Cloud Computing

Secure and Resilient Kafka-Based Messaging System with Istio-Driven Security and HA

Prepared by:
Tharun Reddy Banda - 51793A
Tesfaamanuel Lencho Dekebo- 41533A

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Contents

1 Project Overview

This project focuses on building and deploying a secure, fault-tolerant, and highly available distributed messaging system using Apache Kafka on a Kubernetes cluster. The core objective is to demonstrate key non-functional properties (NFRs) of distributed systems—such as resilience, scalability, security, and observability—through a practical microservice architecture. Kafka serves as the backbone for asynchronous communication between two microservices: a producer and a consumer, both running as Kubernetes deployments to ensure high availability and auto-recovery. Kafka itself is deployed in a highly available setup with three controller nodes, coordinated using the Raft consensus protocol to maintain cluster state and ensure fault tolerance during broker failures. To secure inter-service communication and simplify certificate management, the project integrates Istio as a service mesh. Istio enforces mutual TLS (mTLS) across the cluster, handles automatic certificate provisioning, and applies fine-grained access control via AuthorizationPolicies—eliminating the need for manual TLS setup in each microservice. For data persistence, Kafka brokers are provisioned with PersistentVolumeClaims (PVCs) managed via Helm charts, ensuring reliable storage across restarts. Additionally, a robust observability stack—including Prometheus, Grafana, and Kiali (deployed using Istio addons)— provides real-time monitoring, metrics collection, and mesh-level traffic visualization. This end-to-end setup demonstrates how modern cloud-native tools can be combined to achieve a production-grade message queue system with strong guarantees around reliability, security, and operational transparency.

2 Objectives

- Deploy a fault-tolerant, secure Kafka cluster on Kubernetes.
- Demonstrate Kafka message flow between producer and consumer microservices.
- Apply Istio to enforce mTLS, encryption, and authentication without manually managing TLS certificates.
- Leverage observability tools to monitor cluster state, message flow, and system health.
- Simulate failure conditions to validate resilience and HA mechanisms

3 Architecture and Technology Stack

Component	Technology
Messaging Queue	Apache Kafka (3 controller nodes, Raft)
Container Orchestration	Kubernetes
Service Mesh	Istio
Microservices	Kafka Producer/Consumer (Bitnami image)
Kafka Docker Image	docker.io/bitnami/kafka:latest
Deployment	Helm charts, YAML configs
Storage	Kubernetes PVCs
Observability	Kiali, Prometheus, Grafana

4 System Architecture

The Kafka cluster comprises:

- 3 Kafka controller nodes coordinated using the Raft protocol to ensure high availability and consistent metadata management.
- Persistent Volumes (PVs) provisioned using PVCs for Kafka broker and controller state persistence.
- Kafka deployed via Helm charts, enabling modular and scalable configurations.
- Two Kafka microservices: a producer and a consumer, deployed as individual pods, interacting with Kafka topics.
- Istio sidecars injected into all pods for secure mesh communication.
- Monitoring stack with Prometheus, Grafana, and Kiali for observability.

5 Kafka Deployment Details

5.1 Helm-Based Deployment

Kafka was installed using Bitnami Helm charts, allowing:

- Declarative configuration of brokers and controllers
- Simplified PVC setup for persistent data
- Parameterized customization (replica count, storage size, etc.)

```
# Setps for deployment of kafka KRaft using Helm

#1. Bitnami Helm Repo

helm repo add bitnami https://charts.bitnami.com/bitnami
helm repo update

#kafka-values.yaml
# Creating  a values.yaml for Kafka with KRaft

replicaCount: 2
persistence:
  enabled: true
  size: 8Gi
  storageClass: standard
kraft:
  enabled: true
  controllerQuorumVoters: "0@kafka-0.kafka-headless.default.svc.cluster.local:9093,1@kafka-1.kafka-headless.default.svc.cluster.local:9093"
listeners:
  client:
    protocol: PLAINTEXT
  controller:
    protocol: PLAINTEXT
auth:
  enabled: false
zookeeper:
  enabled: false

# 3 Installing Kafka using Helm in Default Namespace
helm install kafka bitnami/kafka -n default -f kafka-values.yaml
```

5.2 Raft-Based Controller Nodes

Kafka cluster deployed with 3 dedicated controller nodes running Raft protocol, providing:

- Metadata fault tolerance
- Improved failover during controller node failure
- Centralized controller architecture

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods
NAME                                READY   STATUS    RESTARTS        AGE
kafka-client-5dbb5f6cc9-596gz       2/2     Running   7 (48m ago)     13h
kafka-client-5dbb5f6cc9-76k2l       2/2     Running   8 (48m ago)     13h
kafka-controller-0                  2/2     Running   20 (13h ago)    12d
kafka-controller-1                  2/2     Running   20 (13h ago)    12d
kafka-controller-2                  2/2     Running   20 (13h ago)    12d
kafka-producer-fc49cccc8-jfj7f      2/2     Running   0               28m
(base) THARUN@MacBook-Pro-M2 ~ %
```

5.3 Persistent Storage

Used PVCs for both brokers and controllers to ensure:

- Data durability in the event of pod rescheduling
- StatefulSets ensured consistent pod identities
- Underlying storage provisioned using dynamic volume claims

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pv
NAME                                       CAPACITY   ACCESS MODES   RECLAIM POLICY   STATUS   CLAIM                          STORAGECLASS   VOLUMEATTRIBUTESCLASS   REASON   AGE
pvc-0f1afa8f-4b35-46f8-8109-f3bb7cd22f77   8Gi        RWO            Delete           Bound    default/data-kafka-controller-1   standard       <unset>                          12d
pvc-7c12a68b-d977-46c0-b43e-6afe8036ba9b   8Gi        RWO            Delete           Bound    default/data-kafka-controller-0   standard       <unset>                          12d
pvc-f43066f3-5e15-4d9d-bf36-5ba04f02e8d5   8Gi        RWO            Delete           Bound    default/data-kafka-controller-2   standard       <unset>                          12d
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pvc
NAME                     STATUS   VOLUME                                     CAPACITY   ACCESS MODES   STORAGECLASS   VOLUMEATTRIBUTESCLASS   AGE
data-kafka-controller-0   Bound    pvc-7c12a68b-d977-46c0-b43e-6afe8036ba9b   8Gi        RWO            standard       <unset>                 12d
data-kafka-controller-1   Bound    pvc-0f1afa8f-4b35-46f8-8109-f3bb7cd22f77   8Gi        RWO            standard       <unset>                 12d
data-kafka-controller-2   Bound    pvc-f43066f3-5e15-4d9d-bf36-5ba04f02e8d5   8Gi        RWO            standard       <unset>                 12d
```

6 Security with Istio

6.1 Istio Service Mesh Integration for Secure Kafka Communication

To enforce secure communication and minimize configuration overhead, Istio was integrated as a service mesh within the Kubernetes cluster. This enabled a zero-trust architecture by default and provided seamless encryption, authentication, and traffic control for all microservices—including Kafka producer, consumer, and the Kafka brokers themselves.

