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Abstract

Anonymous Communication designs such as Tor build their security on distributed trust over many volunteers running relays in diverse global locations. In practice, this distribution leads to a heterogeneous network in which many versions of the Tor software co-exist, each with differing sets of protocol features. Because of this heterogeneity, Tor developers employ *forward-compatible protocol design* as a strategy to maintain network extensibility. This strategy aims to guarantee that different versions of the Tor software interact without unrecoverable errors. In this work, we cast *protocol tolerance* that is enabled by forward-compatible protocol considerations as a fundamental security issue. We argue that, while being beneficial for the developers, protocol tolerance has resulted in a number of strong attacks against Tor in the past fifteen years.

To address this issue, we propose Flexible Anonymous Network (FAN), a new software architecture for volunteer-based distributed networks that shifts the dependence away from protocol tolerance without losing the ability for developers to ensure the continuous evolution of their software. We i) instantiate an implementation, ii) evaluate its overheads and, iii) experiment with several of FAN's benefits to defend against a severe attack still applicable to Tor today.

CCS Concepts

• **Security and privacy → Distributed systems security**; • **Software and its engineering → Software design engineering**; *Software evolution*; *Maintaining software*; Just-in-time compilers.

Keywords

Tor; Anonymous Communications; Software Design

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1 Introduction

The Robustness Principle, as expressed in connection with the standardization of the TCP/IP protocols [36], a cornerstone of the Internet, is stated as: "Be conservative in what you do, be liberal in what you accept from others". This principle, buoyed by the success of TCP/IP, has become accepted good practice for subsequent protocol design. Fundamentally, it advises protocol designs to tolerate, without failing, unexpected messages. From a systems engineering perspective, this law enables protocols to be *forward compatible* and sustain *extensible* protocol designs. Protocols that are forward compatible allow processing messages from future versions of the same software, where there may be parts that the now older version does not know how to process and still perform correctly. The application of the Robustness principle has had a considerable beneficial effect on implementation, maintenance, and deployment of protocol features and underlying distributed systems, making compatibility straightforward between multiple protocol versions. When the TCP/IP protocols were being designed, and the Robustness principle was established, it was difficult to foresee the security and privacy implications and the extent of what the Internet would eventually become.

Since its initial design in the early 2000s, the Tor routing protocol [11] also implements the Robustness principle when processing data and control information. Indeed, robustness is crucial in a distributed and volunteer-based network composed of nodes running many different versions of the Tor routing protocol. Nodes running older versions of the codebase must tolerate messages with extra or updated data formats from nodes running the latest version. Rochet and Pereira [43] showed that, as a *threat vector*, protocol tolerance could be exploited to convey information between malicious relays that easily defeat the anonymity enabled by Tor's incremental circuit design. In the same vein, we make the observation that other researchers have also unknowingly exploited this threat vector, such as fast and reliable Onion Service's Guard discovery [5, 33, 43] or efficient Denial of Service [21, 22]. Furthermore, a real-world attack sponsored by a state agency has been observed in the Tor network using the same threat vector [2, 3]. All these attack designs fundamentally exploited some form of protocol tolerance embedded in Tor, which was purposefully engineered for forward compatibility reason. Altogether, these developments raise awareness of the role this principle plays in efficiently and reliably implementing well-known theoretical attacks, like end-to-end traffic confirmation.

Our contributions are (in order of appearance):

(1) Inspired by prior work [43], we trace the history of recent significant vulnerabilities in Tor and shed light on the inherent tension that robustness introduces between allowing system designers enough latitude to create a maintainable network and limiting the surface area for the adversary to leverage (Section 2.2).

(2) Flexible Anonymous Networking (FAN), a novel methodology that builds on a new programming paradigm and execution model to address the risks inherent to protocol robustness. FAN's unique properties allow authorized developers to globally re-program the nodes of the network without operator intervention (Section 3).

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It supports the network's extensibility through network-wide reprogramming instead of built-in protocol tolerance. In brief, FAN is a design methodology for the software making up the distributed network as a core, stable set of basic features — A network engine, a Cryptography engine, and FAN components. These latter components are a JIT compiler able to compile "plugin" programs written in a high-level language such as `C` or `Rust` and compiled to a RISC VM, such as `eBPF`, and finally a Plugin Manager that manages the logic of these new capabilities. Moreover, FAN must support an OS-independent secure protocol update mechanism to enable unattended upgrades of relays issued by the authorities. One efficient update mechanism is empirically evaluated in this work.

(3) A Transparency mechanism to address potential governance issues linked to FAN's capabilities that enables relay operators to transparently audit the plugin issuance process, enabling trust through proof of correct behavior (Sections 2.2 & 3).

