# Multiparty Nonrepudiation: A Survey

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Nonrepudiation is a security service that plays an important role in many Internet applications. Traditional two-party nonrepudiation has been studied intensively in the literature. This survey focuses on multiparty scenarios and provides a comprehensive overview. It starts with a brief introduction of fundamental issues on nonrepudiation, including the types of nonrepudiation service and cryptographic evidence, the roles of trusted third-party, nonrepudiation phases and requirements, and the status of standardization. Then it describes the general multiparty nonrepudiation problem, and analyzes state-of-the-art mechanisms. After this, it presents in more detail the 1-N multiparty nonrepudiation solutions for distribution of different messages to multiple recipients. Finally, it discusses advanced solutions for two typical multiparty nonrepudiation applications, namely, multiparty certified email and multiparty contract signing.



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## 1. FUNDAMENTALS OF NONREPUDIATION

Repudiation is one of the fundamental security issues existing in paper-based and electronic environments. Dispute of transactions is a common issue in the business world. Transacting parties want to seek a fair settlement of disputes, which brings the need nonrepudiation services in their transactions. The motivation for nonrepudiation services is not just the possibility that communicating parties may try to cheat each other. It is also the fact that no system is perfect, and that different and unexpected circumstances can arise in which two parties end up with different views of something that happened. Network failure during the protocol run is a representative example.

We define a *basic transaction* as the transferring of a message $M$ (e.g., electronic goods, electronic cash, or electronic contracts) from user A to user B, and represent this event with the following message flow: $A \rightarrow B : M$. Thus, typical disputes that may arise in a basic transaction with a deadline $T$ could be:

—A claims that it has sent $M$ to B, while B denies having received it;

—B claims that it received $M$ from A, while A denies sending it; and

—A claims that it sent $M$ before $T$, while B denies receiving it before $T$.

Fair nonrepudiation can be considered as an extended *fair exchange* problem in which non repudiability is made an integral requirement of the exchange (in general, it may not be required). We can find various instances of the general exchange problem in different types of commercial activities: purchase, contract signing, certified mail, or, more generally, in any barter conducted by means of digital networks.

An exchange is said to be *fair* if, at the end of the exchange, either each player receives the item it expects or neither player receives any additional information about the other's item. For instance, in payment protocols, fair exchange can ensure that a customer receives digital goods from a vendor if and only if the vendor receives payment from the customer.

The features of the transaction will decide the type of nonrepudiation service to be deployed. For any nonrepudiation service, evidence is a crucial object, and the processing of evidence usually involves the assistance from Trusted Third Parties (TTPs). There are different activities at each phase of processing. The nonrepudiation policy defines the behavior of these activities. Finally, the eventual success of nonrepudiation depends upon technical and legal supports.

Non repudiation is, thus, one of the essential security services in computer networks defined by the ITU in X.813 [ITU-T X.813 1996]. Following, we establish the characteristics of this security service and survey the progress of standardization of nonrepudiation in general. Further in this survey, we analyze this service when multiple entities are involved.

### 1.1. Specific Nonrepudiation Services

Nonrepudiation services help the transacting parties to settle possible disputes over whether a particular event or action has taken place in a transaction. We define a *nonrepudiation protocol* as a message flow in which entities exchange digital evidence in order to provide such nonrepudiation services.

In an electronic transaction, message transfer is the building block and there are two possible ways of transferring a message (see Figure 1):

—The originator O sends the message to the recipient R directly; or

—The originator O submits the message to a *delivery agent* D which then delivers the message to the recipient R.

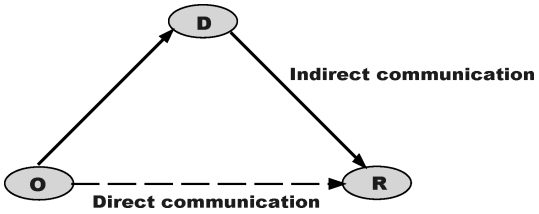


**Fig. 1**. Models of message transfer.

In the direct communication model, because the originator and the recipient eventually do not trust each other, the originator is not sure that the recipient will acknowledge a message it has received. On the other hand, the recipient will only acknowledge messages it has received. In order to facilitate a fair exchange of a message and its receipt in which neither party will gain an advantage during the transaction, a TTP will usually be involved. Of course, the extent of the TTP's involvement varies among different protocols, which allows to provide a protocol distinction.

To establish the accountability for the actions of originator and recipient, the following nonrepudiation services are required.

—*Nonrepudiation of Origin (NRO)* is intended to protect against the originator's false denial of having originated the message. Evidence of Origin (EOO) is generated by the originator or a TTP on its behalf, and will be held by the recipient.

—*Nonrepudiation of Receipt (NRR)* is intended to protect against the recipient's false denial of having received the message. Evidence of Receipt (EOR) is generated by the recipient or a TTP on its behalf, and will be held by the originator.

In the indirect communication model, a delivery agent is involved to transfer a message from originator to recipient. In order to support the settlement of possible disputes between originator and delivery agent or between originator and recipient, the following nonrepudiation services are required.

—*Nonrepudiation of Submission (NRS)* is intended to provide evidence that the originator submitted the message for delivery. Evidence of Submission (EOS) is generated by the delivery agent, and will be held by the originator.

—*Nonrepudiation of Delivery (NRD)* is intended to provide evidence that the message has been delivered to the recipient. Evidence of Delivery (EOD) is generated by the delivery agent, and will be held by the originator. Similarly, we should be aware that evidence provided by this service cannot be used to make further deductions about the delivery status without some sort of assumption on the communication channel.

### 1.2. Evidence

The evidence is the data or information that can be used if a dispute arises. It can be either generated and stored by the local user or by a third party. Its format depends on the cryptographic mechanisms agreed in the service, such as *digital signatures* (public-key cryptography) and *secure envelopes* (secret-key cryptography). Whichever the format is, this evidence has to be composed on common information that helps to clearly identify a transaction and thus resolve a possible dispute in a more deterministic way. Some of these common elements are:

—nonrepudiation service to which evidence is related;

—nonrepudiation policy identifier;

—originator identity;

—recipient identity;

—third-party identity if evidence generator differs from the originator;

—message or a digital fingerprint;

—message identifier;

—information needed for verifying evidence (i.e., digital certificate, symmetric secret key information) if it is not publicly available;

—TTP's identifier and role (see Section 1.3) when involved in the service;

—unique evidence identifier; and

—time information (time and date in which evidence was generated, expiry date, etc.). If this data is certified by a Time-Stamping Authority (TSA), it could include a time-stamp service identifier.

When a secure envelope is used to provide evidence, data is stamped with a secret key known only by the TTP, thus being the generator and verifier of evidence as requested by users.

TTP participation can be relaxed through the use of smartcards or manipulation-resistent modules [ITU-T X.813 1996] in which secret keys are properly installed. In this case, the smartcard plays the role of a distributed TTP. The generator smartcard is used for evidence generation, while the verifier's is only for validation. The latter cannot be used to generate evidence with the secret key (even if it is the same one), such that only the user who owns the generator smartcard could have created the evidence. This is achieved by correctly installing the secret key and the module which controls whether the user can use its smartcard for generation or verification. This module is tamper-proof and different for the generator and the verifier such that it performs just one of the two possible functions.

The secure envelope maintains integrity of the information using a digital fingerprint (i.e., hash function) and confidentiality (e.g., symmetric cipher with the secret key).

When a digital signature is used to provide evidence, information is enclosed in a data structure digitally signed by a Certification Authority (CA) such that only the CA can sign the data and other participants (recipients and TTP) can verify it. Unforgeable digital signatures provide a clear statement of the essential components of handwritten signatures, namely, a user's ability to sign by itself, a universally agreed verification procedure, and the assertion that it is unfeasible (or at least very hard) to selectively forge signatures in a manner that passes the verification process without being detected.

In order to bring all of this into reality, digital signatures used as evidence in a nonrepudiation service need an infrastructure backing them up. There will be a third party certifying participants' link between their identity and public key. Only in this way can any recipient can verify the digital signature. Digital signatures introduce a new disrupting element in the nonrepudiation service, as the link certified by the CA (often referred to as *digital certificate*) may have an expiry date. This fact has to be checked when evidence is verified either by the recipient or a TTP (e.g., an adjudicator). If this link has expired, evidence will be valid only if it was generated before. For this reason, time information has to be included in the evidence generated.

In general, it is more efficient, in terms of computation, for users to use secure envelopes with symmetric encryption techniques, since the TTP (or smartcard) is in charge of the generation/verification process. Nevertheless, in this case, the following holds.

—Principals have to *unconditionally trust* a third party for evidence generation and verification;

—TTP's online availability is needed in order to participate in the service when requested; and
—if users are to relax the TTP participation as stated previously, then they need to use dedicated hardware to avoid the TTP becoming a bottleneck.

So, users would likely prefer to use digital signatures for the following reasons.

—It only needs an *implicit trust* over the CA computing the digital certificates. But this trust can be relaxed with legal agreements between users and authorities, audited registration processes, and a quite advanced standardization [ITU-T X.509 2000].
—*Trust* imposed over the CA is *less critical* than in the former case, since it certifies the existence of a binding between a user and a public key, verifying at the same time that this uniquely corresponds to a private key. But this TTP need not know the key itself. So, there is no danger of this entity accessing the content, or even being able to generate it (as with secure envelopes).

Additionally, Maurer [2004] proposed a novel view of digital evidence called *digital declarations*, based on a digital recording of a willful act indicating agreement to a document or contract. This proposal tries to address some of the problems mentioned before that digital signatures bring with them. It also includes new elements in the digital evidence (as willful acts) to augment the concept of evidence, bringing it nearer to that used in human judgements. Among all the concepts introduced by Maurer, the semantics of certificates is very important. He proposes that when registering the public key, the user must explicitly commit to be liable for signatures with respect to this public key. Evidence confirming this commitment, designated as change, has several important implications for us.

—The certificate has absolutely no value as evidence in court, only the commitment declaration does.
—Only the recipient of a signature (evidence) must trust the CA.
—An expiration date stated on the commitment declaration must be interpreted differently. It specifies until what time evidence can be presented as valid, regardless of when generated. In other words, evidence expires, not public keys. As a consequence of this view, the validity period of evidence should be kept short.
—A commitment declaration cannot be revoked. Revocation of a public key is impossible (not needed).

Actually, with these definitions, the signature seems to be more insecure than in the traditional view when revocation is possible while the commitment declaration is valid. But, on the other hand, it seems to be closer to the business model if we consider the discussed users' liability in the traditional approach.[1] Maurer proposes the concept of delegation signatures (digital signatures assisted by TTPs) to strengthen its security.

Furthermore, this digital declaration and commitments comprise a new approach to digital evidence, with no implications on how nonrepudiation protocols handle the evidence.

### 1.3. Roles of the TTP

One of the main features which allows us to classify TTPs is their role on a nonrepudiation service. A TTP which does not participate actively in the nonrepudiation service

[1]In the current digital signature laws, the main "hot potato" does not come from the technical aspects, but from the user's liability when it does not understand the technical process or when this is done without its knowledge.

(i.e., it will be invoked only when there is something wrong in a transaction) is referred to as *offline* TTP. An *online* TTP participates in the generation and verification of evidence throughout the protocol instance. An *inline* TTP acts as an intermediary in all interactions among users. The difference between third parties that are used only in case of exceptions and those that are actively involved in a protocol was first explained in DeMillo and Merritt [1983]. Obviously, the first type is preferred if efficiency is the major concern, but in some situations and e-commerce applications, to have a delivery agent or intermediary could be the best practical solution.

Other roles have appeared as a consequence of research achieved in the domain of exchange protocols. These new approaches aim at eliminating the involvement of the TTP completely, but need strong requirements; either all involved parties must have the same computational power, as in *gradual exchange*, or fairness depends on the number of protocol rounds [Markowitch and Roggeman 1999], as in *probabilistic protocols*.

Finally, an additionally existing trusted third party is the *adjudicator*. This is the party which drives a resolution process to a conclusion, depending on evidence presented by the entities and, optionally, contacting the TTP which participated in the protocol. In order to facilitate its task, a well-defined dispute resolution process in accordance with the nonrepudiation policy must exist. This dispute resolution process has to take into consideration the legal framework in which it is defined. New or established Online Dispute Resolution (ODR) processes can be used [Brannigan 2004].

### 1.4. Nonrepudiation Phases

Nonrepudiation services establish accountability of an entity related to a particular event or action to support dispute resolution. Provision of these services can be divided into different phases, such as generation, transfer, verification, storage, and dispute resolution.

*1.4.1. Evidence Generation.* Evidence generation is the first phase in the provision of a nonrepudiation service. Depending on the nonrepudiation service being provided and the nonrepudiation protocol being used, evidence could be generated by the originator, the recipient, and/or the TTP. The elements of nonrepudiation evidence and the algorithms used for evidence generation are determined by the nonrepudiation policy in effect. When NRO and NRR services are required, evidence of origin and receipt are usually generated by the originator and the recipient, respectively, if digital signature is used for evidence generation. When NRS and NRD services are required, evidence of submission and delivery will be generated by a TTP, like a notary or a delivery authority. If a secure envelope is used for evidence generation, it should always be generated by a TTP on behalf of the originator or recipient.

A TTP may also generate and provide supporting evidence in a nonrepudiation service. For example, in a fair nonrepudiation protocol [Zhou and Gollmann 1996], the notary will digitally sign the message key provided by the originator and make the confirmed message key available to both originator and recipient. The confirmed message key will serve as part of nonrepudiation evidence to prove that the message key was sent from the originator (via the notary), and is available to the recipient.

*1.4.2. Evidence Transfer.* Evidence transfer is the most challenging phase in the provision of a nonrepudiation service. It mainly consists of the sending and reception of evidence among participants. Actually, it represents the core of a nonrepudiation protocol. It is greatly influenced by the communication channel properties. The different options are as follows.

—The communication channel is unreliable. In this case, data can be lost.

—The communication channel is resilient (also called an asynchronous network). In this case, data is delivered after a finite but unknown amount of time.
—The communication channel is operational (also called a synchronous network). In this case, data is delivered after a known, constant amount of time.

An unreliable channel will in most cases be transformed into a resilient channel by the use of appropriate transport protocol (e.g., retransmissions).

*1.4.3. Evidence Verification.* Newly received evidence should be verified to gain confidence that the supplied evidence will indeed be adequate in the event of a dispute arising. The verification procedure is closely related to the mechanism of evidence generation.

If evidence is generated through a secure envelope, it should be verified by a TTP at the request of the user because the secret key for evidence generation and verification is only held by the TTP. Obviously, the extra communication between user and TTP will cause a substantial delay, which might be unacceptable for many online electronic transactions.

*1.4.4. Evidence Storage.* Because loss of evidence could result in the loss of a future possible dispute resolution, verified evidence needs to be stored safely. The duration of storage will be defined in the nonrepudiation policy. For extremely important evidence aimed at long-term nonrepudiation, it could be deposited with a TTP.