6.2 Mutual TLS (mTLS) for Pod-to-Pod Encryption

- Istio's automatic mTLS was enabled at the namespace level, ensuring that all traffic between services was transparently encrypted using TLS.
- Sidecar proxies (Envoy) were automatically injected into each pod and managed the encryption and decryption of traffic.
- This ensured data confidentiality and integrity for Kafka messages exchanged between producer, consumer, and Kafka brokers—even within the internal cluster network.

6.3 Authentication and Authorization

- Workload identity was enforced using Istio's strong service-to-service authentication based on SPIFFE (Secure Production Identity Framework for Everyone).
- An Istio AuthorizationPolicy was configured to allow access only to specific defult namespace (e.g., Kafka producer and consumer), blocking unauthorized traffic from other namespaces.
- Attempted communication from an unauthorized pod was successfully denied during testing, proving the effectiveness of the RBAC policies.

6.4 Simplified Certificate Management

With Istio, complex TLS configurations were eliminated:

- No manual certificate generation or distribution was required.

- No custom TLS setup needed in Kafka configuration files for producer or consumer.
- Certificates were automatically provisioned, rotated, and expired by Istio's Citadel component (or Istiod in newer versions), significantly reducing operational overhead and human error.

6.5 Benefits Gained

- End-to-end secure channel for all Kafka communications
- Fine-grained access control with minimal effort
- Automatic certificate management, saving configuration time and reducing security risks
- Enhanced observability through Istio's telemetry integration with Prometheus, Kiali, and Grafana

Installing Istio on k8's ,

```
# Download Istio

curl -L https://istio.io/downloadIstio | sh -
cd istio-*
export PATH=$PWD/bin:$PATH

# Install Istio with mTLS enabled by default
istioctl install --set profile=demo -y
```

To configure the istio to automatically create sidecar container deployed in the default namespace,

```
# To Enable automatic sidecar injection for default namespace
kubectl label namespace default istio-injection=enabled
```

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods -n istio-system
NAME                                    READY   STATUS    RESTARTS       AGE
grafana-65bfb5f855-khl9n                1/1     Running   7 (14h ago)    9d
istio-ingressgateway-7f7bcf6bb9-xd7v9   1/1     Running   11 (14h ago)   13d
istiod-85c68488c4-fftwm                 1/1     Running   11 (14h ago)   13d
kiali-6d774d8bb8-76gxt                  1/1     Running   10 (14h ago)   12d
prometheus-689cc795d4-bgp56             2/2     Running   14 (14h ago)   9d
```

7 Microservice Demonstration

To validate the core Kafka functionality and its integration with the distributed system infrastructure, two microservices were deployed on the Kubernetes cluster using the Bitnami Kafka image. These services were designed to simulate a producer-consumer architecture within a secure and fault-tolerant environment.

7.1 Kafka Producer Microservice

- Image: `docker.io/bitnami/kafka:latest`
- Functionality: Periodically sends test messages to a Kafka topic.
- Deployment Method: Deployed as a Kubernetes Deployment to ensure:
  - Auto-healing: In case of a pod failure, a new pod is automatically recreated by the deployment controller.
  - Scalability: Can be scaled horizontally to run multiple producer instances.
- Security: Configured to securely connect with the Kafka cluster inside the Istio service mesh using mutual TLS and sidecar injection.

```
kubectl apply -f - <<EOF
apiVersion: apps/v1
kind: Deployment
metadata:
  name: kafka-producer
  namespace: default
spec:
  replicas: 1
  selector:
    matchLabels:
      app: kafka-producer
  template:
    metadata:
      labels:
        app: kafka-producer
    spec:
      containers:
      - name: kafka-producer
        image: docker.io/bitnami/kafka:latest
        command:
          - "/bin/bash"
          - "-c"
          - |
            echo "Kafka producer pod is running. Exec into this pod to use kafka-console-producer.sh"
            tail -f /dev/null
      restartPolicy: Always
EOF
```

7.2 Kafka Consumer Microservice

- Image: docker.io/bitnami/kafka:latest
- Functionality: Subscribes to the Kafka topic and logs received messages.
- Consumer Group: Part of a Kafka Consumer Group to enable:

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get deployments
NAME             READY   UP-TO-DATE   AVAILABLE   AGE
kafka-client     2/2     2            2           14h
kafka-producer   1/1     1            1           78m
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods
NAME                              READY   STATUS    RESTARTS        AGE
kafka-client-5dbb5f6cc9-596gz     2/2     Running   7 (98m ago)     14h
kafka-client-5dbb5f6cc9-76k2l     2/2     Running   8 (98m ago)     14h
kafka-controller-0                2/2     Running   20 (14h ago)    12d
kafka-controller-1                2/2     Running   20 (14h ago)    12d
kafka-controller-2                2/2     Running   20 (14h ago)    12d
kafka-producer-fc49cccc8-jfj7f    2/2     Running   0               78m
```

  - Load Balancing: Distributes message consumption across multiple instances.
  - Parallelism: Enables parallel processing of messages from different partitions.

- Deployment Method: Deployed as a Kubernetes Deployment to ensure:
  - Auto-recovery of the consumer pod in the event of failure.
  - High availability through support for multiple replicas.

