Security analysis of Review training events authenticated lifecycle

19.8.0 · ProVerif+ Agent report

Documents	5G System; Network Data Analytics Services; Stage 3 (protocol definition); Security architecture and procedures for 5G system (supporting)
Properties examined	12: 4 hold, 8 fail (8 attacks)
Findings	3

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1 Protocol and scope

The Nnwdaf_MLModelTraining service lets an NF service consumer ask the NWDAF that contains the MTLF to train an ML model: the consumer subscribes to ML model training events, may change the subscription, receives notifications at a callback URI, and unsubscribes. The parties are the consumer, the NWDAF, and the NRF, which issues the OAuth 2.0 access token that authorizes NF service access.

At the end of a subscription the consumer knows which NWDAF instance accepted it and, for each notification it accepts, which subscription the notification belongs to. The NWDAF knows which NF instance subscribed, which callback URI to post to, and that the request carried a token for this service issued to that instance.

The parties:

- **NF service consumer**: subscribes to ML model training events. Holds: NF Instance Id, TLS certificate, its own scope.
- **NWDAF (MTLF)**: trains the model and sends the notifications. Holds: NF Instance Id, NRF public key, scope nnwdaf-mlmodeltraining.
- **NRF**: OAuth 2.0 authorization server. Holds: NRF signing key, NF profiles.

Figure 1 shows the exchange as the documents specify it.

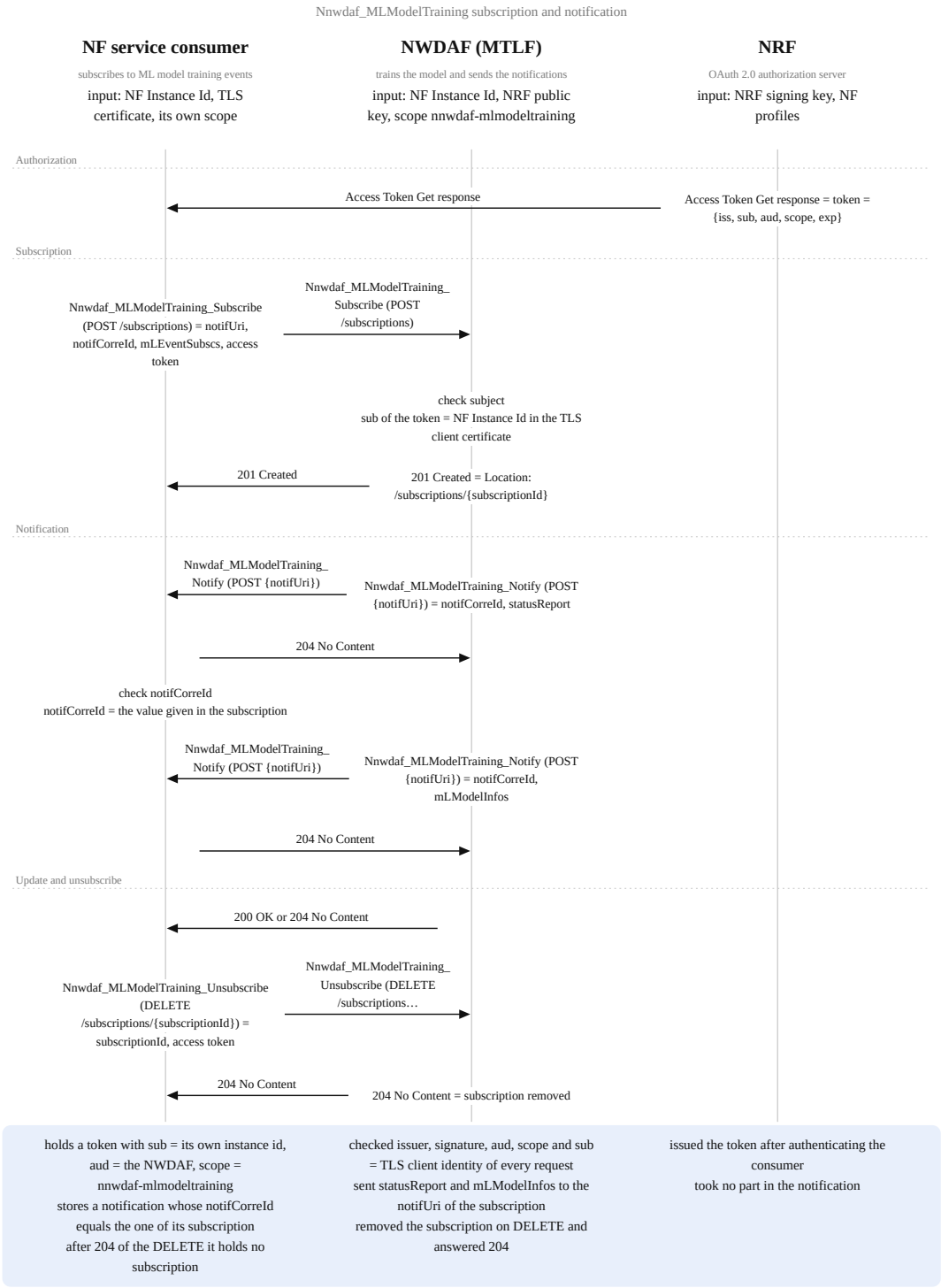


Figure 1. The protocol as specified.

The scope of the analysis is in Appendix D: what was analysed, what was left out, and the sections of the documents it is built from.

2 Findings

The analysis has 3 findings: what follows is not stated in the documents. For 2 of them it is unclear whether the documents state them.

The service authorizes and correlates subscriptions as documented, but the notification path is not authenticated by the fields the API defines, so a legitimate NF can push notifications the NWDAF never sent. Two further weaknesses are shown: a notification can be accepted again after replay because the API defines no notification instance, and the subscription resource carries no authorization, so any NF holding the service token and a subscriptionId can remove or rewrite another consumer's subscription. Isolation of trained models between consumers holds against the network and against another consumer. Wrapping the two pages: compare the sender identity against the NWDAF of the subscription to close the first weakness, and add a notification sequence number to close the second; token expiry, indirect communication through an SCP and an in-flight notification after a DELETE are outside the model.

The attack figures use the columns of Figure 1. Red is what the attacker does. Yellow marks a message that a party sends although the specified exchange does not have it at that point, and the outcome that the attack breaks.

2.1 A legitimate NF can send notifications the NWDAF never sent

Kind	Weakness of the protocol as specified
New	Unclear: the documents state it in part, or could not be searched
Value	high
Properties	A02, D01, U01, Z05, Z05.12 (section 3)
Source text	s0129, s0321, s0138, s0445
Shown by	ProVerif attack queries `a02l`, `u01l`; Figures 2, 3, 4, 5 and 6

What happens. The notification operation is not covered by OAuth 2.0, and the API requires the consumer to check only that notifCorreId equals the value of its subscription. A consumer that checks exactly that accepts a POST to its callback URI from any NF instance that knows the URI and the correlation value, and stores the body as the result of its own training.

What the attacker needs. A registered NF instance with its own TLS credentials, the notifUri of the victim consumer and its notifCorreId; both are consumer-chosen values that the specification does not require to be secret.

What the attacker gains. The attacker decides what the victim believes about training that never happened: a fabricated model location, a fabricated status report, or a termTrainReq that makes the victim stop waiting for its model.

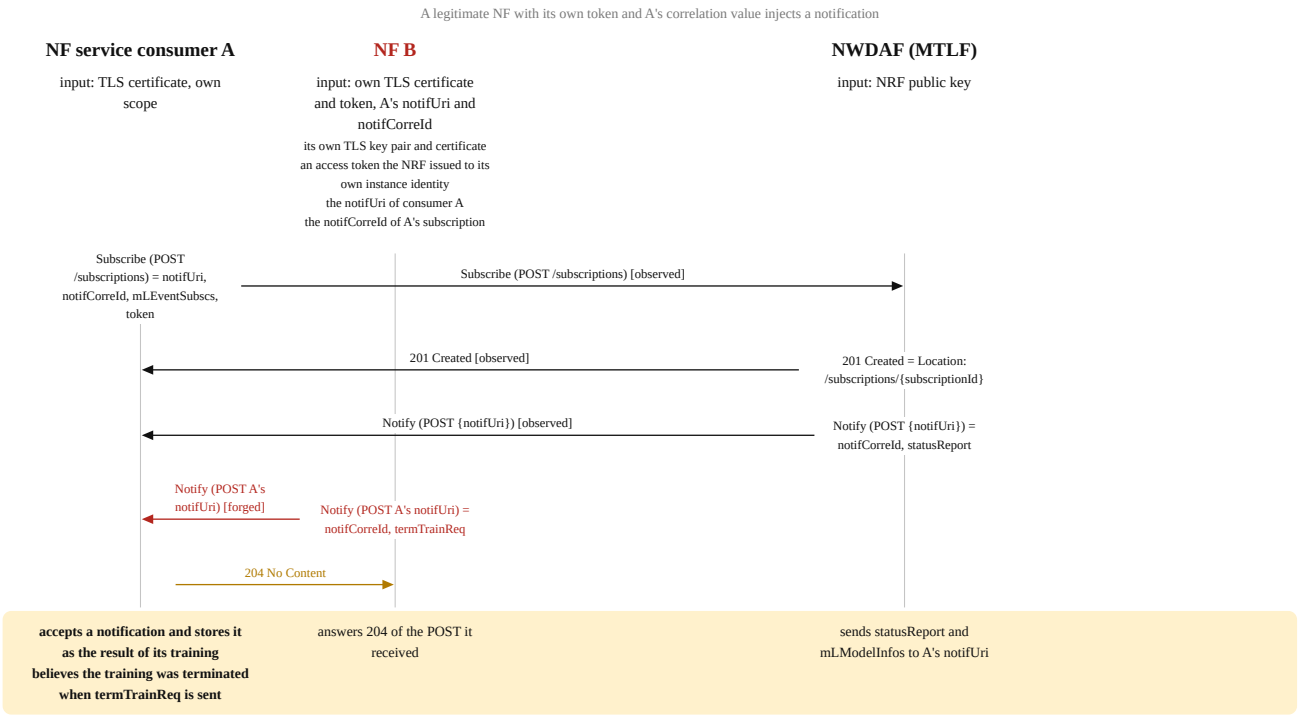


Figure 2. A legitimate NF with its own token and A's correlation value injects a notification. Property A02; attack query a02l.

