FLEXCRYPT: Kernel Support for Heterogeneous Full Drive Encryption

Paper #9

Abstract

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1   Introduction

Security is a very important property of storage systems. Decades of systems and storage research in this space have looked into security in the context of disk controllers/FTL and secure hardware [37, 78, 87, 89]; filesystems [13, 18, 28, 29, 38, 46, 86]; network storage and cloud storage [10, 22, 32, 43, 49, 51, 53, 54, 59, 60, 64, 66, 69, 72, 80, 83], de-duplication and secure erasure [19, 70, 81]; as well as kernels, databases, and other software [20, 57, 71, 77].

For local storage, the state of the art for securing data at rest—such as the contents of a laptop's SSD—is Full Drive Encryption (FDE). Popular FDE solutions include dm-crypt [1, 8] for Linux and BitLocker for Windows [30, 63]. Behind these implementations is the industry standard AES *block cipher* in XTS mode: AES-XTS [5, 6, 67]. Unfortunately, using AES-XTS introduces overhead that drastically impacts system performance and energy consumption. The story of FDE on Google's Android OS illustrates the problem. Android supported FDE with the release of Android 3.0, yet it was not enabled by default until Android 6.0 [24]. Two years prior, Google attempted to roll out FDE by default on Android 5.0 but had to backtrack. In a statement to Engadget, Google blamed "'performance issues on some partner devices' ... for the backtracking" [76]. At the same time, AnandTech reported a "62.9% drop in random read performance, a 50.5% drop in random write performance, and a staggering 80.7% drop in sequential read performance" versus Android 5.0 unencrypted storage for various workloads [40].

Fortunately, in the last two years there have been significant advancements in Full Drive Encryption; specifically, the slow AES block cipher can be replaced with fast *stream* ciphers like CHACHA20. For instance, constructions like Google's HBSH (hash, block cipher, stream cipher, hash)/Adiantum [23] and StrongBox [27] bring stream cipher based FDE to devices that do not or cannot support hardware accelerated AES, generally providing improved performance along the way [27]. A key to efficiently adopting stream ciphers into the storage layer is to pair it with a Log-structured File System (LFS) such as F2FS on flash devices. This is because LFSes naturally avoid writing to the same location multiple times, which requires an expensive re-keying operation when using stream cipher based FDE.

Traditionally, FDE at the block level requires enciphering drive contents *homogeneously* (with a single cipher), but these advancements reveal a new opportunity: storage systems that operate beyond the rigid constraints of prior work to support flexible *heterogeneous* FDE. Yet we find no storage system or OS that can support such a feature. To see where this might be useful, suppose the user of an mobile device is required to encrypt their drive with cipher FREESTYLE because it has the useful cryptographic property of being safe to back up to cloud storage. In exchange for this property, FREESTYLE uses a significant amount of energy when executing. Further suppose this device enters a critical battery state and the user wishes to conserve as much energy as possible. It would be beneficial if an energy-aware storage system could also enter a battery saving state. With heterogeneous FDE, such a flexible configuration is now achievable: such a system can temporarily switch out the energy-inefficient FREESTYLE for the extremely energy-efficient CHACHA20 when accessing data. Since data encrypted with CHACHA20 is not suitable for cloud backups, we pause backups until we leave the critical battery state and switch ciphers again—saving even more energy.

We present FLEXCRYPT, to the best of our knowledge the *first* storage system to provide block level kernel support for heterogeneous FDE. As FDE's impact on drive performance and energy efficiency depends on a multitude of choices, different ciphers expose different performance and energy efficiency characteristics. By supporting heterogeneous FDE, FLEXCRYPT permits cipher choice to be be viewed as a dynamically configurable parameter as opposed to a static choice made at format or boot time. As a result, FLEXCRYPT enables

the storage system to adapt to changes that arise at runtime, including: resource availability and environment, desired security properties, and the OS's energy budget. This empowers users to perform cipher switching in space and time (*e.g.,* using more secure storage for more sensitive files, and/or dynamically switching between ciphers for one file), allowing the system to navigate the tradeoff space made by balancing competing security and latency requirements. FLEXCRYPT is composed primarily of three components that realize these benefits. These represent the three main contributions of this work.

First, we introduce FLEXSWITCH, a kernel configuration that exposes three switching models: *Forward*, *Mirrored* and *Selective*. Switching allows us to "re-cipher" storage units dynamically, enabling us to tradeoff different performance and security properties of various configurations at runtime. These switching models define what the I/O layer should do upon the ongoing read/write I/Os during the switching. These three switching models are motivated by real case studies. For example, Forward switching is motivated by the battery case study above; Mirrored switching is motivated by scenarios where system administrators want to change ciphers with zero downtime and without re-initializing the filesystem or device mapper; and Selective switching is motivated by cases where users require certain files (*e.g.,* legal documents) to be stored more securely than others.

Second, to support the switching models above, we implement FLEXAPI, a block layer kernel module that contains encryption implementations ("crypts") that have been restructured to support switching. Prior work encrypts targets with a single cipher—*i.e.,* homogeneous FDE—where the choice of cipher implementation is integrated into the file/block layer system directly [8,27]. The key challenge with supporting heterogeneous FDE—where multiple ciphers coexist on the same storage system—is that different ciphers take disparate inputs and produce disparate outputs. For example: CHACHA20's implementation requires a key and nonce, FREESTYLE's additionally requires configuration for output randomization, and AES-CTR's instead requires plaintext and sector information. At the same time, FREESTYLE and CHACHA20's implementations output a keystream that needs to be XORed with the plaintext to yield the ciphertext while AES-CTR outputs the ciphertext directly. Thus, we introduce a novel design substantively expanding prior FDE work by wholly decoupling cipher implementations from the encryption process. In FLEXAPI, we write hooks that effectively normalize the inputs and outputs required when switching between ciphers.

Finally, we present FLEXTRADE, a scheme that attempts to *quantify* the tradeoffs in the the rich configuration space of stream ciphers made available by the above. Using this scheme, we define a tradeoff space of cipher configurations over competing concerns: total energy use, desirable security properties, read and write performance (latency), total writable space on the drive, and how quickly the contents of

the drive can converge to a single encryption configuration. FLEXTRADE helps users in understanding their cipher choices as they come with a variety of performance, energy efficiency, and security properties in the FDE context.

