Adaptive Service Sync for Distributed Enterprise Systems

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Abstract

The ever-growing demand for a rapid introduction of new applications and services, coupled with the wide adoption of microservices architecture and its supporting cloud ecosystem — including public IaaS, PaaS, and serverless — has led enterprise infrastructures to become strongly distributed and heterogeneous in nature. Despite these evolutions, enterprise environments still need to provide consistent-yet-adaptive service interactions and execution modes that transparently support the reliability, performance, data, and security requirements of the applications that are being executed. This paper argues for and sketches the architecture and protocols of adaptive service synchronization across distributed enterprise infrastructure platforms that efficiently tackle the service interaction and execution-related trustworthiness aspects of heterogeneous enterprise application deployments.

Enterprise microservices infrastructures have emerged as one of the major enablers for rapidly creating and deploying enterprise applications. The need for a decentralized, modular application structure, along with the recognized advantages of separating and offloading the execution of auxiliary concerns from the application logic, led to the adoption of architectures based on Business Process (BP) models and Service-Oriented Architectures (SOA). More recently, the introduction of the Service Mesh operational abstraction for BPs has further enhanced the distributed and heterogeneous nature of enterprise deployments. However, the continuous demand for adapting the quality of the provided services in terms of performance, data, and security strongly relies on the capabilities of the business BPs and external services to provide consistent coordination and safeguard time and state consistency.

Keywords: Adaptive Service Synchronization,Distributed Enterprise Infrastructure,Service Orchestration,Cross-Platform Integration,Real-Time Data Consistency,Event-Driven Architecture,Microservices Coordination,Cloud-Native Synchronization,Fault-Tolerant Distributed Systems,Infrastructure Interoperability.

1. Introduction

Coordination and synchronization are a critical part of the distributed systems ecosystem. Properly synchronized service infrastructures enable coherent operation across multiple enterprise platforms, delivering a consistent interface to application clients, and maintaining robust data consistency and integrity. In a multi-platform enterprise ecosystem, service synchronization and coordination become an order of magnitude more complex, as there may be little or no shared resources or consensus between the distributed platforms. Diverse languages, protocols and implementation paradigms may also be used in the multi-cloud implementation domains and there may be weaker hierarchy and trust relationships among the platforms. The lack of resource awareness, disregard to platform constraints, non-fault tolerance, operational irrelevance, and lack of performance optimization are symptomatic of existing solutions, promoting the use of dedicated cross-cloud consolidation engines. These cross-platform service publishers and update consolidation engines guarantee consistent cloud operations via a phase-based approach on adaptive service updates.

Table 1. Adaptive Synchronization Strategy Comparison

Synchronization Strategy	Communication Mode	Resource Consumption	Fault Tolerance	Consistency Level	Suitable Environment
Direct Synchronization	Point-to-Point	Medium	Moderate	Strong	Small-scale enterprise systems
Synchronous Replication	Blocking Communication	High	High	Very Strong	Mission-critical services
Asynchronous Replication	Non-Blocking	Low	High	Eventual	Distributed cloud infrastructures
Event-Driven Synchronization	Message Broker-Based	Medium	High	Adaptive	Microservices ecosystems
Scheduled Synchronization	Time-Triggered	Low	Moderate	Moderate	Batch-oriented enterprise workloads

1.1. Resource Awareness and Constraint Handling

Analysis of adaptive service synchronization serving fault tolerance and recovery shows that they can cause substantial resource consumption. Thus, it is important to adapt their execution in consideration of the available resources in the execution environment. This can be achieved by defining different resource awareness levels and employing corresponding constraints. Two types of resource-aware service-synchronization execution profiles are introduced. During runtime, the currently available resources can be profiled, and this information can be employed to select the most suitable adaptive service-synchronization execution profile, applying optional adaptation at the synchronization protocol side to alleviate the resource usage.

Evaluating the dynamic resource conditions in a passing service provides awareness for resource-consumption constraints. These can be defined on the expected operating condition either directly or indirectly through a set of predefined levels—for example, low, medium, high, or other ordinal numerical discrete values of resource usage or availability: low for little resource availability in processing, memory, or bandwidth and high for the opposite. Each such condition can indicate a corresponding type of service interaction—direct, synchronous, asynchronous, and so on—whose profiles reside in the service model. Service usage not exceeding the defined limits in the specification allows executing the adaptation control and assigning the most suited option, thereby resuming the overall secondary consumption to the agent's availability. Other evaluations can also be traced over a background resource profile, offering guidelines for syncing consumption.

