

Cybersecurity Architecture For Autonomous Telecommunication Networks

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Abstract

The development of telecommunication networks for highly autonomous operation in the 5G-Advanced and emerging 6G environment has brought fundamental cybersecurity challenges that cannot be sufficiently addressed by legacy perimeter-based security models. Autonomous networks are based on zero-touch provisioning, closed-loop control, intent-based management and artificial intelligence (AI)-assisted decision making; all of these factors vastly increase the attack surface and reduce the feasibility of human-in-the-loop security controls. In this context, cybersecurity requires being ingrained as a core architectural property and not as an external function or a reactionary function. This paper proposes a reference architecture for cybersecurity for autonomous telecommunication networks that will support high levels of autonomy, combining the principles of zero trust, artificial intelligence (AI)-native security intelligence, intent-aware policy enforcement, closed-loop security automation, and end-to-end observability and verification. The study uses a Design Science Research methodology and validates the proposed architecture using analytical reasoning, threat-control mapping, comparative analysis and standards alignment. The results show that the architecture offers complete threat coverage, enables autonomy Levels 4-5, and is in line with the up-and-coming telecom and cybersecurity frameworks. This work adds an organized architectural foundation for the security of next generation of autonomous telecommunication networks.

Keywords Autonomous Telecommunication Networks; Cybersecurity Architecture; Zero Trust; AI-Driven Security; 6G Networks.

1. Introduction

Telecommunication networks are experiencing a deep transformation from manually operated and centrally controlled telecommunication networks to highly autonomous self-managing telecommunication networks that can continue to operate with minimal or no human intervention. This transition is driven by the exponential growth in network scale, heterogeneity and service diversity together with growing performance and latency/reliability requirements. Traditional operational models which involve a large degree of human-driven configuration, monitoring and fault management are no longer sustainable in this rapidly evolving landscape. Comparable moves in the direction of autonomy have already taken place in other complex systems where system-level accountability and self-awareness have been found key to ensuring safe, resilient and dependable operation [1]. As the telecommunication networks move towards 5G - by Advanced and early 6G environments, autonomy is no longer a strategic enhancement, but a foundation to scalable, responsive, and efficient operation.

The shift to autonomous networking is facilitated by a number of architectural and technological developments, such as cloud native network functions, software-defined control planes, network slicing, and large-scale virtualization. These capabilities are used to support automation throughout the service lifecycle from provision, configuration, optimization, and assurance. As a result, modern telecom systems are increasingly developing towards zero-touch provisioning, closed-loop control and intent-driven management in order to create real-time adaptability. However, while these mechanisms are an additional step toward making operations more efficient, they also create new complexities and risks. Studies in the domain of autonomous cyber-physical and

distributed systems have shown that conventional security assumptions, such as static trust boundaries and predictable system behavior, no longer hold up when systems are able to configure themselves and make decisions on their own [2]. In such environments, security mechanisms will have to evolve along with autonomy as it's impossible to have human controls in the loop at the speed and scale needed to handle machine driven networks.

Legacy architectures for telecommunication security were developed for relatively static environments in which network topology and traffic patterns and service relationships slowly and predictably changed. These architectures are very perimeter-centric and reactive, based on predefined rules, signature-based detection and manual incident response processes. While effective in the previous generations of telecom networks, such approaches are becoming out of step with autonomous operation. Research in the area of autonomous systems has shown time and again that static security controls cannot cope with threats coming from dynamic system behavior, cross-domain interactions, and automated decision loops [3]. In autonomous networks security incidents can quickly spread through orchestration pipelines and control planes and often before human operators are aware of the threat, let alone able to intervene.

The increasing dependence on artificial intelligence and data-based intelligence in telecommunication also adds to these difficulties. AI-driven analytics and control mechanisms are now part of network optimization, and fault prediction and service assurance. However, the management systems enhanced by AI present new attack surfaces such as the manipulation of telemetry data, the poisoning of learning models, the exploitation of automated policy decisions and the adversarial interference with closed-loop control processes. Prior studies highlight the need for AI-based telecom systems to have security mechanisms that can understand the context of behavior and adapt to changing and evolving threats rather than solely static, rule-based systems to detect them [4]. Lack of such adaptive security features can make the autonomous security appear to enhance the cyber threats instead of enhancing the network performance aspects.

Going forward, future projections on 6G and next-generation autonomous networks continue to support the necessity of security conscious architecture developed concurrently with autonomy. Future networks are expected to support extreme densification, ultra low latency services, integrated terrestrial and non terrestrial and pervasive intelligence in the network fabric. In such environments, cybersecurity cannot be an external overlay or something that is considered after implementation. Research conducted in the field of autonomous and intelligent systems has shown that cybersecurity must be considered from the very beginning, i.e., implemented directly into the system architecture, instead of being tacked on after deployment, in order to ensure resilience, trustworthiness and safety of operation [5]. This is especially true of telecom systems, where control plane decisions can have consequences across the system.

Recent developed AI-based cybersecurity models for the autonomous domains frequently emphasize the need to integrate the detection, decision-making, and response in the same control model. These models propose that in order to provide effective security for autonomous systems, tight coupling between sensing, analysis, and enforcement mechanisms is necessary so that timely and coordinated responses to developing threats can be made [6]. However, many of these contributions are still conceptual or domain-specific contributions dealing with specific classes of autonomous systems rather than large scale, multi-domain telecommunication networks.

Despite the recent awareness of the issues of autonomy with respect to cybersecurity, much of the literature to date has been disconnected and domain-specific. A great deal of work is done in the area of autonomous vehicles, robotics, or in isolated cyber-physical systems. While these are important studies in providing insights into the principles of

cybersecurity-by-design and the importance of security integration into system architectures [7], they do not completely address the unique characteristics of telecommunication networks. Telecom systems have a multi-administrative-domain, multi-service-type network with all types of network slicing and are based on complex interactions between OSS, BSS, orchestration platforms and service-based control planes. These characteristics present security challenges that are different in both scale and complexity from those faced in other areas of autonomy.

Furthermore, many of the existing studies focus on vulnerability analysis and threat enumeration which often aim at specific attack vectors or individual components. While such analyses are important, they often fall short of outlining holistic architectural resolutions that can help address security challenges throughout the lifecycle of the autonomous network as a whole. Research exploring the susceptibility of cybersecurity in autonomous environments points to this imbalance, stating that defensive methods are also reactive and localized, as opposed to systemic and architectural in nature [8]. As a result, the security controls may address individual threats, they may fail to address the underlying architectural weakness that is enabling the threat to emerge.

More recent research on AI assisted cybersecurity guarantee stresses the importance of system-level frameworks that can think about autonomy, risk, and verification in an integrated fashion. These approaches put emphasis on the importance of continuous assurance, where security decisions are not only automated but also checked and auditable [9]. Such capabilities are especially important in the case of autonomous telecom networks where regulatory compliance, service level guarantees and cross-domain trust relationships must be maintained at a time where control decisions are delegated to machines.