*1.4.5. Dispute Resolution.* Dispute resolution is the last phase in a nonrepudiation service. This phase will not be activated unless disputes related to a transaction arise. When a dispute arises, an adjudicator will be invoked to settle the dispute according to the nonrepudiation evidence provided by the disputing parties and the nonrepudiation policy in effect. This policy should be agreed in advance by the parties involved in the service.

The adjudicator needs to verify the evidence, probably with assistance from other TTPs, for example, from a notary when evidence was generated through a secure envelope. Nowadays, different online arbitrator platforms[2] exist, which allows for dispute resolution being processed through document and evidence transactions, as well as the cooperation of online parties.[3] The dispute resolution process can either be registered in one of these platforms and use its services, or use its own rules for the definition of an online arbitrator.

### 1.5. Nonrepudiation Requirements

Different targets of each nonrepudiation service may influence the protocol design. Nevertheless, there are several common requirements in the design of a good nonrepudiation protocol, described next.

—*Fairness*. Repudiation can only be prevented when each party is in possession of proper evidence and no party is in an advantageous position during a transaction. The reliability of communication channels affects evidence transfer. Moreover, a dishonest party may abort a transaction, which could leave another party without evidence. Various fair nonrepudiation protocols with different features have been proposed. Some can be found in Kremer et al. [2002] and Gürgens et al. [2003]. Asokan defined two levels of fairness [Asokan 1998]. A protocol fulfills *strong fairness* if, when the exchange

[2]Note that these platforms themselves may need to implement a nonrepudiation service.
[3]http://www.ietf.org/html.charters/ltans-charter.html or http://www.disputemanager.com/mediation/what.asp or http://www.dr.bbb.org.

is completed, A can at least prove to an arbitrator that B has received (or can still receive) the item, without any further intervention from A. On the other hand, a protocol fulfills *weak fairness* if, when the exchange is completed for A, it can prove to an arbitrator that B has received (or can still receive) the item, or otherwise an affidavit can be presented to demonstrate that B misbehaved or a network failure occurred.

—*Efficiency*. TTPs will usually be involved in nonrepudiation services and this involvement will be essential in order to determine the efficiency of the protocol. Fair nonrepudiation protocols, proposed in Asokan et al. [1997, 1998, 2000], Zhou and Gollmann [1997], Pfitzmann et al. [1998], Markowitch and Saeednia [2001], and Micali [2003], meet the criterion of efficiency and are often called *optimistic* protocols. Some authors define this property as *effectiveness*; that is, if no error occurs and no party misbehaves, then the TTP should not intervene.

—*Timeliness*. This is also desirable in evidence transfer. For various reasons, a transaction may be delayed or terminated. Hence, the transacting parties may not know the final status of a transaction on time, and would like to unilaterally bring a transaction to completion in a finite amount of time without losing fairness.

—*Policy*. This has to perfectly define all parameters needed by the service, some of which can be rules for evidence generation and verification, as well as for evidence storage, evidence use, and the dispute resolution process.

There are optional requirements, and their fulfillment depends on the application itself. If the application requires them, they turn out to be as critical as the common ones previously defined.

—*Verifiability of TTP*. This property adds one level of security to the protocol itself when a strong trust relationship does not exist between participants and the TTP which collaborates in the protocol. If the TTP misbehaves, resulting in a loss of fairness for any participating entity, all harmed parties will be able to prove this to an arbitrator or verifier. It can be very useful during the initial setup of a nonrepudiation infrastructure, as well as in those scenarios in which the TTP has to be selected by entities on-the-fly (e.g., in an ad hoc network). This usually assumes that when the TTP misbehaves, the rest of the entities are honest.

—*Transparency of TTP*. This also appears in the literature as *invisible* TTP. If the TTP is contacted to help in the protocol, the resulting evidence will be similar to that obtained in the case where the TTP is not involved. This is especially important in practical cases, in which an institution does not wish to change the existing processes to accommodate the new signatures or affidavits generated by TTPs. At the same time, this property helps in preserving the privacy of users with respect to possible use of a TTP during the protocol run.

Unfortunately, the last two properties are often incompatible (achieving one of them increases the difficulty in fulfilling the other) and a trade-off has to be assumed when designing such protocols.

### 1.6. Analysis of Standards

ISO and ITU standards provide a guideline for engineering and should reflect the state-of-the-art of science and technology. Nonrepudiation is one of the security services in the ISO/OSI security framework, and is especially important for securing electronic commerce. Many efforts have been devoted to the standardization of nonrepudiation services and mechanisms. However, some issues have not yet been well addressed.

There are two international standards dealing with nonrepudiation: ISO/IEC 10181-4 [ISO/IEC 1996][4] and ISO/IEC 13888 [ISO/IEC 2004, 1998, 1997]. The first one refines and extends the concept of nonrepudiation services as described in ISO 7498-2 and provides a framework for the development and provision of these services. In this framework, the goal of nonrepudiation and types of nonrepudiation services are defined. The basic mechanisms for nonrepudiation services and the general management requirements for these services are identified. The roles that a TTP plays in nonrepudiation services are listed. The relationship of nonrepudiation services to other security services is explained. As a general framework, this standard does not include specific nonrepudiation mechanisms. This remains as an open issue, treated in [ISO/IEC 1998, 1997].

ISO/IEC 13888 "Information technology-Security techniques-Nonrepudiation" is composed of three parts. The first [ISO/IEC 2004][5] serves as a general model for subsequent parts specifying nonrepudiation mechanisms using cryptographic techniques. It establishes two main types of evidence, the nature of which depends on cryptographic techniques employed: the secure envelopes and digital signatures generated by an evidence generator (which can be the user itself), or an evidence-generating authority using asymmetric cryptographic techniques.

In ISO/IEC [1998, 1997], a set of nonrepudiation mechanisms based on symmetric and asymmetric cryptographic techniques are identified. All are final international standards in the different phases that ISO/IEC applies to its documents. The history of this multipart standard being developed by ISO/IEC JTC1/SC27 dates back to August 1991 [ISO/IEC 1991]. Zhou's book [Zhou 2001] analyzes the ISO/IEC 13888 nonrepudiation mechanisms, and points out their weaknesses and limitations. It also discusses problems in defining the roles of time-stamps in ISO/IEC 13888 nonrepudiation evidence.

In 2006, and in response to a request of ISO's Subcommittee 27 (SC27), Secretariat, the Working Group 2 (WG2) of the same subcommittee, agreed to revise ISO/IEC 13888-2 as well as ISO/IEC 13888-3. The same occurrence happened later with ISO/IEC 13888-1. Though drafts of the three parts have been circulated within WG2, no final documents are available at the moment. But it seems that the changes will not be dramatic.

On the other hands, ITU defines a general framework for the provision of nonrepudiation services in X.813 [ITU-T X.813 1996] similar to ISO/IEC 10181-4. It defines nonrepudiation as "the ability to prevent entities from denying later that they performed an action." The nonrepudiation framework extends the concepts of nonrepudiation security services as described in X.800 and provides a framework for the development of these services.

## 2. DESCRIPTION OF THE GENERAL MPNR PROBLEM

As commerce applications like e-voting, e-bidding, etc., usually involve several parties, we have focused in this survey on the multiparty scenario. For identifying the Multiparty Nonrepudiation (MPNR) problem, we studied several existing approaches of multiparty scenarios in related topics such as fair exchange, contract commitment, etc.

### 2.1. Definitions

Extracted from the different multiparty applications and protocols, let us define our view of an MPNR scenario.

[4]Revised by 10181-4:1997 Information technology – Open Systems Interconnection – Security frameworks for open systems: Nonrepudiation framework.
[5]This document revises ISO/IEC 13888-1:1997, which is withdrawn.

*Definition* 2.1 In a general MPNR scenario, $n \mid n > 2$ entities agree to use a nonrepudiation protocol for exchanging messages (general- or specific-purpose) and collecting evidence of the transactions performed for the exchange of these messages.

Of course, different topologies are possible (e.g., one-to-many, ring, mesh), but some seem more natural than others. For instance, sending the same message to several entities is an action more related to existing Internet applications than that of one entity receiving the same message from different originators. Nevertheless, all the topologies need to be considered as long as applications exist for them. We should not forget that there are applications in the collaborative and e-learning areas in which many-to-many messages are a reality. For example, in Asokan et al. [1996] a *simultaneous payment for receipt* is presented as an instantiation of a many-to-one application, and in Asokan et al. [1998] a many-to-many contract-signing protocol is depicted.

Let us imagine the following scenario which sketches a virtual application for managing market shares. Several, $n$, users (or machines) which are market share-holders meet up in order to bid for each other's stocks (some users could share one or several stocks). We can represent the bids as a set of messages $Set_i = m_1, \ldots, m_m$. For a user $U_i$, there are $n - 1$ entities to which offers from the set can be sent. The same offer can be submitted to all or a subset of the entities. Also, different offers can be sent to all entities or any combination therefore. Once the offers are sent, user $U_i$ will wait for a response. This response could be made individually, or could require several recipients gathering for replying with an offer. This is a typical example of a many-to-many application, which can be represented by a binary matrix, in which "1" in the $(i, j)$ position indicates that user $U_i$ sends a bidding message to user $U_j$.

Each user $U_i$ may need evidence of receipt of the message sent, while receivers may need evidence of the origin of the offer received. Many other multiparty applications and protocols can be represented using a matrix. For instance, in the case of the Multiparty Contract-Signing (MPCS) protocol mentioned earlier, a matrix in which all elements are "1" except for the diagonal represents mathematically the topology used.

This could be seen as a typical multiparty fair exchange scenario as described in Asokan et al. [1996]. Even though general MPNR and multiparty fair exchange protocols have a common design goal (fairness), several differences can be found.

—In a fair exchange protocol each entity offers an a priori known item (i.e., something is known about the item a priori, but not its precise content) and receives another item, also known a priori. In a multiparty fair exchange protocol, we can imagine sending an item to one entity and receiving an item from a different one. In nonrepudiation it does not make sense that one entity receives some data and a different entity sends the corresponding receipt of that data.

—With a general message $M$, nonrepudiation is more related to a certified email service, in which the receipt has to be sent by the receiver in order to be able to disclose the message received and obtain the evidence of origin for it. Therefore, a ring topology is not applicable in a general MPNR service.

—Due to the fact that a nonrepudiation service is not an exchange of items, MPNR protocols have to continue and finish, even if some parties do not reply. Only parties following the protocol correctly should be able to disclose the message and obtain evidence of origin for it.

—In some MPNR applications, the message content is previously revealed and known by the recipients. In these applications the origin and occurrence of the transmission, that is, the fair exchange of EOO and EOR, are more important.

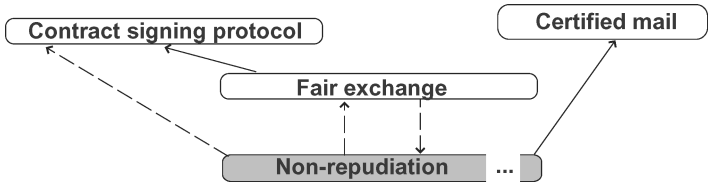


**Fig. 2**. Nonrepudiation service.

—There is no *exclusion-free* property, as defined in González-Deleito and Markowitch [2002], in MPNR protocols. Since there is no need for a setup phase to agree on participants and items, no danger of excluding participants exists.

The reason these differences is also due to the classification of fair exchange and nonrepudiation as services or applications. Although it seems clear that nonrepudiation comprises a service,[6] sometimes it is referred in the literature as an application and the authors compare it with fair exchange. Actually, fair exchange can also be considered as a service. While nonrepudiation might provide a service to applications like certified electronic mail, fair exchange can provide service to other upper-layer applications as well, like payment protocols or digital contract signing. Although nonrepudiation should be a security service in these kinds of applications, they can be designed without it (see Figure 2). Note that this view is not contrary, but complementary, to the one provided in Markowitch et al. [2002].

Other types of application in which multiparty protocols appear (either for fair exchange, nonrepudiation, contract signing, certified electronic mail, or any other evidence-generating exchange) are those in which the participants play different roles in the same application. Imagine an electronic shopping application which involves a customer, a merchant, a credit card company, and a delivery company. Different existing two-party nonrepudiation protocols could be selected for providing a nonrepudiation service in this scenario; nevertheless, several questions (mainly regarding efficiency) arise. The solution achieved is not optimal for a real application, since the correlation among different parties in a unique transaction is lost.

The grounds for focusing on the multiparty problem as a different one come from the fact that the solutions to be provided are different. The first step towards creating multiparty environments consists of revising the requirements defined in Section 1.5.

*Definition* 2.2 (*Fairness*). A multiparty protocol is said to be fair if, at the end of the protocol, all honest parties receive what they expect or none receive any valuable information.

It is very important to detail what *is* valuable information. Most existing definitions do not specify the valuable elements and it is not always straightforward to identify these elements. In a general fair MPNR protocol, the recipients either already know the message to be received and thus only evidence is considered as valuable elements for the exchange (i.e., they can refuse to run the protocol even if they get the message, and we say the protocol fulfills *light* fairness), or they must send an NRR in order to get the message. Thus, in the latter case, instantiating the previous definition, we say that an MPNR protocol is fair if, at the end of the protocol, either the originator receives the NRR and the recipient(s) receive(s) the message and corresponding NRO, or none of them obtains any of these items.

[6]In fact, as mentioned in previous section, it has been standardized as a service.

Note that all participants must be in the same state at the end of the protocol. In other words, corrupted parties should receive their outputs if and only if the honest parties also receive them [Lindell 2003].

*Definition* 2.3 (*Confidentiality*). A multiparty protocol is said to be confidential if only the targeted honest recipients can disclose the message.

This means that the TTP cannot disclose the message, either. Nevertheless, though it is a must in multiparty protocols that others do not disclose the message, it is optional whether the TTP is able to do so.

*Definition* 2.4 (*Efficiency*). A multiparty protocol is said to be efficient if, assuming that participating entities of the protocol are honest, the TTP does not intervene.

Different instances of a nonrepudiation protocol in which different entities participate could make the TTP become a bottleneck. An optimistic protocol in which an offline TTP participates only in the case of an exception seems to be the solution, as we already explained for two-party protocols. Nevertheless, many entities could be participating in each instance of a multiparty protocol. In this multiparty environment, even only in case of exception, the TTP needs to act in a light way such that it does not become a bottleneck.

*Definition* 2.5 (*Timeliness*). A multiparty protocol is said to respect timeliness if all honest entities are able to terminate the protocol in a finite amount of time without losing fairness.

Honest transacting parties may not know the final status of a transaction in time, and would like to unilaterally bring a transaction to completion at any time without losing fairness. It should be noted that, from the definition of timeliness, two versions of this property appear.

