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DNS privacy considerations
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Abstract

This document describes the privacy issues associated with the use of the DNS by Internet users. It is intended to be an analysis of the present situation and does not prescribe solutions.

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1. Introduction

This document is an analysis of the DNS privacy issues, in the spirit of section 8 of [RFC6973].

The Domain Name System is specified in [RFC1034] and [RFC1035] and many later RFCs, which have never been consolidated. It is one of the most important infrastructure components of the Internet and often ignored or misunderstood by Internet users (and even by many professionals). Almost every activity on the Internet starts with a DNS query (and often several). Its use has many privacy implications and this is an attempt at a comprehensive and accurate list.

Let us begin with a simplified reminder of how the DNS works. (See also [I-D.ietf-dnsop-dns-terminology].) A client, the stub resolver, issues a DNS query to a server, called the recursive resolver (also called caching resolver or full resolver or recursive name server). Let's use the query "What are the AAAA records for www.example.com?" as an example. AAAA is the QTYPE (Query Type), and www.example.com is the QNAME (Query Name). (The description which follows assumes a cold cache, for instance because the server just started.) The recursive resolver will first query the root nameservers. In most cases, the root nameservers will send a referral. In this example, the referral will be to the .com nameservers. The resolver repeats

the query to one of the .com nameservers. The .com nameservers, in turn, will refer to the example.com nameservers. The example.com nameserver will then return the answer. The root name servers, the name servers of .com and the name servers of example.com are called authoritative name servers. It is important, when analyzing the privacy issues, to remember that the question asked to all these name servers is always the original question, not a derived question. The question sent to the root name servers is "What are the AAAA records for www.example.com?", not "What are the name servers of .com?". By repeating the full question, instead of just the relevant part of the question to the next in line, the DNS provides more information than necessary to the nameserver.

Because DNS relies on caching heavily, the algorithm described just above is actually a bit more complicated, and not all questions are sent to the authoritative name servers. If a few seconds later the stub resolver asks to the recursive resolver, "What are the SRV records of _xmpp-server._tcp.example.com?", the recursive resolver will remember that it knows the name servers of example.com and will just query them, bypassing the root and .com. Because there is typically no caching in the stub resolver, the recursive resolver, unlike the authoritative servers, sees all the DNS traffic. (Applications, like Web browsers, may have some form of caching which do not follow DNS rules, for instance because it may ignore the TTL. So, the recursive resolver does not see all the name resolution activity.)

It should be noted that DNS recursive resolvers sometimes forward requests to other recursive resolvers, typically bigger machines, with a larger and more shared cache (and the query hierarchy can be even deeper, with more than two levels of recursive resolvers). From the point of view of privacy, these forwarders are like resolvers, except that they do not see all of the requests being made (due to caching in the first resolver).

Almost all this DNS traffic is currently sent in clear (unencrypted). There are a few cases where there is some channel encryption, for instance in an IPsec VPN, at least between the stub resolver and the resolver.

Today, almost all DNS queries are sent over UDP [thomas-ditl-tcp]. This has practical consequences when considering encryption of the traffic as a possible privacy technique. Some encryption solutions are only designed for TCP, not UDP.

Another important point to keep in mind when analyzing the privacy issues of DNS is the fact that DNS requests received by a server were triggered by different reasons. Let's assume an eavesdropper wants

to know which Web page is viewed by a user. For a typical Web page, there are three sorts of DNS requests being issued:

Primary request: this is the domain name in the URL that the user typed, selected from a bookmark or chose by clicking on an hyperlink. Presumably, this is what is of interest for the eavesdropper.

Secondary requests: these are the additional requests performed by the user agent (here, the Web browser) without any direct involvement or knowledge of the user. For the Web, they are triggered by embedded content, CSS sheets, JavaScript code, embedded images, etc. In some cases, there can be dozens of domain names in different contexts on a single Web page.

