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**NIST Special Publication
NIST SP 800-215 ipd**

Guide to a Secure Enterprise Network Landscape

Initial Public Draft

Ramaswamy Chandramouli

This publication is available free of charge from:
<https://doi.org/10.6028/NIST.SP.800-215.ipd>

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Ramaswamy Chandramouli
*Computer Security Division
Information Technology Laboratory*

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August 2022



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57 **Publication History**

58 Approved by the NIST Editorial Review Board on YYYY-MM-DD [will be added upon final publication]

59 **How to Cite this NIST Technical Series Publication:**

60 Chandramouli R (2022) Guide to a Secure Enterprise Network Landscape. (National Institute of Standards and
61 Technology, Gaithersburg, MD), NIST Special Publication (SP) NIST SP 800-215 ipd.
62 <https://doi.org/10.6028/NIST.SP.800-215.ipd>

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65 **Public Comment Period**

66 August 5, 2022 – September 19, 2022

67 **Submit Comments**

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85 **Abstract**

86 Access to multiple cloud services, the geographic spread of enterprise IT resources (including
87 multiple data centers), and the emergence of microservices-based applications (as opposed to
88 monolithic ones) have significantly altered the enterprise network landscape. This document is
89 meant to provide guidance to this new enterprise network landscape from a secure operations
90 perspective. Hence, it starts by examining the security limitations of the current network access
91 solutions to the enterprise network. It then considers security feature enhancements to traditional
92 network appliances in the form of point security solutions, network configurations for various
93 security functions (e.g., application security, cloud access security, device or endpoint security,
94 etc.), security frameworks that integrate these individual network configurations, and the
95 evolving wide area network (WAN) infrastructure to provide a comprehensive set of security
96 services for the modern enterprise network landscape.

97 **Keywords**

98 cloud access security broker (CASB); firewall; microsegmentation; secure access service edge
99 (SASE); secure web gateway (SWG); security orchestration, automation, and response (SOAR);
100 software-defined perimeter (SDP); software-defined wide area network (SD-WAN); virtual
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128	Table of Contents	
129	Executive Summary	1
130	1. Introduction	2
131	1.1. Structural Implication of Drivers on Enterprise Network Landscape	2
132	1.2. Security Implication of Drivers for the Enterprise Network Landscape	3
133	1.3. The Need for a Security Guide	4
134	1.4. Scope	4
135	1.5. Target Audience	4
136	1.6. Organization of This Document.....	4
137	2. Traditional Enterprise Network Access Approaches and Their Limitations	6
138	2.1. Limitations of Network Perimeter-based Protections	6
139	2.2. Limitations of VPN-based Access	6
140	2.3. Limitation of MPLS Technology as Enterprise WANs	7
141	2.4. Limitation of User Identity-based Controls	7
142	3. Network Security Appliances in Enterprise Network Landscape	9
143	3.1. Cloud Access Security Broker (CASB).....	9
144	3.2. Enhanced Firewall Capabilities	10
145	3.3. Appliance-set with Integrated Functions	11
146	3.4. Requirements for Network Automation Tools.....	11
147	3.4.1. Network Monitoring and Observability Tools	12
148	3.4.2. Automated Network Provisioning Tools	13
149	3.5. Networking Appliances as Services	14
150	4. Enterprise Network Configurations for Hybrid Application Environments	15
151	4.1. Network Configuration for Device Management.....	15
152	4.2. Network Configuration for User Authentication	15
153	4.3. Network Configuration for Device Authentication and Health Monitoring.....	16
154	4.4. Network Configuration for Authorizing Application Access	16
155	4.5. Network Configuration for Preventing Attack Escalation (Microsegmentation).....	16
156	4.5.1. Prerequisites for Implementing Microsegmentation.....	16
157	4.5.2. Microsegmentation – Implementation Approaches.....	17
158	4.6. Security Frameworks Governing Network Configurations.....	19
159	4.6.1. Conceptual Underpinnings – Contextual Information	19
160	4.6.2. Network Security Framework – Software-defined Perimeter (SDP)	20
161	4.6.3. Network Security Framework – Zero Trust Network Access (ZTNA).....	21
162	5. Secure Wide Area Network Infrastructure for an Enterprise Network	22
163	5.1. Common Requirements for a Secure SD-WAN	22

164	5.2.	Specific Requirements for WANs for Cloud Access.....	23
165	5.3.	Requirements for an Integrated Security Services Architecture for SD-WAN.....	24
166	6.	Summary and Conclusions.....	26
167		References.....	27
168		List of Figures	
169	Fig. 1.	Segment-based Microsegmentation.....	18
170			

171 **Acknowledgments**

172 The author would like to express his thanks to Isabel Van Wyk of NIST for her detailed editorial
173 review.

174 **Executive Summary**

175 The enterprise network landscape has undergone tremendous changes in the last decade due to
176 the following three drivers:

- 177 1. Enterprise access to multiple cloud services,
- 178 2. The geographical spread of enterprise-based (on-premises) IT resources (e.g., multiple
179 data centers and branch offices), and
- 180 3. Changes to application architecture from being monolithic to a set of loosely coupled
181 microservices.

182 The impact of these drivers on the security of the enterprise network landscape include:

- 183 • Disappearance of the concept of a network perimeter that can be protected and the
184 necessity to protect each endpoint (device or service) that treats it as a perimeter
- 185 • Increase in attack surface due to sheer multiplicity of IT resources (computing,
186 networking, storage) and components
- 187 • Sophistication of the attackers in their ability to escalate attacks across several network
188 boundaries and leverage connectivity features

189 This document is meant to provide guidance to this new enterprise network landscape from a
190 secure operations perspective. The adopted methodology considers the security challenges that
191 the network poses and then examines the limitations of current network access technologies and
192 how solutions have evolved from being security function-specific to a security framework to a
193 comprehensive security infrastructure that provides a holistic set of security services. Specific
194 areas addressed include:

- 195 • Feature enhancements to traditional network security appliances
- 196 • Secure enterprise networking configurations for various scenarios
- 197 • Security frameworks that integrate individual network configurations
- 198 • Evolving wide area network (WAN) infrastructure that provides a comprehensive set of
199 security services

200 What is termed as the enterprise network in this document encompasses the various local
201 networks on enterprise premises and that portion of wide area network that is used to connect its
202 various geographically dispersed locations and cloud service access points.

203 **1. Introduction**

204 The enterprise network landscape has undergone a significant transformation in the last decade.
205 The drivers for this transformation are (a) enterprise access to multiple cloud services, (b) the
206 geographic spread of enterprise-owned (on-premises) IT resources (e.g., in a central office,
207 multiple branch offices, and data centers), and (c) changes to application architecture from being
208 monolithic to a set of loosely coupled microservices – often with a dedicated infrastructure
209 (called the service mesh) that provides all application services, including security. The high-level
210 impact of these drivers on the security of the current enterprise network landscape are (a)
211 disappearance of the concept of a perimeter associated with the enterprise network; (b) an
212 increase in attack surface due to the sheer multiplicity of IT resource components associated with
213 application services, storage, and network appliances; and (c) sophistication of the attackers in
214 their ability to escalate attacks across several network boundaries and leverage connectivity
215 features. This document will consider these impacts by identifying the structural components of
216 the new network landscape as well as specific security threats that they have opened up.

