# A Reference Architecture for Observability and Compliance of Cloud Native Applications

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**Abstract**—The evolution of Cloud computing led to a novel breed of applications known as Cloud-Native Applications (CNAs). However, observing and monitoring these applications can be challenging, especially if a CNA is bound by compliance requirements.

To address this challenge, we explore the characteristics of CNAs and how they affect CNAs' observability and compliance. We then construct a reference architecture for observability and compliance pipelines for CNAs. Furthermore, we sketch instances of this reference architecture for single- and multi-cloud deployments.

The proposed architecture embeds observability and compliance into the CNA architecture and adopts a "battery-included" mindset. This architecture can be applied to small and large CNA deployments in regulated and non-regulated industries. It allows Cloud practitioners to focus on what is critical, namely building their products, without being burdened by observability and compliance requirements. This work may also interest academics as it provides a building block for generic CNA architectures.

**Index Terms**—Cloud Computing; Cloud-native; Cloud-native Applications; Cloud Observability; Cloud Monitoring; Cloud Compliance; Reference Architecture

# 1 Introduction

Cloud computing has become the preferred platform for both small and enterprise businesses. Companies are actively looking for ways to replace their traditional Information Technology (IT) infrastructure with modern Cloudbased infrastructures. The transition to Cloud-centric digital infrastructure accelerates following the pandemic [1]. As predicted by the International Data Corporation FutureScape, 80% of enterprises will put a mechanism in place to shift to Cloud-centric infrastructure and applications twice as fast as before the pandemic [1]. Advanced Cloud computing features such as elasticity, serverless, and high availability make Cloud infrastructure more time- and cost-effective than before. Cloud Service Consumers (CSCs) no longer need massive upfront capital to buy servers and computing resources and can enjoy the pay-as-you-go billing

model of the Cloud. Organizations prefer the pay-as-yougo model because recurring costs of Cloud services can be offset by business revenue. In addition to lower upfront cost compared to traditional IT infrastructure, the low cost of resources on Cloud and flexible commitment options make Cloud computing even more attractive to organizations of various sizes [2].

The high adoption rate of the Cloud translates to increased business and higher revenue streams for Cloud Service Providers (CSPs). However, these incentives do not come for free, and CSPs must constantly evolve and improve their offerings. That means, in addition to millions of existing physical and virtual resources, more and more resources and services must be added to the offering catalogs. As the number of managed resources by the CSPs increases, so does the complexity of the underlying architecture, maintenance, and monitoring. To deal with this complexity, CSPs have adopted advanced Cloud management and monitoring tools, such as New Relic [3], Dynatrace [4], and Datadog [5]. These tools allow CSPs to have a holistic view of the operation of the provided services at any time and can be used for incident and problem management. Among the most crucial Cloud management tools for the maintenance of Cloud resources are monitoring tools that are responsible for offering a comprehensive view of all kinds of resources on the Cloud, including both the hardware resources (e.g., bare-metal servers, routers, and switches) and the virtual resources (e.g., virtual servers, virtual network devices, and software-defined data centers).

Small, medium, and large enterprises are switching from traditional, on-premises infrastructure to off-premises Cloud-based infrastructure. The motivation behind these migrations stems from more than just the lower upfront cost. Traditional IT infrastructure requires massive up-front capital, large in-house IT departments, 24/7 Site Reliability Engineers, and high expenditures on Internet, storage, software, servers, network equipment, and electricity. Cloud providers, on the other hand, cover the most challenging re-

sponsibilities, such as maintenance and monitoring, in their offerings. Besides good financial feasibility, Cloud computing offers various technically appealing advantages. Scalability, Geo-distributed systems, Geo-redundant deployments with wider clientele opportunities, business agility, easier disaster recovery planning, and managed privacy and security are among the essential technical advantages that Cloud computing delivers. With the lower up-front cost, feasible recurring cost, less responsibility, and more technological advantages, organizations find it difficult not to switch to Cloud [6].

# 1.1 History

Cloud computing has taken many directions, and each direction has uniquely empowered businesses. Since its inception in 1961 by McCarthy at MIT [7], Cloud computing has gone through many iterations and has evolved into the most dominant deployment platform. Along the way, Cloud computing has incorporated the best features of its predecessors, such as Grid computing, Parallel computing, and Utility computing. It took nearly three decades for Cloud computing to become mainstream, but since the launch of Salesforce in 1999 [7], the iterations have become shorter and shorter. In its current sense, the term "Cloud" was first used by Eric Schmidt, the CEO of Google, in 2006 to describe the Cloud as an enabling business model that allows companies to provide a wide range of services to their clients through the Internet [8]. The same year, Amazon launched the first publicly accessible Cloud named Amazon Web Services (AWS). It took only four years for IBM and Microsoft to launch their public Clouds, named IBM Cloud and Microsoft Azure, respectively. Two years later, Google launched the Google Cloud platform and joined the club [7]. Today, AWS, Azure, Google Cloud, and IBM Cloud are among the top Cloud computing players. To properly define Cloud computing here, we refer to the official definition provided by the National Institute of Standards and Technology (NIST). NIST defines Cloud computing as "[...] a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [9].

As the maturity of Cloud computing is increasing, so does its popularity and impact on businesses. While the popularity of Cloud computing has resulted in faster growth in the business domain, Cloud computing itself has gone through a massive change to keep up with this high demand. Hence, it is equally important to understand the recent advancements in Cloud computing as it is to review its history. In the last decade, many new features have been added to the Cloud offerings, and such features are made possible by underlying changes in Cloud practices by CSPs and CSCs. Although these changes have happened in various aspects, the primary drivers of such changes can be traced to a few fundamental shifts, namely the changes in the underlying Cloud computing infrastructure, the architectural changes for Cloud applications, and the modern approaches to application development and deployment on the Cloud [10].

# 1.2 Evolution

## 1.2.1 Infrastructure

The underlying Cloud computing infrastructure and technologies surrounding that are constantly changing. The so-called software-defined Cloud computing is becoming increasingly popular, and CSPs use advanced virtualization techniques to convert all data center resources to virtualized ones. For example, software-defined networks are replacing traditional networks, and software-defined storage solutions are replacing traditional storage options. On a macrolevel, CSPs are evolving their infrastructure management approaches to achieve software-defined data centers [11].

#### 1.2.2 Architecture

In addition to the infrastructure changes, the architecture of applications on the Cloud has undergone massive changes. Cloud architects are moving away from traditional two-, and three-tier monolith architecture and are adopting a multi-layer, microservice architecture. Heavy Virtual Machines (VMs) are replaced with light Containers [12] that offer faster boot-up time, flexible deployment, and advanced orchestration options. To address the demand raised by these changes in architecture, CSPs have developed and released services that allow CSCs to deploy their microservice, multi-layer applications to the Cloud. In addition to the high adoption rate for containers and container management/orchestration solutions such as Kubernetes [13], a new trend for computing platforms is evolving. Serverless computing promises efficient use of resources by using them only at active run-time episodes [14].

## 1.2.3 Development and deployment

From the development and deployment perspective, the environment on Cloud is so different from the traditional environment that a new breed of applications, known as Cloudnative, has emerged. Cloud-native Applications (CNAs) are designed, implemented, and maintained using Cloud technologies. In other words, they are native to Cloud!

Cloud Native Computing Foundation (CNCF) defines CNA as applications that specifically take advantage of innovations in Cloud computing. The CNCF argues that applications not designed based on Cloud computing offerings and features cannot take advantage of the Cloud environment's resiliency and scalability [15].

