Optimally Efficient Multi-Party Fair Exchange and Fair Secure Multi-Party Computation

Handan Kılınç[1](✉) and Alptekin Küpçü[2]

[1] EPFL, Koç University, Istanbul, Turkey
handan.kilinc@epfl.ch
[2] Koç University, Istanbul, Turkey
akupcu@ku.edu.tr

Abstract. Multi-party fair exchange (MFE) and fair secure multi-party computation (fair SMPC) are under-studied fields of research, with practical importance. We examine MFE scenarios where every participant has some item, and at the end of the protocol, either every participant receives every other participant's item, or no participant receives anything. This is a particularly hard scenario, even though it is directly applicable to protocols such as fair SMPC or multi-party contract signing. We further generalize our protocol to work for any exchange topology. We analyze the case where a trusted third party (TTP) is optimistically available, although we emphasize that the trust put on the TTP is only regarding the *fairness*, and our protocols preserve the *privacy* of the exchanged items even against a malicious TTP.

We construct an *asymptotically optimal* (for the complete topology) multi-party fair exchange protocol that requires a constant number of rounds, in comparison to linear, and $O(n^2)$ messages, in comparison to cubic, where n is the number of participating parties. We enable the parties to efficiently exchange any item that can be efficiently put into a verifiable escrow (e.g., signatures on a contract). We show how to apply this protocol on top of *any* SMPC protocol to achieve a fairness guarantee with very little overhead, especially if the SMPC protocol works with arithmetic circuits. Our protocol guarantees fairness in its strongest sense: even if all $n - 1$ other participants are malicious and colluding, fairness will hold.

Keywords: Fair exchange · Optimistic model · Secure and fair computation · Electronic payments

1 Introduction

An exchange protocol allows two or more parties to exchange items. It is *fair* when the exchange guarantees that either all parties receive their desired items or none of them receives any item. Examples of such exchanges include signing electronic contracts, certified e-mail delivery, and fair purchase of electronic goods over the internet. In addition, a fair exchange protocol can be adopted by secure two- or multi-party computation protocols [7,10,17,26,29,36,45] to achieve fairness [30].

Even in two-party fair exchange scenarios, preventing unfairness completely and efficiently without a trusted third party (TTP) is shown to be impossible [21,41]. The main reason is that one of the parties will be sending the last message of the protocol, regardless of how the protocol looks like, and may choose not to send that message, potentially causing unfairness. In an *optimistic* protocol, the TTP is involved in the protocol *only* when there is a malicious behavior [3,4]. However, it is important not to give a lot of work to the TTP, since this can cause a bottleneck. Furthermore, the TTP is required *only* for *fairness*, and should not learn more about the exchange than is required to provide fairness. In particular, **in our protocols, we show that the TTP does *not* learn the *items*** that are exchanged.

Fair exchange with two parties have been extensively studied and efficient solutions [4,9,32–34] have been proposed, but the multi-party case does not have efficient and general solutions. Multi-party fair exchange (MFE) can be described based on *exchange topologies*. For example, a *ring topology* describes an MFE scenario where each party receives an item from the previous party in the ring [5,27,38,38]. A common scenario with the ring topology is a customer who wants to buy an item offered by a provider: the provider gives the item to the customer, the customer sends a payment authorization to her bank, the customer's bank sends the payment to the provider's bank, and finally the provider's bank credits the provider's account.

Ring topology cannot be used in scenarios like contract-signing and secure multi-party computation (SMPC), since in such scenarios the parties want items from all other parties. In particular, in such settings, **we want that either every participant receives every other participant's item, or no participant receives anything**. This corresponds to the contract being signed only if everyone agrees, or the SMPC output to be revealed only when every participant receives it. We call this kind of topology a *complete topology*. We can think of the parties as nodes in a complete graph and the edges between parties show the exchange links. The complete topology was researched mostly in the contract-signing setting [8,24,25], with one exception [3]. Unfortunately, all these protocols are inefficient compared to ours (see Table 1). Since there was no an efficient MFE protocol that achieves the complete topology, the fairness problem in SMPC protocols still could not be completely solved. Existing fair SMPC solutions either work with inefficient gradual release [23], or require the use of bitcoins [1,11].

Our Contributions: We suggest a new optimistic multi-party fair exchange protocol that guarantees fairness in every topology, including the complete topology, efficiently.

– Our MFE requires only $\mathbf{O(n^2)}$ messages and **constant** number of rounds for n parties, being much more efficient than the previous works (see Table 1). These are asymptotically **optimal** for a complete topology, since each party

Table 1. Efficiency comparison with previous works. n is the total number of parties, t is number of dishonest parties, and MPCS means multi-party contract signing protocol.

	Solution for	**Topology**	**Round Complexity**	**Number of Messages**	**Broadcast**
[25]	MPCS	Complete	$O(n^2)$	$O(n^3)$	Yes
[8]	MPCS	Complete	$O(tn)$	$O(tn^2)$	Yes
[40]	MPCS	Complete	$O(n)$	$O(n^3)$	Yes
[39]	MPCS	Complete	$O(n)$	$O(n^2)$✓	Yes
[3]	MFE ✓	Any ✓	$O(1)$ ✓	$O(n^3)$	Yes
Ours	MFE ✓	Any ✓	$O(1)$ ✓	$O(n^2)$ ✓	No ✓

should send his item to all the other parties, even in an unfair exchange. Furthermore, our MFE does *not* necessitate a *broadcast*.
- Our MFE **optimally** guarantees fairness (for honest parties) even when $n-1$ out of n parties are malicious and colluding.
- Our MFE has an easy setup phase, which is employed only **once** for exchanging **multiple** sets of items, thus improving efficiency even further for *repeated exchanges* among the same set of participants.
- The TTP for fairness in our MFE is in the *optimistic* model [4]. The TTP has a very low workload, since the parties only employ efficient discrete-logarithm-based sigma proofs to show their honesty. More importantly, the TTP does *not* learn any exchanged item, so **privacy against the TTP** is preserved.
- We show how to employ our MFE protocol for **any exchange topology**, with the performance improving as the topology gets sparser.
- We formulate MFE as a secure multi-party computation protocol. We then **prove** security and fairness **via ideal-real world simulation** [30]. To the best of our knowledge, no multi-party fair exchange protocol was proven as an SMPC protocol before.
- Based on the definition in [30], we provide an ideal world definition for *fair SMPC*, and prove via simulation that our MFE can be employed **on top of any SMPC protocol** to obtain a *fair* SMPC protocol, with the fairness extension leaking nothing about the inputs, and without necessitating a payment system.