Tertiary requests: these are the additional requests performed by the DNS system itself. For instance, if the answer to a query is a referral to a set of name servers, and the glue records are not returned, the resolver will have to do additional requests to turn name servers' names into IP addresses. Similarly, even if glue records are returned, a careful recursive server will do tertiary requests to verify the IP addresses of those records.

It can be noted also that, in the case of a typical Web browser, more DNS requests than strictly necessary are sent, for instance to prefetch resources that the user may query later, or when autocompleting the URL in the address bar. Both are a big privacy concern since they may leak information even about non-explicit actions. For instance, just reading a local HTML page, even without selecting the hyperlinks, may trigger DNS requests.

For privacy-related terms, we will use here the terminology of [RFC6973].

2. Risks

This document focuses mostly on the study of privacy risks for the end-user (the one performing DNS requests). We consider the risks of pervasive surveillance ([RFC7258]) as well as risks coming from a more focused surveillance. Privacy risks for the holder of a zone (the risk that someone gets the data) are discussed in [RFC5936] and [RFC5155]. Non-privacy risks (such as cache poisoning) are out of scope.

2.1. The alleged public nature of DNS data

It has long been claimed that "the data in the DNS is public". While this sentence makes sense for an Internet-wide lookup system, there are multiple facets to the data and metadata involved that deserve a more detailed look. First, access control lists and private namespaces notwithstanding, the DNS operates under the assumption that public facing authoritative name servers will respond to "usual" DNS queries for any zone they are authoritative for without further authentication or authorization of the client (resolver). Due to the lack of search capabilities, only a given QNAME will reveal the resource records associated with that name (or that name's non-existence). In other words: one needs to know what to ask for, in order to receive a response. The zone transfer QTYPE [RFC5936] is often blocked or restricted to authenticated/authorized access to enforce this difference (and maybe for other reasons).

Another differentiation to be considered is between the DNS data itself and a particular transaction (i.e., a DNS name lookup). DNS data and the results of a DNS query are public, within the boundaries described above, and may not have any confidentiality requirements. However, the same is not true of a single transaction or sequence of transactions; that transaction is not/should not be public. A typical example from outside the DNS world is: the Web site of Alcoholics Anonymous is public; the fact that you visit it should not be.

2.2. Data in the DNS request

The DNS request includes many fields but two of them seem particularly relevant for the privacy issues: the QNAME and the source IP address. "source IP address" is used in a loose sense of "source IP address + maybe source port", because the port is also in the request and can be used to differentiate between several users sharing an IP address (behind a CGN for instance [RFC6269]).

The QNAME is the full name sent by the user. It gives information about what the user does ("What are the MX records of example.net?" means he probably wants to send email to someone at example.net, which may be a domain used by only a few persons and therefore very revealing about communication relationships). Some QNAMEs are more sensitive than others. For instance, querying the A record of a well-known Web statistics domain reveals very little (everybody visits Web sites which use this analytics service) but querying the A record of www.verybad.example where verybad.example is the domain of an organization that some people find offensive or objectionable, may create more problems for the user. Also, sometimes, the QNAME embeds the software one uses, which could be a privacy issue. For instance,

`_ldap._tcp.Default-First-Site-Name._sites.gc._msdcs.example.org`.
There are also some BitTorrent clients that query a SRV record for
`_bittorrent-tracker._tcp.domain.example`.

Another important thing about the privacy of the QNAME is the future usages. Today, the lack of privacy is an obstacle to putting potentially sensitive or personally identifiable data in the DNS. At the moment your DNS traffic might reveal that you are doing email but not with whom. If your MUA starts looking up PGP keys in the DNS [I-D.wouters-dane-openpgp] then privacy becomes a lot more important. And email is just an example; there would be other really interesting uses for a more privacy-friendly DNS.