CNAs are often designed based on microservice architectures and are deployed over orchestrated containers. When needed, CNAs utilize feasible serverless computing for batch processing or fire-and-forget tasks. As for deployment, CNAs use modern Continuous Integration and Continuous Deployment (CI/CD) pipelines to automate the testing and deployment phases of software delivery [16]. While automating the delivery of the CNAs, some practitioners have taken a step further and expanded the automated delivery to the infrastructure. Approaches such as Infrastructure-as-Code (IaC) [17] declare the infrastructure using machine-readable code and bring consistency and automation to the infrastructure. Tools such as Terraform [18], Chef [19], and Ansible [20] are specifically designed to address the need for infrastructure automation.

The above-indicated exciting advancements come at a price for both CSPs and CSCs. The CSPs must ensure an everevolving platform's reliability, scalability, and security. Similarly, the CSCs need to monitor their solutions to meet the promised Service-level Agreements (SLAs) to their internal/external users. Hence, both CSPs and CSCs are interested in Cloud monitoring. We have explored the challenging landscape of Cloud monitoring in our previous works [21], [22], [23]. However, these works were mainly concerned with challenges related to infrastructure monitoring, namely defining health-state, unified monitoring environments, high-availability monitoring, and large-scale component monitoring. In this work, we expand this set of challenges and focus on challenges associated with modern Cloud technologies, specifically CNAs. CNAs are designed and deployed with having Cloud in mind. They are designed around Cloud services and have been purposely engineered to maximize the use of Cloud features. As the popularity of CNAs grows, so does the importance of monitoring practices for them. CNAs have unique characteristics that impose unique monitoring challenges. CNAs rely on microservice architectures, which distributes complexity among narrowly focused and independently implemented computation units. This architecture leads to a high level of complexity [24]. Monitoring a complex system of systems with complex interdependencies is a challenging task. Given the atomic nature of each service in a microservice architecture, containers, and serverless environments are a more suitable computing option compared to traditional VMs that are used to host monolith applications. Monitoring container and serverless is challenging due to the high level of abstraction used in these software-defined computing environments. Moreover, a microservice architecture translates to several smaller services interacting over a network. To construct a holistic view of the CNAs, the virtual network and deployed services on top of that, the containers or serverless components deployed to execute the business logic of the CNAs need to be monitored simultaneously, leading to a challenging practice known as distributed monitoring [25].

CSPs deploy hundreds or thousands of resources and unify them under a resource pool and share them with the CSCs, and each of these resources can be interrelated and impact each other. Hence, Cloud monitoring requirements are both complex and complicated. In recent years, the Cloud has become such a mission-critical platform that just a few hours of downtime will cost enterprise CSPs millions of dollars [26], [27]. The traditional corrective measures promoted by traditional monitoring practices have become infeasible. Hence, CSPs opt-in for detective or, better yet, preventive measures. In other words, CSPs need to detect an issue before it happens, or at least in real-time or nearreal-time. These preventive and detective measures translate to a new set of heavy and challenging monitoring requirements that demand a higher order of monitoring known as observability. Observability is defined as the ability to deduce the status of a complex system based on the system's outputs [28].

# 1.2.5 Compliance

In recent years, many enterprises from various industries have shifted their IT deployment models from off-premises to Cloud. Many such enterprises operate within regulated industries. For a solution to be approved for operation in a regulated industry, the solution must be compliant with a set of functional and non-functional requirements enforced by governments or regulatory bodies. The rise of Cloud services in regulated industries has pushed compliance challenges to CSPs. It is now expected from CSP to offer services that are compliant with the Payment Card Industry (PCI), Data Security Standard (DSS), Health Insurance Portability and Accountability Act (HIPAA), or General Data Protection Regulation (GDPR) policies [29]. Even in non-regulated industries, CSCs offer services to their end-users that are SLAgoverned. In general, SLAs and compliance are interrelated as they both share the same goal: meeting a list of predefined requirements. We argue that observability can be used to verify conformance with SLA or compliance requirements. Therefore, throughout this paper, we use SLAs and compliance interchangeably unless otherwise indicated.

#### 1.3 Our Contribution

In this paper, our *objective* is to explore challenges associated with CNA's observability and compliance and investigate the key components of a reference architecture for the observability and compliance of CNAs. More specifically, we intend to answer the following two Research Questions (RQs).

**RQ1**: What observability and compliance challenges do CNAs impose?

**RQ2**: What are the key components of a reference architecture for the observability and compliance of CNAs?

The above RQs are carefully chosen, and each represents a milestone toward the main contribution of this paper. That is, each RQ contributes to the curation of the body of knowledge that is needed to construct the main **contribution** of this paper, namely the proposed reference architecture for observability and compliance of CNAs. To answer RQ1, we first review the key characteristics of CNAs in Section 2.2 and then explore the key challenges associated with observability and compliance of CNAs in Section 2.4. To answer RQ2, we prospect the key components of a reference architecture for observability and compliance of CNAs in Section 3 and propose the reference architecture in Section 4. The proposed reference architecture can be used as a guide by Cloud practitioners in designing and implementing CNAs, especially in regulated industries. We believe that including observability and compliance as the embedded pillars of our reference architecture significantly reduces the effort that Cloud practitioners need to invest in bringing external observability and compliance components to their CNA solutions.

The rest of this paper is structured as follows. In Section 2, we review CNAs and shed light on their characteristics and explore the rise of observability and compliance in the context of CNAs. We conclude this section by reviewing CNA observability and compliance challenges. In Section 3, we explore the desired requirements and components of a reference architecture for the observability and compliance

of CNAs. In the wake of answering the two proposed RQs, we use the generated insight to present the proposed reference architecture in Section 4 and instantiate real-world examples of the proposed reference architecture in Section 5. In Section 6, we provide a subset of related literature on CNAs and the challenges associated with monitoring them and review existing monitoring tools for CNAs. We conclude the paper in Section 7.

### 2 Background and Motivation

In Section 2.1, we provide the background information needed to establish a solid understanding of CNAs and then explore CNA's unique characteristics in Section 2.2. Section 2.3 we explore the rise of observability and compliance in the context of CNAs. In Section 2.4, we review challenges associated with CNA caused by their characteristics, hence, answering RQ1.

# 2.1 Cloud Native Applications

CNAs are the results of modern approaches to application design, development, and deployment. These modern approaches have one major binding characteristic, they are all designed to run on the Cloud, as opposed to traditional onpremises platforms. Gannon et al. [30] acknowledge these modern approaches and shed more light on the characteristics of CNAs. The authors note that CNAs are often designed with global scale in mind and are expected to scale well with thousands of concurrent users. Hence, a high degree of parallelism is needed, along with the support of horizontal scaling. Another interesting characteristic of the CNA is that they assume the infrastructure is elastic and could change over time based on volatile demand. From a development and deployment perspective, CNAs are much more demanding than traditional applications. CNAs are designed based on seamless delivery methods governed by CI/CD pipelines. Additionally, the authors indicate that CNAs are composed of many moving pieces. The security and health of each component need to be verified, hence emphasizing the importance of monitoring as a critical instrument for CNAs.

The concept of Cloud-native is not new, but it has gained momentum in recent years. Kratzke and Quint [31] provide a systematic mapping study on the topic of CNAs and note the rise of popularity in CNAs from 2015 onwards. The authors review more than 45 publications in the realm of CNAs and assess whether they offer validation, evaluation, solution, survey, opinion, or experience. The authors find that the majority of these publications are around automation platforms, the design of CNAs, and microservices, hence the lack of research on the monitoring of CNAs.

The lack of research content and our professional experience in managing and monitoring CNAs has *motivated* us to write this manuscript.

# 2.2 Characteristics of Cloud Native Applications

CNAs are designed, developed, deployed, and maintained using Cloud services. Cloud is the native environment for CNAs, and they are bound only to use Cloud resources. Given the hype around CNA, many practitioners assume

that running an application over a virtualized infrastructure on the Cloud makes the application a CNA. This is a wrong assumption because while virtualization and Cloud infrastructure are fundamentals for implementing CNAs, bundling a few virtualized applications and deploying them on the Cloud does not cover all the characteristics of CNAs [32]. Hence, it is important to identify key characteristics of CNAs so practitioners can differentiate between Cloud-based applications and CNAs. This distinction is crucial as one needs to find appropriate monitoring and observability solutions based on the nature of the deployed application. If the application is simply a Cloud-based one, traditional monitoring and observability approaches can be used, but in the case of CNAs, more modern monitoring and observability approaches must be employed. Here, we list the key characteristics of CNAs and explain each one briefly.

