

Better Secret-Sharing via Robust Conditional Disclosure of Secrets

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Abstract

A secret-sharing scheme allows to distribute a secret s among n parties such that only some pre-defined “authorized” sets of parties can reconstruct the secret, and all other “unauthorized” sets learn nothing about s . For over 30 years, it was known that any (monotone) collection of authorized sets can be realized by a secret-sharing scheme whose shares are of size $2^{n-o(n)}$ and until recently no better scheme was known. In a recent breakthrough, Liu and Vaikuntanathan (STOC 2018) have reduced the share size to $2^{0.994n+o(n)}$, which was later improved to $2^{0.892n+o(n)}$ by Applebaum et al. (EUROCRYPT 2019).

In this paper we improve the exponent of general secret-sharing schemes down to 0.637. For the special case of linear secret-sharing schemes, we get an exponent of 0.762 (compared to 0.942 of Applebaum et al.). As our main building block, we introduce a new *robust* variant of conditional disclosure of secrets (robust CDS) that achieves unconditional security even under bounded form of re-usability. We show that the problem of general secret-sharing schemes reduces to robust CDS protocols with sub-exponential overhead and derive our main result by implementing robust CDS with a non-trivial exponent. The latter construction follows by presenting a general immunization procedure that turns standard CDS into a robust CDS.

Key words. Secret-sharing schemes, Conditional disclosure of secrets, Robust conditional disclosure of secrets.

1 Introduction

Secret-sharing schemes, introduced by Shamir [49] and Blakley [16], are a central cryptographic tool with a wide range of applications including secure multiparty computation protocols [13, 18], threshold cryptography [23], access control [44], attribute-based encryption [32, 52], and oblivious transfer [50, 51]. In its general form [35], an n -party secret-sharing scheme for a family of authorized sets $F \subseteq 2^{[n]}$ (referred to as *access structure*) allows to distribute a secret s into n shares, s_1, \dots, s_n , one for each party, such that: (1)

every authorized set of parties, $A \in F$, can reconstruct s from its shares; and (2) every unauthorized set of parties, $A \notin F$, cannot reveal any partial information on the secret even if the parties are computationally unbounded. For example, in the canonical case of threshold secret sharing the family F contains all the sets whose cardinality exceeds some certain threshold. For this case, Shamir’s scheme [49] provides a solution whose complexity, measured as the total share-size $\sum_i |s_i|$, is quasi-linear, $O(n \log n)$, in the number of parties n . Moreover, Shamir’s scheme is *linear*, that is, each share can be written as a linear combination of the secret and the randomness that are taken from a finite field. This form of linearity turns to be useful for many applications. (See Section 3 for a formal definition of secret sharing and linear secret sharing.)

The complexity of general secret-sharing schemes. Determining the complexity of general access structures is a basic, well-known, open problem in information-theoretic cryptography. Formally, given a (monotone) access structure¹ F we let $SS(F) := \min_{\mathcal{D} \text{ realizes } F} |\mathcal{D}|$, where $|\mathcal{D}|$ denotes the total share size of a secret-sharing scheme \mathcal{D} .² For over 30 years, since the pioneering work of Ito et al. [35], all known upper-bounds on $SS(F)$ are tightly related to the computational complexity of the characteristic function F . Here we think of F as the monotone function that given a vector $x \in \{0, 1\}^n$ outputs 1 if and only if the corresponding characteristic set $A = \{i : x_i = 1\}$ is an authorized set. Specifically, it is known that the complexity of an access structure is at most polynomial in the representation size of F as a monotone CNF or DNF [35], as a monotone formula [14], as a monotone span program [38], or as a multi-target monotone span program [15]. This leads to an exponential upper-bound of $2^{n(1-o(1))}$ for any n -party access structure F .

On the other hand, despite much efforts, the best known lower-bound on the complexity of an n -party access structure is $\Omega(n^2/\log n)$ due to [22]. Moreover, we have no better lower-bounds even for *non-explicit* functions!³ This leaves a huge exponential gap between the upper-bound and the lower-bound. For the case of linear schemes, a counting argument (see, e.g., [9]) shows that for most monotone functions $F : \{0, 1\}^n \rightarrow \{0, 1\}$, the complexity of the best linear secret-sharing scheme, denoted by $LSS(F)$, is at least $2^{n/2-o(n)}$.⁴ Furthermore, Pitassi and Robere [47] (building on results of [48, 46]) prove that for every n there exist an explicit n -input function F such that $LSS(F) = 2^{\Omega(n)}$. In his 1996 thesis [6], Beimel conjectured that an exponential lower-bound of $2^{\Omega(n)}$ also holds for the general case. Resolving this conjecture has remained one of the main open problems in the field of secret sharing [7]. Taking a broader view, similar exponential communication-complexity gaps exist for a large family of information-theoretic secure computation tasks [26, 34, 5, 30, 11]. Among these, secret-sharing is of special interest due to its elementary nature: Secret data is only *stored and revealed* without being processed or manipulated.

The LV construction. In a recent breakthrough, Liu and Vaikuntanathan [39] (hereafter referred to as LV) showed, for the first time, that it is possible to construct secret-sharing schemes in which the total share size

¹Monotonicity here means that for any $A \subset B$ it holds that $A \in F \Rightarrow B \in F$. It is not hard to see that a non-monotone access structure does not admit a secret-sharing scheme, and therefore this requirement is necessary.

²This complexity measure essentially ignores the bit-length of the secret. The alternative *information-ratio* measure normalizes the bit length of the longest share by the length of the secret, and is therefore more suitable to the case of long secrets. Indeed, recent results [2] suggest that the ratio achievable for (very) long secrets may be significantly better than the ratio achievable for short secrets.

³In contrast, in the computational complexity setting, counting-based methods lead to exponential lower-bounds on the complexity of most monotone functions over n -bits for various computational models including the ones mentioned above. These bounds can be shown to be tight for a random (monotone) function; see, e.g., [37].

⁴The bound holds for any finite field. From now on when the field is unspecified we take it, by default, to be the binary field. This only makes our positive results stronger.

is $2^{cn+o(n)}$ with an exponent c strictly smaller than 1. In particular, they showed that every access structure can be realized by a linear scheme of complexity $2^{0.999n+o(n)}$, and by a non-linear scheme of complexity $2^{0.994n+o(n)}$. In a nutshell, for a balancing parameter $\delta > 0$, the LV construction decomposes an access structure F into three access structures: (1) The “middle slice” $F_{\text{mid},\delta}$ that agrees with F on all sets whose density is in $(0.5 - \delta, 0.5 + \delta)$ and assigns zero to sets of smaller density and one to sets of larger density; and (2) Two other “extreme slices”, $F_{\text{bot},\delta}$ and $F_{\text{top},\delta}$, that essentially agree with F on bottom inputs of density smaller than $0.5 - \delta$ and on top inputs of density larger than $0.5 + \delta$ (a more accurate definition appears in [39]). The extreme slices can be realized by a secret-sharing scheme with exponent smaller than 1 since they admit a monotone formula (or even a monotone CNF/DNF) of this size. Thus, the main effort in [39] is devoted to realizing $F_{\text{mid},\delta}$ with a non-trivial, smaller-than-one, exponent. Towards this end, LV show that the function $F_{\text{mid},\delta}$ can be computed by an exponential-size constant-depth formula with a non-trivial exponent of $M_{\text{LV}}(\delta) < 1$ that employs standard AND/OR-gates together with a special form of *block-regular* gates. Roughly speaking, in such a gate, $G : \{0, 1\}^n \rightarrow \{0, 1\}$, the n -bit input is partitioned into equal-sized blocks of size B each, and the main feature is that G is defined only on inputs $x \in \{0, 1\}^n$ that hit exactly b of the indices in each block for some integer parameter b . Equivalently, the parties are partitioned into B -size committees and we can determine whether a set A is authorized or not for every set A that consists of exactly b members out of each committee.

Example 1.1. Assume that $n = 8, B = 4, b = 2$, and consider the partition to the first 4 coordinates and last 4 coordinates. The gate G is defined on all 8-bit strings for which both the left half and the right half consist of exactly 2 ones, and so G is defined over exactly $\binom{4}{2}^2$ inputs. E.g., G should be defined on the input 10100110, and is not defined on the input 11100001.

LV then show how to implement block-regular gates with sub-exponential complexity of $2^{o(n)}$ based on recent sub-exponential constructions of *Conditional Disclosure of Secrets* (CDS) protocols from [41]. (We postpone the description of CDS protocols to a later point.) Taken together, this allows to realize $F_{\text{mid},\delta}$ with complexity of $2^{M_{\text{LV}}(\delta)n}$. The final result is obtained by choosing a parameter δ that balances the cost of $F_{\text{mid},\delta}$ with the cost of $F_{\text{bot},\delta}$ and $F_{\text{top},\delta}$.

In a follow-up work, Applebaum et al. [3] improved the LV bound to $2^{0.942n+o(n)}$ in the linear case, and to $2^{0.892n+o(n)}$ in the non-linear case. This was done by reducing the problem of realizing the extreme slices $F_{\text{bot},\delta}$ and $F_{\text{top},\delta}$ to realizing (many) general secret-sharing problems over a smaller domain, leading to a recursive construction. However, the complexity of mid-slice access structures has remained unchanged.

2 Our Contribution

In light of the exponential gap between the lower bounds and the upper-bounds, we believe that it is both important and useful to study the best-achievable *exponent* of secret-sharing schemes. Formally, we define the *secret-sharing exponent* \mathbf{S} to be $\mathbf{S} = \limsup_{n \rightarrow \infty} \max_{F \in \mathcal{M}(n)} \frac{1}{n} \log \text{SS}(F)$, where $\mathcal{M}(n)$ is the family of all n -party access structures (equivalently, all monotone functions over $\{0, 1\}^n$). The *linear exponent*, \mathbf{S}_ℓ , is defined analogously except that $\text{SS}(F)$ is replaced with $\text{LSS}(F)$, the minimal complexity of a linear scheme that realizes F . Under this definition, it holds that $0.5 \leq \mathbf{S}_\ell \leq 0.942$ and $0 \leq \mathbf{S} \leq 0.892$. The existence of sub-exponential secret-sharing schemes would imply that $\mathbf{S} = 0$, whereas Beimel’s conjecture asserts that \mathbf{S} is strictly positive.

In this work, we improve the upper-bounds on \mathbf{S} and \mathbf{S}_ℓ , and, more qualitatively, provide new directions that may eventually lead to sub-exponential solutions. Along the way, we introduce a new notion of *robust* conditional disclosure of secrets, which may be of independent interest. We proceed with a detailed account of our results.

2.1 Better Secret-Sharing Schemes

We significantly improve the secret-sharing exponent both for the linear and non-linear case.

Theorem 2.1 (Main Theorem). *Every access structure over n parties can be realized by a secret-sharing scheme with a total share-size of $2^{0.637n+o(n)}$ and by a linear secret-sharing scheme with a total share size of $2^{0.762n+o(n)}$, that is, $\mathbf{S} \leq 0.637$ and $\mathbf{S}_\ell \leq 0.762$.*

The proof of Theorem 2.1 is based on a new secret-sharing schemes for mid-slice access structures. Recall that a mid-slice access structure with parameter δ is a monotone function $F_{\text{mid},\delta} : \{0, 1\}^n \rightarrow \{0, 1\}$ that takes the value zero on all inputs of Hamming weight smaller than $(0.5 - \delta)n$, takes the value one on all inputs of Hamming weight larger than $0.5 + \delta$, and may take arbitrary values in-between. As already mentioned, LV showed that such functions can be implemented by a formula over OR/AND gates and block-regular gates of exponential size $2^{\text{MLV}(\delta)n}$. We begin by showing that if one considers a more powerful basis that consists of *somewhat-regular* gates (together with general threshold gates), then this can be done by a linear-size formula with only $O(n)$ gates.

A somewhat-regular gate $G : \{0, 1\}^n \rightarrow \{0, 1\}$ is parameterized by a pair of integers, (a, b) , a block-size parameter B where $a \leq b \leq B$, and a partition Π of $[n]$ to B -size blocks. An input $x \in \{0, 1\}^n$ is parsed to B -size sub-strings $(x_1, \dots, x_{n/B})$ according to Π , and the gate can be arbitrarily programmed on inputs that each of their components x_i has Hamming weight between a and b . Such an input is referred to as (Π, a, b) -regular. (Under the committee-based terminology, in each committee the set x has between a and b members.) We *do not care* what value G takes over all other inputs.⁵

Example 2.2. Assume that $n = 8, B = 4, a = 1, b = 2$, and consider the partition to the first 4 coordinates and last 4 coordinates. The gate G is defined on all 8-bit strings for which both the left half and the right half consist 1 or 2 ones, and so G is defined over $\binom{4}{1} + \binom{4}{2}$ inputs. E.g., G is defined on the inputs 10100110 and 10100001, and is not defined on the input 11100001.

From somewhat-regular gates to mid-slice functions. We can realize any mid-slice access function $F_{\text{mid},\delta}$ by a formula that makes use of $\lambda = O(n)$ somewhat-regular gates with parameters $B = \sqrt{n}$, $a \approx (0.5 - \delta)B$ and $b \approx (0.5 + \delta)B$. Roughly speaking, we show (via the probabilistic method) that one can choose $\lambda = O(n)$ B -partitions $\Pi_1, \dots, \Pi_\lambda$ of $[n]$ such that any input $x \in \{0, 1\}^n$ of Hamming weight $\text{wt}(x) \in [(0.5 \pm \delta)n]$ is (Π_i, a, b) -regular (that is, each committee contains between a and b parties from x) with respect to a majority of the Π_i 's. In contrast, LV used regular partitions and they needed exponentially many partitions to guarantee that an input x has exactly b ones in each part of the partition.

By programming the i -th gate G_i according to the restriction of $F_{\text{mid},\delta}$ to the (Π_i, a, b) -regular inputs, we can realize $F_{\text{mid},\delta}$ by computing majority over all the somewhat-regular gates. (One still has to make sure that the formula works well for light/heavy inputs x of Hamming weight $\text{wt}(x) \notin [(0.5 \pm \delta)n]$, however, this can be achieved easily with few additional threshold gates.) Using standard secret-sharing techniques, the resulting formula allows us to efficiently reduce the problem of realizing a general mid-slice access structure $F_{\text{mid},\delta}$ to the problem of realizing somewhat-regular access structures with parameters $B = \sqrt{n}$, $a \approx (0.5 - \delta)B$ and $b \approx (0.5 + \delta)B$. Our next goal is therefore to realize somewhat-regular access structures. For this, we will have to present a new notion of robust conditional disclosure of secrets.

⁵Technically, this means that the corresponding access structure is viewed as a *partial* (or *promise*) access structure. Interestingly, it turns out that the freedom to work with partially-defined specifications as components (without enforcing a full specification on each such sub-component) significantly simplifies the overall construction.

2.2 Robust Conditional Disclosure of Secrets

Conditional Disclosure of Secrets (CDS) protocols were introduced by Gartner et al. [29] in the context of private information retrieval, and since then were used in many cryptographic applications, such as attribute based encryption [28, 4, 53], priced oblivious transfer [1], and, as already mentioned, secret-sharing schemes [39, 12, 3]. In a CDS protocol, there are k servers⁶ and a referee; each server i holds a private input $x_i \in X_i$, a common secret s , and a common random string r . The referee holds all private inputs (x_1, \dots, x_k) but, prior to the protocol, it does not know neither the secret nor the random string. The goal of the protocol is to let the referee learn the secret if and only if the inputs of the servers satisfy some pre-defined condition $f : X^k \rightarrow \{0, 1\}$. The challenge is that the communication model is minimal – each server sends one message to the referee, without seeing neither the inputs of the other servers nor their messages.

Example 2.3 (CDS for equality). One can define a 2-server CDS protocol for the equality function $\text{EQ} : X \times X \rightarrow \{0, 1\}$ (where $\text{EQ}(x, y) = 1$ if and only if $x = y$) as follows. The common randomness consists of an hash function $h : X \rightarrow \{0, 1\}$ that is sampled from a pair-wise independent hash function family, the first server sends the message $h(x_1)$ and the second server sends the message $h(x_2) \oplus s$. The second message “perfectly-encrypts” the secret under the “key” $h(x_2)$, and the first message releases the key if $x_1 = x_2$ and otherwise consists of a random independent element.

It is shown in [39] that secret-sharing schemes for general regular gates with block-size of B can be efficiently realized based on CDS protocols for $k = (n/B)$ servers for general functions over the domain $\{0, 1\}^B \times \dots \times \{0, 1\}^B$. Loosely speaking, any set of secret-sharing parties $x = (x_1, \dots, x_k) \in (\{0, 1\}^B)^k$ gets to learn, for every server $i \in [k]$, the CDS message that the i -th server computes over the input x_i (see Section 5.1 for full details). While this leads to an efficient implementation of regular secret-sharing schemes based on the recent CDS constructions of [40], the transformation fails to produce the more powerful form of somewhat-regular secret-sharing schemes. The problem is that a somewhat-regular set of secret-sharing parties $x = (x_1, \dots, x_k) \in (\{0, 1\}^B)^k$ gets to learn the CDS messages that correspond to all inputs $x' \leq x$ where \leq stands for the standard partial order over binary strings. Furthermore, all these CDS messages are computed with the same randomness. In such a case, the privacy guarantees of the CDS are completely lost, even if none of the inputs satisfy the CDS function f .

To get a better understanding of the problem, let us consider, for example, the CDS for equality from Example 2.3. Suppose that the first server releases the CDS messages that correspond to two inputs, x_1 and x'_1 , that are both unequal to the second server’s input x_2 . Assuming that h is implemented via a random affine function, the CDS privacy completely breaks. Given the values of $h(x_1)$ and $h(x'_1)$ together with x_1 and x'_1 (which are known to the referee), the referee can fully recover the description of h , evaluate it over x_2 (which is also public), and recover the secret s from $h(x_2) \oplus s$.

We remedy the situation by showing that if one starts with a stronger form of CDS protocols, then the LV transformation does lead to somewhat-regular secret-sharing schemes. Specifically, we introduce the following new notion of *robust* CDS (RCDS) that may be of independent interest.

Robust conditional disclosure of secrets. We say that a CDS protocol is robust if it provides information-theoretic privacy even if it is invoked on a bounded number of multiple inputs using the same randomness. The general notion of robustness is parameterized by the input sets over which the protocol may be re-used. For now, let us consider the special case where each server i may re-use the randomness over any set of t different inputs. Since this may happen simultaneously for all servers, the randomness may be re-used over a

⁶ We use the term servers for the participants in a CDS protocol to distinguish them from the parties in a secret-sharing scheme.

set of t^k inputs. We present a general transformation that takes any CDS protocol, and “immunizes” a single server. By applying the construction to each server separately, we derive t -robustness with an overhead of roughly $(\tilde{O}(t \log u))^k$, where u is the number of possible input tuples that may be re-used together by a single server. For example, if all sets of t inputs can be re-used, then $u = \binom{|X|}{t}$ and the overhead is upper-bounded by $(\tilde{O}(t^2 \log(|X|/t)))^k$. In our use of robust CDS protocols for constructing secret-sharing schemes, it will hold that $u \ll \binom{|X|}{t}$.

We start by explaining how to take a non-robust CDS protocol for some function $f : X^k \rightarrow \{0, 1\}$ and immunize the first server, denoted Q_1 . As a warm-up, assume that we want robustness when the first server can send messages for two inputs (and all other servers send one message). The idea is to partition the set of inputs X of Q_1 to two sets X_1 and X_2 , and execute the non-robust CDS protocol for f twice with independent randomness. Server Q_1 holding an input $x \in X_j$ for some $j \in \{1, 2\}$ sends its message on input x only in the j -th execution. All other servers send their messages in both executions. Now, if the first server sends two messages on two inputs $x_1 \in X_1$ and $x'_1 \in X_2$, and each other server sends one message on input x_i , then in each execution the referee gets one message from each server, so it does not get any information on the secret s (assuming that $f(x_1, x_2, \dots, x_k) = f(x'_1, x_2, \dots, x_k) = 0$). However, if $x_1, x'_1 \in X_1$, then there are no security guarantees.

To overcome the problem in the above transformation, we consider λ partitions of X , denoted by $(X_1^1, X_2^1), \dots, (X_1^\lambda, X_2^\lambda)$, such that for every $x_1, x'_1 \in X$ there exists at least one partition (X_1^i, X_2^i) such that $x_1 \in X_1^i$ and $x'_1 \in X_2^i$ (or vice versa). For $\lambda = \log |X|$, partitions satisfying the above requirement exist. The robust CDS protocol in which Q_1 can send two messages is as follow: We choose λ random bits s_1, \dots, s_λ such that $s = s_1 \oplus \dots \oplus s_\lambda$, and for every $i \in [\lambda]$ we execute the non-robust CDS protocol twice with the secret s_i and independent random strings, where Q_1 with input x only sends a message in the execution j_i such that $x \in X_{j_i}^i$. Now, if Q_1 sends messages for two inputs x_1, x'_1 , then for at least one i the referee gets only one message from Q_1 in each execution of the non-robust CDS with secret s_i , thus, the referee does not have any information on s_i and, therefore, on s . To conclude, we get a CDS protocol in which Q_1 can send two messages and its message size is $O(\log |X|)$ times the message size of the non-robust CDS protocol. We can take this protocol and now immunize the second server, enabling it to send two messages, and repeat this process for all servers. We obtain a robust CDS protocol in which each server can send two messages and its message size is $O((\log |X|)^k)$ times the message size of the non-robust CDS protocol.

To construct a k -server CDS protocol in which server Q_1 can send t messages, we use partitions of X to $O(t^2)$ sets such that for every set T with t inputs, there exists at least one partition such that each input in T is in a different part. Such partitions are obtained using a family of perfect hash functions $H = \{h_i : X \rightarrow [t^2]\}$ [27]. Such family with $\lambda = O(t \log |X|)$ functions exists, and the message size in the resulting CDS protocol in which server Q_1 can send t messages is $O(t^3 \log |X|)$ times the message size of the non-robust CDS protocol. We again repeat this process k times and obtain a robust CDS protocol in which each server can send t messages and its message size is $O((t^3 \log |X|)^k)$ times the message size of the non-robust CDS protocol.

To improve the message size we use two levels of hashing, similar to the tracing traitors protocol of [20]. We first use a family of hash functions with range of size $2t$. This ensures that for every set of inputs T of size at most t , there is at least one hash function such that there is no $\log t$ -collusion on X . Thereafter, we can use the $\log t$ -robust scheme described above.

In Section 7, we present an alternative immunization procedure that is inspired by construction of [31]. We also present an abstraction of CDS immunization at the form of “Channel immunization problem”

together with a general solution concept (“select and share”) that captures both solutions.

We do not know if there is a more direct, cheaper approach for constructing a robust CDS. As a positive sign, in Section 6, we show that the best known linear CDS constructions already achieve some partial form of robustness. Indeed, for the linear case, it is cheaper to use these robust schemes, than to apply the immunization procedure. The existence of similar cheaper non-linear robust CDS remains as an intriguing open question, whose resolution may lead to further improvement in the complexity of general secret-sharing schemes.

Organization. Secret-sharing schemes and CDS protocols are defined in Section 3. Robust CDS protocols are defined and constructed in Section 4. The construction of secret-sharing schemes from RCDS protocols is described in Section 5. A proof that a variant of the linear k -server CDS protocol of [12] is already robust for half of the servers is depicted in Section 6; this protocol is used in Section 5 to construct the linear secret-sharing schemes for arbitrary access structures. An abstraction of the immunization construction that is used to transform a CDS protocol to a RCDS protocol as well as an alternative immunization construction appears in Section 7.

