

SEPIA: Privacy-Preserving Aggregation of Multi-Domain Network Events and Statistics

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Abstract

Secure multiparty computation (MPC) allows joint privacy-preserving computations on data of multiple parties. Although MPC has been studied substantially, building solutions that are practical in terms of computation and communication cost is still a major challenge. In this paper, we investigate the practical usefulness of MPC for multi-domain network security and monitoring. We first optimize MPC comparison operations for processing high volume data in near real-time. We then design privacy-preserving protocols for event correlation and aggregation of network traffic statistics, such as addition of volume metrics, computation of feature entropy, and distinct item count. Optimizing performance of parallel invocations, we implement our protocols along with a complete set of basic operations in a library called SEPIA. We evaluate the running time and bandwidth requirements of our protocols in realistic settings on a local cluster as well as on PlanetLab and show that they work in near real-time for up to 140 input providers and 9 computation nodes. Compared to implementations using existing general-purpose MPC frameworks, our protocols are significantly faster, requiring, for example, 3 minutes for a task that takes 2 days with general-purpose frameworks. This improvement paves the way for new applications of MPC in the area of networking. Finally, we run SEPIA's protocols on real traffic traces of 17 networks and show how they provide new possibilities for distributed troubleshooting and early anomaly detection.

1 Introduction

A number of network security and monitoring problems can substantially benefit if a group of involved organizations aggregates private data to jointly perform a computation. For example, IDS alert correlation, e.g., with DOMINO [49], requires the joint analysis of private alerts. Similarly, aggregation of private data is useful for alert signature extraction [30], collaborative anomaly

detection [34], multi-domain traffic engineering [27], detecting traffic discrimination [45], and collecting network performance statistics [42]. All these approaches use either a trusted third party, e.g., a university research group, or peer-to-peer techniques for data aggregation and face a delicate privacy versus utility tradeoff [32]. Some private data typically have to be revealed, which impedes privacy and prohibits the acquisition of many data providers, while data anonymization, used to remove sensitive information, complicates or even prohibits developing good solutions. Moreover, the ability of anonymization techniques to effectively protect privacy is questioned by recent studies [29]. One possible solution to this privacy-utility tradeoff is MPC.

For almost thirty years, MPC [48] techniques have been studied for solving the problem of jointly running computations on data distributed among multiple organizations, while provably preserving data privacy without relying on a trusted third party. In theory, any computable function on a distributed dataset is also securely computable using MPC techniques [20]. However, designing solutions that are practical in terms of running time and communication overhead is non-trivial. For this reason, MPC techniques have mainly attracted theoretical interest in the last decades. Recently, optimized basic primitives, such as comparisons [14, 28], make progressively possible the use of MPC in real-world applications, e.g., an actual sugar-beet auction [7] was demonstrated in 2009.

Adopting MPC techniques to network monitoring and security problems introduces the important challenge of dealing with voluminous input data that require online processing. For example, anomaly detection techniques typically require the online generation of traffic volume and distributions over port numbers or IP address ranges. Such input data impose stricter requirements on the performance of MPC protocols than, for example, the input bids of a distributed MPC auction [7]. In particular, network monitoring protocols should process potentially

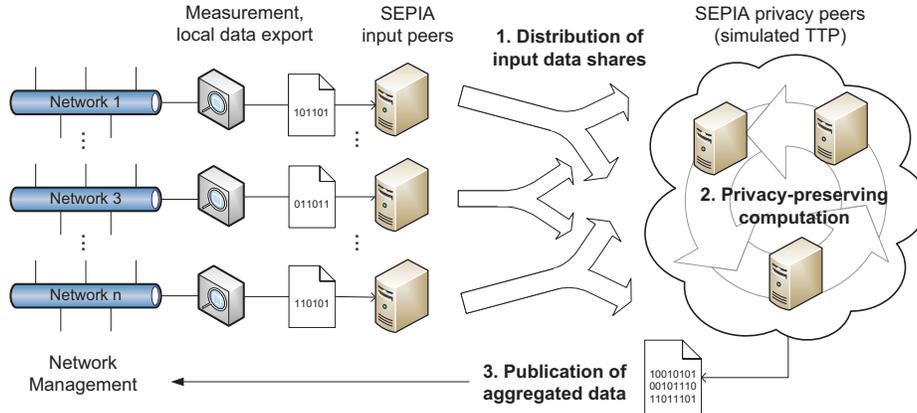


Figure 1: Deployment scenario for SEPIA.

thousands of input values while meeting *near real-time* guarantees¹. This is not presently possible with existing general-purpose MPC frameworks.

In this work, we design, implement, and evaluate SEPIA (Security through Private Information Aggregation), a library for efficiently aggregating multi-domain network data using MPC. The foundation of SEPIA is a set of optimized MPC operations, implemented with performance of parallel execution in mind. By not enforcing protocols to run in a constant number of rounds, we are able to design MPC comparison operations that require up to 80 times less distributed multiplications and, amortized over many parallel invocations, run much faster than constant-round alternatives. On top of these comparison operations, we design and implement novel MPC protocols tailored for network security and monitoring applications. The *event correlation* protocol identifies events, such as IDS or firewall alerts, that occur frequently in multiple domains. The protocol is generic having several applications, for example, in alert correlation for early exploit detection or in identification of multi-domain network traffic heavy-hitters. In addition, we introduce SEPIA’s *entropy* and *distinct count* protocols that compute the entropy of traffic feature distributions and find the count of distinct feature values, respectively. These metrics are used frequently in traffic analysis applications. In particular, the entropy of feature distributions is used commonly in anomaly detection, whereas distinct count metrics are important for identifying scanning attacks, in firewalls, and for anomaly detection. We implement these protocols along with a vector addition protocol to support additive operations on time-series and histograms.

A typical setup for SEPIA is depicted in Fig. 1 where individual networks are represented by one *input peer* each. The input peers distribute shares of secret input data among a (usually smaller) set of *privacy peers* using Shamir’s secret sharing scheme [40]. The privacy

peers perform the actual computation and can be hosted by a subset of the networks running input peers but also by external parties. Finally, the aggregate computation result is sent back to the networks. We adopt the semi-honest adversary model, hence privacy of local input data is guaranteed as long as the majority of privacy peers is honest. A detailed description of our security assumptions and a discussion of their implications is presented in Section 4.

Our evaluation of SEPIA’s performance shows that SEPIA runs in near real-time even with 140 input and 9 privacy peers. Moreover, we run SEPIA on traffic data of 17 networks collected during the global Skype outage in August 2007 and show how the networks can use SEPIA to troubleshoot and timely detect such anomalies. Finally, we discuss novel applications in network security and monitoring that SEPIA enables. In summary, this paper makes the following contributions:

1. We introduce efficient MPC comparison operations, which outperform constant-round alternatives for many parallel invocations.
2. We design novel MPC protocols for event correlation, entropy and distinct count computation.
3. We introduce the SEPIA library, in which we implement our protocols along with a complete set of basic operations, optimized for parallel execution. SEPIA is made publicly available [39].
4. We extensively evaluate the performance of SEPIA on realistic settings using synthetic and real traces and show that it meets near real-time guarantees even with 140 input and 9 privacy peers.
5. We run SEPIA on traffic from 17 networks and show how it can be used to troubleshoot and timely detect anomalies, exemplified by the Skype outage.

The paper is organized as follows: We specify the computation scheme in the next section and present our optimized comparison operations in Section 3. In Sec-

tion 4, we specify our adversary model and security assumptions, and build the protocols for event correlation, vector addition, entropy, and distinct count computation. We evaluate the protocols and discuss SEPIA’s design in Sections 5 and 6, respectively. Then, in Section 7 we outline SEPIA’s applications and conduct a case study on real network data that demonstrates SEPIA’s benefits in distributed troubleshooting and early anomaly detection. Finally, we discuss related work in Section 8 and conclude our paper in Section 9.

2 Preliminaries

Our implementation is based on Shamir secret sharing [40]. In order to *share* a secret value s among a set of m players, the dealer generates a random polynomial f of degree $t = \lfloor (m - 1)/2 \rfloor$ over a prime field \mathbb{Z}_p with $p > s$, such that $f(0) = s$. Each player $i = 1 \dots m$ then receives an evaluation point $s_i = f(i)$ of f . s_i is called the share of player i . The secret s can be reconstructed from any $t + 1$ shares using Lagrange interpolation but is completely undefined for t or less shares. To actually *reconstruct* a secret, each player sends his shares to all other players. Each player then locally interpolates the secret. For simplicity of presentation, we use $[s]$ to denote the vector of shares (s_1, \dots, s_m) and call it a *sharing* of s . In addition, we use $[s]_i$ to refer to s_i . Unless stated otherwise, we choose p with 62 bits such that arithmetic operations on secrets and shares can be performed by CPU instructions directly, not requiring software algorithms to handle big integers.