Microservice architecture. The most dominant feature of CNAs is the microservice architecture [31], [33]. The microservice architecture allows large and complex applications to be divided into atomic, isolated services that interact with each other via lightweight mechanisms, often in the form of RESTful APIs [34]. The microservice architecture promotes the concepts of componentization and decentralization [35]. Given that each component is responsible for atomic business logic and the amount of computation power needed to run each component is limited, containers are often a better fit for microservice architecture compared to VMs [36], [37].

Containers as computing platform. Microservice architecture often translates to the use of containers as the computing platform [38], [39], [40]. Containers allow an application to be comprised of many independently operating components. Each container can be easily managed, replicated, and scaled. Containers are contrasted with other virtualized computing platforms, such as VMs. As containers running on the same hardware often share the same core operating system kernel, the same hardware can be utilized to host more isolated containers than isolated virtual machines [41], [42]. Microservices are atomic business logic implemented as code and, therefore, in most cases, are not resource-hungry. Cloud computing is about proper resource utilization and higher efficiency, so containers are a far more promising computing platform for microservices than VMs. In response, CSPs have recognized the increasing demand for containers and enhanced their offering to run, manage, and orchestrate containers.

CSPs have developed and released services, such as AWS Elastic Kubernetes Service [43], Azure Kubernetes Services [44], Google Cloud Kubernetes Engine [45], and IBM Cloud Kubernetes Service [46] to provide CSCs with container and container management options.

Serverless as computing platform. CNAs are composed of various components with different run-time requirements. For instance, while the user-interface components and Online Transaction Processing services need to be up and running almost 24/7, batch processing tasks, aggregations, and backup operations demand a shorter and less frequent run-time. Thus, dedicating a VM or container to a service that runs once or a few times a day is an infeasible under-utilization [47]. The better utilization of resources

on the CSPs translates to a more feasible solution for the CSCs [48]. CSPs have brought up a new computing platform known as serverless to address schedule-able workloads. Serverless computing hides server usage from developers and runs the associated code on-demand, only charging the user based on the time that code is running [49]. Interestingly, serverless computing and microservices have a lot of common characteristics. If a microservice does not need to be up and running at all times, a serverless computing platform can bring even more financial feasibility than containers [50], [51].

CSPs have developed and released services such as AWS Lambda [52], Azure Serverless [53], Google Cloud Serverless Computing [54], and IBM Cloud Code Engine [55].

State isolation. CNAs are built and implemented with clear separation between stateless and stateful services. In the context of CNAs, even if stateless services interact with stateful services, this interaction is often managed via a set of exposed APIs [16]. This separation allows different scalability practices for each stateless and stateful component. Stateless components, often implemented as containers or serverless functions, require less effort for scalability and reliability. In contrast, stateful component scalability and reliability are not as straightforward and require architectural consideration, including replication and storing the state at any given time. An isolated state is one of the desired characteristics of the CNAs [31], [56].

CI/CD compliance. CNAs take advantage of the most recent advancements in the CI/CD domain and are designed based on the DevOps paradigm [31]. As CNAs often consist of microservices deployed over containers, each microservice can be deployed using an independent pipeline [57], allowing different teams to simultaneously deliver updates to various components of the CNA [16].

**IaC compliance.** CNAs' delivery, deployment, and management are highly automated [57], [58]. Such a level of automation is usually achieved by deploying the application using IaC [59]. Using IaC is one of the desired features for CNAs [60].

Here, we review the concepts associated with the observability and compliance of CNAs. Section 2.3 brings details as to why observability and compliance are significantly important for CNAs. In Section 2.4, we provide details related to observability and compliance challenges associated with CNAs.

# 2.3 The Rise of Observability and Compliance

CNAs are good candidates for enterprise application development and deployment. Their flexible characteristics make them a feasible option for large-scale software development. Enterprise applications are controlled by functional and non-functional requirements expressed as SLAs and compliance requirements. In regulated industries, such as healthcare and finance, applications must meet predefined expectations and support audit requirements [61]. CNAs deployed and used in regulated industries must take a proactive approach to monitoring. Classical reactive monitoring approaches commonly used in traditional applications cannot offer the level of verbosity regulated industries expect from CNAs. Hence, a new approach for monitoring CNAs is

surfacing [37]. Monitoring, tracing, logging, telemetry, and instrumenting all come together to create observability [62].

The term *observability* was coined in the 1960s by Rudolf E. Kálmán [63], who indicated that if any engineering system is controlled, one can work backward from the output to find out what is causing it to produce its result; thus, one can infer what is inside the black box [64]. Given the dynamic nature of CNAs and their components, one can consider the entire solution as a black box and use observability to infer the current state of the components in the black box at any time.

To provide a better understanding of observability, we compare it with monitoring. *Monitoring* is defined as collecting, processing, aggregating and displaying real-time quantitative data about a system [65]. Observability and monitoring complement each other. In other words, monitoring tells you when something is wrong, while observability enables you to understand why [66]. In other words, observability indicates to what degree infrastructure and applications and their interactions can be monitored [67].

# 2.4 Cloud Native Observability and Compliance Challenges

Here, we aim to provide an answer to **RQ1**: what observability and compliance challenges do CNAs impose? The question is mainly concerned with the observability and compliance challenges associated with CNAs. Due to the dynamic and heterogeneous nature of components and infrastructures, designing and implementing observability and compliance platforms for CNAs is not trivial.

Microservice observability challenges. Microservice architecture imposes a few different types of observability challenges. Given their distributed nature, each microservice is deployed on an isolated computing platform such as a container. Often, there is a high degree of dependency among microservices, and failure in one may cause a ripple effect, and the entire system may be impacted. Hence, in addition to the internal observability of the microservices and their computing platform, one needs to observe the complex relationships among them to construct a representative view of the entire deployed CNA [68].

Serverless observability challenges. CSPs that offer Function-as-a-Service (FaaS), also known as serverless platforms, often provide generic dashboards to monitor the current state of processes running on FaaS platforms. However, these dashboards offer limited features such as visualizing the workload, reports on resource utilization, and run-time logs. As the root access to the underlying operating system is not provided in a FaaS offering, installation and configuration of any additional observability tool on them is not possible [69].

Container observability challenges. Containers are among the essential building blocks of CNAs. Microservices are often deployed over a wide range of containers that may or may not be part of the same cluster. Collecting and analyzing telemetry from widely distributed containers is already a challenging task [70]. As the number and nature of the containers running a particular CNA are dynamic, the observability solution must be aware of any potential changes to the infrastructure. That is why many practi-

tioners use Observability on top of container orchestration solutions, such as Kubernetes [71].

Heterogeneous observability data. CNAs consist of various types of computing platforms. Each type of platform generates its own type of telemetry. Logs, metrics, and traces are among the most crucial type of generated telemetry and are considered the three pillars of observability [72]. Metrics often represent the most valuable of the three. Metrics are efficient, are frequently generated and can be used to correlate across infrastructure elements. As the second most crucial type of observability data, logs provide more indepth information about resources than metrics. Traces are usually associated with a specific application operation [73], [74]. Given the microservice nature of CNAs, traces are critical for troubleshooting issues. Some observability platforms allow different traces to be merged to construct a span that can be used to create a holistic view of the user experience through multiple services [75]. Due to the diversity of generated observability data, the analysis portion is more challenging as the data need to be cleaned, formatted, and cross-referenced using time as the common denominator.