(4) An open-source implementation instance of the FAN methodology applied to the Tor codebase (Section 4).

(5) A case study of our FAN instance applied to defending Tor against the Dropmark attack [35, 43], where we implement and evaluate a FAN-enabled defense against a powerful attack on Tor that is relevant today. We argue that efficiently and provably defending against the Dropmark is infeasible without FAN's specific properties (Section 6).

2 Motivation

2.1 Threat Model

Tor assumes a local adversary who can observe some fraction of the network traffic, operate or compromise some fractions of relays, and interact with clients and other relays by injecting, modifying, dropping, or delaying traffic. Adversaries' goals may vary, from disrupting or denying availability to linking clients to their destinations. The adversary, and the traffic it generates, may also deviate from the Tor protocol. As we shall discuss below, this deviation is tolerated and is historically the result of a desire for Robustness to enable forward-compatible protocols, which has been used by adversaries to achieve the mentioned goals.

2.2 Robustness: A Blessing and a Curse

We now trace several recent examples of protocol tolerance in action that led to critical attacks against anonymity or availability of the Tor network, leading us to argue that it is a systemic problem; a tension between developers who try to ensure the continuous evolution of their protocol design and adversaries taking advantage of the "freedom" built into the design. Directly linked to this research, the Tor developers recently (August 2023) publicly acknowledged the Robustness principle as an engineering issue leading to "highly-severe" attacks [35].

An Illustration: Extending Tor Circuits. The current three-hop default for Tor circuits is a trade-off between performance and anonymity. However, this default is not hard-coded, and circuits of other lengths are possible. This design choice to parameterize the default allows it to be easily changed when needed. However, because path length was not restricted, this allowed researchers to discover a practical congestion attack [14] using infinite hops with the same relay selected multiple times in a Tor circuit. The Tor project introduced the new `RELAY_EARLY` cell type to mitigate this attack [9], while maintaining protocol tolerance. Unfortunately, three years later in 2014, this mitigation enabled a state-level agency to exploit the still present protocol malleability to correlate traffic with absolute certainty, which reliably broke Tor's anonymity [2, 3]. The Tor protocol was then made more *conservative* (commit `68a2e4ca4baa5`) to prevent tolerance abuse of the new cell type.

Moreover, deploying the new `RELAY_EARLY` cell type required backward compatibility with relays that have not yet updated to the latest version of the protocol, and these relays were still susceptible to the congestion attack. A tension exists between the desire to quickly close an attack vector while also retaining most of the relays in the network. A grace period allows maximizing the number of updated relays before making the version mandatory and evicting out-of-date relays. In this case, it took three years from proposal to implementation (version 0.2.1.3-alpha) and another year to full deployment (commit `9bcb18738747e`), while the congestion attack was still possible to perform in the intervening four years.

To summarize, this historical review highlights that designers and developers desire the elimination of flaws in their protocols without limiting extensibility. From above, and other historically similar events [5, 21, 22, 33, 43], we see that extensibility, through protocol tolerance, not only enables new features but also unforeseen vectors for attack. Finally, we note the uptake of corrective measures may take multiple years, leaving the network and its users vulnerable in the interim.

The key challenge. Developers require the *agility* to enable new features, including security fixes, to be quickly and widely propagated. A natural, and naive, solution is *automated updates*. However, in our setting, it is radically more difficult. Automated updates are usually seen from a client's perspective, where a program, upon execution, first checks and fetches the latest version (if available), before running. In a distributed system such as Tor, where we are concerned with volunteer-run *relays*, the situation is different. These relays are usually left unattended and running on a dedicated machine with the only task of relaying traffic—as advised by the Tor project. The update pace of the network depends today on individual relay operators, either following their OS distribution package update policy, or choosing one of their own. As Ajmani *et al.* point out in their generic solution for distributed systems [1], the availability requirement makes the problem difficult. In Tor's case, it is even more challenging; essentially, a distributed network is required to migrate altogether to a new version, without disruption of service, and without privacy degradation during the process (e.g., network partition). Fulfilling these requirements as well as practical issues such as (1) the risk of failing to bootstrap the network, (2) the need for per-OS init scripts and the cost of maintaining them, and (3) the security concerns that an auto-update system based on current practices may cause to volunteers, altogether explain why auto-updates for a distributed system such as Tor do not exist.

2.3 Tor Project's Direction & Our Vision

Tor developers produce new versions of Tor and make both the source and binaries available on their software repositories and make announcements about the availability of new versions on their official channels.

