Blast-RADIUS

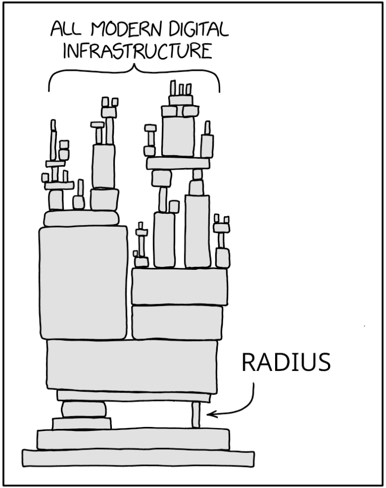
Breaking Enterprise Network Authentication

Sharon Goldberg[1], **Miro Haller[2]**, **Nadia Heninger[2]**, Mike Milano[3], Dan Shumow[4], Marc Stevens[5], **Adam Suhl[2]**

[1]Cloudflare, [2]**UC San Diego**, [3]BastionZero, [4]Microsoft Research, [5]Centrum Wiskunde & Informatica

CNS 2025; May 9, 2025

What is RADIUS? Where is it used?



modified XKCD from [5]

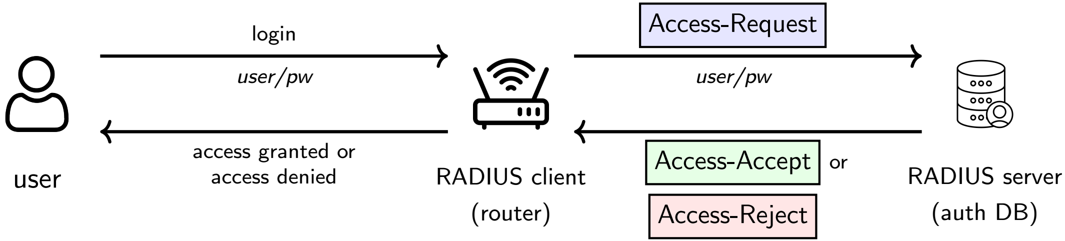
- *RADIUS:* standard protocol for enterprise network authentication.
- RADIUS is *everywhere*:

  RADIUS is [...] supported by essentially every switch, router, access point, and VPN concentrator product sold in the past twenty-five years.

  (Alan DeKok [3])
- Used for backbone routers, non-cable ISP, IoT devices, identity providers (Okta, Duo), 802.1X, enterprise WiFi, eduroam...

Blast-RADIUS on a Single Slide

How does RADIUS work?



- RADIUS uses a custom MD5-based MAC and sends most traffic over UDP.
- *Our protocol vulnerability:* MITM can change Access-Reject to Access-Accept.
- *Impact:* authenticate as any user; accelerate RADIUS/UDP deprecation.
- *Mitigation:* responsible disclosure with over 90 vendors (incl. Cisco, Microsoft, ...).

icons from [4]

THE RADIUS PROTOCOL

RADIUS Packet Formats

$$\text{Access-Request} = \underbrace{\boxed{\text{Request Header}}}_{\texttt{4 bytes}}\underbrace{\boxed{\text{Request Nonce}}}_{\texttt{16 random bytes}}\underbrace{\boxed{\text{Attributes}}}_{\substack{\texttt{User-Name test}\\ \texttt{Password Mjg2NzU1z}}}$$

$$\text{Access-Accept} = \underbrace{\boxed{\text{Accept Header}}}_{\texttt{4 bytes}}\underbrace{\boxed{\text{Response Authenticator}}}_{\texttt{16 byte ``MAC''}}\underbrace{\boxed{\text{Attributes}}}_{\substack{\texttt{Reply-Message Welcome test!}\\ \texttt{Exec-Privilege 4}}}$$

$$\text{Access-Reject} = \underbrace{\boxed{\text{Reject Header}}}_{\texttt{4 bytes}}\underbrace{\boxed{\text{Response Authenticator}}}_{\texttt{16 byte ``MAC''}}\underbrace{\boxed{\text{Attributes}}}_{\texttt{Reply-Message Access denied}}$$

Response Authenticator

Goal: Prevent forgery of packets (e.g., by MITM attacker).

