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A. Mishra
Inria
A. Losty
A. M. Mandalari
UCL
J. Mozley
Infoblox
M. Cunche
INSA-Lyon & Inria
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Abstract

This document outlines best current practices for Internet of Things (IoT) device providers regarding the implementation of DNS stub resolvers, with the aim of mitigating security threats, enhancing privacy, and resolving operational challenges. It also provides guidelines for network operators on mitigating the risks identified in this draft as DNS resolution includes services outside of the stub-resolver, and for device providers' management zones.

About This Document

This note is to be removed before publishing as an RFC.

The latest revision of this draft can be found at <https://miishra.github.io/IoT-DNS-Guidelines/draft-mishra-iotops-iot-dns-guidelines-latest.html>. Status information for this document may be found at <https://datatracker.ietf.org/doc/draft-ietf-iotops-iot-dns-guidelines/>.

Source for this draft and an issue tracker can be found at <https://github.com/miishra/IoT-DNS-Guidelines>.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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Table of Contents

1. Introduction	3
2. Conventions and Definitions	4
3. Recommendations for IoT Device Stub Resolvers	4
3.1. Configuration of DNS servers used by IoT Stub Resolvers	4
3.2. Source Port and Transaction ID Randomization	5
3.3. Handling of TTL Values	5
3.4. Support of EDNS(0)	6
3.5. Improve Device Behavior in Response to Resolution Problems	6
3.6. Compliance with Encrypted DNS Standards	7
3.7. Use of DNSSEC	7
3.7.1. Stub-resolver Checking for Validation	9
3.7.2. Stub-resolver Performing Full Validation	9
4. Recommendations for Network Operators	10
4.1. Resolvers Supporting DNSSEC	10
4.2. Blocking of Unmanaged or Malicious DNS Traffic	10
4.3. Availability	10
5. Recommendations for Manufacturer Authoritative DNS Zones	11
5.1. Zone Signing	11
5.2. TTL Values	11
6. Security Considerations	11
7. IANA Considerations	11
8. References	11
8.1. Normative References	12

8.2. Informative References	12
Acknowledgments	14
Authors' Addresses	14

1. Introduction

Research into the DNS behavior of IoT devices [UCLandInriaPaper] shows widespread non-compliance with protocol standards, gaps in protocol support, and security vulnerabilities. This leads to unpredictable operational behavior and exposes devices to fingerprinting and denial-of-service attacks.

While the recommendations in this BCP may apply to all DNS stub resolver behavior, we treat IoT devices as a specific case where targeted recommendations are useful for the following reasons:

- * The recommendations address specific IoT-related security concerns not seen in the DNS behavior of general-purpose operating systems
- * IoT devices have different resource characteristics from general-purpose devices, such as constrained power consumption, meaning incorrect software implementations can have an increased operational impact
- * IoT devices do not typically have security agents installed on them
- * There are many DNS RFCs, and this BCP can be used to identify those related to specific security issues observed through research into IoT devices, with the aim of making it easier to address these vulnerabilities
- * IoT devices may be deployed at scale on dedicated networks, and these recommendations will be useful to network security teams in mitigating vulnerabilities, especially where device behavior cannot be changed
- * Manufacturers may use standard software distributions aimed at IoT devices without considering DNS behavior. This BCP provides recommendations that can be used as part of the criteria to evaluate these distributions
- * IoT devices typically perform the same set of DNS queries on start-up, which makes them both more vulnerable because of this predictable behavior and also more prone to fingerprinting

DNS terminology in this draft conforms to RFC 9499. In this context, Stub Resolver refers to the IoT device, and Resolver refers to the DNS server used by the IoT device.

The BCP is primarily concerned with device-to-cloud communication [RFC7452], but DNS may be used in other IoT device communication patterns. Hence recommendations would apply to any deployment type where DNS is used, but decisions on implementation may be proportionate to security risks and operational considerations. For example the implementation of {#configuring-resolvers} and Section 3.2 would be appropriate to any implementation, where as Section 3.6 may not be proportionate in industrial automation environments where devices do not encrypt other types of traffic [RFC9150].

2. Conventions and Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Recommendations for IoT Device Stub Resolvers

3.1. Configuration of DNS servers used by IoT Stub Resolvers

IoT devices have been observed to fall back to hard-coded IP addresses for DNS resolvers, such as well-known open resolvers, or ignore addresses assigned to them via automated configuration methods such as DHCP Option 6. This may result in an insecure communication channel, and the open resolvers used in these hard-coded configurations may be blocked by network policy, preventing the device from working.

