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

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(45) **Date of Patent: Jan. 15, 2019**

(54) **METHODS AND SYSTEMS TO ENHANCE IDENTIFYING SERVICE-LEVEL-OBJECTIVE DEGRADATION IN A DATA CENTER**

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(72) Inventors: **Ashot Nshan Harutyunyan**, Yerevan (AM); **Naira Movses Grigoryan**, Yerevan (AM); **Arnak Poghosyan**, Yerevan (AM)

(73) Assignee: **VMware, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 218 days.

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(51) **Int. Cl.**

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H04L 12/24	(2006.01)
H04L 12/26	(2006.01)

(52) **U.S. Cl.**

CPC ***H04L 41/5016*** (2013.01); ***H04L 43/08*** (2013.01); ***H04L 43/16*** (2013.01)

(58) **Field of Classification Search**

CPC H04L 41/0213; H04L 29/08072; H04L 29/06; H04L 41/22; H04L 41/12; H04L 41/5016; H04L 43/08; H04L 43/16; G06Q 10/06393; G06Q 10/06; G06Q 10/063; G06Q 10/0639; G06Q 10/00

USPC 705/7.39; 709/223

See application file for complete search history.

(56) **References Cited**

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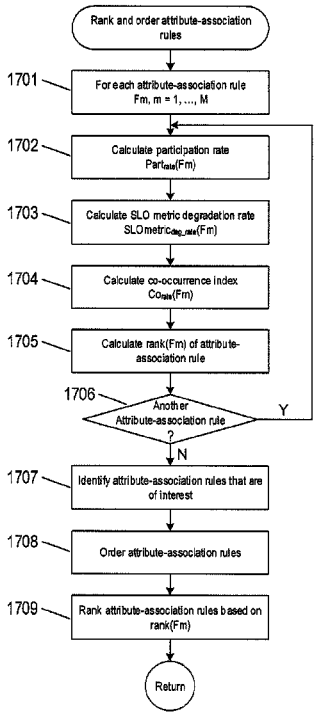
Primary Examiner — Robert B Harrell

(74) *Attorney, Agent, or Firm* — Clayton, McKay & Bailey, PC

(57) **ABSTRACT**

Methods recommend to data center customers those attributes of a data center infrastructure and application program that are associated with service-level objective ("SLO") metric degradation and may be recorded in problem definitions. In other words, a data center customer is offered to "codify" problems primarily with atomic abnormality conditions on indicated attributes that decrease the SLO by some degree that the data center customer would like to be aware. As a result, the data center customer is warned of potentially significant SLO decline in order to prevent unwanted loss and take any necessary actions to prevent active anomalies. Methods also generate patterns of attributes that constitute core structures highly associated with degradation of the SLO metric.

15 Claims, 23 Drawing Sheets



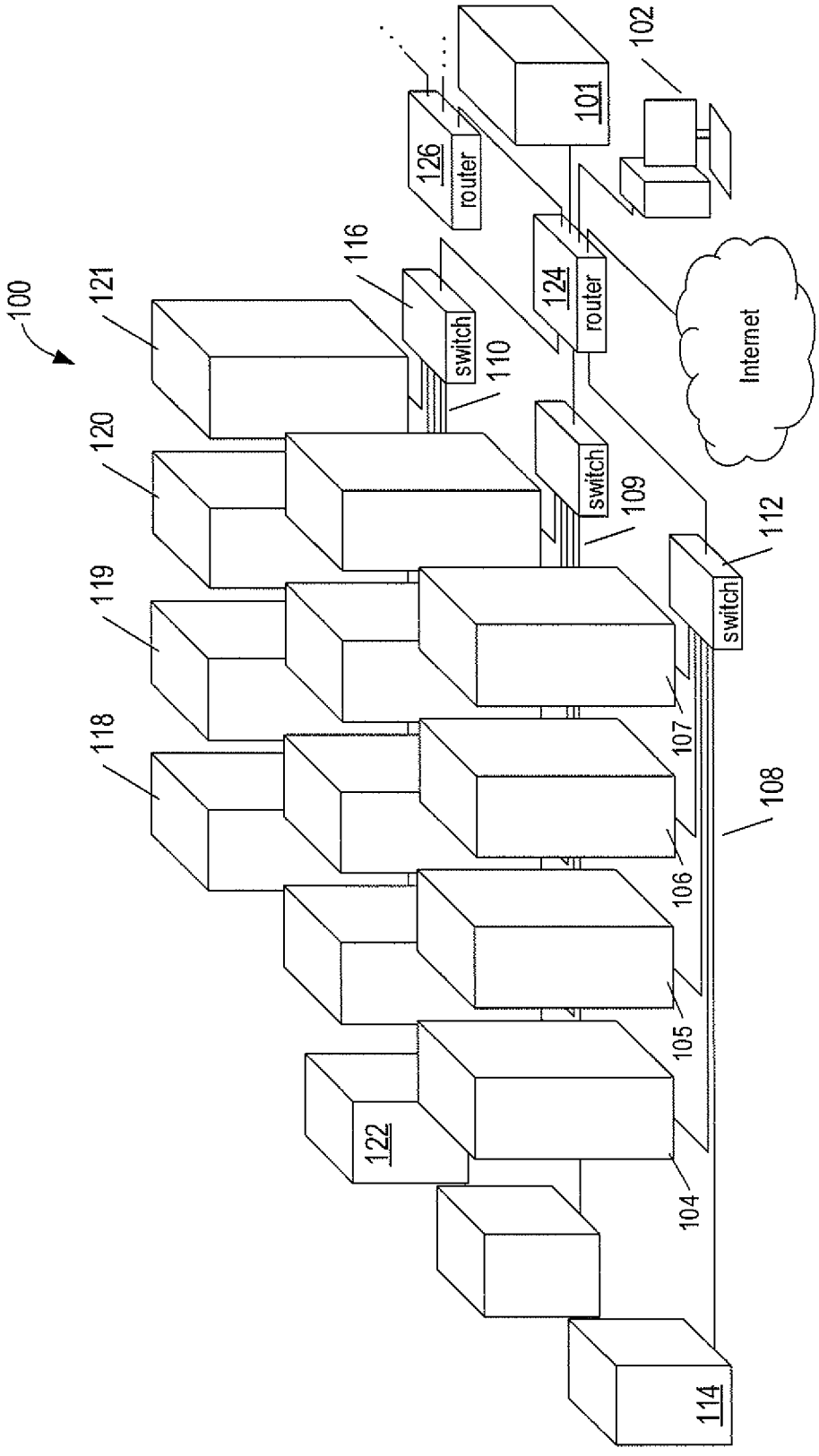

100
121
120
119
118
116
110
109
112
107
108
106
105
104
122
114
126
router
124
router
101
102
switch
switch
switch
Internet

FIG. 1

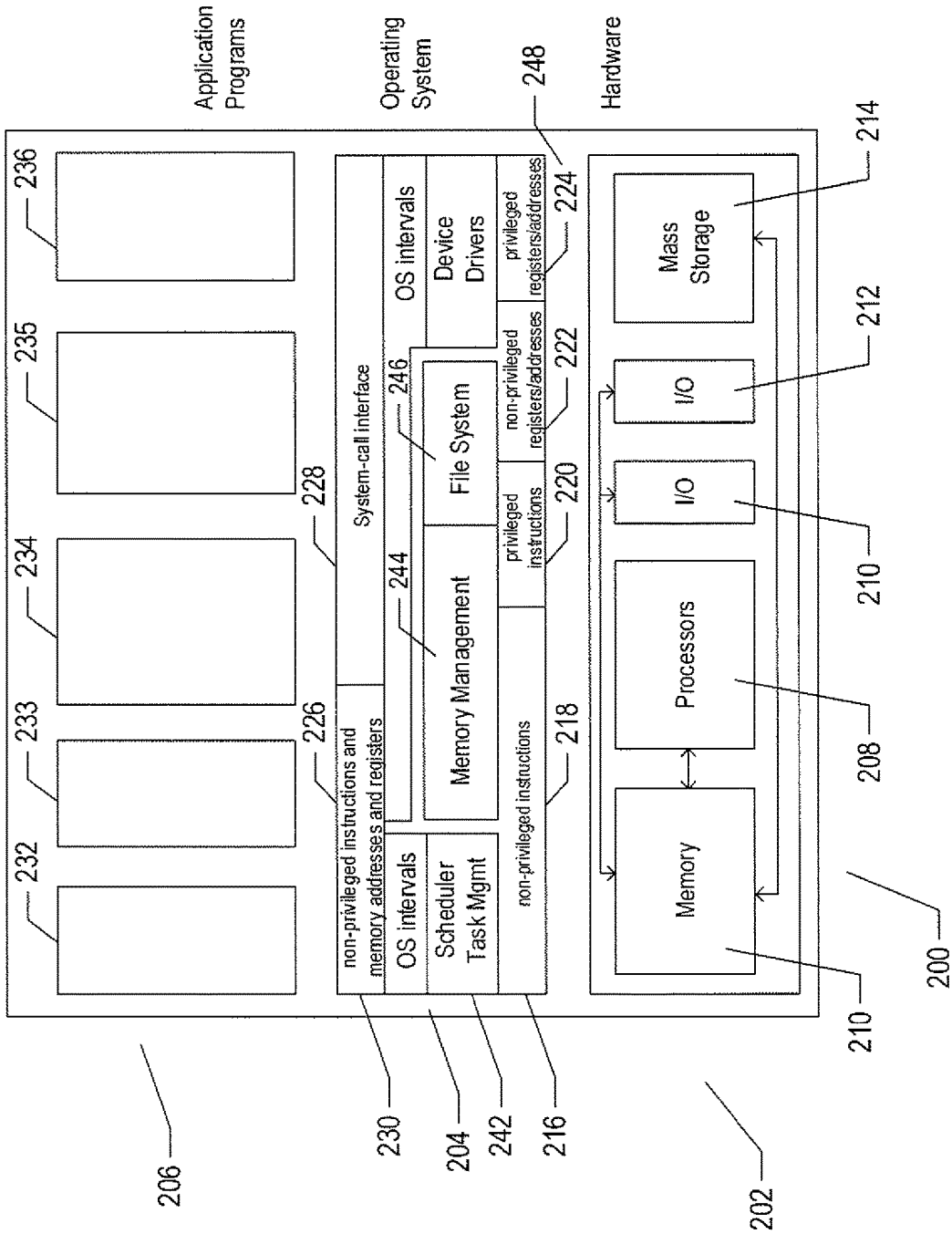

Application Programs
Operating System
Hardware
232
233
234
235
236
226
228
non-privileged instructions and memory addresses and registers
System-call interface
OS intervals
Scheduler Task Mgmt
Memory Management
File System
Device Drivers
non-privileged instructions
privileged instructions
non-privileged registers/addresses
privileged registers/addresses
218
220
222
224
244
246
248
Memory
Processors
I/O
I/O
Mass Storage
210
208
212
214
200
202
204
206
210
216
230
242

FIG. 2

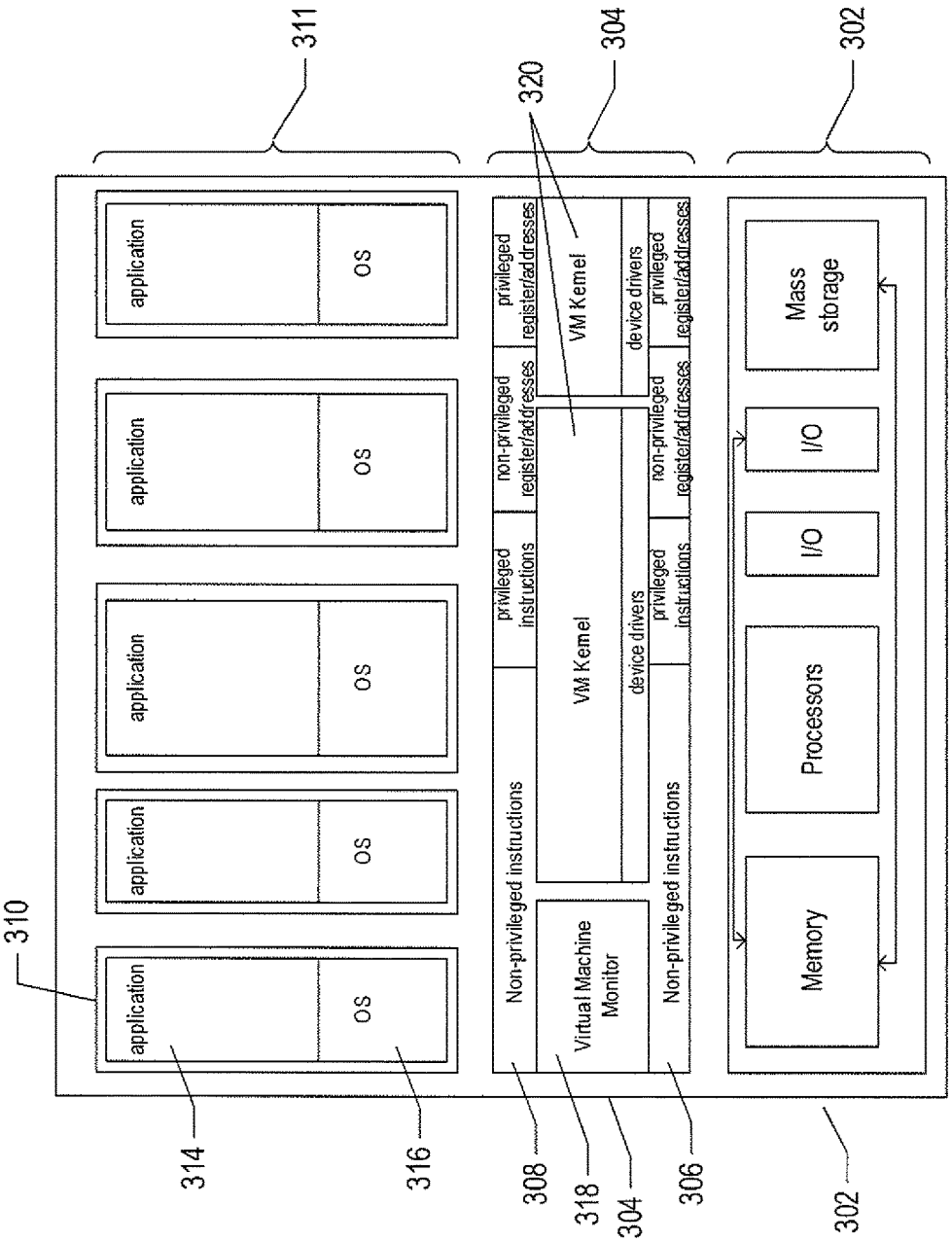

310
311
320
304
302
application
OS
Non-privileged instructions
Virtual Machine Monitor
privileged instructions
non-privileged register/address
VM Kernel
device drivers
privileged register/address
Memory
Processors
I/O
Mass storage
314
316
308
318
304
306
302
300

FIG. 3A

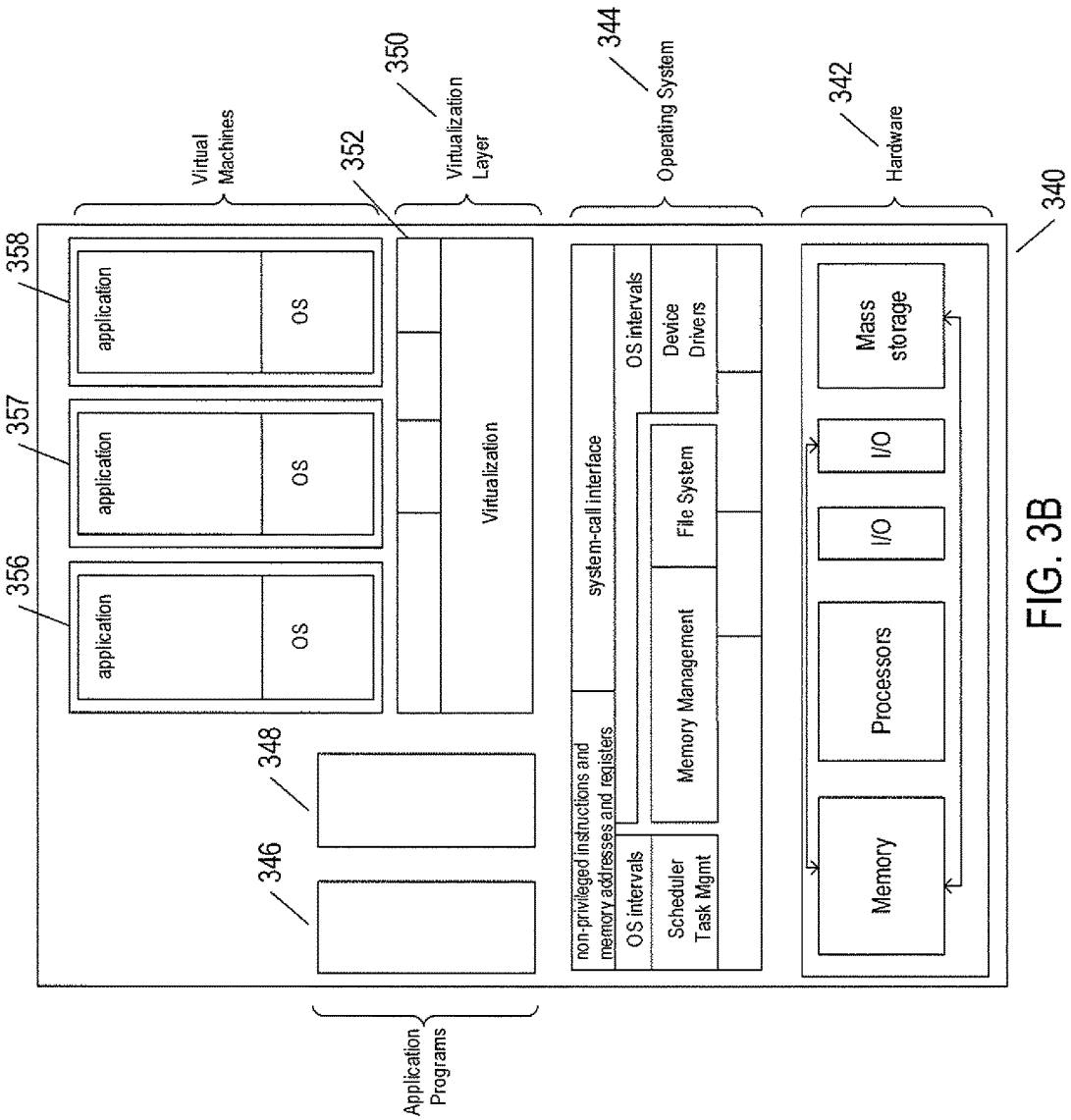

Virtual Machines
352
350
Virtualization Layer
344
Operating System
342
Hardware
340
358
357
356
application
OS
Virtualization
348
346
non-privileged instructions and memory addresses and registers
system-call interface
OS intervals
Scheduler Task Mgmt
Memory Management
File System
Device Drivers
Memory
Processors
I/O
I/O
Mass storage
Application Programs