Despite these advances, comprehensive reference architectures with focused emphasis on autonomous telecommunication networks do not exist in large numbers. Surveys of autonomous cybersecurity research have repeatedly observed that lack of architecture-centric guidance is a major missing element in the field [10], whereby many proposed solutions address a single mechanism and not a comprehensive architectural design. This gap grows larger the higher the level of autonomy telecom networks are seeking, where isolated security controls are inadequate to handle systemic risk.

Similar observations have been made in the other large-scale autonomous domains such as the maritime and transportation domain, where the lack of common security architectures has impeded safe deployment and certification at higher levels of autonomy [11]. These domains share a few features with telecommunication networks, such as distributed control and safety and high regulation. Experiences in these areas imply that to attain credible autonomy, it is important that clearly outlined architectural bases are involved that clearly unite security, governments, and audits.

Recent evaluations of autonomous system cybersecurity preparedness are additional indications of the urgency of the challenge. Studies assessing the readiness of autonomous platforms have always led to the conclusion that current security strategies do not suffice for the full self-driving operation, especially in an environment with a high level of complexity and dynamic behavior [12]. These results highlight the importance of developing novel architecture models that make cybersecurity a fundamental enabler of autonomy and not a secondary consideration.

1.1 Research Objectives

Based on the identified research gaps and the architectural focus of this study, the specific objectives of this research are as follows:

- To identify and formalize the cybersecurity requirements of autonomous telecommunication networks.

- To design a reference cybersecurity architecture tailored for autonomous telecommunication networks.
- To integrate zero-trust principles, AI-native security intelligence, and intent-aware policy enforcement within a unified architectural framework.
- To incorporate closed-loop security automation and end-to-end observability as foundational architectural capabilities.
- To analytically validate the proposed architecture against autonomy-driven security requirements and threat scenarios.
- To align the proposed cybersecurity architecture with existing telecom and autonomy standards while addressing their limitations.

2. Background and Related Work

The development of telecommunication networks towards autonomous operation requires a re-evaluation of the current cybersecurity concepts, models, and architectures. While a lot of research has been done in cybersecurity in 5G networks, autonomous systems and other cyber-physical domains, these areas of research are still very fragmented. This section is meant to review relevant background and previous research within the fields of telecommunications, autonomous systems, and elsewhere in the interest of putting the need for a dedicated cybersecurity architecture for autonomous telecommunication networks in perspective.

2.1 Cybersecurity in 5G and Emerging Telecom Architectures

The migration to 5G has seen the fundamental architectural building blocks for telecommunication networks changed with cloud-native design and service-based interfaces, virtualization, and extensive API exposure. Security analyses of global 5G architectures stress that these changes are creating new threat surfaces in the key areas of core, edge and management domains, especially in the signaling, network slicing and orchestration workflows [13]. Traditional security mechanisms have been built for tightly coupled and static infrastructures and are challenged to deal with the distributed and dynamic nature of modern telecom environments.

While 5G security frameworks establish mechanisms for authentication, authorization, and encryption at the level of individual network functions, they assume, for the most part, the supervision of humans who operate the network and establish static trust relationships. As networks start to move towards higher degrees of automation and autonomy, these assumptions become invalid. Existing studies call attention to the need for 5G security considerations to go beyond function-level security to system-level system resilience and continuous assurance, particularly because control decisions will become automated. However, current telecom-focused literature stops short in general of proposing holistic cybersecurity architectures that are explicitly focused on autonomous operation.

2.2 Cybersecurity in Autonomous and Connected Systems

A considerable amount of research has been conducted on cybersecurity challenges facing autonomous and connected systems, specifically the field of connected and autonomous vehicles (CAVs). Surveys in this domain identify a wide range of threats, including propagation of malware, spoofing, data manipulation and unauthorised control, all exacerbated due to automation and connectivity [14]. Comparative studies of the automotive electronics and electrical architectures also confirm that a higher degree of autonomy and intelligence changes the security requirements fundamentally: the focus of security changes from component-level protection to system-wide trust and coordination [15].

Research dealing with resilience to malware and the mitigation of attacks in autonomous environments emphasises the limitations of reactive and rule-based defence strategies, and calls for the adoption of adaptive and intelligent security mechanisms [16]. This view is supported by wider scans of related and automated transportation systems that mention autonomy presents closely coupled relationships among sensing, decision-making and actuation that needs hasty security approaches [17].

Despite their relevance, these studies are still very domain-specific and focus on vehicles or transportation infrastructures rather than on large-scale communication networks. While these give valuable insights into security issues related to autonomy, they do not fully address telecom-specific characteristics such as multi-operator coordination, network slicing, service-based control planes and large-scale orchestration. As a result their applicability to autonomous telecommunication networks is limited..

2.3 Architecture-Centric Cybersecurity in Distributed and Autonomous Domains

Beyond transportation systems, architecture-centric cybersecurity research has been developed in areas such as industrial Internet of Things (IIoT), critical infrastructures and distributed cyber-physical systems. Studies in IIoT security highlight the importance of architectural models that integrate security at the device, communication and management layers of a heterogeneous system [18].

These works draw attention to the fact that security cannot be successfully retrofitted onto complex autonomous systems but has to be part of architectural design. Other studies on data-driven and AI-enabled security also highlight the increased importance of analytics and automation in the protection of autonomous systems [19]. This group of methods can show how effective behavioral analysis and cross-domain correlation can be but also recognize issues of trust, explainability, and governance. Systematic reviews of autonomous response systems in cybersecurity also make the same point, that while automation can dramatically improve response time, it is necessary to be guided by strong architectural frameworks to avoid unintended consequences [20].

Further surveys on the topic of cybersecurity and digital forensics in autonomous systems also involve the challenge of ensuring accountability and traceability in autonomous decisions [21]. Roadmaps for autonomous system security all seem to call for integrated architectures involving combinations of detection, response, verification, and governance, not isolated tools or mechanisms [22].

Related issues have also been found in other large-scale autonomous areas, such as maritime autonomous surface ship [23] and satellite communication system [24]. Such studies highlight that distributed control, safety critical operations and cross domain coordination creates systemic security threats which cannot be attributed to localized defenses. Importantly, they point to a lack of unity in cybersecurity architectures that are aware of autonomy as a key barrier to safe deployment.

2.4 Research Gap and Motivation

In telecommunications, autonomous vehicles, industrial systems, maritime platforms, and satellite networks, available studies are consistent in identifying autonomy as a multiplier of cybersecurity threat. However, much of the existing work is threat-analysis based, component-based, or domain-specific. Comprehensive, architecture-centric cybersecurity models that explicitly address the needs of autonomous telecommunication networks are still very few.

