Semi-trusted Hosts and Mobile Agents: Enabling Secure Distributed Computations[*]

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Abstract. Secure distributed computing addresses the problem of performing a computation with a number of mutually distrustful participants, in such a way that each of the participants has only limited access to the information needed for doing the computation. In the presence of a third party, completely trusted by all participants the problem is trivially solvable. However, this assumption is in many applications non-realistic. Over the past two decades, a number of solutions requiring no trusted third party have been developed using cryptographic techniques. The disadvantage of these cryptographic solutions is the excessive communication overhead they incur.
In this paper, we will show how to overcome these disadvantages and thus enable secure distributed computations in practice. Our approach uses mobile agents employing these cryptographic techniques to provide for a trade-off between communication overhead and trust. The communication overhead problem would be solved if the communicating parties were brought close enough together. Our solution is to use mobile agents to execute the cryptographic protocols. Of course, a mobile agent needs to trust his execution platform, but we show that the trust requirements in this case are much lower than for a classical trusted third party.

1 Introduction

Secure distributed computing (SDC) addresses the problem of distributed computing where some of the algorithms and data that are used in the computation must remain private. Usually, the problem is stated as follows, emphasizing privacy of data. Let f be a publicly known function taking n inputs, and suppose there are n parties (named $p_i, i = 1 \ldots n$), each holding one private input x_i. The n parties want to compute the value $f(x_1, \ldots, x_n)$ without leaking any information about their private inputs (except of course the information about x_i that is implicitly present in the function result) to the other parties. An example is voting: the function f is addition, and the private inputs represent yes ($x_i = 1$)

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or no ($x_i = 0$) votes. In case you want to keep an algorithm private, instead of just data, you can make f an interpreter for some (simple) programming language, and you let one of the x_i be an encoding of a program.

In descriptions of solutions to the secure distributed computing problem, the function f is usually encoded as a boolean circuit, and therefore secure distributed computing is also often referred to as *secure circuit evaluation.*

It is easy to see that an efficient solution to the secure distributed computing problem would be an enabling technology for a large number of interesting distributed applications across the Internet. Some example applications are: auctions ([13]), charging for the use of algorithms on the basis of a usage count ([14, 15]), various kinds of weighted voting, protecting mobile code integrity and privacy ([15, 11]), ...

Secure distributed computing is trivial in the presence of a globally trusted third party(TTP): all participants send their data and code to the TTP (over a secure channel), the TTP performs the computation and broadcasts the results. The main drawback of this approach is the large amount of trust needed in the TTP.

However, solutions without a TTP are also possible. Over the past two decades, a fairly large variety of solutions to the problem has been proposed. An overview is given by Franklin [7] and more recently by Cramer [5]. These solutions differ from each other in the cryptographic primitives that are used, and in the class of computations that can be performed (some of the solutions only allow for specific kinds of functions to be computed). The main drawback of these solutions is the heavy communication overhead that they incur. For a case-study investigating the communication overhead in a concrete example application, we refer the reader to [12].

Mobile agents employing these cryptographic techniques can provide for a trade-off between communication overhead and trust. The communication overhead is alleviated if the communicating parties are brought close enough together. In our approach, every participant sends its representative agent to a trusted execution site. The agent contains a copy of the private data x_i and is capable of running a SDC-protocol. Different participants may send their agents to different sites, as long as these sites are located closely to each other. Of course, a mobile agent needs to trust his execution platform, but we show that the trust requirements in this case are much lower than for a classical TTP. Also, in contrast with protocols that use unconditionally TTPs, the trusted site is not involved directly. It simply offers a secure execution platform: i.e. it executes the mobile code correctly, does not spy on it and does not leak information to other mobile agents. Moreover, the trusted host does not have to know the protocol used between the agents. In other words, the combination of mobile agent technology and secure distributed computing protocols makes it possible to use a *generic* TTP that, by offering a secure execution platform, can act as TTP for a wide variety of protocols in a uniform way. A detailed discussion of the use of mobile agent technology for advanced cryptographic protocols is given in section 3.