FIG. 3B

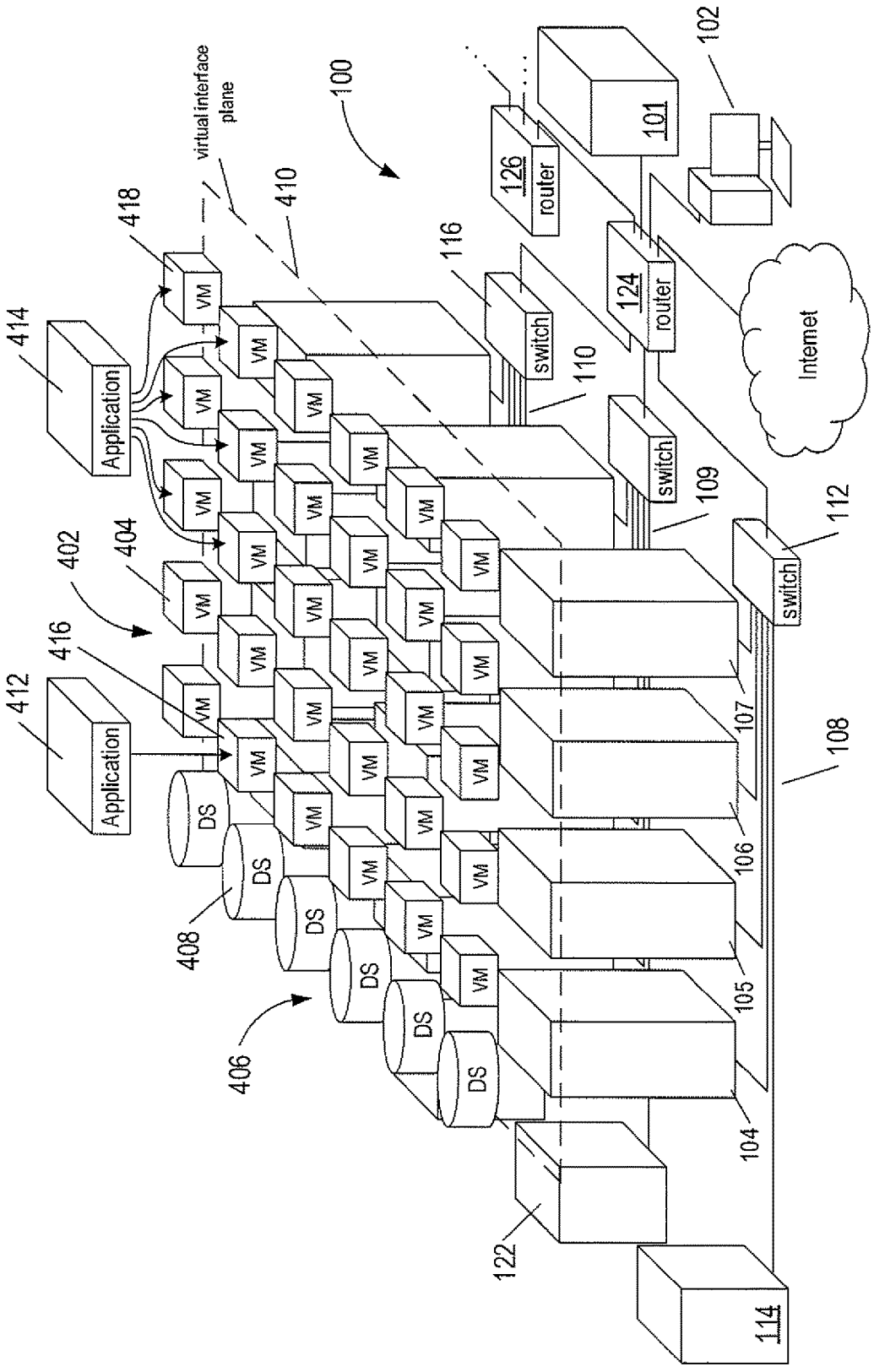

100
102
101
126
router
124
router
Internet
116
switch
110
switch
109
112
switch
107
108
106
105
104
114
122
virtual interface plane
410
418
414
Application
412
Application
416
402
404
VM
DS
408
406

FIG. 4

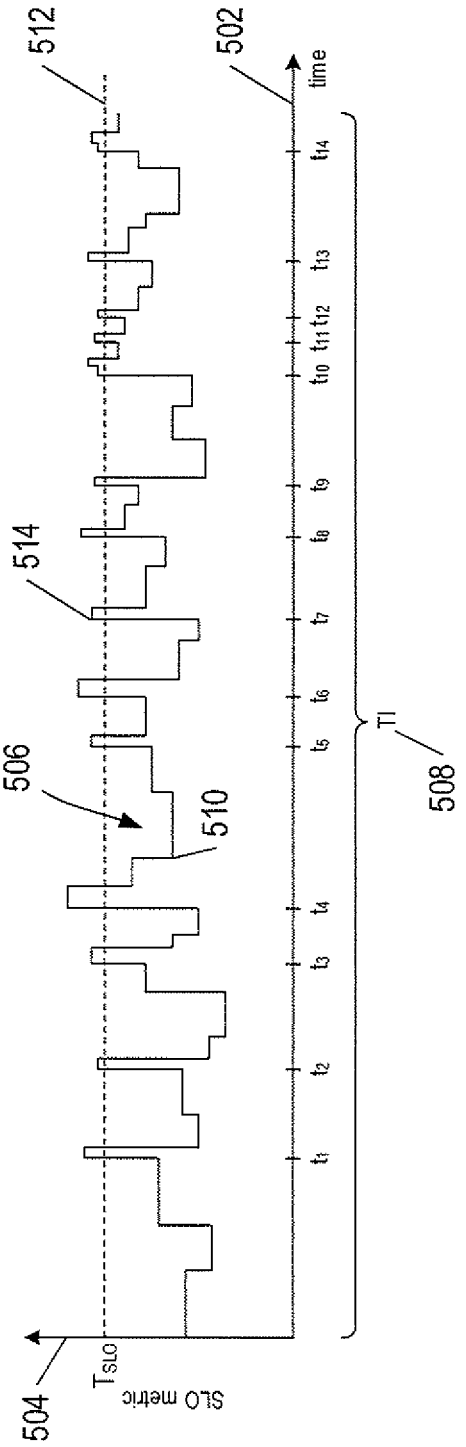

512
502
time
514
506
510
508
TI
504
SLO metric
T_{SLO}
t_1 t_2 t_3 t_4 t_5 t_6 t_7 t_8 t_9 t_{10} t_{11} t_{12} t_{13} t_{14}

FIG. 5

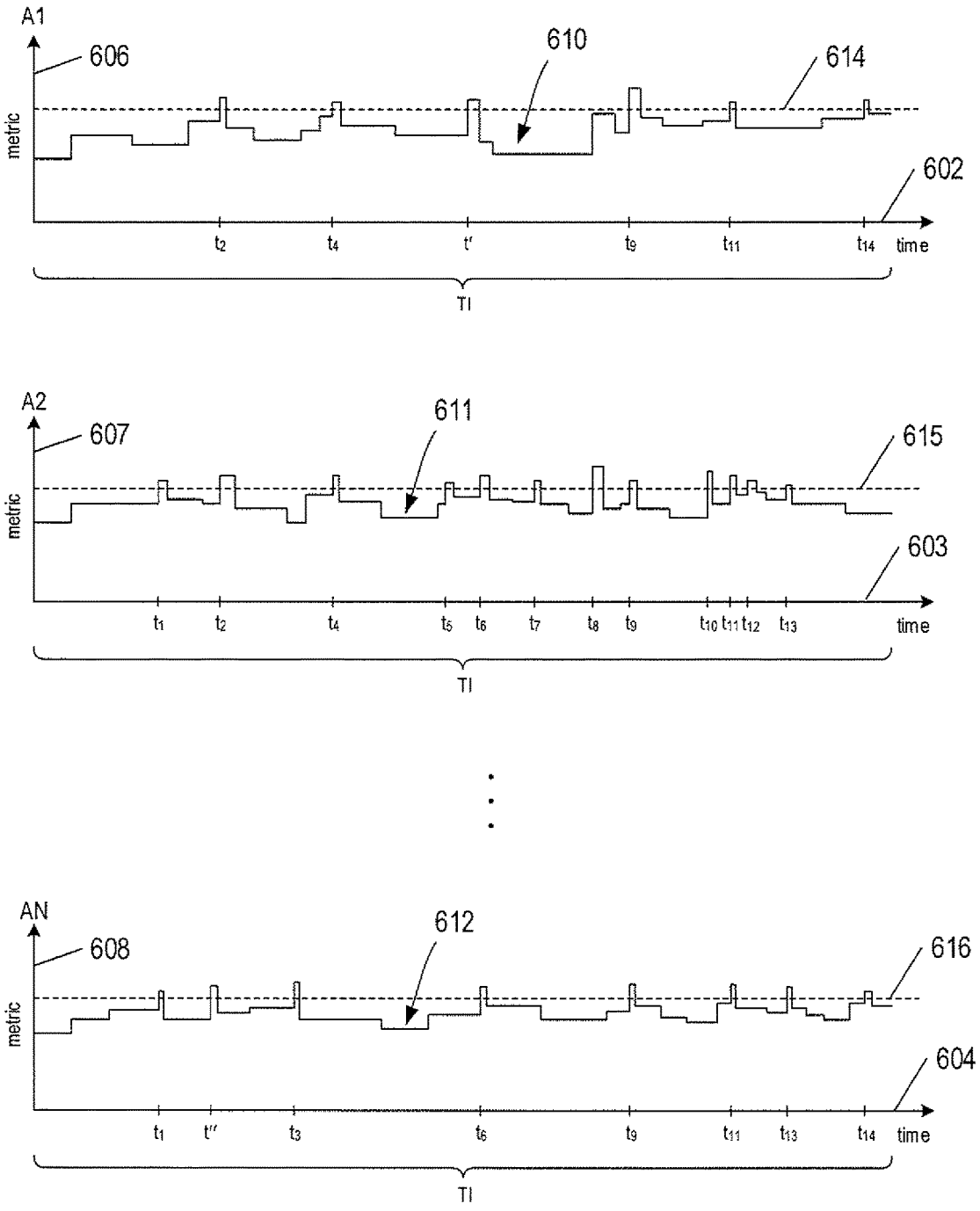

A1
606
610
614
602
metric
t2
t4
t'
t9
t11
t14
time
TI
A2
607
611
615
603
metric
t1
t2
t4
t5
t6
t7
t8
t9
t10
t11
t12
t13
time
TI
AN
608
612
616
604
metric
t1
t''
t3
t6
t9
t11
t13
t14
time
TI

FIG. 6

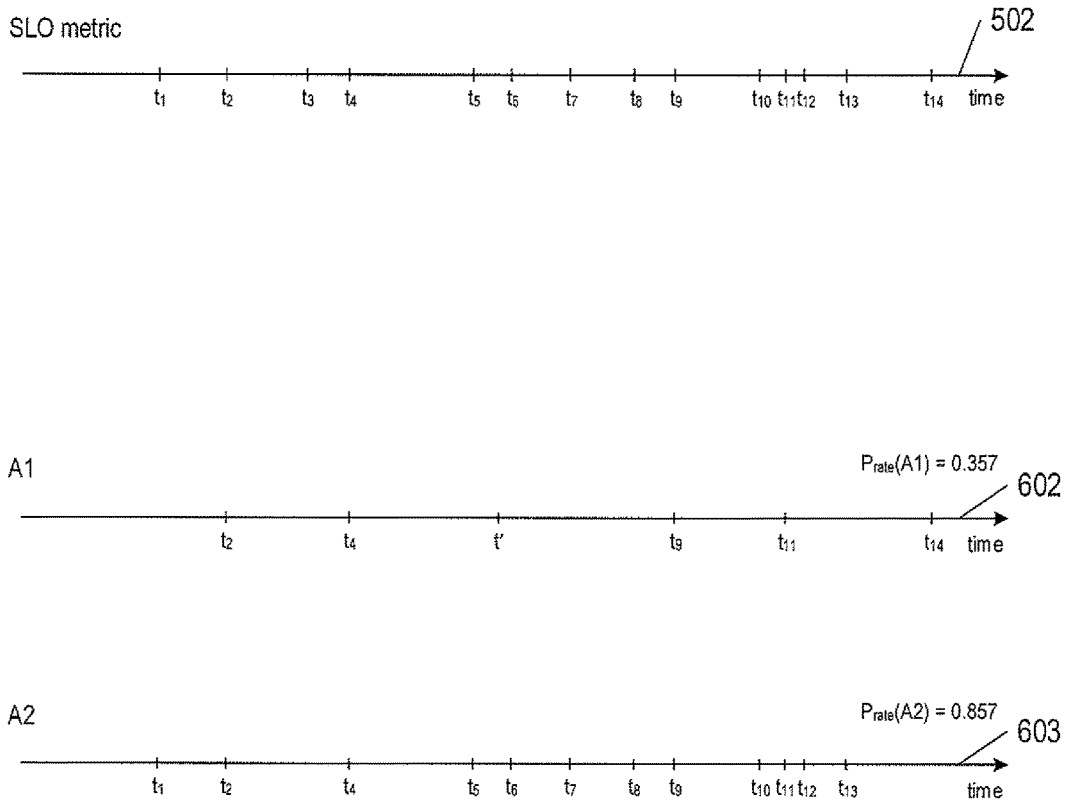

SLO metric
502
t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 t14 time
A1
Prate(A1) = 0.357
602
t2 t4 t' t9 t11 t14 time
A2
Prate(A2) = 0.857
603
t1 t2 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 time

