SERVFAIL: 
The Unintended Consequences of Algorithm Agility in DNSSEC

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ABSTRACT
Cryptographic algorithm agility is an important property for DNSSEC: it allows easy deployment of new algorithms if the existing ones are no longer secure. Significant operational and research efforts are dedicated to pushing the deployment of new algorithms in DNSSEC forward. Recent research shows that DNSSEC is gradually achieving algorithm agility: most DNSSEC supporting resolvers can validate a number of different algorithms and domains are increasingly signed with cryptographically strong ciphers.

In this work we show for the first time that the cryptographic agility in DNSSEC, although critical for making DNS secure with strong cryptography, also introduces a severe vulnerability. We find that under certain conditions, when new algorithms are listed in signed DNS responses, the resolvers do not validate DNSSEC. As a result, domains that deploy new ciphers, risk exposing the validating resolvers to cache poisoning attacks.

We use this to develop DNSSEC-downgrade attacks and show that in some situations these attacks can be launched even by off-path adversaries. We experimentally and ethically evaluate our attacks against popular DNS resolver implementations, public DNS providers, and DNS services used by web clients worldwide. We validate the success of DNSSEC-downgrade attacks by poisoning the resolvers: we inject fake records, in signed domains, into the caches of validating resolvers. We find that major DNS providers, such as Google Public DNS and Cloudflare, as well as 70\% of DNS resolvers used by web clients are vulnerable to our attacks.

We trace the factors that led to this situation and provide recommendations.

1 INTRODUCTION
DNSSEC [RFC4033-RFC4035] was designed to prevent DNS cache poisoning attacks. Proposed and standardised in the 90s, DNSSEC is slowly gaining traction and increasingly more networks are now supporting DNSSEC. Our measurements from October 2021 indicate that 5.54\% of the most popular domains on Tranco list are signed and 39.4\% of the Internet clients use DNSSEC-validating DNS resolvers; we explain this in Section 4. Despite the growing deployment, DNSSEC-validating DNS resolvers still support a limited set of algorithms and many domains are signed with algorithms that are no longer considered secure. Unfortunately, replacing existing ciphers or adding new ciphers to DNSSEC is challenging.

Cryptographic algorithms agility. The research and operational communities invest significant efforts to explore obstacles towards deployment of new ciphers in DNSSEC, to add new ciphers to DNSSEC, as well as to measure the currently supported ciphers. Initially, the DNSSEC standard allowed domains to use either DSA/SHA1 or RSA/SHA1 for signing their zones [RFC4034] - these are no longer deemed secure. Since then, additional algorithms were included in DNSSEC [RFC5155,5702,5933,6605,8080]. The domain owners can now use any subset of 13 algorithms for signing their zones [1]. Although it still takes long to standardise new algorithms and remove deprecated ones, it is generally believed that DNSSEC has already partially achieved algorithm agility [32]. However, to this day no work has been carried out to understand the implications of deployment of new algorithms on the security of DNS.

We show for the first time that the current algorithm agility in DNSSEC introduces a vulnerability, we demonstrate how to exploit it to downgrade DNSSEC. Through analysis of the DNSSEC RFCs, public DNS resolvers’ behaviour and DNS implementations we identify the central factor for the vulnerabilities to be the vague recommendations for handling new ciphers.

Unclear specifications for handling unknown ciphers. According to DNSSEC standard, when returning a lookup result in a signed zone a DNSSEC supporting resolver should either return correctly validated records with an AD flag set, to signal authenticated data, or should return SERVFAIL when the data cannot be authenticated. However, the DNSSEC standard does not clearly specify the recommended behaviour for DNS resolvers when faced with new ciphers. Should the resolvers accept records that are signed with unknown algorithms or reject them? How should the validation proceed when a domain supports multiple algorithms, only some of which are unknown? How should the resolvers react in case of inconsistencies in keys between the parent and the child zones? We experimentally show that this lack of clear specification in the DNSSEC standard leads to different vulnerable behaviour implementations at the resolvers: in presence of unknown algorithms in DNSSEC records the resolvers accept the records in the responses without validating them. Even if the signatures are invalid or if a chain of trust cannot be established to the root, some resolvers do not return SERVFAIL, but instead accept the DNS records without validation.

Adding new ciphers can downgrade DNSSEC security. In this work we find that domains that adopt new ciphers, e.g., ED448 [RFC8080], under some conditions risk downgrading the DNSSEC protection of DNS resolvers that do not support the new ciphers. The cause is the lack of clarity and rigor in defining and implementing DNSSEC for new ciphers. While some public DNS providers, such as Cisco Umbrella, already support ED448, most DNS implementations and DNS service providers still do not. In our Internet measurements of resolvers we discover that even large public DNS providers, such as Google Public DNS, are vulnerable to such passive downgrade of DNSSEC.

DNSSEC downgrade attacks. More significantly, we show that resolvers may be vulnerable to downgrade attacks even for zones that are signed with widely known algorithms, such as RSA/SHA1. The idea behind our attacks is to manipulate the algorithm numbers in DNSSEC records, e.g., DNSKEY, DS, RRSIG records. This causes DNSSEC-supporting resolvers not to apply DNSSEC validation
over DNS records, and exposes them to cache poisoning attacks. Although DNSSEC aims to provide security against on-path Man in the Middle (MitM) adversaries we show that our downgrade attacks can be launched even with off-path adversaries. In an off-path model, in addition to the vulnerable implementation in resolvers, the attack surface also depends on the specific off-path attack methodology. After downgrading DNSSEC, the adversary can inject spoofed records, e.g., for nameservers to hijack a domain or even replace the keys with its own key pair by injecting fraudulent DS/DNSKEY records.

The role of standards. The standards typically aim and need to offer some flexibility of implementation in order to allow for competition among products meeting the standard. On the other hand, it is important to avoid standards that wind up allowing implementations that defeat the purpose of the standard. In this context an interesting question is what kind of analysis of new standards should be undertaken before they are adopted and how implementations should be evaluated against the standard. These are fundamental issues raised by the vulnerabilities found in our, as well as prior, works, e.g., [14, 25]. Therefore, our work raises the question of how we solve not only this particular problem with this particular standard, but also the more general problem for existing and future standards.

Ethics and disclosure. We took preliminary steps to address these vulnerabilities by contacting the DNS software vendors and public DNS providers. We experimentally evaluated the attacks reported in this work against servers that we set up as well as against open DNS resolvers and public DNS resolvers, and against resolvers of web clients in the Internet using domains that we control. This allowed us to validate the downgrade attacks without downgrading the DNSSEC-security of real domains. We also took measures to ensure that our evaluations were ethical and avoided impact on web clients.

- Minimal load: to minimise load on clients we reduced significantly the number of queries from the stub resolvers to only one query that is sent to the recursive resolver. The pop-under carrying our investigation script takes only 150KB on wire. The loaded web resources (images; up to 70 per client) each have a negligible size of mere 84B on wire. Afterwards the communication was performed against the recursive resolvers. This increased the failures during our tests, therefore our results showed a lower bound and more resolvers are vulnerable than those that our evaluations identified. The volume of the packets we exchanged with the recursive resolvers did not exceed those in other studies of DNS, e.g., [26]. In our tests a single referral response was required, we also introduced 50ms delay between the queries to the recursive resolvers.
- User consent: from the users’ perspective, our measurements over an ad-network were simply advertisements and third party content that are loaded when visiting web sites. Hence we could assume with good reason that the users agreed with the measurements as much as they agreed to receiving advertisements.
- Privacy: the data we collect is processed and analysed during the communication with the recursive resolvers, storing only the statistics of the analysis on our server. Our online service provides a privacy policy and displays only information about the computed statistics, ensuring data and source privacy.

Contributions. We make the following contributions:

- We develop a taxonomy of DNSSEC validation by resolvers through analysis of resolvers’ behavior as described in the standard and compare it to the behaviour in the wild and in the lab.
- We systematically analyse the different conditions under which DNS resolvers can be forced to skip DNSSEC validation and develop methodologies for evaluating the DNSSEC validation in DNS resolvers. We find that the validation logic in popular DNS implementations and in public DNS resolvers is often flawed. We develop attacks, including for injecting adversary’s keys into the victim resolver’s cache for a secure zone and for disabling a validation for a secure zone.
- We find that some major DNS providers, such as Google Public DNS and Cloudflare, are vulnerable to our downgrade attacks. In our Internet wide study, we also find almost 67% of open resolvers and almost 70% of the resolvers used by web clients to be vulnerable to downgrade attacks.
- We find that 8% of the signed domains can be exploited even for off-path DNSSEC downgrade attacks against all the vulnerable DNS resolvers. We also experimentally find that 8% of the resolvers vulnerable to off-path downgrade attacks are also vulnerable to off-path DNS cache poisoning.
- We explore key factors causing the vulnerabilities and provide recommendations for preventing our DNSSEC downgrade attacks. We also implement a tool for testing vulnerable DNSSEC validation behaviour at https://www.servfail-dnssec.net/.

