Interactive Non-Malleable Codes Against Desynchronizing Attacks in the Multi-Party Setting

Nils Fleischhacker[1⋆], Suparno Ghoshal[1⋆⋆], and Mark Simkin[2⋆⋆⋆]

[1] Ruhr University Bochum
[2] Ethereum Foundation

Abstract. Interactive Non-Malleable Codes were introduced by Fleischhacker et al. (TCC 2019) in the two party setting with synchronous tampering. The idea of this type of non-malleable code is that it "encodes" an interactive protocol in such a way that, even if the messages are tampered with according to some class $\mathcal{F}$ of tampering functions, the result of the execution will either be correct, or completely unrelated to the inputs of the participating parties. In the synchronous setting the adversary is able to *modify* the messages being exchanged but cannot drop messages nor desynchronize the two parties by first running the protocol with the first party and then with the second party. In this work, we define interactive non-malleable codes in the non-synchronous multi-party setting and construct such interactive non-malleable codes for the class $\mathcal{F}^{s}_{\mathsf{bounded}}$ of bounded-state tampering functions. The construction is applicable to any multi-party protocol with a fixed message topology.

1 Introduction

There is a long line of research that aims to make communication resilient to tampering, starting with error correcting codes. Error correcting codes allow a sender to encode a message m into a codeword c, such that a receiver can always recover the message m even from a tampered codeword c' as long as the tampering is done in some restricted way. Specifically, the class of tampering functions tolerated by traditional error correcting codes are those that erase or modify at most a constant fraction of the symbols in codeword c. If the tampering function, however, behaves in any other way, there is no longer any guarantee on the output of the decoding algorithm. Error *detecting* codes are a relaxation that allows the decoder to also output a special symbol $\perp$ when m is not recoverable from c'. But these codes, again, cannot tolerate, i.e. will decode incorrectly when tampered with, many simple tampering functions such as a constant function.

Dziembowski, Pietrzak, and Wichs [DPW10] introduced a further relaxation which they called non-malleable codes (NMC). Very informally, an encoding scheme $(\mathsf{Enc}, \mathsf{Dec})$ is an NMC for a class of tampering functions, $\mathcal{F}$, if the following holds: given a tampered codeword $c' = f(\mathsf{Enc}(m))$ for some $f \in \mathcal{F}$, the decoded message $m' = \mathsf{Dec}(c')$ is either the original message m or *completely unrelated* to m. I.e., the tampering function can only "destroy" the information being transferred, but not modify it in a meaningful way. Obviously, NMCs can still not exist for the set of *all* tampering functions $\mathcal{F}_{\mathsf{all}}$. To see this, consider the tampering function that retrieves $m = \mathsf{Dec}(c)$, chooses a message m' related to m and encodes $c' = \mathsf{Enc}(m')$. This tampering trivially defeats the requirement above. In light of this observation, a rich line of works has dealt with constructing non-malleable codes for different classes of tampering attacks (see Section 1.2 for a discussion).

Non-malleable codes have the obvious advantage that we can obtain meaningful guarantees for larger classes of tampering functions (compared to error correcting codes) and they have also found a number of interesting applications in cryptography such as tamper-resilient cryptography [DPW10, LL12, FMNV14, FMNV15]. They have also been useful as a building block in constructing non-malleable encryption [CDTV16], round optimal non-malleable commitments [GPR16], and non-malleable secret sharing schemes [GK18a, GK18b, BS19].

⋆ mail@nilsfleischhacker.de
⋆⋆ suparno.ghoshal@rub.de
⋆⋆⋆ mark.simkin@ethereum.org

Interactive Coding. Traditional codes, whether error correcting, error detecting or non-malleable are only concerned with the scenario where a sender sends a single message to a receiver. Interactive Coding, introduced by Schulman [Sch92, Sch93, Sch96], generalizes (error correcting) codes to arbitrary interactive protocols between two or more [RS94] parties. Consider the following scenario: n parties, each with their own input, are running an interactive protocol to perform some task involving their inputs, such as computing a joint function on them. Now, say an adversary can get access to their communication channels and tamper with the messages being sent in the protocol. An interactive code for a class of tampering functions $\mathcal{F}$ is essentially a wrapper around the protocol that would guarantee that, as long as the tampering is performed using a function $f \in \mathcal{F}$, the protocol will conclude correctly and all participants will be able to recover their correct output.

Interactive Non-Malleable Codes. In interactive coding, just as in the case of error correcting codes, there are strong limits on which classes of tampering can be dealt with. To achieve meaningful guarantees for larger classes of tampering functions Fleischhacker et al. [FGJ+19] introduced the notion of interactive *non-malleable* codes (INMC). Just as interactive coding generalizes error correcting codes, INMCs generalize NMCs, by encoding "active communication" instead of "passive data". An INMC is supposed to give a similar guarantee as an NMC. Informally, that means that the participants of the protocol should either be able to recover the correct output from the protocol or the correct output would be completely "destroyed" and the participants would recover something completely unrelated to their inputs. Fleischhacker et al. in fact define two seperate notion of non-malleability, weak non-malleability only requires the outputs to be unrelated from *other* parties' inputs, while *strong* non-malleability requires the outputs to be unrelated even to the party's own input. We are only interested in the *strong* non-malleability notion, which we will simply call non-malleability. It turns out that strong non-malleability somewhat counterintuitively actually implies error detection in the interactive case.

Fleischhacker et al. [FGJ+19] define three classes of tampering functions, bounded-state tampering, a variation of split-state tampering, and sliding-window tampering. For each class they give a construction of a strongly non-malleable INMC.

However, both the definitions and the constructions are limited, because they only apply to the two party setting and they only consider *synchronous* tampering. Consider a protocol between two parties, Alice and Bob. In the synchronous setting, when Alice sends a message m to Bob, the tampering function can arbitrarily *modify* m, but it *must* then forward it to Bob without further delay. I.e., at all times, even in a tampered execution of the protocol, Alice and Bob remain in sync and the tampering function can *not* choose to, e.g., first finish the protocol with Alice, before later resuming the communication with Bob.

1.1 Results and Technical Overview

In this work, we aim to remedy the shortcomings of the previous work by Fleischhacker et al. [FGJ+19]. In Section 3 we introduce new definitions for arbitrary (potentially desynchronizing) tampering with interactive protocols between $n \geq 2$ parties, define interactive non-malleability and formalize the class of bounded-state tampering functions. In Section 4 we construct an INMC for bounded-state tampering functions.

The "Obvious" Solution. When faced with the task of constructing an interactive non-malleable code it may seem tempting to directly apply the huge body of work around regular non-malleable codes and try to build an INMC by simply applying an NMC on a per-message basis. While we might not get guarantees against the *same* class of tampering functions, we might still hope to get *some* useful guarantees. Sadly, this is not the case for general protocols. Consider a protocol between Alice and Bob, where Alice has input (x_1, x_2) and Bob has no input. In the protocol, Alice first sends x_1 to Bob, Bob replies with some arbitrary message and then Alice sends x_2. At the end Alice outputs nothing and Bob outputs (x_1, x_2).

If we encode the messages in this protocol individually, a tampering function can simply leave all the messages related to x_1 intact and replace the messages related to x_2 with constant messages that will decode to some x'_2, causing Bob to output (x_1, x'_2), an output very much *not* unrelated (x_1, x_2). This attack works for any class of tampering functions that allow to tamper with the entire message, no matter how restrictive.

Technical Overview On a technical level, our construction is heavily inspired by the bounded-state INMC of [FGJ+19] and follows the same basic idea: At the beginning of the protocol, each pair of parties runs a key-exchange protocol that is secure against a bounded state attacker with full control of the communication channel. Once the key material has been successfully exchanged, the parties will engage in the underlying protocol while encrypting all messages with an information theoretically secure encryption scheme and authenticating each message with an information theoretically secure message authentication code.