Relay operators monitor these official channels to keep track of new releases, which they update to at their own discretion. On the other hand, Linux distributions do not monitor these channels. Instead, it is the Tor project, or some party that wishes to make Tor software available on the distribution, that produces a package (that adheres to the distribution's rules) and submits it for inclusion. It is to the distribution's discretion if the package is included or not (and this applies to updated version of already accepted packages). Often, as is the case with many popular mainstream Linux distributions, the packaged version of Tor is many versions behind the official latest release. One critical outcome of the discretionary nature of deploying/adopting versions, is that the current Tor network consists of relays running several major Tor versions. This fact forces the Tor developers to adopt techniques to build tolerance within their protocol design and features, in an attempt to avoid issues over time, especially since tolerance avoids evicting relays running older versions from locations and volunteers that together contribute to Tor's diversity, which is critical for Tor's security model. This was the situation up to 2019, but since then, the Tor project decided to slowly move away from Robustness by enabling strict protocol negotiation, and eventually with the plan to reject messages that are invalid according to authorized versions. Such a plan leads to End-of-Life cycles, in which relays running software versions that are no longer supported are rejected from the network, even when their contribution is meaningful in terms of bandwidth or specific security attributes (e.g., location diversity).

As of early 2024, Tor has, however, the downsides of both approaches. Indeed, the Tor routing protocol is still applying the Robustness principle, which still enables stealthy attacks such as the Dropmark [43], and applies protocol negotiation with end-of-life policies, rejecting hundreds of relays every year [49]. By the end of 2024, the Tor project should have implemented Proposal 349 [34] "Client-Side Command Acceptance Validation" which employs state machines to check and verify the various Tor protocols' state on the client, and tear down any circuit that receives an invalid message that would not yield a valid state transition. This approach seems so far to only be considered for clients, and Robustness is maintained on relays

We believe protocol negotiation that rejects relays is particularly unfit for a volunteer-based system, with operators in many cases not directly responsible for running an outdated relay (e.g., the default OS distribution repository providing an outdated package). Programming languages and compiler tools have sufficiently improved to revisit how we build and distribute a distributed system, and that we can obtain the benefits of the Robustness principle without its security downsides, as well as the benefits of protocol negotiation without rejecting anyone. Our technical proposal to successfully achieve these two seemingly contradicting properties is our main contribution. We furthermore show in our case study (Section 6) that with these two properties in hand, we can solve and prevent one of the most efficient attack vectors against Tor's anonymity.

Our approach involves a new kind of protocol negotiation design, where instead of only negotiating the version to use and rejecting non-compliant nodes, we additionally offer a method to *re-program* parts of the software of non-compliant nodes, hence propagating new code as part of the negotiation protocol within circuit creation. The challenge is to enable this without disruption, and without partitioning the network. Moreover, this process should be transparent and auditable to Tor clients and Tor operators, and should not depend on a particular distribution or operating system to maintain diversity and the ability to run the Tor program on any operating system. The system should also have safety guarantees in case of a bootstrapping error. We also require minimization of the bandwidth overhead that such a protocol could create.

Unfortunately, this list of requirements is so restrictive under the current methods that we need to re-think how we build and distribute software. We believe that such a challenging task can be solved by having the software of a distributed system such as Tor include a Just-in-Time compiler (JIT), which would be leveraged by a specific and secure version negotiation protocol to propagate and update portion(s) of the binary to change its features and effectively "update" the network. We propose a method for a distributed system that provides the ability to re-write and extend itself while it is running, enabling new connections to switch to the new code, while the existing connections finish operating over the old code. In this paper, we use the eBPF bytecode compilation target to propagate the updates, and an eBPF-to-x86/arm JIT compiler to locally re-write the binary once the update is received without restarting the service and causing any disruption and network partition.

2.4 Background on eBPF, LLVM and JIT Compilation

Our solution reconciles protocol tolerance and its potential risks by developing a novel architecture to secure distributed networks. This architecture takes advantage of recent progress in programming language and compilers, such as simplification of compiling `C` or `Rust` code to machine-independent RISC instruction sets. eBPF [12] (also called BPF) is an example and mainly known for being used in the Linux Kernel to improve the kernel's flexibility to specific needs.

However, eBPF is a *general*-purpose RISC instruction set and independent of the Linux Kernel. One can write programs in a subset of `C` and compile to the BPF architecture using the LLVM [25, 27] clang frontend and LLVM backend to obtain a BPF program. This BPF program contains bytecode instructions matching the BPF Virtual Machine, and can be either interpreted or compiled once more to native opcodes. This process of compiling or translating from the BPF bytecode to native opcodes is called JIT (Just-In-Time) compilation, and it elegantly provides code portability and efficiency. In our solution, eBPF programs execute within the same process as their caller and adhere to the host OS's security model. To further isolate the eBPF program from its caller, we also enable sandboxing of the memory accesses of the eBPF programs, which we describe in Section 4.