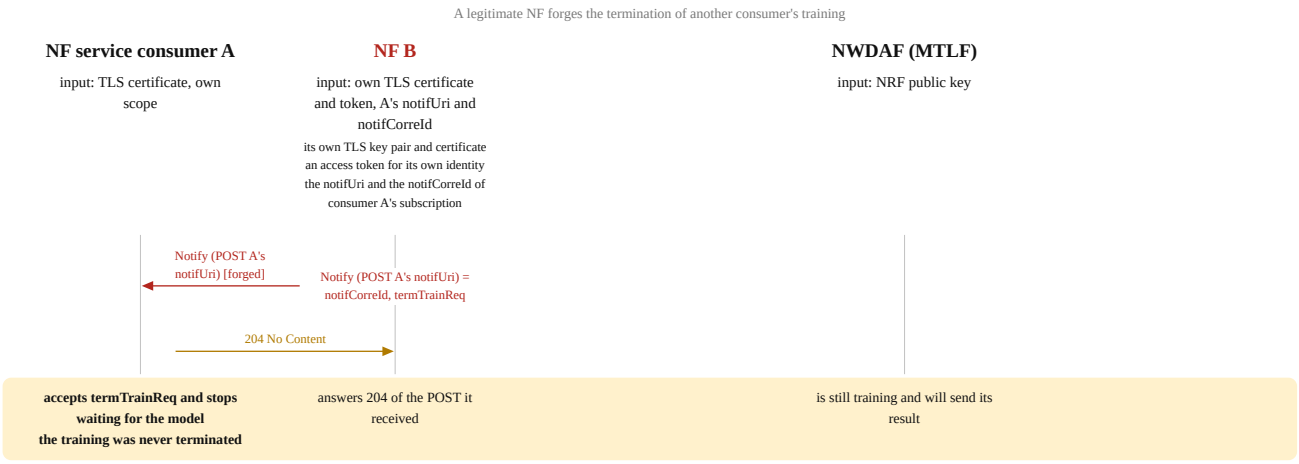


Figure 3. A legitimate NF forges the termination of another consumer's training. Property U01; attack query u01l.

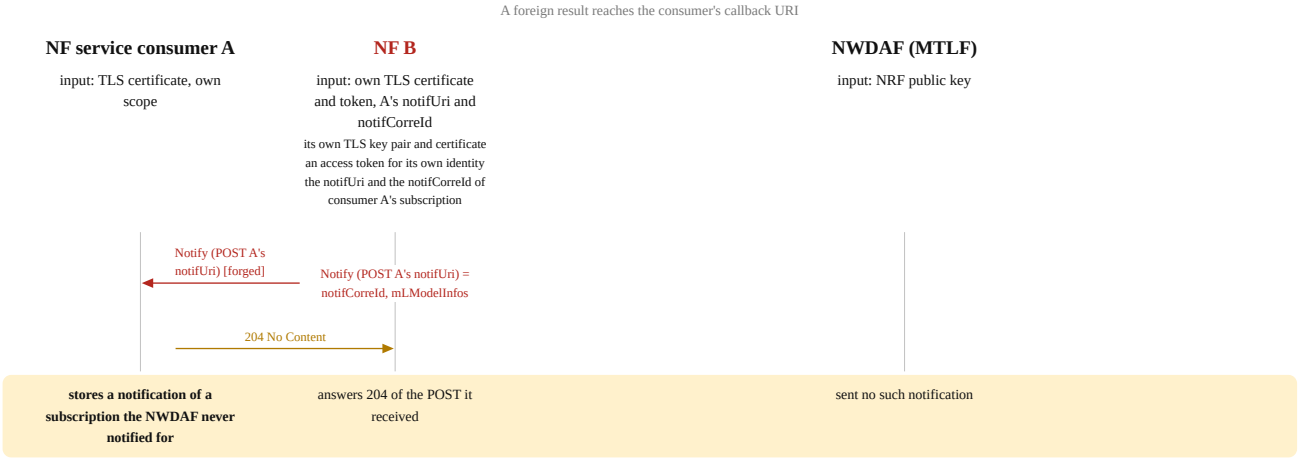


Figure 4. A foreign result reaches the consumer's callback URI. Property Z05; attack query a02l.



Figure 5. A foreign ML procedure's result is accepted as A's own. Property Z05.12; attack query a02l.

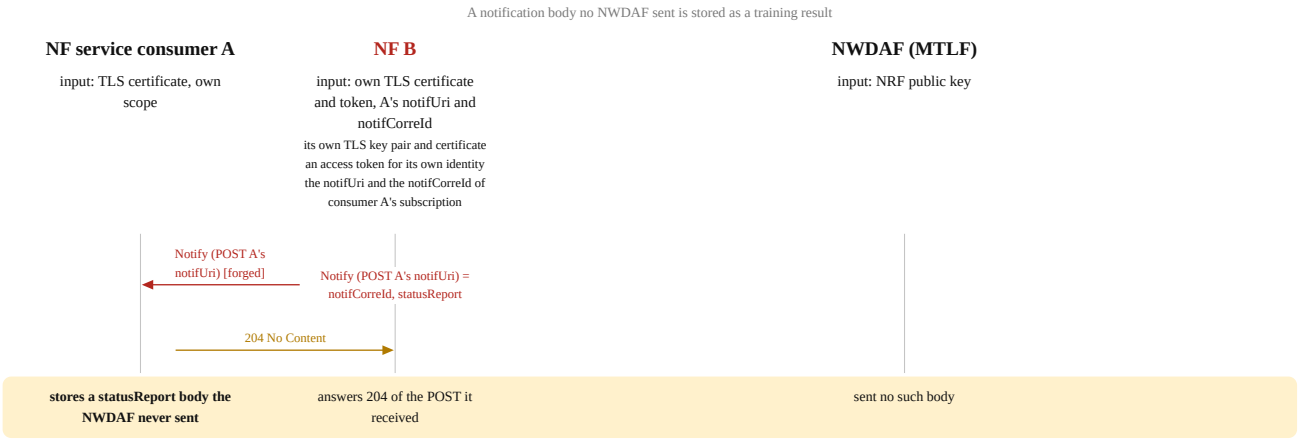


Figure 6. A notification body no NWDAF sent is stored as a training result. Property D01; attack query a02l.

Proposed change. Require the consumer to compare the authenticated TLS client identity of the notification POST with the NF Instance ID of the NWDAF instance that created the subscription, and to reject the notification when they differ. The model's validating consumer performs exactly this comparison: with it the authentication query holds and the forged notification is rejected.

Check of the change with ProVerif. The change was put into a copy of the model: The consumer compares the authenticated SBA identity of a notification with the NF Instance Id of the NWDAF that created its subscription and rejects the notification when they differ, instead of checking only that notifCorreId equals the value of the subscription. ProVerif still finds the attack for `a02l`: the change does not remove it. The normal run of the protocol is still found. Of the other recorded answers, 16 still hold and 1 changed: `u01l` (U01, was attack) is now verified. Changed model: `records/fixes/0068-fix-sender.pv`.

2.2 A notification is accepted again when it is replayed

Kind	Weakness of the protocol as specified
New	Yes: the documents do not state it
Value	high
Properties	A04, A04.10 (section 3)
Source text	s0129, s0321
Shown by	ProVerif attack query `a04`; Figures 7 and 8

What happens. NwdafMLModelTrainNotif carries the correlation identifier of the subscription and no notification instance or sequence number. A consumer cannot tell a second delivery of a notification it already accepted from a new notification, and two subscriptions of the same NF that share a notifCorreId are indistinguishable, so the notification of one is accepted for the other.

What the attacker needs. Only the network: the notification is taken from the wire and delivered again, or a second subscription of the same NF instance is created with the same notifCorreId.

What the attacker gains. The consumer repeats a status report or a completion, and mixes up the notifications of its own subscriptions; the NWDAF's state and the consumer's view of the training diverge with no error on either side.

