BlindBox: Deep Packet Inspection over Encrypted Traffic

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EXTENDED TECHNICAL REPORT

ABSTRACT

Many network middleboxes perform *deep packet inspection* (DPI), a set of useful tasks which examine packet payloads. These tasks include intrusion detection (IDS), exfiltration detection, and parental filtering. However, a long-standing issue is that once packets are sent over HTTPS, middleboxes can no longer accomplish their tasks because the payloads are encrypted. Hence, one is faced with the choice of *only one* of two desirable properties: the functionality of middleboxes and the privacy of encryption.

We propose *BlindBox*, the first system that simultaneously provides *both* of these properties. The approach of BlindBox is to perform the deep-packet inspection *directly on the encrypted traffic*. BlindBox realizes this approach through a new protocol and new encryption schemes. We demonstrate that BlindBox enables applications such as IDS, exfiltration detection and parental filtering, and supports real rulesets from both open-source and industrial DPI systems. We implemented BlindBox and showed that it is practical for settings with long-lived HTTPS connections. Moreover, its core encryption scheme is 3-6 orders of magnitude faster than existing relevant cryptographic schemes.

1. INTRODUCTION

Many network middleboxes perform *deep packet inspection* (DPI) to provide a wide range of services which can benefit both end users and network operators. For example, Network Intrusion Detection/Prevention (IDS/IPS) systems (e.g., Snort [9] or Bro [39]) detect if packets from a compromised sender contain an attack. Exfiltration prevention devices block accidental leakage of private data in enterprises by searching for document confidentiality watermarks in the data transferred out of an enterprise network [47]. Parental filtering devices prevent children from accessing adult material in schools, libraries, and homes [13]. These devices and many others [6, 8, 7] all share the common feature that they inspect packet payloads; the market for such DPI devices is expected to grow to over $2B by 2018 [46].

At the same time, HTTPS and other encryption protocols have seen dramatic growth in usage in recent years [38]; encryption protects users' private data from eavesdroppers anywhere in the network, including at a middlebox. Unfortunately, HTTPS poses a long-standing challenge for DPI devices. Since packet payloads are encrypted, network middleboxes can no longer inspect payloads [38] and accomplish their tasks. To enable middlebox processing, some currently deployed middlebox systems support HTTPS in an *insecure* way: they mount a man-in-the-middle attack on SSL and decrypt the traffic at the middlebox [30, 29]. This approach violates the end-to-end security guarantees of SSL and thus causes an unfortunate set of issues as surveyed in [30]. Moreover, users and clients have criticized this approach [53, 33, 44, 50], some expressing worry that the private data logged at the middlebox is given to marketers.

Therefore, one is faced with an unfortunate choice of *only one* of two desirable properties: the functionality of the middleboxes and the privacy given by encryption. At a first glance, it may appear that these two properties are fundamentally at odds with each other: how can a network appliance make decisions based on connection contents when it cannot see these contents?

In this paper, we demonstrate that it is possible to build a system that satisfies both of these seemingly conflicting properties. We present *BlindBox*, the first system that provides both the benefits of encryption and functionality at a DPI middlebox. The name "BlindBox" denotes that the middlebox cannot see the private content of traffic.

Our approach is to perform *the inspection directly on the encrypted payload*, without decrypting the payload at the middlebox. Building a practical such system is challenging: networks operate at very high rates requiring cryptographic operations on the critical path to run in micro or even nano seconds; further, some middleboxes require support for rich operations, such as matching regular expressions. A potential candidate is expressive cryptographic schemes such as fully homomorphic or functional encryption [25, 24, 28], but these are prohibitively slow, decreasing network rates by many orders of magnitude.

To overcome these challenges, BlindBox explores and specializes on the network setting. BlindBox enables two classes of DPI computation each having its own privacy guarantees: *exact match privacy* and *probable cause privacy*. Both of BlindBox's privacy models are much stronger than the state-of-the-art "man in the middle" approach deployed today. In both of these models, BlindBox protects the data with strong randomized encryption schemes providing similar security guarantees to the well-studied notion of searchable encryption [48, 31]. Depending on the class of computation, BlindBox allows the middlebox to learn a small amount of information about the traffic to detect rules efficiently.

The first class of computation consists of DPI applications that rely only on exact string matching, such as watermarking, parental filtering, and a limited IDS. Under the associated privacy model, exact match privacy, the middlebox learns at which positions in a flow attack keywords occur; for substrings of the flow that do not match an attack keyword, the middlebox learns virtually nothing.

The second class of computation can support all DPI applications, including those which perform regular expressions or scripting. The privacy model here, probable cause privacy, is a new network privacy model: the middlebox gains the ability to see a (decrypted) individual packet or flow *only if the flow is suspicious*; namely, the flow contains a string that matches a known attack keyword. If the stream is not suspicious, the middlebox cannot see the (decrypted) stream. Hence, privacy is affected *only with a cause*. BlindBox allows users to select which privacy model they are most comfortable with.

To implement these two models, we developed the following techniques:

- **DPIEnc** and **BlindBox Detect** are a new searchable encryption scheme [48] and an associated fast detection protocol, which can be used to inspect encrypted traffic for certain keywords efficiently. As we explain in §3, existing searchable encryption schemes [48, 31, 15] are either deterministic (which can enable fast protocols, but provide weak security) or randomized (which have stronger security, but are slow in our setting). DPIEnc with BlindBox Detect achieve both the speed of deterministic encryption and the security of randomized encryption; detection on encrypted traffic runs as fast as on unencrypted traffic.
- **Obfuscated Rule Encryption** is a technique to allow the middlebox to obtain encrypted rules based on the rules from the middlebox and the private key of the endpoints, without the endpoints learning the rules or the middlebox learning the private key. This technique builds on Yao's garbled circuits [52] and oblivious transfer [37, 42, 23].
- **Probable Cause Decryption** is a mechanism to allow flow decryption when a suspicious keyword is observed in the flow; this is the mechanism that allows us to implement our probable cause privacy model.

We implemented BlindBox as well as a new secure transport protocol for HTTP, which we call BlindBox HTTPS. We evaluated BlindBox HTTPS using several real DPI applications: data watermarking [47], parental filtering, and intrusion detection. We used attack signatures from the open-source community (Snort [9]) and industrial IDSes (McAfee Stonesoft and Lastline).

We show that BlindBox's performance is practical for many settings. For example, the rate at which the middlebox can inspect packets is as high as 186Mbps per core in our experiments. Given that standard IDS implementations, such as Snort [9], peak at under 100Mbps, this performance is competitive with existing deployments. We achieve this performance due to DPIEnc and BlindBox Detect. When compared to two strawmen consisting of a popular searchable encryption scheme [48] and a functional encryption scheme [32], DPIEnc with BlindBox Detect are 3-6 orders of magnitude faster. Nevertheless, a component of BlindBox is not yet as fast as desirable: the setup of an HTTPS connection. This setup performs obfuscated rule encryption and it takes time proportional to the number of attack rules. For rulesets with tens of keywords, this setup completes in under a second; however, for large IDS installations with thousands of rules, the setup can take up to 1.5 minutes to complete. Hence, BlindBox is most fit for settings using long or persistent connections through SPDY-like protocols or tunneling, and not yet practical for short, independent flows with many rules.

We see BlindBox as a first step towards a general protocol that will allow middleboxes and end-to-end encryption to coexist, without sacrificing the benefits of either. BlindBox shows that this coexistence is possible for the class of middleboxes performing deep packet inspection. A future, general protocol will devise mechanisms to address the full range of middleboxes including those that process packet headers, modify packet payloads (such as transcoders and WAN optimizers), or terminate sessions (such as Web or SIP proxies). Consequently, the subject of our current and future work focuses on achieving this end goal: a general protocol to allow all middleboxes to coexist with encryption.

2. OVERVIEW

Fig. 1 presents the system architecture. There are four parties: sender (S), receiver (R), middlebox (MB), and rule generator (RG) – these reflect standard middlebox deployments today. RG generates attack rules (also called signatures) to be used by MB in detecting attacks. Each rule attempts to describe an attack and it contains fields such as: one or more keywords to be matched in the traffic, offset information for each keyword, and sometimes regular expressions. The RG role is performed today by organizations like Emerging Threats [3], McAfee [4], or Symantec [11]. S and R send traffic through MB. MB allows S and R to communicate unless MB observes an attack rule in their traffic.

Network administrators today deploy in-network middleboxes in this way because it gives them a central point of control to enforce security policies in their network (since they often do not control the endpoints). Moreover, having a single in-network device is also easy to manage and upgrade. Some research [22] considered alternative (edge) deployments in which endpoints perform all middlebox processing on their own traffic and rules are distributed to the endpoints. BlindBox instead aims to make changes compatible with the network approach in widespread use today. Further, this edge-based model is not compatible with the requirement of keeping rules hidden from endpoints, which

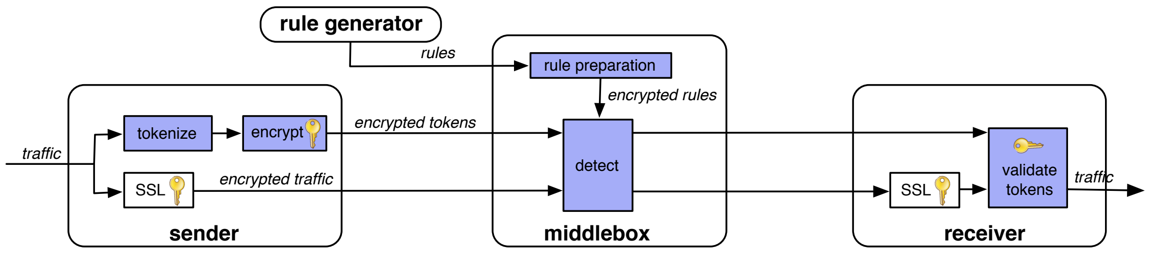

Figure 1: System architecture. Shaded boxes indicate algorithms added by BlindBox.

we discuss in §2.2.1.

In today's deployments, MB can read any traffic sent between S and R. With BlindBox, MB should be able to detect if attack rules generated by RG match the traffic between R and S, but should not learn the contents of the traffic that does not match RG's attack rules.

2.1 Usage Scenarios

Before formalizing our threat model, we illustrate our usage scenario with three examples. For each individual in these examples, we indicate the party in our model (R, S, MB, or RG) that they correspond to.

Example #1: University Network. Alice (R or S) is a student at the University of SIGCOMM and brings her own laptop to her dorm room. However, university policy requires that all student traffic be monitored for botnet signatures and illegal activity by a middlebox (MB) running an IDS. Alice is worried about her computer being infected with botnet software, so she also desires this policy applied to her traffic. McAfee (RG) is the service that provides attack rules to the middlebox and Alice trusts it. However, she is uncomfortable with the idea of someone she doesn't know (who has access to the middlebox) potentially being able to read her private Facebook messages and emails. Alice installs BlindBox HTTPS with McAfee's public key, allowing the IDS to scan her traffic for McAfee's signatures, but not read her private messages.

Example #2: ISP Service. Bob has two young children (S or R) at home, and registers for parental filtering with his ISP so that all traffic is filtered for adult content. However, Bob has read stories in the news of ISPs selling user browsing data to marketers [50] and wants to prevent his ISP (MB) from using his data in this way. Bob trusts the Electronic Filtering Foundation (RG), a non-profit which generates rulesets for filtering and pledges not to sell user data. Bob installs BlindBox HTTPS on his home computer with the Electronic Filtering Foundation's public key, allowing his traffic to be scanned for EFF rules, but no other data.

In the above examples, Alice and Bob want to have a middlebox in their network check *for the attack rules the corresponding trusted parties permit*, but the middlebox should not learn anything else about the content of the traffic. A key requirement is that there exists an RG which Alice, Bob and the MB trust with rule generation; if this is not the case, the parties cannot use BlindBox.

Anti-Example #1: Political Dissident. Charlie (R or S) is a political dissident who frequently browses sensitive websites, and is concerned about government monitoring. If the government coerces one of MB or RG, Charlie remains protected. However, BlindBox should not be used in a setting in which *both* MB and RG can be controlled by an attacker: in this case, RG can produce signatures for sensitive terms and MB will use these to match the traffic. Hence, if the government can coerce both MB and RG together, Charlie should not use BlindBox. Similarly, if the government can coerce root certificate generators, Charlie should not use vanilla HTTPS either because it may allow man-in-the-middle attacks on his traffic.