However, since [FGJ+19] was restricted to two parties and worked in a strictly synchronized setting, it is unsurprising that directly lifting their protocol to the multi-party unsynchronized setting causes it to fail in several ways. The key-exchange of [FGJ+19] works as follows: The two parties P_1, P_2 each choose random strings α_1, β_1 and α_2, β_2 of sufficient length. They then send these in alternating order, use a 2-non-malleable extractor to agree on a key $k := \mathsf{nmExt}(\alpha_A, \beta_A) \oplus \mathsf{nmExt}(\alpha_B, \beta_B)$ and go on to exchange key-confirmation messages to confirm that both parties have received the same key. Once we allow the tampering function to desynchronize the two parties this key exchange becomes trivially broken. Consider the tampering function f that simply ignores P_2 and their messages. Instead, when P_1 sends α_1, the tampering function immediately sends back α_1 and likewise for β_1. This means that P_1 will now derive the constant key $\mathsf{nmExt}(\alpha_1, \beta_1) \oplus \mathsf{nmExt}(\alpha_1, \beta_1) = 0^\kappa$. This key is of course trivially known to the tampering function in future rounds meaning the tampering function can simply engage in the underlying protocol pretending to be P_2 with some arbitrary input y' of its own choice. If the protocol is meant to evaluate a function g on the joint inputs, P_1 will now output $g(x, y')$ which is in general neither the correct result nor independent of (x, y).

To fix this problem, we split each bidirectional communication channel into two unidirectional channels and negotiate separate keys. The two parties still choose random strings α_1, β_1 and α_2, β_2 of sufficient length and send them in separate messages. However the parties agree on two separate keys $k_1 := \mathsf{nmExt}(\alpha_1, \beta_1)$ and $k_2 := \mathsf{nmExt}(\alpha_2, \beta_2)$. Each party P_i then uses k_i to *encrypt* messages *sent to* the other party and to *verify* the authentication tags on messages *received from* the other party. This way, each party always uses a key that is known to be *untampered* to perform the security critical operations.

It is still critical, that keys are confirmed and bound to a specific channel. If keys are not explicitly confirmed, a tampering function could replace one of the keys, say k_2 without any of the parties realizing. If P_2 would now send a message to P_1, this message would be *authenticated* using k_1 which was not tampered with, meaning P_1 would accept it. However they would then go on to *decrypt* the message with an incorrect key k_2'. This would likely result in P_1 passing a random string to the underlying protocol and there is no guarantee how the underlying protocol would behave in that case. If the key was not explicitly bound to a specific channel, a tampering function could potentially "swap" two parties. Say there's a protocol where P_3 and P_2 do not communicate with one another but *do* communicate with P_1. The tampering function could swap all messages from the channel between P_1 and P_2 to the channel between P_1 and P_3 and vice versa. If P_2 and and P_3 behave identically in the protocol and never explicitly identify themselves, this would lead P_1 to output $g(x_1, x_3, x_2)$ which again is obviously neither correct nor independent of (x_1, x_2, x_3) in general.

To prevent all these and other problems introduced by the existence of multiple parties and the ability of the tampering function to desynchronize the parties each message is always authenticated together with the identifier of the channel it is being sent on and the message counter.

Fixed Message Topology. The INMC for bounded-state tampering functions presented in Section 4 is still somewhat restricted and does not apply to *all* protocols. Specifically the INMC only applies to protocols that have a "fixed message topology". This means we require that the message flow of the protocol is a priori known and independent of inputs and randomness. I.e., when party P_i is invoked for the r^{th} time, we a priori know from which parties they *should be receiving* messages and to which parties they *should be sending.* If we did not restrict the protocol, there would be several issues. Some are clearly fixable for others fixing is an open question: The most obvious problem is input dependent message topology. If, whether P_i sends a message to P_j when invoked for the rth time depends on the value x_i, we can easily come up with ways to leak x_i to the tampering function, which would make non-malleability impossible. This problem is theoretically fixable by introducing dummy messages between all non-communicating parties. However, this would obviously come at great communication cost.

A more subtle issue are protocols that *misbehave* if messages are reordered or dropped. Consider a protocol between two parties. In an untampered execution P_1 would receive a message from P_2 in its first invocation. At the end both parties output 0. Now we can modify this protocol to *misbehave* if the messages from P_2 never arrives. In this case P_1 could simply output x_1, which is neither correct nor unrelated to (x_1, x_2).

If we, however, *know* which messages should be arriving in which order, we can abort any party that did not receive messages as specified in the protocol preventing them from misbehaving. It remains unclear if this problem can be solved for general protocols.

1.2 Related Works

To the best of our knowledge, the only previous work on non-malleable codes in the interactive setting has been the already mentioned work of Fleischhacker et al. [FGJ+19].

In contrast, non-malleable codes in the non-interactive setting have been studied extensively for a large variety of different classes of tampering functions. The most extensively studied class in the non-interactive setting are certainly split-state tampering functions [LL12, DKO13, ADL14, CG14, CZ14, ADKO15, CG16, Li17, KOS17, KOS18, ADN+19]. But other classes of tampering functions have been studied such as tampering circuits of limited size or depth [FMVW14, BDKM16, CL17, BDKM18, BDG+18], tampering functions computable by decision trees [BGW19], memory-bounded tampering functions [FHMV17] where the size of the available memory is a priori bounded, bounded polynomial time tampering functions [BDK+19], bounded *parallel*-time tampering functions [DKP21], and non-malleable codes against streaming tampering functions [BDKM18]. Non-malleable codes were also generalized in several ways, such as continuously non-malleable codes in [FMNV14, CMTV15, CDTV16, OPVV18, FNSV18, CFV19, ADN+19] and locally decodable and updatable non-malleable codes [DLSZ15, CKR16, DKS17].

As a general rule non-malleable codes are usually considered in the information theoretic setting. However, there has also been some work in the computational setting. [AAG+16, AGM+15a, AGM+15b, BDKM18]

2 Preliminaries

In this section we introduce our notation and recall some definitions needed for our constructions and proofs.

2.1 Notation

We denote the security parameter by $\lambda \in \mathbb{N}$. For an integer $n \in \mathbb{N}$, denote $[n] = \{1, \dots, n\}$.

Let $\boldsymbol{M}$ be a matrix. We denote by $\mathbf{row}_i(\boldsymbol{M})$ the i-th row vector and by $\mathbf{col}_j(\boldsymbol{M})$ the j-th column vector of $\boldsymbol{M}$. If $\boldsymbol{M}$ is square, we denote by $\mathbf{diag}(\boldsymbol{M})$ the vector representing the main diagonal of $\boldsymbol{M}$.

Let S and S' be sets, let $P : S \to \{\mathsf{true}, \mathsf{false}\}$ be a predicate, let $f : S \to S'$ be a function, and let $L = (x_1, \dots, x_\ell) \in S^\ell$ be a list. We denote by $\big(f(x) \mid x \in L \wedge P(x)\big)$ the list that contains $f(x_i)$ iff $P(x_i) = \texttt{true}$ and preserves the relative order of the elements.

For $x' \in S$ we denote by $L \circ x'$ the list $(x_1, \dots, x_\ell, x')$, i.e. the list resulting from appending x' to L. Further, we write L_i to denote the ith entry of L and $L_{\leq i}$ to denote the length i prefix of L, i.e. $L_{\leq i} = (x_1, \dots, x_i)$.

Let D be some distribution over S. We denote by $f(D)$ the distribution over S' sampled by first sampling x according to D and then applying f to x. For a pair D_1, D_2 of distributions over a domain S, we denote their statistical distance by

$$\mathsf{SD}(D_1, D_2) = \frac{1}{2} \sum_{v \in S} \Big| \Pr[x \leftarrow D_1 : x = v] - \Pr[x \leftarrow D_2 : x = v] \Big|.$$

If $\mathsf{SD}(D_1, D_2) \leq \epsilon$, we say that D_1, D_2 are ϵ-close.

For an arbitrary set S we define the function

$$\mathsf{replace} : S \cup \{\mathsf{same}\} \times S \to S$$

as

$$\mathsf{replace}(x, y) := \begin{cases} y & \text{if } x = \mathsf{same} \\ x & \text{otherwise.} \end{cases}$$

and the function

$$\mathsf{indicate} : S \to \{\mathsf{same}, \bot\}$$

as

$$\mathsf{indicate}(x) := \begin{cases} \mathsf{same} & \text{if } x \neq \bot \\ \bot & \text{otherwise.} \end{cases}$$

We extend replace and indicate to n-tuples in the natural way by applying them component-wise, i.e. $\mathsf{replace}(\boldsymbol{x}, \boldsymbol{y}) := (\mathsf{replace}(x_1, y_1), \dots, \mathsf{replace}(x_n, y_n))$ and $\mathsf{indicate}(\boldsymbol{x}) := (\mathsf{indicate}(x_1), \dots, \mathsf{indicate}(x_n))$.