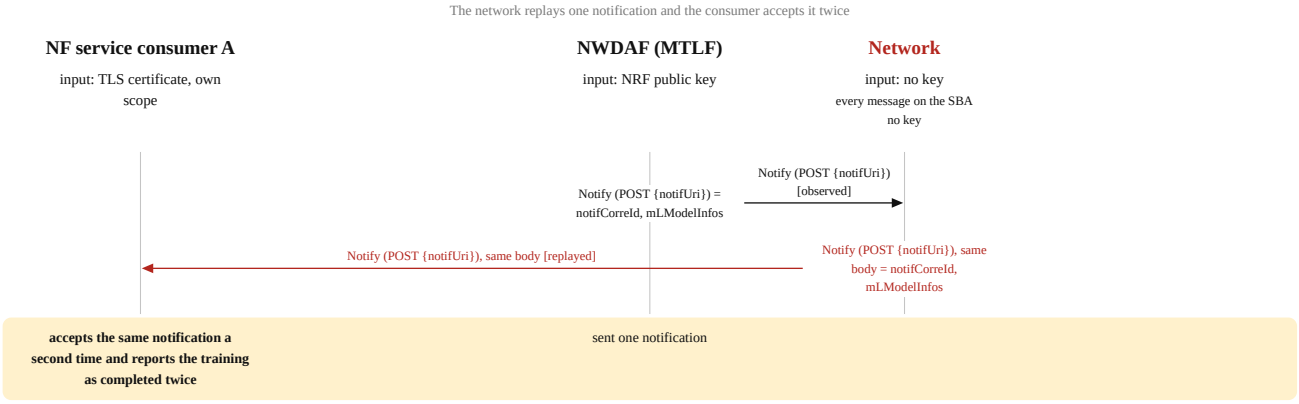


Figure 7. The network replays one notification and the consumer accepts it twice. Property A04; attack query a04.

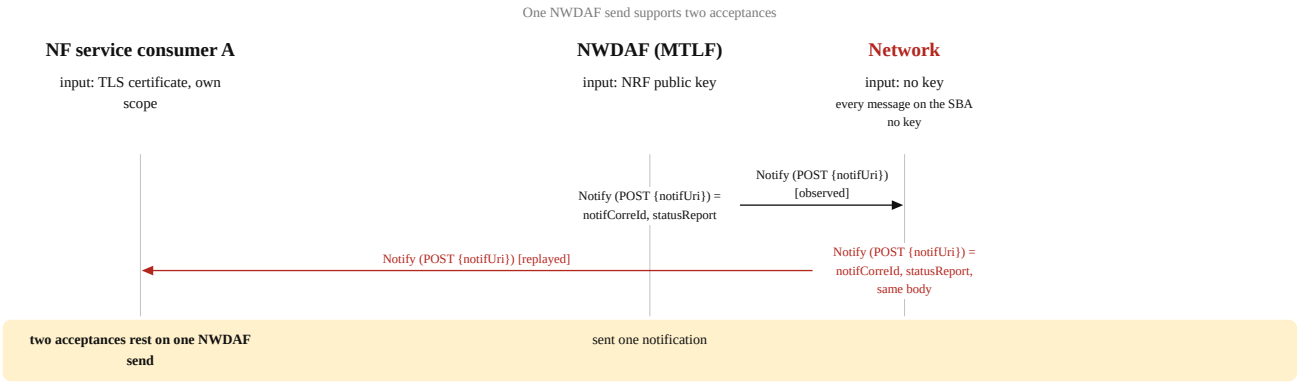


Figure 8. One NWDAF send supports two acceptances. Property A04.10; attack query a04.

Proposed change. Add a per-subscription notification sequence number to NwdafMLModelTrainNotif, incremented by the NWDAF for every notification of a subscription, and require the consumer to reject a value it has already accepted and a value lower than the last one accepted. The sequence number must be minted by the NWDAF: the

notification correlation identifier is chosen by the consumer and cannot serve as an instance identifier.

Check of the change with ProVerif. Not checked: The consumer would keep the last accepted number, a value that changes with every notification; that needs the unrolled subscription lifecycle model, which was not built in this analysis, so the change is proposed without a prover check.

2.3 The subscription resource has no authorization of its own

Kind	Weakness of the protocol as specified
New	Unclear: the documents state it in part, or could not be searched (main:492)
Value	high
Properties	A03 (section 3)
Source text	s0378, s0442, s0105
Shown by	ProVerif attack query `a03b`; Figure 9

What happens. The API defines a single scope for the whole service and no scope at resource level, and the NWDAF acts on the subscriptionId named in the URI for any consumer that presents a valid token. Once another NF instance knows the subscriptionId, it can unsubscribe the subscription or rewrite it, for instance by replacing the notifUri.

What the attacker needs. A legitimate NF instance with its own token, and the subscriptionId of the victim's subscription, read from where the NWDAF stores it or from signalling monitoring.

What the attacker gains. The attacker silently cancels another consumer's training or diverts its future notifications, including the trained model, to its own callback URI.

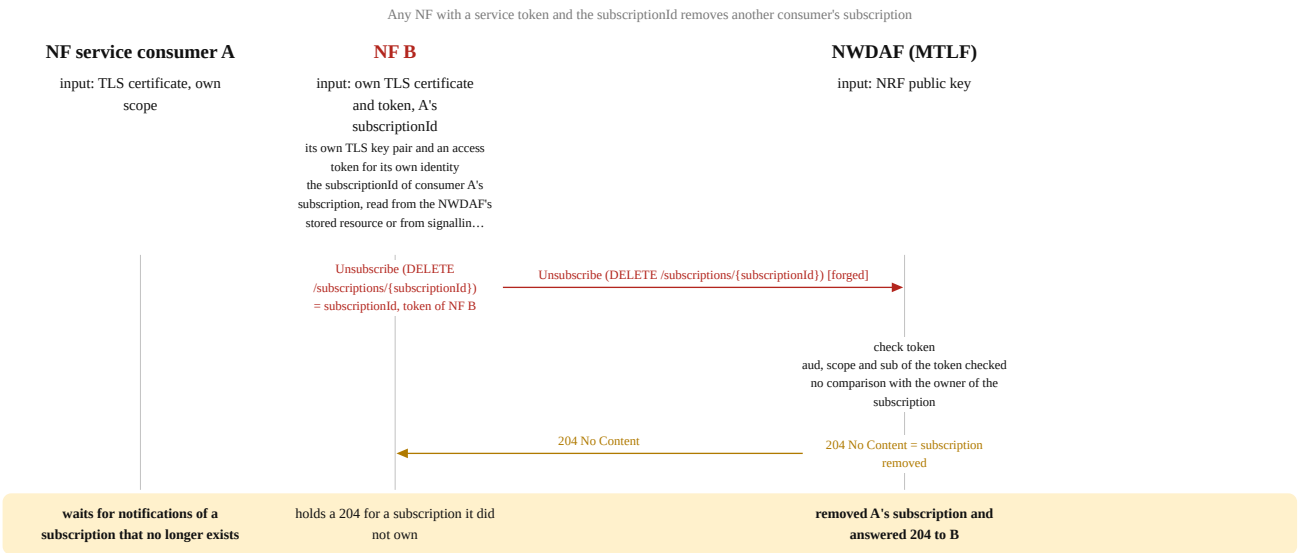


Figure 9. Any NF with a service token and the subscriptionId removes another consumer's subscription. Property A03; attack query a03b.

Proposed change. Define an additional scope that names the resources a consumer may address, as TS 33.501 already allows, and require the NWDAF to compare the subject and additional scope of the access token with the consumer that created the subscriptionId before PUT, PATCH and DELETE.

Check of the change with ProVerif. Not checked: The model carries the service-level scope only; an additional scope claim and the NWDAF's comparison with the stored owner are a change of the token content, which is outside the analysed baseline.

No figure was given for these attacks of a finding: A02: u01l, D01: u01l, U01: a02l, Z05.12: u01l, Z05: u01l.

3 Properties examined

Each row is one property put to ProVerif. The result is ProVerif's answer on the analyst's model of the protocol; value and whether the documents already state the result are the analyst's judgement, with the reasons in Appendix A.

ID	Property	Compromise assumed	Result	Value	In the documents
A02	**Authenticated peer of requests and notifications.** Every time NWDAF accepts a subscription/update/cancellation request for a consumer example, or a consumer accepts a notification of NWDAF, the alleged counterpart must have actually run the agreement on its own.	no compromise	Fails (1 attack)	high	unclear
A03	**Notification and subscription correlation.** When a consumer receives a notification, there must be a matching self-subscribe to run,notifCorreId、notifUri、mlCorreId、roundInd(a) Consistency;NWDAFWhen receiving updates/cancellations,subscriptionIdIt must belong to the consumer.	no compromise	Fails (1 attack)	high	unclear
A04	**Each notification event accepted once.** Consumer acceptance of an example of the same notice at most once; If the unserialized field is regulated, the nature of the field cannot be guaranteed by the norm.	no compromise	Fails (1 attack)	high	no
D01	**Notification payload integrity.** Every notification accepted by the consumer to which the sender subscribesNWDAFandmLModelInfos、statusReport、termTrainReqWaiting for loads andNWDAFPractically sent the same.	no compromise	Fails (1 attack)	high	unclear
K01	**Long-term credentials stay secret.** The assailant cannot extrapolate the private signature key of NRF or any long-term authentication certificate of NF.	no compromise	Holds	low	yes
Z01	**Service access requires a valid token.** NWDAF When submitting a subscription/update/cancellation operation, there must be a NRF token that matches a scope and does not expire for the consumer, and the token object corresponds to the identity of the TLS client certificate.	no compromise	Holds	medium	yes
Z03	**Token claims bound to the request.** Subject, Audience, scope, validity and context-specific binding of tokens; The aggressor cannot use a consumer's token for another consumer's identity, another example of NWDAF, or an operation outside of scope.	no compromise	Holds	medium	yes
Z05	**Results isolated between consumers.** Subject to allowing control of other consumer domains, the notification received by the target consumer includes only its own subscription and its own training results of mlCorreId; The results of other consumers are invisible and cannot be staggered with subscriptions.	no compromise	Fails (1 attack)	medium	no
S05	**No notification after termination.** Unsubscribed successfully or receivedtermTrainReqAfter that,NWDAFNo new announcements are being sent to the subscriber concerned; The old subscription sign cannot be re-entitled to notification.	no compromise	Holds	low	yes