2.2 Security and Threat Model

The goal of our work is to protect the privacy of user traffic from MB. Any solution must satisfy a set of systems requirements we discuss in §2.2.1. We then discuss the threat model in §2.2.2 and the privacy guarantees BlindBox provides in §2.2.3.

2.2.1 *System Requirements*

BlindBox retains key system goals of traditional IDS deployments today: (1) BlindBox must maintain MB's ability to enforce its policies (i.e., detect rules and drop/alert accordingly), and (2) endpoints must not gain access to the IDS rules. The rationale behind the second requirement is twofold. First, in order to make IDS evasion more difficult for an attacker at the user, the rules should be hidden from the endpoints [39]. Second, most vendors (e.g., Lastline and McAfee Stonesoft) rely on the secrecy of their rulesets in their business model, as their value added against competitors often includes more comprehensive, more efficient, or harder to evade rules.

BlindBox maintains these two requirements, and adds an additional one: (3) that the middlebox cannot read the user's traffic, except the portions of the traffic which are considered *suspicious* based on the attack rules.

2.2.2 *Threat Model*

There are two types of attackers in our setup.

The original attacker considered by IDS. This is the same attacker that traditional (unencrypted) IDS consider and we do not change the threat model here. Our goal is to detect such an attacker over *encrypted* traffic. As in traditional IDS, one endpoint can behave maliciously, but at least one endpoint must be honest. This is a fundamental requirement of any IDS [39] because otherwise two malicious endpoints can agree on a secret key and encrypt their traffic under that key with a strong encryption scheme, making prevention impossible by the security properties of the encryption scheme. Similarly, the assumption that one endpoint is honest is also the default for exfiltration detection and parental filtering today. Parental filters can assume one endpoint is innocent under the expectation that 8-year-olds are unlikely replace their network protocol stack or install tunneling software. Commercial exfiltration detection devices primarily target *accidental* exfiltration (e.g., where an otherwise innocent employee attaches the wrong file to an email), recognizing that deliberate exfiltration requires control of the end host.

The attacker at the middlebox. This is the new attacker in our setting. This attacker tries to subvert our scheme by attempting to extract private data from the encrypted traffic passing through the middlebox. We assume that the middlebox MB performs the detection honestly, but that it tries to learn private data from the traffic and violate the privacy of the endpoints. In particular, we assume that an attacker at MB reads *all* the data accessible to the middlebox, including traffic logs and other state. Given this threat model, BlindBox's goal is to hide the content of the traffic from MB, while allowing MB to do DPI. We do not seek to hide the attack rules from the MB itself; many times these rules are hardcoded in the MB.

2.2.3 Privacy Models

We now describe our privacy models.

Exact Match Privacy gives the following guarantee: the middlebox will be able to discover only those substrings of the traffic that are exact matches for known attack keywords. For example, if there exists a rule for the word "ATTACK", the middlebox will learn at which offset in the flow the word "ATTACK" appears (if it appears), but does not learn what the other parts of the traffic are. Traffic which does not match a suspicious keyword remains unreadable to the middlebox.

Probable Cause Privacy gives a different guarantee: that the middlebox will be able to *decrypt a flow* only if a substring of the flow is an exact match for a known attack keyword. Probable cause privacy is useful for IDS tasks which require regular expressions or scripting to complete their analysis. This model is inspired from two ideas. First, it is inspired from the notion of probable cause from United States' criminal law: one should give up privacy *only* if there is a reason for suspicion. Second, most rules in Snort that contain regular expressions first attempt to find a suspicious keyword in the packet – this keyword is selective so only a small fraction of the traffic matches this string and is passed through the regexp. Indeed, the Snort user manual [49] urges the presence of such selective keywords because otherwise, detection would be too slow. Since rules are structured this way, it becomes easier to implement our probable cause privacy model by decrypting the stream if there is a match to the suspicious keyword.

Exact match privacy provides security guarantees as in searchable encryption [48], which are well-studied. Probable cause privacy is a new privacy model, and we believe it may be useful in other network domains beyond middleboxes (e.g. network forensics or search warrants), although we leave such investigation to future work. We formalize and prove the security guarantees of BlindBox using standard indistinguishability-based definitions in the Appendix. Both models are stronger than the "man in the middle" approach in deployment today, where all traffic is decrypted regardless of suspicion. A user who prefers exact match privacy over probable cause privacy can indicate so within BlindBox HTTPS.

2.3 System Architecture

We now return to Fig. 1 to explain each module and how BlindBox functions from a high level; we delve into the protocol and implementation details in the following sections.

Prior to any connection, RG generates a set of *rules* which contain a list of suspicious keywords known to formulate parts of attacks; RG signs these rules with its private key and shares them with MB, its customer. S and R, who trust RG, install a BlindBox HTTPS configuration which includes RG's public key. Beyond this initial setup, RG is never directly involved in the protocol. We now discuss the interactions between R, S, and MB when R and S open a connection in a network monitored by MB.

Connection setup. First, the sender and receiver run the regular SSL handshake which permits them to agree on a key k_0. The sender and receiver use k_0 to derive three keys (e.g., using a pseudorandom generator):

- k_{SSL}: the regular SSL key, used to encrypt the traffic as in the SSL protocol,
- k: used in our detection protocol, and
- k_{rand}: used as a seed for randomness. Since both endpoints have the same seed, they will generate the same randomness.

At the same time, MB performs its own connection setup to be able to perform detection over S and R's traffic. In an exchange with S and R, MB obtains each rule from RG deterministically encrypted with key k – this will later enable MB to perform the detection. However, this exchange occurs in such a way that MB *does not learn the value of* k and in such a way that R and S *do not learn what the rules are*. We call this exchange *obfuscated rule encryption* and we describe how it is implemented in the following section.

Unlike the above handshake between S and R, which bootstraps off the existing SSL handshake, obfuscated rule encryption is a new exchange. In existing deployments, clients typically do not communicate directly with DPI middleboxes (although for other kinds of middleboxes, such as explicit proxies [17] or NAT hole-punching [21], they may do so). Even though this step removes the complete "transparency" of the DPI appliance, it is an incremental change that we consider an acceptable tradeoff for the benefits of BlindBox.

Sending traffic. To transmit, the sender: (1) encrypts the traffic with SSL as in a non-BlindBox system; (2) tokenizes the traffic by splitting it in substrings taken from various offsets (as discussed in §3); and (3) encrypts the resulting tokens using our DPIEnc encryption scheme.

Detection. The middlebox receives the SSL-encrypted traffic and the encrypted tokens. The detect module will search for matchings between the encrypted rules and the encrypted tokens using BlindBox Detect (Sec. 3.2). If there is a match, one can choose the same actions as in a regular (unencrypted IDS) such as drop the packet, stop the connection, or notify an administrator. After completing detection, MB forwards the SSL traffic and the encrypted tokens to the sender.

Receiving traffic. Two actions happen at the receiver. First, the receiver decrypts and authenticates the traffic using regular SSL. Second, the receiver checks that the encrypted tokens were encrypted properly by the sender. Recall that, in our threat model, one endpoint may be malicious – this endpoint could try to cheat by not encrypting the tokens correctly or by encrypting only a subset of the tokens to eschew detection at the middlebox. Since we assume that at least one endpoint is honest, such verification will prevent this attack.

Because BlindBox only supports attack rules at the HTTP application layer, this check is sufficient to prevent evasion. Almost all the rules in our datasets were in this category. Nonetheless, it is worth noting that, if an IDS were to support rules that detected attacks on the client driver or NIC – before verification –, an attacker *could* evade detection by not tokenizing.

2.4 Protocols

BlindBox provides three protocols. In Protocol I, a rule consists of one keyword. MB must be able to detect if the keyword appears at any offset in the traffic based on equality match. This protocol suffices for document watermarking [47] and parental filtering [13] applications, but can support only a few IDS rules. In Protocol II, a rule consists of multiple keywords as well as position information of these keywords. This protocol supports a wider class of IDS rules than Protocol I, as we elaborate in §8. Protocol I and II provide Exact Match Privacy, as discussed in §2.2.3. Protocol III additionally supports regular expressions and scripts, thus enabling a full IDS. Protocol III provides Probable Cause Privacy, as discussed in §2.2.3.

3. PROTOCOL I: BASIC DETECTION

Protocol I enables matching a suspicious keyword against the encrypted traffic. An attack rule in this protocol consists of one keyword. Even though this protocol is the simplest of our protocols, it introduces the majority of our techniques. The other protocols extend Protocol I.

To detect a keyword match on encrypted text, one naturally considers searchable encryption [48, 31]. However, existing searchable encryption schemes do not fit our setting for two reasons. First, the setup of searchable encryption requires the entity who has the secret key to encrypt the rules; this implies, in our setting, that the endpoints see the rules (which is not allowed as discussed in §2.2.2). Our obfuscated rule encryption addresses this problem.

Second, none of the existing schemes meet both of our security and network performance requirements. There are at least two kinds of searchable encryption schemes: deterministic and randomized. Deterministic schemes [15] leak whether two words in the traffic are equal to each other (even if they do not match a rule). This provides weak privacy because it allows an attacker to perform frequency analysis. At the same time, these schemes are fast because they enable MB to build fast indexes that can process each token (e.g. word) in a packet in time logarithmic in the number of rules. On the other hand, randomized schemes [48, 31] provide stronger security guarantees because they prevent frequency analysis by salting ciphertexts. However, the usage of the salt in these schemes requires combining each token with each rule, resulting in a processing time linear in the number of rules for each token; as we show in §8, this is too slow for packet processing. In comparison, our encryption scheme DPIEnc and detection protocol BlindBox Detect achieve the best of both worlds: the detection speed of deterministic encryption and the security of randomized encryption.

Let us now describe how each BlindBox module in Fig. 1 works in turn. Recall that S and R are the sender and receiver, MB the middlebox and RG the rule generator.

Tokenization. The first step in the protocol is to tokenize the input traffic. We start with a basic tokenization scheme, which we refer to as "window-based" tokenization because it follows a simple sliding window algorithm. For every offset in the bytestream, the sender creates a token of a fixed length: we used 8 bytes per token in our implementation. For example, if the packet stream is "alice apple", the sender generates the tokens "alice ap", "lice app", "ice appl", and so on. Using this tokenization scheme, MB will be able to detect rule keywords of length 8 bytes or greater. For a keyword longer than 8 bytes, MB splits it in substrings of 8 bytes, some of which may overlap. For example, if a keyword is "maliciously", MB can search for "maliciou" and "iciously". Since each encrypted token is 5 bytes long and the endpoint generates one encrypted token per byte of traffic, the bandwidth overhead of this approach is of $5\times$.

We can reduce this bandwidth overhead by introducing some optimizations. First, for an HTTP-only IDS (which does not analyze arbitrary binaries), we can have senders ignore tokenization for images and videos which the IDS does not need to analyze. Second, we can tailor our tokenization further to the HTTP realm by observing how the keywords from attack rules for these protocols are structured. The keywords matched in rules start and end before or after a delimiter. Delimiters are punctuation, spacing, and special symbols. For example, for the payload "login.php?user=alice", possible keywords in rules are typically "login", "login.php", "?user=", "user=alice", but not "logi" or "logi.ph". Hence, the sender needs to generate only those tokens that could match keywords that start and end on delimiter-based offsets; this allows us to ignore redundant tokens in the window. We refer to this tokenization as "delimiter-based" tokenization. In §8, we compare the overheads and coverage of these two tokenization protocols.

3.1 The DPIEnc Encryption Scheme

In this subsection, we present our new DPIEnc encryption scheme, which is used by the Encrypt module in Fig. 1. The sender encrypts each token t obtained from the tokenization with our encryption scheme. The encryption of a token t in DPIEnc is:

$$\boxed{\mathsf{salt},\ \mathsf{AES}_{\mathsf{AES}_k(t)}(\mathsf{salt}) \bmod \mathsf{RS}, \qquad (1)}$$

where salt is a randomly-chosen value and RS is explained below.

Let us explain the rationale behind DPIEnc. For this purpose, assume that MB is being handed, for each rule r, the pair $(r, \mathsf{AES}_k(r))$, but not the key k. We explain in §3.3 how MB actually obtains $\mathsf{AES}_k(r)$.

