BreakSPF: How Shared Infrastructures Magnify SPF Vulnerabilities Across the Internet

by Wang *et al.*, NDSS '24

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Summarized by Subin Song (sbsong@mmlab.snu.ac.kr)

Table of Contents

- Introduction
- Background
- BreakSPF Attack Explained
  - Attack Model
  - Cross-Protocol Email Spoofing Attack
  - Exploitation Workflow
- Results
  - SPF Deployment Analysis Results
  - Shared IPs Collection Results
  - BreakSPF Attack Results
- Mitigations

Introduction

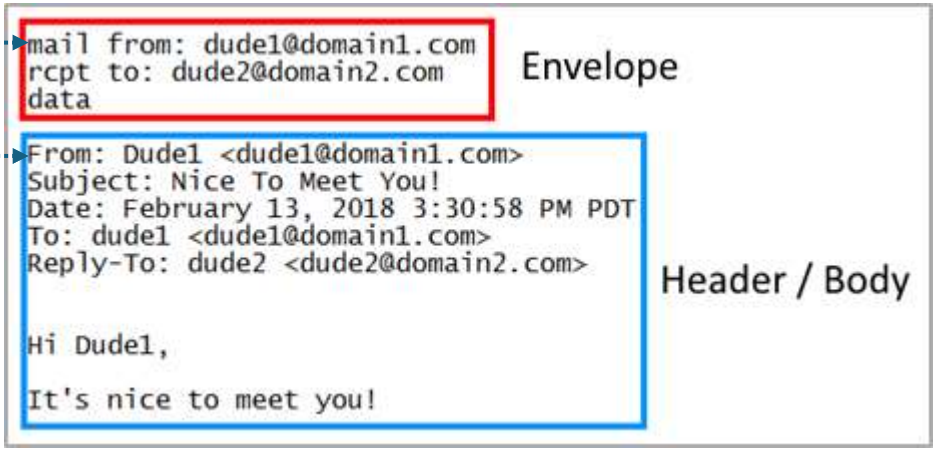
- **SPF (Sender Policy Framework)** is a protocol to prevent email spoofing attacks, by specifying IP addresses allowed to send emails from the domain
- Idea of *BreakSPF* attack
  - Step 1. Obtain IP addresses from cloud service providers, proxy services, etc.
  - Step 2. Find domains with SPF records that allow the IP addresses obtained in Step 1
  - Step 3. Send spoofing emails from IP addresses & domains found in previous steps
- Such vulnerabilities are magnified due to shared infrastructures of SPF records (i.e., `include`, `redirect` mechanisms)

Background

Email Spoofing Attack

- **SMTP** (Simple Mail Transfer Protocol) *doesn’t* have a built-in method for “from” address authentication
- Therefore, attackers can forge “from” addresses when sending emails
  - “`MAIL FROM`” in SMTP envelope
  - “`From`” in SMTP header
- Defense: Authentication chain
  - **SPF**, DKIM, DMARC, ARC

    i.e., Sender Policy Framework / DomainKeys Identified Mail / Domain-based Message Authentication, Reporting and Conformance / Authenticated Received Chain



```
mail from: dude1@domain1.com
rcpt to: dude2@domain2.com
data
```

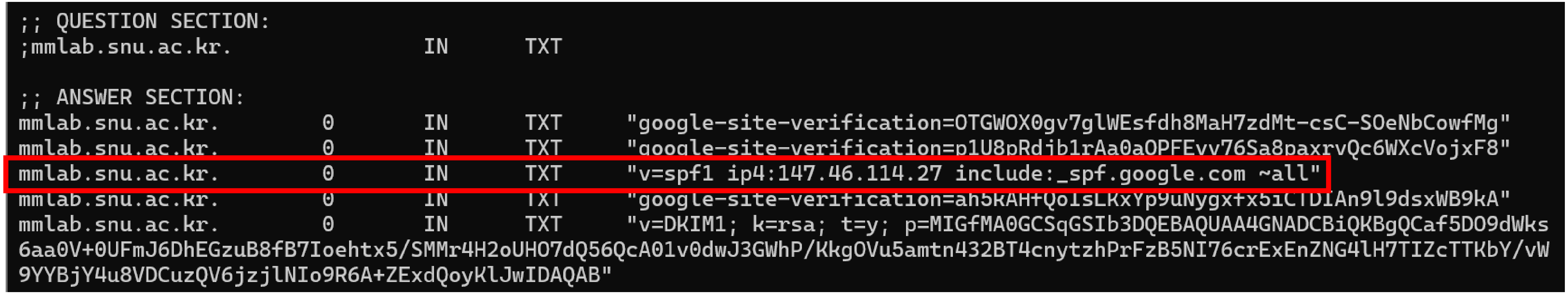
```
From: Dude1 <dude1@domain1.com>
Subject: Nice To Meet You!
Date: February 13, 2018 3:30:58 PM PDT
To: dude1 <dude1@domain1.com>
Reply-To: dude2 <dude2@domain2.com>


Hi Dude1,

It's nice to meet you!
```

Image source: https://www.proofpoint.com/us/corporate-blog/post/how-does-email-spoofing-work-and-why-it-so-easy

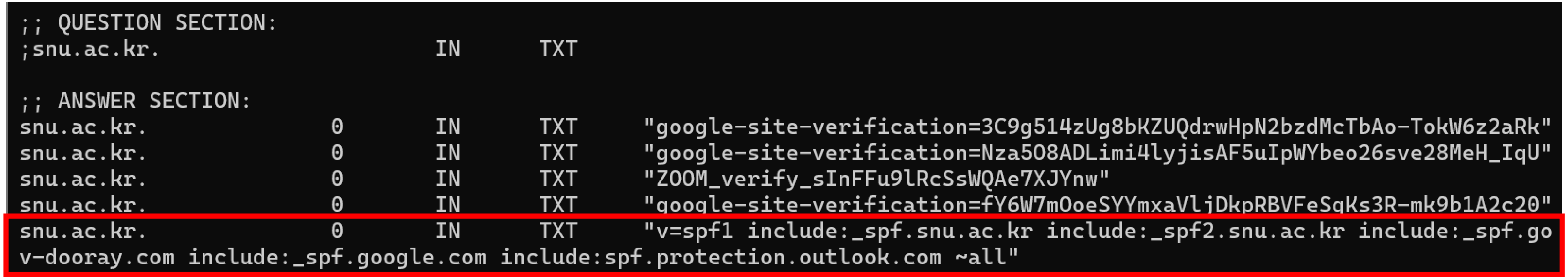
SPF (Sender Policy Framework)

- An IP-based email authentication standard to prevent spam, spoofing, and phishing
- An *SPF record* lists IP addresses that are approved to send emails from the current domain
  - Provided as a DNS TXT record
- The receiving mail server checks the sender’s IP address against the SPF record of the received email’s “`MAIL FROM`” domain