3 FAN Architecture

Based on new software execution models enabled by technologies such as LLVM, Flexible Anonymous Networks (FAN) is a design for deploying and maintaining an anonymous network that can seamlessly change its behavior—through the addition and/or removal of protocol features and components—without having to restart relays or disturb users' connections.

3.1 FAN Design Features

We have argued in Section 2.2 that the current method for designing, iterating, and deploying features central to a security property (anonymity in the case of Tor) is lacking the necessary control to handle unforeseen issues.

We now take a step back and consider a more general view and aim at establishing a set of design features that would allow a distributed system to grow beyond what an auto-update mechanism for classical software can achieve, discuss potential drawbacks and illustrate some of the benefits through a case study.

Built-in Extensibility. FAN enables high-levels of **expressiveness** by exposing internal data structures, memory, and functions to the plugins, leading to similar expressive abilities as high-level languages. FAN supports **ease of deployment** by offering fine-grained control of the ability to remotely re-program components of the network by sending plugins to them. In addition, this novel capability offers **speedy propagation** of patches or feature updates throughout the network, as they become available. This contrasts with the current update lifecycle of distributed networks such as Tor which can take up to several years to propagate major changes. Compared to a classical auto-update mechanism which would swap binaries and restart the program, FAN achieves better safety and robustness, and unlocks novel properties for Anonymous Communication: FAN `plugins` can be **connection specific**, and different plugins can be applied at the same code location depending on the context. This capability leads to a novel extensibility paradigm that could potentially allow different applications, under an appropriate threat model and safety & fairness considerations, to make relays behave differently for their own set of users through connection-specific re-programmed features.

Security & Safety. FAN-based networks depend on multiple layers of security. For **operational security**, the virtualization technology (detailed in Section 4) provides the sandboxing and resource management capabilities that ensure that FAN `plugins` may not exceed their memory consumption limit, and provides the necessary control to safely handle other failure modes of plugins. The **secure deployment** of FAN `plugins` ensures that only *trustworthy* and *authentic* code may be deployed in a FAN. We control these aspects through our FAN Plugin Transparency design, detailed in Section 3.3.

High-performance. FANs introduce **negligible overhead**, in terms of computation, storage, and latency. The analysis is provided in Section 5.3.

Stronger Feature Control. Due to the various existing packaging policies in OSes that conflict with a distributed network deployment cycle (e.g., Tor and Ubuntu [10]), and due to inattention from some relay operators, it is difficult to deploy new major features in volunteer-based systems. Recall from section 2.2 that this has historically created many protocol-level vulnerabilities that are not bugs, but design flaws caused by a lack of control over the software's deployment. We expect a FAN binary to be composed

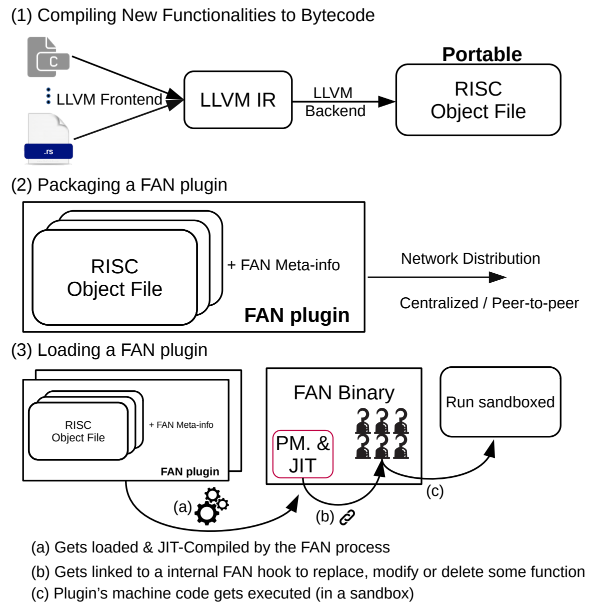

Figure 1: Flexible Anonymous Network generic architecture. The hooked plugins can be global or connection specific. That is, multiple different plugins can potentially be called from a same hook. PM. stands for Plugin Manager.

of a few very stable core features and follows a release cycle that matches operating systems' major release lifecycle. For example, a new core might be released every 4 years, matching Ubuntu LTS's lifecycle. Plugins should not be expected to be compatible to more than 2 cores at any given time. Any update of the core system within its expected lifetime follows regular packaging as it is done today, and should be limited to quality of life improvements and vulnerability fixes covering the core code.

