The Case for Real Time DNS Exfiltration Detection and Prevention

By: Yarin Ozery
yozery@akamai.com

Agenda

- DNS exfiltration overview
  - How it is performed
  - Risks imposed by DNS exfiltration
- Existing detection methods
  - General overview
  - Limitation of existing methods
- Proposed solution
- Evaluation
  - Comparison with prominent methods on synthetic dataset
  - Real-world evaluation
- Discussion and Conclusion
  - Limitations
  - Future Work

About the Presenter

- Senior software engineer and security researcher at Akamai Technologies, inc.
- M.Sc Student at the software and system information department at Ben-Gurion University of the Negev, Beer Sheva, Israel.

What is DNS tunneling and exfiltration?

- The practice of establishing covert communication channel over the DNS protocol to enable unauthorized data exchange [1]
- Malicious use cases:
  - Botnets communication with C&C servers [2]
  - Bypassing paid WiFi captive portals [3]
  - Data exfiltration out of protected networks [3]
- Some benign (yet, unintended) use cases:
  - DNS-based anti malware and anti spam services [4]
  - Antivirus agents file signature search [4]

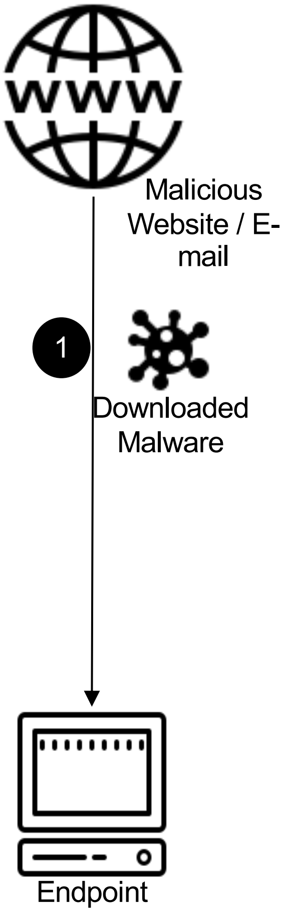
Different Information Vectors

- Query name based - encoding data as a prefix of the DNS query name to be resolved
  - Up to 255 Bytes per packet
- Query type based - encoding data within the requested DNS query resource record type, known as QTYPE
  - Up to 2 Bytes per packet
- Timing based - encoding data based on DNS queries timing
  - Not unique to DNS

DNS Exfiltration In Practice

- Register a domain name (or multiple domain names)
- Setting an authoritative domain nameserver to the registered domain
- Encoding data within DNS packets
- Many publicly available tools:
  - Iodine [5]
  - DNS2tcp [6]
  - DNSCat2 [7]
  - Heyoka [8]
  - Many more

* Based on a figure from [4]



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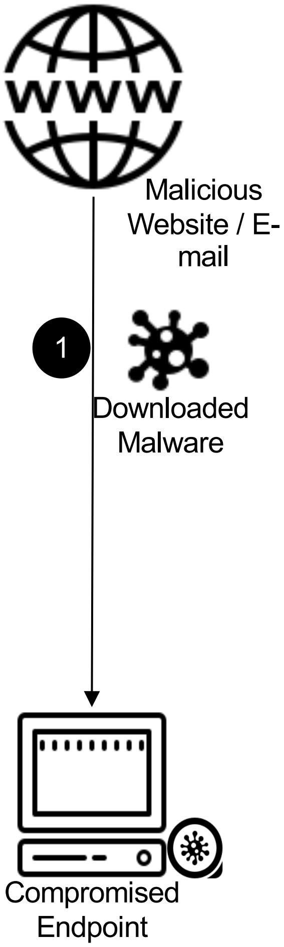

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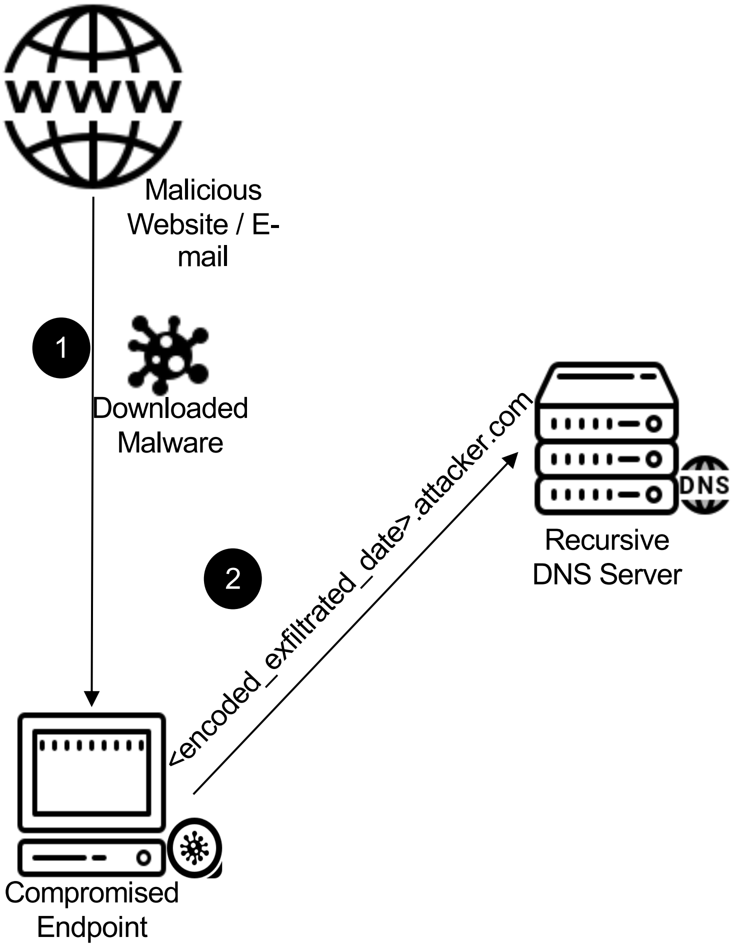

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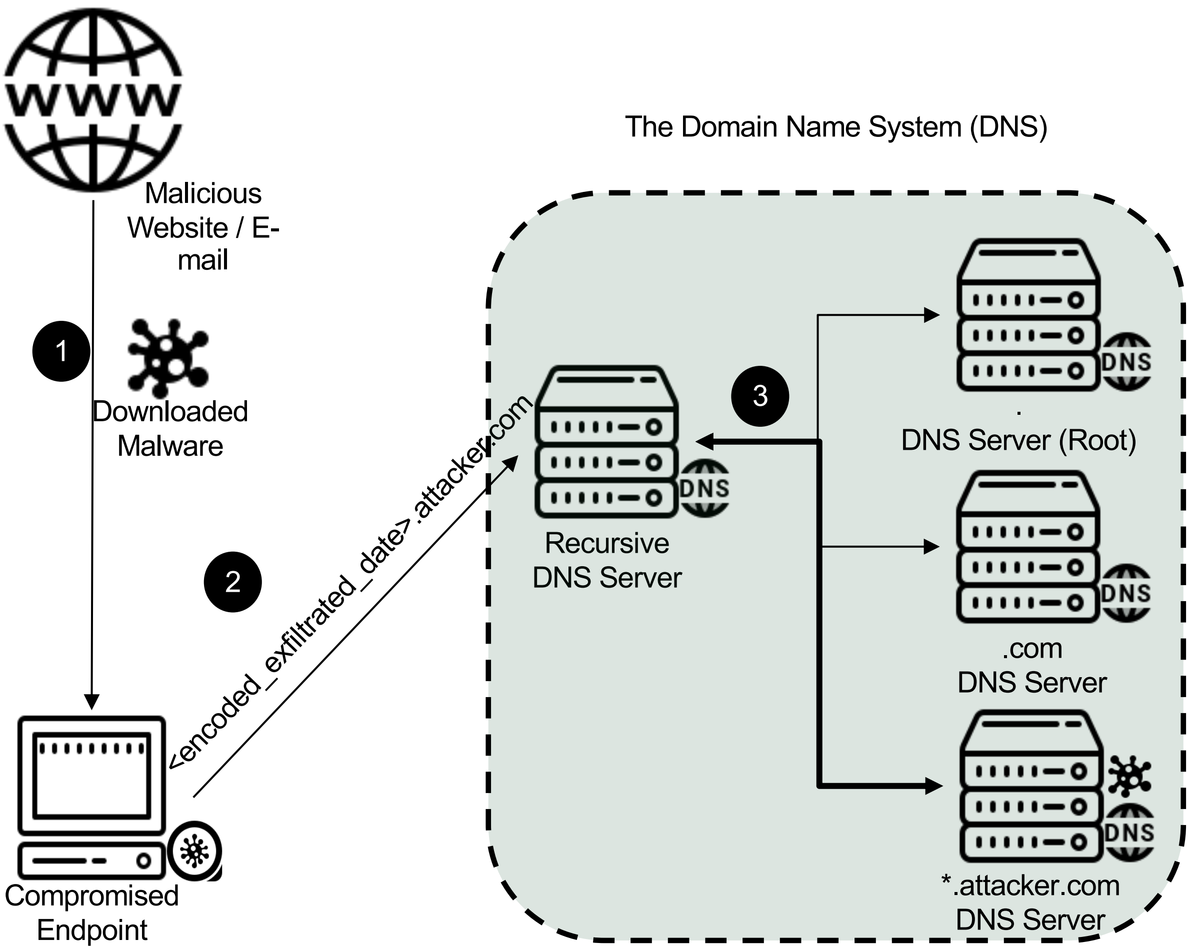