In particular, current literature lacks:

- Reference architectures that integrate zero trust, AI-driven intelligence, intent-aware policy enforcement, and closed-loop automation at a system level

- Security models designed explicitly for high autonomy levels with minimal human oversight
- Unified architectural approaches that span management, control, and network domains in telecom environments

These gaps provide an impetus to developing a dedicated cybersecurity architecture that can recognize security as an integral enabler of autonomous telecommunication networks rather than a sideshow. The next sections build on this background to define autonomy driven security requirements and a reference architecture to address these challenges.

3. Security Requirements for Autonomous Telecommunication Networks

The move to autonomous telecommunication networks changes the security problem space fundamentally. In contexts where the network functions are dynamically instantiated, the policies are enforced programmatically and the operational decisions are executed without human intervention, cybersecurity can no longer be considered as an outside control layer or a post-deployment addition. Instead, security requirements need to be built into the autonomy's architectural structures themselves. Autonomous telecom networks - especially those for 5G-Advanced and early 6G deployments use closed-loop control systems from provisioning, orchestration, assurance to optimisation. These systems are based on continuous telemetry, AI-drive analytics and intent-based management to help to achieve the real-time adaptability. As a result, security mechanisms need to be equally fast, scale and autonomous in terms of performance; with tight guarantees in terms of trust, integrity, and resilience. Traditional security requirements based on static trust boundaries, manual supervision and reactive incident handling are not sufficient in such environments.

Autonomous networks bring new types of risks such as compromised control loop, poisoned learning models, or unaligned intents, lateral attack propagation between cloud-native microservices, etc. To deal with these risks, it is important to revise the security requirements so that they distinctly consider the autonomy, automation of decision making, and continuous reconfiguration. This section establishes the basic security requirements for any cybersecurity architecture for autonomous telecommunication networks. These requirements are based on the operational characteristics of zero touch networks and are based on emerging industry guidelines from standards bodies such as ETSI, TM Forum and 3GPP. Together, they provide the design constraints and functional expectations that are used to develop the proposed architecture, later in this paper.

3.1 Zero-Trust by Design

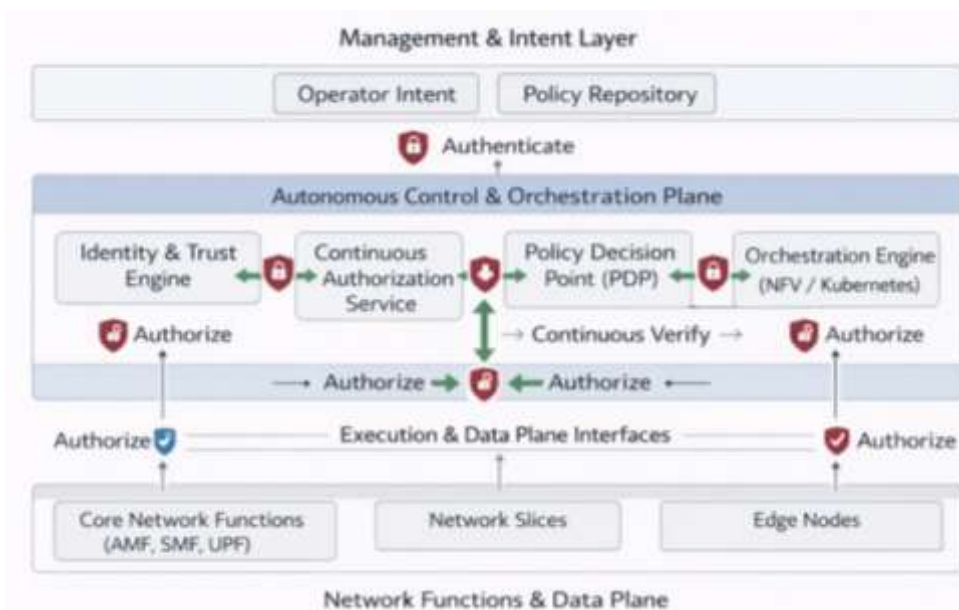
Zero-trust by design is also a basic requirement for autonomous telecommunication networks for which implicit trust assumptions are not safe to hold. In cloud native, service based architectures, network functions, microservices, APIs and orchestration components dynamically interact in distributed environments. In such situations, trust is something that must be constantly created, not just something that is taken for granted. A zero trust security model dictates that activities must be explicitly authenticated, authorized and contextual validations must be performed for every entity (human or machine) with every interaction. This principle goes beyond the user access, and includes network functions, orchestration workflows, provisioning transactions, and inter-domain interfaces.

Autonomous networks thus increase the importance of this requirement, since actions taken by the machine can happen at sub-second time frames without validating the actions by a human. Zero-trust by design in the telecom control plane means that all control-plane interfaces are identity-first interfaces, control-plane transactions are continuously authorised, and the execution is limited to least privilege. Each provisioning/

configuration action needs to be evaluated against the context of current identity posture, behavioral history and policy intent before it is allowed to proceed.

Unlike approaches that focus on perimeter, zero trust architectures assume that breaches are inevitable and focus on limiting blast radius and preventing lateral movement. This is especially important in an autonomous environment where if one part goes wrong, it could then affect more than one closed-loop decision. This can make autonomous networks more resilient by ensuring that they can persist when under partial compromise by forcefully implementing the concept of zero-trust directly into control planes and orchestration layers. The implementation of zero-trust protection within service-based interactions and orchestration workflows of control-plane in autonomous telecom worlds is shown in Figure 1.

Figure 1: Zero-Trust Enforcement Across Autonomous Telecom Control Planes



3.2 AI-Driven Threat Detection and Prediction

Autonomous telecommunication networks need security mechanisms that can operate at machine speed and adapt to ever changing system states. The environments that have dynamic, orchestrated network topology, service composition, and traffic patterns cannot be adequately defended with static, rule based controls. As a result, AI powered threat detection and prediction becomes a fundamental security requirement rather than an optional security enhancement.

To provide AI-native security in autonomous networks, machine learning and advanced analytics are used to define behavioral baselines in various fields, which include: control-plane signaling, provisioning workflows, API interactions and slice-level traffic patterns. Through standard operation behavior, AI-based systems are able to identify anomalies which may be signs of misconfiguration, insider threats, horizontal movement or even early-stage attacks by cybercriminals who might otherwise slip past signature-based detection systems.

Apart from reactive anomaly detection, autonomous telecom security architectures need to facilitate predictive threat modeling. Predictive capabilities allow to spot the attack precursors, e.g., anomalous orchestration sequences, anomalous intent translations, gradual privilege escalation, before the service is degraded or compromised. This

prospective stance is especially important in closed-loop systems where the delay in detection can result in the malicious behavior spreading into automated decision processes.