The Response Authenticator from packet

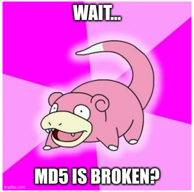
Response Header	Response Authenticator	Attributes

is computed as

copied from request   fixed, pre-configured

$$\mathrm{MD5}\left(\boxed{\text{Response Header}}\ \boxed{\text{Request Nonce}}\ \boxed{\text{Attributes}}\ \boxed{\text{Shared Secret}}\right).$$

copied from response



90s Cryptography In RADIUS

RADIUS must be broken.

Sharon Goldberg

Let's do it!

Nadia Heninger

As of the writing of this specification, RADIUS/UDP is still widely used, even though it depends on MD5 and "ad hoc" constructions for security. While MD5 has been broken, it is a testament to the design of RADIUS that there have been (as yet) no attacks on RADIUS Authenticator signatures which are stronger than brute-force.

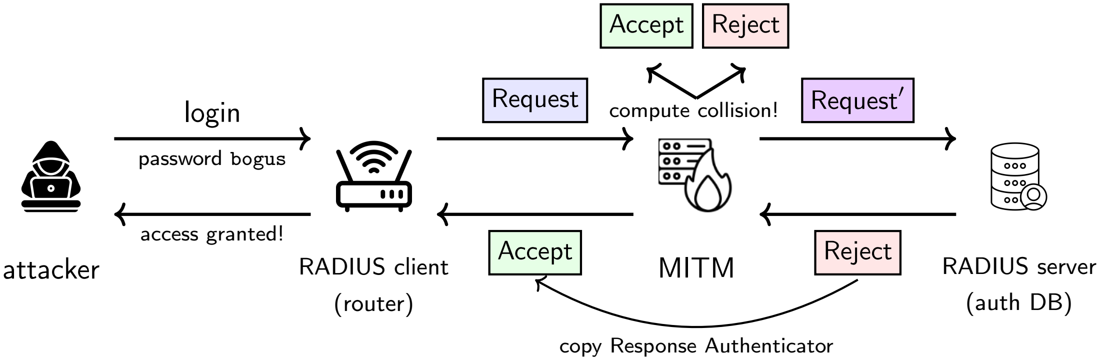
("Deprecating Insecure Practices in RADIUS" IETF draft, 2023)

THE BLAST-RADIUS ATTACK

Blast-RADIUS: Attack Overview

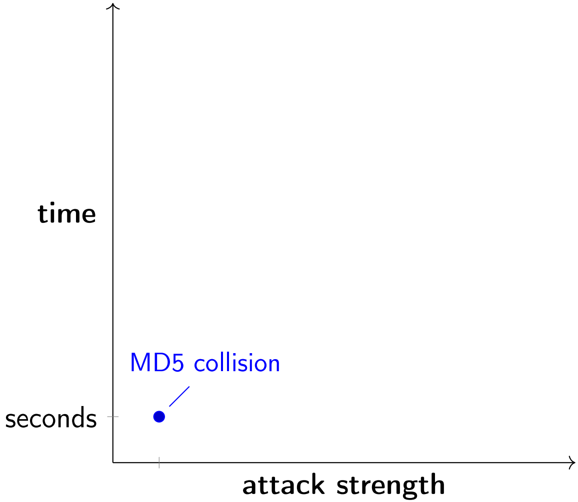
Goal: Forge Access-Accept without knowing shared secret.