- Security: Communicates over a secure channel within the service mesh and adheres to Istio's access control and encryption policies.

```
kubectl apply -f - <<EOF
apiVersion: apps/v1
kind: Deployment
metadata:
  name: kafka-client
  namespace: default
spec:
  replicas: 2  # Runs 2 consumer pods
  selector:
    matchLabels:
      app: kafka-client
  template:
    metadata:
      labels:
        app: kafka-client
    spec:
      containers:
      - name: kafka-client
        image: docker.io/bitnami/kafka:latest
        command:
          - "/bin/bash"
          - "-c"
          - |
            echo "Starting Kafka consumer in consumer group: my-consumer-group"
            kafka-console-consumer.sh \
              --bootstrap-server kafka.default.svc.cluster.local:9092 \
              --topic my-topic \
              --group my-consumer-group
EOF
```

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get deployments
NAME             READY   UP-TO-DATE   AVAILABLE   AGE
kafka-client     2/2     2            2           14h
kafka-producer   1/1     1            1           83m
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods
NAME                              READY   STATUS    RESTARTS        AGE
kafka-client-5dbb5f6cc9-596gz     2/2     Running   7 (103m ago)    14h
kafka-client-5dbb5f6cc9-76k2l     2/2     Running   8 (103m ago)    14h
kafka-controller-0                2/2     Running   20 (14h ago)    12d
kafka-controller-1                2/2     Running   20 (14h ago)    12d
kafka-controller-2                2/2     Running   20 (14h ago)    12d
kafka-producer-fc49cccc8-jfj7f    2/2     Running   0               83m
```

8 Observability and Monitoring

To ensure the system is transparent, observable, and easy to troubleshoot, a robust observability stack was deployed. This monitoring setup covered Kafka's operations, Kubernetes resource usage, and Istio's service mesh traffic. All observability tools were installed and configured using the Istio-provided add-ons, ensuring seamless integration and minimal manual setup.

8.1 Prometheus

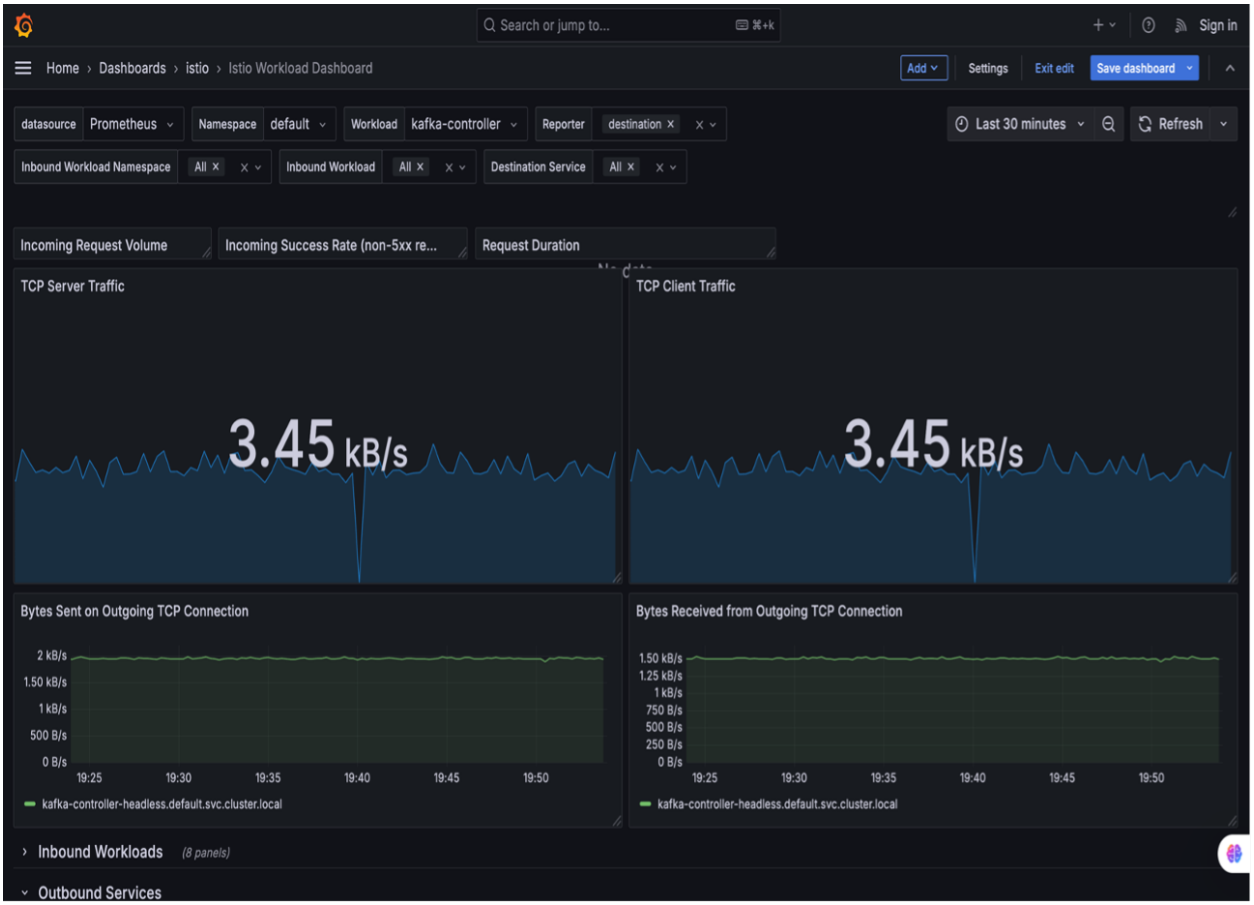
- Installation: Deployed from the official Istio add-ons, which included a preconfigured Prometheus setup tailored to Istio's metrics.
- Functionality:
  - Scrapes metrics from multiple sources, including:
    - Kafka brokers and pods (via JMX exporters or sidecar scraping)
    - Kubernetes nodes and system components
    - Istio proxies and control plane
  - Metrics collected included:
    - Kafka topic throughput, partition lag, and broker health
    - Pod CPU/memory utilization
    - mTLS status, request latency, error rates, and policy enforcement data

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods -n istio-system
NAME                                    READY   STATUS    RESTARTS        AGE
grafana-65bfb5f855-khl9n                1/1     Running   7 (15h ago)     9d
istio-ingressgateway-7f7bcf6bb9-xd7v9   1/1     Running   11 (15h ago)    13d
istiod-85c68488c4-fftwm                 1/1     Running   11 (15h ago)    13d
kiali-6d774d8bb8-76gxt                  1/1     Running   10 (15h ago)    12d
prometheus-689cc795d4-bgp56             2/2     Running   14 (15h ago)    9d
```