Addition and Multiplication Given two sharings $[a]$ and $[b]$, we can perform private addition and multiplication of the two values a and b . Because Shamir’s scheme is linear, addition of two sharings, denoted by $[a] + [b]$, can be computed by having each player locally add his shares of the two values: $[a + b]_i = [a]_i + [b]_i$. Similarly, local shares are subtracted to get a share of the difference. To add a public constant c to a sharing $[a]$, denoted by $[a] + c$, each player just adds c to his share, i.e., $[a + c]_i = [a]_i + c$. Similarly, for multiplying $[a]$ by a public constant c , denoted by $c[a]$, each player multiplies its share by c . Multiplication of two sharings requires an extra round of communication to guarantee randomness and to correct the degree of the new polynomial [4, 19]. In particular, to compute $[a][b] = [ab]$, each player first computes $d_i = [a]_i[b]_i$ locally. He then shares d_i to get $[d_i]$. Together, the players then perform a distributed Lagrange interpolation to compute $[ab] = \sum_i \lambda_i [d_i]$ where λ_i are the Lagrange coefficients. Thus, a distributed multiplication requires a synchronization round with m^2 messages, as each player i sends to each player j the share $[d_i]_j$. To specify protocols, composed of basic operations, we use a shorthand notation. For instance, we

write $foo([a], b) := ([a] + b)([a] + b)$, where foo is the protocol name, followed by input parameters. Valid input parameters are sharings and public constants. On the right side, the function to be computed is given, a binomial in that case. The output of foo is again a sharing and can be used in subsequent computations. All operations in \mathbb{Z}_p are performed modulo p , therefore p must be large enough to avoid modular reductions of intermediate results, e.g., if we compute $[ab] = [a][b]$, then a , b , and ab must be smaller than p .

Communication A set of independent multiplications, e.g., $[ab]$ and $[cd]$, can be performed in parallel in a single round. That is, intermediate results of all multiplications are exchanged in a single synchronization step. *A round simply is a synchronization point where players have to exchange intermediate results* in order to continue computation. While the specification of the protocols is synchronous, we do not assume the network to be synchronous during runtime. In particular, the Internet is better modeled as asynchronous, not guaranteeing the delivery of a message before a certain time. Because we assume the semi-honest model, we only have to protect against high delays of individual messages, potentially leading to a reordering of message arrival. In practice, we implement communication channels using SSL sockets over TCP/IP. TCP applies acknowledgments, timeouts, and sequence numbers to preserve message ordering and to retransmit lost messages, providing FIFO channel semantics. We implement message synchronization in parallel threads to minimize waiting time. Each player proceeds to the next round immediately after sending and receiving all intermediate values.

Security Properties All the protocols we devise are compositions of the above introduced addition and multiplication primitives, which were proven correct and *information-theoretically* secure by Ben-Or, Goldwasser, and Wigderson [4]. In particular, they showed that in the semi-honest model, where adversarial players follow the protocol but try to learn as much as possible by sharing the information they received, no set of t or less corrupt players gets any additional information other than the final function value. Also, these primitives are *universally composable*, that is, the security properties remain intact under stand-alone and concurrent composition [11]. Because the scheme is information-theoretically secure, i.e., it is secure against computationally unbounded adversaries, the confidentiality of secrets does not depend on the field size p . For instance, regarding confidentiality, sharing a secret s in a field of size $p > s$ is equivalent to sharing each individual bit of s in a field of size $p = 2$. Because we use SSL for implementing secure channels, the *overall system* relies on PKI and is only computationally secure.

3 Optimized Comparison Operations

Unlike addition and multiplication, comparison of two shared secrets is a very expensive operation. Therefore, we now devise optimized protocols for equality check, less-than comparison and a short range check. The complexity of an MPC protocol is typically assessed counting the number of distributed multiplications and rounds, because addition and multiplication with public values only require local computation. Damgård *et al.* introduced the bit-decomposition protocol [14] that achieves comparison by decomposing shared secrets into a shared bit-wise representation. On shares of individual bits, comparison is straight-forward. With $l = \log_2(p)$, the protocols in [14] achieve a comparison with $205l + 188l \log_2 l$ multiplications in 44 rounds and equality test with $98l + 94l \log_2 l$ multiplications in 39 rounds. Subsequently, Nishide and Ohta [28] have improved these protocols by not decomposing the secrets but using bitwise shared random numbers. They do comparison with $279l + 5$ multiplications in 15 rounds and equality test with 81l multiplications in 8 rounds. While these are constant-round protocols as preferred in theoretical research, they still involve lots of multiplications. For instance, an equality check of two shared IPv4 addresses ($l = 32$) with the protocols in [28] requires 2592 distributed multiplications, each triggering m^2 messages to be transmitted over the network.

Constant-round vs. number of multiplications Our key observation for improving efficiency is the following: For scenarios with many parallel protocol invocations it is possible to build much more practical protocols by not enforcing the constant-round property. Constant-round means that the number of rounds does not depend on the input parameters. We design protocols that run in $O(l)$ rounds and are therefore not constant-round, although, once the field size p is defined, the number of rounds is also fixed, i.e., not varying at runtime. The overall local running time of a protocol is determined by i) the local CPU time spent on computations, ii) the time to transfer intermediate values over the network, and iii) delay experienced during synchronization. Designing constant-round protocols aims at reducing the impact of iii) by keeping the number of rounds fixed and usually small. To achieve this, high multiplicative constants for the number of multiplications are often accepted (e.g., $279l$). Yet, both i) and ii) directly depend on the number of multiplications. For applications with few parallel operations, protocols with few rounds (usually constant-round) are certainly faster. However, with many parallel operations, as required by our scenarios, the impact of network delay is amortized and the number of multiplications (the actual workload) becomes the dominating factor. Our evaluation results in Section 5.1 and 5.4 con-

firm this and show that CPU time and network bandwidth are the main constraining factors, calling for a reduction of multiplications.

Equality Test In the field \mathbb{Z}_p with p prime, Fermat’s little theorem states

$$c^{p-1} = \begin{cases} 0 & \text{if } c = 0 \\ 1 & \text{if } c \neq 0 \end{cases} \quad (1)$$

Using (1) we define a protocol for equality test as follows:

$$equal([a], [b]) := 1 - ([a] - [b])^{p-1}$$

The output of *equal* is [1] in case of equality and [0] otherwise and can hence be used in subsequent computations. Using square-and-multiply for the exponentiation, we implement *equal* with $l + k - 2$ multiplications in l rounds, where k denotes the number of bits set to 1 in $p - 1$. By using carefully picked prime numbers with $k \leq 3$, we reduce the number of multiplications to $l + 1$. In the above example for comparing IPv4 addresses, this reduces the multiplication count by a factor of 76 from 2592 to 34.

Besides having few 1-bits, p must be bigger than the range of shared secrets, i.e., if 32-bit integers are shared, an appropriate p will have at least 33 bits. For any secret size below 64 bits it is easy to find appropriate p s with $k \leq 3$ within 3 additional bits.

Less Than For less-than comparison, we base our implementation on Nishide’s protocol [28]. However, we apply modifications to again reduce the overall number of required multiplications by more than a factor of 10. Nishide’s protocol is quite comprehensive and built on a stack of subprotocols for least-significant bit extraction (LSB), operations on bitwise-shared secrets, and (bit-wise) random number sharing. The protocol uses the observation that $a < b$ is determined by the three predicates $a < p/2$, $b < p/2$, and $a - b < p/2$. Each predicate is computed by a call of the LSB protocol for $2a$, $2b$, and $2(a - b)$. If $a < p/2$, no wrap-around modulo p occurs when computing $2a$, hence $LSB(2a) = 0$. However, if $a > p/2$, a wrap-around will occur and $LSB(2a) = 1$. Knowing one of the predicates in advance, e.g., because b is not secret but publicly known, saves one of the three LSB calls and hence 1/3 of the multiplications.

Due to space restrictions we omit to reproduce the entire protocol but focus on the modifications we apply. An important subprotocol in Nishide’s construction is *PrefixOr*. Given a sequence of shared bits $[a_1], \dots, [a_l]$ with $a_i \in \{0, 1\}$, *PrefixOr* computes the sequence $[b_1], \dots, [b_l]$ such that $b_i = \bigvee_{j=1}^i a_j$. Nishide’s *PrefixOr* requires only 7 rounds but 17l multiplications. We implement *PrefixOr* based on the fact that

$b_i = b_{i-1} \vee a_i$ and $b_1 = a_1$. The logical OR (\vee) can be computed using a single multiplication: $[x] \vee [y] = [x] + [y] - [x][y]$. Thus, our *PrefixOr* requires $l - 1$ rounds and only $l - 1$ multiplications.