SPF Record Examples



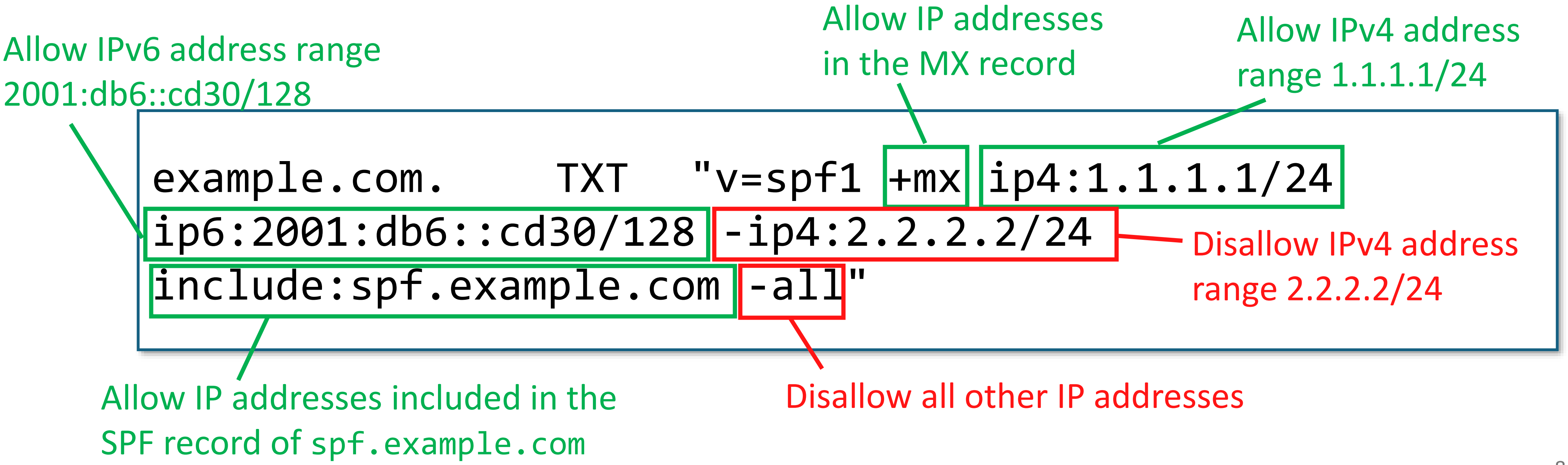
```
;; QUESTION SECTION:
;mmlab.snu.ac.kr.               IN      TXT

;; ANSWER SECTION:
mmlab.snu.ac.kr.        0       IN      TXT     "google-site-verification=OTGWOX0gv7glWEsfdh8MaH7zdMt-csC-SOeNbCowfMg"
mmlab.snu.ac.kr.        0       IN      TXT     "google-site-verification=p1U8pRdjb1rAa0aOPFEvy76Sa8paxrvQc6WXcVojxF8"
mmlab.snu.ac.kr.        0       IN      TXT     "v=spf1 ip4:147.46.114.27 include:_spf.google.com ~all"
mmlab.snu.ac.kr.        0       IN      TXT     "google-site-verification=ah5kAH+Qo1sLKxYp9uNygx+x51CTDIAn9l9dsxWB9kA"
mmlab.snu.ac.kr.        0       IN      TXT     "v=DKIM1; k=rsa; t=y; p=MIGfMA0GCSqGSIb3DQEBAQUAA4GNADCBiQKBgQCaf5DO9dWks
6aa0V+0UFmJ6DhEGzuB8fB7Ioehtx5/SMMr4H2oUHO7dQ56QcA01v0dwJ3GWhP/KkgOVu5amtn432BT4cnytzhPrFzB5NI76crExEnZNG4lH7TIZcTTKbY/vW
9YYBjY4u8VDCuzQV6jzjlNIo9R6A+ZExdQoyKlJwIDAQAB"
```



```
;; QUESTION SECTION:
;snu.ac.kr.                     IN      TXT

;; ANSWER SECTION:
snu.ac.kr.              0       IN      TXT     "google-site-verification=3C9g514zUg8bKZUQdrwHpN2bzdMcTbAo-TokW6z2aRk"
snu.ac.kr.              0       IN      TXT     "google-site-verification=Nza5O8ADLimi4lyjisAF5uIpWYbeo26sve28MeH_IqU"
snu.ac.kr.              0       IN      TXT     "ZOOM_verify_sInFFu9lRcSsWQAe7XJYnw"
snu.ac.kr.              0       IN      TXT     "google-site-verification=fY6W7mOoeSYYmxaVljDkpRBVFeSqKs3R-mk9b1A2c20"
snu.ac.kr.              0       IN      TXT     "v=spf1 include:_spf.snu.ac.kr include:_spf2.snu.ac.kr include:_spf.go
v-dooray.com include:_spf.google.com include:spf.protection.outlook.com ~all"
```

SPF Record Format

- Starts with “v=spf1”, consists of multiple elements in `[qualifier]mechanism:value` format
  - Qualifier : `+` (pass) | `-` (hard fail) | `?` (neutral) | `~` (soft fail)
  - Mechanism : `all` | `include` | `redirect` | `ip4` | `ip6` | `mx` | …



```
example.com.    TXT   "v=spf1 +mx ip4:1.1.1.1/24
ip6:2001:db6::cd30/128 -ip4:2.2.2.2/24
include:spf.example.com -all"
```

Allow IPv6 address range 2001:db6::cd30/128

Allow IP addresses in the MX record

Allow IPv4 address range 1.1.1.1/24

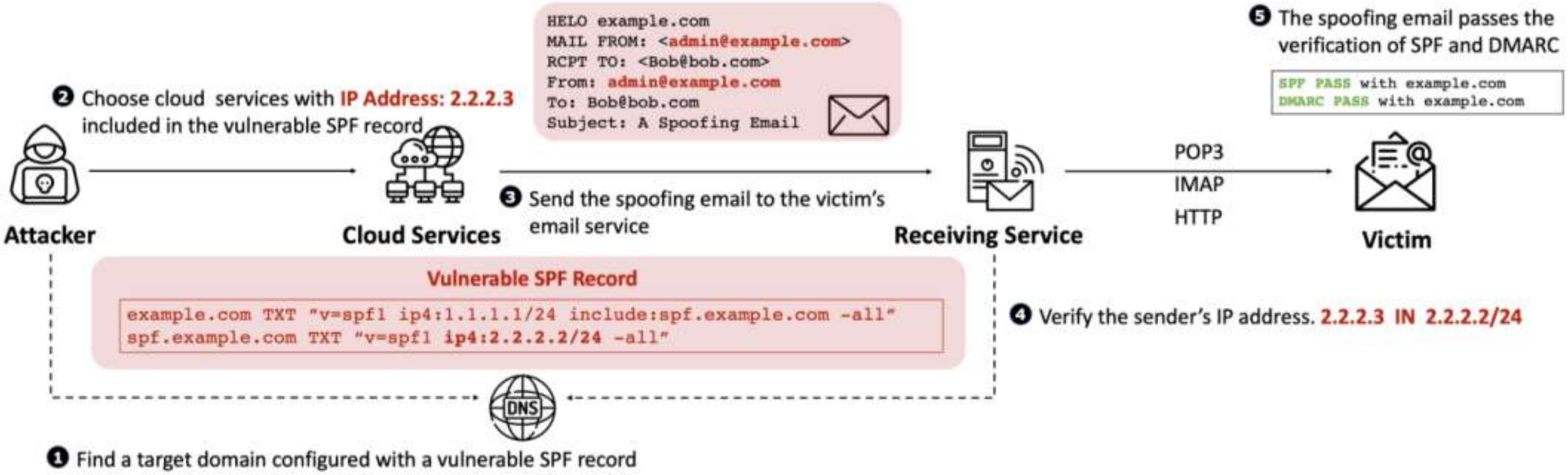
Disallow IPv4 address range 2.2.2.2/24

Allow IP addresses included in the SPF record of `spf.example.com`

Disallow all other IP addresses

BreakSPF Attack Explained

BreakSPF Attack Model



❶ Find a target domain configured with a vulnerable SPF record

❷ Choose cloud services with **IP Address: 2.2.2.3** included in the vulnerable SPF record

❸ Send the spoofing email to the victim's email service

```
HELO example.com
MAIL FROM: <admin@example.com>
RCPT TO: <Bob@bob.com>
From: admin@example.com
To: Bob@bob.com
Subject: A Spoofing Email
```

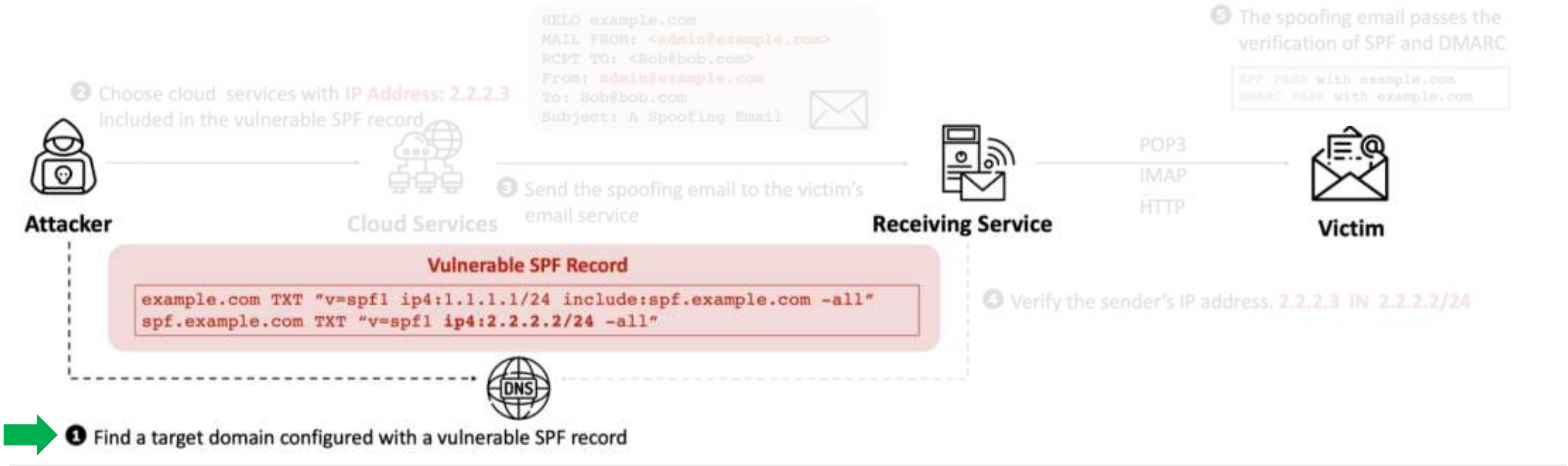
❹ Verify the sender's IP address. **2.2.2.3 IN 2.2.2.2/24**

```
example.com TXT "v=spf1 ip4:1.1.1.1/24 include:spf.example.com -all"
spf.example.com TXT "v=spf1 ip4:2.2.2.2/24 -all"
```

❺ The spoofing email passes the verification of SPF and DMARC

```
SPF PASS with example.com
DMARC PASS with example.com
```