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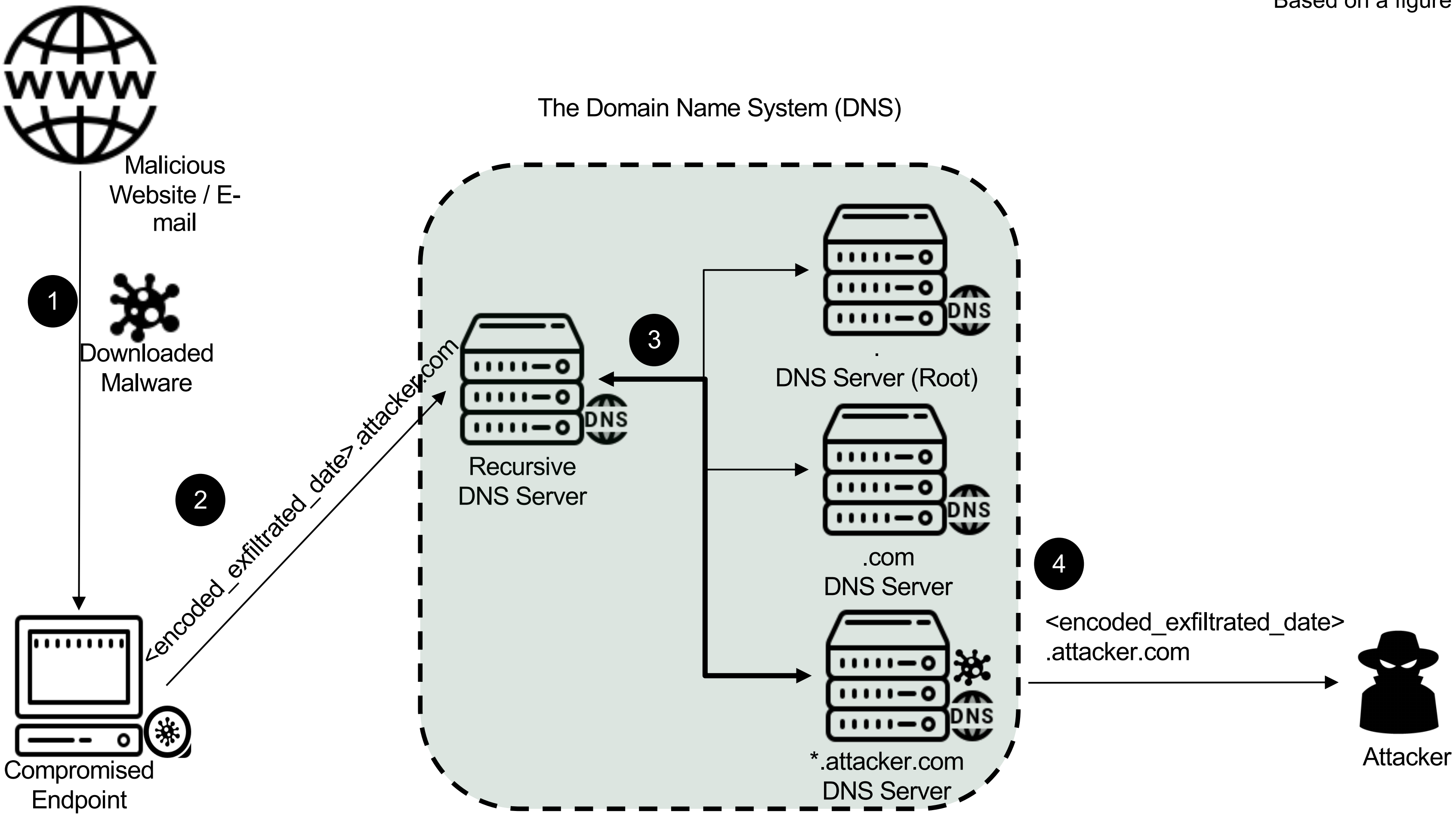

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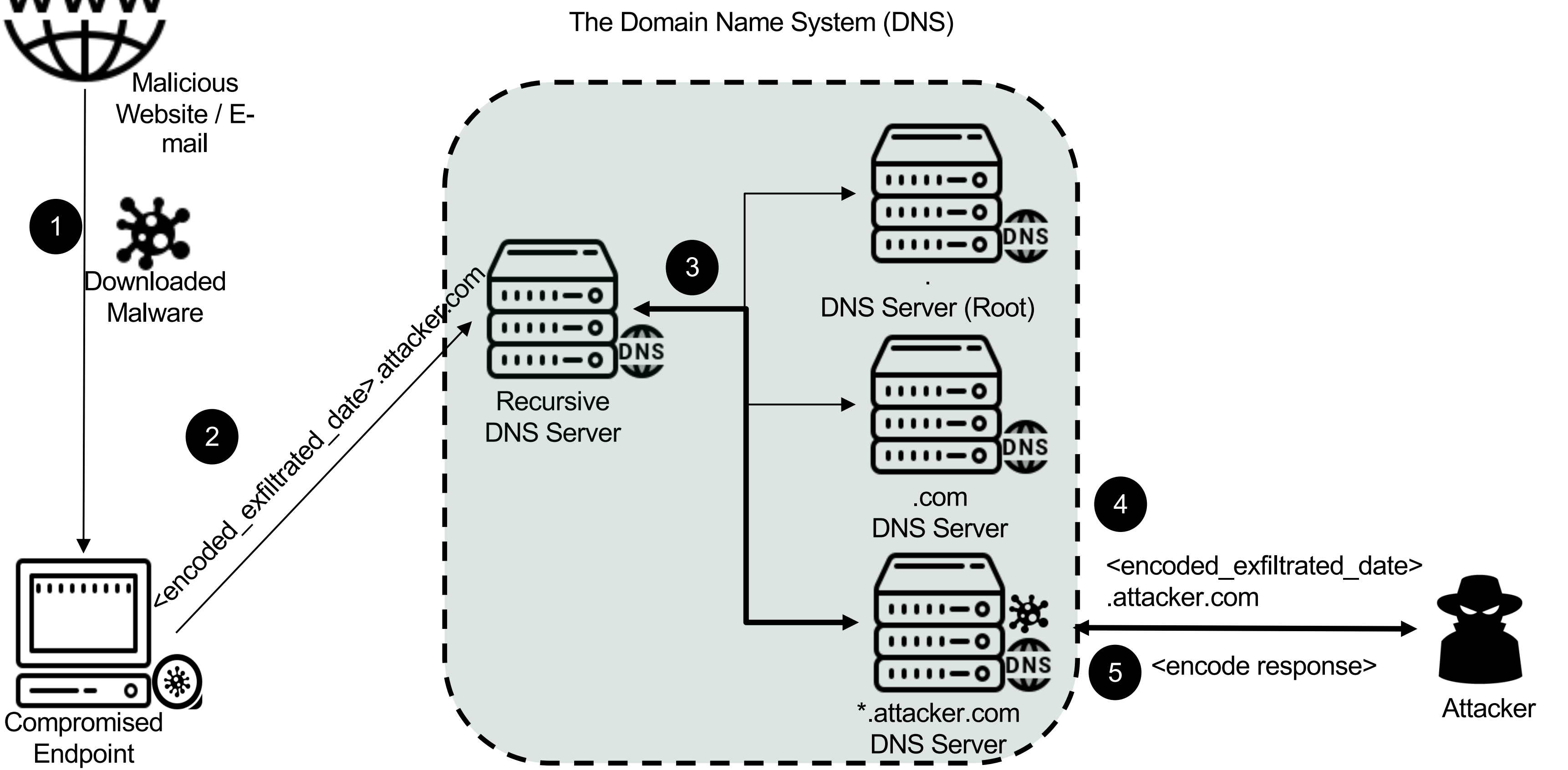

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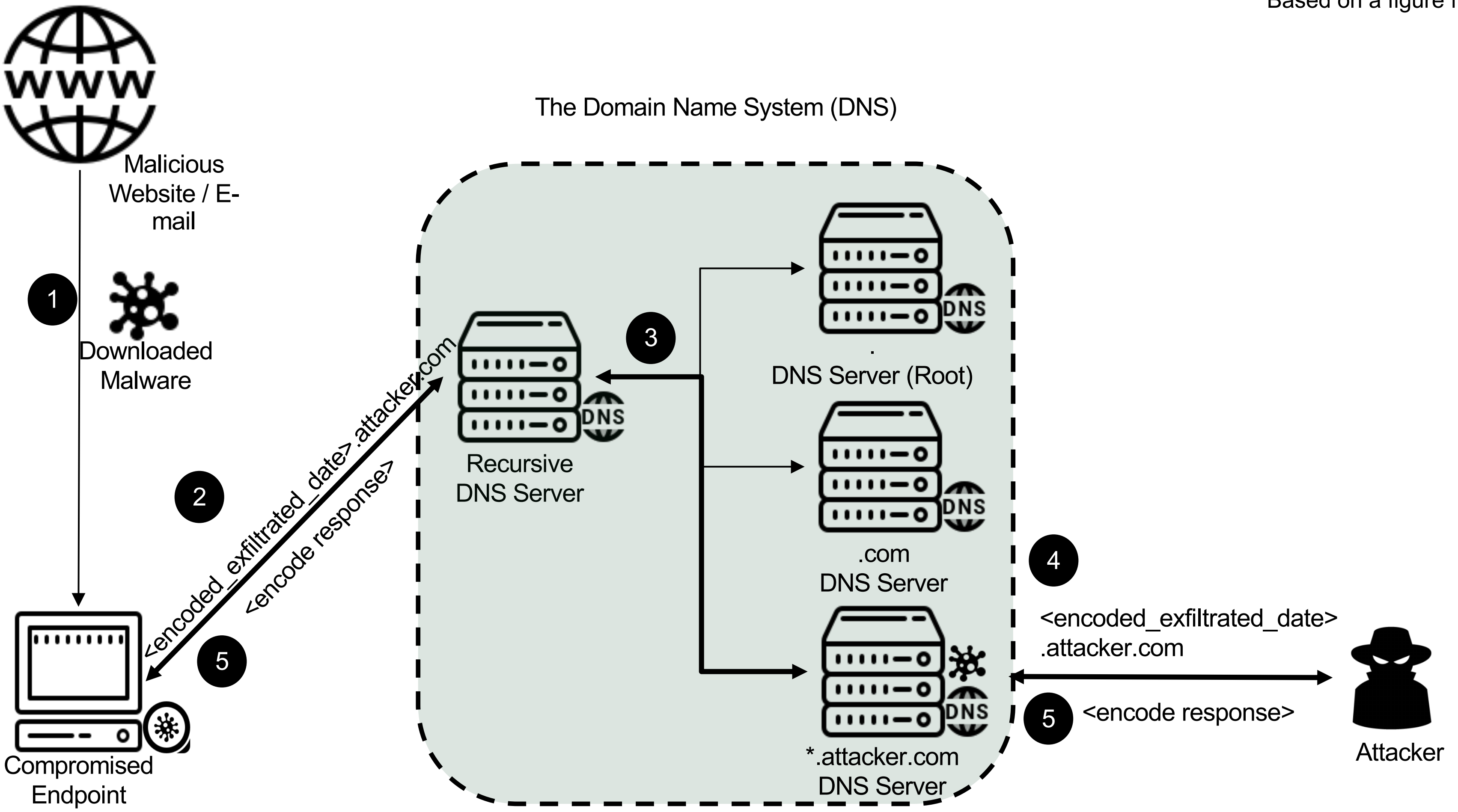