Organisation. We review related work and provide an overview of DNS, cache poisoning and defences in Section 2. In Section 3 we analyse the standard recommendations for validation of DNSSEC. In Section 4 we introduce the datasets of resolvers and domains that we study in this work, and provide our measurements of the deployment of DNSSEC. In Section 5 we describe our DNSSEC downgrade attacks. In Section 6 we explain our evaluation of the downgrade attacks against DNSSEC-validating resolvers in the Internet in an on-path model and in Section 7 we develop off-path methodologies for downgrading DNSSEC. We discuss countermeasures in Section 8 and conclude this work in Section 9.

2 DNS CACHE POISONING AND DEFENCES

Domain Name System (DNS) [28] cache poisoning is an attack in which an adversary injects malicious records into a victim’s DNS cache, to hijack a victim domain. Such attacks are especially effective against caching DNS resolvers. Once the attack is successful, the fake records are cached, subsequent requests for the poisoned resource are responded to with the malicious value from the cache, redirecting all the clients of the compromised resolver to an adversarial host. The attacker can intercept the traffic between the services (such as web, email, FTP) in the victim domain and the hosts that use the poisoned cache. SSL/TLS would prevent such attacks, since the redirection would cause a certificate error. Nevertheless, DNS cache poisoning can also be exploited to issue fraudulent certificates, in which case no error messages would be issued and even security savvy users may not detect the attacks [4, 5, 9]. To make cache poisoning attacks difficult to launch, defences and best practices were developed.
2.1 DNS cache poisoning chronicle
DNS experts have been warning for over two decades that source ports and Transaction Identifiers (TXID) have to be sufficiently random to make DNS cache poisoning attacks impractical. Vixie recommended to randomise the source ports already in 1995 [42] and Bernstein in 2002 [3]. In 2007 Klein identified vulnerability in Bind9 [21] and in Windows DNS [22] resolvers allowing to reduce the entropy in the TXID. In 2008 Kaminsky [20] presented a practical cache poisoning attack even against truly randomised TXID, by generating multiple DNS responses, each with a different TXID value. Following the Kaminsky attack, DNS resolvers were patched against cache poisoning [18], and most resolvers randomised the UDP source ports in queries. Despite multiple efforts to randomise the ports, every improvement was often met with a new derandomisation technique. In 2012 [12] developed side channels to infer the source ports in DNS requests. The attacks targeted DNS resolvers located behind NAT devices. In 2013 [13] showed how to exploit fragmentation to inject spoofed records into DNS responses. In 2015 [37] showed how to apply fragmentation to infer the source port of resolvers that use upstream forwarders. That work was subsequently extended by [45] with poisoning the forwarding devices. A followup work demonstrated effectiveness of such cache poisoning attacks also against stub resolvers [2]. Side channels were also used to predict the ports due to vulnerable PRNG in Linux kernel [23], these are however difficult to apply in practice. [26] developed a method to leverage ICMP errors to infer the UDP source ports selected by DNS resolvers. The attacker exploits a global ICMP rate limit, which leaks information about the selected UDP port. A recent work [27] improved an ICMP based side channel, developing an attack that uses ICMP probes to infer a source UDP port. The vulnerabilities are being gradually patched and the remaining practical off-path approach for injecting poisoned records into the caches is considered to be [13] via spoofed fragment reassembly; in our work we use this method for evaluating off-path DNS cache poisoning attacks against DNSSEC-supporting DNS resolvers.

2.2 Defences against off-path poisoning
In this section we describe the recommended countermeasures to prevent attacks by off-path adversaries. These recommendations are typically randomisation of challenges which the off-path adversaries cannot see. The query of the resolver contains certain fields that the resolvers are required to randomise [RFC5452] [18]. These include a random 16 bit UDP source port and the 16 bit DNS transaction identifier (TXID); additional defences include name-server randomisation [18] and 0x20 encoding [8]. The nameservers copy these fields from the DNS request to the DNS response. DNS resolvers accept the first DNS response with the correctly echoed challenge values and ignore any responses with incorrect values. In addition to challenges randomisation against off-path adversaries it is also recommended that the resolvers adhere to BCP140 [10] and not respond to queries they receive from external sources. Nevertheless, there are techniques that external attackers can employ to cause resolvers to issue queries, for instance by sending an Email to the target domain or by uploading an object to popular website which once downloaded causes browsers to issue queries [24].

Once triggering a query, the adversary needs to guess the correct challenge values and make sure that its spoofed response arrives before the genuine response from the real nameserver. This is easy for an on-path (man-in-the-middle) adversary, which can copy the values from the request to the response. In the next section we describe the cryptographic countermeasures that were standardised and are being deployed to prevent attacks by on-path adversaries.

2.3 Defences against on-path poisoning
Cryptographic signatures with DNSSEC [RFC6840] [43] aim to prevent on-path attacks: the domain signs the records, and provides to the resolvers all the required cryptographic material (keys, signatures, etc...) to validate that the records were not modified. The deployment of DNSSEC is progressing slowly, e.g., in 2017 [6] found that only 12% of the resolvers validate DNSSEC. Our measurements showed a slight increase in DNSSEC adoption; we provide the results in Section 4. In addition, deploying DNSSEC was shown to be cumbersome and error-prone [7, 38].

An important research direction in DNSSEC is cryptographic algorithm agility, which was initiated by [44] who explored the changes needed to deploy new algorithms. [30] explored challenges towards deployment of new quantum secure cryptographic algorithms. Recently [32] studied the lifetime of algorithms for DNSSEC using data from 6.7M signed domains. They found that creating standards for new algorithms or deprecating insecure algorithms takes years. Existing work on algorithm agility focuses mostly on measuring support of algorithms on DNS, or explores addition of new algorithms or removal of insecure ones. In this work we perform the first research on the security considerations of algorithm agility and the possible implications of introduction of new algorithms on the security of DNS.

In addition to DNSSEC, there are also proposals for encryption of DNS traffic, such as DNS over HTTPS [15] and DNS over TLS [17], although vulnerable to traffic analysis [36, 40], may also enhance resilience to cache poisoning. However, even these mechanisms do not prevent our downgrade attacks against DNSSEC: some do not protect the entire resolution path and they are not yet supported.

3 DNS RECORDS VALIDITY
Our downgrade attacks exploit the vague specification for resolver behavior in presence of: (1) unknown algorithms in DNSSEC records, as well as (2) mismatches between the algorithms defined in DS record set (RSet) at the parent, the DNSKEY record at the apex and the RRSIG records. We next explain the validation behaviour recommended in the standard and the gaps which create avenues for misinterpretations and vulnerabilities. We also refer an interested reader to the code analysis of an example DNS resolver software in Appendix, Section A.

To prevent downgrade attacks by stripping DNSSEC material from the DNS records the standard specifies that the resolvers are required to identify if DNSSEC validation should be applied. The resolvers enforce this by inspecting the RRSets and related data, and distinguishing between four cases: “secure” (successful validation), “insecure” (no validation path), “indeterminate” (external validation obstacles such as network timeout), and “bogus”, which is defined as an RRsSet for which the resolver believes that it ought to be able
to establish a chain of trust but for which it is unable to do so, either due to signatures that for some reason fail to validate or due to missing data that the relevant DNSSEC RRs indicate should be present.

If there is (at least) one validation path for an RRs [RFC4035] explicitly specifies that if there is a valid signature, the RRset qualifies as “secure” ([RFC4035, Section 4.3]), and otherwise (in the “bogus” case), return code 2 (SERVFAIL) is mandatory when answering a recursive query. As the Checking Disabled (CD) bit is not set in regular resolution queries, returning unauthenticated data is prohibited. For the special case where the resolver does not support any of the algorithms for which keys are announced in the DS record set, the specification allows returning non-validated data. This provision explicitly requires that none of the algorithms contained in the DS record set are supported; it does not apply when several algorithms are present of which only some are unsupported, or when the chain of trust is otherwise broken, such as when an RRset is not signed with a supported (a) algorithm that is referenced in the DS record set. Another general problem is that the DNSSEC specification does not detail how to handle bogus RRs, and the specific behaviour of resolvers in such cases depends on the choices made by the developers. Some resolvers return the bogus RRs as if DNSSEC was not enabled, while others return a SERVFAIL response code instead (to keep unauthenticated data away from the client). In addition, the variations in the interpretation of the standard and choices made by developers and operators indicate the lack of understanding and the lack of consensus on best practices.

We summarise the recommended resolver behaviour in cases of known and unknown algorithms in Table 1. The first row lists DNSSEC material (in DS records or in RRSIG records) and the second line indicates the recommended behaviour for the listed scenario in the standard. The second column captures cases when DS contains any combination of supported and unsupported algorithms, but the RRSIG are missing, then the recommended validation result is bogus. The third column presents a scenario with only supported algorithms in DS records and dangling RRs SIG records, in this case the recommended validation result is bogus. For instance, if a DNSKEY and DS have algorithm 13 but RRSIG is with 8, then the RRSIG is dangling. The fourth column captures DS records with supported and unsupported algorithms, with any combination of RRSIG records (supported only, unsupported only, or both). Finally, if all the DS and RRSIG contain unknown algorithms, it is recommended to treat the records as insecure.

| DS algorithms | RRSIG algorithms | RFC behavior |
|---------------|-----------------|--------------|
| any           | none            | bogus        |
| supported only| dangling        | bogus        |
| supported only| supported only  | SERVFAIL     |
| supported and unsupported | both | SERVFAIL |
| unsupported only| unsupported only| unsupported | unsupported only |

Table 1: Resolver behavior for unusual and invalid combinations of DS, DNSKEY, RRSIG algorithms.

