Novel and Practical SDN-based Traceback Technique for Malicious Traffic over Anonymous Networks

Zhen Ling*, Junzhou Luo*, Danni Xu*, Ming Yang*, and Xinwen Fu‡
*Southeast University, Email: {zhenling, jluo, dannyxu, yangming2002}@seu.edu.cn
‡University of Central Florida, Email: xinwenfu@ucf.edu

***Abstract*—Diverse anonymous communication systems are widely deployed as they can provide the online privacy protection and Internet anti-censorship service. However, these systems are severely abused and a large amount of anonymous traffic is malicious. To mitigate this issue, we propose a novel and practical traceback technique to confirm the communication relationship between the suspicious server and the user. We leverage the software-defined network (SDN) switch at a destination server side to intercept target traffic towards the server and alter the advertised TCP window sizes so as to stealthily vary the traffic rate at the server. By carefully varying the traffic rate, we can successfully modulate a secret signal into the traffic. The traffic carrying the signal passes through the anonymous communication system and reaches the SDN switch at the user**

way, we can stealthily vary the outgoing traffic rate of the destination on demand so as to modulate a secret signal into the target traffic. We are the first to regulate the advertised TCP window size and embed a signal into traffic for traceback. This approach can be easily deployed over SDN.

- We carefully analyze TCP sliding window mechanism and calculate the minimum and maximum values of the regulatable advertised window size so as to exert minimal effects on the target traffic rate. Moreover, we employ repetition error correcting codes to enhance the robustness of our embedded signal.
- Our traceback technique is evaluated using three major anonymous communication systems including SSH tunnel, OpenVPN tunnel, and Tor. The real-world experimental results demonstrate that the detection rates can approach 100% for SSH tunnel and OpenVPN tunnel and 95% for Tor while the false positive rates for all the three communication systems are approximately 0%.

The idea of confirming the communication relationship between Alice and Bob can be generalized to perform full fledged traceback in a complicated network like Tor, where there are three hops between Alice and Bob in general. If SDN is pervasively deployed, the confirmation can be performed hop-by-hop starting at one side of the communication. Each time, the SDN is used to determine the next hop along the path until the other side of the communication is reached.

The rest of this paper is organized as follows. We introduce anonymous communication network and the software-defined network in Section II. Then we present the SDN-based traceback technique, including the basic idea and the detailed design of our system in Section III. In Section IV, we perform theoretical analysis on the selection of TCP window size and performance metrics. In Section V, we conduct extensive real-world experiments to demonstrate the feasibility and effectiveness of the traceback technique. We review related work in Section VI. Finally, we conclude this paper in Section VII.

II. Background

In this section, we briefly introduce the anonymous communication network and the software defined network.

A. Anonymous communication network

Diverse low-latency anonymous communication network systems are pervasively deployed around the world for protecting users' communication privacy and providing anti-censorship services. In light of the length of the anonymous communication connections, they can be categorized into two classes: single-hop and multi-hop anonymous communication network systems. In the single-hop anonymous network systems (e.g., SSH and OpenVPN), only one proxy server is used to relay a user's traffic to a destination server. Since the server can only observe the IP address of the proxy server, it cannot know the user's real IP address. However, the user's communication privacy can be exposed if the proxy server is compromised. In the multi-hop anonymous communication network systems (e.g., Tor), a user first communicates with the directory servers in the Tor network and downloads the information of Tor relay servers. Then the user chooses three relay servers and establishes a three-hop path hop by hop. Finally, she commands the last relay server along the Tor path

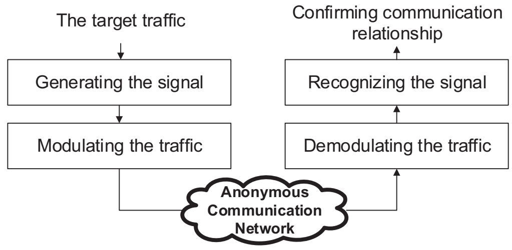

Fig. 1. Workflow of the SDN-based traceback technique

to build a TCP connection to the destination server. In this way, the user can anonymously communicate with the server. Since the Tor relay servers in the path can only know the IP addresses of their adjacent relay servers in the path, one single compromised server can hardly confirm the communication relationship between the user and the server.