DNS resolvers on devices MUST be configurable via network configuration protocols. Stub resolvers MUST NOT fall back to hard-coded resolvers.

Devices SHOULD use the following priority order for selecting a resolver. The first one that results in a discovered service should be selected.

1. Manual user configuration
2. Device management software

3. IPv6 Router Advertisement (RA) [RFC8106], DHCPv6 [RFC8415] (if M=1 bit in RA), IPv4 DHCP [RFC2132]. When Encrypted resolver options are present in DHCP and IPv6 Router Advertisements [RFC9463], then they SHOULD be used.

If the selected resolver is a plain IP address (e.g. from option 3) this implies unencrypted DNS. In such cases Discovery of Designated Resolvers (DDR) [RFC9462] SHOULD be performed to upgrade to encrypted access, where available.

3.2. Source Port and Transaction ID Randomization

Some IoT devices have been observed to have insufficient or no randomization in the source ports of DNS queries or DNS transaction IDs. This leaves them vulnerable to spoofed responses. A combination of Source Port and Transaction ID is used, amongst other criteria, by the stub resolver when accepting a DNS response.

IoT devices MUST undergo adequate Source Port and Transaction ID randomization in their DNS queries as a mitigation against cache poisoning from spoofed responses. Having both of these values correctly randomized decreases the chances of a successful spoofed attack. Stub resolvers MUST follow the recommendations of [RFC5452] as described in Section 4.5 to ensure Source Port randomization and Transaction ID randomization as required by [RFC1035].

3.3. Handling of TTL Values

IoT devices have been observed making unexpectedly high numbers of DNS queries even when DNS record Time-To-Live values (TTLs) would mean this should be unnecessary. Devices have also been observed issuing DNS queries at fixed, highly predictable intervals for the same domain names, regardless of operational changes or TTL values.

Unnecessary queries may lead to a drain of power in resource-constrained IoT devices. Conversely, very high TTLs may impact device operations such as communicating with management servers, receiving software updates, or other changes, which may lead to security issues. Deterministic querying behavior increases the risk of device fingerprinting by adversaries who can profile query timing to identify specific device models or firmware versions.

The ideal operational scenario is for the owners of the authoritative zones used to manage the devices setting TTL values appropriately for the zones and specific records within them. Devices would then query these records only as needed.

IoT devices MUST cache DNS responses and SHOULD honour TTLs when caching. If for operational reasons this is not ideal, such as the case where a management server record could be cached for an extended period preventing failover or change, then minimum and maximum TTLs MAY be configurable on the device but MUST NOT be hardcoded values. Where IoT stub resolvers cannot be configured with minimum and maximum TTL values, this can be mitigated by setting these on the network resolver.

If certain device operational requirements necessitate periodic revalidation of critical domains (e.g. management servers), these repeated queries SHOULD use non-deterministic inter-query timing to avoid fixed intervals.

In case of unsuccessful resolution, such as when the resolver is unavailable, IoT devices should implement exponential back-off strategies.

3.4. Support of EDNS(0)

Devices have been observed having limited support for EDNS(0), causing them to revert to TCP for queries over 512 bytes, affecting the device's efficiency. Other research findings include consuming additional processing resources and failing to maintain their network connectivity when responses to DNS requests exceed 512 bytes.

IoT devices MUST support EDNS(0) and send a supported UDP packet size via OPT 41 [RFC6891]. To avoid fragmentation of UDP packets, which may be dropped by intervening networks, the maximum packet size SHOULD be set to 1220 bytes as a default, although device configuration MAY allow this to be configurable. Although the networks to which IoT devices connect may support larger packet sizes than 1220 bytes, the nature of these devices in being deployed on many network types and DNS queries traversing networks controlled by different operators means it is operationally more effective to use this value. In addition, IoT devices MUST support using TCP for queries when a TC bit is returned from the resolver [RFC1035].

3.5. Improve Device Behavior in Response to Resolution Problems

When resolving domain names, IoT devices may be unable to obtain an answer, and as a result, surges in the number of queries and retries have been observed, or an increase in queries using an alternate protocol (more aggressively querying via IPv6 rather than IPv4).