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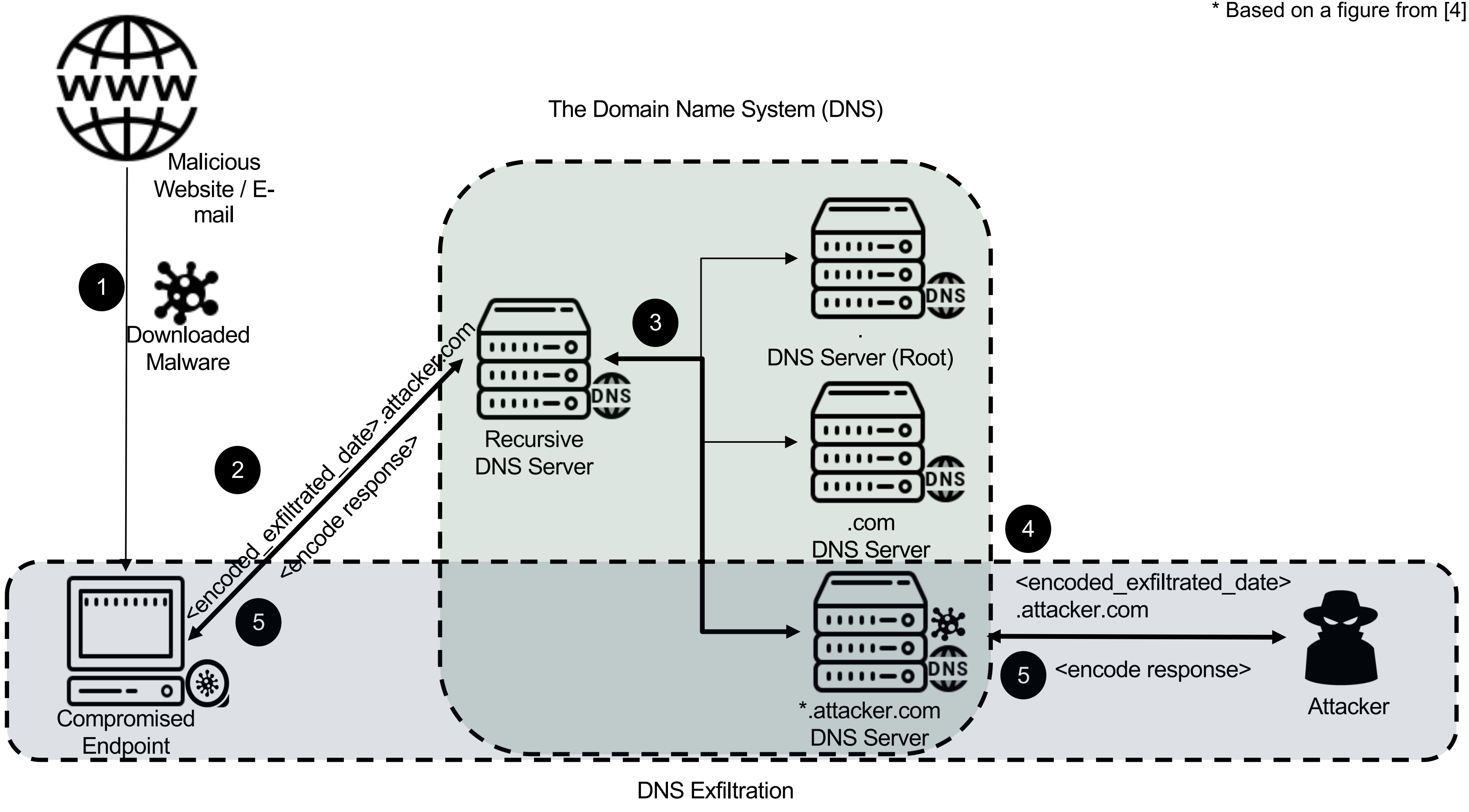


DNS Tunneling and Exfiltration in the Wild

[9]

Software used by Home Depot hackers different from Target attack

The malware used against Home Depot is a different type than that used against Target. Its name, FrameworkPOS, is derived from the McAfee Inc. antivirus agent it impersonates.

[10]

Feederbot Botnet Using DNS as Carrier for Command and Control (C2)

[27]

New Linux botnet exploits Log4J, uses DNS tunneling for comms

[11]

OilRig Deploys "ALMA Communicator" – DNS Tunneling Trojan

[12]

Wekby APT Gang Using DNS Tunneling for Command and Control

[13]

RANSOMWARE ACTORS LEANING ON DNS TUNNELING

Existing DNS Exfiltration Detection Solutions

- Over 30 research papers have been published on the topic in recent years[17]
- Two main strains:
  - Payload based - classification is done on a per-packet (or per small number of packets)
  - Traffic based - classification is done based on overall DNS traffic.
- Most focus dedicated to machine learning based solutions
  - Supervised learning
  - Unsupervised learning
  - Deep learning
  - Also, some statistics-based and rule-based solutions

Features Used for DNS Exfiltration Detection [26]

- Size of DNS requests and responses
- Length of destination hostname
- Entropy of hostname
- Volume of DNS traffic per destination
- Volume of DNS traffic from source
- Volume of uncommon DNS query types
  - NULL
  - TXT
- Signatures of specific tools

Paxson et al. [14]

- DNS queries are aggregated daily per client and registered domain
- Information quantification is done by compressing the information vector and taking the length of the output as the information quantity
- All queries over the time window are needed to be stored
  - substantial computation and memory requirements
- Can be applied to any information vector

Nadler et al. [15]

- Traffic-based unsupervised machine learning model
  - Based on the isolation forest algorithm
- Feature extraction is based on a per domain basis in a sliding window manner
  - Requires holding all the queries in each classification window
  - Data is needed to be kept up to six hours for a successful detection in some cases
  - ”Expensive” features – average longest meaningful word, average entropy
- Can detect very slow campaigns
  - As slow as 0.11 B/s

Ahmed et al. [16]

- Payload-based unsupervised machine learning model
  - Based on the isolation forest algorithm
  - Only needs to store the trained model in memory
- Feature extraction is done based on the query name
  - Ten different features are extracted for every query
  - Example: query name length, subdomain length, query name entropy
- True real time solution
  - Questionable scalability

Limitation of Existing Methods

- Most focus dedicated to increasing detection efficacy
  - Not as much effort put into designing fast real-time scalable solutions
- Result: Significant amounts of data exfiltrated by the time of detection
- Solution: DNS exfiltration detection method that can classify DNS queries as they are resolved
  - Preferably, directly on the recursive DNS resolver
  - Must have a small memory footprint and fast classification

Information-based Heavy Hitter (ibHH) for Real-time DNS Exfiltration Detection

- Idea: Quantify the amount of information transmitted to a registered **domain** through DNS queries based on the length of **unique** subdomains, raise alert if the amount exceeds a predefined threshold
  - We call these **information heavy hitter** domains
  - Inspired by the works of Paxson et al. [14] and Afek et al. [23]
- Problem: Exact solution requires memory linearly proportional to the DNS queries stream size and long computation time
- Solution: approximate information quantities with sketching algorithms

Sketching Algorithms [19]

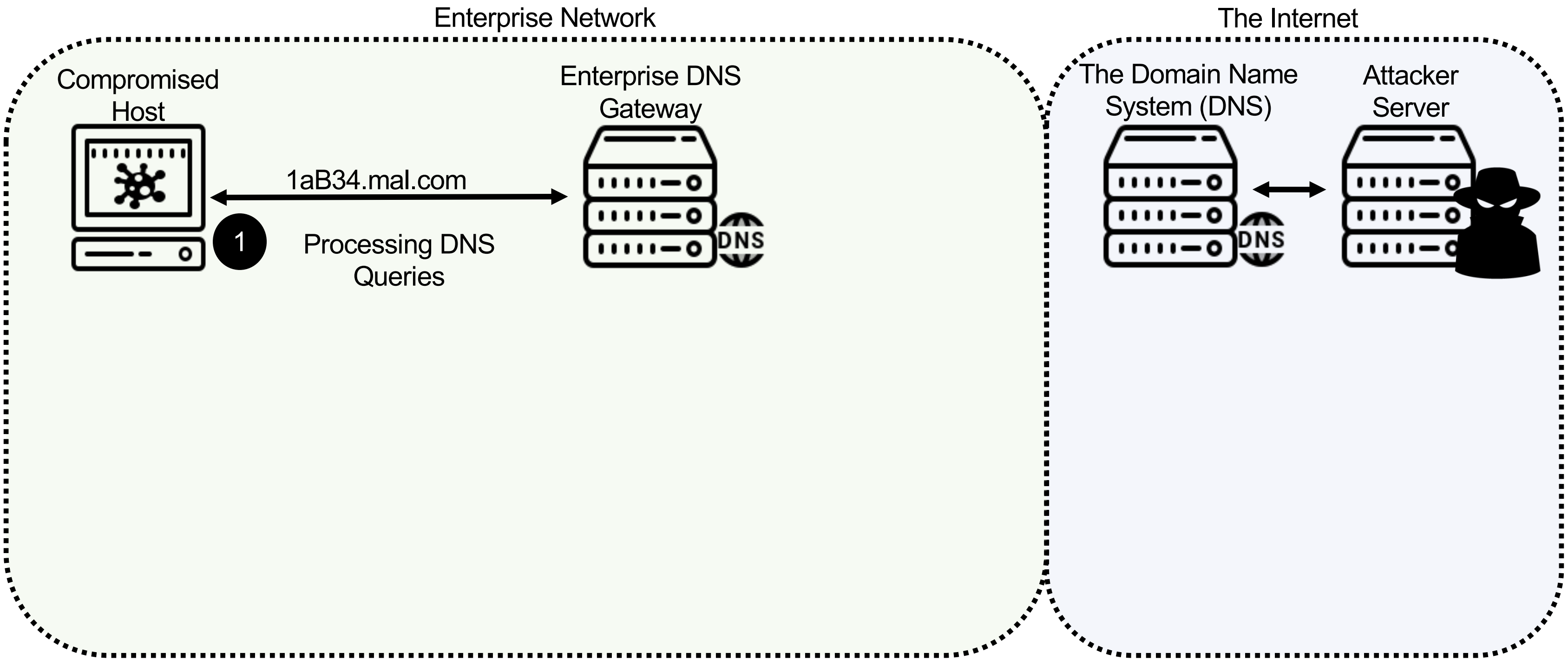
- A compressed representation of a stream of data
  - In the streaming model, each item is observed once [18]
  - Cannot store the entire stream in memory
- Enable accurate estimations of tasks that require inspection of the entire stream
- Examples
  - Count Min Sketch [20] – approximates the **frequencies** of elements in a stream
  - HyperLogLog (HLL) [21] – approximates the **number of distinct** elements in a stream
- Use cases
  - Traffic engineering: load balancing in high throughput environments [22]
  - DNS-based DDoS protection [23]