2 Related Works

Multi-party Fair Exchange: Asokan et al. [3] described a generic optimistic fair exchange with a general topology. The parties are restricted to exchange *exchangeable items*, requiring the TTP to be able to replace or revoke the items, greatly decreasing the applicability of their protocol. In addition, broadcast is used to send the items, rendering their protocol inefficient.

Ring Topologies: Bao et al. [6] proposed an optimistic multi-party fair exchange protocol based on the ring topology. In their protocol, one of the participants is

Table 2. Efficiency comparison with previous works in the ring topology. n is number of parties. 'All or None' represents our fairness definition, where either the whole topology is satisfied, or no exchange occurs.

	Number Messages	**All or None**	**TTP-Party Dependency**	**TTP Privacy**
[6]	$O(n)$	No	Yes	Not Private
[27]	$O(n^2)$	No	Yes	Not Private
[38]	$O(n)$	No	Yes	Not Private
Ours	$O(n^2)$	Yes ✓	No ✓	Private ✓

the initiator, who starts the first and second phases of the protocol. The initiator is required to contact the TTP to acknowledge the completion of the first phase of the protocol. Thus, firstly, this is not a strictly optimistic protocol, secondly, there is a necessity of trusting the initiator.

Later, Gonzales-Deleito and Markowitch [27] solved the malicious initiator problem of Bao et al. [6]. But, the problem in their protocol is in the recovery protocol: when one of the participants contacts the TTP, the TTP has to contact the previous participant in the ring. This is not preferable because it is not guaranteed that previous participant will be available. The protocol in [38] have also the problem in the recovery protocol.

Understanding Fairness: There is an important difference between our understanding of fairness, and existing ring-topology protocols' [6,27,38]. According to their definition, in the end, there will be no party such that he does not receive his desired item from the previous party but sends his item to the next party. It means that *there can be some parties who received their desired items and some other parties who did not receive or send anything.* Whereas, **according to our definition, either the whole topology is satisfied (all the necessary exchanges are complete), or no exchange takes place**.

Complete Topologies: Multi-party contract signing indeed corresponds to a complete topology. Garay and Mackenzie [24] proposed the first optimistic multi-party contract signing protocol that requires $O(n^2)$ rounds and $O(n^3)$ messages. Because of its inefficiency, Baum-Waidner and Waidner [8] suggested a more efficient protocol, whose complexity depends on the number of dishonest parties, and if the number of dishonest parties is $n-1$, its efficiency is the same as [24]. Mukhamedov and Ryan [40] decreased the round complexity to $O(n)$. Lastly, Mauw et al. [39] gave the lower bound of $O(n^2)$ for the number of messages to achieve fairness. Their protocol requires $O(n^2)$ messages, but the round complexity is not constant. **We achieve both lower bounds ($\mathbf{O(n^2)}$ messages and constant round) for the first time.**

Fair Secure Multi-party Computation: Secure multi-party computation had an important position in the last decades, but its fairness property did not receive a lot of attention. One SMPC protocol that achieves fairness is designed by Garay et al. [28]. It uses gradual release, which is the drawback of this protocol, because each party broadcasts its output gradually in each round. At each round the number of messages is $O(n^3)$ and there are a lot of rounds due to gradual release.

Another approach is using bitcoin to achieve fairness using a TTP in the optimistic model [1,11]. When one of the parties does not receive the output of the computation, he receives a bitcoin instead. This fairness approach was used by Lindell [35] for the two-party computation case, and by Küpçü and Lysyanskaya [33] and Belenkiy et al. [9] for peer-to-peer systems. However, this approach is not appropriate for multi-party computation since **we do not necessarily know how valuable the output will be before evaluation**. Finally, reputation-based fairness solutions [2] talk about fairness probabilities.

3 Definitions and Preliminaries

3.1 Preliminaries

Threshold Public Key Encryption: In such schemes, encryption is done with a single public key, generated jointly by n decrypters, but decryption requires at least k decrypters to cooperate. It consists of the probabilistic polynomial time (PPT) protocols *Key Generation, Verification, Decryption* and a PPT algorithm for *Encryption* [44]. We describe these via the *ElGamal* $(n, k = n)$ threshold encryption scheme we will employ, as follows:

- *Key Generation:* It generates a list of private keys $SK = \{x_1, ..., x_n\}$, where $x_i \in \mathbb{Z}_p$, public key $PK = (g, h)$, where g is a generator of a large prime p-order subgroup of $\mathbb{Z}_q^*$ with q prime, together with $h = g^{\sum x_i}$, and public verification key $VK = \{vk_1, ..., vk_n\} = \{g^{x_1}, ..., g^{x_n}\}$, where $n \geq 1$. Note that this can be done in a distributed manner [43].
- *Encryption:* It computes the ciphertext for plaintext m as $E = (a, b) = (g^r, mh^r)$ where $r \in \mathbb{Z}_p$.
- *Verification:* It is between a verifier and a prover. Verifier, using VK, E, and the given decryption share of the prover $d_i = g^{rx_i}$, outputs *valid* if prover shows that $\log_g vk_i$ is equal to $\log_a d_i$. Otherwise, it outputs *invalid*.
- *Decryption:* It takes as input n decryption shares $\{d_1, ..., d_n\}$, where $d_i = g^{rx_i}$, VK, and E. Then, it outputs a message m with the following computation (in $\mathbb{Z}_q^*$),

$$\frac{b}{\prod d_i} = \frac{mh^r}{g^{r \sum x_i}} = \frac{mh^r}{h^r} = m$$

  or $\perp$ if the decryption shares are invalid.