2.2 Encryption and Message Authentication Codes

Our constructions relies exclusively on information theoretically secure primitives, specifically perfectly indistinguishable encryption and statistically secure message authentication codes. For notational convenience we formalize encryption as stateful which allows us not burden the description of the protocol with keeping track of key-usage.

Definition 1 (Stateful t-time Encryption with Perfect Indistingishability). *A correct stateful t-time encryption scheme $\mathcal{E}$ for message space $\{0,1\}^\ell$ and keyspace $\{0,1\}^\kappa$ consists of a pair of deterministic stateful algorithms $(\mathsf{Enc}, \mathsf{Dec})$, such that for all keys $k \in \{0,1\}^\kappa$ and all messages $(m_1, \dots, m_t) \in (\{0,1\}^\ell)^t$ we have that for $c_1 := \mathsf{Enc}(k, m_1), \dots, c_\ell := \mathsf{Enc}(k, m_t)$ and $m'_1 := \mathsf{Dec}(k, c_1), \dots, m'_\ell := \mathsf{Dec}(k, c_t)$ it holds that $m_i = m'_i$ for all $i \in [t]$.*

Let LoR be the stateful "left-or-right" algorithm defined as $\mathsf{LoR}(k, b, m_0, m_1) := \mathsf{Enc}(k, m_b)$ for the first t invocations and as $\bot$ afterwards. A stateful t-time encryption scheme is perfectly indistinguishable if for any unbounded algorithm $\mathcal{A}$ it holds that

$$\Pr\big[k \leftarrow \{0,1\}^\kappa : \mathcal{A}^{\mathsf{LoR}(k,0,\cdot,\cdot)} = 0\big] = \Pr\big[k \leftarrow \{0,1\}^{t\ell} : \mathcal{A}^{\mathsf{LoR}(k,1,\cdot,\cdot)} = 0\big].$$

For convenience we extend the notation of encryption schemes to vectors in the natural way by applying the algorithm component wise. I.e., for $\boldsymbol{m} \in (\{0,1\}^\ell)^n$ and $\boldsymbol{k} \in (\{0,1\}^\kappa)^n$ we write $\boldsymbol{c} := \mathsf{Enc}(\boldsymbol{k}, \boldsymbol{m})$ to denote the vector consisting of $c_i := \mathsf{Enc}(k_i, m_i)$. Similarly we write $\boldsymbol{m'} := \mathsf{Dec}(\boldsymbol{k}, \boldsymbol{c})$ for the vector consisting of $m'_i := \mathsf{Dec}(k_i, c_i)$.

Remark 1. *A stateful t-time encryption scheme with perfect indistinguishability can easily be instantiated using the one-time pad where the key k is split into keys $k_1, \dots, k_r \in \{0,1\}^\ell$ and c_i is computed as $m_i \oplus k_i$. The perfect indistinguishability follows from the regular perfect secrecy of the one-time pad.[Sha49] In this case $\kappa = t\ell$.*

Definition 2 (Statistically Unforgeable t-time MACs). *A t-time message authentication code $\mathcal{M}$ for message space $\{0,1\}^\ell$ and keyspace $\{0,1\}^\kappa$ consists of a pair of deterministic algorithms $(\mathsf{MAC}, \mathsf{Vf})$, such that for all keys $k \in \{0,1\}^\kappa$ and all messages $m \in \{0,1\}^\ell$ it holds that $\mathsf{Vf}(k, m, \mathsf{MAC}(k, m)) = 1$.*

Let $n \in \mathbb{N}$ and let $\widetilde{\mathsf{MAC}}$ be the algorithm defined as $\widetilde{\mathsf{MAC}}(k_1, \dots, k_n, i, m) := \mathsf{MAC}(k_i, m)$. A t-time message authentication code is ϵ-unforgeable, if for all unbounded algorithms $\mathcal{A}$ it holds that

$$\Pr\begin{bmatrix} k_1, \dots, k_n \leftarrow \{0,1\}^\kappa & : & \mathsf{Vf}(k_i, m, t) = 1 \\ (i, m, t) \leftarrow \mathcal{A}^{\widetilde{\mathsf{MAC}}(k_1, \dots, k_n, \cdot, \cdot)}() & & \wedge\, (m, t) \notin Q_i \wedge |Q_i| \leq t \end{bmatrix} \leq \epsilon$$

where Q_i denotes the set of message-answer pairs, queried by $\mathcal{A}$ for index i.

Similar to encryption schemes, we extend the notation of message authentication codes to vectors in the natural way by applying the algorithm compnent wise. I.e., for $\boldsymbol{m} \in (\{0,1\}^\ell)^n$ and $\boldsymbol{k} \in (\{0,1\}^\kappa)^n$ we write $\boldsymbol{t} := \mathsf{MAC}(\boldsymbol{k}, \boldsymbol{m})$ to denote the vector consisting of $t_i := \mathsf{MAC}(k_i, m_i)$.

Remark 2. *Statistically unforgeable t-time MACs can be instantiated using any family of $t+1$-wise independent hash functions such as the family of degree t polynomials over $\mathbb{F}_{2^{\max\{\ell,\lambda\}}}$ [WC81]. In this case $\kappa = (t+1) \cdot \max\{\ell, \lambda\}$ and $\epsilon = 2^{-\max\{\ell,\lambda\}}$.*

2.3 2-Non-Malleable Extractors

Our construction also makes use of 2-non-malleable extractors. These were first defined by Cheraghchi and Guruswami [CG14, CG17] but constructing them was left as an open problem. The definition was finally instantiated by Chattopadhyay, Goyal, and Li [CGL16]. Such an extractor allows to non-malleably extract an almost uniform random string from two sources with a given min-entropy that are being tampered by a split-state tampering function. We closely follow the definition from [CGL16].

Definition 3 (2-Non-Malleable Extractor). *A function $\mathsf{nmExt} : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}^m$ is a 2-non-malleable extractor for sources with min-entropy $k < n$ and with error ϵ if it satisfies the following property: If X, Y are independent sources of length n with min-entropy k and $f = (f_0, f_1)$ is an arbitrary 2-split-state tampering function, then there exists a distribution D_f over $\{0,1\}^m \cup \{\mathsf{same}\}$, such that*

$$\mathsf{SD}\big(\big(\mathsf{nmExt}(X,Y), \mathsf{nmExt}(f_0(X), f_1(Y))\big), \big(U_m, \mathsf{replace}(D_f, U_m)\big)\big) \leq \epsilon$$

where both U_m refer to the same uniform m-bit string.

Remark 3. *The required 2-non-malleable extractor can be instantiated with the construction of Chattopadhyay Goyal and Li [CGL16] or a number of other construction. [Li17, Li19, COA21].*

3 Interactive Protocols and Tampering Model

We consider protocols Π between n parties $P_1, \ldots, P_n$ for evaluating functionalities $g = (g_1, \ldots, g_n)$ of the form $g_i : X_1 \times \cdots \times X_n \to Y_i$, where X_i, Y_i are finite domains. Each party P_i holds an input $x_i \in X_i$ and randomness $\omega_i \in \Omega_i$ and the goal of the protocol is to interactively evaluate the functionality, such that at the end of the protocol party P_i outputs $g_i(x_1, \ldots, x_n) \in Y_i$.

Formally, an interactive protocol Π between n parties can be described either using interactive Turing machines, or using next-message functions. The two formalizations are equivalent up to a slight computational overhead. We will switch between the two formalizations whenever this is convenient for exposition.

Interactive Protocols as Interactive Turing Machines In this formalization an interactive protocol Π between n parties is described by an n-tuple of interactive Turing machines P_i. Each interactive Turing machine P_i has an input tape containing x_i, a random tape containing ω_i, an internal work tape, as well as an incoming communication tape and an outgoing communication tape for each party P_j with $j \neq i$ and an output tape.