We conclude with a comprehensive evaluation of FLEXCRYPT. First, we show that FLEXCRYPT successfully supports a wide variety of ciphers; specifically we have integrated *7 ciphers* and a total of *15 cipher configurations* into FLEXCRYPT in 7,048 lines of code as a kernel block module [1], and can act as an off-the-shelf replacement for dm-crypt. The ciphers are ChaCha [15], Freestyle [12], Salsa [16], AES in counter mode (AES-CTR) [4], Rabbit [17], Sosemanuk [14], HC-128 [44]. Second, we showcase the benefits of FLEXCRYPT with experiments illustrating three real-world case studies (*i.e.,* storage system responds to critical battery state, filesystem-agnostic file-level encryption, and datacenter downtime avoidance) and show the performance/energy tradeoffs. Finally, we perform several benchmarks to demonstrate the flexibility and performance of the individual ciphers and show the switching overhead of the three switching models we provide.

2 Background and Motivation

In this section we discuss recent advancements and limitations in stream cipher based Full Drive Encryption (FDE), then provide three case studies that motivate our work.

2.1 The Homogeneous FDE Problem

The major issue with FDE is its homogeneous nature; users must commit to one FDE storage configuration at initialization time [8]. Suppose we have an ultra-low-voltage netbook provided by our employer who requires that the drive is 1) fully encrypted at all times and 2) backed up to an offsite system whenever possible. Given that the FDE industry standard is AES-XTS, we consider initializing our drive with it. At this point, three primary concerns present themselves: performance, vulnerability and inflexibility.

First, it is well known that AES-XTS adds significant latency and power overhead to I/O operations, especially on mobile and battery-constrained devices [24, 40, 76]. As the drive must be encrypted at all times, we must accept this hit to performance and battery life. Worse, if our device does not support hardware accelerated AES (which is hardly ubiquitous) performance will be degraded even further; I/O latency can be as high as 3–5x [27]. To provide the security without the overhead, there are *faster, more energy-efficient* stream ciphers we might consider instead.

Second, AES-XTS is designed to mitigate threats to drive data "at rest," which assumes an attacker cannot access snapshots of our encrypted data nor manipulate our data without those manipulations being immediately obvious to us. Access to multiple snapshots of a drive's AES-XTS-encrypted

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[1]FLEXCRYPT source: https://github.com/ananonrepo2/SwitchCrypt

contents presents a vulnerability: an attacker can passively glean information about the plaintext over time by contrasting those snapshots, leading to confidentiality violations in some situations [5, 73]. Unfortunately, the backups required by this scenario function as snapshots for an attacker. There are *ciphertext randomizing* stream ciphers we can use that can be safely backed up, but they are known to be an additional source of latency and power overhead [12].

Third, our device is battery constrained, placing a cap on our energy budget that can change at any moment as we transition from line power to battery power and back. Our storage system should respond to these changing requirements, including reducing energy use when the user wants to conserve power (i.e. "battery saver mode"), all without violating any other concerns.

The fundamental challenge is that there is no single cipher that addresses all concerns simultaneously; however, these concerns change over time (e.g., energy efficieny is more important when battery is low). Hence, a homogeneous FDE solution will always sacrifice one concern for the other where a flexible *heterogeneous* approach may not.

2.2 Recent Advancements

Broadly speaking, an FDE storage system can be implemented in two ways: using *block* ciphers or using *stream* ciphers. Block ciphers were the de facto solution for storage while stream ciphers were prevalent in networking and elsewhere. The relevant difference: encryption using a stream cipher is simpler and thus faster than a block cipher, especially in software; however, stream ciphers have their own non-trivial problems (*i.e.,* rollback attacks and overwrites) and are hence not a drop-in replacement for block ciphers [27]. There have been major advancements in the FDE technology that moves us away from slower block ciphers and towards the adoption of faster stream cipher based FDE [23, 27].

There are two technological shifts that enable secure, high-performance storage with stream ciphers. First, devices today commonly employ solid-state storage with Flash Translation Layers (FTL), which operate similarly to Log-structured File Systems (LFS) [45, 47, 74]. The no in-place update "overwrite-averse" nature of FTL and LFS-like storage allows stream cipher based FDE to be efficiently implemented (*e.g.,* ChaCha20 with F2FS performs on average 1.72× better than ext4 [27]). Second, mobile devices now support trusted hardware, such as Trusted Execution Environments (TEE) [52, 79] and secure storage areas [9], which means the system has access to persistent, monotonically increasing counters that can be used to prevent rollback attacks when overwrites do occur.

2.3 No One-Size-Fits-All Case Studies

Recent advancements demonstrate that stream cipher based FDE can be implemented in an efficient manner, which opens up an opportunity for the storage layer to support multiple encryption technologies in various modes and configurations. For instance, such a system could switch from using an energy-inefficient but backup-safe cipher to an energy-efficient cipher to save battery life when entering battery saver mode and later switch back (and resume uploading backups) after leaving battery-saver mode. Clearly, there is no one-size-fits-all encryption solution and some flexibility is demanded. Below we present three such case studies.

"Battery saver" mode and Forward switching. In situations like the netbook example above, the user might want to prioritize reducing the total energy use when the battery is low. While in this "battery saver mode," it would be beneficial if the storage system could switch to a more energy-efficient cipher and pause the cloud backup momentarily. A user would be willing to accept this tradeoff knowing that within a few hours they will have access to power and could resume uploads when the storage system switches back, which is no different from an internet connection problem. This case is pervasive [11, 34, 35, 48, 62].

Cipher upgrade and Mirrored switching. From mobile devices, we now turn to server-side storage where we might require an encryption upgrade [21, 39, 41]. A server provider might decide to completely upgrade from one encryption technology (*e.g.,* that has been superseded) to another. Ideally, during the switch, the server would maintain its service-level agreements without any restarts or downtime. However, without kernel-level support, the server provider must write application-level software that performs the whole switching operation and manually redirects users to the appropriate files. It would be beneficial if this could be handled entirely at the storage layer instead.

Scalable encryption and Selective switching. It is known that systems communicating over a network transmit both high- and low-priority data and those priority levels should be encrypted differently [33]. It would be beneficial if our storage system could take advantage of the heterogeneous block-by-block "scalable" nature of such an encryption requirement to reduce latency and conserve energy. Examples of data with variable encryption requirements include corporate and government documents where information is routinely classified/redacted, credit card or information in a shopping transaction [33], and directory or file-level encryption transparent to the filesystem.

3 FLEXCRYPT Design

FLEXCRYPT is a block layer kernel module that can replace other state-of-the-art block-level encryption technologies such as the popular dm-crypt. FLEXCRYPT does not require any modification in the application and, when using the Selective switching model, only a small modification in the file system layer to include cipher choice in writes to the block layer. The choice to implement FLEXCRYPT at the block

layer (as dm-crypt [8] does) is important to ensure the core logic of file systems does not have to be modified and that all metadata is encrypted and protected. Just like any other encryption technology, FLEXCRYPT must have a unit of encryption/decryption. In this paper we call that unit a "nugget," which can be configured as one or more sequential blocks.