The combination of cryptographic techniques for secure computing and mobile code has been investigated from another point of view by Sander and Tschudin ([14, 15]). In their paper on mobile cryptography, they deal with the protection of mobile agents from possibly malicious hosts. Hence, the focus in their work is on the use of cryptographic techniques for securing mobile code. The security concerns posed by the mobile agent protection problem are code privacy (Can a mobile agent conceal the program it wants to have executed?), code and execution integrity (Can a mobile agent protect itself against tampering by a malicious host?) and computing with secrets in public (Can a mobile agent remotely sign a document without disclosing the user's private key?). To address some of these concerns, cryptographic secure computation techniques can be used. We discuss this in more detail in section 2.3, which is part of our survey on secure distributed computing protocols.
The structure of this paper is as follows. In the next section, we start of with a survey of existing cryptographic solutions to the secure computing problem. In section 3, we introduce and compare three possible ways to implement secure distributed computing, making use of both cryptographic techniques, and trusted parties. The comparison is done based on a simple model of the trust and communication requirements for each of the solutions. Finally, in section 4, we summarize the main outcome of this comparison.

2 Survey of SDC protocols

Various kinds of solutions for the secure distributed computing problem have been proposed in the literature (often using different terminology than the one used in this paper).

2.1 Using probabilistic encryption

One class of techniques to compute with encrypted data is based on *homomorphic probabilistic encryption.* An encryption technique is *probabilistic* if the same cleartext can encrypt to many different ciphertexts. To work with encrypted bits, probabilistic encryption is essential, otherwise only two ciphertexts (the encryption of a zero and the encryption of a one) would be possible, and cryptanalysis would be fairly simple. An encryption technique is *homomorphic* if it satisfies equations of the form $E(x \quad \mathbf{op} \quad y) = E(x) \quad \mathbf{op}' \quad E(y)$ for some operations **op** and $\mathbf{op}'$. A homomorphic encryption scheme allows operations to be performed on encrypted data, and hence can be used for secure circuit evaluation.
Abadi and Feigenbaum present a protocol for two-player secure circuit evaluation using a homomorphic probabilistic encryption scheme based on the Quadratic Residuosity Assumption (QRA) in [1]. This protocol allows A who has a secret function f and B who has secret data x to calculate $f(x)$ without revealing their secrets.
Let k be the product of two primes p and q, each congruent to 3 mod 4. An integer $a \in Z_k^*[+1]$ — the integers relatively prime to k with Jacobi symbol 1 — is a quadratic residue mod k if there exists an $x \in Z_k^*[+1]$

such that $a = x^2 \bmod k$. The QRA states that determining if an integer a is a quadratic residue mod k is a hard problem if the factorization of k is unknown but is easy to solve if p and q are given.
If we encrypt a zero by a quadratic residue and a one by a quadratic nonresidue mod k, we can define the encryption of a bit b as

$$E_k(b) = (-1)^b \cdot r^2 \bmod k$$

with $r \in_R Z_k^*[+1]$ chosen at random. This probabilistic encryption scheme has two homomorphic properties that will come in handy in the protocol:

$$E_k(\bar{b}) = (-1) \cdot E_k(b) \bmod k$$

$$E_k(b_1 \oplus b_2) = E_k(b_1) \cdot E_k(b_2) \bmod k$$

B starts the protocol by choosing p and q and multiplying them to produce k. B sends k and the encryption of his data bits $E_k(x_1), \ldots, E_k(x_n)$ to A. B keeps the factorization of k secret. A then starts evaluating her secret circuit. If she has to evaluate a NOT gate with input $E_k(b)$, she simply calculates $-E_k(b) \bmod k$. An XOR with inputs $E_k(b_1)$ and $E_k(b_2)$ is also easy to evaluate: A just takes $E_k(b_1) \cdot E_k(b_2) \bmod k$ as the output of the gate. To evaluate the AND of inputs $E_k(b_1)$ and $E_k(b_2)$, she needs B's help. A chooses two bits c_1 and c_2 at random and sends $E_k(b_1 \oplus c_1)$ and $E_k(b_2 \oplus c_2)$ to B. B decrypts the bits A just sent him as d_1 and d_2 (he can do so because he knows p and q) and sends the tuple