Verifiable Encryption: It is an encryption that enables the recipient to verify, using a public key, that the plaintext satisfies some relation, without performing any decryption [14,15]. A public non-malleable label can be attached to a verifiable encryption [44].

Verifiable Escrow: An escrow is a ciphertext under the public key of the TTP. A *verifiable* escrow [4,15] is a *verifiable* encryption under the public key of the TTP. We employ *ElGamal* verifiable encryption scheme [13,20].

Notation. The n parties in the protocol are represented by P_i, where $i \in \{1, ..., n\}$. P_h is to show the honest parties, and P_c is to show the corrupted parties controlled by the adversary $\mathcal{A}$.

VE_i and VS_i is used to show the verifiable encryption and escrow prepared by P_i, respectively. The descriptive notation for verifiable encryption and escrow is $V(E, pk; l)\{(v, \xi) \in R\}$. It denotes the verifiable encryption and escrow for the ciphertext E whereby ξ –whose relation R with the public value v can be verified– is encrypted under the public key pk, and labeled by l. For escrows, pk is the TTP's public key.

$PK(v)\{(v, \xi) \in R\}$ denotes a zero-knowledge proof of knowledge of ξ that has a relation R with the public value v. All relations R in our protocols have an honest-verifier zero-knowledge three-move proof of knowledge [18], so can be implemented very efficiently. ⓩ shows the number z in the Figure 1.

3.2 Definitions

Optimistic Fair Secure Multi-Party Computation: A group of parties with their private inputs w_i desire to compute a function ϕ [8,26]. This computation is *secure* when the parties do not learn anything beyond what is revealed by the output of the computation. It is *fair* if either all of the parties learn the output in the end of the computation, or none of them learns the output. For an *optimistic* protocol, the TTP is involved *only* when there is a dispute about fairness between parties. This is formalized by ideal-real world simulations, defined below.

Ideal World: It consists of an adversary $\mathcal{A}$ that corrupts the set $\mathcal{P}_c$ of m parties where $m \in \{1, ..., n-1\}$, the set of remaining honest party(s) $\mathcal{P}_h$, and the universal trusted party U (*not the TTP*). The ideal protocol is as follows:

1. U receives inputs $\{w_i\}_{\{i \in \mathcal{P}_c\}}$ or the message ABORT from $\mathcal{A}$, and $\{w_j\}_{\{j \in \mathcal{P}_h\}}$ from the honest party(s). If the inputs are invalid or $\mathcal{A}$ sends the message ABORT, then U sends $\perp$ to all of the parties and halts.
2. Otherwise U computes $\phi(w_1, ..., w_n) = (\phi_1(w_1, ..., w_n), ..., \phi_n(w_1, ..., w_n))$. Let $\phi_i = \phi_i(w_1, ..., w_n)$ be the i^{th} output. Then he sends $\{\phi_i\}_{\{i \in \mathcal{P}_c\}}$ to $\mathcal{A}$ and $\{\phi_j\}_{\{j \in \mathcal{P}_h\}}$ to the corresponding honest party(s).

The outputs of the parties in an ideal execution between the honest party(s) and $\mathcal{A}$ controlling the corrupted parties where U computes ϕ is denoted $\mathsf{IDEAL}_{\phi, \mathcal{A}(aux)}(w_1, w_2, ...w_n, \lambda)$, where $\{w_i\}_{1 \le i \le n}$ are the respective private inputs of the parties, aux is an auxiliary input of $\mathcal{A}$, and λ is the security parameter.

Real World: There is no U for a real protocol π to compute the functionality ϕ. There is an adversary $\mathcal{A}$ that controls the set $\mathcal{P}_c$ of corrupted parties and a TTP involved in the protocol when there is an unfair behavior. The pair of outputs of the honest party(s) P_h and $\mathcal{A}$ in the real execution of the protocol π, possibly employing the TTP, is denoted $\mathsf{REAL}_{\pi,\mathbf{TTP},\mathcal{A}(aux)}(w_1, w_2, ...w_n, \lambda)$, where $w_1, w_2, ...w_n, aux$, and λ are like above.

Note that U and TTP are not related to each other. TTP is the part of the real protocol to solve the fairness problem when it is necessary, but U is not real (just an ideal entity).

Definition 1 (Fair Secure Multi-Party Computation). *Let π be a probabilistic polynomial time (PPT) protocol and let ϕ be a PPT multi-party functionality. We say that π computes ϕ **fairly and securely** if for every non-uniform PPT real world adversary $\mathcal{A}$ attacking π, there exists a non-uniform PPT ideal world simulator S so that for every $w_1, w_2, ..., w_n$, $\lambda \in \{0,1\}^*$, the ideal and real world outputs are computationally indistinguishable:*

$$\{\mathsf{IDEAL}_{\phi,S(aux)}(w_1, w_2, ..., w_n, \lambda)\} \equiv_c \{\mathsf{REAL}_{\pi,\mathsf{TTP},\mathcal{A}(aux)}(w_1, w_2, ..., w_n, \lambda)\}$$

The standard secure multi-party ideal world definition [37] lets the adversary $\mathcal{A}$ to abort *after* learning his output but *before* the honest party(s) learns her output. Thus, proving protocols secure using the old definition would not meet the fairness requirements. Therefore, we prove our protocols' security and fairness under the modified definition above. Canetti [16] gives general definitions for security for multi-party protocols with the same intuition as the security and fairness definition above. Further realize that since the TTP T does not exist in the ideal world, the simulator should also simulate its behavior.

Optimistic Multi-Party Fair Exchange: The participants are $P_1, P_2, ..., P_n$. Each participant P_i has an item f_i to exchange, and wants to exchange his own item f_i with the other parties' items $\{f_j\}_{j \neq i}$, , where $i, j \in \{1, ..., n\}$. Thus, at the end, every participant obtains $\{f_i\}_{1 \leq i \leq n}$ in a complete topology, or some subset of it defined by some other exchange topology.