217 **1.1. Structural Implication of Drivers on Enterprise Network Landscape**

218 In order to have a good structural view of the current enterprise network landscape, it is
219 necessary to look at the current enterprise IT environment in general. The IT environment now
220 consists of:

- 221 • Subscription to multiple cloud services, such as IaaS for computing, SaaS for software,
222 PaaS for an application development platform, and other cloud services (e.g., IDaaS for
223 authentication)
- 224 • Enterprise IT applications (on-premises) located in corporate headquarters and
225 geographically distributed branch offices and data centers
- 226 • IT applications range from being monolithic to ones that are made up of loosely coupled
227 microservices, each of them hosted on heterogeneous platforms
- 228 • Presence of edge computing devices, such as IoTs, in some environments

229 The above scenarios call for widespread connectivity between IT systems that now defines the
230 current enterprise network landscape. Connectivity, in turn, involves:

- 231 • Connectivity between IT resources (servers for computing and storage) in data centers
232 (network fabric)
- 233 • Connectivity between IT resources within a corporate office or branch office (Wi-Fi,
234 LAN, VLAN)
- 235 • Connectivity for users to remotely access to IT resources from home, travel locations,
236 branch offices, and corporate offices using WANs, which use multiple networks such as
237 the internet, MPLS, and – in some instances – cellular networks (e.g., 4G/LTE, 5G, etc.)
- 238 • Connectivity to cloud services through a cloud service provider (CSP), virtual private
239 networks (VPN), or subscription to WAN services (premises based equipment licenses
240 or cloud-based)

241 **1.2. Security Implication of Drivers for the Enterprise Network Landscape**

242 The beginning of this section stated the following as the drivers for the state of the current
243 enterprise network landscape:

- 244 • Subscription to multiple cloud services
- 245 • Geographically distributed IT resources
- 246 • Changes in application architecture

247 Now consider the immediate security implications of these drivers.

248 Subscription to multiple cloud services: Accessing cloud services from multiple cloud providers
249 has become the norm for many enterprises. This trend is motivated not only by the need to avoid
250 a cloud-vendor locked-in situation but also by different CSPs offering different value-added
251 functions for different services (e.g., IaaS, SaaS). The consequence of this trend is that – from an
252 enterprise point of view – the following networks have become extensions of the enterprise
253 network and, thus, come under the scope of enterprise network management with attendant
254 responsibilities for ensuring security protections becoming a critical function.

- 255 • Network used for accessing the cloud services
- 256 • Inter-cloud network (since communication between one CSP and another may be
257 inevitable)
- 258 • The network inside the cloud provider that needs to be navigated to access the subscribed
259 services (e.g., VPC, VNET, etc.)

260 Geographically distributed IT resources: The implication of distributed IT resources is that the
261 users are also geographically distributed. Applications are now accessed by users not only from
262 the enterprise premises, such as the corporate office and branch offices (through the enterprise
263 network), but also from home and public locations (e.g., hotels and cafes) through multiple
264 devices, such as desktops, laptops, and mobile phones. Ensuring secure access from these
265 multiple locations and devices becomes the responsibility of the enterprise.

266 Changes in application architecture: Application architectures – especially those of cloud-native
267 applications – have changed from being monolithic to being microservices-based, with the
268 distributed nature increasing the communication channels between the components across a
269 network (instead of just being local procedure/function calls). These applications have enlarged
270 the threat and attack surface due to:

- 271 • Inherent architectures (multiple independent microservices and APIs),
- 272 • Automation tools used during software development and deployment, and
- 273 • Agile development and deployment methodologies, such as DevSecOps, that contain
274 CI/CD pipeline code (workflows).

275 Attacks include data breaches, distributed denial of service (DDoS), account takeover (ATO) due
276 to credential theft, and insider threats.

277 **1.3. The Need for a Security Guide**

278 Based on these considerations for security implementation, the arguments for the need for a
279 security guide to the current enterprise network landscape are:

- 280 • Ubiquitous access locations, ubiquitous hosting locations of the application components,
281 and multiple WAN transport protocols have caused shifts in security focuses, goals, and
282 principles.
- 283 • The security focus has enlarged from being network-centric (i.e., internal/corporate
284 network versus external/public internet) to user- and device/endpoint-centric.
- 285 • The new trust relationship has to be based not just on identity or the location of the access
286 but enhanced to include validation of each access request (not just at the beginning of an
287 access session), as well as the applicable set of contextual information associated with the
288 user, device, or service.

289 **1.4. Scope**

290 The scope of this document includes:

- 291 • A structural view of the enterprise network landscape based on the distribution of IT
292 resources and the consequent security challenges it poses
- 293 • Emerging and state-of-practice solutions in terms of feature sets and requirements to
294 address the security challenges; solutions discussed will focus on the functional and
295 operational levels

296 **1.5. Target Audience**

297 This guidance is intended for network design architects and network security solution architects
298 in organizations with a hybrid IT environment (consisting of both on-premises and cloud-based
299 applications) with a combination of legacy and microservices-based (i.e., cloud-native)
300 applications.

301 **1.6. Organization of This Document**

302 The organization of this document is as follows:

- 303 • Chapter 2 considers traditional network access principles and technologies and their
304 limitations in the context of the current enterprise network landscape.
- 305 • Chapter 3 provides a brief functional description of network security appliances – some
306 new, some traditional (e.g., firewall) – that have enhanced capabilities to meet the
307 security needs of the current network landscape.
- 308 • Chapter 4 outlines various network configurations that have evolved specifically for
309 meeting the current network landscape (e.g., secure cloud access). It then considers the
310 frameworks that integrate two or more of these stand-alone configurations in terms of
311 their conceptual underpinnings and overall architectures.

- 312 • Chapter 5 focuses on the evolution of the WAN portion of the enterprise network
- 313 landscape and enhanced offerings of the WAN services with global spread with a built-in
- 314 security service infrastructure.
- 315 • Chapter 6 provides the summary and conclusions.

316 2. Traditional Enterprise Network Access Approaches and Their Limitations

317 Section 1 outlined the drivers for the current enterprise network landscape. Both drivers (change
318 in application architectures and access to cloud-based applications) have impacted the mechanics
319 of secure access to those applications through the network. Now consider the security limitations
320 of the traditional enterprise network access approaches in the current enterprise network
321 landscape context.

- 322 • Limitation of network perimeter-based protections
- 323 • Limitations of VPN-based access
- 324 • Limitations of MPLS technology as enterprise WANs
- 325 • Limitation of user identity-based controls

326 2.1. Limitations of Network Perimeter-based Protections

327 Early solutions for secure enterprise network access were geared toward environments with well-
328 defined network perimeters. All enterprise IT resources were endpoints of enterprise LANs
329 (usually defined as a floor in a large enterprise, building, or small campus), and multiple LANs
330 connected together inside a defined building or campus constituted the internal corporate
331 network. Entry points into this corporate network were protected using devices called firewalls,
332 which were initially implemented as hardware appliances and later used software. In this
333 environment, all devices and users within firewalls were totally trusted and, hence, considered
334 safe for accessing application resources. However, the following factors have annulled the
335 concept of that perimeter:

- 336 • Distributed nature of the application into ones located within a corporate data center,
337 remote branch offices, and multiple cloud locations
- 338 • Perimeter approach based on the premise that the threat originates outside of the network,
339 which is why most perimeter security solutions (e.g., IPS, IDS, firewalls) focus only on
340 north-south traffic. However, over 75 % of network traffic is now east-west or server-to-
341 server (due to applications being microservices-based), which is largely invisible to
342 security teams. Any threat that is already inside of a network can move laterally and
343 remain undetected for days or even months.
- 344 • Edge computing [1], where much of the computing takes place close to the location of
345 multiple IoT devices
- 346 • Users located both within and outside of the corporate network, such as in homes, remote
347 branch offices, and public locations (e.g., hotels, pubs, etc.). Some enterprises must also
348 provide access to ecosystem partners, who may be on their own corporate networks.

349 The above scenarios have greatly expanded the attack surface.

350 2.2. Limitations of VPN-based Access

351 The increase in teleworking employees due to the pandemic has necessitated a means for secure
352 access to IT resources inside an enterprise network in the form of virtual private networks
353 (VPNs). A VPN allows organizations to extend a perimeter-based security across a public

354 network. Security is enabled by setting up a secure tunnel in the public network using protocols
355 such as IPSEC and TLS.