AI-driven threat detection must also be holistic over what are traditionally siloed domains. Autonomous networks blur the lines between OSS, BSS, orchestration platforms and network functions and need security intelligence that can correlate telemetry from these layers. Localized detections should not be done without a cross-domain view and correlation, as they might not be able to identify system-wide attack patterns or a coordinated adversarial behavior.

Importantly, however, AI-driven security in autonomous telecom networks is not centralized analytics. To meet the latency requirements, scalability requirements, and resilience requirements, threat detection capabilities must distribute its capabilities across the core, edge, and management layers. This allows for timely action to be taken at the point of need, with localized response while having global situational awareness.

By integrating the threat detection and prediction capability of AI directly into the security architecture, autonomous telecom networks can move from reactive threat defense to proactive and self-protecting operation, a necessary capability for autonomy Levels 4 and 5. Table 1 brings together the requirements for autonomy in security and summarises the corresponding architectural implications for the design in Section 5.

Table 1: Security Requirements and Architectural Implications for Autonomous Telecom Networks

Security Requirement	Key Objective	Architectural Implication
Zero-Trust by Design	Eliminate implicit trust	Identity-first control planes and continuous authorization
AI-Driven Threat Detection	Detect and predict attacks	Embedded AI analytics across OSS, orchestration, and network layers
Intent-Aware Policy Enforcement	Align actions with intent	Policy interpretation tied to declarative intents
Closed-Loop Automation	Minimize response time	Autonomous mitigation integrated into control loops
End-to-End Observability	Maintain verification	Continuous telemetry and post-action validation

3.3 Intent-Aware Policy Enforcement

Intent-aware policy enforcement is an important security requirement in autonomous telecommunication networks, where high-level operational objectives are converted into machine-executable actions with no human intervention. In intent-driven systems, the operators define what they want the network to do - eg performance, availability, security objectives - and it is up to the network to decide how to achieve them. This abstraction presents some special security problems, because it is possible to directly affect the behavior of the network through misinterpreted, conflicting, or malicious intents.

Conventional policy execution systems work under fixed settings and hard-coded policies, supposed network stability and manual authentication. In opposition, autonomous networks are in a state of continual intent generation and refinement in provisioning, orchestration and assurance layers. Security architectures must therefore ensure that all

intents are validated contextually, policy compliant and security aware before they are executed.

Intent aware policy enforcement involves the integration of security semantics in the intent translation pipeline. This involves checking intents against organizational security policies, regulatory restrictions, and real time risk posture then they are broken down into control-plane actions. For example, an intent to dynamically scale a network slice will have to be considered for identity trust, resource isolation and potential exposure before orchestration takes place.

In autonomous environments the enforcement of policy should also be adaptive. As network context changes with topology changes, as a result of detected threats, or changes in service requirements, security policies must be re-evaluated and adjusted automatically. Intent-aware enforcement helps to ensure that security controls stay aligned with their operator's objectives and the current risk situation so that the controls do not drift from the operator's policies or take unsafe actions autonomously.

Incorporating security-conscious intent interpretation directly within orchestration and control systems, autonomous telecom networks can apply identical policies to interdomain policies, and retain the dynamism necessary to autonomy in real time. This is a capability that is critical for ensuring trust, accountability and safety for networks where decisions are made and executed at machine speed. The security-conscious intent translation pipeline is summarised in figure 2 and has validation, constraint checking and policy binding stages before intent execution.

Figure 2: Security-Aware Intent Translation and Policy Enforcement Workflow



3.4 Closed-Loop Security Automation

Closed-loop security automation is one of the defining requirements of autonomous telecommunication networks, in which manual intervention is inconsistent with the speed, scale, and complexity of network operations. In fully or near-fully-autonomous environments, security mechanisms must not only be able to detect threats but also respond, adapt and check outcomes, without human involvement. This requires integration of security directly into the closed-loop control systems of the network.

A closed loop security model operates on a constant sense-analyze-decide-act-verify loop. Telemetry is always collected from the control plane, data plane, orchestration platforms and management systems. This data is done in real-time to detect the threats, anomalies or violation of policy. According to the analysis, the system automatically chooses and implements suitable mitigation measures, including the isolation of compromised network functions, slowing down of suspicious transactions, credential revocation, or

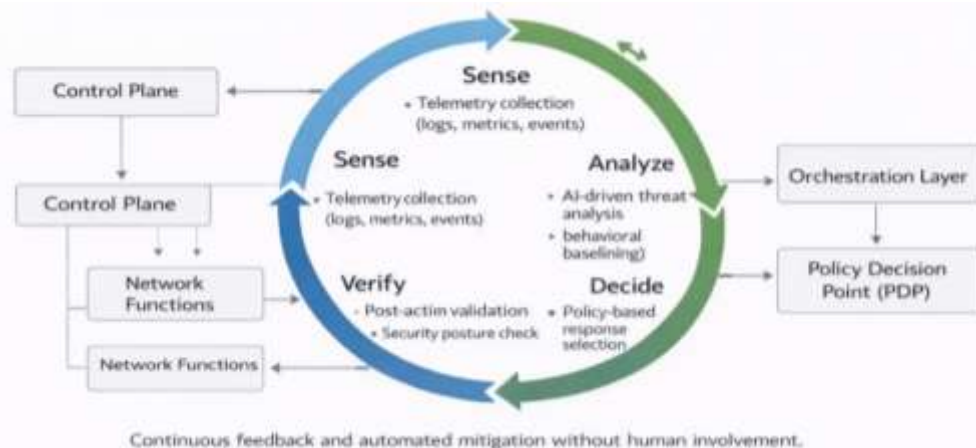
dynamically changing security policies. Finally, the system checks on the effectiveness of these actions and uses the results for continuous learning and adaptation.

In autonomous telecom networks, closed-loop security must be able to work on multiple levels. At the control-plane level, it establishes the fact that the unauthorized or anomalous signaling does not flow through service-based interfaces. On the orchestration level, it blocks unsafe provisioning behavior and imposes corrective reconfiguration in case deviation is identified. At the service level, it allows to quickly isolate slices or edges that are affected without affecting the availability of the overall network.

The closed-loop security automation is effective when there is tight coupling between the detection, policy and enforcement components. Delays or manual inspection points severely hamper autonomy and expose it to ripple effects of a failure. In turn, security architectures need to be structured to enable deterministic and policy-based responding which are auditable, reversible and aligned with operator intent.

By incorporating closed loop automation into the cybersecurity architecture, autonomous telecom networks will have the ability to rapidly contain and recover from a security incident, allowing them to remain resilient even in the face of sophisticated and fast moving threats. Figure 3 illustrates the sense analyze decide act verify cycle and its verification feedback path which ensures the continuation of unsafe loop is stopped.

