Towards Operational and Security Best Practices for DNS in the Internet of Things

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SYNOPSIS

The Domain Name System (DNS) is vital for Internet operation, but its lack of standards for Internet of Things (IoT) devices raises security and reliability concerns. This paper investigates inconsistencies in IoT DNS operations, revealing both security risks and irregular behaviors. We analyze DNS on a large IoT testbed through passive traffic inspection and active testing, uncovering serious anomalies. Our findings highlight vulnerabilities to cache poisoning, fingerprinting, and DoS attacks. We assess standardization gaps in IoT DNS security and move towards proposing guidelines to enhance resilience.

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1 INTRODUCTION

The Domain Name System (DNS) is crucial for Internet connectivity, translating domain names into IP addresses. However, the lack of standards that define DNS behavior for Internet of Things (IoT) devices raises concerns about their operational consistency, security, and efficiency.

Leveraging a large-scale IoT testbed and conducting hundreds of automated experiments, we systematically analyze the DNS behavior of IoT devices, revealing operational discrepancies such as frequent DNS queries, failure to adhere to Time-To-Live (TTL) values, reliance on hard-coded DNS resolvers, and inconsistent retry mechanisms. It also evaluates IoT adoption of secure DNS technologies such as DNS over HTTPS (DoH), DNS over TLS (DoT), DNSSEC, and IPv6 support on IoT devices.

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Although RFC 5452 was published in 2009 [37], many devices exhibit serious security flaws, such as fixed source ports and predictable transaction IDs, that leave them vulnerable to DNS spoofing and cache poisoning. Additionally, predictable query behaviors expose devices to fingerprinting and traffic analysis attacks. With the growing prevalence of IoT devices, these inconsistencies pose risks to network security and stability.

This study emphasizes the need for standardized DNS handling practices to improve security, efficiency, and interoperability in IoT networks. We aim to compile all our findings/irregularities and turn them into specific guidelines/recommendations for IoT devices.

2 NEED FOR IOT DNS GUIDELINES

2.1 Limited IoT resources

IoT devices are subject to CPU and energy limitations that may restrict their ability to perform complex tasks, potentially hindering support for both encryption (DoH/DoT) and data integrity/authentication (DNSSEC) [20, 34]. Limited memory capacity constrains DNS caching, resulting in increased latency and higher network utilization [39].

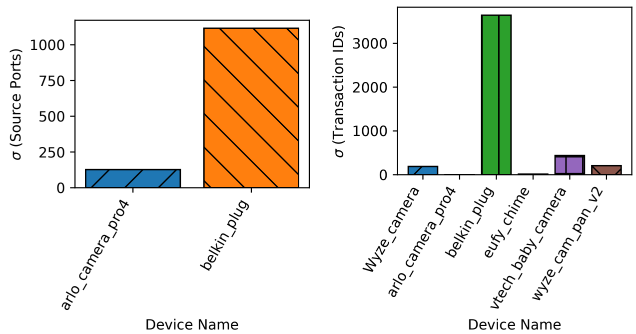
2.2 Absence in existing frameworks

DNS operations were initially defined in 1983 by RFCs 882 and 883 and later superseded by RFCs 1034 and 1035 [1–4]. Security standards were introduced through RFCs 8484 (`DNS over HTTPS`) [35], 7858 (`DNS over TLS`) [36], and `DNSSEC` (RFCs 4033–4035) [36, 40–42]. While standards define DNS operations, they lack explicit guidance for IoT devices.

European Telecommunications Standards Institute (`ETSI`): Seven standards are examined to identify operational recommendations for DNS security in IoT devices; none mandate IoT support for DNSSEC, DNS over HTTPS (DoH), or DNS over TLS (DoT). Although some reference DNS in general terms, none address IoT-specific DNS security or operations [23–29].

National Institute of Standards and Technology (`NIST`): This study reviews all relevant NIST standards to identify operational controls for DNS services on IoT platforms; however, it does not identify any specific controls [6, 9, 21, 30–33].

European Commission: Provides a comprehensive cybersecurity framework that is applicable to all products with



(a) Source ports. **(b) Transaction IDs.**

Figure 1: Poor randomness in DNS query fields.

digital elements. However, the `framework` lacks specific recommendations for `IoT DNS` [5].