356 However, there are some limitations and security risks associated with VPNs.

- 357 • An increasing trend involves the movement of corporate resources to the cloud and the
358 use of mobile devices. The VPN connections that remote users establish terminate at the
359 VPN concentrators located at the edge of the corporate network. Hence, using a process
360 called hair pinning, the traffic that lands at the corporate internet edge is routed back to
361 the internet to access the cloud resources. This extra path increases network latency and
362 has the potential to cause traffic bottlenecks.
- 363 • The mobile devices used by many employees, such as smartphones and tablets, can
364 connect directly to software-as-a-service (SaaS) applications and data in the cloud. These
365 mobile devices are especially prone to phishing attacks that steal credentials or deliver
366 malware. Thus, the VPN becomes an entry point by which a bad actor could compromise
367 a device and enter an organization's infrastructure.
- 368 • Two recent vulnerabilities were discovered in some VPNs [2]. One was "session
369 hijacking," where malicious actors access a valid session ID through brute-force attacks
370 or reverse engineering. The second vulnerability involved pulling a unique ID for an
371 account, leveraging web browser development tools to manually set a value to the ID,
372 and using that to obtain unauthenticated access to the VPN administrator console. That
373 access was then used to remotely connect to internal systems, harvest passwords, move
374 laterally in the network, and – in many cases – deploy ransomware.

375 **2.3. Limitation of MPLS Technology as Enterprise WANs**

376 Multi-protocol label switching (MPLS) technology is used for enterprise WANs, but the wide
377 geographic span of an enterprise network due to multiple data centers and cloud services has
378 imposed some limitations on its use.

- 379 • The geographic span of enterprise IT resources and subsequent networking connections
380 have made traversal through internet inevitable for many portions of its enterprise's
381 access network. Since MPLS is a different network, it provides access to the internet only
382 through designated and limited access points. This increases latency for time-sensitive
383 corporate applications.
- 384 • Given the different networking technology, the appliances and subsequent configuration
385 procedures are different, making networking management a complex task.

386 **2.4. Limitation of User Identity-based Controls**

387 In traditional monolithic applications, all invocations of applications are either directly from the
388 user or through scripts written and programmed to run by the user. Hence, the only parameters
389 for access validation are the user identity or attributes associated with the user.

390 Changes in application architectures expand the validation parameters beyond user identity and
391 attributes. The initial changes to application architectures are found in web-based and API-based
392 applications where access can take place from any device located in any network (e.g., home,

393 public WiFi, etc.). The latest changes are found in microservices-based applications (often called
394 cloud-native applications because this architecture is the predominant one among cloud-hosted
395 applications). This class of application consists of loosely coupled microservices that require the
396 generation of multiple interservice requests to complete a business process or transaction. The
397 limitations of identity-based controls can be seen from the following expanded security
398 requirements for microservices-based applications:

- 399 • Validation is required not only for the identity of the users initiating the transaction but
400 also for the identity of each service (service identity) making the request and the device
401 on which the service is hosted (authorized device).
- 402 • The location of the service and device may change due to the virtualized nature of the
403 application hosting environment (e.g., migration to VMs located in a different subnet,
404 more powerful hosting devices and storage mechanisms, etc.), necessitating the need for
405 validating an application request based not only on user identity and attributes but also on
406 attributes associated with the device, network, geolocations, etc.
- 407 • The validation of identity (authentication) and authorization need to be done continuously
408 (and not just at the beginning of an application invocation session) as the risk profile of
409 an access may change due to there being multiple entities involved or changes in
410 behavioral patterns that need to be included as a validation parameter (and monitored).

411 3. Network Security Appliances in Enterprise Network Landscape

412 This section will consider some new network security appliances as well as enhanced features in
413 established appliances for meeting the security needs of the current landscape. These can be
414 viewed simply as point security solutions, but evaluating their functions and features will provide
415 an understanding of the effectiveness of network configurations and technologies that form part
416 of the integrated solutions that are going to be discussed in Sections 4 and 5, respectively.

417 3.1. Cloud Access Security Broker (CASB)

418 Given the increasing subscription to multiple clouds in many enterprises, one of the most
419 important pieces of software is the cloud access security broker (CASB). Just like IAM systems,
420 a CASB can be run either on-premises or as a cloud-based service. It sits on the network between
421 the cloud service customers (CSC) and the cloud service providers (CSP). The evolution of
422 CASB functionality can be traced as follows [3]:

- 423 • The primary function of the first generation of CASBs was the discovery of resources.
424 They provided visibility into all of the cloud resources that the enterprise users accessed,
425 thus preventing or minimizing the chances of shadow IT. Shadow IT is the practice of
426 some users using cloud applications that are not authorized by the enterprise IT
427 management from home or the office using enterprise desktops. An example of this is the
428 use of unapproved software-as-a-service (SaaS) applications for file sharing, social
429 media, collaboration, and web conferencing by some enterprise users [4]. This generation
430 of CASBs also provides some statistics, such as software-as-a-service (SAAS) utilization.
- 431 • The current generation of CASBs enforces security and governance policies for cloud
432 applications, thus enabling enterprises to extend their on-premises policies to the cloud.
433 Specific security services provided by CASBs include:
 - 434 ○ Protection of enterprise data that lives in cloud service providers' servers (due to
435 SAAS or IAAS subscriptions), as well as data inflow and data outflow from those
436 servers
 - 437 ○ Tracking of threats, such as account hijacking and other malicious activities.
438 Some can detect anomalies in users' cloud access behavior (through robust user
439 and entity behavior analytics, or UEBA, functionality) and stop insider threats and
440 advanced cyberattacks [5].
 - 441 ○ Detection of misconfigurations in the enterprise's subscribed infrastructure as a
442 service (IaaS) and cloud servers. These misconfigurations pose serious security
443 risks such as data breaches. Alerts generated by CASB due to misconfigurations
444 in the enterprise's IaaS deployments direct the enterprise to follow guidelines,
445 such as the Center for Internet Security's (CIS) benchmarks for public cloud
446 services, thus improving the overall security profile of the enterprise for cloud
447 access [4].

448 3.2. Enhanced Firewall Capabilities

449 The security functions in firewalls have enlarged alongside the changing network landscape.
450 Firewalls started as hardware appliances that prevented network packets from a device with a
451 particular network location (e.g., combination of IP address and port) in one subnet (e.g.,
452 external network or internet) from accessing a device on another network location or subnet
453 (e.g., intranet or DMZ or corporate network). In that setup, it primarily secured a network
454 perimeter. The evolution of firewall functions can be traced based on the following feature sets
455 [6]:

- 456 • Packet filters and network address translation: Packet filtering and NAT are used to
457 monitor and control packets moving across a network interface, apply predetermined
458 security rules, and obscure the internal network from the public internet.
- 459 • Stateful inspection: Stateful firewalling, also known as dynamic packet filtering, monitors
460 the state of connections and makes determinations on what types of data packets
461 belonging to a known active connection are allowed to pass through the firewall.
- 462 • Threat detection and response: Modern firewalls can gather and analyze enough data
463 across multiple packets and sessions to detect threats and security incidents targeted at a
464 particular system or a family of systems. The data from multiple firewalls can also be
465 directed toward security information and event management (SIEM) and correlated with
466 data from other security tools and IT systems to detect enterprise-wide attacks that span
467 multiple systems and network layers. In addition, this data can be used to understand
468 evolving threats and define new access rules, attack patterns, and defensive strategies [6].
- 469 • Logging and auditing capabilities: Logging and auditing capabilities result in the
470 construction of network events that can be used to identify patterns of performance and
471 security issues.
- 472 • Access control functions: Access control functions enforce granular sophisticated access
473 control policies.
- 474 • Multiple locations and functions: Firewalls reside at different locations to perform
475 different functions. Firewalls at the network edge perform the network perimeter
476 protection function by filtering disallowed sources and destinations and blocking packets
477 of potential threats. Firewalls inside a data center can create segmentation of the internal
478 network to prevent the lateral movement of traffic and isolate sensitive resources (e.g.,
479 services and data stores). Device-based firewalls prevent malicious traffic in and out of
480 endpoints.
- 481 • Open APIs integrate with many networking products.
- 482 • Some features centrally define or merge policies so that consistent policies are applied to
483 different class of users (e.g., those on-premises and on private and public clouds).
- 484 • Web application firewalls (WAF): This class of firewalls has been used ever since web
485 applications accessed through web protocols, such as HTTP, came into existence. A
486 feature advancement in this class of firewalls is advanced URL filtering. This is the
487 ability to detect traffic from malicious URLs and thus prevent web-based threats and