FIG. 7

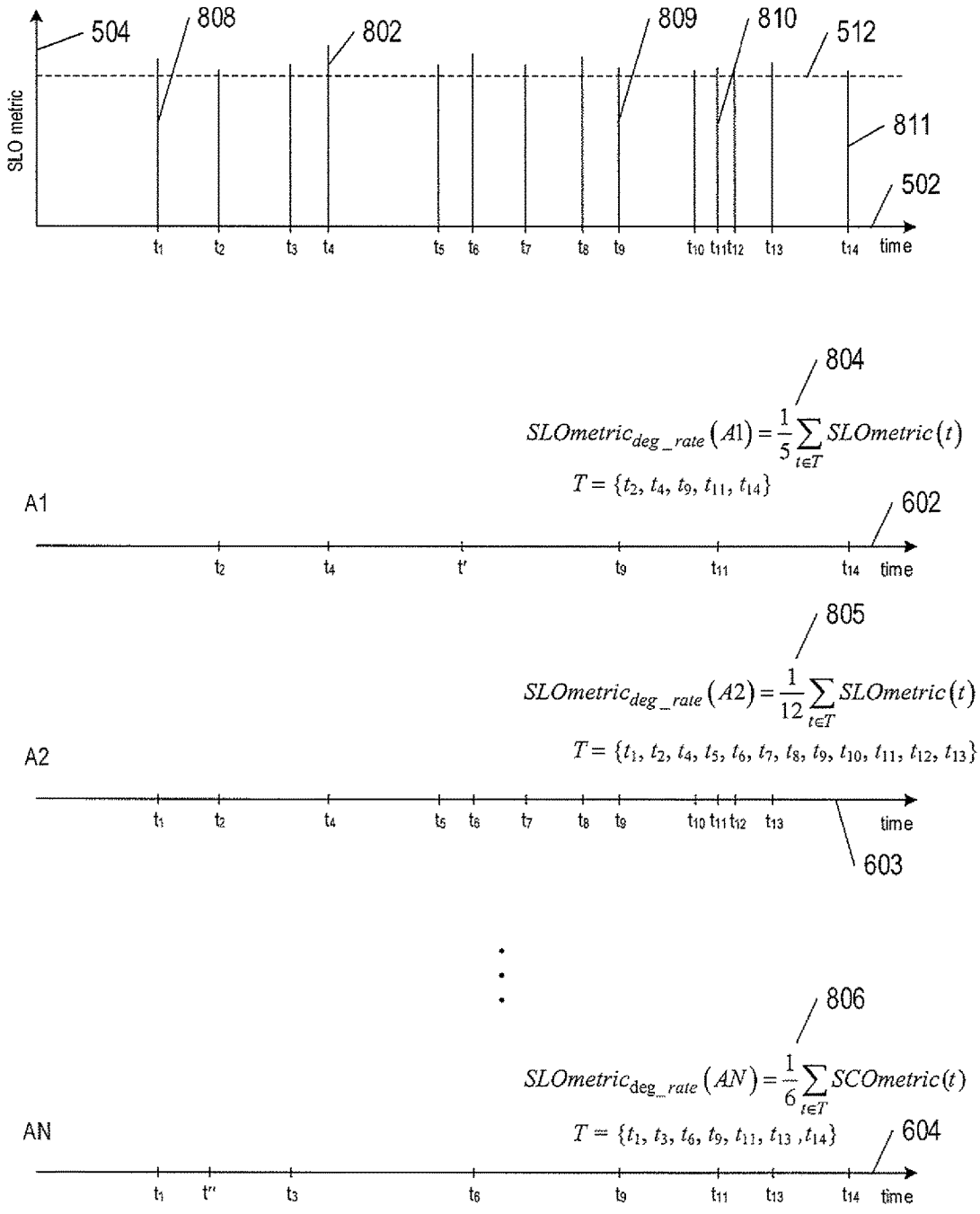

504
808
802
809
810
512
811
502
SLO metric
t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 t14 time
804
$SLOmetric_{deg\_rate}(A1) = \frac{1}{5}\sum_{t \in T} SLOmetric(t)$
$T = \{t_2, t_4, t_9, t_{11}, t_{14}\}$
A1
602
t2 t4 t' t9 t11 t14 time
805
$SLOmetric_{deg\_rate}(A2) = \frac{1}{12}\sum_{t \in T} SLOmetric(t)$
$T = \{t_1, t_2, t_4, t_5, t_6, t_7, t_8, t_9, t_{10}, t_{11}, t_{12}, t_{13}\}$
A2
t1 t2 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 time
603
806
$SLOmetric_{deg\_rate}(AN) = \frac{1}{6}\sum_{t \in T} SCOmetric(t)$
$T = \{t_1, t_3, t_6, t_9, t_{11}, t_{13}, t_{14}\}$
AN
604
t1 t'' t3 t6 t9 t11 t13 t14 time

FIG. 8

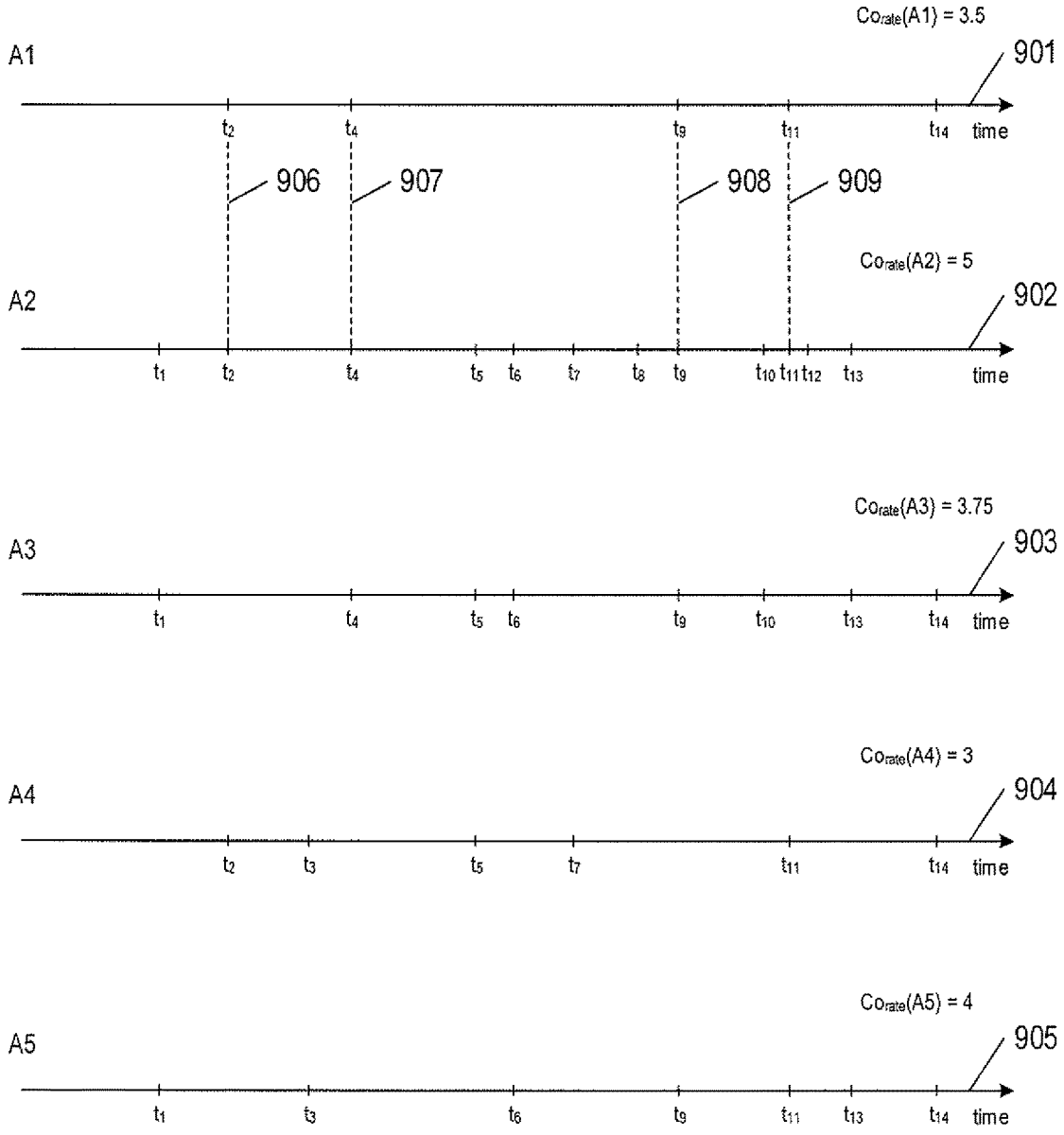

A1
Corate(A1) = 3.5
901
t2
t4
t9
t11
t14
time
906
907
908
909
A2
Corate(A2) = 5
902
t1
t2
t4
t5
t6
t7
t8
t9
t10
t11
t12
t13
time
A3
Corate(A3) = 3.75
903
t1
t4
t5
t6
t9
t10
t13
t14
time
A4
Corate(A4) = 3
904
t2
t3
t5
t7
t11
t14
time
A5
Corate(A5) = 4
905
t1
t3
t6
t9
t11
t13
t14
time

FIG. 9

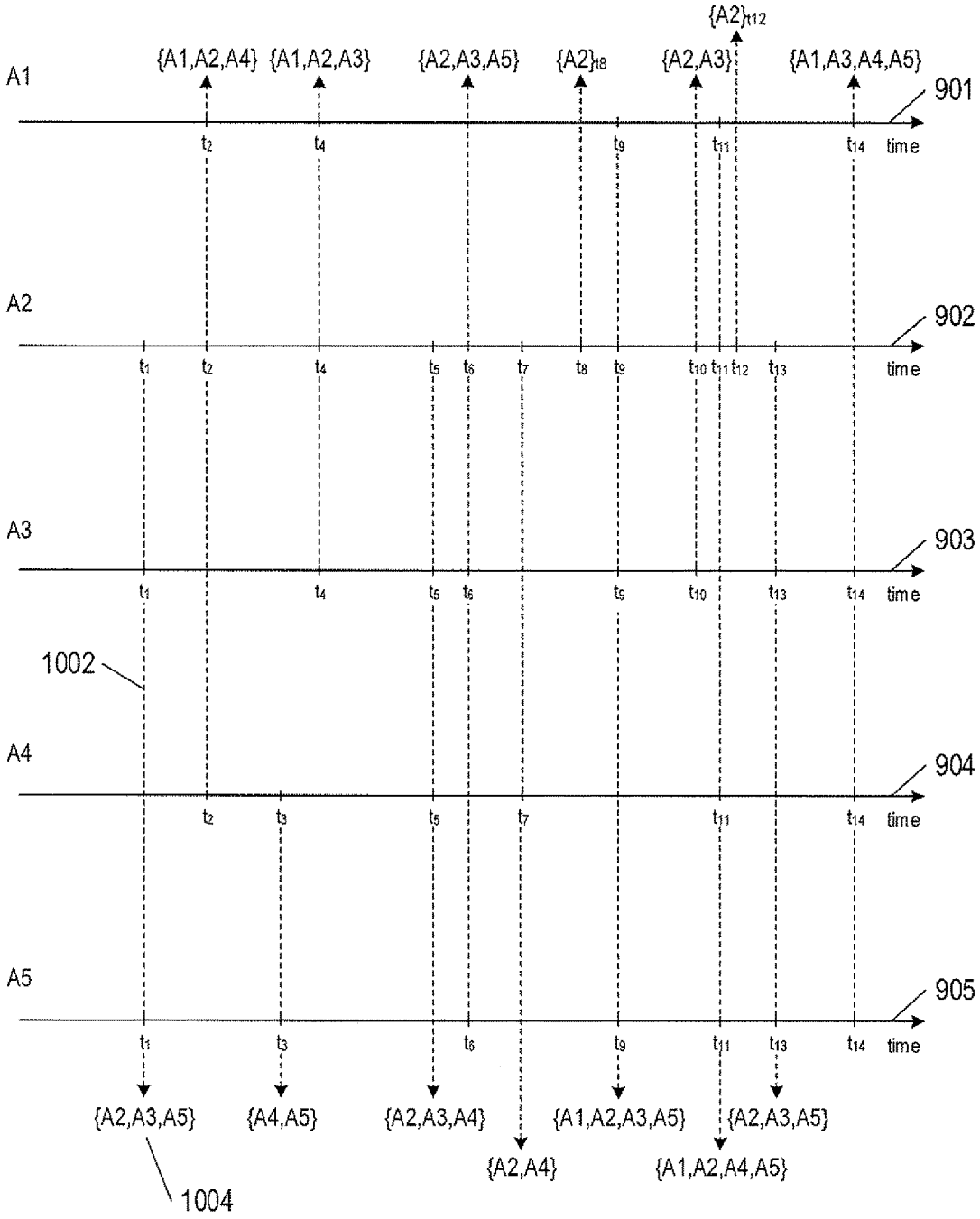
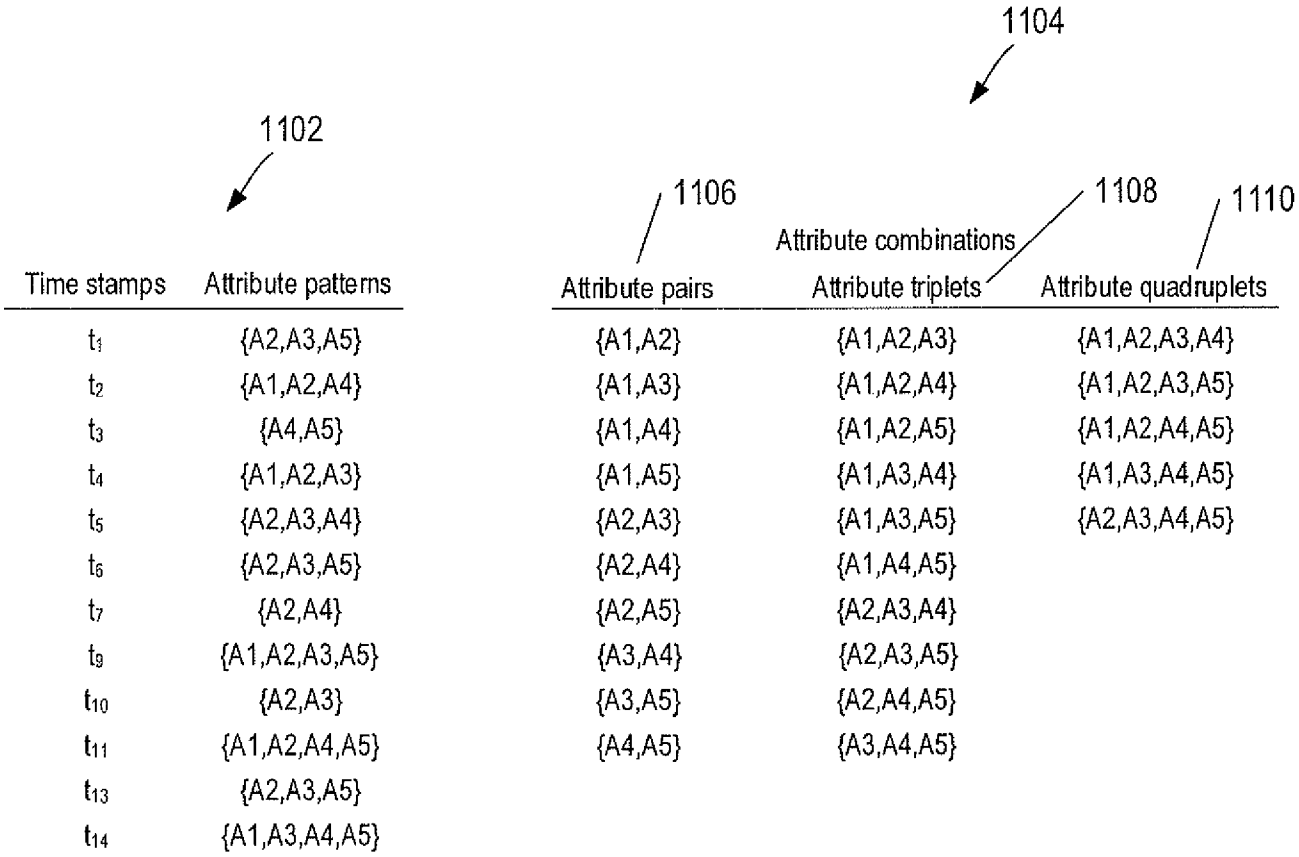

A1
A2
A3
A4
A5
901
902
903
904
905
time
{A1,A2,A4}
{A1,A2,A3}
{A2,A3,A5}
{A2}t8
{A2,A3}
{A2}t12
{A1,A3,A4,A5}
1002
{A2,A3,A5}
{A4,A5}
{A2,A3,A4}
{A2,A4}
{A1,A2,A3,A5}
{A1,A2,A4,A5}
{A2,A3,A5}
1004

FIG. 10



Time stamps	Attribute patterns
t_1	{A2,A3,A5}
t_2	{A1,A2,A4}
t_3	{A4,A5}
t_4	{A1,A2,A3}
t_5	{A2,A3,A4}
t_6	{A2,A3,A5}
t_7	{A2,A4}
t_9	{A1,A2,A3,A5}
t_{10}	{A2,A3}
t_{11}	{A1,A2,A4,A5}
t_{13}	{A2,A3,A5}
t_{14}	{A1,A3,A4,A5}

Attribute pairs	Attribute triplets	Attribute quadruplets
{A1,A2}	{A1,A2,A3}	{A1,A2,A3,A4}
{A1,A3}	{A1,A2,A4}	{A1,A2,A3,A5}
{A1,A4}	{A1,A2,A5}	{A1,A2,A4,A5}
{A1,A5}	{A1,A3,A4}	{A1,A3,A4,A5}
{A2,A3}	{A1,A3,A5}	{A2,A3,A4,A5}
{A2,A4}	{A1,A4,A5}	
{A2,A5}	{A2,A3,A4}	
{A3,A4}	{A2,A3,A5}	
{A3,A5}	{A2,A4,A5}	
{A4,A5}	{A3,A4,A5}	

