

# Cryptographic analysis of P2DPI

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Mihai-Alexandru Bogatu  
Politehnica University of Bucharest,  
Faculty of Automatic Control and Computer Science

**Abstract.** This paper represents an analysis of the recently proposed P2DPI encryption scheme for deep packet inspection. Later in the article, some constructs of the algorithm are challenged and it can be observed that the algorithm in this state suffers from serious integrity risks. Later in the article, there is proof that P2DPI can compromise user privacy, unlike their claims.

## 1. Introduction

In the context of increasing encrypted channel communication and at the same time the number of cybersecurity threats, the need for deep packet inspection is at rise. On the other hand, Intrusion Detection System/Intrusion Prevention Systems (IDS/IPS) providers wish to hide the detection rules for threats to minimize the possibility of an evasion, as leakage of the rules may result in clever modifications of packets to bypass the implemented security systems.

The focus of this paper is to analyze “P2DPI: Practical and Privacy-Preserving Deep Packet Inspection” proposed recently by Jongkil K. et al. This paper identifies multiple weaknesses in the P2DPI algorithm, including a compromise using exhaustive message search and proposes some countermeasures to integrity and identify proof that misses.

## 2. P2DPI system

### 2.1 Definitions

The P2DPI system is based on the property of key-homomorphic functions. A well documented premises on the usage of key-homomorphism but also detailed definitions of the cryptographic primitives used in the algorithm can be found in the original paper [1] this article analyzes. The author highly encourages reading the mentioned article before hopping into the sections detailing the attacks. The next sections use definitions based on the paper without detailing or proving the underling terms or motivations.

Note that this article refers to “*tokenize*” as the application of the token generating method over the message  $m$ .

The parties involved in the system:

The **Rule Generator (RG)** refers to the system responsible of generating IDS/IPS rules. In most of the cases RG is a third party to an organization network. The generated rules must be kept secret from other parties with the exception of the MiddleBox. The RG should not be able to decrypt traffic or otherwise guess plain-texts from S/R.

**MiddleBox (MB)** is the actual system that must implement the IDS/IPS detection phase. It receives rules from RG and matches an obfuscated version of them against obfuscated tokenized traffic that comes from S/R. In the case of a match, MB should take actions or alert other entities. MB should not be able to see the plain-text traffic (or otherwise decrypt the traffic) from S to R. The MiddleBox also should not be able to create its own rules.

The **Sender (S)** and **Receiver (R)** are parties interested in communicating with each-other over a private channel. S/R should not be able to see the plain-text rules. In the case one of them is compromised, by inspecting the rules a malicious actor may be able to evade the detection systems. The RG entity may also want to preserve its intellectual property.

#### Notations used in the system:

- $G_p$  finite cyclic group of prime order  $p$ . This paper considers that  $G_p$  is constructed from the generator  $f$
- $H_1(x)$  programmable random oracle used in rule/token initial obfuscation
- $H_2(c_i, x)$  programmable random oracle that takes a key and a counter-based seed
- $k_{MB}$  key shared securely from RG to MB
- $k_{SR}$  key shared securely from S to R for IDS/IPS traffic tokens obfuscation and intermediate rule encryption
- $r_i$  plain-text rule
- $R_i$  obfuscated rule
- $sig_{RG}(R_i)$  secure signature of  $R_i$ , signed by RG
- $I_i$  intermediary obfuscated rule for session
- $S_i$  obfuscated session rule
- $t_i$  plain-text traffic token
- $T_i$  obfuscated traffic token

## 2.1 P2DPI algorithm

P2DPI [1] authors propose that S and R have a channel such as TLS that is used for the actual communication and each of them have a connection to MB that is used for rules matching. The TLS channel will be ignored in this paper and all traffic will refer to traffic intended for the P2DPI algorithm.

A summary of the algorithm can be found below, adapted from the original paper.