BreakSPF Attack Model



❷ Choose cloud services with IP Address: 2.2.2.3 included in the vulnerable SPF record
Attacker
Cloud Services
❸ Send the spoofing email to the victim's email service
Receiving Service
POP3
IMAP
HTTP
Victim
❺ The spoofing email passes the verification of SPF and DMARC
❹ Verify the sender's IP address. 2.2.2.3 IN 2.2.2.2/24
Vulnerable SPF Record
DNS

```
HELO example.com
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RCPT TO: <Bob@bob.com>
From: admin@example.com
To: Bob@bob.com
Subject: A Spoofing Email
```

```
SPF PASS with example.com
DMARC PASS with example.com
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example.com TXT "v=spf1 ip4:1.1.1.1/24 include:spf.example.com -all"
spf.example.com TXT "v=spf1 ip4:2.2.2.2/24 -all"
```
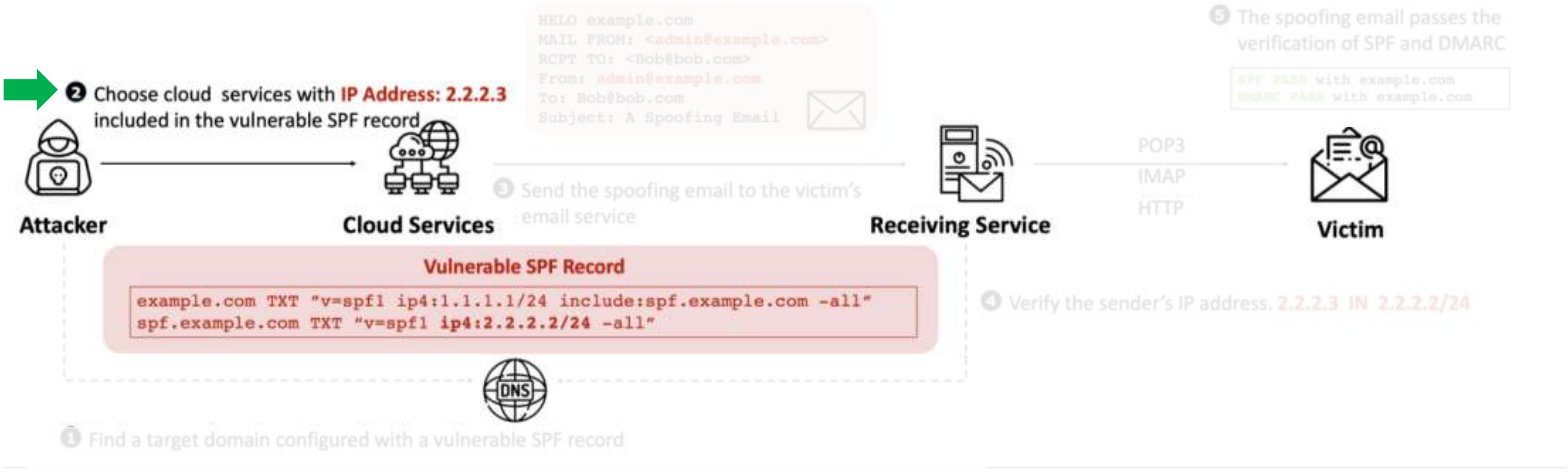

❶ Find a target domain configured with a vulnerable SPF record

BreakSPF Attack Model



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❸ Send the spoofing email to the victim's email service

Vulnerable SPF Record

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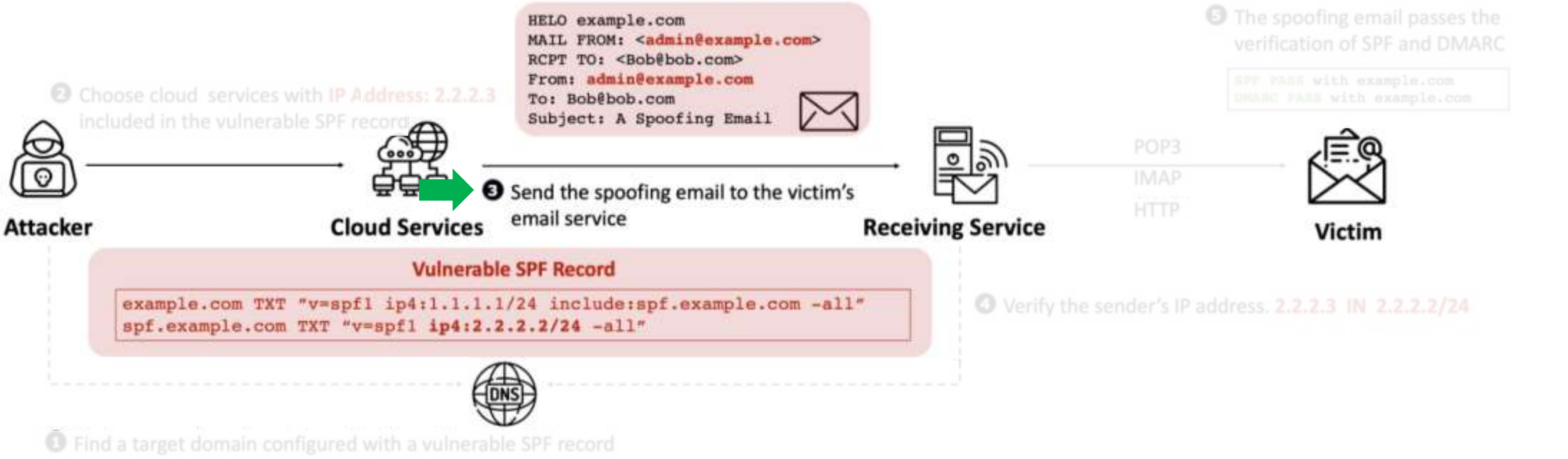
❶ Find a target domain configured with a vulnerable SPF record

BreakSPF Attack Model



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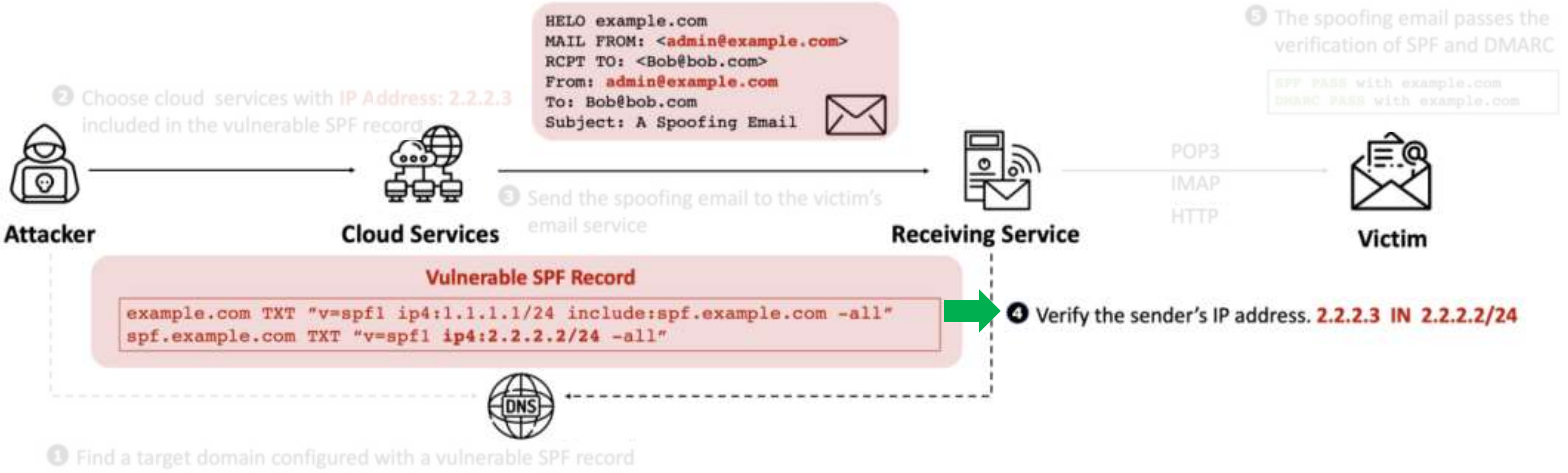
BreakSPF Attack Model



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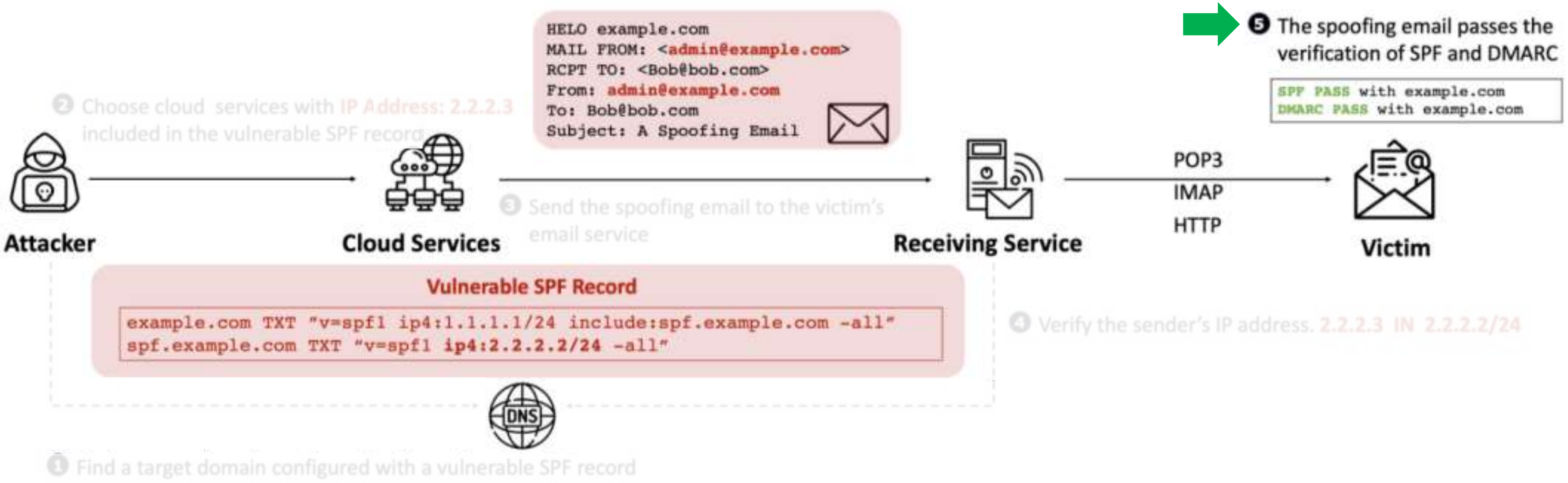