The paper contains several appendices. Some additional probability background (especially, on negatively associated random variables) that is being used in the immunization is presented in Appendix A. A simple construction of a secret-sharing scheme with exponent less than 1 is described in Appendix B. A linear 2-server RCDS protocol for arbitrary functions is discussed in Appendix C; this protocol is robust for every zero-set $Z_1 \times Z_2$, where $|Z_1| \leq t$ and there are no bounds on the size of Z_2 . Finally, an optimized construction of an RCDS protocol construction for longer secrets, deriving better communication cost per bit, appears in Appendix D.

3 Preliminaries

3.1 Secret-Sharing Schemes

We present the definition of secret-sharing schemes, similar to [8, 21]. For the privacy of these schemes, we use the following notation: For two random variables X and Y , we say that $X \equiv Y$ if they are identically distributed.

Definition 3.1 (Partial access structures). *Let $P = \{P_1, \dots, P_n\}$ be a set of parties. A partial access structure is a pair of collections $\Gamma = (\Gamma_{\text{no}}, \Gamma_{\text{yes}})$, where $\Gamma_{\text{no}}, \Gamma_{\text{yes}} \subseteq 2^P$ are non-empty collections of sets such that $B \not\subseteq A$ for every $A \in \Gamma_{\text{no}}, B \in \Gamma_{\text{yes}}$.⁷ Sets in Γ_{yes} are called authorized, and sets in Γ_{no} are called unauthorized. If $\Gamma_{\text{no}} \cup \Gamma_{\text{yes}} = 2^P$ then Γ is called an access structure and will be denoted by the collection of authorized sets Γ_{yes} . We represent a subset of parties $A \subseteq P$ by its characteristic string $x_A = (x_1, \dots, x_k) \in \{0, 1\}^n$, where for every $j \in [n]$ it holds that $x_j = 1$ if and only if $P_j \in A$. A partial access structure $\Gamma = (\Gamma_{\text{no}}, \Gamma_{\text{yes}})$ will also be described by the partial function $F : \{0, 1\}^n \rightarrow \{0, 1\}$, where $F(x_A) = 1$ for every subset of parties $A \in \Gamma_{\text{yes}}$ and $F(x_A) = 0$ for every set $A \in \Gamma_{\text{no}}$.*

Definition 3.2 (Secret-sharing schemes). *A secret-sharing scheme, with domain of secrets S , domain of random strings R , and finite domains of shares S_1, \dots, S_n , is a deterministic function $\mathcal{D} : S \times R \rightarrow S_1 \times \dots \times S_n$. A dealer distributes a secret $s \in S$ according to \mathcal{D} by first sampling a random string $r \in R$ with uniform distribution, computing a vector of shares $\mathcal{D}(s, r) = (s_1, \dots, s_n)$, and privately communicating*

⁷We do not require that $2^P \setminus \Gamma_{\text{no}}$ and Γ_{yes} are equal or that they are monotone (this simplifies our presentation).

each share s_i to party P_i . For a set $A \subseteq P$, we denote $\mathcal{D}_A(s, r)$ as the restriction of $\mathcal{D}(s, r)$ to its A -entries (i.e., the shares of the parties in A).

A secret-sharing scheme \mathcal{D} realizes a partial access structure $\Gamma = (\Gamma_{\text{no}}, \Gamma_{\text{yes}})$ if the following two requirements hold:

Perfect Correctness. *The secret s can be reconstructed by any authorized set of parties. That is, for any set $B = \{P_{i_1}, \dots, P_{i_{|B|}}\} \in \Gamma_{\text{yes}}$ there exists a reconstruction function $\text{Recon}_B : S_{i_1} \times \dots \times S_{i_{|B|}} \rightarrow S$ such that for every secret $s \in S$ and every random string $r \in R$, it holds that $\text{Recon}_B(\mathcal{D}_B(s, r)) = s$.*

Perfect privacy. *Any unauthorized set cannot learn anything about the secret from its shares. Formally, for any set $T = \{P_{i_1}, \dots, P_{i_{|T|}}\} \in \Gamma_{\text{no}}$, every pair of secrets $s, s' \in S$, it holds that $\mathcal{D}_T(s, r) \equiv \mathcal{D}_T(s', r)$, where r is sampled with uniform distribution from R .*

The secret size in a secret-sharing scheme \mathcal{D} is defined as $\log |S|$ and the share size of the scheme \mathcal{D} is defined as the largest share size, i.e., $\max_{1 \leq i \leq n} \{\log |S_i|\}$.⁸ The scheme \mathcal{D} is a linear secret-sharing scheme over a finite field \mathbb{F} if $S = \mathbb{F}$, $R = \mathbb{F}^\ell$ for some integer $\ell \geq 1$, the sets S_1, \dots, S_n are vector spaces over \mathbb{F} , and the function $\mathcal{D} : \mathbb{F}^{\ell+1} \rightarrow S_1 \times \dots \times S_n$ is a linear mapping over \mathbb{F} . By default, linearity is defined over the binary field \mathbb{F}_2 .

Next, we define threshold secret-sharing schemes, and provide some known result for such schemes.

Definition 3.3 (Threshold secret-sharing schemes). *We say that an n -party secret-sharing scheme is a k -out-of- n secret-sharing scheme if it realizes the access structure $\Gamma_{k,n} = \{A \subseteq P : |A| \geq k\}$.*

Theorem 3.4 ([49]). *For every integers $1 \leq k \leq n$, there is a linear k -out-of- n secret-sharing scheme realizing $\Gamma_{k,n}$ for secrets of size m in which the share size is $\max\{m, O(\log n)\}$.*

3.2 Conditional Disclosure of Secrets Protocol

We consider a model where k servers Q_1, \dots, Q_k hold a secret s and a common random string r . In addition, every server Q_i holds an input x_i of some k -input function f . In a CDS protocol for f , for every $i \in [k]$, server Q_i sends a message to a referee, based on r, s , and x_i , such that the referee, which holds the inputs x_1, \dots, x_k and sees the messages from the servers, can reconstruct the secret s if $f(x_1, \dots, x_k) = 1$, and it cannot learn any information about the secret s if $f(x_1, \dots, x_k) = 0$.

Definition 3.5 (Conditional disclosure of secrets protocols). *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a k -input function. A k -server CDS protocol \mathcal{P} for f , with domain of secrets S , domain of common random strings R , and finite message domains M_1, \dots, M_k , consists of k deterministic message computation functions $\text{ENC}_1, \dots, \text{ENC}_k$, where $\text{ENC}_i : X_i \times S \times R \rightarrow M_i$ for every $i \in [k]$. For an input $x = (x_1, \dots, x_k) \in X_1 \times \dots \times X_k$, secret $s \in S$, and randomness $r \in R$, we let $\text{ENC}(x, s, r) = (\text{ENC}_1(x_1, s, r), \dots, \text{ENC}_k(x_k, s, r))$. We say that a protocol \mathcal{P} is a CDS protocol for f if it satisfies the following properties:*

Perfect correctness. *There is a deterministic reconstruction function $\text{DEC} : X_1 \times \dots \times X_k \times M_1 \times \dots \times M_k \rightarrow S$ such that for every input $x = (x_1, \dots, x_k) \in X_1 \times \dots \times X_k$ for which $f(x_1, \dots, x_k) = 1$, every secret $s \in S$, and every common random string $r \in R$, it holds that $\text{DEC}(x, \text{ENC}(x, s, r)) = s$.*

⁸The share size is sometimes defined to be the total share size, i.e., $\sum_{1 \leq i \leq n} \log |S_i|$. However, since the two differ by at most a linear factor of n , the difference is not important in our context.

Perfect privacy. For every input $x = (x_1, \dots, x_k) \in X_1 \times \dots \times X_k$ for which $f(x_1, \dots, x_k) = 0$ and every pair of secrets $s, s' \in S$ it holds that $\text{ENC}(x, s, r) \equiv \text{ENC}(x, s', r)$, where r is sampled with uniform distribution from R .

The message size of a CDS protocol \mathcal{P} is defined as the size of the largest message sent by the servers, i.e., $\max_{1 \leq i \leq k} \log |M_i|$. The normalized message size of a CDS protocol \mathcal{P} is defined as the size of the message size of the protocol divided by the size of the secret, i.e., $\max_{1 \leq i \leq k} \log |M_i| / \log |S|$.

The protocol \mathcal{P} is a linear CDS protocol over a finite field \mathbb{F} if $S = \mathbb{F}$, $R = \mathbb{F}^\ell$ for some integer $\ell \geq 1$, M_1, \dots, M_k are vector spaces over \mathbb{F} , and the function $\text{ENC}_i : \mathbb{F}^{\ell+1} \rightarrow M_i$ is a linear function over \mathbb{F} for every $i \in [k]$. By default, we take \mathbb{F} to be the binary field \mathbb{F}_2 .

3.3 Notation

We denote the logarithmic function with base 2 and base e by \log and \ln , respectively. For $0 \leq \alpha \leq 1$, we denote the binary entropy of α by $H_2(\alpha) = -\alpha \log \alpha - (1 - \alpha) \log(1 - \alpha)$ (where $H_2(0) = H_2(1) = 0$). It is known that $\binom{n}{k} = \Theta(k^{-1/2} 2^{H_2(k/n)n})$.

Sets and strings. We use the notation $[n]$ to denote the set $\{1, \dots, n\}$. For a set A , we let 2^A denote the collection of all subsets of A , let $\binom{A}{k}$ denote the collection of all subsets of A of size k and let $\binom{A}{\leq k}$ denote the collection of all subsets of A of size at most k .

Given two binary strings of the same length, $a = a_1 a_2 \dots a_n$ and $b = b_1 b_2 \dots b_n$, we say that $a \leq b$ if $a_i \leq b_i$ for every $i \in [n]$. We denote $\text{wt}(a)$ as the Hamming weight of the string a .

4 Robust CDS: Definition and Construction

4.1 Definition of Robust CDS

In the definition of CDS protocols in [29] (as presented in Definition 3.5), if a server sends messages for two different inputs with the same randomness, then the privacy is not guaranteed and the referee can possibly learn information on the secret s . We generalize the notion of CDS protocols to robust CDS (RCDS) protocols, where the secret is hidden even if the referee sees multiple messages of servers computed on different inputs with the same randomness. Of course, this requirement makes sense only if all the corresponding inputs are zero inputs of f .

Definition 4.1 (Zero sets and robustness collections.). Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a k -input function. We say that a set of inputs $Z \subseteq X_1 \times \dots \times X_k$ is a zero set of f if $f(x) = 0$ for every $x \in Z$.

A robustness collection is a product of k collections of inputs $\mathcal{Z} = \mathcal{Z}_1 \times \dots \times \mathcal{Z}_k \subseteq 2^{X_1} \times \dots \times 2^{X_k}$, where each \mathcal{Z}_i is downward closed, i.e., if $Z \in \mathcal{Z}_i$ and $Z' \subset Z$ then $Z' \in \mathcal{Z}_i$, and contains all singletons, i.e., $\{x_i\} \in \mathcal{Z}_i$ for every $x_i \in X_i$. A robustness collection is a (u, t) -collection if each of the collections $\mathcal{Z}_1, \dots, \mathcal{Z}_k$ contains at most u maximal sets, and each of these sets is of size at most t . We denote the collection by $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$.

For sets $\mathcal{Z}_1, \dots, \mathcal{Z}_k$ we denote $\text{ENC}_i(\mathcal{Z}_i, s, r) = (\text{ENC}_i(x_i, s, r))_{x_i \in \mathcal{Z}_i}$, and $\text{ENC}(\mathcal{Z}_1 \times \dots \times \mathcal{Z}_k, s, r) = (\text{ENC}_1(\mathcal{Z}_1, s, r), \dots, \text{ENC}_k(\mathcal{Z}_k, s, r))$.

Definition 4.2 (Robust conditional disclosure of secrets (RCDS) protocols). Let \mathcal{P} be a k -server CDS protocol for a k -input function $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ and $Z = \mathcal{Z}_1 \times \dots \times \mathcal{Z}_k \subseteq X_1 \times \dots \times X_k$ be a zero set of f . We say that \mathcal{P} is robust for the set Z if for every pair of secrets $s, s' \in S$, it holds that

$\text{ENC}(Z, s, r) \equiv \text{ENC}(Z, s', r)$. Let \mathcal{Z} be a robustness collection. We say that \mathcal{P} is a \mathcal{Z} -RCDS protocol if it is robust for every zero set $Z \in \mathcal{Z}$.

For example, the original (non-robust) definition of privacy of CDS protocols is $\mathcal{Z}_1 \times \dots \times \mathcal{Z}_k$ -robust, where \mathcal{Z}_i contains all singletons, i.e., $\mathcal{Z}_i = \{\{x_i\} : x_i \in X_i\} \cup \{\emptyset\}$.⁹ We next discuss some choices made in our definition of robustness.

Rectangles. Suppose that a 2-server CDS protocol is robust for a zero set Z that contains the inputs $(x, y), (x', y')$. This means that the messages $\text{ENC}((x, y), s, r) = (\text{ENC}_1(x, s, r), \text{ENC}_2(y, s, r))$, and $\text{ENC}((x', y'), s, r) = (\text{ENC}_1(x', s, r), \text{ENC}_2(y', s, r))$ perfectly hide the secret s . Observe that given these messages, the referee can also compute the messages $\text{ENC}((x', y), s, r)$ and $\text{ENC}((x, y'), s, r)$, which correspond to the inputs (x, y') and (x', y) , i.e., the referee can try to reconstruct the secret for every input in the minimal combinatorial rectangle that contains $(x, y), (x', y')$.¹⁰ For this reason, we always use combinatorial rectangles as sets for robustness.

Monotonicity. We also observe that if a protocol is robust for a zero set $Z = Z_1 \times \dots \times Z_k$ then it is also robust for every sub-rectangle of Z . It will be convenient to keep this property even when Z is not a zero-set. That is, we will always make sure that if Z is a member of our robustness collection \mathcal{Z} then so are all sub-rectangles of Z , i.e., \mathcal{Z}_i will always be downward closed collection for every $i \in [k]$.

Product collections. For simplicity of notations, we focus on the case of *product collections*, i.e., $\mathcal{Z} = \mathcal{Z}_1 \times \dots \times \mathcal{Z}_k$, where $\mathcal{Z}_i \subseteq 2^{X_i}$. We always require that \mathcal{Z}_i contains all the singletons of X_i , thus, \mathcal{Z} -robustness implies privacy as defined in Definition 3.5.

Example 4.3 (t-RCDS). Consider the case where each server may output, simultaneously, messages for any subset of its inputs of size at most t . This notion, referred to as *t-RCDS*, can be captured by the product collection $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ where $\mathcal{Z}_i = \binom{X_i}{\leq t}$. Consequently, this is a (u, t) -robustness collection, where $u = \max_{1 \leq i \leq k} \left\{ \binom{|X_i|}{t} \right\}$.

4.2 Construction of Robust CDS Protocols

In the rest of this section we show how to convert a CDS protocol for a function f to a \mathcal{Z} -RCDS protocol for f , where $\mathcal{Z} = \mathcal{Z}_1 \times \dots \times \mathcal{Z}_k$ is a (u, t) -robustness collection. The message size in the resulting RCDS protocol is only $\tilde{O}(t \log u)^k$ times the message size of the CDS protocol. The construction of the RCDS protocol is done in k steps, where in the k' -th step we immunize the messages of the server $Q_{k'}$, that is, we start with a protocol that is robust when servers $Q_1, \dots, Q_{k'-1}$ can send messages for many inputs and servers $Q_{k'}, \dots, Q_k$ can only send a single message and transform it to a protocol that is robust also when server $Q_{k'}$ can send messages for many inputs.

To simplify notation, we say that a CDS protocol is a $(\mathcal{Z}_1, \mathcal{Z}_2, \dots, \mathcal{Z}_{k'})$ -RCDS if it is \mathcal{Z} -RCDS for $\mathcal{Z} = (\mathcal{Z}_1, \dots, \mathcal{Z}_{k'}, \mathcal{Z}_{k'+1}, \dots, \mathcal{Z}_k)$, where $\mathcal{Z}_i = \{\{x_i\} : x_i \in X_i\} \cup \{\emptyset\}$ for every $i \in \{k'+1, \dots, k\}$ (i.e., \mathcal{Z}_i contains all singletons).

⁹ One can ensure that a CDS protocol is robust when $Z_i = \emptyset$ by first sharing the secret with a $(k+1)$ -out-of- $(k+1)$ secret-sharing scheme, i.e., $s = s_0 + s_1 + \dots + s_k$, and the message of server Q_i is the message of the CDS protocol with the secret s_0 and s_i .

¹⁰ A set $Z \subseteq X_1 \times \dots \times X_k$ is a combinatorial rectangle if it can be written as a product set $Z = Z_1 \times \dots \times Z_k$, where $Z_i \subseteq X_i$.

Theorem 4.4 (Immunization Theorem). *Let $1 \leq k' \leq k$ be integers, $f : X_1 \times \cdots \times X_k \rightarrow \{0, 1\}$ be a function, and $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'}) \subseteq 2^{X_1} \times \cdots \times 2^{X_{k'}}$ be a (u, t) -robustness collection. Suppose there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1})$ -RCDS protocol $\mathcal{P}_{k'-1}$ for a secret taken from a domain S in which the size of the messages of server Q_i , for $i \in [k]$, is c_i . Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}_{k'})$ -RCDS protocol $\mathcal{P}_{k'}$ for a secret taken from the domain S in which the size of the messages of server Q_i , for $i \in [k] \setminus \{k'\}$, is $O(c_i t \log^3 t \log |X_i| \log u)$, and the size of the messages of server $Q_{k'}$ is $O(c_{k'} \log t \log |X_i| \log u)$. Moreover, if $\mathcal{P}_{k'-1}$ is linear, then so is $\mathcal{P}_{k'}$.*

The main idea of our construction for immunizing a server $Q_{k'}$ is to partition the input domain $X_{k'}$ of the server into sets and for each set to execute a CDS protocol with independent randomness. If the server sends encodings of a few inputs such that each input is in a different set, then the referee gets at most one encoding from each execution and the privacy of the CDS protocol implies the robustness of the new protocol. However, one partition of the inputs is not good for all sets of inputs so we use several partitions. We use a family of perfect hash functions to specify the partitions.

To reduce the message size in the construction, we use two levels of hashing. To provide robustness for t inputs, we first use a family of hash functions with range of size $2t$. This will ensure that for at least one partition, the server sends encodings of at most $\log t$ inputs in the same execution of the CDS protocol. Thus, the CDS protocol should be robust for $\log t$ inputs; this is done by a second level of hashing using a family of perfect hash functions with range of size $\log^2 t$. The idea of using two levels of hashing is similar to the construction of traitor-tracing schemes in [20].

By taking the best known CDS constructions and iteratively applying the immunization theorem, we derive the following results.

Theorem 4.5. *Let $f : X_1 \times \cdots \times X_k \rightarrow \{0, 1\}$ be a k -input function, where $|X_i| \leq 2^\ell$, and $(\mathcal{Z}_1, \dots, \mathcal{Z}_k) \subseteq 2^{X_1} \times \cdots \times 2^{X_k}$ be a (u, t) -robustness collection. Then,*

- *There is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol with a 1-bit secret, where the size of the messages of each server is $2^{\tilde{O}(\sqrt{k\ell})} \tilde{O}(t)^{k-1} (\ell \log u)^k$, and*
- *If k is odd, then there is a linear $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol with a 1-bit secret, where the size of the messages of each server is $\tilde{O}(t 2^\ell \log u)^{(k-1)/2}$.*

The rest of the section is organized as follows. In Section 4.2.1, we provide some results on families of hash functions. In Section 4.3, we prove an immunization lemma, which is used for both levels of hashing, and prove the immunization theorem (Theorem 4.4) using the immunization lemma. Finally, in Section 4.4, we show how to use the immunization theorem to construct RCDS protocols and prove Theorem 4.5.

4.2.1 Families of Hash Functions

We next present the definition of a family of t' -collision free perfect hash functions; the original definition of perfect hash functions [27] refers to the case that $t' = 1$.

Definition 4.6 (Families of t' -collision free hash functions). *A set of functions $H_{n,t,t',v} = \{h_d : [n] \rightarrow [v] : d \in [\lambda]\}$ is a family of t' -collision free hash functions for a collection $\mathcal{T} \subseteq \binom{[n]}{\leq t}$ if for every set $T \in \mathcal{T}$ there exists at least one function $h \in H_{n,t,t',v}$ for which for every $b \in [v]$ it holds that $|\{x \in T : h(x) = b\}| \leq t'$, that is, h restricted to T is at most t' -to-one. A family $H_{n,t,v}$ is a family of perfect hash functions if it is a family of 1-collision free hash functions.*

The following lemma is a well-known result, which can be proved, e.g., using the probabilistic method.

Lemma 4.7. *Let n be an integer and $t \in [\sqrt{n}]$. Then, there exists a family $H_{n,t,t^2} = \{h_i : [n] \rightarrow [t^2] : i \in [\lambda]\}$ of perfect hash functions (i.e., 1-collision free) for $\binom{[n]}{t}$, where $\lambda = 16t \ln n$.*

The next lemma is proved in Appendix A.2.

Lemma 4.8. *Let n be an integer, $t \in \{15, \dots, n/2\}$, $\mathcal{T} \subseteq \binom{[n]}{\leq t}$, and u be the number of maximal sets in \mathcal{T} . Then, there exists a family of $\log t$ -collision free hash functions $H_{n,t,\log t,2t}$ of size $\lambda = 16 \ln u$.*

4.3 The Immunization

The next lemma, called the immunization lemma, improves the immunization of server $Q_{k'}$, that is, it takes a protocol that is robust when $Q_{k'}$ sends encodings of $t' < t$ messages, and constructs a protocol that is robust when $Q_{k'}$ sends encodings of t messages. This is done using a few copies of the original protocol and a family of t' -collision free hash functions.

Lemma 4.9. *Let $f, k', \mathcal{Z}_1, \dots, \mathcal{Z}_{k'}$, and t be as in Theorem 4.4 and $\mathcal{Z}'_{k'} = \binom{X_{k'}}{\leq t'}$ for some integer $t' \leq t$. Suppose there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}'_{k'})$ -RCDS protocol \mathcal{P} with domain of secrets S in which the size of the messages of server Q_i , for $i \in [k]$, is c_i . Furthermore, suppose there is a family of t' -collision free hash functions $H_{|X_{k'}|,t',v} = \{h_1, \dots, h_\lambda\}$. Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}_{k'})$ -RCDS protocol \mathcal{P}' with secrets from S in which the size of the messages of server Q_i , for $i \in [k] \setminus \{k'\}$, is $O(c_i v \lambda)$ and the size of the messages of server $Q_{k'}$ is $O(c_{k'} \lambda)$. Moreover, the transformation preserves linearity.*

Proof. Let R be the set of random strings of \mathcal{P} and let ENC_i be the encoding function of server Q_i in this protocol. The encoding function ENC'_i of Q_i in the RCDS protocol \mathcal{P}' for f is as follows:

- Common inputs: a secret $s \in S$, randomness r consisting of $s_1, \dots, s_{\lambda-1} \in S$ and $(r_{d,j})_{d \in [\lambda], j \in [v]}$, where each $r_{d,j} \in R$.
- Private input of server Q_i : $x_i \in X_i$.
- Let $s_\lambda = s - (s_1 + \dots + s_{\lambda-1})$, where the sum is in S .
(If S is not a group, choose an injective mapping from S to $\mathbb{Z}_{|S|}$ and use addition modulo $|S|$.)
- If $i \neq k'$, then $\text{ENC}'_i(x_i, s, r) = (\text{ENC}_i(x_i, s_d, r_{d,j}))_{d \in [\lambda], j \in [v]}$.
- $\text{ENC}'_{k'}(x_{k'}, s, r) = (\text{ENC}_{k'}(x_{k'}, s_d, r_{d,h_d(x_{k'})}))_{d \in [\lambda]}$.