ISO/IEC (International Organization for Standardization / International Electrotechnical Commission): Seven standards related to IoT security, interoperability, and cybersecurity are reviewed. However, no pertinent references to IoT DNS are identified [8, 10–18].

3 TOWARDS IOT DNS BEST PRACTICES

We perform a passive evaluation of IoT devices with respect to regular DNS traffic, and we also aim to actively evaluate devices in the presence of potential malicious actors.

3.1 Testbed and Dataset Collection

We analyze 30 consumer IoT devices from various categories, representing a typical smart home network: Appliance (4), Baby Monitor (2), Camera (5), Doorbell (4), Hub (2), Light (6), Pet (2), Plug (1), Medical (1), Sensor (2), and Speaker (5).

3.2 Uncovering DNS Anomalies Passively

Compliance to secure/privacy-preserving standards: We reveal *no support* for encrypted DNS (DoH/DoT), leaving devices vulnerable to interception and manipulation. Additionally, *no device implements* DNSSEC, increasing susceptibility to DNS spoofing and cache poisoning. Furthermore, five devices *use hard-coded DNS servers*, potentially bypassing security monitoring.

Irregularities in setting packet fields: We find considerable inconsistencies in DNS query behavior, such as *failure to follow* Time-To-Live (TTL) values, resulting in unpredictable intervals between queries. Some devices made an unexpectedly high number of domain queries, showing extreme fluctuations in query frequency and *increasing DNS queries tenfold when a resolver is unavailable*. We observe limited support for *EDNS(0)*, which causes devices to fragment frames for queries exceeding 512 bytes and thereby reduces their efficiency.

Poor source port randomization in requests: Several IoT devices *fail to properly randomize source port numbers* in DNS queries, increasing susceptibility to DNS cache poisoning attacks. Although most operating systems comply with RFC-6335 [22] using dynamic source ports in the 49152–65535 range, and some platforms support broader ranges [7], we observe that certain IoT devices operate within significantly narrower ranges, with a standard deviation (σ) of ≤ 1000. As shown in Figure 1a, devices such as (`arlo_camera_pro4`) and (`belkin_plug`) exhibit extremely poor randomization.

Non-randomized transaction IDs: Several IoT devices demonstrate insufficient DNS Transaction ID randomization, with some failing to implement effective randomization or employing predictably sequential values within the 16-bit range (0–65535). This deficiency in entropy increases susceptibility to DNS spoofing, man-in-the-middle (MITM), and amplification attacks. As illustrated in Figure 1b, the low standard deviation of transaction IDs in devices such as cameras (Wyze_camera), smart plugs (belkin_plug), and doorbells (eufy_chime) reflects inadequate randomization.

3.3 Active Evaluation – Advancing Inquiry

Mitigating Malformed RR Exploits: Malformed Resource Records (RRs) pose security risks by enabling manipulation of encodings, injection of invalid values, and abuse of optional fields [38, 43]. We test IoT devices to evaluate resilience by altering RR types, padding lengths, domain/IP values, answered RR content, encoding, etc.

TTL Management: TTL manipulation poses risks of cache poisoning and query inconsistency. [19]. We subject test devices to deliberate manipulation of TTL values in DNS responses to create conditions associated with an increased risk of poisoning. We also examine the handling of extreme TTL values by injecting abnormal values into DNS responses and analyzing the responses of IoT devices. '

Denial-of-Service Protection: To mitigate DoS attacks originating from compromised IoT devices, we focus on query anomaly detection, identifying deviations in DNS query patterns to detect botnet-driven DDoS and exfiltration attempts. We also stress-test the resolvers with queries.

4 CONCLUSION

As IoT devices continue to proliferate and integrate into critical infrastructure, ensuring their secure and efficient operation becomes increasingly vital. Our systematic analysis of DNS behavior across a range of IoT devices reveals alarming inconsistencies in their DNS practices.

Our findings underscore the urgent need for clear, standardized DNS handling practices tailored to the IoT ecosystem. In the absence of such standards, device manufacturers risk perpetuating insecure behaviors that threaten the stability and security of global networks. As a next step, we are consolidating our observations into actionable recommendations and best practices to guide the development of more robust and secure IoT DNS implementations.

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