488 attacks by receiving real-time data analyzed by machine learning algorithms [7][8].
489 Specifically, this class of firewalls can inspect threat vectors for SQL Injection, OS
490 command injections, and cross-site scripting attacks, as well as prevent inbound attacks.
491 They are used in content delivery networks (CDN) and to prevent distributed denial-of-
492 (DDoS) attacks. Some additional features found in this class of firewalls are:

- 493 1. Ability to specify allowable list of services (control at the application level)
- 494 2. Traffic matches the intent of allowed ports
- 495 3. Filtering of some unwanted protocols

496 3.3. Appliance-set with Integrated Functions

- 497 • Unified threat management (or UTM)s: UTM devices combine many of the most critical
498 security functions – firewall, intrusion prevention system (IPS), VPN concentrator,
499 gateway antivirus, content filtering, and WAN load balancing – into a single device,
500 usually with a unified management console.
- 501 • Next-generation firewall (NGFW): This all-in-one security appliance is based on the
502 UTM model but is combined with enterprise-class scalability and performance and a
503 focus on the granular inspection of Layer 7 application traffic. NGFWs have added
504 capabilities to facilitate internal segmentation, integration with sandboxing products,
505 secure sockets layer (SSL) inspection, and SD-WAN. Processing at the edge benefits
506 from on-premises firewalls, which apply processing on-site. They are more energy-
507 efficient than virtual machines and reduce latency because they avoid the “round trip” to
508 the cloud. NGFWs come with high-performance threat protection (e.g., intrusion
509 prevention, web filtering, anti-malware, application control) for known attacks, SSL/TLS
510 inspection, and antivirus [9].
- 511 • Web application and API protection (WAAP): This is a comprehensive security approach
512 and an enhancement over web application firewalls (WAF). WAF is an integral
513 component for API security, BOT defense, and DDOS protection.
- 514 • These can be offered as a product suite or as a cloud-based service [10][11].
- 515 • Secure web gateway (SWG)s: SWGs are appliances utilized for policy-based access to
516 and control of cloud-based applications for enterprise users in ubiquitous locations (e.g.,
517 headquarters, branch offices, home, remote locations). A SWG is fundamentally a web
518 filter that protects outbound user traffic through HTTP or HTTPS inspection [12]. They
519 also protect user endpoints from web-based threats that can occur when users click on
520 links to malicious websites or to websites infected with malware. They centralize control,
521 visibility, and reporting across many locations and types of users. They are not a
522 replacement for WAFs, which protect websites housed in enterprise data centers and
523 large headquarter sites from inbound attacks.

524 3.4. Requirements for Network Automation Tools

525 Network automation tools automate the entire life cycle processes involved in deployment,
526 observability/monitoring, threat intelligence gathering/reporting (e.g., generating alerts of
527 security violations for security personnel to take timely action), and – in some instances –

528 automatic remediation. These automated tools are an indispensable part of a complex enterprise
529 network landscape. The requirements for these tools can be broadly classified into generic and
530 functional requirements. These requirements are described below. Each generic requirement is
531 tagged with the abbreviation NAUT-GR-x, while each functional requirement is tagged with
532 NAUT-FR-x, where x in both types of tags stand for the numerical sequence.

- 533 • NAUT-GR-1: Scale to meet the volume, velocity, and variety of today’s application
534 development deployment and maintenance paradigms [13]. This requirement is critical in
535 environments where DevSecOps is used to deploy not only applications but also
536 infrastructures, the latter using infrastructure-as-code (IaC) tools. These tools are made an
537 integral part of the smart automated workflows called CI/CD pipelines, which invoke
538 these tools to deploy servers (computing), networking, and storage infrastructure. Hence,
539 this class of network automation tools can be seamlessly integrated into the
540 corresponding CI/CD pipelines.
- 541 • NAUT-GR-2: They should have the capability to minimize human intervention for
542 security remediation, which is slow and prone to error. In other words, the more
543 automated remediation features built into the tool, the better.

544 The minimum functional requirements of network automation tools should be:

- 545 • NAUT-FR-1 (enhanced threat intelligence and protection): The tools should have
546 advanced threat intelligence, real-time threat prevention capabilities for known and zero-
547 day vulnerabilities, and sandboxing features for isolating malicious traffic.
- 548 • NAUT-FR-2 (leveraging knowledge of previous events): The tools should have features
549 for matching current events to past ones and for leveraging the remediation measures
550 performed for those instances in the current solution. This brings about reduction to the
551 average outage time [14].

552 The network monitoring and observability tools and IaC tools are important classes of network
553 automation tools, and the requirements and feature set are discussed in the following subsections.

554 **3.4.1. Network Monitoring and Observability Tools**

555 This class of tools gathers the data for obtaining visibility into the entire network. The data is
556 then used to generate a dashboard that presents the topography of the enterprise network by
557 showing all connections and presenting key operating parameters (e.g., latency, network traffic
558 level, etc.). Some of the data generated by this class of tool and their uses are:

- 559 • Identification of interfaces: Monitoring tools identify the interfaces for defining the
560 parameters for network resources provisioning and help the IaC generate the relevant
561 code for invoking those interfaces.
- 562 • Measurement of drift: Despite using IaC to deploy the network infrastructure,
563 unauthorized or ad hoc changes in network configuration can alter the performance and
564 security parameters for application execution (called the drift). Monitoring tools should
565 have the ability to monitor these parameters (e.g., bandwidth availability, unwanted
566 traffic, etc.) and alert for corrective action.

- 567 • Secure overlay designs for cloud service access: Monitoring tools can generate data to
568 enable centralized network management tools to perform security functions, such as
569 building a virtual network segmentation on top of the native network segmentation
570 features offered by CSP, provided that suitable APIs are available.
- 571 • Support for incidence response process: Sophisticated network monitoring tools generate
572 network security alerts and threat intelligence feeds. Handling these alerts and feeds is
573 part of the incidence response (IR) process in an enterprise and is carried out by members
574 of a security operations center (SOC). A security strategy that has evolved in recent years
575 to automate the IR process is called security orchestration, automation, and response
576 (SOAR). Some of the state of practice applications of SOAR include threat detection and
577 response, vulnerability prioritization, compliance checks, and security audits with
578 potential applications in many emerging areas, such as IoT management [15].