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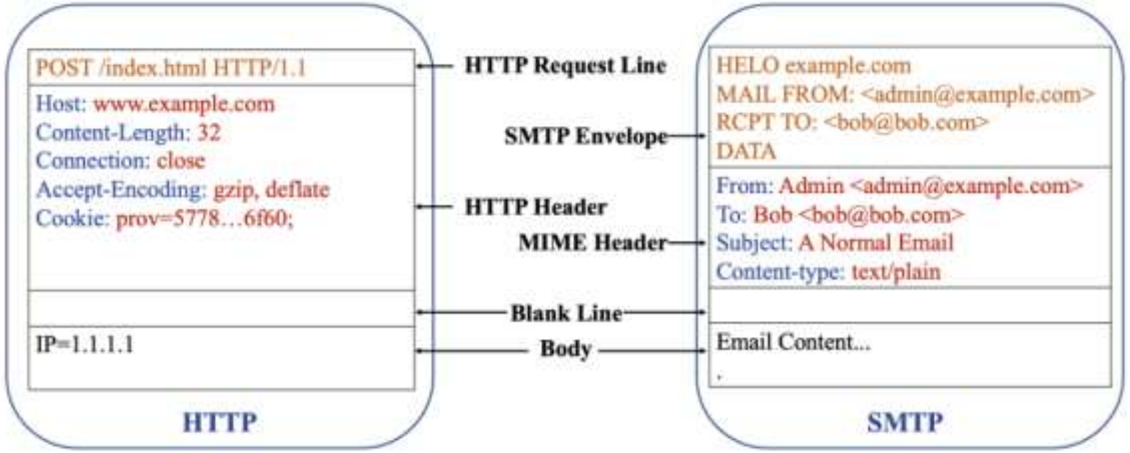
Cross-Protocol Email Spoofing Attack

- Leverages the similarities of HTTP and SMTP
  - Header-body structure
  - Usage of MIME* headers

    * Multipurpose Internet Mail Extensions



```
POST /index.html HTTP/1.1
Host: www.example.com
Content-Length: 32
Connection: close
Accept-Encoding: gzip, deflate
Cookie: prov=5778…6f60;

IP=1.1.1.1
```

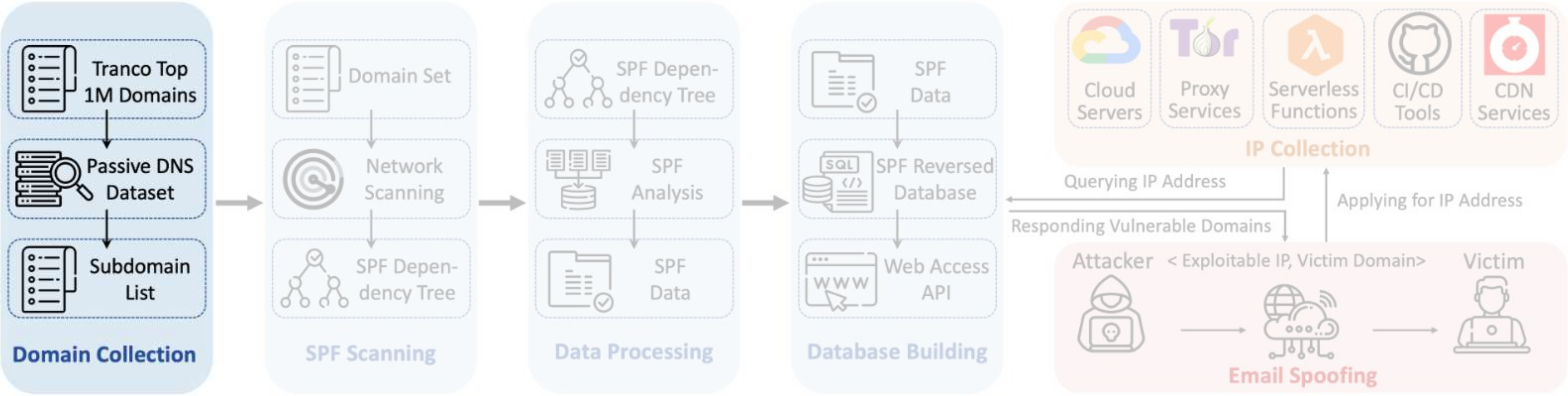
```
HELO example.com
MAIL FROM: <admin@example.com>
RCPT TO: <bob@bob.com>
DATA
From: Admin <admin@example.com>
To: Bob <bob@bob.com>
Subject: A Normal Email
Content-type: text/plain

Email Content...
.
```

- Use HTTP forwarding services (e.g., HTTP proxy, CDN) to send email packets
  - Email servers are fault-tolerant to some extent, so they can treat HTTP header fields as unidentified SMTP commands and ignore them

Exploitation Workflow

Step 1. Domain collection

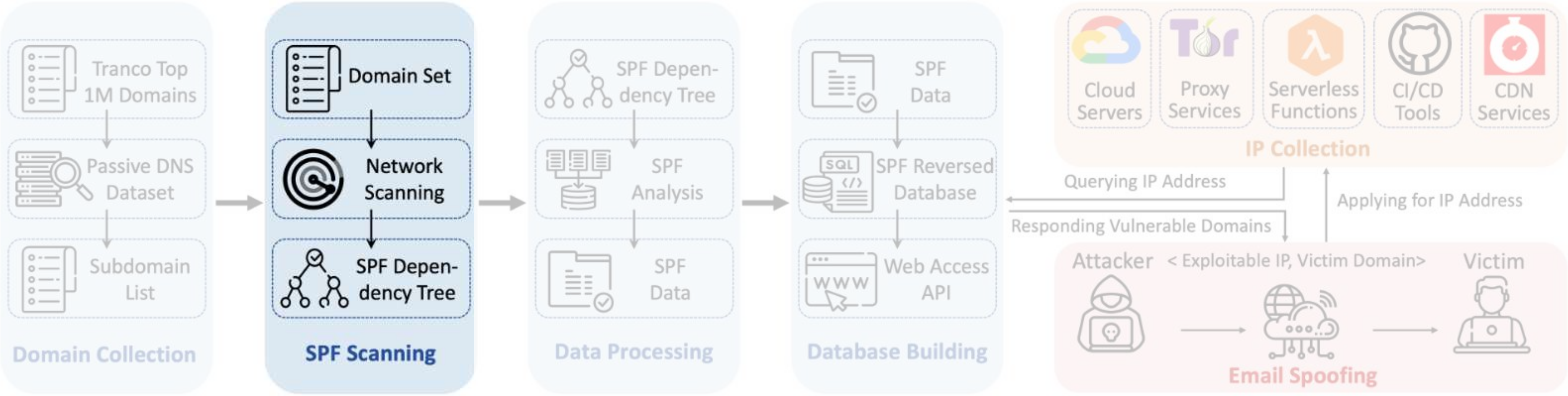
- Collect total of 7,183,870 domains (Tranco Top 1M domain names and their subdomains)



Exploitation Workflow (Cont’d)

Step 2. SPF scanning

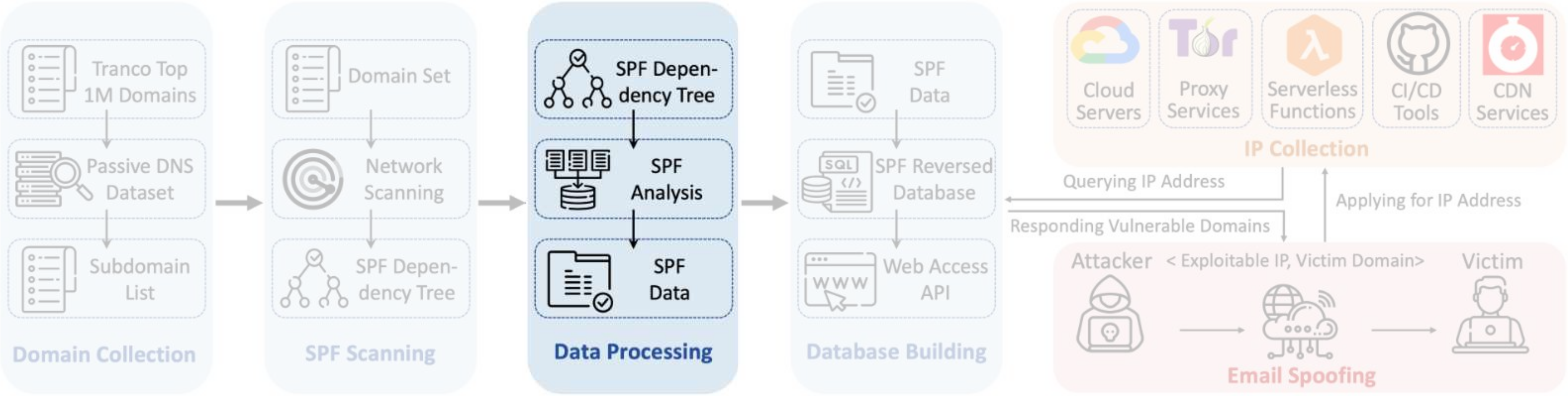
- Query the TXT records of the domains & filter out SPF records
- Then, build a SPF dependency tree, based on the `redirect` and `include` relationships in the SPF records



