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Enhancing Observability and Reliability in Wireless Networks with Service Mesh Technologies

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Abstract: *In the ever-changing evolution of wireless networks, it is always challenging to maintain the reliability of the networks and also its ability to support important applications. This paper examines the possibility of using service mesh technologies such as Istio and Linkerd to handle these challenges by improving media resilience and observability. Service meshes add a strong fundamental layer that aids in the communication between services and can include services such as load balancing, service discovery, traffic management and failure containment. Metrics, logs, and traces help reduce network traffic, are crucial for real-time decision-making and compensate for wireless intricacies such as signal fading or mobility as well as power limitations. This research introduces a fresh approach to utilizing service mesh solutions for enhancing and strengthening wireless networks, providing a much-needed guide on the effectiveness of these tools in contemporary network settings.*

Keywords: Service Mesh, Wireless Networks, Reliability, Observability, Linkerd, Security

I. INTRODUCTION

In microservice architectures, a service mesh is another layer of structure that enables managing these microservices interactions and ensuring the delivery of requests across the service graph. There is no strict rule of splitting but notably, the service mesh is often conceptualized into two layers known as control plane and data plane. Modern proxies like Istio and Linkerd offer the framework required for reliability and communication between microservices [1].

Software system dependability is defined as the capacity to operate without failure when subjected to expected loads. High reliability can be gotten by design and test along with the continuous monitoring of the system[2]. Real-time supervision ensures that before the manifestation of significant problems, organizational systems can be diagnosed to determine whether they are healthy and constantly stable or not[3].

To address the issue of faults spreading to an application level, service mesh solutions such as Istio and Linkerd work with 'sidecars' that track microservice performance for failure and slowness. These sidecars perform fault correction actions like shedding off or bypassing the faulty microservices and only ensure the architecture of the entire application is stable[4].

Wireless communication has the highest stakes in certain applications, such as in industries and automobiles; reliability is paramount [5]. These applications usually view 5 minutes of unavailability annually as sufficiently acceptable, which corresponds to 99.999% reliability. Reliability is not only important at the beginning of the use but is important to check it recurrently to increase the chance of not going through expensive breakdowns[6].

A. Motivation and Contribution of the Study

The motivation for this study lies in the need for reliable and observable wireless networks to support critical applications where downtime is unacceptable. Istio and Linkerd provide solutions by handling communication between a set of services, proactively measuring system health, and embedding the capacity to self-recover from faults. This paper explores their potential to enhance reliability and observability in wireless networks, meeting stringent operational demands. Key contributions include:

- Introduces the concept of service mesh as a solution for managing service-to-service communication in cloud-native applications.
- Emphasises load balancing, authentication, circuit breaking, service discovery, traffic monitoring, and other critical characteristics of the service mesh.
- Provides an overview of the service mesh design with an emphasis on the control plane (administration and policy enforcement) and the data plane (sidecar proxies).
- Mobility, signal attenuation, power supply, data rates, security, and quality of service are among the issues discussed in this section with regard to wireless networks..
- Explores how service mesh improves wireless network reliability through traffic management, load balancing, circuit breaking, and observability.

B. Structure of the paper

The structure of this paper is as follows: Section II provides an overview of service mesh technologies and their role in modern networks; Section III explores the Challenges and requirements of wireless networks; Section IV discusses observability improvements in wireless networks enabled by service mesh frameworks; Section V presents a comparative analysis of popular service mesh frameworks and their applicability to wireless networks; Section VI reviews relevant literature and case studies; and Section VII offers conclusions and suggestions for future research directions.

II. OVERVIEW OF SERVICE MESH TECHNOLOGIES

An infrastructure layer specifically designed to manage communication between services is known as a service mesh. Its job is to ensure that requests are reliably sent via the intricate network of services that make up a contemporary, cloud-native app. The service mesh is usually put into action by deploying a series of small network proxies containing application code. In this way, the application doesn't even have to be aware that the mesh is there [7][8].

The two logical components of a service mesh architecture are the data plane and the control plane. A group of smart proxies, usually used as sidecars, make up the data plane [9]. These proxies act as middlemen and regulate the flow of data between microservices on the network [10]. Discovering services, assessing their health, routing them, balancing their loads, authenticating and authorizing users, and maintaining visibility into all network packets are the primary functions of the data plane. In order to route traffic, the control plane oversees and sets up the proxies. In order to gather telemetry and enforce regulations, the control plane also configures the appropriate components. In a service mesh, the control plane is like the central nervous system. It is not necessary to be able to see the network traffic for it to operate[11].