Let's start by considering a simple deterministic encryption scheme instead of DPIEnc: the encryption of t is $\mathsf{AES}_k(t)$. Then, to check if t equals a keyword r, MB can simply check if $\mathsf{AES}_k(t) \overset{?}{=} \mathsf{AES}_k(r)$. Unfortunately, the resulting security is weak because every occurrence of t will have the same ciphertext. To address this problem, we need to randomize the encryption.

Hence, we use a "random function" H together with a random salt, and the ciphertext becomes: $\mathsf{salt}, H(\mathsf{salt}, \mathsf{AES}_k(t))$. Intuitively, H must be pseudorandom and not invertible. To perform a match, MB can then compute $H(\mathsf{salt}, \mathsf{AES}_k(r))$ based on $\mathsf{AES}_k(r)$ and salt, and again perform an equality check. The typical instantiation of H is SHA-1, but SHA-1 is not as fast as AES (because AES is implemented in hardware on modern processors) and can reduce BlindBox's network throughput. Instead, we implement H with AES, but this must be done carefully because these primitives have different security properties. To achieve the properties of H, AES must be keyed with a value that MB does not know when there is no match to an attack rule – hence, this value is $\mathsf{AES}_k(t)$. Our algorithm is now entirely implemented in AES, which makes it fast.

Finally, RS simply reduces the size of the ciphertext to reduce the bandwidth overhead, but it does not affect security. In our implementation, RS is 2^{40}, yielding a ciphertext length of 5 bytes. As a result, the ciphertext is no longer decryptable; this is not a problem because BlindBox always decrypts the traffic from the primary SSL stream.

Now, to detect a match between a keyword r and an encryption of a token t, MB computes $\mathsf{AES}_{\mathsf{AES}_k(r)}(\mathsf{salt}) \bmod \mathsf{RS}$ using salt and its knowledge of $\mathsf{AES}_k(r)$, and then tests for equality with $\mathsf{AES}_{\mathsf{AES}_k(t)}(\mathsf{salt}) \bmod \mathsf{RS}$.

Hence, naïvely, MB performs a match test for every token t and rule r, which results in a performance per token linear in the number of rules; this is too slow. To address this slowdown, our detection algorithm below makes this cost logarithmic in the number of rules, the same as for vanilla inspection of unencrypted traffic. This results in a significant performance improvement: for example, for a ruleset with 10000 keywords to match, a logarithmic lookup is four orders of magnitude faster than a linear scan.

3.2 BlindBox Detect Protocol

We now discuss how our detection algorithm achieves logarithmic lookup times, resolving the tension between security and performance. For simplicity of notation, denote $\mathsf{Enc}_k(\mathsf{salt}, t) = \mathsf{AES}_{\mathsf{AES}_k(t)}(\mathsf{salt})$.

The first idea is to precompute the values $\mathsf{Enc}_k(\mathsf{salt}, r)$ for every rule r and for every possible salt. Recall that MB can compute $\mathsf{Enc}_k(\mathsf{salt}, r)$ based only on salt and its knowledge of $\mathsf{AES}_k(r)$, and MB does not need to know k. Then, MB can arrange these values in a search tree. Next, for each encrypted token t in the traffic stream, MB simply looks up $\mathsf{Enc}_k(\mathsf{salt}, t)$ in the tree and checks if an equal value exists. However, the problem is that enumerating all possible salts for each keyword r is infeasible. Hence, it would be desirable to use only a few salts, but this strategy affects security: an attacker at MB can see which token in the traffic equals which other token in the traffic whenever the salt is reused for the same token. To maintain the desired security, every encryption of a token t must contain a different salt (although the salts can repeat across different tokens).

To use only a few salts and maintain security at the same time, the idea is for the sender to *generate salts based on the token value* and *no longer send the salt in the clear along with every encrypted token*. Concretely, the sender keeps a *counter table* mapping each token encrypted so far to how many times it appeared in the stream so far. Before sending encrypted tokens, the sender sends one initial salt, salt_0, and MB records it. Then, the sender no longer sends salts; concretely, for each token t, the sender sends $\mathsf{Enc}_k(\mathsf{salt}, t)$ but not salt. When encrypting a token t, the sender checks the number of times it was encrypted so far in the counter table, say ct_t, which could be zero. It then encrypts this token with the salt $(\mathsf{salt}_0 + \mathsf{ct}_t)$ by computing $\mathsf{Enc}_k(\mathsf{salt}_0 + \mathsf{ct}_t, t)$. Note that this provides the desired security because no two equal tokens will have the same salt.

For example, consider the sender needs to encrypt the tokens A, B, A. The sender computes and transmits: salt_0, $\mathsf{Enc}_k(\mathsf{salt}_0, A)$, $\mathsf{Enc}_k(\mathsf{salt}_0, B)$, and $\mathsf{Enc}_k(\mathsf{salt}_0 + 1, A)$. Not sending a salt for each ciphertext both reduces bandwidth and is required for security: if the sender had sent salts, MB could tell that the first and second tokens have the same salt, hence they are not equal.

To prevent the counter table from growing too large, the sender resets it every P bytes sent. When the sender resets this table, the sender sets $\mathsf{salt}_0 \leftarrow \mathsf{salt}_0 + \max_t \mathsf{ct}_t + 1$ and announces the new salt_0 to MB.

For detection, MB creates a table mapping each keyword r to a counter ct^*_r indicating the number of times this keyword r appeared so far in the traffic stream. MB also creates a search tree containing the encryption of each rule r with a salt computed from ct^*_r: $\mathsf{Enc}_k(\mathsf{salt}_0 + \mathsf{ct}^*_r, r)$. Whenever there is a match to r, MB increments ct^*_r, computes and inserts the new encryption $\mathsf{Enc}_k(\mathsf{salt}_0 + \mathsf{ct}^*_r, r)$ into the tree, and deletes the old value. We now summarize the detection algorithm.

BlindBox Detect: The state at MB consists of the counters ct^*_r for each rule r and a fast search tree made of $\mathsf{Enc}_k(\mathsf{salt}_0 + \mathsf{ct}^*_r, r)$ for each rule r.

```
1:  For each encrypted token $\mathsf{Enc}_k(\mathsf{salt}, t)$ in a packet:
    1.1:  If $\mathsf{Enc}_k(\mathsf{salt}, t)$ is in the search tree:
          1.1.1:  There is a match, so take the corresponding action for this match.
          1.1.2:  Delete the node in tree corresponding to $r$ and insert $\mathsf{Enc}_k(\mathsf{salt}_0 + \mathsf{ct}^*_r + 1, t)$
          1.1.3:  Set $\mathsf{ct}^*_r \leftarrow \mathsf{ct}^*_r + 1$
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With this strategy, for every token t, MB performs a simple tree lookup, which is logarithmic in the number of rules. Other tree operations, such as deletion and insertion, happen rarely: when a malicious keyword matches in the traffic. These operations are also logarithmic in the number of rules.

3.3 Rule Preparation

The detection protocol above assumes that MB obtains $\mathsf{AES}_k(r)$ for every keyword r, every time a new connection (having a new key k) is setup. But how can MB obtain these values? The challenge here is that no party, MB or S/R, seems fit to compute $\mathsf{AES}_k(r)$: MB knows r, but it is not allowed to learn k; S and R know k, but are not allowed to learn the rule r (as discussed in §2.2.2).

Intuition. We provide a technique, called *obfuscated rule encryption*, to address this problem. The idea is that the sender provides to the middlebox an "obfuscation" of the function AES with the key k hardcoded in it. This obfuscation hides the key k. The middlebox runs this obfuscation on the rule r and obtains $\mathsf{AES}_k(r)$, without learning k. We denote this obfuscated function by ObfAES_k.

Since practical obfuscation does not exist, we implement it with Yao garbled circuits [52, 36], on which we elaborate below. With garbled circuits, MB cannot directly plug in r as input to $\mathsf{ObfAES}_k()$; instead, it must obtain from the endpoints an encoding of r that works with ObfAES_k. For this task, the sender uses a protocol called oblivious transfer [37, 14], which does not reveal r to the endpoints. Moreover, MB needs to obtain a fresh, re-encrypted garbled circuit $\mathsf{ObfAES}_k()$ for every keyword r; the reason is that the security of garbled circuits does not hold if MB receives more than one encoding for the same garbled circuit.

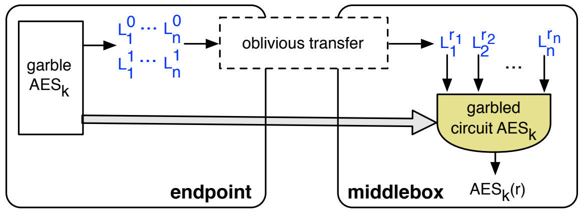


Figure 2: Rule preparation. The endpoint has a key k and the middlebox has a keyword r.

A problem is that MB might attempt to run the obfuscated encryption function on rules of its choice, as opposed to rules from RG. To prevent this attack, rules from RG must be signed by RG and the obfuscated (garbled) function must check that there is a valid signature on the input rule before encrypting it. If the signature is not valid, it outputs null.

Let us now present the building blocks and our protocol in more detail.

Yao garbling scheme [52, 36]. At a high level, a garbled circuit scheme, first introduced by Yao, consists of two algorithms Garble and Eval. Garble takes as input a function F with n bits of input and outputs a garbled function ObfF and n pairs of labels $(L_1^0, L_1^1), \ldots, (L_n^0, L_n^1)$, one pair for every input bit of F. Consider any input x of n bits with x_i being its i-th bit. ObfF has the property that $\mathsf{ObfF}(L_1^{x_1}, \ldots, L_n^{x_n}) = F(x)$. Basically, ObfF produces the same output as F if given the labels corresponding to each bit of x. Regarding security, ObfF and $L_1^{x_1}, \ldots, L_n^{x_n}$ do not leak anything about F and x beyond $F(x)$, as long as an adversary receives labels for only one input x.

1-out-of-2 oblivious transfer (OT) [37, 14]. Consider that a party A has two values, L^0 and L^1, and party B has a bit b. Consider that B wants to obtain the b-th label from A, L^b, but B does not want to tell b to A. Also, A does not want B to learn the other label L^{1-b}. Hence, B cannot send b to A and A cannot send both labels to B. Oblivious transfer (OT) enables exactly this: B can obtain L^b without learning L^{1-b} and A does not learn b.

Rule preparation. Fig. 2 illustrates the rule preparation process for one keyword r. One endpoint could be malicious and attempt to perform garbling incorrectly to eschew detection. To prevent such an attack, both endpoints have to prepare the garbled circuit and send it to MB to check that they produced the same result. If the garbled circuits and labels match, MB is assured that they are correct because at least one endpoint is honest (as discussed in Sec. 2.2.2). To enable this check, the endpoints must use the same randomness obtained from a pseudorandom generator seeded with k_{rand} (discussed in Sec. 2.3).