Interactive Protocols as Next Message Functions In this formalization an interactive protocol Π between n parties is described by a an n-tuple of "next message" functions π_i and an n-tuple of output functions out_i. The next message function π_i takes as input the view of P_i, i.e., the input x_i, the randomness ω_i, and the sequence of message vectors received by P_i thus far and outputs the vector $\boldsymbol{s}_i \in \{0,1\}^* \cup \{\perp\}$ of messages to be sent by P_i. The output function out_i takes as input the final view of P_i, i.e., x_i, ω_i, and received message vectors and outputs P_i's protocol output.

Equivalence of Formalizations The two formalizations are equivalent up to a slight computational overhead. To see this consider the following two simple conversions: Given an interactive Turing machine P_i, the equivalent next message function π_i can be computed on input $x_i, \omega_i, \boldsymbol{m}_i$ by simulating the Turing machine on input x_i and randomness ω_i, writing the received messages for each round on the appropriate incoming communication tapes until the current round is reached. The content of the outgoing communication tapes can then be output as $\boldsymbol{s}_i$. Similarly, given a next message function π_i, the equivalent interactive Turing machine P_i will simply store the contents of its incoming communication tapes on its internal work tape, evaluate π_i on its input x_i, randomness ω_i and all incoming messages, and write the output of π_i to its outgoing communication tapes.

3.1 Correctness and Encodings

We denote by $\Pi(\boldsymbol{x})$ the joint distribution of the outputs of an honest execution of the protocol Π using inputs $\boldsymbol{x}$ and uniformly sampled randomness $\boldsymbol{\omega}$. Further, we denote by $g(\boldsymbol{x})$ the vector $(g_1(x_1, \ldots, x_n), \ldots, g_1(x_1, \ldots, x_n))$.

Definition 4 (Correctness). *A protocol Π, is said to ϵ-correctly evaluate a functionality $g = (g_1, \ldots, g_n)$ if an untampered execution of the protocol correctly computes g with probability at least $1 - \epsilon$. I.e.,*

$$\Pr[\boldsymbol{y} \leftarrow \Pi(\boldsymbol{x}) : \boldsymbol{y} = g(\boldsymbol{x})] \geq 1 - \epsilon,$$

where the probability is taken over the uniform choice of the random tape of all parties.

Definition 5 (Encoding of an Interactive Protocol). *An encoding $\mathcal{E}$ of n-party interactive protocols is defined by n interactive oracle machines Enc_i.*

Let Π be an arbitrary interactive n-party protocol that ϵ-correctly evaluate a functionality g. The encoded *protocol is then the interactive n-party protocol between interactive Turing machines $(Q_1, \ldots, Q_n)$ defined as follows: On input x_i, Q_i samples uniform randomness ω_i, initiates the oracle $\mathsf{O}_{\boldsymbol{x},\boldsymbol{\omega}'} = P_i(x_i; \omega_i)$ and then executes $\mathsf{Enc}_i^{\mathsf{O}_{\boldsymbol{x},\boldsymbol{\omega}'}}()$, giving it direct access to all communication tapes. Once $\mathsf{Enc}_i^{\mathsf{O}_{\boldsymbol{x},\boldsymbol{\omega}'}}()$ terminates with some output y, Q_i also outputs y. $\mathcal{E}$ is a δ-correct protocol encoding for Π if for all inputs $\boldsymbol{x}$, the protocol $\mathcal{E}(\Pi) = (Q_1, \ldots, Q_n)$ $\epsilon + \delta$-correctly evaluates the functionality g.*

3.2 Tampering Model

The transcript of a protocol executed under tampering needs to specify for each round of execution both the messages sent by each party and the messages received by each party. Remember that, due to the presence of the tampering function, the messages received are not necessarily related in any way to the messages sent.

We consider a scenario in which each party has a point-to-point channel to each other party, but not to itself. I.e., a protocol among n parties is executed over a complete directed communication graph (excluding loops) with n nodes P_i.

For each round, the transcript needs to label each edge (P_i, P_j) for $i \neq j$ in the graph with the message P_i sent to P_j and the message P_j received from P_i, the two of which need not be related. We will denote this with two $n \times n$ matrices $\boldsymbol{S}$ and $\boldsymbol{R}$ of labels per round of execution, where a label is either an arbitrary bitstring or the special symbol $\perp$ denoting that *no* message was sent or received respectively.

Definition 6 (Transcripts). *Let $\mathcal{M} = \{0,1\}^* \cup \{\perp\}$ be the set of possible labels for the edges of the communication graph. The set of possible transcripts is then the set of lists of pairs of matrices $\boldsymbol{S}_i, \boldsymbol{R}_i \in \mathcal{M}^{n \times n}$ such that the diagonal of both matrices only contains $\perp$. I.e.,*

$$\mathcal{T} = \left(\left\{\boldsymbol{M} \in \mathcal{M}^{n\times n} \mid \mathbf{diag}(\boldsymbol{M}) \in \{\perp\}^n\right\}^2\right)^*.$$

For any transcript $\tau = \big((\boldsymbol{S_1}, \boldsymbol{R_1}), \ldots, (\boldsymbol{S_\ell}, \boldsymbol{R_\ell})\big)$, $\mathbf{row}_j(\boldsymbol{S_i})$ denotes the vector of messages sent by P_j in round i of the execution, while $\mathbf{col}_j(\boldsymbol{R_i})^\top$ denotes the vector of messages received by P_j in round i of the execution.

A party's view of the transcript consists exactly of the vectors of messages it receives. In particular, if a party does not receive any messages in a particular round of the execution, this round is not included in the party's view. This models that a party is not necessarily capable of detecting that desynchronization happens and allows general tampering functions to arbitrarily desynchronize different parties during protocol execution.

Definition 7 (Views). *Let τ be a transcript. The corresponding view of party P_i is then defined as*

$$V_i(\tau) = \left(\mathbf{col}_i(\boldsymbol{R})^\top \;\middle|\; (\boldsymbol{S}, \boldsymbol{R}) \in \tau \wedge \mathbf{col}_i(\boldsymbol{R})^\top \notin \{\bot\}^n\right).$$

The interactive non-malleable code presented in Section 4 is restricted to protocols with a fixed message topology. This means that the number of messages exchanged over each channel is fixed, the expected relative ordering of all the messages received by a single party is a priori known, and whether or not a party sends a message along a communication channel does not depend on their input or their received messages. I.e., the "structure" of each vector in a party's view as well as the output vector in any particular round of execution is fixed in an untampered execution. We define this formally as follows.

Definition 8 (Fixed Message Topology). *An interactive protocol Π with n parties defined by next message functions π_i and output functions out_i is said to have a fixed message topology, if there exists a function $\mu : [n] \times \mathbb{N} \to \{0,1\}^n \times \{0,1\}^n$, such that for all vectors of inputs $\boldsymbol{x}$, all randomness vector $\boldsymbol{\omega}$ and the transcript trans of an honest untampered execution of Π on $\boldsymbol{x}$ with $\boldsymbol{\omega}$, all $i \in [n]$, and all $r \in [|V_i(\tau)|]$ it holds that $\mu(i,r) = (\boldsymbol{v}', \boldsymbol{s}')$, where*

$$v'_j := \begin{cases} 0 & \text{if } V_i(\tau)_{r,j} = \bot \\ 1 & \text{otherwise} \end{cases} \qquad s'_j := \begin{cases} 0 & \text{if } \pi_i(x_i, \omega_i, V_i(\tau)_{\leq r})_j = \bot \\ 1 & \text{otherwise} \end{cases}$$

for $j \in [n]$ and for all $r \geq |V_i(\tau)|$ it holds that $\mu(i,r) = (0^n, 0^n)$. We further define the function $\nu[n] \times [n] \to \mathbb{N}$

$$\nu(i,j) := \sum_{r \in \mathbb{N}} \mu(i,r)_{1,j} = \sum_{r \in \mathbb{N}} \mu(j,r)_{2,i}$$

as the exact number of messages received by party i from j during an execution of the protocol.