A. Fundamental Features

The paper in question explains and elaborates upon the many basic aspects that service mesh is intended to provide. These are only a few of the most popular features:

- **Service Discovery:** Microservice systems are dynamic, meaning that the quantity and placement of services are always evolving. A significant difficulty to be handling production quality applications is, therefore, tooling to find the service and their location[12]. The usual method for finding service instances is to monitor a register that records the addition and removal of services [13].
- **Load balancing:** The capacity to route traffic across networks is the primary focus of this feature. Topics like as latency and the instance's state (e.g., health status and current variable load) are also addressed, in contrast to basic routing mechanisms like round robin and random routing[14]. Additionally, programmers have the option to include their own logic into the network via the use of a set of custom filters [15].
- **Traffic monitoring:** Volumes per target, latency measurements, success and error rates, and every other kind of communication should be recorded and reported [16]. Famed projects from the Cloud Native Computing

Foundation, such as Grafana and Prometheus, are mostly used for this purpose and are compatible with the majority of service meshes.

- **Authentication and access control:** This feature enables services to identify the host from which an incoming request originated or selectively allow requests that fit the rules provided in a network filter to pass through the gateway. Disabling requests from unauthenticated services is another important step[17].
- **Circuit Breaking:** If an overloaded service is being accessed via an unexpectedly late request, a service mesh will stop the service from entering a broker state and will deny the request from ever reaching the gateway[18].

B. Service Mesh Architecture

Managing communication between microservices is the responsibility of the application infrastructure layer known as service mesh, which sits atop the microservice architecture. It consists of a control plane and a data plane as a layer. As a concept, service mesh lacks a universally accepted description that details all of its constituent parts [19]. The parts that are used and approved by the research and software groups are detailed below.

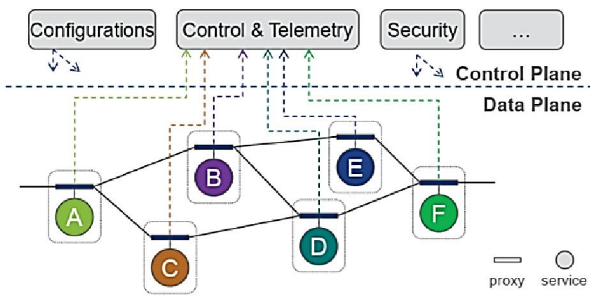

Fig. 1. Service Mesh Architecture

The various parts of the service mesh are shown in Figure 1. Each of the control and data planes proposes the following broad components.

- **Data plane:** The "sidecar" proxy is the primary part of the data plane. The services to which these proxies are bound remain unaware of their deployment; it sit independently alongside all service components. The control plane might manage the service mesh using these proxies[20].
- **Control plane:** Governance, policymaking, and configuration management are all responsibilities of the control plane [21]. Further, authentication and authorization services are provided by the control plane to provide safe communication between microservices.

C. Service Mesh Frameworks

Service mesh frameworks are designed to manage the complexities of microservices communication by providing features like service discovery, traffic routing, observability, and security[22]. Below are some of the most popular service mesh frameworks:

- **Linkerd:** The CNCF has distributed an open-source Kubernetes service mesh with an Apache v2 license. With its data plane and control plane architecture, Linkerd is comparable to Istio. To automate traffic management, it deploys transparent proxies within each Pod. Since Linkerd2-proxy is its own lightweight micro-proxy and not Envoy, it differs from Istio[23].
- **Istio:** An open-source service mesh based on Envoy that has gained widespread use. The control plane handles proxy management and traffic routing, whereas the data plane contains sidecar proxies that are based on Envoy. Featuring cutting-edge capabilities, including extensive analytics, it was the pioneering Kubernetes-native solution[24].
- **Cilium:** An open-source initiative designed to integrate with container orchestration technologies such as Kubernetes. By removing the need for sidecars altogether, Cilium's service mesh differs from those of Istio and Linkerd. It uses eBPF to move the handling of proxy containers from each pod to the host and kernel[25].

III. WIRELESS NETWORKS: CHALLENGES AND REQUIREMENTS

Computer networks that link their nodes over wireless data links are known as wireless networks. Wireless networks have seen meteoric expansion in recent years, much as the internet did in the previous decade. There has been and will be exponential growth in the wireless communication industry, particularly in the cellular phone, internet, and home networking sectors [26]. The introduction of Wireless LAN (WLAN) technology allowed computer networks to communicate with a practical bandwidth without relying on wall outlets [27]. Another option is to utilize a WPAN, which allows users to connect devices in a limited space that is typically within human reach. For instance, a WPAN that combines Bluetooth radio with invisible infrared light may link a laptop and a headset[28]. Figure 2 depicts the wireless networks is given below below:

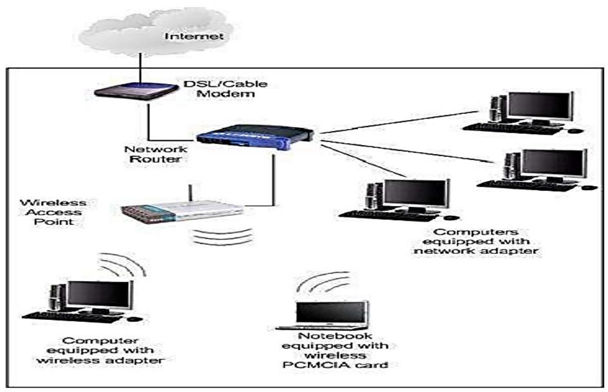

Fig. 2. Wireless Networks

A. Challenges of Wireless Network

Data rate increases, minimising size, cost, low power networking, user security, and QoS are some of the fundamental problems in wireless networks, which are inherently constrained by the physical requirements of wireless devices and the bandwidth limitations of wireless networks.

1. Signal Fading

Since wireless media travel across an open, unprotected, dynamic medium with uneven boundaries, signals may be distorted or weakened in comparison to wired media [29]. Even before it reaches the receiver, the signal could be scattered and diverted in many ways as a result of reflection, diffraction, and obstructions [30].

2. Mobility

All devices in a wireless network are unrestricted in their movement since that are not connected to each other by wires. Maintaining a connection when a user moves about is essential for mobility support. When a mobile host transitions from one base station's or access point's service area to another, this is called a handoff in an infrastructure network [31]. Therefore, a procedure is necessary to guarantee a smooth handoff. This involves making decisions about the timing of handoffs and the routing of data during them.

3. Power and Energy

Although a mobile device is often portable, compact, and designed to carry out a certain set of tasks, its power supply may not be as capable of providing as much power as one placed in a permanent device [32]. It is sometimes difficult to get a constant source of power when a device is free to move about.

4. Data Rate

If multimedia services are to be offered, it is absolutely necessary to enhance the existing data rates in order to accommodate future high-speed applications. Several variables determine the data rate, including the data transmission protocol, power regulation, interference mitigation via error-resistant coding, and data compression algorithms [33][34].

5. Security

Particularly for mobile and online purchases, wireless network security is an important consideration. A wireless network's security is heightened when users are mobile. Authentication and data encryption on the air interface are methods used by current wireless networks to ensure user security.

6. Quality of Service (QoS)

A metric used to assess network performance, QoS takes into account both service availability and transmission quality. QoS may be defined by four factors for every network traffic flow: Bandwidth, Delay, Jitter, and Reliability [35]. A few key features of wireless networks include handoff, dynamic connections, and the ability to activate transport quality of service. When switching between wireless networks, a phenomenon known as handoff may cause connections to momentarily drop[30].

B. Benefits of Wireless Network

These are some important benefits of wireless networks are as follows:

- **Convenience:** Anything within the range of the wireless network, or even a public Wi-Fi hotspot, will provide us access to the network's resources.
- **Mobility:** You and your staff may now have virtual meetings in public spaces, freeing you from the constraints of a desk-bound, wired connection [36].
- **Productivity:** Wireless Internet connection, together with your company's critical apps and resources, boosts productivity and teamwork.
- **Easy setup:** The installation process may be efficient and economical since wires do not need to be strung.
- **Expandable:** In contrast to wired networks, which may need the installation of new cables, wireless networks may be readily expanded using preexisting hardware.
- **Security:** Improvements in wireless networks have resulted in more powerful security measures [37].
- **Cost:** Generally, wireless networks may entail lower operating costs than wired networks, whereby wiring costs may be eliminated or reduced [38].

IV. ENHANCING OBSERVABILITY IN WIRELESS NETWORKS

Maintainability is another important characteristic of controlling and supporting wireless networks since it reveals how the components and components of a system interact with each other when integrated. Due to its seamless ability to gather and analyze telemetry data, service mesh has become an important component of contemporary network management's focus on observability [39].

A. Role of Service Mesh in Real-Time Monitoring

Monitoring distributed systems is the continuous process of collecting, processing, aggregating, and displaying quantitative data and is an essential component in detecting and debugging possible faults in the system [40]. Monitoring can be applied at different levels in the system and with different purposes. Monitoring can be divided into two categories: white-box and black-box monitoring. White-box monitoring is the metrics exposed by the system itself, which are often the metrics used to detect problems and failures.