B. Software Defined Network

The software-defined network provides network programmability for dynamically managing and controlling the network via open APIs and protocols. The architecture of a software-defined network consists of three layers, including the data plane, control plane, and application plane. The data plane is composed of networking devices, e.g., SDN switches, used for forwarding network traffic. The flow entries in flow tables are stored at the switches and work as the forwarding rules. These flow entries are confibured by the SDN controller. The control plane is composed of SDN controllers that control a set of networking devices in the data plane. The SDN controllers execute the requests from the SDN applications and make the low-level network services, e.g., network topology, available to the application plane via open APIs. The application plane is composed of a set of applications that can access the low-level network services provided by the SDN controllers. The applications can send high-level policies to the control plane that implements the policies as flow entries and sends them to the flow table on the networking devices. Since the SDN controllers are responsible for confiburing all of the flow entries, they play a crucial role in managing and controlling the network.

III. SDN-based Traceback Technique

In this section, we first present the basic idea of the SDN-based traceback technique. Then we elaborate on the crucial steps of our technique.

A. Basic Idea

Our goal is to determine the communication relationship between the Alice (client) and the Bob (server) who are communicating with each other through anonymous network systems (e.g., VPN or Tor). It is assumed that the SDN switches are pervasively deployed over the Internet in the near future. Ideally, if the suspicious traffic traverses all of the SDN switches controlled by ourselves, we can trace back the traffic hop by hop to discover all servers in the entire path. However, it is resource-consuming to completely discover all the proxy servers. Instead, just by controlling two SDN switches that respectively approach the client and the server, we can observe the traffic from the client and the server via these two SDN switches. The SDN switch that observes the traffic from the server Bob is referred to as the *server-side*

SDN switch and the one that observes the traffic from the client Alice is referred to as the *client-side* SDN switch. Then we can design traceback techniques in an attempt to confirm the communication relationship between the Alice and the Bob. The traceback can be performed on either the server-side SDN switch or the client-side SDN switch. In the rest of the paper, we focus on the traceback just using the two SDN switches while our techniques can be used to perform the traceback hop-by-hop. In addition, it is assumed that the traceback is initiated at the server-side SDN switch.

Figure 1 illustrates the workflow of our SDN-based traceback technique. We first select target traffic at the server-side SDN switch and leverage the server-side controller to send a flow entry to the switch so as to force the switch to forward the traffic to the controller. Then we modify the TCP packets towards the server by changing the advertised TCP window size in the TCP packet header in order to alter the send window size of the server Bob. According to the TCP protocol, Bob has to change the send window size in light of the advertised TCP window size from the proxy servers (e.g., Tor relay servers and SSH proxy servers) so as to vary the server's traffic rate. As a result, we can generate a signal (i.e.,a series of signal bits) and modulate it into the traffic by carefully regulating the traffic rate sent from Bob. The traffic traverses the anonymous network and arrives at the client-side SDN switch. The client-side SDN switch can demodulate the traffic and discover a signal based on the demodulation. If the discovered signal is the same or similar to the original one, we can confirm the communication relationship between Alice and Bob.

B. Step 1: Generating the signal

is the step of the sliding window and stop the skipping as long as the signal is detected. We discuss the practical selection of the sliding window and its step in Section V in detail. The traffic starting at $o + W_i * q$ is divided into segments using half of the time interval $T_I/2$. A traffic rate time series can be obtained by calculating the traffic rate in each time interval $T_I/2$. Denote a pair of traffic rate in the m^{th} time interval $T_I(m)$ as $< x_1(m), x_2(m) >$, where $x_1(m)$ and $x_2(m)$ are the traffic rates in the first and the second subinterval, i.e., $T_{I,1}(m)$ and $T_{I,2}(m)$, respectively. Then we can obtain the time series of traffic rate by

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$$\begin{aligned} X(T_I) = \{ &< x_1(1), x_2(1) >, \ldots, < x_1(m), x_2(m) >, \\ &\ldots, < x_1(N), x_2(N) > \}. \end{aligned} \tag{5}$$