Let Π be a protocol with n parties defined by next message functions π_i and output functions out_i. For ease of notation we define the function Next_Π which describes computation of all messages sent during a particular round of execution depending on the protocol specification, the vector of inputs $\boldsymbol{x} = (x_1, \ldots, x_n)$ and the partial transcript $\tau \in \mathcal{T}$.

```
Next_Π(x, ω, τ)
----------------------------------------
parse τ = ((S_1, R_1), ..., (S_ℓ, R_ℓ))
for 1 ≤ i ≤ n do
  if τ = ∅ ∨ col_i(R_ℓ)^⊤ ≠ ⊥^n
    s_i := π_i(x_i, ω_i, V_i(τ))
  else
    s_i := ⊥^n
return [s_1, ..., s_n]^⊤
```

Let $F : \mathcal{T} \times \mathcal{M}^{n \times n} \to \mathcal{M}^{n \times n}$ be an arbitrary tampering function. We describe execution of Π on inputs $\boldsymbol{x} = (x_1, \ldots, x_n)$ under tampering by F using the algorithm $\mathsf{Execute}_{\Pi,F}$.

$$
\begin{array}{l}
\underline{\mathsf{Execute}_{\Pi,F}(\boldsymbol{x};\boldsymbol{\omega})} \\
\tau := \emptyset \\
\boldsymbol{S} := \mathsf{Next}(\Pi, \boldsymbol{x}, \boldsymbol{\omega}, \tau) \\
\boldsymbol{R} := F(\tau, \boldsymbol{S}) \\
\textbf{while } \boldsymbol{R} \neq \bot^{n\times n} \\
\quad \tau := \tau \circ (\boldsymbol{S}, \boldsymbol{R}) \\
\quad \boldsymbol{S} := \mathsf{Next}(\Pi, (x), \tau) \\
\quad \boldsymbol{R} := F(\tau, \boldsymbol{S}) \\
\textbf{return } \big(\mathsf{out}_1(x_1, V_1(\tau)), \ldots, \mathsf{out}_n(x_n, V_n(\tau))\big)
\end{array}
$$

Let $I : \mathcal{T} \times \mathcal{M}^{n\times n} \to \mathcal{M}^{n\times n}$ be the function defined as $I(\tau, \boldsymbol{S}) := \boldsymbol{S}$. We call I the identity tampering function. Note that the distribution $\Pi(\boldsymbol{x})$ is identical to the distribution $\mathsf{Execute}_{\Pi,I}(\boldsymbol{x})$.

Definition 9 (Protocol Non-malleability). *An n-party protocol Π for functionality g is ϵ-protocol non-malleable for a family $\mathcal{F}$ of tampering functions if for every tampering function $F \in \mathcal{F}$ there exists a distribution D_F over $\{\bot, \mathsf{same}\}^n$ such that for all $\boldsymbol{x}$, it holds that*

$$\mathsf{SD}(\mathsf{Execute}_{\Pi,F}(\boldsymbol{x}), \mathsf{replace}(D_F, \Pi(\boldsymbol{x}))) \leq \epsilon.$$

Definition 10 (Interactive Non-Malleable Code). *A protocol encoding $\mathcal{E}$ is called a $(\delta, \epsilon)-$*interactive non-malleable code *for a family $\mathcal{F}$ of tampering functions and a class of protocols, if for any protocol Π of this class, $\mathcal{E}(\Pi)$ δ-correctly encodes Π and $\mathcal{E}(\Pi)$ is ϵ-protocol non-malleable for $\mathcal{F}$.*

3.3 Bounded State Tampering

We now define bounded state tampering functions for multi-party protocols. This is a natural model in which the adversary can *arbitrarily* and *jointly* tamper with *all* channels, however there exists an a priori upper bound on the size of the state they can hold. Similar classes of adversaries have already been considered starting with the work of Cachin and Maurer [CM97] which proposed encryption and key exchange protocols secure against computationally unbounded adversaries. With respect to non-malleable codes Faust et al. [FHMV17] introduced the notion of non-malleable codes against space-bounded tampering. Our formalization closely follows the one of Fleischhacker et al. [FGJ+19] but adapted to the multi-party case. This means that we do not limit the size of the memory available for computing the tampering function in each round of tampering. Instead, we only limit the size of the state that can be carried over to the next round of tampering. I.e., an adversary in this model can jointly tamper with all of the messages exchanged in one round of execution depending on some function of *all* previously exchanged messages. *But* the function can only depend on up to some fixed number of s bits of information about previous messages. This is formalized as follows.

Definition 11 (Bounded State Tampering Functions). *Functions of the class of s-bounded state tampering functions $F \in \mathcal{F}^s_{\mathsf{bounded}}$ for an interactive protocol are defined by a function*

$$f : \{0,1\}^s \cup \{\bot\} \times \mathcal{M}^{n\times n} \to \{0,1\}^s \times \mathcal{M}^{n\times n}$$

The function f takes as input a previous state of the tampering function and a matrix of sent messages and outputs an updated state and a matrix of received messages.

The full tampering function $F : \mathcal{T} \times \mathcal{M}^{n\times n} \to \mathcal{M}^{n\times n}$ is then defined in terms of f as

$$
\begin{array}{l}
\underline{F(\tau, \boldsymbol{S})} \\
\sigma := \bot \\
\textbf{for } (\boldsymbol{S'}, \boldsymbol{R'}) \textbf{ in } \tau \\
\quad (\sigma, \boldsymbol{R}) := f(\sigma, \boldsymbol{S'}) \\
(\sigma, \boldsymbol{R}) := f(\sigma, \boldsymbol{S}) \\
\textbf{return } \boldsymbol{R}
\end{array}
$$

4 An INMC for Bounded-State Tampering Functions

We devise an interactive non-malleable code for bounded state tampering functions that can be applied to any multi-party protocol Π' with *fixed message topology*, i.e., to any protocol where for every party P_i and every invocation r of the next message function π_i, whether or not a message is sent to party P_j is a priori known and does *not* depend on any of $\pi_i's$ inputs. The basic idea is that each pair of parties will first run a key-exchange in which they will exchange enough key-material to the execute the original protocol encrypted under an information theoretically secure encryption scheme and authenticated with a statistically unforgeable MAC. Besides making sure that the tampering function cannot replay, redirect or omit messages by binding the authentication to a specific channel and including message counters in the authentication, the main challenge is to construct a key exchange that is secure against a computationally unbounded but bounded state adversary. We achieve this using a 2-non-malleable extractor. Essentially each party chooses a key by choosing two random sources α, β which will be much longer than the bounded state of the tampering function and extracting a key $k := \mathsf{nmExt}(\alpha, \beta)$. They will be using this key which they *know* is untampered to *encrypt* messages and to *verify* authentication tags. The two sources α, β are then sent in seperate rounds, ensuring that they cannot be tampered jointly, except for some amount of leakage through the state of the tampering function and potentially conditional aborts. This leakage can be handled by reinterpreting the sources as coming from a different distribution with slightly less min-entropy. Once the keys are exchanged, the parties verify that the keys were not modified in transit by sending a MAC computed over the ID of the channel with the key they *received* from the other party.

4.1 Defining the Next Message Function

The INMC is restricted to protocols with a fixed message topology as defined in Definition 8. To formally describe the next message function and output function of the INMC, we need an algorithm that checks whether the sequence of messages received from the other parties involved in the protocol conform to the fixed message topology. The function $\mathsf{CheckMsgOrder}$ defined as follows allows to perform this check.

$\mathsf{CheckMsgOrder}(V)$

$\boldsymbol{r} = 0^n$
for $j \in [n] \setminus \{i\}$ **do**
  if $V_{|V|,j} \neq \bot$
    $r_j := 1$
if $\mu(i, |V| - 3)_1 \neq \boldsymbol{r}$
  return 0
return 1

Now that we have defined the $\mathsf{CheckMsgOrder}$ function we are ready to define the next message function in Figure 1. Remember, that according to Definition 5 an encoding is specified by an oracle machine or equivalently a next message function that is defined relative to an stateful oracle representing the next message function of the underlying protocol. The next message function $\pi_i^{\mathsf{O}_{i,\boldsymbol{x},\boldsymbol{\omega'}}}$ has three phases. In the initial phase every party shares their keys with the rest of the parties taking part in the protocol. In the next phase all of the parties confirms their respective keys with the other parties by sending a key confirmation value. The last phase of the execution of the next message function just deals with the actual message exchanges that happens between all the parties taking part in the protocol Π'.