To provide kernel support for heterogeneous FDE and live cipher switching, we must address three key challenges:

1. We must provide switching models that cover the temporal and spatial nature of storage access to support the flexible heterogeneous encryption that users demand. For this, we introduce the FLEXSWITCH (§3.1) component of FLEXCRYPT that exposes three switching models to users: Forward, Selective and Mirrored switching.

2. We must allow arbitrary cipher implementations to be easily integrated into FLEXCRYPT. This is non-trivial, however, as different ciphers and encryption modes require different inputs, generate disparate outputs, and are often tightly coupled to the storage/encryption layer itself. For this, we introduce the FLEXAPI (§3.2) component where we decouple cipher implementations from the core encryption algorithm by providing wrapper interfaces that allow different encryption algorithms ("crypts") to co-exist in the storage layer.

3. We must help users understand the tradeoffs of different cipher configurations, hence we introduce FLEXTRADE (§3.3), a method that quantifies the desirable properties of different cipher configurations using several metrics such as the round count, ciphertext randomization, and ciphertext expansion cost.

3.1 FLEXSWITCH: Cipher Switching Models

Though not a technical limitation, it is helpful to think of FLEXCRYPT as having a single *active cipher configuration* among several available. With FLEXSWITCH, our storage system has the flexibility to switch from one cipher configuration to another, or even employ multiple configurations in a way unachievable with prior work. When a cipher switch is triggered, a different configuration becomes the active configuration, and "re-ciphering" must be done, *i.e.,* using the deactivated configuration to decrypt a nugget's contents and using the active configuration to re-cipher it.

The challenge here is to accomplish re-ciphering while minimizing overhead. A naive approach would switch every nugget to the active configuration immediately, but the latency and energy cost would be unacceptable. Hence, a more strategic approach is is necessary. For example, depending on the use case, it may make the most sense to re-cipher a nugget immediately, or eventually, or to maintain several areas of differently-ciphered nuggets concurrently. Our models allow for nuggets to be re-ciphered in a variety of cases with minimal impact on performance and battery life and without

	Read	Write
Forward	1st read: D_{C_1} then E_{C_2} Nth read: D_{C_2} Or variant version: 1st read: D_{C_1} 2nd read: D_{C_1} then E_{C_2} Nth read: D_{C_2}	E_{C_2} (only if necessary)
Mirrored	When migrating: D_{C_1} from C_1's region After migrating: D_{C_2} from C_2's region	I/O is duplicated: E_{C_1} to C_1's region and E_{C_2} to C_2's region
Selective	Encrypted with C_1: D_{C_1} Encrypted with C_2: D_{C_2}	Should use C_1: E_{C_1} Should use C_2: E_{C_2}

Table 1: **Switching Models and Re-ciphering.** This table summarizes for each switching model what happens on I/Os to a nugget when FLEXCRYPT switches from cipher C_1 to cipher C_2 (see §3.1). "Read" denotes returning data during the switch. "Write" denotes committing new data. E_X denotes encryption (*i.e.,* re-ciphering) and D_X denotes decryption using cipher X.

compromising security; they are: Forward, Mirrored, and Selective. How FLEXCRYPT reacts to I/Os under each model is summarized in table 1.

Forward switching. In the case of the battery saver mode example, we want to switch from cipher "C_1", a highly-secure, energy-expensive cipher to cipher "C_2," a less-secure but more energy-efficient cipher. However, for efficiency, *we only switch nuggets on demand*; *i.e.,* we change those nuggets that are touched during I/O. This switching model would be enabled as part of a higher-level policy (*i.e.,* battery saver mode) enacted by the OS or user.

Table table 1 summarizes what happens on I/Os immediately after the active cipher is switched to C_2. For nugget-sized writes, new data is ciphered with C_2 and committed as normal. For intra-nugget writes, the nugget is first decrypted using C_1 and then re-ciphered using C_2 with the new data included. The new nugget is then committed as normal. Re-ciphering only occurs when necessary; once a nugget is ciphered with C_2, no further switching is required. For reads, the nugget is decrypted using C_1, it is re-ciphered with C_2, and then the data is returned. On subsequent reads, the nugget is decrypted with C_2 and read as normal.

Later, when battery saver mode is turned off and C_1 becomes the active cipher again, nuggets are not automatically re-ciphered as, again, that would be inefficient. Nuggets will be re-ciphered on demand using the converse of the process described above. In general, Forward switching limits the performance and battery impact of cipher switching to the individual nuggets being accessed. The data at rest (ciphered with C_1) that is never accessed during the switch remains in its original state.

We note that there can be variants to the Forward switching

model. For instance, a variation on read operations: we consider the first, second, and nth read accesses distinctly. On the first read, the nugget is decrypted using C_1 and the data returned. Only if that same nugget is read a second time is it re-ciphered with C_2 before the data is returned. On subsequent reads, the nugget is decrypted with C_2 and read as normal. The intuition is that Forward switching only happens temporarily (*e.g.,* while the battery is low), hence data being read might only be read once and stay in memory. However, if the nugget is read the second time, then the data is re-ciphered to C_2. This and other possible variants are left for future work. So far, we find our version of Forward switching suits a common battery-saving scenario.

Mirrored switching. Next, we consider a different scenario where "C_1" is a cipher that has been superseded by "C_2", a newly recommended cipher that has just been added to FLEXCRYPT's latest kernel/module upgrade. Let us imagine a datacenter storage operator who wants to upgrade from C_1 to C_2 without any service interruptions. Anticipating this, our operator partitions available storage into two regions. That is, to support a full-drive cipher switch supported by the block layer and without application/file system modification, we must pay the space cost to anticipate such a switch.

During the migration, as summarized in Table table 1, all write operations that hit C_1's region will be mirrored to C_2's region. Meanwhile, in the background, the data in C_1's region is incrementally re-ciphered and written to C_2's region. Until the migration is complete, read operations will be served by C_1's region. This is very similar to VM live migration [75]. After the migration completes, one can use a mechanism such as SSD Instant/Secure Erase [2, 3, 65] to securely erase the previous storage region's data.

In general, Mirrored switching allows us to converge a drive volume to a single cipher configuration without losing any data, suffering outages or downtime, requiring onerous manual effort, or violating any critical service-level agreements. We note that, after the migration, the previous region's data needs to be securely erased to complete the upgrade; here, not overlapping the two regions makes Instant/Secure Erase straightforward [2, 3].