Multi-Party fair exchange is also a multi-party computation where the functionality ϕ is defined via its parts ϕ_i as below (we exemplify using a complete topology):

$$\phi_i(f_1, ..., f_n) = (f_1, f_2, ..., f_{i-1}, f_{i+1}, ..., f_n)$$

The actual ϕ_i would depend on the topology. For example, for the ring topology, it would be defined as $\phi_i(f_1, ..., f_n) = f_{i-1}$ if $i \neq 1$, $\phi_i(f_1, ..., f_n) = f_n$ if $i = 1$. Therefore we can use Definition 1 as the security definition of the multi-party fair exchange, using the ϕ_i representing the desired topology.

Adversarial Model: When there is dispute between the parties, the TTP resolves the conflict *atomically*. We assume that the adversary cannot prevent the honest party(s) from reaching the TTP before the specified time interval. Secure channels are used to exchange the decryption shares and when contacting the TTP. The adversary may control up to $n-1$ out of n parties in the exchange, and is probabilistic polynomial time (PPT).

4 Description of the Protocol

Remember that our aim is to create efficient multi-party fair exchange protocols for every topology. The most important challenges of these kind of protocols are the following:

- Even if there are $n-1$ colluding parties, the protocol has to guarantee the fairness. Consider a simple protocol for the complete topology: each party first sends the verifiable escrow of the his/her item to the other parties, and after all the verifiable escrows are received, each of them sends the (plaintext) items to each other. If one of the parties comes to the TTP for resolution, the TTP decrypts the verifiable escrow(s) and stores the contacting party's item for the other parties.
  Assume now that P_i and P_j are colluding, and P_i receives verifiable escrow of the honest party P_h. Then P_i contacts the TTP, receives f_h via the decryption of the verifiable escrow of P_h, and gives his item f_i to the TTP. At this moment, if P_i and P_j leave the protocol before P_j sends his verifiable escrow to P_h, then fairness is violated because P_h never gets the item of P_j, whereas, by colluding with P_i, P_j also received f_h.
  Thus, it is important *not* to let a party learn some item *before all the parties are guaranteed* that they will get all the items. We used this intuition while designing our protocols. Therefore, we oblige **parties to depend on some input from every party in every phase of the protocol**. Hence, even if there is only one honest party, the dishonest ones have to contact and provide their correct values to the honest party so that they can continue with the protocol.
- It is desirable and more applicable to use a semi-honest TTP. Hence, privacy against the TTP needs to be satisfied. In the protocol above, the privacy against the TTP is violated since the TTP learns the items of the parties.
- The parties do not receive or send any item to some of the other parties in some topologies (e.g., in the ring topology, P_2 receives an item only from P_1 and sends an item to P_3 only). Yet, a multi-party fair exchange protocol must ensure that either the whole topology is satisfied, or no party obtains any item. Previous protocols fail in this regard, and allow, for example P_2 to receive the item of P_1 as long as she sends her item to P_3, while it may be the case that P_4 did not receive the item of P_3. The main issue here is that, if a multi-party fair exchange protocol lets the topology to be partially satisfied, we might as well replace that protocol with multiple executions of two-party fair exchange protocols. The main goal of MFE is to ensure that either the whole topology is satisfied, or no exchange happens.

We succeed in overcoming the challenges above with our MFE protocol. We first describe the protocol for the complete topology for the sake of simplicity. Then, we show how we can use our MFE protocol for other topologies in Section 5. All zero-knowledge proof of knowledge protocols are executed non-interactively in the random oracle model [12].

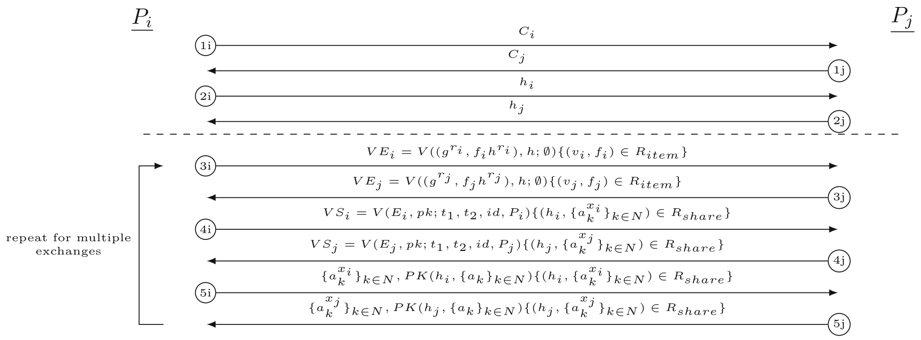
P_i
P_j
1i
C_i
C_j
1j
2i
h_i
h_j
2j
repeat for multiple exchanges
3i
$VE_i = V((g^{r_i}, f_i h^{r_i}), h; \emptyset)\{(v_i, f_i) \in R_{item}\}$
$VE_j = V((g^{r_j}, f_j h^{r_j}), h; \emptyset)\{(v_j, f_j) \in R_{item}\}$
3j
4i
$VS_i = V(E_i, pk; t_1, t_2, id, P_i)\{(h_i, \{a_k^{x_i}\}_{k \in N}) \in R_{share}\}$
$VS_j = V(E_j, pk; t_1, t_2, id, P_j)\{(h_j, \{a_k^{x_j}\}_{k \in N}) \in R_{share}\}$
4j
5i
$\{a_k^{x_i}\}_{k \in N}, PK(h_i, \{a_k\}_{k \in N})\{(h_i, \{a_k^{x_i}\}_{k \in N}) \in R_{share}\}$
$\{a_k^{x_j}\}_{k \in N}, PK(h_j, \{a_k\}_{k \in N})\{(h_j, \{a_k^{x_j}\}_{k \in N}) \in R_{share}\}$
5j

Fig. 1. Our MFE Protocol. Each (i, j) message pair can be performed in any order or in parallel within a step.

4.1 Multi-Party Fair Exchange Protocol (MFE)

There is a trusted third party (TTP) that is involved in the protocol when a dispute happens between the participants about fairness. His public key *pk* is known to every participant.