—*Asynchronous Timeliness*. A multiparty protocol is said to respect asynchronous timeliness if all honest entities are able to terminate the protocol at any time without losing fairness. In this case, there are no deadlines for participants in the protocol, but a serious practical implication makes this property hard to achieve: For this property to be fulfilled, an infinite state (or at least until evidence expiry date if it is the case) has to be maintained by the TTP. Otherwise, if responsible for distributing evidence, the TTP needs to retry until recipients of evidence acknowledge reception. An alternative solution can be to extend the channel reliability between TTP and users (in this direction).

—*Synchronous Timeliness*. A multiparty protocol is said to respect synchronous timeliness if all honest entities are able to terminate the protocol in a finite *and known* amount of time without losing fairness. In this case, deadlines are used and the TTP clock is assumed as the reference time (i.e., users' clocks need to be synchronized with the TTP's clock). Though more difficult for users, the TTP need not maintain evidences for long time periods (*stateless* TTP).

*Definition* 2.6 (*Policy*). A MPNR protocol needs a complete nonrepudiation policy that supports the participation of several entities in possible dispute resolution processes.

As with two entities, this has to define perfectly all the parameters needed by the service. There is no important distinction in multiparty environments, except for the fact that multiple disputes and agreements can arise among participants. The arbiter to judge the dispute needs to be explicitly mentioned in the policy definition.

### 2.2. State-of-the-Art and Analysis

The first work that appears in general MPNR problems can be found in Kremer and Markowitch [2000a] and Markowitch and Kremer [2000]. Those papers propose generalizations of two protocols: one based on the online approach [Zhou and Gollmann 1996] and the other based on an optimistic approach (also known as offline TTP) [Kremer and Markowitch 2000b]. As stated before, other related works also existed and are still under research in the field of multiparty fair exchange [Asokan et al. 1996; Franklin and Tsudik 1998; Bao et al. 1999; González-Deleito and Markowitch 2002, 2001; Khill et al. 2001], contract signing [Asokan et al. 1998; Baum-Waidner and Waidner 2000, 1998; Garay and MacKenzie 1999; Ferrer-Gomila et al. [2004, 2001]; Baum-Waidner 2001; Chadha et al. 2004] and certified email [Ateniese et al. 2001; Ferrer-Gomila et al. 2002]. Due to its practicality, works on MPNR and Certified Electronic Mail (CEM) use a one-to-many topology, whereas multiparty fair exchange and contract-signing appears either in mesh or ring configurations.

*2.2.1. Multiparty Fair Exchange (MPFE).* The general optimistic multiparty fair exchange protocol in Asokan et al. [1996] is the first to achieve a scenario with multiple entities in which nonrepudiation evidence needs to be generated together with the fair exchange of the items. Asokan et al. [1996] proposed the use of a matrix of descriptions as information of the items to be exchanged for all entities. Depending on the type of item (confidential data, public data, and payment) and number of entities (one-to-many, etc.), the generic service described can be instantiated as a particular application; for example, one-to-many topology in which confidential data is exchanged by public data corresponds to a reliable certified broadcast application.

In this way, the basic idea of the generic multiparty fair exchange protocol is that each party signs the expected global description or local view (i.e., the whole description matrix) of the exchange and commits to the items he will send to every other party. If all parties signed the same description matrix, the parties send the promised items. If someone does not receive what was expected, two-party recovery procedures are started with the TTP.

Additionally, the authors introduced the notion of *revocable* items (e.g., the payment could be cancelled by the bank even when the order was already transmitted) and *generatable* items (e.g., the bank could order, on behalf of one of its clients, a payment to another client). In this protocol, the TTP can guarantee strong fairness if the items involved are either all revocable or all generatable, otherwise weak fairness is achieved.

The resolution process of this protocol, though complete, is not efficient. Having the TTP observing every exchange between two parties when a problem exists and, if not sufficient, running recovery resolution processes, is not a practical solution for an application aimed at use over the Internet.

In Franklin and Tsudik [1998], the authors also develop a classification of types of multiparty fair exchange schemes and present new protocols which assume the presence of a *semitrusted neutral party* in ring topologies. A malicious semitrusted neutral party must be unable to cheat as long as the other parties remain honest. For achieving fairness, the protocol makes use of a special mathematical function $f$ which allows to make checks without revealing content. This is similar to the *verifiable encryption scheme* appearing in some approaches [Bao et al. 1999]. The TTP acts in an inline manner (i.e., it is involved in every exchange) and neither learns about the items exchanged nor the topology (it knows it is a ring but does not know the sequence).

In Bao et al. [1999], the authors propose a multiparty fair exchange protocol with a ring topology making use of an offline TTP. In this protocol, no honest party is left in an unfair situation, no matter how maliciously the dishonest parties behave.

Nevertheless, some parties could be excluded from the ring in the exchange (not affecting, however, fairness). The main design, which uses a verifiable encryption scheme as a tool for commitment, is linear with respect to the number of rounds ($2n$ rounds) and the TTP needs to contact the originator of the protocol. This makes efficiency an important issue to be improved. In fact, two main improvements are proposed for enhancing efficiency: reducing the number of sequential rounds and avoiding the contact of the TTP with the initiator of the protocol. In González-Deleito and Markowitch [2001], the protocol is improved such that participants need only trust the TTP (and not the initiator). Moreover, under certain circumstances, if there are participants excluded from the exchange, they can prove to an external adjudicator that a problem occurred.

Markowitch tackles the exclusion-freeness property in multiparty fair exchange protocols one year later in González-Deleito and Markowitch [2002]. This time, the authors demonstrate the exclusion problem in Franklin and Tsudik's [1998] protocol. They provide a formal definition of the exclusion-freeness property and propose a multiparty fair exchange protocol with online TTP which respects the strongest definition of the property defined.

In Khill et al. [2001], the authors propose a protocol for multiparty fair exchange with a ring topology. Although it is not optimal, it presents an extensive complexity study with respect to Asokan et al. [1996]. The protocol consists of three phases, in which a matrix of elements are exchanged from the initiator to the next party in the ring (the sequence is predefined). Upon receiving the message, each party checks it and pulls out the information components destined to it from the matrix. It may load the next sequenced components into the matrix with regard to the accepted components at this point. The TTP participates in the exchange in abnormal cases. It tries to recover from the abnormality by observing and controlling all transferred messages. In such cases each message from one party to the next party is not transmitted directly, but relayed by the TTP.

*2.2.2. Multiparty Contract Signing.* A particular application of multiparty fair exchange protocols is MPCS, although MPCS protocols can also be used to design multiparty fair exchange protocols when the signed contract is used as evidence (*verifiable commitment*), which preserves fairness in the exchange. In Asokan et al. [1998], the authors propose the first optimistic MPCS for synchronous networks. Assuming that the TTP is not corrupted, in the all-honest case, only two rounds of communication are needed. In the first round, each party who wishes to sign the contract broadcasts a signed promise to sign. In the second round, each party who receives all promises from the previous round signs the contract and broadcasts its real signature. Obviously, this works if all parties wish to sign. If at least one party does not wish to sign, it will not send the signed promise, and thus no party will sign in round 2.

If some party cheats, two more rounds are added to the protocol, such that everybody who has all signed promises from round 1 can get them converted into a valid contract by the TTP. If the TTP issues an affidavit, it broadcasts it to all parties in round 4. Thus, each party who did not receive all promises in round 1 waits until round 4. If it receives an affidavit from the TTP, the decision is `signed`, otherwise `failed`. On asynchronous networks, the previous "otherwise" would not be effective, since a party could not decide whether an affidavit was not sent, or just not delivered yet. In fact, due to this synchronicity, termination of the protocol is ensured by the network itself in a fixed number of rounds (four in the all-honest case and six in the worst case). Using this protocol as a building block, Asokan et al. designed a generic multiparty fair exchange and a multiparty certified electronic-mail protocol (see next subsection for further reference).

In Baum-Waidner and Waidner [1998], the first optimistic MPCS for asynchronous networks is presented. Again, assuming that the TTP is not corrupted, $n+4$ rounds of communication and $O(n^2)$ messages are needed in the worst case, taking into account that the number of dishonest parties is not known a priori. It consists of $n+1$ rounds in the all-honest case. In round 1 each party that starts with `sign` signs a promise to sign the contract and broadcasts this promise. In each subsequent round each party collects all signatures from the previous round, countersigns this set of $n$ signatures, and broadcasts them. The result of the (n + 1)-th round becomes the real contract. Three additional rounds are needed if the TTP is contacted.

A party who becomes tired of waiting for some signatures in some round (i.e., there is a local timeout) can call the third party. The TTP analyzes the situation and decides either failed or signed: If the first request received comes from a party in the first round, then the TTP must decide failed (the TTP cannot know whether some parties might have started the protocol with `reject`). If the TTP receives a request from a party in the last round, then the TTP must decide signed because other parties might already have the signed contract. Besides, if the TTP receives multiple requests somewhere in the middle between the first and the last round, the TTP might have to change the decision from failed to signed.

The problem is that the TTP can do this only if all parties that received failed before are probably dishonest. Therefore, the TTP needs $n+1$ rounds in order to check this behavior. If dishonest parties call the TTP one after the other starting with round 1, then the first request must be answered with failed, as already explained. After that, for $i > 2$, the request by party $i$[7] shows that party $i-2$ to first party are all dishonest: Party $i$ calling in round $i$ means that it has seen all messages of round $i-1$, because otherwise, party $i$ would have called the TTP already then. These include messages from party $i-2$ to the first one, which could not exist if these would have stopped in round $i-2$ to the first, as supposed. Thus, whenever the TTP receives a request for a certain round $i$ ($i \geq 2$) such that it has not answered a request for round $i-1$ yet, then it can safely switch from failed to signed (since parties who previously obtained the failed token are clearly dishonest).

As a consequence of the number of rounds, asynchronous timeliness is achieved; that is, no deadlines are used and each party can finish the protocol when desired. Using this protocol as a building block, the authors designed a scheme which provides fairness to any general secure multiparty function evaluation protocol. These protocols allow several users to calculate the output of a function $f$ without revealing to the rest of the participants their inputs. With the added fairness, dishonest parties have no advantage over honest parties in learning the function outcome (basically composing this outcome in such a manner that a signed contract protocol is used for exchanging one of the components needed for learning the other component which is the real function output).

In Garay and MacKenzie [1999], the authors construct a general multiparty optimistic asynchronous contract-singing protocol which requires $O(n^3)$ messages in $O(n^2)$ rounds. The protocol is also *abuse-free*, meaning that at no point can a participant prove to others that he is capable of choosing whether to validate or invalidate the contract. This is the first abuse-free optimistic contract-signing protocol that was developed for $n > 2$ parties. They also showed a linear lower bound of $n$ rounds of any $n$-party optimistic contract-signing protocol.

For this purpose, a crypto tool called the Private Contract Signature (PCS) is used. Upon receiving a PCS, a party convinces himself of its validity, but cannot convince anybody else, and he also knows that the TTP appointed by the signatory can convert it into a regular (self-authenticating) signature. The full formal definition described

[7] $i$ establishes the order of rounds and a party $i$ is the party requesting the TTP in round $i$.

in Garay and MacKenzie [1999] presents invisibility; that is, no one can determine if a conversion was performed by the original signer or the TTP. This, of course, allows the TTP to be transparent.

Nevertheless, the more important contribution of this work is not the protocol itself, which is rather complicated and not optimal, but the theorem presented at the end of the paper.

> *Any complete and optimistic asynchronous contract-signing protocol with n participants requires at least n rounds in an optimistic run.*

Describing the theorem, Garay et al. stated that

> "for each party $P_i$ out of $n$, when it sends a message that can be used (together with other information) by other entities to obtain a valid contract, as the protocol is fair, it must have received in a previous round, a message from the rest of participants in order to be able to get a valid contract too, no matter how others behave (probably with TTP's help)".

By an inductive argument, they showed the number of rounds is at least $n$.

We found another argument which, perhaps, better explains the theorem stated before from a more practical point of view. Bearing in mind the technical requirements for fulfillment of fairness in an asynchronous contract-signing protocol, we base our argument on the number of rounds a TTP needs to determine whether a party is misbehaving when requesting resolution (i.e., it requests cancel to the TTP but continues the main protocol).

THEOREM 2.7 *The TTP cannot determine whether a party is misbehaving until* $round = round_{current} + 1$*, since the TTP needs to wait to the next round to see whether this entity cheated and continued the protocol. This means that if* $n-1$ *dishonest parties exist in the worst case, and each of them requests TTP's cancel subprotocol in a different round, n rounds are the minimum required to satisfy fairness in an asynchronous optimistic contract-signing protocol.*

This is the argument used by other solutions to reduce the number of rounds and steps when the number of dishonest parties $t$ is limited and known a priori. In Baum-Waidner [2001], by assuming $t$, the protocols presented achieve an improvement in comparison with the state-of-the-art. The number of rounds is reduced from $O(t)$ to $O(1)$ for all $n \geq 2t + 1$, and for $n < 2t + 1$, it grows slowly compared with the number of rounds in $O(t)$: If $t \approx \frac{k}{k+1}n$ then the number of rounds $\approx 2k$. Nevertheless, in the worst case ($t = n - 1$), the number of rounds is (obviously) still $t + 2 = n + 1$. From a theoretical point of view, the main unrealistic assumption of this work is assuming a known a priori set of dishonest parties. In any case, from a practical point of view, these could be protocols with a determined tolerance which could work in real applications in which parties assume the risk on the limited number of dishonest parties (especially in relative trust environments). Furthermore, these protocols could be used in combination with others such that they are used when at least one-half of the participating entities have previously demonstrated their good behavior, thus taking advantage of the better efficiency. As these protocols use a threshold, we will refer to them in the rest of this protocols as *threshold protocols*.

*2.2.3. Composition of Secure Multiparty Protocols.* When research on multiparty protocols is conducted, there is another important issue to be taken into account, namely the composition of secure multiparty protocols. In Lindell [2003], it is demonstrated that obtaining security under (even rather weak notions of) composition can be strictly harder than the stand-alone execution of the protocols. In other words, interactions

between different executions of the same multiparty protocol more often reduce security. MPNR protocols themselves need to be studied to see how different executions interact with each other and how this affects security. For instance, MPNR protocols might make use of multiparty primitives as broadcasts, and it has been demonstrated that it is impossible to achieve broadcast if a third or more of the parties are corrupted. And this is under parallel self-composition, which is weaker than the concurrent self-composition we foresee for MPNR protocols.

A protocol is said to be *self-composed* if it remains secure when it alone is executed many times in a network. It is *parallel self-composed* if all executions begin at the same time and proceed at the same rate (i.e., in synchronous fashion). It is *concurrent self-composed* if several executions of the same protocol start and finish in an arbitrary way or are determined by the adversary (i.e., in asynchronous fashion).