For the communication between the stub resolver and the recursive resolver, the source IP address is the address of the user's machine. Therefore, all the issues and warnings about collection of IP addresses apply here. For the communication between the recursive resolver and the authoritative name servers, the source IP address has a different meaning; it does not have the same status as the source address in a HTTP connection. It is now the IP address of the recursive resolver which, in a way "hides" the real user. However, hiding does not always work. Sometimes [I-D.ietf-dnsop-edns-client-subnet] is used (see its privacy analysis in [denis-edns-client-subnet]). Sometimes the end user has a personal recursive resolver on her machine. In both cases, the IP address is as sensitive as it is for HTTP [sidn-entrada].

A note about IP addresses: there is currently no IETF document which describes in detail all the privacy issues around IP addressing. In the meantime, the discussion here is intended to include both IPv4 and IPv6 source addresses. For a number of reasons their assignment and utilization characteristics are different, which may have implications for details of information leakage associated with the collection of source addresses. (For example, a specific IPv6 source address seen on the public Internet is less likely than an IPv4 address to originate behind a CGN or other NAT.) However, for both IPv4 and IPv6 addresses, it's important to note that source addresses are propagated with queries and comprise metadata about the host, user, or application that originated them.

2.3. Cache snooping

The content of recursive resolvers' caches can reveal data about the clients using it (the privacy risks depend on the number of clients). This information can sometimes be examined by sending DNS queries with RD=0 to inspect cache content, particularly looking at the DNS TTLs [grangeia.snooping]. Since this also is a reconnaissance

technique for subsequent cache poisoning attacks, some counter measures have already been developed and deployed.

2.4. On the wire

DNS traffic can be seen by an eavesdropper like any other traffic. It is typically not encrypted. (DNSSEC, specified in [RFC4033] explicitly excludes confidentiality from its goals.) So, if an initiator starts a HTTPS communication with a recipient, while the HTTP traffic will be encrypted, the DNS exchange prior to it will not be. When other protocols will become more and more privacy-aware and secured against surveillance, the DNS may become "the weakest link" in privacy.

An important specificity of the DNS traffic is that it may take a different path than the communication between the initiator and the recipient. For instance, an eavesdropper may be unable to tap the wire between the initiator and the recipient but may have access to the wire going to the recursive resolver, or to the authoritative name servers.

The best place to tap, from an eavesdropper's point of view, is clearly between the stub resolvers and the recursive resolvers, because traffic is not limited by DNS caching.

The attack surface between the stub resolver and the rest of the world can vary widely depending upon how the end user's computer is configured. By order of increasing attack surface:

The recursive resolver can be on the end user's computer. In (currently) a small number of cases, individuals may choose to operate their own DNS resolver on their local machine. In this case the attack surface for the connection between the stub resolver and the caching resolver is limited to that single machine.

The recursive resolver may be at the local network edge. For many/most enterprise networks and for some residential users the caching resolver may exist on a server at the edge of the local network. In this case the attack surface is the local network. Note that in large enterprise networks the DNS resolver may not be located at the edge of the local network but rather at the edge of the overall enterprise network. In this case the enterprise network could be thought of as similar to the IAP (Internet Access Provider) network referenced below.

The recursive resolver can be in the IAP (Internet Access Provider) premises. For most residential users and potentially

other networks the typical case is for the end user's computer to be configured (typically automatically through DHCP) with the addresses of the DNS recursive resolvers at the IAP. The attack surface for on-the-wire attacks is therefore from the end user system across the local network and across the IAP network to the IAP's recursive resolvers.

The recursive resolver can be a public DNS service. Some machines may be configured to use public DNS resolvers such as those operated today by Google Public DNS or OpenDNS. The end user may have configured their machine to use these DNS recursive resolvers themselves - or their IAP may have chosen to use the public DNS resolvers rather than operating their own resolvers. In this case the attack surface is the entire public Internet between the end user's connection and the public DNS service.

2.5. In the servers

Using the terminology of [RFC6973], the DNS servers (recursive resolvers and authoritative servers) are enablers: they facilitate communication between an initiator and a recipient without being directly in the communications path. As a result, they are often forgotten in risk analysis. But, to quote again [RFC6973], "Although [...] enablers may not generally be considered as attackers, they may all pose privacy threats (depending on the context) because they are able to observe, collect, process, and transfer privacy-relevant data." In [RFC6973] parlance, enablers become observers when they start collecting data.