$$< E_k(d_1 \wedge d_2), E_k(d_1 \wedge \overline{d_2}), E_k(\overline{d_1} \wedge d_2), E_k(\overline{d_1} \wedge \overline{d_2}) >$$

to A. A takes the first element of this tuple as the output of the AND gate if she chose $c_1 = c_2 = 0$, the second if she chose $c_1 = 0$ and $c_2 = 1$, the third if she chose $c_1 = 1$ and $c_2 = 0$ and the last one if she chose $c_1 = c_2 = 1$. Proceeding this way from gate to gate, A ends with the encrypted result $E_k(f(x))$ and sends it for decryption to B.
Note the large amount of communication overhead in the protocol: for each AND gate to be evaluated, a large amount of communication is necessary. Concrete estimates of the communication overhead in a realistic example can be found in [12]

2.2 Protocols based on oblivious transfer

In [9], Goldreich, Micali and Wigderson present a two-party protocol for the problem of *combined oblivious transfer* which is equivalent to the problem of secure circuit evaluation. The setting is slightly different than in the previous protocol. Here, two parties A and B want to evaluate a publicly known boolean circuit. This circuit takes input from both A and B, but each party wants to keep his part of the data private. In contrast, in the previous protocol, the circuit was private to A, and the data was private to B. Recall from the introduction that these two settings are essentially equivalent: by making the publicly known circuit a universal circuit, it is still possible to hide functions instead of data.
The basic idea of the protocol we are about to describe is the following: A will evaluate the circuit, not on the actual bits, but on encodings of

those bits. The encoding of the bits is known only to B. So A evaluates the circuit, but can not make sense of intermediary results because she doesn't know the encoding. B knows the encoding but never gets to see the intermediary results. When the final result is announced by A (in encoded form), B will announce a decoding for this final result.
We give a more detailed description of the protocol. B assigns two random bit strings r_i^0 and r_i^1 to every wire i in the circuit, which represent an encoded 0 and 1 on that wire. This defines a mapping $\phi_i : r_i^b \mapsto b$ for every wire i. B also chooses a random bit string R that will allow A to check if a decryption key is correct. The general idea of the protocol is that, if b is the bit on wire i in the evaluation of the circuit for A's and B's secret inputs, A will only find out about r_i^b and will never get any information about $\phi_i(r_i^b)$ or $r_i^{\overline{b}}$. In other words, A evaluates the circuit with encoded data.
We use the notation $E(M, r)$ for a symmetric encryption function of the message M with secret key r. To encrypt a NOT-gate with input wire i and output wire o, B constructs a random permutation of the tuple

$$< E(R \cdot r_o^1, r_i^0), E(R \cdot r_o^0, r_i^1) >$$

where $\cdot$ denotes the concatenation of bit strings. To encrypt an AND-gate with input wires l and r and output wire o, B constructs a random permutation of the tuple

$$\begin{gathered} < E(R \cdot r_o^0, r_l^0 \oplus r_r^0), E(R \cdot r_o^0, r_l^0 \oplus r_r^1), \\ E(R \cdot r_o^0, r_l^1 \oplus r_r^0), E(R \cdot r_o^1, r_l^1 \oplus r_r^1) > \end{gathered}$$