ID	Property	Compromise assumed	Result	Value	In the documents
A04.10	**DistinctNWDAFsend per acceptance.** Consumers accept the same notice example at most once and each acceptance is differentNWDAFSend run.	no compromise	Fails (1 attack)	high	no
U01	**Termination not confusable with a result.** In the notification of consumer acceptance,termTrainReqandmLModelInfos/statusReport♪ And the emergence andNWDAFFields actually sent are identical and the two cannot be impersonated.	no compromise	Fails (1 attack)	high	no
Z05.12	**Foreign results not accepted as own.** Subject to allowing control of other consumer domains, the notification received by the target consumer includes only its own subscription and its own training results of mlCorreId.	no compromise	Fails (1 attack)	high	no

The questions asked, and the analyst's answers:

Question	Answer	Rests on
Q1: Whether the recalibration of certified messages still meets the relevant semantics permitted by the norm	No: an authenticated notification can be delivered again and accepted again, because the notification carries the subscription's correlation identifier but no instance or sequence number. Two subscriptions of the same NF that use the same correlation identifier are also conflated, so the accepted notification is not reliably tied to the send it came from.	A04, A04.10
Q2: Whether the confusion between the termination of the event and the ordinary result is eliminated by the actual normative field	Only partly: the field values distinguish a termination from a result, but nothing in the API ties the received field to the sender, so an NF that knows the callback URI and the correlation value makes the consumer accept a termination the NWDAF never sent. A consumer that also compares the authenticated sender with the NWDAF of its subscription cannot be confused.	U01, A02, D01
Q3: Segregation of results between different consumers and training missions	Confidentiality holds: a trained model is delivered only to the consumer named as notifUri, and neither the network nor another consumer learns it. Isolation does not hold against injection or against the subscription resource: another legitimate NF can push a result into the consumer's callback URI, and an NF that knows the subscriptionId can rewrite or cancel the subscription.	Z05, Z05.12, A03, A02

4 Limits of this analysis

A result here is a result on a model of the protocol: it says what the specified messages and checks give or fail to give, with cryptography taken as ideal, and nothing about an implementation.

What this analysis does not cover, as the analyst states it:

- The SBA transport is modelled as public-key encryption plus a signature, with the NF instance identity being the certified public key; TLS session establishment, resumption, cipher suites and certificate chains are not modelled.
- The token is validated for issuer, subject, audience, scope and integrity, but not for its expiration time: the model has no clock.
- The notification callback is modelled as an endpoint identity, not as a URI; redirect responses (307, 308) for notifications and for subscription requests are not modelled.
- Indirect communication through SCP or SEPP, where TS 33.501 notes there is no mutual authentication between consumer and producer, is not modelled; only direct SBA endpoints are.
- The consumer handles two notifications per subscription; the bound of at most two status reports per training that the review states is not in the source units and is not modelled.

- mlCorreId and roundInd are not modelled as checks; the consumer correlates a notification to its subscription by notifCorreId only, which is what the API states.
- PUT and PATCH are modelled as one update operation; partial update semantics are not distinguished.
- Deletion is modelled by the lifetime of the subscription process, not by a table, so a notification already in flight that arrives after the DELETE is not modelled; a replayed notification after the DELETE is covered only through the replay result.
- The trained model is modelled as one value per consumer, not as model content; the correctness of the model itself is outside the symbolic model.
- The analysis does not prove the computational security of the signature, the token or the transport encryption, nor resistance to quantum attack.
- The recommendation to compare the notification sender was checked on a copy of the model (fix-sender.pv); the recommendation to add a notification sequence number and the one on resource-level authorization were not checked on a model.

What stays open for each property, and what would settle it, is in Appendix A.

Appendix A: Reading of each property

The analyst's own reading of the prover's answers, not an answer of the prover: what the answers mean for the protocol, what the reading rests on, whether it can be used as it stands, and what it is worth.

A02: Authenticated peer of requests and notifications

Every time NWDAF accepts a subscription/update/cancellation request for a consumer example, or a consumer accepts a notification of NWDAF, the alleged counterpart must have actually operated the agreement to its own end.

A consumer that compares the authenticated SBA identity of a notification with the NWDAF instance of its subscription accepts only notifications that instance sent. A consumer that performs only the check the API states, the equality of notifCorreId, accepts notifications from any legitimate NF that knows its callback URI and correlation value.

- Result: Fails (1 attack); answers what is asked: yes; usable with caveats
- Value high: It separates the two readings of the same API text and shows that the API's own checks do not authenticate a notification; the documents do not state this consequence.
- Stated in the documents: unclear. Source text it rests on: ts-33-501:2871, ts-33-501:2875, s0129, s0321, s0445
- Rests on: The SBA transport is modelled as encryption to the receiver's public key plus a signature by the sender, with the instance identity being the certified public key.; Two consumer behaviours are modelled: one validates the sender, one performs only the check the API states.; notifCorreId is modelled as a value the attacker may know, since the specification requires no secrecy of it.
- Open: Whether the NWDAF instance ID that the consumer must compare against is available to it in every deployment (it comes from discovery or from the subscription response).; Whether an SCP in the notification path changes what the consumer can check.
- Next step: Model indirect communication through an SCP and ask the same property under that attacker.

A03: Notification and subscription correlation

When a consumer receives a notification, there must be a matching self-subscribe to run,notifCorreId、 notifUri、 mlCorreId、 roundInd(a) Consistency;NWDAFWhen receiving updates/cancellations,subscriptionIdIt must belong to the consumer.

Correlating a notification to a subscription by notifCorreId holds: only a consumer's own subscription value is accepted. The subscription resource itself is not authorized — the token authorizes the service, not the resource — so an NF that knows a subscriptionId can remove or rewrite another consumer's subscription.

- Result: Fails (1 attack); answers what is asked: partly; usable with caveats
- Value high: The resource-level gap is a weakness of the specification that the documents do not state; the attack needs the subscriptionId, which the model grants as a separate attacker.
- Stated in the documents: unclear. Source text it rests on: main:492, s0378, s0442, s0105
- Rests on: The NWDAF stores the owner of a subscription and performs no comparison with it, because the specification defines no resource-level authorization.; The subscriptionId is modelled as unknown to the network attacker and as known to the sid_read attacker.; PUT and PATCH are modelled as one update operation.
- Open: Whether implementations add an owner check although the API defines none.; How guessable subscriptionId values are in practice, which decides whether the sid_read attacker is realistic.

- Next step: Model PUT with a change of notifUri and ask whether a foreign notification then reaches the attacker under the sid_read attacker.

A04: Each notification event accepted once

Consumer acceptance of an example of the same notice at most once; If the unserialized field is regulated, the nature of the field cannot be guaranteed by the norm.

The consumer cannot tell a repeated delivery from a new notification. A notification taken from the wire and delivered again is accepted a second time, and two subscriptions of the same NF that share a notifCorreId are indistinguishable, so the notification of one is accepted for the other.

- Result: Fails (1 attack); answers what is asked: yes; usable
- Value high: It shows mechanically that the notification definition has no field on which a replay check could be built, and finds the attack with the network alone.
- Stated in the documents: no. Source text it rests on: s0129, s0321
- Rests on: Each send is given a fresh instance identifier in the model, which no specification field provides; the injective query states exactly what the API is missing.; The consumer handles two notifications per subscription and keeps no state about what it has already accepted.; notifCorreId is modelled as a public value.
- Open: Whether a deployment's notifUri differs per subscription, which would limit the conflation but not the replay.
- Next step: Build an unrolled consumer that keeps the last accepted notification and check whether an added sequence number removes the replay.

D01: Notification payload integrity

Each notification accepted by the consumer to which the sender subscribesNWDAFandmLModelInfos 、statusReport、termTrainReqWaiting for loads andNWDAFPractically sent the same.

When the consumer validates the authenticated sender, every body it accepts — mLModelInfos, statusReport or termTrainReq — is a body the NWDAF of its subscription sent. When it performs only the API's checks, any legitimate NF can put a body of its choice into the consumer's callback URI.

- Result: Fails (1 attack); answers what is asked: yes; usable with caveats
- Value high: It shows that payload integrity for notifications rests on a check the API does not require.
- Stated in the documents: unclear. Source text it rests on: ts-33-501:2875, s0128, s0131, s0133, s0137
- Rests on: Transport as public-key encryption plus signature, identity being the certified public key.; The two consumer behaviours described for A02.
- Open: Whether a conforming consumer in the field compares the notification sender; the API does not require it and TS 33.501 requires validation only in general terms.
- Next step: Ask the same property for a consumer that validates the payload type against the subscription's subscribed events.

K01: Long-term credentials stay secret

The assailant could not extrapolate the token signature private key of NRF or any long-term authentication certificate of NF.

Neither the NRF's token signing key nor the long-term keys of the NF instances can be derived from anything visible on the network, including the certified public keys. This is a property of the symbolic primitives, not a statement about their computational strength.

- Result: Holds; answers what is asked: yes; usable with caveats
- Value low: It follows directly from the assumption that the primitives are sound, which the analysis does not test.
- Stated in the documents: yes. Where the documents say it: ts-33-501:2773, ts-33-501:2795, s0438, s0508
- Rests on: Signature and encryption are assumed unforgeable and non-invertible without the key.
- Open: Whether the NRF's key management keeps the signing key in hardware, which the task leaves out.
- Next step: None for the symbolic model; key management is outside it.

Z01: Service access requires a valid token

NWDAFExistence when submitting subscriptions/updates/cancellationsNRFAn unexpired token issued for the consumer that matches the audience with the scope, and the token object is used withTLSClient certificate identity is consistent.