An infrastructural layer that oversees communication between services is a service mesh. It inherently includes capabilities for real-time monitoring by intercepting all network traffic between services[41]. This interception provides the opportunity for the service mesh to collect metrics about requests, including their rates of latency, errors, and volume, which are useful for understanding the behavior of an application without having to make changes to its source code. Tools like Istio and Linkerd are service meshes that work hand in hand with other tools for observation, simplifying how network administrators check profile metrics and signs of instability.

B. Metrics, Logs, and Tracing with Service Mesh

People typically prefer to use a service mesh because of its observability, which plays a crucial role in "debugging" and other aspects of the architecture. Service meshes enhance observability by providing a unified framework for collecting and managing the three pillars of observability:

- **Metrics:** A system, service, or network component's overall behavior over time may be understood by looking at its metrics, which are numerical representations of data used by operations teams. Metrics like as error rate, latency, and traffic volume allow one to track the service mesh's overall health[42]. Automatically get the data you need for fundamental network measurements with the help of Envoy proxies.
- **Logs:** In a service mesh, logging is restricted to network traffic since it would be required to modify the microservice itself otherwise. Logs reveal erratic and emergent behaviors exhibited by microservices components[43][44]. It signify varying degrees of seriousness and is simple to create.
- **Tracing:** The ability to trace requests as they go through various services allows administrators to identify faults and bottlenecks with pinpoint accuracy. As a request or action travels through a distributed system, its whole trip is shown by traces[45]. Although metrics and logs are great for analyzing the performance and behavior of a single system, they don't always shed light on the request lifecycle in a distributed IT system[46].

V. ENHANCING RELIABILITY IN WIRELESS NETWORKS WITH SERVICE MESH

Enhancing reliability in wireless networks with a service mesh involves using a distributed networking framework to improve communication, scalability, and fault tolerance across devices and applications. The applications and nature of the network dictate the reliability metrics for wireless networks. It is clearly communication problems that satisfy certain connection requirements for a telecommunications network[47]. The sensor network, on the other hand, is concerned with data collection, processing, and transmission in order to fulfill connection and coverage requirements. The availability of a network to provide the intended accommodation to the cessation user is at the heart of any reliability metric. It is possible to describe or quantify a network's dependability using a variety of criteria.

A. Service Mesh Contributions to Improving Reliability

A service mesh enhances the reliability of wireless networks by introducing advanced mechanisms to manage service-to-service communication, traffic flow, and fault tolerance[48]. Its contributions to improving reliability can be explained through the following key mechanisms:

1. Traffic Management

- **Dynamic Routing:** Service meshes allow dynamic traffic routing, ensuring that requests are routed to healthy instances of services. This minimizes the impact of failures.
- **Load Balancing:** Built-in load balancing distributes requests evenly among service instances, avoiding overloading a single instance. It monitors and distributes the requests evenly over the service instances in order to avoid a service instance overload. Such approaches as round-robin, weighted, or least-connection guarantee efficiency of resource application[4].
- **Circuit Breaking:** Service meshes implement circuit breaker patterns to prevent cascading failures. If a service is unresponsive, the mesh can block further requests to it. The introduction of circuit breaker patterns was a response to the need to strengthen software stack resilience and manage run-time failure in microservice applications [49]. For instance, if there are more than 20 pending requests, the system will produce an HTTP 503 error message because the circuit breaker pattern has been activated[50].

2. Monitoring and Observability

- Service mesh can connect with tools such as metrics, logging, and tracing to get the real-time result of the network.
- Such proactive monitoring helps network operators to counter-check areas that may cause inconvenience to the user [51].

- The Metrics Collection gathers such data points as latency or outfacing error ratios with the aim of monitoring and addressing problems at an early stage [6].

VI. LITERATURE REVIEW

This section provides a review of literature on the use of service mesh technologies for improving reliability and observability in wireless networks. The review focuses on their application to achieve scalable, fault-tolerant, and highly observable network architectures. Additionally, the key findings are summarized in Table I for clarity and comparison.

Hu, Cai and Pan (2021) use a novel method to determine the dependability of the mesh network; this method outperforms the state-of-the-art in terms of both computing cost and scalability. The HSA is used to derive the closed-form network reliability, which is a polynomial representation of link reliability, from a Markov model. Additionally, they provide two measures to aid in the selection of network connections for routing in order to guarantee performance while minimizing link cost. Results from analyses and simulations show that URLL services may benefit by investigating route variety[52].

Chen et al. (2019) provide three methods for designing networks that adhere to the tenets of minimum router traffic, shortest hops, and a combination of the two. Then, for each specified factory architecture, they build the network deployment by implementing the suggested methods. Evident from the simulation findings is the existence of a performance trade-off among these three methods. In addition, a simulator for NS-2 Wireless HART networks has been used to construct and evaluate the provided algorithms. investigate industrial wireless mesh networks with a focus on great dependability, minimal latency, and economical network design[53].