Without compromising security properties, we replace the *PrefixOr* in Nishide’s protocol by our optimized version and call the resulting comparison protocol *lessThan*. A call of *lessThan*($[a], [b]$) outputs $[1]$ if $a < b$ and $[0]$ otherwise. The overall complexity of *lessThan* is $24l + 5$ multiplications in $2l + 10$ rounds as compared to Nishide’s version with $279l + 5$ multiplications in 15 rounds.

Short Range Check To further reduce multiplications for comparing small numbers, we devise a check for short ranges, based on our *equal* operation. Consider one wanted to compute $[a] < T$, where T is a small public constant, e.g., $T = 10$. Instead of invoking *lessThan*($[a], T$) one can simply compute the polynomial $[\phi] = [a]([a] - 1)([a] - 2) \dots ([a] - (T - 1))$. If the value of a is between 0 and $T - 1$, exactly one term of $[\phi]$ will be zero and hence $[\phi]$ will evaluate to $[0]$. Otherwise, $[\phi]$ will be non-zero. Based on this, we define a protocol for checking short public ranges that returns $[1]$ if $x \leq [a] \leq y$ and $[0]$ otherwise:

$$\text{shortRange}([a], x, y) := \text{equal}(0, \prod_{i=x}^y ([a] - i))$$

The complexity of *shortRange* is $(y - x) + l + k - 2$ multiplications in $l + \log_2(y - x)$ rounds. Computing *lessThan*($[a], y$) requires $16l + 5$ multiplications (1/3 is saved because y is public). Hence, regarding the number of multiplications, computing *shortRange*($[a], 0, y - 1$) instead of *lessThan*($[a], y$) is beneficial roughly as long as $y \leq 15l$.

4 SEPIA Protocols

In this section, we compose the basic operations defined above into full-blown protocols for network event correlation and statistics aggregation. Each protocol is designed to run on continuous streams of input traffic data partitioned into time windows of a few minutes. For sake of simplicity, the protocols are specified for a single time window. We first define the basic setting of SEPIA protocols as illustrated in Fig. 1 and then introduce the protocols successively.

Our system has a set of n users called *input peers*. The input peers want to jointly compute the value of a public function $f(x_1, \dots, x_n)$ on their private data x_i without disclosing anything about x_i . In addition, we have m players called *privacy peers* that perform the computation of $f()$ by simulating a trusted third party (TTP).

Each entity can take both roles, acting only as an input peer, privacy peer (PP) or both.

Adversary Model and Security Assumptions We use the semi-honest (a.k.a. honest-but-curious) adversary model for privacy peers. That is, honest privacy peers follow the protocol and do not combine their information. Semi-honest privacy peers do follow the protocol but try to infer as much as possible from the values (shares) they learn, also by combining their information. The privacy and correctness guarantees provided by our protocols are determined by Shamir’s secret sharing scheme. In particular, the protocols are secure for $t < m/2$ semi-honest privacy peers, i.e., as long as the majority of privacy peers is honest. Even if some of the input peers do not trust each other, we think it is realistic to assume that they will agree on a set of most-trusted participants (or external entities) for hosting the privacy peers. Also, we think it is realistic to assume that the privacy peers indeed follow the protocol. If they are operated by input peers, they are likely interested in the correct outcome of the computation themselves and will therefore comply. External privacy peers are selected due to their good reputation or are being payed for a service. In both cases, they will do their best not to offend their customers by tricking the protocol.

The function $f()$ is specified *as if* a TTP was available. MPC guarantees that no information is leaked *from the computation process*. However, just learning the resulting value $f()$ could allow to infer sensitive information. For example, if the input bit of all input peers must remain secret, computing the logical AND of all input bits is insecure in itself: if the final result was 1, all input bits must be 1 as well and are thus no longer secret. *It is the responsibility of the input peers to verify that learning $f()$ is acceptable*, in the same way as they have to verify this when using a real TTP. For example, we assume input peers are not willing to reconstruct item distributions but consider it safe to compute the overall item count or entropy. To reduce the potential for deducing information from $f()$, protocols can enforce the submission of “valid” input data conforming to certain rules. For instance, in our event correlation protocol, the privacy peers verify that each input peer submits no duplicate events. More formally, the work on *differential privacy* [17] systematically randomizes the output $f()$ of database queries to prevent inference of sensitive input data.

Prior to running the protocols, the m privacy peers set up a secure, i.e., confidential and authentic, channel to each other. In addition, each input peer creates a secure channel to each privacy peer. We assume that the required public keys and/or certificates have been securely distributed beforehand.

Privacy-Performance Tradeoff Although the number of privacy peers m has a quadratic impact on the total communication and computation costs, there are also m privacy peers sharing the load. That is, if the network capacity is sufficient, the overall running time of the protocols will scale linearly with m rather than quadratically. On the other hand, the number of tolerated colluding privacy peers also scales linearly with m . Hence, the choice of m involves a privacy-performance tradeoff. The separation of roles into input and privacy peers allows to tune this tradeoff independently of the number of input providers.

4.1 Event Correlation

The first protocol we present enables the input peers to privately aggregate arbitrary network events. An event e is defined by a key-weight pair $e = (k, w)$. This notion is generic in the sense that keys can be defined to represent arbitrary types of network events, which are uniquely identifiable. The key k could for instance be the source IP address of packets triggering IDS alerts, or the source address concatenated with a specific alert type or port number. It could also be the hash value of extracted malicious payload or represent a uniquely identifiable object, such as popular URLs, of which the input peers want to compute the total number of hits. The weight w reflects the impact (count) of this event (object), e.g., the frequency of the event in the current time window or a classification on a severity scale.

Each input peer shares at most s local events per time window. The goal of the protocol is to reconstruct an event if and only if a minimum number of input peers T_c report the same event and the aggregated weight is at least T_w . The rationale behind this definition is that an input peer does not want to reconstruct local events that are unique in the set of all input peers, exposing sensitive information asymmetrically. But if the input peer knew that, for example, three other input peers report the same event, e.g., a specific intrusion alert, he would be willing to contribute his information and collaborate. Likewise, an input peer might only be interested in reconstructing events of a certain impact, having a non-negligible aggregated weight.

More formally, let $[e_{ij}] = ([k_{ij}], [w_{ij}])$ be the shared event j of input peer i with $j \leq s$ and $i \leq n$. Then we compute the aggregated count C_{ij} and weight W_{ij} according to (2) and (3) and reconstruct e_{ij} iff (4) holds.

$$[C_{ij}] := \sum_{i' \neq i, j'} \text{equal}([k_{ij}], [k_{i'j'}]) \quad (2)$$

$$[W_{ij}] := \sum_{i' \neq i, j'} [w_{i'j'}] \cdot \text{equal}([k_{ij}], [k_{i'j'}]) \quad (3)$$

$$([C_{ij}] \geq T_c) \wedge ([W_{ij}] \geq T_w) \quad (4)$$

Reconstruction of an event e_{ij} includes the reconstruction of k_{ij} , C_{ij} , W_{ij} , and the list of input peers reporting it, but the w_{ij} remain secret. The detailed algorithm is given in Fig. 2.

Input Verification In addition to merely implementing the correlation logic, we devise two optional input verification steps. In particular, the PPs check that shared weights are below a maximum weight w_{max} and that each input peer shares distinct events. These verifications are *not* needed to secure the computation process, but they serve two purposes. First, they protect from misconfigured input peers and flawed input data. Secondly, they protect against input peers that try to deduce information from the *final computation result*. For instance, an input peer could add an event $T_c - 1$ times (with a total weight of at least T_w) to find out whether any other input peers report the same event. These input verifications mitigate such attacks.

Probe Response Attacks If aggregated security events are made publicly available, this enables probe response attacks against the system [5]. The goal of probe response attacks is not to learn private input data but to identify the sensors of a distributed monitoring system. To remain undiscovered, attackers then exclude the known sensors from future attacks against the system. While defending against this in general is an intractable problem, [41] identified that the suppression of low-density attacks provides some protection against basic probe response attacks. Filtering out low-density attacks in our system can be achieved by setting the thresholds T_c and T_w sufficiently high.

Complexity The overall complexity, including verification steps, is summarized below in terms of operation invocations and rounds:

<i>equal</i> :	$O((n - T_c)ns^2)$
<i>lessThan</i> :	$(2n - T_c)s$
<i>shortRange</i> :	$(n - T_c)s$
<i>multiplications</i> :	$(n - T_c) \cdot (ns^2 + s)$
<i>rounds</i> :	$7l + \log_2(n - T_c) + 26$

The protocol is clearly dominated by the number of *equal* operations required for the aggregation step. It scales quadratically with s , however, depending on T_c , it scales linearly or quadratically with n . For instance, if T_c has a constant offset to n (e.g., $T_c = n - 4$), only $O(ns^2)$ *equals* are required. However, if $T_c = n/2$, $O(n^2s^2)$ *equals* are necessary.