### I. Setup:

1. RG generates  $g, h \in G_p$ ,  $k_{MB}$  and shares them with MB
2. For each detection rule  $r_i$ , RG generates  $R_i$  and  $sig_{RG}(R_i)$  and shares them with MB.  $R_i$  is computed as follows:

$$R_i = (g^{H_1(r_i)} h)^{k_{MB}}$$

3. S and R start a connection with MB
4. MB send  $R_i$  and  $sig_{RG}(R_i)$  that is verified by S/R. If a signature fails, output  $\perp$ .
5. S/R compute intermediate rules  $I_i$  and sends them to MB. The intermediary rules are calculated as:

$$I_i = R_i^{k_{SR}}$$

6. If the values from  $I_i$  S and R do not match, MB outputs  $\perp$ . Otherwise MB computes the session rules  $S_i$  as follows:

$$S_i = I_i^{1/k_{MB}} = (g^{H_1(r_i)} h)^{k_{SR}}$$

### II. Token generation:

S/R must tokenize the traffic for the algorithm to work. The authors of P2DPI proposed 2 methods. One of the method is as follows:

For each message  $m$  of length  $k$  bytes, make tokens of length  $b$  bytes where  $b$  is agreed on both S/R and MB/RG. Split the message  $m$  in bytes  $m[0], m[1], \dots, m[k-1]$ . Form the tokens as:

$$t_0 = m[0] \parallel m[1] \parallel \dots \parallel m[b]$$

$$t_1 = m[1] \parallel m[2] \parallel \dots \parallel m[b+1]$$

And so on. At the last bytes, there must be agreed to form padded messages or end the algorithm when the last byte of the message would be the last byte of the last token.

For experimental tests, the authors of P2DPI used 8 byte tokens.

### III. Detection:

1. S and R tokenizes traffic into  $t_i$  and computes a random  $c$  and  $T_i$ . One of them (suppose S) Sends them to MB and R, where  $T_i$  is equal to:

$$T_i = H_2(c + i, (g^{H_1(t_i)} h)^{k_{SR}})$$

2. One of S or R (suppose R) verifies the obfuscated token  $T_i$  from the plain token and counter. If it is a mismatch, notify MB.
3. MB compares  $T_i$  with each  $H_2(c + i, S_j)$  for  $j$  in the number of session tokens.

### 3. Attacks against P2DPI

This section of the article presents attacks discovered against P2DPI. Section 3.1 tackles the issue that only RG can know the plain-text rules. Section 3.1 presents the issues with insufficient data integrity checks and too-permissive trust. Section 3.3 presents an attack on the algebra formulation that gives room to exhaustive message search attack. Section 3.4 turns the attack from the previous section into a complete session decryption attack, proving a complete compromise of user privacy.

#### 3.1 Rules are only known by the Rule Generator

Algorithm 1 ( page 13) [1] mentions that RG generates  $g, h \in G_p$  and  $k_{MB}$  shares them with MB. Afterwards it generates the encrypted rules  $R_i$  and their signature  $sig_{RG}(R_i)$ . MB however can only confirm that the rules come from RG by the signature, but it can not check if the rules have malicious intentions. The function construct using  $g$  and  $h$  may be irreversible, depending on the random oracle  $H_1$  so even by knowing  $k_{MB}$ , MB can not get  $r_i$  from  $R_i$  as it will need to compute the inverse of  $H_1(r_i)$ , however computing the inverse of the random oracle used in the experiments environments would not be a trivial task. S/R and MB can agree on the number of rules, however they can not know what the rules contains.

This flaw allows RG to forge any kind of rule without any other party being able to verify it's intentions. As such, RG can forge rules intended to compromise S/R privacy, limited only to the number of rules the other parties agree to accept. However, this alone is not enough to compromise the encryption scheme. Even if RG generates a low entropy data that wants to match against S/R, it will not receive any information as long as MB dose not exfiltrate alerts to RG.

A more secure algorithm would be to send  $r_i'$ , an encrypted rule with a key MB also possesses, and  $sig_{RG}(R_i)$  to MB. MB will then compute  $R_i$  by first decrypting  $r_i'$  and check against  $sig_{RG}(R_i)$ . That way, MB can inspect for ill-intended rules in the case of the RG threat.

However, this attack can be chained with the next section of the article for an effective compromise.