Exploitation Workflow (Cont'd)

Step 3. Data processing

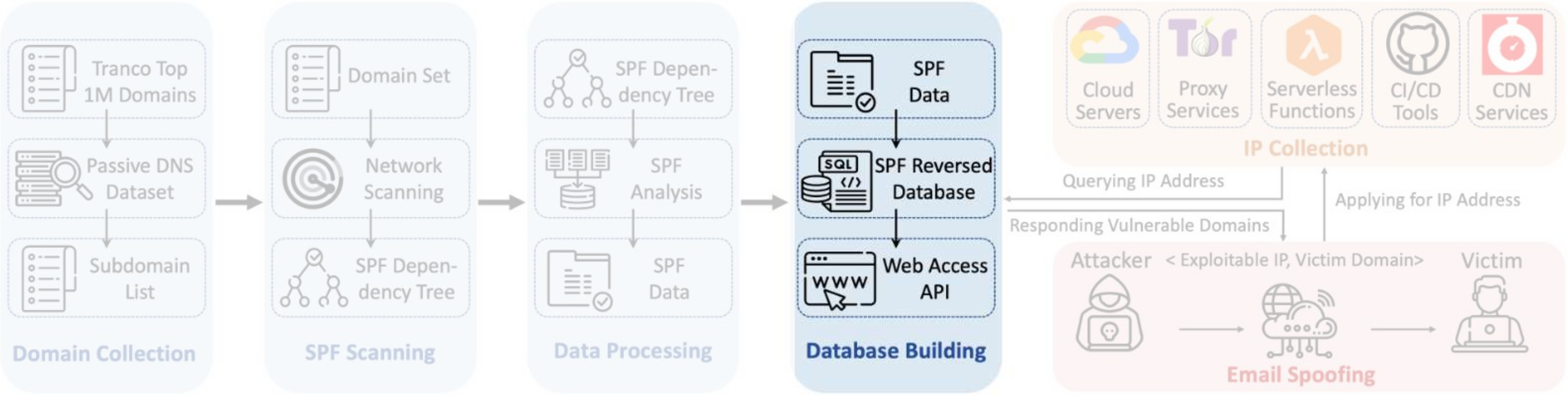
- Analyze the results of SPF scanning
  - e.g., Adoption rate of SPF, grammatical analysis, `include` mechanism analysis, IP coverage of SPF records



Exploitation Workflow (Cont’d)

Step 4. Database building

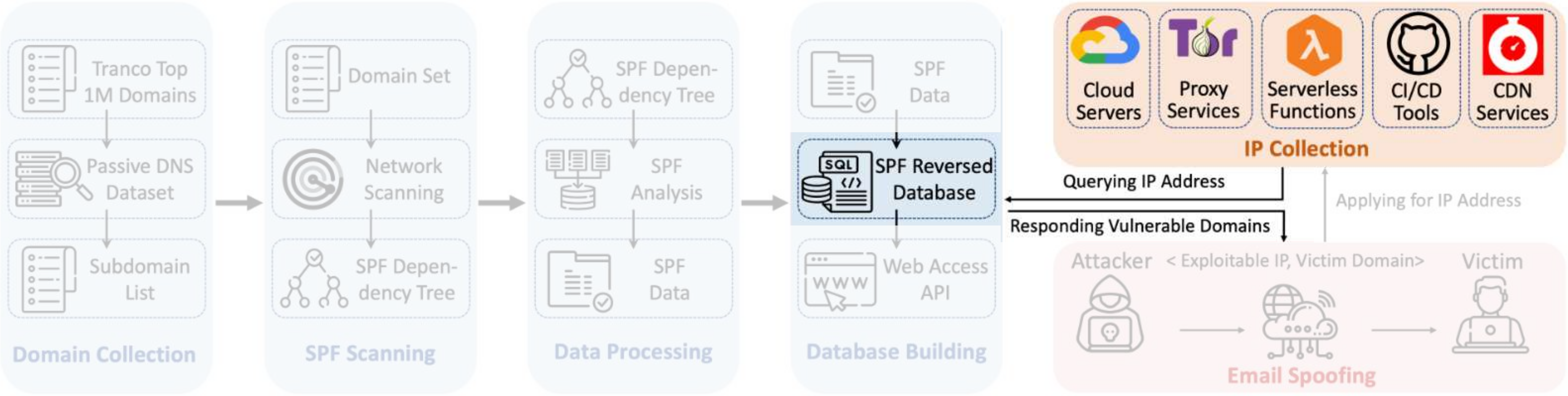
- Construct a SPF reverse lookup database (i.e., given an IP address, we can find out which domains include the IP address in their SPF records & which other domains depend on those domains)



Exploitation Workflow (Cont’d)

Step 5. IP address collection

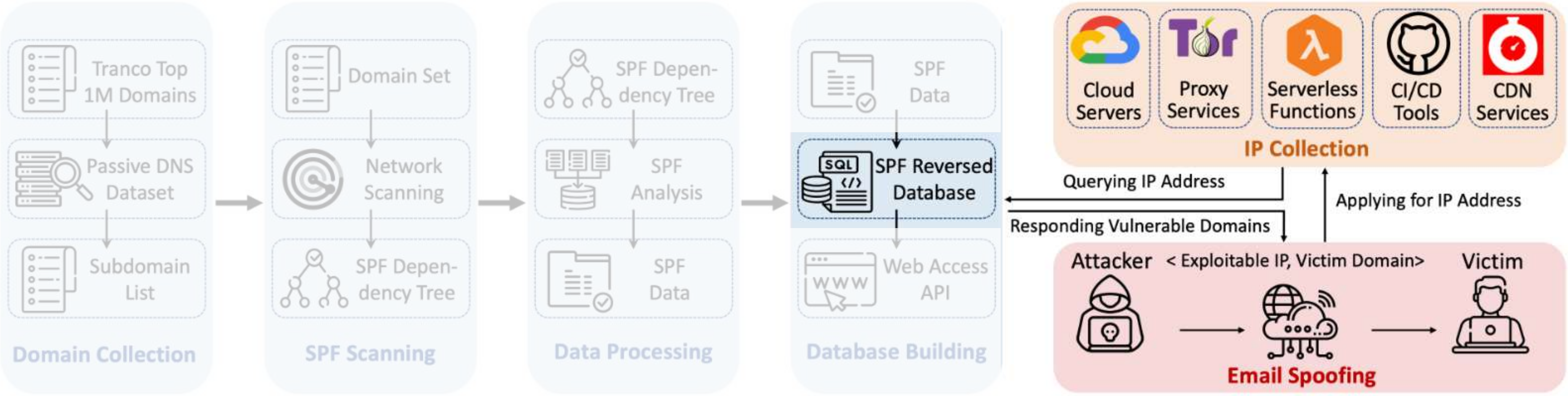
- Try to obtain as many IP addresses as possible
  - Cloud servers, proxy services, serverless functions, CI/CD tools, CDN services
- Then, use the previously constructed SPF reverse lookup database to identify <u>domain names vulnerable to spoofing using these IP addresses</u>



Exploitation Workflow (Cont’d)

Step 6. Email spoofing attack!