Optimizations To avoid the quadratic dependency on s , we are working on an MPC-version of a binary search algorithm that finds a secret $[a]$ in a sorted list of secrets $\{[b_1], \dots, [b_s]\}$ with $\log_2 s$ comparisons by com-

1. **Share Generation:** Each input peer i shares s distinct events e_{ij} with $w_{ij} < w_{max}$ among the privacy peers (PPs).
2. **Weight Verification:** Optionally, the PPs compute and reconstruct $lessThan([w_{ij}], w_{max})$ for all weights to verify that they are smaller than w_{max} . Misbehaving input peers are disqualified.
3. **Key Verification:** Optionally, the PPs verify that each input peer i reports distinct events, i.e., for each event index a and b with $a < b$ they compute and reconstruct $equal([k_{ia}], [k_{ib}])$. Misbehaving input peers are disqualified.
4. **Aggregation:** The PPs compute $[C_{ij}]$ and $[W_{ij}]$ according to (2) and (3) for $i \leq \hat{i}$ with $\hat{i} = \min(n - T_c + 1, n)$.² All required $equal$ operations can be performed in parallel.
5. **Reconstruction:** For each event $[e_{ij}]$, with $i \leq \hat{i}$, condition (4) has to be checked. Therefore, the PPs compute

$$[t_1] = shortRange([C_{ij}], T_c, n), \quad [t_2] = lessThan(T_w - 1, [W_{ij}])$$

Then, the event is reconstructed iff $[t_1] \cdot [t_2]$ returns 1. The set of input peers with $i > \hat{i}$ reporting a reconstructed event $\bar{r} = (\bar{k}, \bar{w})$ is computed by reusing all the $equal$ operations performed on \bar{r} in the aggregation step. That is, input peer i' reports \bar{r} iff $\sum_j equal([k], [k_{i'j}])$ equals 1. This can be computed using local addition for each remaining input peer and each reconstructed event. Finally, all reconstructed events are sent to all input peers.

Figure 2: Algorithm for event correlation protocol.

1. **Share Generation:** Each input peer i shares its input vector $\mathbf{d}_i = (x_1, x_2, \dots, x_r)$ among the PPs. That is, the PPs obtain n vectors of sharings $[\mathbf{d}_i] = ([x_1], [x_2], \dots, [x_r])$.
2. **Summation:** The PPs compute the sum $[\mathbf{D}] = \sum_{i=1}^n [\mathbf{d}_i]$.
3. **Reconstruction:** The PPs reconstruct all elements of \mathbf{D} and send them to all input peers.

Figure 3: Algorithm for vector addition protocol.

paring $[a]$ to the element in the middle of the list, here called $[b_*]$. We then construct a new list, being the first or second half of the original list, depending on $lessThan([a], [b_*])$. The procedure is repeated recursively until the list has size 1. This allows us to compare all events of two input peers with only $O(s \log_2 s)$ instead of $O(s^2)$ comparisons. To further reduce the number of $equal$ operations, the protocol can be adapted to receive *incremental updates* from input peers. That is, input peers submit a list of events in each time window and inform the PPs, which event entries have a different key from the previous window. Then, only comparisons of updated keys have to be performed and overall complexity is reduced to $O(u(n - T_c)s)$, where u is the number of changed keys in that window. This requires, of course, that information on input set dynamics is not considered private.

4.2 Network Traffic Statistics

In this section, we present protocols for the computation of multi-domain traffic statistics including the aggregation of additive traffic metrics, the computation of feature entropy, and the computation of distinct item count. These statistics find various applications in network monitoring and management.

1. **Share Generation:** Each input peer holds an r -dimensional private input vector $\mathbf{s}^i \in \mathbb{Z}_p^r$ representing the local item histogram, where r is the number of items and s_k^i is the count for item k . The input peers share all elements of their \mathbf{s}^i among the PPs.
2. **Summation:** The PPs compute the item counts $[s_k] = \sum_{i=1}^n [s_k^i]$. Also, the total count $[S] = \sum_{k=1}^r [s_k]$ is computed and reconstructed.
3. **Exponentiation:** The PPs compute $[(s_k)^q]$ using square-and-multiply.
4. **Entropy Computation:** The PPs compute the sum $\sigma = \sum_k [(s_k)^q]$ and reconstruct σ . Finally, at least one PP uses σ to (locally) compute the Tsallis entropy $H_q(Y) = \frac{1}{q-1}(1 - \sigma/S^q)$.

Figure 4: Algorithm for entropy protocol.

4.2.1 Vector Addition

To support basic additive functionality on timeseries and histograms, we implement a vector addition protocol. Each input peer i holds a private r -dimensional input vector $\mathbf{d}_i \in \mathbb{Z}_p^r$. Then, the vector addition protocol computes the sum $\mathbf{D} = \sum_{i=1}^n \mathbf{d}_i$. We describe the corresponding SEPIA protocol shortly in Fig. 3. This protocol requires no distributed multiplications and only one round.

4.2.2 Entropy Computation

The computation of the entropy of feature distributions has been successfully applied in network anomaly detection, e.g. [23, 9, 25, 50]. Commonly used feature distributions are, for example, those of IP addresses, port numbers, flow sizes or host degrees. The Shannon entropy of a feature distribution Y is $H(Y) = -\sum_k p_k \cdot \log_2(p_k)$, where p_k denotes the probability of an item k . If Y is a distribution of port numbers, p_k is the probability of

port k to appear in the traffic data. The number of flows (or packets) containing item k is divided by the overall flow (packet) count to calculate p_k . Tsallis entropy is a generalization of Shannon entropy that also finds applications in anomaly detection [50, 46]. It has been substantially studied with a rich bibliography available in [47]. The 1-parametric Tsallis entropy is defined as:

$$H_q(Y) = \frac{1}{q-1} \left(1 - \sum_k (p_k)^q \right). \quad (5)$$

and has a direct interpretation in terms of moments of order q of the distribution. In particular, the Tsallis entropy is a generalized, non-extensive entropy that, up to a multiplicative constant, equals the Shannon entropy for $q \rightarrow 1$. For generality, we select to design an MPC protocol for the Tsallis entropy.

Entropy Protocol A straight-forward approach to compute entropy is to first find the overall feature distribution Y and then to compute the entropy of the distribution. In particular, let p_k be the overall probability of item k in the union of the private data and s_k^i the local count of item k at input peer i . If S is the total count of the items, then $p_k = \frac{1}{S} \sum_{i=1}^n s_k^i$. Thus, to compute the entropy, the input peers could simply use the addition protocol to add all the s_k^i 's and find the probabilities p_k . Each input peer could then compute $H(Y)$ locally. However, the distribution Y can still be very sensitive as it contains information for each item, e.g., per address prefix. For this reason, we aim at computing $H(Y)$ without reconstructing any of the values s_k^i or p_k . Because the rational numbers p_k can not be shared directly over a prime field, we perform the computation separately on private numerators (s_k^i) and the public overall item count S . The entropy protocol achieves this goal as described in Fig. 4. It is assured that sensitive intermediate results are not leaked and that input and privacy peers *only* learn the final entropy value $H_q(Y)$ and the total count S . S is not considered sensitive as it only represents the total flow (or packet) count of all input peers together. This can be easily computed by applying the addition protocol to volume-based metrics. The complexity of this protocol is $r \log_2 q$ multiplications in $\log_2 q$ rounds.

4.2.3 Distinct Count

In this section, we devise a simple distinct count protocol leaking no intermediate information. Let $s_k^i \in \{0, 1\}$ be a boolean variable equal to 1 if input peer i sees item k and 0 otherwise. We first compute the logical OR of the boolean variables to find if an item was seen by any input peer or not. Then, simply summing the number of variables equal to 1 gives the distinct count of the items. According to De Morgan's Theorem, $a \vee b = \neg(\neg a \wedge \neg b)$.

1. **Share Generation:** Each input peer i shares its negated local counts $c_k^i = \neg s_k^i$ among the PPs.
2. **Aggregation:** For each item k , the PPs compute $[c_k] = [c_k^1] \wedge [c_k^2] \wedge \dots \wedge [c_k^n]$. This can be done in $\log_2 n$ rounds. If an item k is reported by any input peer, then c_k is 0.
3. **Counting:** Finally, the PPs build the sum $[\sigma] = \sum [c_k]$ over all items and reconstruct σ . The distinct count is then given by $K - \sigma$, where K is the size of the item domain.

Figure 5: Algorithm for distinct count protocol.

This means the logical OR can be realized by performing a logical AND on the negated variables. This is convenient, as the logical AND is simply the product of two variables. Using this observation, we construct the protocol described in Fig. 5. This protocol guarantees that only the distinct count is learned from the computation; the set of items is *not* reconstructed. However, if the input peers agree that the item set is not sensitive it can easily be reconstructed after step 2. The complexity of this protocol is $(n-1)r$ multiplications in $\log_2 n$ rounds.