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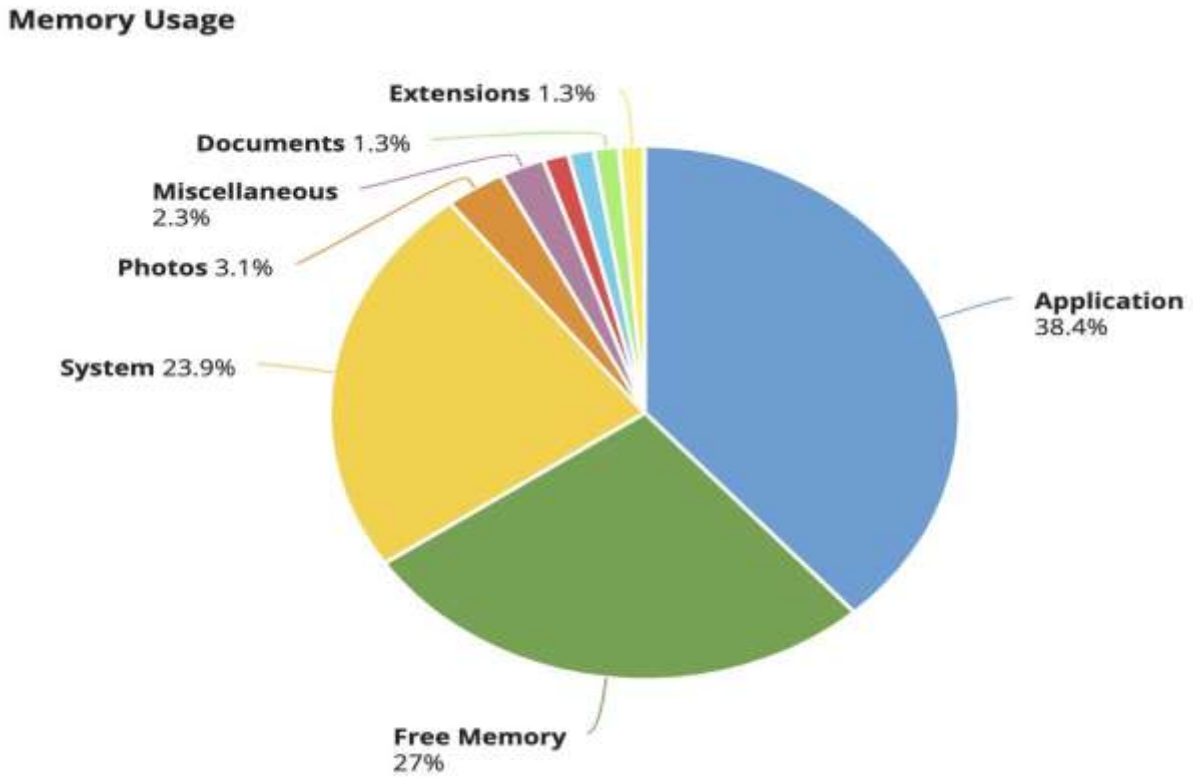

2. Background and Related Work

Enterprise-scale systems need rapid handling of faults both on the infrastructure side and application side. The Cloud paradigm guarantees that resources failure can be easily accepted and substituted. However, powering up and configuration of resources may take longer than the actual occurring service faults. This section focuses on two main issues on the application side of fault handling: how to tolerate and recover from faults, and how to apply multi-level redundancy to applications.

Area-wide geographic redundancy can be achieved by the current Cloud service model. However, due to the limited size of a specific resource zone and its availability with respect to time (the zone cannot be used as the execution environment of all services for a long time), shallow applications with few and unimportant data can only be partially tolerant to area-wide faults. Most of the enterprise applications in the Cloud cannot be operated fully synchronous and need an adaptive support for their fault handling as well as for their general dynamic reconfiguration.

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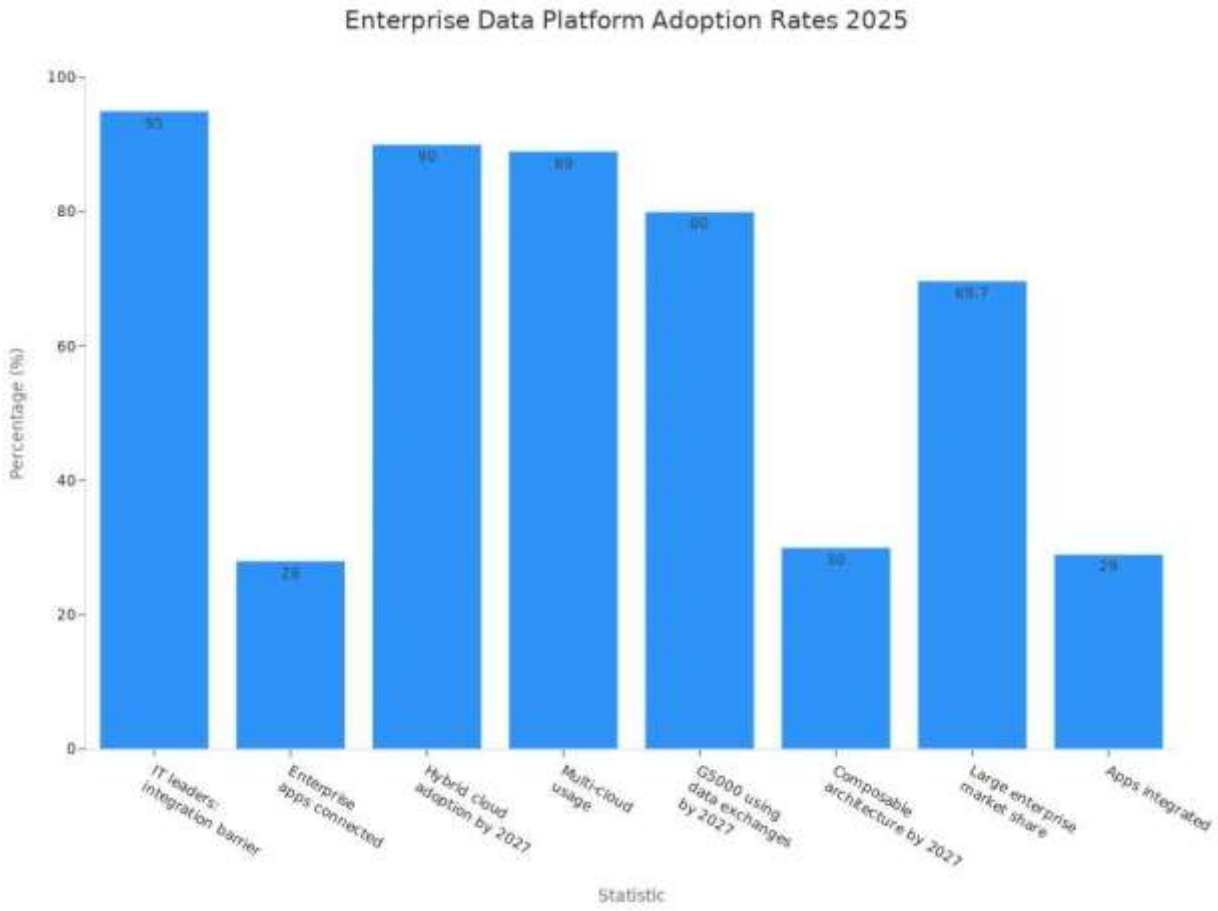