- Conduct cross-protocol email spoofing attacks using IP addresses collected in the previous step

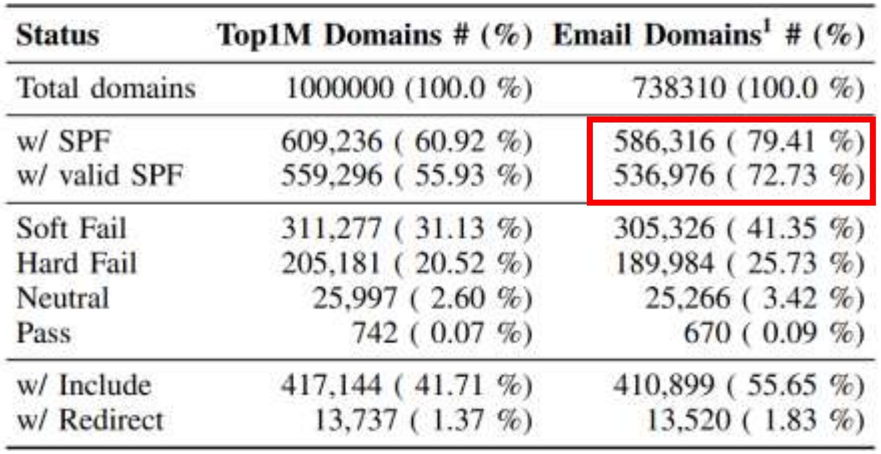


Results

SPF Deployment Analysis Results

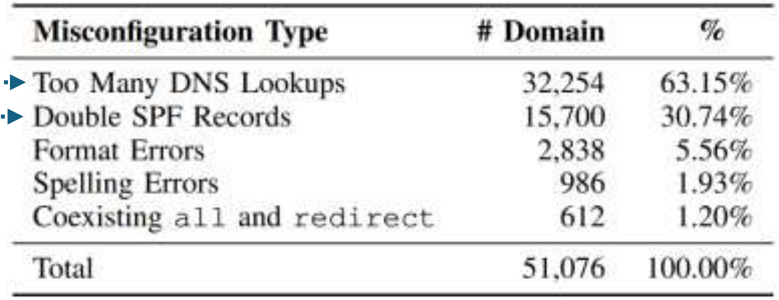
- Adoption rate of SPF
  - **79.4%** of email domains* have SPF records
  - **72.7%** of email domains* have *valid* SPF records

* Domains with MX records, or that provide email services on port 25 in their A records



Status	Top1M Domains # (%)	Email Domains[1] # (%)
Total domains	1000000 (100.0 %)	738310 (100.0 %)
w/ SPF	609,236 (60.92 %)	586,316 (79.41 %)
w/ valid SPF	559,296 (55.93 %)	536,976 (72.73 %)
Soft Fail	311,277 (31.13 %)	305,326 (41.35 %)
Hard Fail	205,181 (20.52 %)	189,984 (25.73 %)
Neutral	25,997 (2.60 %)	25,266 (3.42 %)
Pass	742 (0.07 %)	670 (0.09 %)
w/ Include	417,144 (41.71 %)	410,899 (55.65 %)
w/ Redirect	13,737 (1.37 %)	13,520 (1.83 %)

- Grammatical analysis of SPF records
  - **8.4%** of SPF records have grammar errors
    - **63.2%** of them are "too many DNS lookups"
      - More than 10 DNS queries per resolution → error!
    - **30.7%** of them are "multiple SPF records per domain"

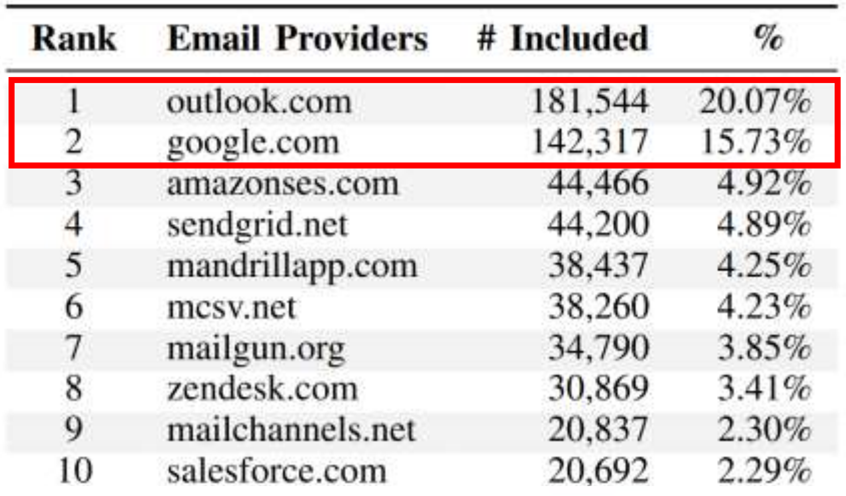


Misconfiguration Type	# Domain	%
Too Many DNS Lookups	32,254	63.15%
Double SPF Records	15,700	30.74%
Format Errors	2,838	5.56%
Spelling Errors	986	1.93%
Coexisting `all` and `redirect`	612	1.20%
Total	51,076	100.00%

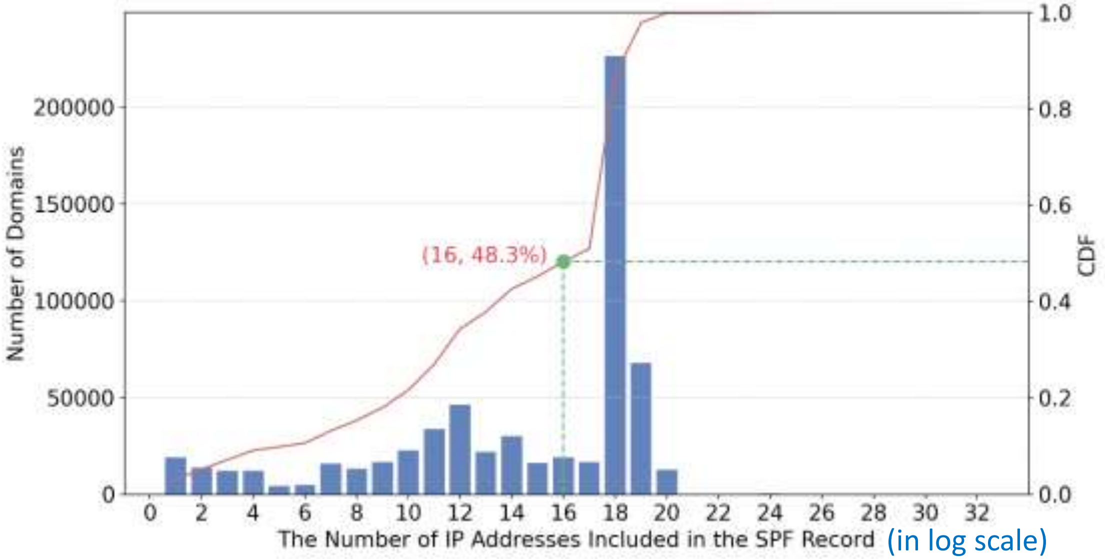
SPF Deployment Analysis Results (Cont’d)

- `include` mechanism analysis
    - **73.5%** of domains with SPF records contain `include`
    - **20%** of all SPF records recursively include `outlook.com`, and **15.7%** include `google.com`

- IP coverage of SPF records
    - **51.7%** of SPF records have more than 655,536 (2^{16}) IP addresses included



Rank	Email Providers	# Included	%
1	outlook.com	181,544	20.07%
2	google.com	142,317	15.73%
3	amazonses.com	44,466	4.92%
4	sendgrid.net	44,200	4.89%
5	mandrillapp.com	38,437	4.25%
6	mcsv.net	38,260	4.23%
7	mailgun.org	34,790	3.85%
8	zendesk.com	30,869	3.41%
9	mailchannels.net	20,837	2.30%
10	salesforce.com	20,692	2.29%



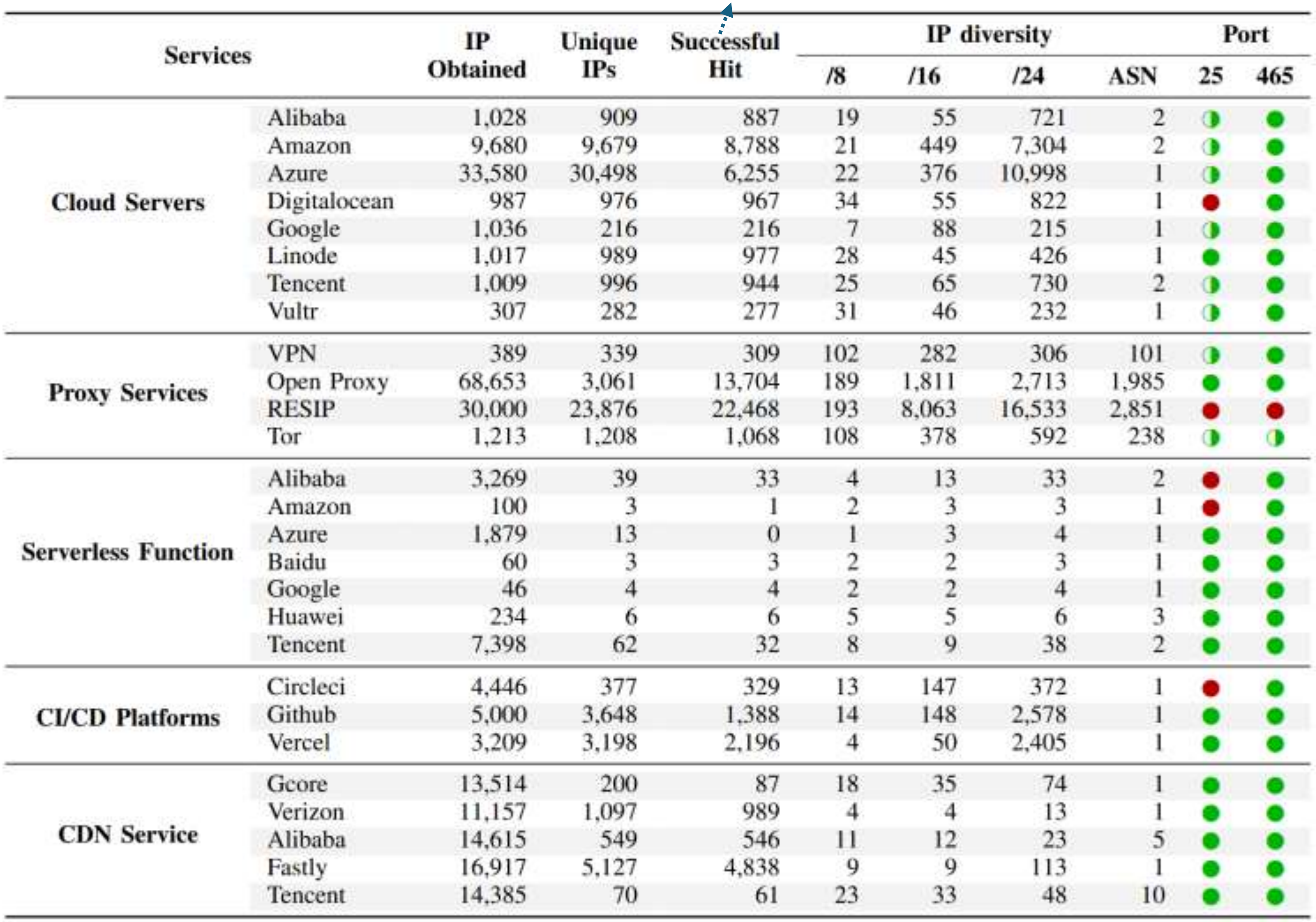
(in log scale)