Overview: The protocol has three phases. In the first phase, parties jointly generate a public key for the threshold encryption scheme using their private shares. This phase needs to be done only once among the same set of participants. In the second phase, they send to each other the verifiable encryptions of the items that they want to exchange. If anything goes wrong up till here, the protocol is aborted. In the final phase, they exchange decryption shares for each item. If something goes wrong during the final phase, resolutions with the TTP are performed. The details are below (see also Figure 1).

Phase 1 (① and ② in Figure 1): All participants agree on the prime p-order subgroup of $\mathbb{Z}_q^*$, where q is a large prime, and a generator g of this subgroup. Then each P_i does the following [43]:

– P_i randomly selects his share x_i from $\mathbb{Z}_p$ and computes the verification key $h_i = g^{x_i}$. Then he commits to h_i and sends the commitment C_i to other parties [43].

– After receiving all commitments from the other parties, P_i opens C_i and obtains all other parties' h_j.
Note that this must be done after exchanging all the commitments, since otherwise we cannot claim independence of the shares, and then the threshold encryption scheme's security argument would fail. But with the two steps above, the security proof for threshold encryption holds here.

– After receiving all h_i values successfully, P_i computes the threshold encryption's public key

$$h = \prod_i h_i = \prod_i g^{x_i} = g^{\sum_i x_i} = g^x.$$

Phase 1 is executed only once. Afterward, the same set of parties can exchange as many items as they want by performing only Phase 2 and Phase 3.

Phase 2 (③ in Figure 1): Firstly, parties agree on two time parameters t_1 and t_2, and identification id of the protocol. (Time parameters can also be agreed in Phase 1.) Each participant P_i does the following:

– P_i sends a verifiable encryption of his item f_i as

$$VE_i = V((g^{r_i}, f_i h^{r_i}), h; \emptyset)\{(v, f_i) \in R_{item}\}$$

where r_i is randomly selected from $\mathbb{Z}_p$. For the notation simplicity, we denote $(a_i, b_i) = (g^{r_i}, f_i h^{r_i})$. VE_i includes the encryption of the item f_i with public key h and it can be verified that the encrypted item f_i and the public value v_i has the relation R_{item}. Shortly, P_i proves he encrypts desired item. (e.g., if f_i is a signature on a contract, then v_i contains the signature verification key of P_i together with the contract, and R_{item} is the relation that f_i is a valid signature with respect to v_i.)

Note that without knowing n decryption shares, no party can decrypt any VE_j and learn the items. Thus, if anything goes wrong up to this point, the parties can locally abort the protocol. After this point, they need to obtain all the decryption shares. This is done in the following phase.

Phase 3 (④ and ⑤ in Figure 1): No party begins this phase without completing Phase 2 and receiving all verifiable encryptions VE_j correctly.

– P_i sends to other parties a verifiable escrow VS_i that includes the decryption shares for each verifiable encryption VE_j. VS_i is computed as

$$VS_i = V(E_i, pk; t_1, t_2, id, P_i)\{(h_i, \{a_k^{x_i}\}_{1 \le k \le n}) \in R_{share}\}$$

where E_i is the encryption of $a_1^{x_i}, a_2^{x_i}, ..., a_n^{x_i}$ with the TTP's public key pk. The relation R_{share} is:

$$\log_g h_i = \log_{a_k} a_k^{x_i} \text{ for each } k. \tag{1}$$

Simply, the verifiable escrow VS_i includes the encryption of the decryption shares of P_i that will be used to decrypt the encrypted items of all parties. It can be verified that it has the correct decryption shares. In addition, only the TTP can open it. The label t_1, t_2, id, P_i contains the public parameters of the protocol, and P_i is just a name that the participant chooses. Here, we assume that each party knows the other parties' names.

Remark: The name P_i is necessary to show the VS_i belongs him. It is not beneficial to put a wrong name in a verifiable escrow's label, since a corrupted party can convince TTP to decrypt VS_i by showing P_i is dishonest. The other labels id, t_1, t_2 are to show the protocol parameters to the TTP. Exchange identifier id is necessary to prevent corrupted parties to induce TTP to decrypt VS_j for another exchange. Consider that some exchange protocol ended unsuccessfully, which means nobody received any item. The corrupted party can go to the TTP as if VS_j is the verifiable escrow of the next protocol, and have it decrypted, if we were not using exchange identifiers. We will see in our resolution protocols that **cheating in the labels do not provide any advantage to an adversary**. Furthermore, the party names can be random and distinct in each exchange, as long as the parties know each others' names, and so it does not violate the privacy of the parties.

- P_i waits for VS_j from each P_j. If anything is wrong with some VS_j (e.g., verification fails or the label is not as expected), or P_i does not receive the verifiable escrow from at least one participant, he executes **Resolve 1** before t_1. Otherwise, P_i continues with the next step.
- P_i sends his decryption shares $(a_1^{x_i}, a_2^{x_i}, ..., a_n^{x_i})$ to each P_j. In addition, he executes the zero-knowledge proof of knowledge showing that these are the correct decryption shares

$$PK(h_i, \{a_k\}_{k \in N})\{(h_i, \{a_k^{x_i}\}_{1 \leq k \leq n}) \in R_{share}\}. \tag{2}$$

- P_i waits for $(a_1^{x_j}, a_2^{x_j}, ..., a_n^{x_j})$ from each P_j, together with the same proof that he does. If one of the values that he receives is not as expected or if he does not receive them from some P_j, he performs **Resolve 2** protocol with the TTP, before t_2 and after t_1. Otherwise, P_i continues with the next step.
- After receiving all the necessary values, P_i can decrypt each VE_i and get all the items. The decryption for item f_j is as below:

$$b_j / \prod_k a_j^{x_k} = f_j h^{r_j} / g^{r_j \sum_k x_k} = f_j h^{r_j} / (g^{\sum_k x_k})^{r_j} = f_j h^{r_j} / h^{r_j} = f_j$$

Resolve 1. The goal of Resolve 1 is to *record* the corrupted parties that did *not* send their verifiable escrow in ④. Resolve 1 needs to be done **before $\mathbf{t_1}$**. Parties do *not* learn any decryption shares here. They can just complain about other parties to the TTP. The TTP creates a fresh *complaintList* for the protocol with parameters id, t_1, t_2. The *complaintList* contains the names of pairs of parties having a dispute because of the missing VS. The ***complainant*** is the party that complains, whose name is saved as the first of the pair, and the ***complainee*** is saved as the second of the pair. The TTP saves also *complainee's verification key* given by the complainant; in the case that the complainee contacts the TTP, he will be able to prove that he is the complainee. See Algorithm 1.