Notice that the encoding of server $Q_{k'}$ contains one encoding from \mathcal{P} for each s_d , namely, with the random string $r_{d,h_d(x_{k'})}$; this will provide the robustness. In contrast, the encoding of any other server contains many encodings from \mathcal{P} for each s_d (each one with an independent random string); this will ensure the correctness of the protocol.

We first show the correctness of the RCDS protocol \mathcal{P}' . For an input $(x_1, \dots, x_k) \in X_1 \times \dots \times X_k$ such that $f(x_1, \dots, x_k) = 1$, the referee can reconstruct s_d , for every $d \in [\lambda]$, using the decoding function of \mathcal{P} on the encodings of the inputs x_1, \dots, x_k with the secret s_d and random string $r_{d,h_d(x_{k'})}$. Overall, the referee can learn all the strings s_1, \dots, s_λ , so it can reconstruct the secret s by summing these strings.

For the robustness of the protocol \mathcal{P}' , let $Z_1 \times \dots \times Z_k$ be a zero set of f such that $Z_i \in \mathcal{Z}_i$ for every $1 \leq i \leq k'$ and $|Z_i| = 1$ for every $k' + 1 \leq i \leq k$, and let $Z_{k',d,j} = \{x \in Z_{k'} : h_d(x) = j\}$ for every $d \in [\lambda]$ and $j \in [v]$. Since $H_{|X_{k'}|,t',v}$ is a family of t' -collision free hash functions, there is at least one $d \in [\lambda]$ for which h_d restricted to $Z_{k'}$ is at most t' -to-one. Fix a $j \in [v]$; by the collision freeness,

$|Z_{k',d,j}| \leq t'$. The referee only gets the encodings of the inputs in $Z_{k',d,j}$ from server $Q_{k'}$ in the execution of the RCDS protocol \mathcal{P} for the secret s_d and random string $r_{d,j}$, i.e., it gets at most t' encodings from $Q_{k'}$ for $r_{d,j}$. Furthermore, in this execution the referee gets encoding of messages of server Q_i on inputs $Z_i \in \mathcal{Z}_i$ for $1 \leq i \leq k' - 1$ and an encoding of at most one message from server Q_i for $k' + 1 \leq i \leq k$. Since \mathcal{P} is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}'_{k'})$ -RCDS protocol, the referee cannot learn any information about s_d from this execution, that is, for $Y^{d,j} = Z_1 \times \dots \times Z_{k'-1} \times Z_{k',d,j} \times Z_{k'+1} \times \dots \times Z_k$ and two secrets $s_d, s'_d \in S$

$$\text{ENC}(Y^{d,j}, s_d, r_{d,j}) \equiv \text{ENC}(Y^{d,j}, s'_d, r_{d,j}).$$

For two secrets $s, s' \in S$, fix $s_1, \dots, s_{\lambda-1}$. Let $s_\lambda = s - (s_1 + \dots + s_{\lambda-1})$, and $s'_e = s_e$ for $e \neq d$ and $s'_d = s_d + s' - s$. Note that s_1, \dots, s_λ are used when the secret is s , while s'_1, \dots, s'_λ are used when the secret is s' . Since the random strings $\{r_{e,j}\}_{e \in [\lambda], j \in [v]}$ are statistically independent,

$$(\text{ENC}(Y^{e,j}, s_e, r_{e,j}))_{e \in [\lambda], j \in [v]} \equiv (\text{ENC}(Y^{e,j}, s'_e, r_{e,j}))_{e \in [\lambda], j \in [v]}.$$

Hence, the referee cannot learn any information on the secret s .

The message size of each server Q_e , for $e \neq k'$, in protocol \mathcal{P}' is $O(v|H_{|X_{k'}|,t,t',v}|) = O(v\lambda)$ times its message size in \mathcal{P} (where v is the size of the output of the hash function and λ is the number of functions in the family) and the message size of server $Q_{k'}$ in protocol \mathcal{P}' is $O(|H_{|X_{k'}|,t,t',v}|) = O(\lambda)$ times its message size in \mathcal{P} . \square

We next prove Theorem 4.4, the Immunization Theorem, by using two levels of the construction of Lemma 4.9.

Proof of Theorem 4.4. Let $t' = \log t$, $\mathcal{Y}_{k'} = \binom{X_{k'}}{\leq t'}$, and $H_{|X_{k'}|,t',t'^2}$ be the family of perfect hash functions of size $\lambda = O(t' \log |X_{k'}|)$ guaranteed by Lemma 4.7. Note that this family is 1-collision free. By Lemma 4.9 applied to $\mathcal{P}_{k'-1}$ and $H_{|X_{k'}|,t',t'^2}$, there exists a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Y}_{k'})$ -RCDS protocol $\mathcal{P}'_{k'}$, where the message size of server Q_i , for $i \neq k'$, is $O(c_i \cdot t'^2 \cdot t' \log |X_{k'}|) = O(c_i \log^3 t \log |X_{k'}|)$, and the message size of server $Q_{k'}$ is $O(c_{k'} \log t \log |X_{k'}|)$.

We next apply Lemma 4.9 using $\mathcal{P}'_{k'}$. Let $H_{|X_{k'}|,t,\log t,2t}$ be the family of $\log t$ -collision free hash functions for $\mathcal{Z}_{k'}$ of size $\lambda = O(\log u)$ guaranteed by Lemma 4.8 (where u is the number maximal sets in $\mathcal{Z}_{k'}$). By Lemma 4.9 applied to $\mathcal{P}'_{k'}$ and $H_{|X_{k'}|,t,\log t,2t}$, there exists a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}_{k'})$ -RCDS protocol where the message size of server Q_i , for $i \neq k'$, is $O((c_i \log^3 t \log |X_{k'}|) \cdot 2t \cdot \log u)$, and the message size of server $Q_{k'}$ is $O(c_{k'} \log t \log |X_{k'}| \log u)$. \square

4.4 Constructing RCDS Protocols

In this section we present our constructions of RCDS protocols, proving Theorem 4.5. We begin by applying Theorem 4.4 k times, immunizing all parties.

Lemma 4.10. *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a k -input function, where $|X_i| \leq 2^\ell$, and $(\mathcal{Z}_1, \dots, \mathcal{Z}_k) \subseteq 2^{X_1} \times \dots \times 2^{X_k}$ be a (u, t) -robustness collection. Suppose there exists a CDS for f where the message size of server Q_i is c_i . Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol, where the size of the messages of server Q_i , for $i \in [k]$, is $c_i \cdot O(t)^{k-1} \cdot \log^{3k-2} t \cdot (\ell \log u)^k$. Moreover, this transformation preserves linearity.*

Proof. We use Theorem 4.4 k times iteratively, starting with the original CDS protocol. In the k' -th iteration, we transform a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1})$ -RCDS protocol to a $(\mathcal{Z}_1, \dots, \mathcal{Z}_{k'-1}, \mathcal{Z}_{k'})$ -RCDS protocol. The communication overhead in each step is $\tilde{O}(t \log u)$ for the immunized server and $\tilde{O}(t \ell \log u)$ for all other servers. Since every server is immunized once, the total communication overhead is $\tilde{O}(t)^{k-1} (\ell \log u)^k$. \square

We move on, and prove Theorem 4.5.

Proof of Theorem 4.5. The non-linear RCDS protocol is obtained by applying Lemma 4.10 to the CDS protocol of [41], which has message size $2^{\tilde{O}(\sqrt{k\ell})}$.

For the linear RCDS protocol, we start with the variant of the linear CDS protocol of [12] with message size $O(2^{\ell(k-1)/2})$ (a protocol with a similar message size also appears in [41]), and prove in Lemma 6.1 that when k is odd, this protocol is already immune for $(k+1)/2$ servers. Thus, we need to immunize, using Theorem 4.4, only $(k-1)/2$ servers. The resulting RCDS protocol has message size $\tilde{O}(t2^\ell \log u)^{(k-1)/2}$. \square

In Appendix D, we present an RCDS protocol for longer secret with improved normalized message size.

4.5 (a, b) -Monotone RCDS

An important example of a robustness collection is the case of *monotone robustness* in which whenever a server Q_i , holding a string $x \in \{0, 1\}^\ell$, sends all the messages that correspond to inputs $x' \leq x$. In fact, we consider a more refined version of this scenario where the above happens only when x is of Hamming weight at most b and x' is of Hamming weight at least a for some integers $a < b \leq \ell$.

Definition 4.11 ((a, b) -monotone RCDS). *For an input $x \in X_i$, define the set $S_{x,a} \subset X_i$ as*

$$S_{x,a} = \{x' \in X_i : x' \leq x \text{ and } \text{wt}(x') \geq a\}.$$

Furthermore, for $i \in \{1, \dots, k\}$, we let \mathcal{Z}_i denote the collection of all sets $\{S_{x,a}\}_{x \in X_i, a \leq \text{wt}(x) \leq b}$ together with all their subsets. An (a, b) -monotone RCDS protocol is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol.

Let $X_i \subseteq \{0, 1\}^\ell$. Each string of weight exactly b correspond to a maximal set of \mathcal{Z}_i . Hence, the collection \mathcal{Z} is a (u, t) -collection where

$$u = \binom{\ell}{b} \quad \text{and} \quad t = \sum_{i=a}^b \binom{b}{i}. \quad (1)$$

5 Secret-Sharing Schemes for General Access Structures

In this section, we realize any access structure based on RCDS protocols. By plugging the RCDS constructions from Theorem 4.5, we prove our main theorem – Theorem 2.1. We follow the outline sketched in the introduction: We begin by realizing somewhat-regular access structures, then move to handle mid-slice access structures, and end up by realizing general access structures. Throughout this section we will identify an access structure with its characteristic Boolean function F , as described in Definition 3.1. We also make use of partial (or promise) access structures.

5.1 Somewhat-Regular Secret-Sharing Schemes from RCDS Protocols

Definition 5.1 ((k, a, b) -somewhat-regular access structure). *Let Π be a partition of the set of n parties P to k equal-sized sets (I_1, \dots, I_k) . A (partial) access structure $\Gamma = (\Gamma_{\text{no}}, \Gamma_{\text{yes}})$ over n parties is (Π, a, b) -somewhat-regular if for every $A \in \Gamma_{\text{no}} \cup \Gamma_{\text{yes}}$ and every $i \in [k]$,*

$$a \leq |A \cap I_i| \leq b. \quad (2)$$

In other words, Γ puts no restriction on sets $A \subset [n]$ that violates (2) for some i . We sometimes omit Π and refer to Γ as being (k, a, b) -somewhat-regular.

Remark 5.2 (Function notation). Using the terminology of functions and strings, the partial function F describing a (k, a, b) -somewhat-regular access structure is defined only on n -bit strings $x \in \{0, 1\}^n$ with the following property. For every $i \in [k]$, the string $x[I_i]$, obtained by restricting x to the index set I_i , has Hamming weight of at least a and at most b . That is, x can be parsed to (x_1, \dots, x_k) where $x_i \in \{0, 1\}^{n/k}$ and we care only about the case where the Hamming weight of each x_i is in between a and b .

Remark 5.3. We can take a fully defined access structure F and “puncture it” according to a given partition Π and parameters (a, b) and derive a (Π, a, b) -somewhat-regular version of F , denoted by $F_{\Pi, a, b}$, where $F_{\Pi, a, b}$ is undefined on inputs x for which some x_i has weight greater than b or smaller than a .

As the first step towards secret-sharing schemes for general access structures, we build secret-sharing schemes for any (k, a, b) -somewhat-regular access structures over n parties based on (a, b) -monotone robust CDS protocols for k servers. (The latter notion is defined in Definition 4.11.)

Construction 5.4. Let Π be a partition of n parties to k equal-sized sets (I_1, \dots, I_k) and let F be a (Π, a, b) -somewhat-regular access structure over n parties for integers $a < b$. We share a secret s as follows.

1. Let $X_i = \{0, 1\}^{n/k}$ and let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be some function that agrees with F .¹¹ Sample a random string r for a k -server (a, b) -monotone RCDS protocol $\mathcal{P} = (\text{ENC}_i)_{i \in [k]}$ for f .
2. For every $i \in k$, and $x_i \in X_i$ such that the Hamming weight $w = \text{wt}(x_i)$ of x_i is in the interval $[a, b]$, compute the message of the i -th server of \mathcal{P} :

$$y(i, x_i, s) := \text{ENC}_i(x_i, s, r),$$

and share it between all the w parties in (the set that corresponds to) x_i via a w -out-of- w secret-sharing scheme (using fresh randomness R_{i, x_i} for each x_i). We denote the share of $j \in x_i$ by $y(i, x_i, s, j)$.

3. The share of the j -th party (which is in a set I_i) is $(y(i, x_i, s, j))_{x_i: j \in x_i}$.

Lemma 5.5. *Construction 5.4 realizes F with share sizes of $m \cdot \sum_{j=a}^b \binom{n/k}{j}$ for each party, where m is the message size of the underlying RCDS protocol.*

Proof. We start by proving correctness. Let $x = (x_1, \dots, x_k)$ be a string with $a \leq \text{wt}(x_i) \leq b$ for every $i \in [k]$ and $F(x) = 1$. For every $i \in [k]$, the parties represented by x_i can reconstruct the RCDS message $\text{ENC}_i(x_i, s, r)$ of the i -th server of \mathcal{P} . Since the RCDS function f agrees with F , it holds that $f(x) = 1$, and by the correctness of the RCDS protocol the parties can compute the secret s from the k RCDS messages.

We move on to prove privacy. Fix a string $x = (x_1, \dots, x_k)$ that corresponds to an unauthorized set. Consider a pair of secret s_0 and s_1 . Our goal is to show that the corresponding shares of the parties in x , denoted by $\mathcal{D}_x(s_0)$ and $\mathcal{D}_x(s_1)$, are identically distributed. To see this, consider a modified construction in which for every $i \in [k]$ and every $u \in X_i$ for which $u \not\leq x_i$, the random variable $y(i, u, s_0)$ (which is shared via a $\text{wt}(u)$ -out-of- $\text{wt}(u)$ secret-sharing scheme) is replaced with some fixed string $y(i, u)$ of appropriate length (say the all zero string). We claim that, in the modified scheme, the view $\mathcal{D}'_x(s_0)$ of the parties in x is distributed identically to $\mathcal{D}_x(s_0)$. Indeed, since $u \not\leq x_i$ there exists at least one party $j \in u$ that does not participate in x . Therefore, by the privacy of the $\text{wt}(u)$ -out-of- $\text{wt}(u)$ secret-sharing scheme, and since

¹¹We say that a pair of partial functions f and g agree with each other if they take the same value on every input x for which both functions are defined.

each $y(i, u, s_0)$ is shared with fresh randomness, the random variables $\mathcal{D}_x(s_0)$ and $\mathcal{D}'_x(s_0)$ are identically distributed. Similarly, $\mathcal{D}_x(s_1)$ and $\mathcal{D}'_x(s_1)$ are identically distributed, and so it suffices to show that $\mathcal{D}'_x(s_0)$ is distributed identically to $\mathcal{D}'_x(s_1)$. Let us condition on some fixing of the shares of $y(i, u)$ for all $u \in X_i$ for which $u \not\leq x_i$. By the robustness of the RCDS, the remaining random variables

$$\{y(i, v, s_0) : i \in [k], v \leq x_i\} \text{ and } \{y(i, v, s_1) : i \in [k], v \leq x_i\}$$

are identically distributed, so the corresponding shares are also identically distributed and privacy follows.

For every $j \in [n]$, the share of party P_j contain a share of the RCDS protocol for every string x_i of length n/k and weight between a and b such that $j \in x_i$. Then the share size of P_j is $m \cdot \sum_{j=a}^b \binom{n/k}{j}$. \square

5.2 Mid-slice Secret-Sharing Schemes from Somewhat-Regular Secret-Sharing Schemes

Definition 5.6 (Mid-slice access structure [39]). *An n -party access structure F is a δ mid-slice access structure with parameter $\delta \in (0, 0.5)$ if:*

1. F takes the value 0 for every input x of Hamming weight $\text{wt}(x) < (0.5 - \delta)n$;
2. F takes the value 1 for every input x of Hamming weight $\text{wt}(x) > (0.5 + \delta)n$;

A “middle-slice” input x of weight $(0.5 - \delta)n \leq \text{wt}(x) \leq (0.5 + \delta)n$ can be assigned any value (as long as monotonicity is preserved).

A partial mid-slice access structure is defined similarly except that we drop the requirements (1) and (2), and F is undefined over light inputs ($\text{wt}(x) < (0.5 - \delta)n$) and over heavy inputs ($\text{wt}(x) > (0.5 + \delta)n$).

We now turn to build a secret-sharing scheme for mid-slice access structures from (k, a, b) -somewhat-regular secret-sharing schemes. Fix some parameter $\delta \in (0, 0.5)$ and set a proximity parameter ϵ to be $n^{-0.1}$. Let $\Pi = (I_1, \dots, I_k)$ be a partition of $[n]$ to $k = \sqrt{n}$ subsets of size $n/k = \sqrt{n}$ each.¹² In the following, we say that an input $x \in \{0, 1\}^n$ is *good* for the i -th block of Π , if the sub-string $x_i \in \{0, 1\}^{\sqrt{n}}$ is of Hamming weight at least $(0.5 - \delta - \epsilon)\sqrt{n}$ and at most $(0.5 + \delta + \epsilon)\sqrt{n}$. We say that x is good for the partition Π if x is *good* for all the blocks $i \in [k]$ of Π . If x is not good then it is called bad. We will use the following lemma.

Lemma 5.7. *For every constant $\delta > 0$, there exists a collection of $\lambda = O(n)$ partitions $\Pi_1, \dots, \Pi_\lambda$ of $[n]$ to \sqrt{n} subsets of size \sqrt{n} each, such that every n -bit string x of Hamming weight $(0.5 - \delta)n \leq \text{wt}(x) \leq (0.5 + \delta)n$ is good for at least 0.7λ of the partitions.*

The hidden constant in the big-O notation depends on δ .

Proof. We use the probabilistic method to choose at random such a collection of size $\lambda = O(n)$, and see that with positive probability all inputs are good for at least 0.7λ of the partitions.

Fix an input x of weight $(0.5 - \delta)n \leq \text{wt}(x) \leq (0.5 + \delta)n$. We start the analysis by sampling a partition Π with uniform distribution. We first focus on a single block i , and denote by $Y_{j,i}$ the indicator random variable that is equal to 1 if and only if the j -th bit of the i -th block is 1. For every $i \in [\sqrt{n}]$, the \sqrt{n} variables $\{Y_{j,i}\}_{j \in [\sqrt{n}]}$ are negatively associated (see the Claim A.7). We now denote $Y_i = \sum_j Y_{j,i}$ to be the random variable representing the number of ones of x that are placed in the i -th block of Π . Due to the linearity of expectation, and to x being of “middle” weight, we get that the expectation μ of Y_i

¹²The choice of \sqrt{n} is somewhat arbitrary and any choice of block size $\omega(\log n) < |B| < o(n)$ suffices for the final result.

satisfies $(0.5 - \delta) \sqrt{n} \leq \mu \leq (0.5 + \delta) \sqrt{n}$. The probability that x is bad for the i -th block is a sum of two probabilities, that x puts too many ones or too few. These probabilities behave the same asymptotically, so we will analyze only the former probability. By the negative associativity we can use the Chernoff bound, and get

$$\Pr [Y_i \geq (0.5 + \delta + \epsilon) \sqrt{n}] \leq e^{-\frac{\epsilon^2 c^2 \mu}{3}} = e^{-\Omega(c^2 n^{0.3})},$$

where $c = 1/(0.5 + \delta)$ and the last equation follows since $\epsilon = n^{-0.1}$.

Now by union bound over all blocks, the probability that x is bad for the partition Π is at most

$$p = \sqrt{n} e^{-\Omega(c^2 n^{0.3})} = o(1).$$

Finally, if we independently sample λ partitions, the probability that x is bad for at least 0.3λ of the partitions is, by a Chernoff bound, at most $2^{-\Omega(\lambda)}$. By taking $\lambda = Cn$ for sufficiently large constant C , the latter probability is smaller than 2^{-n} , so the lemma follows by applying a union bound over all possible inputs. \square

We can now realize a mid-slice access structure.

Lemma 5.8. *Let F be a mid-slice access structure over n parties with parameter $\delta \in (0, 0.5)$. Then, F can be realized by a secret-sharing scheme with share size of $m' \cdot O(n \log n)$, assuming that any (k, a, b) -somewhat-regular access structure can be realized by a secret-sharing scheme with share size of m' , where*

$$k = \sqrt{n}, \quad a = (0.5 - \delta - n^{-0.1}) \sqrt{n}, \quad \text{and} \quad b = (0.5 + \delta + n^{-0.1}) \sqrt{n}.$$

Proof. We start by considering a partial mid-slice access structure. Recall (Definition 5.6) that such an access structure is defined only over the middle slice, i.e., over inputs whose Hamming weight is in the interval $[0.5n \pm \delta n]$.

Construction 5.9. We realize such an access structure F as follows:

1. Let $L = (\Pi_1, \dots, \Pi_\lambda)$ be the list of partitions of length $\lambda = O(n)$ promised by Lemma 5.7.
2. Share s into λ shares $(\sigma_1, \dots, \sigma_\lambda)$ via a $\lambda/2$ -out-of- λ threshold secret-sharing scheme (using fresh randomness).
3. For every $i \in [\lambda]$ share each σ_i with a different random string r_i by a secret-sharing scheme realizing the (k, a, b) -somewhat-regular access structure $F_{\Pi_i, a, b}$ (as defined in Remark 5.3).

We analyze the construction. Fix some input x of Hamming weight $(0.5 - \delta) \leq \text{wt}(x) \leq (0.5 + \delta)$. Let $I \subset [\lambda]$ denote the set $\{i : x \text{ is good for } \Pi_i\}$, and recall that, by Lemma 5.7, the set I is of size at least 0.7λ . Observe that $F(x) = F_{\Pi_i, a, b}(x)$ for every $i \in I$. If $F(x) = 1$ then at least 0.7λ shares σ_i , where $i \in I$, can be reconstructed by the parties in x and s can be recovered. If $F(x) = 0$ then at least 0.7λ shares σ_i , where $i \in I$, are kept perfectly hidden (due to the privacy of $F_{\Pi_i, a, b}$) and so s remains perfectly hidden (i.e., we can perfectly simulate the view of the parties that participate in x).¹³

We use Shamir's secret-sharing scheme [49] to implement the threshold part and so each σ_i is of length $O(\log \lambda)$ (see Theorem 3.4). Hence, the share size per party is $O(m' \lambda \log \lambda) = O(m' n \log n)$ where m' is the size of shares of the underlying somewhat-regular scheme.