Selective switching. Finally, we consider the case of "scalable encryption." The key insight lies in recognizing that, when storing classified materials, corporate secrets, intellectual property, and other information that requires the highest level of discretion, such sensitive information often appears within a (much) larger amount of data that is valued less. For example, perhaps banking transaction information is littered throughout a PDF; perhaps passwords and other sensitive information exists within several much larger log files. Using prior techniques, either all the data would be stored with high-overhead cipher, the critical data would be stored without the mandated cipher type, or the data would have to be split among separate files requiring a complex and potentially error-prone encryption management scheme.

FLEXCRYPT allows us to sidestep these issues by supporting heterogeneous FDE, *i.e.,* encrypting different nuggets with different cipher configurations in the same drive volume and even the same file. With Forward switching, we toggled nuggets between two cipher configurations to trade off battery life and security; with Selective switching, we want to select a specific cipher configuration each time we encrypt a nugget to trade off performance and security.

Table table 1 summarizes what happens on I/Os when FLEXCRYPT is initialized using the Selective model with two available cipher configurations: the high-overhead high-security C_1 and the low-overhead reduced-security C_2. Suppose we have a multi-gigabyte corporate document that needs to be continually disseminated to and consumed by multiple parties. On writes, we want certain high priority secrets in this document to be available to only a subset of receivers, so we should use our powerful but resource-intensive C_1 to encrypt nuggets containing these secrets. On the other hand, the remainder of surrounding nuggets should use the more performant C_2, allowing other parties to interact with the low-priority data (perhaps on a lightweight mobile device) without experiencing degraded storage performance. On reads, FLEXCRYPT uses its own metadata to automatically determine which cipher configuration to use for decryption.

3.2 FLEXAPI: Cipher Wrapper Interface

One of the goals of FLEXCRYPT is that we might use any stream cipher regardless of its implementation details. However, allowing these ciphers to co-exist in the same volume is entirely non-trivial since there are many cipher implementations that we might use with FLEXCRYPT, each with unique input requirements and output considerations. For instance, Salsa and Chacha implementations require a certain IV and key size and handle plaintext input through successive invocations of a single state update function [31]. Using OpenSSL's AES implementation in CTR mode requires manually tracking the counter state and individual ciphertext blocks are retrieved though corresponding function invocations [68]. Freestyle's reference implementation requires we calculate the extra space necessary per nugget (due to ciphertext expansion) along with configuration-dependent minimum and maximum rounds-per-block, hash interval, and pepper bits [12]. HC-128 and other ciphers have similarly disparate requirements.

Further, unlike prior work, FLEXCRYPT must be able to encrypt and decrypt arbitrary nuggets *with any of these ciphers* at any moment with low overhead and without tight coupling to any specific implementation detail. Hence, we must abstract away these input and output requirements by decoupling cipher implementations from the core encryption process. We present FLEXAPI, a collection of interfaces that allow implementors to write light (<100 LOC) wrapper functions around cipher implementations without modifications to

third-party code; we call these wrapped ciphers *crypts*. Crypts present FLEXCRYPT with a uniform encryption and decryption interface for each cipher, enabling normally incompatible ciphers to encrypt and decrypt arbitrary nuggets.

The ability for disparate cipher implementations to co-exist in this way forms the foundation for FLEXCRYPT's ability to switch the system between different cipher configurations efficiently and effectively. To facilitate this, FLEXAPI presents the cryptographic driver with a single uniform encryption/decryption model. FLEXCRYPT receives I/Os from the operating system at the block device level like any other device-mapper. These I/Os come in the form of either reads or writes. When a read is received, the OS hands FLEXCRYPT an offset and a length and expects a response with plaintext of that specific length starting at that specific offset taken from the beginning of storage. When a write is received, the OS hands FLEXCRYPT an offset, a length, and a buffer of plaintext and expects that plaintext to be encrypted and committed to storage such that the plaintext is later retrievable given that same offset and length in a future read. Crypts handle these I/Os by implementing either `xor_interface` or both `read_interface` and `write_interface`.

`xor_interface` executes independently of FLEXCRYPT internals and treats encryption and decryption as the same operation. Crypts receive an integer offset F, an integer length L, a key buffer K corresponding to the current nugget, and an empty L-length XOR buffer. FLEXCRYPT expects the XOR buffer to be populated with L bytes of keystream output from some stream cipher seeked to offset F with respect to key K. The length of the key buffer will always be exactly what the cipher implementation expects, alleviating the burden of key management; similarly, the XOR buffer will be XOR-ed with the appropriate portion of nugget contents automatically, alleviating the burden of drive access and other tedious calculations.

`read_interface` and **`write_interface`**, on the other hand, treat encryption and decryption as distinct concerns. `read_interface` handles decryption and re-ciphering during reads. `write_interface` handles encryption and re-ciphering during writes. Crypts receive full access to FLEXCRYPT internals, giving wrapper code deep hooks into the encryption and decryption process and allowing implementers to bypass parts of the nugget-based storage layout if necessary. This comes at the cost of increased code complexity and potential performance implications, since FLEXCRYPT must account for not having absolute control over its internal data structures when using this crypt.

For this work we have implemented 15 crypts using 7 ciphers—ChaCha, Freestyle, AES-CTR, AES-XTS, Rabbit, Sosemanuk, HC-128—each in under 100 LOC (excluding the cipher algorithm itself).

3.3 FLEXTRADE: Evaluation Framework

To reason about when to switch cipher configurations, users must have a way to compare and evaluate their utility in the novel context of heterogeneous FDE. However, different ciphers have a wide range of desirable security properties, performance profiles, and output characteristics, including those that randomize their outputs and those with non-length-preserving outputs. To address this need, we propose FLEXTRADE, a novel evaluation framework that quantifies stream ciphers according to three features relevant to heterogeneous FDE: *relative rounds*, which gives users a sense for the strength of the implementation; *ciphertext randomization*, which gives a sense for how safe a cipher's output is to backup/snapshot (see §2); and *ciphertext expansion*, which gives users a sense for how a cipher configuration impacts the total available drive space. Taken together, these features illustrate a rich tradeoff space of cipher configurations optimizing for different combinations of energy-efficiency, security, and performance concerns.