FIG. 11

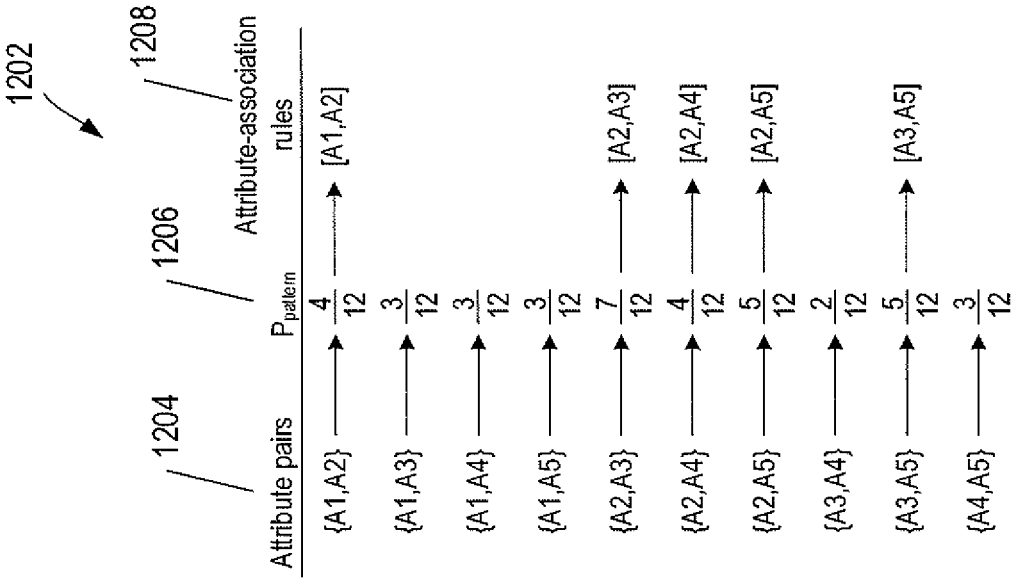

1202
1204
1206
1208
Attribute pairs
$P_{pattern}$
Attribute-association rules
{A1,A2} 4/12 [A1,A2]
{A1,A3} 3/12
{A1,A4} 3/12
{A1,A5} 3/12
{A2,A3} 7/12 [A2,A3]
{A2,A4} 4/12 [A2,A4]
{A2,A5} 5/12 [A2,A5]
{A3,A4} 2/12
{A3,A5} 5/12 [A3,A5]
{A4,A5} 3/12

FIG. 12A

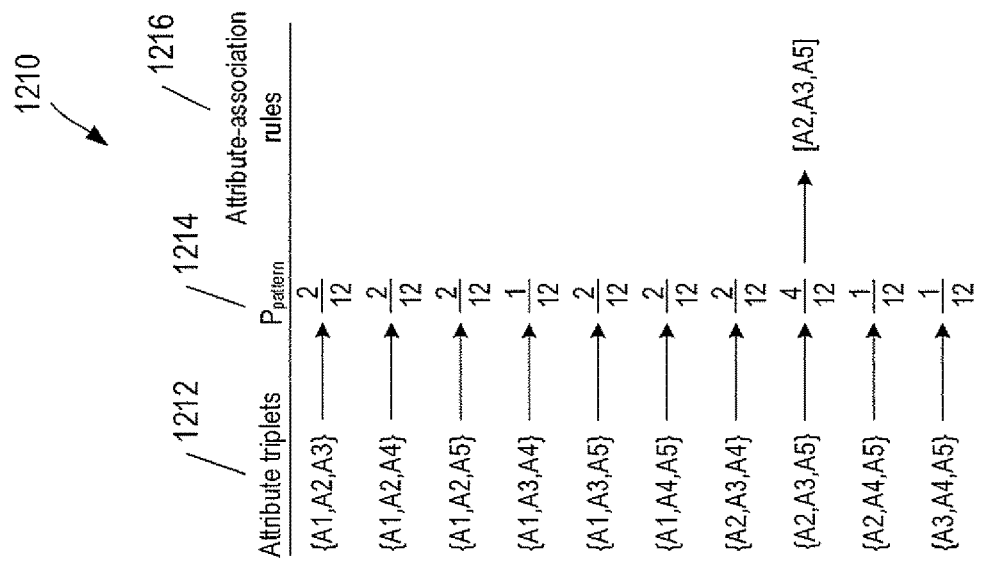


FIG. 12B

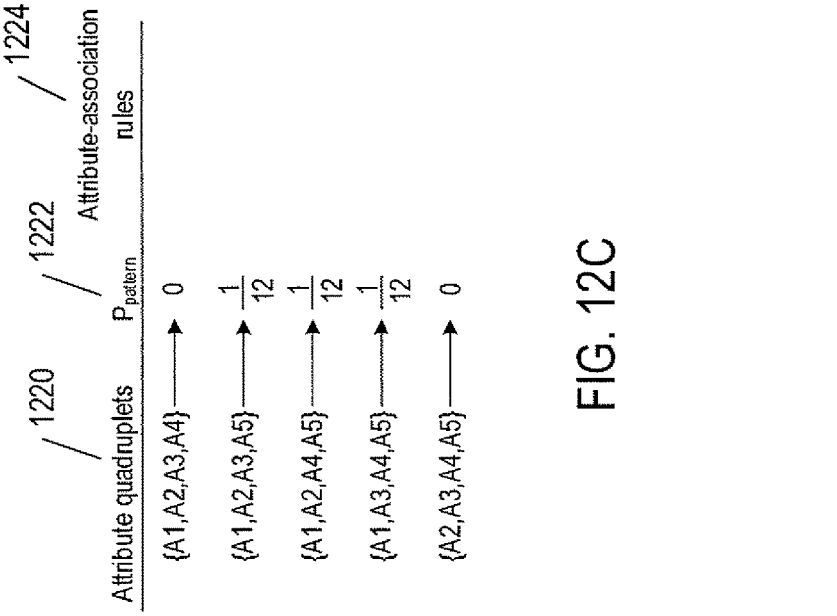


FIG. 12C

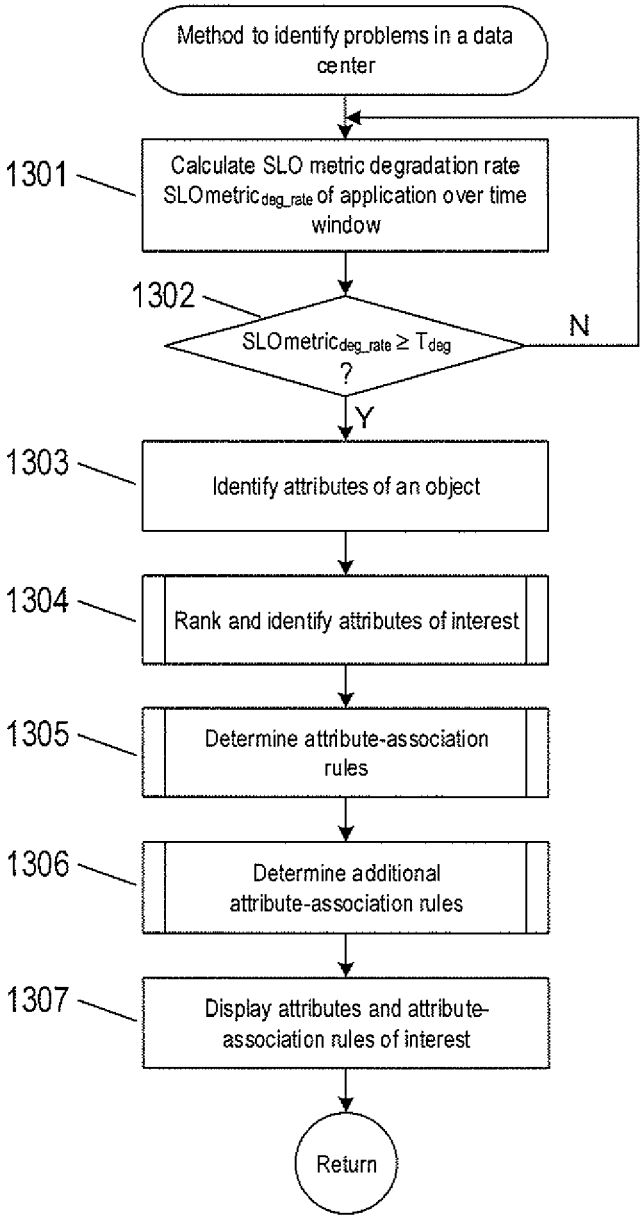

Method to identify problems in a data center
1301
Calculate SLO metric degradation rate SLOmetric deg_rate of application over time window
1302
SLOmetric deg_rate ≥ T deg ?
N
Y
1303
Identify attributes of an object
1304
Rank and identify attributes of interest
1305
Determine attribute-association rules
1306
Determine additional attribute-association rules
1307
Display attributes and attribute-association rules of interest
Return

FIG. 13

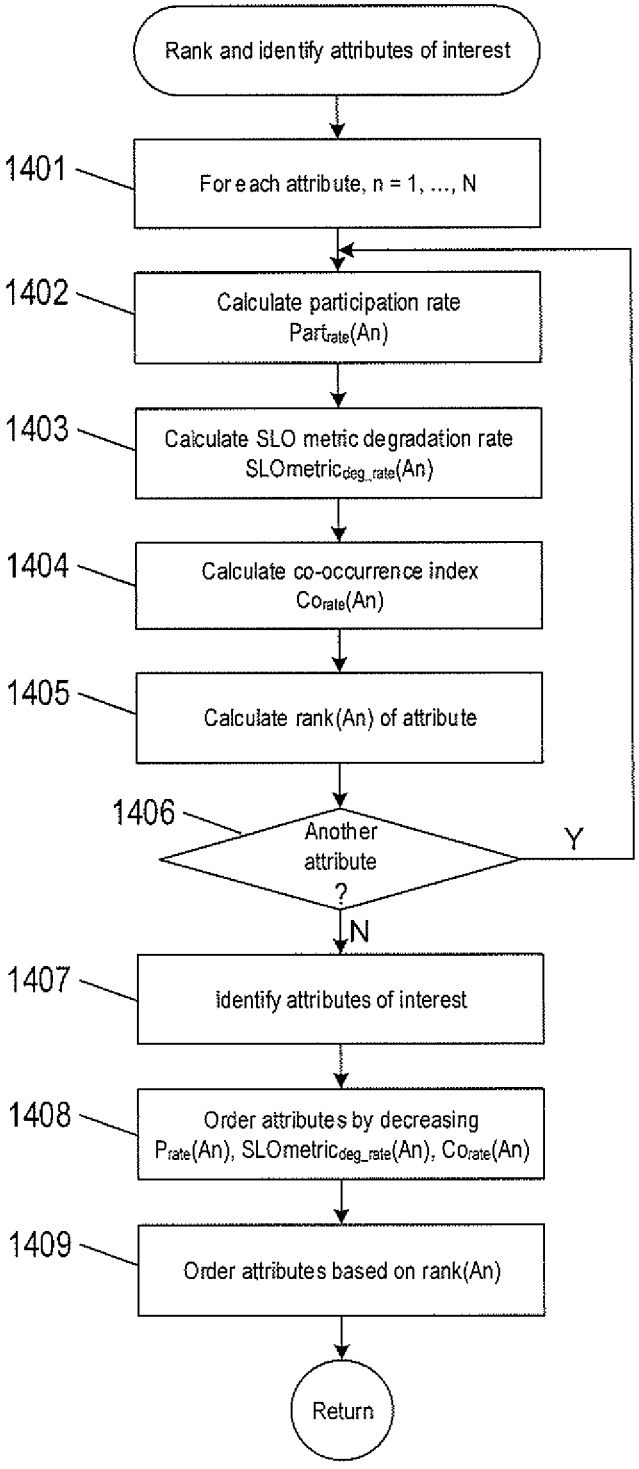

Rank and identify attributes of interest
1401
For each attribute, n = 1, ..., N
1402
Calculate participation rate
Part_rate(An)
1403
Calculate SLO metric degradation rate
SLOmetric_deg_rate(An)
1404
Calculate co-occurrence index
Co_rate(An)
1405
Calculate rank(An) of attribute
1406
Another attribute ?
Y
N
1407
identify attributes of interest
1408
Order attributes by decreasing
P_rate(An), SLOmetric_deg_rate(An), Co_rate(An)
1409
Order attributes based on rank(An)
Return

FIG. 14

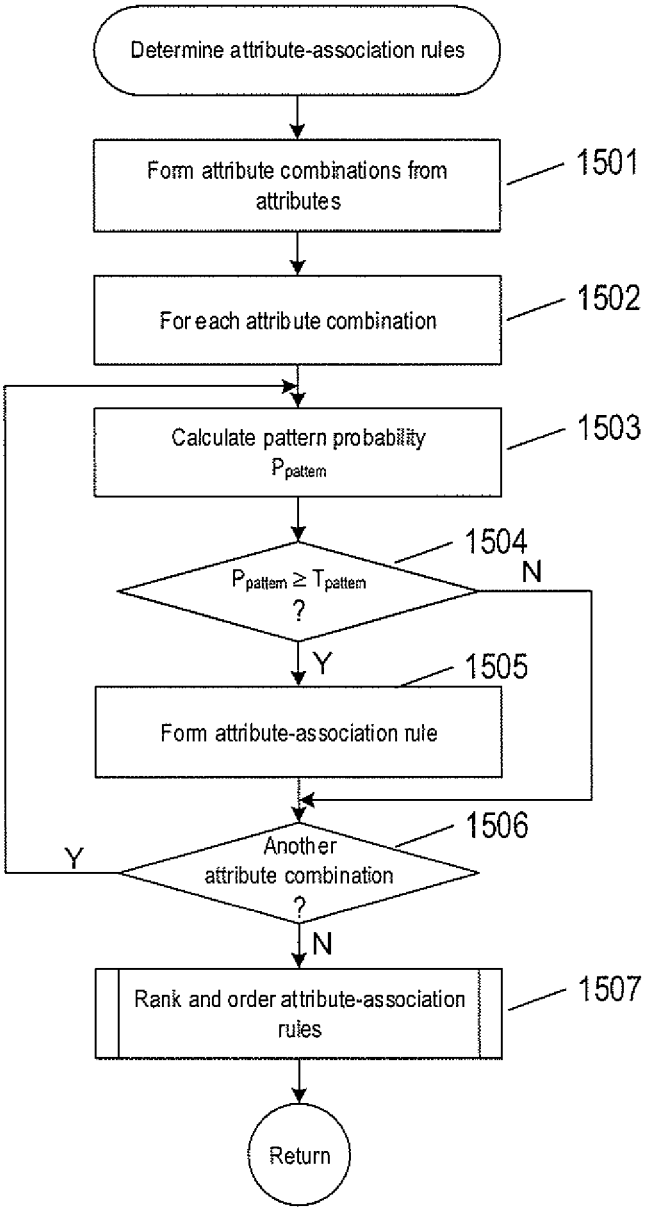

Determine attribute-association rules
Form attribute combinations from attributes
1501
For each attribute combination
1502
Calculate pattern probability $P_{pattern}$
1503
$P_{pattern} \geq T_{pattern}$?
1504
N
Y
Form attribute-association rule
1505
Another attribute combination ?
1506
Y
N
Rank and order attribute-association rules
1507
Return

FIG. 15

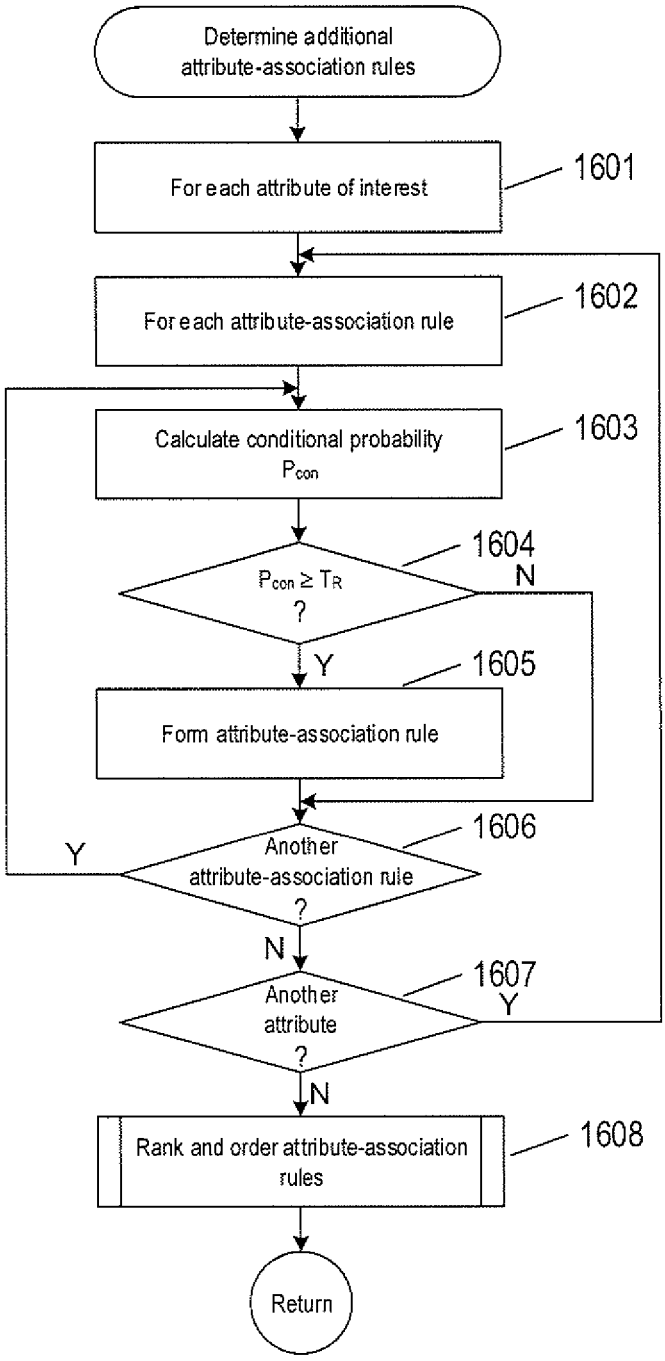

Determine additional attribute-association rules
For each attribute of interest
1601
For each attribute-association rule
1602
Calculate conditional probability P_{con}
1603
$P_{con} \geq T_R$?
1604
N
Y
Form attribute-association rule
1605
Another attribute-association rule ?
1606
Y
N
Another attribute ?
1607
Y
N
Rank and order attribute-association rules
1608
Return