Every creation, update and removal of a subscription requires an NRF-signed token whose issuer is the NRF, whose audience is this NWDAF instance and whose scope is the nnwdaf-mlmodeltraining service. A request without such a token changes nothing.

- Result: Holds; answers what is asked: yes; usable with caveats
- Value medium: The guarantee holds but rests on a model without time; the expiry check is the part a reader would most want covered.
- Stated in the documents: yes. Where the documents say it: main:338, ts-33-501:2867, s0375, s0507, s0515, s0518
- Rests on: The token is a signature over its claims; the producer verifies it with the NRF public key.; Expiration is not modelled: a token value is modelled as permanently valid.
- Open: Token revocation is not supported by the documents, so a token stays usable until expiry; the model does not model expiry at all.
- Next step: Add a token expiry and a second phase to ask whether a stored token is still accepted after it should have expired.

Z03: Token claims bound to the request

Subject, udience, scope, validity and context-by-text attachment of tokens; The aggressor cannot use a consumer's token for another consumer's identity, another example of NWDAF, or an operation outside of scope.

The subject of the token that authorizes a request is the authenticated TLS client identity, so a token issued to one NF instance cannot be used by another. The audience is this NWDAF instance and the scope is the service name, so a token for another service or another instance is refused.

- Result: Holds; answers what is asked: yes; usable with caveats
- Value medium: It reproduces the claim binding of TS 33.501 in a model where the claims are actually checked.
- Stated in the documents: yes. Where the documents say it: ts-33-501:2795, ts-33-501:2801, s0483, s0513, s0515, s0518
- Rests on: The consumer identity is the certificate identity, modelled as a public key.; A single NWDAF instance and a single service scope are modelled.

- Open: Whether the NF type or NF set claims are used in deployments; the model fixes the audience to one instance.
- Next step: Model an NRF set and two NWDAF instances of the same type and ask whether a token for one audience is accepted by the other.

Z05: Results isolated between consumers

Subject to allowing control over other consumer domains, the notification received by the target consumer includes only its own subscription and its own training results of mlCorreId; The results of other consumers are invisible and cannot be staggered with subscriptions.

A trained model reaches only the consumer named as notifUri: another consumer and the network do not learn it. A consumer still accepts a notification for its own subscription that another legitimate NF produced, so confidentiality of the content holds while its origin is not protected.

- Result: Fails (1 attack); answers what is asked: yes; usable with caveats
- Value medium: It separates the confidentiality half, which holds, from the origin half, which does not, and the documents state neither for the notification operation.
- Stated in the documents: no. Source text it rests on: s0128, s0129, s0378
- Rests on: The notification is sealed to the endpoint named as notifUri.; The trained model is modelled as one value per consumer.
- Open: Whether an SCP or a redirect changes the callback path of a notification.
- Next step: Model an SCP between the NWDAF and the consumer's callback.

S05: No notification after termination

Unsubscription successfully or receivedtermTrainReqAfter that,NWDAFNo new announcements are being sent to the subscriber concerned; The old subscription sign cannot be re-entitled to notification.

In the modelled lifecycle a notification is sent only while the subscription exists: the NWDAF sends nothing for a subscription it has removed, and a new subscription always gets a fresh identifier. The proof rests on the order the model fixes, not on a state the NWDAF compares.

- Result: Holds; answers what is asked: yes; usable with caveats
- Value low: The property holds by the order the model fixes rather than by a check in the protocol, so it says little beyond the text.
- Stated in the documents: yes. Where the documents say it: main:343, main:347, s0107, s0117, s0133
- Rests on: The subscription lifetime is the process chain of the producer, so no notification step exists after the removal step.; A replayed notification can still be accepted by the consumer after it has unsubscribed; that is the replay result, not covered here.
- Open: A notification already in flight when the DELETE is processed is not modelled; whether it may be delivered after the removal is left open.
- Next step: Model the DELETE and an in-flight notification in the unrolled lifecycle and ask whether the notification is still accepted.

A04.10: Distinct NWDAF send per acceptance

Consumers accept the same example of notification at most once, and each acceptance corresponds to a different NWDAF dispatch.

An acceptance cannot be matched one-to-one to a send, because the API gives the consumer nothing that identifies a notification instance. ProVerif finds two acceptances for one send, by replay and by two subscriptions that share a correlation identifier.

- Result: Fails (1 attack); answers what is asked: yes; usable
- Value high: It is the exact statement of what the notification definition lacks, shown by a trace.
- Stated in the documents: no. Source text it rests on: s0129, s0321
- Rests on: The model's fresh instance identifier stands for the field the API lacks.; The consumer keeps no record of accepted notifications.
- Open: Same as A04.
- Next step: Same as A04: add a notification sequence number and check the injective query in the unrolled lifecycle.

U01: Termination not confusable with a result

In the notification of consumer acceptance,termTrainReqandmLModelInfos/statusReport ♪ And the emergence andNWDAFFields actually sent are identical and the two cannot be impersonated.

The notification body distinguishes an intermediate result, a completion and a termination, and a consumer that validates the sender cannot be made to take one for the other. A consumer that checks only the correlation identifier accepts a termination notification that the NWDAF never sent, and stops waiting for its model.

- Result: Fails (1 attack); answers what is asked: yes; usable with caveats
- Value high: It shows that the termination signal, the most damaging notification of this API, is not bound to its sender by the fields the API requires.
- Stated in the documents: no. Source text it rests on: s0133, s0321, s0350
- Rests on: The kind of a notification is a field of the body, not a separate message.; The two consumer behaviours described for A02.
- Open: Whether a consumer could use roundInd or mlCorreId to notice a forged termination; the model does not check them.
- Next step: Model mlCorreId as a value the consumer checks and see whether the forged termination is still accepted without knowing it.

Z05.12: Foreign results not accepted as own

Subject to allowing control of other consumer domains, the notification received by the target consumer only includes its own subscription, its own training results of mlCorreId.

A training result is not disclosed to another consumer or to the network. A consumer accepts a result produced by another legitimate NF, so a foreign result can be presented as its own even though it cannot be read off the wire.

- Result: Fails (1 attack); answers what is asked: yes; usable with caveats
- Value high: It states the isolation failure that the API's own correlation rule allows, which the documents do not mention.
- Stated in the documents: no. Source text it rests on: s0129, s0135, s0321
- Rests on: The notification is sealed to the notifUri endpoint.; The consumer correlates by notifCorreId only.
- Open: Whether a deployment's notifUri and notifCorreId are unique per subscription and hard to guess, which decides how practical the injection is.
- Next step: Model a guessable correlation identifier and ask the same property under the network attacker alone.

Appendix C: Claims and prover answers

The prover's record for each target: the level reached, the query that reached it, whether a control was checked, and the attacks with the analyst's verdict on each.

target	level	bound	lemma	control	attacks	claims
A02	proved		a02s	checked	a02l (holds_in_source)	1 proved, 1 attack
A03	proved		a03a	checked	a03b (holds_in_source)	1 proved, 1 attack
A04	none				a04 (holds_in_source)	1 attack
D01	proved		a02s	checked	a02l (holds_in_source)	1 proved, 1 attack
K01	proved		k01	checked		1 proved
Z01	proved		z01	checked		3 proved
Z03	proved		z01	checked		2 proved
Z05	proved		z05a	checked	a02l (holds_in_source)	1 proved, 1 attack
S05	proved		s05	checked		1 proved
A04.10	none				a04 (holds_in_source)	1 attack
U01	proved		a02s	checked	u01l (holds_in_source)	1 proved, 1 attack
Z05.12	proved		z05a	checked	a02l (holds_in_source)	1 proved, 1 attack

Claim by claim, in the analyst's wording of each claim; the answer to each is the prover's:

target	claim	attacker	answer	query	control
A02	A consumer that validates the authenticated transport identity of a notification against the NWDAF instance of its subscription (as TS 33.501 requires every NF to validate incoming messages) accepts only notifications that NWDAF actually sent.	`network`	proved	a02s	checked
A02	The notification checks the API itself states — the notification carries the notifCorreId of the subscription and is delivered to its notifUri — authenticate the sender: a consumer doing exactly these checks accepts only notifications the NWDAF sent.	`legit_nf`	attack (holds_in_source)	a02l (the control of a03a)	
A03	The NWDAF accepts an update or an unsubscribe only from the consumer that owns the subscriptionId: the subscription named in the URI belongs to the requesting NF instance.	`sid_read`	attack (holds_in_source)	a03b	
A03	An accepted notification belongs to a subscription the consumer itself created: its notifCorreId equals the one of the consumer's subscription.	`network`	proved	a03a	checked
A04	The consumer accepts one notification once: each acceptance corresponds to a distinct notification sent by the NWDAF.	`network`	attack (holds_in_source)	a04	
D01	The body of every notification a consumer accepts, including its kind (intermediate result, completion or termination), equals the body of a notification the NWDAF of its subscription sent, when the consumer validates the authenticated sender as TS 33.501 requires.	`network`	proved	a02s	checked
D01	A consumer that performs only the checks the API states accepts notification bodies — mLModelInfos, statusReport, termTrainReq — that no NWDAF sent, from a legitimate NF other than the one it subscribed to.	`legit_nf`	attack (holds_in_source)	a02l (the control of a03a)	