¹³ Note that when $i \notin I$ there are no guarantees on the share σ_i , e.g., it is possible that $F(x) = 0$ and the parties in x can recover σ_i or that $F(x) = 1$ and the parties in x would have no information on σ_i . However, since we use a threshold scheme to share s , this does not affect the correctness and privacy of the construction.

We move on to handle the case where F is defined over all inputs. This part of the construction is quite straightforward. Recall (Definition 5.6) that such an access structure takes the value 0 over light inputs, the value 1 over heavy inputs and may take arbitrary values over the middle slice. Letting F' denote the partial mid-slice access structure that agrees with F over the mid slice, we realize F as follows:

1. Share s via a $((0.5 + \delta)n + 1)$ -out-of- n secret-sharing scheme and give the i -th share, denoted by u_i , to the i -th party.
2. Share s via 2-out-of-2 secret-sharing into s_0 and s_1 .
3. Share s_0 via a $(0.5 - \delta)n$ -out-of- n secret-sharing scheme and give the i -th share, denoted by v_i , to the i -th party.
4. Share s_1 to all parties according to F' (using Construction 5.9) and give the i -th share, denoted by w_i , to the i -th party.

Correctness: Any input x of weight at least $(0.5 + \delta)n + 1$ can reconstruct s via the u shares, and any middle-slice input x which is authorized (i.e., $F(x) = 1$) can recover s_0 and s_1 (via the v and w shares) and can therefore recover s .

Privacy: A coalition that corresponds to a light inputs learns nothing from the u shares and from the v shares (due to the privacy of the threshold schemes) and therefore learns nothing about s . A medium-slice coalition that is unauthorized (i.e., $F(x) = 0$) learns nothing from the u shares (due to the privacy of the threshold scheme) and learns nothing from the w shares (due to the privacy of the F' scheme) and so it learns nothing on s .

Since each w_i is of length $O(m'n \log n)$ and the bit-length of u_i and v_i is $O(\log n)$, the share size per party is $O(m'n \log n) + O(\log n) = O(m'n \log n)$. \square

5.3 The Exponent of Mid-Slice Access Structures

Let us denote by $\mathbf{M}(\delta)$ the exponent of mid-slice access structure with parameter δ . Namely,

$$\mathbf{M}(\delta) = \limsup_{n \rightarrow \infty} \max_{F \in \mathcal{M}(\delta, n)} \frac{1}{n} \log \text{SS}(F),$$

where $\mathcal{M}(\delta, n)$ is the family of all n -party δ -mid-slice access structures. The linear exponent, $\mathbf{M}_\ell(\delta)$, is defined analogously except that $\text{SS}(F)$ is replaced with $\text{LSS}(F)$.

In [39] it was shown that $\mathbf{M}(\delta) \leq \text{H}_2(0.5 - \delta) + 0.2h(10\delta) + 10\delta - 0.2 \log(10)$, and for the linear case $\mathbf{M}_\ell(\delta) \leq \text{H}_2(0.5 - \delta) + 0.2 \text{H}_2(10\delta) + 2 \log(26)\delta - 0.1 \log(10)$. Based on Lemma 5.8, and our constructions for robust CDS protocols we prove a better bound:

Lemma 5.10. *For every $\delta \in (0, 0.5)$ the following holds*

$$\mathbf{M}(\delta) \leq \begin{cases} (0.5 + \delta) \text{H}_2\left(\frac{1/2 - \delta}{1/2 + \delta}\right) & \text{if } \delta < 1/6 \\ (0.5 + \delta) & \text{if } \delta \geq 1/6 \end{cases}.$$

For the linear case, when $\delta < 1/6$, it holds that

$$\mathbf{M}_\ell(\delta) \leq 0.5 + 0.5 (0.5 + \delta) \text{H}_2((0.5 - \delta)(0.5 + \delta)).$$

Proof. Using the secret-sharing schemes with properties promised by Lemma 5.5 and Lemma 5.8, a mid-slice secret-sharing scheme for an access structure $F_{\text{mid},\delta}$ over n parties can be realized from an (a, b) -monotone RCDS protocols with k servers for functions $f : (\{0, 1\}^\ell)^k \rightarrow \{0, 1\}$ where $k = \ell = \sqrt{n}$, and $a = (0.5 - \delta - \epsilon) \sqrt{n}$, $b = (0.5 + \delta + \epsilon) \sqrt{n}$, where $\epsilon = n^{-0.1}$. Assuming that these RCDS protocols have communication complexity m , we get a secret-sharing scheme for $F_{\text{mid},\delta}$ with complexity

$$m \cdot O(n \log n) \cdot \sum_{j=a}^b \binom{n/k}{j} = m \cdot \text{poly}(n) \cdot O(2^{\sqrt{n}}) = m \cdot 2^{o(n)}.$$

Similarly, we get a linear secret-sharing scheme of complexity $m_\ell \cdot 2^{o(n)}$ where m_ℓ is the share size of an underlying linear robust CDS protocols. So, the exponent is derived solely from the cost of the underlying robust CDS protocol. By definition (see (1)) an (a, b) -monotone collection is a (u, t) -collection where

$$u = \binom{\ell}{b} \quad \text{and} \quad t = \sum_{i=a}^b \binom{b}{i}. \quad (3)$$

So, by applying Theorem 4.5, we can realize (a, b) -monotone robust CDS with complexity of

$$\begin{aligned} m &= 2^{o(n)} \cdot \left[\sum_{j=0}^{2\delta\sqrt{n}} \binom{(0.5 + \delta + \epsilon) \sqrt{n}}{(0.5 - \delta - \epsilon) \sqrt{n} + j} \right]^{\sqrt{n}-1} \\ &\quad \cdot \left[\sqrt{n} \log \left(\frac{\sqrt{n}}{(0.5 + \delta + \epsilon) \sqrt{n}} \right) \right]^{\sqrt{n}}. \end{aligned}$$

For the linear case, Theorem 4.5 yields the bound $m_\ell \leq O_t(2^\ell t \log u)^{\sqrt{n}/2}$ which, under our choice of parameters, simplifies to

$$\begin{aligned} m_\ell &\leq O(2^{n/2}) \\ &\quad \cdot \left[\sum_{j=0}^{2\delta\sqrt{n}} \binom{(0.5 + \delta + \epsilon) \sqrt{n}}{(0.5 - \delta - \epsilon) \sqrt{n} + j} \log \left(\frac{\sqrt{n}}{(0.5 + \delta + \epsilon) \sqrt{n}} \right) \right]^{\frac{\sqrt{n}}{2}}. \end{aligned}$$

Both terms m and m_ℓ have different asymptotic behavior for $\delta < 1/6$ or $\delta \geq 1/6$. Specifically, recalling that $\epsilon = n^{-0.1}$, and using the standard entropy-based bound for the binomial coefficients, we get that

$$m = \begin{cases} 2^{(0.5+\delta) \text{H}_2\left(\frac{1/2-\delta}{1/2+\delta}\right)n+o(n)} & \text{if } \delta < 1/6 \\ 2^{(0.5+\delta)n+o(n)} & \text{if } \delta \geq 1/6 \end{cases},$$

For linear CDS we get

$$m_\ell = 2^{0.5n+0.5(0.5+\delta) \text{H}_2\left(\frac{1/2-\delta}{1/2+\delta}\right)n+o(n)}$$

when $\delta < 1/6$, and $m_\ell = \Omega(2^n)$ when $\delta \geq 1/6$. □

5.4 Putting It Altogether (Proof of Theorem 2.1)

In [39] the exponent of general access structures was reduced to the exponent of mid-slice access structures. To realize an access structure F , they realize the mid-slice of F and in addition they realize the access structure whose minterms are the light minterms of F and the access structure whose maxterms are the heavy maxterms of F (where a minterm is a minimal authorized set and a maxterm is a maximal unauthorized set); the latter two access structures are realized by the trivial schemes. In [3] more efficient schemes realizing the latter two access structures were presented (using schemes with exponent smaller than 1). Using the current notation, we get the following lemma:

Lemma 5.11 ([3]). *For every $\delta \in (0, 0.5)$ it holds that*

$$\mathbf{S} \leq \max(\mathbf{X}'(\delta), \mathbf{M}(\delta)) \quad \text{and} \quad \mathbf{S}_\ell \leq \max(\mathbf{X}'(\delta), \mathbf{M}_\ell(\delta))$$

where

$$\mathbf{X}'(\delta) = H_2(0.5 - \delta) - (0.5 - \delta) \log((0.5 + \delta)(0.5 - \delta)).$$

The proof of Theorem 2.1 follows directly from the combination of Lemma 5.10 and Lemma 5.11 with $\delta \sim 0.1429$ for the general case, and $\delta_\ell \sim 0.09$ for the linear case. Indeed, Lemma 5.11 yields exponents of 0.637 in the general case and 0.762 in the linear case.

6 A Linear k -Server RCDS Protocol

We show that for an odd k a (non-optimized) variant of the linear CDS protocol of [12] is robust when half of the servers can send an unbounded number of messages (a variant of this protocol has similar properties when k is even). We assume without loss of generality that for the k -input function f , for every $j \in \{(k+3)/2, \dots, k\}$ there exists an input $a_j \in X_j$ such that $f(i_1, \dots, i_{j-1}, a_j, i_{j+1}, \dots, i_k) = 0$ for every $i_1 \in X_1, \dots, i_{j-1} \in X_{j-1}, i_{j+1} \in X_{j+1}, \dots, i_k \in X_k$ (this can be done by adding a dummy element to the input domain of server Q_j).

Lemma 6.1. *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a function, where $|X_i| \leq 2^\ell$, for some odd integer $k > 2$. Then, for every finite field \mathbb{F} , protocol \mathcal{P}_k , described in Figure 1, is a linear k -server $(2^{X_1}, \dots, 2^{X_{(k+1)/2}})$ -RCDS protocol for f with domain of secrets \mathbb{F} , in which the message size is $2^{\ell(k-1)/2} \log |\mathbb{F}|$.*

Proof. For proving the correctness of the protocol \mathcal{P}_k let x_1, \dots, x_k be inputs such that $f(x_1, \dots, x_k) = 1$. In this case, server Q_1 sends s_{x_1, \dots, x_k} to the referee (in addition to other elements), server Q_j , for $2 \leq j \leq k'$, sends $q_{x_1, \dots, x_{k'}}^j$ to the referee, and for every $(i_{k'+1}, \dots, i_k) \neq (x_{k'+1}, \dots, x_k)$ at least one server Q_j (where $k'+1 \leq j \leq k$) sends $r_{i_{k'+1}, \dots, i_k}$. Since $f(x_1, \dots, x_k) = 1$, the random element $r_{x_{k'+1}, \dots, x_k}$ does not appear in s_{x_1, \dots, x_k} . Thus, the referee can compute the expression in step 5 of \mathcal{P}_k , which equals s .

For the robustness of the protocol, recall that $k' = (k+1)/2$. Assume that each server Q_j for $k'+1 \leq j \leq k$ sends a message of a single input $x_j \in X_j$,¹⁴ and each server Q_j for $1 \leq j \leq k'$ sends messages for a subset of inputs $Z_j \subseteq X_j$ such that $f(x_1, \dots, x_{k'}, x_{k'+1}, \dots, x_k) = 0$ for every $(x_1, \dots, x_{k'}) \in Z_1 \times \dots \times Z_{k'}$. We prove below that these messages are statistically independent from the secret.

The referee gets the following messages:

¹⁴If such server does not send any message, we will assume that it sends the message of the dummy input a_j .

Protocol \mathcal{P}_k

The secret: An element $s \in \mathbb{F}$.

Inputs: Servers Q_1, \dots, Q_k hold the inputs $x_1 \in X_1, \dots, x_k \in X_k$, respectively.

Common randomness: Let $k' = (k + 1)/2$. The k servers hold the following uniformly distributed and independent random elements.

- $q_{i_1, \dots, i_{k'}}^j \in \mathbb{F}$ for every $j \in \{2, \dots, k'\}$ and every $i_1 \in X_1, \dots, i_{k'} \in X_{k'}$.
- $r_{i_{k'+1}, \dots, i_k} \in \mathbb{F}$ for every $i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k$.

The protocol:

1. Define $q_{i_1, \dots, i_{k'}} = \sum_{j=2}^{k'} q_{i_1, \dots, i_{k'}}^j$ for every $i_1 \in X_1, \dots, i_{k'} \in X_{k'}$.
2. Server Q_1 sends to the referee the elements

$$s_{x_1, i_2, \dots, i_{k'}} = s + q_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_k)=0} r_{i_{k'+1}, \dots, i_k}$$

for every $i_2 \in X_2, \dots, i_{k'} \in X_{k'}$.

3. For every $j \in \{2, \dots, k'\}$, server Q_j sends to the referee the elements $q_{i_1, i_2, \dots, i_{j-1}, x_j, i_{j+1}, \dots, i_{k'}}^j$ for every $i_1 \in X_1, \dots, i_{j-1} \in X_{j-1}, i_{j+1} \in X_{j+1}, \dots, i_{k'} \in X_{k'}$.
4. For every $j \in \{k'+1, \dots, k\}$, server Q_j sends to the referee the elements $r_{i_{k'+1}, \dots, i_k}$ for every $i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k$ such that $i_j \neq x_j$.
5. If $f(x_1, \dots, x_k) = 1$, the referee computes

$$s_{x_1, x_2, \dots, x_{k'}} - q_{x_1, \dots, x_{k'}} - \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, \dots, x_{k'}, i_{k'+1}, \dots, i_k)=0} r_{i_{k'+1}, \dots, i_k}$$

Figure 1: A linear k -server CDS protocol \mathcal{P}_k for a function $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$.

The messages of Q_1 . The elements

$$s_{x_1, i_2, \dots, i_{k'}} = s + q_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_{k'}, i_{k'+1}, \dots, i_k) = 0} r_{i_{k'+1}, \dots, i_k}$$

for every $(i_2, \dots, i_{k'}) \in X_2 \times \dots \times X_{k'}$ and every $x_1 \in Z_1$.

The messages of $Q_2, \dots, Q_{k'}$. The elements $q_{i_1, i_2, \dots, i_{k'}}^j$ for every $j \in \{2, \dots, k'\}$ and every $i_1 \in X_1, \dots, i_{k'} \in X_{k'}$ such that $i_j \in Z_j$. In particular, for every $(x_1, \dots, x_{k'}) \in Z_1 \times \dots \times Z_{k'}$, the referee gets the elements $q_{x_1, \dots, x_{k'}}^2, q_{x_1, \dots, x_{k'}}^3, \dots, q_{x_1, \dots, x_{k'}}^{k'}$, thus it can compute $q_{x_1, \dots, x_{k'}}$.

The messages of $Q_{k'+1}, \dots, Q_k$. The elements $r_{i_{k'+1}, \dots, i_k}$ for every $i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k$ except for $r_{x_{k'+1}, \dots, x_k}$.

Intuitively, for every $(x_1, \dots, x_{k'}) \in Z_1 \times \dots \times Z_{k'}$, the element $r_{x_{k'+1}, \dots, x_k}$ acts as a one-time-pad protecting s in $s_{x_1, x_2, \dots, x_{k'}}$, and for every $x_1 \in Z_1$ and every $(i_2, \dots, i_{k'}) \notin Z_2 \times \dots \times Z_{k'}$, the element $q_{x_1, i_2, \dots, i_{k'}}$ acts as a one-time-pad protecting s in $s_{x_1, i_2, \dots, i_{k'}}$.

Formally, for every two secrets $s, s' \in \mathbb{F}$ we show a bijection ϕ from the randomness of \mathcal{P}_k to itself such that the messages in \mathcal{P}_k with secret s and randomness r are the same as the messages in \mathcal{P}_k with secret s' and randomness $r' = \phi(r)$. Consider the random elements

$$r = \left((q_{i_1, \dots, i_{k'}}^j)_{j \in \{2, \dots, k'\}, i_1 \in X_1, \dots, i_{k'} \in X_{k'}}, (r_{i_{k'+1}, \dots, i_k})_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k} \right)$$

and the messages generated from them for the secret s . The bijection is as follows:

1. Define $r'_{i_{k'+1}, \dots, i_k} = r_{i_{k'+1}, \dots, i_k}$ for every $(i_{k'+1}, \dots, i_k) \neq (x_{k'+1}, \dots, x_k)$ and $r'_{x_{k'+1}, \dots, x_k} = r_{x_{k'+1}, \dots, x_k} + s - s'$. Since no server sends $r_{x_{k'+1}, \dots, x_k}$, these values and the secret s' generate the same messages of $Q_{k'+1}, \dots, Q_k$ as the messages in \mathcal{P}_k with the secret s and randomness r .
2. For every $x_1 \in Z_1$ and every $i_2 \in X_2, \dots, i_{k'} \in X_{k'}$ such that $f(x_1, i_2, \dots, i_{k'}, x_{k'+1}, \dots, x_k) = 0$ (in particular, for every $(x_1, i_2, \dots, i_{k'}) \in Z_1 \times \dots \times Z_{k'}$): Define $q'_{x_1, i_2, \dots, i_{k'}} = q_{x_1, i_2, \dots, i_{k'}}$ and for every $j \in \{2, \dots, k'\}$ let $q'_{x_1, i_2, \dots, i_{k'}}^j = q_{x_1, i_2, \dots, i_{k'}}^j$.

Since $f(x_1, i_2, \dots, i_{k'}, x_{k'+1}, \dots, x_k) = 0$, the element $r_{x_{k'+1}, \dots, x_k}$ appears in the sum in $s_{x_1, i_2, \dots, i_{k'}}$ and

$$\begin{aligned} s_{x_1, i_2, \dots, i_{k'}} &= s + q_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_{k'}, i_{k'+1}, \dots, i_k) = 0} r_{i_{k'+1}, \dots, i_k} \\ &= s' + q'_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_{k'}, i_{k'+1}, \dots, i_k) = 0} r'_{i_{k'+1}, \dots, i_k}. \end{aligned}$$

Thus, the same message $s_{x_1, i_2, \dots, i_{k'}}$ is generated for s and s' with r and $r' = \phi(r)$, respectively.

3. For every $x_1 \in Z_1$ and every $i_2 \in X_2, \dots, i_{k'} \in X_{k'}$ such that $f(x_1, i_2, \dots, i_{k'}, x_{k'+1}, \dots, x_k) = 1$, let j_0 be the minimal index such that $i_{j_0} \notin Z_{j_0}$ and define $q'_{x_1, i_2, \dots, i_{k'}}^{j_0} = q_{x_1, i_2, \dots, i_{k'}}^{j_0} + s - s'$ and $q'_{x_1, i_2, \dots, i_{k'}}^j = q_{x_1, i_2, \dots, i_{k'}}^j$ for every $j \neq j_0$, thus,

$$q'_{x_1, i_2, \dots, i_{k'}} = \sum_{j=2}^{k'} q_{x_1, i_2, \dots, i_{k'}}^j = \sum_{j=2}^{k'} q_{x_1, i_2, \dots, i_{k'}}^j + s - s' = q_{x_1, i_2, \dots, i_{k'}} + s - s'.$$

Since $f(x_1, i_2, \dots, i_{k'}, x_{k'+1}, \dots, x_k) = 1$, the element $r_{x_{k'+1}, \dots, x_k}$ does not appear in the sum in $s_{x_1, i_2, \dots, i_{k'}}$ and

$$\begin{aligned} s_{x_1, i_2, \dots, i_{k'}} &= s + q_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_{k'}, i_{k'+1}, \dots, i_k) = 0} r_{i_{k'+1}, \dots, i_k} \\ &= s' + q'_{x_1, i_2, \dots, i_{k'}} + \sum_{i_{k'+1} \in X_{k'+1}, \dots, i_k \in X_k, f(x_1, i_2, \dots, i_{k'}, i_{k'+1}, \dots, i_k) = 0} r'_{i_{k'+1}, \dots, i_k}. \end{aligned}$$

Thus, the same message $s_{x_1, i_2, \dots, i_{k'}}$ is generated for s and s' with r and $r' = \phi(r)$, respectively. Since $q'_{x_1, i_2, \dots, i_{k'}}^{j_0}$ is not sent by Q_{j_0} , these values and the secret s' generate the same messages of $Q_2, \dots, Q_{k'}$ as the messages in \mathcal{P}_k with the secret s and randomness r .

4. For every $i_1 \notin Z_1, i_2 \in X_2, \dots, i_{k'} \in X_{k'}$ and every $j \in \{2, \dots, k'\}$, let $q_{i_1, i_2, \dots, i_{k'}}^{j'} = q_{i_1, i_2, \dots, i_{k'}}^j$.

To conclude, the messages have the same probability for s and s' . which implies the robustness. \square

9

7 Immunizing CDS Servers: Abstraction and an Alternative Construction

In this section we provide an abstraction of the construction in Theorem 4.4, which shows how to “immunize” a single server. For starters, it will be instructive to consider the following more abstract “secure channel” setting.

7.1 How to Immunize a Channel?

Suppose that a sender wishes to send t private messages to a receiver. The messages arrive in on online manner, one after the other, and the sender is connected to the receiver via N unidirectional channels that offer one-time privacy. That is, once a channel is being used twice all the messages that were sent over it are revealed to everyone. The goal is to minimize N as a function of t while maintaining perfect privacy for all messages. Our sender is stateless, and so it cannot even remember how many messages have been sent so far. In particular, the trivial solution of sending the i -th message over the i -th channel is inapplicable.

Fortunately, each message m_i arrives with some (non-private) unique tag $x_i \in X$ that is available to both parties. Therefore, we can naively solve the problem with $N = |X|$ channels by allocating a channel to each possible tag. The question is can we do better when t is significantly smaller than $|X|$? More generally, say that we know ahead of time that the sequence of t tags belong to one of u possible t -subsets $Z_1, \dots, Z_u \subset X$ which are a-priori fixed. How small can N be as a function of t and u ?

The Select-and-Share approach. A natural way to solve the problem is to *secret share* each message $m \in M$ to shares $(s_1, \dots, s_N) \in M^N$ via some secret-sharing scheme \mathcal{D} , and deliver these shares over a subset of the channels that is *selected* according to the tag x . That is, we send s_i over the i -th channel if i is in the set $H(x)$ where H is some “hash” function that maps a tag $x \in X$ to subsets of N . Correctness is guaranteed as long as $H(x)$ is an authorized set of the secret-sharing scheme for every $x \in X$. On the other hand, as long as the pair-wise intersections of $H(x)_{x \in Z}$ forms an unauthorized set, we get privacy for the set of inputs Z . The immunization question now boils down to designing such an admissible hash-function/secret-sharing pair (\mathcal{D}, H) for a given sequence of t -size input sets $Z_1, \dots, Z_u \subset X$ while minimizing N .

Concrete instantiations We describe two different solutions for the problem that achieve $N = (t \text{ polylog } u)$ complexity. In both cases, the starting point is an inefficient construction with quadratic overhead. The first approach is essentially the one described in the introduction and in Section 4.3. Take a family of λ *perfect hash functions* $H = \{h_1, \dots, h_\lambda : X \rightarrow [t^2]\}$ for the set family $(Z_i)_{i \in [u]}$. That is, for every $i \in [u]$ there exists a function $h \in H$ that perfectly hashes the elements of Z_i to t distinct values. We place the N channels on a $\lambda \times t^2$ matrix, and given a message m labeled by x , we share m via λ -out-of- λ secret-sharing scheme to (s_1, \dots, s_λ) , and send the secret s_i over the channel (i, j) iff $h_i(x) = j$. Accordingly, a subset of channels is authorized iff it contains at least a single channel in each row. Clearly, every message is delivered over an authorized set of channels. On the other hand, since $h_j \in H$ is perfect over Z_i , the pair-wise intersections of $H(x)_{x \in Z_i}$ completely avoids the j -th row of channels.