Nevertheless, composition of secure multiparty protocols is a large area of research out of the scope of this article. Furthermore, we can base the design of MPNR protocols on the fact that Universal Composition (UC) protocols can be achieved if a reference string is used in the composition (i.e., a setup phase). Thus, we assume this setup phase for allowing the composition of these multiparty protocols, even though we do not raise this issue any more. As an example, in this setup phase, transaction identifiers (or labels) have to be perfectly defined in order to distinguish among different executions of the same protocol and participants must be aware of not engaging in an exchange in which it has been already participating. Details for protocols for UC realizing any multiparty functionality in the common reference string model can be found in Chapter 4 in Lindell [2003].

*Remark* 2.8 Including the common reference model, and hence a setup phase for secure composition of MPNR protocols, produces the exclusion problem. Nevertheless, in MPNR protocols there is no exchange of a priori known items or promises. In other words, the recipient does not know from what it has been excluded, and therefore the exclusion-freeness decreases its importance, as in fair exchange or contract-signing protocols.

### 2.3. Description of the 1-N MPNR Problem

Several applications, like email and multicast of content in general, present a 1-N topology. In some of these applications, the originator sends a message which should not be revealed unless the recipients confirmed their reception. Let us define what is our view of a 1-N MPNR scenario.

*Definition* 2.9 A 1-N MPNR application is an instantiation of the general MPNR problem; one entity $O$ is willing to send a (several) message(s) to a set of recipients $R$ such that a subset $S \subseteq R$ obtain the message and evidence of origin if and only if they have sent evidence of receipt.

As previously mentioned, Kremer and Markowitch proposed generalizations of two protocols: one based on the online approach and the other based on an optimistic approach (also known as with offline TTP). For both of them, the originator sends an initial commitment (message encrypted with key $k$) and, once a group of recipients reply to this commitment, it sends the message to which it was committed (i.e., it sends the key $k$ which allows the recipients to decipher the expected message) and waits for evidence of receipt. As the same message is distributed, only one key needs to be distributed to those recipients which replied, and a group encryption scheme based on the Chinese Reminder theorem is used for this purpose [Chiou and Chen 1989].

The online-based approach uses the TTP in a lightweight manner to distribute the key for each execution of the protocol. In this way, the originator submits the key together with evidence of submission, and the TTP publishes this key along with its final signature (needed by all entities to complete their evidence). As explained before, only those who behaved correctly can decipher the key and thus the message.

In the optimistic approach, and if no exception arises, the TTP does not take part. Otherwise, entities can recover the protocol if needed after a deadline fixed by the originator with respect to the TTP's clock. The originator will contact the TTP when not receiving final evidence from recipients to which it sent the key. Recipients will contact the TTP when not receiving the key while having sent evidence of receipt of the commitment. Once the TTP is contacted for resolving the protocol, and assuming this happens after the fixed deadline, the TTP needs to access an originator database in which recipients who replied are marked. The originator needs to be notified of the TTP's successful access and must stop immediately the main protocol. Of course, the authors assume that the channel between originator and TTP is bidirectionally resilient. If the TTP receives all necessary information, it sends evidence of confirmation to all entities, which substitute evidence not received (maybe due to a channel failure) by participating entities. The authors showed that the improvement with respect to $n$ parallel executions of a two-party nonrepudiation protocol is in terms of number of messages, as well as the number of needed digital signatures.

For multiparty certified email applications, different protocols can also be found. Asokan et al. instantiated (and optimized some steps) their generic multiparty fair exchange, explained in the previous section, to design a reliable broadcast application. Moreover, Asokan et al. presented an optimistic multiparty certified email protocol as an application of an MPCS protocol, presented in Asokan et al. [1998]. Specifically, the MPCS protocol is used as a building block. The block can be asynchronous or synchronous, depending on the type of network the certified email application is running on. It follows the following schema.

(1) The sender prepares the message $M$ and *tid* (a transaction id) to be sent to all the recipients encrypting it with the TTP's public key. This $cipher = E_{TTP}(M, tid)$ turns out to be a contract to be signed by all parties.

(2) All participants sign the contract, using the MPCS building block and tid as the contract-signing transaction identifier. Only if the final decision of the signing process is signed does the protocol continue. The signed contract will be the receipt for the sender.

(3) The sender sends to all the recipients the cleartext mail $M$. If any of the recipients does not receive this message, it contacts the TTP sending the signed contract (*tid*, *cipher*). The TTP checks the consistency of tid after decrypting cipher. If the contract is valid and decryption succeeds, then the TTP signs the cleartext $M$ for the recipient, otherwise it signs a null message.

In the original paper, a proof can be found based on demonstrating two properties: No information is leaked on $M$ unless the sender has a receipt; and the sender cannot get a receipt without revealing $M$. In this work, Asokan et al. also define other possible types of multiparty certified email applications with many-to-one and mesh topologies. All of them can be solved following the same schema described before.

The only apparent difference with respect to the general MPNR protocols described in the previous section is that, as the authors indicated, honest recipients should receive the message even if some dishonest parties do not follow the protocol correctly and thus the MPCS block outputs *failed*. The main privacy problem of this solution is that, since it uses an MPCS as a building block, each recipient can identify the rest of addressees in the protocol.

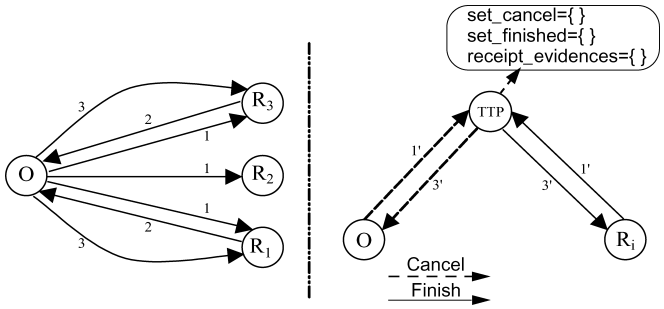


**Fig. 3**. Ferrer et al. solution for multiparty certified email.

With this in mind, Ferrer et al. presented a realistic protocol for multiparty certified electronic mail in Ferrer-Gomila et al. [2002], which can be seen as an instantiation of an MPNR service. If we compare this protocol with Kremer's optimistic proposition already discussed, the former is more efficient (only three steps in the main exchange, which will be the only one executed in the majority of executions) and solves some of the problems found in the latter.

In this protocol (see Figure 3), the sender commits itself to the message, and sends the necessary information (encrypted with the TTP's public key) to open this commitment together with evidence of origin. Then, honest recipients send evidence of receipt, and finally the sender opens the commitment and sends the required evidence to those recipients who replied. With respect to the MPNR properties, the protocol is efficient, can be terminated in a timely manner thanks to the existence of two subprotocols (*cancel* and *finish*), and defines a sufficient dispute resolution process. Furthermore, the TTP behavior is verifiable (unless colluding with and other entity, the TTP cannot misbehave without being discovered).

If the sender does not get some receipts from some participants, it initiates a cancel subprotocol in which those recipients are included in a cancelled set if they have not finished the protocol yet. On the other hand, if some recipients do not receive step 3 of the main exchange protocol, they contact the TTP in order to finish it, and those who have not been cancelled yet by the sender receive the key to open the commitment, thereby obtaining the cleartext message. Otherwise, they receive a cancel token. In this finish sub-protocol, recipients need to send their receipts to the TTP, which will store and forward them to the sender if required. A weakness can be found in the dispute resolution process: The arbiter needs to contact both disputing parties in order to be able to maintain fairness, that is, an entity and its evidence cannot be sufficient to prove its claim.

We introduce Tables I and II in order to summarize the different advantages, properties, disadvantages, and functionalities of the fair protocols presented so far, as well as our own solutions.

## 3. MPNR PROTOCOL WITH DIFFERENT MESSAGES

In the existing MPNR solutions a message can be multicasted to several recipients. In that way no personal and confidential messages can be sent to these parties without loss of privacy. In this section we review the new solutions.[8]

[8]The work in this section has been partially published in Onieva et al. [2004, 2003].

**Table I.** Multiparty Protocols' Properties Summary

| Protocols | App. | Properties | Advantages | Drawbacks | Topology |
|---|---|---|---|---|---|
| Asokan'96 | MPFE | optimistic, generic service, revocable and generatable items | asynchronous timeliness, NR evidence generated, strong and weak fairness | not efficient | N-N |
| FraTsu'98 | MPFE | in-line TTP | semitrusted neutral party, confidentiality | no exclusion-free | ring |
| Bao'99 | MPFE | offline TTP, verifiable encryption scheme | asynchronous timeliness | no exclusion-free, not efficient | ring |
| GDM'02 | MPFE | online TTP | exclusion-free | | ring |
| Asokan'98 | MPCS | optimistic, synchronous | 4 rounds | synchronous timeliness | ring |
| BW'98 | MPCS | optimistic, asynchronous | asynchronous timeliness | n+4 rounds, $O(n^2)$ messages | ring |
| Garay'99 | MPCS | optimistic, asynchronous, PCS crypto tool | timeliness, transparent TTP, abuse-free | $O(n^2)$ rounds, $O(n^3)$ messages | ring |
| BW'01 | MPCS | optimistic, asynchronous, threshold | optimal efficiency | | ring |
| KM'00 | MPNR | group encryption scheme | light TTP, one key | same message, online TTP | 1-N |
| MK'00 | MPNR | group encryption scheme | offline TTP, one key | synchronous timeliness, same message | 1-N |
| Asokan'98 | CEM | based on MPCS protocol, a/synchronous | optimistic | no privacy | 1-N |
| Ferrer'02 | CEM | | optimistic, efficient, timeliness, verifiable TTP | arbitrator needs to contact disputing parties | 1-N |

### 3.1. Online MPNR Protocol for Distribution of Several Messages

Sending (the same or different) messages to several recipients could mean a single transaction in a specific application. Therefore, it would be better to store the same key and evidence in the TTP record for every protocol run. In those types of applications, the storage and computation requirements of the TTP are reduced and it will be easy to distinguish between different transactions, regardless of how many entities are involved. An example application which can take advantage of these kinds of security protocols is the notification system. These systems notify different users with customized messages and need evidence of having notified them (e.g., a paper acceptance notification system for scientific conferences). In this type of applications we will

**Table II.** Our Solutions' Properties Summary

| Protocols | App. | Properties | Advantages | Drawbacks | Topology |
|---|---|---|---|---|---|
| OZCL'03 | MPNR | different messages for different recipients | privacy, lightweight TTP | online TTP | 1-N |
| OZL'04 | MPNR | optimistic, different messages for different recipients | privacy, transparent TTP, asynchronous timeliness, efficient | | 1-N |
| ZOL'05 | CEM | optimistic, no split of message in delivery | asynchronous timeliness, very efficient, recipient collusion resistance | more TTP overhead when TTP involved | 1-N |
| ZOL'06 | MPCS | optimistic, threshold cancel for weak asynchronous timeliness | abuse-free, very efficient, 3 rounds and $3(n-1)$ steps | | in-and-out |

distinguish between whether the recipients already know or do not know the content of the message to be received (see Section 3.3 for further details).

Some useful notation in the protocol description follows:

—$O$: an originator;
—$R$: set of intended recipients;
—$R'$: subset of R that replied to O with the evidence of receipt;
—$M_i$: message being sent from O to a recipient $R_i \in R$;
—$n_i$: random value generated by O;
—$v_i = E_{u_{R_i}}(n_i)$: encryption of $n_i$ with $R_i$'s public key;
—$k$: key being selected by O;
—$k_i = k \; xor \; n_i$: a key for $R_i$;
—$c_i = E_{k_i}(M_i)$: encrypted message for $R_i$ with key $k_i$;
—$l_i = h(O, R_i, TTP, h(c_i), h(k))$: label[9] of message $M_i$;
—$L'$: labels of all the messages sent to $R'$;
—$t$: a timeout chosen by O, before which the TTP has to publish some information;
—$E_{R'}(k)$: a group encryption scheme that encrypts $k$ for the group $R'$;
—$EOO_i = S_O(feoo, R_i, TTP, l_i, t, v_i, u_{R_i}, c_i)$: evidence of origin for $R_i$;
—$EOR_i = S_{R_i}(feor, O, TTP, l_i, t, v_i, u_{R_i}, c_i)$: evidence of receipt from $R_i$;
—$Sub_k = S_O(fsub, R', L', t, E_{R'}(k))$: evidence of submission of the key to the TTP; and
—$Con_k = S_{TTP}(fcon, O, R', L', t, E_{R'}(k))$: evidence of confirmation of the key by the TTP.

In this extension, the use of the same key for all users creates a new problem that did not appear in Kremer's online multiparty nonrepudiation protocol. Because messages are different, when the same key $k$ is used for encryption, and after the key $k$ is published, any recipient will be able to read the messages addressed to the other recipients (by eavesdropping on the messages that are transmitted between O and R). This problem is solved in this extended multiparty nonrepudiation protocol, introducing some extra cost for the extended functionality over Kremer and Markowitch [2000a].

[9]There might be a potential attack [Gürgens and Rudolph 2002] when the label $l$ is constructed as $h(m, k)$ in the early literature, so this label is unique in each run and verifiable by any party. Note that the labels can be computed offline.

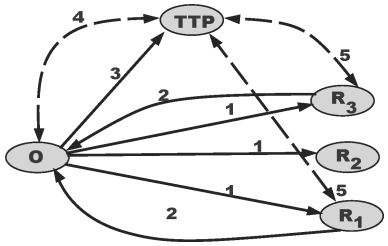


**Fig. 4**. Protocol with different messages.

*3.1.1. Protocol.* Here, we describe the protocol (see Figure 4, where a dotted line indicates a *fetch* operation).

(1) $O \rightarrow R_i$ : $feoo, R_i, TTP, l_i, h(k), t, u_{R_i}, v_i, c_i, EOO_i$ for each $R_i \in R$
(2) $R_i \rightarrow O$ : $feor, O, l_i, EOR_i$ where $R_i \in R$
(3) $O \rightarrow TTP$ : $fsub, R', L', t, E_{R'}(k), Sub_k$
(4) $O \leftrightarrow TTP$ : $fcon, O, R', L', E_{R'}(k), Con_k$
(5) $R'_i \leftrightarrow TTP$ : $fcon, O, R', L', E_{R'}(k), Con_k$ where $R'_i \in R'$

The protocol works in the following way.

*Step 1*. O sends to every $R_i$ evidence of origin corresponding to the encrypted message $c_i$, together with $v_i$. In this way, O distributes $|R|$ messages in a batch operation and each $R_i$ gets the encrypted message as well as $n_i$. Moreover, O selects the intended public key $u_{R_i}$ being used in the encryption of $n_i$. If $R_i$ disagrees (i.e., its authentication digital certificate has expired or been revoked), it should stop the protocol at this step. There is no breach of fairness if the protocol stops at step 1 because $c_i$ cannot be obtained without key $k$, and it cannot be derived from message 1.

*Step 2*. Some entities (or all of them) send evidence of receipt of $c_i$ back to O after checking evidence and labels. Again, there is no breach of fairness if the protocol stops.