FIG. 16

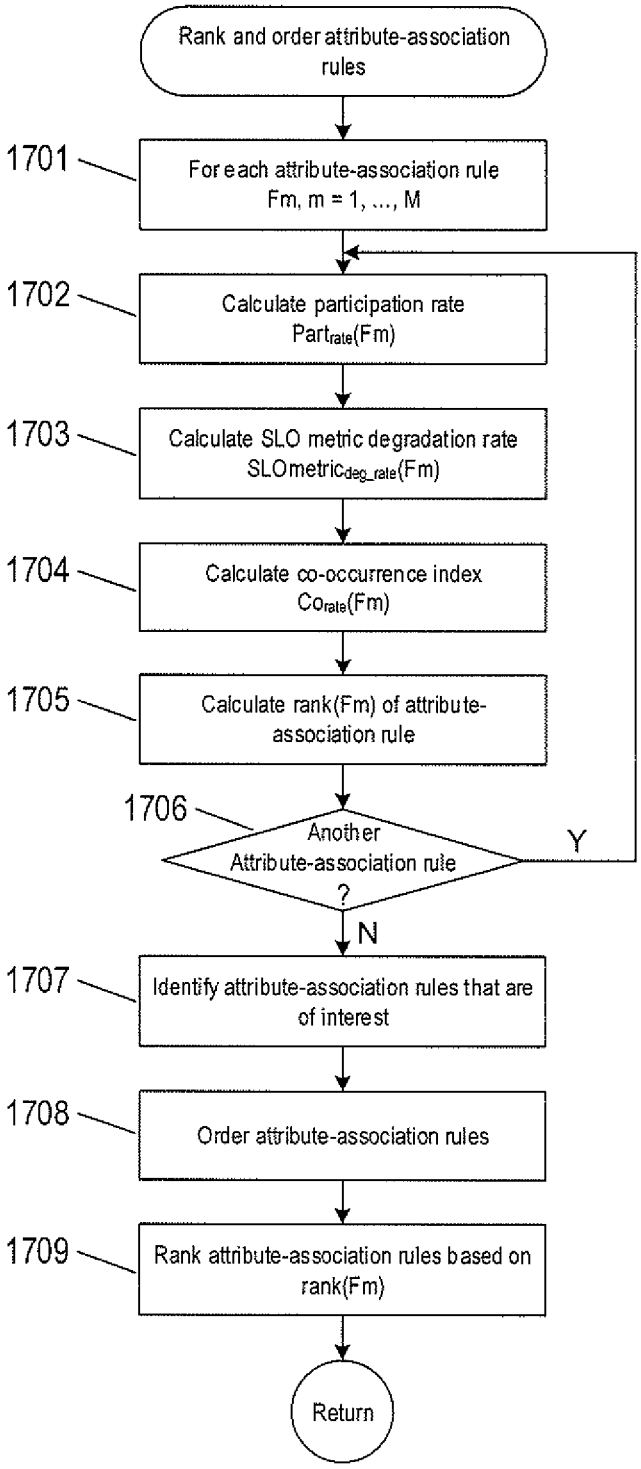

Rank and order attribute-association rules
1701
For each attribute-association rule Fm, m = 1, ..., M
1702
Calculate participation rate $Part_{rate}(Fm)$
1703
Calculate SLO metric degradation rate $SLOmetric_{deg\_rate}(Fm)$
1704
Calculate co-occurrence index $Co_{rate}(Fm)$
1705
Calculate rank(Fm) of attribute-association rule
1706
Another Attribute-association rule ?
Y
N
1707
Identify attribute-association rules that are of interest
1708
Order attribute-association rules
1709
Rank attribute-association rules based on rank(Fm)
Return

FIG. 17

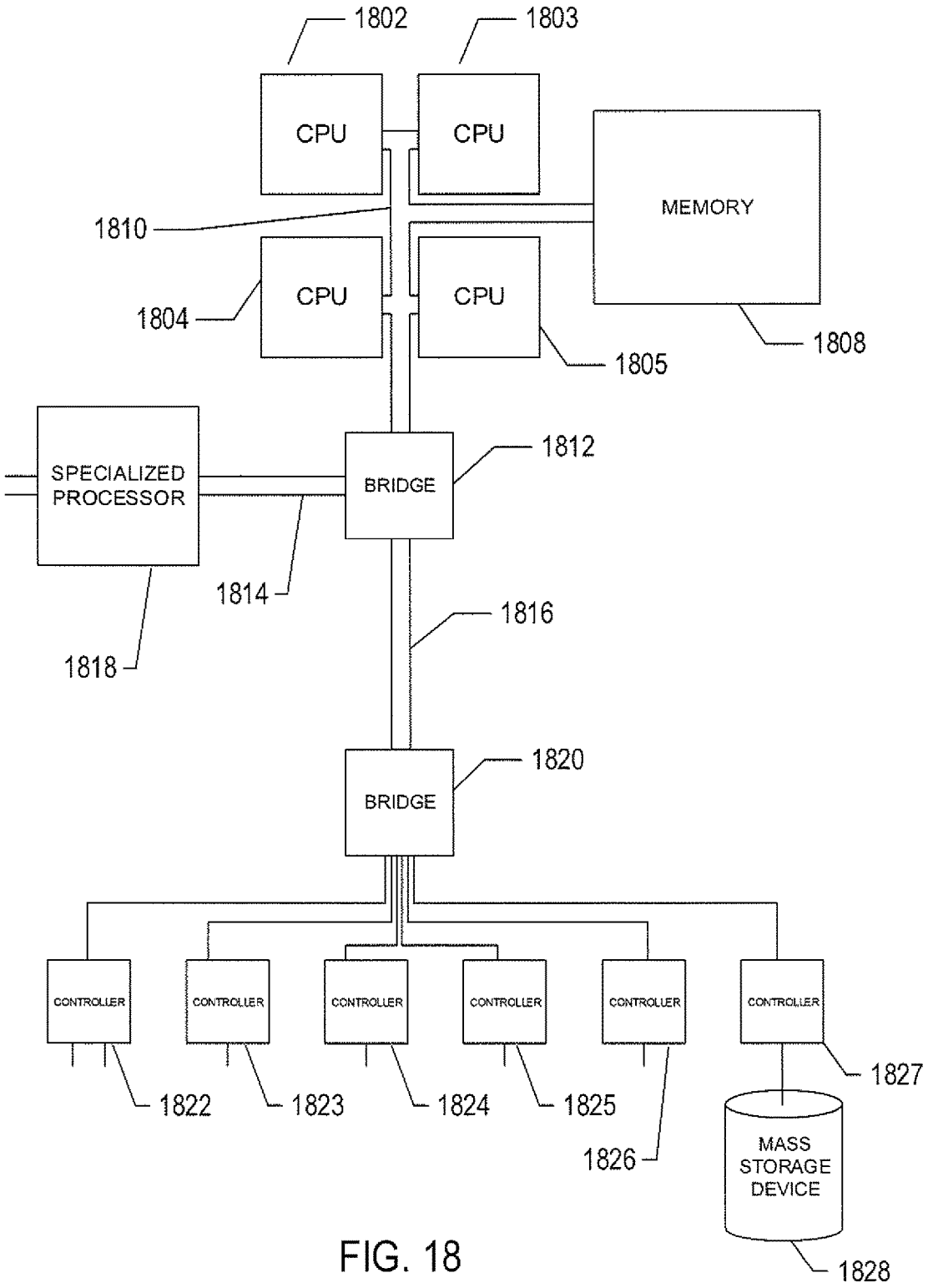

1802
1803
CPU
CPU
MEMORY
1810
CPU
CPU
1804
1805
1808
SPECIALIZED PROCESSOR
BRIDGE
1812
1814
1816
1818
BRIDGE
1820
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
CONTROLLER
1827
1822
1823
1824
1825
1826
MASS STORAGE DEVICE
1828

FIG. 18

Attribute Name	Participation Rate	SLO Degradation	Co-Occurrence
guestfilesystem|percentage	0.069515329	69.27306962	21.60331492
guestfilesystem|usage	0.039960315	70.57748417	22.61211189
diskspace|activeNotShared	0.035213034	72.51677391	18.95279549
net|bytesTx_average	0.033532347	73.73089287	24.49056126
cpu|usagemhz_average	0.032520415	74.15538118	30.6764751
net|transmitted_average	0.027097779	74.60375061	24.49056126
cpu|idle_summation	0.027055982	72.73632003	29.06165204
cpu|used_summation	0.027025184	73.9015873	29.60117031
net|usage_average	0.026134244	72.33703704	27.79802596
cpu|readyPct	0.02158055	71.1617737	24.34258644
cpu|ready_summation	0.02158055	71.1617737	24.34258644
cpu|wait_summation	0.021327567	71.9719443	29.07785985
net|packetsTxPerSec	0.019558886	70.77449106	20.45256233
net|received_average	0.019013322	73.30718501	30.07037915
net|packetsRxPerSec	0.018766939	73.3249326	34.96926952
datastore|write_average	0.018390764	74.2972488	24.36028461
guestfilesystem|freespace_total	0.018333568	70.33813295	22.91046567
datastore|maxObserved_Write	0.018236774	78.09529554	24.19758745
guestfilesystem|usage_total	0.018091584	71.15673638	23.0043785
guestfilesystem|percentage_total	0.018047587	70.57081911	22.67926829
diskspace|used	0.017499824	72.50207417	18.98566398
mem|host_usage	0.016316304	71.23634893	23.6698584
net|bytesRx_average	0.016122717	71.82139446	30.07037915
datastore|maxObserved_NumberWrite	0.016045722	78.0128873	20.73320537
mem|guest_usage	0.014745609	70.91660451	23.22265334
mem|consumed_average	0.014745609	70.91660451	23.22265334
datastore|totalLatency_average	0.014629017	72.99518797	36.62518968
mem|guest_dynamic_entitlement	0.014059255	70.79987482	23.18607932
mem|shared_average	0.013641283	71.34623448	26.79996774
virtualDisk|commandsAveraged_average	0.013350903	69.04448838	29.49126638
cpu|numberToRemove	0.013183714	74.86183881	25.68463207
datastore|commandsAveraged_average	0.013141917	69.37931034	30.98793161
disk|usage_average	0.01293953	72.95239714	32.37131231
datastore|maxObserved_NumberRead	0.012530358	78.16994382	31.19803371
virtualDisk|totalReadLatency_average	0.012402767	78.46541327	33.53739445
virtualDisk|numberWriteAveraged_average	0.012312573	74.32535287	35.39077299
cpu|swapwait_summation	0.011584422	69.04785416	23.8504902
virtualDisk|usage	0.011404034	73.06635802	33.78087081

FIG. 19

Size	Rules	Participation Rate	SLO Degradation	Co-Occurrence
2	[guestfilesystem|percentage, guestfilesystem|usage]	0.695	69.27	22
	[guestfilesystem|percentage, net|bytesTx_average]	0.396	69.27	24
	[cpu|usagemhz_average, guestfilesystem|percentage]	0.362	69.27	30
	[cpu|usagemhz_average, net|bytesTx_average]	0.232	73.73	35
	[cpu|usagemhz_average, diskspace|activeNotShared]	0.216	72.51	28
	[diskspace|activeNotShared, net|bytesTx_average]	0.20	72.51	22
3	[diskspace|activeNotShared, guestfilesystem|percentage, guestfilesystem|usage]	0.44	69.27	21
	[guestfilesystem|percentage, guestfilesystem|usage, net|bytesTx_average]	0.4	69.27	24
	[cpu|usagemhz_average, guestfilesystem|percentage, guestfilesystem|usage]	0.37	69.27	30
	[cpu|usagemhz_average, guestfilesystem|percentage, net|bytesTx_average]	0.2	69.27	35
4	[cpu|usagemhz_average, diskspace|activeNotShared, guestfilesystem|percentage, guestfilesystem|usage]	0.22	69.27	28
	[diskspace|activeNotShared, guestfilesystem|percentage, guestfilesystem|usage, net|bytesTx_average]	0.201	69.27	23
	[cpu|usagemhz_average, guestfilesystem|percentage, guestfilesystem|usage, net|bytesTx_average]	0.20	69.27	35
5	[cpu|usagemhz_average, diskspace|activeNotShared, guestfilesystem|percentage, guestfilesystem|usage, net|bytesTx_average]	0.17	69.27	36

FIG. 20

Attribute_Name	Other Attributes in the Rule
guestfilesystem |percentage	guestfilesystem|usage, guestfilesystem|usage_total, guestfilesystem|percentage_total, guestfilesystem|freespace_total, diskspace|activeNotShared
cpu|usagemhz_average	cpu|used_summation, cpu|numberToRemove, virtualDisk|usage, virtualDisk|totalReadLatency_average, datastore|maxObserved_Write
cpu|idle_summation	guestfilesystem|percentage, guestfilesystem|usage, cpu|wait_summation, cpu|usagemhz_average, cpu|used_summation]

FIG. 21

METHODS AND SYSTEMS TO ENHANCE IDENTIFYING SERVICE-LEVEL-OBJECTIVE DEGRADATION IN A DATA CENTER

TECHNICAL FIELD

The present disclosure is directed to identifying problems in a data center based on performance of application programs running in the data center.

BACKGROUND

Cloud-computing facilities provide computational bandwidth and data-storage services much as utility companies provide electrical power and water to consumers. Cloud computing provides enormous advantages to customers without the devices to purchase, manage, and maintain in-house data centers. Such customers can dynamically add and delete virtual computer systems from their virtual data centers within public clouds in order to track computational-bandwidth and data-storage needs, rather than purchasing sufficient computer systems within a physical data center to handle peak computational-bandwidth and data-storage demands. Moreover, customers can completely avoid the overhead of maintaining and managing physical computer systems, including hiring and periodically retraining information-technology specialists and continuously paying for operating-system and database-management-system upgrades. Furthermore, cloud-computing interfaces allow for easy and straightforward configuration of virtual computing facilities, flexibility in the types of applications and operating systems that can be configured, and other functionalities that are useful even for owners and administrators of private cloud-computing facilities used by a customer.

In order to maintain a data center infrastructure and satisfy the computational and data storage demands of customers, data center managers typically rely on cloud management products to monitor operation of the data center infrastructure. But most cloud management products do not adequately bridge the gap between defined data center infrastructure problems and application performance problems. For example, a number of cloud management products allow customers to manually select the types of abnormal conditions that customers perceive as precursors to important deviations from normal operations of their respective applications and receive alerts when abnormal conditions arise. Other cloud management products allow customers to define an alert definition workspace and alert workflow to follow when abnormal conditions occur. By allowing customers to select the types of abnormal conditions in advance assumes that the customer-defined abnormal conditions will also impact data center operations that are worth paying attention to and as a result provide a user-controlled warning system. However, customer-defined abnormal conditions do not identify objects of the data center, such as virtual and physical machine components, that may be responsible for abnormal operations of their applications. Moreover, a customer-define abnormal conditions creates issues in terms of unrealistic manual and ad-hoc configuration efforts for large-scale data centers that are not tractable by expert knowledge. As a result, customer-defined abnormal conditions may increase the risk of high rates of missed and false negative alerts with respect to data center operations.

SUMMARY

Service-level objectives ("SLOs") between a data center service provider and a data center customer are described in a service-level agreement ("SLA"). The SLOs are agreed to by the service provider and the customer and the SLOs are quantified in an SLO metric that serves as a key performance indicator of the level of services provided by the cloud computing service provider. Methods described in the present disclosure identify attributes of a data center infrastructure and application program that are associated with SLO metric degradation and may be recorded in problem definitions. In other words, a data center customer is offered to "codify" problems with atomic abnormality conditions on indicated attributes that are able to decrease the SLO by some degree that the data center customer would like to be aware. As a result, the data center customer may be warned of potentially significant SLO decline in order to prevent unwanted loss and take actions to prevent active anomalies. Methods are also generate patterns of attributes that constitute core structures highly associated with degradation of the SLO metric.