Figure 3: Closed-Loop Security Automation in Autonomous Telecom Networks



3.5 End-to-End Observability and Verification

End-to-end observability and verification are fundamental security needs of autonomous telecommunication networks where decisions are taken automatically and continually by distributed domains. In the absence of human supervision, the network needs to have the ability to observe its own behavior, check the correctness of autonomous actions and provide evidence of policy compliance and security posture. In an autonomy environment, observability goes beyond the conventional monitoring of performance and faults. Security-related observability must have an in-depth view of control-plane signaling, orchestration processes, provisioning deals, AI decision makings, and enforcement measures.

This visibility can be used to detect minor deviations, including the accidental configuration drift, the abnormal behavior of control-loops, or the slow reaction to security incidents. Verification is a supplement to observability: it makes sure that autonomous behavior can be used to achieve the desired effects, and that it does not break security or regulatory policies. Verification in closed-loop security systems checks the

effectiveness of mitigation measures; e.g., slice isolation, policy changes, or credential rotation, in reducing risk without creating new vulnerabilities or service failures.

The verified results are then fed back about the control loop to revise the future decisions. End-to-end observability is also critical to trust assurance and accountability. Autonomous networks should have the capability to prove explainability, audits as well as guidelines with the stated purposes and policies. This capability is crucial especially in multi-operator, multi-vendor and regulated environments, where transparency and compliance are mandatory. With observability and verification as first-class architecture elements, autonomous telecom network may provide persistent security guarantees, and may help operators trust machine-rendered decisions, and may help permit safe advance to greater levels of autonomy.

4. Research Methodology

This study uses a Design Science Research (DSR) methodology in order to develop and validate a cybersecurity architecture for autonomous telecommunication networks. DSR is especially suitable for this research context because the main contribution of the research is a new architectural artifact rather than software implementation, algorithm or performance-optimized system. The goal is to solve a real world and industry-relevant problem (securing highly autonomous telecom networks) for which large-scale empirical data sets, homogeneous benchmarks and stable testbeds are not yet widely available.

Autonomous telecommunication networks that have higher levels of autonomy (Levels 4-5) are also an emerging paradigm, and fast evolving standards, architectures, and operational models. In these types of situations, experimental validation is not enough to judge the long-term architectural suitability of them, since implementations can rapidly become obsolete, or tailored too closely to specific platforms. Architectural reasoning and analytical validation therefore represents a more appropriate and rigorous way to evaluate whether a proposed cybersecurity design can systematically meet autonomy-driven security requirements under a variety of deployment scenarios.

The methodology adopted is focused on the issues of conceptual clarity, traceability of requirements, alignment to standards so that the proposed architecture is both theoretically and relevant. Rather than performance measurements, this research takes into consideration architectural effectiveness through logical consistency, coverage of determined security requirements, and relationship to the operational realities of autonomous telecom environments .

4.1 Design Science Research Framework

Design Science Research is concerned with the design and testing of artifacts (such as models, frameworks, methods, or architectures) whose purpose is to solve identified problems. In this research, the artifact is a reference cybersecurity architecture for a particular area of autonomous telecommunication network and is uniquely intended to solve the challenges related to it. DSR allows a disciplined method to the innovation of architecture, as well as academic rigor and openness.

The research process proceeds according to the basic phases of the DSR: problem identification, requirement definition, artifact design and analytical validation. Problem identification is based on the inadequacy of the traditional models of perimeter-based security when applied to cloud-native, intent-driven and self-managing telecom systems. Requirement definition is built on top of this problem analysis to identify security capabilities that are needed to perform safe and reliable autonomous operation. Artifact design is the process of translating these requirements into a coherent architectural structure, while analytical validation is the process of determining whether or not the artifact satisfies the requirements for which it was designed. Instead of measuring

performance measures like accuracy of detection or response time, the research will determine if the proposed architecture meets the autonomy-based security objectives in a logically consistent, scalable and standards-conformant way. This approach is consistent with what is known about good DSR practices in systems and architecture research, especially in areas where full empirical validation is limited by system maturity.

4.2 Requirement Extraction Process

Security requirements were developed by a detailed analysis of the operational characteristics of autonomous telecommunication networks. This was done in terms of features that characterise the difference between autonomous systems and conventionally operated networks such as zero-touch provisioning, closed-loop control, AI-directed decision-making, and continuous reconfiguration of distributed environments.

The requirement extraction process is a synthetic process that ties together all the insights gained from existing telecom architecture, autonomy models and new industry guidance to identify security capabilities that are fundamentally needed in machine-driven environments. Particular attention was paid to the interaction between automation and security because autonomous systems increase the speed and consequences of misconfigurations, components, and malicious actions. Through this analysis, certain requirements like zero trust by design; AI-based threat detection and prediction; intent-aware policy enforcement; closed loop security automation; end-to-end observability and verification were identified as baseline constraints. These requirements are not specific to implementation, but define what the security architecture needs to obtain in order to safely support autonomous operation. Collectively, they are the basis of architectural design and further analytical validation.

4.3 Architectural Design Approach

The proposed architecture of cybersecurity is designed with the help of a layered and modular approach, which helps to have a clear separation of concerns and also allows for tight integration between security and control and orchestration functions. By doing this, individual elements of a architecture are free to develop in isolation of the rest without losing the system coherence which is a critical property in long lived telecom infrastructures.

Architectural components are placed according to functional responsibility, not on technology implementation, to ensure that the model is applicable to heterogeneous platforms offered by vendors, models of deployment, and domains of the network. This abstraction allows the architecture to be a reference model and not an implementation blue print. Security is considered a first-class architectural aspect, which is incorporated into control planes, orchestration processes, and management systems. This is opposed to the traditional practices of applying security as an external or afterthought. By weaving security into the very fabric of the architecture, the design is able to ensure that the execution of autonomous actions is constantly under the control of trust, policy and verification measures..

4.4 Analytical Validation Method

Validation is performed using architectural and analytical rather than experimental evaluation. Each architectural component is in turn rigorously mapped to the security requirements specified in Section 3, and how the design solves for certain threat classes, autonomy challenges and operation constraints inherent in autonomous telecom environments. Analytical validation is concerned with the coverage of requirements, internal consistency, and functional completeness.

The study investigates whether it is possible for the architecture to be logically capable of autonomous detecting, decision-making, enforcement and verification without relying on human intervention. Comparative analysis is also used to compare the proposed architecture with the traditional perimeter-based telecom security models while showing the improvement in adaptability, resilience and suitability for high autonomy levels. No datasets, simulations or testbeds are used in this study.