Blast-RADIUS attack: Create MD5 collision s.t. Access-Accept and Access-Reject produce same Response Authenticator: MD5(Access-Accept) = MD5(Access-Reject).



icons from [4]

MD5 Collisions

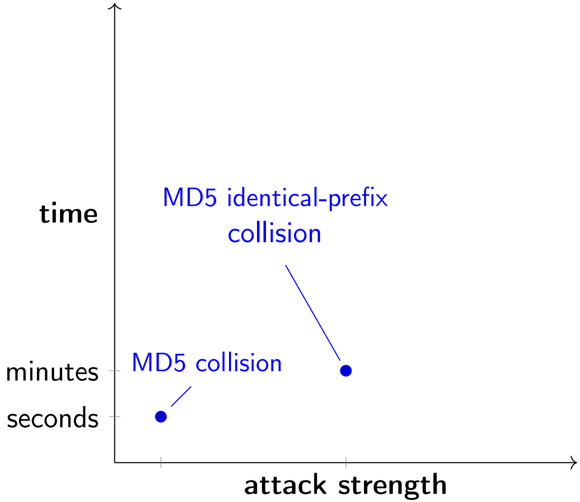


2004: MD5 collision [12]

Produce unstructured strings G_1, G_2 such that

$$\mathrm{MD5}(G_1) = \mathrm{MD5}(G_2).$$

MD5 Collisions



2004: Identical-prefix collision [12]

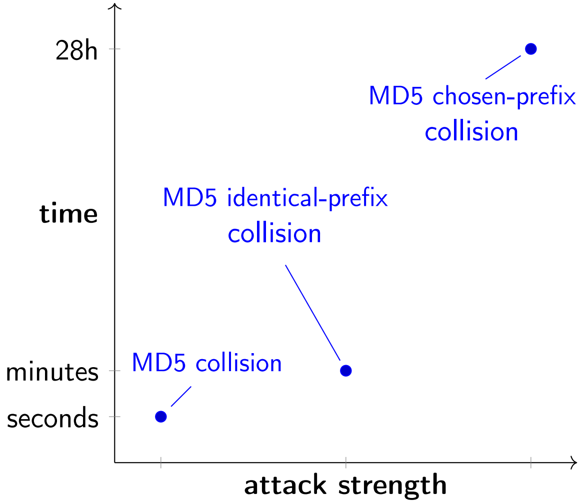
Given prefix P, produce G_1, G_2 such that

$$\text{MD5}(P||G_1) = \text{MD5}(P||G_2).$$

SHATTERED

famous non-MD5 example of an identical-prefix collision [8]

MD5 Collisions



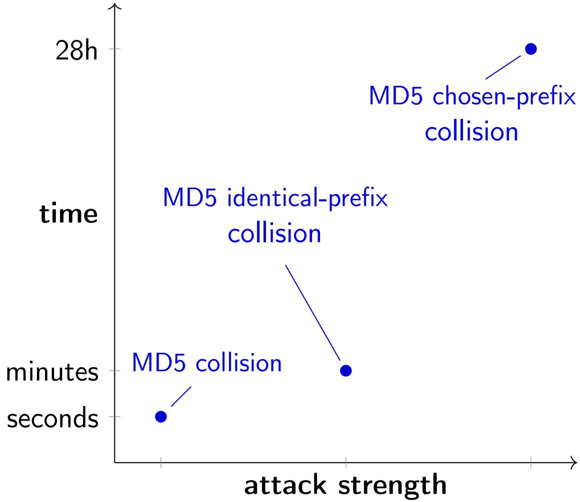
2007: MD5 chosen-prefix collision [9]

Given prefixes P_1, P_2, produce G_1, G_2 such that

$$\mathrm{MD5}(P_1 || G_1) = \mathrm{MD5}(P_2 || G_2).$$

215 PS3 for Rogue TLS CA cert [10]

MD5 Collisions



2007: MD5 chosen-prefix collision [9]