2.1. Fault Tolerance and Recovery

Failure of a service instance can happen at any moment and recovery may take longer than expected. Hence, it requires mechanisms that can be tightly integrated with the service architecture. The use of a provider-based model enables the use of a service proxy, which can remain stable and detect service faults. Furthermore, the identification of an active provider through an underlying service mesh removes most of the complexity in fault recovery. The resource awareness of the synchronization mechanisms allows a provider to take over as the supervisor of a long-running operation. This enhances the visibility of the long-running activity across the entire system. Operation supervision ensures that the sudden stop of the active provider does not cause a failure in the long-running operation and that it can effectively compensate for it. Hence, even when a long-running operation is supervised by a

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different provider, this context and information, including the current operational state, are available and accessible, allowing a seamless recovery.

Improving the handling of service failures during runtime is based on the management and coordination of operation compensation. This is implemented through a coordination protocol that provides the operation state and the available compensation plans of the service. The novelty lies in the content being propagated by a dedicated operation manager that keeps track of the state and compensation plans of ongoing long-running operations within the enterprise infrastructure, be it a private cloud, public cloud, or hybrid cloud. Such type of feature representation captures the progress of the overall operation being executed in multiple services. Different strategies manage the state of ongoing operations: the use of coordination protocols helps in identifying active components of a long-running operation, maintaining the progress of the operation, and providing mechanisms for recovering from dynamic changes in the system.

Adaptive Service Synchronization Architecture

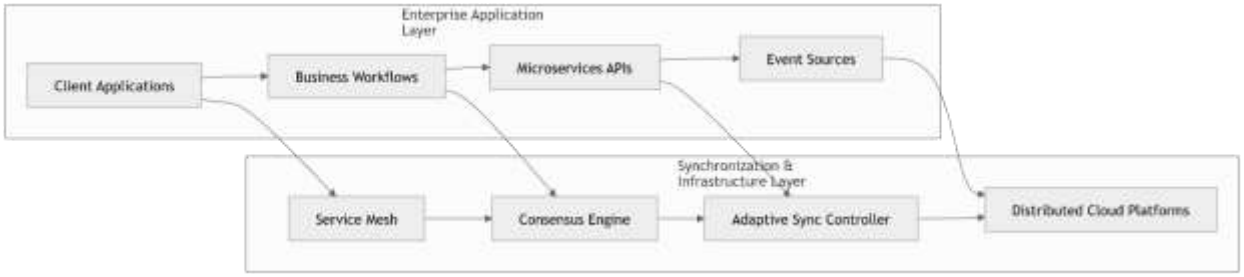

Table 2. Resource Awareness Profiles in Adaptive Service Synchronization

Resource Level	CPU Availability	Memory Availability	Network Bandwidth	Preferred Synchronization Mode	Adaptation Behavior
Low	Limited	Limited	Constrained	Asynchronous	Reduce synchronization frequency
Medium	Balanced	Moderate	Stable	Event-Driven	Dynamic adaptive coordination
High	Abundant	High	High Throughput	Synchronous	Full consistency enforcement
Critical Recovery State	Variable	Variable	Degraded	Hybrid Recovery Synchronization	Fault compensation enabled

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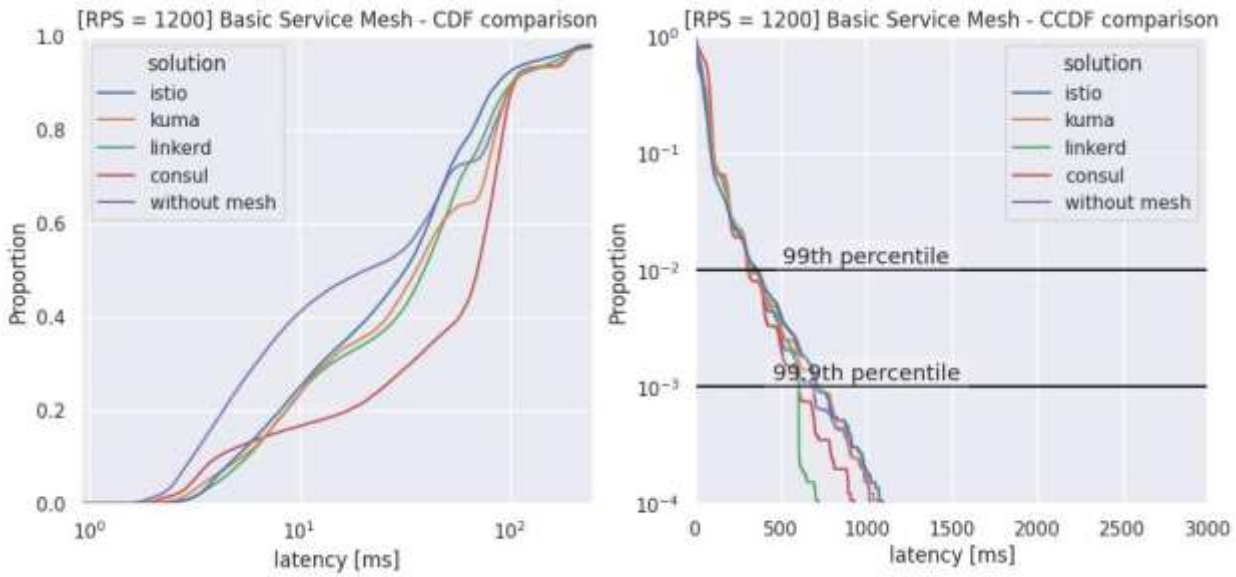
3. Core Concepts of Adaptive Service Synchronization

The term adaptive service synchronization denotes the manner in which general service replication and consistency strategies are applied during service-oriented enterprise application integration between different computing infrastructures. Service synchronization is the process of establishing the consistency of services across distributed enterprise computing resource infrastructures. Adaptive service synchronization incorporates resource-awareness and constraint-handling considerations into service synchronization. In distributed computing infrastructures, the resources required to synchronize a service are different from those required to execute the service. When synchronizing a service, these resources are taken from the available resources in different infrastructures. However, constraints may limit the capacity of a computing infrastructure to synchronize a particular service across its service replicas.