#### 3.2 Insufficient signatures/certificates

Sub-section 3.2.1-3.2.3 present vulnerabilities related to insufficient signatures/certificates from different angles. Section 3.2.4 proposes some countermeasures to the attacks.

### 3.2.1 Middlebox identity

By not certifying MB's messages, an attacker can use Man-in-the-middle (MITM) attack to impersonate MB. The rules are however encrypted and signed by RG. If the signature algorithm is secure, this attack has no benefits to an ordinary eavesdropper since P2DPI uses counter-based encryption of messages. However, if the threat actor is RG having MITM capabilities, it can essentially cut the MB from the encryption scheme as it contains all the secrets MB has for the encrypted communication.

This would mean that even if MB could decrypt/deobfuscate the rules  $R_i$  to  $r_i$  and deny them based on their intentions, a MITM RG threat could still send the rules to S/R and intercept the encrypted tokens. Since S/R can not decrypt the rules by any means (as this is intended in the definition of security proposed by P2DPI), they would have to trust MB. However in this case MB can be subtracted by the encryption scheme in a MITM attack due to missing a certificate and signature. Further combined with the reasons mentioned in the 3.1 section, MB can not decrypt the traffic either, so even if it had a certificate, S/R and MB must still blindly trust the rules from RG.

This vulnerability will be further chained with an other issue to an effective privacy compromise for S and R.

### 3.2.2 Corruption of intermediary encrypted rules

P2DPI lacks validation of messages from S/R designed to be used in the IDS/IPS system.

Since data from S/R is not securely validated (e3. with HMAC) in the setup process, an MITM adversary can corrupt the messages from S and R to MB containing the intermediate encrypted tokens  $I_i$ . Consider an adversary positioned both in between S-MB and R-MB or positioned in any of the mentioned connections and fully controlling the other host(R-MB and controlling S or S-MB and controlling R). After  $I_i$  conversion to  $S_i$ , they will not have the expected values. Any attempt to match a token with a rule will fail as their decryption is not the same, as such, a MITM attack in the setup process fully compromises any further matching attempt.

### 3.2.3 Corruption of validation phase or replay-attacks

As in the section before, P2DPI lacks validation of messages from S/R designed to be used in the IDS/IPS system. The algorithm proposed to defend against random obfuscated traffic tokens has vulnerabilities as well.

An other problem comes from not validating the integrity of tokens and counter (c,Ti) from R/S. In this case the algorithm is different however even less secure. In this case only S sends the encrypted tokens  $T_i$  and the counter  $c$  used in  $H_2(c_i, x)$ . R verifies them and

warns MB if a mismatch is made. R is considered trusted, however the following attack applies in the reversed role of R and S as well. An adversary sets a MITM attack on the traffic MB-R and either controls S or has a MITM attack on S-MB. The attacker changes the counter or some high-risk tokens values to something random (in the case of tokens, the random value should still be located on the cyclic group). The attacker then captures the traffic from R. If MB just waits passively a warning, the adversary could just drop all warning requests before they reach MB. If however MB waits actively for warnings, requesting the status of any mismatch, the adversary could just drop the reply from R that contains the status of the warning and sends a reply-attack with a clean status. Since there is no mention of a counter-mode based encryption with secure signatures of the alert to MB, this attack is possible.

### **3.2.4 Countermeasures to integrity compromise**

To circumvent the risk mentioned in section 3.2.1, MB should compute the signature through a secure signing algorithm and send it alongside the previous signatures to S/R. RG should not possess the key to sign messages in the name of MB. In this case S/R can verify that the obfuscated rules  $R_i$  are in-fact from RG and they are verified by MB.

Both 3.2.2 and 3.2.3 requires that all three parties: MB, S and R sign their messages. MB will be able to verify S and R messages integrity and S/R verify MB messages integrity. However in the case of 3.2.3 the recommendation is for both parties to send the obfuscated tokens as having a one-sided validation on the hosts is not the best practice and should be done centralized at the MB. In any case, MB should be the one raising alerts in a network-based IDS/IPS environment anyways.