8.2 Grafana

- Installation: Also deployed using the Istio bundled Helm configuration.
- Usage:
  - Used to visualize real-time and historical performance metrics.
  - Pre-configured dashboards were customized to include:
    * Kafka metrics: Broker availability, topic activity, partition distribution, consumer lag
    * Kubernetes resource dashboards: Pod usage, node health, cluster capacity
    * Istio dashboards: mTLS status, success/error rates, request volumes, latency per service.
- Benefits:
  - Quick insights into the system's health
  - Immediate identification of bottlenecks or failures in the Kafka pipeline or service mesh

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods -n istio-system
NAME                                    READY   STATUS    RESTARTS       AGE
grafana-65bfb5f855-khl9n                1/1     Running   7 (15h ago)    9d
istio-ingressgateway-7f7bcf6bb9-xd7v9   1/1     Running   11 (15h ago)   13d
istiod-85c68488c4-fftwm                 1/1     Running   11 (15h ago)   13d
kiali-6d774d8bb8-76gxt                  1/1     Running   10 (15h ago)   12d
prometheus-689cc795d4-bgp56             2/2     Running   14 (15h ago)   9d
```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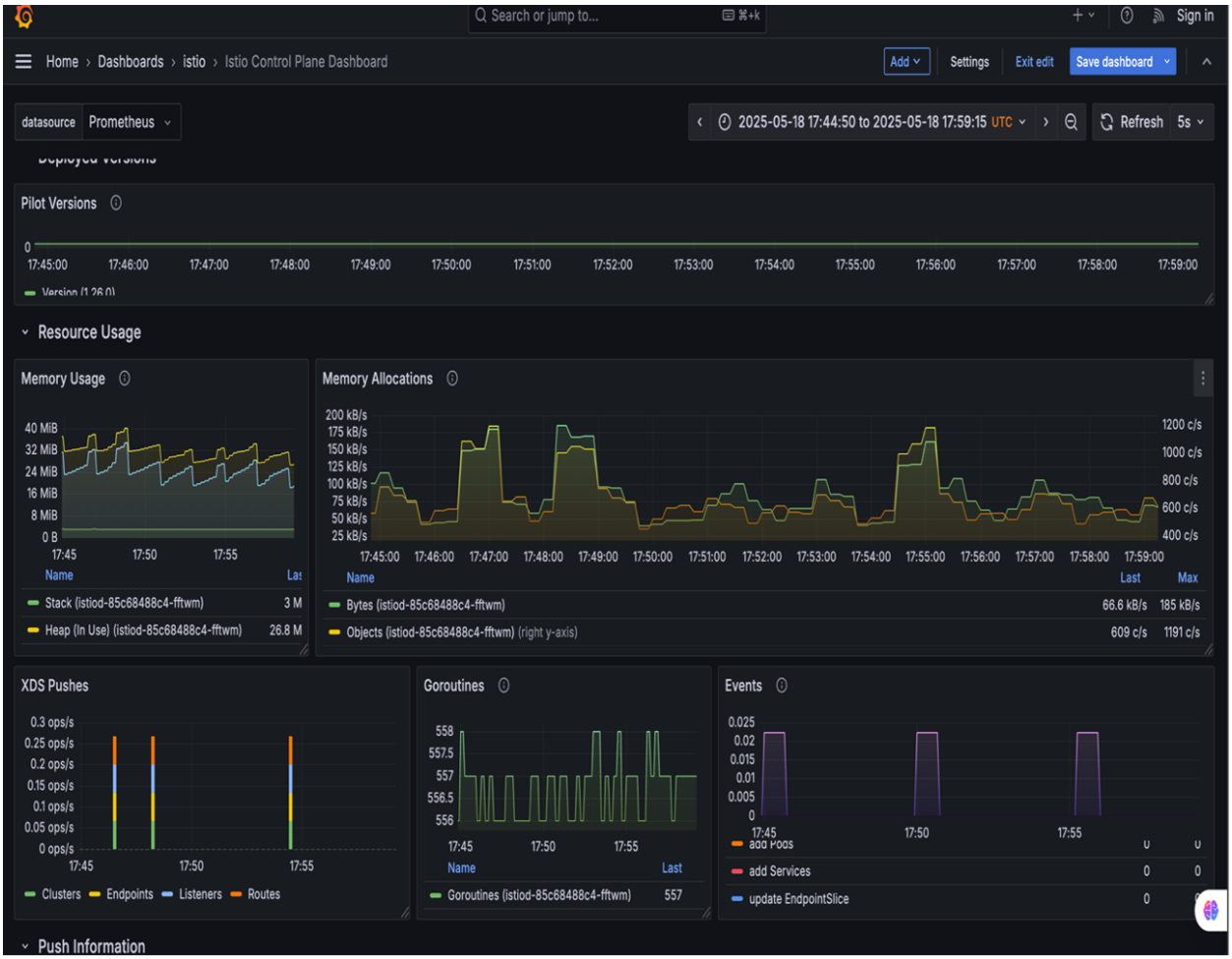
Home › Dashboards › istio › Istio Workload Dashboard
Add
Settings
Exit edit
Save dashboard
datasource Prometheus
Namespace default
Workload kafka-controller
Reporter destination
Last 30 minutes