The use of serve-stale [RFC8767] by resolver software on the IoT device may mitigate the impact of failed resolution, such as when authoritative servers are unavailable. If the stub-resolver has this capability, device manufacturers should consider the benefits and any impact of using this.

3.6. Compliance with Encrypted DNS Standards

The majority of IoT devices use unencrypted DNS over port 53, which means this traffic can be captured and is open to interception and manipulation. Encrypted DNS protocols are not mandated for compliance with DNS standards, but the use of encrypted DNS may be mandated by some regulators and advised by competent authorities [ENISAGuidanceForNIS2] in deployment guidelines. Encrypted DNS support is widely deployed and it is possible for IoT devices to discover DNS resolver support for this as described in Section 3.1.

IoT devices SHOULD support encrypted DNS protocols such as DNS over TLS (DoT) [RFC7858], DNS over QUIC (DoQ) [RFC9250], or DNS over HTTPS (DoH) [RFC8484] for enhanced privacy, security, and compatibility. To mitigate against fingerprinting IoT devices, DNS queries can be padded as detailed in [RFC7830] and [RFC8467].

3.7. Use of DNSSEC

IoT devices can be induced to contact an adversary server or make large volumes of DNS queries via spoofed responses to queries. It would be difficult for manufacturers to mitigate this by implementing checks of data received via DNS queries, such as validating IP addresses in the A/AAAA record RDATA. In addition, any validation of this type does not address the problem of man-in-the-middle (MitM) attacks targeting DNS query responses.

DNSSEC can be implemented by manufacturers to mitigate MitM attacks on DNS query responses. Manufacturers MUST sign public zones used for device management and services to ensure queries can be validated by their device stub-resolvers or more generally network resolvers that may use DNSSEC for validation. This will improve security regardless of whether devices can support checking that queries are validated, as many network operators will implement validation by their resolvers.

Manufacturers MAY improve device security by utilizing DNSSEC validation [RFC9364] on the stub-resolver. Devices would typically adopt one of two models for validation (see Table 1) by setting a combination of the DO and CD bits in DNS queries:

- * Stub-resolver checking for validation - the stub-resolver checks for the Authenticated Data (AD) bit in the response, which is suitable for constrained devices but requires explicit trust in the upstream resolver
- * Stub-resolver performing full validation - local cryptographic checks, providing stronger assurance

Both models improve security over unvalidated queries, but manufacturers should weigh the security considerations, such as trust assumptions, against the operational feasibility when considering which approach to take. Manufacturers should consider the type of network the device is likely to be deployed on, such as a home network vs. other types, in determining the likelihood of DNSSEC validation being available on the network and thus deciding if the device should rely on a validating resolver or making the device independently capable of validation.

Deployment options are summarised below, with two of them being the typical deployment cases:

DO Bit	CD Bit	Resolver Validated?	DNSSEC RRs Returned?	Notes
Y	Y	N	Y	Resolver does not validate. DNSSEC data returned. Stub-resolver performing full validation deployment.
Y	N	Y	Y	Resolver validates. DNSSEC data returned. Stub-resolver can use AD bit to check validation.
N	Y	N	N	Resolver does not validate. No DNSSEC data returned. Do not use.
N	N	Y	N	Resolver validates. No DNSSEC data. Stub-resolver checking for validation deployment.

Table 1: Stub-resolver deployment options

3.7.1. Stub-resolver Checking for Validation

Where a manufacturer does utilize DNSSEC validation on the device the minimum implementation will be a stub-resolver checking the AD bit to see if the answer has been validated. Relying solely on the AD bit assumes that the upstream resolver is trustworthy and uncompromised.

Manufacturers may implement a testing mechanism to determine if the network resolver supports DNSSEC so that it can utilize validation in a network that supports it, or falls back to unvalidated queries. Any test of the resolver will only validate that it supports DNSSEC, given that the resolver is performing the validation it must be explicitly trusted.

In order to check that a DNS query has been validated a stub-resolver MUST check the Authenticated Data (AD) bit [RFC4035] in responses to determine whether data was validated by the resolver it is using. When checking for the AD bit stub-resolvers MUST treat DNSSEC validation failures as fatal. Responses that fail validation MUST NOT be used for name resolution.