4 DATASET COLLECTION

In this section we collect our datasets of DNS resolvers and domains that support DNSSEC. To design our attacks we also collect the ciphers that are used in the signed domains. Throughout our work we run experiments and attacks using these datasets of DNSSEC validating resolvers and DNSSEC signed domains.

4.1 DNSSEC-validating resolvers

We collect the following datasets of resolvers: (1) popular resolver software implementations, (2) Popular free DNS resolver services, (3) DNS resolvers web browsers we targeted with an ad network, (4) open DNS resolvers, (5) resolvers used by the routing infrastructure for collecting the RPKI objects from the RPKI publication points.

A summary of our resolvers’ datasets and their support of DNSSEC algorithms is listed in Table 2. Most of the public DNS resolvers and DNS software implementations do not support algorithm 16 (ED448) with a gradually increasing support of validation of algorithm 15 (ED25519); the mapping between the algorithms’ numbers and their description is provided in Appendix, Table 6.

4.1.1 Popular resolver software. Eight instances of popular publicly available resolver software in popular versions. These instances cover the market of publicly available resolver software solutions (excluding commercial software) that validate DNSSEC and offer maintenance2. This was also indicated in the research that measured the widely used DNS software [24].

4.1.2 DNS resolver services. We use the list of open DNS resolver services at https://www.publicdns.xyz. Public DNS services are used by many different applications and systems, ranging from web clients, email servers to large resolvers of Internet Service Providers (ISPs). In fact, we even found that RPKI, the routing security infrastructure, in large part also uses public DNS providers. Our measurements from 1 November 2021 (results provided in Section 4) reveal that 53% of the relying parties3 (the client side of the RPKI) use public DNS resolvers: 46% use google public DNS and 7% use Cloudflare, both validate DNSSEC.

4.1.3 Open DNS resolvers. This dataset contains publicly accessible resolvers collected via an Internet-wide IPv4 scan for port 53. We obtain a list of 1.8M open resolvers4. We selected only those resolvers that resolved a name in our domain and support DNSSEC, validating ciphers that correspond to any of the tested algorithms. Our dataset does not contain resolvers that did not respond to our queries or do not support DNSSEC validation.

4.1.4 Web clients via ad-net. For collecting resolvers of web clients we deployed an advertisement network. We distributed our test web page as a pop-under to 4,658 users around the globe. Our ad-net study ran for a week. When the investigation web page is loaded in the pop-under, the web browser executes our test script, which instructs it to include a number of images in the document, via URLs containing our test domains. We associate the web clients with the DNS resolvers that they use via a client-specific random token transmitted as a query parameter in each request for an image.

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1 Dangling RRSIG means that the algorithm in the signature does not appear in the chain of trust.

2 https://en.wikipedia.org/wiki/Comparison_of_DNS_server_software

3 Relying party software retrieve the RPKI objects from the public RPKI repositories.

4 https://opendata.rapid7.com/sonar.udp/
We analyse the individual tests by presence of the according web requests. Using our ad network we identified 1308 unique, globally distributed DNS resolvers. The distribution of the algorithms supported by the DNS resolvers we studied using an ad-network and open DNS resolvers are plotted in Figure 1. Most of the resolvers, 62%, support four DNSSEC algorithms; 14% support 5 algorithms, and 17% support 3 algorithms; detailed statistics are listed in Appendix, Table 9.

4.2 DNSSEC-signed domains

Our dataset of domains contains 1M-top Tranco domains and Top Level Domains (TLDs). DNSSEC is currently deployed for the DNS root zone using algorithm 8 (RSASHA256). We measure the DNSSEC support and DNSSEC algorithms on the list of TLDs from IANA\(^5\).

\(^5\)https://data.iana.org/TLD/tlds-alpha-by-domain.txt

4.2.1 Top level domains. Out of 1,498 TLDs, 1,372 (91.59%) have a DS record at the root zone. Out of the DNSSEC-signed domains, 185 (13.48%) are signed with one cipher, 1, 187 (86.52%) are signed with multiple ciphers (4 ciphers max). Measurements of DNSSEC on root and TLDs were done in previous works, e.g., [38], where they also showed that many of the deployments are vulnerable due to reuse of keys.

4.2.2 Second level domains. As a list of second level domains we use the 1M-top Tranco list of domains, out of which 43,181 (4.46%) are DNSSEC signed and have a DS record at the parent. Of those, 21,122 (48.92%) are signed with one cipher, 22,059 (51.09%) with multiple ciphers (with max 7 ciphers).

The distribution of the algorithms (5, 6, 13, 15, 16) are plotted in Figure 2: most domains are signed with a subset of algorithms 5, 8 and 13, and with 5% using additionally algorithm 15. The number of different algorithms that the domains are signed with are plotted in Figure 3, with the maximal number of different algorithms being 7. Detailed statistics are listed in Appendix, Tables 7 and 8.

5 DNSSEC-DOWNGRADE ATTACKS

In this section we develop methodologies for downgrading DNSSEC security of DNSSEC-supporting resolvers for records in signed domains. Our attacks cause the resolvers to accept fake DNS records with invalid signatures, without validating the signatures. In Section 5.1 we describe our attack methodology. Then in Section 5.2 we develop attacks and show their impact on DNSSEC and DNS.

5.1 Attack methodology

The basic idea behind our downgrade attacks is to manipulate the algorithm number in DNSSEC records to an algorithm number that the resolver does not support, in such a way that it allows us to exploit it for clever attacks against DNSSEC and DNS. We explain the steps of the attack and test scenarios.

5.1.1 Attack steps. The attack is illustrated in Figure 4. Adversary causes the recursive resolver to issue a query. There are different ways to do that, in an example in Figure 4 we illustrate query triggering using web clients that download our object via an ad network that we deployed. The client sends a query to the recursive resolver and on Traco 1M-top set\(^6\) of popular domain names. During the measurements we send queries from our client for DS, DNSKEY, and SOA records and for the corresponding RRSIG records.

\(^6\)https://tranco-list.eu/
(step A), which in turn sends it to the authoritative DNS server of the victim domain (step B). The response of the nameserver is in step C changed by an on-path attacker, who manipulates the algorithm field in the RRSIG record according to the vulnerability (we list the scenarios in our evaluation in Section 5.1.2) and injects a malicious DNS record. The new record would not pass DNSSEC validation, since the modified record does not match to the digest in the signature. However, since the algorithm number in an RRSIG was changed to an unknown algorithm, the resolver does not validate DNSSEC for that answer and caches the malicious records that poison its cache, despite the fact that the signature is invalid.

5.1.2 DNSSEC algorithms replacement scenarios. Our scenarios draw on the analysis of DNSSEC validation in Section B. We modify DNSSEC records in DNS responses to contain unknown algorithms and in addition fake DNS records. We then observe the behavior of a validating DNS resolver on such responses. We define 7 different modifications that we apply on the DNS responses:

1. replace signature algorithm number with ED448 (16)
2. replace signature algorithm number with ED25519 (15)
3. replace signature algorithm number with ECDSA-P256-HS256 (13)
4. replace signature algorithm number with RSA-HA256 (8)
5. remove all signatures except ED448
6. remove all signatures except ED25519 and ED448
7. remove all signatures

The first 4 modifications (1-4) replace a known algorithm with a new algorithm number (such as 8, 13, 15 or 16) which the resolver does not support. In our evaluations we test resolvers behaviour when records contain signatures with supported and also signatures with unsupported algorithms (RRSIG column “both” in Table 1). In our evaluations the behaviour does not depend on a specific unsupported algorithm. Namely, when a resolver is vulnerable and does not support algorithms 8, 13, 15, 16, it does not make a difference to which unsupported algorithm the number is changed (it can be an arbitrary number). The last 3 modifications (5-7) remove all signatures except a signature with an unknown algorithm number (RRSIG column “unsupported only” in Table 1). Finally, we also strip all signatures, in addition to adding a fake record.

For the downgrade attack to succeed, the resolver must be susceptible to at least one of the attack scenarios that we defined.

5.2 Attacks against DNSSEC

We explain methods for disabling DNSSEC (which type of records and which type of responses the adversary needs to target) as well as the implications on attacks against the DNS resolvers and the corresponding resources in the victim domains. We identified four attack categories, which include different variations of attacks against DNSSEC and DNS. All the attacks start with manipulating the algorithm number in an RRSIG to an unsupported number, except for an attack against referral type responses, where the records in an authority and additional sections of the response (i.e., nameservers in the child domain) are not signed. The RRSIG that has to be modified depends on the specific attack and the fake record that the adversary aims to inject, details within. This disables the DNSSEC validation and enables injection of fake records into the responses. We develop attacks to hijack a secure DNSSEC delegation by injecting a key pair controlled by an adversary; we show how to disable DNSSEC for an entire DNS tree, such as some victim TLD. Finally, we also show how to disable DNSSEC validation on specific records, for injecting malicious nameservers and hijacking a domain.