DESCRIPTION OF THE DRAWINGS

FIG. **1** shows an example of a cloud-computing facility.

FIG. **2** shows generalized hardware and software components of a server computer.

FIGS. **3A-3B** show two types of virtual machines and virtual-machine execution environments.

FIG. **4** shows an example set of virtual machines and datastores above a virtual interface plane in a cloud-computing facility.

FIG. **5** shows a plot of a service-level objective ("SLO") metric generated for an application program running in a cloud computing facility.

FIG. **6** shows a plot of attributes.

FIG. **7** shows plots of time stamps at which attribute violations of associated attribute thresholds occur and associated participation rates.

FIG. **8** shows plots of time stamps at which attribute violations of associated attribute thresholds occur and associated SLO metric degradation rages.

FIG. **9** shows plots of time stamps at which attribute violations of associated attribute thresholds occur and associated co-occurrence indices.

FIG. **10** shows attribute patterns created from five attributes.

FIG. **11** shows a table of the attribute patterns and associated time stamps.

FIGS. **12A-12C** show an example of determining attribute-association rules from attribute patterns and attribute combinations.

FIG. **13** shows a control-flow diagram of a method to identify problems in a data center.

FIG. **14** shows a control-flow diagram of a method to "rank and identify attributes of interest" called in FIG. **13**.

FIG. **15** shows a control-flow diagram of a method to "determine attribute-association rules" called in FIG. **13**

FIG. **16** shows a control-flow diagram of a method to "determine additional attribute-association rules" called in FIG. **13**.

FIG. **17** shows a control-flow diagram of a method to "rank and order attribute-association rules" called in FIGS. **15** and **16**.

FIG. **18** shows an architectural diagram for various types of computers used to identify problem in a data center.

FIGS. **19-21** show tables of experimental results.

DETAILED DESCRIPTION

FIG. **1** shows an example of a cloud-computing facility **100**. The cloud-computing facility **100** consists of a virtual-

data-center management server **101** and a PC **102** on which a virtual-data-center management interface may be displayed to system administrators and other users. The cloud-computing facility **100** additionally includes a number of hosts or server computers, such as server computers **104-107**, that are interconnected to form three local area networks **108-110**. For example, local area network **108** includes a switch **112** that interconnects the four servers **104-107** and a mass-storage array **114** via Ethernet or optical cables and local area network **110** includes a switch **116** that interconnects four servers **118-1121** and a mass-storage array **122** via Ethernet or optical cables. In this example, the cloud computing infrastructure **100** also includes a router **124** that interconnects the LANs **108-110** and interconnects the LANS to the Internet, the virtual-data-center management server **101**, the PC **102** and to a router **126** that, in turn, interconnects other LANs composed of server computers and mass-storage arrays (not shown). In other words, the routers **124** and **126** are interconnected to form a larger network of server computers.

FIG. **2** shows generalized hardware and software components of a server computer. The server computer **200** includes three fundamental layers: (1) a hardware layer or level **202**; (2) an operating-system layer or level **204**; and (3) an application-program layer or level **206**. The hardware layer **202** includes one or more processors **208**, system memory **210**, various different types of input-output ("I/O") devices **210** and **212**, and mass-storage devices **214**. Of course, the hardware level also includes many other components, including power supplies, internal communications links and busses, specialized integrated circuits, many different types of processor-controlled or microprocessor-controlled peripheral devices and controllers, and many other components. The operating system **204** interfaces to the hardware level **202** through a low-level operating system and hardware interface **216** generally comprising a set of non-privileged computer instructions **218**, a set of privileged computer instructions **220**, a set of non-privileged registers and memory addresses **222**, and a set of privileged registers and memory addresses **224**. In general, the operating system exposes non-privileged instructions, non-privileged registers, and non-privileged memory addresses **226** and a system-call interface **228** as an operating-system interface **230** to application programs **232-236** that execute within an execution environment provided to the application programs by the operating system. The operating system, alone, accesses the privileged instructions, privileged registers, and privileged memory addresses. By reserving access to privileged instructions, privileged registers, and privileged memory addresses, the operating system can ensure that application programs and other higher-level computational entities cannot interfere with one another's execution and cannot change the overall state of the computer system in ways that could deleteriously impact system operation. The operating system includes many internal components and modules, including a scheduler **242**, memory management **244**, a file system **246**, device drivers **248**, and many other components and modules.

To a certain degree, modern operating systems provide numerous levels of abstraction above the hardware level, including virtual memory, which provides to each application program and other computational entities a separate, large, linear memory-address space that is mapped by the operating system to various electronic memories and mass-storage devices. The scheduler orchestrates interleaved execution of various different application programs and higher-level computational entities, providing to each application program a virtual, stand-alone system devoted entirely to the application program. From the application program's standpoint, the application program executes continuously without concern for the need to share processor devices and other system devices with other application programs and higher-level computational entities. The device drivers abstract details of hardware-component operation, allowing application programs to employ the system-call interface for transmitting and receiving data to and from communications networks, mass-storage devices, and other I/O devices and subsystems. The file system **246** facilitates abstraction of mass-storage-device and memory devices as a high-level, easy-to-access, file-system interface. Thus, the development and evolution of the operating system has resulted in the generation of a type of multi-faceted virtual execution environment for application programs and other higher-level computational entities.

While the execution environments provided by operating systems have proved an enormously successful level of abstraction within computer systems, the operating-system-provided level of abstraction is nonetheless associated with difficulties and challenges for developers and users of application programs and other higher-level computational entities. One difficulty arises from the fact that there are many different operating systems that run within various different types of computer hardware. In many cases, popular application programs and computational systems are developed to run on only a subset of the available operating systems, and can therefore be executed within only a subset of the various different types of computer systems on which the operating systems are designed to run. Often, even when an application program or other computational system is ported to additional operating systems, the application program or other computational system can nonetheless run more efficiently on the operating systems for which the application program or other computational system was originally targeted. Another difficulty arises from the increasingly distributed nature of computer systems. Although distributed operating systems are the subject of considerable research and development efforts, many of the popular operating systems are designed primarily for execution on a single computer system. In many cases, it is difficult to move application programs, in real time, between the different computer systems of a distributed computer system for high-availability, fault-tolerance, and load-balancing purposes. The problems are even greater in heterogeneous distributed computer systems which include different types of hardware and devices running different types of operating systems. Operating systems continue to evolve, as a result of which certain older application programs and other computational entities may be incompatible with more recent versions of operating systems for which they are targeted, creating compatibility issues that are particularly difficult to manage in large distributed systems.

For all of these reasons, a higher level of abstraction, referred to as the "virtual machine," ("VM") has been developed and evolved to further abstract computer hardware in order to address many difficulties and challenges associated with traditional computing systems, including the compatibility issues discussed above. FIGS. **3A-3B** show two types of VM and virtual-machine execution environments. FIGS. **3A-3B** use the same illustration conventions as used in FIG. **2**. FIG. **3A** shows a first type of virtualization. The server computer **300** in FIG. **3A** includes the same hardware layer **302** as the hardware layer **202** shown in FIG. **2**. However, rather than providing an operating system layer directly above the hardware layer, as in FIG. **2**, the virtual-

ized computing environment shown in FIG. **3**A features a virtualization layer **304** that interfaces through a virtualization-layer/hardware-layer interface **306**, equivalent to interface **216** in FIG. **2**, to the hardware. The virtualization layer **304** provides a hardware-like interface **308** to a number of VMs, such as VM **310**, in a virtual-machine layer **311** executing above the virtualization layer **304**. Each VM includes one or more application programs or other higher-level computational entities packaged together with an operating system, referred to as a "guest operating system," such as application **314** and guest operating system **316** packaged together within VM **310**. Each VM is thus equivalent to the operating-system layer **204** and application-program layer **206** in the general-purpose computer system shown in FIG. **2**. Each guest operating system within a VM interfaces to the virtualization-layer interface **308** rather than to the actual hardware interface **306**. The virtualization layer **304** partitions hardware devices into abstract virtual-hardware layers to which each guest operating system within a VM interfaces. The guest operating systems within the VMs, in general, are unaware of the virtualization layer and operate as if they were directly accessing a true hardware interface. The virtualization layer **304** ensures that each of the VMs currently executing within the virtual environment receive a fair allocation of underlying hardware devices and that all VMs receive sufficient devices to progress in execution. The virtualization-layer interface **308** may differ for different guest operating systems. For example, the virtualization layer is generally able to provide virtual hardware interfaces for a variety of different types of computer hardware. This allows, as one example, a VM that includes a guest operating system designed for a particular computer architecture to run on hardware of a different architecture. The number of VMs need not be equal to the number of physical processors or even a multiple of the number of processors.

The virtualization layer **304** includes a virtual-machine-monitor module **318** that virtualizes physical processors in the hardware layer to create virtual processors on which each of the VMs executes. For execution efficiency, the virtualization layer attempts to allow VMs to directly execute non-privileged instructions and to directly access non-privileged registers and memory. However, when the guest operating system within a VM accesses virtual privileged instructions, virtual privileged registers, and virtual privileged memory through the virtualization-layer interface **308**, the accesses result in execution of virtualization-layer code to simulate or emulate the privileged devices. The virtualization layer additionally includes a kernel module **320** that manages memory, communications, and data-storage machine devices on behalf of executing VMs ("VM kernel"). The VM kernel, for example, maintains shadow page tables on each VM so that hardware-level virtual-memory facilities can be used to process memory accesses. The VM kernel additionally includes routines that implement virtual communications and data-storage devices as well as device drivers that directly control the operation of underlying hardware communications and data-storage devices. Similarly, the VM kernel virtualizes various other types of I/O devices, including keyboards, optical-disk drives, and other such devices. The virtualization layer **304** essentially schedules execution of VMs much like an operating system schedules execution of application programs, so that the VMs each execute within a complete and fully functional virtual hardware layer.

FIG. **3**B shows a second type of virtualization. In FIG. **3**B, the server computer **340** includes the same hardware layer **342** and operating system layer **344** as the hardware layer **202** and the operating system layer **204** shown in FIG. **2**. Several application programs **346** and **348** are shown running in the execution environment provided by the operating system **344**. In addition, a virtualization layer **350** is also provided, in computer **340**, but, unlike the virtualization layer **304** discussed with reference to FIG. **3**A, virtualization layer **350** is layered above the operating system **344**, referred to as the "host OS," and uses the operating system interface to access operating-system-provided functionality as well as the hardware. The virtualization layer **350** comprises primarily a VMM and a hardware-like interface **352**, similar to hardware-like interface **308** in FIG. **3**A. The virtualization-layer/hardware-layer interface **352**, equivalent to interface **216** in FIG. **2**, provides an execution environment for a number of VMs **356-358**, each including one or more application programs or other higher-level computational entities packaged together with a guest operating system.

In FIGS. **3**A-**3**B, the layers are somewhat simplified for clarity of illustration. For example, portions of the virtualization layer **350** may reside within the host-operating-system kernel, such as a specialized driver incorporated into the host operating system to facilitate hardware access by the virtualization layer.

FIG. **4** shows an example set of VMs **402**, such as VM **404**, and a set of datastores ("DS") **406**, such as DS **408**, above a virtual interface plane **410**. The virtual interface plane **410** represents a separation between a physical resource level that comprises the server computers and mass-data storage arrays and a virtual resource level that comprises the VMs and DSs. The set of VMs **402** may be partitioned to run on different server computers, and the set of DSs **406** may be partitioned on different mass-storage arrays. Because the VMs are not bound physical devices, the VMs may be moved to different server computers in an attempt to maximize efficient use of the cloud-computing infrastructure **100** resources. For example, each of the server computers **104-107** may initially run three VMs. However, because the VMs have different workloads and storage requirements, the VMs may be moved to other server computers with available data storage and computational resources. Certain VMs may also be grouped into resource pools. For example, suppose a host is used to run five VMs and a first department of an organization uses three of the VMs and a second department of the same organization uses two of the VMs. Because the second department needs larger amounts of CPU and memory, a systems administrator may create one resource pool that comprises the three VMs used by the first department and a second resource pool that comprises the two VMs used by the second department. The second resource pool may be allocated more CPU and memory to meet the larger demands. FIG. **4** shows two application programs **412** and **414**. Application program **412** runs on a single VM **416**. On the other hand, application program **414** is a distributed application that runs on six VMs, such as VM **418**.

A service-level agreement ("SLA") between a data center customer and a data center service provider is a contractual agreement that outlines specific service objectives to be provided by the cloud computing service provider to the customer. The SLA describes the services, financial aspects of service delivery, and specific performance metrics that govern service delivery. The SLA describes service-level objectives ("SLOs") that are agreed upon by the service provider and the customer as a means of measuring the performance of the services. An SLO metric may be any individual performance metric or combination of performance metrics that the customer selects as a key perfor-

mance indicator of the services provided by the cloud computing service provider. The SLO metric may be compared with an SLO threshold, denoted by T_{SLO}, that represents when the SLOs are violated.

Equations (1a)-(1e) below are examples of SLO metrics. An SLO metric may be calculated as a sum of performance metrics:

$$SLOmetric(t) = \sum_{j=1}^{J} metric_j(t) \quad (1a)$$

where

t is a time stamp;

$metric_j(t)$ is the jth performance metric generated at time stamp t; and

J is the number of performance metrics.

An SLO metric may be an average of performance metrics generated at each time stamp:

$$SLOmetric(t) = \frac{1}{J}\sum_{j=1}^{J} metric_j(t) \quad (1b)$$

An SLO metric may be the largest performance metric generated at each time stamp:

$$SLOmetric(t)=\max\{metric_j(t)\}_{j=1}^{J} \quad (1c)$$

An SLO metric may be the smallest performance metric generated at each time stamp:

$$SLOmetric(t)=\min\{metric_j(t)\}_{j=1}^{J} \quad (1d)$$

An application program response time may be used as an SLO metric at each time stamp:

$$SLOmetric(t)=responseTime(t) \quad (1e)$$

FIG. **5** shows a plot of an SLO metric generated for an application program running in a data center in a time window of duration TI. Horizontal axis **502** represents time. Vertical axis **504** represents an SLO metric value. Curve **506** represent values of an SLO metric at time stamps within the time window **508**. For example, point **510** is an SLO metric value at a particle time stamp. Dashed line **512** represents an SLO threshold that is used to determine when the SLO is violated. The SLO threshold may be a hard threshold or a dynamic threshold. Time axis **502** includes fourteen marks labeled by t_i, where i=1, . . . 14 that represent time stamps when the SLO metric violates the threshold **512**. For example, the SLO metric **514** that violates the threshold **512** at a time stamp t_7 is denoted by SLOmetric(t_7). A single violation of the SLO threshold at a time stamp is also called an atomic anomaly. The SLO threshold **512** represents a limit on normal behavior. When an atomic anomaly occurs, such as when the SLO metric **514** violates the threshold **512**, an alert may be generated.

Attributes of objects used to run an application program in data center are recorded in the same time window TI. An object may be one or more VMs used to run the application program. For example, suppose a number of VMs are used to run an application program. Each the VMs have the same set of attributes. The attributes of a VM include CPU usage, memory usage, and network usage. Each attribute is represented as time series data and used as attribute performance indicators. For example, three attributes of a VM are time series data of CPU usage, memory usage, and network bandwidth.

FIG. **6** shows plots of three attributes of N attributes used to run the application program with SLO metric plotted in FIG. **5**. The attributes are denoted by An, where n=1, . . . , N, and the attributes are collected in the same time window TI as the SLO metric shown in FIG. **5**. Horizontal axes **602-604** represent time. Vertical axes **606-608** represent metric values. Curves **610-612** represent attributes. For example, attribute A1 may be CPU usage and curve **610** is time series data of CPU usage, attribute A2 may be memory usage and curve **611** is time series data memory usage, and attribute AN may I/O network usage and curve **612** is time series data the network bandwidth. Dashed lines **614-616** represent attribute thresholds associated with each attribute. The time axes **602-604** also include time stamps t_i that represent when an attribute violates an attribute threshold. For example, attributes **610** and **611** violate their associated attribute thresholds **614** and **615** at time stamp t_2. An attribute violation of an associated attribute threshold at a time stamp is also called an atomic anomaly. Atomic anomalies occur at different time stamps but the time stamps may correspond to the time stamps when the SLO metric violates the SLO threshold. For example, attributes A2 and AN both violate their associated attribute thresholds at time stamp t_2, which corresponds to the SLO metric violation of the SLO threshold at time stamp t_2 in FIG. **5**. On the other hand, it may be the case that attributes violate associated attribute thresholds at time stamps that do not correspond to any of the time stamps when the SLO metric violates the SLO threshold. For example, attributes A1 violates associated attribute threshold **614** at time stamp t' and attribute AN violates associated attribute threshold **616** at time stamp t". However, neither of the time stamps t' and t" corresponds to an SLO metric violation of the SLO threshold.