Shared IPs Collection Results

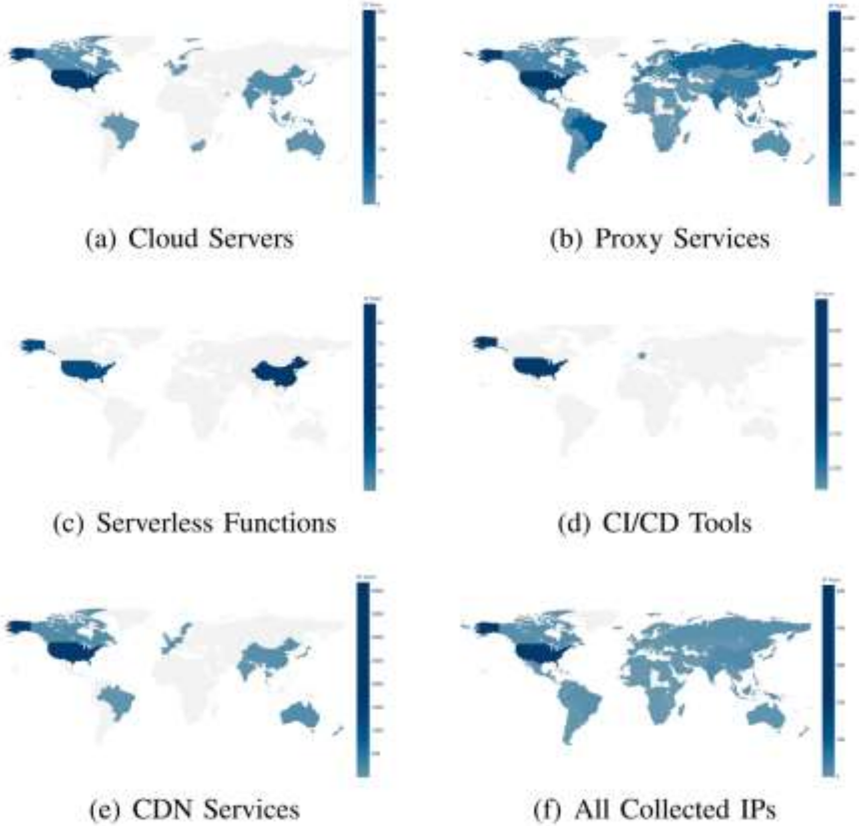
- Obtained total of **87,430** IP addresses
  - Cloud servers, proxy services, serverless functions, CI/CD platforms, CDN services
- Low cost
  - On average, less than $0.01 per IP address
  - This is because most service providers offer free tiers & credits

Shared IPs Collection Results (Cont’d)

# of IP addresses that are included in *some* domain’s SPF record



Services		IP Obtained	Unique IPs	Successful Hit	IP diversity				Port	
					/8	/16	/24	ASN	25	465
Cloud Servers	Alibaba	1,028	909	887	19	55	721	2	◑	🟢
	Amazon	9,680	9,679	8,788	21	449	7,304	2	◑	🟢
	Azure	33,580	30,498	6,255	22	376	10,998	1	◑	🟢
	Digitalocean	987	976	967	34	55	822	1	🔴	🟢
	Google	1,036	216	216	7	88	215	1	◑	🟢
	Linode	1,017	989	977	28	45	426	1	🟢	🟢
	Tencent	1,009	996	944	25	65	730	2	◑	🟢
	Vultr	307	282	277	31	46	232	1	◑	🟢
Proxy Services	VPN	389	339	309	102	282	306	101	◑	🟢
	Open Proxy	68,653	3,061	13,704	189	1,811	2,713	1,985	🟢	🟢
	RESIP	30,000	23,876	22,468	193	8,063	16,533	2,851	🔴	🔴
	Tor	1,213	1,208	1,068	108	378	592	238	◑	◑
Serverless Function	Alibaba	3,269	39	33	4	13	33	2	🔴	🟢
	Amazon	100	3	1	2	3	3	1	🔴	🟢
	Azure	1,879	13	0	1	3	4	1	🟢	🟢
	Baidu	60	3	3	2	2	3	1	🟢	🟢
	Google	46	4	4	2	2	4	1	🟢	🟢
	Huawei	234	6	6	5	5	6	3	🟢	🟢
	Tencent	7,398	62	32	8	9	38	2	🟢	🟢
CI/CD Platforms	Circleci	4,446	377	329	13	147	372	1	🔴	🟢
	Github	5,000	3,648	1,388	14	148	2,578	1	🟢	🟢
	Vercel	3,209	3,198	2,196	4	50	2,405	1	🟢	🟢
CDN Service	Gcore	13,514	200	87	18	35	74	1	🟢	🟢
	Verizon	11,157	1,097	989	4	4	13	1	🟢	🟢
	Alibaba	14,615	549	546	11	12	23	5	🟢	🟢
	Fastly	16,917	5,127	4,838	9	9	113	1	🟢	🟢
	Tencent	14,385	70	61	23	33	48	10	🟢	🟢



(a) Cloud Servers

(b) Proxy Services

(c) Serverless Functions

(d) CI/CD Tools

(e) CDN Services

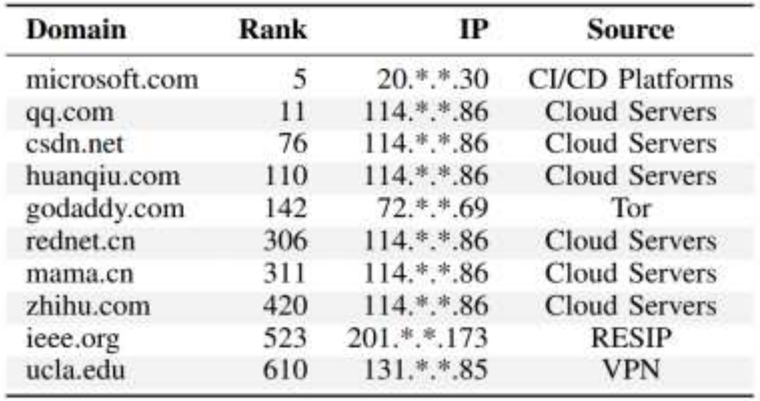
(f) All Collected IPs

Global distribution of collected IP addresses

BreakSPF Attack Results

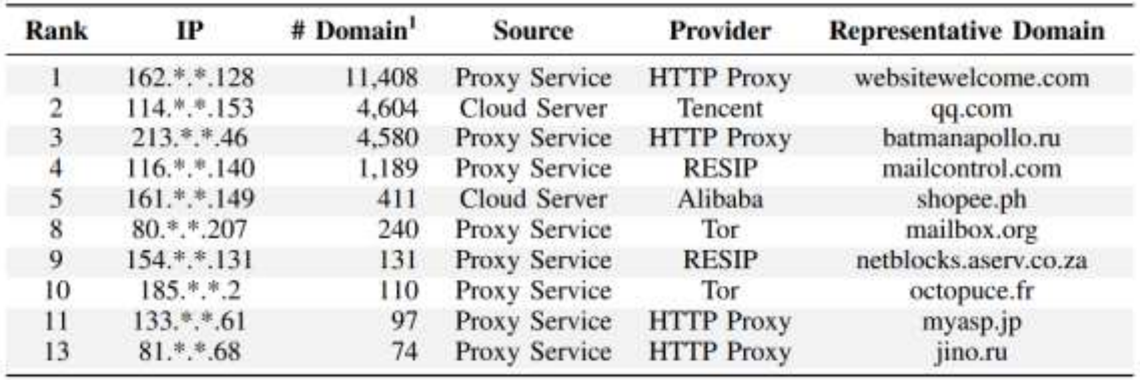
- Well-known domains like `microsoft.com`, `qq.com`, `godaddy.com`, and `ieee.org` were vulnerable to BreakSPF attacks