5.2.1 Hijack secure DNSSEC delegation. The goal of the adversary is to inject a malicious DNSKEY which it can use to sign the records in a victim domain. The adversary targets a referral type response sent by the nameserver to the DNS resolver. In that response the adversary manipulates the algorithm number in an RRSIG RRset over DS RRset to some unsupported algorithm. This is required to disable DNSSEC validation of the DS RRset. The adversary manipulates the DS to correspond to its own key-pair. Adversary has the private key that corresponds to the value in DNSKEY and can now create its own signatures. Once this DNSKEY is stored in cache, the adversary can inject any record of its choice. This attack allows not only to hijack the entire DNSSEC-secure DNS tree but also to forge any records in that tree with correct DNSSEC signatures. Responses from the real domain will fail validation since they will use a different DNSKEY record. This will prevent overwriting of the cached records from the adversary with the genuine values from the real nameservers. We provide a detailed example of this attack in Appendix, Section F.

In addition to downgrading DNSSEC, this attack also disables one of the security mechanisms recommended in [RFC5452]. By injecting its own DNSKEY into the victim resolver, the adversary causes the responses from the real nameservers to become invalidated, since they are signed with the genuine key, which the resolver no longer accepts as valid. Consider for example com, that uses 13 nameservers. If the adversary hijacks only one nameserver and injects its key, invalidating all the other keys, it effectively causes the DNS resolver to only query the adversarial nameserver, since responses from all the other 12 nameservers provide responses with “invalid signatures”.

Another significant side effect of the attack is that it immediately affects all the subdomains of the poisoned domain. In particular, the adversary can further create secure delegations for the subdomains using its own malicious key. Launching this attack against Google public DNS would have severe consequences for all the domains under com.

5.2.2 Disable secure DNSSEC delegation. To disable DNSSEC validation in an entire DNS sub-tree, in addition to manipulating the algorithm number in an RRSIG to an unsupported algorithm in referral responses as in attack in Section 5.2.1, the adversary also changes the DS to contain a key with an unsupported algorithm. These records are cached and subsequent DNS responses from the nameservers in that subdomain are not DNSSEC validated. Since the poisoned DS record carries an algorithm number, which the resolver does not support, the validation path is terminated and all
subsequent signatures are not validated. This downgrades DNSSEC of the child domain, e.g., com., and all its subdomains, i.e., all the second level domains of com.. All the records in those domains delivered to the victim resolver are no longer protected by DNSSEC. The adversary can launch DNS cache poisoning against any signed domain under com..

In contrast to the attack in Section 5.2.1, the victim resolver will also accept responses from real nameservers, just without validating them. The attack demo for disabling secure delegation is provided with example records in Appendix, Section G.

5.2.3 Hijack secure domain. The adversary hijacks a domain by injecting a malicious nameserver: The adversary can manipulate the IP addresses in a referral DNS response. In referrals the glue records are not signed, hence this step does not require a manipulation of the RRSIG to an unknown algorithm. A subsequent authoritative response from the domain will contain signed NS records, which will have higher caching rank than the unsigned NS records in the referral. Therefore, the adversary also needs to perform another step and manipulate the algorithm number in the RRSIG over the NS RRset or/and A RRset, to disable the DNSSEC validation, and inject malicious NS/A records. In all subsequent responses from the adversarial nameservers, the adversary has to also include arbitrary (i.e., dangling) signatures with unsupported algorithm numbers, to continue disabling DNSSEC validation.

5.2.4 Manipulate records in Answer responses. To manipulate genuine records in a DNS response or to inject a fake record to the response the adversary has to change the algorithm number in the RRSIG that covers the manipulated RRset. The adversary can create a new DNSKEY record for a domain or hijacking a resource by manipulating the algorithm and changing the hostname or an IP address.

6 EXECUTING ATTACKS ON-PATH

In this section we describe evaluations of our downgrade attacks in an on-path adversary model. We first describe the infrastructure that we set up for the evaluations and Internet wide measurements. Then we describe the evaluations that we run on our datasets of resolvers and the results.

6.1 Setup

Our setup contains our test domains that we control, authoritative nameservers (based on Knot implementation) in our test domains, a Man-in-the-Middle (MitM) proxy and a client component. The setup is similar to the illustration in Figure 4, with "attacker" being our MitM proxy.

6.1.1 Domains and nameservers. The nameservers of each domain are configured to use 50 zonefiles, each contains a different combination of DS records, DNSKEY records and RRSIG records. The nameservers serve records in each of the 50 zones, signed with all the algorithms that can be found in the corresponding DS records. The domains have been configured to have either exactly one DS algorithm (5, 8, 13, 15, or 16), or a combination of two DS algorithms from this list, see Table 3. In our evaluations we use combinations of known and new algorithms, which most resolvers do not yet support: 8, 13, 15 and 16. The DS records are associated with at most two matching DNSKEY records. We do this as follows: we create DNSKEY records and use them to sign each zone. To create scenarios with dangling RRSIG records we delete some DNSKEY records. In some tests we use one DS record. When evaluating different ciphers we use two DS records per domain, such that each is generated with DNSKEY records that use distinct ciphers.

6.1.2 Reverse MitM proxy. The reverse MitM proxy is developed in python and acts as an on-path adversary. It manipulates the records in the DNS responses according to the attack scenarios defined in Section 5 (i.e., the scenarios listed in Section 5.1.2 and the attacks in Section 5.2). The reverse proxy manipulates or/and strips off signatures and changes the algorithms’ numbers.

6.1.3 Client. We use a client side component to cause the target resolvers to issue queries to our domains. The setup and functionality of the client side component depends on the usage of the DNS: direct and indirect. The former is when the queries to the resolver can be sent directly, while the latter applies when the evaluation is performed indirectly via our script in clients’ browsers.

Direct tests. A client side component is simple, it is located on our measurement infrastructure and triggers queries to the target DNS resolvers directly. We use this setup to test the publicly available implementations of DNS, public DNS providers and open DNS resolvers.

Indirect tests. A script running in a browser issued DNS queries, which are passed on by the stub resolver to the recursive DNS resolver. The setup is illustrated in Figure 5. We use this setup in our Internet wide study of web clients via an advertisement network.

6.2 Evaluation

The client component runs the test scenarios each time triggering requests to our test domains. The requests encode different tests. Upon each request, the nameserver decodes the test from the query name sent by the DNS resolver, and sends the response. The MitM proxy replaces the algorithms’ numbers in the signatures from the responses according to scenarios (1-7) in Section 5.1.2. The replacement is performed via manipulation of the signature number in the RRSIG record (scenarios 1-4) and manipulation of the rdata of at least one the records it covers. Removing all the signatures completely or leaving signatures of specific algorithms (attack scenarios 5-7) is achieved by stripping the RRSIG records from responses and by substituting the rdtypes value of the RRSIG record with an unallocated one1. The effectiveness of a specific attack scenario against a target DNS resolver, depends on the resolver’s vulnerability to downgrade attacks as well as on the DS configuration at the zone.

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1For the sake of forward compatibility, resolvers abiding by [RFC3597] MUST treat unknown rdtypes as legitimate records, that carry unstructured binary data (and even must pass them to the client, if they are relevant for the query) https://datatracker.
We list the results of our evaluations of the downgrade attacks we find that all the three exhibit non-RFC compliant validation were tested in the same lab environment and were not vulnerable. were installed in our lab setup, and evaluated against the domains we found to be vulnerable. The different Windows server versions

| DS Algorithms | Prevalence in Tranco 1M | Prevalence in TLDs |
|---------------|--------------------------|-------------------|
|               | 8 | 8, 13 | 8, 15 | 8, 16 | 13 | 13, 15 | 13, 16 | 15 | 15, 16 | 16 |
| Windows Server 2012 | 51% | 0% | 0% | 0% | 41% | 0% | 0% | 0% | 0% | 0% | 0% |
| Windows Server 2012 R2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Windows Server 2016 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Windows Server 2019 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| AdGuard Public DNS | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cloudflare Resolver | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Google Public DNS | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Open DNS resolvers | 59.2% | 60.2% | 60.2% | 66.8% | 62.2% | 60.5% | 66.8% | 56.9% | 64.8% | 2.3% | 0% |
| DNS resolvers via Ad-net | 30.7% | 20.5% | 36.2% | 29.2% | 22.0% | 16.0% | 69.1% | 60% | 60% | 5% | 0% |

Table 3: Downgrade attacks under certain DS record configurations at the zone’s parent. Percentage missing to validation chain if a DS/DNSKEY pair with a supported algorithm is present [RFC 4035, Section 4.3]; see summarised RFC behaviour in Table 1 - when both cryptographic material with both supported algorithms, this behavior also occurs when there exists a validation path with supported DS algorithms, DNSKEYs and RRSIGs, without regard to whether the supported RRSIG is valid or not. The standard recommends removing SERVFAIL in those cases, however, Cloudflare does not check for any supported signatures that exist for the zone when an unsupported DS/DNSKEY records are present. This behaviour contradicts the requirements of the RFC that the resolvers MUST expect RSets to be signed via a supported validation chain if a DS/DNSKEY pair with a supported algorithm is present [RFC 4035, Section 4.3]; see summarised RFC behaviour in Table 1 - when both cryptographic material with both supported and unsupported algorithms exists the resolvers should perform validation and return SERVFAIL.