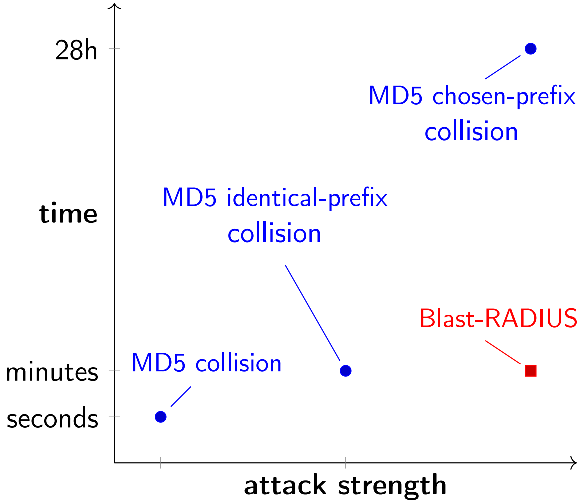
Given prefixes P_1, P_2, produce G_1, G_2 such that

$$\mathrm{MD5}(P_1 || G_1) = \mathrm{MD5}(P_2 || G_2).$$

Due to Merkle-Damgård structure of MD5, can append identical suffix S:

$$\mathrm{MD5}(P_1 || G_1 || S) = \mathrm{MD5}(P_2 || G_2 || S).$$

MD5 Collisions



2024: Blast-RADIUS

A chosen-prefix collision:*
Given prefixes P_1, P_2, produce G_1, G_2 such that (for any suffix S)

$$\text{MD5}(P_1||G_1||S) = \text{MD5}(P_2||G_2||S).$$

*But faster and with some additional conditions!

Blast-RADIUS: Turning Access-Reject into Access-Accept

Attack: MD5 collision to forge Access-Accept with same Response Authenticator as Access-Reject (without knowledge of the shared secret).

MD5 chosen-prefix collision $\text{MD5}(P_1||G_1||S) = \text{MD5}(P_2||G_2||S)$ applied to RADIUS:

$$\boxed{\text{Response Authenticator}}$$

$$= \text{MD5}\Big(\boxed{\text{Accept Header}}\boxed{\text{Request Nonce}}\boxed{\text{Accept Attributes}}\boxed{\text{Accept Gibberish}}\boxed{\text{Secret}}\Big)$$

$$= \text{MD5}\Big(\underbrace{\boxed{\text{Reject Header}}\boxed{\text{Request Nonce}}\boxed{\text{Reject Attributes}}}_{\text{predicted accept/reject prefixes } P_1,\ P_2}\underbrace{\boxed{\text{Reject Gibberish}}}_{\text{gibberish } G_1,\ G_2}\underbrace{\boxed{\text{Secret}}}_{\text{suffix } S \text{ (unknown)}}\Big)$$

That seems easy... too easy?

Challenge 1: Inject MD5 Reject Gibberish In Protocol

Problem: Server must include Reject Gibberish in Response Authenticator computation for Access-Reject.

MD5(Reject Header | Request Nonce | Reject Gibberish | Shared Secret)

Solution: The Proxy-State attribute.

> *This Attribute is available to be sent by a proxy server to another server when forwarding an Access-Request and **MUST be returned unmodified** in the Access-Accept, Access-Reject or Access-Challenge.*
>
> *(RFC 2058, emphasis added)*

Access-Request	=	Request Header	Request Nonce	Proxy-State
Access-Reject	=	Reject Header	Response Authenticator	Proxy-State

Challenge 2: Fitting Gibberish Into Protocol Attributes

Problem: Hiding $\boxed{\text{Reject Gibberish}}$ in single Proxy-State attribute is too slow.

Solution: Spread longer gibberish across multiple Proxy-State attributes by modifying collision algorithm to embed Proxy-State header.

$$\text{PS1 Header}\,\boxed{\text{Reject Gibberish}} = \overbrace{\text{PS1 Header}\,\boxed{\text{Gibberish}}}^{\text{Proxy State 1}}\overbrace{\boxed{\text{PS2 Header}}\,\boxed{\text{Gibberish}}}^{\text{Proxy State 2}}$$

(PS1 Header is part of the MD5 prefix not the gibberish.)