Service reliability and fault tolerance fall within the ambit of adaptive service synchronization. Service reliability is enhanced through the provisioning of multiple service replicas, while service fault tolerance is ensured by invoking asynchronous service synchronization strategies on the service replicas located on different infrastructures. The reliability and consistency of the underlying service mesh framework also affect the adaptive service synchronization strategy. Dynamic inference of the failure statuses of the service proxies and the underlying service mesh frameworks reduces resource usage and avoids the overhead incurred to maintain the consistency of consistently replicated service states.



3.1. Time and State Consistency

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Data inconsistencies claim a huge amount of time and financial resources from enterprises and can affect user experience dramatically. This paper describes a technology for minimizing data inconsistencies when operating in heterogeneous environments with disparate synchronization timing characteristics. The goal is to achieve service synchronization at a platform level (virtualization or container orchestration) rather than at an application level, using replication to improve performance. Consensus and coordination protocols are the main tools used for this kind of consistency, either straightforwardly or as a service. The focus here is on platform-level service synchronization mechanisms. Different microservice synchronization strategies are explored, as well as the need for feedback loops to accommodate dynamic operation.

The implementation models a service mesh in a Kubernetes cluster, synchronizing data with a VMWare cluster through REST services. The timing characteristics of the synchronization processes between groups of microservices are considered to provide hints on the expected consistency level. The impact of data center and network user load on these time characteristics is profiled. Resource awareness is limited to synchronization and storage constraints since the great majority of data center failures are local; recovery is handled by feedback loops influencing the scheduling of the services.

Table 3. Fault Tolerance and Recovery Mechanisms

Mechanism	Description	Recovery Capability	Enterprise Benefit
Service Proxy Supervision	Tracks service availability	Automatic failover	Reduced downtime
Operation Compensation Protocol	Maintains execution state	Rollback & recovery	Transaction continuity
Service Mesh Monitoring	Detects unhealthy services	Dynamic rerouting	Improved resilience
Replicated State Synchronization	Maintains distributed consistency	Replica restoration	High availability
Long-Running Operation Supervision	Tracks multi-stage workflows	Stateful recovery	Reliable enterprise orchestration

4. Architectural Models for Distributed Platforms

Adaptive Service Synchronization Across Distributed Enterprise Infrastructure Platforms.

Enterprise application services have evolved into distributed implementations that often deploy critical application functions across multiple private and public cloud infrastructure environments. These services can be supported as long-running processes orchestrated by workflow engines or as self-sufficient microservices. Events that affect service operations may be generated by external event sources or by remote other services. Synchronizing distributed adaptive application services within and across enterprise infrastructures requires adaptable synchronization mechanisms to overcome the lack of time and state consistency.

In enterprise environments with a microservices architecture and a service mesh, application services are structured as lightweight, distributed, and platform-agnostic units encapsulated in self-sufficient deployable containers. The cloud service mesh coordinates

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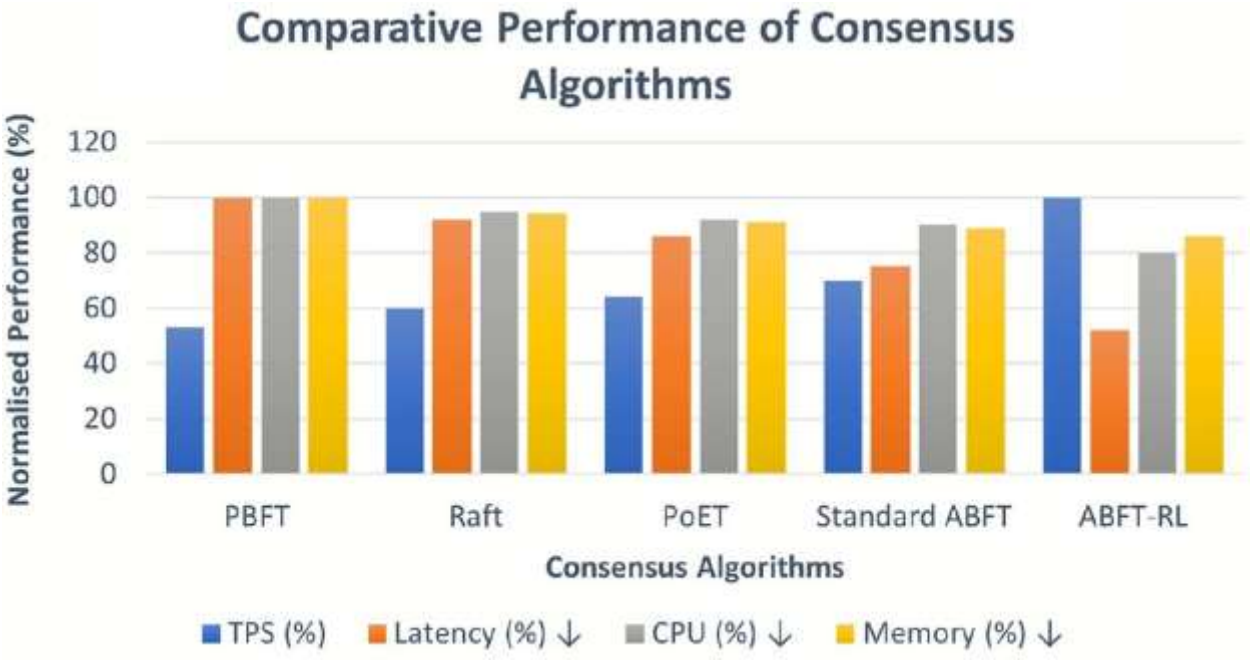
communication between service instances deployed across multiple cloud environments, providing common facilities such as discovery, traffic management, telemetry, and more. Application platform services deployed on public infrastructure also execute adaptive microservices. Event notifications may be produced by external forces, such as a user-triggered purchase of a product, or by call-triggered interactions with external platform service functions that usually reside on private infrastructures.