3.2 FAN Plugin Design

FAN source code, e.g., our FAN Tor-prototype described in Section 4, embeds a JIT-compiler and can link the JIT-compiled plugin bytecode to specific hooks in the FAN software. The FAN source code and the JIT compiler are compiled into the FAN binary. When the execution of this binary comes to a hook, it checks whether a plugin may be executed, otherwise, we run the default code for that hook. Each hook defines all the information required to attach a plugin to that hook in the FAN binary. Depending on the governance model for the FAN, this information includes resource budgets (CPUs cycles, memory allocation size, etc.), external access controls (OS-like file-level authorization, network authorization), internal access controls (i.e., the internal FAN data and structure(s) that a plugin may access, modify, extend, or internal functions that may be called) and required cryptographic authorizations for bytecode verification (described in Section 3.3).

FAN plugin features are written in a high-level language, e.g., C or Rust, and compiled independently of the FAN binary, targeting a bytecode representation. This bytecode targets some Virtual Machine and is not executable right away (Figure 1(1)). The plugin has associated meta-information that specifies the hook location in the FAN binary where the bytecode may be executed and the capabilities it requires (Figure 1(2)). A FAN plugin may attach to one or more hooks with a shared context between the hooked code. The meta-information provides this context, which is instantiated at loading time (e.g., sandboxed memory). Indeed, the FAN plugin may be composed of several bytecode files that may be loaded for the same context but hooked in different locations in the FAN binary (Figure 1(3a)).

The first time the FAN binary loads a plugin (Figure 1(3b)), the plugin bytecode is JIT-compiled to the appropriate machine-level code and then attached to the specified hook. The same process executing the FAN binary may then execute this attached code, as often as needed. Based on the governance and threat models, specific security measures, like sandboxed execution (Figure 1(3c)) and restricted access to resources, take effect while executing the plugin code.

3.3 FAN Transparency Design

To alleviate trust tensions between developers and relay operators (and users) we propose our Plugin Transparency design that is adapted from the design in PQUIC [7], itself inspired from CONIKS [28] used for key management. Our design provides relay operators (and users) the ability to verify transparently, or audit after the fact, the plugin issuance process, which provides public cryptographic evidence of the central authority (i.e. developers) and independent log's misbehavior. Operators can observe when a plugin is issued and when it will be pushed to their node(s). If desired, they can also protest, which is globally transparent. Protests serve as a community signal; while it cannot prevent a plugin to eventually be pushed to the network, it can be a tool for convincing the central authority to withdraw a plugin. The design discretizes system time into epochs, denoted by monotonically increasing integers $\in \mathbb{Z}_0^+$.

The Plugin Transparency design separates the stakeholders into three sets: The FAN/plugin developers and relay authorities (if any), network relays and clients, and **independent** entities hosting the FAN Transparency Log (FTL) (a Merkle Tree *variant* [1] with logarithmic complexity for all request types, and other important properties as detailed next).

The FAN Plugin Transparency design provides several security properties required to build a trustworthy environment. Similar to the threat modeling approach of Certificate Transparency [26] for the web, or Key Transparency [28] for end-to-end encrypted messaging, reputation is gained from public and cryptographic evidence of correct behavior. Any misbehavior is also publicly auditable and the environment supports appropriate reactions to keep the environment reputable. However, we propose design tweaks to improve performance of proof of absence requests, support potential third-parties, and capture and map misbehaviors into an existing legal framework (Trademarks). That is, malicious plugins from a third-party would have to commit an infringement using a name they do not own.

(1) ***Multiple Namespaces*** This paper discusses a centralized governance model in which a single trademark for plugins would be accepted by the loading logic on relays. However, we aim our transparency design to be trivially extensible to many independent trademarks. Therefore, plugins are arranged in the tree following the naming convention: *name := trademark_name/hook_name* leading to a string-based UID for each plugin.

(2) ***Issuance safety and authenticity***. Multiple FAN developers are cryptographically involved in plugin issuance, avoiding a single point of failure. Plugin issuance contains a threshold signature and its meta-data including the plugin's name, version, protest and push epochs, and status ("deployed" or "withdrawn"). Plugins are issued to FTLs. Using TUF [45] to provide key compromise mitigation for this specific task would be an appropriate choice. A plugin's source code to bytecode ahead-of-time-compilation must be reproducible.

(3) ***Detection of spurious plugins***. If an FTL maliciously injects a plugin within a FAN's namespace, the FAN developers can efficiently detect it and cryptographically prove the FTL's misbehavior, with a proof of availability. Both the detection and proof run in $\Theta(D + \frac{N}{2^D})$ for N plugins and D the tree's depth. The detection needs to be done once per epoch, for each existing hook. Note that the detection of a malicious entry in our design runs much faster (logarithmic to N) than typical related works on transparency (linear to N). See Appendix A for more details.