This configuration is vulnerable to DNSSEC downgrade attacks. The adversary needs only add an unsupported algorithm to the DNS responses, to disable the DNSSEC validation and inject fake records using any of the attacks listed in Section 5.2. This enables an adversary to poison the cache for any domain that has a DS record with unsupported algorithm.

When zones are upgraded, among others there may also be added pre-provisioned DS records for unsupported algorithms, without dual-signing (yet), i.e., DS without the corresponding RRSIG. This also exposes to attacks: an adversary just needs to add a fake RRSIG with that algorithm, or to manipulate some other RRSIG in the response to contain that unknown algorithm to disable DNSSEC, then proceed to inject malicious DNS records to the responses to the victim DNS resolver.

The situation is however even worse: if the zone operator adds an unsupported algorithm to the DS RRset and dual-signs the zone...
with this algorithm, it will automatically disable DNSSEC validation for CloudFlare DNS resolvers. It further downgrades the security for all domains that use dual-signing with supported and unsupported algorithms (say, 8 and 16 or 13 and 16). Since large managed DNS operators are introducing dual-signing for many zones, we caution that dual-signing with modern algorithms, such as with ED448 currently, now or in the future decreases security for CloudFlare resolvers as well as resolvers that belong to the Cloudflare DNSSEC validation category, resulting in "no DNSSEC at all".

Google public DNS. Google Public DNS (8.8.8.8) supports algorithms 8, 13 and 15. Google DNS is an example of another non-RFC compliant behaviour. If no RRSIG exists on the queried RRset then SERVFAIL is returned. If there are RRSIG records, then Google checks: (1) if the RRSIG records are with a supported algorithm that matches the key from the DS RRset, Google Public DNS validates the signatures. If the validation succeeds the response is returned with AD bit set. Otherwise, SERVFAIL is returned.

(2) If the RRSIG contains an unknown algorithm number or when the RRSIG is not aligned with the DS RRset (i.e., "dangling RRSIG"), Google Public DNS returns the requested records with AD bit unset. Specifically, Google DNS does not SERVFAIL when all the algorithms in RRSIG records are unsupported, namely, none of the RRSIG records in the response has a supported algorithm, regardless of the DS configuration at the parent. While acceptable when the DS RRset does not contain any supported algorithms, this behavior occurs independently of whether the DS RRset includes a supported algorithm or not. For instance, when there are DS and DNSKEY records for "known" algorithms, such as 8 and 13 but there is signature only for algorithm 15 (see Table 2 for supported algorithms), Google Public DNS does not reject the data, although there is no match between RRSIG and DS records. This allows the adversary to change the algorithms in RRSIG records to unsupported, irrespective of the response from the parent domain, turning DNSSEC validation at google DNS off. Our measurements on 43K signed Tranco domains and 1372 signed TLDs in November 2021 found 140 Tranco and 4 TLD domains (respectively) with dangling records. DNSSEC validation of Google Public DNS is not applied over the records in those domains.

Similar vulnerabilities and behaviour apply when responses contain unknown keys, with known algorithms. Google also does not SERVFAIL when there is an RRSIG record with a supported or unsupported algorithm number, but without a matching DS record ("dangling signature algorithm").

In scenarios above the records are cached and returned to the clients. This enables an adversary to downgrade DNSSEC validation by adjusting the algorithm number of any RRSIG to 16 (currently unsupported by Google), which disables DNSSEC validation at the resolver. This behavior affects all the domains on the Internet, including all TLDs, and the vulnerability will not be mitigated even if the zones create DS records for all possible algorithms, as Google DNS also skips validation when unassigned algorithm number is present in RRSIG and no DS record exists for that algorithm.

The AdGuard public DNS is exhibits the same DNSSEC validation behaviour as Google public DNS and is similarly vulnerable.

6.3.2 DNS Resolvers via ad network. The setup for ad network study is illustrated in Figure 5 and inspired by [19]. When our script is downloaded by the client it iteratively includes resources (img) from test domains, including a non-DNSSEC-signed domain to signal session finish. The web server logs all the requests and delivers the requested resources. A script then analyses the logs to check for vulnerabilities to our DNSSEC downgrade attack. In our ad network study we covered 768 Autonomous Systems (ASes) with publicly routable prefixes. From the covered ASes, our server was accessed by 6.07 clients per AS on average. Similarly, the ad network study spanned 129 countries around the globe, which homed 28.61 clients on average.

We observed different DNS resolvers’ behaviour, out of 1308 distinct DNS resolvers that we studied via an ad network: 302 DNS resolvers were vulnerable to scenario 2 (vulnerable to downgrade attack with domains that use DS with algorithms 15 and 16 concurrently) - we find that 105 of these DNS resolvers belong to Comcast; 225 are vulnerable to scenario 3 (vulnerable to all tested DS configurations); 59 exhibit Google DNS behaviour and are vulnerable in a similar way described in Section 6.3.1; 35 exhibit Cloudflare behaviour and are similarly vulnerable. Our measurement results indicate that a large portion of Internet clients use resolvers that are vulnerable for at least some DS configuration. While the adversary cannot choose the DS configuration of the attack target, for a successful attack it suffices that any of the DS configurations in the target zone’s ancestors has a configuration vulnerable at the resolver. We list the statistics on downgrade vulnerabilities according to geolocations in Table 4. As can be seen, there are no significant differences between the various geolocations, with most being vulnerable to configurations with algorithm 16 (ED448). Detailed statistics on configurations of DS records for which the ad-net resolvers are vulnerable to downgrade attacks are in Table 5. Here too can be seen that most resolvers are vulnerable to configurations.

| DS Algorithms | 8 | 8, 13 | 8, 15 | 8, 16 | 13 | 13, 15 | 13, 16 | any |
|---------------|---|-------|-------|-------|---|--------|--------|-----|
| Prevalence in Tranco 1M | 51% | 0% | 0% | 41% | 0% | 0% | 0% | 0% |
| Prevalence in TLDs | 89% | 0% | 0% | 3% | 0% | 0% | 0% | 0% |

Table 4: Prevalence of resolvers vulnerable to downgrade attacks for zones with the given DS algorithm configuration by world region, relative to the total population of users with validating resolvers.
7 EXECUTING ATTACKS OFF-PATH

DNSSEC was designed to block cache poisoning attacks by MitM on-path adversaries. Obviously, our DNSSEC-downgrade and then cache poisoning attacks against DNSSEC-validating resolvers with DNSSEC signed domains is attractive for on-path adversaries. In this section we show that our downgrade attacks can be launched even by off-path adversaries.

Why evaluate DNSSEC-downgrade attacks in an off-path model? Since DNSSEC, e.g., similarly to SSL/TLS, is meant to thwart attacks by on-path adversaries, to show a vulnerability it suffices to run on-path attacks. The answer is that our off-path attacks demonstrate how alarming the situation really is: even off-path adversaries can, depending on the off-path technique, downgrade DNSSEC validation and poison validating resolvers. Our off-path attacks demonstrate feasibility of subverting DNSSEC even with adversaries that are not on path.

We first explain our off-path adversary model, then introduce techniques for launching off-path downgrade attacks and our measurements of the vulnerable DNS servers. Since running DNS cache poisoning in an off-path model is more challenging than in an on-path model, we also explicitly evaluate the off-path cache poisoning attacks against the resolvers that are vulnerable to DNSSEC downgrade attacks.

7.1 Techniques for off-path attacks

There are different ways to launch attacks against DNS in an off-path adversary model. In practice, most of the publicised attacks against DNS were launched via BGP prefix hijacks [4]. The adversary hijacks a BGP prefix that hosts a DNS nameserver or a DNS resolver to intercept any packets sent to or from the hijacked prefix. Such attacks can be prevented by authenticating the prefixes in RPKI and validating BGP announcements, as recommended in [RFC6482]. Nevertheless, a recent research [14] found that RPKI is vulnerable to downgrade attacks.

BGP prefix hijacks affect the global routing in the Internet, making the attack more visible. The changes in the global routing may also impact the traffic of other ASes, hence we do not use it in our off-path evaluations. We evaluate our downgrade and cache poisoning off-path using a much stealthier technique, which affects only the victim resolver locally and is also based on a different attack methodology, that is not trivial to evaluate in the Internet.

To develop off-path DNSSEC downgrade we manipulate the DNS payload using IP fragmentation technique from [13]. We also use the IP fragmentation from [13] for evaluation of cache poisoning attacks. In contrast to [13] our cache poisoning attacks apply against DNSSEC signed domains. Responses in signed domains are typically larger due to the DNSSEC material (keys and signatures) hence many more domains return fragmented responses and are vulnerable. In an off-path setup it may make sense to use different DNS cache poisoning techniques. For instance, assume responses from a parent domain fragment, but the responses from the target domain do not. The adversary can use fragmented referral responses from the parent domain, to disable DNSSEC for a secure zone. As a result, the adversary can inject fake records into any subdomain without the need to adjust the signatures, for as long as the RRSIG/DS records with unknown algorithms are stored in the cache. Launching such attacks can be done for instance using the newly published ICMP side channel technique [27].