Mathematical Formulas:

1. Distributed Service Synchronization Delay Equation
   To model synchronization latency across distributed enterprise platforms:

$$T_{sync} = T_{net} + T_{queue} + T_{proc} + T_{commit}$$

Where:

- T_{sync}= Total synchronization delay
- T_{net}= Network transmission latency
- T_{queue}= Queue waiting time

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- T_{proc}= Processing time
- T_{commit}= State commit/update propagation time

$$T_{sync} = T_{net} + T_{queue} + T_{proc} + T_{commit}$$

2. Adaptive Resource Awareness Function
This equation represents adaptive synchronization based on resource utilization:

$$A_r = \frac{\alpha C_{cpu} + \beta M_{usage} + \gamma B_{net}}{3}$$

Where:

- A_r= Resource awareness index
- C_{cpu}= CPU utilization
- M_{usage}= Memory usage
- B_{net}= Network bandwidth utilization
- α, β, γ= Weight coefficients

3. Service Reliability Model for Replicated Microservices

$$R_s = 1 - \prod_{i=1}^{n}(1 - R_i)$$

Where:

- R_s= Overall service reliability
- R_i= Reliability of individual replica
- n= Number of service replicas

$$R_s = 1 - \prod\nolimits_{i=1}^{n}(1 - R_i)$$

4. Consensus Coordination Probability

$$P_c = \frac{N_{agree}}{N_{total}}$$

Where:

- P_c= Consensus probability
- N_{agree}= Nodes agreeing on state
- N_{total}= Total participating nodes

5. Event-Driven Synchronization Throughput

$$\lambda_{sync} = \frac{E_t}{T_w}$$

Where:

- λ_{sync}= Synchronization throughput
- E_t= Number of synchronized events
- T_w= Observation time window

6. Fault Recovery Efficiency Equation

$$F_r = \frac{S_r}{F_d + R_t}$$

Where:

- F_r= Fault recovery efficiency
- S_r= Successfully recovered services
- F_d= Failure detection time
- R_t= Recovery execution time

7. Time-State Consistency Model

$$C_{ts} = 1 - \frac{|\, S_c - S_r \,|}{S_c}$$

Where:

- C_{ts}= Time-state consistency score

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- S_c= Current synchronized state
- S_r= Replica state value

8. Adaptive Load Prediction Equation

$$L_p(t+1) = \theta_1 L_t + \theta_2 H_t + \theta_3 D_t$$

Where:

- $L_p(t+1)$= Predicted future load
- L_t= Current workload
- H_t= Historical workload pattern
- D_t= Dynamic demand factor
- $\theta_1, \theta_2, \theta_3$= Prediction coefficients

9. Distributed Synchronization Cost Function

$$C_{sync} = C_{comm} + C_{storage} + C_{compute}$$

Where:

- C_{sync}= Total synchronization cost
- C_{comm}= Communication overhead
- $C_{storage}$= Replication storage cost
- $C_{compute}$= Computational overhead

10. Service Mesh Coordination Efficiency

$$E_m = \frac{S_{success}}{S_{total}} \times 100$$

Where:

- E_m= Service mesh coordination efficiency
- $S_{success}$= Successful synchronized requests

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- S_{total}= Total synchronization requests

11. Dynamic Feedback Loop Adjustment Equation

$$F_a(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt}$$

Where:

- $F_a(t)$= Feedback adjustment value
- $e(t)$= Synchronization error
- K_p, K_i, K_d= PID control parameters

$$F_a(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt}$$

12. Distributed Service Availability Equation

$$A_s = \frac{MTBF}{MTBF + MTTR}$$

Where:

- A_s= Service availability
- $MTBF$= Mean time between failures
- $MTTR$= Mean time to repair

$$A_s = \frac{MTBF}{MTBF + MTTR}$$

4.1. Microservices and Service Meshes

Microservice system architectures are gaining popularity as distributed cloud concepts and the separation of business functions into independent units is becoming common for large enterprises. Microservice applications manifest as a collection of autonomous computing units that form a cohesive service. Each unit has limited, specific business functionality, and it can scale individually or adapt as load changes. Such systems enable resource optimization, and maintenance is simpler because updates can be performed per microapplication without changing the entire service. Nevertheless, these benefits come at the cost of increased complexity. Management requirements and operational overhead also increase. Infrastructure resources may be limited for large deployments,

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and the supporting technology still has to mature. A solution to these problems is the introduction of a service mesh, which adds a platform layer with dedicated components to provide distributed networking, security, performance, monitoring, and logging functionality. Service meshes alleviate many management issues, but they represent a single point of failure and require clustered installations for high availability.

The term "microservice" is descriptive, but the definitions of microservices vary. As microservice applications grow, managing them across data centers and cloud platforms becomes a key challenge. Different application segments may have different geographic dependencies, and these dependencies may change over time. Whether deployed on an enterprise cloud platform or in the data center, synchronization of interdependencies among microservices requires careful management. Understanding the data synchronization requirements and implementing a solution aligned with these requirements can prevent significant development and maintenance efforts without sacrificing availability or performance.