By taking λ to be logarithmic in u (as in the perfect hashing of [27]), we get a quasi-quadratic bound on N . In order to reduce the overhead to $t \text{ polylog } u$, we apply the quadratic solution over the collection $\binom{X}{\log t}$ of all $\log t$ -subsets of X . This effectively upgrades one-time security into a $\log t$ -security. The latter channel can be further immunized via a more liberal combination of hash function/secret-sharing pair: Only $\log t$ -wise intersections of $H(x)_{x \in Z}$ should form an unauthorized set. This condition translates to a weaker version of perfect hashing that can be obtained with poly-logarithmic overhead. Overall, the resulting two-level hashing construction resembles a similar construction of [20], that was suggested in the context of traitor-tracing schemes.

In the following subsections, we present an alternative construction that achieves similar parameters based on “sparse-hashing”. Roughly, the message is secret-shared via a threshold secret-sharing scheme with threshold βN , and each x is mapped to a β -sparse subset of N so that the Z_i -intersection of the sets results in a sparser set of density strictly smaller than β . This construction is inspired by the a similar construction of [31] that was presented in the context of Functional Encryption.¹⁵ To optimize the parameters, we apply it again in a two-level way.

Back to RCDS The channel solution can be immediately adopted to the distributed CDS setting. The servers use their shared randomness to secret-share the CDS secret s according to the secret-sharing scheme \mathcal{D} , and use N copies of CDS with independent random strings to deliver the shares s_1, \dots, s_N . The i -th server, that should be immunized, sends his messages only for the CDS instances that are indexed by $H(x_i)$ and remains silent in all other instances. All other parties send their messages for all the CDS instances. Correctness and privacy follow immediately from the correctness and privacy guarantees of the channel problem. As already mentioned, by immunizing the servers one after the other, we derive a general immunization procedure that transforms a general CDS to a RCDS.

The remainder of this section. In the following subsection (Section 7.2), we present the select-and-share template and prove its validity. In order to avoid additional notation, we present the transformation in the language of CDS. That is, our goal is to transform a CDS protocol that is robust over some collection $I \times \mathcal{Y}$ (where I consists only of singletons of the input of the first server) to a CDS protocol that is robust over $\mathcal{Z} \times \mathcal{Y}$ for some collection \mathcal{Z} . In Section 7.3 we instantiate the transformation via sparse-hashing, and show how to immunize a server over a (u, t) collection that consists of u maximal sets, each of size at most t . By immunizing one server at a time, we derive an alternative immunization procedure whose overhead essentially matches the overhead of Theorem 4.4.

¹⁵Indeed, the fact that the channel abstraction captures previous scenarios suggests that this is a useful notion that may be also applied in future contexts.

7.2 A Template for Immunizing a Single Server

We formalize the select and share approach suggested in the previous subsection. That is, we secret-share s to N shares and send each one of them via an independent copy of a CDS protocol. The immunized server will only use a subset of these copies that will be determined based on the input of the immunized server via the aid of some hash function.

Construction 7.1 (Select and share). Let $f : X_1 \times \cdots \times X_k \rightarrow \{0, 1\}$ be a function for a CDS protocol $\mathcal{P} = (\text{ENC}_i)_{i \in [k]}$ for secrets in S and randomness domain R . Let N be an integer, $H : X_1 \rightarrow 2^{[N]}$ be a mapping, and let \mathcal{D} be a (randomized) sharing function that maps a secrets $s \in T$ into a vector of N shares $(s'_1, \dots, s'_N) \in S^N$ using randomness from the domain R_0 . Define the following new CDS for a secret $s \in T$, and randomness domain of $R_0 \times R^N$:

1. Given $s \in T$ and $(r_0, r_1, \dots, r_L) \in R_0 \times R^N$, each server applies \mathcal{D} to s and r_0 and generates the shares (s'_1, \dots, s'_N) .
2. Each server j computes a vector v_j of N messages

$$v_j = (\text{ENC}_j(x_j, s'_1, r_1), \dots, \text{ENC}_j(x_j, s'_N, r_N)).$$

3. The first server computes the set $H(x_1) \subseteq [N]$ and outputs only the entries $(v_1[i])_{i \in H(x_1)}$.
4. Every other server $j > 1$ outputs its entire vector of messages v_j .

Before analyzing the construction we need the following simple definition. The set of *collisions* of a collection of sets A_1, \dots, A_q is the set of elements that appear in at least two of the sets A_1, \dots, A_q .

Lemma 7.2. *Suppose that: (1) For every $x \in X_1$ the set $H(x)$ is an authorized set of the secret-sharing scheme \mathcal{D} ; (2) The underlying protocol \mathcal{P} is an $\mathcal{I} \times \mathcal{Y}$ -RCDS protocol, where $\mathcal{I} = \{\{x\} : x \in X_1\} \cup \emptyset$; and (3) For every $Z \in \mathcal{Z}_1$, the set of collisions of the set system $\{H(x)\}_{x \in Z}$ is a non-authorized set of the secret-sharing scheme \mathcal{D} . Then Construction 7.1 is a $\mathcal{Z}_1 \times \mathcal{Y}$ -RCDS protocol.*

Proof. We claim that the protocol is perfectly correct. Indeed, fix an input (x_1, y) for which $f(x_1, y) = 1$. Then, the decoder computes the set $A = H(x_1)$ and for every $i \in A$ it applies the decoder of the original CDS protocol to i -th component of the transcript, i.e., to $(v_1[i], \dots, v_k[i])$. By the correctness of the underlying CDS protocol, the value s'_i is recovered. Since A is an authorized set of the secret-sharing scheme (by the lemma's hypothesis) the shares $(s'_i)_{i \in A}$ can be used to recover the secret s .

Next, we prove that the protocol is robust over a zero-set $Z \times Y$, where $Z \in \mathcal{Z}_1$ and $Y \in \mathcal{Y}$. For secret $s \in T$, input (x_1, y) , and randomness $r = (r_0, \dots, r_L)$, let $D(x_1, y, r, s)$ denote the concatenation of the messages that are sent by all the servers. Also, let $D(x_1, y, r, s)[i]$ denote the concatenation of the i -th messages of the servers. (If $i \notin H(x_1)$ then the first entry of $D(x_1, y, r, s)[i]$ is taken to be \perp .) Fix a pair of secrets s and s' , we show that the random variables $D(s) := (D(x_1, y, r, s))_{(x_1, y) \in (Z \times Y)}$ and $D(s') := (D(x_1, y, r, s'))_{(x_1, y) \in (Z \times Y)}$ induced by a uniform choice of r , are distributed identically.

Let $A \subseteq [N]$ be the set of collisions of $\{H(x_1)\}_{x_1 \in Z}$. To prove that $D(s)$ and $D(s')$ are identical, we show that (1) The restriction of $D(s)$ and $D(s')$ to the indices in A is identically distributed; and (2) Conditioned on every fixing of $D(s)[A]$ and $D(s')[A]$, for every $i \notin A$ the random variables $D(s)[i]$ and $D(s')[i]$ are identically distributed, and are independent of all other i 's outside A .

We prove (1). Since the set A of collisions is a non-authorized set, the A -shares $(s_i)_{i \in A}$ of s and the A -shares $(s'_i)_{i \in A}$ of s' , induced by a uniform choice of r_0 , are identically distributed. Hence, for uniformly

chosen r_0 and $r_A = (r_i)_{i \in A}$ (and every fixing of $(r_i)_{i \notin A}$), the A -components of $D(s)$ and $D(s')$ are identically distributed.

We move on to (2). Fix some arbitrary r_0, r_A and let $(s_i)_{i \in \bar{A}}$ and $(s'_i)_{i \in \bar{A}}$ denote the resulting \bar{A} -shares of s and s' . For every $i \in \bar{A}$, let $I_i := \{x_1 \in Z : i \in H(x_1)\}$ denote the set of inputs for which the first server “speaks” in the i -th session. By assumption, $|I_i| \leq 1$ and therefore the underlying CDS is robust over the zero-set $I_i \times Y$. It follows that the i -th components of $D(s)$ and $D(s')$ are identically distributed when r_i is uniformly chosen. Since the r_i ’s are chosen independently, $D(s)$ is distributed identically to $D(s')$. \square

7.3 Instantiating the Template

The above template can be instantiated based on perfect hash functions as shown in Section 4.2. We provide here an alternative instantiation based on sparse hash functions.

Recall that Construction 7.1 makes use of a secret-sharing scheme over a set of N parties. In the following we let $N = N_1 \cdot N_2$, and view the set $[N]$ as $[N_1] \times [N_2]$. Correspondingly a subset M of $[N]$ can be represented as $N_1 \times N_2$ binary matrix. We will need a (partial) access structure for which M is an authorized set if at least β -fraction of the rows have at least γN_2 ones, and M is unauthorized if there are at most 0.5β fraction of the rows with more than $0.6\gamma N_2$ ones. (The parameters N_1, N_2, β, γ will be defined below.) We refer to this access structure as a $(\beta, \gamma, N_1, N_2)$ -access structure. Such an access structure can be easily realized by applying a two-levels threshold secret sharing (or ramp-secret sharing). For example, distribute the secret to N_1 shares s_1, \dots, s_{N_1} , say via Shamir’s secret-sharing scheme with threshold $0.8\beta N_1$, and then distribute each s_i to N_2 shares $s_{i,1}, \dots, s_{i,N_2}$ via Shamir’s secret-sharing scheme with threshold of $0.8\gamma N_2$. The share $s_{i,j}$ is held by the (i, j) -th party.

Fact 7.3. *For every positive integers N_1, N_2 and reals $\beta, \gamma \in (0, 1)$ and every field \mathbb{F} of size at least $\max(N_1, N_2) + 1$, there exists a secret-sharing scheme that realizes the $(\beta, \gamma, N_1, N_2)$ -access structure and maps a secret $s \in \mathbb{F}$ to the shares $(s_{i,j})_{i \in [N_1], j \in [N_2]} \in \mathbb{F}^{N_1 \times N_2}$.*

Next, we need a hash function H that maps $x \in X$ to subsets of $[N_1] \times [N_2]$ (or to $N_1 \times N_2$ binary matrices). We view H as a sequence of N_1 hash functions $h_1, \dots, h_{N_1} : X \rightarrow 2^{[N_2]}$ one for each row. That is, $(i, j) \in H(x)$ if $j \in h_i(x)$. The collection should be compatible with the $(\beta, \gamma, N_1, N_2)$ -access structure and with the collection of input tuples against which we should immunize.

Definition 7.4. *Let X be a set and let Z_1, \dots, Z_u be a sequence of t -subsets of X , i.e., $Z_i \in \binom{X}{t}$ for every i . A $(\beta, \gamma, N_1, N_2)$ hash function family $H = \{h_1, \dots, h_{N_1}\}, h_i : X \rightarrow 2^{[N_2]}$ for Z satisfies the following properties: (1) For every $x \in X$ exactly βN_1 functions in H , map x to a subset of $[N_2]$ of size at least γN_2 ; and (2) For every set of inputs Z_i , where $i \in [u]$, for all but $\beta/2$ -fraction of the hash functions h_j , where $j \in [N_1]$ the family of sets $\{h_j(x)\}_{x \in Z_i}$ has at most $0.6\gamma N_2$ collisions.*

In Section 7.4 we will we prove the following lemma.

Lemma 7.5. *For every X and $Z_1, \dots, Z_u \in \binom{X}{t}$, there exists $(\beta, \gamma, N_1, N_2)$ -hash function H with $N_1 = O(t \log u)$ and $N_2 = \log t \cdot \text{polylog}(t, \log u)$ where for every x the set $H(x) = \bigcup_i h_i(x)$ is of size exactly $\beta\gamma N_1 N_2$, and behaves asymptotically as $\log^2 u \cdot \text{polylog}(t, \log u)$.*

We can now immunize a single server (the (k') -th server) against u different t -subsets Z_1, \dots, Z_u of the server’s input domain (and any subset of these sets). The communication overhead will be $\log^2 u \cdot \text{polylog}(t, \log u)$ for the immunized server, and $\tilde{O}(t \log^2 u)$ for the others. Formally, we prove the following theorem.

Theorem 7.6. *Let $1 \leq k' \leq k$ be integers, $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a function, $(\mathcal{Y}_1, \dots, \mathcal{Y}_{k'-1}, \mathcal{Z}) \subseteq 2^{X_1} \times \dots \times 2^{X_{k'}}$ be a (u, t) -robustness collection and $\mathcal{Y} = (\mathcal{Y}_1, \dots, \mathcal{Y}_{k'-1})$. Suppose there is a $(\mathcal{Y}_1, \dots, \mathcal{Y}_{k'-1})$ -RCDS protocol \mathcal{P} for f . Then there is an $(\mathcal{Y}_1, \dots, \mathcal{Y}_{k'-1}, \mathcal{Z})$ -RCDS \mathcal{P}' for f in which the communication complexity of the k' server grows by a factor of $\log^2 u \cdot \text{polylog}(t, \log u)$, and for all the servers grows by a factor of $\tilde{O}(t \log^2 u)$.*

Proof. We immunize the k' -th server against the sets $Z \in \mathcal{Z}$ by applying Construction 7.1 to the RCDS \mathcal{P} (while treating the $k' + 1$ party as the first party).

Let H be $(\beta, \gamma, N_1, N_2)$ -hash family for (Z_1, \dots, Z_u) as promised by Lemma 7.5 where $N_1 = O(t \log u)$, $N_2 = \log u \cdot \text{polylog}(t, \log u)$ and β, γ are as promised by the lemma. Take $N = N_1 \times N_2 = \tilde{O}(t \log^2 u)$. Let \mathbb{F} be a finite field of size at least $\max(N_1, N_2) + 1 < O(t \log u)$ and let \mathcal{D} denote a secret sharing that realizes the $(\beta, \gamma, N_1, N_2)$ -access structure (as promised in Fact 7.3) that maps a secret $s \in \mathbb{F}$ to $\mathbb{F}^{N_1 \times N_2}$. Furthermore, let us slightly modify the RCDS \mathcal{P} into a RCDS \mathcal{P}_1 that supports secrets from \mathbb{F} . If the original domain S is larger than \mathbb{F} we can simply take \mathcal{P} as \mathcal{P}_1 . Otherwise, this can be achieved by concatenating several elements from S . This modification increases the communication complexity by a factor of at most $\log |\mathbb{F}| = O(\log t + \log \log u)$.

Instantiate Construction 7.1 with the RCDS \mathcal{P}_1 , with the mapping H , and with the secret-sharing scheme \mathcal{D} . (Recall that we view subsets of $[N]$ as $N_1 \times N_2$ binary matrices and we abuse notation and let $H(x)$ denote the matrix whose (i, j) -th cell is 1 iff $j \in h_i(x)$.) Fix some zero-set $Z \times Y$ where $Z \in \mathcal{Z}$, and $Y \subset \mathcal{Y}_1 \times \dots \times \mathcal{Y}_{k'-1} \times \binom{X_{k'+1}}{\leq 1} \times \dots \times \binom{X_k}{\leq 1}$. Recall that Z is a subset a maximal set in \mathcal{Z} . Lemma 7.2 shows that the protocol is robust over $(Z \times Y)$, since the following three conditions hold:

1. By assumption, the RCDS protocol \mathcal{P}_1 is robust for every set of the form $I \times Y$ for every singleton $I \subset Z$.
2. Since H is $(\beta, \gamma, N_1, N_2)$ -hash function for the maximal sets (Z_1, \dots, Z_u) and since $Z \subseteq Z_i$ for some $i \in [u]$, it follows that the set of collisions of $\{H(x)\}_{x \in Z}$ is a non-authorized set of the scheme \mathcal{D} . (Written as a matrix, this set has at most $0.5\beta N_1$ rows that have at least $0.6\gamma N_2$ ones.)
3. For every $x \in X_{k'+1}$ the set $H(x)$ is an authorized set of the secret-sharing scheme \mathcal{D} .

As promised by Lemma 7.5, the immunized server $Q_{k'}$ sends $\beta\gamma N$ messages of the protocol \mathcal{P}_1 and each other server sends N CDS messages. Compared to the original CDS \mathcal{P} , the communication complexity of the immunized server grows by a multiplicative factor of $O(\beta\gamma N \log |\mathbb{F}|) = \log^2 u \cdot \text{polylog}(t, \log u)$, and for all other servers by a factor of $O(N \log |\mathbb{F}|) = \tilde{O}(t \log^2 u)$. \square

By iterating over all parties, we derive the following corollary.

Corollary 7.7. *Let \mathcal{P} be a k -server CDS protocol for a function $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ in which each server has a communication complexity c . Let $\mathcal{Z} = (\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ be a (u, t) -robustness collection. Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS \mathcal{P}' with communication $c \tilde{O}(t^{k-1} \log^{2k} u)$. If the original \mathcal{P} is linear then so is \mathcal{P}' .*

Proof. We use Theorem 7.6 k times iteratively starting with the CDS \mathcal{P} . At the i -th iteration, we transform an $(\mathcal{Z}_1, \dots, \mathcal{Z}_{i-1})$ -RCDS into an $(\mathcal{Z}_1, \dots, \mathcal{Z}_i)$ -RCDS. The communication overhead in each step is $\log^2 u \cdot \text{polylog}(t, \log u)$ for the immunized server, and $\tilde{O}(t \log^2 u)$ for all others. Since every server is immunized once, the overall communication grows by a factor of $\tilde{O}(t^{k-1} \log^{2k} u)$.

Finally, assume that the original protocol \mathcal{P} is linear over a field \mathbb{F} . In order to preserve \mathbb{F} -linearity, it suffices to employ an \mathbb{F} -linear secret sharing in Fact 7.3. This is immediate when \mathbb{F} is larger than

$\max(N_1, N_2) + 1$; When \mathbb{F} is smaller this can be achieved by combining a pair of ramp-secret sharing (e.g., by using random linear codes) over \mathbb{F} or by using an implementation over a larger extension field. \square

7.4 Proof of Lemma 7.5

The proof is via the probabilistic method. We define the family H in two steps. We start by selecting for each x a random βN_1 -subset $I_x \subset [N_1]$. In addition, we select N_1 random functions $h'_i, \forall i \in [N_1]$ from X to γN_2 -subsets of $[N_2]$. The final mapping is defined as follows: For every $i \in [N_1]$ let $h_i(x)$ be the empty set if $i \notin I_x$ and otherwise let $h_i(x) = h'_i(x)$. In matrix terminology, the 1-cells of the matrix $H(X)$ that corresponds to x are selected by first choosing a random βN_1 rows and then choosing random γN_2 cells in each of these rows. Clearly, the mapping satisfies the first property of Definition 7.4 and the ‘‘Moreover’’ part. Let

$$\begin{aligned} N_1 &= 2t \log u, & \beta &= \frac{c \log N_1}{t}, \\ N_2 &= c'(2\beta t)^2 \log(3tN_1) = O(\log^2 N_1 \log(N_1 u)), \end{aligned}$$

and $\gamma = 1/(4c^2 \log^2 N_1)$ where c and c' are some positive constants. Fix some tuple of inputs $Z = (x_1, \dots, x_t)$. We show that, except with probability $1/(3u)$, the collection H satisfies the second property of Definition 7.4 for the input tuple Z , and so the lemma follows by a union bound over all input tuples.

Analyzing I . We say that a ‘‘row’’ $j \in [N_1]$ gets a copy of x if $j \in I_x$. Since each $x \in Z$ is placed in a random βN_1 subset, each row j gets a copy of every $x \in Z$ independently with probability β . Call a row j *bad* if it holds more than $2\beta t$ of the elements of Z , and let χ_j be an indicator random variable that takes the value 1 if the j -th row is bad. By a Chernoff bound, χ_j gets the value 1 with probability $p < e^{-\beta t/3}$. Say that $I = \{I_x\}$ is good for Z if there are less than $\log t < 0.5\beta N_1$ bad rows. Since the random variables $\chi_1, \dots, \chi_{N_1}$ are negatively associated (see proof in the Claim A.5). the probability of having at least $\log u$ bad cells can be upper-bounded by

$$\binom{N_1}{\log u} p^{\log u} \leq (N_1 \cdot p)^{\log u} \leq \frac{1}{3u},$$

where the last inequality holds as long as $p < 1/10N_1$ which holds for $\beta = c \log N_1/q$ for sufficiently large constant c .

Analyzing h'_i . Fix some I and consider a good row $i \in [N_1]$ (i.e., has at most $\ell = 2\beta t$ inputs). We say that h'_i is *good* for Z , if h'_i induces at most $0.6\gamma N_2$ colliding cells. Here an index $j \in [N_2]$ is counted as a collision if at least two distinct inputs $x \neq x' \in Z$ have $i \in h(x) \cap h(x')$ and $j \in h'_i(x) \cap h'_i(x')$. (In matrix notation, both x and x' put 1 in their (i, j) -th cell.) In the above we restrict the attention to good rows; If the i -th row is bad then we treat h'_i as being vacuously good.

Claim 7.8. *Let $\epsilon = 1/(3uN_1)$, and recall that $\gamma = 1/\ell^2$ and that $N_2 = c'\ell^2 \log(1/\epsilon)$. Then, for sufficiently large constant c' , the following holds. For every $i \in [N_1]$, with probability $1 - \epsilon$ over the choice of h'_i , the function h'_i is good (i.e., it yields at most $0.6\gamma N_2$ collisions).*

Proof of claim. Fix some good $i \in [N_1]$. The function $h'_i(x)$ maps every input x independently to a random γN_2 -subsets of $[N_2]$. Therefore every index $j \in [N_2]$ gets x (i.e., $j \in h'_i(x)$) independently with probability

γ . We define an indicator random variable ζ_j that takes the value 1 if the j 'th index in the i 'th row gets more than one input mapped into it. By a union bound,

$$\Pr[\zeta_j = 1] \leq \sum_{x \neq x': i \in I_x \cap I_{x'}} \Pr[j \in h'_i(x)] \cdot \Pr[j \in h'_i(x')].$$

Since i is a good row, there are at most $\binom{\ell}{2} < \ell^2/2$ pairs $x \neq x'$ for which i is in both I_x and $I_{x'}$. Hence, $\Pr[\zeta_j = 1] < 0.5\ell^2\gamma^2$. Next we define the random variable $\zeta = \sum_j \zeta_j$ representing the number of collisions in the i th row. By the linearity of expectation and since $\gamma\ell^2 = 1$ it holds that $E[\zeta] < 0.5\ell^2\gamma^2N_2 = 0.5\gamma N_2$. Finally, since the variables ζ_j are negatively associated (as shown in Claim A.6), we can apply the Chernoff bound and conclude that $\Pr[\zeta > 0.6\gamma N_2] \leq \exp(-\Omega(\gamma N_2)) < \epsilon$, where the inequality holds for sufficiently large constant c' . \square

Since $\epsilon = 1/(3tN_1)$, we can apply union bound over all $i \in [N_1]$ we conclude that all h_i 's are good except with probability $1/3u$. Overall, the event that I and h'_1, \dots, h'_{N_1} are all good for all the u predefined input vectors Z_1, \dots, Z_u happens with probability $1 - u(1/3u + 1/3u) > 1/3$, and the proof follows.