Infrastructure observability challenges. Given the demanding nature of services needed to deploy and deliver a CNA, Infrastructure-as-a-service (IaaS) and Platform-as-a-Service (PaaS) are the most suitable Cloud delivery options. However, Cloud practitioners who opt in for the IaaS and PaaS Cloud delivery models should be aware that observability solutions are needed for the infrastructure of their CNAs. That is, logs, metrics, and traces collected from infrastructure (e.g., network, servers, VMs, containers, serverless functions) need to be merged with other collected telemetry (e.g., application, run-time, OS) to construct a realistic view of the state of the CNA. The challenging landscape of infrastructure monitoring has been denoted in our previous works [21], [22], [23].

Big data characteristics of the telemetry generated by Cloud native applications. The large scale of Cloud components in a CNA translates to hundreds of components. The generated observability data for these components exhibit high volume, velocity, value, and variety [76]. Hence, observability data can be classified as a Big Data problem, and therefore, a Big Data solution should be considered for the storage and analysis of observability data [76], [21], [77], [23], [22].

# 3 DESCRIPTION OF THE REFERENCE ARCHITEC-TURE

This section aims to answer RQ2, which focuses on finding the key components of the reference architecture that we propose for the observability and compliance of CNAs. Here, we provide additional details about the reference architecture by defining its desired non-functional requirements in Section 3.1 and its desired architectural requirement in Section 3.2. The desired construction, deployment, and maintenance requirements are reviewed (in Section 3.3), respectively. Section 3.4 defines a set of required components for the observability and compliance of CNAs to be included in the proposed reference architecture. We developed the architecture based on our empirical research and experience designing and deploying CNAs.

# 3.1 Desired Non-Functional Requirements

Like any software solution, the proposed reference architecture must meet predefined non-functional requirements. Based on our previous experience in designing and implementing CNAs, here is the core set of non-functional requirements that are commonly needed; however, practitioners are advised to review and expand this list if needed.

**Performance and reliability**. The reference architecture uses a software-defined load-balancer to balance the load among clusters to meet the performance and reliability requirements.

**Adaptability**. The reference architecture must be adaptable to various Cloud platforms and CNAs. That is, adapters of this reference architecture should be able to modify the architecture if it is needed.

**Extensibility**. The reference architecture is designed to be as flexible as possible; practitioners can extend it to match their requirements.

**Elasticity.** The reference architecture promotes autoscaling and Intelligent Workload Management (IWM) for relevant components. At the time of writing this paper, most CSPs have IWM offerings to enforce optimized workload strategies [78]. AWS Auto Scaling [79], Azure Autoscale [80], Google Cloud Autoscaling [81], and IBM Cloud Autoscaling [82] are examples of IWM offerings.

**Integrability**. Integrability is a desired non-functional requirement for all software applications [83]. Our proposed architecture ensures that the components are as flexible and replaceable as needed. Therefore, practitioners can integrate the proposed architecture into existing or future platforms.

**High-Availability**. High availability is a major desired non-functional requirement in distributed systems and Cloud computing [84]. High availability would dictate the need for a design with failovers and redundancy upfront [85]. We use common redundancy solutions, such as load balancers and clusters; but for failovers, an auxiliary data bus can be designed and implemented so that communication among components can be carried out even if the primary data bus is out of service.

# 3.2 Desired Architectural Requirements

The proposed reference architecture needs to meet a set of predefined architectural characteristics. These characteristics allow the reference architecture to exhibit the flexibility and reliability expected from the reference architecture.

Layered architecture. The reference architecture employs a layered architecture to meet the non-functional requirements reviewed in Section 3.1. Here, we employ the 7-layered architecture [86], [87] but do not set a limit for the number of layers. The layered architecture allows for controlled, micro-service-based data flow management. We explore how data flows among these layers in Section 4.2. The number of layers needs to be adjusted based on the complexity of the CNA that will be deployed on the Cloud.

Expanding on AWS well-architected framework and IBM Cloud for Financial Services reference architectures. AWS's well-architected framework is a well-known framework among Cloud practitioners that helps Cloud architecture to build secure, high-performing, and efficient Cloud solutions [88]. While designed by AWS for AWS Cloud, the

key concepts, namely the pillar, can be generalized, and the same pillars can be designed for various Cloud solutions. AWS's well-architected framework is built on six pillars: operational excellence, security, reliability, performance efficiency, cost optimization, and sustainability. We expand this framework by adding observability and compliance as new pillars. Additionally, IBM Cloud for Financial Service [89], [90], [91] has helped clients in regulated industries to mitigate risk and accelerate Cloud adoption for sensitive workloads. Security and controls are built into the platform to enable financial institutions and other regulated industries to automate their security and compliance posture.

# 3.3 Desired Construction, Deployment, and Maintenance Requirements

Based on our experience in the field, the proposed reference architecture needs to meet a set of predefined features from development, deployment, and maintenance perspectives. Here is the list of such features.

**Vendor agnostic.** Since all CSPs commonly offer the building blocks of the reference architecture, it should be implementable on all Cloud platforms.

**Support for multi-cloud**. The proposed reference architecture recognizes that many Cloud practitioners may use a multi-cloud approach to achieve a higher level of availability [92]. Therefore, we acknowledge that it is possible to instantiate a version of the reference architecture for each CSP in a multi-cloud solution. An example of a multi-cloud deployment of the reference architecture is later reviewed in Section 5. In multi-cloud cases, Cloud practitioners must consider additional architectural efforts to establish replication for collected observability and compliance data storage deployed on various Cloud platforms. Given the extensive amount of collected telemetry data, one has to be careful to choose the most important subset of the telemetry data to be replicated. Additionally, based on retention policies, hot, warm, or cold storage options can be used to increase the feasibility of storage efforts. While many choose to manually set their storage policies, there exist intelligent methods that offer a balance between cost and high availability for storage options [93]. Irrespective of the manual or intelligent approach, the ultimate goal for these replication practices is to prevent data loss for important collected metrics that are needed to ensure compliance.

Data source and data type agnostic. The reference architecture is designed to have pull and push capabilities for data retrieval and dissemination. The reference architecture promotes the use of common patterns for data management in distributed systems, such as Pub/Sub [94] or Message Queue [95].

Everything-as-Code (XaC). In recent years, treating all parts of a system as code has gained popularity. XaC brings traceability to the infrastructure that is deployed using code [96]. In general, the main goal of XaC is to automate the entire process of IT and software delivery [97]. IaC, configuration-as-code, and policy-as-code are all examples of XaC. In addition to traceability, consistency, scalability, version control, auditability, and portability are among the top benefits of XaC [98]. The reference architecture is designed with the XaC approach in mind and uses source code

management systems, such as GitHub [99], to store the code, and IaC tools, such as Terraform [18], to manage the code.

**GitOps**. To match the speed of software development and delivery, many DevOps practitioners felt the need to expand DevOp's best practices and tooling to infrastructure. As a result, DevOps best practices have evolved to a fully automated state in which everything, including configurations, infrastructure settings, policies, and deployment constraints, can be defined as code. Combining XaC, or at least IaC, and DevOps practices have resulted in a new approach to solution delivery known as GitOps. GitOps is an operational framework that uses IaC and the power of source code management systems to construct a traceable, reversible state that will be deployed using CI/CD [100]. GitOps is a term coined by Weaveworks [101] in 2017, and Weaveworks defines GitOps as a model for operating CNAs by using version control as the single source of truth [102]. The reference architecture is designed based on GitOps principles. Defined by Weaveworks, these principles demand the entire system to be described declaratively, the system desired state to be versioned, and all changes to be approved/rejected through pull-request/merge-request practices. Peculiarly, the last principle of GitOps is closely related to observability and demands that any divergence from the desired state of the system should be detected and corrected [101]. We argue that, currently, GitOps is the most appropriate framework for developing and deploying CNAs (based on current heuristics in continuous deployment [103]).