To determine the signal demodulated from the traffic, we use a decision rule as

$$s'_m = \begin{cases} 1, & x_1(m) < x_2(m) \\ 0, & x_1(m) > x_2(m) \end{cases}. \tag{6}$$

Finally, we can derive a series of demodulated repetition bits as

$$s' = \{s'_1, \ldots, s'_m, s'_{m+1}, \ldots, s'_N\}, (s'_m \in \{0, 1\}). \tag{7}$$

We determine if the above discovered signal is modulated by ourselves in Step 4.

E. Step 4: Recognizing the signal

Once we derive the demodulated repetition signal, we enters the phase of recognizing the original signal. Since we have the indexes of the repetition bits for the original signal, the original signal can be recovered by accumulating the demodulated repetition bits as

$$S'_i = \begin{cases} 1, & \frac{1}{r}\sum_{m \in L_i} s'_m > 0.5 \\ 0, & \frac{1}{r}\sum_{m \in L_i} s'_m < 0.5 \end{cases}. \tag{8}$$

Then we can have the recovered signal $S' = \{S'_1, \ldots, , S'_n\}$. To determine if the recovered signal is embedded by ourselves, we compare the recovered signal S' with the original one S by using the Hamming distance $H(S', S)$. If the Hamming distance between these two signals is smaller than a threshold h ($0 \leqslant h < n$), we can determine that the original signal is recognized and the communication relationship between Alice and Bob can be confirmed.

IV. Analysis

In this section, we first analyze the regulatable range of TCP window size and then define the performance metrics for measuring the feasibility and effectiveness of our SND based traceback technique.

A. Selection of TCP Window Size

We set an appropriate advertised window size of TCP packets from the receiver (i.e., the proxy server) at the server-side switch in order to change the TCP transmission rate of the sender (i.e., the server Bob). Since the selective-repeat sliding window protocol is pervasively used in various modern operating systems, we take this protocol as an example to perform the theoretical analysis in this paper. The send window (*SWND*) is used to control the amount of data transmitted under the limit of the minimum of the sender's congestion window (*CWND*) and the receiver's advertised window (*AWND*). Denote SWND, size of the data that can be sent. Therefore, the size of AWND should be larger than the remaining size of the SWND as

$$W_u \leqslant W_a. \tag{12}$$

Algorithm 1 Calculating a new advertised window size

Require:
(a) δ: the total receive buffer size,
(b) θ: three quarters of the remaining receive buffer size,
(c) ε: a window scaling.
Ensure: a new advertised window size W_n

$\delta = min\{\alpha, \frac{3}{4}\beta\}$
$\theta = \frac{3}{4}\gamma$
if MSS $> \delta$ **then**
  MSS $\leftarrow \delta$
end if
if receiving buffer is half full **then**
  if memory has pressure **then**
    limit R_s under 5840 bytes
  end if
  if $\theta <$ MSS **then**
    return 0
  end if
end if
if $\theta > R_s$ **then**
  $\theta \leftarrow R_s$
end if
$W_n \leftarrow W_a$
if $\varepsilon \neq 0$ **then**
  $W_n \leftarrow \theta$
else if $|W_a - \theta|$==MSS **then**
  $W_n \leftarrow$ (θ/MSS)×MSS
else if θ==MSS and $\theta > W_a + (\delta >> 1)$ **then**
  $W_n \leftarrow \theta$
end if
return W_n

According to Equation (10), (11), and (12), we can derive the range of AWND by

$$max\{min\{\frac{3}{4}\gamma, R_s\} - \text{MSS}, W_u\} < W_a < min\{\frac{3}{4}\gamma, R_s\}. \tag{13}$$

In practice, the first regulated AWND should be smaller than the latest unregulated AWND so as to reduce the size of SWND and the sender's transmission rate. Therefore, we can obtain

$$W_a < W'_a, \tag{14}$$

where W'_a is the latest unregulated AWND. Finally, we can refine the range of AWND by

$$max\{min\{\frac{3}{4}\gamma, R_s\} - \text{MSS}, W_u\} < W_a < min\{\frac{3}{4}\gamma, R_s, W'_a\}. \tag{15}$$