579 **3.4.2. Automated Network Provisioning Tools**

580 As already stated, automated network resource provisioning is enabled by infrastructure as code
581 (IaC) tools. The code that describes the networking infrastructure (in addition to the computing
582 and storage infrastructure) is stored in a code repository. The process of initial deployment of the
583 networking infrastructure and subsequent upgrade is automated by defining a workflow that
584 invokes the IaC (e.g., GitOps workflow) as part of a CI/CD pipeline definition [16]. The
585 advantages of this approach for managing the enterprise networking infrastructure for multi-
586 cloud deployment are the following:

- 587 • Enables the enterprise to have tight version control (tracking changes) so that
588 unauthorized networking devices and unauthorized changes in associated configurations
589 do not open up security vulnerabilities.
- 590 • Enables the enterprise to have a uniform infrastructure across all environments –
591 development, testing, staging, and production.
- 592 • Monitoring the drift (the unintended changes) between the defined infrastructure (as
593 found in IaC) and the operational infrastructure (as measured by monitoring tools
594 described in Section 3.4.1) and taking corrective action to address the drift help to
595 maintain the necessary security posture for the enterprise networking environment.
- 596 • The DevSecOps paradigm consisting of CI/CD pipelines invokes the network
597 provisioning tool (IaC code generator) to automate the initial deployment and subsequent
598 re-configuration of the networking infrastructure. Since the pipelines have a built-in audit
599 process, the changes in network configuration are automatically captured in the audit,
600 which in turn enables the enterprise to demonstrate corporate security policy compliance
601 and regulatory policy compliance for their networks where applicable.
- 602 • Testing the code (IaC code) generated by IaC tools (and invoked by the CI/CD pipeline
603 code that deploys the infrastructure using IaC) ensures that security policies are
604 consistently and uniformly applied across the entire enterprise networking infrastructure
605 (i.e., multiple cloud services).
- 606 • The advantage of having plug-ins for defining network provisioning for different public
607 cloud provider environments is that they can be used to customize the observability tools

608 used for networking monitoring for each of those cloud services that the enterprise has
609 subscribed to [17].

610 **3.5. Networking Appliances as Services**

611 Another trend in the enterprise network landscape is that a portion of network infrastructure can
612 be obtained as a leased service called a network as a service (NaaS) from third-party providers.
613 This service is offered using technologies such as enterprise 5G and edge computing. The
614 advantages of NaaS are as follows:

- 615 • Just like subscriptions to SaaS and IaaS, it reduces capex costs for the enterprise.
- 616 • Being software-defined and virtualized, it is flexible and scalable.
- 617 • As a consequence of the previous advantage, QoS requirements of diverse applications
618 can be met by creating customized traffic flow for each application type [18].
- 619 • New applications that require an increased network footprint can be quickly introduced to
620 the enterprise (agility), thus facilitating business diversification.

621 **4. Enterprise Network Configurations for Hybrid Application Environments**

622 Since the enterprise context in this document refers to enterprises that consist of on-premises and
623 cloud-hosted applications (i.e., hybrid application environments), this document describes the
624 network configurations or designs (and network communication exchanges based on them) that
625 have emerged as state of practice in those enterprises.

626 The state of practice network configuration features (NCF) found in enterprises with hybrid
627 application environments can be classified under the following areas [19]:

- 628 • Network configuration for Device Management
- 629 • Network configuration for User Authentication
- 630 • Network configuration for Device Authentication and Health Monitoring
- 631 • Network configuration for Authorizing Application Access
- 632 • Network configuration for Preventing Attack Escalation (Microsegmentation)

633 Each of the network configuration features are enumerated using the identifier of the form HAE-
634 NCF-x, where HAE denotes a hybrid application environment, NCF denotes the network
635 configuration feature, and x stands for the sequence number of the feature.

636 **4.1. Network Configuration for Device Management**

637 With the disappearance of the network perimeter (Section 2.1) and the distribution of the
638 application targets (being a hybrid application environment), enterprises should adopt an
639 “endpoint is the perimeter” paradigm and have a device management system in place.

640 HAE-NCF-1: All endpoints that will be accessing on-premises and cloud-based applications
641 should be managed using a dedicated management network. Minimal managed tasks should
642 include:

- 643 a) Installation and maintenance of device and service authentication certificates
- 644 b) Installation and maintenance of device health applications
- 645 c) Updates of patches on the devices
- 646 d) Creation and maintenance of white pages that contain device-service mappings to prevent
647 service hijacking (preventing malicious or compromised servers posing as legitimate
648 hosts for the services)

649 **4.2. Network Configuration for User Authentication**

650 HAE-NCF-2: The network should be configured to route the user access request to different
651 destinations for authenticating the user, depending on the target application accessed.

- 652 a) When the user access request is for a cloud-based application (e.g., SaaS), the user should
653 be routed to the enterprise IdP. When the user access request is for an on-premises web
654 application, the user should be directed to a web gateway (reverse proxy). This
655 redirection can be affected through a process called split DNS. If a digital certificate is
656 used as the first authentication factor, the IdP should check the validity of the user

657 certificate (right status and not expired) through mechanisms such as CRL, OCSP, or
658 Active Directory calls.

659 b) A minimum of two authenticator factors must be used to authenticate users. If possession
660 of a valid certificate is the first factor, then the acknowledgement of a push message
661 (using technologies such as DuoMobile, TouchID or Yubikey) or OTP to the cell phone
662 can be used as the second factor.

663 **4.3. Network Configuration for Device Authentication and Health Monitoring**

664 HAE-NCF-3: Device authentication can be performed through certificate validation using
665 appropriate protocols. A device health check can be performed by invoking the resident
666 application.

667 HAE-NCF-4: Microservices-based applications (on-premises or in cloud) should have service
668 proxies installed with each service to provide the necessary connectivity for inter-service
669 communication in addition to performing authentication and authorization services for each
670 service request.

671 **4.4. Network Configuration for Authorizing Application Access**

672 HAE-NCF-4: Standardized protocols, such as OAuth 2.0 [20], should be used to issue access
673 tokens to the validated user, device, or service to enable access to cloud-based applications.

674 **4.5. Network Configuration for Preventing Attack Escalation** 675 **(Microsegmentation)**

676 Microsegmentation is a security design practice where an internal network (e.g., in the data
677 center, cloud provider region) is divided into isolated segments so that the traffic in and out of
678 each segment can be monitored and controlled [21].

679 Things enabled by microsegmentation are:

- 680 • Segments being isolated and relatively small enables close monitoring of the traffic
681 because of better visibility.
- 682 • The consequence of the above capability is that granular access control is possible by
683 defining associated policies.

684 The enablement of the above capabilities restricts the unauthorized lateral movement of a user or
685 application that has either (a) breached the perimeter to enter the internal network or (b) been
686 initiated by users within the internal network itself.

687 **4.5.1. Prerequisites for Implementing Microsegmentation**

688 a) Creation of application identity: The fundamental requirement to enable this is the
689 assignment of a unique identity to each application or service, just like how each user
690 carries a unique identity (e.g., userid). Prior to the era of cloud-based applications, the
691 application requests were validated based on the IP subnet or IP address from which they

692 originated. Ubiquitous access and multi-clouds have eliminated the concept of network
693 perimeters. Hence, authentication and authorization based on those parameters are neither
694 feasible nor scalable. Further, the presence of proxies, network address translation, and
695 load balancers make it impossible for the called application to know the IP address of the
696 calling application in order to make authentication or authorization decisions. A unique
697 application identity is inevitable.

698 b) Establishment of trust in application identity: The created application identity should not
699 be subject to spoofing and should be continuously verifiable. Hence, a cryptographic
700 identity in the form of a public key carried in a certificate issued by a trusted source is
701 required to meet these criteria. Verification of the authenticator associated with this
702 identity is done by the authenticating party by sending a challenge, and insurance against
703 replay attack for the authentication process is ensured by sending a nonce attached to the
704 challenge. A secure directory that provides a mapping of the service to the hosting server
705 should be maintained to ensure that applications or services are hosted only on authorized
706 servers and that spurious versions of services do not exist.

707 c) Discovery of application resources: There should be a robust means for discovering all
708 application resources (e.g., services, networks, etc.).

709 d) Segmentation of workloads: Security requirements for all applications and services must
710 be identified and groupings established based on identical security requirements.