```
Rule preparation:
  1: MB tells S and R the number of rules $N$ it has.
  2: For each rule $1, \ldots, N$, do:
     2.1: S and R: Garble the following function $F$.
          $F$ on input $[x, \mathsf{sig}(x)]$ checks if $\mathsf{sig}(x)$ is a
          valid signature on $x$ using RG's public key.
          If yes, it encrypts $x$ with $\mathsf{AES}_k$ and outputs
          $\mathsf{AES}_k(x)$; else, it outputs $\perp$.
          In the garbling process, use randomness
          based on $k_{\mathsf{rand}}$. Send the resulting garbled circuit and labels to MB.
     2.2: MB: Verify that the garbled circuits from S
          and R are the same, and let $\mathsf{ObfAES}_k$ be this
          garbled circuit. Let $r$ and $\mathsf{sig}(r)$ be the current
          rule and its signature. Run oblivious
          transfer with each of S and R to obtain the
          labels for $r$ and $\mathsf{sig}(r)$. Verify that the labels
          from S and R are the same, and denote them
          $L_1^{r_1}, \ldots, L_n^{r_n}$.
     2.3: MB: Evaluate $\mathsf{ObfAES}_k$ on the labels
          $L_1^{r_1}, \ldots, L_n^{r_n}$ to obtain $\mathsf{AES}_k(r)$.
```

Rule preparation is the main performance overhead of BlindBox HTTPS. This overhead comes from the oblivious transfer and from the generation, transmission and evaluation of the garbled circuit, all of which are executed once for every rule. We evaluate this overhead in §8.

We additionally use a performance optimization that, instead of garbling the verification of sig, it garbles a hash computation while achieving the same security level.

3.4 Validate Tokens

As shown in Fig. 1, the validate tokens procedure runs at the receiver. This procedure takes the decrypted traffic from SSL and runs the same tokenize and encrypt modules as the sender executes on the traffic. The result is a set of encrypted tokens and it checks that these are the same as the encrypted tokens forwarded by MB. If not, there is a chance that the other endpoint is malicious and flags the misbehavior.

3.5 Security Guarantees

We proved our protocol secure with respect to our exact match privacy model; the proofs can be found in the Appendix. We formalized the property that DPIEnc hides the traffic content from MB using an indistinguishability-based security definition. Informally, MB is given encryptions of a sequence of tokens $t'_1, \ldots, t'_n$ and keywords $r_1, \ldots, r_m$. Then, MB can choose two tokens t_0 and t_1 which do not match any of the keywords. Next, MB is given a ciphertext $c = \mathsf{Enc}_k(\mathsf{salt}, t_b)$ for some bit b and salt generated according to the BlindBox Detect protocol. The security property says that no polynomial-time attacker at MB can guess the value of b with chance better than half. In other words, MB cannot tell if t_0 or t_1 is encrypted in c. We can see why this property holds intuitively: if MB does not have $\mathsf{AES}_k(t_b)$, this value is indistinguishable from a random value by the pseudorandom permutation property of AES. Hence, $\mathsf{Enc}_k(\cdot, t_b)$ maps each salt to a random value, and there are no repetitions among these random values due to the choice of salt in BlindBox Detect. Thus, the distributions of ciphertexts for each value of b are essentially the same, and thus indistinguishable.

As part of our privacy model, BlindBox reveals a small amount of information to make detection faster: BlindBox does not hide the number of tokens in a packet. Also, if a suspicious keyword matches at an offset in the traffic stream, MB learns this offset. Hence, BlindBox necessarily weakens the privacy guarantees of SSL to allow efficient detection. (Note that BlindBox preserves the authenticity property of SSL.)

4. PROTOCOL II: LIMITED IDS

This protocol supports a limited form of an IDS. Namely, it allows a rule to contain: (1) multiple keywords to be matched in the traffic, and (2) absolute and relative offset information within the packet. In our industrial dataset, the average *rule* contained three *keywords*; a rule is "matched" if all keywords are found within a flow.

This protocol supports most of the functionality in the rule language of Snort [49]. A few functional commands are not supported, the most notable being *pcre*, which allows arbitrary regular expressions to be run over the payload. This command is supported by Protocol III.

For example, consider rule number 2003296 from the Snort Emerging Threats ruleset:

```
alert tcp $EXTERNAL_NET $HTTP_PORTS
                                  -> $HOME_NET 1025:5000 (
  flow: established,from_server;
  content: "Server|3a| nginx/0.";
  offset: 17; depth: 19;
  content: "Content-Type|3a| text/html";
  content: "|3a|80|3b|255.255.255.255"; )
```

This rule is triggered if the flow is from the server, it contains the keyword "Server|3a| nginx/0." at an offset between 17 and 19, and it also contains the keyword "Content-Type|3a| text/html" and "|3a|80|3b|255.255.255.255". The symbol "|" denotes binary data.

Protocol II builds on Protocol I in a straightforward way. The sender processes the stream the same as in Protocol I (including the encryption) with one exception: if the delimiter-based tokenization is used, the sender attaches to each encrypted token the offset in the stream where it appeared. In the window-based tokenization, the offset information need not be attached to each encrypted token because a token is generated at each offset and hence the offset can be deduced.

Detection happens similarly to before. For each encrypted token, MB checks if it appears in the rule tree. If so, it checks whether the offset of this encrypted token satisfies any range that might have been specified in the relevant rule. If all the fields of the relevant rule are satisfied, MB takes the action indicated by the rule.

Security Guarantee. The security guarantee is the same as in Protocol I: for each rule keyword, the middlebox learns if the keyword appears in the traffic and at what offset, but it learns nothing else about the parts of the traffic that do not match keywords. Note that the security guarantee is defined per keyword and not per rule: MB learns when a keyword matches even if the entire rule does not match.

5. PROTOCOL III: FULL IDS WITH PROBABLE CAUSE PRIVACY

This section enables full IDS functionality, including regexp and scripts, based on our probable cause privacy model. If a keyword from a rule (a suspicious keyword) matches a stream of traffic, MB should be able to decrypt the traffic. This enables the middlebox to then run regexp (e.g., the "pcre" field in Snort) or scripts from Bro [39] on the decrypted data. However, if such a suspicious keyword does not match the packet stream, the middlebox cannot decrypt the traffic (due to cryptographic guarantees), and the security guarantee is the same as in Protocol II.

Protocol insight. The idea is to somehow embed the SSL key k_{SSL} into the encrypted tokens, such that, if MB has a rule keyword r that matches a token t in the traffic, MB should be able to compute k_{SSL}. To achieve this goal, we replace the encrypted token $\mathsf{Enc}_k(\mathsf{salt}, t)$ with $\mathsf{Enc}_k(\mathsf{salt}, t) \oplus k_{\mathsf{SSL}}$, where $\oplus$ is bitwise XOR. If $r = t$, MB has $\mathsf{AES}_k(t)$ and can construct $\mathsf{Enc}_k(\mathsf{salt}, t)$, and then obtain k_{SSL} through a XOR operation. The problem is that this slows down detection to a linear scan of the rules because the need to compute the XOR no longer allows a simple tree lookup of an encrypted token into the rule tree (described in Sec. 3.2).

Protocol. To maintain the efficiency of the detection, we retain the same encrypted token as in DPIEnc and use it for detection, but additionally create an encrypted token that has the key embedded in as above. Now, the encryption of a token t becomes a pair $[c_1 = \mathsf{Enc}_k(\mathsf{salt}, t), c_2 = \mathsf{Enc}^*_k(\mathsf{salt}, t) \oplus k_{\mathsf{SSL}}]$, where $\mathsf{Enc}^*_k(\mathsf{salt}, t) = \mathsf{AES}_{\mathsf{AES}_k(t)}(\mathsf{salt} + 1)$ and the salt is generated as in BlindBox Detect (§3.2). Note that it is crucial that the salt in Enc^*_k differs from the salt in any c_1 encryption of t because otherwise an attacker can compute $c_1 \oplus c_2$ and obtain k_{SSL}. To enforce this requirement across different occurrences of the same token in BlindBox Detect, the sender now *increments the salt by two*: it uses an even salt for c_1 (and so does MB for the rules in the tree), while it uses an odd salt for c_2. MB uses c_1 to perform the detection as before. If MB detects a match with rule r using BlindBox Detect, MB computes $\mathsf{Enc}^*_k(\mathsf{salt}, r)$ using $\mathsf{AES}_k(r)$, and computes $\mathsf{Enc}^*_k(\mathsf{salt},\ r) \oplus c_2$, which yields k_{SSL}. We prove the security of this protocol in the Appendix.

6. DISCUSSION

In this section, we discuss adoption of BlindBox and privacy implications of the choice of rules and tokenization strategy in BlindBox.

6.1 Adoption

ISP Adoption. In enterprises and private networks, BlindBox provides a good trade-off between the desires of users (who want privacy, and may want processing) and the network administrator (who wants to deploy processing primarily, and is willing to respect privacy if able to do so). Hence, deploying BlindBox is aligned with both parties' interests. However, in ISPs, sales of user data to marketing and analytics firms are a source of revenue – hence, an ISP has an incentive *not* to deploy BlindBox. Consequently, deployment in ISPs is likely to take place either under legislative requirement through privacy laws, or through a change in incentives. The growing trend of middlebox processing being offered as a "service" – which users opt in to and pay for – may offer an incentive for an ISP to deploy BlindBox with the promise of a new revenue stream directly from the user.

Client Adoption. BlindBox proposes a new end-to-end encryption protocol to replace HTTPS altogether. A truly ideal solution would require no changes at the endpoints – indeed, the success of middlebox deployments is partly due to the fact that middleboxes can be simply "dropped in" to the network. Unfortunately, existing HTTPS encryption algorithms use strong encryption schemes, which do not support *any* functional operations and cannot be used for our task; hence one must change HTTPS. Nonetheless, we believe that, in the long run, a change to HTTPS to allow inspection of encrypted traffic can be generic enough to support a wide array of middlebox applications, and not just the class of middleboxes in BlindBox. We believe these benefits will merit widespread "default" adoption in end host software suites.

6.2 Privacy implications of choice of rules and tokenization

The choice of rules affects privacy significantly. In the extreme, rules that match each letter 'a', 'b', ..., 'z', result in no privacy at all.

With BlindBox, rule designers must consider privacy implications of the rules they choose: ideally, a keyword should not match benign traffic at all.

Note that we do *not* provide guidelines on how to choose keywords or rules that are safe to use with our protocols; we contribute *only* the mechanism for implementing matching and probable cause decryption once the rules are chosen carefully. Choosing rules in a way that preserves matching and privacy requires careful thought.

In fact, we emphasize that some existing rules are *not safe* to use with our protocols, and need to be changed. This is not surprising considering that existing rules were not written with privacy in mind. For example, in the Snort community rules, there are rules with keywords that match often such as

'.exe'. This can cause frequent matching in Protocol II or frequent decryption in Protocol III.

An interesting future work question is to design a scheme that enables the middlebox to learn if a rule matches in an all-or-nothing way: that is, if a rule has more than one keyword, the middlebox should learn only if all strings match, and not if a subset of them match.

6.2.1 *How to tokenize given rules*

Consider a set of rules. Define "effective keyword" to be a keyword that must be matched by BlindBox on the traffic. For Protocol II, every keyword of each rule is an effective keyword. For Protocol III, there is one effective keyword per rule as defined in §6.2.2. Since effective keywords have different lengths, the tokenization can happen in lengths of 2, 4, 8, 16, 32, 64, and 128. If an effective keyword is of size ℓ, a rule keyword is tokenized using the *largest* token size at most ℓ. For example, if the string is size 65, it is broken into two strings each of size 64 that overlap in 63 positions. One must *not* break the effective keywords in smaller tokens because this will leak more than necessary. Hence, for example, if there is only one effective keyword that is short, say of length 4, tokens of size 4 in the traffic will match only this effective keyword and not other rules.

6.2.2 *Tokenization for Protocol III*

Given a rule for Protocol III, to decrease the frequency of decryption, the probable cause decryption must be triggered by a string in this rule that appears in the traffic as infrequently as possible (ideally, only when the traffic is suspicious). This string can be a keyword or a substring of a regular expression that is matched by equality. Probable cause decryption should be triggered by only one such string per rule (because a rule matches only when all such strings match). For example, for a rule with content ='abc' and content = 'abcdefghij', the trigger should be the second string. If the rule additionally contains pcre = '[1-9]abcdefghij123', the trigger should be 'abcdefghij123'.

Furthermore, our subsequent work on Embark [35] converts a class of regular expressions into exact matching. Thus, for some rules, one can use Protocol II instead of Protocol III and avoid probable cause decryption. For example, for Snort community, BlindBox would resort to Protocol III for 33% of rules, but Embark would only require this for 11.3%. With Snort Emerging Threats, BlindBox would use Protocol III for 58% of rules, but Embark would only do so for 20.2%.

7. SYSTEM IMPLEMENTATION

We implemented two separate libraries for BlindBox: a client/server library for transmission called BlindBox HTTPS, and a Click-based [34] middlebox.

BlindBox library. The BlindBox HTTPS protocol is implemented in a C library. When a client opens a connection, our protocol actually opens three separate sockets: one over normal SSL, one to transmit the "searchable" encrypted tokens, and one to listen if a middlebox on path requests garbled circuits. The normal SSL channel runs on top of a modified GnuTLS [12] library which allows us to extract the session key under Protocol III. On send, the endpoint first sends the encrypted tokens, and then sends the traffic over normal HTTPS. If there is a middlebox on the path, the endpoints generate garbled circuits using JustGarble [16] in combination with the OT Extension library [5].

The middlebox. We implemented the middlebox in multi-threaded Click [34] over DPDK [2]; in our implementation, half of the threads perform detection over the data stream ("detection" threads), and half perform obfuscated rule encryption exchanges with clients ("garble" threads). When a new connection opens, a detection thread signals to a garble thread and the garble thread opens an obfuscated rule encryption channel with the endpoints. Once the garble thread has evaluated all circuits received from the clients and obtained the encrypted rules, it constructs the search tree. The detection thread then runs the detection based on the search tree, and allows data packets in the SSL channel to proceed if no attack has been detected.

When a detection thread matches a rule, under Protocols I and II, the middlebox blocks the connection. Under Protocol III, it computes the decryption key (which is possible due to a match), and it forwards the encrypted traffic and the key to a decryption element. This element is implemented as a wrapper around the open-source ssldump [10] tool. The decrypted traffic can then be forwarded to any other system (Snort, Bro, etc.) for more complex processing. We modeled this after SSL termination devices [18], which today man-in-the-middle traffic before passing it on to some other monitoring or DPI device.

8. EVALUATION

When evaluating BlindBox, we aimed to answer two questions. First, can BlindBox support the functionality of our target applications – data exfiltration (document watermarking), parental filtering, and HTTP intrusion detection? Second, what are the performance overheads of BlindBox at both the endpoints and the middlebox?

8.1 Functionality Evaluation

To evaluate the functionality supported by BlindBox, we answer a set of sub-questions.

Can BlindBox implement the functionality required for each target system? Table 1 shows what fraction of "rules" for different target applications rely solely on single-exact match (as in Protocol I), multiple exact-match strings (as in Protocol II), or regular expressions or scripts (as in Protocol III). We evaluate this using public datasets for document watermarking [47], parental filtering [13], and IDS rules (from the Snort community [9] and Emerging Threats [3]). In addition, we evaluate on two industrial datasets from Lastline and McAfee Stonesoft to which we had (partial) access.

Document watermarking and parental filtering can be completely supported using Protocol I because each system relies only on the detection of a single keyword to trigger an alarm. However, Protocol I can support only between 1.6-5% of the policies required by the more general HTTP IDS applications (the two public Snort datasets, as well as the datasets from McAfee Stonesoft and Lastline). This limitation is due to the fact that most IDS policies require detection of multiple keywords or regular expressions.

Protocol II, by supporting multiple exact match keywords, extends support to 29-67% of policies for the HTTP IDS applications. Protocol III supports all applications including regular expressions and scripting, by enabling decryption when there is a probable cause to do so.

What fraction of existing rules can be used with Protocol II and a given minimum token length? Protocol II allows a middlebox to search for multiple exact-match strings to detect an attack. A rule generator may choose to restrict the minimum size of transmitted tokens to avoid many false positive matches (trivially, the set of rules 'a', 'b'... 'z' would allow a middlebox to decrypt all text), requiring tokens of 4, 8, or 16 bytes. Figure 3 shows the number of rules from the Emerging Threats Snort ruleset such that all search strings in the rule are n characters long or more. This further reduces the number of rules that can be implemented with BlindBox 'as is.' A rule generator may be able to rewrite these rules such that they do not require searches for such short tokens, removing the short terms and potentially adding in additional search terms to avoid increasing false positives. We leave an exploration of such a mechanism to future work.

Does BlindBox fail to detect any attacks/policy violations that these standard implementations would detect? The answer depends on which tokenization technique one uses out of the two techniques we described in §3: window-based and delimiter-based tokenization. The window-based tokenization does not affect the detection accuracy of the rules because it creates a token at every offset. The delimiter-based tokenization relies on the assumption that, in IDSes, most rules occur on the boundary of non-alphanumeric characters, and thus does not transmit all possible tokens – only those required to detect rules which occur between such "delimiters". To test if this tokenization misses attacks, we ran BlindBox over the ICTF2010 [51] network trace, and used as rules the Snort Emerging Threats ruleset from which we removed the rules with regular expressions. The ICTF trace was generated during a college "capture the flag" contest during which students attempted to hack different servers to win the competition, so it contains a large number of attacks. We detected 97.1% of the attack keywords and 99% of the attack rules that would have been detected with Snort. (Recall that an attack rule may consist of multiple keywords.)

8.2 Performance Evaluation

We now investigate BlindBox's performance overheads at both the client and the network. For all experiments, the client software uses Protocol II, which has higher overhead than Protocol I. We do not evaluate Protocol III directly; the differences we would expect from Protocol III relative to II would include a secondary middlebox to perform regular expression processing, and an increase in bandwidth due to the key being embedded in each encrypted token.

Our prototype of the client software runs on two servers with 2.60 GHz processors connected by a 10GbE link. The machines are multicore, but we used only one thread per client. The CPU supports AES-NI instructions and thus the encryption times for both SSL and BlindBox reflect this hardware support. Since typical clients are not running in the same rack over a 10GbE links, in some experiments we reduced throughput to 20Mbps (typical of a broadband home link) and increased latency to 10ms RTT. Our prototype middlebox runs with four 2.6GHz Xeon E5-2650 cores and 128 GB RAM; the network hardware is a single 10GbE Intel 82599 compatible network card. All of our experiments were performed on this testbed. For microbenchmarks (as in Table 2), we measured time to complete a loop of 10,000 iterations and took an average. For flow completion benchmarks we took an average of five runs.

To summarize our performance results, BlindBox is practical for long-lived connections: the throughput of encryption and detection are comparable with rates of current (unencrypted) deployments. Additionally, BlindBox is 3 to 6 orders of magnitude faster than relevant implementations using existing cryptography; these solutions, by themselves, are incomplete in addition to being slow. The primary overhead of BlindBox is setting up a connection, due to the obfuscated rule encryption. This cost is small for small rulesets, but can take as long as 1.5 minutes for rulesets with thousands of

Dataset	I.	II.	III.
Document watermarking [47]	100%	100%	100%
Parental filtering [13]	100%	100%	100%
Snort Community (HTTP)	3%	67%	100%
Snort Emerging Threats (HTTP)	1.6%	42%	100%
McAfee Stonesoft IDS	5%	40%	100%
Lastline	0%	29.1%	100%

Table 1: Fraction of attack rules in public and industrial rule sets addressable with Protocols I, II, and III.

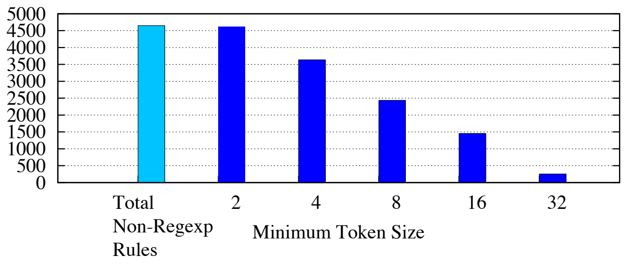


Figure 3: Number of rules in the Emerging Threats dataset which (a) do not require regular expressions, and (b) search for exact match strings of minimum lengths 2 - 32.

rules; hence, BlindBox is not yet practical for systems with thousands of rules and short-lived connections that need to run setup frequently. We now elaborate on all these points.

8.2.1 Strawmen

BlindBox is the only system we know of to enable DPI over encrypted data. Nevertheless, to understand its performance, we compare it to standard SSL as well as two strawmen, which we now describe.

A searchable encryption scheme due to Song et al. [48]: This scheme does not enable obfuscated rule encryption or probable cause decryption, but can implement encryption and detection as in Protocols I and II (but not Protocol III). We used the implementation of Song et al. from [40], but replaced the use of SHA512 with the AES-NI instruction in a secure way, to speed up this scheme.

Generic functional encryption (FE) [24, 28]: Such schemes, if enhanced with our obfuscated rule encryption technique, can in theory perform Protocols I, II, and III. However, such encryption schemes are prohibitively expensive to be run and evaluated. For example, one such scheme [28] nests fully homomorphic encryption twice, resulting in an overhead of at least 10 orders of magnitude. Instead, we chose and implemented a simple and specialized functional encryption scheme due to Katz et al. [32]. The performance of this scheme is a generous lower bound on the performance of the generic protocols (the Katz et al. scheme does not support Protocol III because it can compute only inner product).

8.2.2 Client Performance

How long does it take to encrypt a token? Table 2 provides micro-benchmarks for encryption, detection, and setup using BlindBox, HTTPS, and our strawmen. With HTTPS (using GnuTLS), encryption of one 128-bit block took on average 13ns, and 3μs per 1400 byte packet. BlindBox increases these values to 69ns and 90μs respectively. These figures include the time to perform HTTPS transmission in the primary channel, as well as the overheads from BlindBox: the tokenization process itself (deciding which substrings to tokenize) as well as the encryption process (encrypting and then hashing each token with AES). The searchable strawman performs encryption of a single token on average 2.7μs and 257μs for an entire packet; the primary overhead relative to BlindBox here is multiple calls to `/dev/urandom` because the scheme requires random salts for every token. With fixed or pre-chosen salts, we would expect the searchable strawman to have comparable encryption times to BlindBox. As we discuss, the detection times for this strawman are slower. The FE strawman takes six orders of magnitude longer than BlindBox and is even further impractical: a client using this scheme could transmit at most one packet every 15 seconds.

How long does the initial handshake take with the middlebox? The initial handshake to perform obfuscated rule encryption runs in time proportional to the number of rules. In the datasets we worked with, the average Protocol II rule had slightly more than 3 keywords; a typical 3000 rule IDS rule set contains between 9-10k keywords. The total client-side time required for 10k keywords was 97 seconds; for 1000 keywords, setup time was 9.5s. In a smaller ruleset of 10 or 100 keywords (which is typical in a watermark detection exfiltration device), setup ran in 650ms and 1.6 seconds, respectively. These values are dependent on the clock speed of the CPU (to generate the garbled circuits) and the network bandwidth and latency (to transmit the circuits from client to sender). Our servers have 2.6GHz cores; we assumed a middlebox on a local area network near the client with a 100μs RTT between the two and a 1Gbps connection. Garbling a circuit took 1042μs per circuit; each garbled circuit transmission is 599KB.

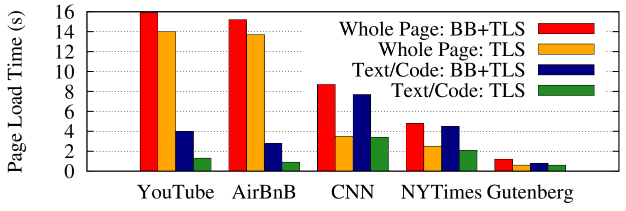


Figure 4: Download time for TLS and BlindBox (BB) + TLS at 20Mbps$\times$10ms.

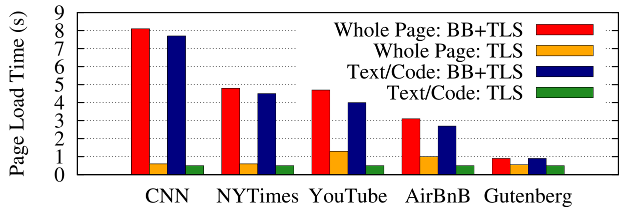


Figure 5: Download time for TLS and BlindBox (BB) + TLS at 1Gbps$\times$10ms.

Neither strawman has an appropriate setup phase that meets the requirement of not making the rules visible to the endpoints. However, one can extend these strawmen with BlindBox's obfuscated rule encryption technique, and encrypt the rules using garbled circuits. In this case, for the scheme of Song et al., the setup cost would be similar to the one of BlindBox because their scheme also encrypts the rule keywords with AES. For the scheme of Katz et al., the setup would be much slower because one needs garbled circuits for modular exponentiation, which are huge. Based on the size of such circuits reported in the literature [16], we can compute a generous lower bound on the size of the garbled circuits and on the setup cost for this strawman: it is at least $1.8 \cdot 10^3$ times larger/slower than the setup in BlindBox.

How long are page downloads with BlindBox, excluding the setup (handshake) cost? Figure 4 shows page download times using our "typical end user" testbed with 20Mbps links. In this figure, we show five popular websites: YouTube, AirBnB, CNN, The New York Times, and Project Guten-

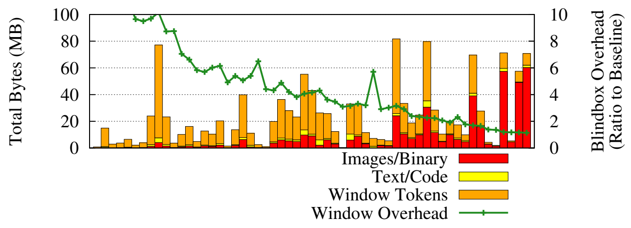
		Vanilla HTTPS	**FE Strawman**	**Searchable Strawman**	**BlindBox HTTPS**
Client	*Encrypt* (128 bits)	13ns	70ms	2.7μs	69ns
	Encrypt (1500 bytes)	3μs	15s	257μs	90μs
	Setup (1 Keyword)	73ms	N/A	N/A	588 ms
	Setup (3K Rules)	73ms	N/A	N/A	97 s
MB	*Detection:*				
	1 Rule, 1 Token	NP	170ms	1.9μs	20ns
	1 Rule, 1 Packet	NP	36s	52μs	5μs
	3K Rules, 1 Token	NP	8.3 minutes	5.6ms	137ns
	3K Rules, 1 Packet	NP	5.7 days	157ms	33μs

Table 2: Connection and detection micro-benchmarks comparing Vanilla HTTPS, the functional encryption (FE) strawman, the searchable strawman, and BlindBox HTTPS. NP stands for not possible. The average rule includes three keywords.

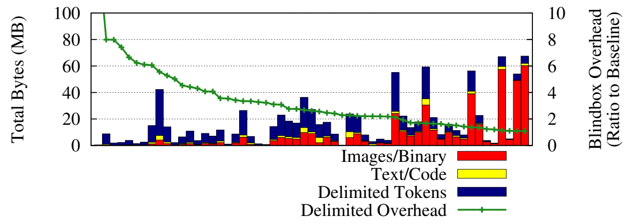
berg. The data shown represents the post-handshake (persistent connection) page download time, with tokenization on 8-byte boundaries. YouTube and AirBnB load video, and hence have a large amount of binary data which is not tokenized. CNN and The New York Times have a mixture of data, and Project Gutenberg is almost entirely text. We show results for both the amount of time to download the page including all video and image content, as well as the amount of time to load only the Text/Code of the page. The overheads when downloading the whole page are at most 2×; for pages with large amount of binary data like YouTube and AirBnB, the overhead was only 10-13%. Load times for Text/Code only – which are required to actually begin rendering the page for the user – are impacted more strongly, with penalties as high as 3× and a worst case of about 2×.

What is the computational overhead of BlindBox encryption, and how does this overhead impact page load times? While the encryption costs are not noticeable in the page download times observed over the "typical client" network configuration, we immediately see the cost of encryption overhead when the available link capacity increases to 1Gbps in Figure 5 – at this point, we see a performance overhead of as much as 16× relative to the baseline SSL download time. For both runs (Figs. 4 and 5), we observed that the CPU was almost continuously fully utilized to transfer data during data transmission. At 20Mbps, the encryption cost is not noticeable as the CPU can continue producing data at around the link rate; at 1Gbps, transmission with BlindBox stalls relative to SSL, as the BlindBox sender cannot encrypt fast enough to keep up with the line rate. This result is unsurprising given the results in Table 2, showing that BlindBox takes 30× longer to encrypt a packet than standard HTTPS. This overhead can be mitigated with extra cores; while we ran with only one core per connection, tokenization can easily be parallelized.

What is the bandwidth overhead of transmitting encrypted tokens for a typical web page? Minimizing bandwidth overhead is key to client performance: less data transmitted means less cost, faster transfer times, and faster detection times. The bandwidth overhead in BlindBox depends on the number of tokens produced. The number of encrypted tokens varies widely depending on three parameters of the page being loaded: what fraction of bytes are text/code which must be tokenized, how "dense" the text/code is in number of delimiters, and whether or not the web server and client support compression.



(a) Window-Based Tokenization



(b) Delimiter-Based Tokenization

Figure 6: Bandwidth overhead over top-50 web dataset.

Figures 6 (a) and (b) break down transmitted data into the number of text-bytes, binary-bytes, and tokenize-bytes using the window-based and delimiter-based tokenization algorithms (as discussed in §3); the right hand axis shows the overhead of adding tokens over transmitting just the original page data. We measured this by downloading the Alexa top-50 websites [1] and running BlindBox over all page content (including secondary resources loaded through AJAX, callbacks, etc.) The median page with delimited tokens sees a 2.5× increase in the number of bytes transmitted. In the best case, some pages see only a 1.1× increase, and in the worst case, a page sees a 14× overhead. The median page with window tokens sees a 4× increase in the number of bytes transmitted; the worst page sees a 24× overhead. The first observable factor affecting this overhead, as seen in these figures, is simply what fraction of bytes in the original page load required tokenization. Pages consisting mostly of video suffered lower penalties than pages with large amounts of

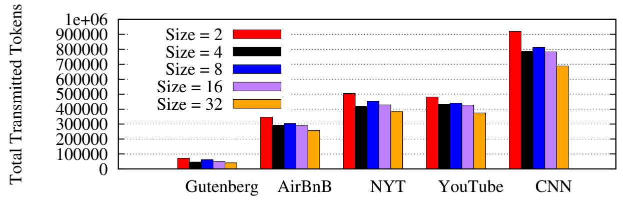


Figure 7: Tokens generated for each of six popular websites using delimiter-based tokenization and a minimum token size between 1-32 bytes.

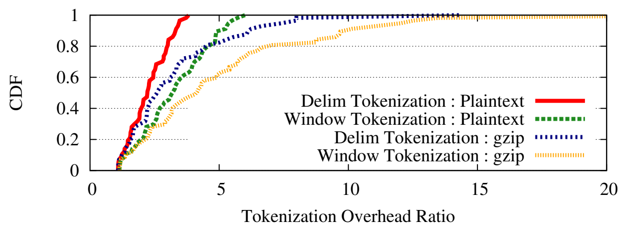


Figure 8: Ratio: transmitted bytes with BlindBox to transmitted bytes with SSL.

text, HTML, and Javascript because we do not tokenize video.

A second factor, better observed in Figures 8 and 9(a) is whether or not the web server hosting the page supports gzip compression. Many web servers will compress content before sending it to clients, which then unzip the data before passing to rendering in the browser. Where window based tokenization imposes a penalty of one token (five bytes) per plaintext byte (and delimiter-based tokenization imposes less than half of a token – 2.2 bytes – by eliminating tokens which are redundant to the DPI engine), compressing the plaintext makes the perceived penalty higher: the baseline data can be compressed, but encrypted tokens cannot. In Figure 8 we show a CDF of the ratio of BlindBox bytes to SSL bytes when gzip is not enabled, and when gzip is enabled exactly as in the original trace (i.e. we compare against the bytes gzipped when we downloaded the dataset from the webservers; if any data was not compressed we left it as-is and did not try to compress it further). When compared against plaintext, both window and delimiter based tokenization have “tight” tails – the worst page with window based tokenization has slightly more than $5\times$ overhead, and the worst page with delimiter tokenization has around $4\times$ overhead. But, for pages which benefit strongly from compression, the penalty can begin to look dramatic at the tail, going as high as $24\times$ for one page (Craigslist.com, which is mostly text/code and benefits strongly from compression). Figure 9(a) shows for each page the number of tokens produced on average per byte, plotted against the page reduction achieved by the web server by using gzip.

The final factor is simply the number of delimiters seen in a page – text-only pages like Project Gutenberg do well

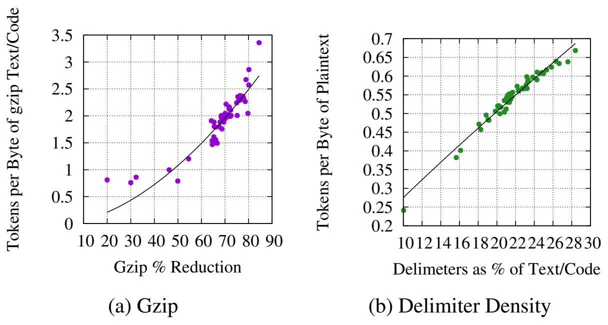


Figure 9: Impact of compression and delimiter density on tokenization overhead for delimiter-based tokenization only.

in this metric, since there are few code-like characters in the text. The worst performers in this area are pages which make large use of compressed javascript code, where a large fraction of characters result in tokenization. Figure 9(b) illustrates this effect for the same dataset as previously.

8.2.3 Middlebox Performance

We investigate performance at the middlebox using both micro-benchmarks and overall throughput.

What throughput can BlindBox sustain and how does this compare to standard IDS? When running our BlindBox implementation over synthetic traffic, we measured a throughput of 166Mbps; when running Snort over the same traffic, we measured a throughput of 85Mbps. Hence, BlindBox performed detection twice as fast as Snort, which inspects *unencrypted* traffic. The reason behind this situation is twofold. First, BlindBox reduces all detection to exact matching, pushing all regular expression parsing to a secondary middlebox, invoked rarely. Second, our implementation is built over DPDK-click, a faster packet-capture library than what Snort uses by default. Hence, it is unsurprising that BlindBox performs detection more quickly. Nevertheless, the point of this experiment is not to show that BlindBox is faster than Snort, but instead to demonstrate that BlindBox provides competitive performance to today’s deployments.

How does BlindBox compare in detection time against other strawmen approaches? While we did not implement a version of BlindBox which relied on our strawmen, we can compare against it using a smaller benchmark. Once again, in Table 2, the FE strawman is seen to be prohibitively impractical: detection over a single packet against a 3000 ruleset takes more than a day.

The searchable strawman is also prohibitively slow: it performs detection over a 1500 byte packet in 157 ms, which is equivalent to no more than 6-7 packets per second. This performance is three orders of magnitude slower than the performance of BlindBox’s middlebox. This overhead results from the fact that the searchable strawman must perform an encryption operation over every keyword to perform a comparison against a client token, resulting in a task linear in the number of keywords. In contrast, BlindBox's DPIEnc scheme encrypts the data in such a way that the middlebox can use a fast, pre-computed search tree (which gives a logarithmic search) to match encrypted tokens to rules.

9. RELATED WORK

Related work falls into two categories: insecure proposals, and work on computing on encrypted data.

9.1 Insecure Proposals

Some existing systems mount a man-in-the-middle attack on SSL [30, 29] by installing fake certificates at the middlebox [33, 44]. This enables the middlebox to break the security of SSL and decrypt the traffic so it can run DPI. This breaks the end-to-end security of SSL, and results in a host of issues, as surveyed by Jarmoc [30].

Some proposals allow users to tunnel their traffic to a third party middlebox provider, e.g. Meddle [43], Beyond the Radio [50], and APLOMB [45]. These approaches allow the middlebox owner to inspect/read all traffic. The situation is preferable to the status queue (from the client's perspective) in that the inspector is one with whom the client has a formal/contractual relationship – but, unlike BlindBox, the client still must grant *someone* access to the plaintext traffic. Further, this approach is not preferable to service providers, who may wish to enforce policy on users in the network, e.g., that no hosts within the network are infected with botnet malware.

9.2 Computing on Encrypted Data

Fully homomorphic encryption (FHE) [25] and general functional encryption [24, 28] are encryption schemes that can compute any function over encrypted data; hence, they can in principle support the complexity of deep packet inspection tasks. However, they do not address all the desired security properties in our threat model, and more importantly, they are prohibitively slow, currently at least 8 orders of magnitude slower than unencrypted computation [26].

Some recent systems such as CryptDB [40] and Mylar [41] showed how to support some specialized computation efficiently on encrypted data. However, these systems perform different tasks than is needed for middleboxes and do not meet our threat model.

There has been a large amount of work on searchable encryption [48, 31, 19, 15]. No searchable encryption scheme provides a strategy for encrypting the rules securely and for supporting arbitrary regexps, both of which BlindBox provides. Moreover, existing schemes cannot provide the performance required for packet processing. For example, BlindBox is three orders of magnitude faster than a system using the symmetric-key searchable scheme of Song et al. [48]. Public-key searchable encryption schemes, such as [19], are even slower because they perform a cryptographic pairing (which takes hundreds of microseconds per pairing), for every pair of token to rule content (a linear, rather than logarithmic task in the number of rules).

10. CONCLUSION

In this paper, we presented BlindBox, a system that resolves the tension between security and DPI middlebox functionality in networks. To the best of our knowledge, BlindBox is the first system to enable Deep Packet Inspection over encrypted traffic without requiring decryption of the underlying traffic. BlindBox supports real DPI applications such as IDS, exfiltration detection, and parental filtering. BlindBox performs best over long-running, persistent connections using SPDY-like or tunneled protocols. Using BlindBox Detect, a middlebox running BlindBox can perform detection on a single core at 186Mbps – competitive with many deployed IDS implementations.

We envisage that BlindBox is the first step towards a *general protocol* to resolve the tension between encryption and all categories of middleboxes. BlindBox currently supports middleboxes for DPI filtering only, however, we believe that the general blueprint BlindBox provides – computation over encrypted traffic – can be extended to implement other middlebox capabilities, including caches, protocol accelerators, compression engines.

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APPENDIX

In this appendix, we treat cryptographically the algorithms in BlindBox: the DPIEnc encryption scheme, BlindBox Detect, and the probable cause privacy protocol.

We first introduce notation and provide the syntax for our scheme, then provide a definition of what it means to be secure, and then prove that DPIEnc achieves this definition under standard cryptographic assumptions. Next, we define security formally for probable cause privacy and prove that our construction achieves it.

A. NOTATION

Let κ denote the security parameter throughout this paper. For a distribution $\mathcal{D}$, we say $x \leftarrow \mathcal{D}$ when x is sampled from the distribution $\mathcal{D}$. If S is a finite set, by $x \leftarrow S$ we mean x is sampled from the uniform distribution over the set S. We use $p(\cdot)$ to denote that p is a function that takes one input. Similarly, $p(\cdot, \cdot)$ denotes a function p that takes two inputs.

We say that a function f is negligible in an input parameter κ, if for all $d > 0$, there exists K such that for all $\kappa > K$, $f(\kappa) < \kappa^{-d}$. For brevity, we write: for all sufficiently large κ, $f(\kappa) = \text{negl}(\kappa)$. We say that a function f is polynomial in an input parameter κ, if there exists a polynomial p such that for all κ, $f(\kappa) \leq p(\kappa)$. We write $f(\kappa) = \text{poly}(\kappa)$.

Let $[n]$ denote the set $\{1, \ldots, n\}$ for $n \in \mathbb{N}^*$. When saying that a Turing machine A is p.p.t. we mean that A is a non-uniform probabilistic polynomial-time machine.

Two ensembles, $X = \{X_\kappa\}_{\kappa \in \mathbb{N}}$ and $Y = \{Y_\kappa\}_{\kappa \in \mathbb{N}}$, are said to be *computationally indistinguishable* (and denoted $\{X_\kappa\}_{\kappa \in \mathbb{N}} \overset{c}{\approx} \{Y_\kappa\}_{\kappa \in \mathbb{N}}$) if for every probabilistic polynomial-time algorithm D,

$$|\Pr[D(X_\kappa, 1^\kappa) = 1] - \Pr[D(Y_\kappa, 1^\kappa) = 1]| = \text{negl}(\kappa).$$

In our security definitions, we will define probabilistic experiments and denote by random variables their outputs. For example, $\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa)$ denotes the random variable representing the output of the experiment with adversary Adv on security parameter κ. Moreover, $\{\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa)\}_{\kappa \in \mathbb{N}}$ denotes the ensemble of such random variables indexed by $\kappa \in \mathbb{N}$.

B. SYNTAX

We now define the syntax for the class of encryption schemes we call middlebox searchable encryption scheme, or shortly MBSE. DPIEnc is such an encryption scheme.

Definition 1 (Syntax)**.** *An MBSE scheme associated with message space $\mathcal{M}$ is is a tuple of p.p.t. algorithms* (Setup, Enc, $\mathsf{RuleEnc}$, Match) *as follows:*

- $\mathsf{Setup}(1^\kappa)$: *Takes as input a security parameter 1^κ and outputs a key k.*
- $\mathsf{Enc}(k, t_1, \ldots, t_n)$: *Takes as input the key k and a set of n tokens each in $\mathcal{M}$ where $n = \text{poly}(\kappa)$, and outputs a salt* salt*, and a set of ciphertexts $[c_1, \ldots, c_n]$.*
- $\mathsf{RuleEnc}(k, r)$: *Takes as input a key k and a keyword $r \in \mathcal{M}$, and outputs an encrypted rule* encr.
- $\mathsf{Match}(\mathsf{encr}, \mathsf{salt}, c_1, \ldots, c_n)$*: Takes as input an encrypted rule* encr *corresponding to a rule r, a salt* salt *and a set of ciphertexts and outputs the set of indexes $\{\mathsf{ind}_1, \ldots, \mathsf{ind}_\ell\}$, where each index is in $[n]$.*

Correctness. *For any polynomial $n(\cdot)$, for every sufficiently large security parameter κ, if $n = n(\kappa)$, for all $[t_1, \ldots, t_n] \in \mathcal{M}^n$, for every rule $r \in \mathcal{M}$, for every index i such that $t_i = r$ and for every index j such that $t_j \neq r$, we have:*

$$\Pr\left[\begin{array}{l} k \leftarrow \mathsf{Setup}(1^\kappa); \\ \mathsf{salt}, c_1, \ldots, c_n \leftarrow \mathsf{Enc}(k, t_1, \ldots, t_n); \\ \mathsf{encr} \leftarrow \mathsf{RuleEnc}(k, r); \\ S \leftarrow \mathsf{Match}(\mathsf{encr}, \mathsf{salt}, c_1, \ldots, c_n) : \\ i \in S \end{array}\right] = 1.$$

and

$$\Pr\left[\begin{array}{l} k \leftarrow \mathsf{Setup}(1^\kappa); \\ \mathsf{salt}, c_1, \ldots, c_n \leftarrow \mathsf{Enc}(k, t_1, \ldots, t_n); \\ \mathsf{encr} \leftarrow \mathsf{RuleEnc}(k, r); \\ S \leftarrow \mathsf{Match}(\mathsf{encr}, \mathsf{salt}, c_1, \ldots, c_n) : \\ j \in S \end{array}\right] = \text{negl}(\kappa).$$

The correctness property above specifies that a match is detected with probability 1 for every token that matches the rule, but for a token that does not match the rule, the probability of a match is negligibly small.

C. SECURITY DEFINITION

Our security definition is standard for searchable encryption schemes. For example, it is similar to the security definition of Song et al. [48]. This is helpful because it means that the security guarantee we provide is well-studied as opposed to new and not well understood.

This security definition is indistinguishability-based: at a high level, given two sets of tokens, and an encryption of one of these two sets of tokens, no polynomial-time adversary can tell with chance better than half, which of the two sets of tokens were encrypted. In other words, the adversary gains no side information from the encryption scheme.

However, when given an encrypted search word (called keyword in our case), the attacker can tell precisely which encrypted token this rule matches, while not learn anything else about the data. This statement is typically formalized by allowing the attacker to choose any two sets of tokens of the same length, any number of rules, and as long as those sets of tokens match the set of rules at the same tokens, no attacker can distinguish between encryptions of the two sets of tokens. Note that the property in the paragraph above follows from this property (in the case that an adversary chooses an empty set of rules).

Our security definition does not specify that keywords are also hidden, which means that the attacker is allowed to learn the rules. (As a side note, the encryption scheme does hide the rules, providing a deterministic encryption guarantee, but in our systems setup, the middlebox will get to know the rules from the rule generator anyways, so formalizing this property is not useful).

Definition 2 (MBSE security)**.** *Consider an MBSE scheme with algorithms* (Setup, Enc, RuleEnc, Match) *and associated message space $\mathcal{M}$. Let* Adv *be a p.p.t. stateful adversary with oracle access to H. Consider the following experiment.*