Algorithm 1. Resolve 1

```
$P_i$ sends $id, t_1, t_2, P_j, h_j$ to the TTP where $P_j$ is the party that did not send $VS_j$ to $P_i$. The TTP does the following:
if $currenttime > t_1$ then
    send $msg$ "Abort Resolve 1"
else
    $complaintList$ = GetComplaintList($id, t_1, t_2$)
    if $complaintList$ == NULL then
        $complaintList$ = EmptyList($id, t_1, t_2$) // initialize empty list
        $solvedList$ = EmptyList($id, t_1, t_2$) // will be used in Resolve 2
    end if
    $complaintList$.add($P_i, (P_j, h_j)$)
    send $msg$ "Come after $t_1$ for Resolve 2"
end if
```

Resolve 2. Resolve 2 is the resolution protocol where the parties come to the TTP to ask him to decrypt verifiable escrows and the TTP solves the complaint problems recorded in Resolve 1. The TTP does *not* decrypt any verifiable escrow until the *complaintList* is *empty*.

The party P_i, who comes for Resolve 2 **between $\mathbf{t_1}$ and $\mathbf{t_2}$**, gives all verifiable escrows that he has already received from the other parties and his own verifiable escrow to the TTP. The TTP uses these verifiable escrows to save the decryption shares required to solve the complaints in the *complaintList*. If the *complaintList* is not empty in the end, P_i comes after t_2 for Resolve 3. Otherwise, P_i can perform Resolve 3 immediately and get all the decryption shares that he requests.

Algorithm 2. Resolve 2

```
$P_i$ gives $\mathcal{M}$, which is the set of verifiable escrows that $P_i$ has. The TTP does the following:
$complaintList$ = GetComplaintList($id, t_1, t_2$)
for all $VS_j$ in $\mathcal{M}$ do
    if $(^*, (P_j, h_j)) \in complaintList$ AND
    CheckCorrectness($VS_j, h_j$) is true then
        $shares_j$ = Decrypt($sk, VS_j$)
        $solvedList$.Save($P_j, shares_j$)
        $complaintList$.Remove($(^*, (P_j, h_j))$)
    end if
end for
if $complaintList$ is empty then
    send msg "Do Resolve 3"
else
    send msg "Come after $t_2$ for Resolve 3"
end if
```

CheckCorrectness(VS_j, h_j) returns *true* if the TTP can verify the relation in equation (1) using verifiable escrow VS_j and h_j. Otherwise it returns *false*.

Resolve 3. If the *complaintList* still has parties, even after t_2, the TTP answers each resolving party saying that the protocol is **aborted**, which means nobody is able to learn any item. If the *complaintList* is *empty*, the TTP decrypts any verifiable escrow that is given to him. Besides, if the complainants in the *solvedList* come, he gives the stored decryption shares. See Algorithm 3.

Algorithm 3. Resolve 3

```
$P_i$ gives $\mathcal{C}$, which is the set of parties that did not perform step ④ or ⑤ with $P_i$, and $\mathcal{V}$, which is the set of verifiable escrows that belongs to parties in $\mathcal{C}$ who performed step ④. The TTP does the following:
$complaintList$ = GetComplaintList($id, t_1, t_2$)

if $complaintList$.isEmpty() then
    for all $P_j$ in $\mathcal{C}$ do
        if $VS_j \in \mathcal{V}$ then
            send Decrypt($sk, VS_j$)
        else
            send $solvedList$.GetShares($P_j$)
        end if
    end for
else if $currenttime > t_2$ then
    send msg "Protocol is aborted"
else
    send msg "Try after $t_2$"
end if
```

4.2 Security

Theorem 1. *The MFE protocol above is fair according to Definition 1, assuming that ElGamal threshold encryption scheme is a secure threshold encryption scheme, the associated verifiable escrow scheme is secure, all commitments are hiding and binding, and the discrete logarithm problem is hard (so that the proofs are sound and zero-knowledge).*

Proof Sketch: The proof of Theorem 1 is in the full version of this paper [31]. Assume the worst-case that adversary $\mathcal{A}$ corrupts $n-1$ parties. The simulator S simulates the honest party in the real world and the corrupted parties in the ideal world. S also acts as the TTP in the protocol if any resolution protocol occurs, so S publishes a public key pk as the TTP, and knows the corresponding secret key. Let's assume that S simulates the honest party P_1 without loss of generality in real world.

S behaves the same as in the real protocol for Phase 1. Then in Phase 2, he encrypts random item $\tilde{f_1}$ since he does not know real f_1 and sends the verifiable encryption $\tilde{VE}_1$ to other parties. While he receives other parties' VEs, he learns the other parties' items behaving as the extractor of verifiable encryption.

He behaves as in Phase 3. Additionally he learns decryption shares of the parties that send verifiable escrow using the extractor.

If he receives all verifiable escrows of the other parties, it means it is guaranteed that the real honest party would obtain her desired items, because S in the real world is now able to learn all the decryption shares from the corrupted parties via resolutions. So he sends the items of the other parties to U and receives f_1. Then he calculates Equation 3 to find the appropriate decryption share d_1 such that the other parties can get the item f_1 from a_1, b_1 using d_1. The other decryption shares are calculated as in the real protocol.

$$d_1 = \frac{b_1}{f_1 a_i^{x_2} \ldots a_i^{x_n}} \tag{3}$$

Otherwise S simulates the resolve protocols and does not send his decryption shares as in real protocol. In the end of t_2, if *complaintList* is empty, S sends items of corrupted parties to U and receives f_1. Then he calculates d_1 from Equation 3. In this point, when some parties come for Resolve 3, S can give every share that they want. If *complaintList* is not empty in the end of t_2, S sends message ABORT to U.