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A Some Probabilistic Facts

A.1 Negative Association

Definition A.1 (Negative association [36]). *Let $X := (X_1, \dots, X_\ell)$ be a vector of random variables. The random variables X are negatively associated if for every two disjoint index sets, $I, J \in [\ell]$,*

$$\mathbb{E}[f(X_i, i \in I) \cdot g(X_j, j \in J)] \leq \mathbb{E}[f(X_i, i \in I)] \cdot \mathbb{E}[g(X_j, j \in J)]$$

for all functions $f : \mathbb{R}^{|I|} \rightarrow \mathbb{R}$ and $g : \mathbb{R}^{|J|} \rightarrow \mathbb{R}$ that are both non-decreasing or both non-increasing.

We are interested in this definition since the Chernoff-Hoeffding bounds are applicable to sums of variables that satisfy the negative association condition [42] (see also [25, Proposition 5]). We will also use the following facts. The first one is presented in [24] in the context of applications of negative associativity in statistical physics, and the description of the Fermi-Dirac occupancy numbers for particle ensembles. Consider the so-called Fermi-Dirac model, in which m balls are thrown into ℓ bins with the restriction that each bin contains at most one ball. Let X_i denote the random variable that counts the number of balls in the i -th bin. The following fact asserts that the X_i are negatively associated.

Fact A.2 ([24, Theorem 10]). *Let $X := (X_1, \dots, X_\ell)$ be random variables that take values in $\{0, 1\}$ and are distributed uniformly over m -weight vectors where $m \leq \ell$. That is, for every $x = (x_1, \dots, x_\ell) \in \{0, 1\}^\ell$ of Hamming weight m it holds that*

$$\Pr[X = x] = \binom{\ell}{m}^{-1},$$

and $\Pr[X = x] = 0$ for every x of Hamming weight $\text{wt}(x) \neq m$. Then, the random variables (X_1, \dots, X_ℓ) are negatively associated.

Fact A.3 ([36, Property 7]). *If two vectors of negatively associated random variables X and Y are mutually independent, then the random variables (X, Y) are negatively associated.*

Fact A.4 ([36, Property 6]). *Let $X := (X_1, \dots, X_\ell)$ be negatively associated random variables, and $I_1, \dots, I_k \subseteq [\ell]$ disjoint index sets, for some positive integer k . For $j \in [k]$, let $h_j : \mathbb{R}^{|I_k|} \rightarrow \mathbb{R}$ be functions that are all non-decreasing or all non-increasing. Then the random variables Y_1, \dots, Y_k defined as $Y_j := h_j(X_i, i \in I_j)$ are also negatively associated. That is, non-decreasing (or non-increasing) functions of disjoint subsets of negatively associated variables are also negatively associated.*

Now we turn to prove that the random variables $\chi_1, \dots, \chi_{N_1}$ defined in the first part of the proof of Lemma 7.5 in Section 7.4 are negatively associated. Recall that these random variables are defined via the following experiment. Given $\ell = N_1$ rows and a list of $k = t$ inputs, each input u is placed in a random $m = \beta N_1$ subset of the rows. We call a row j *bad* if it has more than $\tau = 2\beta t$ inputs mapped into it, and let χ_j be an indicator random variable that takes the value 1 if the j -th row is bad.

Claim A.5. *The random variables χ_1, \dots, χ_ℓ are negatively associated.*

Proof. We call $X_{i,u}$ the indicator random variable that takes the value 1 if the input u was mapped to the i -th row. We notice that when we observe a specific input u' that is mapped uniformly to $m = \beta N$ out of N rows, the random variable $X_{u'} = (X_{i,u'})_{i \in [\ell]}$ is distributed uniformly over ℓ -bit strings of weight m just like in Fact A.2, and so the random variables $(X_{i,u'})_{i \in [\ell]}$ are negatively associated.

Since every input is mapped independently, the k vectors $(X_{1,u_1}, \dots, X_{N,u_1}), \dots, (X_{1,u_k}, \dots, X_{N,u_k})$ each defined by a different input are mutually independent, and therefore due to Fact A.3, all these random variables $(X_{i,u_j})_{i \in [\ell], j \in [k]}$ are collectively negatively associated.

For the last step we use Fact A.4. We partition the random variables $X_{i,u}$ to disjoint sets $Z_i = (X_{i,u_1}, \dots, X_{i,u_k})$ for all $i \in [N]$. We define a non-decreasing mapping

$$h_i(Z_i) = \begin{cases} 1 & \text{if } \sum_{j=1}^k X_{i,u_j} \geq \tau \\ 0 & \text{otherwise,} \end{cases}$$

and get that the random variables $Y_i = h_i(Z_i)$ are negatively associated. We finish the proof by noticing that each Y_i is distributed like an indicator random variable that takes the value 1 if the i -th row is bad. \square

Next we prove a similar claim, that the random variables $\zeta_1, \dots, \zeta_{N_2}$ defined in the second part of the proof of Lemma 7.5 in Section 7.4 are negatively associated. Recall that these random variables are defined via the following experiment. Given N_2 indices and a list of at most $2\beta t$ inputs, each input u is placed in a random γN_2 subset of the indices. We call an index j *bad* if it has more than 2 inputs mapped into it, and let ζ_j be an indicator random variable that takes the value 1 if the j -th index is bad.

Claim A.6. *The random variables $\zeta_1, \dots, \zeta_{N_2}$ are negatively associated.*

Proof. The proof is identical to that of Claim A.5 except that we take $\ell = N_2$, $k = 2\beta t$, $m = \gamma N_2$, and $\tau = 2$. \square

Next we prove a probabilistic statement from the proof of Lemma 5.7.

Claim A.7. *Given a fixed n -bit string x and a uniformly chosen partitions Π of $[n]$ to \sqrt{n} subsets of size \sqrt{n} each, denote by Y_{j,B_i} the random variable that takes the value 1 when the j -th bit in the i -th block is 1. Then for every index $i \in [\sqrt{n}]$, the \sqrt{n} variables $\{Y_{j,B_i}\}_{1 \leq j \leq \sqrt{n}}$ are negatively associated.*

Proof. The $\sqrt{n} \cdot \sqrt{n}$ random variables Y_{j,B_i} for $1 \leq i, j \leq \sqrt{n}$ satisfy the conditions for Fact A.2 for $\ell = n$, $m = \text{wt}(x)$, and they are therefore negatively associated. It is easy to see that any subset of negatively associated variables are also negatively associated [36, Property 4], and with that the proof is completed. \square

A.2 Families of Collision Free Hash Functions

We next prove a stronger version of Lemma 4.8, i.e., show the existence of a family of $\log t$ -collision free hash functions $H_{n,t,\log t,2t}$ of size $\lambda = 16 \ln u$, as in the lemma, with some additional properties (we need this stronger version for our RCDS protocols in Appendices C and D).

Lemma A.8. *Let n be an integer, $t \in \{15, \dots, n/2\}$, $\mathcal{T} \subseteq \binom{[n]}{\leq t}$, and u be the number of maximal sets in \mathcal{T} . Then, there exists a family of $\log t$ -collision free hash functions $H_{n,t,\log t,2t} = \{h_1, \dots, h_\lambda\}$ of size $\lambda = 16 \ln u$, such that for every $i \in [\lambda]$ and every $b \in [2t]$ it holds that $|\{a \in [n] : h_i(a) = b\}| \leq \lceil n/2t \rceil$, and for every subset $T \in \mathcal{T}$ there are at least $\lambda/4$ functions $h \in H_{n,t,\log t,2t}$ such that for every $b \in [2t]$ it holds that $|\{a \in T : h(a) = b\}| < \log t$.*

Proof. Without loss of generality, we assume that t divides n (this can be achieved by increasing n by at most $t - 1$), and let $t' = \log t$. We show that there exists a family of hash function $H_{n,t',2t}$ as above with $\lambda = 16 \ln u$ functions using the probabilistic method. As a first step in the proof, we choose at random a

function $h : [n] \rightarrow [2t]$ such that for every $b \in [2t]$ it holds that $|\{a \in [n] : h(a) = b\}| \leq \lceil n/2t \rceil$, and fix a maximal subset T of \mathcal{T} . The probability that for some $b \in [2t]$ it holds that $|\{a \in T : h(a) = b\}| \geq \log t$ is

$$\begin{aligned} & \Pr[\exists b \in [2t] |\{a \in T : h(a) = b\}| \geq \log t] \\ &= \Pr[\exists j_1 \neq \dots \neq j_{\log t} \in T : h(j_1) = \dots = h(j_{\log t})] \\ &\leq \sum_{j_1 \neq \dots \neq j_{\log t} \in T} \Pr[h(j_1) = \dots = h(j_{\log t})] < \binom{t}{\log t} \cdot \left(\frac{1}{2t}\right)^{\log t - 1} \\ &\leq \left(\frac{et}{\log t}\right)^{\log t} \cdot \frac{1}{(2t)^{\log t - 1}} = \left(\frac{e}{2 \log t}\right)^{\log t} \cdot 2t < \frac{1}{2} \end{aligned}$$

(where the last inequality holds since $t \geq 15$).

Next, we claim that if we choose at random $\lambda = 16 \ln u$ functions as above, we get the desired family $H_{n,t,2t} = \{h_1, \dots, h_\lambda\}$. We bound the probability that for a given maximal subset T of \mathcal{T} of size at most t , there exist at most $\lambda/4$ functions $h \in H_{n,t,t',2t}$ that we choose at random, such that for every $b \in [2t]$ it holds that $|\{a \in T : h(a) = b\}| < t'$.

For every $i \in [\lambda]$, let X_i be a Boolean random variable such that $X_i = 1$ if for every $b \in [2t]$ it holds that $|\{a \in T : h_i(a) = b\}| < \log t$ and $X_i = 0$ otherwise. Additionally, let $X = \sum_{i=1}^{\lambda} X_i$, i.e., X is the number of hash functions h_i such that for every $b \in [2t]$ it holds that $|\{a \in T : h_i(a) = b\}| < \log t$. As we have shown above, $\Pr[X_i = 0] = \Pr[\exists b \in [2t] : |\{a \in T : h_i(a) = b\}| \geq \log t] < \frac{1}{2}$, so by linearity of expectation, $\mathbb{E}(X) = \sum_{i=1}^{\lambda} \mathbb{E}(X_i) = \sum_{i=1}^{\lambda} \Pr[X_i = 1] > \lambda \cdot \frac{1}{2} = \frac{\lambda}{2}$.

Using a Chernoff bound [43] ($\Pr[X \leq (1 - \delta) \cdot \mathbb{E}(X)] \leq e^{-\mathbb{E}(X) \cdot \delta^2 / 2}$ for all $0 < \delta < 1$) we get that

$$\Pr[X \leq \lambda/4] \leq \Pr[X \leq \mathbb{E}(X)/2] \leq e^{-\frac{\mathbb{E}(X)(1/2)^2}{2}} < e^{-\frac{\lambda}{16}} = \frac{1}{e^{\ln u}} = \frac{1}{u}.$$

By the union bound, the probability that there exists a maximal subset T of \mathcal{T} with at most $\lambda/4$ functions h_i such that $\exists b \in [2t] : |\{a \in T : h_i(a) = b\}| \geq \log t$, is less than 1. Thus, there exists a family $H_{n,t,t',2t}$ with $\lambda = 16 \ln u$ hash functions as required. \square

Moreover, using similar arguments we can prove the following strong version of Lemmas 4.7 and B.2.

Lemma A.9. *Let n be an integer and $t \in [\sqrt{n}]$, and $\mathcal{T} \subseteq \binom{[n]}{\leq t}$. Then, there exists a family of hash functions $H_{n,t,t^2} = \{h_i : [n] \rightarrow [t^2] : i \in [\lambda]\}$, where $\lambda = 16 \ln |\mathcal{T}|$, such that for every $i \in [\lambda]$ and every $b \in [t^2]$ it holds that $|\{a \in [n] : h_i(a) = b\}| \leq \lceil n/t^2 \rceil$, and for every subset $T \in \mathcal{T}$ there are at least $\lambda/4$ functions $h \in H_{n,t,t^2}$ for which $|h(T)| = |T|$.*

B A Simple General Scheme with Exponent Less Than One

In this section we present a relatively simple construction of a secret-sharing scheme for an arbitrary n -party access structure with share size 2^{cn} for a constant $c < 1$. To achieve this goal, we present a simple 2-server RCDS protocol in Appendix B.1 and a reduction from secret-sharing schemes to 2-server RCDS protocols in Appendix B.2. The purpose of this section is pedagogical and its aim is to give a full description of this scheme without relying on undescribed schemes, e.g., on the CDS scheme of [41] (which uses a construction of matching vectors of [33]). To understand this section, the reader needs the definitions given in Sections 3 and 4.1; no material from other sections is needed.

B.1 A 2-Server Robust CDS Protocol

We say that an RCDS protocol is a (t_1, t_2) -RCDS if it is robust for every zero-set $Z = Z_1 \times Z_2$ such that $|Z_1| \leq t_1$ and $|Z_2| \leq t_2$. In this section, we present a 2-server $(|X|, t)$ -RCDS protocol for a function $f : X \times Y \rightarrow \{0, 1\}$ (that is, the robustness is guaranteed when server Q_1 can send unbounded number of messages and server Q_2 can send at most t messages). We start by showing that a CDS protocol described in [12] (inspired by the protocol of [28]) is robust when server Q_1 can send unbounded number of messages and server Q_2 can send only one message.

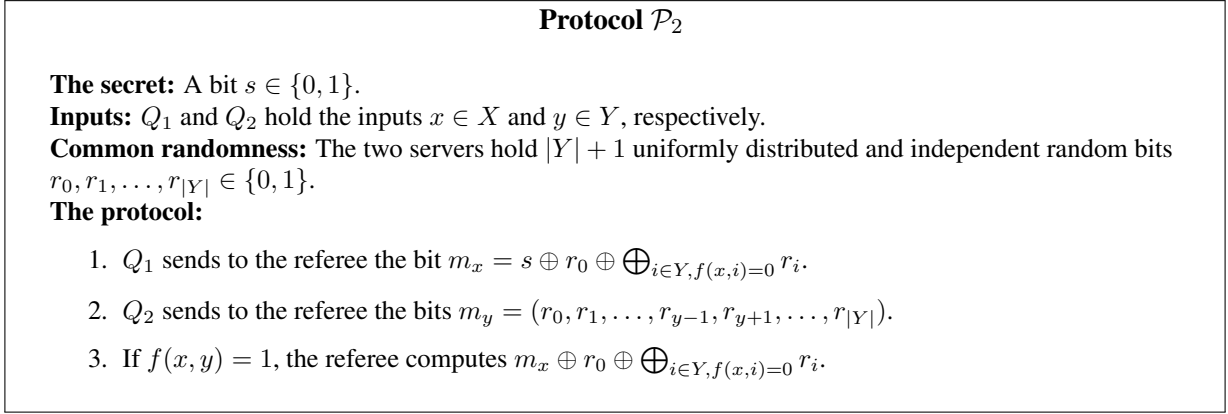


Figure 2: A 2-server CDS protocol \mathcal{P}_2 for a function $f : X \times Y \rightarrow \{0, 1\}$.

Lemma B.1. *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function. Then, protocol \mathcal{P}_2 , described in Figure 2, is a 2-server $(|X|, 1)$ -RCDS protocol for f in which the message size of Q_1 is 1 and the message size of Q_2 is $|Y|$.*

Proof. For the correctness of the protocol \mathcal{P}_2 , consider inputs x, y such that $f(x, y) = 1$. In this case r_y is not part of the exclusive-or in the message m_x sent by Q_1 and server Q_2 sends all r_i 's except for r_y . Thus, the referee can recover s from m_x and m_y as described in \mathcal{P}_2 .

For the robustness of the protocol, assume that Q_2 sends the message of input $y \in Y$ and Q_1 sends multiple messages for a subset of inputs $Z \subseteq X$, such that $f(x, y) = 0$ for every $x \in Z$. We prove below that the probability of these messages is the same for $s = 0$ and $s = 1$. Recall that the referee gets the bits $r_0, \dots, r_{|Y|}$ except for r_y from Q_2 and the bit

$$m_x = s \oplus r_0 \oplus \bigoplus_{i \in Y, f(x,i)=0} r_i \quad r_i = (s \oplus r_y) \oplus r_0 \oplus \bigoplus_{i \in Y \setminus \{y\}, f(x,i)=0} r_i$$

for every $x \in Z$ from Q_1 . For every $x \in Z$, the element r_y acts as a one-time-pad protecting s in m_x , that is, if the messages $(m_x)_{x \in Z}, m_y$ are generated with common randomness $r_0, r_1, \dots, r_{|Y|}$ and the secret $s = 0$, then the same messages are generated from the common randomness $r_0, r_1, \dots, r_{y-1}, \bar{r}_y, r_{y+1}, \dots, r_{|Y|}$ and the secret $s = 1$. \square

Next, we show how to transform the above CDS protocol to a $(|X|, t)$ -RCDS protocol for $|Y|^{1/4} \leq t \leq |Y|^{1/2}$. This is done by immunizing Q_2 using a family of perfect hash functions $H_{|Y|, t, t^2}$ (introduced in [27]), that is, a family of functions $h : Y \rightarrow [t^2]$ such that for every set $T \in \binom{Y}{t}$ there exists at least one $h \in H_{|Y|, t, t^2}$ such that h restricted to T is one-to-one, i.e., $h(y_1) \neq h(y_2)$ for every distinct $y_1, y_2 \in T$.

The following lemma is proved by a simple probabilistic argument (i.e., choosing the hash functions with uniform distribution from the functions satisfying (4)); we omit its proof.

Lemma B.2. *Let n be an integer and $t \in [\sqrt{n}]$. Then, there exists a family of perfect hash functions $H_{n,t,t^2} = \{h_i : [n] \rightarrow [t^2] : i \in [\lambda]\}$, where $\lambda = 16t \ln n$, such that for every $i \in [\lambda]$ and every $b \in [t^2]$ it holds that*

$$|\{a \in [n] : h_i(a) = b\}| \leq \lceil n/t^2 \rceil. \quad (4)$$

Lemma B.3. *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function and $|Y|^{1/4} \leq t \leq |Y|^{1/2}$ be an integer. Then, there is a 2-server $(|X|, t)$ -RCDS protocol for f with one-bit secrets in which the message size is $O(t^3 \log |Y|)$.*

Proof. The desired protocol \mathcal{P}_2^t is described in Figure 3. Let $H_{|Y|,t,t^2} = \{h_i : Y \rightarrow [t^2] : i \in [\lambda]\}$, where $\lambda = \Theta(t \log |Y|)$, be the family of perfect hash functions promised by Lemma B.2.

Protocol \mathcal{P}_2^t

The secret: A bit $s \in \{0, 1\}$.

Inputs: Q_1 and Q_2 hold the inputs $x \in X$ and $y \in Y$, respectively.

Common randomness: The two servers hold $\lambda - 1$ uniformly distributed and independent random bits $s_1, \dots, s_{\lambda-1}$ and λt^2 common random strings for the CDS protocol \mathcal{P}_2 .

The protocol:

1. Compute $s_\lambda = s \oplus s_1 \oplus \dots \oplus s_{\lambda-1}$.
2. For every $i \in [\lambda]$ do:
 - Let $Y_j = \{y \in Y : h_i(y) = j\}$, for every $j \in [t^2]$.
 - For every $j \in [t^2]$, independently execute the CDS protocol \mathcal{P}_2 of Lemma B.1 for the restriction of f to $X \times Y_j$ with the secret s_i . That is, Q_1 with input x sends a message for the restriction of f to $X \times Y_j$, for every $j \in [t^2]$, and Q_2 with input y sends a message only for the restriction of f to $X \times Y_{h_i(y)}$.

Figure 3: A 2-server $(|X|, t)$ -RCDS protocol \mathcal{P}_2^t for a function $f : X \times Y \rightarrow \{0, 1\}$.

For the correctness of the protocol, let $x \in X$ and $y \in Y$ for which $f(x, y) = 1$. Then, for every $i \in [\lambda]$, the input y is in $Y_{h_i(y)}$, so the referee can reconstruct s_i using the messages on the inputs x, y in the CDS protocol \mathcal{P}_2 for the restriction of f to the inputs of $X \times Y_{h_i(y)}$ with the secret s_i . Overall, the referee can learn all the bits s_1, \dots, s_λ , so it can reconstruct the secret s by xoring these bits.

For the robustness of the protocol, let (Z_1, Z_2) be a zero set of f such that $|Z_2| \leq t$. By Lemma B.2, there is at least one $i \in [\lambda]$ for which $|h_i(Z_2)| = |Z_2|$. We prove that the referee cannot learn any information on s_i , and, thus, cannot learn the secret s .

Since h_i is one-to-one on Z_2 , each input of Z_2 is in a different subset Y_j in the partition induced by h_i , and the referee gets at most one message of Q_2 in each execution of the CDS protocol \mathcal{P}_2 for the restriction of f to $X \times Y_j$ with the secret s_i . Since the CDS protocol \mathcal{P}_2 is a $(|X|, 1)$ -RCDS protocol and $f(x, y) = 0$ for every $(x, y) \in Z_1 \times Z_2$, the referee cannot learn any information about s_i from any execution of the CDS protocol \mathcal{P}_2 for the restriction of f to the inputs of $X \times Y_j$ with the secret s_i , for every $j \in [t^2]$. Since each execution of \mathcal{P}_2 for each function h_i is done with independent common random strings, the referee cannot learn any information on s_i , and, hence, it cannot learn any information on the secret s .

We next provide an analyzing of the message size. Consider the execution of step 2 of \mathcal{P}_2^t , i.e., the execution for a single $h_i \in H_{|Y|,t,t^2}$. By Lemma B.2, $|Y_j| = O(|Y|/t^2)$ for every $j \in [t^2]$. The message size of Q_1 is t^2 times the message size of Q_1 in \mathcal{P}_2 , i.e., it is t^2 . The message of Q_2 is single message of Q_2 in \mathcal{P}_2 , i.e., its size is $O(|Y|/t^2)$. Since there are $\lambda = \Theta(t \log |Y|)$ hash functions and $t \geq |Y|^{1/4}$, the message size of both servers is $O(t^3 \log |Y|)$. \square

B.2 A Secret-Sharing Scheme from a 2-Server RCDS Protocol

B.2.1 Liu and Vaikuntanathan Decomposition of Access Structures

As in [39], we decompose an access structure F to three parts, depending on a parameter $\delta \in (0, \frac{1}{2})$: A bottom part $F_{\text{bot},\delta}$, which handles small sets, a middle part $F_{\text{mid},\delta}$, which handles medium-size sets, and a top part $F_{\text{top},\delta}$, which handles large sets. This decomposition presented in the following proposition.