Challenge 3: Fast Collision Computation

Access-Request = $\boxed{\text{Request Header}}\boxed{\text{Request Nonce}}\boxed{\text{Attributes}}$

MD5($\boxed{\text{Reject Header}}\boxed{\text{Request Nonce}}\boxed{\text{Reject Gibberish}}$ Shared Secret)

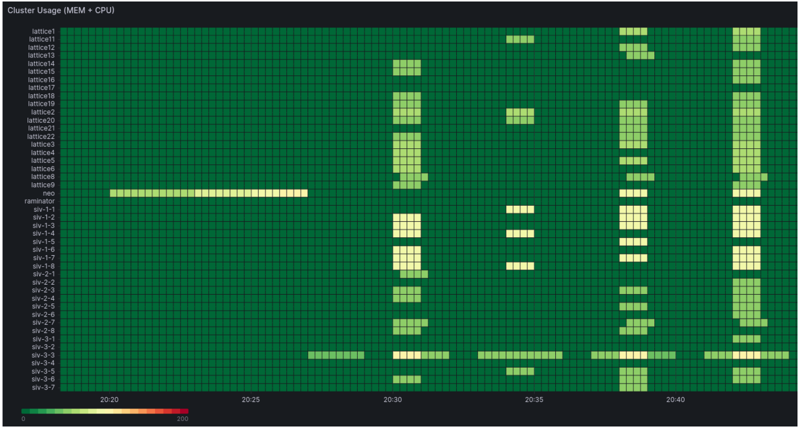
Problem: Computing MD5 prefixes requires $\boxed{\text{Request Nonce}}$.

$\implies$ Must compute collision before RADIUS client times out.

Solution: Reduce collision time from days to $\leq$ 5m (on 47 servers) with algorithmic improvements and parallelization (next).

Challenge 3: Our Optimizations

- Increase precomputation.
- New GPU generator mode for birthday search.
- Parallelize forward phase across machines.
- Tune parameters to trade runtime for success rate.



Execution monitoring during collision optimization.

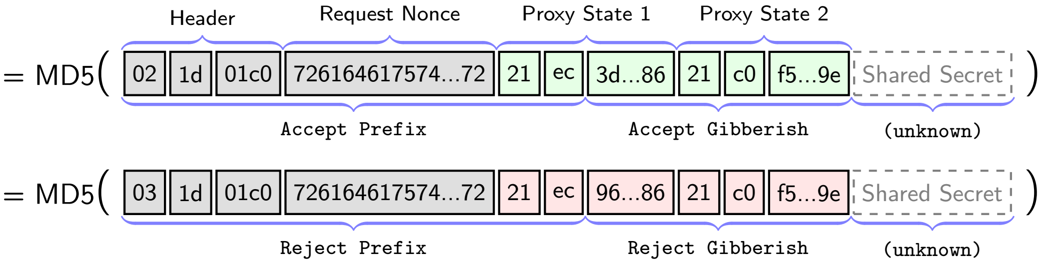
Blast-RADIUS: Example

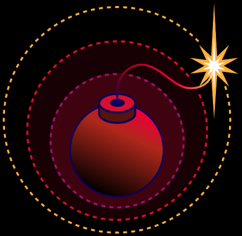
As concrete example, putting everything together, we get the following collision.

PoC example packets

`blastradius.fail/example.py`

$$\overbrace{\boxed{\text{6034d0ff16e4...30}}}^{\texttt{Response Authenticator}}$$





IMPACT

of the Blast-RADIUS attack

Successful PoCs*

Blast-RADIUS allows attacker to authenticate:

- **FreeRADIUS 3.2.3**: "most widely used RADIUS server in the world" [6]
- **Okta**: RADIUS in PAP mode for MFA.
- **Cisco ASA 5505 firewall** using RADIUS to authenticate users for access to serial console, VPN, Telnet, FTP, or HTTPS.
- **PAM**: RADIUS authentication for SSH, sudo.

$\Longrightarrow$ Confirms no Message-Authenticator used, Proxy-State accepted in Access-Accept.

PoC with Cisco ASA 5505 firewall tunneling UDP via TCP to our cluster.

*With longer timeouts than used in practice.

Impact Summary

Affected authentication modes:

- PAP, CHAP, MS-CHAP are vulnerable.
- EAP not vulnerable (more later).

Affected deployments: Requires MITM network access

- RADIUS/UDP over Internet: vulnerable.
    - incl. many non-cable ISPs and major cloud providers.
- RADIUS/UDP over VLAN/IPsec: lateral movement.