**End-to-end compliance**. As compliance is one of the key pillars of the reference architecture, we suggest a four-stage compliance check that leads to end-to-end compliance. The first stage, known as code-level checking, requires constant verification of source code (with every commit and every pull request) against applicable compliance criteria. In the second stage, CI-level checking, components integrated by the CI pipelines are checked against applicable compliance criteria. The third stage, the deployment check, is placed right between CI and CD. This novel approach allows the assessment of the compliant integrated components (through previous stages) to be evaluated against different deployment environments, say staging and production. Deployment check is a crucial stage that serves as a gatekeeper between the CI and CD efforts. A compliance officer team can oversee this gatekeeper to approve any deployment manually. In fact, given the harm that wrong deployments can cause, we advise practitioners to master this stage manually before allocating any automation effort. If the compliance check for the target environment at this stage is passed, the CD processes will be invoked. As the CD processes complete their task and upon deployment, the fourth stage, known as the drift-detection stage, kicks in. Any deviation from the desired state indicated in GitHub, as the source or truth [102] is detected, and corrective measures are taken to match the current state with the desired state. The reference architecture is designed based on end-to-end compliance stages, and both the infrastructure and the CNA can be configured to go through these stages.

# 3.4 Desired Components for Observability and Compliance of Cloud Native Applications

Irrespective of the functionality and features of a CNA, the following key components need to be deployed to ensure the compliance and auditability of a CNA.

Tamper-proof storage. Logs and system-generated telemetry can be used as digital evidence if their authenticity can be proved [104]. In our previous works [105], [22], we have emphasized the importance of immutability for digital evidence to be admissible to the court of law. In these works, we have recommended using Blockchain as a tamper-proof storage option for logs and other evidential documents [106]. However, blockchains are expensive storage solutions [107], [108], and practitioners may find them unfeasible for high-volume data storage. To address this in-feasibility, CSPs have designed and implemented a special type of Cloud storage known as Write Once, Read Many (WORM)<sup>1</sup>. AWS Simple Storage Service (S3) Object Lock [110], Azure [111], Google Cloud Cloud Storage Bucket Lock [112], and IBM Cloud immutable object storage [113] are examples of WORM-based immutable storage options on the Cloud. As authenticity is a key requirement for the admissibility of digital evidence [114], any compliance solution requires an immutable storage option. Therefore, the reference architecture is designed with tamper-proof storage as a key component to achieve compliance.

Converter to unified format for logs. Logs are generated by various resources in the form of textual data. Logs rarely follow standard logging formats [115], [76], and even when they do, there is more than one standard log format. CNAs many store logs in JSON log format, common event format, and extended log format are among such common log formats [116]. Additionally, in recent years, observabilityspecific formats such as Zipkin [117] and Prometheus Open Metric [118] have evolved to allow additional details and tagging to be affiliated with a resource on the Cloud. The reference architecture promotes a unified log format throughout the entire system. Suppose data collection through a unified format is not possible. In that case, the reference architecture suggests the conversation of collected logs to a unified format using a transformer layer, an essential layer in the employed layered architecture [86], [87].

Analytics engines. The ability to analyze and detect any deviation from the source of truth is a vital requirement for compliance. There can be multiple sources of truth, e.g., SLA, compliance requirements, and desired configurations. As a vital component of the reference architecture, the analytics engine analyzes the received logs and compares a resource's current state with the defined desired state. In case of any drift from the ground truth, alerts with different levels of importance must be issued to the proper stakeholders. For example, in our previous works, we have implemented and assessed the usability of such an analytics engine and found it effective for near-real-time analysis of Cloud generated logs [23], [77]. While an analytics engine can be used for any kind of data analysis, for observability and compliance, it needs to carry out three different types of assessments. Namely, explicit, range, or baseline. In the

case of explicit, the analytics engine must identify whether a collected metric matches the defined, explicit values (e.g., four nodes in a Kubernetes cluster). In the case of range, the analytics engine should be able to detect whether collected metrics fall in a range (e.g., database response time below 200 ms). The last type of assessment, known as baseline assessment, is challenging and requires a model to build a baseline<sup>2</sup> for "desired" state and detect any deviation from it.

API gateway. As the reference architecture for CNA observability and compliance is a generic architecture, it assumes that both pull (extract logs from a source like a database or storage) and push (an API to receive logs that are sent) may be used for log collection. Thus, an API gateway component should exist to configure pull or push requests.

Data storage services. As the CSCs demand various options for their data storage needs, the CSPs have prepared a set of software-defined storage options to meet this demand. The reference architecture acknowledges the need for various data storage options and recommends practitioners to use Storage as a Service [119] options provided by CSPs based on the data type, data size, security, accessibility, retention, access time constraints, and immutability requirements. For instance, while AWS S3 [120] is a great option for day-to-day data storage, AWS Glacier [121] offers much better financial feasibility for data archival. Hence, practitioners are advised to compare various Cloud storage options each CSP provides and choose the ones that match their needs.

Data bus. Due to the large volume of Cloud-generated logs [22], a reliable and scalable messaging service is needed. The design and implementation of CNAs are based on a microservice architecture. In order to collaborate, microservices must exchange information. Communication and messaging patterns are not constrained from an architectural standpoint. However, it has been observed empirically that data buses are typically designed to be asynchronous for microservices [122]. Publish/Subscribe (Pub/Sub) and message queue (MQ) are two popular messaging patterns [123], [124]. In recent years, MQ and Pub/Sub have been added to CSPs' offerings. AWS Simple Queue Service [125], Azure Service Bus [126], Google Cloud Pub/Sub [127], and IBM Cloud Message Queue [128] are examples of such services. In our reference architecture, we recommend using Pub/Sub instead of MQ for inter-service communication between components due to its increased flexibility.

Auxiliary data bus. In case of failure in all or some parts of data transfer services, the reference architecture proposes using an auxiliary data bus. The auxiliary data bus can be instantiated using the same components that are used for the primary data bus or using similar components. Additionally, practitioners may choose a peer-to-peer architecture

<sup>1.</sup> WORM is not a new concept, and storage devices with WORM support have been around for years [109].

<sup>2.</sup> It is possible that the baseline is unknown in advance and is not stationary [23], [77].

to implement the auxiliary data bus<sup>3</sup>.

Heterogeneous computing environments. CNAs make use of various computing environments [131]. For instance, for a microservice that demands 24/7 run-time and heavy computing resources (e.g., virtual CPU, virtual GPU, virtual memory), a VM may be a better computing environment than containers or serverless<sup>4</sup>. Similarly, a container may be the right computing platform if a microservice needs to run at different intervals but needs a full-fledged computing platform. Last but not least, serverless computing has brought a higher level of financial and technical feasibility to CNAs in recent years. As a result, many microservices are customized to be deployed on CSP's serverless offerings. The reference architecture should recognize this diversity and offer environment-specific solutions for the observability and compliance of each type of computing environment.

Data collector agents. As the heterogeneous computing environment of CNA demands, the reference architecture is equipped with various data collection solutions. For VMs, a sidecar approach is recommended when the key responsibility of the sidecar is to collect and disseminate collected telemetry to the observability pipeline [133]. For containers, node-based and pod-based approaches are recommended [134]. For serverless computing environments, root access for the configuration and setup of data collection agents is not provided. Hence, the only possible option is to rely on the CSPs logs or to collect desired application-level telemetry through code instrumentation.

High availability heartbeat. Reliability is a critical factor in designing and implementing observability systems. Reliability requires a proactive approach to detecting failures and responding to them with a failover plan. The reference architecture should acknowledge these requirements and propose a heartbeat mechanism between the data collector agents and the observability pipeline.

# 4 PROPOSED REFERENCE ARCHITECTURE

The answers provided to the raised RQs are used to construct the following proposed reference architecture. Hence, let us review the raised RQs before we propose the reference architecture.