Resource-Aware Synchronization Model

Table 4. Enterprise Infrastructure Synchronization Challenges

Challenge	Impact on Enterprise Systems	Proposed ASS Solution
Multi-Cloud Heterogeneity	Inconsistent service coordination	Cross-platform synchronization engine
Resource Constraints	Delayed synchronization	Resource-aware adaptation
Network Partitions	Service unavailability	Consensus-driven coordination
Data Inconsistency	Operational delays	Time and state consistency management
Dynamic Workloads	Performance degradation	Runtime profiling and feedback loops

5. Synchronization Mechanisms and Protocols

A wide variety of synchronization mechanisms and protocols are used for coordinating services across distributed enterprise platforms. Enterprise applications use database replication to prepare for site or node failure and recovery. Replication protocols in existing asynchronous databases focus on availability during network partitions. However, guarantees about during-partition availability and continual success in resolving crashed replicas can make replicated state machines unavailable during wide-area partitions of interactive applications. Therefore, state-machine replication of interactive applications over WANs needs to minimize unavailability during partitions and derive a correctness condition for achieving deterministic execution. Replication solutions for warm standby and active replication of process groups use a primary-backup architecture. In this architecture, the primary handles client requests while the backups are kept up-to-date with logs of requests.

Disaster recovery and business continuity planning are facilitated by a replication framework that integrates continuous data protection with periodic replication for point-in-time recovery. A generic technique based on a recovery-process-generation workflow produces versioned backup processes from execution traces. Consensus and coordination protocols provide consistency guarantees for data sharing and changes in distributed settings. The standard consensus problem has been solved under periods of arbitrary failures of processes with a linear number of bits of resilience by presenting Cesàro-averaged leader election, which allows low-latency failure detection implemented by clients. It is shown that, for certain constants, the scheme is approximately optimal, in the sense that, for any fixed k, no protocol can solve the consensus problem for more than k processes with less than $\Theta(k3)$ bits. Consensus protocols assure that events can be reported and data can be shared across a distributed enterprise platform.

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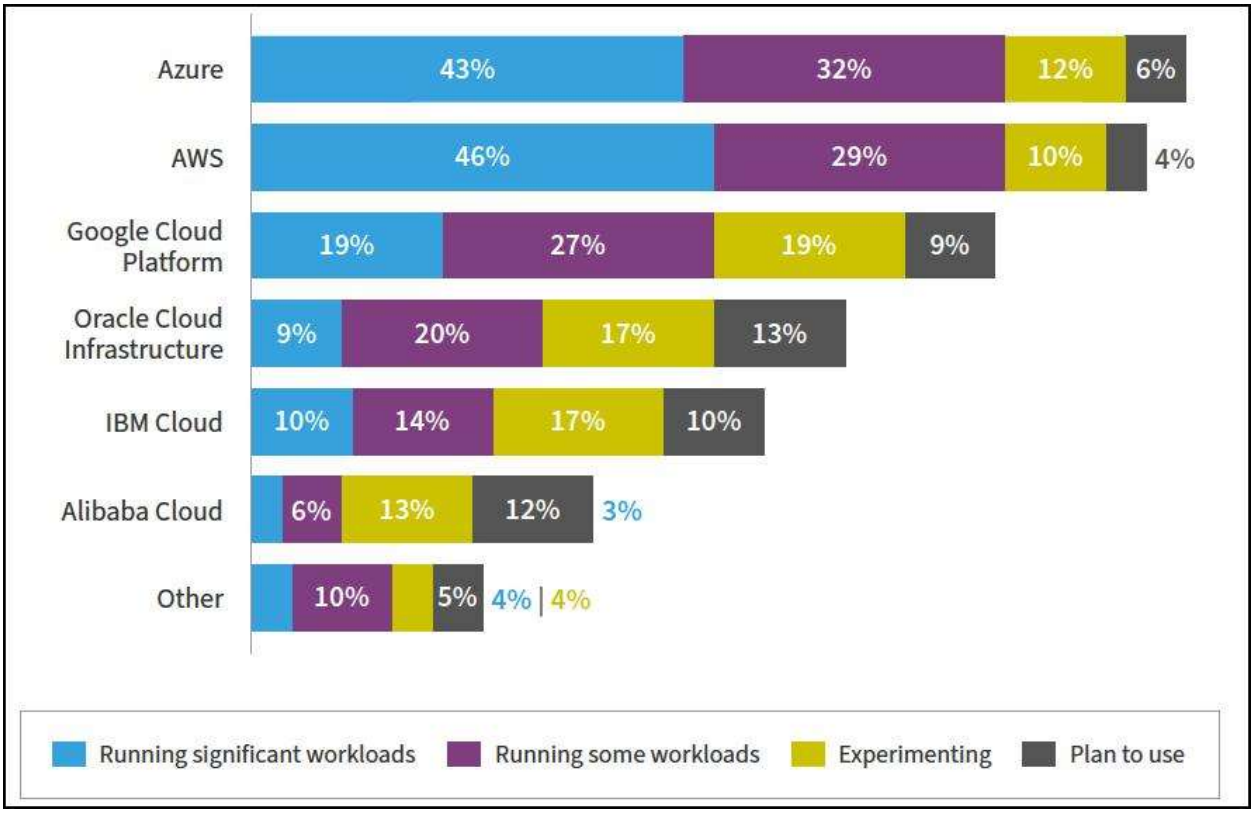

5.1. Consensus and Coordination Protocols

Service synchronization requires coordination among participants and/or consensus about the service execution state. The participants can synchronize by following a coordinator service (e.g., using a two-phase commit protocol). Alternatively, a variety of approaches establish leadership among the participants, using a leader service, an election protocol, or consensus protocols such as Paxos or Raft. Because distributed coordination can be a bottleneck under failure conditions – including service failure, partition, or network problems – the design and deployment of the service execute algorithm must avoid these dependencies as much as possible.