Note that although embodiments are described below for the SLO threshold of FIG. **5** and attribute thresholds of FIG. **6** are represented as upper bounds or limits on normal behavior, methods described below may be used with an SLO threshold and attribute thresholds that are lower bounds or limits on normal behavior. In other words, embodiments are not intended to be limited to the SLO threshold of FIG. **5** and attribute thresholds of FIG. **6** that represented upper bounds or limits on normal behavior.

Methods calculate a participation rate, SLO metric degradation rate, and co-occurrence rate for each attribute over the time window for time stamps that correspond to both attribute violations of an attribute threshold and SLO metric violations of an SLO threshold. The participation rate is a measure how much, or what portion of, an attribute's attribute threshold violations correspond to the number of SLO threshold violations in the time window. For each attribute, a participation rate may be calculated as the fraction of occurrences an attribute violates an associated attribute threshold that correspond to the number of SLO metric violations of the SLO threshold:

$$Part_{rate}(An) = \frac{\text{count}(TS(An) \cap \text{SLO\_metric\_viol})}{\text{count}(\text{SLO\_metric\_viol})} \quad (2)$$

where

TS(An) is the set of time stamps when attribute An violates the associated attribute threshold in the time window TI;

SLO_metric_viol is the set of time stamps when the SLO metric violates SLO threshold in the time window TI;

∩ represents intersection; and

count( ) is a count function that counts the number of elements in a set.

FIG. **7** shows time stamps of attribute violations of associated attribute thresholds for five attributes and time stamps of SLO metric violations of the SLO threshold. FIG. **7** shows the time axis **502** of the SLO metric and the fourteen time stamps of the SLO metric violations of the SLO threshold described above with reference to FIG. **5** and the time axes **602-604** of the attribute violations of the attribute thresholds described above with reference to FIG. **6**. The participation rates of the attributes are calculated according to Equation (2). For example, the set of time stamps of the attribute A1 with attribute violations of the associated attribute threshold that correspond to time stamps in the set of time stamps of the SLO metric violation is given by

$$TS(A1)\cap SLO\_metric\_viol=\{t_2,t_4,t_9,t_{11},t_{14}\}$$

where

$$TS(A1)=\{t_2,t_4,t',t_9,t_{11},t_{14}\};\text{ and}$$

$$SLO\_metric\_viol=\{t_1,t_2,t_3,t_4,t_5,t_6,t_7,t_8,t_9,t_{10},t_{11},t_{12},t_{13},t_{14}\}.$$

The counts are

$$count(TS(An)\cap SLO\_metric\_viol)=5$$

and

$$count(SLO\_metric\_viol)=14$$

which gives a participation rate of $P_{rate}(A1)=0.357$. The participation rate of the attribute A2 is $P_{rate}(A2)=0.857$. For example, $P_{rate}(A1)=0.357$ indicates that attribute A1 corresponds to about 35% of the SLO threshold violations and $P_{rate}(A2)=0.857$ indicates that attribute A2 corresponds to about 85% of the SLO threshold violations.

For each attribute, an attribute's ability to degrade the performance of an application is calculated as an average value of the SLO metric at the time stamps when both the SLO metric violates the SLO threshold and the attribute violates the attribute threshold:

$$SLOmetric_{\deg\_rate}(An)=\frac{1}{\text{count}(T)}\sum_{t\in T}SLOmetric(t) \tag{3}$$

where

$$T=TS(An)\cap SLO\_metric\_viol.$$

FIG. **8** shows a plot of values of the SLO metric that violate the SLO threshold and time axes **602-604** of FIG. **6**. Vertical line segments that extend above the SLO threshold represent the values of the SLO metrics that violate the SLO threshold **512** described above with reference to FIG. **5**. For example, line segment **802** represents the value of the SLO metric at time stamp t_4, SLOmetric(t_4), which is greater than the threshold **512**. FIG. **8** also includes equations **804-806** that represent calculation of the SLO metric degradation rate for the attributes A1, A2, and AN in accordance with Equation (3). For example, $SLOmetric_{deg\_rate}(A1)$ is an average of the SLO metric values represented by line segments **802** and **808-811**.

For each attribute, a co-occurrence index is calculated. The co-occurrence index as an average number of co-occurring attribute threshold violations between two attributes. The time stamps of the co-occurring attribute threshold violations also coincide with the time stamps of the SLO metric violates the SLO threshold. The co-occurrence index is given by:

$$Co_{index}(An)=\frac{1}{N-1}\sum_{\substack{j=1\\ j\neq n}}^{N}\text{count}(An\cap Aj) \tag{4}$$

where count(An∩Aj) is the number of time attributes of the attributes An and Aj violate their respective attribute thresholds at the same time stamps.

FIG. **9** shows time axes **901-905** of five attributes with time stamps of attributes metric violations of associated attribute thresholds. The time stamps coincide with time stamps of SLO metric violations of the SLO threshold shown in FIG. **5**. The count(A1∩A2)=4 is the number of times the attributes of the attributes A1 and A2 violated their respective attribute thresholds at the same time stamps as indicated by dashed lines **906-909**. The quantities count (A1∩A3), count(A1∩A4), and count(A1∩A5) are calculated in the same manner. According to Equation (4), the co-occurrence index is calculated for the attribute A1 as:

$$Co_{index}(A1)=\frac{1}{4}(4+3+3+4)=3.5$$

The co-occurrence indices associated with the attributes A1, A2, A3, A4, and A5 are presented in FIG. **9**.

The participation rate, the SLO metric degradation rate, and the co-occurrence index may be used to identify attributes of interests or interesting attributes. Any one or more of the following conditions may be used to identify an attribute, An, as interesting:

$$Part_{rate}(An)\geq T_P \tag{5a}$$

$$SLOmetric_{deg\_rate}(An)\geq T_{SDR} \tag{5b}$$

$$Co_{index}(An)\geq T_{CO} \tag{5c}$$

where

T_P is the participation rate threshold;

T_{SDR} is the SLO metric degradation rate threshold; and

T_{CO} is the co-occurrence index threshold.

For example, an interesting attribute may be responsible for the SLO degradation of the application.

A rank value of an attribute may be calculated as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index associated with the attribute as follows:

$$Rank(An)=F(P_{rate}(An),SLOmetric_{deg\_rate}(An),Co_{index}(An)) \tag{6}$$

where F represents a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index. Examples of functions F include

$$F(X,Y,Z)=XYZ \tag{7a}$$

$$F(X,Y,Z)=aX+bY+cZ \tag{7b}$$

where

$X=P_{rate}(An)$;

$Y=\text{SLOmetric}_{deg\_rate}(An)$;

$Z=Co_{index}(An)$; and

a, b, and c are weights.

Methods apply association analysis in order to determine relationships between attributes called "attribute-association rules" or "fingerprints." Consider attributes A1, A2, . . . , AN that are of interest because one or more of their corresponding participation rates, SLO metric degradation rates, and co-occurrence indices satisfy the conditions in Equation (5a)-(5c). Attribute patterns comprising two or more attributes that violate their associated attribute thresholds at the same time stamp are determined. For example, the set of attributes {A1, A2} is an attribute pattern, if attribute A2 violates an attribute threshold at the same time stamp that attribute A1 violates an attribute threshold. A third attribute A3 may be combined with the attributes A1 and A2 to form another attribute pattern {A1, A2, A3} if attribute A3 violates an attribute threshold at the same time stamp the attributes A1 and A2 violate their associated attribute thresholds. The attribute patterns are collected to form a set of attribute patterns.

FIG. **10** shows attribute patterns created from the five attributes described above with reference to FIG. **9**. Dashed directional arrows are used to identify attributes that violate associated attribute thresholds at the same time stamps. For example, dashed directional arrow **1002** indicates that attributes A2, A3, and A5 violate associated attribute thresholds at the same time stamp t_1. The attributes A2, A3, and A5 form an attribute pattern {A2, A3, A5} **1004**. Note that attribute A2 is the only attribute that violates an associated attribute threshold at the time stamps t_8 and t_{12}. Therefore, attribute patterns are not formed for the time stamps t_8 and t_{12}.

Possible combinations of attributes that range from the fewest number of attributes in the set of attribute patterns to the largest number of attributes in the set of attribute patterns created. FIG. **11** shows a table **1102** of the attribute patterns and associated time stamps identified in FIG. **10**. The fewest number of attributes in an attribute pattern is two and the largest number of attributes in an attribute pattern is four. Table **1104** is a list of attribute combinations formed from the attributes. Column **1106** list all attribute pairs that can be created from the five attributes A1, A2, A3, A4, and A5; column **1108** list all attribute triplets that can be created from the five attributes A1, A2, A3, A4, and A5; and column **1110** list all attribute quadruplets that can be created from the five attributes A1, A2, A3, A4, and A5.

An attribute-association rule is determined from a pattern probability calculated for each attribute combination. Attribute combinations with an acceptable pattern probability form an attribute-association rule. The pattern probability is calculated as follows:

$$P_{pattern}(\text{attritube comb}) = \frac{freq(\text{attribute comb})}{\text{number of attribute patterns}} \quad (8)$$

where

attribute comb represents an attribute pair, attribute triplet, attribute quadruplet etc.; and

freq(attribute comb) is the number of occurrences of the attribute combination in the attribute patterns of the set of attribute patterns.

When a pattern probability of an attribute combination is greater than an attribute-pattern threshold:

$$P_{pattern}(\text{attribute comb}) \geq T_{pattern} \quad (9)$$

where $T_{pattern}$ is an attribute-pattern threshold, the attribute combination is designated as an attribute-association rule.

FIGS. **12**A-**12**C show an example of determining attribute-association rules from the attribute patterns and attribute combinations displayed in FIG. **11**. In FIG. **12**A, table **1202** includes a column of the attribute pairs **1204** of the five attributes A1, A2, A3, A4, and A5. Column **1206** lists the pattern probabilities calculated for each of the attribute pairs listed in column **1204** calculated according to Equation (8). In this example, using an attribute-pattern threshold of $T_{pattern}=4/12$, as described above with reference to Equation (9), gives attribute-association rules [A1, A2], [A2, A3], [A2, A5], and [A3, A5] listed in column **1208**. In FIG. **12**B, table **1210** includes a column of the attribute triplets **1212** the five attributes A1, A2, A3, A4, and A5. Column **1214** lists the pattern probabilities calculated for each of the attribute triplets according to Equation (8). Using the attribute-pattern threshold of $T_{pattern}=4/12$ as described above with reference to Equation (9) gives only one attribute-association rules [A2, A3, A5] listed in column **1216**. In FIG. **12**C, table **1218** includes a column of the attribute quadruplets **1220** of the five attributes A1, A2, A3, A4, and A5. Column **1222** lists the pattern probabilities calculated for each of the attribute quadruplets according to Equation (8). None of the pattern probabilities is greater than the attribute-pattern threshold of $T_{pattern}=4/12$. As a result, there are no attribute-association rules for the attribute quadruplets.

The participation rate, SLO metric degradation rate, and co-occurrence rate may be calculated for each attribute-association rules:

$$Part_{rate}(att-ass \text{ rule}) = \frac{\text{count}(TS(att-ass \text{ rule}) \cap \text{SLO\_metric\_viol})}{\text{count}(\text{SLO\_metric\_viol})} \quad (10)$$

where

att-ass rule is an attribute-association rule of two or more attributes; and

TS(att-ass rule) is the set of time stamps of the attribute-association rule in the time window TI.

For example, in FIG. **7**, set of time stamps of the attribute-association rule [A1, A2] is given by:

$$TS([A1,A2])=\{t_1,t_2,t_4,t_5,t_6,t_7,t_8,t_9,t_{10},t_{11},t_{12},t_{13},t_{14}\}$$

which is the full set of time stamps when attributes A1 and A2 violate their associated attribute thresholds. As a result, the participation rate of the attribute-association rule [A1, A2] is $Part_{rate}(\text{att-ass rule})=0.92$.

The SLO metric degradation rate of an attribute-association rule is the maximum of the SLO metric degradation rate of the attributes that form the attribute-association rule:

$$\text{SLOmetric}_{deg\_rate}(\text{att-ass rule}) = \max\{\text{SLOmetric}_{deg\_rate}(Aj)\}_{j=1}^{J} \quad (11)$$

where $\text{SLOmetric}_{deg\_rate}(Aj)$ is the SLO metric degradation rate of the jth attribute, Aj, of the attribute-association rule.

The co-occurrence index of an attribute-association rule is the average of the co-occurrence indices of the attributes that form the attribute-association rule:

$$Co_{rate}(att-ass \text{ rule}) = \frac{1}{J}\sum_{j=1}^{J} Co_{rate}(Aj) \quad (12)$$

The participation rate, SLO metric degradation rate, and co-occurrence index of the attribute-association rule may be used to identify attribute-association rules that are of interest based on the same conditions provided in Equations (5a)-(5c). A rank value of an attribute-association rule may be calculated as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index of the attribute-association rule according to Equations (6)-(7).

Attributes of interest may be combined with attribute-association rules to determine if any additional attribute-association rules can be created. Let $\{Ai\}_{i=1}^{J}$ be a set of attributes in which each attribute has been identified as an attribute of interest based on the conditions for identifying attributes of interest in Equations (5a)-(5c) and/or attribute ranks calculated according to Equations (6)-(7). For each attribute of interest Ai, a conditional probability of an attribute of interest, Ai, with respect to an attribute-association rule may be calculated:

$$P_{con}(Ai \mid att-ass \text{ rule}) = \frac{freq(Ai)}{freq(\text{attributes in } att-ass \text{ rule})} \quad (13)$$

where

freq(Ai) is the frequency of the attribute Ai in the set of attribute patterns; and

freq(attributes in att-ass rule) is the frequency of the attributes that form the attribute-association rule in the set of attribute patterns.

When the conditional probability satisfied the following condition:

$$P_{con}(Ai|\text{att-ass rule}) \geq T_R \quad (14)$$

where T_R is a conditional-probability threshold, the attribute Ai may be combined with the attribute-association rule to create another attribute-association rule. For example, the conditional probability of the attribute A4 with respect to the attribute-association rule [A1, A2] is given by

$$P(A4 \mid [A1, A2]) = \frac{freq(A4)}{freq(A1 \text{ and } A2)} = \frac{6}{10+5} = 0.4$$

If the threshold T_R=0.3, then an additional attribute-association rule, [A1, A2, A4], is created.

The participation rate, SLO metric degradation rate, and co-occurrence index may be used to identify additional attribute-association rules that are of interest based on the conditions provided in Equations (5a)-(5c). A rank value of an additional attribute-association rule may be calculated as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index of the additional attribute-association rule according to Equations (6)-(7).

Method described above may be used by data center system administrators to identify those attributes that are highly associated with SLO degradation of a customer's application program and should be added to problem definitions. In other words, a data center customer may be offered to "codify" his/her problems primarily with atomic anomalies based on the attributes and attribute-association rules that are responsible for a decrease in the SLO. As a result, the customer may be forewarned of potentially significant SLO decline in order to prevent unwanted loss and take action to prevent problems whenever the abnormality conditions occur. Moreover, the methods described above employ a machine learning framework that is also able to identify problem attribute patterns in the form of minimum size attribute-association rules that constitute core structures and are highly associated with degradation of the SLO metric of the application program. Identifying also the relevant symptoms that need to be assigned to attributes within the proposed framework may lead to the full definition of alerts in an automatic way.

FIG. **13** shows a control-flow diagram of a method to identify problems in a data center. In block **1301**, an SLO metric degradation rate is calculated at time stamps within a time window for an application running in the data center, as described above with reference to Equations (1a)-(1e). In decision block **1302**, when the SLO metric degradation rate of the application calculated in block **1301** exceeds an SLO threshold in the time window, control flows to block **1303**. In block **1303**, attributes of one or more objects used to run the application are identified. The objects may be VMs and/or server computers. In block **1304**, a routine "rank and identify attributes of interest" is called to rank the attributes in order of increasing contribution to the SLO degradation rate of the application and identify attributes that are of interest. In block **1305**, a routine "determine attribute-association rules" is called determine attribute-association rules comprised of two or more attributes. In block **1306**, a routine "determine additional attribute-association rules" is called determine additional attribute-association rules from the attributes and attribute-association rules. In block **1307**, the attributes and attribute-association rules that are of interest are displayed.

FIG. **14** shows a control-flow diagram of a method to "rank and identify attributes of interest" called in block **1304** of FIG. **13**. A for-loop beginning with block **1401**, repeats the operations represented by blocks **1402-1406**. In block **1402**, a participation rate is calculated for each attribute as described above with reference to Equation (2) and FIG. **7**). In block **1403**, a SLO metric degradation rate is calculated for each attribute as described above with reference to Equation (3) and FIG. **8**. In block **1404**, a co-occurrence index is calculate for each attribute as described above with reference to Equation (4) and FIG. **9**). In decision block **1406**, the operations represented by blocks **1402-1406** are repeated for another attribute, otherwise, control flows to block **1407**. In block **1407**, attributes with participation rates, SLO metric degradation rates, and co-occurrence indices that satisfy any one or more of the conditions given in Equation (5a)-(5c) are identified as attributes of interest. In block **1408**, a rank value is calculated for each attribute based on the participation rate, SLO metric degradation rate, and co-occurrence index. In block **1409**, the attributes are order based on their associated rank values.