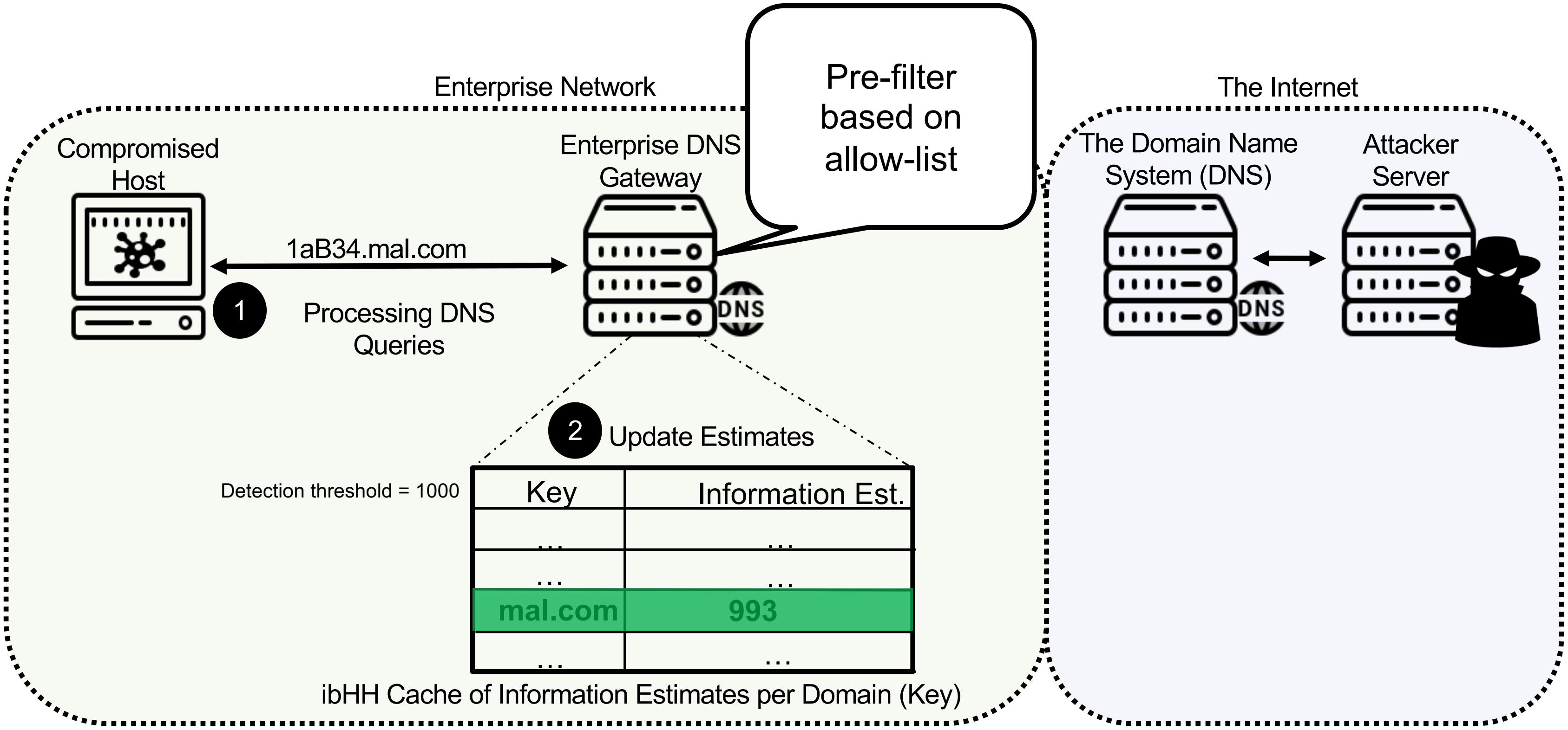
Information-based Heavy Hitters for Real-time DNS Exfiltration Detection

- We model the DNS queries as an online stream of (domain, subdomain) pairs
  - Every DNS query name is split into the registered domain name and the subdomain prefix
  - Example: www.google.com -> **domain** = google.com, **subdomain** = www
- With the use of hashing, weighted sampling technique and a variation of **HLL**, we detect information heavy hitters in the stream
- Hold a cache of **fixed** size *k*, storing information heavy hitter **domains** in the DNS stream and a **HLL** data sketch for every cached domain.
- Alert is raised when the amount of information estimation exceeds the detection threshold

Handling False Positive Alerts

- Popularity-based allow-list to reduce the number of false positive
  - Specifically, the TRANCO [29] top sites ranking was used in our experiments
- Domains in the allow-list are pre-filtered
  - Avoid filling the cache with benign information heavy hitter
- Offers significant reduction in false positive alerts


Enterprise Network
The Internet
Compromised Host
Enterprise DNS Gateway
The Domain Name System (DNS)
Attacker Server
1aB34.mal.com
1
Processing DNS Queries
DNS
DNS


Enterprise Network
Pre-filter based on allow-list
The Internet
Compromised Host
Enterprise DNS Gateway
The Domain Name System (DNS)
Attacker Server
1aB34.mal.com
1
Processing DNS Queries
DNS
DNS
2
Update Estimates
Detection threshold = 1000
Key
Information Est.
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mal.com
993
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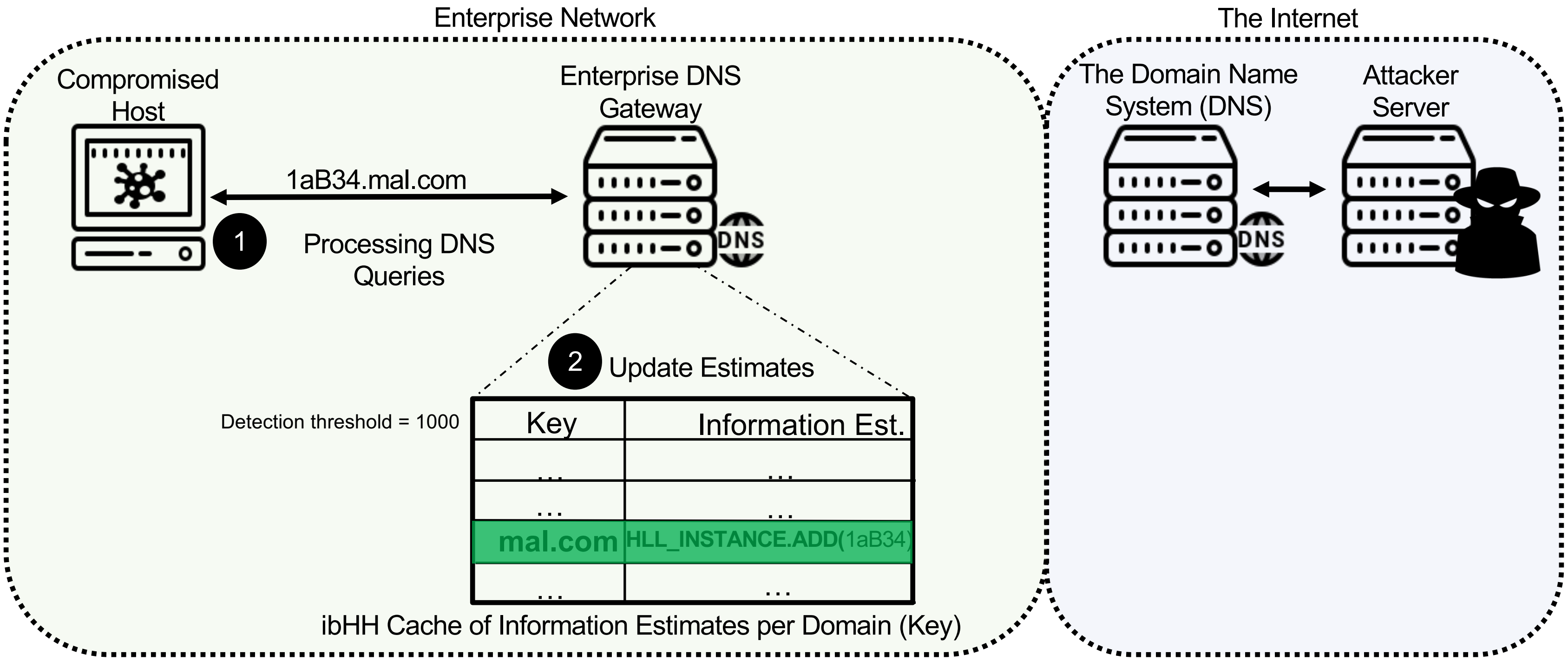
ibHH Cache of Information Estimates per Domain (Key)