Refresh
Inbound Workload Namespace All
Inbound Workload All
Destination Service All
Incoming Request Volume
Incoming Success Rate (non-5xx re...
Request Duration
TCP Server Traffic
3.45 kB/s
TCP Client Traffic
3.45 kB/s
Bytes Sent on Outgoing TCP Connection
2 kB/s
1.50 kB/s
1 kB/s
500 B/s
0 B/s
19:25
19:30
19:35
19:40
19:45
19:50
kafka-controller-headless.default.svc.cluster.local
Bytes Received from Outgoing TCP Connection
1.50 kB/s
1.25 kB/s
1 kB/s
750 B/s
500 B/s
250 B/s
0 B/s
19:25
19:30
19:35
19:40
19:45
19:50
kafka-controller-headless.default.svc.cluster.local
Inbound Workloads (8 panels)
Outbound Services

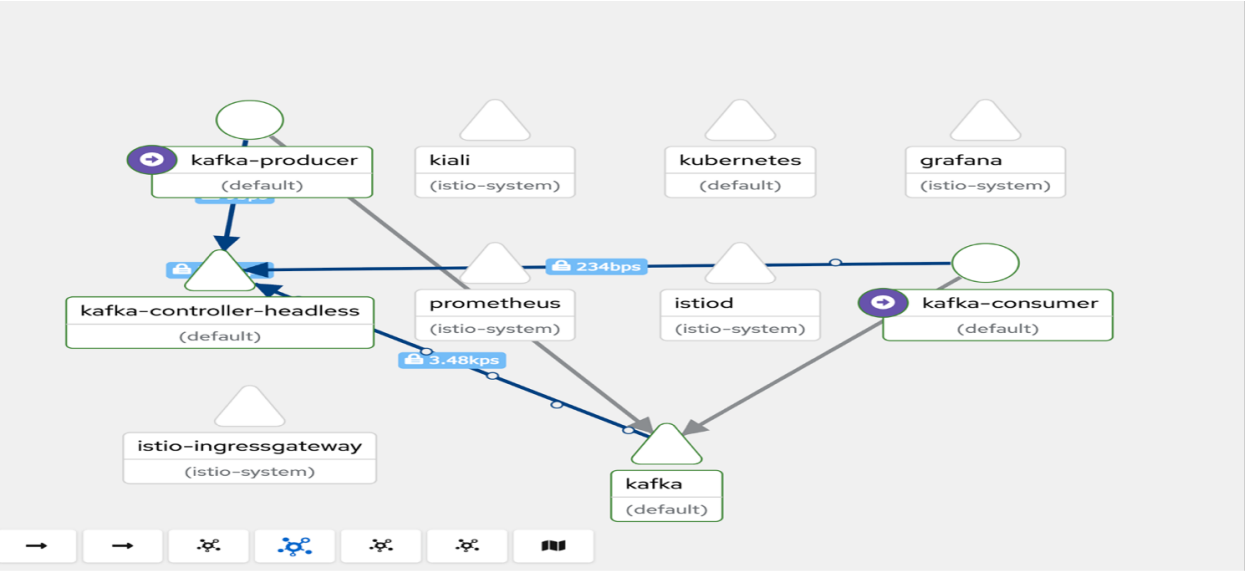


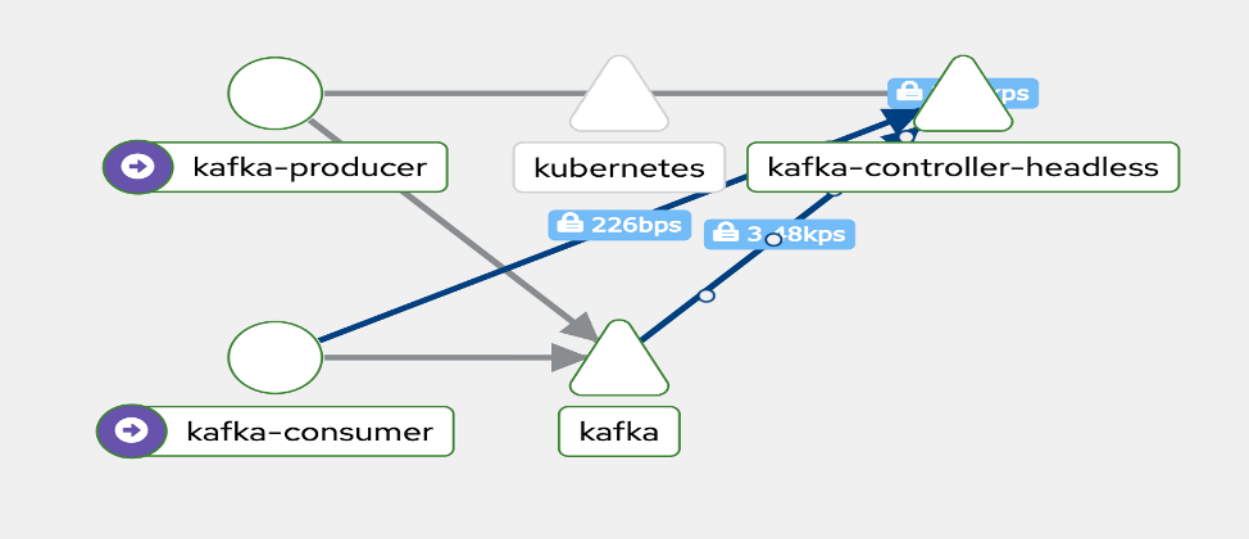
8.3 Kiali

- Installation: Installed using Istio's native add-on deployment (`samples/addons/-kiali.yaml`), which integrates deeply with Istio's telemetry.
- Capabilities:
  - Live visualization of the Kafka producer–broker–consumer communication flow.
  - Highlights mTLS status using padlock indicators (green for encrypted communication).
  - Shows request volume, error rates, and latency in a service-to-service graph.
  - Displays authorization policies, routing decisions, and service versions if enabled.
- Demonstration Use:
  - Used to validate that Kafka traffic was encrypted via mTLS.
  - Confirmed that unauthorized services could not connect to Kafka producer / consumer.

– Enabled visual tracing of Kafka message flow inside the cluster mesh.