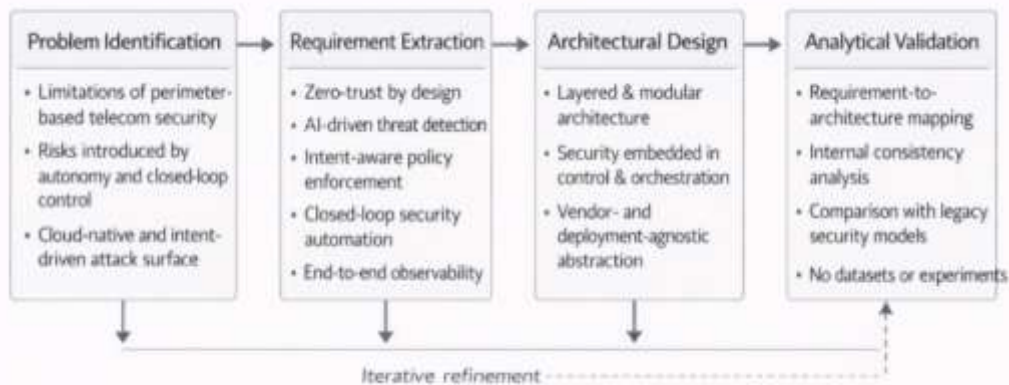
This choice is not accidental and methodologically justified given that the research goal is to establish a reference cybersecurity architecture rather than to optimize or benchmark a given cybersecurity implementation. Validation is hence founded on logical reasoning, architectural tracking and adherence to recognized security and autonomy principles..

4.5 Standards Alignment Approach

To ensure that it is practical and credible, the architecture is conceptually aligned with established and emerging industry frameworks concerning telecom autonomy and cybersecurity. Such alignment will make the proposed design align with the current industry directions and be able to adopt or expand further as standards evolve.

The architecture does not repeat the specifications of other systems but builds on them to support security specifications that come with autonomous operation, including machine-initiated decisions on trust, closed-loop security responses, and continuous verification. This approach is such that the architecture can complement existing standards but fill gaps associated with the design of autonomy-aware cybersecurity. Figure 4 presents the Design Science Research flow applied in this study from the problem identification to the analytical validation.

Figure 4: Design Science Research Methodology Applied to Autonomous Telecom Cybersecurity Architecture



5. Proposed Cybersecurity Architecture for Autonomous Telecommunication Networks

This part introduces a reference cybersecurity architecture that would help autonomous telecommunication networks of high autonomy levels. The architecture is based on the direct derivation of architecture based on the security requirements given in Section 3 and designed on the Design Science Research methodology in Section 4. It is mainly aimed at the aspect of building security as an inherent characteristic of autonomous functioning so that network determinations, control measures and adaptations are trustworthy, resilient and verifiable, devoid of human intervention.

As opposed to the existing telecom security frameworks based on applying fixed trust boundaries and human control, the proposed architecture combines the concept of a zero-

trust frameworks, AI-intelligent security intelligence, intent-aware policy enforcement, and closed-loop automation directly into the economic and operational control and management fabric in the network. With this design, security mechanisms can run as fast and as big as the machine, consistent with the dynamism of autonomous provisioning, orchestration and assurance..

5.1 Architectural Overview

At a top level, the proposed cybersecurity architecture is structured into five closely intertwined layers, which have different security functions each, yet what functions jointly to enable autonomous operation. These layers cut across management, control, and network space, as the current telecom systems are distributed.

The architecture consists of:

1. Security Observability and Telemetry Layer
2. AI-Native Security Intelligence Layer
3. Policy and Intent Management Layer
4. Zero-Trust Control and Enforcement Layer
5. Closed-Loop Security Automation Layer

The layers have a continuous interaction by means of feedback loops and this allows the network to feel the level of security, assess risks, decide on the right response to be taken, apply controls and validate results in real time. Figure 5 gives a summarized picture of the proposed layered architecture and the cyclic feedback of the telemetry, intelligence, policy/intent and enforcement and automation.

Figure 5: Cybersecurity Architecture for Autonomous Telecommunication Networks



5.2 Zero-Trust Control Plane and Enforcement Layer

The zero trust control and enforcement layer is the trust underpinning for the architecture. It guarantees that all interactions inside the autonomous network be it between services, network functions, orchestration components or from external partners are explicitly authenticated, authorised and permanently validated. This layer provides both human and non-human entities with security in the form of identity-first security, including network functions, microservices and automation agents. The dynamically determined access decisions are made on the basis of context based attributes including identity posture, operational state and policy constraints. Least-

privilege principles are uniform in their use in terms of the scope and duration of granted permissions.

The architecture avoids the implicit trust relations by placing the enforcement of zero-trust in control-plane signaling and service-based interfaces and eliminating the possibility of lateral movement to a great extent. Such an ability is especially essential in autonomous settings, where a compromised component may affect numerous decision loops of the automated system.

5.3 AI-Native Security Intelligence Layer

The AI-native security intelligence layer includes the analytical capabilities needed to detect, correlate and predict security threats in autonomous telecom networks. This layer consumes architecture-wide telemetry (telemetry across all layers), such as control-plane messages, orchestration events, provisioning actions, traffic patterns, and policy enforcement outcomes. The AI layer detects abnormalities in the behaviour of the system and these may reflect misconfigurations, insider threats or external attacks by using behavioural baselining and anomaly detection techniques. Notably, analysis is not limited to individual domains but through cross-domain correlation, the system-wide awareness of threats is realized, which depicts the fact that autonomous operations are tightly coupled.

Forecasting functions in this layer facilitate the early detection of attack antecedents and new risk trends. The architecture allows mitigating risks in advance and avoiding cascading failures in closed-loop systems by preventing possible security incidents before they develop to the full extent.

5.4 Policy and Intent Management Layer

The policy and intent management layer is used to ensure that independent actions are consistent with the operators goals, security policies and regulatory limits. High-level intents These are declaratively stated by operators or upper-layer management systems and translated and interpreted into enforceable security-aware policies. This layer introduces security semantics into the intent translation process to make sure that operational goals are checked against prevailing risk posture and trust conditions and only executed. Conflicting or unsafe intents can be detected and limited automatically in order to avoid unintended consequences of autonomous decision-making. Dynamic policy adaptation is also supported, which enables security controls to change according to the threats or changes detected, changes in the context within which the control operates, or changes in the objectives. Through this mechanism, the architecture helps to keep the intent, policy, and enforcement aligned throughout distributed network domains continuously.

5.5 Closed-Loop Security Automation Layer

Autonomous defence is operationalised through the closed-loop system by the security automation layer with the combination of detection, decision-making and enforcement in a loop of continuous control. This layer introduces the sense-analyse-decide-act-verify cycle of Section 3, which makes the responses to security threats fast and deterministic, without human involvement. Upon finding a threat or policy violation, the automation layer determines the right course of action to mitigate the threat or policy violation based on predefined policies and real-time context. Some of the measures could be isolating the impacted network slices, revocation of credentials, throttling of suspicious transactions, or secure reconfiguration.

