Privacy Preserving Detection of Path Bias Attacks in The Onion Router

A tour in Tor

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Introduction

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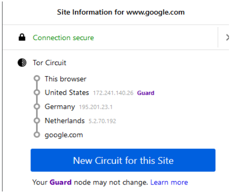
- Uses stream ciphers

Components of TOR

- Guard Node aka Entry Relay/Bridge
- Middle Node
- Exit Relay
- Directory Server
- Hidden Server
- Rendezvous Point



Site Information for www.google.com

Connection secure

Tor Circuit

This browser

United States 172.241.140.26 Guard

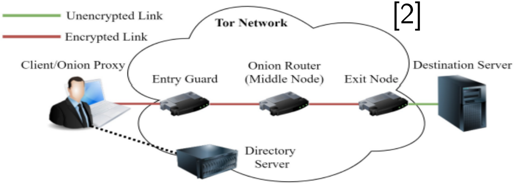
Germany 195.201.23.1

Netherlands 5.2.70.192

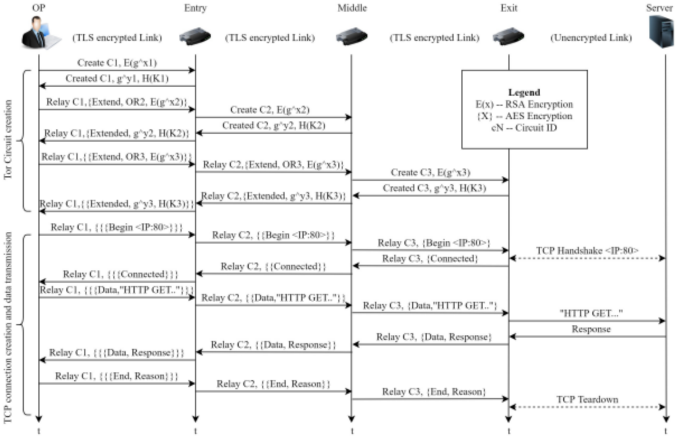
google.com

Your Guard node may not change. Learn more

[2]



How TOR Works


OP
Entry
Middle
Exit
Server
(TLS encrypted Link)
(TLS encrypted Link)
(TLS encrypted Link)
(Unencrypted Link)
Tor Circuit creation
TCP connection creation and data transmission
Create C1, E(g^x1)
Created C1, g^y1, H(K1)
Relay C1,{Extend, OR2, E(g^x2)}
Create C2, E(g^x2)
Created C2, g^y2, H(K2)
Relay C1,{Extended, g^y2, H(K2)}
Relay C1,{{Extend, OR3, E(g^x3)}}
Relay C2,{Extend, OR3, E(g^x3)}
Create C3, E(g^x3)
Created C3, g^y3, H(K3)
Relay C2,{Extended, g^y3, H(K3)}
Relay C1,{{Extended, g^y3, H(K3)}}
Legend
E(x) -- RSA Encryption
{X} -- AES Encryption
cN -- Circuit ID
Relay C1, {{{Begin <IP:80>}}}
Relay C2, {{Begin <IP:80>}}
Relay C3, {Begin <IP:80>}
TCP Handshake <IP:80>
Relay C3, {Connected}
Relay C2, {{Connected}}
Relay C1, {{{Connected}}}
Relay C1, {{{Data,"HTTP GET.."}}}
Relay C2, {{Data,"HTTP GET.."}}
Relay C3, {Data,"HTTP GET.."}
"HTTP GET..."
Response
Relay C3, {Data, Response}
Relay C2, {{Data, Response}}
Relay C1, {{{Data, Response}}}
Relay C1, {{{End, Reason}}}
Relay C2, {{End, Reason}}
Relay C3, {End, Reason}
TCP Teardown
t
t
t
t
t

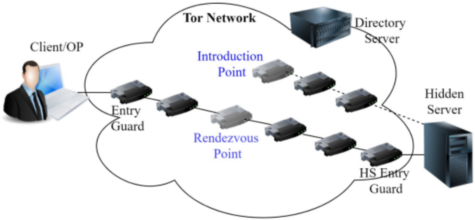
[2]

Client → $Entry : E_{PK_{Entry}}(g^x)$

Entry → $Client : g^y, H(K = g^{xy})$

$E_{K_{Entry}}(E_{K_{Middle}}(E_{K_{Exit}}(M)))$

Hidden Server(.onion)



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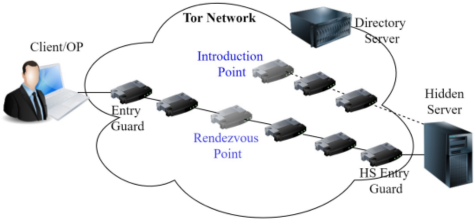

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- Web Server picks random Introduction points