Timing:

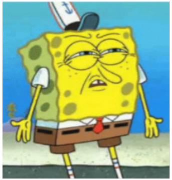
- RADIUS client timeouts $\leq$ 1m, our PoCs take $\approx$ 5m.
- Optimizations possible (parallelizes well, hardware implementation) but time consuming.

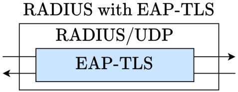
"Lots and lots and lots of people [are] sending [RADIUS/]UDP over the public Internet"

(Alan DeKok)

EAP: It's Complicated.

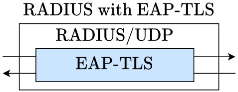
- TLS in EAP-TLS does not protect RADIUS packets.

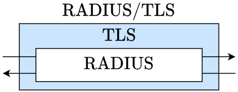


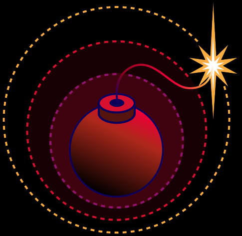


EAP: It's Complicated.

- TLS in EAP-TLS does not protect RADIUS packets.
- Not to be confused with RADIUS/TLS, which properly nests RADIUS inside TLS.
- RFC 3579 requires that EAP-Message has Message-Authenticator attribute [1].
- Unclear client behavior for Access-Accept without EAP-Message.
- In eduroam and 802.1X, key is negotiated inside EAP session $\implies$ would require further attacks.







MITIGATING

the Blast-RADIUS attack

Mitigations

Massive disclosure with 90+ vendors.

Long-term:

- Encapsulate all RADIUS traffic in (D)TLS tunnel.
- Current IETF draft is being standardized [7].

Challenges: widely used, need backwards compatibility.

Short-term:

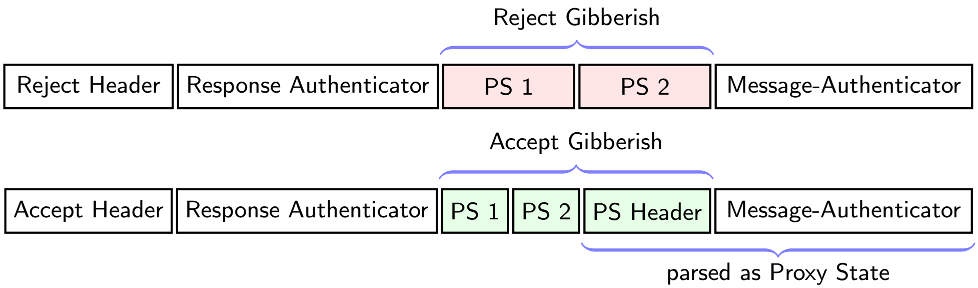
- Message-Authenticator attribute uses HMAC-MD5 not vulnerable to MD5 collisions.
- All requests and responses should include and verify Message-Authenticator.

Some power plants use RADIUS [11].

Mitigation Troubles

Many equipment vendors have upgraded [2], but some challenges remain:

- Juniper vs. Cisco: incompatible Message-Authenticator placement.
- Correct behavior: put as first attribute for sending, mandate presence for receiving.
- Incorrect placement may be vulnerable to **Message-Authenticator hiding attack**:



Blast-RADIUS Attack

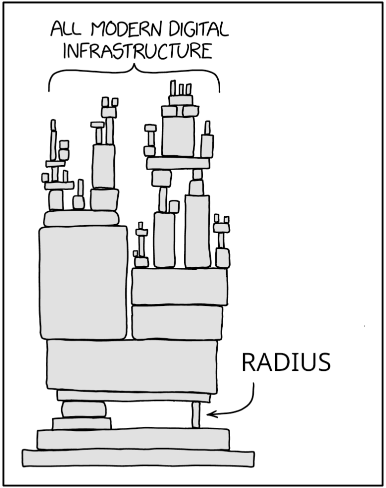
Attack summary: MD5 collision attack on RADIUS authentication by MITM adversary.

https://blastradius.fail

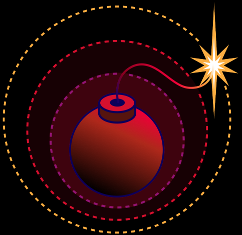
RADIUS/UDP Considered Harmful

Sharon Goldberg, Miro Haller, Nadia Heninger, Mike Milano, Dan Shumow, Marc Stevens, and Adam Suhl.