711 e) Mapping of logical application groupings to physical or virtual infrastructures:
712 Application-centric groupings must be mapped to physical or virtual infrastructures that
713 constitute the data center topology to facilitate actual applications and services
714 deployment.

715 **4.5.2. Microsegmentation – Implementation Approaches**

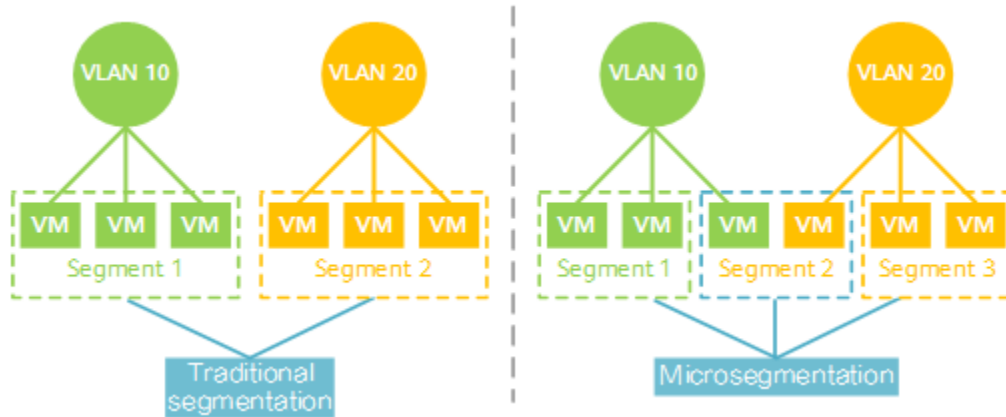
716 The following approaches are employed to implement microsegmentation [22]:

717 a) Segment-based approach: In this approach, the applications and services resources with
718 similar security requirements are grouped into a unique segment, and firewall rules are
719 created to block or allow communication with each group or segment. The segments are
720 created using network layer abstractions, such as VLAN IDs or some other tagging
721 approaches, while policies are defined using network address constructs (e.g., IP addresses
722 and ports). Policies apply to subnets (e.g., VLANs) and not to individual hosts. Each
723 segment is protected by gateway devices, such as intelligent switches and routers or next-
724 generation firewalls (NGFWs), which should have the capacity to react and adapt in
725 response to the threats and changes in the application workflows. Segmentation gateways
726 monitor traffic, stop threats, and enforce granular access across east-west traffic (rarely for
727 north-south traffic) within on-premises data centers or cloud regions. The main difficulty
728 with this approach is the difficulty in mapping the applications security requirements-
729 based segments created to corresponding network segments [23].

730 A schematic diagram of the segment-based microsegmentation is shown in Figure 1.
731 Each numbered microsegment in the figure is a unique VLAN identified by a VLAN ID.
732 The group of applications that will run in that particular VLAN segment can be defined
733 using different criteria. One of the criteria is “all applications with similar security

734 requirements.” Another is that “all tiers (web frontend, application logic servers, and
735 database servers) associated with a particular application” should run in a single
736 microsegment, as shown in the figure.

737



738

739

Fig. 1. Segment-based Microsegmentation

740 b) Virtualized server-based approach: This approach is only applicable to networks that
741 contain virtualized servers since it is implemented in the hypervisor. There are two
742 possible mechanisms:

- 743 1. Using virtual firewalls inside a hypervisor to isolate traffic destined for different
744 VMs inside the hypervisor
745 2. Using encapsulation techniques to create overlays (e.g., VXLAN) that run on top
746 of an underlay network consisting of IP addresses designations; access control
747 policies are enforced on the hypervisor itself outside of the workload (application
748 or microservice)

749 c) Host-based microsegmentation: Alternatively (or additionally), host-based
750 microsegmentation can be implemented using software agents on the endpoint artifacts
751 (e.g., servers). It leverages native firewall functionality built into the host. Software agents
752 can overlay a software-defined segmented network across data centers, cloud, bare metal,
753 and hybrid environments. The agent provides context awareness and visibility for each
754 workload and, hence, enables the definition and enforcement of fine-grained policies.

755 d) Identity-based microsegmentation: Identity-based microsegmentation policies use
756 contextual, application-driven identifiers (e.g., order processing front-end service can
757 communicate with inventory back-end service) instead of network parameters (permit
758 calls from 192.168.10.x subnet to 10.0.0.31) [24]. The identifiers assigned to services are
759 cryptographic identities, which they use for mutual authentication and authorization
760 during each service request and response.

761 The advantages of this type of microsegmentation are:

- 762 • Policies based on service/application identities do not use any infrastructure-related
763 variables (e.g., IP addresses, subnets, etc.), so these policies are environment-agnostic
764 and provide the freedom for the services/applications to be migrated to different
765 environments and still maintain the same policies.

- 766 • Policies being independent of infrastructure enables them to be tested by merely
767 exercising the application and observing the outcomes (e.g., trace of the sequence of
768 service calls and requests/responses instead of configuring the infrastructure correctly for
769 test runs).
- 770 • With the availability of tools for the declarative specification of policies through “policy
771 as code” tools, microsegmentation policies can be defined/implemented by incorporating
772 the code into automated workflows, such as CI/CD pipelines.
- 773 • Microsegmentation enables granular (fine-grained) access control by providing visibility
774 to application call sequences/interdependencies and data flows through host-level tracking,
775 thus enabling the enforcement of security policies for application traffic that is both north-
776 south and east-west, irrespective of the environment (e.g., corporate data center or cloud
777 infrastructure).

778 The reason that identity-based microsegmentation is studied under the enterprise network
779 landscape is that it enables only valid network traffic between the various component services of
780 the application due to the mutual authentication and authorization using service identities, thus
781 enabling the goals of zero trust network access (ZTNA) to be met [25].

782 **4.6. Security Frameworks Governing Network Configurations**

783 The network configurations described in Sections 4.1 through 4.5 are each for specific functions
784 (e.g., user authentication, preventing attack escalation, etc.). In many enterprise environments,
785 these network configurations are not ad hoc but are driven by some conceptual underpinning
786 (e.g., contextual information) and/or some evolving enterprise network security framework that
787 the enterprise has chosen to implement. Examples of such frameworks are software-defined
788 perimeter (SDPs) and zero trust network access (ZTNA).

789 **4.6.1. Conceptual Underpinnings – Contextual Information**

790 Section 2.4 discussed the limitation of using user identity alone to authorize application access.
791 This, however, does not mean that identity verification can be relegated to a secondary
792 requirement. It has been widely recognized that identity validation is the entry point (may be a
793 highly vulnerable point of entry into the system) to an application request [26] since all requests
794 – whether coming from a service (or microservice), user, or device – come with a claimed
795 identity. This identity must be verified using robust, phishing-resistant multi-factor
796 authentication.