The output function out_i of the INMC simply takes the view V' of the underlying protocol that it can extract from it's own view exactly as in the next message function and outputs $\mathsf{out}'_i(\boldsymbol{x}, \boldsymbol{\omega'}, V')$ if the view conforms to the fixed message topoly or $\bot$ otherwise.

Theorem 4. *Let Π' be a protocol between n parties with fixed message topology, with* $\max_{i,j\in[n]}\{\nu(i,j)\} = r$ *and message length ℓ. If* $(\mathsf{MAC}, \mathsf{Vf})$ *is a statistically ϵ_{mac}-unforgeable $r{+}1$-time message authentication code with*

$\pi_i^{\mathsf{O}'_{\boldsymbol{x},\boldsymbol{\omega}'}}(\boldsymbol{\omega}, V_i(\tau))$

```
s := ⊥^n
if |V| = 0
    rec := 0^n, sent := 0^n
    (α_i, β_i) ← (({0,1}^{κnm})^2)^n
    (k_i^{enc}, k_i^{auth}) := Ext(α_i, β_i)
    s := α_i
elseif |V| = 1
    if ⊥ ∈ V_1
        abort
    s := β_i
elseif |V| = 2
    if ⊥ ∈ V_2
        abort
    (k̃_j^{enc}, k̃_j^{auth}) := Ext(V_1, V_2)
    for j ∈ [n] \ {i} do
        s_j := MAC(k̃_{i,j}^{auth}, (i, j))
else
    if |V| = 3
        if ⊥ ∈ V_3
            abort
        for j ∈ [n] \ {i} do
            if Vf(k_i^{auth}, (j, i), V_{3,j}) = 0
                abort
    else
        m := ⊥^n
        if CheckMsgOrder(V) = 0
            abort
        else
            for j ∈ [n] \ {i} do
                if V_{|V|,j} ≠ ⊥
                    (c, t) := V_{|V|,j}, rec_j := rec_j + 1
                    if Vf(k_i^{auth}, (c, j, i, rec_j), t) = 0
                        abort
                    m_j := Dec(k̃_j^{enc}, c)
    s' ← O'_{x,ω'}(m)
    for j ∈ [n] \ {i} do
        if s'_j ≠ ⊥
            c := Enc(k̃_i^{enc}, s'_j), sent_j := sent_j + 1
            s_j := (c, MAC(k̃_j^{auth}, (c, i, j, sent_j)))
return s
```

Fig. 1. The next message function describing the INMC for bounded state tampering functions. For the sake of readability, we write the function as if it were stateful. I.e., in particular the variables rec and sent retain their value accross different invocations of π_i and do not need to be recomputed.

with message length $\ell+2\lceil\log n\rceil+\lceil\log r\rceil$ *and key length* κ_{mac}*,* $(\mathsf{Enc},\mathsf{Dec})$ *is a perfectly indistinguishable stateful* t*-time encryption scheme with message length* ℓ *and key length* κ_{enc}*, and* $\mathsf{nmExt}:\{0,1\}^{\kappa_{nm}}\times\{0,1\}^{\kappa_{nm}}\to\{0,1\}^{\kappa_{mac}+\kappa_{\mathsf{Enc}}}$ *is an* ϵ_{nm}*-non-malleable 2-source extractor for sources with min-entropy at least* $\kappa_{nm}-s-3n\lambda$*, then* Π *as described by* π_i *and* out_i *specified above is a* $(0,(2n^2+n)\cdot 2^{-\lambda}+(n^2-n)\cdot\epsilon_{nm}+\epsilon_{\mathsf{MAC}})$*-interactive non-malleable code for* Π' *for the class* $\mathcal{F}^s_{\mathit{bounded}}$ *of bounded state tampering functions.*

Proof. In order to prove that the protocol Π is a $(0,\epsilon)$-interactive non-malleable code we need to prove the *correctness* as well as *non-malleability* of the protocol as stated in Lemma 5 and Lemma 6.

Lemma 5. *For any protocol* Π'*,* Π *0-correctly encodes* Π'*.*

Proof. The extractor is deterministic and hence all the parties involved in the protocol will extract identical keys in an untampered execution. Since the MAC is correct, and tags are computed and verified with the correct keys, all messages will always verify and no party will abort during the protocol. As the correctness of the stateful encryption scheme Enc allows each party decrypt all received messages correctly all the parties will be able to faithfully execute a perfectly honest untampered execution of the underlying protocol Π. Therefore Π evaluates correctly whith the same probability as Π'. ◻

Lemma 6. *The interactive protocol* Π *is* ϵ*-protocol non-malleable, where* $\epsilon=(2n^2+n)\cdot 2^{-\lambda}+(n^2-n)\cdot\epsilon_{nm}+\epsilon_{\mathsf{MAC}}$*.*

Proof. In order to show that the coding scheme is non-malleable we need to provide a *distribution* D_F as defined in Definition 9. In order to achieve a sampler for the distribution D_F, we start with the output distribution of an honest execution of the actual protocol and modify it through a serie of hyrids, until we reach a distribution that can be sampled independently of $\boldsymbol{x}$. To define the different hybrid distributions, first define a function $\bar{V}_i$ which essentially gives us the equivalent of a party's current view in the protocol, but replaces all received messages, with the messages that were originally sent.

```
V̄(τ)
────────────────────────────
V := V_i(τ)
for j ∈ [n] do
    s := (S_{i,j} | (S,R) ∈ τ ∧ S_{i,j} ≠ ⊥)
    c := 1
    for q ∈ [|V|] do
        if V_{q,j} ≠ ⊥
            V_{q,j} := t_{j,c}
            c = c + 1
return V
```

Now, let $F\in\mathcal{F}^s_{\mathsf{bounded}}$ be an arbitrary tampering function. For $i,j\in[n]$ and $o\in\{\alpha,\beta\}$, let $\zeta_{\alpha,i,j}$ be the probability that the tampering function modifies or drops $o_{i,j}$ during an execution of the protocol. We define the modified tampering function F' which behaves exactly like F, but for any (i,j,o) such that $\zeta_{\alpha,i,j}<2^{-\lambda}$ it always keeps $o_{i,j}$ unmodified. We then further define for $i\in[n]$ and $r\in\{1,2,3\}$, $\gamma_{i,r}$ to be the probability that in an execution tampered by F', π_i aborts in execution round r, i.e., after receiving the αs, after receiving the βs, or after receiving the key confirmation values. Finally, let $\boldsymbol{x}'\in X_1\times\cdots\times X_n$ be arbitrary but fixed. We then define several variants of $\mathsf{Execute},\mathsf{Next}$, and π_i in Figure 2 and Figure 3 respectively and are then finally ready to specify a series of hybrid distribution we construct to reach the distribution that corresponds to $\mathsf{replace}(D_F,\Pi(\boldsymbol{x}))$.

- H_0 : Hybrid 0 is the original output distribution of a tampered execution. I.e, $H_0=\mathsf{Execute}_{\Pi,F}(\boldsymbol{x})$.
- H_1 : Hybrid 1 is still the distribution of a tampered execution, however we replace the tampering function with the modified tampering function F'. I.e., $H_1=\mathsf{Execute}_{\Pi,F'}(\boldsymbol{x})$.