7.2 Setup

We use the domains and the nameservers from our setup in Section 6.1 to evaluate DNSSEC downgrade attacks and then to measure off-path cache poisoning attacks against the fraction of validating resolvers vulnerable to DNSSEC-downgrade. Our dataset of resolvers contains the DNSSEC-validating resolvers that we found vulnerable to on-path DNSSEC downgrade attacks in Section 6 (Table 3).

7.3 DNSSEC-downgrade and cache poisoning

To manipulate the algorithm number in DNS responses, while not being on the communication path between the resolver and the nameserver, we use IP fragmentation [11, 13]. The idea is to create a spoofed second fragment that is reassembled with the first genuine fragment from the nameserver. In the spoofed second fragment we inject a record, e.g., RRSIG, that we simply copy from the nameserver’s response, while changing an algorithm number to some unknown algorithm.

The combined off-path downgrade and cache poisoning attacks are illustrated in Figure 6. The attack consists of the following modules: (1) reduction of MTU on the nameserver, (2) injection of poisoned record in spoofed second fragment and (3) inference of IP ID on the nameserver.

7.3.1 Reduction of MTU. The attack requires that the responses from the nameserver are fragmented. To ensure this, the adversary...
uses an ICMP fragmentation needed message [RFC792] to reduce the MTU on the nameserver (Figure 6). As a result the responses to the resolver are fragmented at an offset that corresponds to the MTU indicated in ICMP error message.

7.3.2 Manipulation of records. The adversary needs to create a fragment with the fake records that should be injected into the genuine response from the nameserver. The records in the created fragment have to be correct and have to be reassembled with the first fragment from the nameserver. To do that, we use the DNS response from the nameserver, and modify in it the specific parts that are needed for our attack; this step is omitted in Figure 6. In our evaluation we tested "hijacking secure delegation (attack in Section 5.2.1) and in addition also injected a new IP address for a nameserver. To obtain the DNS and DNSSEC records that we wish to manipulate we send a query to the target domain. We use these records to create a spoofed second fragment with the correct content and with the manipulated algorithm number in order to disable DNSSEC. We then create a second fragment with a spoofed source IP address of the nameserver. This fragment contains the manipulated record, e.g., the RRSIG record with an unknown algorithm number, a new NS record and a manipulated DS record (according to the attack methodology in Section 5.2.1). We illustrate the formats of the records in Appendix, Section B. The spoofed fragment is sent to the victim DNS resolver (step C, Figure 6). To initiate the attack we use our client to cause the resolver to issue a request for the specific record that we manipulated in the spoofed second fragment (step D, Figure 6). The response is fragmented (step E, Figure 6). The first genuine fragment is reassembled with the second spoofed fragment of the adversary, and the manipulated record is passed on to the resolver. Consequently, the DNSSEC validation for the target domain is turned off and the adversary injected a malicious DS and NS records. It can respond subsequent queries to its nameserver for that domain and sign the DNS records with the key pair that it controls.

7.3.3 IP ID inference. In order to be reassembled with the genuine first fragment from the nameserver, the spoofed second fragment from the adversary must have the same IP ID value as the one assigned by the nameserver to the DNS response sent to the resolver. It was shown that even random IP ID assignment can be hit with high probability given large IP defragmentation cache on the resolver [11]. Since our goal is to show that our attacks apply even in an off-path setting, we develop a proof of concept attack implementation against nameservers that use globally incrementing IP ID assignment. Predicting IP ID value produced from a globally incrementing counter can become challenging when the nameservers receive traffic from other sources, which increment the IP ID values between our probes. For prediction of the next IP ID value in a DNS response from a given nameserver we develop an SVM classifier and evaluate its performance for prediction of the IP ID behavior and the next IP ID value. That is the IP ID value that the nameserver assigns to the DNS response into which the adversary injects a poisoned payload. We first collect the IP ID series from nameservers and then perform the prediction.

Data collection. To collect the IP ID series from nameservers in signed domains we use two IP addresses. We send DNS requests and extract the IP ID values from responses. In each measurement series we send 50 probes from each of the two IP addresses alternately (overall 100 probes per server). We then manually label the IP ID instances.

Prediction. Once the collection is complete, our prediction is carried out in two steps. First, using the classifier, that we developed, we identify nameservers with globally incrementing IP ID counters. In the second step we predict the next IP ID value. This prediction technique assumes that the adversary knows when the client triggers the target query. During an actual attack this is controlled by the adversary. For instance, in open resolvers the adversary directly sends the query to the resolver, while in ad network our script triggers the query. In our dataset of domains that includes Tranco domains and TLDs we found 5.1% nameservers with globally incrementing IP ID counters.

We carry out the evaluation on a host with 16 GiB RAM, Intel Core i7-8565U CPU @ 1.80GHz, Ubuntu 20.04.2 LTS. For the evaluation of the SVM classification model we use the feature for IP ID prediction defined in [35, 39] and compute three macro-averaging values: precision, recall, and F1-score. The three values of SVM classifier are: 99.84%, 99.80% and 99.82%. Our classifier identified all the instances of IP ID counters correctly (per-destination, random and constant) and correctly predicts the next IP ID value for globally incrementing counters.

We also evaluated prediction of IP ID values from global rapidly increasing IP ID counters (on servers that receive high volume traffic). We first selected 173 instances of nameservers in signed domains that have IP ID counters with an average growth rate exceeding 500 IP IDs per second. We collect overall a total of 769 high-speed (greater than 500) instances of IP IDs. The velocity distribution among the collected IP ID examples falls into the range of (500, 12000), and about 769 instances have a relatively high average increment rate of more than 4000 IP IDs per second. The evaluation results on the high-velocity IP ID data with the SVM classifier showed robustness to high fluctuations of the global counter, enabling prediction with over 99% accuracy. On average the SVM achieves the highest accuracy (99.87%) when identifying the high-speed counters.

7.4 Evaluation
We measure vulnerabilities in two steps: first using a domain that we setup and control, against other resolvers in the Internet, and
then using our victim resolver that we set up with our dataset of signed domains.

We find experimentally that the fragmentation attack is well-suited for targeting referrals in vulnerable domains, and hence can be applied to hijack a secure delegation. The adversary can pad the name, pushing the records of interest towards the second fragment (so that they can be manipulated). The NS records are included, typically before the DS, pushing the DS record into the second fragment. The RRSIG records covering the DS are placed at the end of the Authoritative section, with a high likelihood of being contained in the second fragment. Glue records, when included, are contained in the Additional section, which is typically in the second fragment, allowing the adversary to also poison them in the same attack, hence hijacking the entire domain in one single step (details on domain hijacking via cache poisoning follow). We next provide results of the evaluation of the downgrade attack.

7.4.1 Downgrading DNSSEC against victim validating resolvers with our signed domain. First, we evaluate the attack against the resolvers that we do not control, using our domain. We set the MTU of our nameserver to 200 byte, this ensures fragmentation, such that the second fragment contains the signatures or DS records as needed. On our nameserver we set the IP ID value to globally incrementing. Using this setup we confirm that the downgrade attacks apply against the vulnerable resolvers also via injection of spoofed IP fragment off-path.

7.4.2 Downgrading DNSSEC against our validating resolver with victim signed domains. Our off-path technique requires that the response from the nameserver is fragmented. We measure the fraction of responses that fragment at an offset that allows us to manipulate the algorithm number, using our dataset of signed domains. To increase the response size we pad the name to the maximum allowed size in [RFC1035]. We report the results of this measurement in Section 7.5.

7.5 Results

In our experiments in November 2021, we find that 479 out of 1495 TLDs are protected with DNSSEC and are served by nameservers, such that, at least one of them can be forced to fragment responses (to any size, up to 1500 bytes). Out of those, 8 (1.67%) send responses with RRSIG records that can be downgraded, and then cache poisoned, and cover allowed RR types. Out of 43,181 signed Tranco domains 7,756 are served by name servers that can be forced to fragment responses. Of those, 1,458 (18.84%) send responses with RRSIG records that can be downgraded and cover allowed RR types. The results of our measurements are plotted in Figure 7a; details on evaluation are in Appendix, Section D. On the client side we find that 85.00% of adnet users use resolvers that accept fragments of any size, while 30.98% of open resolvers do so. The minimum MTU values we measured are given in Figure 7b. Evaluations are described in Appendix, Section E.

8 COUNTERMEASURES AND CHALLENGES

In this section we provide recommendations for countermeasures and discuss the challenges and obstacles towards their deployment.

Support standard compliant behaviour. DNS developers and public DNS providers should support the validation behaviour recommended in the standard. This would prevent the part of our attacks that exploit non standard behaviour, such as those of Google public DNS, AdGuard and Cloudflare.

Update standard behaviour during bogus validation. Nevertheless, adhering to the standard does not solve all the vulnerabilities. Our analysis of the standard in Section 3 shows that lack of clear behaviour specification for bogus validation outcome introduces a vulnerability which we exploit in our attacks.