*Step 3*. O sends $k$ and $Sub_k$ to the TTP in exchange for $Con_k$. The key $k$ is encrypted using a group encryption scheme where the group of users is $R'$. Hence, only those entities belonging to $R'$ will be able to decrypt and extract the key. Alike, O will obtain evidence only for those recipients included in the set $R'$ that is submitted to the TTP. Note that in this way, O can exclude some recipients which replied, but fairness is maintained.

Before confirming the key, the TTP checks that:

—$|R'| = |L'|$ holds; and
—current time $< t$.

*Step 4*. O fetches $Con_k$ from the TTP and saves it as evidence to prove that $k$ is available to $R'$.

*Step 5*. Each $R_i$ fetches $E_{R'}(k)$ and $Con_k$ from the TTP. They will obtain $k_i$ by computing $k$ xor $n_i$. Also, they save $Con_k$ as evidence to prove that $k$ originated from O.

At the end of the protocol, if successful, the participants get the following evidence:

—NRO for honest recipient $R_i$: $EOO_i, Con_k$; and
—NRR for originator O: $EOR_i, Con_k$ for all honest recipients $i \in R'$.

Even though O can send a different deadline $t$, this is not an interesting option for it. This behavior will not affect fairness, since $Con_k$ will not match with the rest of evidence obtained; that is, no party will obtain valid evidence and the recipients could learn the message.

*3.1.2. Dispute Resolution.* Two kinds of disputes can arise: repudiation of origin and repudiation of receipt. Repudiation of origin arises when a recipient $R_i$ claims having received a message $M_i$ from an originator O who denies having sent it. Repudiation of receipt arises when the originator O claims having sent a message $M_i$ to a recipient $R_i$ who denies having received it.

*Repudiation of origin*. If O denies sending $M_i$, $R_i$ can present evidence $EOO_i$ and $Con_k$ plus $(TTP, t, u_{R_i}, v_i, c_i, n_i, k, E_{R'}(k), M_i, R', L')$ to the arbitrator. The arbitrator will check:

—$v_i = E_{u_{R_i}}(n_i)$;
—$k_i = k$ xor $n_i$;
—$c_i = E_{k_i}(M_i)$;
—$l_i = h(O, R_i, TTP, h(c_i), h(k)) \wedge l_i \in L'$;
—O's signature $EOO_i$; and
—TTP's signature $Con_k$.

*Repudiation of receipt*. If $R_i$ denies receiving $M_i$, O can present evidence $EOR_i$ and $Con_k$ plus $(TTP, t, u_{R_i}, v_i, c_i, n_i, k, E_{R'}(k), M_i, R', L')$ to the arbitrator. The arbitrator will check:

—$R_i \in R'$;
—$v_i = E_{u_{R_i}}(n_i)$;
—$k_i = k$ xor $n_i$;
—$c_i = E_{k_i}(M_i)$;
—$l_i = h(O, R_i, TTP, h(c_i), h(k)) \wedge l_i \in L'$;
—$R_i$'s signature $EOR_i$; and
—TTP's signature $Con_k$.

*3.1.3. Efficiency.* This protocol uses an online TTP which intervenes in every execution in a lightweight manner. We compare this approach with the one where an $n$-instance of a two-party protocol [Zhou and Gollmann 1996] is used in order to send messages to the intended parties. The efficiency of the three principal entities participating in the protocol is analyzed, using an operation comparison. For this comparison we will use the following basic operations:

—signature generation and verification;
—generation of random numbers;
—asymmetric encryption and decryption; and
—store and fetch operation.

Depending on which algorithm is chosen for each of these operations, the bit complexity (as well as the bandwidth requirements) of each of the participating entities will change, although the relation going between them remains. Furthermore, the efficiency analysis also depends on how the group encryption primitive is used along the description of the protocol implemented. We will assume the complexity for a group encryption for $n$

**Table III.** O's Computation Complexity

| n-Instanced Two-Party | | New approach |
|---|---|---|
| **Evidence of origin $EOO_i$** | $=$ | **$EOO_i$** |
| N signatures | | N signatures |
| **Generation of $k_i$** | $\approx$ | **Generation of $n_i$ plus $k$** |
| **Evidence of submission $Sub_{k_i}$** | $\gg$ | **$Sub_k$** |
| N' signatures | | 1 signature |
| **Encrypted key $E_{u_{R_i}}(k_i)$** | $\ll$ | **Encrypted key $E_{R'}(k)$ plus $E_{u_{R_i}}(n_i)$** |
| N' asymmetric encryptions | | N'+N asymmetric encryptions |
| **N fetches operations of $Con_{k_i}$** | $\gg$ | **One fetch operation of $Con_k$** |

**Table IV.** $R_i's$ Computation Complexity

| n-Instanced Two-Party | | New approach |
|---|---|---|
| **Evidence of receipt $EOR_i$** | $=$ | **$EOR_i$** |
| **Fetch $k_i$ and $Con_{k_i}$** | $=$ | **Fetch $k$ and $Con_k$** |
| **Obtain $k_i$** | $<$ | **Obtain $k$ plus $n_i$** |
| Decrypts $E_{u_{R_i}}(k_i)$ | | Decrypt $E_{u_{R_i}}(k)$ Decrypt $E_{u_{R_i}}(n_i)$ |

**Table V.** TTP's Computation Complexity

| n-Instanced Two-Party | | New Approach |
|---|---|---|
| **Store N' keys** | $\gg$ | **Store only one key** |
| **Generation of N' evidences $Con_{k_i}$** | $\gg$ | **Generation of only one evidence $Con_k$** |

parties is equivalent to the cost of $n$ asymmetric encryption operations. We denote as follows.

—$|R| = N$
—$|R'| = N'$ (with $N' \leq N$)
—$\approx$ roughly equal
—$>$ or $<$ greater or smaller
—$\gg$ or $\ll$ much greater or smaller

Hence we can see in Table V the TTP's efficiency is improved when it is generalized to multiple entities. Since communicating entities will usually pay for the TTP services, a more efficient and inexpensive TTP service is achieved. In addition, we can see in Tables III and IV that O's efficiency is improved as well, while $R_i$'s is slightly increased. Furthermore, the asymmetric encryption of $n_i$ can be prepared offline but, on the other hand, the fetch operations must be performed during the protocol run.

### 3.2. An Optimistic MPNR Protocol for Exchange of Different Messages

There is an optimistic approach in nonrepudiation protocols where the entities are likely to behave honestly, thus giving priority to the main protocol and running subprotocols only in case that an exception arises. Here we present an optimistic multiparty nonrepudiation protocol based on Ferrer-Gomila et al. [2002],[10] and use the same solution described in the previous section for the privacy of different messages.

Some additional notation in this protocol description follows:

—$R'' = R - R'$: a subset of $R$ (in plaintext) with which O wants to cancel the exchange;
—$R''\_finished$: a subset of $R''$ that have finished the exchange with the finish subprotocol;

[10]The protocol [Ferrer-Gomila et al. 2002] has some security errors that are being identified in Zhou [2004]. Those problems have been corrected in the design of this new protocol.

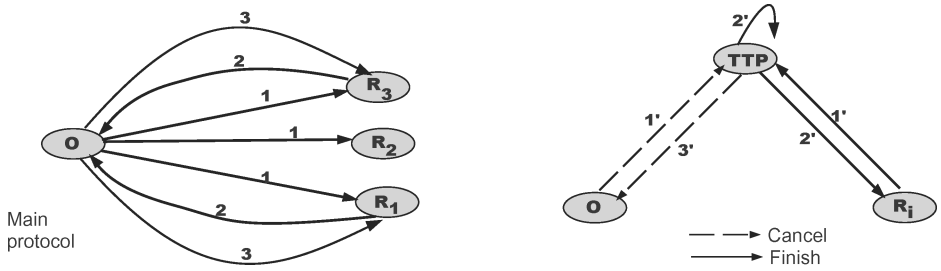


**Fig. 5**. Optimistic protocol with different messages.

—$R''\_cancelled = R'' - R''\_finished$: a subset of $R''$ with which the exchange has been cancelled by the TTP;
—$l = h(M_1, M_2, .., k)$: label[11] that identifies the protocol run computed as the hash outcome of the concatenation of every encrypted message plus the key $k$;
—$k_T = E_{u_{TTP}}(k)$: key $k$ encrypted with the TTP's public key;
—$EOO_i = S_O(feoo, R_i, TTP, k_T, l, v_i, u_{R_i}, h(c_i))$: evidence of origin for $R_i$;
—$EOR_i = S_{R_i}(feor, O, TTP, k_T, l, v_i, u_{R_i}, h(c_i))$: evidence of receipt from each $R_i$;
—$Sub_k = S_O(fsub, R', l, k)$: evidence of submission of the key to recipients;
—$Cancel_{req} = S_O(TTP, R'', l)$: evidence of request of cancellation issued by the originator to the TTP;
—$Cancel_O = S_{TTP}(O, l, R'', R''\_cancelled, Cancel_{req})$: evidence of cancellation issued by the TTP to the originator;
—$Cancel_{R_i} = S_{TTP}(R_i, l, EOR_i, Cancel_{req})$: evidence of cancellation issued by the TTP to $R_i$; and
—$Con_k = S_{TTP}(R_i, l, k)$: confirmation evidence of $k$ issued by the TTP.

*3.2.1. Protocol.* The protocol consists of a *main* protocol (which will be the only one executed by the entities in the normal situation) and two subprotocols: cancel and finish (see Figure 5). The TTP is only involved in the subprotocols in case of any participant's misbehavior or channel failure between the originator and the recipients. Any participant can initiate the corresponding subprotocols to terminate a protocol run at any time without loss of fairness.

The main protocol executed by the final entities is given next.

(1) $O \rightarrow R_i$ : $feoo, R_i, TTP, k_T, l, v_i, u_{R_i}, c_i, EOO_i$ for each $R_i \in R$
(2) $R_i \rightarrow O$ : $feor, O, l, EOR_i$ where $R_i \in R$
(3) $O \Rightarrow R'$ : $fsub, l, E_{R'}(k), Sub_k$

In step 1, the originator sends to each recipient its message encrypted with $k_i$. A recipient can derive $k_i$ from $k$ and a random number $n_i$, both of which are also sent in this step (in a confidential way). Note that the TTP is included in this step, thus there is no confusion about which TTP to use in case it becomes necessary to launch any of the subprotocols. The originator picks each receiver's public key. If any recipient does not want to use such a key (e.g., the correspondent public-key certificate has been revoked), then it stops the protocol. Otherwise, after verifying the data obtained, the recipient

[11]Note that with the reduction to 3 steps in the main protocol, the attack proposed in Gürgens and Rudolph [2002] does not work in this approach.

sends to the originator evidence of receipt at step 2, and the originator sends, to the set of recipients who replied after a reasonable amount of time at step 3, the key and evidence of submission of that key, as a second part of evidence of origin.

If O did not receive a correct message 2 from some of the recipients $R''$, O may initiate the following cancel subprotocol.

$$
\begin{array}{ll}
(1')\ O \rightarrow TTP & : TTP, R'', l, Cancel_{req} \\
(2')\ TTP & \text{FOR (all } R_i \in R'') \\
 & \text{IF } (R_i \in R''\_finished) \text{ THEN retrieves } EOR_i \\
 & \text{ELSE appends } R_i \text{ into } R''\_cancelled \\
(3')\ TTP \rightarrow O & : <\text{all retrieved } EOR_i >, R''\_cancelled, Cancel_O
\end{array}
$$

In this case, the originator communicates to the TTP its intention of revoking the protocol with entities contained in $R''$ and for the protocol run labeled $l$. After verifying O's cancel request, the TTP checks which entities previously resolved the protocol and retrieves their proofs of receipt. The TTP generates evidence of cancellation for the rest of entities and includes everything in a message destined to the originator. No information about the message, keys, and EOO is sent as in Ferrer-Gomila et al. [2002] because a well-defined label for indexing purposes on the TTP side is used.

If some recipient $R_i$ did not receive message 3, $R_i$ may initiate the following finish sub-protocol.

$$
\begin{array}{ll}
(1')\ R_i \rightarrow TTP & : TTP, k_T, l, v_i, u_{R_i}, h(c_i), EOO_i, EOR_i \\
(2')\ TTP \rightarrow R_i & : \text{IF } (R_i \in R''\_cancelled) \text{ THEN } R_i, l, R'', Cancel_{req}, Cancel_{R_i} \\
 & \text{ELSE } \{R_i, l, E_{u_{R_i}}(k), Con_k \text{ AND} \\
 & \text{appends } R_i \text{ into } R''\_finished \text{ and stores } EOR_i\}
\end{array}
$$

The recipient sends to the TTP all the information that it has already got from the originator, along with its evidence of receipt. If this entity does not belong to the group of entities with which the originator has cancelled the exchange, the TTP verifies all the information (digital signatures) and decrypts $k_T$, obtaining the key for the recipient. It also stores $EOR_i$. Note that if the protocol has been cancelled, it should be impossible for the recipient to cheat the TTP in a way that the TTP reveals the key $k$ for that protocol run. For such a reason, the TTP must verify O's signature in the first step and check that $l$ and $k_T$ provided by the recipient fits with the information contained in $EOO_i$. This becomes above all important when confidentiality should be provided, since it prevents using the TTP as a decryption oracle (e.g., a recipient sending in the other execution message $1'$, in an attempt to get $k_T$ decrypted). It also avoids replay attacks, as discovered in some optimistic protocols [Shao et al. 2005].

Otherwise, the TTP sends cancellation evidence to the recipient such that the latter can easily demonstrate to an arbitrator that the exchange was cancelled in case a dispute arises. This evidence includes the request of cancellation, such that the TTP's behavior is verifiable while the TTP need not store all the request evidences from the originator.

Note that the originator has no interest in sending a subset $\bar{R}'' \neq R''$ when requesting to the TTP for cancellation. If $\bar{R}'' \supset R''$, then O will cancel the exchange with those $R_i \in \bar{R}'' - R''$ that have replied with $EOR_i$. If $\bar{R}'' \subset R''$, then $R_i \in R'' - \bar{R}''$ may invoke the finish subprotocol to get the key $k$, but O will not obtain $EOR_i$ from the TTP at the aforesaid cancel subprotocol.

At the end of the protocol, if successful, the participants get the following evidence:

—NRO for honest recipient i: $EOO_i$, $Sub_k$ or $Con_k$; and
—NRR for originator O: $EOR_i$ for all honest recipients $i \in R'$.

*3.2.2. Dispute Resolution.* As we have mentioned, two kinds of disputes can arise. Here we further discuss the rules for their resolution.