(4) ***Secure and human-meaningful plugin names***. Plugins' names are uniquely and cryptographically mapped to the plugin's bytecode, which is a main difference to Certificate Transparency or Key Transparency which do not enforce any mapping. That is, the plugin's position in the tree depends on its name's hash value prefix (matching the tree's depth). The FAN developers periodically check the proof of availability produced by FTLs and verify that no other plugins spoofing the same name are present within their branch. Compared to other transparent tree structures such as indexed trees (e.g., in CONIKS [28]), our choice of ordering the tree from unique plugin names (e.g., fan.project/my_plugin) would force misbehaving entities to commit to a potential trademark infringement, forcing the attacker to use the same namespace, for which a legal framework already exists. Different namespaces may collide to the same prefix, hence the same position in the tree. The tree's leaf holds a list data structure, and the expected number of namespaces per leaf can be directly controlled from the size of the binary tree. Having potentially multiple namespaces per leaf does not conflict with the security property, but adds a "load factor" to the proofs' complexity (the $N/2^D$ term), which can be engineered to be ≈ 1 under a regular uniform hashing output assumption. Thanks to these design constraints, a proof of absence also run in $\Theta(D + \frac{N}{2^D})$ instead of the usual $O(N)$.

(5) ***Non-equivocation***. The FTL cannot equivocate plugin availability to members of the network (e.g., serving a proof of availability to one relay and a proof of absence to another) without collusion with the FAN developers. In the presence of a single honest FTL, the collusion behavior will eventually be detected with cryptographic evidence. (e.g., when the Signed Tree Roots are compared).

Functional Overview. FAN developers have three sets of actions: The first is to issue and withdraw new and old plugins, respectively. To issue a plugin, a name and its attached plugin are sent to the FTLs with meta-information containing a valid threshold signature and a *protest epoch* $E_{protest}$ and *push epoch* E_{push}, where $E_{protest} \leq$

[1] We call it Name-Structured Merkle Tree List. Proving that an element is present or not has the same complexity ($\Theta(D + \frac{N}{2^D})$).

E_{push}. FAN developers can choose to set the protest epoch to the future, allowing relay operators the opportunity to audit the plugin and potentially officially record a protest. For transparency to be effective, it is important to offer a deterministic build system to allow reproducibility of the signed bytecode. To withdraw a plugin, only the name and push epoch is set. If the protest epoch passes and FAN developers do not withdraw the plugin, the push epoch defines the plugin's availability in the ACN. In either case, the plugin will be included in the FTL's Tree at the next epoch. A withdrawn plugin is still included in the Tree but marked as "withdrawn" by appending the signed withdrawal order to the plugin's meta-info within the Tree once the push epoch has passed. Second, FAN developers may ask the FTL for a *proof of availability* for a given plugin, which they can verify to detect the inclusion of spurious plugins (later defined). This proof authenticates the plugin's inclusion in the FTL's Tree. The third action is to broadcast cryptographic evidence of the FTL's misbehavior (e.g., cryptographic evidence of a spurious plugin).

The FTLs have three actions. The first one is building the Tree for each epoch. The Tree includes all plugins available to the network at the current epoch. The second action is to generate proofs and respond to *Proof of availability* or *Proof of absence* requests for a given plugin name. The third action is to collect relays' signed protests against a given plugin received until the protest epoch. The signed protests are appended to the plugin's meta-information.

The relay operators' actions are the following. First, they can verify, fetch or share a *Proof of availability* or *Proof of absence* from an FTL with regard to the epoch values of a given issued plugin. Second, relay operators can optionally interact with the FTLs before the protest epoch elapses to formally protest against an upcoming plugin(s) (using their relay's identity key).

These protests are informational (but globally visible), and FAN developers can then decide to withdraw the plugin or not. If not, then the plugin is pushed to the whole network in the push epoch, as defined in the plugin issuance order. Relay operators can use this information to decide whether to continue participating in the ACN or not.

Plugin Governance. A question remains about how to set a realistic workflow to populate plugins from the central authority, and manage them in interaction with the community. We would suggest a periodic workflow anchored to a periodic event. For example, it could be meaningful that the Plugin Transparency design chooses an epoch of 1 week, making release of new plugins effectively a weekly process, say every Monday Noon UTC. The push epoch can be set once a week as well, and the time difference with the plugin release would define the protest window. We believe that anchoring the release of plugins to a periodic time event would be human-centered and ease community interaction. Once a plugin is released, it would be propagated through a negotiation phase during circuit constructions, when nodes connect to each others to build a circuit. We evaluate this method in Section 5.2.