Failures due to inconsistencies and unknown algorithms. To prevent the attacks we recommend to return SERVFAIL in Table 2 in fourth and fifth columns. However, enforcing this will face obstacles due to practical considerations which may cause them to be seen as controversial by the community. First, insisting on returning SERVFAIL in fifth column may cause failures during key rollover, when a rollover is made to an unknown algorithm and the key that corresponds to a known algorithm is expired. Second, returning SERVFAIL in fourth column prevents key prepublication. Another issue is inconsistency in records between parent and child domains [6, 29, 31, 33, 34, 41]. This can happen, e.g., when the set of the keys in the DS records does not overlap with the keys in the DNSKEY records in the child zone. As a result, the resolver cannot establish a chain of trust to the trust anchor. In our measurements of inconsistencies between the parent and the child domains we found that about 0.27% of popular signed domains have misconfigurations8 for which DNSSEC validation would fail. In our experimental evaluations with resolvers in such cases of inconsistencies we find that public DNS resolvers, such as Google or Cloudflare, do not validate DNSSEC, instead of returning SERVFAIL.

Connectivity or security? Insisting on DNSSEC validation in those cases would break the access to the services in those domains, hence the DNS operators decided to preserve connectivity sacrificing security. Unfortunately, this is exactly the vulnerability that we exploit in our attacks. We show that the current DNSSEC validation behaviour in resolvers exposes to downgrade of DNSSEC.

“No DNSSEC at all” or “most of the time DNSSEC”? This question is closely related to the question of downgrading SSL/TLS to insecure connections. In case of SSL/TLS the browsers made a decision to insist on secure connections and not to allow connections on port 80 when 443 was available, in order to prevent downgrade attacks by on-path adversaries. Not only that our downgrade attacks raise the same conceptual question with respect to

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8 As measured in October 2021, in Tranco 1M-top domains.
DNS/DNSSEC, but also the answer to this question has direct implications for the security of SSL/TLS. In particular, allowing that DNSSEC can under certain conditions be disabled, exposes SSL/TLS to the same downgrade attacks which SSL/TLS was patched to prevent. Specifically, an adversary that can disable DNSSEC can exploit it to downgrade SSL/TLS, as follows: (1) disable DNSSEC, (2) inject spoofed TLSA certificate, and (3) intercept client connections via DNS cache poisoning. This example applies to domains that use TLSA certificates, but similarly the attack can be adjusted to intercept the domain validation of a Certificate Authority (CA) to issue fraudulent certificates [4, 5]. This example demonstrates that DNSSEC may be disabled during an attack has more devastating consequences than not deploying DNSSEC at all.

**Systematic solution.** Trivial solutions, like checking that the algorithm number is within the list of all the standardised algorithm numbers, do not work. New unknown algorithm types may be included in DNSSEC and the DNSSEC records may be provisioned to be used in different ways than they were originally planned. For instance, a recent draft proposes to signal support of DoT using a new DNSKEY algorithm type TDB⁸.

As a systematic solution to prevent downgrade attacks we propose to amend the DNSSEC specification to preclude situations in which adversaries can turn off DNSSEC protection, by imposing a more rigorous requirement for SERVFAIL return codes when an RRset qualifies as "bogus" (see "Our recommendation" in last row in Table 1). This would prevent the attacks without imposing restrictions on the usage of DNSSEC and without limiting the flexibility of deployment of new algorithms.

**Validate DNSSEC in your resolver.** There are tools for validating deployment of DNSSEC on domains, such as DNSViz, which check if the zone is correctly signed, i.e., if signatures are present and chain of trust can be established from the root. Those tools however do not detect the scenarios which make resolvers vulnerable to our downgrade attacks.

We develop the first tool for evaluating the DNSSEC validation in resolvers. Our tool, which we call Resec tests DNSSEC validation behaviour of resolvers in different situations which can be exploited for downgrade attacks. Vulnerabilities are reported in an output with explanations of vulnerable scenarios and recommendations for countermeasures. We make our tool open for public use at https://www.servfail-dnssec.net/.

### 9 CONCLUSIONS

Cryptographic algorithm agility in DNSSEC, i.e., the ability to add and remove algorithms, is an important requirement needed to maintain strong security guarantees. Algorithms may be broken, being able to replace vulnerable algorithms with secure ones efficiently and fast is critical [16, 30].

We show that efficient and fast adoption of algorithms also introduces a challenge: how should resolvers react when faced with records signed using new algorithms? What is the correct behaviour with zones that are signed with a number of algorithms, some of which are known? The standard does not provide clear recommendations for resolvers how to handle DNSSEC records with unknown algorithms and how to handle bogus data, but leaves it open for every resolver to make its own decision how to behave in such cases. On the one hand, flexibility in standards is important, on the other hand, care should be taken to avoid vulnerable implementations. We discover that this vague specification leads to different validation behaviour in popular DNS resolver implementations, which indicates that there is no consensus on what a correct behaviour should be. The implementers and operators often prefer to ignore DNSSEC altogether instead of returning SERVFAIL when the records cannot be validated. This decision is sometimes made to preserve connectivity to domains, since there are also benign situations that can lead to SERVFAIL, e.g., due misconfigurations, deployment of new algorithms or key rollover. However, we show that this tradeoff also leads to vulnerabilities. If an adversary modifies a DNS response, e.g., by manipulating an RRset signature’s algorithm number to an algorithm not listed in the DS RRset, it can cause the RRset to qualify as "bogus" leading to undefined behavior in the specification. In this work we show that resolvers, that handle bogus cases as if the domain were not signed with DNSSEC and the RRset is "insecure", are vulnerable.

Our work calls for a quick action to extend and clarify the standard as well as patch the vulnerabilities to make the cryptographic algorithm agility in DNSSEC secure.

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### REFERENCES

[1] [n.d.]. Domain Name System Security (DNSSEC) Algorithm Numbers. https://www.iana.org/assignments/dns-sec-alg-numbers/dns-sec-alg-numbers.xhtml.

[2] F. Alharbi, J. Chang, Y. Zhou, F. Qian, Z. Qian, and N. Abu-Ghazaleh. 2019. Collaborative Client-Side DNS Cache Poisoning Attack. In IEEE INFOCOM 2019 - IEEE Conference on Computer Communications. https://doi.org/10.1109/INFOCOM.2019.8737514

[3] Dan J. Bernstein. 2002. DNS Forgery. http://cr.yp.to/djbdns/forgery.html.

[4] Henry Bierie-Lee, Yixin Sun, Anne Edmundson, Jennifer Rexford, and Prateek Mittal. 2018. Bamboozling certificate authorities with [BGP]. In 27th {USENIX} Security Symposium ({USENIX} Security 18), 833–849.

[5] Markus Brandt, Tianxiang Dai, Amit Klein, Haya Shulman, and Michael Waidner. 2018. Domain Validation++ For MitM-Resilient PKI. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security. ACM, 2060–2076.

[6] Taejoong Chung, Roland van Rijswijk-Deij, Balakrishnan Chandrasekaran, David Choffnes, Dave Levin, Bruce M Maggs, Alan Mislove, and Christo Wilson. 2017. A longitudinal, end-to-end view of the {DNSSEC} ecosystem. In 26th {USENIX} Security Symposium ({USENIX} Security 17), 1307–1322.

[7] Taejoong Chung, Roland van Rijswijk-Deij, David Choffnes, Dave Levin, Bruce M Maggs, Alan Mislove, and Christo Wilson. 2017. Understanding the role of registrars in DNSSEC deployment. In Proceedings of the 2017 Internet Measurement Conference. 369–383.

[8] David Dagon, Manos Antonakakis, Paul Vixie, Tatuya Jimmie, and Wenke Lee. 2008. Increased DNS forgery resistance through 0x20-bit encoding: security via leaf queries. In ACM Conference on Computer and Communications Security, Peng Ning, Paul F. Syverson, and Somesh Jha (Eds.). ACM, 211–222.

[9] Tianxiang Dai, Haya Shulman, and Michael Waidner. 2021. Let’s Downgrade Let’s Encrypt. In Proceedings of the 2021 ACM SIGSAC Conference on Computer and Communications Security. 1421–1440.

[10] Joao Damas and F. Neves. 2008. Preventing use of recursive namerservers in reflector attacks. Technical Report. BCP 140, RFC 5358, October.

⁸https://datatracker.ietf.org/doc/html/draft-vandijk-dprive-ds-dot-signal-and-pin-01
A DNSSEC VALIDATION CODE ANALYSIS

We explain the DNSSEC validation behavior using as an example an open source implementation of PowerDNS Recorder.\textsuperscript{10} We investigate its behavior in the presence of both an RRSIG with a supported and an unsupported signing algorithm, and with regard to dangling RRSIG records (whose signing key is not referenced in the DS record set).

A.1 Supported and Unsupported RRSIG

The validation setting is considered “Insecure” if and only if no algorithm of any DS record is supported, and “Secure” otherwise (pdns/syncres.cc line 2508).

Validation functions SyncRes::getValidationStatus, SyncRes::validateDNSKeys, SyncRes::validateRecordsWithSigs use function SyncRes::getDSRecords to fetch eligible DS records. A DS record is only considered if both signing and digest algorithm are supported (pdns/syncres.cc line 2570). The presence of a signature with an unsupported algorithm is thus inconsequential, and validation paths are established for those which are supported.