RQ1 is mainly concerned with observability and compliance challenges associated with CNAs. To address this question, we first review the key characteristics of CNAs in Section 2.2 and then explore the observability and compliance challenges associated with CNAs in Section 2.4.

RQ2 is concerned with the key components of a reference architecture for the observability and compliance of CNAs. To answer this question, we explore the desired nonfunctional and architectural requirements in Sections 3.1

- 3. The term peer in peer-to-peer is used in a generic sense here; in other words, "peer" refers to any computing environment (e.g., VMs, containers, serverless). The auxiliary data bus will be a temporary solution until the primary data transfer services are resumed. Cloud practitioners can choose a few different options when it comes to peer-to-peer protocols. For instance, while gossip-based peer-to-peer networks [129] are a common option, some practitioners may choose a more specialized version specifically designed for content distribution [130].
- 4. Note that Kubernetes container orchestrator is currently testing GPU management [132]. Thus, this statement may change in the future.

and 3.2, respectively. Then we explore the construction, deployment, and maintenance requirements of the reference architecture in Section 3.3. We use these requirements to propose the key components needed to construct the reference architecture for the observability and compliance of CNAs in Section 3.4.

This section describes the proposed reference architecture in Section 4.1, explains the data flow among its components in Section 4.2, and discusses the evolution of existing observability pipelines in Section 4.3. Finally, Section 4.4 summarizes information about our reference architecture using an architectural pattern template.

# 4.1 Description

CNAs are designed and built on Cloud technologies. They use microservice architectures and APIs for internal interconnections and CI/CD pipelines for delivery and deployment. CNAs rely on heterogeneous computing environments, such as containers, serverless, and VMs, as well as automated deployment models based on CI/CD pipelines. Being built on the most advanced features of Cloud offerings, CNAs are good candidates for enterprise application development and large-scale software systems. As the non-functional requirements of software dictates, performance, reliability, and stability are among the essential requirements that CSCs need to monitor to ensure the Quality of Service delivered to the end-users matches the ones indicated in SLAs. Similarly, practitioners in regulated industries need to find out if their CNAs can survive a compliance audit.

The proposed reference architecture includes observability and compliance as part of its components. The reference architecture can be used as a guide by Cloud practitioners in designing and implementing CNAs, especially in regulated industries. We believe that including observability and compliance as embedded pillars of our reference architecture significantly reduces the time Cloud practitioners need to invest in bringing external observability and compliance components to their solutions. Our proposed reference architecture is built by Cloud practitioners and researchers who are familiar with the challenges of monitoring largescale systems and deal with them almost daily. Last but not least, an instance of this architecture, with minor modifications, is placed at the heart of Observability practices at IBM Cloud and uses the power of artificial intelligence to detect anomalies in a near real-time fashion [23].

# 4.1.1 Core Characteristics

The reference architecture is shown in Figure 1.

**Multi-vendor Cloud support**. The reference architecture is designed to support a multi-vendor Cloud environment. In Figure 1, multi-vendor Cloud implementation is illustrated by showing two CSPs, namely CSP A and CSP B, that are presented to bring a higher degree of fault tolerance that leads to higher availability.

**Multi-region deployment**. Within each CSP, multiple regions are implemented to address the geo-redundancy requirements and enable end-user location-aware services. There are two regions in Figure 1, Region R1 and Region R2, but the number of regions may vary depending on the

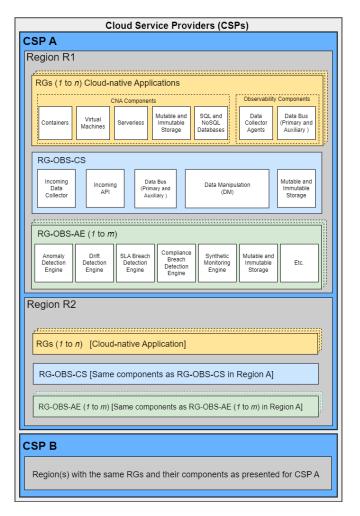


Fig. 1. Graphical representation of the reference architecture.

availability of the service and the presence of the respective CSP in each region.

**End-to-end compliance**. From the IaC and CI/CD perspective, the reference architecture requires the use of Gi-tOps and its primary principles to achieve an end-to-end compliant solution. In other words, from the source code stored in the Git repository, all the way to a deployed solution, each step needs to meet compliance requirements before the entire solution can be called a compliant solution.

# 4.1.2 Resource Group Deployment

Within each CSP and within each region, multiple resource groups (RGs) are implemented as a means to allocate and manage collections of Cloud resources at once. Being a common tool for Cloud resource management, RGs are supported by all major CSPs [135], [136], [137], [138].

RGs for applications. Each CNA is placed in an isolated RG with all its operational components. Within RGs 1 to n, we deploy one CNA per RG (i.e., we will have n CNAs in total).

Let us now examine RGs related to observability practices. The data collection and storage (CS) components and analytics engines<sup>5</sup> (AE), may share a resource group.

5. Analytics engines are responsible for analyzing collected data in real-time or near-real-time and finding actionable insights desired in observability practices, see Section 3.4 for details.

However, our experience has shown that each operations team is interested in running its own analytics. Thus, we recommend separating CS from AE as follows.

RG for centralized observability. An RG, called RG-OBS-CS, holds all the components needed for CS of telemetry data emitted from CNAs deployed in RGs 1 to n. There should be only one instance of RG-OBS-CS, so that all observability data is centralized in one place, giving the operations team a reference view of all CNAs.

RGs for analytics engines. A group of RGs, namely RG-OBS-AE, holds all the AEs. Given the need to separate analytics engines of different teams, m custom analytics solutions will yield m distinct instances of RG-OBS-AE.

#### 4.2 Data Flow

Figure 2 depicts the internal communication among components of the proposed reference architecture.

## 4.2.1 Data Buses

Throughout the reference architecture, for each *primary data* bus, we have allocated an *auxiliary data* bus. If the *primary* data bus is unavailable, the data is sent to the *auxiliary data* bus until the primary one is fixed and is operational (see Section 3.4 for details). For simplicity, we will refer to these two types of data buses as *data* bus.

Data buses often have payload limitations. If one needs to pass a very large object through the data bus that exceeds the allowed payload, then one can save the payload in a database or Cloud storage and exchange its pointer via the data bus [87].

# 4.2.2 Data Flow in RGs

As discussed in Section 4.1.2, there are n RGs used to host CNAs. Within each of these RGs, the *data collector agents* collect telemetry data using push or pull methods from the components of the deployed CNA and submit them to the *data bus* placed in the same RG.

As CNAs may use heterogeneous computing environments such as VMs, containers, and serverless, an appropriate data collector agents should be implemented for each type of computing environment.

#### 4.2.3 Data Flow in RG-OBS-CS

The telemetry data residing in data buses of n RGs are passed to the *incoming data collector* or the *incoming API* components, placed in RG-OBS-CS, using pull or push methods, respectively. The method would be selected based on the design of a specific data bus in RGs.

The *incoming data collector* and the *incoming API* then pass captured telemetry data to the *data bus* in RG-OBS-CS. We then need to massage these raw telemetry data using three data massaging components in RG-OBS-CS, namely, *converter*, *filter*, *aggregator*, and *archiver*. The *converter* transforms the raw data to a unified format; the *filter* selects a subset of data that analytics engines need; the *aggregator* groups the data into the subsets that are consumed by analytics engines, see [86], [87] for details. Finally, the *archiver* 

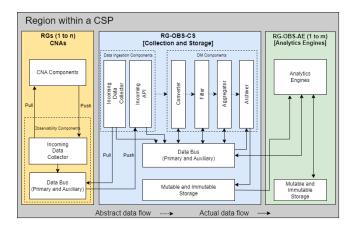


Fig. 2. Internal communication among components of the proposed reference architecture. Figure 1 shows examples of analytics components in RG-OBS-AE. For the sake of brevity, these components are depicted as *Analytics Engines* in this figure.

writes subsets of data, which need to be stored, to mutable and immutable storage.