Relative Rounds (Rounds). The ciphers we examine in this paper are all constructed around the notion of *rounds*, where a higher number of rounds (and/or possibly longer key) is positively correlated with a higher resistance to brute force given no fatal related-key or other attacks [58]. Hence, this feature, scored from 0 (lowest relative round count) to 1 (highest relative round count), represents how many rounds a cipher executes relative to other implementations of the same algorithm. For instance: ChaCha8 (score: 0) is a reduced-round version of ChaCha12 (score: 0.5), which is a reduced-round version of the standardized ChaCha20 (score: 1), all using the ChaCha algorithm [15, 58].

Ciphertext Randomization (Randomization). A cipher with ciphertext randomization generates different ciphertexts non-deterministically given the same key, nonce, and plaintext. This makes it much more difficult to execute chosen-ciphertext attacks (CCA), key re-installation attacks, XOR-based cryptanalysis and other comparison attacks, and other confidentiality-violating schemes where the ciphertext is in full control of the adversary [12]. This property is useful in cases where we cannot prevent the same key, nonce, and plaintext from being reused, such as with data "in motion" (see §2). Ciphers without this property—such as ChaCha20 and AES-XTS on which prior work is based—are trivially broken when key-nonce-plaintext 3-tuples are reused. In StrongBox, this is referred to as an "overwrite condition" or simply "overwrite" [27].

Though there are many ways to achieve ciphertext randomization, the ciphers included in our analysis implement it using a random number of rounds for each block of the message where the exact number of rounds are unknown to the receiver a priori [12]. In configuring the minimum and maximum number of rounds used per block in this non-deterministic mode of operation, we can customize the computational burden an

Cipher	Rounds	Randomization	Expansion
ChaCha8	0	0	1
ChaCha12	0.5	0	1
ChaCha20	1	0	1
Salsa8	0	0	1
Salsa12	0.5	0	1
Salsa20	1	0	1
HC128	0	0	1
HC256	1	0	1
Freestyle*	0	1	0
Freestyle (F)	0	2	0
Freestyle (B)	0.5	2.5	0
Freestyle (S)	1	3	0

Table 2: **Quantifying Ciphers.** 12 cipher crypts (§3.2) evaluated using the FLEXTRADE framework as described in §3.3.

attacker must bear by choosing lower or higher minimums and maximums. Hence, this is not a binary feature; scores range from 0 (no ciphertext randomization support) to 1 (lowest minimum and maximum rounds per block) to 3 (highest minimum and maximum rounds per block).

Ciphertext Expansion (Expansion). A cipher that exhibits ciphertext expansion is non-length-preserving: it outputs more ciphertext than was originally input as plaintext. This can cause major problems in any FDE context. For instance, cryptosystems that rely on AES-XTS (e.g. Linux's dm-crypt [8] and Microsoft's BitLocker [63]) or ChaCha (e.g. StrongBox [27], Google's Adiantum [23]) have storage layouts that hold length-preserving ciphertext output as an invariant, making ciphers that do not exhibit this property incompatible with their implementations; yet, ciphertext expansion is often *but not always* a necessary side-effect of ciphertext randomization. Further, non-length-preserving ciphers *use more drive space* than length-preserving ciphers when encrypting the same plaintext, meaning users will have less total available drive space.

The ciphers included in our analysis that exhibit ciphertext expansion have an overhead of around 1.56% per plaintext message block [12]. Even a single byte of additional ciphertext vs plaintext would make a cipher inappropriate for use with prior work. Hence, this is a binary feature in that a cipher either outputs ciphertext of the same length as its plaintext input or it does not. A cipher scores either a 0 if it *is not* length-preserving in this way or a 1 if the ciphertext is always the same length as the plaintext.

Table table 2 shows the result of using FLEXTRADE to evaluate 12 cipher crypts (see §3.2) as described below. Note that we have included the special crypt *Freestyle** in our analysis, which is a vacuous configuration of our Freestyle implementation (see §4) using the minimum possible ciphertext randomization options.

3.4 Putting It All Together

Here we discuss other details surrounding our three main contributions.

Secure metadata management. The focus of this work is to implement mechanisms and policies to perform flexible switching of cipher configurations. These configurations are built atop an existing block-level encryption module (or "encryption driver") that manages our data structures and provides cryptographic support. There were several open source choices for an encryption driver: Linux's encryption device mapper [1, 8], encryption-ready F2FS filesystem [47], or StrongBox [27]. We decided to build FLEXCRYPT atop StrongBox because it already implements stream cipher based FDE and employs a nugget-based drive layout.

FLEXCRYPT depends on the data structure management provided by StrongBox, such as its *transaction* and *rekeying journals* to avoid overwrite violations [27], *Merkle tree* to avoid rollback and related attacks [27], *monotonic counter* on a trusted hardware to prevent rollbacks, *keycount store* to derive unique encryption keys, and *per-nugget metadata* to store cipher-specific metadata (useful for ciphertext-expanding ciphers). Every FLEXCRYPT volume also has a "head" area that stores implementation-wide data like the master encryption key or which cipher is currently active.

While we reuse some StrongBox components, all of these are tightly integrated to with a special ChaCha20 implementation. We had to untangle this, hence the FLEXAPI contribution, where we expose structured interfaces allowing cipher implementors to easily build crypts from any off-the-shelf stream cipher implementation. Specifically, of the six StrongBox components listed above, only the keycount store and monotonic counter can be reused as is; the others were rewritten to support FLEXSWITCH and FLEXAPI.

Threat model under switching. In terms of *confidentiality*, an adversary should not be able to reveal any information about encrypted plaintext without the proper key. As with prior works, encryption is achieved via a binary additive approach: cipher output (keystream) is combined with plaintext nugget contents using XOR, with metadata to track writes and ensure that pad reuse never occurs during overwrites and that the system can recover from crashes into a secure state.

In terms of *data integrity*, an adversary should not be able to tamper with ciphertext and it go unnoticed. Nugget integrity is tracked by StrongBox's in-memory Merkle tree [27].

Switching strategies add an additional security concern not addressed by prior work: even if we initiate a "cipher switch," there may still be data on the drive that was encrypted with an inactive configuration. Is this a problem? For the Forward model, this implies data may at any time be encrypted using the "least desirable cipher". For the Mirrored and Selective strategies, the drive is partitioned into regions where nuggets are guaranteed to be encrypted with each cipher, including the "least desirable cipher". However, in terms of confidentiality,

Cipher	Source
AES-XTS, AES-CTR	OpenSSL [68] & libsodium [26]
ARM Neon ChaCha	Floodyberry [31]
Freestyle	Babu [12]
eSTREAM Profile 1	libestream [55]

Table 3: **Cipher Implementations.** See §4, §3.2.

the confidentiality guarantee of FLEXCRYPT can be reduced to the individual confidentiality guarantees of the available ciphers used to encrypt nuggets.