with $\oplus$ the bit-wise XOR. Any other binary port can be encrypted in an analogous way.
B sends the encryption of every gate in the circuit together with R, the encoding of his own input bits and the mapping ϕ_m of the output wire m to A. To perform the evaluation of the circuit on encoded data, A first needs encodings of all the input bits. For B's input bits, the encoding was sent to her, but since B doesn't know A's inputs, B can't send an encoding of them. Note that B can't send the encoding of both a 1 and a 0 on A's input wires either, because that would allow A to find out more than just the result of the circuit. The technique that is used to get the encoding of A's input to A is called *one-out-of-two oblivious transfer* ([6]). This is a protocol that allows A to retrieve one of two data items from B in such a way that (1) A gets exactly the one of two items she chose and (2) B doesn't know which item A has got.
Thus, A and B execute a one-out-of-two oblivious bit string transfer (often referred to as $\binom{2}{1}$-OT^k) for each of A's input bits. This guarantees that A only obtains the encoding of her own input bits without releasing any information about her bits to B. A evaluates each gate by trying to decrypt every element of the tuple using the encoding of the bit on the input wire (or the XOR of two input bit encodings) as a key; she will only decrypt one of the elements successfully, thereby obtaining the encoded bit on the output wire. Note that she can verify if a decryption was correct by comparing the first bits of the decrypted string with R.

Proceeding this way through the entire circuit, A obtains the encoding of the final output and applies ϕ_m to reveal the plain output bit.
Another protocol for two-party secure computation based on oblivious transfer is presented in [10]. The basic idea in this protocol is to have the participants compute the circuit on data that is shared by the two parties using a technique known as *secret sharing.*

2.3 Autonomous protocols

The protocols discussed in the two previous subsections require more communication rounds than strictly necessary. The probabilistic encryption based protocol requires one communication round per AND-gate in the circuit. The oblivious transfer based protocol requires one communication round for performing the oblivious transfer of the input, and another for sending the encrypted circuit.
For protecting mobile code privacy and integrity, non-interactive (or autonomous) protocols are necessary ([15]). The idea here is to realize a system where a host can execute an encrypted function without having to decrypt it. Thus, functions would be encrypted such that the resulting transformation can be implemented as a mobile program that will be executed on a remote host. The executing computer will be able to execute the program's instructions but will not be able to understand the function that the program implements. Having function and execution privacy immediately yields execution integrity: an adversary can not modify a program in a goal-oriented way. Modifying single bits of the encrypted program would disturb its correct execution, but it is very hard to produce a desired outcome.
It turns out to be possible to construct such autonomous solutions where the client sends (in one message) an encrypted function f, and it receives from the server an encrypted result $f(x)$ in such a way that f remains private to the client and x remains private to the server.
Various autonomous protocols have been proposed in the literature. Sander and Tschudin ([14, 15]) introduce a technique that allows for a fairly efficient evaluation of polynomials in a ring of integers modulo n using a homomorphic encryption scheme. They also show how an autonomous protocol could be realized using compositions of rational functions.
Sander and Tschudin emphasize in their paper that securing single functions is not sufficient. Consider for example the problem of implementing a digital signing primitive for mobile agents. Even if the real signature routine can be kept secret, still the whole (encrypted but operational) routine might be abused to sign arbitrary documents. Thus, the second task is to guarantee that cryptographic primitives are unremovably attached to the data to which they are supposed to be applied (the linking problem). The general idea behind the solution here is to compose the signature generating function s with the function f of which the output is to be signed. Crucial for the security of this scheme is the difficulty of an adversary to decompose the final function into its elements s and f. An outline of how this could be implemented using rational functions is given in [15].

Loureiro and Molva ([11]) use a public key encryption system based on Goppa codes. Their protocol allows for the evaluation of functions describable by a matrix multiplication. Loureiro and Molva also show how any boolean circuit evaluation can be done by a matrix multiplication. However, the representation of a boolean circuit requires a *huge* matrix (for a circuit with l inputs, one of the dimensions of the matrix is 2^l). It remains an open problem whether more efficient representations of boolean circuits as matrices can be achieved.
Finally, two very recent papers also focus on autonomous protocols: Sander, Young and Yung ([16]) propose an autonomous protocol based on a new homomorphic encryption scheme, and Cachin, Camenisch, Kilian and Müller ([2]) start from an OT-based SDC protocol as in section 2.2, and succeed in merging the two phases of this protocol into one.
It is worth emphasizing that, even though autonomous protocols use the minimal number of messages, they do not solve the communication overhead problem: even though there are only two messages exchanged, these messages are extremely big.