Many programs exist to collect and analyze DNS data at the servers. From the "query log" of some programs like BIND, to tcpdump and more sophisticated programs like PacketQ [packetq] and DNSmezzo [dnsmezzo]. The organization managing the DNS server can use these data itself or it can be part of a surveillance program like PRISM [prism] and pass data to an outside observer.

Sometimes, these data are kept for a long time and/or distributed to third parties, for research purposes [ditl] [day-at-root], for security analysis, or for surveillance tasks. These uses are sometimes under some sort of contract, with various limitations, for instance on redistribution, giving the sensitive nature of the data. Also, there are observation points in the network which gather DNS data and then make it accessible to third-parties for research or security purposes ("passive DNS [passive-dns]").

2.5.1. In the recursive resolvers

Recursive Resolvers see all the traffic since there is typically no caching before them. To summarize: your recursive resolver knows a lot about you. The resolver of a large IAP, or a large public resolver can collect data from many users. You may get an idea of the data collected by reading the privacy policy of a big public resolver [1].

2.5.2. In the authoritative name servers

Unlike what happens for recursive resolvers, observation capabilities of authoritative name servers are limited by caching; they see only the requests for which the answer was not in the cache. For aggregated statistics ("What is the percentage of LOC queries?"), this is sufficient; but it prevents an observer from seeing everything. Still, the authoritative name servers see a part of the traffic, and this subset may be sufficient to violate some privacy expectations.

Also, the end user has typically some legal/contractual link with the recursive resolver (he has chosen the IAP, or he has chosen to use a given public resolver), while having no control and perhaps no awareness of the role of the authoritative name servers and their observation abilities.

As noted before, using a local resolver or a resolver close to the machine decreases the attack surface for an on-the-wire eavesdropper. But it may decrease privacy against an observer located on an authoritative name server. This authoritative name server will see the IP address of the end client, instead of the address of a big recursive resolver shared by many users.

This "protection", when using a large resolver with many clients, is no longer present if [I-D.ietf-dnsop-edns-client-subnet] is used because, in this case, the authoritative name server sees the original IP address (or prefix, depending on the setup).

As of today, all the instances of one root name server, L-root, receive together around 50,000 queries per second. While most of it is "junk" (errors on the TLD name), it gives an idea of the amount of big data which pours into name servers. (And even "junk" can leak information, for instance if there is a typing error in the TLD, the user will send data to a TLD which is not the usual one.)

Many domains, including TLDs, are partially hosted by third-party servers, sometimes in a different country. The contracts between the domain manager and these servers may or may not take privacy into

account. Whatever the contract, the third-party hoster may be honest or not but, in any case, it will have to follow its local laws. So, requests to a given ccTLD may go to servers managed by organizations outside of the ccTLD's country. End-users may not anticipate that, when doing a security analysis.

Also, it seems [aeris-dns] that there is a strong concentration of authoritative name servers among "popular" domains (such as the Alexa Top N list). For instance, among the Alexa Top 100k, one DNS provider hosts today 10 % of the domains. The ten most important DNS providers host together one third of the domains. With the control (or the ability to sniff the traffic) of a few name servers, you can gather a lot of information.

2.5.3. Rogue servers

The previous paragraphs discussed DNS privacy, assuming that all the traffic was directed to the intended servers, and that the potential attacker was purely passive. But, in reality, we can have active attackers, redirecting the traffic, not for changing it but just to observe it.