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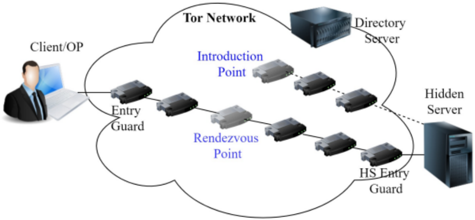

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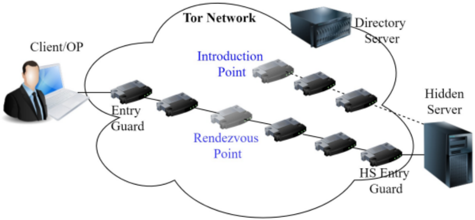

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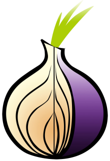

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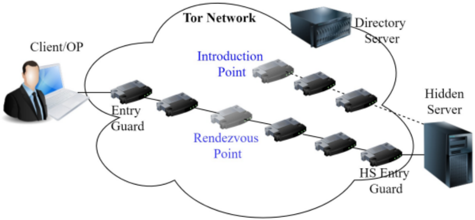

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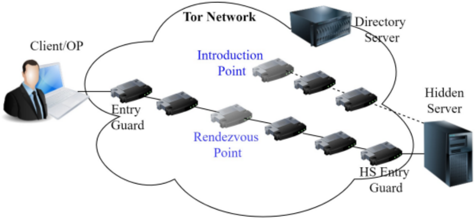

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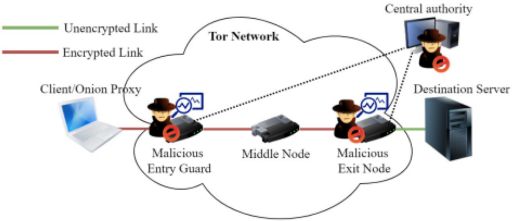
- Server connects to RP of client

Path Bias Attacks



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- Adversary to have access to both entry and exit ORs

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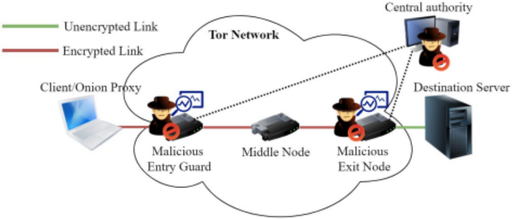

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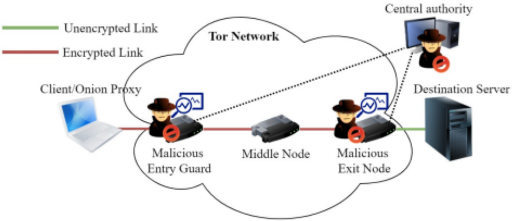

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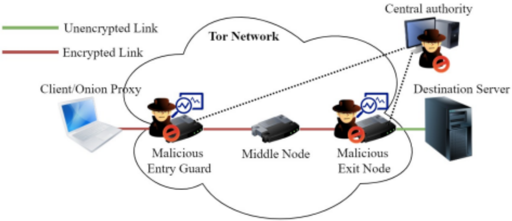

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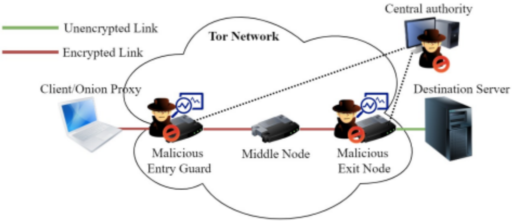

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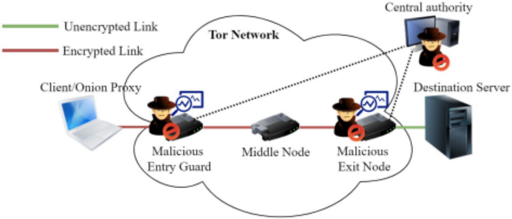

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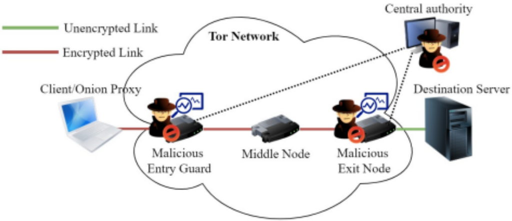

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- Passive Attacks

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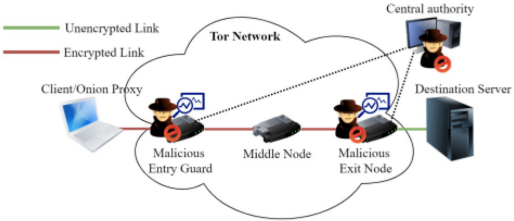

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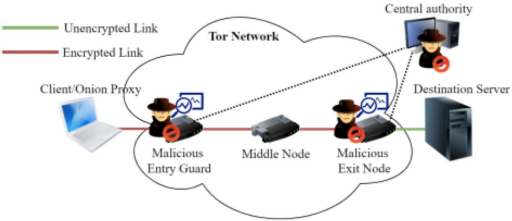