While the MITM on both sides is difficult to achieve, in practice the server-client model could suffer a compromise such that an attacker obtains access to an internal IP from the server's network. Gaining MITM access to the server from the internal network is hard but not necessary impossible and in the case an adversary even with an IDS in place. There are cases a security system is implemented after an attacker achieves a backdoor to the internal network. Other attack vectors include an internal employee threat.

P2DPI system supposes that 2 from hosts that have a connection through MB, at least one is honest, otherwise they could just encrypt the traffic one more layer and the conversations can not be inspected. However in this state of the algorithm, if there are 2 malicious hosts on the sides of MB, all other hosts on either part of MB have can be compromised without an IDS/IPS alert. This attack scenario should be taken in consideration for future privacy-oriented deep packer inspection solutions as in practice, compromise of two hosts should not compromise the entire network capabilities to detect intrusions.

### 3.3 Exhaustive message search vulnerability

Suppose  $g, h \in G_p$  where  $G_p$  is a finite cyclic group of prime order  $p$  generated by  $f$ . Under this consideration, the following equations apply:  $g^\alpha \equiv h^\beta \equiv f$  where  $\alpha$  and  $\beta$  are integers in the domain  $(1, 2, \dots, \# E(G_p))$  where  $\# E(G_p)$  is the order of  $G_p$ .

Under this assumption, the key-homomorphic equation from P2DPI scheme can be rewritten as follows, considering (Abelian) finite cyclic groups proprieties:

$$H(x, k) = (g^{H_1(x)} h)^k \equiv ((f^\alpha)^{H_1(x)} f^\beta)^k = (f^{\alpha H_1(x) + \beta})^k$$

Notice that at page 13 of [1] mentions that RG generates  $g, h \in G_p$ .

The choice of using two functions instead of one is mentioned in Annex 5 of page 11 [1], as the simplified version [2] was used in a previous version of the article but changed to this equation “*due to the malleability of the previous choice*”. However this article demonstrates that RG can in fact reduce the problem to the one before, furthermore it can be exploited to compromise the users privacy.

The encryption scheme makes it such S/R can chose the encrypted rules they want to accept from MB, signed by RG. However the contents of the rules are encrypted and as such they can't know for sure that the rule contains. This was a basis of the algorithm as knowing or decrypting by any means a plain-text rule on any other party than RG or MB compromises their privacy. The issue is that in P2DPI MB can not check the rules. As such a malicious RG can generate any kind of rule, limited to the number of rules MB and S/R agree to accept. This was pointed out in section 3.2.1 of this article. However, the privacy of S/R is the subject of interest for both MB and RG and as such they may cooperate to compromise S/R privacy.

In this context, this article will prove that [1] is vulnerable to exhaustive message search.

Under the new from of equation, alpha and beta are public and S/R can reject a generator group. An example would be an Elliptic curve and generator points that are known to have backdoor or any custom-made curves. However they can not reject a rule based on the plain-text as it is obfuscated.

Let  $\phi$  be the neutral element in the cyclic group  $G_p$ . As an example, in Elliptic Curve Cryptography (ECC),  $\phi$  is the point at infinity. Under a finite cyclic group of prime order, the neutral element is present in any closed group.

By the definition, for any  $f \in G_p$  with an inverse in a closed group following property applies:

$$f * f^{-1} = \phi$$

As such, consider the key  $\sigma$  the smallest value for which  $f^\sigma = \phi$ . One example is to set  $\sigma = p-1$  where  $p$  is the prime order of the group  $G_p$  which is proved by using Fermat's Little Theorem that  $f^{p-1} \equiv 1 \text{ mod } p$ , where 1 is the neutral element by definition.