```
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get pods -n istio-system
NAME                                    READY   STATUS    RESTARTS       AGE
grafana-65bfb5f855-khl9n                1/1     Running   7 (15h ago)    9d
istio-ingressgateway-7f7bcf6bb9-xd7v9   1/1     Running   11 (15h ago)   13d
istiod-85c68488c4-fftwm                 1/1     Running   11 (15h ago)   13d
kiali-6d774d8bb8-76gxt                  1/1     Running   10 (15h ago)   12d
prometheus-689cc795d4-bgp56             2/2     Running   14 (15h ago)   9d
(base) THARUN@MacBook-Pro-M2 ~ % kubectl get svc -n istio-system
NAME                   TYPE           CLUSTER-IP       EXTERNAL-IP   PORT(S)                                      AGE
grafana                ClusterIP      10.102.20.196    <none>        3000/TCP                                     9d
istio-ingressgateway   LoadBalancer   10.100.173.159   127.0.0.1     15021:30940/TCP,80:32500/TCP,443:30586/TCP   13d
istiod                 ClusterIP      10.109.144.100   <none>        15010/TCP,15012/TCP,443/TCP,15014/TCP        13d
kiali                  ClusterIP      10.111.167.247   <none>        20001/TCP,9090/TCP                           12d
prometheus             ClusterIP      10.102.64.206    <none>        9090/TCP                                     9d
(base) THARUN@MacBook-Pro-M2 ~ %
