG. **11**B is an example of pseudocode that may be used to implement the flow **1100** shown in FIG. **11**A. For clarity, the pseudocode **1150** will be described with respect to the distributed environment **1100**. However, other systems may be used to perform the pseudocode **1150** or a similar process.

The pseudocode **1150** can be performed by, for example the activity monitor **122** and the task assigning service **124** in order to select a leader, voters, and replicas from the computing clusters **102-120**. As previously identified, the process may be referred to as "QK" because if first finds a Q quorum then uses K-Means to find replica locations.

The pseudocode **1150** first sets the leader and a quorum of voters and then places the remaining replicas close to the clients. More specifically, each possible leader location in S is considered to find the best quorum for this leader. The quorum is then considered as centroids that are 'pinned' and not moved.

FIG. **12** is a schematic diagram that shows an example of a computing system **1200**. The computing system **1200** can be used for some or all of the operations described previously, according to some implementations. The computing system **1200** includes a processor **1210**, a memory **1220**, a storage device **1230**, and an input/output device **1240**. Each of the processor **1210**, the memory **1220**, the storage device **1230**, and the input/output device **1240** are interconnected using a system bus **1250**. The processor **1210** is capable of processing instructions for execution within the computing system **1200**. In some implementations, the processor **1210** is a single-threaded processor. In some implementations, the processor **1210** is a multi-threaded processor. The processor **1210** is capable of processing instructions stored in the memory **1220** or on the storage device **1230** to display graphical information for a user interface on the input/output device **1240**.

The memory **1220** stores information within the computing system **1200**. In some implementations, the memory **1220** is a computer-readable medium. In some implementations, the memory **1220** is a volatile memory unit. In some implementations, the memory **1220** is a non-volatile memory unit.

The storage device **1230** is capable of providing mass storage for the computing system **1200**. In some implementations, the storage device **1230** is a computer-readable medium. In various different implementations, the storage device **1230** may be a floppy disk device, a hard disk device, an optical disk device, or a tape device.

The input/output device **1240** provides input/output operations for the computing system **1200**. In some implementations, the input/output device **1240** includes a keyboard and/or pointing device. In some implementations, the input/output device **1240** includes a display unit for displaying graphical user interfaces.

Some features described can be implemented in digital electronic circuitry, or in computer hardware, firmware, software, or in combinations of them. The apparatus can be implemented in a computer program product tangibly embodied in an information carrier, e.g., in a machine-readable storage device, for execution by a programmable processor; and method steps can be performed by a programmable processor executing a program of instructions to perform functions of the described implementations by operating on input data and generating output. The described features can be implemented advantageously in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program is a set of instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment.

Suitable processors for the execution of a program of instructions include, by way of example, both general and special purpose microprocessors, and the sole processor or one of multiple processors of any kind of computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for executing instructions and one or more memories for storing instructions and data. Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files; such devices include magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM (erasable programmable read-only memory), EEPROM (electrically erasable programmable read-only memory), and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM (compact disc read-only memory) and DVD-ROM (digital versatile disc read-only memory) disks. The processor and the memory can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

To provide for interaction with a user, some features can be implemented on a computer having a display device such as a CRT (cathode ray tube) or LCD (liquid crystal display) monitor for displaying information to the user and a keyboard and a pointing device such as a mouse or a trackball by which the user can provide input to the computer.

Some features can be implemented in a computer system that includes a back-end component, such as a data server, or that includes a middleware component, such as an application server or an Internet server, or that includes a front-end component, such as a client computer having a graphical user interface or an Internet browser, or any combination of them. The components of the system can be connected by any form or medium of digital data communication such as a communication network. Examples of communication networks include, e.g., a LAN (local area network), a WAN (wide area network), and the computers and networks forming the Internet.

The computer system can include clients and servers. A client and server are generally remote from each other and typically interact through a network, such as the described one. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

What is claimed is:

1. A computer-implemented method comprising:

generating, by data processing hardware, predicted workload data indicating a predicted weighted communication delay for each respective computing cluster of a plurality of computing clusters in performing one or more operations for a client application;

monitoring, by the data processing hardware, interactions between the client application and a distributed database executing the plurality of computing clusters, one of the plurality of computing clusters assigned a leader computing cluster role responsible for proposing operations for the plurality of computing clusters to perform on the distributed database based on the predicted weighted communication delay;

generating, by the data processing hardware and based on the interactions between the client application and the distributed database, historical workload data indicating a historical weighted communication delay for each respective computing cluster of the plurality of computing clusters in performing one or more operations for the client application;

determining, by the data processing hardware, that a different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster based on the historical workload data; and

based on determining that the different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster, assigning, by the data processing hardware, the different computing cluster the leader computing cluster role.