By setting  $g^{H_1(x)} = f^\sigma$  RG can generate the following payload, taking in the consideration the commutativity property of the group:

$$R_r = (g^{H_1(x)} h)^{k_{MB}} = (f^\sigma f^\beta)^{k_{MB}} = (\phi f^\beta)^{k_{MB}} \equiv (f^\beta)^{k_{MB}} = h^{k_{MB}}$$

Note that  $g^{H_1(x)} = \phi$  is a valid element in the group. However it is hard to find  $x$  such that  $H_1(x) = \sigma$  but in P2DPI case, MB dose not require the plain-text values for  $r_i$  and can not compute the inverse of  $R_r$  as it constitutes a hard (discrete logarithm problem, in the case of ECC) to get back  $H_1(x)$  but also depends on the whether  $H_1(x)$  has an inverse. For that reason an adversary can set  $g^{H_1(x)} = \phi$  without computing the actual 3. Also since  $\phi$  is a valid value in the cyclic group, even if MB notices that  $g^{H_1(x)} = \phi$  it can not differentiate coming from a good- or ill-intended rule. The same is true for  $H_1(x) = 1$ , since there is no need to find collision as  $x$  is not visible to MB, just send  $g^{k_{MB}}$ . However having send both,  $g^{k_{MB}}$  and  $h^{k_{MB}}$ , MB is able to rise an alert since the probability of 2 rules hitting those values in the same set of rules is very low. At this point, we conclude that RG still needs MITM access to S or R with the possibility to send messages, which is possible due to the vulnerabilities present in the previous sections.

The attack:

1. RG sends to S/R the obfuscated reduction rules  $R_{rg}, R_{rh}$  and their signatures.

$$R_{rg} = g^{k_{MB}}$$

$$R_{rh} = h^{k_{MB}}$$

2. S/R verifies the signature of the rule and computes the intermediate obfuscated rule and sends them to MB. Since S/R do not hold the key  $k_{MB}$ , it's hard to prove that  $R_{gh}$  and  $R_{rh}$  come from exclusivity  $g$  and  $h$  as they are valid rules anyways.

$$I_{rg} = R_{rg}^{k_{SR}} = (g^{k_{MB}})^{k_{SR}} = g^{k_{MB}k_{SR}}$$

$$I_{rh} = R_{rh}^{k_{SR}} = (h^{k_{MB}})^{k_{SR}} = h^{k_{MB}k_{SR}}$$

3. RG computes the session reduction rules

$$S_{rg} = I_{rg}^{1/k_{MB}} = g^{k_{SR}}$$

$$S_{rh} = I_{rh}^{1/k_{MB}} = h^{k_{SR}}$$

4. Having both  $g^{k_{SR}}$  and  $h^{k_{SR}}$ , RG can now forge any obfuscation of a message  $m$  by computing:

$$S(msg) = (S_{rg})^{H_1(msg)} S_{rh} = (g^{k_{SR}})^{H_1(msg)} h^{k_{SR}}$$

Which, due to commutativity property of the group, can be rewritten as:

$$S(msg) = (g^{H_1(msg)} h)^{k_{SR}}$$



This means that RG can now encrypt any message with the key  $k_{SR}$  without actually knowing it.

5. For each token and counter coming from S/R, store them and apply exhaustive message search on the function

$$T_{msg} = H_2(c+i, S(msg))$$

compared with

$$T_i = H_2(c+i, S_i)$$

When a match is found, the adversary guessed a message.

Note that 2 random parameters  $\varphi, \psi$  could be chosen by RG to send  $R_{rg}^\varphi$  and  $R_{rh}^\psi$ . RG can still compute  $S_{rg} = (S_{rg}')^{1/\varphi}$  and  $S_{rh} = (S_{rh}')^{1/\psi}$  since the values were generated by the attacker. This would further obfuscate RG's intentions to the already oblivious S/R, however the parameters  $\varphi, \psi$  must take the obfuscated rules in the domain space generated of the original obfuscation function. While for  $R_{rh}$  always exists on the domain as there will always be a value for  $H_1(x) = \sigma$ , one must find a value of  $\varphi$  to make sure that  $R_{rg}^\varphi$  is included in the domain of values R outputs.

This attack is realistic since MB dose not sign the messages and even if it would sign them, MB dose not require from RG the plain-text rules. As such, this attack demonstrates that P2DPI is vulnerable to exhaustive message search attack. This would have a big impact on low-entropy data, however by using a counter at each token, the risk is minimized. On the other hand,  $H_2(ci, msg)$  is not modeled as a slow function, as it should not be because it is used in the algorithm extensively for real-time data coming from tokenized traffic. In this case, a brute force on  $H_2$  based on the index is possible on a realistic time to find a collision, as long as the token size is small.