When synchronization is desired but possible failure is not considered, a somewhat wider range of options is open. The cloud may provide a lightweight syntactical and semantic based configuration to instruct how synchronized participant services should behave, thus allowing greater diversity on the implementation logic. Time-stamped state updates can be propagated together with load information from active services to allow other services to leverage them (e.g., a time-based replication strategy). A latter-behavior

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and replay strategy allows coordinating the behavior of service instances that execute the service last and that do not need to exchange information while executing the service.

Table 5. Consensus and Coordination Protocol Analysis

Protocol/Approach	Coordination Type	Scalability	Latency	Reliability
Two-Phase Commit	Centralized	Medium	High	Strong consistency
Paxos	Distributed Consensus	High	Medium	Very High
Raft	Leader-Based Consensus	High	Low	High
Primary-Backup Replication	Replication Coordination	Medium	Medium	High
Event Replay Synchronization	Decentralized Coordination	High	Low	Moderate

6. Adaptive Strategies for Dynamic Environments

Several techniques have been proposed and are currently being developed to adapt synchronization strategies for distributed platforms. One direction relies on runtime profiling and feedback loops to let the system learn which synchronization strategy (none, event-based, scheduled, or synchronous) is most suitable for a particular context. This approach targets much larger time scales than the other two. During runtime, profiling collects the costs of the different kinds of service communication (direct, via an event broker, scheduled or time-triggered, and synchronous). Periodically, the system analyzes the cost profile and changes the strategy for the next phase of operation. As long as the component masses are similar, this approach is effective; the feedback loop changes the strategies ideally one or two times per day. However, dependence on internal profiling can lead to suboptimal decisions with longer time delays compared to an external observer. Thus, some approaches measure the frequency of service calls and adapt the strategy at a finer time granularity with a second-order observer.

The second approach relies on dependency-centric feedback loops that exploit the dependencies already present in the system. The idea is to identify a component group where dependencies are strong and the data latency can be affordably low, and then synchronize these components with a suitable mechanism. To be effective, component and event broker masses should differ significantly; otherwise, all response times slow down, and using a broker instead of direct links adds unnecessary overhead. Finally, the third approach proposes the use of an external observer. A third software entity monitors all service calls and computes the synchronization strategies that minimize the overall system response time for a given set of masses. The strategy relies on a time scale similar to that of a системный-операционный research project and uses a simulation or a more evolved model to make the decisions.

Cross-Platform Service Coordination

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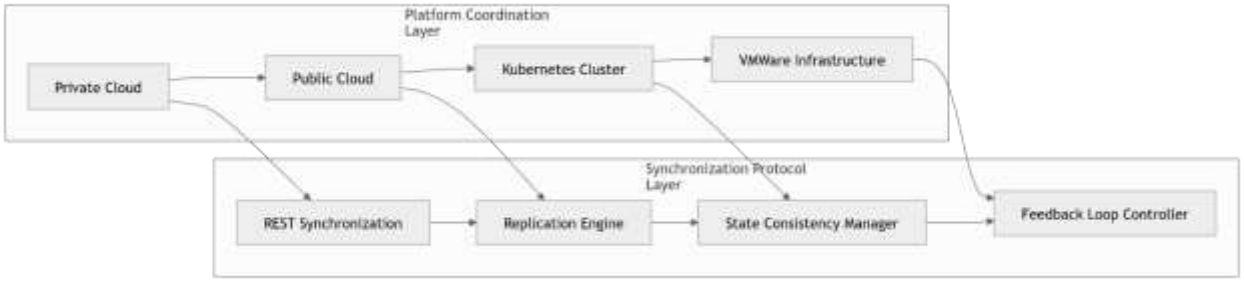