Then mechanisms of verification determine the success of risk reduction and service integrity of the actions applied. The architecture comprehensively provides security

responses in a timely, coordinated, and resilient manner (even in high-speed or complicated attack conditions) by automating security responses in the identical control loops that drive network operation.

5.6 End-to-End Integration Across Network Domains

The key feature of the suggested architecture is end-to-end integration of OSS/BSS, orchestration platforms, control planes, and network functions. Security is not isolated to just one layer or domain, rather it is a continuous capability that runs across core, edge and management environments. This integration will make it possible to enforce trust, policy and verification regularly and across heterogeneous infrastructures and deployment models. It also facilitates multidomain and multiphase, in which autonomous coordination and shared security assurance are more and more demanded. The cybersecurity architecture proposed here will give a structured foundation for cybersecurity that is extensible to secure autonomous telecommunication networks. By combining the zero-trust principles, artificial intelligence (AI) based intelligence, intent aware policy enforcement, and closed loop automation into a cohesive design, the architecture solves the essential security issues that autonomous operation brings. This reference model is used as a foundation for the analytical validation that is given in the next section.

6. Analytical Validation and Discussion

In the absence of experimental datasets or large-scale testbeds, the proposed cybersecurity architecture is validated in terms of analytical reasoning, threat--control mapping and comparative architectural analysis. This approach is well developed in emerging areas where systems are still emerging and empirical infrastructures are immature, such as in autonomous and AI-driven cyber-physical systems [3], [10]. The analysis shows that the proposed design meets the security requirements specified in Section 3 and is structurally appropriate for autonomous telecommunication networks.

6.1 Threat Coverage Analysis

Threat coverage is analytically assessed by matching autonomous telecom environmental dominant threat classes to architectural controls introduced in Section 5. This approach guarantees the systematic reasoning about protection, detection and response capabilities without empirical metrics.

Key threat categories and mitigation mechanisms include:

- **Control-plane and API abuse**
 - Threats: Unauthorized service invocation, signaling manipulation, rogue network functions
 - Architectural mitigation:
 - Zero-trust control plane enforcing continuous authentication and authorization
 - Identity-bound service interactions
 - Least-privilege execution across service-based interfaces
- **Provisioning and orchestration attacks**
 - Threats: Malicious or erroneous automated configuration actions
 - Architectural mitigation:
 - Intent-aware policy validation prior to execution
 - Security-aware orchestration gates
 - Automated rollback through closed-loop automation
- **Lateral movement in cloud-native infrastructures**
 - Threats: East-west traffic exploitation, privilege escalation

- Architectural mitigation:
 - Micro-segmentation enforced through identity-based access
 - Cross-domain observability to detect abnormal service interactions
- **Autonomous decision manipulation**
- Threats: Poisoned telemetry, adversarial influence on AI-driven control loops
- Architectural mitigation:
 - Behavioral baselining and anomaly detection
 - Verification stages embedded in closed-loop security automation
- **Delayed incident response**
- Threats: Human-in-the-loop latency in fast-moving attacks
- Architectural mitigation:
 - Deterministic closed-loop response mechanisms
 - Policy-driven autonomous mitigation actions [20]

Analytical Observation: For each threat class T_i , the architecture provides a combination of preventive and corrective controls, satisfying defence-in-depth principles commonly recommended for autonomous systems [1], [6].

6.2 Comparison with Legacy Security Models

A comparative analysis of limitations of traditional telecom security architecture in the context of autonomous environments.

Legacy security characteristics:

- Perimeter-centric trust assumptions
- Static, rule-based intrusion detection
- Manual or semi-automated incident response
- Siloed security tooling
- Strong dependence on human decision-making

Proposed autonomous security characteristics:

- Zero-trust by design
- AI-driven behavioral analysis
- Fully automated closed-loop response
- Cross-domain security intelligence
- Machine-speed, policy-driven decision execution

Table 2 contrasts legacy telecom security models with the proposed autonomy-aware architecture across trust, detection, response, scalability, and autonomy support.

Table 2: Comparative Table: Legacy vs. Proposed Architecture

Dimension	Legacy Telecom Security	Proposed Autonomous Architecture
Trust Model	Implicit, perimeter-based	Continuous zero trust
Detection	Signature / rule-based	AI-driven behavioral analysis
Response	Manual or delayed	Autonomous, closed-loop
Scalability	Limited by human oversight	Designed for dynamic scale
Autonomy Support	Low (L1–L2)	High (L4–L5)

This comparison in table 2 shows that the legacy models are not compatible with autonomous operation, based on their static assumptions and delayed response mechanisms [10], [13].

6.3 Autonomy Level Compatibility (Levels 4–5)

Autonomy Levels 4 to 5 are characterised by little to no human intervention, which requires security mechanisms that are self-governing, self-protecting and self-verifying [3], [10]. Integrated automation and verification is used in the proposed architecture to fulfill these requirements.

Key autonomy-aligned capabilities include:

- **Self-protection:** AI-driven detection and predictive threat modeling [4], [6]
- **Self-healing:** Automated isolation, reprovisioning, and policy adaptation
- **Self-governance:** Intent-aware enforcement and continuous verification

The security autonomy capability of an autonomous telecommunication network can be expressed using a compact conceptual formulation:

$$S_{\text{aut}} = \alpha ZT + \beta AI + \gamma CL + \delta V, \alpha, \beta, \gamma, \delta > 0$$

Where:

- S_{aut} denotes the security autonomy capability,
- ZT represents zero-trust enforcement,
- AI denotes AI-driven security intelligence,
- CL represents closed-loop security automation, and
- V denotes end-to-end verification and observability.

The positive weighting factors α, β, γ , and δ represent the importance of each architectural capability to the type and extent of security autonomy. To attain Autonomy Levels 4 and 5, all components must be concurrently present and operative. This requirement is achieved by the proposed architectural design that incorporates trust enforcement, analysis, response actions, and verification as part of the autonomous control and management loops.

6.4 Operational Benefits

Beyond threat mitigation the architecture offers a number of significant operational advantages which can be reasoned analytically without empirical benchmarking.

Reduced response time

- Removal of human decision latency
- Response time shifts from minutes or hours to milliseconds or seconds

$$T_{\text{response}}^{\text{auto}} \ll T_{\text{response}}^{\text{manual}}$$

Reduced human dependency

- Security actions executed by policy-driven automation
- Human roles transition from operators to supervisors
- Lower risk of configuration errors and cognitive overload [20]

Improved resilience

- Localized containment prevents cascading failures
- Verification ensures safe recovery before loop continuation

Consistency and predictability

- Deterministic enforcement based on policy and context
- Reduced variability in security outcomes across domains

These benefits are in line with results from other, more general autonomous and AI-driven cybersecurity research, which focuses on the importance of automation, verification and cross-domain awareness as key enablers of resilient systems [1], [6], [19].