B. Performance Metrics

To validate the detection of the signal modulated into the target traffic, we leverage two metrics, i.e., detection rate and false positive rate. P_d is the probability that an original signal bit is correctly recognized. Recall that there are r (repetition) bits in one original signal bit. If $\lfloor r/2 \rfloor + 1$ repetition bits are correctly recognized, the original signal can be identified. Denote the number of correctly recognized repetition bits as Y. We can obtain

$$\begin{aligned} P_d &= P(Y \geqslant \lfloor r/2 \rfloor + 1) \\ &= 1 - P(Y < \lfloor r/2 \rfloor + 1) \\ &= 1 - \sum_{i=0}^{\lfloor r/2 \rfloor} \mathcal{C}_r^i P_r^i (1 - P_r)^{r-i}, \end{aligned} \tag{16}$$

where P_r is the probability that one repetition signal bit is correctly recognized. Since P_d is a monotonously increasing function with respect to the number of redundancy r, we can raise the detection rate by increasing r.

The detection rate $P_{D,n,h}$ is defined as the probability that the number of the unrecognized original signal bits cannot exceed the threshold h of Hamming distance. Denote the number of unrecognized original signal bits as Z. Given P_d for 1-bit original signal, we can derive

$$\begin{aligned} P_{D,n,h} &= P(Z \leqslant h) \\ &= \sum_{i=o}^{h} \mathcal{C}_n^i P_d^{n-i} (1 - P_d)^i. \end{aligned} \tag{17}$$

The false positive rate $P_{F,n,h}$ is the probability that a signal is found in unmodulated traffic. The traffic that does not carry the signal is referred to as the clean traffic. Denote the probability that the original signal bit 0 is detected in the clean traffic as $P_{d,0}$ and the probability that the original signal bit 1 is detected in the clean traffic as $P_{d,1}$. Then the false positive rate can be computed by

$$\begin{aligned} P_{F,n,h} &= P(Z \leqslant h) \\ &= \sum_{i=0}^{h} \mathcal{C}_n^i (\frac{P_{d,0} + P_{d,1}}{2})^{n-i} (1 - \frac{P_{d,0} + P_{d,1}}{2})^i, \end{aligned} \tag{18}$$

where n is the original signal length. As we can see from this equation, we can effectively decrease the false positive rate by raising the original signal length. However, the false positive rate can grow by raising the Hamming distance threshold h.

V. Experimental Evaluation

We implement the SDN-based traceback system in the real-world network environment. In this section, we evaluate the feasibility and effectiveness of our technique using three different anonymous communication systems including SSH, OpenVPN, and Tor. All the experiments are performed in a controlled manner. To avoid legal issues, the TCP traffic used for experiments is generated by our ourselves.

A. Experimental Setup

In our experimental setting, we deploy a client, a web server, a remote proxy server, two SDN switches and two SDN controllers. At the web server side, an Apache web service is installed and a file is put on the web server located on our campus. To evaluate the effectiveness of our trackback technique for different anonymous systems, we install two types of single-hop anonymous systems (i.e., SSH and OpenVPN) and a multi-hop anonymous system (i.e., Tor) at the client side. In addition, the setting of the socks5 proxy is configured in a Firefox browser as the SSH and Tor client provides the socks5 local proxy. For the single-hop anonymous systems,

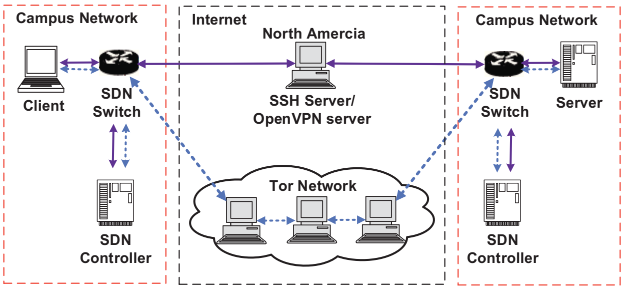


Fig. 3. Experiment setup

both SSH and OpenVPN services are installed in a single-hop anonymous server located in North America. The client leverages the SSH or VPN tunnel to download the file on the server. For the multi-hop anonymous network, the Tor client first chooses three Tor relay servers around the world in terms of the Tor path selection algorithm [4] and establishes a three-hop path in the Tor network. Then we can download the file using the firefox through the Tor client.