```



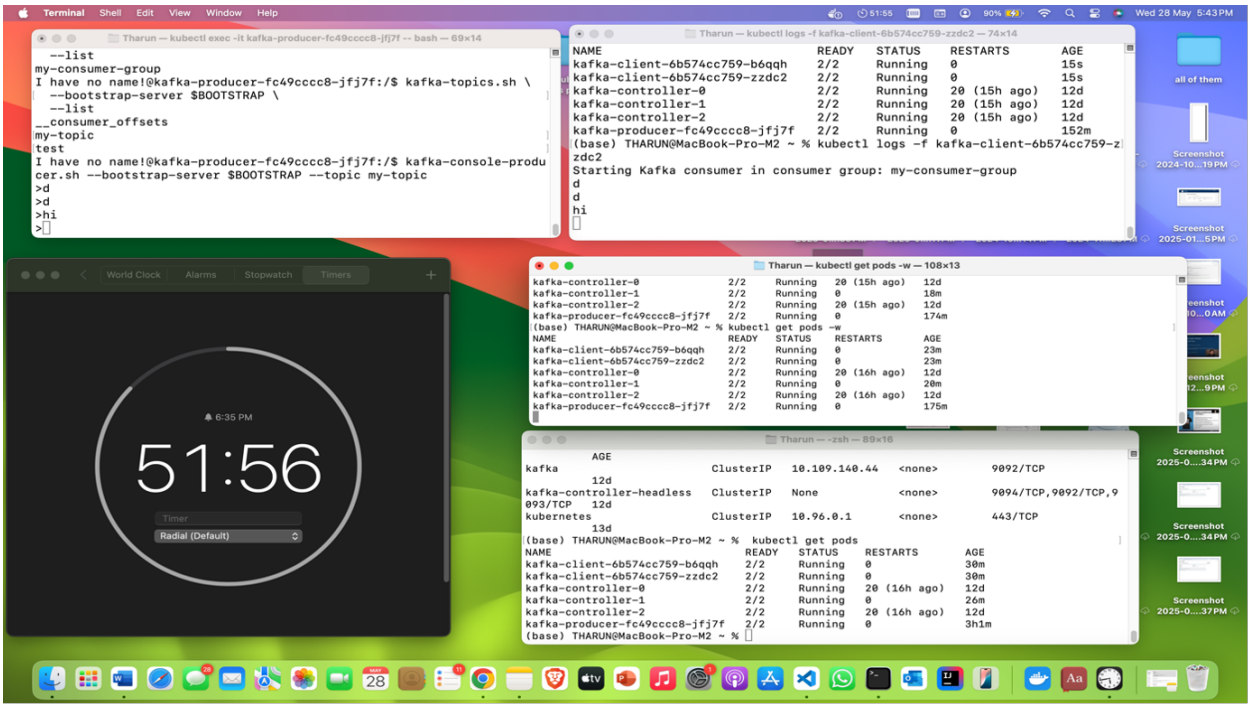


9 Demonstration of non-functional properties

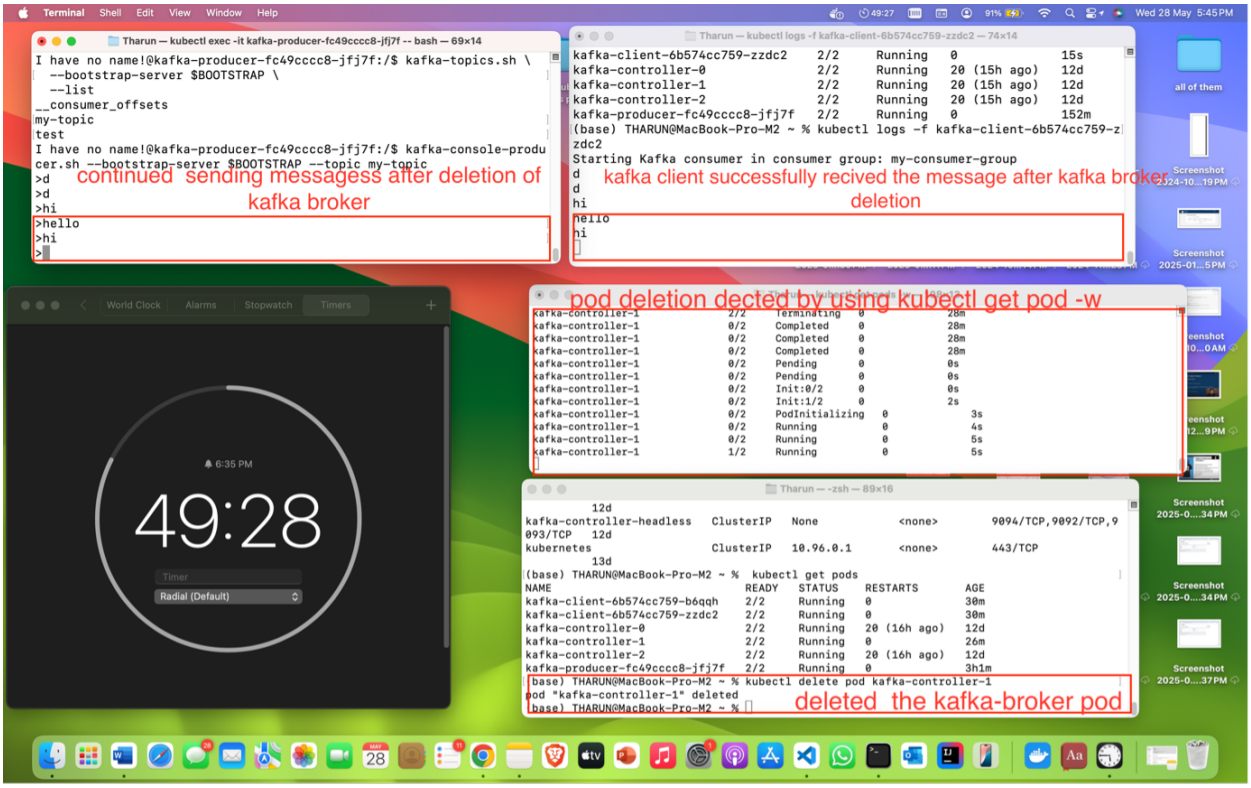
To validate the robustness, availability, and security of the Kafka-based microservice system, a live demonstration was conducted involving fault injection, security policy testing, and automatic certificate handling. Below are the scenarios showcased:

9.1 Fault Tolerance – Kafka Broker Failure

- A Kafka broker pod was manually deleted to simulate failure.
- Kafka's built-in replication and partitioning ensured that the cluster remained operational.
- Producers continued sending messages without errors.
- Consumers successfully received messages, proving no message loss or downtime.
- Kubernetes automatically respawned the deleted broker pod, validating cluster resiliency.



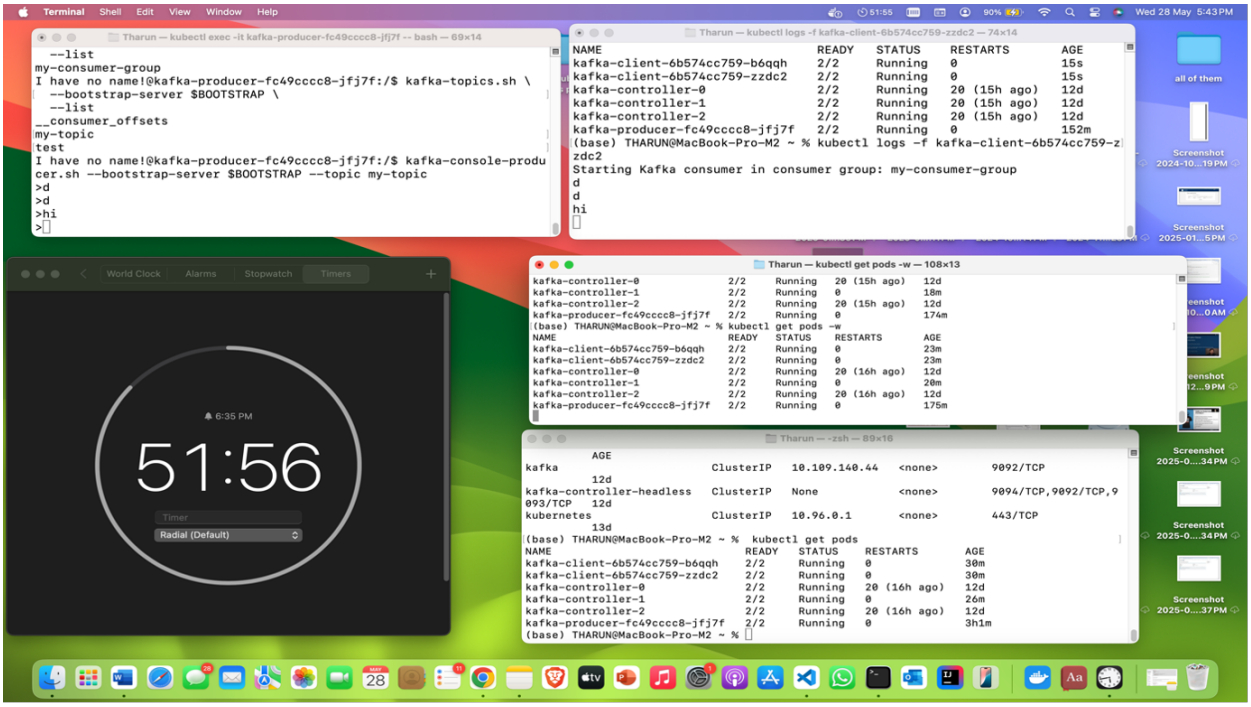
Before deleting the consumer pod



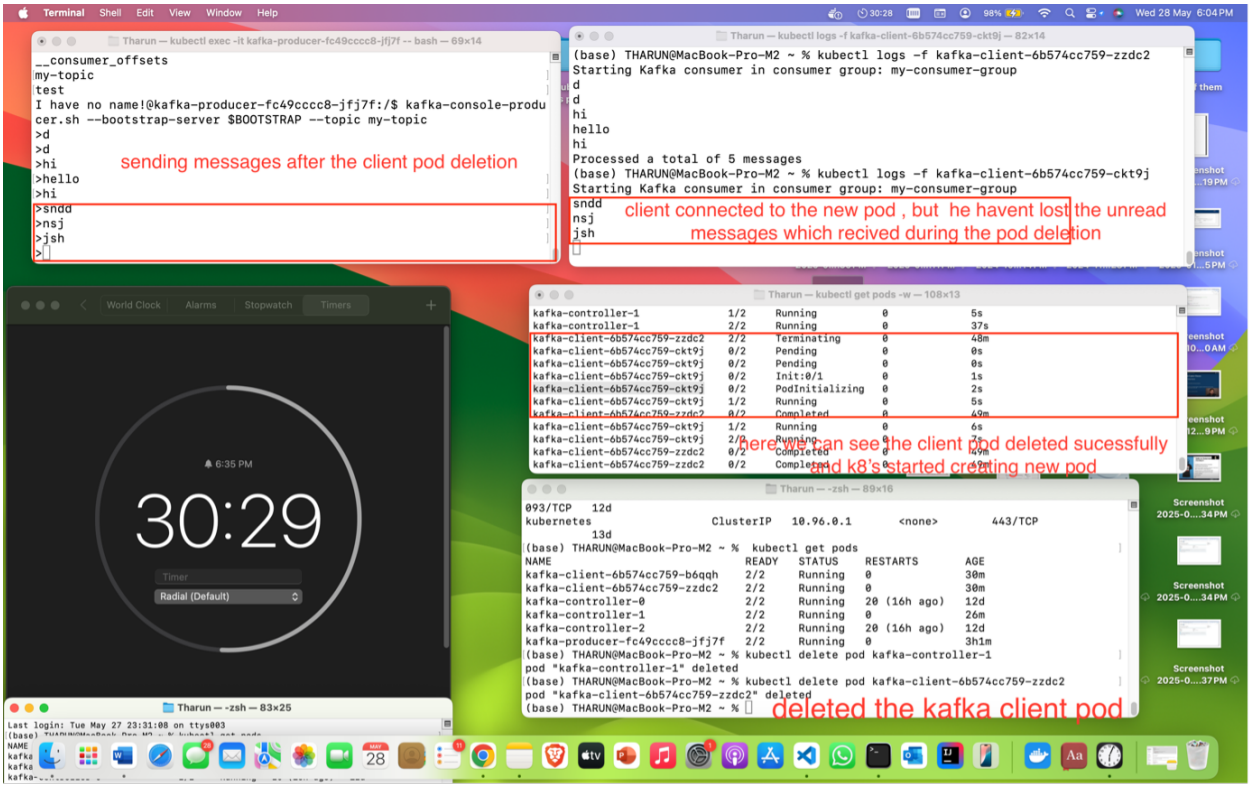
After deleting the consumer pod

9.2 Self-Healing – Consumer Pod Crash Recovery

- A Kafka consumer pod was deleted intentionally.
- Kubernetes immediately recreated the pod using the existing deployment definition.
- After restarting, the new consumer resumed message consumption without data loss.
- Kafka's durability and offset tracking allowed the consumer to continue from where it left off.