target	claim	attacker	answer	query	control
K01	The NRF's token signing key and the long-term keys of the NF instances are not derivable from anything on the network, not even by a party who holds the public keys.	`network`	proved	k01	checked
Z01	The NWDAF creates a subscription only for a consumer presenting an NRF-signed token whose issuer is the NRF, whose audience is this NWDAF instance and whose scope is the nnwdaf-mlmodeltraining service.	`network`	proved	z01	checked
Z01	The NWDAF applies an update of a subscription only to a consumer presenting an NRF-signed token with the right issuer, audience and scope.	`network`	proved	z01u	checked
Z01	The NWDAF removes a subscription only for a consumer presenting an NRF-signed token with the right issuer, audience and scope.	`network`	proved	z01d	checked
Z03	The subject claim of the token which authorizes a request is the authenticated TLS client identity of the requester, so a token issued to one NF instance cannot be used by another.	`network`	proved	z01	checked
Z03	The audience claim is this NWDAF instance and the scope claim is the nnwdaf-mlmodeltraining service, for the token which authorizes a subscription update and a removal.	`network`	proved	z01u	checked
Z05	With another consumer's domain under the attacker's control, the target consumer accepts only notifications of its own subscription and of the NWDAF it subscribed to.	`legit_nf`	attack (holds_in_source)	a02l (the control of a03a)	
Z05	The trained model of consumer C's subscription is disclosed to no other party: the notification carrying it is sealed to the endpoint named as notifUri, so neither the network nor another NF learns the model value.	`network`	proved	z05a	checked
S05	A notification is sent only within a subscription that the NWDAF created and still holds; nothing is sent after the subscription is removed.	`network`	proved	s05	checked
A04.10	Each acceptance of a notification corresponds to a distinct send by the NWDAF; the same send is never accepted twice.	`network`	attack (holds_in_source)	a04	
U01	When the consumer validates the authenticated sender, the kind of every accepted notification (including a training termination, termTrainReq) equals the kind of a notification the NWDAF sent, so a result cannot be taken for a termination or the reverse.	`network`	proved	a02s	checked
U01	A consumer that performs only the checks the API states accepts a termination notification (termTrainReq) that the NWDAF never sent.	`legit_nf`	attack (holds_in_source)	u01l (the control of a02s)	
Z05.12	The target consumer accepts no training result of another consumer or of another ML procedure as its own.	`legit_nf`	attack (holds_in_source)	a02l (the control of a03a)	
Z05.12	A training result of consumer C's subscription is not disclosed to another consumer or to the network, so it cannot be taken over from the wire.	`network`	proved	z05a	checked

Appendix D: How the analysis was run

An LLM analyst builds the model of the protocol from the documents and puts each property to ProVerif; every result in section 3 is an answer of the prover.

ProVerif+ Agent session session-20261114T235758, 2026-11-14. Status: finished. Model: deepseek-v4-1-flash-261017. Steps: 70, prover 76 s, wall 21 min, cost 0.192 USD.

ProVerif: 112 proofs run, 110 decided, 2 without an answer, 53 s, 31 answers recorded.

What was analysed

Protocol	Review training events authenticated lifecycle
Version	19.8.0
Analysed	First round of reviewMLModelTrainingEvent subscription/update/notification/cancellation, realSBAEndpoint authentication isolated from key; Up to two training status reports with a clear distinction between intermediate results, completion, failure and cancellation; Serial numbers cannot be invented without notification and are attributed to the norm and are not disguised as being deleted by a single abbreviation.
Not analysed	Symbolic models do not support the calculation of algorithms as safe or as resistant to quantum security; The trajectory of the attack is established only under clear assumptions and is not directly equivalent to a normative loophole. Each nature must be subject to accessibility/proportional controls. FixedRel-19。 Distinguishing between an outside cyber attacker and an ill-intentioned and legitimate person holding his own evidence.NF； TLSAuthenticate encryption modeling by endpoint, validNFCan not open messageNFIt's...TLSSession.OAuth2Subject/udience/scope/expiry andTLS(a) The identity is bound in accordance with the attached baseline; Service scope does not automatically equal ownership of resources. Single-modules cannot simulate real deletions, and the life cycle of a limited state must be clearly defined. Targets are specified.APISubprocess, not complete 5G secure.
Source text	694 numbered passages (323317 bytes) from the sections listed below. A reference such as s0001 in this report is one of these passages

The sections of the documents the analysis is built from:

Document	Section	Title
main	4.6	Nnwdaf_MLModelTraining Service
main	4.6.1	Service Description
main	4.6.1.1	Overview
main	4.6.1.2	Service Architecture
main	4.6.1.3	Network Functions
main	4.6.1.3.1	Network Data Analytics Function (NWDAF)
main	4.6.1.3.2	NF Service Consumers
main	4.6.2	Service Operations
main	4.6.2.1	Introduction
main	4.6.2.2	Nnwdaf_MLModelTraining_Subscribe service operation
main	4.6.2.2.1	General
main	4.6.2.2.2	Subscription for event notifications

Document	Section	Title
main	4.6.2.2.3	Update subscription for event notifications
main	4.6.2.2.4	Partial update subscription for event notifications
main	4.6.2.3	Nnwdaf_MLModelTraining_Unsubscribe service operation
main	4.6.2.3.1	General
main	4.6.2.3.2	Unsubscribe from event notifications
main	4.6.2.3.3	Unsubscribe from event notifications providing additional information
main	4.6.2.4	Nnwdaf_MLModelTraining_Notify service operation
main	4.6.2.4.1	General
main	4.6.2.4.2	Notification about subscribed event
main	5.5	Nnwdaf_MLModelTraining Service API
main	5.5.1	Introduction
main	5.5.2	Usage of HTTP
main	5.5.2.1	General
main	5.5.2.2	HTTP standard headers
main	5.5.2.2.1	General
main	5.5.2.2.2	Content type
main	5.5.2.3	HTTP custom headers
main	5.5.3	Resources
main	5.5.3.1	Resource Structure
main	5.5.3.2	Resource: NWDAF ML Model Training Subscriptions
main	5.5.3.2.1	Description
main	5.5.3.2.2	Resource definition
main	5.5.3.2.3	Resource Standard Methods
main	5.5.3.2.3.1	POST
main	5.5.3.2.4	Resource Custom Operations
main	5.5.3.3	Resource: Individual NWDAF ML Model Training Subscription
main	5.5.3.3.1	Description
main	5.5.3.3.2	Resource definition
main	5.5.3.3.3	Resource Standard Methods
main	5.5.3.3.3.1	PUT
main	5.5.3.3.3.2	PATCH
main	5.5.3.3.3.3	DELETE
main	5.5.3.3.4	Resource Custom Operations
main	5.5.3.3.4.1	Overview
main	5.5.3.3.4.2	Operation: unsubscribe-info
main	5.5.3.3.4.2.1	Description

Document	Section	Title
main	5.5.3.3.4.2.2	Operation Definition
main	5.5.4	Custom Operations without associated resources
main	5.5.5	Notifications
main	5.5.5.1	General
main	5.5.5.2	Event Notification
main	5.5.5.2.1	Description
main	5.5.5.2.2	Operation Definition
main	5.5.6	Data Model
main	5.5.6.1	General
main	5.5.6.2	Structured data types
main	5.5.6.2.1	Introduction
main	5.5.6.2.2	Type NwdafMLModelTrainSubsc
main	5.5.6.2.3	Type NwdafMLModelTrainSubscPatch
main	5.5.6.2.4	Void
main	5.5.6.2.5	Type MLModelTrainInfo
main	5.5.6.2.6	Type MLTrainReportInfo
main	5.5.6.2.7	Type FailureEventInfoForMLModelTrain
main	5.5.6.2.8	Type NwdafMLModelTrainNotif
main	5.5.6.2.9	Void
main	5.5.6.2.10	Type DataAvReq
main	5.5.6.2.11	Type DelayEventNotif
main	5.5.6.2.12	Type StatusReportInfo
main	5.5.6.2.13	Type TrainDataInfo
main	5.5.6.2.14	Type TrainingUnsubscribeInfo
main	5.5.6.3	Simple data types and enumerations
main	5.5.6.3.1	Introduction
main	5.5.6.3.2	Simple data types
main	5.5.6.3.3	Enumeration: FailureCodeTrain
main	5.5.6.3.4	Enumeration: TermTrainCause
main	5.5.6.3.5	Enumeration: DelayCause
main	5.5.6.3.6	Enumeration: FLServerTermCause
main	5.5.7	Error handling
main	5.5.7.1	General
main	5.5.7.2	Protocol Errors
main	5.5.7.3	Application Errors
main	5.5.8	Feature negotiation

Document	Section	Title
main	5.5.9	Security
ts-33-501	13.4	Authorization of NF service access
ts-33-501	13.4.1	OAuth 2.0 based authorization of Network Function service access
ts-33-501	13.4.1.0	General
ts-33-501	13.4.1.1	Service access authorization within the PLMN
ts-33-501	13.4.1.1.1	OAuth 2.0 roles
ts-33-501	13.4.1.1.2	Service Request Process
ts-33-501	13.4.1.1.3	Access token requests in deployments with several NRFs
ts-33-501	13.4.1.1A	Service access authorization in interconnect scenarios
ts-33-501	13.4.1.2	Service access authorization in roaming scenarios
ts-33-501	13.4.1.2.1	OAuth 2.0 roles
ts-33-501	13.4.1.2.2	Service Request Process
ts-33-501	13.4.1.3	Service access authorization in indirect communication scenarios
ts-33-501	13.4.1.3.1	Authorization for indirect communication without delegated discovery procedure
ts-33-501	13.4.1.3.1.1	With mutual authentication between NF Service Consumer and NRF at the transport layer
ts-33-501	13.4.1.3.1.2	Without mutual authentication between NF and NRF at the transport layer
ts-33-501	13.4.1.3.2	Authorization for indirect communication with delegated discovery procedure
ts-33-501	13.4.1.4	Service access authorization in inter NF mobility scenario
ts-33-501	13.4.1.5	Service access authorization in interconnect and roaming scenarios with indirect communication
ts-33-501	13.4.1.5.1	General
ts-33-501	13.4.1.5.2	Authorization with NF selection at source network
ts-33-501	13.4.1.5.2.1	General
ts-33-501	13.4.1.5.2.2	Authorization for indirect communication with or without delegated discovery procedure
ts-33-501	13.4.1.5.3	Authorization with NF selection at target network
ts-33-501	13.4.1.5.3.1	General
ts-33-501	13.4.1.5.3.2	Authorization for indirect communication without delegated discovery procedure
ts-33-501	13.4.1.5.3.3	Authorization for indirect communication with delegated discovery procedure

The process of the review as the source step listed it in the documents:MLModelTrainingEvent subscription/update/notification/cancellation, realSBAEndpoint authentication isolated from key; Up to two training status reports with a clear distinction between intermediate results, completion, failure and cancellation; Serial numbers cannot be invented without notification and are attributed to the norm and are not disguised as being deleted by a single abbreviation.