FIG. **15** shows a control-flow diagram of a method to "determine attribute-association rules" called in block **1305** of FIG. **13**. In block **1501**, attribute combinations are formed from the attributes as described above with reference to FIG. **11**. A for-loop beginning with block **1502**, repeats the operations represented by block **1503-1505** for each attribute combination. In block **1503**, a pattern probability is calculated for each attribute combination. In decision block **1504**, when the pattern probability is greater than attribute-pattern threshold, an attribute-association rule is created from the pattern combination as described above with reference to FIGS. **12**A-**12**C. In decision block **1506**, the operations represented by blocks **1503-1505** are repeated for another attribute, otherwise, control flows to block **1507**. In decision block **1507**, a routine "rank and order attribute-

association rules" is called to rank the attribute-association rules and identify attribute-association rules that are of interest.

FIG. **16** shows a control-flow diagram of a method to "determine additional attribute-association rules" called in block **1306** of FIG. **13**. A for-loop beginning with block **1601**, repeats the operations represented by block **1602-1607** for each attribute. A for-loop beginning with block **1602**, repeats the operations represented by block **1603-1606** for each attribute-association rule. In block **1603**, a conditional probability is calculated for each attribute and attribute-association rule as described above with reference to Equation (13). In decision block **1604**, when the conditional probability is greater than attribute-combination threshold, an additional attribute-association rule is created from the attribute and the attribute-association rule, as described above with reference to Equation (14), an additional attribute-association rule is created. In decision block **1606**, the operations represented by blocks **1603-1605** are repeated for another attribute-association rule, otherwise, control flows to block **1607**. In decision block **1607**, the operations represented by blocks **1602-1606** are repeated for another attribute, otherwise, control flows to block **1608**. In decision block **1608**, a routine "rank and order attribute-association rules" is called to rank the additional attribute-association rules and identify attribute-association rules that are of interest.

FIG. **17** shows a control-flow diagram of a method to "rank and order attribute-association rules" called in block **1507** of FIG. **15** and block **1608** of FIG. **16**. A for-loop beginning with block **1701**, repeats the operations represented by blocks **1702-1706**. In block **1702**, a participation rate is calculated for each attribute-association rule denoted by Fm, as described above with reference to Equation (10). In block **1703**, a SLO metric degradation rate is calculated for each attribute-association rule as described above with reference to Equation (11). In block **1704**, a co-occurrence index is calculate for each attribute-association rule as described above with reference to Equation (12). In decision block **1706**, the operations represented by blocks **1702-1706** are repeated for another attribute-association rule, otherwise, control flows to block **1707**. In block **1707**, attribute-association rules with participation rates, SLO metric degradation rates, and co-occurrence indices that satisfy any one or more of the conditions given in Equation (5a)-(5c) are identified as attribute-association rule of interest. In block **1708**, a rank value is calculated for each attribute-association rule based on the participation rate, SLO metric degradation rate, and co-occurrence index. In block **1709**, the attribute-association rules are order based on their associated rank values.

FIG. **18** shows an architectural diagram for various types of computers that may be used to execute the methods described above. Computers that receive, process, and store event messages may be described by the general architectural diagram shown in FIG. **18**, for example. The computer system contains one or multiple central processing units ("CPUs") **1802-1805**, one or more electronic memories **1808** interconnected with the CPUs by a CPU/memory-subsystem bus **1810** or multiple busses, a first bridge **1812** that interconnects the CPU/memory-subsystem bus **1810** with additional busses **1814** and **1816**, or other types of high-speed interconnection media, including multiple, high-speed serial interconnects. These busses or serial interconnections, in turn, connect the CPUs and memory with specialized processors, such as a graphics processor **1818**, and with one or more additional bridges **1820**, which are interconnected with high-speed serial links or with multiple controllers **1822-1827**, such as controller **1827**, that provide access to various different types of mass-storage devices **1828**, electronic displays, input devices, and other such components, subcomponents, and computational devices. It should be noted that computer-readable data-storage devices include optical and electromagnetic disks, electronic memories, and other physical data-storage devices.

EXPERIMENTAL RESULTS

Experiments were performed on a data center of active usage for the VM objects to investigate attributes of the objects in terms of their individual scores, as well as patterns making attribute-association rules. The input data parameters were 50 VM's with 700 attributes, 86 attributes violated associated thresholds, time window of monitoring metrics was 30 days, and 454,437 threshold violation events were analyzed.

In the experiments, the anomalies score of those VM's in vR Ops as a SLO metric is considered. The anomalies score represents how abnormal the behavior of the object is, based on historical metric data. The anomaly score is calculated as the total number of SLO threshold violations for all metrics of object and any child or lower level objects. The number of metrics of that are violating their dynamic thresholds to determine trends and normal levels of threshold violations. Based on these trends, the Anomalies score is calculated using the total number of threshold violations for all metrics for the selected object and its child objects. A low Anomalies score indicates that an object is behaving in accordance with the object's established historical parameters. Most or all of the object metrics, including the object key performance indicators ("KPIs"), are within their thresholds. Because changes in behavior often indicate developing problems, if the metrics of an object violate calculated thresholds, the anomalies score for the object increases. As more metrics violate associated thresholds, anomalies continue to increase. Violations by KPI metrics increase the Anomalies score more than violations by non-KPI metrics. A low anomalies score indicates that an object is behaving in accordance with its historical normalcy. In other words, most or all of the object metrics are within their respective thresholds. A high number of anomalies usually indicates a problem (statistically) or at least a situation that requires attention. Therefore, within this setting, looking for attributes of interest and attribute-association rules was equivalent to identifying patterns that statistically coincide with other attribute anomalies.

FIG. **19** shows a table of attributes observed in SLO violation with larger than 0.01 participation rate, where the SLO threshold was set to 50 for all 50 VM's. FIG. **20** shows a table of attribute-association rules formed form the top 5 attributes of the table of FIG. **19**. In this case, the participation rate of an attribute is measured as a conditional probability of its occurrence over all assembles associated with the SLO degradation rate with equal or larger size. In the meantime, the SLO degradation rate is the the same for nearly every attribute-association rule with the attribute "guestfilesystem|percentage." In general, it is observed that only a few of the attributes are associated with the anomalies score degradation with the specified threshold above. In FIG. **19**, a dominant group of attributes was not observed. The attributes have close SLO degradation rates, with some diversity in the co-occurrence index. However, in case of attribute-association rules displayed in FIG. **20**, the diversity becomes significant, both in terms of the participation rate,

as well as the co-occurrence index, where we see that the attribute-association rules include the attributes

"cpu|usagemhz_average,"

"diskspace|activeNotShared,"

"guestfilesystem|percentage,"

"guestfilesystem|usage," and

"net|bytesTx_average"

determined the maximum number of other attributes. This example demonstrates that there are dangerous combinations of attributes that can result in higher rate of anomaly propagation over the object. FIG. **20** shows a table with some attribute-association rules discovered with the principle of maximum confidence transition represented by the conditional probability in Equation (13). This table reveals that different attributes of "guestfilesystem" that represent various quantifications of the same process, which appears to be a redundant attribute-association rule. However, the attribute-association rule reveals that these attributes have simultaneously generated anomaly events that increased the anomalies score of VM's above the acceptable degree.

There are many different types of computer-system architectures that differ from one another in the number of different memories, including different types of hierarchical cache memories, the number of processors and the connectivity of the processors with other system components, the number of internal communications busses and serial links, and in many other ways. However, computer systems generally execute stored programs by fetching instructions from memory and executing the instructions in one or more processors. Computer systems include general-purpose computer systems, such as personal computers ("PCs"), various types of servers and workstations, and higher-end mainframe computers, but may also include a plethora of various types of special-purpose computing devices, including data-storage systems, communications routers, network nodes, tablet computers, and mobile telephones.

It is appreciated that the various implementations described herein are intended to enable any person skilled in the art to make or use the present disclosure. Various modifications to these implementations will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of the disclosure. For example, any of a variety of different implementations can be obtained by varying any of many different design and development parameters, including programming language, underlying operating system, modular organization, control structures, data structures, and other such design and development parameters. Thus, the present disclosure is not intended to be limited to the implementations described herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

The invention claimed is:

1. A method to enhance identification of problems in a data center, the method comprising:

calculating a service level objective ("SLO") degradation rate of an application program running in the data center in a time window;

identifying attributes of an object that runs the application program when the SLO degradation rate violates an SLO threshold;

ranking and identifying attributes of interest based on the SLO degradation rate of the application and attribute violations of associated attribute thresholds;

determining attribute-association rules based on combinations of the attributes of interest; and

ranking and identifying attribute-association rules of interest,

wherein ranking and identifying the attributes of interest further comprises:

for each attribute,

calculating a participation rate as a fraction of attribute threshold violations relative to a total number of SLO metric violations,

calculating an SLO metric degradation rate as an average value of the SLO metric at time stamps when both SLO metric of the application program violates the SLO threshold and the attribute violates the associated attribute threshold,

calculating a co-occurrence index as an average number of co-occurring attribute threshold violations between two attributes,

calculating a rank value of the attribute as a function of the attribute participation rate, SLO metric degradation rate, and co-occurrence index, and

identifying the attribute as an attribute of interest when one or more of the participation rate, SLO metric degradation rate, and co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attributes based on each attribute's associated rank value.

2. The method of claim **1**, wherein determining the attribute-association rules further comprises:

forming attribute combinations from the attributes;

forming a set of attribute patterns from attributes that violate associated attribute threshold at the same time stamps; and

for each attribute combination,

calculating a pattern probability as a fraction of a number of occurrences of the attribute combination in attribute patterns of the set of attribute patterns; and

forming an attribute-association rule for the attribute combination with the pattern probability that is greater than an attribute-pattern threshold.

3. The method of claim **2**, further comprising:

for each attribute of interest,

for each attribute-association rule,

calculating a conditional probability as a fraction of a frequency of the attribute of interest in the set of attribute patterns and a frequency of the attributes that form the attribute-association rule in the set of attribute patterns; and

forming an additional attribute-association rule from the attribute of interest and attribute-association rule when the conditional probability is greater than a conditional-probability threshold.

4. The method of claim **1**, wherein calculating the SLO degradation rate of the application comprises calculating a sum of SLO performance metrics.

5. The method of claim **1**, wherein ranking and identifying attribute-association rules of interest further comprises:

for each attribute-association rule,

calculating a second participation rate as a fraction of occurrences of attribute threshold violations for attributes that form the attribute-association rule relative to the total number of SLO metric violations;

calculating a second SLO metric degradation rate as a maximum of the SLO metric degradation rates of the attributes that form the attribute-association rule;

calculating a second co-occurrence index as an average of the co-occurrence rate of the attributes that form the attribute-association rule;

calculating a second rank value of the attribute-association rule as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index; and

identifying the attribute-association rule as an attribute of interest when one or more of the second participation rate, second SLO metric degradation rate, and second co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attribute-association rules based on each attribute-association rule's associated rank value.

6. A system to enhance identification of problems in a data center, the system comprising:

one or more processors;

one or more data-storage devices; and

machine-readable instructions stored in the one or more data-storage devices that when executed using the one or more processors controls the system to carry out

calculating a service level objective ("SLO") degradation rate of an application program running in the data center in a time window;

identifying attributes of an object that runs the application program when the SLO degradation rate violates an SLO threshold;

ranking and identifying attributes of interest based on the SLO degradation rate of the application and attribute violations of associated attribute thresholds;

determining attribute-association rules based on combinations of the attributes of interest; and

ranking and identifying attribute-association rules of interest,

wherein determining the attribute-association rules further comprises:

forming attribute combinations from the attributes;

forming a set of attribute patterns from attributes that violate associated attribute threshold at the same time stamps;

for each attribute combination,

calculating a pattern probability as a fraction of a number of occurrences of the attribute combination in attribute patterns of the set of attribute patterns; and

forming an attribute-association rule for the attribute combination with the pattern probability that is greater than an attribute-pattern threshold.

7. The system of claim **6**, wherein calculating the SLO degradation rate of the application comprises calculating a sum of SLO performance metrics.

8. The system of claim **6**, wherein ranking and identifying the attributes of interest further comprise:

for each attribute,

calculating a participation rate as a fraction of attribute threshold violations relative to a total number of SLO metric violations of the SLO threshold,

calculating an SLO metric degradation rate as an average value of the SLO metric at time stamps when both SLO metric of the application program violates the SLO threshold and the attribute violates the associated attribute threshold,

calculating a co-occurrence index as an average number of co-occurring attribute threshold violations between two attributes,

calculating a rank value of the attribute as a function of the attribute participation rate, SLO metric degradation rate, and co-occurrence index, and

identifying the attribute as an attribute of interest when one or more of the participation rate, SLO metric degradation rate, and co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attributes based on each attribute's associated rank value.

9. The system of claim **6**, further comprising:

for each attribute of interest,

for each attribute-association rule,

calculating a conditional probability as a fraction of a frequency of the attribute of interest in the set of attribute patterns and a frequency of the attributes that form the attribute-association rule in the set of attribute patterns; and

forming an additional attribute-association rule from the attribute of interest and attribute-association rule when the conditional probability is greater than a conditional-probability threshold.

10. The system of claim **6**, wherein ranking and identifying attribute-association rules of interest further comprises:

for each attribute-association rule,

calculating a participation rate as a fraction of occurrences of attribute threshold violations for attributes that form the attribute-association rule relative to the total number of SLO metric violations of the SLO threshold;

calculating an SLO metric degradation rate as a maximum of the SLO metric degradation rates of the attributes that form the attribute-association rule;

calculating a co-occurrence index as an average the co-occurrence rate of the attributes that form the attribute-association rule;

calculating a rank value of the attribute-association rule as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index; and

identifying the attribute-association rule as an attribute of interest when one or more of the participation rate, SLO metric degradation rate, and co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attribute-association rules based on each attribute-association rule's associated rank value.

11. A non-transitory, computer-readable medium encoded with machine-readable instructions that implement a method carried out by one or more processors of a computer system to perform the operations of:

calculating a service level objective ("SLO") degradation rate of an application program running in the data center in a time window;

identifying attributes of an object that runs the application program when the SLO degradation rate violates an SLO threshold;

ranking and identifying attributes of interest based on the SLO degradation rate of the application and attribute violations of associated attribute thresholds;

determining attribute-association rules based on combinations of the attributes of interest; and

ranking and identifying attribute-association rules of interest,

wherein ranking and identifying attribute-association rules of interest further comprises:

for each attribute-association rule,

calculating a participation rate as a fraction of occurrences of attribute threshold violations for attributes that form the attribute-association rule relative to the total number of SLO metric violations of the SLO threshold;

calculating an SLO metric degradation rate as a maximum of the SLO metric degradation rates of the attributes that form the attribute-association rule;

calculating a co-occurrence index as an average the co-occurrence rate of the attributes that form the attribute-association rule;

calculating a rank value of the attribute-association rule as a function of the participation rate, the SLO metric degradation rate, and the co-occurrence index; and

identifying the attribute-association rule as an attribute of interest when one or more of the participation rate, SLO metric degradation rate, and co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attribute-association rules based on each attribute-association rule's associated rank value.

12. The medium of claim **11**, wherein determining the attribute-association rules further comprises:

forming attribute combinations from the attributes;

forming a set of attribute patterns from attributes that violate associated attribute threshold at the same time stamps; and

for each attribute combination,

calculating a pattern probability as a fraction of a number of occurrences of the attribute combination in attribute patterns of the set of attribute patterns; and

forming an attribute-association rule for the attribute combination with the pattern probability that is greater than an attribute-pattern threshold.

13. The medium of claim **12**, further comprising:

for each attribute of interest,

for each attribute-association rule,

calculating a conditional probability as a fraction of a frequency of the attribute of interest in the set of attribute patterns and a frequency of the attributes that form the attribute-association rule in the set of attribute patterns; and

forming an additional attribute-association rule from the attribute of interest and attribute-association rule when the conditional probability is greater than a conditional-probability threshold.

14. The medium of claim **11**, wherein calculating the SLO degradation rate of the application comprises calculating a sum of SLO performance metrics.

15. The medium of claim **11**, wherein ranking and identifying the attributes of interest further comprise:

for each attribute,

calculating a second participation rate as a fraction of occurrences of attribute threshold violations relative to a total number of SLO metric violations of the SLO threshold,

calculating a second SLO metric degradation rate as an average value of the SLO metric at time stamps when both SLO metric of the application program violates the SLO threshold and the attribute violates the associated attribute threshold,

calculating a second co-occurrence index as an average number of co-occurring attribute threshold violations between two attributes,

calculating a second rank value of the attribute as a function of the attribute participation rate, SLO metric degradation rate, and co-occurrence index, and

identifying the attribute as an attribute of interest when one or more of the second participation rate, second SLO metric degradation rate, and second co-occurrence index is greater than one or more of a corresponding participation rate threshold, SLO metric degradation rate threshold, and co-occurrence index threshold; and

ordering the attributes based on each attribute's associated rank value.

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