Proposition B.4 (Liu and Vaikuntanathan [39]). *Let F be an access structure over a set of n parties and $\delta \in (0, \frac{1}{2})$. Define the following access structures $F_{\text{top},\delta}$, $F_{\text{bot},\delta}$, and $F_{\text{mid},\delta}$.*

$$\begin{aligned} A \notin F_{\text{top},\delta} &\iff \exists A' \notin F, A \subseteq A' \text{ and } |A'| > \left(\frac{1}{2} + \delta\right)n, \\ A \in F_{\text{mid},\delta} &\iff A \in F \text{ and } \left(\frac{1}{2} - \delta\right)n \leq |A| \leq \left(\frac{1}{2} + \delta\right)n, \text{ or } |A| > \left(\frac{1}{2} + \delta\right)n, \\ A \in F_{\text{bot},\delta} &\iff \exists A' \in F, A' \subseteq A \text{ and } |A'| < \left(\frac{1}{2} - \delta\right)n. \end{aligned}$$

Then, $F = F_{\text{top},\delta} \cap (F_{\text{mid},\delta} \cup F_{\text{bot},\delta})$. Therefore, if $F_{\text{top},\delta}$, $F_{\text{bot},\delta}$, and $F_{\text{mid},\delta}$ can be realized by secret-sharing schemes with share size $O(2^{cn})$ then also F can be realized by a secret-sharing scheme with share size $O(2^{cn})$.

As mentioned in Proposition B.4, $F = F_{\text{top},\delta} \cap (F_{\text{mid},\delta} \cup F_{\text{bot},\delta})$. Thus, by standard closure properties of secret-sharing schemes, realizing F can be reduced to realizing $F_{\text{top},\delta}$, $F_{\text{bot},\delta}$, and $F_{\text{mid},\delta}$ (that is, choose a random bit s_1 , share $s_1 \oplus s$ with a scheme realizing $F_{\text{top},\delta}$ and independently share s_1 with schemes realizing $F_{\text{mid},\delta}$ and $F_{\text{bot},\delta}$). In [39], the access structures $F_{\text{bot},\delta}$ was realized by sharing the secret independently for each minimal authorized set, resulting in a scheme realizing $F_{\text{bot},\delta}$ with share size $\binom{n}{(\frac{1}{2}-\delta)n} \leq O(2^{\text{H}_2(\frac{1}{2}-\delta)n})$ (where $\text{H}_2(\cdot)$ is the binary entropy function). A similar construction was used for $F_{\text{top},\delta}$. The properties of the resulting scheme for F are stated in the following lemma.

Lemma B.5 ([39]). *Let F be an access structure and $\delta \in (0, \frac{1}{2})$, and assume that $F_{\text{mid},\delta}$ can be realized by secret-sharing schemes with share size $2^{M(\delta)n}$. Then, F can be realized by a secret-sharing scheme with share size $2^{(\max\{\text{H}_2(\frac{1}{2}-\delta), M(\delta)\})n}$.*

B.2.2 Secret-Sharing Schemes Realizing the Access Structure $F_{\text{mid},\delta}$

Our main construction in this section is a secret-sharing scheme realizing the middle access structure $F_{\text{mid},\delta}$ whose exponent is smaller than 1. Towards this construction, we defined balanced access structures in Definition B.6, represent $F_{\text{mid},\delta}$ as a union of a polynomial number of balanced access structures, and show how to realize each such access structure using an RCDS protocol. By closure properties of secret-sharing schemes, we can realize $F_{\text{mid},\delta}$ using the schemes for the balanced access structures, and, hence, we can realize F with a smaller share size.

Definition B.6 (The access structure $F_{B,\text{mid},\delta}$). Let F be an access structure with n parties, $\delta \in (0, \frac{1}{2})$, and B be a subset of parties. The access structure $F_{B,\text{mid},\delta}$ is the access structure that contains all subsets of parties of size greater than $(\frac{1}{2} + \delta)n$, and all subsets of parties that contain authorized subsets $A' \in F$ of size between $(\frac{1}{2} - \delta)n$ and $(\frac{1}{2} + \delta)n$ that contain exactly $\lfloor |A'|/2 \rfloor$ of their parties from B . That is,

$$F_{B,\text{mid},\delta} = \{A : \exists A' \in F, A' \subseteq A, \left(\frac{1}{2} - \delta\right)n \leq |A'| \leq \left(\frac{1}{2} + \delta\right)n, \text{ and } |A' \cap B| = \lfloor |A'|/2 \rfloor\} \\ \cup \{A : |A| > \left(\frac{1}{2} + \delta\right)n\}.$$

Example B.7. Consider the access structure F with 4 parties P_1, P_2, P_3, P_4 , where

$$F = \{\{P_1, P_2\}, \{P_1, P_3\}\} \cup \{A \subseteq \{P_1, P_2, P_3, P_4\} : |A| \geq 3\}.$$

Then, the sets in $F_{\{P_1, P_2\}, \text{mid}, 0}$ that contain 2 parties are all the sets in F that contain exactly 1 party from $\{P_1, P_2\}$, namely, $\{P_1, P_3\} \in F_{\{P_1, P_2\}, \text{mid}, 0}$ and $\{P_1, P_2\} \notin F_{\{P_1, P_2\}, \text{mid}, 0}$. Notice that

$$F = F_{\{P_1, P_2\}, \text{mid}, 0} \cup F_{\{P_1, P_3\}, \text{mid}, 0}.$$

Following the above definition, we present our main secret-sharing scheme, which realizes the access structure $F_{B,\text{mid},\delta}$.

Lemma B.8. Let F be an access structure over a set of n parties, $\delta \in (0.027, \frac{1}{6})$, and B be a subset of parties such that $|B| = n/2$. Then, there is a secret-sharing scheme realizing $F_{B,\text{mid},\delta}$ with a one-bit secret in which the share size is $2^{(\frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta}))(\frac{3}{4} + \frac{3\delta}{2}) + o(1)n}$.

Proof. Assume without loss of generality that n is even (this can be done by adding dummy parties). Define

$$\mathcal{B}_1 = \left\{ S_1 \subseteq B : \left(\frac{1}{4} - \frac{\delta}{2}\right)n \leq |S_1| \leq \left(\frac{1}{4} + \frac{\delta}{2}\right)n \right\}$$

and

$$\mathcal{B}_2 = \left\{ S_2 \subseteq \overline{B} : \left(\frac{1}{4} - \frac{\delta}{2}\right)n \leq |S_2| \leq \left(\frac{1}{4} + \frac{\delta}{2}\right)n \right\}.$$

Note that $|\mathcal{B}_1| = |\mathcal{B}_2| < 2^{n/2}$. Moreover, define the function $f : \mathcal{B}_1 \times \mathcal{B}_2 \rightarrow \{0, 1\}$, where $f(S_1, S_2) = 1$ if and only if $S_1 \cup S_2 \in F$, $(\frac{1}{2} - \delta)n \leq |S_1 \cup S_2| \leq (\frac{1}{2} + \delta)n$, and $|S_1| = |S_2|$ or $|S_1| = |S_2| - 1$. The scheme $\mathcal{D}_{B,\text{mid}}$ realizing $F_{B,\text{mid}}$ is described in Figure 4.

For the correctness of the scheme, take a minimal authorized set $A \in F_{B,\text{mid},\delta}$, that is, $A = S_1 \cup S_2$ for some $S_1 \subseteq B, S_2 \subseteq \overline{B}$ such that $S_1 \cup S_2 \in F$, $(\frac{1}{2} - \delta)n \leq |S_1 \cup S_2| \leq (\frac{1}{2} + \delta)n$, and $|S_1| = |S_2|$ or $|S_1| = |S_2| - 1$. The parties in $A = S_1 \cup S_2$ can reconstruct the messages of Q_1 and Q_2 when holding the inputs S_1 and S_2 , respectively, in the first RCDS protocol (i.e., the protocol of step 4), and can reconstruct s_1 from these messages using the reconstruction function of this protocol (since $f(S_1, S_2) = 1$). By symmetric arguments, the parties in A can reconstruct s_2 (using the protocol of step 5), and, thus, the parties in A can reconstruct the secret s by xoring s_1 and s_2 . Authorized sets of size greater than $(\frac{1}{2} + \delta)n$ can reconstruct the secret s using the $((\frac{1}{2} + \delta)n + 1)$ -out-of- n secret-sharing scheme (i.e., the scheme of step 1).

For the privacy of the scheme, take an unauthorized set $A \notin \Gamma_{B,\text{mid},\delta}$, that is, $A = S_1 \cup S_2$ such that $S_1 \subseteq B, S_2 \subseteq \overline{B}$ and $|S_1 \cup S_2| \leq (\frac{1}{2} + \delta)n$ (subsets of size greater than $(\frac{1}{2} + \delta)n$ are authorized), and assume without loss of generality that $|S_1| \leq (\frac{1}{4} + \frac{\delta}{2})n$ (otherwise, $|S_2| \leq (\frac{1}{4} + \frac{\delta}{2})n$ and we consider the second

Scheme $\mathcal{D}_{B,\text{mid},\delta}$

The secret: A bit $s \in \{0, 1\}$.

The scheme:

1. Share the secret s among the n parties using a $((\frac{1}{2} + \delta)n + 1)$ -out-of- n secret-sharing scheme.
2. Choose a random bit $s_1 \in \{0, 1\}$ and define $s_2 = s \oplus s_1$.
3. Let $t = O\left(n2^{\text{H}_2(\frac{1-2\delta}{1+2\delta})(\frac{1}{4}+\frac{\delta}{2})n}\right)$ (this choice of t will be explained later).
4. Execute the 2-server $(|\mathcal{B}_1|, t)$ -RCDS protocol of Lemma B.3 for the function f with the secret s_1 ; for every $S_1 \in \mathcal{B}_1$ (respectively, $S_2 \in \mathcal{B}_2$) share the message of Q_1 (respectively, Q_2) when holding the input S_1 (respectively, S_2) among the parties of S_1 (respectively, S_2) using an $|S_1|$ -out-of- $|S_1|$ (respectively, $|S_2|$ -out-of- $|S_2|$) secret-sharing scheme.
5. Execute the 2-server $(t, |\mathcal{B}_2|)$ -RCDS protocol of Lemma B.3 for the function f with the secret s_2 ; for every $S_1 \in \mathcal{B}_1$ (respectively, $S_2 \in \mathcal{B}_2$) share the message of Q_1 (respectively, Q_2) when holding the input S_1 (respectively, S_2) among the parties of S_1 (respectively, S_2) using an $|S_1|$ -out-of- $|S_1|$ (respectively, $|S_2|$ -out-of- $|S_2|$) secret-sharing scheme.

Figure 4: A secret-sharing scheme $\mathcal{D}_{B,\text{mid},\delta}$ realizing the access structure $F_{B,\text{mid},\delta}$.

RCDS protocol, i.e, the protocol of step 5). In the first RCDS protocol (i.e, the protocol of step 4), the parties in S_1 know a message of Q_1 on an input $S'_1 \in \mathcal{B}_1$ if and only if $S'_1 \subseteq S_1$. That is, they can reconstruct the messages of the inputs (which are sets) in \mathcal{B}_1 for the set $T_{S_1} \triangleq \{S'_1 \in \mathcal{B}_1 : S'_1 \subseteq S_1, |S'_1| \geq (\frac{1}{4} - \frac{\delta}{2})n\}$. The number of subsets in T_{S_1} is at most

$$t \triangleq \sum_{i=(\frac{1}{4}-\frac{\delta}{2})n}^{(\frac{1}{4}+\frac{\delta}{2})n} \binom{(\frac{1}{4}+\frac{\delta}{2})n}{i}.$$

Since $\delta < \frac{1}{6}$, we have that $(\frac{1}{4} - \frac{\delta}{2})n > 1/2(\frac{1}{4} + \frac{\delta}{2})n$ and

$$t = O\left(n \cdot \binom{(\frac{1}{4}+\frac{\delta}{2})n}{(\frac{1}{4}-\frac{\delta}{2})n}\right) = O\left(n2^{\text{H}_2(\frac{1-2\delta}{1+2\delta}) \cdot (\frac{1}{4}+\frac{\delta}{2})n}\right).$$

For every $S'_1 \subseteq S_1$ and $S'_2 \subseteq S_2$, we have that (S'_1, S'_2) is a zero set of f , and the parties in $A = S_1 \cup S_2$ (which learn the messages on the inputs of T_{S_1} of Q_1 and possibly many messages of Q_2) learn only messages of the zero set $T_{S_1} \times \{S'_2 \in \mathcal{B}_2 : S'_2 \subseteq S_2\}$ in the first RCDS protocol. Thus, by the robustness of the RCDS protocol, the parties in A cannot learn any information on s_1 , and, hence, they cannot learn any information on the secret s .

Overall, in the resulting scheme each party P_i gets a share of size $\log n$ from the threshold scheme of step 1 and less than $|\mathcal{B}_1| = |\mathcal{B}_2| < 2^{n/2}$ shares from the threshold schemes of step 4 (respectively, step 5), one for each message of the RCDS protocol for f on an input S such that $P_i \in S$. Thus, since $\delta > 0.027$ implies that $t = 2^{\text{H}_2(\frac{1-2\delta}{1+2\delta})(\frac{1}{4}+\frac{\delta}{2}+o(1))n} > 2^{n/8} > |\mathcal{B}_2|^{1/4}$, the message size of the RCDS protocols osstep 4 and step 5 is $O(t^3n)$, and the share size of each party in the scheme $\mathcal{D}_{B,\text{mid},\delta}$ is

$$O(2^{n/2} \cdot t^3n) = 2^{(\frac{1}{2}+\text{H}_2(\frac{1-2\delta}{1+2\delta})(\frac{3}{4}+\frac{3\delta}{2})+o(1))n}.$$

□

We use the following family of subsets, in which every set of medium size is equally partitioned by one of the subsets in the family (a similar family appears in [3]). The proof of the claim is by a simple use of the probabilistic method.

Claim B.9. *Let P be a set of n parties for some even n and $\delta \in (0, \frac{1}{2})$. Then, there are $\lambda = \Theta(n^{3/2})$ subsets $B_1, \dots, B_\lambda \subseteq P$, each of them of size $n/2$, such that for every subset $A \subseteq P$ for which $(\frac{1}{2} - \delta)n \leq |A| \leq (\frac{1}{2} + \delta)n$ it holds that $|A \cap B_i| = \lfloor |A|/2 \rfloor$ for at least one $i \in [\lambda]$.*

We use the above scheme and the family of “balancing” subsets of Claim B.9 to construct a scheme that realizes the access structure $F_{\text{mid},\delta}$.

Theorem B.10. *Let F be an access structure over a set of n parties and $\delta \in (0.027, \frac{1}{6})$. Then, there is a secret-sharing scheme realizing $F_{\text{mid},\delta}$ with a one-bit secret in which the share size is $2^{(\frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta}))(\frac{3}{4} + \frac{3\delta}{2}) + o(1)n}$.*

Proof. As in Lemma B.8, assume without loss of generality that n is even. By Claim B.9, there exist $\lambda = \Theta(n^{3/2})$ subsets $B_1, \dots, B_\lambda \subseteq P$, where $|B_i| = n/2$ for every $i \in [\lambda]$, such that for every subset A such that $(\frac{1}{2} - \delta)n \leq |A| \leq (\frac{1}{2} + \delta)n$, it holds that $|A \cap B_i| = \lfloor |A|/2 \rfloor$ for at least one $i \in [\lambda]$. Thus, we get that $F_{\text{mid},\delta} = \cup_{i=1}^\lambda F_{B_i,\text{mid},\delta}$. By Lemma B.8, for every $i \in [\lambda]$ there is a secret-sharing scheme $\mathcal{D}_{B_i,\text{mid},\delta}$ realizing the access structure $F_{B_i,\text{mid},\delta}$ with a one bit secret in which the share size is $2^{(\frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta}))(\frac{3}{4} + \frac{3\delta}{2}) + o(1)n}$. For every $i \in [\lambda]$, we independently share the secret s using the secret-sharing scheme $\mathcal{D}_{B_i,\text{mid},\delta}$ realizing the access structure $F_{B_i,\text{mid},\delta}$. The combined scheme is a secret-sharing scheme realizing the access structure $F_{\text{mid},\delta}$ in which the share size is $O(n^{3/2}) \cdot 2^{(\frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta}))(\frac{3}{4} + \frac{3\delta}{2}) + o(1)n} = 2^{(\frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta}))(\frac{3}{4} + \frac{3\delta}{2}) + o(1)n}$. □

B.2.3 Secret-sharing Schemes Realizing any Access Structure

Theorem B.11. *There exists a constant $c < 1$ such that for every n and every n -party access structure F there is a secret-sharing scheme realizing F with a one-bit secret in which the share size is $2^{(c+o(1))n}$.*

Proof. By Lemma B.5 and Theorem B.10, for every $\delta \in (0.027, \frac{1}{6})$ the access structure F can be realized by a secret-sharing scheme with share size

$$2^{(\max\{H_2(\frac{1}{2}-\delta), \frac{1}{2} + H_2(\frac{1-2\delta}{1+2\delta})(\frac{3}{4} + \frac{3\delta}{2})\}) + o(1)n}. \quad (5)$$

By taking $\delta \approx 0.04063789$ (i.e., $t \approx O(2^{0.165076564n})$) the above two expressions in the exponent are equal, and we achieve share size of $2^{(c+o(1))n}$ for $c = 0.99523$. □

C A Linear 2-Server RCDS Protocol

In this section, we present a linear 2-server RCDS protocol that is robust for every zero-set $Z_1 \times Z_2$, where Z_1 can be an arbitrary subset of the inputs of Q_1 and Z_2 can be an arbitrary subset of size at most t of the inputs of Q_2 , in which the message size is $\tilde{O}((t + 2^{\ell/2}) \log |Z_2|)$. This protocol can be used to construct an alternative linear secret-sharing scheme for arbitrary n -party access structures with the same share size as the linear secret-sharing scheme of Theorem 2.1 (see [45]). Furthermore, when the secret contains $\log |Z_2|$ field elements, the share size remains $\tilde{O}((t + 2^{\ell/2}) \log |Z_2|)$, i.e, the normalized share size (the share size divided by the secret size) is only $\tilde{O}(t + 2^{\ell/2})$.

We start with the protocol \mathcal{P}_2 , as described in Figure 5. Similarly to Lemma 6.1, the protocol \mathcal{P}_2 is (2^X) -RCDS protocol, that is it robust when Q_1 sends an unbounded number of messages and Q_2 sends one message. This protocol is a simple generalization of the protocol described in Figure 2 to an arbitrary field; its properties, as described in Lemma C.1, follow from the same arguments as in the proof of Lemma B.1.

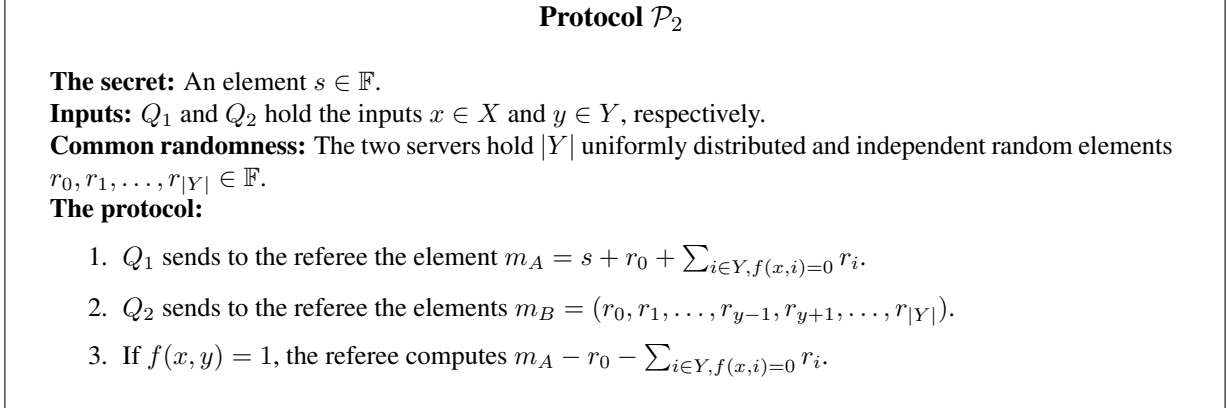


Figure 5: A linear 2-server CDS protocol \mathcal{P}_2 for a function $f : X \times Y \rightarrow \{0, 1\}$.

Lemma C.1. *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function. Then, for every finite field \mathbb{F} , protocol \mathcal{P}_2 , described in Figure 5, is a linear 2-server (2^X) -RCDS protocol for f with domain of secrets \mathbb{F} secrets, in which the message size of Q_1 is $\log |\mathbb{F}|$ and the message size of Q_2 is $|Y| \log |\mathbb{F}|$.*

The next protocol, originally appearing in [10], balances the sizes of messages of Q_1 and Q_2 . Its idea is to partition the set of inputs of Q_2 to disjoint sets and execute the protocol \mathcal{P}_2 independently for every set of inputs.

Claim C.2 ([10]). *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function. Then, for every finite field \mathbb{F} and every $d \leq |Y|$ there is a linear 2-server (2^X) -RCDS protocol $\mathcal{P}_2^{\text{balanced}}$ for f with one-element secrets in which the message size of Q_1 is $O(d \log |\mathbb{F}|)$ and the message size of Q_2 is $O((|Y|/d) \log |\mathbb{F}|)$.*

Proof. The description of the protocol $\mathcal{P}_2^{\text{balanced}}$ is as follows: Let s be the secret, and partition the set Y to d disjoint sets Y_1, \dots, Y_d of size at most $\lceil |Y|/d \rceil$, that is, every input $y \in Y$ is in exactly one set Y_i . For every $i \in [d]$, we execute the linear CDS protocol \mathcal{P}_2 independently for the restriction of f to the inputs of $X \times Y_i$ with the secret s . Server Q_1 , when holding the input $x \in X$, sends the messages in all the above independent protocols. Server Q_2 , when holding the input $y \in Y$, only sends the message in the protocol for the restriction of f to the inputs of $X \times Y_i$ for which $y \in Y_i$.

For the correctness of the protocol, if $f(x, y) = 1$ then the referee can reconstruct the secret from the messages of the CDS protocol for the restriction of f to the inputs of $X \times Y_i$ for which $y \in Y_i$. For the robustness of the protocol, let $Z_1 \subseteq X$ and $y \in Y$ such that $f(x, y) = 0$ for every $x \in Z_1$. The referee cannot learn any information on the secret from the messages on y and the inputs of Z_1 from each of the above independent protocols, which follows by the robustness of each of these protocols. Thus, the resulting protocol $\mathcal{P}_2^{\text{balanced}}$ is (2^X) -RCDS protocol.

The message of Q_1 contains d field elements and the message of Q_2 contains at most $\lceil |Y|/d \rceil$ field elements (since it sends a message in one execution of \mathcal{P}_2 in which the input domain size of Q_2 is at most $\lceil |Y|/d \rceil$). □

Next, in Lemma C.5 we show how to transform the above CDS protocol to a $(2^X, \binom{Y}{\leq t})$ -RCDS protocol. This is done by immunizing Q_2 as in Theorem 4.4, that is, we use two levels of hashing. However, in this case we optimize the share size by using the fact that each copy of the CDS protocol is applied to a function with a smaller domain of Q_2 .

Furthermore, using the generalized Stinson decomposition [], we improved the normalized message size (i.e., the ratio between the messages and the size of the secret). For these improvement we need the definition of ramp secret-sharing schemes [17] and a result about an efficient ramp secret-sharing scheme implicit in [19].