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Processing DNS Queries
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Update Estimates
Detection threshold = 1000
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mal.com
HLL_INSTANCE.ADD(1aB34)
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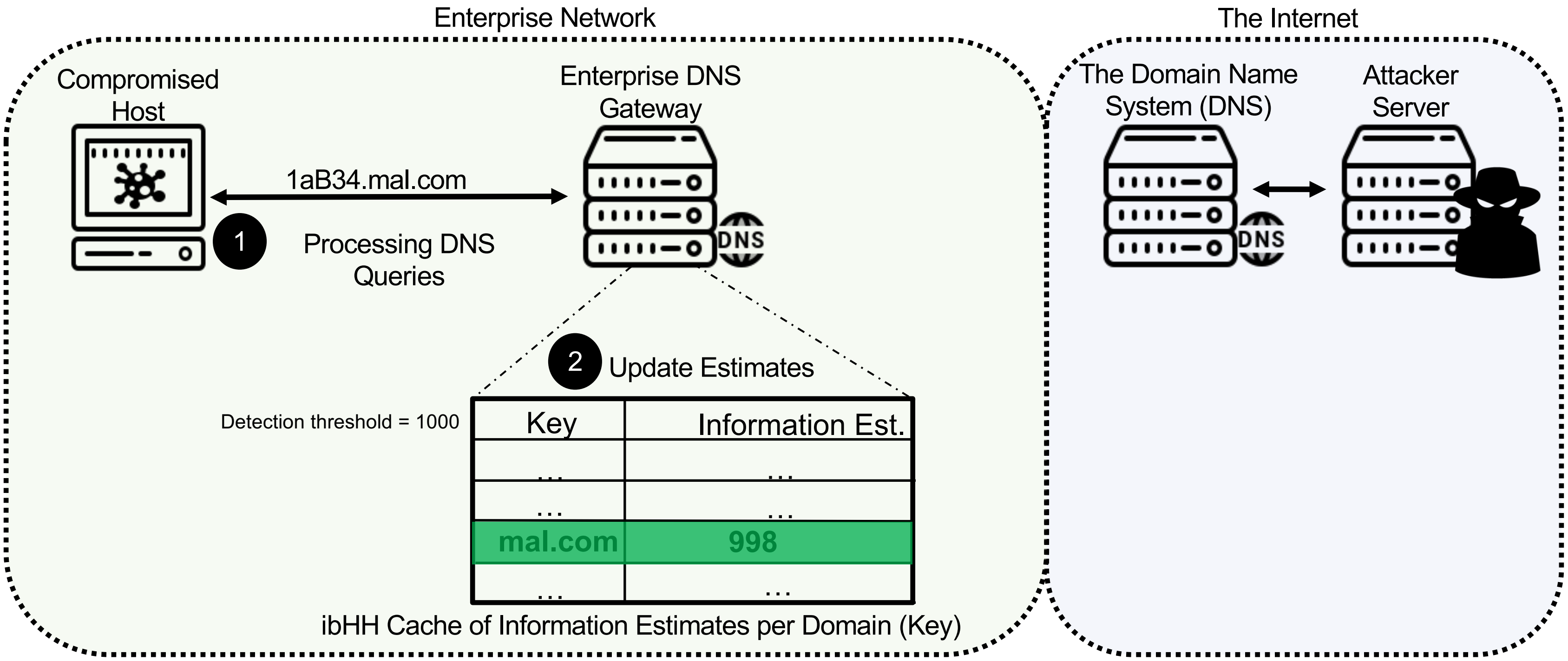
ibHH Cache of Information Estimates per Domain (Key)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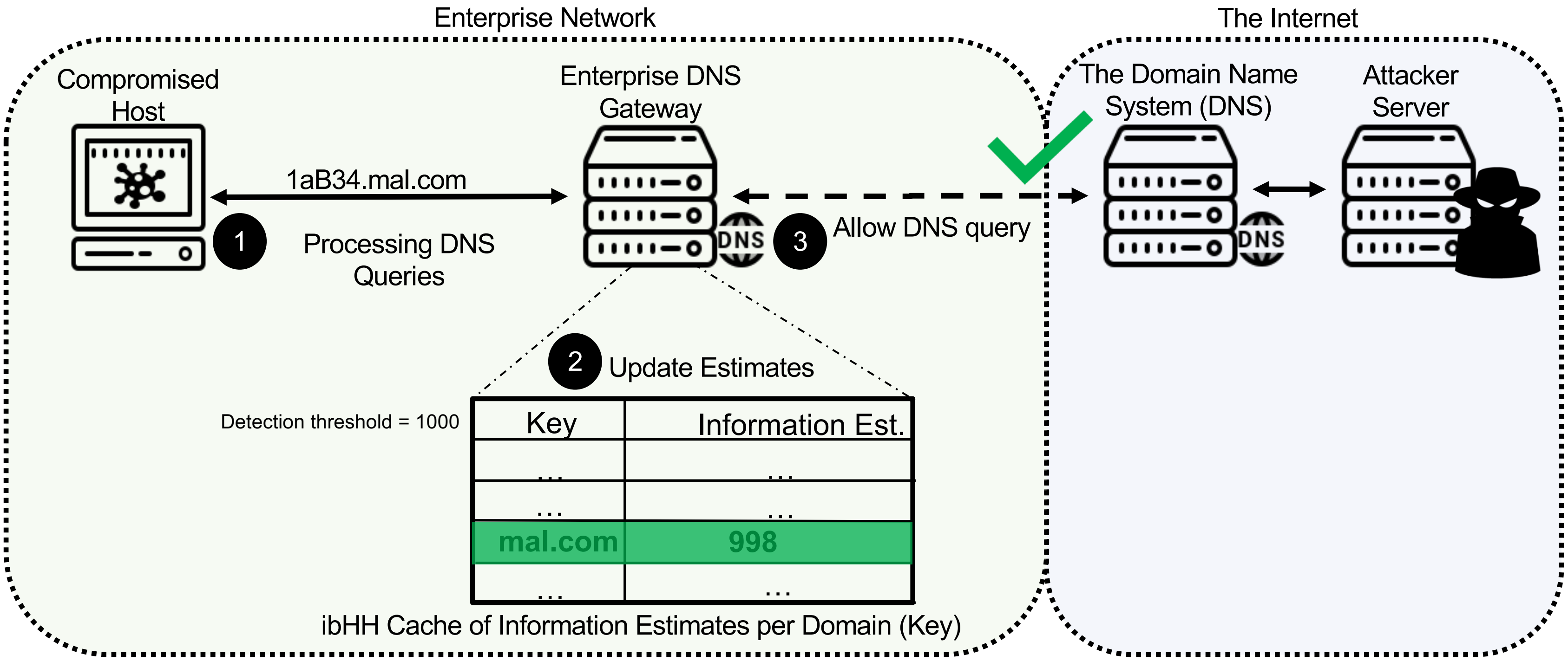

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The Internet
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1aB34.mal.com
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Processing DNS Queries
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Allow DNS query
DNS
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Update Estimates
Detection threshold = 1000
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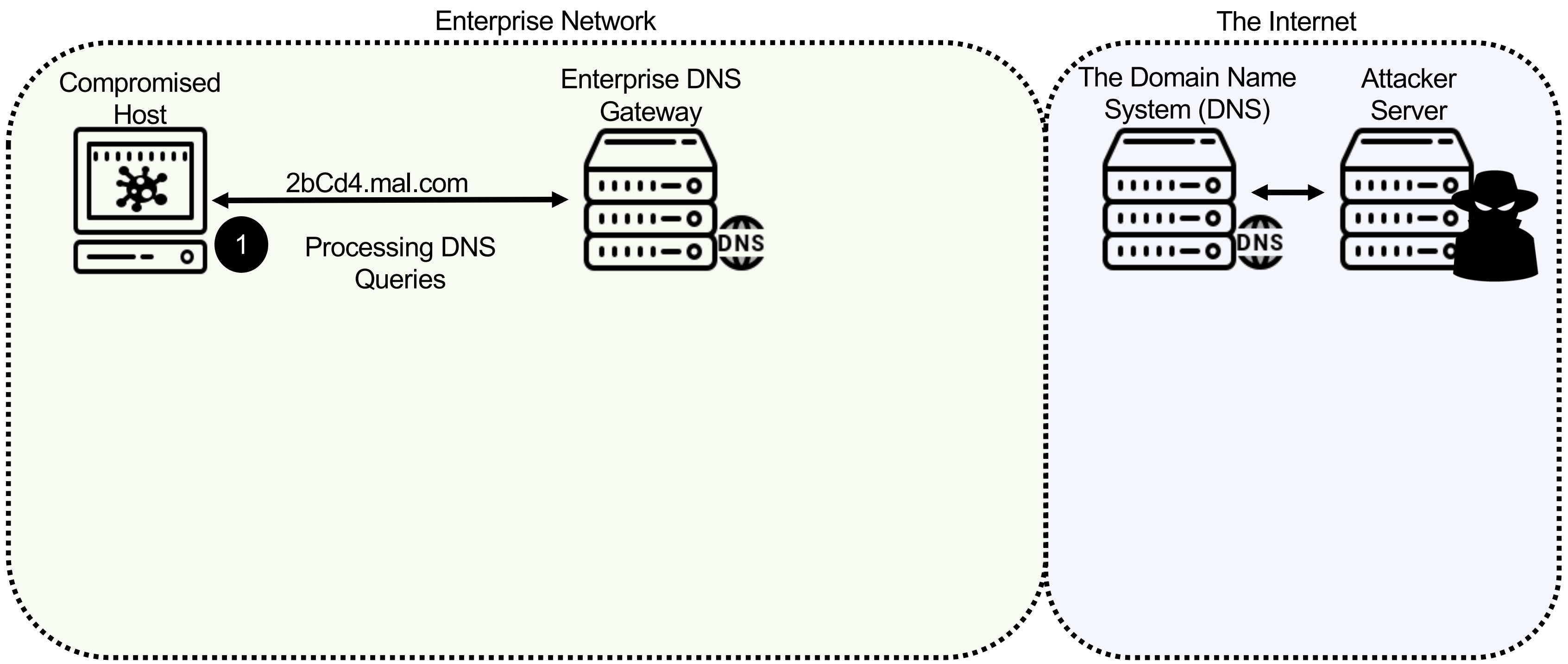