- A single IP address could be used to perform BreakSPF attack for up to 10,000 domains



Domain	Rank	IP	Source
microsoft.com	5	20.*.*.30	CI/CD Platforms
qq.com	11	114.*.*.86	Cloud Servers
csdn.net	76	114.*.*.86	Cloud Servers
huanqiu.com	110	114.*.*.86	Cloud Servers
godaddy.com	142	72.*.*.69	Tor
rednet.cn	306	114.*.*.86	Cloud Servers
mama.cn	311	114.*.*.86	Cloud Servers
zhihu.com	420	114.*.*.86	Cloud Servers
ieee.org	523	201.*.*.173	RESIP
ucla.edu	610	131.*.*.85	VPN

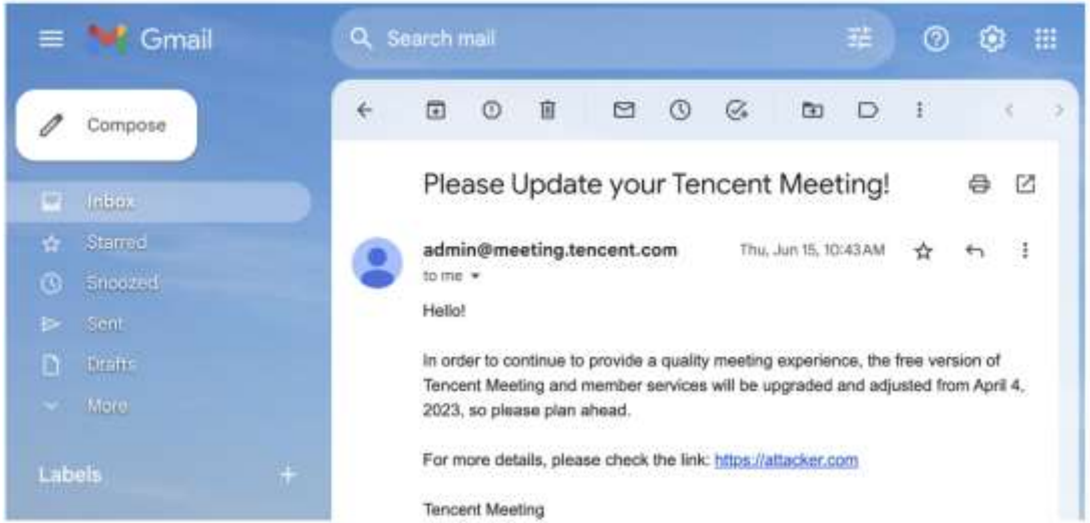
10 well-known domains vulnerable to BreakSPF attack



Rank	IP	# Domain[1]	Source	Provider	Representative Domain
1	162.*.*.128	11,408	Proxy Service	HTTP Proxy	websitewelcome.com
2	114.*.*.153	4,604	Cloud Server	Tencent	qq.com
3	213.*.*.46	4,580	Proxy Service	HTTP Proxy	batmanapollo.ru
4	116.*.*.140	1,189	Proxy Service	RESIP	mailcontrol.com
5	161.*.*.149	411	Cloud Server	Alibaba	shopee.ph
8	80.*.*.207	240	Proxy Service	Tor	mailbox.org
9	154.*.*.131	131	Proxy Service	RESIP	netblocks.aserv.co.za
10	185.*.*.2	110	Proxy Service	Tor	octopuce.fr
11	133.*.*.61	97	Proxy Service	HTTP Proxy	myasp.jp
13	81.*.*.68	74	Proxy Service	HTTP Proxy	jino.ru

Top 10 IP addresses that can attack multiple domains

BreakSPF Attack Results: Example



Please Update your Tencent Meeting!

admin@meeting.tencent.com Thu, Jun 15, 10:43 AM
to me

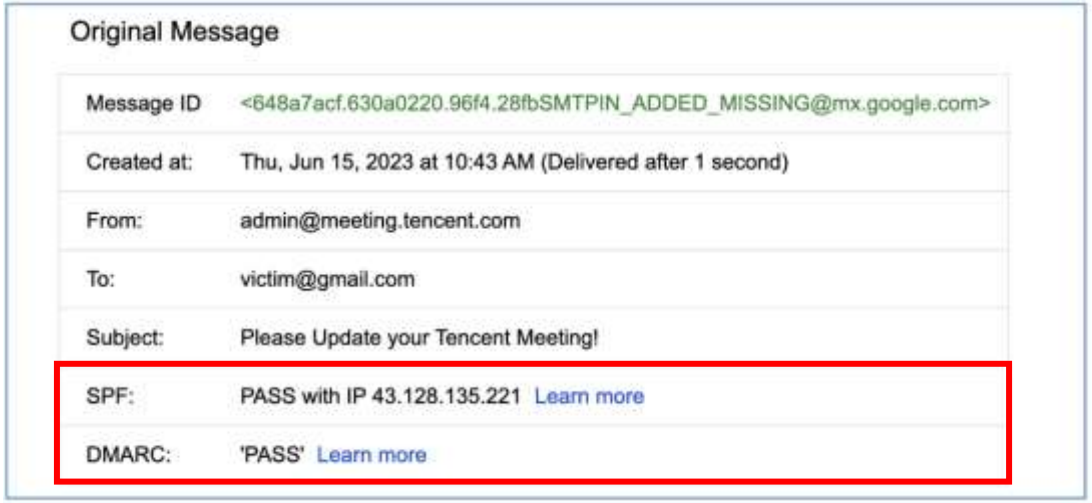
Hello!

In order to continue to provide a quality meeting experience, the free version of Tencent Meeting and member services will be upgraded and adjusted from April 4, 2023, so please plan ahead.

For more details, please check the link: https://attacker.com

Tencent Meeting

A spoofed email sent with BreakSPF attack
(From: admin@meeting.tencent.com)



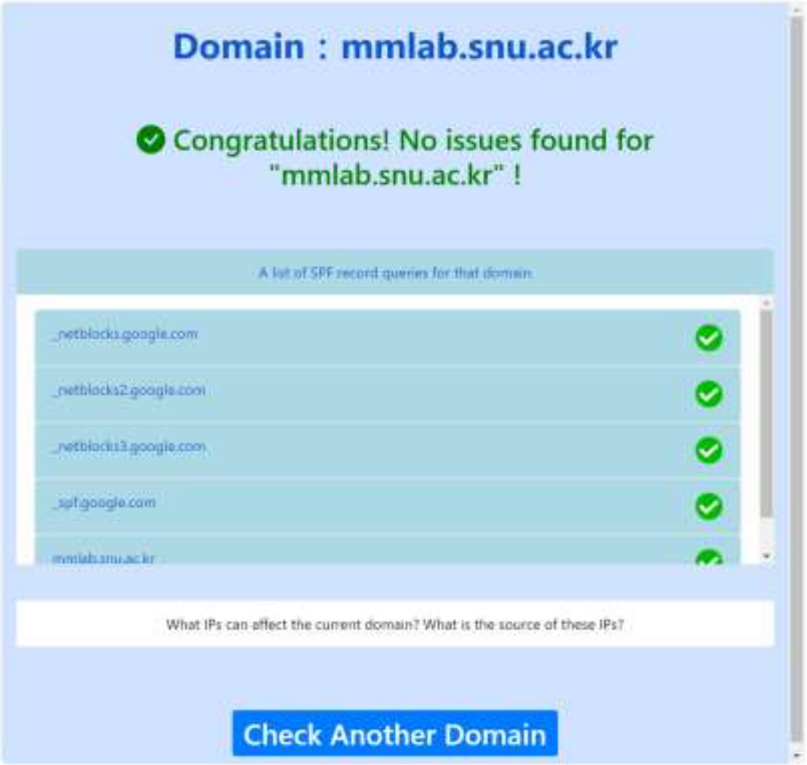
Original Message

Message ID	<648a7acf.630a0220.96f4.28fbSMTPIN_ADDED_MISSING@mx.google.com>
Created at:	Thu, Jun 15, 2023 at 10:43 AM (Delivered after 1 second)
From:	admin@meeting.tencent.com
To:	victim@gmail.com
Subject:	Please Update your Tencent Meeting!
SPF:	PASS with IP 43.128.135.221 Learn more
DMARC:	'PASS' Learn more

Validation result of the spoofed email

Mitigations

- **Port management.** Cloud services, proxy services, etc. should restrict egress communication to port 25, 465, etc.
- **Online detection services.** https://breakspf.cloud/
- **DMARC* reports.** Recipients who receive emails can aggregate & send validation results to the domain owner.



Domain : mmlab.snu.ac.kr

✓ Congratulations! No issues found for "mmlab.snu.ac.kr" !

A list of SPF record queries for that domain

_netblocks.google.com	✓
_netblocks2.google.com	✓
_netblocks3.google.com	✓
_spf.google.com	✓
mmlab.snu.ac.kr	✓

What IPs can affect the current domain? What is the source of these IPs?

* ***DMARC** (Domain-based Message Authentication, Reporting and Conformance)*
: A protocol that aligns the domain name in “From” header and the authenticated “MAIL FROM” address from *SPF* or *DKIM (DomainKeys Identified Mail)*