Higher-level integration. FLEXCRYPT expects a higher-level integration/policy that communicates what kind of switching should be performed and when. An example is the battery saver scenario, where the OS battery saver application is expected to notify FLEXCRYPT when to move to an energy-efficient crypt versus a backup-ready crypt using Forward switching. See §5 for more integrations.

Generality. FLEXCRYPT can be seen as a drop-in replacement for the popular Linux dm-crypt layer (encryption driver). For performance reasons, like StrongBox, FLEXCRYPT recommends a Log-structured File System (LFS) such as F2FS, YAFFS, or LogFS, which are commonly used for flash devices. The reason for this is that supporting streaming ciphers is more efficient in storage systems with no in-place updates [27]. Though FLEXCRYPT is a software solution, the same LFS-based logic can be adopted by hardware like flash devices. For example, the LFS-like "no in-place updates" nature of Flash Transition Layers (FTL) would allow heterogeneous FDE implementations be performant at the device controller level, allowing the use of other popular in-place update file systems such as ext4, btrfs, and xfs.

4 Implementation

Our FLEXCRYPT implementation consists of 7,048 lines of C code (excluding StrongBox components we re-use as is). To ensure high quality code, we also wrote a 4,944 line test suite. Our implementation is available open source [1]. We deploy FLEXCRYPT on top of the BUSE virtual block device [7] as our mock device controller. BUSE is a thin (200 LoC) wrapper around the standard Linux Network Block Device (NBD), allowing our system to transact block layer requests in user space, reducing implementation complexity.

Among the many ciphers our implementation supports, we focus on five in this research: ChaCha8, ChaCha20 [15], and Freestyle [12] in three different configurations: a "fast" mode with parameters FFast(R_{min}=8, R_{max}=20, H_I=4, I_C=8), a "balanced" mode with parameters FBalanced(R_{min}=12, R_{max}=28, H_I=2, I_C=10), and a "strong" mode with parameters FStrong(R_{min}=20, R_{max}=36, H_I=1, I_C=12).

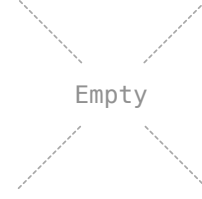Table table 3 shows the cipher implementations we use

Figure 1: **Battery saver use case.** Energy-security tradeoff given strict energy budget as discussed in §5.1.

(wrapped into crypts with FLEXAPI; see §3.2).

5 Case Studies

In this section, we provide three case studies demonstrating the practical utility of heterogeneous FDE not achievable with prior work. We cover a wide range of situations, highlighting concerns like meeting latency goals, trading off security and writable space, and keeping within an energy budget, all demonstrating the utility of our switching models. All experiments are repeated multiple times.

5.1 Battery Saver Mode

In this first case study, we revisit the motivational example. Here, the mobile device is "forced" to locally encrypt files with Freestyle Balanced Cipher ("C_1") for safely backing up the file to the backend cloud, but when the battery saver mode is on, the device will switch to a more energy-efficient cipher, ChaCha8 ("C_2"), and at the same time pausing the backup upload to the cloud momentarily (*e.g.,* the company does not want files to be saved in the cloud without C_1 encryption. Our goal is to complete I/Os as much as we can before the device dies.

To simulate I/O activity, we begin randomly writing 10 40MB files using the Freestyle Balanced cipher for 2 minutes. After the first 5 seconds, the device enters "battery saver" mode, which we simulate by underclocking the cores to their lowest frequencies and using `taskset` to transition FLEXCRYPT processes to the energy-efficient LITTLE cores. In this "battery saver" mode, FLEXCRYPT switches to the ChaCha8 cipher.

(HSG$_0$: I don't understand fig. 1. You said after 5 seconds. we switch to ChaCha8. But why the FB+ChaCha line is still going up? Why it doesn't flat out like the ChaCha line?? and why do even need to show the ChaCha8 only line?)

(HSG$_1$: we should exlude ChaCha8 only, unless you have a major point here)

fig. 1 shows the time versus energy used. At 0 seconds, we begin writing. At 5 seconds, the "battery saver" event occurs, causing the system to be underclocked. At 120 seconds, the system will die. If we blow past our energy ceiling, the system will die. The figure shows two lines: **(1)** *Freestyle Balanced only*, that favors security even when backups are paused; the
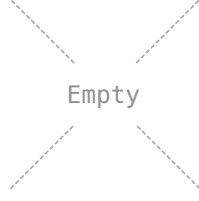
Figure 2: **Cipher upgrade without downtime.** Switching storage system encryption with zero downtime as discussed in §5.2.

Figure 3: **Filesystem-agnostic encryption use case.** Filesystem-agnostic file-level encryption as discussed in §5.3.

device dies before the I/Os complete. **(2)** *Freestyle Balanced + ChaCha8*, that performs the switch when the system enters the low power state. Our results show that, while the system uses slightly more power in the short term, we stay within our energy budget and finish before the devices dies. When we get the device to a charger (not shown), the cloud backup is enabled again and when the nuggets are read, FLEXCRYPT automatically converges them back to Freestyle Balanced.

On average, using forward switching resulted in a 3.3x total energy reduction compared to exclusively using Freestyle Balanced, allowing us to remain within our energy budget. (HSG$_2$: **I don't see this 3.3x in the graph. Did you accidentally label the lines incorrectly?**). We note, however, that the energy savings is not the point of this experiment. Rather, the lesson learned is that FLEXCRYPT enables the system to move to the right point in the energy/security tradeoff space so that the current task can still be accomplished before the battery is drained and without compromising backup security at any point.

5.2 No-Downtime Encryption Upgrade

In fig. 2 [TODO: finish sentence] . (HSG$_3$: **we must have a short case study here. Otherwise no point of talking about mirrored switch).**

5.3 Select Data Encryption

This use case illustrates utility of selective switching to achieve a performance win—if only a small percentage of the data needs the strongest encryption, then only a small percentage of the data should have that associated overhead, while the rest can use a minimalist encryption. As mentioned before, this feature requires users to annotate certain files with a special tag via file system calls, which would then be stored in the inode. Because the FLEXCRYPT layer is file oblivious, every block I/O through the FLEXCRYPT layer will be labeled with the corresponding cipher.

We begin by with 10 5MB and 4KB write-read operations to two FLEXCRYPT drive instances: one using ChaCha8 and the other using Freestyle Strong. They represent two extreme where ChaCha8 is a low-latency cipher and Freestyle Strong exhibits a very high overhead. We then run another FLEXCRYPT instance with a 7:3 ratio where 30% of the data considered highly sensitive uses Freestyle Strong.