797 However, other attributes associated with the user and the information associated with other
798 entities involved in an application access request, such as devices and services, are required in
799 current enterprise IT environments and are collectively called contextual information. This
800 contextual information set may vary from one enterprise to another and is also based on the level
801 of trust that the organization requires for a particular access request. Since the role of contextual
802 information in potential attacks may not be known, the set to be included in the access decision is
803 a risk-based decision. Contextual information may broadly belong to the following five key areas
804 [27]:

- 805 1. Information about the user requesting access – Apart from user identity, attributes
806 associated with the user, such as their role in the organization, current assignments, and
807 status (cross verification of identity in the enterprise IDM vs enterprise directory)
- 808 2. Information about the device from which access is being requested – Establishing trust in
809 the device through a combination of health and risk profiles of the device. For example,
810 the risk profile of the device can be obtained through an out-of-the-box posture check
811 (risk of the device [28]) with or without integrating with an endpoint protection tool for
812 the device. Other crucial information (provided by telemetry data) needed to assess the
813 security status of the endpoint devices [29] include (a) device support label (the device is
814 managed or corporate-owned) and (b) device posture information (whether it has been
815 compromised). All of these factors go into a policy evaluation for determining the level
816 of trust and must be channeled into authentication and monitoring decisions [30].
- 817 3. Information about real-time contextual data – Date, time, and geolocation at which the
818 access request occurs
- 819 4. Information about IT services (e.g., app, data, etc.) being accessed
- 820 5. Information about the security of the environment hosting the IT services being accessed

821 The requirements for contextual information [27]:

- 822 • Should include not only that which is collected by the native platform (the platform on
823 which the application is hosted) but also that which can be obtained from third-party
824 platforms and can provide more detailed information
- 825 • Should be available in real time so that user experience with access is not affected
- 826 • Should be prioritized based on the value each provides
- 827 • Should be consistent with the level of risk associated with each access request

828 No application and/or data access in the modern enterprise network context can be deemed
829 secure by ignoring relevant contextual information when the access scenario involves allowing a
830 user, device, or service from any network channel (e.g., corporate network, home network,
831 public network, or branch office) to access a resource located anywhere (on-premises or cloud).

832 **4.6.2. Network Security Framework – Software-defined Perimeter (SDP)**

833 One conceptual underpinning for secure network access to IT resources is the software-defined
834 perimeter (SDP) [31]. In SDP, the separation between networks is not defined by network
835 address group or VLANs, making it network-agnostic. It is logically and dynamically defined for
836 each user and each particular request. In other words, for each user request, the subset of IT
837 resources to which the user has access is dynamically allocated irrespective of the location of the
838 resource (e.g., corporate data center, branch office, private or public cloud, etc.). The salient
839 principles of SDP include:

- 840 • The SDP concept involves making all IT resources invisible (e.g., ports, workloads, and
841 applications) and making them known and accessible only after the user is authenticated
842 and authorized. Only a network connection between the user and the allowed IT
843 resources is established, thus following the least privilege principle.

- 844 • The access level determined by the previous process is continuously reevaluated during
845 the user session and recalibrated if required. In other words, as the context surrounding
846 the identity changes in real time, so can the user’s entitlements [31].
- 847 • Reduce the attack surface by preventing lateral movement [32] through techniques like
848 microsegmentation, as described in Section 4.4. With the increasing deployment of
849 microservices, the inter-services resource requests (generator of east-west traffic)
850 dominate external application requests (north-south traffic). Application of this principle
851 thus secures east-west traffic.

852 **4.6.3. Network Security Framework – Zero Trust Network Access (ZTNA)**

853 ZTNA is the consequence of a zero trust architecture, which in turn is a realization of zero trust
854 principles. NIST defines zero trust and zero trust principles as [33]:

- 855 • Zero trust (ZT) is the term for an evolving set of cybersecurity paradigms that move
856 defenses from static, network-based perimeters to focus on users, assets, and resources. It
857 is a set of security primitives rather than a particular set of technologies. Zero trust
858 assumes that there is no implicit trust granted to assets or user accounts based solely on
859 their physical or network location (i.e., local area networks versus the internet) or based
860 on asset ownership (enterprise or personally owned). Zero trust focuses on protecting
861 resources (e.g., assets, services, workflows, network accounts, etc.) rather than network
862 segments, as the network location is no longer seen as the prime component to the
863 security posture of the resource.
- 864 • A zero trust architecture (ZTA) uses zero trust principles to plan industrial and enterprise
865 infrastructure and workflows.

866 NIST’s guidance on ZTA [33] contains an abstract definition of zero trust architecture (ZTA)
867 and gives general deployment models and use cases where zero trust could improve an
868 enterprise’s overall information technology security posture. From the NIST vision of ZTA and
869 state of practice implementations [34], the following have emerged as the three building blocks
870 of ZTA:

- 871 1. **Client or Browser:** The point of entry for all users to access any resources hosted in
872 multi-cloud and on-premises environments
- 873 2. **The Controller:** The policy decision engine, which manages the policies, conditions, and
874 entitlements that grant access for all users, devices, and workloads from a single
875 dashboard or via API
- 876 3. **The Gateway:** The policy enforcement point. Gateways control the flow of access to
877 protected resources. It dynamically builds micro-segmentation rules based on granted
878 entitlements.

879 In all security frameworks for current enterprise network environments, the common principles
880 that underly application-specific requirements – such as low latency, high data transfer rates, and
881 high reliability – that were applicable in previous network landscapes remain the same.

882 **5. Secure Wide Area Network Infrastructure for an Enterprise Network**

883 The wide area network (WAN) became an integral part of the enterprise network when
884 organizations needed to connect their local area networks (LANs) across multiple geographically
885 distributed locations (within the country and, in some cases, globally) starting in the 1980s. The
886 initial WAN technology involved point-to-point (P2P) leased lines followed by Frame Relay.
887 The first IP-based network was multiprotocol label switching (MPLS), which enabled multiple
888 types of traffic – such as voice, video, and data – to travel on the same line.

889 With the advent of technologies such as virtualization and increasing enterprise access to cloud
890 services, enterprises have begun to adopt a new WAN technology called the software-defined
891 wide area network (SD-WAN). SD-WAN technology removes the tight coupling between the
892 control plane and data plane functions of the network and enables the centralized specification of
893 various policies, such as access control, routing, and application traffic prioritization.

894 Another development involved integrating all of the point security solutions provided by various
895 network security appliances (Section 3) into a network security services infrastructure. Industry
896 and industry consortiums use the term secure access service edge (SASE) [35] to refer to a
897 comprehensive framework that offers wide area networking and various security services. SASE
898 can be looked upon as the networking counterpart of the application’s service mesh, which
899 provides a comprehensive set of application services, including security for cloud-native
900 applications.

901 Based on the above discussion, this section will focus on the following topics:

- 902 • Requirements for a secure SD-WAN
- 903 • Requirements for an integrated security services architecture for SD-WAN

904 **5.1. Common Requirements for a Secure SD-WAN**

905 In addition to CSP-provided VPNs, a networking technology that provides network connectivity
906 for accessing cloud-based services for enterprises is the software-defined wide area networking
907 (SD-WAN).

908 The design goals and common features in all SD-WAN offerings include:

- 909 • Extensive connectivity: To securely connect users located anywhere (e.g., home, public
910 location, branch office, corporate office, etc.) to applications and resources hosted
911 anywhere (e.g., data center, single or multiple cloud services) using any WAN transport
912 (e.g., MPLS, Broadband Internet, 4G, LTE, 5G wireless)
- 913 • Application awareness: To monitor the network traffic and dynamically choose the best
914 path available based on (a) the type of network traffic, (b) network load conditions, and
915 (c) the application’s business priority. This capability is enabled using techniques such as
916 bandwidth utilization, load balancing, and the optimization of speed by reducing jitters,
917 latency, and packet loss. Addressing application’s business priority is only possible if the
918 SD-WAN solution has the ability to identify different types of applications (e.g.,
919 messaging/email application, social media application, general storage-related
920 applications, supply chain applications) and allocate routing priorities and WAN
921 resources accordingly.

- 922 • Integration of security and networking functions: Use of appliances that contain a
923 combination of networking and security functions (e.g., the presence of a firewall and
924 secure web gateway [SWG] functions in a WAN router) [36]
- 925 • Centralized visibility and management capabilities: Includes the ability to recognize and
926 authenticate newly connected appliances and bring them under the defined management
927 workflows as nodes so as to configure a uniform set of policies that cover all components
- 928 • Integration with remote LAN locations: An additional preferred but non-essential feature
929 is the integration of WAN and LAN functions in a single appliance (the latter going by
930 the name SD-Branch), which can be managed using a single management console, thus
931 providing better visibility into both components. This feature enables the connectivity of
932 SD-WAN into the local LAN at the remote branch offices.