The properties against the documents

Before a query was written, the analyst set the drafted list of properties against what the documents themselves say the protocol is for. The name, what a property is about and what the documents say are the analyst's reading; the places named exist in the documents.

ID	Name	About	What the documents say	Where
A02	Authenticated peer of requests and notifications	The NWDAF containing MTLF is assured that a subscribe/update/unsubscribe request was sent by the NF instance whose instance identity it authenticates at the transport layer; the NF service consumer is assured that a notification it processes comes from the NWDAF it subscribed to.	TS 33.501 requires mutual authentication between NF Service Consumer and NF Service Producer for direct communication and that each NF validates incoming messages; the notification is a POST to the consumer's notifUri with no OAuth protection.	ts-33-501:2871, ts-33-501:2875, main:344, s0128, s0138, s0505, s0522
A03	Notification and subscription correlation	The consumer accepts a notification only for a subscription it created (notifCorreId, notifUri, mlCorreId, roundInd consistent); the NWDAF accepts an update or an unsubscribe only for the consumer that owns the subscriptionId.	notifCorreId shall be set to the same value as in the subscription; the notification is delivered to the notifUri of the subscription; the API defines only one service-wide scope and no scope at resource level, so resource ownership is not authorized by the token.	main:351, main:347, main:492, s0037, s0042, s0129, s0321, s0378
A04	Each notification event accepted once	The NF service consumer accepts one notification once per NWDAF send; the specification defines no notification sequence number, only notifCorreId.	NwdafMLModelTrainNotif carries notifCorreId and no notification sequence or instance identifier; the documents say nothing about replay of notifications.	s0129, s0321
D01	Notification payload integrity	Every notification the consumer accepts was sent by the NWDAF of the subscription, with the same mLModelInfos, statusReport and termTrainReq contents the NWDAF sent.	The consumer stores the notification on receipt; the notification operation is not covered by OAuth2 and the documents require no payload-origin check at the consumer.	main:349, ts-33-501:2807, s0128, s0131, s0133, s0137, s0138
K01	Long-term credentials stay secret	The NRF's access-token signing key and the long-term authentication credentials of the NF instances are kept from every other party.	Access tokens are JWS-protected with the NRF key and the producer validates them with the NRF public key; NF credentials must be kept confidential by their holder.	ts-33-501:2773, main:340, s0438, s0508, s0375
Z01	Service access requires a valid token	The NWDAF accepts a subscribe, update or unsubscribe only when the consumer presents an NRF-signed access token whose issuer, audience and scope match this NF service.	Access to the Nnwdaf_MLModelTraining API may be authorized with OAuth2, the NRF is the authorization server, and the producer verifies issuer, signature, audience and scope of the token.	main:338, ts-33-501:2867, s0375, s0507, s0515, s0518
Z03	Token claims bound to the request	The token subject is bound to the authenticated TLS client instance, the audience to this NWDAF instance and the scope to this service, so a token issued for one consumer cannot be used by another or for another service.	The producer checks that the subject claim matches the NF Instance ID in the TLS client certificate, that the audience matches its own identity, and that the scope matches the requested service operation.	ts-33-501:2795, ts-33-501:2801, s0483, s0513, s0515, s0518
Z05	Results isolated between consumers	With another consumer's domain under the attacker's control, the target consumer's notifications carry only its own subscription and its own training results, and other consumers' results are not disclosed to it.	The notification is delivered to the notifUri of the subscription and carries the notifCorreId and the mlCorreId of that subscription; the API defines no resource-level scope, so isolation depends on correlation and on the transport identity.	main:492, main:349, s0027, s0128, s0129, s0135
S05	No notification after termination	After the NWDAF removes a subscription, or requests the termination of the training with termTrainReq, no further notification is sent for that subscription, and the identifier cannot be used again for a new subscription.	On a successful DELETE the NWDAF removes the corresponding subscription; termTrainReq indicates that no further notifications related to this subscription will be provided.	main:343, main:347, s0107, s0117, s0133
A04.10	Distinct NWDAF send per acceptance	Each acceptance of a notification by the consumer corresponds to a distinct send by the NWDAF; the same send is never accepted twice.	The notification structure carries no sequence number or instance identifier that would let the consumer tell a repeated delivery from a new one; the documents state nothing about it.	s0129, s0321

ID	Name	About	What the documents say	Where
U01	Termination not confusable with a result	A notification accepted by the consumer as a training termination (termTrainReq) was sent as a termination by the NWDAF; a result or a status report cannot be taken for a termination or the reverse.	At least one of delayEventNotif, mLModelInfos or termTrainReq shall be present and some of these are mutually exclusive, but nothing binds the received field to the sender.	main:346, s0133, s0137, s0321, s0350
Z05.12	Foreign results not accepted as own	With another consumer's domain under the attacker's control, the target consumer accepts no training result of another consumer or another ML procedure as its own.	The notification carries the notifCorreId of the subscription and optionally the mlCorreId; the consumer relates a notification to its subscription by notifCorreId only.	main:351, s0129, s0135, s0321

The analyst added no property: the drafted list covers what the documents state.

The security statements of the documents, paragraph by paragraph

The host listed the 398 paragraphs of the sections in which the documents say what the protocol protects and against what, and the analyst said of each what it made of it: a property, an attacker, or why neither. Taken up: 28. Not taken: 370. Which paragraphs are listed follows from the layout of the standard; where each went is the analyst's judgement.

Paragraphs	Where	Taken up as	Why not
P001 to P002	rfc6749:2778-2786	No goal stated	Introductory text of the security considerations; it states no requirement of its own.
P003 to P006	rfc6749:2790-2823	Z01, Z03	
P007 to P008	rfc6749:2827-2838	A02, Z03, `legit_nf`	
P009 to P010	rfc6749:2840-2850	Outside the scope	Resource owner authentication and repeated authorization requests belong to the authorization code grant; this API uses the client credentials grant with no resource owner.
P011 to P015	rfc6749:2859-2881	Z03, K01	
P016 to P021	rfc6749:2885-2917	Outside the scope	Refresh tokens are not part of the client credentials grant used by NF service access.
P022 to P025	rfc6749:2921-2943	Outside the scope	Authorization codes are not used by the client credentials grant.
P026 to P029	rfc6749:2947-2980	Outside the scope	Redirection URIs of the authorization code grant; the NF notification URI is a subscription attribute, handled by A03 and Z05.
P030 to P033	rfc6749:2984-3003	Outside the scope	The resource owner password credentials grant is not used.
P034 to P035	rfc6749:3013-3019	K01, Z05, `network`	
P036	rfc6749:3023-3028	A02, Z01, `network`	
P037 to P039	rfc6749:3032-3041	K01, `network`	
P040 to P042	rfc6749:3045-3066	Outside the scope	Phishing of end users; no end user takes part in NF service access.

Paragraphs	Where	Taken up as	Why not
P043 to P048	rfc6749:3070-3110	Outside the scope	Cross-site request forgery needs a browser-based client and user credentials; SBA requests are made by NFs over mutual TLS.
P049 to P050	rfc6749:3119-3138	Outside the scope	Clickjacking concerns user-agent rendering; there is no user agent in this protocol.
P051 to P052	rfc6749:3142-3150	The prover cannot be asked	Robustness of input validation against code injection is an implementation property that a symbolic protocol model cannot express.
P053 to P054	rfc6749:3154-3167	Outside the scope	Open redirectors in browser flows; the redirection of an SBA request is a 3xx response inside the operator network and is not modelled.
P055 to P062	rfc6749:3170-3210	Outside the scope	Implicit grant and its access-token misuse do not apply to the client credentials grant.
P063	ts-33-501:2491-2491	Outside the scope	Bidding-down of security algorithms is excluded by the task: the analysis does not model algorithm negotiation or computational strength.
P064 to P072	ts-33-501:2495-2511	Outside the scope	Authentication and authorization between UE and network (SUPI authentication, serving network authorization) — the task covers the Nnwdaf_MLModelTraining API subprocedure, not 5G access authentication.
P073 to P074	ts-33-501:2515-2517	Outside the scope	Key requirements on 5GC and NG-RAN, outside the SBI API subprocedure.
P075 to P125	ts-33-501:2523-2631	Outside the scope	User data and signalling data confidentiality, integrity and subscriber privacy over NAS/AS and in the UDM/UDR; not the NF service API examined here.
P126 to P198	ts-33-501:2637-2811	Outside the scope	Requirements on the gNB, ng-eNB, SEAF, AMF and on access-network signalling protection; outside the SBI API subprocedure.
P199 to P213	ts-33-501:2819-2853	Outside the scope	Subscriber privacy requirements on SEPP, UDM and SIDF; not the NF service API examined here.
P214	ts-33-501:2859-2859	No goal stated	It describes the trust boundaries of the 5G system and imposes no requirement that can be attacked.
P215	ts-33-501:2865-2865	Z01, A04, `network`	
P216	ts-33-501:2867-2867	Z01, `network`	
P217	ts-33-501:2869-2869	Outside the scope	Topology hiding between administrative domains concerns SEPP-based inter-domain communication, which is outside this direct SBA subprocedure.
P218	ts-33-501:2871-2871	A02, `network`, `legit_nf`	
P219	ts-33-501:2873-2873	Outside the scope	The NOTE concerns indirect communication through SCP or SEPP, where there is no mutual authentication; the task models direct SBA endpoints only.