2. The computer-implemented method of claim **1**, wherein the distributed database comprises one or more voters that are configured to accept or deny the proposed operations of the one of the plurality of computing clusters assigned the leader computing cluster role.

3. The computer-implemented method of claim **2**, wherein the distributed database comprises one or more replicas that replicate at least a portion of the distributed database.

4. The computer-implemented method of claim **3**, wherein the operations further comprise, in response to assigning the different computing cluster the leader computing cluster role, assigning, by the data processing hardware, one or more new voters and one or more new replicas for the distributed database.

5. The computer-implemented method of claim **4**, wherein a quantity of the one or more new voters is equal in number to a quantity of the one or more voters.

6. The computer-implemented method of claim **4**, wherein a quantity of the one or more new replicas is equal in number to a quantity of the one or more replicas.

7. The computer-implemented method of claim **1**, wherein the operations further comprise, for each respective computing cluster:

determining, by the data processing hardware and based on the historical workload data, a communication delay for the respective computing cluster interacting with the client application;

identifying, by the data processing hardware, a frequency of the interactions; and

determining, by the data processing hardware, the historical weighted communication delay based on the communication delay and the frequency of the interactions.

8. The computer-implemented method of claim **1**, wherein the historical workload data comprises logs of the interactions between the client application and the distributed database.

9. A system comprising:

data processing hardware; and

memory hardware in communication with the data processing hardware, the memory hardware storing instructions that when executed on the data processing hardware cause the data processing hardware to:

generate predicted workload data indicating a predicted weighted communication delay for each respective computing cluster of a plurality of computing clusters in performing one or more operations for a client application;

monitor interactions between the client application and a distributed database executing the plurality of computing clusters, one of the plurality of computing clusters assigned a leader computing cluster role responsible for proposing operations for the plurality of computing clusters to perform on the distributed database based on the predicted weighted communication delay;

generate, based on the monitored interactions between the client application and the distributed database, historical workload data indicating a historical weighted communication delay for each respective computing cluster of the plurality of computing clusters in performing one or more operations for the client application;

determine that a different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster based on the historical workload data; and

based on determining that the different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster, assign the different computing cluster the leader computing cluster role.

10. The system of claim **9**, wherein the distributed database comprises one or more voters that are configured to accept or deny the proposed operations of the one of the plurality of computing clusters assigned the leader computing cluster role.

11. The system of claim **10**, wherein the distributed database comprises one or more replicas that replicate at least a portion of the distributed database.

12. The system of claim **11**, wherein the instructions further cause the data processing hardware to, in response to assigning the different computing cluster the leader computing cluster role, assign one or more new voters and one or more new replicas for the distributed database.

13. The system of claim **12**, wherein a quantity of the one or more new voters is equal in number to a quantity of the one or more voters.

14. The system of claim **12**, wherein a quantity of the one or more new replicas is equal in number to a quantity of the one or more replicas.

15. The system of claim **9**, wherein the instructions further cause the data processing hardware to, for each respective computing cluster:

determine, based on the historical workload data, a communication delay for the respective computing cluster interacting with the client application;

identify a frequency of the interactions; and

determine the historical weighted communication delay based on the communication delay and the frequency of the interactions.

16. The system of claim **9**, wherein the historical workload data comprises logs of the interactions between the client application and the distributed database.

17. A non-transitory computer-readable storage medium encoded with instructions that, when executed by one or more processors of a computing system, cause the one or more processors to:

generate predicted workload data indicating a predicted weighted communication delay for each respective computing cluster of a plurality of computing clusters in performing one or more operations for a client application;

monitor interactions between the client application and a distributed database executing the plurality of computing clusters, one of the plurality of computing clusters assigned a leader computing cluster role responsible for proposing operations for the plurality of computing clusters to perform on the distributed database based on the predicted weighted communication delay;

generate, based on the monitored interactions between the client application and the distributed database, historical workload data indicating a historical weighted communication delay for each respective computing cluster of the plurality of computing clusters in performing one or more operations for the client application;

determine that a different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster based on the historical workload data; and

responsive to determining that the different computing cluster of the plurality of computing clusters has less historical weighted communication delay than the leader computing cluster, assign the different computing cluster the leader computing cluster role.

18. The non-transitory computer-readable storage medium of claim **17**, wherein the distributed database comprises one or more voters that are configured to accept or deny the proposed operations of the one of the plurality of computing clusters assigned the leader computing cluster role.

19. The non-transitory computer-readable storage medium of claim **18**, wherein the distributed database comprises one or more replicas that replicate at least a portion of the distributed database.

20. The non-transitory computer-readable storage medium of claim **19**, wherein the instructions further cause the one or more processors to, in response to assigning the different computing cluster the leader computing cluster role, assign assigning one or more new voters and one or more new replicas for the distributed database.

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