Definition C.3 (Ramp secret-sharing schemes[17]). *Let \mathcal{D} be a secret-sharing scheme on a set of n parties and let $0 \leq k_1 < k_2 \leq n$. The scheme \mathcal{D} is a (k_1, k_2, n) -ramp secret-sharing scheme if each subset of parties of size at least k_2 can reconstruct the secret and each subset of parties of size at most k_1 cannot learn any information about the secret. There are no restrictions on other subsets of parties.*

Claim C.4 (Implicit in [19]). *For every constants $0 \leq b < a \leq 1$ there is p_0 such that for every prime-power $q > p_0$, there is a linear (bn, an, n) -ramp secret-sharing scheme over the field \mathbb{F}_q in which each share is a field element (where p_0 is independent of n).*

Lemma C.5. *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function, and $t \leq \sqrt{|Y|}$ be an integer. Then, for every finite field \mathbb{F} , there is a linear 2-server $(2^X, \binom{Y}{\leq t})$ -RCDS protocol for f with one-element secrets in which the message size of Q_1 is $O((t^3 + |Y|t/\sqrt{|X|}) \log |Y| \log |\mathbb{F}|)$ and the message size of Q_2 is $O(\sqrt{|X|}t \log |Y| \log |\mathbb{F}|)$. Furthermore, there is p_0 such that for every prime-power $q > p_0$, there is a multi-linear 2-server $(2^X, \binom{Y}{\leq t})$ -RCDS protocol for f over \mathbb{F}_q with secrets of size $\Theta(qt \log |Y|)$ in which the normalized message size of Q_1 is $O(t^2 + |Y|/\sqrt{|X|})$ and the normalized message size of Q_2 is $O(\sqrt{|X|})$.*

Proof. The desired protocol \mathcal{P}_2^t , described in Figure 6, is a special case of the protocol of Lemma 4.9, when $k = k' = 2, t' = 1$, and \mathcal{P} is the protocol of Claim C.2 with $d = \max\{1, |Y|/(\sqrt{|X|}t^2)\}$. Let $H_{|Y|, t, t^2} = \{h_i : Y \rightarrow [t^2] : i \in [\lambda]\}$, where $\lambda = \Theta(t \log |Y|)$, be the family of perfect hash functions promised by Lemma A.9.

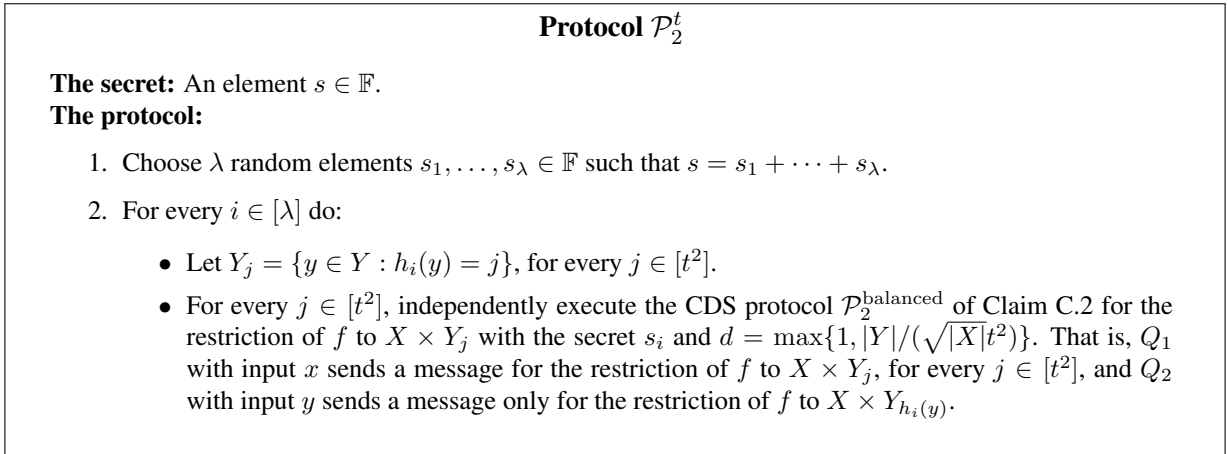


Figure 6: A linear 2-server $(2^X, \binom{Y}{\leq t})$ -RCDS protocol \mathcal{P}_2^t for a function $f : X \times Y \rightarrow \{0, 1\}$.

The correctness and privacy of \mathcal{P}_2^t follow by Lemma 4.9. We next provide a refined analyzing of its message size. Consider the execution of step 2 of \mathcal{P}_2^t . By Lemma A.9, $|Y_j| = O(|Y|/t^2)$ for every $j \in [t^2]$. The

message of Q_1 contains t^2 messages of Q_1 in $\mathcal{P}_2^{\text{balanced}}$, i.e., it contains $t^2 d = t^2 \cdot \max\{1, |Y|/(\sqrt{|X|}t^2)\} = O(t^2 + |Y|/\sqrt{|X|})$ field elements. The message of Q_2 contains one message of Q_1 in $\mathcal{P}_2^{\text{balanced}}$, i.e., it contains $O(|Y_{h_i(y)}|/d) = O\left(\frac{|Y|/t^2}{\max\{1, |Y|/(\sqrt{|X|}t^2)\}}\right) = O(\min\{|Y|/t^2, \sqrt{|X|}\}) \leq O(\sqrt{|X|})$ field elements. Since there are $\lambda = \Theta(t \log |Y|)$ hash functions, the sizes of the messages is as in the lemma.

To construct the desired protocol for long secrets, let $s = (s'_1, \dots, s'_{\lambda/4}) \in \mathbb{F}_q^{\lambda/4}$ be the secret. We change step 1 in the protocol \mathcal{P}_2^t (described in Figure 6) such that $s_1, \dots, s_\lambda \in \mathbb{F}_q$ are the shares of a $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of the secret $s = (s'_1, \dots, s'_{\lambda/4}) \in \mathbb{F}_q^{\lambda/4}$, where p_0 is the constant from Claim C.4 and $q > p_0$.

As before, for every inputs $x \in X, y \in Y$ such that $f(x, y) = 1$, the referee can learn all the secrets in those λ protocols from the messages on the inputs x, y , so it can reconstruct the secret s using the reconstruction function of the ramp scheme. Moreover, for every zero set (Z_1, Z_2) of f such that $|Z_2| \leq t$, by Lemma 4.7, there are at least $\lambda/4$ values of $i \in [\lambda]$ for which $|h_i(Z_2)| = |Z_2|$. Thus, the referee cannot learn any information on at least $\lambda/4$ of the shares s_1, \dots, s_λ in the above λ protocols from the messages on the inputs of Z_1, Z_2 . By the security of the ramp scheme, the referee cannot learn any information on the secret s . \square

We improve our linear robust 2-server CDS protocol using the family of hash functions of Lemma 4.8.

Theorem C.6. *Let $f : X \times Y \rightarrow \{0, 1\}$ be a function, where $|X| = |Y| = 2^\ell$. Then, for every finite field \mathbb{F} , every integer $t \leq |X|/(2 \log^2 |X|) \leq 2^{\ell-1}/\ell^2$, and every $\mathcal{Z}_2 \subseteq \binom{Y}{\leq t}$, there is a linear 2-server $(2^X, \mathcal{Z}_2)$ -RCDS protocol for f with one-element secrets in which the message size is $O((t \log^2 t + 2^{\ell/2})\ell \log t \log |\mathcal{Z}_2| \log |\mathbb{F}|)$. Furthermore, there is p_0 such that for every prime-power $q > p_0$, there is a multi-linear 2-server $(\binom{X}{\leq |X|}, \mathcal{Z}_2)$ -RCDS protocol for f over \mathbb{F}_q with secrets of size $\Theta(\ell \log t \log^2 |\mathcal{Z}_2| \log q)$ in which the normalized message size is $O(t \log^2 t + 2^{\ell/2})$.*

Proof. As the protocol of Lemma C.5, the desired protocol $\mathcal{P}_{\text{L2RCDS}}$ is a special case of the protocol of Lemma 4.9, when $k = k' = 2, t' = \log t$, and \mathcal{P} is the protocol \mathcal{P}_2^t of Lemma C.5. Let $H_{|Y|, t, \log t, 2t} = \{h_i : Y \rightarrow [2t] : i \in [\lambda]\}$, where $\lambda = \Theta(\log |\mathcal{Z}_2|)$, be the family of hash functions promised by Lemma A.8 for \mathcal{Z}_2 (that is, for every $Z_2 \in \mathcal{Z}_2$, at least $\lambda/4$ hash functions prevent a collision of $\log t$ elements of Z_2).

The protocol $\mathcal{P}_{\text{L2RCDS}}$ is described explicitly in Figure 7. It contains $2t\lambda = O(t \log |\mathcal{Z}_2|)$ executions of the protocol $\mathcal{P}_2^{t'}$ with $t' = \log t$ and $|Y'| = |Y|/(2t)$ (since $t \leq |X|/(2 \log^2 |X|)$, we have that $\log t \leq \sqrt{|X|/(2t)}$ as required). Since Q_1 sends $2t$ messages of $\mathcal{P}_2^{t'}$ for every $h_i \in H_{|Y|, t, 2t}$, her message contains

$$O\left(\left(\log^3 t + \frac{2^\ell \log t/(2t)}{2^{\ell/2}}\right)\ell \cdot 2t \log |\mathcal{Z}_2|\right) = O((t \log^2 t + 2^{\ell/2})\ell \log t \log |\mathcal{Z}_2|)$$

field elements. Since Q_2 sends only one message of $\mathcal{P}_2^{t'}$ for every $h_i \in H_{|Y|, t, 2t}$, its message contains $O(2^{\ell/2}\ell \log t \log |\mathcal{Z}_2|)$ field elements.

To construct the desired protocol for long secrets, let $s = (s'_1, \dots, s'_{\lambda/4}) \in (\mathbb{F}^{\lambda'})^{\lambda/4}$ be the secret, where $\lambda' = \Theta(\lambda \log t)$. Similarly to the multi-linear protocol of Lemma C.5, we change step 1 in the protocol $\mathcal{P}_{\text{L2RCDS}}$ such that $s_1, \dots, s_\lambda \in \mathbb{F}^{\lambda'}$ are the shares of a $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of the secret $s = (s'_1, \dots, s'_{\lambda/4}) \in (\mathbb{F}^{\lambda'})^{\lambda/4}$, but now in step 2 we execute the multi-linear 2-server $(2^X, \binom{Y}{\leq \log t})$ -RCDS protocol of Lemma C.5, instead of the linear protocol.

Overall, we results in a 2-server $(2^X, \mathcal{Z}_2)$ -RCDS protocol for f with secrets of size $\Theta(\lambda' \lambda \log |\mathbb{F}|) = \Theta(\log t \log^2 |\mathcal{Z}_2| \log |\mathbb{F}|)$ in which the normalized message size is $O(t \log^2 t + 2^{\ell/2})$. \square

Protocol $\mathcal{P}_{\text{L2RCDS}}$

The secret: An element $s \in \mathbb{F}$.

The protocol:

1. Choose λ random elements $s_1, \dots, s_\lambda \in \mathbb{F}$ such that $s = s_1 + \dots + s_\lambda$.
2. For every $i \in [\lambda]$ do:
 - Let $Y_j = \{y \in Y : h_i(y) = j\}$, for every $j \in [2t]$.
 - For every $j \in [2t]$, independently execute the linear 2-server $(2^X, \binom{Y}{\leq \log t})$ -RCDS protocol $\mathcal{P}_2^{\log t}$ of Lemma C.5 for the restriction of f to $X \times Y_j$ with the secret s_i . That is, Q_1 with input x sends a message for the restriction of f to $X \times Y_j$ for every $j \in [2t]$, and Q_2 with input y sends a message only for the restriction of f to $X \times Y_{h_i(y)}$.

Figure 7: A linear 2-server $(2^X, \mathcal{Z}_2)$ -RCDS protocol $\mathcal{P}_{\text{L2RCDS}}$ for a function $f : X \times Y \rightarrow \{0, 1\}$.

D An Improved RCDS Protocol for Longer Secrets

In the RCDS protocol of Theorem 4.5 the secret is a bit. In this section we construct a k -server RCDS protocol with nearly the same messages complexity as in the RCDS of Theorem 4.5 even when the length of the secret is $\tilde{O}(\ell^2 k^2 t)$ (where ℓ is the number of bits in the inputs). Specifically, we construct an RCDS protocol that is robust when each server can send at most t messages and has normalized message size (i.e., the number of bits sent per bit of secret) $2^{\tilde{O}(\sqrt{k\ell})} \tilde{O}(tk^3)^{k-1}$, compared to $2^{\tilde{O}(\sqrt{k\ell})} \tilde{O}(t)^{k-1} (\ell^2 t)^k$ in the protocol of Theorem 4.5 (when $t \leq 2^{\ell/2}$). This protocol is more efficient when $k^3 < \ell^2 t$.

The improvement requires two ingredients. The first ingredient (similar to Lemma C.5 and Theorem C.6 for longer secrets) is using a family of hash functions with λ functions such that for every set T there are at least $\lambda/4$ sets that are good for T (see Lemmas A.8 and A.9). This will enable us to improve Lemma 4.9, the immunization lemma. In Lemma 4.9 we share a secret $s \in S$ with a λ -out-of- λ threshold secret-sharing scheme (i.e., generating random s_1, \dots, s_λ such that $\sum_{i=1}^\lambda s_i = s$). Here, we take a secret from $S^{\lambda/4}$ and share it using the $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of Claim C.4, that is, a secret-sharing scheme with λ parties in which $3\lambda/4$ parties (or less) learn no information on the secret and all the λ parties together can reconstruct the secret (see Definition C.3). Each share is only one element of S . We can now proceed as in Lemma 4.9 and get an RCDS whose normalized message size is only $O(v)$ times the normalized message size of the original RCDS (where v is the output domain size of the hash functions). We can repeat this immunization for all servers using the family of hash functions of Lemma A.8 and obtain an RCDS protocol whose normalized message size is $O(t^k)$ times the normalized message size of a (non-robust) CDS for the function. However, the secret length grows in each immunization step, resulting in a secret whose length is exponential. The second ingredient is using one family of hash functions for immunizing the k servers (instead of using one family per server). The family that we use is applied to sets of size kt (i.e., to the union of t inputs from each server). This enables us to get the same normalized message size as above with shorter secrets.

Lemma D.1. *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a function, $t' \leq t$ be integers, and $\mathcal{Z}_i = \binom{X_i}{\leq t}$ and $\mathcal{Z}'_i = \binom{X_i}{\leq t'}$ for every $i \in [k]$. Suppose there is a $(\mathcal{Z}'_1, \dots, \mathcal{Z}'_k)$ -RCDS protocol \mathcal{P} with domain of secrets S and normalized message size \tilde{c} . Furthermore, let $X = \cup_{i \in [k]} X_i$ and suppose there is a family of t' -collision*

free hash functions $H_{|X|,kt,t',v} = \{h_1, \dots, h_\lambda\}$ such that for every set $T \subset X$ of size kt , at least $\lambda/4$ functions $h \in H_{|X|,kt,t',v}$ are at most t' -to-1. Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol \mathcal{P}'' with secrets from $S^{\lambda/4}$, message size $O(\tilde{c} \lambda v^{k-1} \log |S|)$, and normalized message size $O(\tilde{c} v^{k-1})$.

Proof. We describe the RCDS protocol \mathcal{P}'' in Figure 8. In this protocol, R is the set of random strings of \mathcal{P} and ENC_i is the encoding of server Q_i in this protocol. Protocol \mathcal{P}'' uses the $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of Claim C.4. For this scheme, we need to assume that the size of the domain of secrets is a prime-power greater than some p_0 . This only increases the secret size by a constant.

Protocol \mathcal{P}''

The secret: A vector $s = (a_1, \dots, a_{\lambda/4}) \in S^{\lambda/4}$.

Common randomness: A string r consisting of randomness for the $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of Claim C.4 and $(r_{d,j_1, \dots, j_k})_{d \in [\lambda], j_1, \dots, j_k \in [v]}$, where each $r_{d,j_1, \dots, j_k} \in R$.

Private input of server Q_i : $x_i \in X_i$.

The protocol:

- Let s_1, \dots, s_λ be shares of the $(3\lambda/4, \lambda, \lambda)$ -ramp secret-sharing scheme of Claim C.4 for the secret $s = (a_1, \dots, a_{\lambda/4})$.
- For every $i \in [k]$,

$$\text{ENC}_i''(x_i, s, r) = \left(\text{ENC}_i(x_i, s_d, r_{d,j_1, \dots, j_{i-1}, h_d(x_i), j_{i+1}, \dots, j_k}) \right)_{d \in [\lambda], j_1, \dots, j_{i-1}, j_{i+1}, \dots, j_k \in [v]}.$$

Figure 8: An RCDS protocol for longer secrets.

We first show the correctness of the RCDS protocol \mathcal{P}'' . For input $(x_1, \dots, x_k) \in X_1 \times \dots \times X_k$ such that $f(x_1, \dots, x_k) = 1$, the referee can reconstruct s_d , for every $d \in [\lambda]$, using the decoding function of \mathcal{P} on the encodings of the inputs x_1, \dots, x_k with the secret s_d and random string $r_{d, h_d(x_1), \dots, h_d(x_k)}$. Overall, the referee can learn all the strings s_1, \dots, s_λ , so it can reconstruct the secret s by using the reconstruction function of the ramp secret-sharing scheme of Claim C.4.

For the robustness of the protocol \mathcal{P}'' , let $Z_1 \times \dots \times Z_k$ be a zero set of f such that $Z_i \in \mathcal{Z}_i$ for every $i \in [k]$ and let $Z = \cup_{i \in [k]} Z_i$. By the properties of the family of t' -collision free hash functions $H_{|X|,kt,t',v}$, there are at least $\lambda/4$ indices $d \in [\lambda]$ for which h_d restricted to Z is at most t' -to-one; denote this set of indices by A .

Fix $d \in A$ and $j_1, \dots, j_k \in [v]$ and denote

$$Z_{i,d,j_i} = \{x : x \in Z_i, h_d(x) = j_i\};$$

by the collision freeness, $|Z_{i,d,j_i}| \leq t'$ for every $i \in [k]$. For every $i \in [k]$, the referee gets the encodings of the inputs in Z_{i,d,j_i} from server Q_i in the execution of the RCDS protocol \mathcal{P} for the secret s_d and random string r_{d,j_1, \dots, j_k} , i.e., it gets at most t' encodings from each server for r_{d,j_1, \dots, j_k} . Since \mathcal{P} is a $(\mathcal{Z}'_1, \dots, \mathcal{Z}'_k)$ -RCDS protocol, the referee cannot learn any information about s_d from this execution, that is, for $Y^{d,j_1, \dots, j_k} = Z_{1,d,j_1} \times \dots \times Z_{k,d,j_k}$ and two secrets $s_d, s'_d \in S$

$$\text{ENC}(Y^{d,j_1, \dots, j_k}, s_d, r_{d,j_1, \dots, j_k}) \equiv \text{ENC}(Y^{d,j_1, \dots, j_k}, s'_d, r_{d,j_1, \dots, j_k}). \quad (6)$$

For two secrets $s = (a_1, \dots, a_{\lambda/4}), s' = (a'_1, \dots, a'_{\lambda/4}) \in S^{\lambda/4}$, fix shares $(s_i)_{i \in [k]}$ and $(s'_i)_{i \in [k]}$ for s and s' respectively such that $s_i = s'_i$ for every $i \notin A$. By the privacy of the ramp schemes and since

$|A| \geq \lambda/4$, the shares $(s_i)_{i \notin A} = (s'_i)_{i \notin A}$ have the same probability for s and s' . Since the random strings $\{r_{d,j_1,\dots,j_k}\}_{d \in [\lambda], j_1, \dots, j_k \in [v]}$ are statistically independent,

$$(\text{ENC}(Y^{d,j_1,\dots,j_k}, s_d, r_{d,j_1,\dots,j_k}))_{d \in [\lambda], j_1, \dots, j_k \in [v]} \equiv (\text{ENC}(Y^{d,j_1,\dots,j_k}, s'_d, r_{d,j_1,\dots,j_k}))_{d \in [\lambda], j_1, \dots, j_k \in [v]},$$

(since either $d \notin A$ and $s_d = s'_d$ or $d \in A$ and (6) holds). Hence, the referee cannot learn any information on the secret s .

The message size of each server in protocol \mathcal{P}'' is $O(v^{k-1}|H_{|X|,tk,t',v}|) = O(v^{k-1}\lambda)$ times its message size in \mathcal{P} and the normalized message size of each server in protocol \mathcal{P}'' is $O(v^{k-1}O(v^{k-1}))$ times its message size in \mathcal{P} (since the secret in \mathcal{P}'' contains λ elements from S). \square

Theorem D.2. *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a k -input function, where $|X_i| \leq 2^\ell$, let t be an integer such that $2kt + k \log t < 2^\ell$, and $\mathcal{Z}_i = \binom{X_i}{\leq t}$ for every $i \in [k]$. Suppose there is a CDS protocol \mathcal{P} with domain of secrets S and normalized message size \tilde{c} . Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol with a $O(\ell^2 k^2 t \log t \log |S|)$ -bit secret, message size $O(\tilde{c} \cdot \ell^2 k^2 t \log t (2k^3 t \log^2 t)^{k-1} \log |S|)$, and normalized message size $O(\tilde{c} \cdot (2k^3 t \log^2 t)^{k-1})$.*

Proof. Without loss of generality, we assume that $X_i = \{0, 1\}^\ell$ for every $i \in [k]$. Let $t' = \log t$, $\mathcal{Z}'_i = \binom{X_i}{\leq t'}$ for $i \in [k]$, and $H_{2^\ell, kt', k^2 t'^2}$ be the family of perfect hash functions for the set $\mathcal{T} = \binom{X}{kt'}$ guaranteed by Lemma A.9, whose size is $O(kt'\ell)$. Note that this family is 1-collision free. By Lemma D.1 applied to \mathcal{P} and $H_{2^\ell, kt', k^2 t'^2}$, there exists a $(\mathcal{Z}'_1, \dots, \mathcal{Z}'_k)$ -RCDS protocol \mathcal{P}' , where the size of the secret is $O(\ell k \log t \log |S|)$, the message size is $\tilde{c} \ell \cdot O(k \log t)^{2k-1} \log |S|$, and the normalized message size is $\tilde{c} \cdot O(k \log t)^{2k-2}$.

We apply Lemma D.1 again, this time using \mathcal{P}' . Let $H_{2^\ell, kt, \log t, 2kt}$ be the family of $\log t$ -collision free hash functions for $\mathcal{T} = \binom{X}{kt}$ guaranteed by Lemma A.8, whose size is $O(kt\ell)$. By Lemma D.1 applied to \mathcal{P}' and $H_{2^\ell, kt, \log t, 2kt}$, there exists a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol, where the size of the secret is $O(\ell^2 k^2 t \log t \log |S|)$, the message size is $O(\tilde{c} \ell^2 k^2 t \log t (2k^3 t \log^2 t)^{k-1} \log |S|)$, and the normalized message size is $O(\tilde{c} (2k^3 t \log^2 t)^{k-1})$. \square

By using the k -server CDS protocol of [41] in Theorem D.2 we obtain the following corollary.

Corollary D.3. *Let $f : X_1 \times \dots \times X_k \rightarrow \{0, 1\}$ be a k -input function, where $|X_i| \leq 2^\ell$, let t be an integer such that $2kt + k \log t < 2^\ell$, and $\mathcal{Z}_i = \binom{X_i}{\leq t}$ for every $i \in [k]$. Then, there is a $(\mathcal{Z}_1, \dots, \mathcal{Z}_k)$ -RCDS protocol with a $O(\ell^2 k^2 t \log t)$ -bit secret whose normalized message size is $2^{\tilde{O}(\sqrt{k\ell})} \tilde{O}(tk^3)^{k-1}$.*