Enterprise Network
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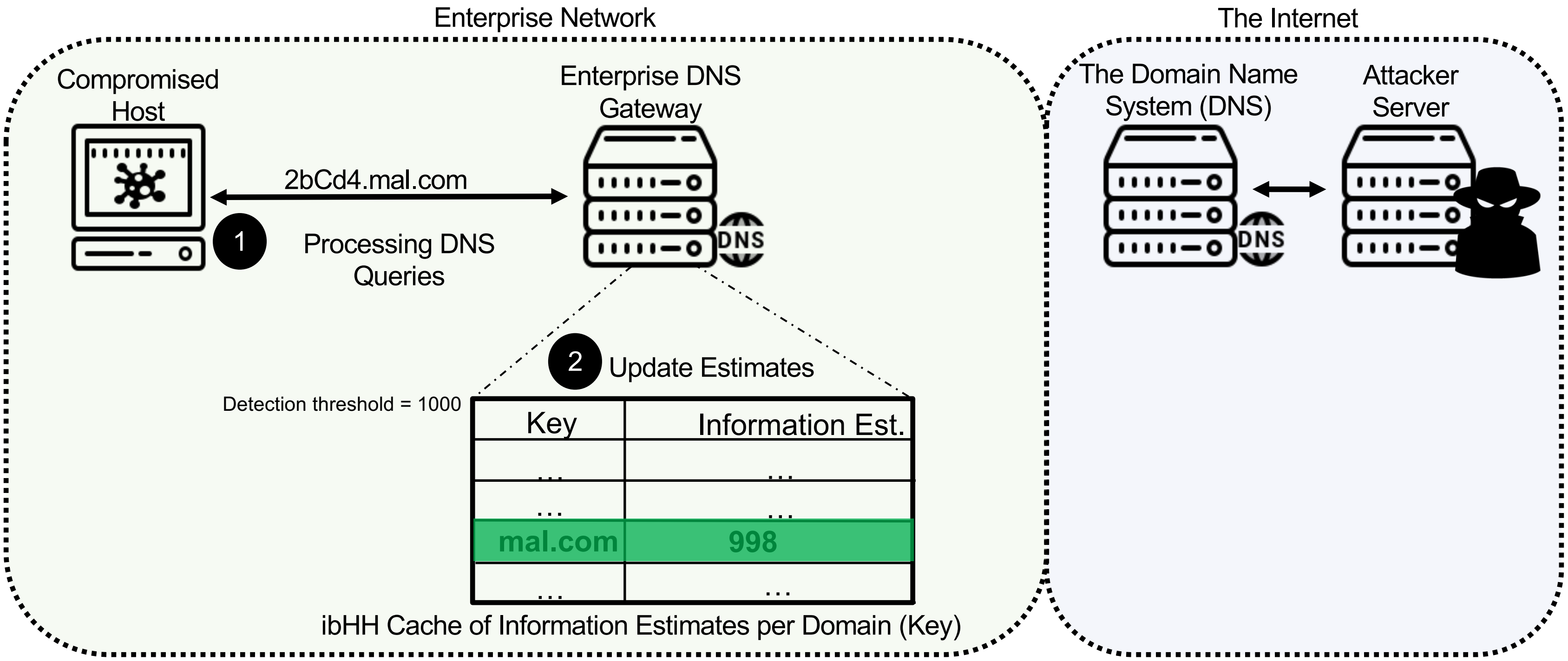
Enterprise DNS Gateway
The Domain Name System (DNS)
Attacker Server
2bCd4.mal.com
1
Processing DNS Queries
DNS
DNS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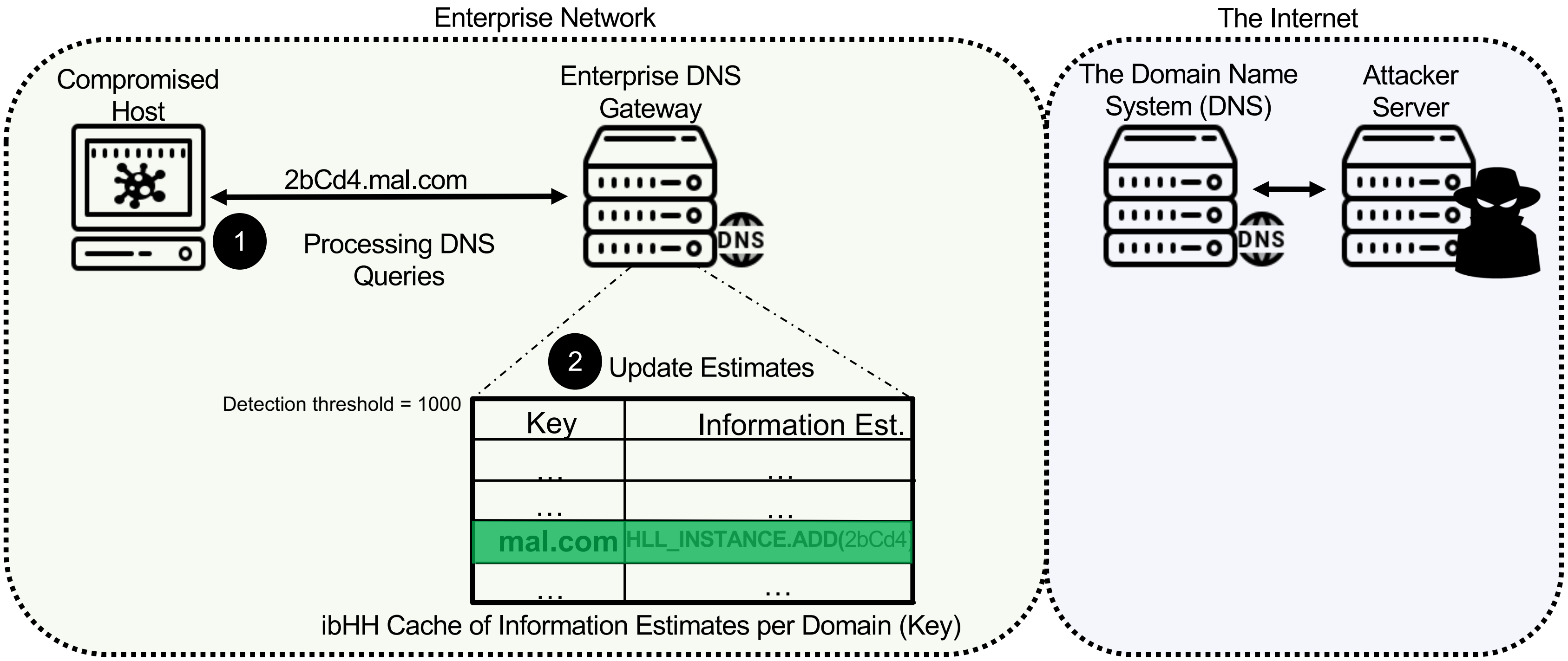