A pair of a Pica8 SDN switch [19] and a Floodlight controller [21] is deployed at the server side and the other pair is installed at the client side. Since the setup at both the client side and the server side is the same, we take the setup at the server side as an example. We use a Pica8 P-3297 switch that contains a serial console port, $2 \times 1Gb$ management ports, $48 \times 1Gb$ ethernet ports, and $4 \times 10Gb$ SFP+ ports. The Pica8 P-3297 switch runs an open network operating system that supports Open-vSwitch (OVS) and OpenFlow protocol. We use a computer equipped with two Ethernet interfaces as the SDN controller and install Floodlight on the machine. One Ethernet interface on the computer is connected to the serial console port of the SDN switch so as to configure the switch. The other Ethernet interface on the computer is connected to a management port on the SDN switch in order to allow the controller to communicate with the SDN switch using the OpenFlow protocol. We first configure the setup of the SDN switch through the serial console port. We set the mode of the SDN switch as OVS and the version of the OpenFlow protocol as 1.3. Then we configure a bridge on the switch and add two Ethernet ports to the bridge. These two Ethernet ports in the switch are used to connect our campus network and the server. In addition, the IP address of the controller and the Floodlight service port are set to allow the OVS in the SDN switch to connect to the Floodlight service in the controller through the management port. Once the configuration is done, the controller can communicate with the SDN switch. Then a flow entry is sent to the SDN switches so as to force the switch to forward the target traffic to our controller. The same process goes through at the client side. Finally, we modify the packet message processing module of the Floodlight source code in the controller to implement the functionalities of the signal modulation at the server side and signal recognition at the client side, respectively.

B. Experimental Results

To evaluate the effectiveness of the traceback technique, the client downloads the file 50 times using SSH tunnel, OpenVPN, and Tor, respectively. At the server-side SDN switch, we generate a random signal with 24 bits. Upon completing the TCP 3-way handshake between the proxy server and the web sever, we set the time offset o as 10 seconds. After that, we initiate to modulate the signal into the traffic by varying the TCP advertised window size of the packets from the proxy server. At the client-side SDN switch, we record the timestamps and packet sizes of the rest of the TCP packets from the proxy server after the TCP 3-way handshake between the client and the proxy server. The default values of the ratio of the current AWND size W_a to the latest unregulated AWND size W_a', the time interval T_I, redundancy r, Hamming distance threshold h, and signal length n used in the experiments are 3/4, 800 ms, 6, 7, and 24 bits, respectively. The default sliding window size for SSH and OpenVPN is 50 ms, while the default sliding window size for Tor is 200 ms. We evaluate the detection rate by varying the value of one of these variables while keeping other variables at the default values.

To validate the false positive rate, we let the client respectively downloads 50 files using SSH tunnel, OpenVPN, and Tor again. However, no signal is modulated into the traffic at the server-side SDN switch this time. Then we generate random signals and demodulate signals from the traffic at the client-side switch. By computing the number of signal bits detected in the traffic, we can derive the false positive rate.

Figure 4 illustrates the relationship between the detection rate and the sliding window size for Tor. In light of the empirical cumulative distribution function of the one-way delay over Tor [20], the longest one-way delay is around 2 seconds. Since an end-to-end anonymous communication path in the Tor network includes four TCP connections, the average longest one-way delay between two hosts in a TCP connection is around 500 microseconds in the Tor network. After determining the longest one-way delay in the Tor network, we should carefully choose the step of the sliding window to check when the traffic carrying the signal arrives at the client-side switch. As shown in Figure 4, the detection rate is the highest by using the sliding window size W_i as 200 ms. Therefore, we set the sliding window size W_i at 200ms in order to determine the time delay. The results of the detection rates for Tor are shown in Figure 5 by varying the step of the sliding window. According to the figure, when the step of sliding window reaches 5, that is, the time delay is 1000 ms, we can obtain the best detection rate. Note that, the time offset o