USENIX Security, August 2024.



XKCD modified from [5]



BONUS MATERIAL

End-to-End Example Attack (1/4)

$$\text{Access-Request} = \underbrace{\boxed{01}}_{\texttt{code}}\underbrace{\boxed{1d}}_{\texttt{ID}}\underbrace{\boxed{0047}}_{\texttt{length}}\underbrace{\boxed{726164617574\ldots72}}_{\texttt{Request Nonce}}\underbrace{\boxed{010674\ldots3a}}_{\text{attributes}}$$

$$\text{Access-Accept} = \underbrace{\boxed{02}}_{\texttt{code}}\underbrace{\boxed{1d}}_{\texttt{ID}}\underbrace{\boxed{0027}}_{\texttt{length}}\underbrace{\boxed{a268dc70e8a2\ldots1d}}_{\texttt{Response Authenticator}}\underbrace{\boxed{120f57\ldots04}}_{\text{attributes}}$$

$$\text{Access-Reject} = \underbrace{\boxed{03}}_{\texttt{code}}\underbrace{\boxed{1d}}_{\texttt{ID}}\underbrace{\boxed{0024}}_{\texttt{length}}\underbrace{\boxed{357bf27e8c0a\ldots e5}}_{\texttt{Response Authenticator}}\underbrace{\boxed{121041\ldots2e}}_{\text{attributes}}$$

End-to-End Example Attack (2/4)

1. Attacker triggers Access-Request.
2. MITM attacker observes Access-Request.

01	1d	0047	726164617574...72	010674...3a
			Request Nonce	

PoC example packets

`blastradius.fail/example.py`

3. MITM attacker predicts the following prefixes

Accept Prefix =	02	1d	01c0	726164617574...72	21	ec
Reject Prefix =	03	1d	01c0	726164617574...72	21	ec
					PS (1/2)	

to compute the MD5 chosen-prefix collision gibberish.

Accept Gibberish =	3d...86	21	c0	f5...9e	(428 bytes)
Reject Gibberish =	96...86	21	c0	f5...9e	(428 bytes)
	PS (2/2)	Proxy State (PS)			

End-to-End Example Attack (3/4)

4. MITM sends Access-Request with appended `Reject Gibberish` to server.

01	1d	0047	726164617574...72	010674...3a	21	ec	96...86	21	c0	f5...9e

`Reject Gibberish`

5. MITM intercepts Access-Reject, learning the Response Authenticator.

03	1d	01c0	6034d0ff16e4...30	21	ec	96...86	21	c0	f5...9e

`Response Authenticator`

6. MITM puts Response Authenticator in Access-Accept packet with appended `Accept Gibberish`.

02	1d	01c0	6034d0ff16e4...30	21	ec	3d...86	21	c0	f5...9e

`Accept Gibberish`

End-to-End Example Attack (4/4)

7. Access-Accept and Access-Reject produce the same Response Authenticator, and hence pass the RADIUS client authentication check.

$$\overbrace{\boxed{\text{6034d0ff16e4...30}}}^{\texttt{Response Authenticator}}$$

$$= \mathrm{MD5}\Big(\underbrace{\boxed{02}\,\boxed{1d}\,\boxed{01c0}\,\boxed{726164617574...72}\,\boxed{21}\,\boxed{ec}}_{\texttt{Accept Prefix}}\,\underbrace{\boxed{3d...86}\,\boxed{21}\,\boxed{c0}\,\boxed{f5...9e}}_{\texttt{Accept Gibberish}}\,\underbrace{\boxed{\text{Shared Secret}}}_{\texttt{(unknown)}}\Big)$$

$$= \mathrm{MD5}\Big(\underbrace{\boxed{03}\,\boxed{1d}\,\boxed{01c0}\,\boxed{726164617574...72}\,\boxed{21}\,\boxed{ec}}_{\texttt{Reject Prefix}}\,\underbrace{\boxed{96...86}\,\boxed{21}\,\boxed{c0}\,\boxed{f5...9e}}_{\texttt{Reject Gibberish}}\,\underbrace{\boxed{\text{Shared Secret}}}_{\texttt{(unknown)}}\Big)$$