2.4 Multi-party protocols

All the previous protocols concentrate on the two-party case: only two parties are involved in the secure computation process. It is clear that the multi-party case is even more interesting from an application-oriented point of view. The multi-party case has also received considerable interest in the literature.
Chaum, Damgård and van de Graaf present a multi-party protocol in [3] that starts with the truth table of every gate in the circuit. Each player in turn receives a "scrambled" version of the truth tables from the previous player, transforms the truth tables by adding his own encryptions and permutations, commits to his encryptions and sends these transformed truth tables to the next player. When the last player finished his transformation, all players evaluate the scrambled circuit by selecting the appropriate row from the truth tables.
Franklin and Haber present an elegant multi-party protocol based on group-oriented cryptography in [8]. All parties send each other an ElGamal alike joint encryption of their input bits and evaluate the entire circuit together. The evaluation of a NOT-gate can be done without interaction while the evaluation of an AND-gate requires broadcasting encrypted bits and "decryption witnesses". Finally, each party sends a decryption witness for the output bit.
Even information-theoretically secure multi-party computation can be achieved (as opposed to only computationally secure). A possible realisation is discussed in [5].
The communication overhead for multi-party protocols is even more serious than that for the two-party protocols.

3 Trust versus Communication Overhead

In this section, the different options for implementing secure distributed computation are discussed. It will be shown that there is a trade-off between trust and communication overhead in secure computations. If all participants are distrustful of each other, the secure computation can be performed using protocols surveyed in the previous section with a prohibitive huge amount of communication. However, if a TTP is involved, the communication overhead can be made minimal.

Recall from section 1 that f is a publicly known function taking n inputs. Assume that there are n distrustful participants $p_1, ..., p_n$, each holding one private input x_i. The n participants want to compute the value of $f(x_1, ..., x_n)$ without leaking information of their private inputs to the other participants.

To compare the trust requirements of the different approaches, we use the following simple trust model. We say a participant *trusts* an execution site if it believes that:

- the execution site will correctly execute any code sent to it by the participant;
- the execution site will correctly (i.e. as expected by the participant) handle any data sent to it by the participant.

It also implies that the execution site will maintain the privacy of the data or the code if this is expected by the participant.

If p trusts E, we denote this as:

$$\begin{tikzcd}\overset{\mathbf{p}}{\bullet} \arrow[r] & \overset{\mathbf{E}}{\bullet}\end{tikzcd}$$

To compare bandwidth requirements (for communication overhead), we make the following simple distinction. *High* bandwidth is required to execute a SDC protocol. *Low* bandwidth suffices to transmit data or agent code. We assume low bandwidth communication is available between any two sites. If high bandwidth communication is possible between E_i and E_j, we denote this as follows:

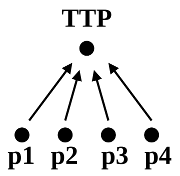
$$\begin{tikzcd}\overset{\mathbf{Ei}}{\bullet} \arrow[r, dash, dashed] & \overset{\mathbf{Ej}}{\bullet}\end{tikzcd}$$

To see that this simple two-valued model of bandwidth requirements is sufficient for our case, we refer the reader to [12]. In that paper, a case-study investigating the communication overhead for a so-called *Secret Query Database* is given. In this application, A has a query q and B owns a database with records x. The Secret Query Database allows them to cooperate in such a way that they can compute $q(x)$ while A preserves the secrecy of q and B preserves that of x. The communication overhead to solve this concrete case with SDC protocols is in the order of magnitude of 100 megabytes. On the other hand, sending just the query data, or sending an agent containing the query requires only a few kilobytes of communication. The large difference in amount of communication shows that our simplified model of high and low bandwidth requirements is realistic.

Based on these simple models of communication and trust, we compare the three options for implementing secure distributed computations.