```
Exp_Adv(1^κ):
1: $k \leftarrow \mathsf{Setup}(1^\kappa)$
2: $T^0 = (t_1^0, \dots, t_n^0), T^1 = (t_1^1, \dots t_n^1) \leftarrow \mathsf{Adv}(1^\kappa)$
3: $b \leftarrow \{0,1\}$, a random bit.
4: $\mathsf{salt}, c_1, \dots, c_n \leftarrow \mathsf{Enc}(k, t_1^b, \dots, t_n^b)$
5: $r_1, \dots, r_\ell \leftarrow \mathsf{Adv}(\mathsf{salt}, c_1, \dots, c_n)$
6: $\mathsf{encr}_1, \dots, \mathsf{encr}_\ell \leftarrow \mathsf{RuleEnc}(k, r_1), \dots \mathsf{RuleEnc}(k, r_\ell)$
7: $b' \leftarrow \mathsf{Adv}(\mathsf{encr}_1, \dots, \mathsf{encr}_\ell)$
8: Let $I_i^0$ be the set of indexes that match $r_i$ in $T^0$ and $I_i^1$ be the set of indexes that match $r_i$ in $T^1$. If $b' = b$ and $I_i^0 = I_i^1$ for
   all $i$, output "Success" else output "Fail".
```

We say that the scheme is secure if for all p.p.t. stateful adversaries Adv*, and for all sufficiently large κ:*

$$\Pr[\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa) = \text{"Success"}] \le 1/2 + \mathrm{negl}(\kappa).$$

In this security definition, the adversary Adv chooses two sets of tokens T^0 and T^1, receives an encryption of one of these at random (the bit b controls which set of tokens will be encrypted) and then tries to guess b by outputting b'. Adv is also allowed to choose the rules. As with typical searchable encryption security definitions, the adversary succeeds if his guess b' equals b and only if he chose rules that do not automatically distinguish T^0 and T^1: these rules must match T^0 and T^1 at the same indexes; otherwise, the functionality we desire from the scheme will enable anyone to distinguish these two sets of tokens trivially. We want to ensure that the attacker dos not learn anything from the scheme other than the pattern of matching, hence, he only succeeds if he chooses sets of tokens with the same pattern of matchings with the rules.

D. CONSTRUCTION

For preciseness, we provide the construction of the scheme here too. This construction consists of DPIEnc enhanced with the encryption from BlindBox Detect. Here, we are concerned only with security. Hence, we do not include in the construction the data structure BlindBox Detect builds at the middlebox which is only meant for performance and has no implication on security. However, we do include the enhanced encryption due to BlindBox Detect which chooses salts in specific ways, because we do need to prove that this mechanism does not weaken security.

Also, in this treatment, we do not include the rule encryption step using Yao garbled circuits: the security of the overall scheme with the Yao garbled circuits follows trivially from composing the security of this scheme with the security guarantees of Yao garbled circuits.

Let H be a hash function modeled as a random oracle.

The setup algorithm $\mathsf{Setup}(1^\kappa)$**:** Generate AES key k as in AES.

The encryption algorithm $\mathsf{Enc}(k, t_1, \dots, t_n)$**:**