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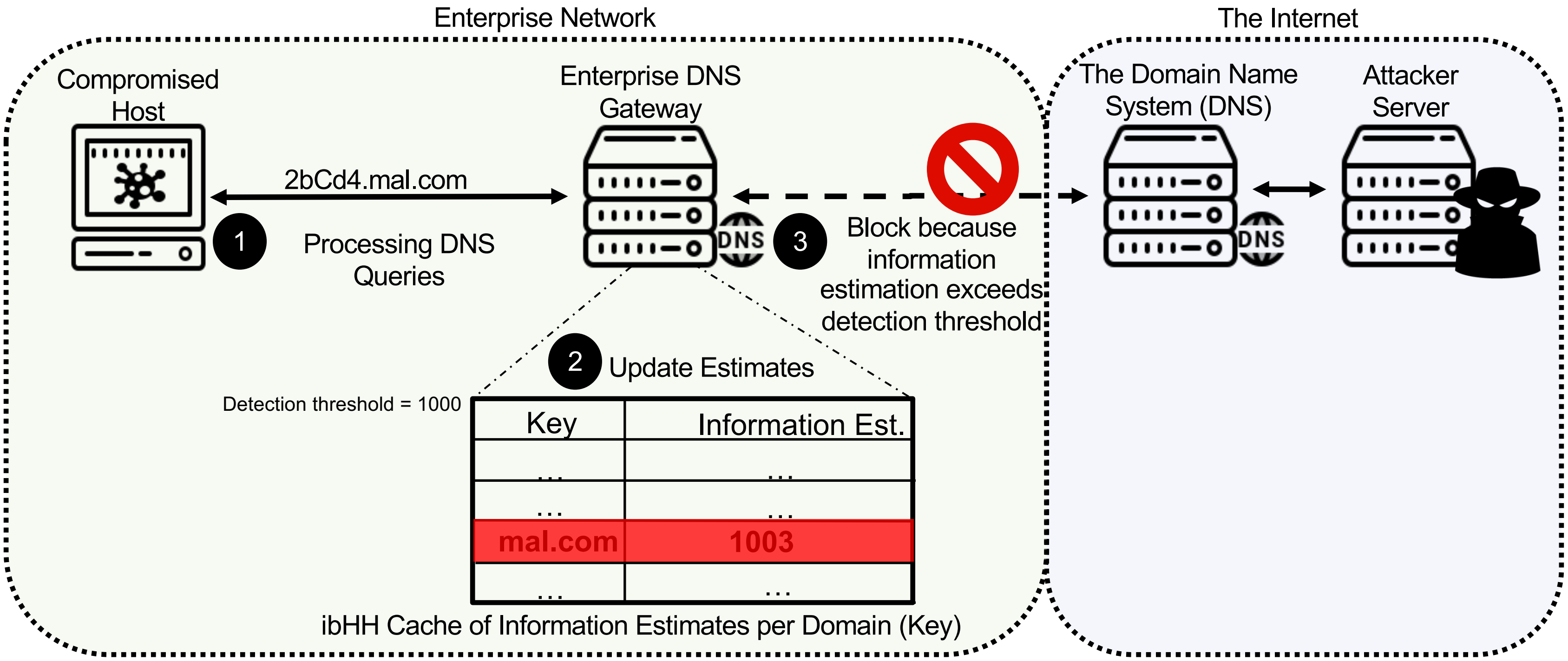
Enterprise Network
The Internet
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Attacker Server
2bCd4.mal.com
1
Processing DNS Queries
DNS
3
Block because information estimation exceeds detection threshold
DNS
2
Update Estimates
Detection threshold = 1000
Key
Information Est.
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mal.com
1003
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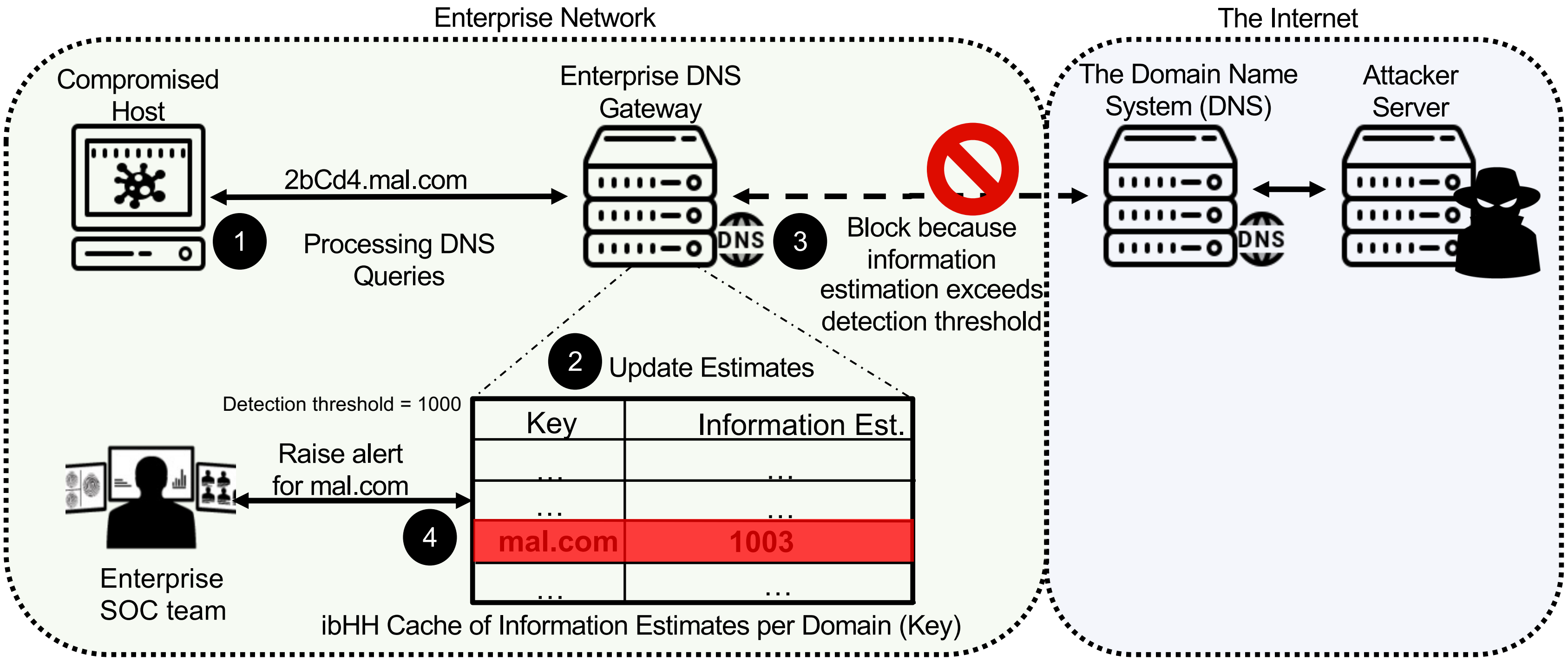
...
ibHH Cache of Information Estimates per Domain (Key)



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2bCd4.mal.com
1
Processing DNS Queries
DNS
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Block because information estimation exceeds detection threshold
2
Update Estimates
Detection threshold = 1000
Key
Information Est.
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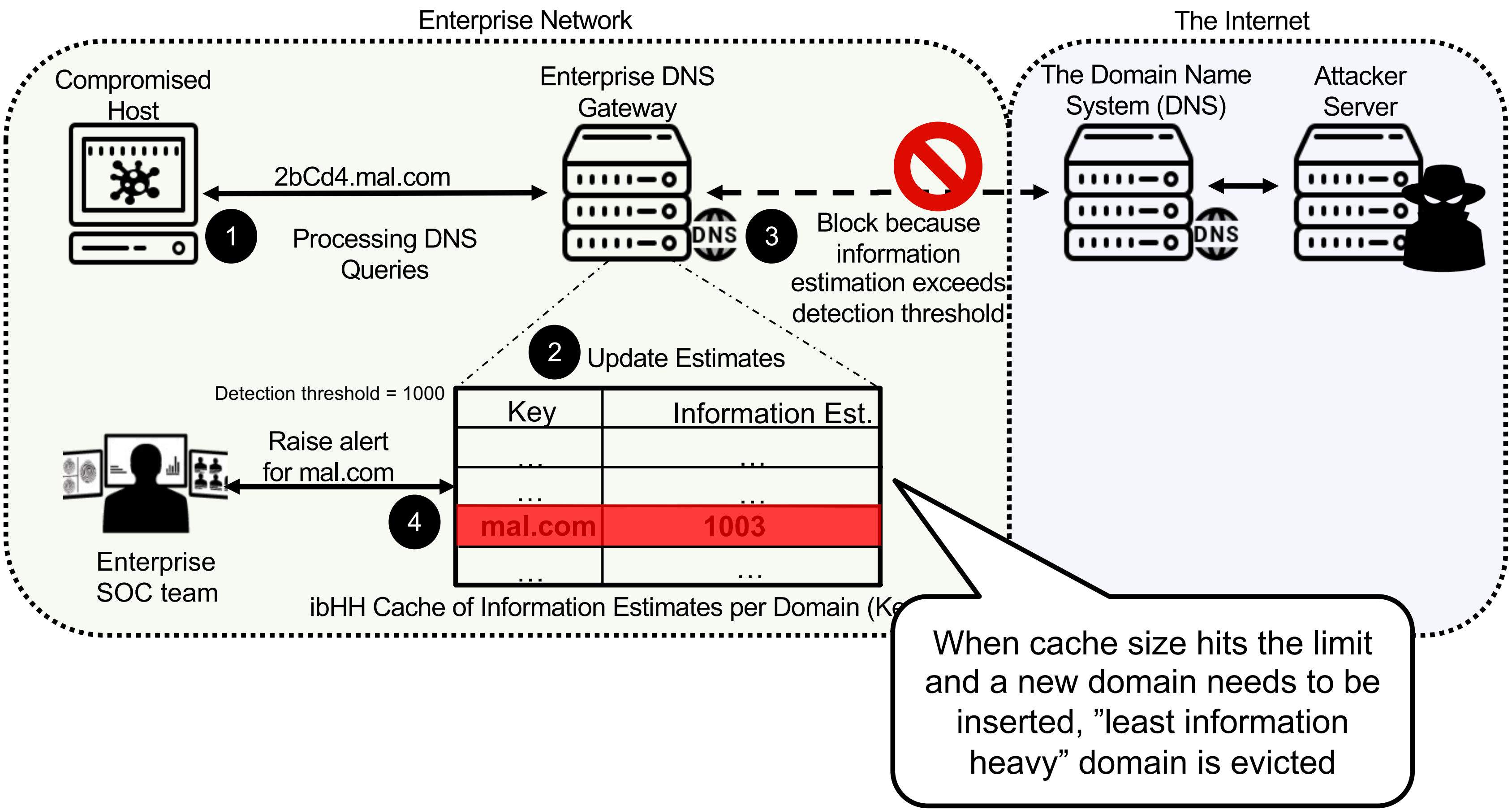
mal.com
1003
Raise alert for mal.com
4
Enterprise SOC team
ibHH Cache of Information Estimates per Domain (Key)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4
Enterprise SOC team
ibHH Cache of Information Estimates per Domain (Ke
When cache size hits the limit and a new domain needs to be inserted, ”least information heavy” domain is evicted

Experiments

- Dataset:

# DNS queries	# Unique registered domains	Timespan
50,853,030,033	43,310,209	8 Days

- **Anonymized** monitored data of enterprise organizations customers

Methodology

- Injecting synthetic malicious DNS exfiltration traffic with 1,300 distinct domains to the dataset
- Malicious traffic generated with:
  - Iodine [5] – publicly available DNS tunneling tool, simulates browsing over
  - FrameworkPOS [24] – simulates exfiltration of credit card details, sending three queries per second
  - Backdoor.Denis [25] – simulates C2 communication over DNS, sending a query every 1.5 seconds.
- Each method trained with different acceptable false positive rates
  - Ranging between 0.01 to 0.0001
- Measure true positive rate (TPR) and false positive rate (FPR) of each method
  - Based on the count of **registered** domain alerts
- TRANCO top 1M allow-list applied to all methods

Results

Method	Dataset	FPR=0.01				FPR=0.001				FPR=0.0001			
		TD[1]	FPR	TPR	DER[1]	TD[1]	FPR	TPR	DER[1]	TD[1]	FPR	TPR	DER[1]
	$DS_p + I$	1734	**0.0037**	**1.0**	0.7	1420	**0.001**	**1.0**	5	1343	<0.001	**1.0**	65
ibHH	$DS_p + F$	1743	**0.0038**	**1.0**	0.7	1430	**0.001**	**1.0**	5	1298	<0.001	**0.98**	65
	$DS_p + D$	1728	**0.0037**	**1.0**	0.7	1417	**0.001**	**1.0**	5	1252	<0.001	**0.98**	65
	$DS_p + I$	3015	0.007	**1.0**		2132	0.0012	**1.0**		1342	<0.001	**1.0**	
Nadler et al.	$DS_p + F$	3015	0.007	0.99	N/A	2085	0.0012	0.96	N/A	1267	<0.001	**0.98**	N/A
	$DS_p + D$	3015	0.007	0.98		2058	0.0012	0.94		1240	<0.001	0.97	
	$DS_p + I$	3200	0.008	**1.0**		2659	0.014	**1.0**		1314	<0.001	**1.0**	
Ahmed et al.	$DS_p + F$	3214	0.008	**1.0**	N/A	2631	0.014	0.98	N/A	1107	<0.001	0.85	**N/A**
	$DS_p + D$	3170	0.008	0.98		2599	0.014	0.95		1039	<0.001	0.8	
	$DS_p + I$	1927	0.0041	**1.0**	0.9	1771	0.0023	**1.0**	12	1314	<0.001	**1.0**	70
Paxson et al.	$DS_p + F$	1927	0.0041	**1.0**	0.9	1771	0.0023	**1.0**	12	1249	<0.001	0.96	70
	$DS_p + D$	1927	0.0041	0.98	0.9	1771	0.0023	**1.0**	12	1230	<0.001	0.95	70