3.1 A Trusted Third Party

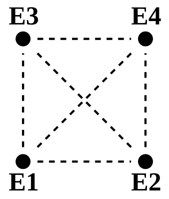
The first, perhaps most straightforward option, is to use a globally trusted third party. Every p_i sends its private input x_i to the TTP who will compute $f(x_1, ..., x_n)$ and disseminate the result to the participants $p_i, i = 1..n$.
Of course, before sending its private data to the TTP, every p_i must first authenticate the TTP, and then send x_i through a safe channel. This can be accomplished via conventional cryptographic techniques.
It is clear that this approach has a very low communication overhead: the data is only sent once to the TTP; later, every participant receives the result of the computation. However, every participant should unconditionally trust the TTP. For the case of 4 participants, the situation is as follows:



It is not clear whether n distrustful participants will easily agree on one single trustworthy execution site. This requirement of one single globally trusted execution site is the main disadvantage of this approach.

3.2 Cryptographic Secure Distributed Computing

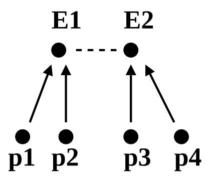
The second option is the use of cryptographic techniques (as surveyed in section 2) that make the use of a TTP superfluous.
The trust requirements are really minimal: every participant p_i trusts its own execution site E_i, and expects that the other participants provide correct values for their own inputs.
Although this option is very attractive, it should be clear from the previous sections and from [12] that the communication overhead is far too high to be practically useful in a general networked environment. High bandwidth is required between all of the participants. For the case of 4 participants, the situation can be summarized as follows:



3.3 A Virtual Trusted Third Party

Finally, our solution tries to combine the two previous options: the communication overhead of SDC-techniques are remedied by introducing semi-trusted execution sites and mobile agents.

In this approach, every participant p_i sends its representative, agent a_i, to a trusted execution site E_j. The agent contains a copy of the private data x_i and is capable of running a SDC-protocol.
It is allowed that that different participants send their agents to different sites. The only restriction being that the sites should be located closely to each other, i.e. should have high bandwidth communication between them.
Of course, every execution site needs a mechanism to safely download an agent. However, that can be easily accomplished through convential cryptographic techniques.
The amount of large distance communication is moderate: every participant sends its agent to a remote site, and receives the result from its agent. The agents use a SDC-protocol, which unfortunately involves a high communication overhead. However, since the agents are executing on sites that are near each other, the overhead of the SDC-protocol is acceptable.
For a situation with 4 participants, we could have the following situation:



No high bandwidth communication between the participants is necessary, and there is no longer a need for one single trusted execution site. p_1 for example, does not need to trust site E_2. The agents that participate in the secure computation are protected against malicious behaviour of other (non-trusted) execution sites by the SDC-protocols. That is sufficient to make this approach work.
Moreover, in contrast with the approach where one uses an unconditionally trusted third party, the trusted sites are not involved directly. They simply offer a secure execution platform: the trusted hosts do *not* have to know the protocol used between the agents. In other words, the combination of mobile agent technology and secure distributed computing protocols makes it possible to use *generic* trusted third parties that, by offering a secure execution platform, can act as trusted third party for a wide variety of protocols in a uniform way.
Finally, the question remains whether it is realistic to assume that participants can find execution sites that are close enough to eachother. Given the fact however that these execution sites can be *generic*, we believe that providing such execution sites could be a commercial occupation. Various deployment strategies are possible. Several service providers, each administering a set of geographically dispersed "secure hosts", can propose their subscribers an appropriate site for the secure computation. The site is chosen to be in the neighbourhood of a secure site of the other service providers involved. Another approach is to have execution parks, offering high bandwidth communication facilities, were companies can install their proprietary "secure site". The park itself could be managed by a commercial or government agency.

4 Conclusion

This paper shows how the use of semi-trusted hosts and mobile agents can provide for a trade-off between communication overhead and trust in secure distributed computing. There is no need for one generally trusted site, nor does the program code have to be endorsed by all participants. The trusted execution sites are generic and can be used for a wide variety of of applications. The communication overhead of secure distributed computing protocols is no longer prohibitive for their use since the execution sites are located closely to each other.

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