*Repudiation of origin*. If O denies sending $M_i$, then $R_i$ can present evidence $EOO_i$ and $Sub_k$ (or $Con_k$) plus $(TTP, l, u_{R_i}, v_i, c_i, n_i, k, k_T, M_i)$ to the arbitrator. The arbitrator will check:

—$v_i = E_{u_{R_i}}(n_i)$;
—$k_i = k$ xor $n_i$;
—$c_i = E_{k_i}(M_i)$;
—O's signature on $EOO_i$;
—O's signature on $Sub_k$, or TTP's signature on $Con_k$; and
—$R_i$ is in the signed token $Con_k$ or $R_i \in R'$ as signed in $Sub_k$.

*Repudiation of receipt*. If $R_i$ denies receiving $M_i$, then O can present evidence $EOR_i$ plus $(TTP, l, u_{R_i}, v_i, c_i, n_i, k, k_T, M_i)$ and $(R'', R''\_cancelled, Cancel_O)$, if it has. The arbitrator will check:

—$v_i = E_{u_{R_i}}(n_i)$;
—$k_i = k$ xor $n_i$;
—$c_i = E_{k_i}(M_i)$;
—$R_i$'s signature on $EOR_i$; and
—(TTP's signature on $Cancel_O$) $\wedge$ $(R_i \notin R''\_cancelled)$.

O will win the dispute if all the aforesaid checks are positive. If all checks but the last are positive and O cannot present evidence $Cancel_O$, the arbitrator must further interrogate $R_i$. If the latter cannot present $Cancel_{R_i}$ (or this token is not properly constructed including $Cancel_{req}$ from O), then O also wins the dispute. Otherwise, $R_i$ can repudiate having received the message $M_i$.

We can also see that evidence provided by the TTP is self-contained, that is, the TTP need not be contacted in case a dispute arises regarding the occurrence or not of the cancel subprotocol launched by O. Thus, the TTP is efficiently verifiable. For instance, if the TTP cheats and distributes evidence of cancellation to $R_i$ when O did not cancel the protocol for it, TTP's misbehavior will be visible (either the cancellation token will not be properly constructed with O's evidence of request embedded or it will reveal TTP's misconduct, since $R_i \notin R''$). Additionally, it is important to know that the adjudicator does not need to check that $k_T = E_{u_{TTP}}(k)$ holds.

*3.2.3. Efficiency.* This protocol is very efficient in the case of good behavior of the participating entities. In fact, three steps is the minimum number of steps that could be reached without breaking fairness in nonrepudiation protocols. Even with multiple recipients for exchange of different messages, it manages to use only one key for evidence distribution, thus decreasing the computation and verification requirements for the originator and the TTP. For this new feature, public-key encryption and decryption of temporal random numbers comprise the main extra cost added.

It is straightforward to see that this protocol is more efficient than any combination of two-party protocols, since it permits to send different messages in a confidential way

**Table VI.** General Offline Solution Comparison

| | New Approach | Markowitch's |
|---|---|---|
| 1. Number of steps in main protocol | 3 | 4 |
| 2. Number of steps in subprotocol | 2 (finish)<br>2 (cancel) | 2 (if recovered or early)<br>4 (if not recovered yet) |
| 3. Timeliness | Async | Sync |
| 4. Items to be stored in the TTP | P+1 | 1 |
| 5. Additional interrogation needed in the dispute resolution process | Yes | No |
| 6. TTP network access (reliability in the inverse direction) | No | Yes |
| 7. Risk of unfairness | No | Yes (O must stop main protocol) |
| 8. Transparency | Yes | No |

to multiple entities, as well as to cancel the protocol for a group of entities $R''$ in only one run of the cancel subprotocol.

In addition, this protocol achieves asynchronous timeliness because each entity can terminate, if needed, the protocol at any time at its own discretion while maintaining fairness. Nevertheless, asynchronous timeliness, though desirable for users, augments the requirements on the communication channel between the TTP and users. With the model assumed, the TTP could set-up an evidence server (e.g., FTP server) such that users participating in the protocol can access (only with the read permission) and retrieve evidence. By *policy*, we mean there must exist a deadline after which evidence cannot be retrieved. (This deadline can match evidence validity depending on the TTP's storage capacity.) With this transformation, the protocol is adapted with respect to timeliness in a similar way as the online version.

It seems to us very important to compare this offline solution with that proposed by Markowitch and Kremer [2000], even though the latter did not address multiple messages. On the other hand, this is the only one we can compare with as an offline multiparty nonrepudiation protocol. Since the protocol has already been briefly described in the previous section, we present here Tables VI and VII to make the comparison straightforward. For efficiency comparisons, the following measurement units have been taken into account[12]:

—public key operations (containing encryption and decryption as well as digital signature and verification);

—number of items in the storage;

—number of steps as the number of messages which need to be sent over the network;

—$P$ as the number of recipients which need to contact the TTP for help and succeed; and

—$N = |R|$ as the number of participating recipients.

In Table VI, we can observe that, generally and when possible, this protocol improves Markowitch's version. Note that, for instance, it is not possible to reduce the number of items the TTP needs to store as a consequence of there being different messages, and thus different evidences of receipt (since the transparency property for O is maintained). This storage capacity request could be easily avoided by allowing the TTP to issue an affidavit for the finished entities, but then transparency would be lost. There is an

[12]When several actions are possible, we consider the worst case.

**Table VII.** Public Key Operations Comparison

| | New Approach | Markowitch's |
|---|---|---|
| 1. O's main protocol | 4+2P+N | 4+2P |
| 2. $R_i$'s main protocol | 3 | 4 |
| 3. O's cancel/recovery protocol | 2+P (cancel) | 1 (recovery) |
| 4. $R_i$'s finish protocol | 2 | 2 |
| 5. TTP's cancel protocol | 2 (once) | - |
| 6. TTP's finish protocol | 5 | 5 |

improvement in the number of steps needed in the main protocol, which fortunately will be the most frequently used, but the cost is the need of rarely having to interrogate an additional entity in case of disputes.

In Table VII, we can observe how, in general, this protocol seems to perform worse. But if we analyze the table, we will discover that this is due to the new functionality introduced and, as such, is unavoidable. Specifically, operations of O's main protocol are augmented in $N$ because of the number of different messages to be sent. For the same reason mentioned in the previous paragraph, O needs to verify $P$ different evidences of receipt from honest entities which contacted the TTP for finishing the protocol on time. For the rest of steps, both protocols perform in a similar way.

### 3.3. Fairness vs. Collusion

As has been introduced in this article, there exist different levels of fairness. This protocol provides two different levels, depending on the initial assumptions made; thus, depending on these assumptions, the applications that make use of them will vary.

In the description of the previous protocols we assume that no collusion is possible between recipients. This will preserve a strong fairness property and the applications that can benefit these kind of protocols can be of any type.

Nevertheless, $R_i$ could get $c_i$ in the initial steps of the protocol and quit. Then, colluding with any other party and getting the unique key $k$, it could decrypt $c_i$ without providing any evidence of receipt. Note that this issue is very difficult to solve, as it is not possible to prevent one (semi-) honest entity from sharing a secret once it decrypts it. However, it is also important to note that when a recipient misbehaves and colludes with a (semi-) honest recipient in order to get the key and thus (only) the message intended for him, it will not in any case obtain evidence of origin unless the originator obtains evidence of receipt. This is what has been defined as light fairness.

There are multiple applications which only need light fairness in their transactions. A common feature in these applications is that the exchange of evidence is more important than the message content itself. In other words, it is critical that both or none of the entities obtains evidence. For instance, some notification systems only need light fairness. This happens when the message itself is known by the recipient (e.g., birthday certificate) but in the notification, the receiver wants to be able to demonstrate to a third party its origin (e.g., official administration office) and the originator wants to be able to demonstrate, if necessary, that the message was indeed delivered to the intended receiver.

## 4. APPLICATION: EXTENSIONS TO OPTIMISTIC FAIR CEM

In this section we analyze and provide extensions to a fast and simple optimistic fair CEM protocol [Micali 2003] for achieving timeliness and multiparty fair exchange.[13] Firstly, we briefly describe Micali's optimistic protocol for CEM.

[13]The work in this section has been partially published in Zhou et al. [2005].

### 4.1. A Protocol for Fair CEM with Deadline Time

Although Micali explained different fair CEM protocols in Micali [2003], we describe here the most complete one that supports confidentiality, fairness, and synchronous timeliness. Because it is an optimistic protocol, if both parties behave honestly, the TTP (which is also referred to as the post office, or PO, here) will not be involved. Each user in the system has a unique identifier. Before sending the plaintext message $M$ to the recipient, the originator computes a secret $Z$ protected with the TTP's encryption key as $Z = E_{PO}(O, R, E_R(M))$. To reach timeliness, Micali proposed a deadline solution, where the originator chooses a time $t$ after which the TTP should not help the recipient in the conclusion of the protocol.

(1) $O \rightarrow R$ : $t, Z, S_O(t, Z)$
(2) $R \rightarrow O$ : $S_R(Z)$
(3) $O \rightarrow R$ : $E_R(M)$

Whenever R reaches step 1 and verifies O's signature, it must extract the deadline $t$ and estimate whether it will have enough time to contact the PO in case of O's misbehavior or channel failure. Variable $t_D$ denotes the maximum possible time discrepancy that R believes to exist between his clock and that of the PO. If R receives step 1 in time $t_R$ (i.e., recipient's local time) such that $t_R + t_D$ is greater than or equal to $t$, then R halts; otherwise it proceeds to step 2. After verifying R's signature, O sends the message $M$ to the recipient at step 3.

After replying at step 2, if the recipient does not get the message within a reasonable amount of time, or $Z = E_{PO}(O, R, E_R(M))$ does not hold, R contacts the PO in a *resolve* subprotocol.

(1′) $R \rightarrow PO$ : $t, Z, S_O(t, Z), S_R(Z)$
(2′) IF ($t_{stiPO} < t$) AND (valid signatures)
$PO \rightarrow R$ : $X$
$PO \rightarrow O$ : $S_R(Z)$

In this subprotocol, the PO verifies whether R's request arrives before O's deadline and also whether both signatures are correct. If so, the PO decrypts $Z$ with its private key and, if the result is a triplet consisting of $O$, $R$, and an unknown string $X$, it sends $X$ to the recipient and forwards R's signature to the originator.

Note that the semantics of the deadline $t$ is different from the previous solutions where clock shifts between the entities could not lead to a security problem, but rather to a timeliness problem. Even though the deadline parameter is used for finalization of the protocol and consequently for timeliness, the meaning is different, due to the optimistic approach. When the TTP participates in an online manner, the deadline establishes a point after which the protocol is resolved and the recipients can contact the TTP. In this case, the deadline indicates the point before which the recipients must contact the TTP if needed, because afterwards, it will not help (and thus fairness will be damaged).

It can be argued that, at the end, both solutions need a point of time in which the TTP cannot help any more and if recipients do not access in advance, fairness will be also damaged. Nevertheless, there is a very important difference in both approaches, which will be perhaps better appreciated in noting Figure 6.

When evidence deletion occurs at the TTP, the latter will not be able to help entities any more. This event can coincide with evidence expiration, depending on the TTP's storage resources. Nevertheless, the time (deadline $t$) at which the state is final

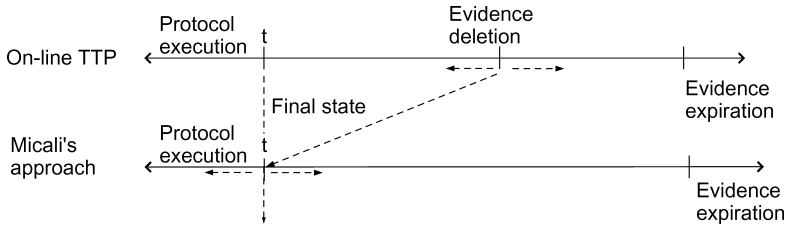


**Fig. 6**. Deadlines in fair CEM.

(synchronous timeliness) is different from that of evidence deletion. In this way, entities can know beforehand when the protocol has a definitive state and then, if needed, seek the TTP's help. On the other hand, Micali's solution unifies deadline and evidence deletion.[14] If this deadline is selected too early, mail recipients could not have enough time to resolve the protocol. If overly late, entities will need to wait in order to know the final state of the protocol, perhaps more than what is desired.

### 4.2. Extension to Fair CEM with Asynchronous Timeliness

Here, a different solution for timeliness, *asynchronous timeliness* (i.e., either party can finish the protocol at any time, without loss of fairness) is proposed. In Micali's proposal, even if the recipient approximately calculates in each run the time to contact the PO, there can be always a situation in which the PO is unaccessible later. In such a case, the recipient will not get the item from the (un-)fair exchange protocol and it will be difficult to figure out who bears the responsibility for this breach of fairness.

With the resolve subprotocol, the recipient will be able to finish the protocol at any time. Similarly, if O does not want to wait for the resolution of the protocol, it can abort it with cancel subprotocol at any time as well. The revised main protocol, in which O's signature is not needed anymore[15] in step 1 due to the omission of the deadline, is as follows.

(1) $O \rightarrow R \ : \ Z$
(2) $R \rightarrow O \ : \ S_R(Z)$
(3) $O \rightarrow R \ : \ E_R(M)$

The revised resolve subprotocol, which will be requested by the recipient under the same conditions as the original one, is as follows.

(1′) $R \rightarrow PO \ : \ Z, S_R(Z)$
(2′) $R \leftrightarrow PO \ :$ IF cancelled THEN $S_O(cancel, Z)$
ELSE $E_R(M)$

When the PO receives such a request, it first checks R's signature on $Z$. If valid, the PO further decrypts $Z$ and extracts the identities of sender and recipient of $Z$. If R is the intended recipient of $Z$ and the exchange has not been cancelled by O, the PO marks the exchange status related to $(O, R, h(Z))$ as resolved, sends $E_R(M)$ to R, and stores $S_R(Z)$, which will be collected by O when it initiates the cancel subprotocol. If the exchange has been cancelled by O, the PO forwards $S_O(cancel, Z)$ to R, and R can use this evidence to prove that O has cancelled the exchange.

[14]There is no deletion event, but the meaning is the same; that is, the TTP's help is not available.
[15]In CEM applications, only nonrepudiation of receipt is mandatory.

The new cancel subprotocol is as follows.

$$(1') \; O \rightarrow PO \; : \; Z, E_{PO}(S_O(cancel, Z))$$
$$(2') \; O \leftrightarrow PO \; : \; \text{IF resolved THEN } S_R(Z) \text{ ELSE } ack$$

When the PO receives such a request from the originator, it first checks O's signature after decrypting with its corresponding asymmetric key.[16] If valid, the PO further decrypts $Z$ and extracts the identities of sender and recipient. If O is the sender of $Z$ and the exchange status related to $(O, R, h(Z))$ is marked as resolved, the PO forwards $S_R(Z)$ to O. Otherwise, the PO marks the exchange status related to $(O, R, h(Z))$ as cancelled, and acknowledges O's cancelation.