Attack Extensions

- Adversary can add arbitrary attributes in prefix for Access-Accept.

$$\text{AcceptPrefix} = \boxed{02}\,\boxed{1d}\,\boxed{01c0}\,\boxed{726164617574...72}\,\underbrace{\boxed{1a0b000007db1d04}}_{\substack{\text{Attribute:} \\ \texttt{Exec-Privilege 04}}}\,\boxed{21}\,\boxed{ec}$$

- Proxy-State attributes are *not* the only way to inject the `RejectGibberish`.
  - Any reflected user input could work, e.g. User-Name or Vendor-Specific attributes.
    - In Access-Request:
      `User-Name: 0PZjN-_ayr83S-nc6q...Mt85`
    - In Access-Reject:
      `Reply-Message: Login for 0PZjN-_ayr83S-nc6q...Mt85 failed!`
  - The client does not need to support or parse these attributes.

REFERENCES

References I

[1] Pat R. Calhoun and Dr. Bernard D. Aboba. *RADIUS (Remote Authentication Dial In User Service) Support For Extensible Authentication Protocol (EAP)*. RFC 3579. Sept. 2003. DOI: 10.17487/RFC3579. URL: https://www.rfc-editor.org/info/rfc3579.

[2] Alan DeKok. *Personal Communication*.

[3] Alan DeKok. *RADIUS and MD5 Collision Attacks*. https://networkradius.com/assets/pdf/radius_and_md5_collisions.pdf. 2024.

[4] *Icons from https://www.flaticon.com*. visited on Dec 4, 2024.

[5] Randall Munroe. *Dependency (Comic #2347)*. https://www.xkcd.com/2347/. Aug. 2020.

[6] The FreeRADIUS Server Project and Contributors. *FreeRADIUS*. https://freeradius.org/.

References II

[7] Jan-Frederik Rieckers and Stefan Winter. *(Datagram) Transport Layer Security ((D)TLS Encryption for RADIUS*. Internet-Draft draft-ietf-radext-radiusdtls-bis-02. Work in Progress. Internet Engineering Task Force, July 2024. 38 pp. URL: https://datatracker.ietf.org/doc/draft-ietf-radext-radiusdtls-bis/02/.

[8] *SHAttered*. https://shattered.io/. Accessed March 20, 2025.

[9] Marc Stevens, Arjen K. Lenstra, and Benne de Weger. "Chosen-Prefix Collisions for MD5 and Colliding X.509 Certificates for Different Identities". In: *EUROCRYPT*. Vol. 4515. Lecture Notes in Computer Science. Springer, 2007, pp. 1–22.

[10] Marc Stevens et al. "Short Chosen-Prefix Collisions for MD5 and the Creation of a Rogue CA Certificate". In: *CRYPTO*. Vol. 5677. Lecture Notes in Computer Science. Springer, 2009, pp. 55–69.

References III

[11] Henrik Thejl, Nagaraja K S, and Karl-Georg Aspacher. "A method for user management and a power plant control system thereof for a power plant system". Pat. 2765466. Siemens Gamesa Renewable Energy A/S. Jan. 24, 2014. URL: https://data.epo.org/publication-server/rest/v1.0/publication-dates/20190904/patents/EP2765466NWB1/document.pdf.

[12] Xiaoyun Wang and Hongbo Yu. "How to Break MD5 and Other Hash Functions". In: *EUROCRYPT*. Vol. 3494. Lecture Notes in Computer Science. Springer, 2005, pp. 19–35.