933 **5.2. Specific Requirements for WANs for Cloud Access**

934 Enterprises can gain cloud access in two ways: (1) through the VPN services provided by the
935 cloud providers or by (2) integrating their own SD-WAN with cloud providers' private networks,
936 often called the cloud WAN. The advantage of the second approach is that enterprises can extend
937 their existing WANs into and across a cloud provider's private network, enabling consistent
938 enterprise networking and security policy enforcement. Two of the advantages of this extension
939 are:

- 940 1. Complete end-to-end visibility between "access endpoint" and IT resource (application or
941 data) endpoint even though the latter is located in a cloud provider's network
- 942 2. Application of the network segmentation logic deployed for accessing on-premises
943 resources to the cloud-based resources [37]

944 This orchestration of the cloud provider's private network can be achieved by designing a
945 customized overlay network on top of the cloud provider's network as the underlay network.
946 This feature is contingent upon CSPs offering API integrations for different SD-WAN offerings
947 [38][39][40].

948 An architecture has emerged for managing enterprise networks that are connected to multiple
949 CSPs. A portion of the industry calls the collection of appliances in this architecture a cloud
950 network platform. The requirements for this multi-cloud networking platform are [41]:

- 951 • It should deliver common operational visibility and control across native network access
952 provided by multiple cloud providers. The big challenge is that public cloud providers
953 have different proprietary architectures using their own "constructs." In order to provide
954 a networking architecture that can "cross clouds," one needs to leverage the cloud-native
955 functionality (especially native cloud networking constructs) of each cloud; abstract that
956 functionality with APIs; add advanced data plane features for high-availability, security,
957 and operational visibility/control; and provide the tools to manage these features
958 dynamically or automatically [42].
- 959 • It should deliver a common ingress and egress security policy for application
960 environments (e.g., VPCs, VNETs, VCNs, etc.) across clouds.

- 961 • It should enable end-to-end encryption inside of the cloud as well as high-performance
962 encryption from the data center to the cloud.
- 963 • It should support automation for deployment and configuration.

964 Based on the above requirements, multi-cloud networking platform offerings have emerged with
965 the following architectural elements:

- 966 • An abstraction layer that sits on top of the native network access offered by individual
967 CSPs to their services. This layer enables the enterprise to manage the entire enterprise
968 network – consisting of connectivity to multiple clouds, intra-cloud connections, and the
969 on-premises data center network fabrics – as one unit. To enable this, complete visibility
970 into the entire enterprise network landscape is needed. Hence, this layer needs input from
971 sophisticated observability and monitoring tools to carry out its functions.
- 972 • Choosing an infrastructure configuration (e.g., virtual private cloud configuration with
973 isolated network segments) for hosting applications in the network infrastructure
974 provided by the CSP is facilitated by a class of tools called IaC tools, which have features
975 with network configuration definitions of major CSPs built in as plug-ins. This facilitates
976 initial networking resource provisioning and subsequent modification of networking
977 configuration and resources for hosting enterprise applications in clouds.

978 There are four industry trends [43] that may have security implications with regard to SD-WAN
979 [44]:

- 980 1. SD-WAN access is acquired as a cloud-based service under the umbrella of network as a
981 service (NaaS), just like IaaS and SaaS.
- 982 2. AI-based algorithms are used for monitoring networks for security-related conditions; for
983 resiliency-improving measures, such as throttling for certain destinations; and for
984 dynamic routing decisions to maintain QoS parameters, such as latency and bandwidth.
- 985 3. Wireless networks are used for last mile connectivity using a 5G Radio Access Network
986 (RAN).
- 987 4. Secure remote access functionalities provided by technologies such as VPN are combined
988 into SD-WAN [45].

989 **5.3. Requirements for an Integrated Security Services Architecture for SD-WAN**

990 An integrated security services architecture for SD-WAN has integrated within it both
991 networking and security functions. The network access and security functions capabilities are
992 offered as a cloud service that are accessible for enterprises through strategic network locations
993 spread over a wide area called Point of Presence (PoP). The term coined by Gartner in 2019 to
994 denote an architecture that converges networking and security functions and delivered at a global
995 scale as a cloud service is called Secure Access Service Edge (SASE) [46]. The networking and
996 security services delivered by a service called SASE are not new but just delivered together as a
997 single package instead of through point security solutions (chapter 3). The various points of
998 connectivity from the enterprise to SASE PoPs are called enterprise edges. The enterprise edges
999 can be either:

- 1000 • Clients (Users accessing through desktops, laptops and mobile devices either from branch
1001 offices or remote locations such as Home, or IoTs)

- 1002 • IT Resources (Internal Apps hosted in data centers or branch offices, Cloud-based Apps
1003 (SaaS, IaaS))

1004 The SASE network infrastructure thus becomes an integral part of the enterprise network
1005 whenever one or more of the enterprise edges get connected to various PoPs of SASE cloud
1006 service.

1007 The three primary functions delivered by SASE are [46]:

- 1008 • Optimization of Network Traffic for different types of Traffic – Reduce Latency and
1009 Improve Availability
- 1010 • Access Control for accessing different types of IT resources -Applications, Databases etc.
- 1011 • Threat Prevention – Monitoring, Gathering threat and attack information, remedial action

1012 Some of the structural features in SASE offerings are:

- 1013 • Globally distributed point of presence (PoP): A global SD-WAN service with its own
1014 private backbone network consisting of worldwide points of presence (PoPs) intended to
1015 minimize latency problems. In some instances, major cloud vendors' PoPs may also be
1016 leveraged.
- 1017 • Security agent on devices: The security agent on the end user's device undertakes
1018 networking decisions and directs traffic from different applications. Specific capabilities
1019 include dynamically allowing or denying connections to services and applications based
1020 on an organization's defined business rules.

1021 The following are the minimal security services found in an integrated architecture:

- 1022 • Firewall services
- 1023 • Secure web gateway services
- 1024 • Anti-malware services
- 1025 • IPS services
- 1026 • CASB services
- 1027 • DLP services

1028 Some of the advanced security features found in SASE offerings include:

- 1029 • Browser isolation technology: This is often combined with secure web gateway solutions
1030 and provides improved web activity security to tackle threats in real time.
- 1031 • Continuous adaptive risk and trust assessment (CARTA) strategy: This strategy involves
1032 constantly monitoring sessions and performs adaptive behavior analysis on monitoring
1033 parameters to dynamically change security levels and permissions if the trust profile (e.g.,
1034 trust deficit) of a device changes.

1035 **6. Summary and Conclusions**

1036 The purpose of this document is to provide insights into the current enterprise network landscape
1037 in terms of topology, traffic flows, and security threats. It takes the view that changes in
1038 application architecture and technologies (monolithic to microservices-based, bare metal to
1039 virtualization/containers) and increased subscriptions to various types of cloud services (e.g.,
1040 IaaS, SaaS) are drivers of the current state of enterprise networks.

1041 It outlines the limitations of existing network access security assumptions and technologies due
1042 to changes in network topologies in modern enterprise networks. The emergence of new network
1043 appliances (e.g., CASB), enhanced features in existing appliances (firewalls), network
1044 automation tools for gathering data for visibility/monitoring, threat detection and remedial
1045 actions, and tools for automated network provisioning for different public CSP environments
1046 (enabled by IaC tools invoked as part of the smart workflows called CI/CD pipelines defined
1047 under the DevSecOps paradigm) are all discussed under point security solutions. Various
1048 networking configurations for user, device, and service authentication and authorization as well
1049 as microsegmentation to prevent the escalation of attacks are also discussed.

1050 Finally, this document discusses the latest WAN technologies that form part of the current
1051 enterprise network landscape, as well as the features of WAN offerings with global PoP and
1052 integrated security services called SASE.

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