5 Performance Evaluation

In this Section we evaluate the event correlation protocol and the protocols for network statistics. After that we explore the impact of running selected protocols on PlanetLab where hardware, network delay, and bandwidth are very heterogeneous. This section is concluded with a performance comparison between SEPIA and existing general-purpose MPC frameworks.

We assessed the CPU and network bandwidth requirements of our protocols, by running different aggregation tasks with real and simulated network data. For each protocol, we ran several experiments varying the most important parameters. We varied the number of input peers n between 5 and 25 and the number of privacy peers m between 3 and 9, with $m < n$. The experiments were conducted on a shared cluster comprised of several public workstations; each workstation was equipped with a 2x Pentium 4 CPU (3.2 GHz), 2 GB memory, and 100 Mb/s network. Each input and privacy peer was run on a *separate* host. In our plots, each data point reflects the average over 10 time windows. Background load due to user activity could not be totally avoided. Section 5.3 discusses the impact of single slow hosts on the overall running time.

5.1 Event Correlation

For the evaluation of the event correlation protocol, we generated artificial event data. It is important to note that our performance metrics do not depend on the actual

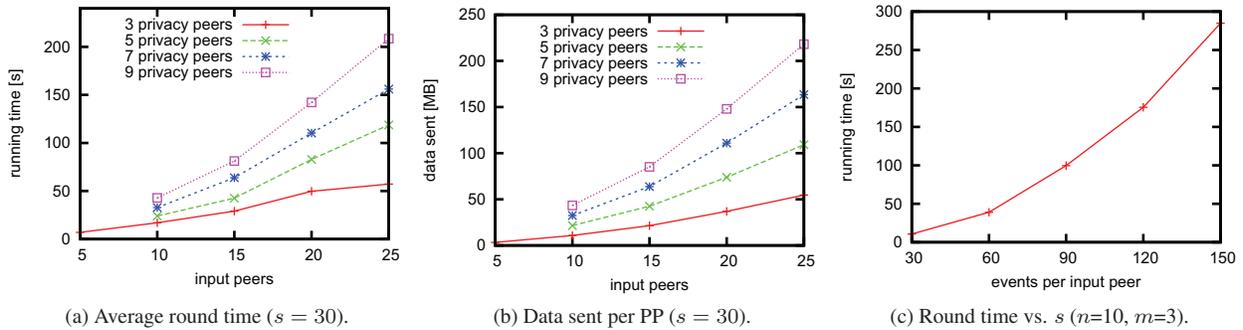


Figure 6: Round statistics for event correlation with $T_c = n/2$. s is the number of events per input peer.

values used in the computation, hence artificial data is just as good as real data for these purposes.

Running Time Fig. 6 shows evaluation results for event correlation with $s = 30$ events per input peer, each with 24-bit keys for $T_c = n/2$. We ran the protocol including weight and key verification. Fig. 6a shows that the average running time per time window always stays below 3.5 min and scales quadratically with n , as expected. Investigation of CPU statistics shows that with increasing n also the average CPU load per privacy peer grows. Thus, as long as CPUs are not used to capacity, local parallelization manages to compensate parts of the quadratical increase. With $T_c = n - const$, the running time as well as the number of operations scale linearly with n . Although the total communication cost grows quadratically with m , the running time dependence on m is rather linear, as long as the network is not saturated. The dependence on the number of events per input peer s is quadratic as expected without optimizations (see Fig. 6c).

To study whether privacy peers spend most of their time waiting due to synchronization, we measured the user and system time of their hosts. All the privacy peers were constantly busy with average CPU loads between 120% and 200% for the various operations.³ Communication and computation between PPs is implemented using separate threads to minimize the impact of synchronization on the overall running time. Thus, SEPIA profits from multi-core machines. Average load decreases with increasing need for synchronization from multiplications to *equal*, over *lessThan* to event correlation. Nevertheless, even with event correlation, processors are very busy and not stalled by the network layer.

Bandwidth requirements Besides running time, the communication overhead imposed on the network is an important performance measure. Since data volume is dominated by privacy peer messages, we show the average bytes sent *per privacy peer* in one time window

in Fig. 6b. Similar to running time, data volume scales roughly quadratically with n and linearly with m . In addition to the transmitted data, each privacy peer receives about the same amount of data from the other input and private peers. If we assume a 5-minute clocking of the event correlation protocol, an average bandwidth between 0.4 Mbps (for $n = 5$, $m = 3$) and 13 Mbps (for $n = 25$, $m = 9$) is needed per privacy peer. Assuming a 5-minute interval and sufficient CPU/bandwidth resources, the maximum number of supported input peers before the system stops working in real-time ranges from around 30 up to roughly 100, depending on protocol parameters.

5.2 Network statistics

For evaluating the network statistics protocols, we used unsampled NetFlow data captured from the five border routers of the Swiss academic and research network (SWITCH), a medium-sized backbone operator, connecting approximately 40 governmental institutions, universities, and research labs to the Internet. We first extracted traffic flows belonging to different customers of SWITCH and assigned an independent input peer to each organization’s trace. For each organization, we then generated SEPIA input files, where each input field contained either the values of volume metrics to be added or the local histogram of feature distributions for collaborative entropy (distinct count) calculation. In this section we focus on the running time and bandwidth requirements only. We performed the following tasks over ten 5-minute windows:

1. **Volume Metrics:** Adding 21 volume metrics containing flow, packet, and byte counts, both total and separately filtered by protocol (TCP, UDP, ICMP) and direction (incoming, outgoing). For example, Fig. 10 in Section 7.2 plots the total and local number of incoming UDP flows of six organizations for an 11-day period.

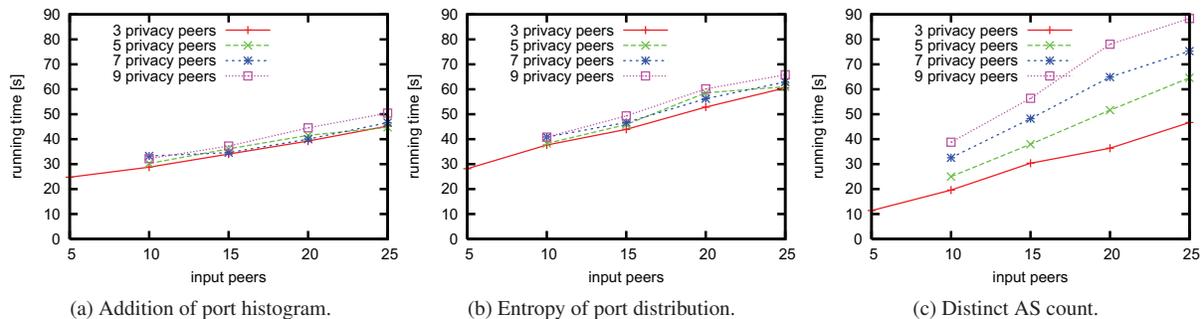


Figure 7: Network statistics: avg. running time per time window versus n and m , measured on a department-wide cluster. All tasks were run with an input set size of 65k items.

2. **Port Histogram:** Adding the full destination port histogram for incoming UDP flows. SEPIA input files contained 65,535 fields, each indicating the number of flows observed to the corresponding port. These local histograms were aggregated using the addition protocol.
3. **Port Entropy:** Computing the Tsallis entropy of destination ports for incoming UDP flows. The local SEPIA input files contained the same information as for histogram aggregation. The Tsallis exponent q was set to 2.
4. **Distinct count of AS numbers:** Aggregating the count of distinct source AS numbers in incoming UDP traffic. The input files contained 65,535 columns, each denoting if the corresponding source AS number was observed. For this setting, we reduced the field size p to 31 bits because the expected size of intermediate values is much smaller than for the other tasks.

Running Time For task 1, the average running time was below 1.6 s per time window for all configurations, even with 25 input and 9 privacy peers. This confirms that addition-only is very efficient for low volume input data. Fig. 7 summarizes the running time for tasks 2 to 4. The plots show on the y -axes the average running time per time window versus the number of input peers on the x -axes. In all cases, the running time for processing one time window was below 1.5 minutes. The running time clearly scales linearly with n . Assuming a 5-minute interval, we can estimate by extrapolation the maximum number of supported input peers before the system stops working in real-time. For the conservative case with 9 privacy peers, the supported number of input peers is approximately 140 for histogram addition, 110 for entropy computation, and 75 for distinct count computation. We observe, that for single round protocols (addition and entropy), the number of privacy peers has only little impact on the running time. For the distinct count protocol, the

running time increases linearly with both n and m . Note that the shortest running time for distinct count is even lower than for histogram addition. This is due to the reduced field size (p with 31 bits instead of 62), which reduces both CPU and network load.