Core components in RG-OBS-CS interact via the *data* bus placed in RG-OBS-CS.

#### 4.2.4 Data Flow in RG-OBS-AE

Within each RG-OBS-AE, one or more *analytics engines* are placed<sup>6</sup>. Each of these engines analyzes the telemetry data from a unique observability point of view. The insights generated by analytics engines will be sent to mutable and immutable storage options placed within the same RG-OBS-AE and are to be stored in mutable or immutable storage according to data storage compliance requirements.

RG-OBS-CS acts as the source of data for all the analytics engines deployed in RG-OBS-AE 1 to m. The analytics engines receive real-time data from the data bus and read historic data from mutable and immutable storage in RG-OBS-CS.

# 4.2.5 Components' Desirability

Now that we have explained the data flow among internal components of the proposed reference architecture, let us explore the mapping between these components and the desired components for observability and compliance of CNAs, explored in Section 3.4.

The first desired component, *tamper-proof storage*, is needed to store evidential data. In the proposed reference architecture, given the critical role of this component in the observability and compliance domain, immutable storage is placed in both RGs: RG-OBS-CS and RG-OBS-AE.

The second desired component, converter to unified format for logs, is presented in the reference architecture as the converter component in RG-OBS-CS. The third desired

6. Often, multiple analytics engines generate alerts that have to be analyzed and aggregated further to find real problems and reduce false alerts (reducing "alert fatigue" [23]). To enable this functionality, analytics engines should be able to send alerts to a topic in the data bus; a correlation analytics component will listen to the alerts from different sources and identify real ones (e.g., based on predefined rules or machine learning models). We can achieve this by having a bidirectional flow between *data bus* in RG-OBS-CS and *analytics engines* in RG-OBS-AE.

component, analytics engines is placed in RG-OBS-AE. Note that all kinds of analytics engines can be used to assess the conformance of a given metric with a desired state. For instance, an anomaly detection engine can detect anomalies in real or near-real-time fashion.

The reference architecture also needs a way to accept ingress data. The *API gateway*, the fourth desired component, is placed in RG-OBS-CS as *incoming data collector* (pull) and *incoming API* (push) and accepts ingress data. While we recommend a Pub/Sub messaging pattern, which uses only the push method, we are not limiting ourselves to Pub/Sub (see Section 3.4 for details). Therefore, we add components for both the push and pull methods.

The fifth desired component, data storage services can be instantiated in RG-OBS-CS and RG-OBS-AE using the same or different underlying services provided by the CSP, depending on our needs. Examples of such services range from simple object stores (e.g., AWS S3 or IBM COS) to NoSQL databases (e.g., AWS Dynamo or IBM Cloudant).

The sixth and seventh desired components, namely data bus and auxiliary data bus are placed in RGs 1 to n and RG-OBS-CS. Despite the fact that the data buses in RGs and RG-OBS-CS are separated in the diagram, it is acceptable to use one data bus service if the CSP offers it (e.g., AWS Kinesis [139] or IBM Event Streams [140]).

The next desired component, the eighth in the list, is the support for *heterogeneous computing environments*. The CNA itself is equipped with various computing environments, such as containers, virtual machines, or serverless functions, all of which reside in RGs 1 to n. Additionally, Cloud practitioners can choose various computing environments for the components presented in RG-OBS-CS and RG-OBS-AE.

All components deployed in RGs 1 to n are equipped to interact with the data collector agents, the ninth desired component. The data collector agents are responsible to collect and disseminate telemetry data from various components of the CNA to the data bus presented in RGs 1 to n.

Last but not least, Cloud practitioners may set external *high availability heartbeat* to ensure the health of deployed components in RG-OBS-CS and RG-OBS-AE. Given that the architecture of the *high availability heartbeat* is outside of the scope of this work, it is not shown in Figure 2.

# 4.3 Evolution of an Existing Observability Pipeline and Reuse of Existing Observability Solutions

Most of the time, we do not build our own observability platform; rather, we use existing commercial products, such as Mezmo [141], Splunk [142], or Sysdig [143]. It is common to end up with 3 to 5 of these products (monitoring apps in RGs simultaneously). The reason for this is that different platforms provide slightly different functionality. There is also some overlap in these functionalities, which leads to duplication. Furthermore, these platforms only offer some of the desired features, so customers must develop additional custom monitoring components.

Thus, a typical observability platform in a large organization will combine commercial platforms and custom components monitoring RGs. Using this approach has some

benefits: customers do not have to develop (and maintain) complex observability components. But there are also draw-backs: fragmentation of data sources (independent dashboards and UIs, making it difficult to monitor apps in RGs holistically), cost of ownership (especially for large data stores of different platforms), and cost of operators' training.

What is the appropriate way to evolve such an existing observability stack using our architecture? The idea of building a brand-new observability platform from scratch may be tempting, but it is usually unfeasible for economic and political reasons. Instead, we can incorporate some of these platforms into our architecture. By leveraging the existing telemetry gathering infrastructure of existing platforms (e.g., Mezmo and SysDig), we can instantiate "Data Collector Agents" in RG-OBS-CS. Additionally, we could import alerts from existing observability platforms into our aggregated observability dashboard, reusing some of their analytics components.

We can either dynamically pull these data (in a federated manner) or clone them from external platforms' data stores into ours. The data will be standardized using our Data Manipulation (DM) components in both cases. There are cons to both approaches: increased ingress costs in case of repetitive queries for the former and increased storage costs for the latter. These approaches may increase computing, storage, and network costs, but they will also save us human resources, as we will not have to build data collection and (sometimes) storage from scratch.

Even when building a brand-new observability platform, we do not recommend building each component from scratch. Several open-source products, such as Elasticsearch, Logstash, and Kibana, can instantiate some components [144]. Often, these products are offered as services, which reduces maintenance needs.

Lastly, the adopters of the reference architecture will be able to instantiate other instances from the same components in a fraction of the time it takes to build the original implementation if they use IaC.

## 4.4 Architectural Pattern

Finally, we summarize information about our reference architecture using an architectural pattern template [145, Sec. 13.1] as follows.

## 4.4.1 Context

From an architectural and implementation point of view, CNAs are among the most evolved forms of applications. Nevertheless, they require monitoring and observability infrastructure in order to operate reliably.

#### 4.4.2 Problem Description

CNAs' core characteristics, such as heterogeneous computing platforms and microservice architecture, make the maintenance, monitoring, and compliance practices challenging. Each computing platform requires its log collection and analysis method. While a detailed view of each component is needed, a holistic view of the entire platform is also needed to render a realistic picture of the system's current state. A detailed explanation of such challenges is presented in Section 2.4.

# 4.4.3 Solution Description

The proposed reference architecture utilizes the authors' experiences in dealing with monitoring, observability, and compliance of CNAs. It is intended for Cloud practitioners responsible for designing and implementing CNAs in regulated and non-regulated industries. To further assist these practitioners with monitoring and observability, the reference architecture uses a battery-included mindset and includes both observability and compliance as embedded pillars.

Advantages. The proposed reference architecture has been used in CNA settings and has evolved to address complex monitoring and observability requirements. The reference architecture consists of a layered, modular architecture, and practitioners can easily customize its component to match their needs. Moreover, since the reference architecture is Cloud- and technology-agnostic, it can be applied to a wide selection of Cloud service offerings. The reference architecture is designed based on the most recent advancements in Cloud computing, reviewed in Section 1.2. Moreover, it can be used to build an observability pipeline from scratch or evolve an existing one, as discussed in Section 4.3.