```
1: Let salt be a random salt as in AES.
```

```
2:   For each $i \in [n]$, do:
  2.1:   let $\mathsf{ct}$ be the number of times that $t_i$ repeats in the sequence $t_1, \ldots, t_{i-1}$. $\mathsf{ct}$ could be $0$.
  2.2:   Compute $c_i = H(\mathsf{salt} + \mathsf{ct}, \mathsf{AES}_k(t_i)) \bmod RS$.
3:   Output $\mathsf{salt}, c_1, \ldots, c_n$.
```

Note that the strategy above for generating salts is from BlindBox Detect.

The rule encryption algorithm $\mathsf{RuleEnc}(k, r)$**:** Output $\mathsf{encr} = \mathsf{AES}_k(r)$.

We do not include a second description of the matching algorithm here. The reason is that it has no bearing on security: it does not show up in the security definition (Def. 2). This makes sense because matching is performed on data that is *already* available to the attacker from other algorithms such as Enc and RuleEnc. It provides no new information to the attacker (and in fact it is ran by the attacker). The matching algorithm is involved only in the correctness of functionality of our scheme, which we already explained in the body of the paper.

E. SECURITY PROOF

The security of our scheme relies on the standard cryptographic assumption that AES is pseudorandom permutation [27], and on H being a random oracle.

Theorem 1. *Assuming that* AES *is a pseudorandom permutation and H is a random oracle, our construction in Sec. D is a secure MBSE scheme.*

Proof. It is easy to check why this construction satisfies the syntax of MBSE as described in Sec. B.

We now prove security. We prove security through a sequence of two hybrids. The first hybrid replaces the AES encryption of tokens with deterministic random values, based on the pseudorandom security property of AES. The second hybrid then replaces the random oracle with deterministic random values based on the property of the random oracle. This results in an experiment in which the distribution of encryptions of T^0 and T^1 are statistically equal and thus indistinguishable, proving our theorem.

Hybrid 1. The Enc algorithm is changed to replace $\mathsf{AES}_k(\cdot)$ with random values. Concretely:
$\mathsf{Hybrid1.Enc}(k, t_1, \ldots, t_n)$**:**