Bandwidth Requirements For all tasks, the data volume sent per privacy peer scales perfectly linear with n and m . Therefore, we only report the maximum volume with 25 input and 9 privacy peers. For addition of volume metrics, the data volume is 141 KB and increases to 4.7 MB for histogram addition. Entropy computation requires 8.5 MB and finally the multi-round distinct count requires 50.5 MB. For distinct count, to transfer the total of $2 \cdot 50.5 = 101$ MB within 5 minutes, an average bandwidth of roughly 2.7 Mbps is needed per privacy peer.

5.3 Internet-wide Experiments

In our evaluation setting hosts have homogeneous CPUs, network bandwidth and low round trip times (RTT). In practice, however, SEPIA’s goal is to aggregate traffic from remote network domains, possibly resulting in a much more heterogeneous setting. For instance, *high delay* and *low bandwidth* directly affect the waiting time for messages. Once data has arrived, the *CPU model and clock rate* determine how fast the data is processed and can be distributed for the next round.

Recall from Section 4 that each operation and protocol in SEPIA is designed in rounds. Communication and computation during each round run in parallel. But before the next round can start, the privacy peers have to synchronize intermediate results and therefore wait for the slowest privacy peer to finish. The overall running time of SEPIA protocols is thus affected by the slowest CPU, the highest delay, and the lowest bandwidth rather than by the average performance of hosts and links. Therefore we were interested to see whether the performance of our protocols breaks down if we take it out of the homogeneous LAN setting. Hence, we ran

	LAN	PlanetLab A	PlanetLab B
Max. RTT	1 ms	320 ms	320 ms
Bandwidth	100 Mb/s	≥ 100 Kb/s	≥ 100 Kb/s
Slowest CPU	2 cores	2 cores	1 core
	3.2 GHz	2.4 GHz	1.8 GHz
Running time	25.0 s	36.8 s	110.4 s

Table 1: Comparison of LAN and PlanetLab settings.

Framework	SEPIA	VIFF	FairplayMP
Technique	Shamir sh.	Shamir sh.	Bool. circuits
Platform	Java	Python	Java
Multipl./s	82,730	326	1.6
Equals/s	2,070	2.4	2.3
LessThans/s	86	2.4	2.3

Table 2: Comparison of frameworks performance in operations per second with $m = 5$.

SEPIA on PlanetLab [31] and repeated task 4 (distinct AS count) with 10 input and 5 privacy peers on globally distributed PlanetLab nodes. Table 1 compares the LAN setup with two PlanetLab setups A and B.

RTT was much higher and average bandwidth much lower on PlanetLab. The only difference between PlanetLab A and B was the choice of some nodes with slower CPUs. Despite the very heterogeneous and globally distributed setting, the distinct count protocol performed well, at least in PlanetLab A. Most important, it still met our near real-time requirements. From PlanetLab A to B, running time went up by a factor of 3. However, this can largely be explained by the slower CPUs. The distinct count protocol consists of parallel multiplications, which make efficient use of the CPU and local addition, which is solely CPU-bound. Let us assume, for simplicity, that clock rates translate directly into MIPS. Then, computational power in PlanetLab B is roughly 2.7 times lower than in PlanetLab A. Of course, the more rounds a protocol has, the bigger is the impact of RTT. But in each round, the network delay is only a constant offset and can be amortized over the number of parallel operations performed per round. For many operations, CPU and bandwidth are the real bottlenecks.

While aggregation in a heterogeneous environment is possible, SEPIA *privacy peers* should ideally be deployed on dedicated hardware, to reduce background load, and with similar CPU equipment, so that no single host slows down the entire process.

5.4 Comparison with General-Purpose Frameworks

In this section we compare the performance of basic SEPIA operations to those of general-purpose frameworks such as FairplayMP [3] and VIFF v0.7.1 [15]. Besides performance, one aspect to consider is, of course,

usability. Whereas the SEPIA library currently only provides an API to developers, FairplayMP allows to write protocols in a high-level language called SFDL and VIFF integrates nicely into the Python language. Furthermore, VIFF implements asynchronous protocols and provides additional functionality, such as security against malicious adversaries and support of MPC based on homomorphic cryptosystems.

Tests were run on 2x Dual Core AMD Opteron 275 machines with 1Gb/s LAN connections. To guarantee a fair comparison, we used the same settings for all frameworks. In particular, the semi-honest model, 5 computation nodes, and 32 bit secrets were used. Unlike VIFF and SEPIA, which use an information-theoretically secure scheme, FairplayMP requires the choice of an adequate security parameter k . We set $k = 80$, as suggested by the authors in [3].

Table 2 shows the average number of parallel operations per second for each framework. SEPIA clearly outperforms VIFF and FairplayMP for all operations and is thus much better suited when performance of parallel operations is of main importance. As an example, a run of event correlation taking 3 minutes with SEPIA would take roughly 2 days with VIFF. This extends the range of *practically* runnable MPC protocols significantly. Notably, SEPIA’s *equal* operation is 24 times faster than its *lessThan*, which requires 24 times more multiplications, but at the same time also twice the number of rounds. This confirms that with many parallel operations, the number of multiplications becomes the dominating factor. Approximately 3/4 of the time spent for *lessThan* is used for generating sharings of random numbers used in the protocol. These random sharings are independent from input data and could be generated prior to the actual computation, allowing to perform 380 *lessThans* per second in the same setting.

Even for multiplications, SEPIA is faster than VIFF, although both rely on the same scheme. We assume this can largely be attributed to the completely asynchronous protocols implemented in VIFF. Whereas asynchronous protocols are very efficient for dealing with malicious adversaries, they make it impossible to reduce network overhead by exchanging intermediate results of all parallel operations at once in a single big message. Also, there seems to be a bottleneck in parallelizing large numbers of operations. In fact, when benchmarking VIFF, we noticed that after some point, adding more parallel operations significantly slowed down the average running time per operation.

Sharemind [6] is another interesting MPC framework using *additive* secret sharing to implement multiplications and greater-or-equal (GTE) comparison. The authors implement it in C++ to maximize performance. However, the use of additive secret sharing makes the im-

plementations of basic operations dependent on the number of computation nodes used. For this reason, Sharemind is currently restricted to 3 computation nodes only. Regarding performance, however, Sharemind is comparable to SEPIA. According to [6], Sharemind performs up to 160,000 multiplications and around 330 GTE operations per second, with 3 computation nodes. With 3 PPs, SEPIA performs around 145,000 multiplications and 145 *lessThans* per second (615 with pre-generated randomness). Sharemind does not directly implement *equal*, but it could be implemented using 2 invocations of GTE, leading to ≈ 115 operations/s. SEPIA's *equal* is clearly faster with up to 3,400 invocations/s. SEPIA demonstrates that operations based on Shamir shares are not necessarily slower than operations in the additive sharing scheme. The key to performance is rather an implementation, which is optimized for a large number of parallel operations. Thus, SEPIA combines speed with the flexibility of Shamir shares, which support any number of computation nodes and are to a certain degree robust against node failures.

6 Design and Implementation

The foundation of the SEPIA library is an implementation of the basic operations, such as multiplications and optimized comparisons (see Section 3), along with a communication layer for establishing SSL connections between input and privacy peers. In order to limit the impact of varying communication latencies and response times, each connection, along with the corresponding computation and communication tasks, is handled by a separate thread. This also implies that SEPIA protocols benefit from multi-core systems for computation-intensive tasks. In order to reduce synchronization overhead, intermediate results of parallel operations sent to the same destination are collected and transferred in a single big message instead of many small messages. On top of the basic layers, the protocols from Section 4 are implemented as standalone command-line (CLI) tools. The CLI tools expect a local configuration file containing privacy peer addresses, paths to a folder with input data and a Java keystore, as well as protocol-dependent parameters. The tools write a log of the ongoing computation and output files with aggregate results for each time window. The keystore holds certificates of trusted input and privacy peers to establish SSL connections. It is possible to delay the start of a computation until a minimum number of input and privacy peers are online. This gives the input peers the ability to define an acceptable level of privacy by only participating in the computation if a certain number of other input/privacy peers also participate.

SEPIA is written in Java to provide platform independence. The source code of the basic library and the four

```

ShamirSharing sharing = new ShamirSharing();
sharing.setFieldPrime(1401085391); // 31 bit
sharing.setNrOfPrivacyPeers(nrOfPrivacyPeers);
sharing.init();

// Secret1: only a single value
long[] secrets = new long[]{1234567};
long[][] shares = sharing.generateShares(secrets);

// Send shares to each privacy peer
for (int i=0; i<nrOfPrivacyPeers; i++) {
    connection[i].sendMessage(shares[i]);
}

```

Figure 8: Example code for an input peer that shares a secret, e.g., a millionaire sharing his amount of wealth.