Disadvantages. While the majority of CNAs use similar Cloud technologies, their architectural structure is often inspired by their features and can vary from solution to solution. Hence, adopters of this reference architecture may need to cautiously evaluate its applicability to their desired CNA architecture and hand-pick components that match their architectural style. Additionally, while the reference architecture denotes required and desired components of the architecture, it does not offer guidance on implementation and available options for each component. It is up to practitioners to choose the technology for each component.

# 5 REAL-WORLD INSTANTIATION OF THE PRO-POSED REFERENCE ARCHITECTURE

In this section, we demonstrate how the proposed reference architecture can be constructed using real-world Cloud computing components.

Figure 3 depicts the instantiated architecture using AWS components. Similarly, Figure 4 depicts the instantiated architecture using IBM Cloud components.

As many CNAs require multi-cloud deployments to meet the high-availability requirements, in Figure 5, we present an instantiation of the reference architecture for multi-cloud deployment using AWS and IBM as two CSPs. To establish connections among RGs, practitioners can use CSPs networking tools and services. Generally, if components of an RG need to interact with components of another RG hosted on a separate CSP, many network-based solutions such as IPSec and VPN exist that allow practices to establish such connections [146].

# 6 RELATED LITERATURE

Here, we review the recent literature related to CNAs and their monitoring and observability practices in Section 6.1 and the existing tools related to monitoring and observability of CNA in Section 6.2.

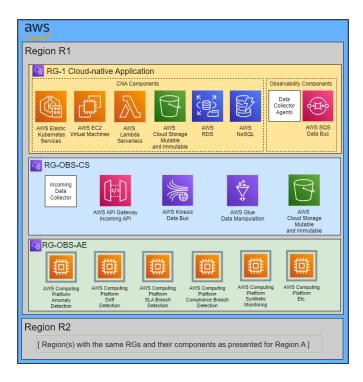


Fig. 3. Instantiated architecture using AWS Cloud components.

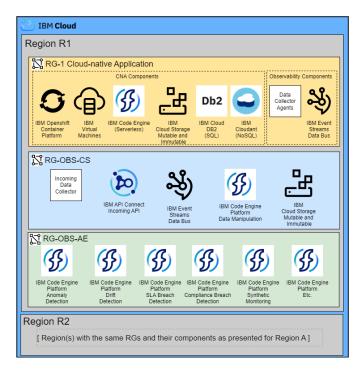


Fig. 4. Instantiated architecture using IBM Cloud components.

# 6.1 Cloud Native Application Monitoring and Observability

Monitoring CNAs is a non-trivial task. CNAs are deployed over an elastic platform, a mixture of the computing environment (VMs, containers, serverless), and are designed based on microservice architecture. The diversity of involved components calls for several different monitoring approaches, yet, a holistic view of the entire application is needed for the efficient maintenance of CNAs.

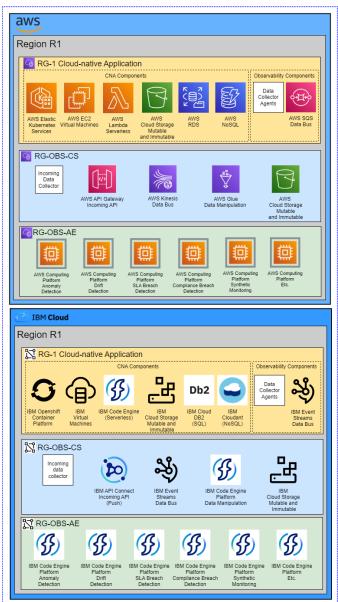


Fig. 5. Instantiated multi-cloud architecture using AWS and IBM Cloud service providers and their components.

Brunner et al. [147] indicate that CNAs are designed with inherent support for self-management, scalability, and resilience across clustered units of application logic. The authors acknowledge that while Cloud-native systematic design is promising, no dominant application development model exists for CNAs. As Cloud architects, we have faced the same lack of a dominant model for the observability and compliance of CNAs, hence our motivation for this work.

Oliveira et al. [148] note that operational visibility is an important administrative capability, especially in deciding the success or failure of a Cloud service. The authors acknowledge the complexity of monitoring practices in the Cloud and note that the target endpoints to monitor are becoming increasingly varied in terms of their heterogeneity, cardinality, and lifecycles. Furthermore, the authors indicate that monitoring solutions should be able to track both persistent and volatile system state and offer services such

as log analysis, software discovery, behavioural anomaly detection, and drift analysis. In their work, the authors present a unified monitoring and analytics pipeline, named OpVis, to provide operational visibility that overcomes the limitations of traditional monitoring solutions. The authors recognize the need for a unified monitoring approach and indicate that their proposed solution eliminates the need for installing and maintaining multiple siloed monitoring solutions. Moreover, to adapt to the ever-changing Cloud landscape, the authors highlight the extensibility model that enables custom data collection and analytics based on the Cloud user's requirements. Despite OpVis' ability to monitor heterogeneous computing environments, it does not provide CSP-backed services such as Relational Databases (RD)-as-a-Service. However, CNA compliance requires monitoring of all components, hence the need for our reference architecture.

# 6.2 Existing Tools and Practices in Monitoring of Cloud Native Applications

Toka et al. [149] note that the quality of services provided by Cloud applications is often affected by faults in the underlying Cloud platform and infrastructure. The authors propose an open-source, lightweight, and Cloud-native monitoring solution that can detect useful patterns in metrics collected from Cloud infrastructure or applications. The proposed solution has a 4-tier architecture consisting of exporters, collectors, a database, and a visualization engine. Collectors gather data from various sources and submit them to Prometheus [150] (used for time-series storage and advanced quering mechanism [151]). Grafana [152] is used as a visualization engine. Practitioners often combine collection, storage, analysis, and visualization tools to achieve monitoring and observability goals. While such combination is common in today's Cloud monitoring and observability software solutions, we have pointed out the issues it causes in Section 4.3. Our paper attempts to address these issues.

Wang et al. [153] acknowledge the importance of root cause analysis in Cloud environments and propose CloudRanger, a novel root cause analysis tool dedicated to CNAs. CloudRanger relies on establishing dynamic, casual relationship analysis to construct impact graphs amongst applications without a defined topology. CloudRanger takes four steps to carry out its performance management tasks. The first step is anomaly detection. Once an anomaly is detected, an impact graph is constructed as the second step. CloudRanger constructs impact graphs based on dynamic casual relationship analysis against the observed performance metrics. The third step is to use a heuristic investigation algorithm based on the second-order random walk against the constructed graph, and at last, in the final step, CloudRanger identifies the problematic services. Wang et al. emphasize that Cloud applications are often deployed over dynamic infrastructure, and CloudRanger immunity against backend dynamics makes it a robust and reliable tool for Cloud monitoring. The elasticity of infrastructure for CNAs makes the monitoring even more challenging as the monitoring tool should be able to monitor transient, short-lived components that will be dynamically added and removed to and from the resource pools. Though CloudRanger offers anomaly detection, correlation analysis, and root-cause

analysis for CNAs, it does not provide a complete view of a CNA's state. In addition, CloudRanger does not include tamper-proof storage, data bus, and converter to a unified format, all of which are critical to ensuring the observability and compliance of CNAs (see Section 3.4 for more details on the components needed to design and implement an observability and compliance solution for CNAs), which is why our reference architecture was developed.

## 7 CONCLUSION

In this paper, we examine CNAs and their characteristics, monitoring and observability challenges, and tools commonly used in today's Cloud observability practices. Next, we discuss observability's importance for regulated industries. Following this, we describe the requirements and characteristics of the reference architecture for the observability pipeline. This architecture is aimed at small and large CNA deployments in regulated and non-regulated industries. Then, we present a reference architecture for the observability pipeline and discuss its advantages and disadvantages. Finally, we give examples of its implementation in single- and multi-cloud scenarios.

Practitioners interested in implementing CNAs will find this reference architecture useful. Its modular design allows architects to replace its components without adhering rigidly to the reference architecture. Academics may also be interested in this work because it provides a building block for generic CNA architectures.

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