```
1:   Let salt be a random salt as in AES.
2:   **For each $i \in [n]$, generate a random value $R_i$ in the ciphertext space of $\mathsf{AES}_k$, with the only restriction that it preserves equality. Namely, iff $t_i = t_j$, $R_i = R_j$.**
  2.1:   let $\mathsf{ct}$ be the number of times that $t_i$ repeats in the sequence $t_1, \ldots, t_{i-1}$. $\mathsf{ct}$ could be $0$.
  2.2:   **Compute** $c_i = H(\mathsf{salt} + \mathsf{ct}, R_i) \bmod RS$**.**
3:   Output $\mathsf{salt}, c_1, \ldots, c_n$.
```

The rows in bold indicate differences from the regular encryption.

We also define $\mathsf{Hybrid1.RuleEnc}(k, r)$ to output R_i if $r = t_i$ for some t_i, otherwise to output a fresh random value R. A future rule $r' = r$ should also be assigned the same random value as r.

One can define $\mathsf{Exp}_{\mathsf{Adv},\mathsf{Hybrid\ 1}}(1^\kappa)$ in the same way as $\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa)$ by replacing Enc with Hybrid1.Enc and RuleEnc with Hybrid1.RuleEnc.

Lemma 2. *Assuming AES is a pseudorandom permutation, for all p.p.t. stateful adversaries* Adv, *for all sufficiently large κ:*

$$\Pr[\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa) = \text{“Success”}] \leq \Pr[\mathsf{Exp}_{\mathsf{Adv},\textit{Hybrid 1}}(1^\kappa) = \text{“Success”}] + \mathrm{negl}(\kappa).$$

Proof. The proof follows directly from the pseudorandom property of AES, which means that AES_k is computationally indistinguishable from a random oracle. □

Hybrid 2. The Enc algorithm is changed to replace H with random values.
$\mathsf{Hybrid2.Enc}(k, t_1, \ldots, t_n)$**:**

```
1:   Let salt be a random salt as in AES.
2:   **For each $i \in [n]$, generate a random value $R_i$ in the ciphertext space of $[0, RS-1]$ bits and let $c_i = R_i$.**
3:   Output $\mathsf{salt}, c_1, \ldots, c_n$.
```

The rows in bold indicate differences from Hybrid 1. Unlike Hybrid 1, there is no restriction on the random values R_i any more.

We also define $\mathsf{Hybrid2.RuleEnc}(k, r)$ to output a random value R for each rule r to be encrypted, with the only restriction that any keyword $r' = r$ is also assigned to R.

In the case of Hybrid 2, we also need to program the random oracle H. When Adv gives as input to H salt^*, $\mathsf{Hybrid2.RuleEnc}(k, r)$, for r such that $r = t_i$ for some i and $\mathsf{salt}^* = \mathsf{salt} + \mathsf{ct}_i$, H returns R_i.

One can define $\mathsf{Exp}_{\mathsf{Adv},\text{Hybrid 2}}(1^\kappa)$ in the same way as $\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa)$ by replacing Enc with $\mathsf{Hybrid2.Enc}$ and $\mathsf{RuleEnc}$ with $\mathsf{Hybrid2.RuleEnc}$.

Lemma 3. *Assuming H is a programmable random oracle, for all p.p.t. stateful adversaries Adv, for all sufficiently large κ:*

$$\Pr[\mathsf{Exp}_{\mathsf{Adv},\textit{Hybrid 1}}(1^\kappa) = \textit{“Success”}] \leq \Pr[\mathsf{Exp}_{\mathsf{Adv},\textit{Hybrid 2}}(1^\kappa) = \textit{“Success”}] + \mathrm{negl}(\kappa).$$

Proof. The proof follows directly from the properties of the random oracle. □

Lemma 4. *For all p.p.t. stateful adversaries Adv,*

$$\Pr[\mathsf{Exp}_{\mathsf{Adv},\textit{Hybrid 2}}(1^\kappa) = \textit{“Success”}] = 1/2.$$

Proof. We can see that Hybrid 2 loses all the information about $t_1, \ldots, t_n$ and the rules r except for the pattern of matching between the rules and the tokens $t_1, \ldots, t_n$. In other words, all encryptions are random values preserving the pattern of matching between rules and tokens. This pattern is the same for T^0 and T^1. Hence, the two distributions for T^0 and T^1 are statistically the same, which means that any adversary Adv has a chance of distinguishing them of exactly half. □

By Lemmas 2, 3, and 4, we obtain:

$$\Pr[\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa) = \text{“Success”}] \leq \Pr[\mathsf{Exp}_{\mathsf{Adv},\text{Hybrid 2}}(1^\kappa) = \text{“Success”}] + \mathrm{negl}(\kappa) = 1/2 + \mathrm{negl}(\kappa),$$

which concludes our proof.

□

F. PROBABLE CAUSE SECURITY

The security of the probable cause algorithm specifies that the middlebox should obtain k_{SSL} if and only if there is a match of a keyword against a token. This security guarantee is similar to the one of attributed-based encryption schemes [20] (shortly denoted ABE). Hence, we formalize the security of probable cause in a similar way to ABE security.

In this security definition, Adv is allowed to choose two SSL keys k^0_{SSL} and k^1_{SSL}, one of these gets selected at random and then encrypted along with the tokens. The challenge to the adversary Adv is to guess which one of these keys were encrypted, when no keyword matches any of the contents.

We call such an encryption scheme, probable cause MBSE. The syntax of a probable cause MBSE scheme is the same as the syntax of MBSE (Sec. B) except for the encryption and match algorithms. The encryption algorithm takes an additional element k_{SSL}: $\mathsf{Enc}(k, t_1, \ldots, t_n, k_{\mathsf{SSL}})$. The matching algorithm additionally produces k_{SSL} upon a match.

Definition 3 (Probable cause security)**.** *Consider a probable cause MBSE scheme with algorithms* (Setup, Enc, $\mathsf{RuleEnc}$, Match) *and associated message space $\mathcal{M}$. Let Adv be a p.p.t. stateful adversary with oracle access to H. Consider the following experiment.*

```
                         $\underline{\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa)}$:
1: $k \leftarrow \mathsf{Setup}(1^\kappa)$
2: $k^0_{\mathsf{SSL}}, k^1_{\mathsf{SSL}} \leftarrow \mathsf{Adv}(1^\kappa)$
3: $T = t_1 \ldots t_n \leftarrow \mathsf{Adv}(1^\kappa)$
4: $b \leftarrow \{0, 1\}$, a random bit
5: $\mathsf{salt}, c_1, \ldots, c_n \leftarrow \mathsf{Enc}(k, t_1, \ldots, t_n, k^b_{\mathsf{SSL}})$
6: $r_1 \ldots r_\ell \leftarrow \mathsf{Adv}(\mathsf{salt}, c_1, \ldots, c_n)$
7: $\mathsf{encr}_1, \ldots, \mathsf{encr}_\ell \leftarrow \mathsf{RuleEnc}(k, r_1), \ldots \mathsf{RuleEnc}(k, r_\ell)$
8: $b' \leftarrow \mathsf{Adv}(\mathsf{encr}_1, \ldots, \mathsf{encr}_\ell)$
9: If $b' = b$ and none of the rules $r_j$ match any token in $T$, output “Success” else output “Fail”.
```

We say that the scheme has probable cause security if for all p.p.t. stateful adversaries Adv, and for all sufficiently large κ:

$$\Pr[\mathsf{Exp}_{\mathsf{Adv}}(1^\kappa) = \textit{“Success”}] \leq 1/2 + \mathrm{negl}(\kappa).$$

F.1 Probable Cause Construction

Let us recall the probable cause construction. As before, the matching algorithm has no bearing to security so we do not review it here. The setup and rule encryption algorithms are the same as in the regular construction.

Let H and H_2 be hash functions modeled as random oracles.

The setup algorithm $\mathsf{Setup}(1^\kappa)$**:** Generate AES key k as in AES.

The encryption algorithm $\mathsf{Enc}(k, t_1, \ldots, t_n, k_{\mathsf{SSL}})$**:**

```
1: Let salt be a random salt as in AES.
2: For each $i \in [n]$, do:
    2.1: let ct be the number of times that $t_i$ repeats in the sequence $t_1, \ldots, t_{i-1}$. ct could be 0.
    2.2: Compute $c_i = (H(\mathsf{salt}, \mathsf{AES}_k(t_i)) \bmod \mathsf{RS}, H_2(\mathsf{salt}, \mathsf{AES}_k(t_i)) \oplus k_{\mathsf{SSL}})$.
3: Output salt, $c_1, \ldots, c_n$.
```

The rule encryption algorithm $\mathsf{RuleEnc}(k, r)$**:** Output $\mathsf{encr} = \mathsf{AES}_k(r)$.

F.2 Security Proof

Theorem 5. *Assuming that AES is a pseudorandom permutation, and H and H_2 are random oracles, the construction above has probable cause security.*

Proof. As before, we prove security through a sequence of hybrids.

Hybrid 1. The Enc algorithm is changed to replace $\mathsf{AES}_k(\cdot)$ with random values. Concretely:

$\mathsf{Hybrid1.Enc}(k, t_1, \ldots, t_n, k_{\mathsf{SSL}})$**:**

```
1: Let salt be a random salt as in AES.
2: For each $i \in [n]$, generate a random value $R_i$ in the ciphertext space of $\mathsf{AES}_k$, with the only restriction that it preserves equality. Namely, iff $t_i = t_j$, $R_i = R_j$.
    2.1: let ct be the number of times that $t_i$ repeats in the sequence $t_1, \ldots, t_{i-1}$. ct could be 0.
    2.2: Compute $c_i = (H(\mathsf{salt}, R_i) \bmod \mathsf{RS}, H_2(\mathsf{salt}, R_i) \oplus k_{\mathsf{SSL}})$.
3: Output salt, $c_1, \ldots, c_n$.
```

The rows in bold indicate differences from the regular encryption.

We also define $\mathsf{Hybrid1.RuleEnc}(k, r)$ to output R_i if $r = t_i$ for some t_i, otherwise to output a fresh random value R. A future rule $r' = r$ should be assigned the same random value.

Hybrid 2. The Enc algorithm is changed to replace H and H_2 with random values.

$\mathsf{Hybrid2.Enc}(k, t_1, \ldots, t_n, k_{\mathsf{SSL}})$**:**

```
1: Let salt be a random salt as in AES.
2: For each $i \in [n]$, generate a random value $R_i, R'_i$ in the ciphertext space of $[0, RS-1]$ bits and let $c_i = (R_i, R'_i \oplus k_{\mathsf{SSL}})$.
3: Output salt, $c_1, \ldots, c_n$.
```

The rows in bold indicate differences from Hybrid 1.

We also define $\mathsf{Hybrid2.RuleEnc}(k, r)$ to output a random value R for each rule r to be encrypted, with the only restriction that any keyword $r' = r$ is also assigned to R.

Hybrid 3. The Enc algorithm is changed to completely lose k_{SSL}. Concretely $R'_i \oplus k_{\mathsf{SSL}}$ becomes R'_i.

$\mathsf{Hybrid2.Enc}(k, t_1, \ldots, t_n, k_{\mathsf{SSL}})$**:**

```
1: Let salt be a random salt as in AES.
2: For each $i \in [n]$, generate a random value $R_i, R'_i$ in the ciphertext space of $[0, RS-1]$ bits and let $c_i = (R_i, R'_i)$.
3: Output salt, $c_1, \ldots, c_n$.
```

The rows in bold indicate differences from Hybrid 2.

The rule encryption algorithm does not chance in this hybrid: $\mathsf{Hybrid3.RuleEnc}(k, r) = \mathsf{Hybrid2.RuleEnc}(k, r)$.

By the pseudorandom properties of AES, Hybrid 1 is computationally indistinguishable from the original security game. By the random oracle properties of H and H_2, Hybrid 1 and 2 are computationally indistinguishable. Hybrid 2 and 3 are statistically indistinguishable because $R'_1 \ldots R'_n$ are independent and random values and they preserve the same distribution when xor-ed with k_{SSL}. In Hybrid 3, no adversary Adv can distinguish between k^0_{SSL} and k^1_{SSL} because these keys are not used in the encryption, thus concluding our proof.

□