CLI tools is available under the LGPL license on the SEPIA project web page [39]. The web page also provides pre-configured examples for the CLI tools and a user manual. The user manual describes usage and configuration of the CLI tools and includes a step-by-step tutorial on how to use the library API to develop new protocols. In the library API, all operations and sub-protocols implement a common interface `IOperation` and are easily composable. The class `ProtocolPrimitives` allows to schedule operations and takes care of performing them in parallel, keeping track of operation states. A base class for privacy peers implements the `doOperations()` method, which runs all the necessary computation rounds and synchronizes data between privacy peers in each round. Fig. 8 shows example code for input peers that want to privately compare their secrets. First, each input peer generates shares of its secret. The shares are then sent to the PPs, for which example code is shown in Fig. 9. The PPs first schedule and execute *lessThan* comparisons for all combinations of input secrets. In a second step, they run the reconstruction operations and output the results.

Future Work Note that with Shamir shares, reconstruction of results is assured as long as $t + 1$ PPs are online and responsive. This can be used directly to extend SEPIA protocols with robustness against node failures. Also, weak nodes slowing down the entire computation could be excluded from the computation. We leave this as a future extension.

The protocols support any number of input and privacy peers. Also, the item set sizes/events per input peer are configurable and thus only limited by the available CPU/bandwidth resources. However, running the network statistics protocols (e.g., distinct count) on very large distributions, such as the global IP address range, requires to use sketches as proposed in [37] or binning (e.g., use address prefixes instead of addresses). As an example, we have recently used sketches in combination with SEPIA to efficiently compute top- k reports for dis-

```

... // receive all the shares from input peers
ProtocolPrimitives primitives = new ProtocolPrimitives(fieldPrime, ...);

// Schedule comparisons of all the input peer's secrets
int id1=1, id2=2, id3=3; // consecutive operation IDs
primitives.lessThan(id1, new long[]{shareOfSecret1, shareOfSecret2});
primitives.lessThan(id2, new long[]{shareOfSecret2, shareOfSecret3});
primitives.lessThan(id3, new long[]{shareOfSecret1, shareOfSecret3});
doOperations(); // Process operations and synchronize intermediate results

// Get shares of the comparison results
long shareOfLessThan12 = primitives.getResult(id1);
long shareOfLessThan23 = primitives.getResult(id2);
long shareOfLessThan13 = primitives.getResult(id3);

// Schedule and perform reconstruction of comparisons
primitives.reconstruct(id1, new long[]{shareOfLessThan12});
primitives.reconstruct(id2, new long[]{shareOfLessThan23});
primitives.reconstruct(id3, new long[]{shareOfLessThan13});
doOperations();

boolean secret1_lessThan_secret2 = (primitives.getResult(id1)==1);
boolean secret2_lessThan_secret3 = (primitives.getResult(id2)==1);
boolean secret1_lessThan_secret3 = (primitives.getResult(id3)==1);

```

Figure 9: Example code for a PP receiving shares of secrets from 3 input peers. It then compares the secrets privately, e.g., to find which of the millionaires is the richest.

tributed IP address distributions with up to 180,000 distinct addresses [10].

As part of future work, we also plan to investigate the applicability of polynomial set representation to our statistics protocols, to reduce the linear dependency on the input set domain. Polynomial set representation, introduced by Freedman *et al.* [18] and extended by Kissner *et al.* [22], represents set elements as roots of a polynomial and enables set operations that scale only logarithmically with input domain size. However, these solutions use homomorphic public-key cryptosystems, which come with significant overhead for basic operations. Furthermore, they do not trivially allow to separate roles into input and privacy peers, as each input provider is required to perform certain non-delegable processing steps on its own data.

7 Applications

We envision four distinct aggregation scenarios using SEPIA. The first scenario is aggregating information coming from multiple domains of one large (international) organization. This aggregation is presently not always possible due to privacy concerns and heterogeneous jurisdiction. The second scenario is analyzing private data owned by independent organizations with a mutual benefit in collaborating. Local ISPs, for example, might collaborate to detect common attacks. A third scenario provides access to researchers for evaluating and validating traffic analysis or event correlation prototypes over multi-domain network data. For example, national research, educational, and university networks could provide SEPIA input and/or privacy peers that allow analyz-

ing local data according to submitted MPC scripts. Finally, one last scenario is the privacy-preserving analysis of end-user data, i.e., end-user workstations can use SEPIA to collaboratively analyze and cross-correlate local data.

7.1 Application Taxonomy

Based on these scenarios, we see three different classes of possible SEPIA applications.

Network Security Over the last years, considerable research efforts have focused on distributed data aggregation and correlation systems for the identification and mitigation of coordinated wide-scale attacks. In particular, aggregation enables the (early) detection and characterization of attacks spanning multiple domains using data from IDSes, firewalls, and other possible sources [2, 16, 26, 49]. Recent studies [21] show that coordinated wide-scale attacks are prevalent: 20% of the studied malicious addresses and 40% of the IDS alerts accounted for coordinated wide-scale attacks. Furthermore, strongly correlated groups profiting most from collaboration have less than 10 members and are stable over time, which is well-suited for SEPIA protocols.

In order to counter such attacks, Yegneswaran *et al.* [49] presented DOMINO, a distributed IDS that enables collaboration among nodes. They evaluated the performance of DOMINO with a large set of IDS logs from over 1600 providers. Their analysis demonstrates the significant benefit that is obtained by correlating the data from several distributed intrusion data sources. The major issue faced by such correlation systems is the lack

of data privacy. In their work, Porras *et al.* survey existing defense mechanisms and propose several remaining research challenges [32]. Specifically, they point out the need for efficient privacy-preserving data mining algorithms that enable traffic classification, signature extraction, and propagation analysis.

Profiling and Performance Analysis A second category of applications relates to traffic profiling and performance measurements. A global profile of traffic trends helps organizations to cross-correlate local traffic trends and identify changes. In [38] the authors estimate that 50 of the top-degree ASes together cover approximately 90% of global AS-paths. Hence, if large ASes collaborate, the computation of global Internet statistics is within reach. One possible statistic is the total traffic volume across a large number of networks. This statistic, for example, could have helped [37] in the dot-com bubble in the late nineties, since the traffic growth rate was overestimated by a factor of 10, easing the flow of venture capital to Internet start-ups. In addition, performance-related applications can benefit from an “on average” view across multiple domains. Data from multiple domains can also help to locate a remote outage with higher confidence, and to trigger proper detour mechanisms. A number of additional MPC applications related to performance monitoring are discussed in [36].

Research Validation Many studies are obliged to avoid rigorous validation or have to re-use a small number of old traffic traces [13, 43]. This situation clearly undermines the reliability of the derived results. In this context, SEPIA can be used to establish a privacy-preserving infrastructure for research validation purposes. For example, researchers could provide MPC scripts to SEPIA nodes running at universities and research institutes.

7.2 Case Study: The Skype Outage

The Skype outage in August 2007 started from a Windows update triggering a large number of system restarts. In response, Skype nodes scanned cached hostlists to find supernodes causing a huge distributed scanning event lasting two days [35]. We used NetFlow traces of the actual up- and downstream traffic of the 17 biggest customers of the SWITCH network. The traces span 11 days from the 11th to 22nd and include the Skype outage (on the 16th/17th) along with other smaller anomalies. We ran SEPIA’s total count, distinct count, and entropy protocols on these traces and investigated how the organizations can benefit by correlating their local view with the aggregate view.

We first computed per-organization and aggregate timeseries of the UDP flow count metric and applied a simple detector to identify anomalies. For each time-

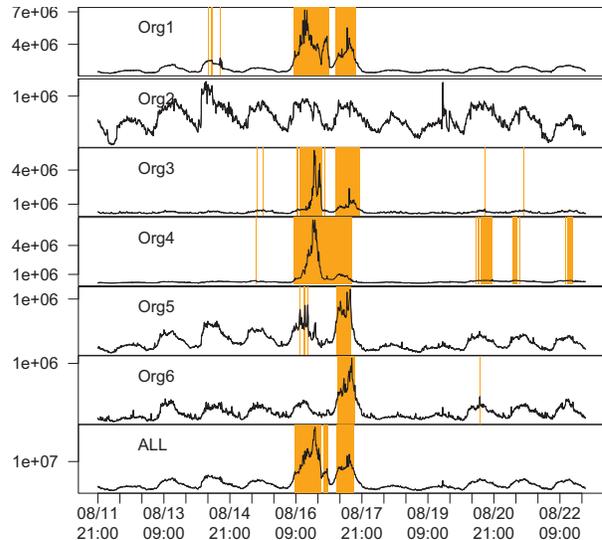


Figure 10: Flow count in 5’ windows with anomalies for the biggest organizations and aggregate view (ALL). Each organization sees its local and the aggregate traffic.