The left-side and right-side bars in fig. 3 show the two extremes; ChaCha8 exhibits a low latency, consistently less

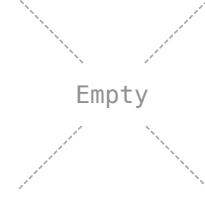than 1 second across the workloads, while Freestyle Strong exhibits 5 to 20 second latency depending on the workload. The selective switching (middle bars) shows a reduction of 3.1x to 4.8x for read latency and 1.6x to 2.8x for write latency, all without compromising the security needs of the most sensitive data. Thus, selective switching keeps our sensitive data at the mandated security level while keeping the performance (and also battery life) benefits of using a fast cipher for the majority of I/O operations.

6 Evaluation

We implement FLEXCRYPT and our experiments on a Hardkernel Odroid XU3 ARM big.LITTLE system with Samsung Exynos 5422 A15/A7 heterogeneous multi-processing quad core CPUs at maximum clock speed, 2 gigabyte LPDDR3 RAM at 933 MHz, and an eMMC5.0 HS400 backing store running Ubuntu Trusty 14.04.6 LTS, kernel version 3.10.106. Energy monitoring was provided by the Odroid's integrated INA-231 power sensors polled every ≈ 260 milliseconds (not including noise/overhead).

We evaluate FLEXCRYPT using a Linux RAM disk (tmpfs). The maximum theoretical memory bandwidth for this Odroid model is 14.9GB/s. Our observed maximum memory bandwidth is 4.5GB/s. Using a RAM disk focuses the evaluation on the performance differences due to different ciphers.

In each experiment below, we evaluate FLEXCRYPT on two high level workloads: sequential and random I/O. In both workloads, a number of bytes are written and then read (either 4KB, 512KB, 5MB, 40MB) 10 times. Each workload is repeated three times for a total of 240 tests per cipher (720 runs per cipher pair/ratios, explained below); 30 results per byte size, 120 results per workload. Results are accumulated and the median is taken for each byte size.

When evaluating switching strategies, a finer breakdown in workloads is made using a pre-selected pair of ciphers we call the *primary cipher configuration* and *secondary cipher configuration*. FLEXCRYPT is initialized at the primary configuration. Once we trigger a cipher switch, FLEXCRYPT moves towards the secondary configuration via switching model.

The cipher switch is triggered according to a certain *ratio* of I/O operations. For example: given 10 40MB read-write operations, we may write and then read back 40MB 3 times using the primary cipher, initiate a cipher switch, and then
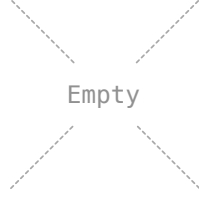
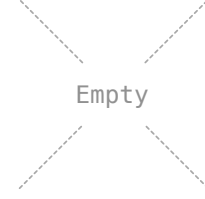Figure 4: **Baseline I/O performance.** Median sequential and random I/O baseline as discussed in §6.1.

Figure 5: **Forward I/O performance.** Median sequential and random I/O compared to baseline. Each cluster of 3 dots between configurations represents the 7:3, 5:5, and 3:7 ratios as discussed in §6.2.

write and then read back (write-read) 40MB 7 times. This would be a 3:7 ratio. It follows that there are three ratios we use to evaluate FLEXCRYPT's performance in this regard: 7:3, 5:5, and 3:7. Respectively, that is 7 file write-read operation in the primary cipher for every 3 file write-read operations in the secondary cipher (7:3), 7 file write-read operation in the primary cipher for every other file write-read operation in the secondary cipher (5:5), and 3 file write-read operations in the primary cipher for every 7 file write-read operation in the secondary cipher (3:7).

To reason about the desirability of cipher configurations, we define the *security vector*, R+R, as a vector consisting of a configuration's relative rounds (Rounds) quantification and its ciphertext randomization (Randomization) quantification defined in §3. We define the norm over this vector as the sum of its components. Hence, we consider a cipher configuration "stronger" if it has higher ciphertext randomization and uses more rounds, *i.e.,* has a higher normed R+R.

All experiments are performed with basic Linux I/O commands, bypassing system caching.

In this section we answer the following questions:

1. What shape does the cipher configuration tradeoff space take under our workloads? (§6.1)

2. Can FLEXCRYPT achieve dynamic security/energy tradeoffs by reaching configuration points not accessible with prior work? (§6.2)

3. What is the performance and storage overhead of each cipher switching model? (§6.3)

6.1 Switching Strategies Under Workloads

fig. 4 shows the normalized relative rounds and ciphertext randomization (normed R+R vector) versus median normalized latency tradeoff between different stream cipher configurations for our sequential and random I/O workloads. Trends for median hold when looking at tail latencies as well. Each line represents one workload: 4KB, 512KB, 5MB, and 40MB respectively (see legend). Each symbol represents one of our ciphers: ChaCha8, ChaCha20, Freestyle Fast, Freestyle Balanced, and Freestyle Strong. Of the ciphers we tested, those with higher rounds and higher ciphertext randomization scores resulted in higher overall latency and increased energy use for I/O operations. The relationship between these

concerns is not always linear, however, which exposes a rich tradeoff space.

Besides the 4KB workload, the shape of each workload follows a similar trend, hence we will focus on 40MB and 4KB workloads going forward. Due to the overhead of metadata management and the fast completion time of the 4KB workloads (*i.e.,* little time for amortization of overhead), ChaCha8 and ChaCha20 take longer to complete than Freestyle Fast. This advantage is not enough to make Freestyle Balanced or Secure workloads complete faster than the ChaCha variants, however.

Though ChaCha8 is faster than ChaCha20, there is some variability in our timing setup when capturing extremely fast events occurring close together in time. This is why ChaCha8 sometimes appears with higher latency than ChaCha20 for normalized 4KB workloads. ChaCha8 is not slower than ChaCha20.

6.2 Reaching Between Static Configurations

fig. 5 shows the normalized relative rounds and ciphertext randomization (normed R+R vector) versus median normalized latency tradeoff between different stream ciphers for our sequential and random I/O workloads with cipher switching using the Forward model. After a certain number of write-read I/O operations, a cipher switch is initiated and FLEXCRYPT begins using the secondary cipher to encrypt and decrypt data. For each pair of ciphers, this is repeated three times: once at every ratio point *between* our static configuration points (*i.e.,* 7:3, 5:5, and 3:7 described above).