5 All Topologies for MFE

In this section, we adapt our MFE protocol to every topology. Our fairness definition remains the same: either the whole topology is satisfied, or no party learns any item. As an example, consider the ring topology as in Figure 3. Parties want an item from only the previous party. For example, P_2 only wants P_1's item f_1. However, P_2 should contact all other parties because of our all-or-none fairness condition. Besides, we are not limited with a topology that follows a specific pattern such as the number of parties and items being necessarily equal. For example, it is possible to provide fairness in the topology in Figure 5 even though P_2, P_3, and P_4 do not have exchange item with each other.

	f_1	f_2	f_3	f_4
P_1		$\odot$		
P_2			$\odot$	
P_3				$\odot$
P_4	$\odot$			

Fig. 2. Desired items by each parties in matrix form in the ring topology

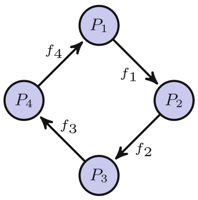

Fig. 3. Graph representation of the ring topology

	f_1	f_2	f_3	f_4	f_5
P_1		$\odot$	$\odot$	$\odot$	$\odot$
P_2	$\odot$				
P_3	$\odot$				
P_4	$\odot$				

Fig. 4. Matrix representation of a topology

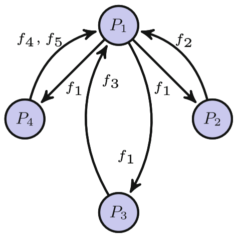

Fig. 5. Graph representation of a topology in Figure 4

Consider some arbitrary topology described by the matrix in Figure 6. If a party desires an item from another party, he should have all the shares of the item as shown in Figure 7. In general, we can say that if a party P_i wants the item f_t he should receive $\{a_t^{x_j}\}_{\{1 \le j \le n\}}$ from all the parties $\{P_j\}_{\{1 \le j \le n\}}$. Therefore, our MFE can be applied to any topology with the same fairness condition, which is **all parties will receive all their desired items or none of them receives anything** in the end of the protocol.

	f_1	f_2	f_3	f_4	f_5
P_1	$\odot$		$\odot$		
P_2	$\odot$			$\odot$	$\odot$
P_3	$\odot$		$\odot$		
P_4	$\odot$	$\odot$	$\odot$		$\odot$

Fig. 6. Each party wants the marked items corresponding to his/her row. P_i has f_i, except P_4 has both f_4 and f_5.

	f_1	f_2	f_3	f_4	f_5
P_1		$\{a_2^{x_i}\}$	$\{a_3^{x_i}\}$		$\{a_5^{x_i}\}$
P_2	$\{a_1^{x_i}\}$			$\{a_4^{x_i}\}$	$\{a_5^{x_i}\}$
P_3	$\{a_1^{x_i}\}$		$\{a_3^{x_i}\}$		
P_4	$\{a_1^{x_i}\}$	$\{a_2^{x_i}\}$	$\{a_3^{x_i}\}$		$\{a_5^{x_i}\}$

Fig. 7. Necessary shares for each party to get the desired items that are shown in Figure 6. Sets are over $i \in \{1, 2, ..., 5\}$

Our strong fairness condition requires that all parties have to depend each other. Even though P_i does not want an item f_j from P_j, getting his desired item has to also depend on P_j. Therefore we cannot decrease number of messages even in a simpler (e.g., ring) topology.

On the other hand, the size of the verifiable escrow, meaning that the number of shares in the verifiable escrow, decreases in topologies other than the complete one. If we represent the topology in a matrix form as in Figure 6, each party P_i

has to add the number of $\odot$ many shares corresponding to the row of the party P_j to the verifiable escrow that is sent to P_j. We can conclude that the total size of the verifiable escrows that a party sends is $O(\#\odot)$ where $\odot$ is as in Figure 6.

6 Efficient Fair Secure Multi-Party Computation

In this section, we show how to adapt the MFE protocol to **any** secure multi-party computation (SMPC) protocol [7,10,17,26,46] to achieve fairness.

Assume n participants want to compute a function $\phi(w_1, ..., w_n) = (\phi_1(w_1, ..., w_n), ..., \phi_n(w_1, ..., w_n))$, where w_i is the input and $\phi_i = \phi_i(w_1, ..., w_n)$ is the output of party P_i.

- P_i randomly chooses a share $x_i \in \mathbb{Z}_p$. Then P_i gives his share and w_i to an SMPC protocol that outputs the computation of the functionality ψ where $\psi_i(z_1, z_2, ..., z_n) = (E_i(\phi_i(w_1, ..., w_n)), \{g^{x_j}\}_{1 \leq j \leq n})$ is the output to, and $z_i = (w_i, x_i)$ is the input of P_i. This corresponds to a circuit encrypting the outputs of the original function ϕ using the shares provided as input, and also outputting the verification shares of all parties to everyone. Encryption E_i is done with the key $h = g^{\sum_{j=1}^{n} x_j}$ as follows:

$$E_i(\phi_i(w_1, ..., w_n)) = (g^{r_i}, \phi_i h^{r_i})$$

  where $r_i \in \mathbb{Z}_p$ are random numbers chosen by the circuit (or they can also be inputs to the circuit), similar to the original MFE protocol.
  It is expected that everyone learns the output of ψ before a fair exchange occurs. If some party did not receive his output at the end of the SMPC protocol, then they do not proceed with the fair exchange, and hence no party will be able to decrypt and learn their output.
- If everyone received their output from the SMPC protocol, then they execute the Phase 3 of the MFE protocol above, using g^{x_i} values obtained from the output of ψ as verification shares, and x_i values as their secret shares. Furthermore, the a_i, b_i values are obtained from E_i.
  Note that each function output is encrypted with all the shares. But, for party P_i, she need not provide her decryption share for f_i to any other party. Furthermore, instead of providing n decryption shares to each other party as in a complete topology, she needs to provide only one decryption share, $a_j^{x_i}$, to each P_j. Therefore, the Phase 3 of MFE here is a more efficient version. Indeed, the verifiable escrows, the decryption shares, and their proofs each need to be only on a *single* value instead of n values.