Through analytical threat mapping, architectural comparison and reasoning at the level of autonomy, this section shows that the proposed cybersecurity architecture offers complete threat coverage, is better than legacy security models, and is structurally

compatible with high-autonomy telecommunication networks. The analysis confirms that architectural validation might be effective to substitute experimental evaluation in new domains where empirical infrastructures are not yet mature.

7. Standards and Industry Alignment

The proposed cybersecurity architecture is conceptually aligned with major telecommunication as well as cybersecurity standards in order to ensure practical relevance, interoperability, and future extensibility. Rather than duplicating the existing specifications, architecture builds upon them by explicitly considering security challenges introduced by autonomous, AI-driven and closed-loop network operation, which are covered to some extent in existing frameworks.

7.1 Alignment with ETSI Zero-Touch Service Management (ZSM)

ETSI ZSM provides an outline of a reference model of zero-touch, automated management of networks and services with a focus on closed-loop control, decision-making with the aid of AI, and end-to-end automation. The proposed architecture is very much in line with ZSM principles as it embeds security directly into the same close-loop mechanisms for autonomous management.

Specifically, the architecture:

- Integrates security observability and analytics into management loops, consistent with ZSM monitoring and analytics functions.
- Supports closed-loop security automation, extending ZSM's operational loops to include autonomous threat response and verification.
- Treats security as an intrinsic property of zero-touch operation rather than an external function.

Extension beyond ZSM: While ZSM defines management automation, it provides limited guidance on autonomy-aware cybersecurity. The proposed architecture extends ZSM by:

- Incorporating zero-trust enforcement into control and management loops.
- Introducing verification stages to ensure the correctness of autonomous security actions.

7.2 Alignment with TM Forum Autonomous Networks Framework

The TM Forum Autonomous Networks model provides a maturity model of network autonomy, between assisted operation and autonomous systems. It is clearly stated that this proposed architecture is intended to facilitate higher levels of autonomy (L4-L5) in which human intervention is at the lowest level or even nonexistent.

Alignment is achieved through:

- **Intent-aware policy enforcement**, consistent with TM Forum's intent-driven management concepts.
- **AI-driven analytics** supporting self-monitoring, self-optimization, and self-healing behaviors.
- **Closed-loop automation**, enabling autonomous decision execution and validation.

Extension beyond TM Forum: TM Forum frameworks are mainly focused on operational autonomy and business processes. The proposed architecture extends these models by:

- Embedding cybersecurity decision-making into intent translation pipelines.
- Ensuring that autonomous actions are continuously governed by trust, policy, and verification constraints.

7.3 Alignment with 3GPP 5G and Emerging 6G Architectures

The proposed cybersecurity architecture is aligned with the 3GPP 5G Service Based Architecture (SBA), and it stresses on cloud-native network functions, service-based

interfaces, and extensive exposure of application programming interfaces (APIs). In this context, the architecture ensures security of interactions, both control plane and service-based, ensuring that security controls are consistently applied throughout the service lifecycle. Key areas of alignment include: the adoption of identity-first security for service-based interfaces, the protection of network slicing, orchestration and network management functions, support for highly distributed deployments across core, edge and non-terrestrial network environments [13].

While 3GPP specifications define security mechanisms to the level of individual network functions, there is no prescription for a holistic and autonomy-aware cybersecurity architecture. The proposed design is extending existing 3GPP concepts with Zero Trust principles in respect of autonomous control loops and AI-driven security intelligence across operations support systems (OSS), orchestration layers and network domains in order to address emerging requirements of 5G evolution and early 6G architectures..

7.4 Conceptual Alignment with Zero Trust (NIST)

The proposed architecture is conceptually consistent with the NIST Zero Trust model, especially its main principles of not assuming implicit trust, continuously verifying, and using least privilege. These concepts are applied to non-humans to cover functions in a network, autonomous agents, and orchestration workflows, and all members of the system are evaluated and enforced on the same basis. Unlike traditional Zero Trust deployments, which usually assume that there is substantial human supervision and human decision points, the proposed architecture is a step ahead, which allows machine-based trust decisions, incorporates trust enforcement into autonomous control and orchestration layers, as well as continuous verification processes without manual checkpoints.

8. Conclusion and Future Research Directions

This paper has presented the reference cybersecurity architecture for telecommunication networks to operate autonomously, and addressing the fundamental security challenges introduced by zero-touch operation, AI-based decision-making and closed-loop automation in 5G-Advanced and emerging 6G environments. By considering cybersecurity as an architectural first-class component, the proposed architecture departs from the classical architecture of perimeter-based and reactive security, which becomes more and more insufficient in cloud-native, highly distributed, and self-governing telecom systems.

The architecture unites the concept of zero-trust, AI-native security intelligence, intent-sensitive policy enforcement, closed-loop security automation, and end-to-end observability into one systems architecture. Through analytical validation, the work shows that this design offers good threat coverage, supports autonomy Levels 4-5 and can allow security mechanisms to run at machine speed without the need of constant human intervention. The correspondence to ETSI ZSM, TM Forum Autonomous Networks, 3GPP 5G/6G architecture, and the principles of Zero Trust also determine the practical topicality and compatibility of the proposed solution in the future.

In spite of these contributions, a number of limitations need to be acknowledged. First, the validation of the architecture is analytical and conceptual, rather than empirical. While this approach is methodologically proper considering the emerging nature of fully autonomous telecom networks, physical deployments and testbeds will be required to quantify the performance metrics such as detection accuracy, response latency and operational overhead. Second, the architecture is introduced as a technology neutral reference model, which deliberately flattens vendor-specific implementation and

deployment limitations. As a result, more effort will need to be put into the design to adapt to concrete platforms and operational environments.

The limitations of the current study naturally suggest important directions for future research. One important direction is to experimentally test the proposed architecture with simulated or pilot 5G/6G environments and make quantitative assessment of security effectiveness and operational efficiency. The second potential avenue that could be explored is the analysis of AI models in threat detection and prediction that include resistance to adversarial manipulation and concept drift under dynamic network conditions. Other possibilities of future work involve formal verification methods to offer more robust assurances on the validity and safety of autonomous security judgments.

Further investigation is justified in the domains of cross-domain trust management of multi-operative and multi-vendor ecosystems, privacy-sensitive security analytics of edge and non-terrestrial networks and governance structures to establish accountability and compliance in machine-powered security operations. As telecom networks keep moving toward full autonomy, these research directions will be important to help turn architectural notions into operationally resilient and trustworthy systems.

In conclusion, this work offers a basic blueprint of the architecture to secure autonomous telecommunication networks. The proposed architecture will make a contribution to the current work of delivering safe, resilient, and self-defending networks by explicitly considering the intersection of autonomy, AI, and cybersecurity to support the next generation of the global communications infrastructure.

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