This is in accordance with [RFC4035, Section 5.5]. In particular, when a supported signing algorithm is signaled through the DS record set, PowerDNS does not fall back to “Insecure”, even when additional unsupported algorithms are present.

A.2 Dangling RRSIG

In pdns/syncres.cc, validation functions SyncRes::validateDNSKeys and SyncRes::validateRecordsWithSigs call validateDNSKeysAgainstDS and validateWithKeySet, respectively. Both these functions iterate over the signatures present and skip those for which the associated key is not found in the set of eligible DNSKEYs (pdns/syncres.cc lines 1129 and 962, respectively). The presence of a signature whose key is not referenced in the validation path is thus inconsequential.

This has implications for the case when there is no other validation path. This can occur, for example, when the only RRSIG is “dangling” because it uses a signing algorithm that is not referenced in the DS record set. Such situations qualify as “bogus”, and the
We list the encoding of the algorithms according to IANA

(5) query A-type for a padded name in an existing subdomain

(2) query NS-type record at zone apex

7a. We send requests for the following DNS records:

11 numbers.xhtml

records, along in answers, and that these represent viable targets

name servers send infrastructure data, i.e., NS and according address records, along in answers, and that these represent viable targets by themselves. In responses to queries for the ANY type, we allow any of the aforementioned to become a target.

We separately checked, whether the RRSIG signatures in the responses can be downgraded, and whether the values covered by those signatures can be attacked. For the values covered, we require at least one RR from the RRset to have its rdata part located completely not within in the first fragment.

E MEASUREMENTS OF MTU ON RESOLVERS

We cause the resolvers to issue six different requests to our name server. The name server responds with messages, that are fragmented according to five MTU values 68, 300, 580, 1280 and 1500, and sends one response unfragmented. We judge by the responses to the client whether the resolver has accepted the response from our name server or not. By that we derive whether it accepts fragments and with which minimum MTU.

F ATTACK DEMO: HIJACK SECURE DELEGATION

We created an attack demo in which we demonstrate how to hijack an entire secure delegation under some TLD. We first replace a genuine DS record of a victim domain with a malicious DS record that corresponds to the key pair of the adversary. In the course of the attack we manipulate the DS record of a zone at the authoritative nameserver of the zone’s parent. Subsequently the adversary can hijack the domain by replacing the NS or A records of the domain since it can forge signatures.

The zonefile contains among others the nameserver records (NS RRSIG), delegation signer records (DS RRSIG) needed for establishing a chain of trust from the target domain to the trust anchor - this is a pointer to the key used to sign the data of the child zone, and the signatures over the DS records (RRSIG records)\footnote{The NS RRSIG is per RFC 6841 does not have RRSIGs}. Both RRSIG records over the DS records are valid. The DS records do not match the DNSKEY of our domain: mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.dowgrade.example.io, which is hosted at ns1.test.io and ns2.test.org.

The nameserver returns a referral response in which it delivers the following NS and DS records for domain mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.dowgrade.example.io

In this section we list the encoding of the algorithms according to IANA\footnote{https://www.iana.org/assignments/dns-sec-alg-numbers/dns-sec-alg-numbers.xhtml} in Table 6.

| Number | Description          | Reference |
|--------|----------------------|-----------|
| 5      | RSASHA1              | RFC3110   |
| 8      | RSASHA256            | RFC5702   |
| 13     | ECDSAP256SHA256      | RFC6605   |
| 15     | ED25519              | RFC8080   |
| 16     | ED448                | RFC8080   |

Table 6: DNSSEC algorithm numbers used in our work.

C FORMAT OF DNSSEC RECORDS

In this section we list the format of the DNSSEC records relevant to the attacks in our work. In all the DNSSEC records (DNSKEY, DS and RRSIG), the algorithm number field is known to the adversary, and can be modified. We plot the format of DNSKEY in Figure 8, the DS records in Figure 9 and the RRSIG records in Figure 10.

D MEASUREMENTS OF MTU ON NAMESERVERS

In this section we provide details for measurements plotted in Figure 7a. We send requests for the following DNS records:

(1) query A-type record at zone apex

(2) query NS-type record at zone apex

(3) query MX-type record at zone apex

(4) query ANY-type record at the zone apex

(5) query A-type for a padded name in an existing subdomain

In queries for A or NS records, we allow signatures and record data of A, AAAA, and NS records to be manipulated. In queries for MX records, we additionally allow MX-typed records and the RRSIG records covering them to be targeted. The rationale being that many nameservers send infrastructure data, i.e., NS and addressing address records, along in answers, and that these represent viable targets.
IN NS ns1.test.io.
IN NS ns2.test.org.
IN DS 29449 13 2 FFFFFF.....FFFF
IN DS 29449 13 4 FFFFFF.....FFFF
IN RRSIG DS 8
IN RRSIG DS 16

The hashes digest of both DS records correspond to the genuine DNSKEY of domain mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.downgrade.example.io, which the adversary does not control (in this example FF...FF). The goal is therefore to replace the DS records with new digests that correspond to the DNSKEY of the adversary. To do that, the adversary manipulates the algorithm numbers in the RRSIG and replaces the digest of the DS records as follows:

IN NS ns1.test.io.
IN NS ns2.test.org.
IN DS 29449 13 2 bd638a....4303
IN DS 29449 13 4 000c3f.....ef07
IN RRSIG DS 16 // invalid
IN RRSIG DS 16 // invalid

Since the DS records were changed, the signatures in the RRSIG records are now invalid. In this case Google DNS returns SERVFAIL. However, as a result of the algorithm modification to 16 in the RRSIG, the DNS resolver does not attempt to validate the signatures. This response causes the Google public DNS to ignore the RRSIG and not perform DNSSEC validation. Instead the resolver accepts and caches the new DS records that correspond to the keys of the adversary. The adversary can then manipulate any records for that domain, sign them with its DNSKEY. The DNSSEC validation of the resolver will be successful. In our demo we replaced the nameserver records, redirecting the resolver to the hosts controlled by the adversary: ns1.desec.io or ns2.desec.org. We validate the attack by looking up a TXT resource that we set up:

> dig TXT mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.downgrade.example.io
> @8.8.8.8 +short

The attack is successful when evil is returned. In this attack, once we replace the DS record with the one that corresponds to the key of the adversary, Google checks the signatures using the fraudulent DS records of the adversary.

By replacing the DS record to the one that corresponds to the adversarial DNSKEY, the adversary ensures that the validation for any subdomain is performed against its own keys. Any malicious records that the adversary sends need to be signed with the malicious DNSKEY. The downside of this attack is that the poisoned resolver will not accept correctly signed genuine responses from the real nameserver (since the DNSKEY will not match to the adversarial DS record). However, since most probably the adversary will also redirect the victim resolver to the nameserver records that it controls, there will be no queries to the real nameserver.

G  ATTACK DEMO: DISABLE SECURE DELEGATION

The nameserver returns a referral response in which it delivers the following NS and DS records for domain

mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.downgrade.example.io

IN NS ns1.test.io.
IN NS ns2.test.org.
IN DS 29449 13 2 FFFFFF.....FFFF
IN DS 29449 13 4 FFFFFF.....FFFF
IN RRSIG DS 8
IN RRSIG DS 16

The hashes digest of both DS records correspond to the genuine DNSKEY of domain mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.downgrade.example.io, which the adversary does not control (in this example FF...FF). The goal is therefore to replace the DS records with new digests that correspond to the DNSKEY of the adversary. To do that, the adversary manipulates the algorithm numbers in the RRSIG and replaces the digest of the DS records as follows:

IN NS ns1.test.io.
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> dig TXT mitm-rs16-rd.ds8-ds16-dnskey8-dnskey16.downgrade.example.io
> @8.8.8.8 +short

The attack is successful when evil is returned. In this attack, once we replace the DS record with the one that corresponds to the key of the adversary, Google checks the signatures using the fraudulent DS records of the adversary.

By replacing the DS record to the one that corresponds to the adversarial DNSKEY, the adversary ensures that the validation for any subdomain is performed against its own keys. Any malicious records that the adversary sends need to be signed with the malicious DNSKEY. The downside of this attack is that the poisoned resolver will not accept correctly signed genuine responses from the real nameserver (since the DNSKEY will not match to the adversarial DS record). However, since most probably the adversary will also redirect the victim resolver to the nameserver records that it controls, there will be no queries to the real nameserver.

H  BGP PREFIX HIJACKS

The adversary can hijack a prefix or a sub-prefix of the victim Autonomous System (AS). Sub-prefix attacks are highly effective since the routers prefer more specific IP prefixes over less specific ones, e.g., 12.3.4.5 would match both 12.2.0/23 and 12.3.0/24, but the longest-matching prefix (/24) gets chosen over the less-specific prefix (/23). Therefore, all the traffic from any Internet AS is sent to the adversary instead of the victim AS. The effectiveness of the same-prefix hijack attacks depends on the topological relationship between the adversary, the victim resolver and the nameservers in a domain. The same-prefix hijack only attracts traffic from ASes that have shorter path (i.e., less hops) to the adversary. Once an AS accepts the hijacking announcement it will send all the traffic for that sub-prefix to the attacker.