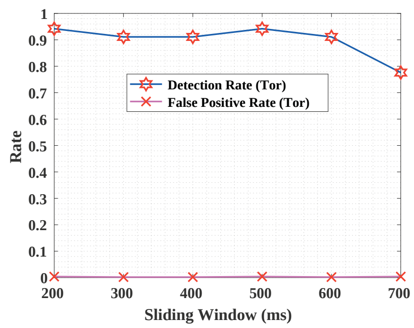
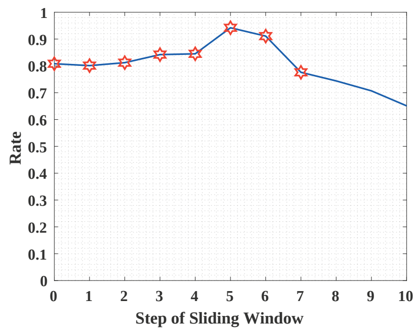


Fig. 4. Detection rate for Tor versus Sliding Window



When we use Hamming distance threshold of 7, the detection rates for SSH and OpenVPN can approach 100%. However, due to the unstable network performance of Tor, the detection rate for Tor is 94.2% using Hamming distance threshold of 7. Furthermore, the false positive rates for the three anonymous network systems are very low (less than 0.5%) although they slightly grow by increasing the Hamming distance threshold.

Figure 11 depicts the correlation between the detection rate and signal length. As shown in the figure, the detection rates for the three anonymous network systems are almost the same given the same signal lengths. However, the false positive rates are considerably decreased. The false positive rates are below 0.5% using a 24-bit signal, while the false positive rates approach zero using a 32-bit signal. This matches our theoretical analysis in Section IV-B. Since it requires more time to modulate a longer signal, we use the 24-bit signal as the default signal length in our experiments.

Figure 12 illustrates the relationship between the detection rate and the ratio of the current AWND size W_a to the latest original AWND size W'_a. We vary the ratio of W_a to W'_a to empirically evaluate the maximum and minimum values of regulatable advertised TCP window size in Equation (15). As we can see from the figure, when the range of the ratio of W_a to W'_a is between 0.5 and 0.8, the detection rates are optimal (100% for SSH and OpenVPN and 94.2% for Tor) and the false positive rates are fairly low (less than 0.5% for the three anonymous network systems). It matches our theoretical analysis in Section IV-A. However, smaller the ratio is, lower the traffic rate is. To avoid considerably reducing the traffic rate and keep our traceback more stealthy, we use 3/4 as the ratio of W_a to W'_a.

VI. RELATED WORK

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watermarking schemes based the arriving time of packets with high accuracy and low error rates.

Research efforts also presented how to trace the Tor hidden service [3], [11], [15], [17], [30]. For example, Ling *et al.* propose a protocol-level Tor hidden server traceback technique. The attacker actively forces the hidden server to produce a protocol feature and tries to discover the feature at the Tor entry node. Once the feature is confirmed, the IP address of the hidden server can be identified. Tian *et al.* [25] investigate how to perform traceback over the Freenet.

VII. Conclusion

In this paper, to address the increasingly serious abuse issues of anonymous communication systems, we introduce a novel and practical SDN-based traceback technique to confirm the communication relationship between users and servers. At the server-side SDN switch, we leverage the SDN controller to intercept the traffic and change the advertised TCP window size of the packets which are transmitted towards the target server. In this way, we can modulate a secret signal into the traffic by varying its traffic rate at the server. Repetition error correcting codes are applied to enhance the robustness of the modulated signal. Furthermore, based on the comprehensive theoretical analyses, we perform extensive empirical experiments to discover the regulatable range of the advertised TCP window size so as to exert a minimal impact on the traffic rate. Finally, extensive real-world experiments are conducted using three anonymous communication systems, i.e., SSH, OpenVPN, and Tor to verify the feasibility and effectiveness of our traceback technique.

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