Because there is no deadline for the recipient, the originator can abort the protocol as desired. As we can see, the PO provides access to the items that any of the parties needs. The parties can access the data at any time and it is not the responsibility of the PO as to whether the users get the messages they expect. The PO is not stateless and needs to maintain (within a reasonable amount of time) a table with entries $(O, R, h(Z), state)$ and to store the signatures for serving the users. Therefore, the server implementing the PO must secure this information (although confidentiality is not needed).

In case of a dispute, both parties must agree which arbitrator will evaluate the final outcome of the protocol based on the evidence provided by the users. Consequently, if the recipient denies having received a message $M$ in a CEM protocol run, the originator should provide $(Z, S_R(Z))$ and the arbitrator settles that the originator sent the message $M$ to the recipient if:

—$Z = E_{PO}(O, R, E_R(M))$ holds;
—the recipient's signature on Z is valid; and
—the recipient cannot provide $S_O(cancel, Z)$.

It is easy to notice that integrity of the message is not ensured. Any external attacker (or R itself) can create a message $Z' = E_{PO}(O, R, E_R(M'))$. In this case, the originator will obtain a proof for a message it did not send and will try to cancel the protocol. If it is not possible (R having already resolved the protocol), the recipient will have a message the originator did not send but cannot demonstrate it (the process is anonymous because there are no digital signatures). So this protocol does not ensure the service, but it does ensure that the recipient can read the message the originator sent if and only if the originator obtains evidence of receipt. If integrity and authenticity of the message for ensuring the service are properties needed by the originator, then it needs to digitally sign $Z$ at step 1 and the receiver needs to provide O's signature at step 1' of the resolve subprotocol for PO's verification.

### 4.3. Extension to Multiparty Fair CEM

There are scenarios in which the participation of multiple entities can result in an important improvement. CEM is one of them. We can easily figure out applications in which sending email to several users is feasible and useful. In Section 2 several

[16]As pointed out in González-Deleito [2005], O needs to encrypt its own signature in order to avoid an attack which allows the recipient to get the cancel token (eavesdropping on O's request from message 1′) when the protocol has been previously resolved by the recipient (and thus making the originator believe the exchange succeeded).

solutions for multiparty CEM were pointed out. Based on Micali's CEM protocol, this extension provides a new feature such that the sender can distribute in a certified manner a message $M$ to several recipients. Some additional notation in the protocol description is:

—$R$: a set of intended recipients.

—$Header$: a header indicating in which position the recipient has to look for its information (e.g., $[R_i, j]$).

—$M$: message being sent from the originator to the recipients $R$.

—$R'' = R - R'$: a subset of $R$ (in plaintext) with which the originator wants to cancel the exchange.

—$R''\_resolved$: a subset of $R''$ that have resolved the exchange with the *resolve* subprotocol.

—$R''\_cancelled = R'' - R''\_resolved$: a subset of $R''$ with which the exchange has been cancelled by the PO.

—$u_R = u_{R_1}, u_{R_2}, ...$: concatenation of public keys from group $R$.

—$E_R(M)$: an group encryption of $M$ for group $R$.

—$Z = E_{PO}(O, R, E_R(M))$: a secret $Z$ protected with the PO's encryption key.

The PO will participate, if requested by any entity, in a mutually exclusive way (i.e., atomic execution of the subprotocols for each user). Here, we describe the protocol.

The main protocol executed by the final entities is the following.

(1) $O \Rightarrow R$ : $Header, u_R, Z$
(2) $R_i \rightarrow O$ : $S_{R_i}(u_{R_i}, Z)$ where each $R_i \in R$
(3) $O \Rightarrow R'$ : $E_{R'}(M)$

In step 1, the originator sends the secret $Z$ and all the recipients' public keys such that if any recipient does not agree with its public encryption key (e.g., the corresponding public-key certificate has been revoked), then it stops the protocol. Otherwise, after verifying the data obtained, the recipient sends evidence of receipt to the originator at step 2, and the latter sends the (encrypted) message $M$ at step 3 to the set of recipients who replied.

If the originator did not receive a correct message 2 from some of the recipients $R''$, she may initiate the following cancel subprotocol.

(1′) $O \rightarrow PO$ : $Z, R'', S_O(cancel, R'', Z)$
(2′) $PO$ FOR (all $R_i \in R''$)
IF ($R_i \in R''\_resolved$) THEN retrieves $S_{R_i}(u_{R_i}, Z)$
ELSE appends $R_i$ into $R''\_cancelled$
(3′) $O \leftrightarrow PO$ : all retrieved $S_{R_i}(u_{R_i}, Z)$, $S_{PO}(R''\_cancelled, Z)$

In this case, the originator communicates to the PO its intention of revoking the protocol with entities contained in $R''$. After verifying the originator's cancel request, the PO checks which entities previously resolved the protocol and gets their proofs of receipt.

Then, the PO generates evidence of cancelation for the rest of the entities and includes everything in a message destined to the originator.

If some recipient $R_i$ did not receive the message 3 or it was not valid, $R_i$ may initiate the following resolve subprotocol.

$$
\begin{aligned}
&(1') \; R_i \rightarrow PO \; : \; Header, u_{R_i}, Z, S_{R_i}(u_{R_i}, Z) \\
&(2') \; R_i \leftrightarrow PO \; : \; \text{IF } (R_i \in R''\_cancelled) \text{ THEN } S_{PO}(R''\_cancelled, Z) \\
&\qquad\qquad\quad \text{ELSE } \{E_{R_i}(M) \\
&\qquad\qquad\quad \text{appends } R_i \text{ into } R''\_resolved \text{ and stores } S_{R_i}(u_{R_i}, Z)\}
\end{aligned}
$$

The recipient sends to the PO all the information that it has already gotten from the originator, along with its evidence of receipt. If this entity does not belong to the group of entities with which the originator cancelled the exchange, the PO verifies all the information (digital signatures) and decrypts $Z$. It also stores $S_{R_i}(u_{R_i}, Z)$. Note that if the protocol has been cancelled, it should be impossible for the recipient to cheat the PO in such a way that the PO reveals the message for that protocol run. For this reason, the PO must verify the recipient's signature as well as the integrity of $Z$ in the first step.

Note that the recipient can cheat the TTP by manipulating the Header field. Nevertheless, this will not disclose any other message, since it is encrypted with the intended recipient's public key. Furthermore, this action is nonsense, due to two reasons: (i) Message M is similar for every recipient, regardless of the position in $E_R(M)$; and (ii) $R_i$ will bring itself to an unfair situation, since it will not be able to get the message while the originator can obtain from the TTP its receipt signature.

If this entity belongs to the group of entities with which the originator cancelled the exchange, the PO sends a cancelation evidence to the recipient such that the latter can easily demonstrate to an arbitrator that the exchange was cancelled in case a dispute arises.

If $R_i$ denies having received $M$, the originator can present evidence $Z, E_R(M)$, $S_{R_i}(u_{R_i}, Z)$, $S_{PO}(R''\_cancelled, Z)$ and the arbitrator settles that the recipient received the message $M$ from the originator if:

—$R_i$ can decrypt $E_R(M)$ with $u_{R_i}$ and the outcome is $M$;

—$Z = E_{PO}(O, R, E_R(M))$ holds;

—$R_i$'s signature on $Z$ and its encryption public key is valid; and

—PO's signature on $S_{PO}(R''\_cancelled, Z) \wedge R_i \notin R''\_cancelled$.

The originator will succeed on the dispute if all the preceding checks are positive. If all the checks but the last are positive and it cannot present evidence of cancelation, then the arbitrator must further interrogate $R_i$. If the latter cannot present $S_{PO}(R''\_cancelled, Z)$ in which $R_i \in R''\_cancelled$, the originator also wins the dispute. Otherwise, $R_i$ can repudiate having received the message $M$. Therefore, evidence provided by the PO is self-contained, that is, the PO need not be contacted in case a dispute arises regarding the occurrence of a cancellation subprotocol launched by the originator.

## 5. APPLICATION: MULTI-PARTY CONTRACT SIGNING

In this section, we explain a new synchronous multiparty contract-signing protocol that, with $n$ parties, reaches a lower bound of $3(n-1)$ steps in the all-honest case and $4n-2$ steps in the worst case (i.e., all parties contact the TTP). This is so far the most efficient

synchronous multiparty contract-signing protocol in terms of the number of messages required. It also considers additional features like timeliness and abuse-freeness in an improved version.[17]

In all practical schemes, contract signing involves a TTP which plays the role of a notary in paper-based contract-signing and somehow shares the legal duties the former ones have. In fact, designing and implementing a contract-signing protocol using an inline TTP should not be a complicated task. In this case, if Alice and Bob wish to enter into a contract, they each sign a copy of the contract and send it to the TTP through a secure channel. The TTP will forward the signed contracts only when it has received valid signatures from both Alice and Bob.

In our continuous search for speeding-up our daily life activities, it is desirable not to use a TTP in a contract-signing protocol. Additionally, if the TTP is not involved, the notary fee could be avoided. Some protocols appear in the literature trying to eliminate the TTP's involvement using *gradual* or *probabilistic exchange* of signatures [Blum 1981; Even et al. 1985]. In Even et al. [1985], the authors propose a contract-signing protocol which makes use of *oblivious transfer*. This allows the transfer of a recognizable (e.g., signed) message M such that the recipient can read it with a probability one-half while the originator has no way of knowing whether the recipient could read it. With this tool, they provided a probabilistic contract-signing protocol with a very high success (fairness) probability.

Nevertheless, and, specially for contract-signing protocols, a signer would not like to risk one million dollars when the deal is done. Therefore, these solutions may not be accepted by signatories. Furthermore, users always deal with the presence of TTPs when important contracts are to be signed (e.g., the act of selling a house, in which usually a notary is involved) in the paper-based world.

Thus, in this section, we focus on deterministic optimistic contract-signing protocols. A synchronous model is used, in which we assume messages sent among participants can be lost in the network, but a message from a participant reaches the TTP in a finite and known amount of time. Attackers can insert, delete, and modify messages, but it is assumed that attackers cannot break the clock synchronization of the network and cannot forge digital signatures. Under this model, the number of rounds can be made independent of the number of participants.

### 5.1. Improved Synchronous MPCS Protocol

Here, we first present a simple synchronous protocol for multiparty contract-signing. As in Asokan's approach, this is also based on two differentiated phases: a promise to sign, and a real signature that a party releases only after receiving all promises from the rest of the participants. Again, in the same manner, this protocol reaches a lower bound of $4(n-1)$ steps in the all-honest case, and $5n-3$ steps in the worst case when all parties contact the TTP. This result will be further improved in the optimal version by reducing the number of steps to $3(n-1)$ in the all-honest case and $4n-2$ in the worst case.

*5.1.1. A Simple Version.* Let us consider the following simple solution which uses verifiable encryption of signatures based on a ring architecture for achieving *transparency* of the TTP. Assume that the channel between any participant and the TTP is functional

[17]The work in this section has been partially published in Zhou et al. [2006].

and not disrupted. The following notation is used in the protocol description.

—$C = [M, P, id, t]$: a contract text $M$ to be signed by each party $P_i \in P (i = 1, \cdots, n)$, a unique identifier id for the protocol run, and a deadline $t$ agreed upon by all parties to contact the TTP.

—$Cert_i$: a certificate with which anyone can verify that the ciphertext is the correct signature of the plaintext, and can be decrypted by the TTP; see CEMBS (Certificate of an Encrypted Message Being a Signature) in Bao et al. [1998].

A simple linear protocol for multiparty contract signing is sketched as follows.

| | | |
|---|---|---|
| (1) | $P_1 \rightarrow P_2$ | : $m_1[= C, e_{TTP}(S_{P_1}(C)), Cert_1]$ |
| (2) | $P_2 \rightarrow P_3$ | : $m_1, m_2[= C, e_{TTP}(S_{P_2}(C)), Cert_2]$ |
| $(n-1)$ | $P_{n-1} \rightarrow P_n$ | : $m_1, .., m_{n-1}[= C, e_{TTP}(S_{P_{n-1}}(C)), Cert_{n-1}]$ |
| $(n)$ | $P_n \rightarrow P_{n-1}$ | : $m_n[= C, e_{TTP}(S_{P_n}(C)), Cert_n]$ |
| $(n+1)$ | $P_{n-1} \rightarrow P_{n-2}$ | : $m_{n-1}, m_n$ |
| $(2(n-1))$ | $P_2 \rightarrow P_1$ | : $m_2, m_3, .., m_n$ |
| $(2n-1)$ | $P_1 \rightarrow P_2$ | : $S_{P_1}(C)$ |
| $(2n)$ | $P_2 \rightarrow P_3$ | : $S_{P_1}(C), S_{P_2}(C)$ |
| $(3(n-1))$ | $P_{n-1} \rightarrow P_n$ | : $S_{P_1}(C), S_{P_2}(C), .., S_{P_{n-1}}(C)$ |
| $(3n-2)$ | $P_n \rightarrow P_{n-1}$ | : $S_{P_n}(C)$ |
| $(3n-1)$ | $P_{n-1} \rightarrow P_{n-2}$ | : $S_{P_{n-1}}(C), S_{P_n}(C)$ |
| $(4(n-1))$ | $P_2 \rightarrow P_1$ | : $S_{P_2}(C), S_{P_3}(C), .., S_{P_n}(C)$ |

The preceding main protocol is divided into two phases. The parties first exchange their commitments in an in-and-out manner. Note that $P_1$ can choose $t$ in the first message (and others can halt if they do not agree). Only after the first phase is finished at step $2(n-1)$ are the final signatures exchanged. Following this simple approach, only $4(n-1)$ steps are needed.

If there is no exception (e.g., network failure or misbehaving party), the protocol will not need the TTP's help. Otherwise, the following resolve subprotocol helps to drive the contract-signing process to its end. $P_i$ can contact the TTP before the deadline $t$.

(1) $P_i \rightarrow TTP$ : $resolve_{P_i} = m_1, .., m_n$
(2) $TTP$ : IF $NOT\ resolved\ AND\ resolve_{P_i}$ is received before $t$ THEN
decrypts $m_1..m_n$
publishes $S_{P_1}(C), .., S_{P_n}(C)$
$resolved$=true

Boolean variable $resolved$ is initialized to false. If the main protocol is not completed successfully, some parties may not hold all the commitments $(m_1, .., m_n)$. Then, they just wait until the deadline $t$ and check with the TTP whether the contract has been resolved by other parties. If not, the contract is cancelled. Otherwise, they get the valid contract $(S_{P_1}(C), .., S_{P_n}(C))$ from the TTP.

If a party has all the commitments when the main protocol is terminated abnormally, it could initiate the aforesaid subprotocol. Then the TTP will help to resolve the contract if the request is received before the deadline $t$, and the contract will be available to all the participants (even after the deadline $t$). After the deadline, the TTP will not accept such requests any more. In other words, the status of the contract will be determined at the latest by the deadline $t$. Note that no party can cheat the TTP using a distinct deadline because in this case they will be cancelling or resolving a different contract. If parties do not want to advertise this data in the contract itself since timeout is

not part of the text agreed, then the deadline can be somehow (hashed together with) included in the unique id, which is the main variable used by the TTP to distinguish between different protocol instances as a contract reference. In this protocol, the TTP intervention is simple, elegant, and lightweight.