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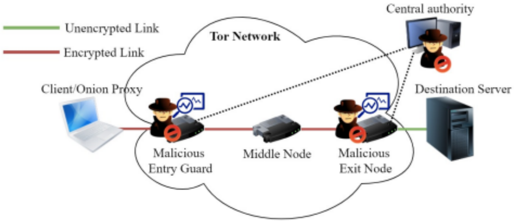

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  - Water Marking attacks

Path Bias Detection scheme

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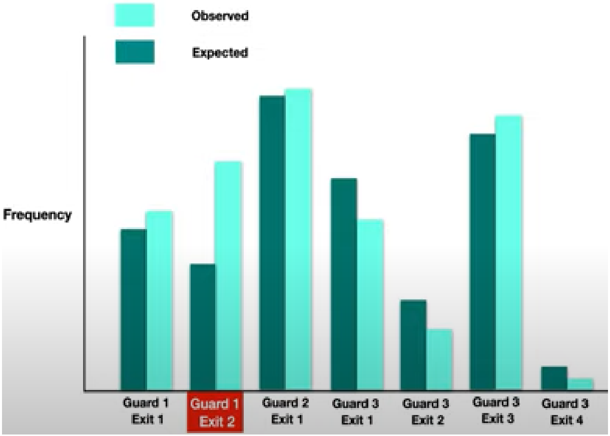

[4]

Path Bias Detection scheme

- Adversary repeats rejection of circuits if nodes are not compromised
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- Bandwidth determines prob of a node, $E_{gx} = n(\frac{BW_g}{BW_G})(\frac{BW_x}{BW_X})$ [3]

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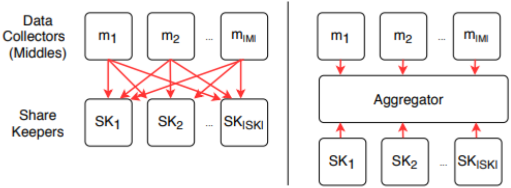
- Uses additive secret sharing to intialize secret shares $x_1, x_2, \ldots ,x_k$
- Middle guard shares $C - (x_1 + x_2 + \ldots +x_k)$ to Aggregator

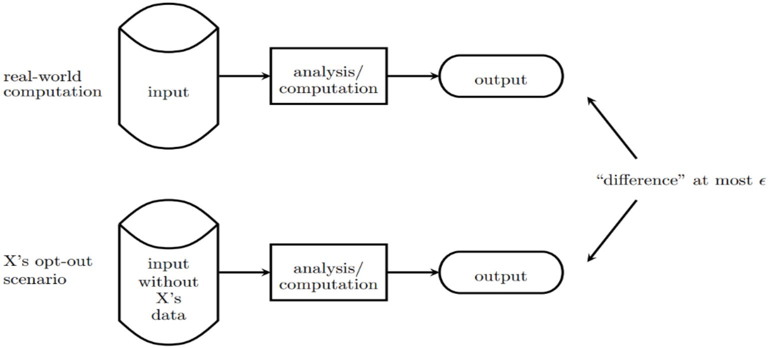


[3]

Differential Privacy

A Randomized algorithm K operating on the database satisfies ϵ-differential privacy if given any two neighbouring databases D and D' and a set of outputs S $\subseteq$ Range(K)

$$P[K(D) \in S] \leq e^{\epsilon}(P[K(D') \in S] \tag{1}$$



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Count C(by middle relay) $\Rightarrow C + \gamma$

Enhanced Detection Algorithm

- Low probability exits will have very small count, $\gamma >> C$

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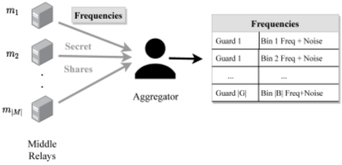

Frequencies	
Guard 1	Bin 1 Freq + Noise
Guard 1	Bin 2 Freq + Noise
...	...
Guard |G|	Bin |B| Freq+Noise

[3]

Voting scheme

- If adversary compromises q middle relays??

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- If total no of votes exceeds threshold , outlier pair
- Reduce influence of misreporting relays
- High probability for detection of an outlier pair

Conclusion

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References

- Cynthia Dwork, Frank McSherry, Kobbi Nissim, and Adam Smith, *Calibrating noise to sensitivity in private data analysis*,2006.

- Ishan Karunanayake, Nadeem Ahmed, Robert Malaney, Rafiqul Islam and Sanjay Jha *Anonymity with Tor: A Survey on Tor Attacks*,2020.

- Lauren Watson*, Anupam Mediratta, Tariq Elahi, and Rik Sarkar *Privacy Preserving Detection of Path Bias Attacks in Tor* ,2020.

- Privacy Preserving Detection of Path Bias Attacks in Anonymity Networks. `https://www.youtube.com/watch?v=zfT16ZIMMMk`

- Kobbi Nissim, et al *Differential Privacy: A Primer for a Non-technical Audience.*, 2018.

Thank You!