An attacker has to do  $2^{64}$  comparisons per token for an 100% chance of success in the case of truly random plain-text data tokenized by 8 characters (as used in the demonstration section of P2DPI algorithm). However, since protocols are predictable, and in most situations data transferred is composed of printable characters or otherwise encoded with a transformation of the data in a printable format (such as base64), the attack complexity is reduced further. For example, for a complete ASCII encoding that uses 7 bits of data out of a byte, an attack would be halved, reducing the complexity to  $2^{32}$ , which can be reduced further with other techniques.

In this section, of this paper demonstrated attacks where only one of the directly involved member is malicious.

However the authors of P2DPI pointed on the section 2.2 Threat Model that a collaborating MB and RG could not compromise S/R confidentiality more than S/R agrees to. However by using 2 specially crafted rules, the author of this article demonstrates that MB

and RG could in fact compromise the entire confidentiality of S and R sessions by getting a single token from the session, under the presumptions of the attack. As such even if sufficient integrity checks are taken in place, this attack would still break S/R confidentiality if MB/RG collaborate.

### 3.4 Byte-at-a-time attack

Under the presumptions of the previous section, that RG with MITM capabilities or RG with the collaboration of MB could generate the algorithm reduction parameters and construct  $S(msg) = (g^{H_1(msg)} h)^{k_{SR}}$  without the knowledge of the key  $k_{SR}$ , this section demonstrates that in the case of a token generation method used by P2DPI and mentioned in BlindBox [3] as well, an adversary controlling the mentioned possible threats obtaining a single token plain-text could compromise the entire confidentiality of S/R.

Lets assume that MB/RG obtained the token  $t_i$ . Since  $t_{i-1}$  and  $t_{i+1}$  differ by a single byte, obtaining the adjective tokens by knowing their obfuscation  $T_{i-1}, T_{i+1}$  and having access to the encryption algorithm that feeds before  $H_2(ci, S_i)$  as in the form of encryption oracle, the attack is no different than an byte-at-a-time ECB attack.

For  $t_{i+1}$ , the attacker sets  $t_{i+1}[0:b-1] := t_i[1:b]$  with where b is the token size. The last byte of  $t_{i+1}$  is then brute-forced until  $H_2(ci, S_i) = H_2(ci, S(t_i))$ . When a match is found, then we obtained the token  $t_{i+1}$ . This can be repeated for each byte of the message.

This attack concludes that a single guessed token from the session compromises the confidentiality of all the other bytes of the message. This can be done easily on predictable tokens such as by targeting headers in HTTP protocol.

## 4. Definition Middle Box Searchable Encryption deficit

Although the proofs of the definitions of MSBE security present in P2DPI are correct, the actual definitions of MSBE security present on P2DPI article are incomplete.

Below are listed the definitions of MSBE security as found in the article.

**Definition 4 (MBSE)** *Middlebox searchable encryption consists of five algorithms, namely Setup, RuleEnc, Encrypt and Match:*

- **Setup**  $[1^\lambda \rightarrow (sk, pk)]$  accepts a security parameter  $1^\lambda$  and outputs an encryption key  $sk$  and a public parameter  $pk$ .
- **RuleEnc**  $[(sk, r, pk) \rightarrow S]$  accepts  $sk$  and  $r$  from a message space  $\mathcal{M}$ , and outputs an obfuscated rule  $S$ .
- **Encrypt**  $[(sk, \mathcal{T}, pk) \rightarrow (param, \mathcal{ET})]$  accepts  $sk$  and a set of tokens  $\mathcal{T} = \{t_1, \dots, t_n\}$  from  $\mathcal{M}$  for  $n = \text{poly}(\lambda)$  and outputs encryption parameters  $param$  and encrypted tokens  $\mathcal{ET} = \{T_1, \dots, T_n\}$ .
- **Match**  $[(param, \mathcal{ET}, S) \rightarrow \mathcal{I}]$  accepts  $param$ ,  $\mathcal{ET}$  and  $S$ . It outputs the set of indices  $\mathcal{I} = \{i | t_i = r\}$ .