For instance, a rogue DHCP server, or a trusted DHCP server that has had its configuration altered by malicious parties, can direct you to a rogue recursive resolver. Most of the time, it seems to be done to divert traffic, by providing lies for some domain names. But it could be used just to capture the traffic and gather information about you. Other attacks, besides using DHCP, are possible. The traffic from a DNS client to a DNS server can be intercepted along its way from originator to intended source; for instance by transparent DNS proxies in the network that will divert the traffic intended for a legitimate DNS server. This rogue server can masquerade as the intended server and respond with data to the client. (Rogue servers that inject malicious data are possible, but is a separate problem not relevant to privacy.) A rogue server may respond correctly for a long period of time, thereby foregoing detection. This may be done for what could be claimed to be good reasons, such as optimization or caching, but it leads to a reduction of privacy compared to if there were no attacker present. Also, malware like DNSChanger [dnschanger] can change the recursive resolver in the machine's configuration, or the routing itself can be subverted (for instance [turkey-googledns]).

A practical consequence of this section is that solutions for DNS privacy may have to address authentication of the server, not just passive sniffing.

2.6. Re-identification and other inferences

An observer has access not only to the data he/she directly collects but also to the results of various inferences about these data.

For instance, a user can be re-identified via DNS queries. If the adversary knows a user's identity and can watch their DNS queries for a period, then that same adversary may be able to re-identify the user solely based on their pattern of DNS queries later on regardless of the location from which the user makes those queries. For example, one study [herrmann-reidentification] found that such re-identification is possible so that "73.1% of all day-to-day links were correctly established, i.e. user u was either re-identified unambiguously (1) or the classifier correctly reported that u was not present on day t+1 any more (2)". While that study related to web browsing behaviour, equally characteristic patterns may be produced even in machine-to-machine communications or without a user taking specific actions, e.g. at reboot time if a characteristic set of services are accessed by the device.

For instance, one could imagine, for an intelligence agency to identify people going to a site by putting in a very long DNS name and looking for queries of a specific length. Such traffic analysis could weaken some privacy solutions.

The IAB privacy and security programme also have a work in progress [I-D.iab-privsec-confidentiality-threat] that considers such inference based attacks in a more general framework.

3. Actual "attacks"

A very quick examination of DNS traffic may lead to the false conclusion that extracting the needle from the haystack is difficult. "Interesting" primary DNS requests are mixed with useless (for the eavesdropper) secondary and tertiary requests (see the terminology in Section 1). But, in this time of "big data" processing, powerful techniques now exist to get from the raw data to what the eavesdropper is actually interested in.

Many research papers about malware detection use DNS traffic to detect "abnormal" behaviour that can be traced back to the activity of malware on infected machines. Yes, this research was done for the good; but, technically, it is a privacy attack and it demonstrates the power of the observation of DNS traffic. See [dns-footprint], [dagon-malware] and [darkreading-dns].

Passive DNS systems [passive-dns] allow reconstruction of the data of sometimes an entire zone. They are used for many reasons, some good,

some bad. Well-known passive DNS systems keep only the DNS responses, and not the source IP address of the client, precisely for privacy reasons. Other passive DNS systems may not be so careful. And there is still the potential problems with revealing QNAMEs.

The revelations (from the Edward Snowden documents, leaked from the NSA) of the MORECOWBELL surveillance program [morecowbell], which uses the DNS, both passively and actively, to surreptitiously gather information about the users, is another good example showing that the lack of privacy protections in the DNS is actively exploited.

4. Legalities

To our knowledge, there are no specific privacy laws for DNS data, in any country. Interpreting general privacy laws like [data-protection-directive] (European Union) in the context of DNS traffic data is not an easy task and we do not know a court precedent here. An interesting analysis is [sidn-entrada].

5. Security considerations

This document is entirely about security, more precisely privacy. It just lays out the problem, it does not try to set requirements (with the choices and compromises they imply), much less to define solutions. Possible solutions to the issues described here are discussed in other documents (currently too many to all be mentioned), see for instance [I-D.ietf-dnsop-qname-minimisation] for the minimisation of data, or [I-D.ietf-dprive-start-tls-for-dns] about encryption.

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7. IANA considerations

This document has no actions for IANA.

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8.3. URIs

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