The point of this experiment is to determine if FLEXCRYPT can effectively transition the drive between ciphers without devastating performance. For the 40MB, 5MB, and 512KB workloads (40MB is shown), we see that FLEXCRYPT can achieve dynamic security/energy tradeoffs reaching points not accessible with prior work, all with minimal overhead.

Again, due to the overhead of metadata management for non-Freestyle ciphers (see §4) and the fast completion time of the 4KB workloads preventing FLEXCRYPT from taking advantage of amortization, ChaCha8 and ChaCha20 take longer to complete than Freestyle Fast for 4KB reads. We also see very high latency for ratios between Freestyle Fast
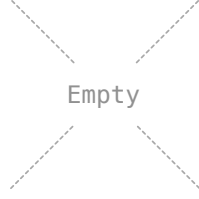
Figure 6: **Mirrored and Selective I/O performance.** Median sequential and random I/O compared to baseline. Each cluster of 3 dots between configurations represents the 7:3, 5:5, and 3:7 ratios as discussed in §6.2.

and Freestyle Strong cipher configurations. This is because Freestyle is not length-preserving, so extra write operations must be performed, and the algorithm itself is generally much slower than the ChaCha variants (see fig. 4). Doubly invoking Freestyle in a ratio configuration means these penalties are paid more often.

fig. 6 show the performance of the Mirrored and Selective strategies with the same configuration of ratios as fig. 5.

For the 40MB, 5MB, and 512KB workloads (40MB is shown), we see that Mirrored and Selective *read* workloads and the Selective *write* workload achieve parity with the Forward model experiments. This makes sense, as most of the overhead for Selective and Mirrored reads is determining which part of the drive to commit data to. The same applies to Selective writes. For the 4KB Mirrored and Selective *read* workloads and the Selective *write* workload, we see behavior similar to that in fig. 5, as expected.

Mirrored writes across all workloads are very slow. This is to be expected, since the data is being mirrored across all areas of the drive. In our experiments, the drive can be considered partitioned in half. This overhead is most egregious for the 4KB Mirrored write workload. This makes Selective preferable to Mirrored. However, it is a tradeoff; Selective cannot quickly converge the drive to a single cipher configuration or survive the loss of an entire region.

6.3 Cipher Switching Overhead

We calculate that Forward switching has average overhead at 0.08x/0.10x for 40MB, 5MB and 512KB read/write workloads compared to baseline I/O, demonstrating FLEXCRYPT's amortization of cipher switching costs. Average overhead is 0.38x/0.44x for 4KB read/write workloads when FLEXCRYPT is unable to amortize cost. There is no spatial overhead with the Forward switching model.

Similarly, we calculate that Selective switching has average overhead at 0x/0.3x for 40MB, 5MB and 512KB read/write workloads compared to baseline I/O. Average overhead is 0.22x/0.71x for 4KB read/write workloads. Spatial overhead in our experiment was half of all writable space on the drive.

Finally, we calculate that Mirrored switching has average overhead at 0.25x/0.61x for 40MB, 5MB and 512KB

read/write workloads compared to baseline I/O, with high write latency due to mirroring. Average overhead is 0.55x/0.77x for 4KB read/write workloads. Spatial overhead in our experiment was half of all writable space on the drive.

These overhead numbers are the penalty paid for the additional flexibility of being able to reach configurations points that are unachievable without FLEXCRYPT. FLEXCRYPT's design keeps these overheads acceptably low in practice, achieving the desired goal of flexibly navigating latency/security tradeoffs for FDE.

7   Related Work

We break this section into three groups: prior work with stream cipher based FDE, prior work trading off security for other concerns, and prior work on energy-aware mobile devices.

Stream cipher based FDE. The standard approach to FDE, using AES-XTS, introduces significant overhead [25]. Recently, it has been established that encryption using *stream ciphers* for FDE is faster than using AES [27], but accomplishing this in practice is non-trivial. Prior work explores several approaches: a non-deterministic CTR mode (Freestyle [12]), a length-preserving "tweakable super-pseudorandom permutation" (Adiantum [23]), and a stream cipher in a binary additive (XOR) mode leveraging LFS overwrite-averse behavior to prevent overwrites (StrongBox [27]).

Unlike StrongBox and other work, which focuses on optimizing performance despite re-ciphering due to overwrites, FLEXCRYPT maintains overwrite protections while abstracting the idea of re-ciphering nuggets out into cipher switching models and crypts; instead of myopically pursuing a performance win, FLEXCRYPT gives us the flexibility to pursue energy/battery and security wins as well.

Trading security for other concerns. Further, trading off security for energy, performance, and other concerns is not a new research area [33, 36, 50, 61, 82, 84, 85]. Goodman et al. introduced selectively decreasing the security of some data to save energy [33]. However, their approach is designed for communication and only considered iteration/round count, thus it did not anticipate the need for FLEXSWITCH, FLEXAPI, or FLEXTRADE. Wolter and Reinecke study approaches to quantifying security in several contexts [82]. This study anticipates the value of dynamically switching ciphers but proposes no mechanisms to enable this in FDE. Similarly, companies like LastPass and Google have explored performance-security tradeoffs. Google's Adiantum uses a reduced-round version of ChaCha in exchange for performance [23]. While not an FDE solution, LastPass has dealt with scaling the number of iterations of PBKDF#2, trading security for performance during login sessions [42].

Energy-aware mobile devices. On mobile energy/battery life, prior works have shown the importance of energy-saving

mode and bugs that drain energy [56, 88]. FLEXCRYPT brings the benefits of a dynamic energy-saving mode to the storage layer.

8 Conclusion

This paper advocates for a more flexible approach to FDE where the storage system can dynamically adjust the tradeoffs between security and latency/energy. To support this vision of heterogeneous FDE, we 1) identified three switching modes to switch ciphers with low overhead and no downtime, 2) demonstrated an interface that allows multiple stream ciphers to be composed in a generic manner, and 3) proposed a quantification framework for determining when to use one cipher over another. Our case studies show how different switching modes can be used to optimize for different goals. We believe heterogeneous encryption will become increasingly important as users demand storage systems be able to balance conflicting operational requirements. We hope this work inspires further research in achieving this balance. Our work is publicly available open source [1].

(HSG$_4$: Other notes:
- double check figure/table captions to be consistent to what the text says
- Add "as explained in cref" in every table/figure caption.
- Put figures on the same page where they are being described. - Make sure figure captions explain the x-axis and y-axis properly. Do explicitly state "the x-axis shows ..., the y-axis shows ...". Do put more annotations inside the figure/graph to help reviewers read the final conclusion.)

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