MSBE Base [1 definition 4, page 15 ]

**Definition 5 (MBSE Security)** *Let  $\mathcal{A}$  be a stateful PPT adversary. Consider the following security game  $\text{Exp}_{\mathcal{A}}^{\text{MBSE}}(1^\lambda)$ :*

- **Init:** The challenger  $\mathcal{C}$  runs **Setup** with a security parameter  $1^\lambda$  to generate rule encryption keys  $sk$  and public parameter  $pk$ . It sends  $pk$  to  $\mathcal{A}$ .
- **Query:**  $\mathcal{A}$  queries  $\mathcal{C}$  with a set of rules  $\{r_1, \dots, r_q\}$ .  $\mathcal{C}$  invokes **RuleEnc** with  $sk$  and returns  $\{S_1, \dots, S_q\}$  to  $\mathcal{A}$ .
- **Challenge:**  $\mathcal{A}$  generates two sets of tokens  $\mathcal{T}_0 = \{t_{0,1}, \dots, t_{0,n}\}$  and  $\mathcal{T}_1 = \{t_{1,1}, \dots, t_{1,n}\}$  from the message space  $\mathcal{M}$  such that  $\forall i \in [q], r_i \notin \mathcal{T}_0 \cup \mathcal{T}_1$ . It sends both to  $\mathcal{C}$ .  $\mathcal{C}$  randomly sets  $\beta \in \{0, 1\}$  and runs **Encrypt** for  $\mathcal{T}_\beta$  to get  $(param, \mathcal{ET})$ .  $\mathcal{C}$  returns  $(param, \mathcal{ET})$  to  $\mathcal{A}$ .
- **Guess:**  $\mathcal{A}$  outputs  $\beta'$ . If  $\beta = \beta'$ ,  $\mathcal{A}$  wins and the game outputs 1. Otherwise, the game outputs 0.

We say that MBSE is secure if for all PPT stateful adversaries  $\mathcal{A}$ , there exists a negligible function  $\text{negl}$  such that

$$\Pr[\text{Exp}_{\mathcal{A}}^{\text{MBSE}}(1^\lambda) = 1] = \frac{1}{2} + \text{negl}(\lambda).$$

MSBE user Privacy [ 1 definition 5, page 16]

The construction of P2DPI makes it hard to get a plain-text of rule  $r_i$  by having the obfuscated rule  $R$  and the key  $k_{MB}$  due to the random oracle  $H_1$ . However this does not mean that an adversary could not send to the users for session generation a specially crafted  $R$  that would otherwise be hard to compute the original function. As long as  $R$  is still a value on the cyclic group  $G_p$ , a user has no reason not to accept the rule as long as the number of rules is not excessive.

As a more complete definition, RuleEnc should accept a plain-text rule and output an obfuscated rule form the rule-generator. An additional step, GenerateSessionRules should be included, that generates the session rule based on the obfuscated rule. As such, in the definition 5, the adversary A could use the output of RuleEnc to feed an obfuscated rule to GenerateSessionRules or it may want to craft by hand a specially obfuscated rule that may be hard to generate through RuleEnc and feed the output to GenerateSessionRules.

In the current definitions, P2DPI would preserve user privacy, however this article proved that is not the case. As such the definitions of MSBE security present in P2DPI article are incorrect and incomplete. This article proved that the theory present in P2DPI that promises privacy should not be taken in consideration as a valid theoretical proof of security under the real attack-surface of the algorithm.

## 4. Conclusions

P2DPI promised a high security level, however at this stage of the algorithm, even though it is faster than the competing methods to achieve privacy-based deep-packed inspection, the security level provided at this stage is inadequate for use as it breaks searchable encryption promise of confidentiality for the hosts that want to communicate through a private channel. As such its privacy level is equivalent to an intercepting-proxy, however since it lacks enough message integrity proofs, its efficiency in detecting intrusions can be compromised by having an intercepting attacker on both sides of the MiddelBox.

## 5. References

- [1] Jongkil Kim, et al. P2DPI: practical and privacy-preserving deep packet inspection, <https://eprint.iacr.org/2021/789.pdf>, Accessed: December 23'th, 2021
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