$\mathsf{Execute}^{\chi}_{\Pi,F}(\boldsymbol{x};\boldsymbol{\omega})$

$\tau \coloneqq \emptyset$
$\boldsymbol{S} \coloneqq \mathsf{Next}^1(\Pi, \boldsymbol{x}, \boldsymbol{\omega}, \tau)$ // $\chi = 1$
$\boldsymbol{R} \coloneqq F(\tau, \boldsymbol{S})$
while $\boldsymbol{R} \neq \bot^{n \times n}$
  $\tau \coloneqq \tau \circ (\boldsymbol{S}, \boldsymbol{R})$
  $\boldsymbol{S} \coloneqq \mathsf{Next}^1(\Pi, \boldsymbol{x}, \boldsymbol{\omega}, \tau)$ // $\chi = 1$
  $\boldsymbol{R} \coloneqq F(\tau, \boldsymbol{S})$
return $\big(\mathsf{out}_1(x_1, V_1(\tau)), \cdots, \mathsf{out}_n(x_n, V_n(\tau))\big)$ // $\chi = 1$
return $\big(\mathsf{indicate}(\mathsf{out}_1(x_1, V_1(\tau))), \cdots, \mathsf{indicate}(\mathsf{out}_n(x_n, V_n(\tau)))\big)$ // $\chi = 2$

$\mathsf{Next}^1_{\Pi}(\boldsymbol{x}, \boldsymbol{\omega}, \tau)$

parse $\tau = ((\boldsymbol{S_1}, \boldsymbol{R_1}), \ldots, (\boldsymbol{S_\ell}, \boldsymbol{R_\ell}))$
for $1 \leq i \leq n$ **do**
  if $\tau = \emptyset \ \vee\ \mathbf{col}_i(\boldsymbol{R_\ell})^\top \neq \bot^n$
    $\boldsymbol{s_i} \coloneqq \pi^l_i(x_i, \omega_i, V_i(\tau), \bar{V}_i(\tau))$
  else
    $\boldsymbol{s_i} \coloneqq \bot^n$
return $\begin{bmatrix} \boldsymbol{s_1} \\ \vdots \\ \boldsymbol{s_n} \end{bmatrix}^\top$

Fig. 2. Variants of Execute and Next as used in the hybrid distributions. Differences from the original are highlighted in gray. Different variants are specified by comments.

H_2 : In hybrid 2, we switch to using the modified execution algorithm $\mathsf{Execute}^1$ and Π^1. This change gives the next message function access to the message it *should* have received, i.e., those that were originally sent. I.e., $H_2\mathsf{Execute}^1_{\Pi^1,F'}(\boldsymbol{x})$.

H_3 : In hybrid 3 we switch to using Π^2, which means that parties that abort with overwhelming probability during the key exchange or key confirmation phase, now abort with probability 1. I.e., $H_3 = \mathsf{Execute}^1_{\Pi^2,F'}(\boldsymbol{x})$.

H_4 : In hybrid 4, we switch to using Π^3 which means that the keys are now no longer extracted but instead sampled uniformly at random on the sender's side and according to D_f on the receiver's side, where f is a split state tampering function induced by F'. I.e., $H_4 = \mathsf{Execute}^1_{\Pi^3,F'}(\boldsymbol{x})$.

H_5 : Hybrid 5 switches to using Π^4, which means that instead of verifying MACs the next message functions now directly check if messages were modified or not. I.e., $H_5 = \mathsf{Execute}^1_{\Pi^4,F'}(\boldsymbol{x})$.

H_6 : In hybrid 6 we switch to $\mathsf{Execute}^2$. This means that the execution no longer outputs the actual outputs of the parties. Instead it only indicates which parties produced an output and which aborted. The outputs of all non-aborting parties are then replaced by the outputs of an honest untampered execution of $\Pi(\boldsymbol{x})$. I.e., $H_6 = \mathsf{replace}(\mathsf{Execute}^2_{\Pi^4,F'}(\boldsymbol{x}), \Pi(\boldsymbol{x}))$.

H_7 : Finally in hybrid 7, we replace the input $\boldsymbol{x}$ of the tampered execution with the arbitrary fixed input $\boldsymbol{x'}$. I.e., $H_7 = \mathsf{replace}(\mathsf{Execute}^2_{\Pi^4,F'}(\boldsymbol{x'}), \Pi(\boldsymbol{x}))$.

We note, that in H_7, the distribution of $\mathsf{Execute}^2_{\Pi^4,F'}(\boldsymbol{x'})$ no longer depends on $\boldsymbol{x}$. I.e., we define D_F as $\mathsf{Execute}^2_{\Pi^4,F'}(\boldsymbol{x'})$ and it is then sufficient to bound that $\mathsf{SD}(H_0, H_7)$ to prove the Lemma. We do so by bounding the statistical distance of each pair of neighboring hybrids.

Claim 7. $\mathsf{SD}(H_0, H_1) \leq 2(n^2 - n) \cdot 2^{-\lambda}$.

$\pi_i^{d,\mathsf{O}'_{\boldsymbol{x},\boldsymbol{\omega}'}}(\boldsymbol{\omega}, V_i(\tau))$

$\boldsymbol{s} := \bot^n$
if $|V| = 0$
$\mathsf{rec} := 0^n, \mathsf{sent} := 0^n$
$(\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i) \leftarrow ((\{0,1\}^{\kappa_{nm}})^2)^n$
$(\boldsymbol{k}_i^{enc}, \boldsymbol{k}_i^{auth}) := \mathsf{Ext}(\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i)$ // $d < 3$
$(\boldsymbol{k}_i^{enc}, \boldsymbol{k}_i^{auth}) \leftarrow \{0,1\}^{\kappa_{enc}+\kappa_{mac}}$ // $d \geq 3$
$\boldsymbol{s} := \boldsymbol{\alpha}_i$
elseif $|V| = 1$
if $\bot \in V_1$ // $d < 2$
if $\bot \in V_1$ **or** $\gamma_{i,1} > 1 - 2^{-\lambda}$ // $d \geq 2$
abort
$\boldsymbol{s} := \boldsymbol{\beta}_i$
elseif $|V| = 2$
if $\bot \in V_2$ // $d < 2$
if $\bot \in V_2$ **or** $\gamma_{i,2} > 1 - 2^{-\lambda}$ // $d \geq 2$
abort
$(\tilde{\boldsymbol{k}}_j^{enc}, \tilde{\boldsymbol{k}}_j^{auth}) := \mathsf{Ext}(V_1, V_2)$ // $d < 3$
$(\tilde{\boldsymbol{k}}_j^{enc}, \tilde{\boldsymbol{k}}_j^{auth}) := \mathsf{replace}(D_f, (\boldsymbol{k}_j^{enc}, \boldsymbol{k}_j^{auth}))$ // $d \geq 3$
for $j \in [n] \setminus \{i\}$ **do**
$s_j := \mathsf{MAC}(\tilde{k}_{i,j}^{auth}, (i,j))$
else
if $|V| = 3$
if $\bot \in V_3$ // $d < 2$
if $\bot \in V_3$ **or** $\gamma_{i,3} > 1 - 2^{-\lambda}$ // $d \geq 2$
abort
for $j \in [n] \setminus \{i\}$ **do**
if $\mathsf{Vf}(k_i^{auth}, (j,i), V_{3,j}) = 0$ // $d < 4$
if $(\tilde{k}_i \neq k_i)$ **or** $\bar{V}_{3,j} \neq V_{3,j}$ // $d \geq 4$
abort
else
$\boldsymbol{m} := \bot^n$
if $(\mathsf{CheckMsgOrder} = 0)$
abort
else
for $j \in [n] \setminus \{i\}$ **do**
if $V_{|V|,j} \neq \bot$
$(c,t) := V_{|V|,j}, \mathsf{rec}_j := \mathsf{rec}_j + 1$
if $\mathsf{Vf}(k_i^{auth}, (c, j, i, \mathsf{rec}_j), t) = 0$ // $d < 4$
if $\bar{V}_{|V|,j} \neq V_{|V|,j}$ // $d \geq 4$
abort
$m_j := \mathsf{Dec}(\tilde{k}_j^{enc}, c)$
$\boldsymbol{s}' \leftarrow \mathsf{O}'_{\boldsymbol{x},\boldsymbol{\omega}'}(\boldsymbol{m})$
for $j \in [n] \setminus \{i\}$ **do**
if $s'_j \neq \bot$
$c := \mathsf{Enc}(\tilde{k}_i^{enc}, s'_j), \mathsf{sent}_j := \mathsf{sent}_j + 1$
$s_j := (c, \mathsf{MAC}(\tilde{k}_j^{auth}, (c, i, j, \mathsf{sent}_j)))$
return $\boldsymbol{s}$

Fig. 3. The modified next message function used in the hybrid distributions. Differences from the original are highlighted in gray. Different variants are specified by comments.