4 Design Implementation

We implement a prototype FAN instance using Tor's codebase forked from Tor version 0.4.5.7. As a virtual machine abstraction, we use eBPF [12], which is also used in the Linux Kernel [46]. That is, eBPF is the chosen bytecode compilation target for this prototype depicted in Figure 1 and offers code portability. In this research work, we wrote the extended features in `C` and compile them to eBPF using LLVM's clang compiler that supports compiling from a subset of the `C` language towards eBPF. This capability leveraged from the `LLVM` project and integrated in our Tor instance offers the required *expressiveness* to add, modify or replace existing protocols and features within Tor. Plugins can include headers from the Tor source code, indirectly call existing functions within the Tor source code or access fields and variables through the plugin manager interface.

As Figure 1 shows, to execute plugins, we first need to compile the eBPF bytecode to native machine code. This capability offers *high performance* to our FAN design (see Section 5 for details). We add a modified version of uBPF [37], a JIT compiler of eBPF bytecode for x86 and arm64 targets. In the original Tor codebase we implement a *plugin manager* module. It can load, compile, and link within the Tor codebase and execute eBPF bytecodes with a shared context, using a shared area of memory for all the bytecode files belonging to the same namespace (i.e., each plugin has a namespace). Each of the bytecode files defines what we call an *entry point* for the plugin, i.e., a function that can be *hooked* and called from within the Tor binary similar to a `main()` function. When a plugin is loaded, we create a new mapping in the virtual address space of the host, which is intended to hold the plugin's code. We change this new memory region's flags to give read and executable rights for the host (using the syscall `mprotect()`). At execution, when the code meets an entry point, it jumps to the host's paged memory linked to the entry point, and continues its execution with the code that was stored there when the loader JIT-compiled the plugin from eBPF to machine code. Eventually, the entry point's function return instruction jumps back to its caller as regular x86/arm64 would do.

Each plugin has its addressable memory sandboxed within the host's (i.e. FAN) process. The memory allocated within plugins belongs to a dedicated continuous buffer allocated by the FAN process when JIT-compiling it. During this process, the compiler adds instructions to check boundaries for the dereferenced memory, and cleanly exits the plugin's execution if it tries to access memory outside its allocated range. The plugin receives a virtual address space, and the host (the FAN process) records an unsigned offset to translate the plugin's address space back to the process' address space. When the plugin dereferences a pointer, the JIT-compiled instruction checks if the memory address translated back to the host's memory address space and size requested are correct (i.e., below the highest address within the dedicated continuous buffer). This design also means that plugins cannot directly access structures and memory allocated by the FAN process, since they would be outside their allocated range. To access them, our FAN implementation supports indirect getter and setter functions for various protocol-related data structures. This method also allows the host to expose what it judges necessary to plugins, while also supporting extensibility (i.e., the indirect access can also get extended, and data structures can also be extended). This design makes the distributed network robust to faulty plugins, and hardens against the exploitation of potential memory vulnerabilities within the plugins themselves.

The plugin manager module of FAN uses human-readable instructions to load the entry points. The file is parsed according to the plugin manager's specification, and the plugin is then hooked as indicated within the `.plugin` file if the core protocol supports the selected hook.

Our prototype integration (Plugin Manager) and plugins contain several thousand lines of `C`. The modified version of uBPF contains several tens of thousands lines of `C`. While we merely modified a fraction of these to fit our purposes, such code would need to be maintained for a real integration. FAN's architecture allows independence between the design of the anonymous distributed network, and the design of the virtual machine linked to each node. Therefore, in the future, recent initiatives such as the *Wasmer* [51] project or *Wasmtime* [6] project would be good fits for providing such a security-wise critical abstraction, in the same way some projects have been fit to write cryptography independently of any system, such as OpenSSL, which is the current embedded cryptography engine in Tor. Our code is available online: https://github.com/flexanon/tor_ebpf.

4.1 Engineering Hooks' location

Within the core of the distributed software's source code, there is no technical restriction on the location of hooks. However, we recommend adding hooks for protocol operations where Robustness was initially engineered, to essentially replace forward compatibility built from the Robustness principle which currently benefits both the developers (having many versions deployed without incompatibility) and the adversary (exploiting protocol tolerance). Forward compatibility would then be built from hooks and Robustness would be gained from the ability to hook code to deal with otherwise previously unknown message. As a result, by default, any unknown message that cannot be handled by an existing plugin would be invalid, rejected and any required cleanup would need to take place (e.g., circuit tear-down), effectively ensuring no tolerance policy for unknown messages, but still retaining the ability to add/modify or delete a protocol message and its code processing logic globally to the network.