Paragraphs	Where	Taken up as	Why not
P220	ts-33-501:2875-2875	A02, D01, U01, `legit_nf`	
P221 to P227	ts-33-501:2879-2891	Z01, Z03, `network`	
P228 to P241	ts-33-501:2895-2923	Outside the scope	Security requirements on NEF and SCP are about exposure and indirect communication, not the direct Nnwdaf_MLModelTraining access analysed here.
P242 to P292	ts-33-501:2929-3031	Outside the scope	General security, SEPP and roaming interconnect requirements; the task excludes roaming and interconnect.
P293 to P314	ts-33-501:3035-3081	Outside the scope	Messages generated by roaming intermediaries, protection of attributes over N32 and IPUPS; outside the direct SBA subprocedure.
P315 to P318	ts-33-501:3085-3091	Outside the scope	The 3gpp-Sbi-Originating-Network-Id header serves inter-PLMN routing; roaming and network identifiers are outside this analysis.
P319 to P337	ts-33-501:3097-3141	Outside the scope	Signalling monitoring and security visibility/configuration concern operator processes, not the protocol messages.
P338 to P369	ts-33-501:3149-3215	Outside the scope	Ciphering and integrity algorithm identifiers and algorithm selection: the task excludes the computational strength of primitives and algorithm negotiation.
P370 to P396	ts-33-501:3219-11443	Outside the scope	Requirements on 5G-RG, NSSAAF, N3, EAP-TLS access, IAB and MBS; none of them concerns the Nnwdaf_MLModelTraining API subprocedure.
P397 to P398	ts-33-501:11899-11901	Outside the scope	NEF-specific requirements about UE identifiers and VFL communication; the NEF is not part of this API subprocedure.

The parties and the protected values, one by one

The host listed the 25 parties and protected values that the drafted properties name, and the analyst said of each which attacker controls the party or holds the value, or why no such attacker was set. With an attacker: 6. Without: 19. The list follows from the properties; what was made of each entry is the analyst's judgement.

ID	Party or value	Kind	Attacker	Why none
S01	NF Consumers of services	party	`legit_nf`	
S02	NWDAF	party	Everything lost by definition	With the NWDAF itself under the attacker's control every notification it sends is sent by the attacker, so the properties about the producer's honesty are lost by definition; the documents ask no other property of this API under a dishonest producer.
S03	NRF	party	Everything lost by definition	With the authorization server and its signing key in the attacker's hands every token claim can be minted; the analysis asks no property of this API under a compromised NRF.
S04	Consumer A	party	Everything lost by definition	Consumer A is the party whose own subscription and results are the asset; if A itself is dishonest there is nothing left that A is to be assured of.

ID	Party or value	Kind	Attacker	Why none
S05	Consumer B	party	`legit_nf`	
S06	NF Example Identity	value	Nothing gained	The NF instance identity is the subject of the certificate and of the token; it is public by construction and holding it adds nothing beyond the network.
S07	Subscription resources	value	`sid_read`	
S08	notifCorreId	value	Nothing gained	notifCorreId is chosen by the consumer itself, is echoed in every notification for the subscription and is not required to be secret by the specification.
S09	notifUri	value	Nothing gained	notifUri is the consumer's own callback address, published so that the NWDAF can reach it; knowing it does not let a party read notifications sealed to the consumer's endpoint.
S10	mlCorreId	value	Nothing gained	mlCorreId names the ML procedure and is carried in the subscription and in the notification for Federated Learning; it is an identifier, not a credential.
S11	roundInd	value	Nothing gained	roundInd is a round counter carried in the clear inside the subscription and the notification.
S12	subscriptionId	value	`sid_read`	
S13	Examples of notifications	value	Nothing gained	The specification defines no notification instance identifier at all, so there is no value of this kind that a party could hold; the model introduces one only to state the property.
S14	mLModelInfos	value	Nothing gained	mLModelInfos is the payload of the notification, sealed to the consumer's endpoint; holding it is exactly the asset protected by Z05 and is not an attacker capability.
S15	statusReport	value	Nothing gained	statusReport is part of the notification payload, sealed to the consumer's endpoint.
S16	termTrainReq	value	Nothing gained	termTrainReq is part of the notification payload, sealed to the consumer's endpoint.
S17	delayEventNotif	value	Nothing gained	delayEventNotif is part of the notification payload, sealed to the consumer's endpoint.
S18	NRF token signature private key	value	Everything lost by definition	If the attacker holds the NRF signing key, every token is forgeable and every authorization property of this API is lost by definition; that is the meaning of K01 failing, not an attacker the documents give for the other targets.
S19	NF Proof of long-term certification	value	`legit_nf`	
S20	Access tokens	value	Nothing gained	An access token is sealed to the endpoint of the consumer it was issued for; another party cannot read it, and a token of one's own identity is what legit_nf already has.
S21	scope	value	Nothing gained	The scope of this API is a single public service name, nnwdaf-mlmodeltraining.
S22	audience	value	Nothing gained	The audience is the public identity of the NWDAF instance, published in the NF profile.
S23	expiration	value	Nothing gained	The expiration time is a public claim of the token; the model does not model time, and holding the expiry value gives nothing.
S24	subject	value	Nothing gained	The subject is the public NF instance identity of the consumer.
S25	Subscription Status	value	`sid_read`	

The properties under each attacker

The attackers are the analyst's, set before a query was written; each answer was recorded under one of them. A cell is the prover's answer for the property under that attacker; "No answer" is an attacker set for the property under which the prover left a claim undecided or nothing was recorded; an empty cell is an attacker the analyst did not set for the property.

Attacker	Has	Basis	Where
`network`	the network only: it reads, drops, changes and sends messages, and holds no secret of a party		
`legit_nf`	A malicious but legitimate NF service consumer: its own long-term TLS key pair and the access tokens the NRF issues to its own instance identity, so it can open an SBA connection to any endpoint and issue requests under its own identity. It holds no key or token of another NF.	TS 33.501 requires mutual authentication between consumer and producer and makes the OAuth2 framework mandatory for NF service access; a registered NF therefore holds credentials and tokens of its own, and nothing in the documents prevents a registered NF from being malicious.	ts-33-501:2889, ts-33-501:2873, s0438, s0505
`sid_read`	The legit_nf attacker plus the subscriptionId of another consumer's subscription, read from where the NWDAF stores the subscription resource or from signalling monitoring.	The subscriptionId is the only value that names a subscription resource in PUT/PATCH/DELETE, and the API defines a single service-wide scope and no authorization at resource level, so ownership rests on knowing the identifier; the documents grant NF monitoring of 5GC signalling.	ts-33-501:3097, main:492, s0105, s0378, s0442

ID	`network`	`legit_nf`	`sid_read`
A02	Holds	Fails	
A03	Holds		Fails
A04	Fails		
D01	Holds	Fails	
K01	Holds		
Z01	Holds		
Z03	Holds		
Z05	Holds	Fails	
S05	Holds		
A04.10	Fails		
U01	Holds	Fails	
Z05.12	Holds	Fails	

Notes on the prover and the model

What the analyst named for targets:

step	targets	features	reason
53	A02, A03, A04, D01, K01, Z01, Z03, Z05, S05, A04.10, U01, Z05.12	plain_primitives, many_sessions	The model uses only signatures and public-key encryption (the SBA transport) as plain primitives, plus the NRF's signed token; no algebraic laws beyond that. The properties are asked for any number of consumer and producer sessions, and no target depends on a counter or sequence number that a party keeps and changes — the absence of such a value in the notification is exactly what the replay result shows.

The analyst's closing note

All 12 targets are answered claim by claim, with controls, and the flow and nine attack figures are drawn. Proved for any number of sessions: service access and every subscription change require an NRF-signed token whose issuer, audience, scope and subject (bound to the TLS client identity) are checked (Z01, Z03, K01); a consumer that validates the authenticated sender accepts only notifications that NWDAF sent, with the body and kind it sent (A02, D01, U01); a trained model is disclosed to nobody but the consumer named as notifUri (Z05, Z05.12); a notification is sent only within a subscription the NWDAF created and still holds (S05); an accepted notification carries the notifCorreId of the consumer's own subscription (A03). Attacks, all holds_in_source: an API-literal consumer accepts notifications forged by a legitimate NF (A02, D01, U01, Z05, Z05.12); a notification is accepted again on replay and two subscriptions sharing a notifCorreId are conflated, because the notification carries no instance number (A04, A04.10); any NF with a service token and the victim's subscriptionId can remove or rewrite the subscription, since the API authorizes the service and not the resource (A03, attacker sid_read). Three findings, two high and one with unclear novelty because main:492 states the single-scope rule without its consequence; the sender-comparison recommendation was checked on a copy of the model. Blocking more: token expiry, an in-flight notification after DELETE and the added sequence number need an unrolled lifecycle and time (Tamarin+ Agent); indirect communication through an SCP is outside the model.