Proof. In H_1 we replaced F with the modified tampering function F'. This function is modified such that a series of low probability events (that $o_{i,j}$ for $o \in \{\alpha, \beta\}$ and $i, j \in [n]$ is modified by F) does not happen. Each event happens with probability less than $2^{-\lambda}$. The number of events is bounded by two times the number of edges in the communication graph. This is a directed complete graph, i.e., the number of edges is $n^2 - n$. Hence, by a union bound over all events, the statistical distance between hybrids H_0 and H_1 can be bounded by $2(n^2 - n) \cdot 2^{-\lambda}$. □

Claim 8. $\mathsf{SD}(H_2, H_2) = 0$

Proof. In hybrids H_1, H_2, it is easy to see that the only differences between the hybrids are syntactic. I.e., the next message function receives the additional input $\bar{V}_i(\tau)$ in H_2, but does not actually use it yet. Therefore the output distributions remain identical. □

Claim 9. $\mathsf{SD}(H_2, H_3) \leq 3n \cdot 2^{-\lambda}$

Proof. In hybrid H_3 we eliminate another series of low probability events. If F' causes any of the parties to abort with overwhelming probability $> (1 - 2^{-\lambda})$ in the first three rounds of the protocol, i.e., during key-exchange or key-confirmation, the party now aborts at the same point in time with probability 1. I.e., each eliminated event, i.e. the "non-abort", happens with probability less than $2^{-\lambda}$. The number of eliminated events is bounded by three times the number of parties in the protocol. Therefore a union bound over all eliminated events gives us that the statistical distance between H_2 and H_3 can be bounded by $3n \cdot 2^{-\lambda}$. □

Claim 10. $\mathsf{SD}(H_3, H_4) \leq (n^2 - n) \cdot \epsilon_{nm}$.

Proof. For any i, j, let $f_{i,j}$ be the tampering function for $\alpha_{i,j}, \beta_{i,j}$ induced by F. We observe that the changes that were made in H_4 are that rather than using the extracted keys the sender uses uniformly chosen keys while the receiver either receives keys that are distributed according to $D_{f_{i,j}}$ that is *independent* of the actual key, or it receives the same uniformly distributed key used by the sender.

Now, *if* $f_{i,j}$ were split state, then the non-malleability of the extractor would imply that the statistical distance caused by each replaced key can be at most ϵ_{nm}. The main issue is that $f_{i,j}$ is in fact *not* split state. The tampering function can use both, its bounded state as well as conditional aborts (and non-aborts) of the individual parties to leak information from the first part of the tampering function to the second part and from both parts to the rest of the protocol. However, if we can *bound* the amount of information that can be leaked, then we can change our perspective and look at $f_{i,j}$ as a split state tampering functions, that tampers with sources sampled from a distribution defined by sampling almost uniformly, but conditioned on the leakage.

It remains to actually bound the leakage. Clearly a tampering function in $\mathcal{F}^s_{\mathsf{bounded}}$ can leak s bits simply through its persistent state. Additional leakage is obtained by causing any of the parties to abort or not to abort with low probability. However, due to the elination of low probability events in previous hybrids, we know that each of these events happens with probability at *least* $2^{-\lambda}$. Per party there exist three abort/non-abort events, i.e. the tampering function can leak at most $3n \log \frac{1}{2^{-\lambda}} = 3n\lambda$ additional bits of information.

We can thus reinterpret $f_{i,j}$ as a split-state tampering function on sources with min-entropy $\kappa_{nm} - s - 3n\lambda$. Since, nmExt is specified as working with sources of this type, we have that each replaced key increases the statistical distance by at most ϵ_{nm}. As there are, as mentioned before, $(n^2 - n)$ keys to deal with, we can bound the total statistical distance between the hybrids H_1 and H_2 with $(n^2 - n) \cdot \epsilon_{nm}$. □

Claim 11. $\mathsf{SD}(H_4, H_5) \leq \epsilon_{\mathsf{MAC}}$

Proof. Here we bound the statistical distance between the hybrids using a reduction from the statistical unforgeability of the MAC. The output distribution of the two hybrids only differs, if at any point one of the parties receives a ciphertext and tag pair (c, t) such that for some (i, j, r), $\mathsf{Vf}(k^{auth}_{i,j}, (c, i, j, r), t) = 1$ but where none of the parties ever computed $\mathsf{MAC}(k^{auth}_{i,j}, (c, i, j, r))$. That means that the statistical distance between the hybrids is equal to the probability that the above event occurs. We can then construct an attacker $\mathcal{A}$ against the MAC scheme as follows: $\mathcal{A}$ executes H_4 as specified, except that it ignores the actual authentication keys and instead uses the MAC oracle to compute all tags. When the event specified above occurs, $\mathcal{A}$ outputs $(c, i, j, r), t, i$. If the event never occurs, $\mathcal{A}$ aborts. Clearly $\mathcal{A}$ forges a MAC with probability $\mathsf{SD}(H_4, H_5)$. Since the MAC is ϵ_{mac}-statistically unforgeable, we therefore have $\mathsf{SD}(H_4, H_5) \leq \epsilon_{\mathsf{MAC}}$ as claimed. □

Claim 12. $\mathsf{SD}(H_5, H_6) = 0$.

Proof. Due to the changes in the previous hybrids, we know that all messages received by any party that does not abort are exactly those messages that were originally sent. Further, whenever a party aborts it does not send any more messages, ensuring that all messages that *are* sent are computed solely based on untampered messages. Additionally, since the protocol has a fixed message topology and both the next message function as well as the output function check that the view conforms to this topolgy, we know that any party that does not abort computed their output based on a complete view consisting of honestly computed messages that were received in the correct order. I.e., in H_5 the outputs of the *non-aborting* parties are distributed according to the same distribution as in a completely untampered execution of Π on $\boldsymbol{x}$. In H_6, $\mathsf{Execute}^2_{\Pi^4,F}(\boldsymbol{x})$ returns $\perp$ for all aborting parties and same for all non-aborting parties. The function $\mathsf{indicate}$ then replaces the same entries with consistent outputs of an honest execution of $\Pi(\boldsymbol{x})$. Therefore the two distributions are identical. □

Claim 13. $\mathsf{SD}(H_6, H_7) = 0$.

Proof. Since the message topology is fixed in both the hybrids, the "shape" of the transcripts of the underyling protocol during the execution in both the hybrids are identical, only the *content* of the messages might differ based on the inputs $\boldsymbol{x}$ and $\boldsymbol{x}'$. However, due to the perfect indistingishability of the stateful encryption scheme, the distribution of the *ciphertexts* is identical. Therefore the distributions of the overall transcripts observed by the tampering function are identical and therefore, so are the output distributions. □

Using the triangle inequality over the bounds from Claim 7 through Claim 13 we can thus conclude that

$$
\begin{aligned}
&\mathsf{SD}(\mathsf{Execute}_{\Pi,F}(\boldsymbol{x}), \mathsf{replace}(D_F, \Pi(\boldsymbol{x}))) \\
=&\mathsf{SD}(\mathsf{Execute}_{\Pi,F}(\boldsymbol{x}), \mathsf{replace}(\mathsf{Execute}^2_{\Pi^4,F}(\boldsymbol{x}'), \Pi(\boldsymbol{x}))) \\
=&\mathsf{SD}(H_0, H_7) \\
\leq&\sum_{i=1}^{7} \mathsf{SD}(H_{i-1}, H_i) \\
=&(2(n^2 - n) \cdot 2^{-\lambda}) + (3n \cdot 2^{-\lambda}) + ((n^2 - n) \cdot \epsilon_{nm}) + \epsilon_{\mathsf{MAC}} \\
=&(2n^2 + n) \cdot 2^{-\lambda} + (n^2 - n) \cdot \epsilon_{nm} + \epsilon_{\mathsf{MAC}}
\end{aligned}
$$

as claimed. □

The theorem finally follows immediately from Lemma 5 and Lemma 6. □

5 Acknowledgements

Nils Fleischhacker and Suparno Ghoshal were supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2092 CASA - 390781972.

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