[1] Total Detections (#Distinct Hosts)
[2] Detectable Exfiltration Rate (B/s)

Real-world Evaluation

- Executed ibHH algorithm over the course of a month in a test environment, with different detection thresholds.
- Results:

Detection Threshold (B/s)	Number of Alerted Domains	True Positive	False Positive
50	1	1	0
25	2	1	1
15	**7**	**2-3**	**5-6**
10	15	2-3	12-13
5	38	-	-

Alerts by day

Date	Primary Domain	Classification
Day 1	TP_domain_1.com	TP
Day 3	FP_domain_1.com	FP
Day 14	TP_domain_2.com	TP
Day 21	TP_domain_3.com	TP
Day 27	FP_domain_2.com	FP
Day 27	FP_domain_3.com	FP
Day 28	FP_domain_2.com	FP
Day 30	FP_domain_4.com	FP

Examples of real DNS exfiltration queries detected

domain	subdomain	Response
TP_domain_1.com	vaaaakawgba.t1	VACK$ÔøΩ!4
TP_domain_1.com	schrqs.t1	Base128
TP_domain_1.com	pajymnaa.t1	<Base 128 encoded response>
TP_domain_1.com	pabajczq.t1	<Base 128 encoded response>
TP_domain_1.com	<Long base128 encoded data>	<Base 128 encoded response>

Examples of real DNS exfiltration queries detected

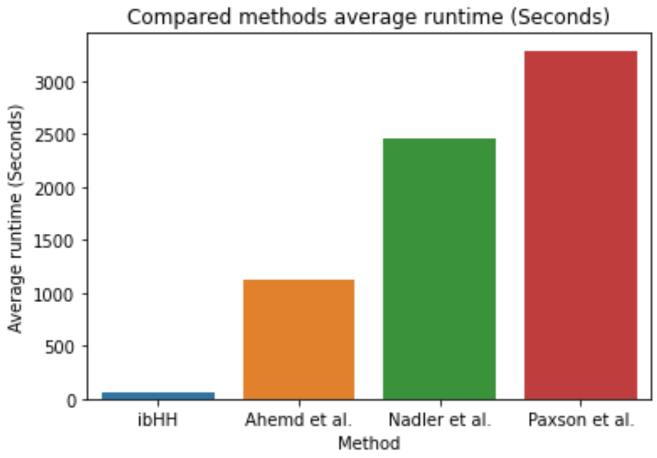
domain	subdomain	Response
TP_domain_2.com	6Ngv7RHeGapGXYnUupVf8te.tunnel.	divSaqh8aAr7F- SDRy10l2R75UijruRDGzuSNzZPx- JA04hvi+tmecvRX4SMirzRbi4sR40kPTSaB 4PmIfT8mWZC8iIGE5monrr2i5DkiekvUzyR E0zYCJMh0FJyCVO9- j+BGlTyaoBQGOzzJzauoZisladhA1kFWZW 2Bnr0Dhfo+vKNWoNZ3a2DxMT8B5-7YA- CR6p3M9GhW2HpradpFzIicUm3BVxEFfZ PEXfObQEMV4I_z++nAS16rQ__
TP_domain_2.com	6Ngv7RHeGapGTUYtcom7NmR.tunnel.	dk3Vaqh8asWwoVRUwe+srlG…xUeZJjuO xnF9v1XTJAYwMawiM8Or04UTXAkxLHv_ yUuOHE+wIuSm33Ha1v4zjiyqOIquYrB3N8 Ejin9Ec4Qtr5Pwwj-e73dT
TP_domain_2.com	backbxyqw0qkkbn6a28gtg4b.tunnel.	dmIZaqh8aok0- 3Qfz5B2Q1udf2wrJ2X3nvpd_2+9Mh0qT3+ y4iFSXKu…yZ_K0aqz0ACYF9sM7TRd+- 7eKJlih7QOEl5cfBi2quk
TP_domain_2.com	backbxyqw0qkkjdha28jdg8b.tunnel.	dlwbaqh8asifqKr5h6erYU8oB6q++_FwO6i RNpVV- AihJV9KsMJwsn9m…2D2MLO8eYFsAVZzi DoZYI9mGarqdfliljwQVAMLHHk0LHyHITS MfbT_BAVEt0iZwF+kIlC16fp1

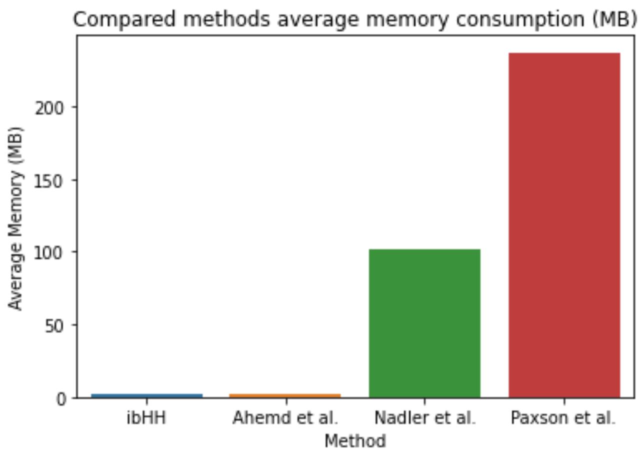
Examples of real DNS exfiltration queries detected

domain	subdomain	response
TP_domain_3.com	5F0AB605DD071A89DA7F0CF64D56FCFC.387E8330C4325908D01EDD0695F49C0A.A2523141909EE6042793C5A5ABE74428.9ED38D606EF60B8439AFA1D5EEB5182B.AA49A26C65950D76EDAAFF51E24A22AB.6EB1EF1714AFA54A884ADC9CB83EC9DC.5557B2CBE47259ACA25015EA423B6C1B.10000041.3	600ab663c9bf60d63d3b585b8ea4dee18f442c8f82676de3735cb10839dfa5ccef27771e209032d6f4703feae07eeb7a011551ab0c02a5ba0e75006e9089e2c05ef92200cc99dc4cb3ccfccae4926202142d88d50901ec409fb98e302c1d2875
TP_domain_3.com	620BB605C7DDA3F4B972F6E76AF5D4C1.8181A8FC39C43FEF218FFA3891F0A593.CEDA4CE8E0A530F320384542E06D5B49.7E8CF3B38686A5C2B9E1FB81139E892D.6616A2F9AC79B1482C891A2E895FF885.0CC811DBCEAFBD0513406E25CC931F3F.49D8436B4733B0A0771286066023EE05.10000041.3	800ab6630f605c3c55cce69532f7cbdc97f0ccce2…81f
TP_domain_3.com	7F0AB605FF19183C4759F65D438781BD.86B397A2E2DD29A06CB51B6FDDA7F753.F03DEE2EB4DFD038AC80B362C7D4FB70.78A220BF4F85502B04BB1210D92FF707.207D53598B0B4A470F8BCCA2D3E76BA7.EAE5BAB2DE292CAC4F02FD12335217D0.442DC982217C860B66E932371FAEBE83.10000041.3	a70ab663dfcf8ce89ed78c0f64953d1e55e7a57acfc2d226f624d43aba520b…7f05
TP_domain_3.com	A60AB6055189DBFC9FA928EAD924FFBC.DCA58B5CDAD104057B84E8627C5F9A96.19088BD33511DEFEA9A1FCE1D49B3CD9.46BCA5F7681E61EAE10812851A92FD30.D02A5AF882FE97D902923AC43F8D0B01.670E7776AF69092D3D7E961EBF086E35.CB0BA48E9251220EB496325B9E6A38FA.10000041.3	8d0ab66365271bdc516fd8bb…26d7c
TP_domain_3.com	680BB605F8D918950C9D5A39E4AD504E.4C095977F235232838E699BFC8991097.256DF8EE2AB2C66C46CC624E57D99C5F.8314C325AF9E811DB580A08B5EC6D12B.AD2D65449D5464B8496D3C507AF40176.65180EFD2205AAED93B081977F469EF4.1A5F094FF9F053FA8F1C4949BDFD1827.10000041.3	600ab663c9bf60d63d3b585b8ea4dee18f442c8f82676de3735cb10839dfa5ccef27771e209032d6f4703feae07eeb7a011551ab0c02a5ba0e75006e9089e2c05ef92200cc99dc4cb3ccfccae4926202142d88d50901ec409fb98e302c1d2875

Performance Evaluation

- Simulated DNS queries stream
  - 35M DNS queries total
  - Machine with a 6 core Intel CPU and 16 GB RAM





Limitations

- Only query name based exfiltration is detectable
    - Applies to most other detection methods
- Unlikely to detect exfiltration campaigns spread across many domains
    - Idea (**unverified**): instead of detecting domain heavy hitter, detect source host heavy hitters
- Cannot detect DNS exfiltration of encrypted DNS traffic
    - Such as DoH and DoT
    - Enterprises should avoid external DNS resolvers for encrypted traffic [28]
- Information counting is based only on unique subdomains

Conclusions and Future Work

- ibHH: Simple yet effective and scalable real time DNS exfiltration detection method with explainable results
- Competitive results on synthetic dataset with state-of-the-art methods
- Real-world detections with minimal false positive alerts
- Future: Deploy on real DNS resolvers
- Future: Test the ability to detect compromised hosts instead of malicious domains
    - Adjust the ibHH algorithm to detect source IP information heavy hitter instead of destination domain information heavy hitters

Questions

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