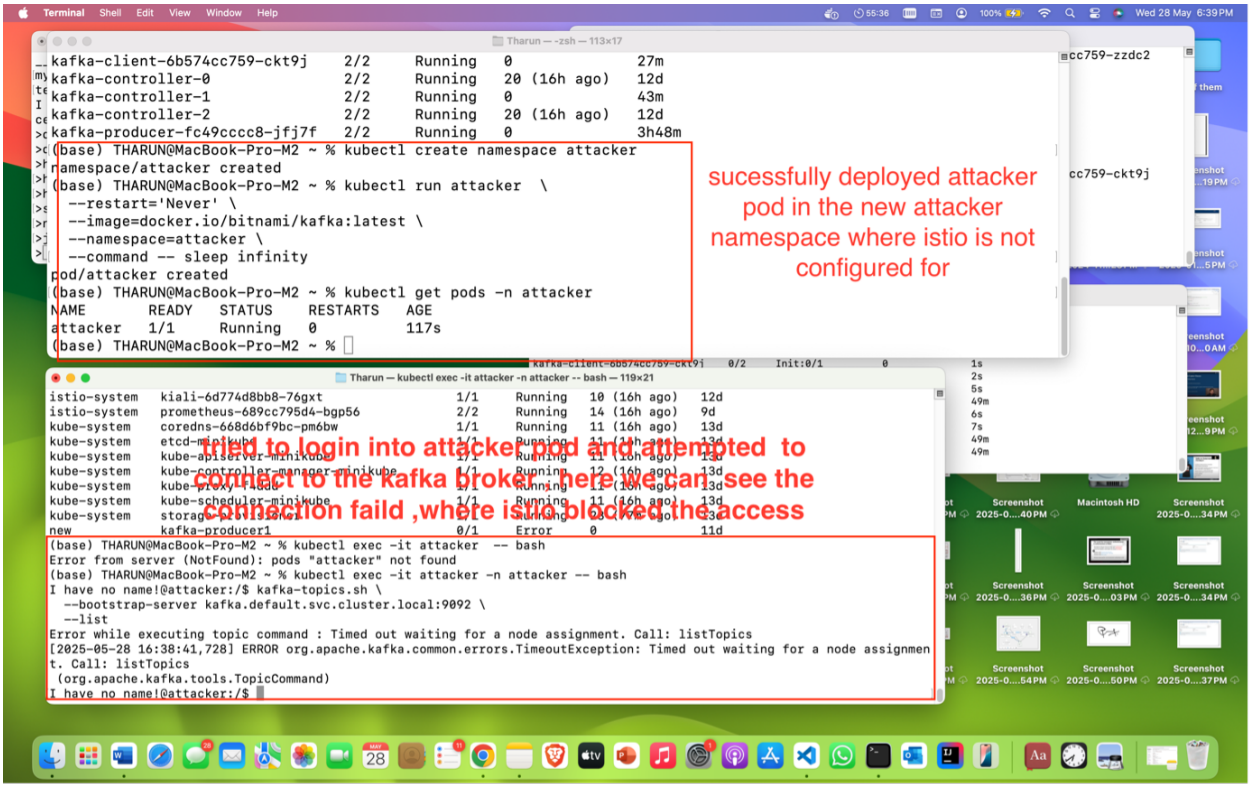
Before deleting the consumer pod



After deleting the consumer pod

9.3 Security Enforcement – Unauthorized Access Prevention

- A rogue pod named attacker was deployed to test unauthorized access attempts.
- An Istio AuthorizationPolicy was configured to allow only authenticated service accounts to interact with the producer.
- When the attacker pod attempted to access the producer service, the connection was denied (403 error), confirming that Istio RBAC and mTLS policies were effectively enforced. Screenshot of this demonstration lunching the attacker pod and trying to access the Kafka-broker



Launching the attacker pod and trying to access the Kafka-broker

10 Conclusion

The project demonstrated how Kafka, when deployed on Kubernetes with proper architectural choices, can meet the rigorous non-functional requirements of modern distributed systems. The integration with Istio simplified security enforcement, and the use of Raft protocol, PVCs, and Helm ensured system robustness, availability, and resilience. This solution offers a production-ready Kafka microservices architecture capable of secure communication, real-time data streaming, and resilient behavior under adverse conditions.

Project Repository: `https://github.com/BandaTharun/Secure-and-Resilient-Kafka-Based-Mess`