3.7.2. Stub-resolver Performing Full Validation

Device stub-resolvers can perform validation themselves in cases where the network resolver does not validate queries or the device does not trust the network resolver to do so.

Considerations for device manufacturers in implementing full validation include:

- * Devices performing local validation gain end-to-end trust but at higher computational cost
- * Devices should cache results including intermediate validation results to reduce repeated computation
- * Devices will need to be shipped with a root trust anchor and have a mechanism to securely update this

To implement full local validation stub-resolvers MUST conform to [RFC4035] section 4.9. In practice it is likely to be easier for manufacturers to implement a minimum footprint validating recursive server on the device, configured to forward queries to the network resolver(s), rather than develop this capability in any stub resolver.

4. Recommendations for Network Operators

Most IoT devices do not have specific security software agents installed on them, as is typically the case with general-purpose operating systems, and supply chain vulnerabilities may mean that these devices are compromised before reaching the consumer. Network operators can use DNS resolvers to mitigate these risks. Manufacturers should be aware of network operator DNS deployment options as devices will use these resolvers, even though this infrastructure is not under manufacturer control.

As some aspects of DNS security rely on the stub-resolver, resolver, and authoritative server resolution process and record types (notably DNSSEC), it is also necessary for network operators to implement DNS in such a way as to support some of the recommendations in Section 3.

4.1. Resolvers Supporting DNSSEC

In order to support improving device DNS security as described in Section 3.7 resolvers SHOULD be configured to validate DNS responses using DNSSEC.

4.2. Blocking of Unmanaged or Malicious DNS Traffic

Private network operators may block DNS traffic to any resolvers other than those managed by the operator, so that traffic is not bypassing any DNS security controls such as response policy zones or DNS traffic logging. This is more likely to be the case on enterprise or other private networks rather than service providers that don't want to limit customers using alternate resolvers.

Where operators have networks dedicated to IoT devices, they MAY limit DNS resolution to only domain names used by those IoT devices to mitigate any impact in the event of a compromise to the device. Manufacturers SHOULD provide domain names used for communication to facilitate this and other security measures used to secure devices and identify those that are compromised. Manufacturer Usage Descriptions (MUDs) can provide details of domain names used in device operations that can then be added to DNS security controls.

4.3. Availability

Providers SHOULD alter resolver configuration to mitigate some of the security risks or operational issues identified in this BCP where it does not impact the operation of other types of DNS clients.

Network operators SHOULD configure DNS resolvers to use serve-stale [RFC8767] for networks supporting IoT devices, especially where these networks are dedicated to this type of device, to limit any operational impact on IoT devices when resolution fails. Network operators MUST support IoT devices with dual-stack resolvers, rather than providing only IPv4 resolvers when devices are configured with both IPv4 and IPv6.

DNS queries are most commonly carried over UDP and compromised devices have been used in DoS attacks by sending queries with forged source addresses, hence network operators MUST implement [RFC2827] network ingress filtering. Network operators should implement DNS Response Rate Limiting (RRL) on resolvers to mitigate high query volumes from devices causing DoS to the DNS infrastructure.

5. Recommendations for Manufacturer Authoritative DNS Zones

5.1. Zone Signing

Zones supporting the management and data collection of devices MUST be DNSSEC signed in order to support the behavior described in Section 3.7 and Section 4.1. The zones used for these purposes SHOULD be publicly listed for network operators to use in securing their networks as described in Section 4.2.

5.2. TTL Values

As stated in Section 3.3 manufacturers MUST consider setting TTL values for management zone records that are appropriate for device operations, considering a balance between devices performing excess queries, continuous operation in the event of resolvers being unreachable, and the potential for changes in RDATA such as management IP addresses.

6. Security Considerations

This document does not include protocol changes so there are no specific security considerations in this draft related to new protocol implementations, rather the BCP focusses on security improvements by implementing existing protocols as in the sections above.

7. IANA Considerations

This document has no IANA actions.

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Authors' Addresses

Abhishek Mishra
Inria
Email: abhishek.mishra@inria.fr

Andrew Losty
UCL
Email: andrew.losty.23@ucl.ac.uk

Anna Maria Mandalari
UCL
Email: a.mandalari@ucl.ac.uk

Jim Mozley
Infoblox

Email: jmozley@infoblox.com

Mathieu Cunche
INSA-Lyon & Inria
Email: mathieu.cunche@inria.fr