In this case, the dispute resolution process is straightforward. If a party holds all the signatures, the contract is assumed valid.

*5.1.2. An Optimal Version.* The simple-version protocol has two clearly differentiated phases: exchange of commitments and exchange of digital signatures. The number of steps can be further reduced if more available information is sent at each step and then both phases are merged. This will result in an improvement of the previous simple-version protocol.

Using the same notation, an optimal synchronous protocol for multiparty contract-signing is outlined as follows.

$$
\begin{array}{lll}
(1) & P_1 \rightarrow P_2 & : m_1[= C, e_{TTP}(S_{P_1}(C)), Cert_1] \\
(2) & P_2 \rightarrow P_3 & : m_1, m_2[= C, e_{TTP}(S_{P_2}(C)), Cert_2] \\
(n-1) & P_{n-1} \rightarrow P_n & : m_1, .., m_{n-1}[= C, e_{TTP}(S_{P_{n-1}}(C)), Cert_{n-1}] \\
(n) & P_n \rightarrow P_{n-1} & : m_n[= C, e_{TTP}(S_{P_n}(C)), Cert_n], S_{P_n}(C) \\
(n+1) & P_{n-1} \rightarrow P_{n-2} & : m_{n-1}, m_n, S_{P_{n-1}}(C), S_{P_n}(C) \\
(2(n-1)) & P_2 \rightarrow P_1 & : m_2, m_3, .., m_n, S_{P_2}(C), S_{P_3}(C), .., S_{P_n}(C) \\
(2n-1) & P_1 \rightarrow P_2 & : S_{P_1}(C) \\
(2n) & P_2 \rightarrow P_3 & : S_{P_1}(C), S_{P_2}(C) \\
(3(n-1)) & P_{n-1} \rightarrow P_n & : S_{P_1}(C), S_{P_2}(C), .., S_{P_{n-1}}(C)
\end{array}
$$

The resolve subprotocol used by participants to request the TTP's help does not change. Note that, even though the two phases are merged, no party releases its plaintext signature of the contract without having first received all the commitments. If any party decides to quit before releasing its plaintext signature of the contract, the rest of participants can obtain all plaintext signatures of the contract with the TTP's help. As the protocol is similar to the previous one, the same requirements are fulfilled and the identical dispute resolution process is used by the adjudicator.

This optimal version allows overlapping the dispatch of promises with real signatures without losing fairness. It improves the simple version presented in Section 5.1.1 by reducing the number of steps to $3(n-1)$ in the all-honest case and $4n-2$ in the worst case. Note that for $n = 2$, three messages are sufficient and optimal, as shown in Pfitzmann et al. [1998].

### 5.2. Achieving Abuse-Freeness

The MPCS protocol presented in the previous section improved the lower bound of steps in existing synchronous MPCS protocols. However, it does not satisfy the properties of abuse-freeness and asynchronous timeliness. Here the protocol is further improved to address these properties.

Although it is not possible to force a participant to keep on following the steps of the protocol, the protocol can be designed in such a manner that it has no way to demonstrate to an outsider that the contract is under its control. For this purpose, it uses a *blind commitment* that only the TTP can verify. With this concept of design in mind, the previous protocol can be modified to eliminate the illustrative information. The main protocol remains the same, but $Cert_i$ is not included in $m_i$. Instead, evidence

of origin of the blind commitment $Commit_i$ is generated. We have

$$Commit_i = S_{P_i}(h(C), e_{TTP}(S_{P_i}(C))),$$

where $h(C)$ is the hash value of $C$ to be used to establish a unique link between $Commit_i$ and $C$.

$$\begin{array}{lll}
(1) & P_1 \rightarrow P_2 & : m_1[= C, e_{TTP}(S_{P_1}(C)), Commit_1] \\
(2) & P_2 \rightarrow P_3 & : m_1, m_2[= C, e_{TTP}(S_{P_2}(C)), Commit_2] \\
(n-1) & P_{n-1} \rightarrow P_n & : m_1, .., m_{n-1}[= C, e_{TTP}(S_{P_{n-1}}(C)), Commit_{n-1}] \\
(n) & P_n \rightarrow P_{n-1} & : m_n[= C, e_{TTP}(S_{P_n}(C)), Commit_n], S_{P_n}(C) \\
(n+1) & P_{n-1} \rightarrow P_{n-2} & : m_{n-1}, m_n, S_{P_{n-1}}(C), S_{P_n}(C) \\
(2(n-1)) & P_2 \rightarrow P_1 & : m_2, m_3, .., m_n, S_{P_2}(C), S_{P_3}(C), .., S_{P_n}(C) \\
(2n-1) & P_1 \rightarrow P_2 & : S_{P_1}(C) \\
(2n) & P_2 \rightarrow P_3 & : S_{P_1}(C), S_{P_2}(C) \\
(3(n-1)) & P_{n-1} \rightarrow P_n & : S_{P_1}(C), S_{P_2}(C), .., S_{P_{n-1}}(C)
\end{array}$$

Each party needs to check whether all the blind commitments it has received are valid before releasing its real signature of the contract. A *valid* blind commitment $Commit_i$ means it is from $P_i$ (by checking its signature), linked to $C$ (by checking $h(C)$), but does not guarantee that $e_{TTP}(S_{P_i}(C))$ in $Commit_i$ matches $S_{P_i}(C)$. $Commit_i$ is correct if it is valid and also matches $S_{P_i}(C)$.

If there is no exception (e.g., network failure or misbehaving party), the protocol will not need the TTP's help. Otherwise, a modified resolve subprotocol helps to drive the contract-signing process to its end. $P_i$ can contact the TTP before the deadline $t$.

(1) $P_i \rightarrow TTP$ : $resolve_{P_i} = m_1, .., m_n$
(2) $TTP$ : IF *NOT resolved AND* $resolve_{P_i}$ is received before $t$
AND all $Commit_i$ are valid THEN
decrypts & verifies $m_1..m_n$
*resolved*=true
IF $S_{P_1}(C), .., S_{P_n}(C)$ ok THEN
publishes $S_{P_1}(C), .., S_{P_n}(C)$
ELSE IF $P_i \notin group_f$
publishes $fail, group_f, S_{TTP}(fail, C, group_f)$

Boolean variable *resolved* is initialized to false. When a party holding all the valid blind commitments initiates the preceding subprotocol, the TTP will help to resolve the contract if the request is received before the deadline $t$. The TTP decrypts and verifies $m_1, \cdots, m_n$. If they are all correct, the TTP will publish $S_{P_1}(C), \cdots, S_{P_n}(C)$. Otherwise, the TTP will invalidate the contract by publishing a fail token $S_{TTP}(fail, C, group_f)$, where $group_f$ indicates the parties which misbehaved in generating their commitments.

The dispute resolution process is changed when the fail token is introduced. If a party can show this token, the contract is invalid. Therefore, with respect to the simple dispute resolution process defined previously, now the arbiter needs to interview both parties disputing the validity of the contract.

Furthermore, at the end of the main protocol, each party needs to check whether $e_{TTP}(S_{P_i}(C))$ in $Commit_i$ matches $S_{P_i}(C)$ for $i = 1, \cdots, n$ (assuming the encryption algorithm is deterministic). If not, it should initiate the aforementioned subprotocol to get the fail token. A party $P_i$ cannot get any advantage by providing different $Commit_i$ in the main protocol and the resolve subprotocol. If $P_i$ provides correct $Commit_i$ in the

main protocol but incorrect $Commit_i'$ in the subprotocol, $P_i$ will not get the fail token (i.e., cannot cancel a protocol instance whose final state is signed). On the other hand, if $P_i$ provides incorrect $Commit_i$ in the main protocol but correct $Commit_i'$ in the subprotocol, $P_i$ may get the signed contract if other parties did not misbehave in generating their commitments, but any other honest party can initiate the resolve subprotocol to get the fail token; thus the contract is still invalid.

*Remark* 5.1 It seems that an external adversary could generate valid-looking or even fake blind commitments himself. This would allow him to abort the protocol when desired, but use of evidence of origin avoids this situation.

The blind commitment does not allow a participant to demonstrate that the protocol state is under its control. In fact, in this case, getting all $m_i$ does not mean being able to solve the protocol, as in previous protocols presented in this section. Thus, it provides an abuse-freeness feature. Proof is straightforward, since there is no point in a protocol in which an entity can ensure, even to itself, that the contract is signed until plaintext signatures are obtained. The solution allows to maintain the same number of steps as the optimal protocol in Section 5.1.2. Furthermore, the TTP is still transparent in this subprotocol because the signed contract published by the TTP is the same as the one obtained in the main protocol.

### 5.3. Achieving Timeliness

In the protocols just presented, a deadline $t$ is selected by the first participant. If other participants disagree with the deadline, they can simply abort execution of the protocol. Of course, this deadline could be negotiated among the participants before the contract-signing protocol is initiated.

If the main protocol is not completed successfully, some participants may hold all the commitments while others may only hold part of them. For those holding all the commitments, they have the freedom to either resolve the contract with the TTP's help before the deadline $t$, or to take no action and just let the contract become automatically cancelled after the deadline $t$.

As we have already mentioned, asynchronous timeliness is not fulfilled in these protocols, where a deadline $t$ is used, forcing all the participants to approximately synchronize their clocks with the TTP's clock. This task has been widely studied and standard solutions exist (such as the *network time protocol* [Mills 1992]). Nevertheless, asynchronous timeliness fits better with users' desires in MPCS protocols, since, for instance, contract conditions can also change with time, no longer being favorable for a group of entities.

For those only holding part of the commitments, they have no option but to wait until the deadline $t$ to know the status of the contract. Obviously, this is unfavorable to these participants in terms of timeliness. They should also have the right to decide the status of the contract before the deadline $t$. As they only hold part of the commitments, they are unable to resolve the contract, so they can only choose to cancel the contract. (Note that in this in-and-out architecture of commitment exchange, for those participants only holding part of the commitments, even if all of them collaborate, their combined commitments are still incomplete to resolve the contract.)

Here we present a $(j, n)$-threshold cancel subprotocol. As long as there are at least $j$ out of $n$ participants that wish to cancel the contract before the deadline $t$, the contract could be cancelled. The cancel subprotocol is as follows, where *counter* (initial value equals zero) records the number of cancel requests received by the TTP, and $group_c$ records the participants which made cancel requests. For simplicity of description, it

is built based on the main protocol in Section 5.1.2 without considering abuse-freeness (but can be easily merged with it).

(1) $P_i \rightarrow TTP$ : $cancel_{P_i} = C, cancel, S_{P_i}(C, cancel)$
(2) $TTP$ : IF $cancel_{P_i}$ is received before $t$ AND $C$ is not resolved
AND $C$ is not cancelled THEN
stores $cancel_{P_i}$; $group_c = group_c + P_i$;
$counter++$;
IF $counter \geq j$ THEN
sets $C$ as cancelled
publishes $cancel, group_c, S_{TTP}(cancel, C, group_c)$

The resolve subprotocol is modified as follows.

(1) $P_i \rightarrow TTP$ : $resolve_{P_i} = C, m_1, .., m_n, S_{P_i}(C, m_1, .., m_n)$
(2) $TTP$ : IF $resolve_{P_i}$ is received before $t$ AND $C$ is not cancelled
AND C is not resolved
decrypts $m_1..m_n$
sets $C$ as resolved
publishes $S_{P_1}(C), .., S_{P_n}(C)$

With the aforesaid cancel and resolve subprotocols, each participant has at least one option to determine the status of the contract before deadline $t$ if the main protocol is not completed successfully. Thus timeliness is achieved, and the extent of timeliness depends on the threshold value $j$: strong timeliness when $j = 1$, and weak timeliness when $j = n$.

However, the threshold value $j$ should be selected carefully. If $j$ is too small, a few parties may collude to invalidate a contract. If $j$ is too big, it might be hard to establish a valid cancel request among $j$ parties. A possible option is $j = [n/2] + 1$, with a weak majority to vote for the validity of a contract.

In the dispute resolution, the cancel token issued by the TTP has the top priority. In other words, if a participant presents the cancel token, then the contract is invalid. This implies that if there are at least $j$ out of $n$ participants who want to cancel the contract before the deadline, even if they have released their plaintext signatures in the main protocol, they together can still change their mind before that deadline. This is a reasonable scenario in the real world because the situation defined in the contract may change with time, even during the process of contract-signing, and each participant wishes to pursue the maximum benefit by taking appropriate actions (resolve or cancel).

As the cancel token from the TTP has higher priority than the signed contract, those parties that have received the signed contract in the main protocol may need to double check with the TTP about the status of the contract by the deadline $t$. (Note that the double check does not mean the involvement of the TTP itself, but just a query to a public file maintained by the TTP.) If they do not want to wait until this deadline, they can send the resolve request to the TTP instead, thus blocking other parties to enable the TTP to issue the cancel token.

## 6. CONCLUSIONS

Repudiation is one of the fundamental security threats existing in paper-based and electronic environments. In order to give an answer to such a threat, nonrepudiation is defined by the ITU as one of the main security services. As such, this topic has received

relatively enough attention from the scientific community, especially the issues of assuring fairness and designing more efficient protocols. But this has been mainly focused towards protocols (or applications) in which two entities take part. Some applications nowadays assume the existence of several participating users and the requirements with respect to fairness and efficiency then change significantly. Thus, this service needs to be fully considered in multiparty environments.

We provided a survey which starts from the inherent fundamentals of the nonrepudiation service, defining the different elements, roles, phases, requirements, and state-of-the-art standard analysis of the basic (two-entity oriented) nonrepudiation services. This allows us to address the definitions and revisit the requirements of multiparty schemes. In this survey we split multiparty scenarios into two main categories: 1-N and N-N scenarios. With this classification we surveyed the existing work and provided an analysis of the existing research literature.

We stepped forward, providing a novel solution for the 1-N multiparty case in which a message can be multicasted to several recipients. We designed our general protocols in a way that allows the participating entities to send personal and confidential messages to other entities without loss of privacy, in two different approaches, namely online and optimistic, thus enabling different types of applications. Requirements analysis and comparison in terms of efficiency with previous solutions are provided as well.

We moved towards the application field, reading up on applications for multiparty certified electronic mail and contract-signing. In both cases we contributed with new solutions. In the first case we generalized a fast and simple, optimistic fair certified electronic-mail protocol to the multiparty case and integrated and analyzed an asynchronous timeliness property. We also improved existing solutions for synchronous multiparty contract-signing protocols based on two differentiated phases: a promise to sign, and a real signature that a party releases only after receiving all promises from the remaining participants. Merging both phases we achieved an improvement on the number of steps with respect to the surveyed literature.

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