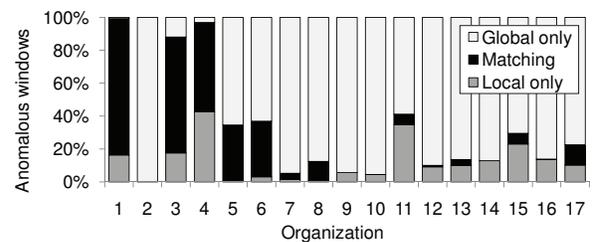


Figure 11: Correlation of local and global anomalies for organizations ordered by size (1=biggest).

series, we used the first 4 days to learn its mean μ and standard deviation σ , defined the normal region to be within $\mu \pm 3\sigma$, and detected anomalous time intervals. In Fig. 10 we illustrate the local timeseries for the six largest organizations and the aggregate timeseries. We rank organizations based on their decreasing average number of daily flows and use their rank to identify them. In the figure, we also mark the detected anomalous intervals. Observe that in addition to the Skype outage, some organizations detect other smaller anomalies that took place during the 11-day period.

Anomaly Correlation Using the aggregate view, an organization can find if a local anomaly is the result of a global event that may affect multiple organizations. Knowing the global or local nature of an anomaly is important for steering further troubleshooting steps. Therefore, we first investigate how the local and global anomalous intervals correlate. For each organization, we compared the local and aggregate anomalous intervals and measured the total time an anomaly was present: 1) only

in the local view, 2) only in the aggregate view, and 3) both in the local and aggregate views, i.e., the *matching anomalous intervals*. Fig. 11 illustrates the corresponding time fractions. We observe a rather small fraction, i.e., on average 14.1%, of local-only anomalies. Such anomalies lead administrators to search for local targeted attacks, misconfigured or compromised internal systems, misbehaving users, etc. In addition, we observe an average of 20.3% matching anomalous windows. Knowing an anomaly is both local and global steers an affected organization to search for possible problems in popular services, in widely-used software, like Skype in this case, or in the upstream providers. A large fraction (65.6%) of anomalous windows is only visible in the global view. In addition, we observe significant variability in the patterns of different organizations. In general, larger organizations tend to have a larger fraction of matching anomalies, as they contribute more to the aggregate view. While some organizations are highly correlated with the global view, e.g., organization 3 that notably contributes only 7.4% of the total traffic; other organizations are barely correlated, e.g., organizations 9 and 12; and organization 2 has no local anomalies at all.

Anomaly Troubleshooting We define *relative anomaly size* to be the ratio of the detection metric value during an anomalous interval over the detection threshold. Organizations 3 and 4 had relative anomaly sizes 11.7 and 18.8, which is significantly higher than the average of 2.6. Using the average statistic, organizations can compare the relative impact of an attack. Organization 2, for instance, had anomaly size 0 and concludes that there was a large anomaly taking place but they were not affected. Most of the organizations conclude that they were indeed affected, but less than average. Organizations 3 and 4, however, have to spend thoughts on why the anomaly was so disproportionately strong in their networks.

An investigation of the full port distribution and its entropy (plots omitted due to space limitations) shows that affected organizations see a sudden increase in scanning activity on specific high port numbers. Connections originate mainly from ports 80 and 443, i.e., the fallback ports of Skype, and a series of high port numbers indicating an anomaly related to Skype. For organizations 3 and 4, some of the scanned high ports are extremely prevalent, i.e., a single destination port accounts for 93% of all flows at the peak rate. Moreover, most of the anomalous flows within organizations 3 and 4 are targeted at a single IP address and originate from thousands of distinct source addresses connecting repeatedly up to 13 times per minute. These patterns indicate that the two organizations host popular supernodes, attracting a lot of traffic to specific ports. Other organizations mainly host client nodes and see uniform scanning, while organiza-

Org #	3	5	6	7	13	17
lag [hours]	1.2	2.7	23.4	15.5	4.8	3.6

Table 3: Organizations profiting from an early anomaly warning by aggregation.

tion 2 has banned Skype completely. Based on this analysis, organizations can take appropriate measures to mitigate the impact of the 2-day outage, like notifying users or blocking specific port numbers.

Early-warning Finally, we investigate whether the aggregate view can be useful for building an early-warning system for global or large-scale anomalies. The Skype anomaly did not start concurrently in all locations, since the Windows update policy and reboot times were different across organizations. We measured the lag between the time the Skype anomaly was first observed in the aggregate and local view of each organization. In Table 3 we list the organizations that had considerable lag, i.e., above an hour. Notably, one of the most affected organizations (6) could have learned the anomaly almost one day ahead. However, as shown in Fig. 11, for organization 2 this would have been a false positive alarm. To profit most from such an early warning system in practice, the aggregate view should be annotated with additional information, such as the number of organizations or the type of services affected from the same anomaly. In this context, our event correlation protocol is useful to decide whether similar anomaly signatures are observed in the participating networks. Anomaly signatures can be extracted automatically using actively researched techniques [8, 33].

8 Related Work

Most related to our work, Roughan and Zhan [37] first proposed the use of MPC techniques for a number of applications relating to traffic measurements, including the estimation of global traffic volume and performance measurements [36]. In addition, the authors identified that MPC techniques can be combined with commonly-used traffic analysis methods and tools, such as time-series algorithms and sketch data structures. Our work is similar in spirit, yet it extends their work by introducing new MPC protocols for event correlation, entropy, and distinct count computation and by implementing these protocols in a ready-to-use library.

Data correlation systems that provide strong privacy guarantees for the participants achieve data privacy by means of (partial) data sanitization based on bloom filters [44] or cryptographic functions [26, 24]. However, data sanitization is in general not a lossless process and

therefore imposes an unavoidable tradeoff between data privacy and data utility.

The work presented by Chow *et al.* [12] and Applebaum *et al.* [1] avoid this tradeoff by means of cryptographic data obfuscation. Chow *et al.* proposed a two-party query computation model to perform privacy-preserving querying of distributed databases. In addition to the databases, their solution comprises three entities: the randomizer, the computing engine, and the query frontend. Local answers to queries are randomized by each database and the aggregate results are de-randomized at the frontend. Applebaum *et al.* present a semi-centralized solution for the collaboration among a large number of participants in which responsibility is divided between a proxy and a central database. In a first step the proxy obviously blinds the clients' input, consisting of a set of keyword/value pairs, and stores the blinded keywords along with the non-blinded values in the central database. On request, the database identifies the (blinded) keywords that have values satisfying some evaluation function and forwards the matching rows to the proxy, which then unblinds the respective keywords. Finally, the database publishes its non-blinded data for these keywords. As opposed to these approaches, SEPIA does not depend on two central entities but in general supports an arbitrary number of distributed privacy peers, is provably secure, and more flexible with respect to the functions that can be executed on the input data. The similarities and differences between our work and existing general-purpose MPC frameworks are discussed in Sec. 5.4.

9 Conclusion

The aggregation of network security and monitoring data is crucial for a wide variety of tasks, including collaborative network defense and cross-sectional Internet monitoring. Unfortunately, concerns regarding privacy prevent such collaboration from materializing. In this paper, we investigated the practical usefulness of solutions based on secure multiparty computation (MPC). For this purpose, we designed optimized MPC operations that run efficiently on voluminous input data. We implemented these operations in the SEPIA library along with a set of novel protocols for event correlation and for computing multi-domain network statistics, i.e., entropy and distinct count. Our evaluation results clearly demonstrate the efficiency and scalability of SEPIA in realistic settings. With COTS hardware, near real-time operation is practical even with 140 input providers and 9 computation nodes. Furthermore, the basic operations of the SEPIA library are significantly faster than those of existing MPC frameworks and can be used as building blocks for arbitrary protocols. We believe that our

work provides useful insights into the practical utility of MPC and paves the way for new collaboration initiatives. Our future work includes improving SEPIA's robustness against host failures, dealing with malicious adversaries, and further improving performance, using, for example, polynomial set representations. Furthermore, in collaboration with a major systems management vendor, we have started a project that aims at incorporating MPC primitives into a mainstream traffic profiling product.

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Notes

¹We define *near real-time* as the requirement of fully processing an x -minute interval of traffic data in no longer than x minutes, where x is typically a small constant. For our evaluation, we use 5-minute windows.

²For instance, if $n = 10$ and $T_c = 7$, each event that needs to be reconstructed according to (4) must be reported by at least one of the first 4 input peers. Hence, it is sufficient to compute the C_{ij} and W_{ij} for the first $n - T_c + 1 = 4$ input peers.

³When run on a 32-bit platform, up to twice the CPU load was observed, with similar overall running time. This difference is due to shares being stored in `long` variables, which are more efficiently processed on 64-bit CPUs.