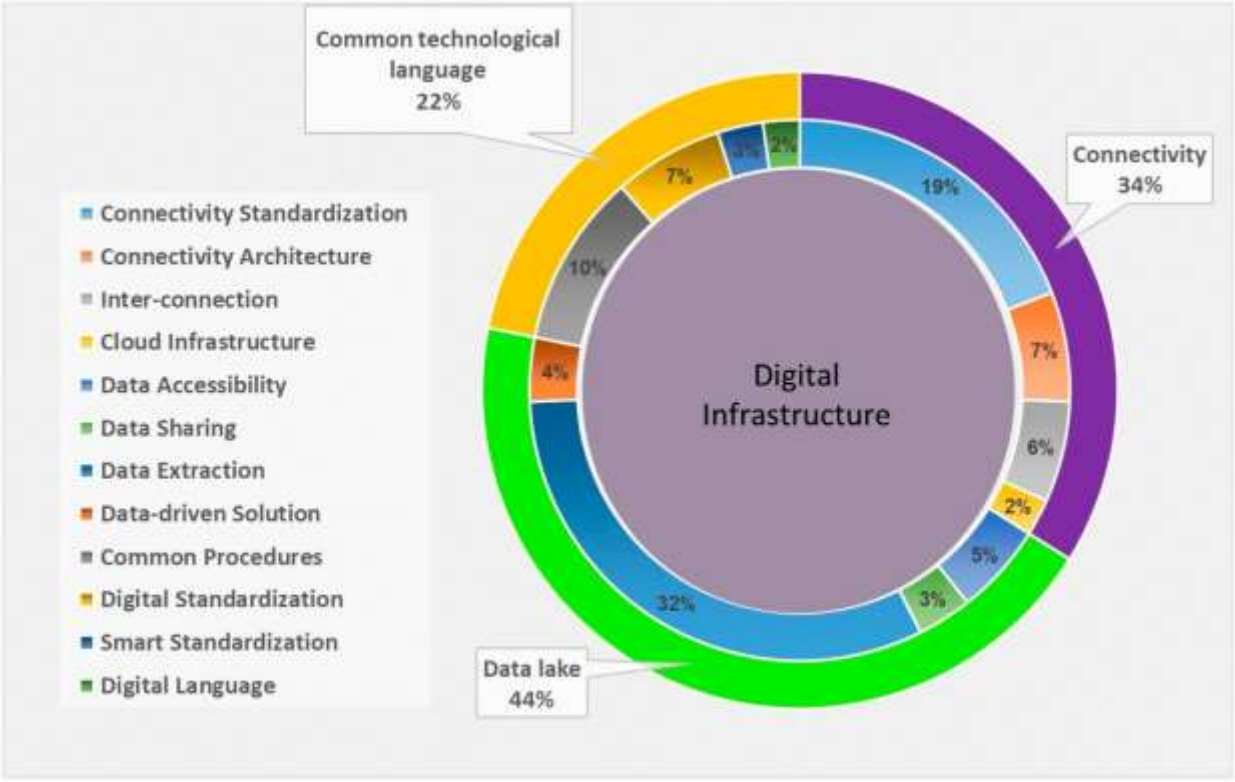

6.1. Runtime Profiling and Feedback Loops

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Management processes need to refer to system-wide property ranges in unit of resource demand/resource availability—demand→ availability and availability→demand relationships (thus requiring consideration of all connected resources), and also in unit of sum-pattern-temporal-quality (and possibly-order). The mediation of demands requiring immediate resource access; their provisioning and provisioning confirmation; and resource reconnection is a different issue.

When dynamic state behaviour is being managed using feedback loops, it is advisable to employ runtime profiling of workloads. In this process, individual service workloads are monitored for changes over time, and temporal profiles are generated to retain a shape representation of the general service processing behaviour (i.e. processing time exhibits variability around its mean per sampled period). These profiles are used to control the feedback-loop share between two business cycles of different service/activity pattern, allowing adjusted load distribution.

The share may then be changed at schedule change time without the imposition of abrupt change. The Load Prediction Control algorithm is capable of anticipating loads with high degree of precision, and proved its worth in the processes of modelling and control of a water treatment plant, attaining a best-performing factor of 3. The algorithm has also successfully coped with the operation of a public transport system of a large urban area (as related to mean point-to-point passenger flow prediction), attaining a best-performing factor of 1.9. Proper redesign allowed using it for load forecasting of a Brazilian hydroelectric storage system.

Table 6. Adaptive Runtime Profiling Metrics

Metric	Monitoring Objective	Enterprise Value
Service Latency	Detect synchronization delays	Faster response optimization
CPU Utilization	Measure resource pressure	Efficient workload balancing
Memory Consumption	Identify bottlenecks	Stability improvement
Event Frequency	Analyze communication overhead	Synchronization tuning
Failure Recovery Time	Measure resilience efficiency	Reduced service disruption
Synchronization Accuracy	Validate consistency	Improved operational trust

7. Conclusion

Enterprise systems increasingly rely on an ecosystem of loosely-coupled services composed and deployed across multiple infrastructure platforms, both on-premises and in the cloud. Sample application domains include finance, healthcare, supply chain, trades, and the IoT. Future implementations will require dynamic multi-platform service compositions that span legacy IBM Mainframes, Solaris, or Windows datacenters, Public Clouds such as AWS or Azure, and Private Clouds powered by Kubernetes and Hyperconverged Infrastructure. Yet enterprise service compositions can be disrupted by configuration errors, code bugs, or

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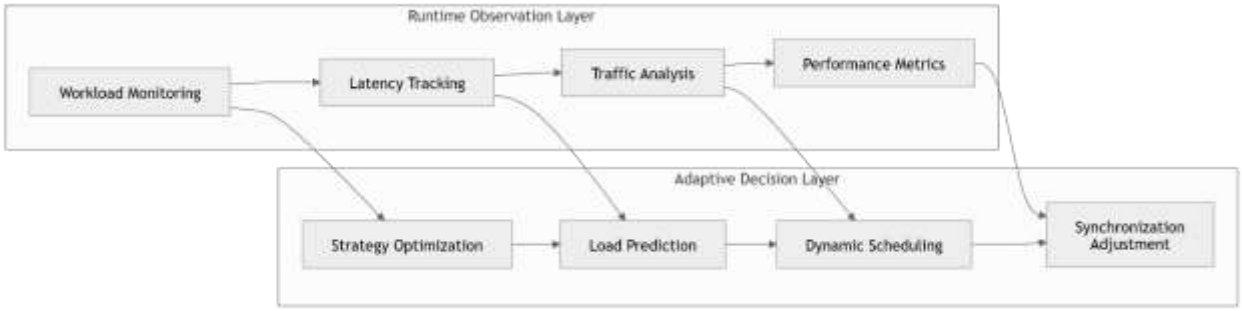
sudden changes in resource demand. Currently, when such disruptions occur, corrective measures often take a while because involved services need to be individually inspected, understood, and restored.

Fault-tolerance mechanisms can be employed to lessen the impact of disruptions or to restore service availability sooner. However, most existing mechanisms do not address a critical aspect of enterprise services, namely the consistency of the enterprise process. Therefore, when services involved in a multi-step enterprise process, which require a strict order or time interval between their executions, become unavailable, or when such a service becomes available but its upstream services cannot provide the expected data, decisions on what actions to take next are delays until the complete correctness of the process can be determined, even if at that moment all involved services have passed the inspection. This unwanted interim state of process uncertainty is referred to as pseudo-blocking.

Runtime Profiling and Adaptive Feedback



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