Phases 1 and 2 of the fair exchange protocol have already been done during the modified SMPC protocol, since the parties get the encryption of the output that is encrypted by their shares. Since the SMPC protocol is secure, it is guaranteed to output the correct ciphertexts, and we do not need further verification. We also do not need to commit to x_i values, since the SMPC protocol ensures independence of inputs as well. So, the parties only need to perform Phase 3.

In the end of the exchange, each party can decrypt only their own output, because they do not disclose their own decryption shares. Indeed, if a symmetric functionality is desired for SMPC, $\psi(z_1, z_2, ..., z_n) = \{E_i(\phi_i(w_1, ..., w_n)), g^{x_i}\}_{1 \leq i \leq n}$ may be computed, and since P_i does not give the decryption share of f_i to anyone else, each party will still only be able to decrypt their own output. Hence, ***a symmetric functionality SMPC protocol may be employed to compute an asymmetric functionality fairly using our modification***. Note also that we view the SMPC protocol as *black box.*

Our overhead over performing *unfair* SMPC is minimal. Even though the input and output sizes are extended additionally by $O(n)$ values and the circuit is extended to perform encryptions, these are minimal requirements, especially if the underlying SMPC protocol works over *arithmetic circuits* (e.g., [7,46]). In such a case, performing ElGamal and creating verification values g^{x_i} are very easy. Afterward, we only add two rounds of interaction for the sake of fairness (i.e., Phase 3 of MFE, with smaller messages). Moreover, all the benefits of our MFE protocol apply here as well.

Theorem 2. *The SMPC protocol above is fair and secure according to Definition 1 for the functionality ϕ, assuming that ElGamal threshold encryption scheme is a secure, the discrete logarithm assumption holds, and the underlying SMPC protocol that computes functionality ψ is secure.*

Proof Sketch: The proof of Theorem 2 is in the full version of this paper [31]. Assume that $\mathcal{A}$ corrupts $n-1$ parties, which is the worst possible case. The simulator S simulates the honest party in the real world and the corrupted parties in the ideal world. S uses random input and acts as the simulator of underlying SMPC protocol. The only difference between simulator of SMPC and S is that S does not send inputs of the corrupted parties to U directly after learning inputs of them because he needs to be sure that all parties will receive output before sending inputs to U. The output of the simulated SMPC protocol is encryptions of random outputs. Because of the security of ElGamal encryption, these encryptions are indistinguishable from real ones.

In the end, S behaves as the simulator of MFE protocol for Phase 3 to simulate the exchange. If it is guarantee all parties learn outputs, S sends inputs of P_c's to U and receives the output of P_h. Then he calculates each share d_i as in Equation 3. Otherwise he sends the message ABORT to U.

Table 3 compares our fair SMPC solution. Our advantage is in terms of **efficiency**, having **no requirement for an external payment mechanism**, and **proving security and fairness together** via ideal/real simulation.

7 Performance and Privacy Analysis

MFE: Each party P_i in MFE prepares one verifiable encryption and one verifiable escrow, and sends them to $n-1$ parties. The verification of them are efficient because the relation they show can be proven using discrete-logarithm-based honest-verifier zero-knowledge three-move proofs of knowledge [18]. In the end, P_i sends a message including decryption shares to $n-1$ parties, again with an efficient proof of knowledge. So, for each party P_i, the number of messages

Table 3. Comparison of our fair SMPC solution with previous works. NFS indicates simulation proof given but not for fairness, FS indicates full simulation proof including fairness, and λ is the security parameter.

Solutions	**Technique**	**TTP**	**Number of Rounds**	**Proof Technique**
[23]	Gradual Release	No	$O(\lambda)$	NFS
[11]	Bitcoin	Yes	Constant ✓	NFS
[1]	Bitcoin	Yes	Constant ✓	NFS
Ours	MFE	Yes	Constant ✓	FS ✓

that he sends is $O(n)$. Since there are n parties, the total message complexity is $O(n^2)$. Note that there is *no* requirement to have these messages broadcast; just ensuring all previous step's messages are received before moving further is enough for security. Table 1 shows the comparison to the previous works, MFE is much more efficient, obtaining **optimal asymptotic efficiency**.

When there is a malicious party or a party suffering from network failure, MFE protocol ends at the latest, immediately after t_2. In the worst case, n parties contact the TTP, so it is important to reduce his workload. TTP's duties include checking some list from his records, verifying efficient zero-knowledge proofs of knowledge from some number of parties (depending on the size of the *complaintList*), and decrypting verifiable escrows. These actions are all efficient.

Moreover, the **privacy against the TTP is preserved**. He just learns some decryption shares, but he cannot decrypt the encryption of exchanged items, since he never gets the encrypted items.

We used ElGamal threshold encryption for presentation simplicity. Instead, any threshold encryption scheme such as the Pailler cryptosystem [42], Franklin and Haber's cryptosystem [22], or Damgard-Jurik cryptosystem [19] can be used.

Finally, our MFE protocol achieves the intuitive fairness definition of 'either the whole topology is satisfied, or no item is exchanged' for any topology. Such a strong fairness definition necessitates that the exchanges depend on all parties, necessitating quadratic number of messages.

Fair MPC: The overhead of our fairness solution on top of an existing unfair SMPC protocol is increased input/output size, and additional computation of encryptions and verification shares. If an arithmetic circuit is used in the underlying SMPC protocol [7,17,46], then there are only $O(n)$ additional exponentiations required, which does not extend circuit size a lot. If boolean circuits are used, the size of the circuit increases more than arithmetic circuits would have, but it is still tolerable considering in comparison to the related work.

As seen in Table 3, [23] uses gradual release for fairness. However, this brings many extra rounds and messages to the protocol. Each round each party releases his item by broadcasting it. Recent, bitcoin-based approaches [1,11] also require broadcasting in the bitcoin network, which increases message complexity. Our only overhead is a constant number of rounds, and $O(n^2)$ messages. Remember again that these are asymptotically optimal, since fair SMPC necessitates a complete topology.

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