Duong and Kim (2023) suggest a 5G core network that use the Cillium CNI plugin that is based on the Service Mesh. If implemented, Service Mesh might make the 5G Core (5GC) network more secure and easier to monitor. The suggested architecture enhances the 5Gc network's Service Mesh performance with the help of the Cillium. A comparison is made between the suggested design and the standard design based on qualitative features[54].

Alboqmi, Jahan and Gamble (2022) Integrate a security assurance case into the architecture of a service mesh evaluation component; use it to establish the threat model and conduct dynamic application assessments in response to new or changed environmental conditions. Istio is an open-source service mesh platform that they test out with a sample app called Book info to make it self-protecting. They treat some of the service request parameters as if they were external factors. They find the likelihood of breaching a security requirement for authorized and regulated information flow by comparing those parameters to the threat model[55].

Magaseng and Mathonsi (2023) intend to lessen the pressure on relays, increase network performance, and decrease end-to-end latency. They are striving for better gateway placement performance with their Rec-GT algorithm. Using the MATLAB platform, they will simulate and compare its performance to ensure its effectiveness in terms of network speed, end-to-end latency, and relay load. A mesh client, router, and gateway are the three main components of a wireless mesh network (WMN). Gateways act as routers connected to the Internet and are directly connected to wired infrastructure[56]

Table 1: Presents the summary of literature review based on wireless network with service mesh technologies

References	Focus On	Key Findings	Objectives	Challenges	Future Work
Hu, Cai, and Pan (2021)	Mesh network reliability using Hop-State Algorithm (HSA)	Lower computational cost and scalable approach; Polynomial expression for link reliability; Path diversity supports URLL services.	Derive a scalable and cost-efficient method to compute network reliability.	Balancing computational cost with scalability, ensuring path diversity for URLL services.	Extend the approach to support more complex network scenarios and dynamic link conditions.
Chen et al. (2019)	Network planning for industrial	Performance trade-off between shortest hops, least routers, and	Develop cost-effective and reliable network	Managing trade-offs among reliability	Explore additional optimization techniques for

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	wireless mesh networks	balanced planning; Validated using NS-2 simulator.	planning algorithms for industrial applications.	latency, and cost in network planning.	dynamic factory layouts and real-time scenarios.
Duong and Kim (2023)	Service Mesh in 5G Core networks using Cilium CNI plugin	Improved security and observability in 5GC; Enhanced performance of Service Mesh compared to traditional designs.	Design a secure and observable 5G Core network leveraging Service Mesh technology.	Integration challenges with existing 5G networks, ensuring seamless scalability.	Investigate broader Service Mesh applications in other 5G network components.
Alboqmi, Jahan, and Gamble (2022)	Security assurance in Service Mesh using Istio	Dynamic threat assessment; Self-protection enabled through environmental condition evaluation.	Design a dynamic security assurance mechanism within Service Mesh to address environment changes.	Adapting security models to rapidly changing environmental conditions.	Extend the approach to support diverse applications and complex threat models.
Magaseng and Mathonsi (2023)	Gateway positioning in Wireless Mesh Networks (WMNs)	Enhanced network throughput; Reduced end-to-end delay; Minimized relay load using Rec-GT algorithm.	Optimize gateway positioning to improve WMN performance.	Achieving balance between throughput, delay, and relay load.	Validate Rec-GT in real-world WMN deployments and explore hybrid gateway positioning methods.

VII. CONCLUSION AND FUTURE WORK

The integration of service mesh technologies into wireless networks presents a promising solution to enhance their reliability, performance, and management. In conclusion, service mesh technologies offer a promising solution to enhance the reliability, resilience, and observability of wireless networks, addressing key challenges such as signal fading, mobility, and power constraints. By providing a unified platform for managing network traffic and enabling real-time monitoring, service meshes can significantly improve service-to-service communication and fault tolerance. The integration of these technologies into wireless networks holds the potential to revolutionize network performance, ensuring high-quality communication for critical applications.

Future work will focus on further optimizing the service mesh framework to cater to the unique demands of wireless networks, such as dynamic topology and varying network conditions. Additionally, exploring the integration of advanced machine learning algorithms for traffic prediction, anomaly detection, and resource allocation will be crucial in enhancing the adaptive capabilities of service meshes. Further research is also needed to evaluate the scalability and performance of service mesh solutions in large-scale, real-world wireless network deployments, ensuring their feasibility and effectiveness across diverse use cases.

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