In our prototype implementation, we replace with hooks the existing Robustness within the Relay protocol and within the Circuit padding protocol implemented in C-Tor [23]. The inserted hooks are able to handle any new protocol event, and support extensions to add new capabilities to major pieces of Tor. Other parts and subprotocols of the Tor system may also receive hooks, however, in this work we cover only the main locations required for our use cases and proof of concept demonstrations. An example of a hook written in C-Tor is provided in Appendix C.

5 Performance Evaluation

5.1 Methodology

We focus our performance analysis on three questions: First, we are interested in *the time it takes to propagate new code over the whole network*. To answer this question, we use Shadow [18] and experiment with new plugin deployments from different vantage points. Second, once we have received the plugin, we're interested in *the time it takes to load it, compile it, and be ready for execution.* This analysis is performed by recording statistics from the plugin manager module when it loads plugins. Finally, we are interested in *the runtime overhead of a typical plugin.* To answer this question, we build a testbed designed to stress-test the usage of plugins. Altogether, this analysis should demonstrate the feasibility of our solution.

5.2 Time to propagate within the full network

We evaluate how long it takes for a new plugin to be distributed across the network. To this end, we created a lightweight negotiation and exchange protocol which negotiates and propagates the latest code during the circuit construction phase, as a simple extension to Tor's circuit handshake. Therefore, nodes synchronize on the latest version that is used directly in the handshake phase, and update each other if necessary—independent of the OS and hardware used on each relay. When the circuit is built, every node is guaranteed to run the same (latest) version on the circuit.

We set up a Shadow simulation with a 10% scaled-down version of the Tor network as of April 2021 (660 relays) to carry out the measurements. Five plugins were deployed during the simulation (see Table 1), which are later also used in the case study in Section 6. We measure the time between the introduction of the plugin in the network and the reception by the relays. Two scenarios are simulated: seeding[2] the new plugins from the three authorities in the simulation and seeding the plugins from the three fastest relays in the simulation. The measurements are shown on the left of Figure 2.

From the left graph in Figure 2, we observe a fast and steady propagation of the new plugin across the network. The propagation directly depends on the overall client activity, as exchange happens during circuit creation. Fast relays have a higher selection probability for circuits, hence seeding these will provide the fastest expected propagation.

From our experimental measurements, it takes 12.9 seconds for a new plugin to be distributed to 90% of the relays and after 72.8 seconds, more than 99% of the relays received the new plugin (in the worst case simulation). During the first few seconds of distribution, the number of relays receiving the plugin grows exponentially.

We compare the time needed for our plugin distribution method with the time needed for new Tor versions to be adopted, depicted in the right graph in Figure 2, based on metrics from the Tor Project [48]. It is clear that it takes time for independent volunteers to adopt new versions and this forces Tor to employ forward compatibility to ensure tolerance between the various behaviors across co-existing version. These observations are not specific to Tor; any distributed network has similar software distribution issues. Note, Tor version 0.4.5 is a long-term support version of Tor, with a lifetime of 2 years (104 weeks) [47]. According to the metrics, it took nearly half the lifetime of the version to reach 90% of the relays.

5.3 Overhead Analysis

5.3.1 Loading Plugins. We evaluate how much CPU time it takes for typical plugins to be ready to execute. It includes acquiring the bytecode, the JIT compilation CPU time, and the plugin environment setup in our modified Tor version. Acquiring plugins

[2] Seeding: making the plugin first available on those relays and relying on the protocol to propagate them to the other relays. Among the thousands of operators, we may assume that some of them are actively tracking latest releases and pull the last version when available, seeding their node in the process.

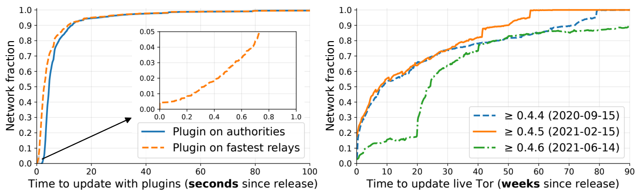

Figure 2: (Left) Shows plugin propagation within a simulated network using the FAN architecture (automated and unattended "push" of new code). (Right) Shows Tor's situation based on historical metrics (a fraction of volunteers perform automated "pull" of new code). Note the units.

Plugin	#LoC	#hooks	Bytecode size	Loading Time
hello_world	10	1	1,048B	204 μs
sendme_1	25	1	1,672B	202 μs
sendme_2	67	2	3,840B	385 μs
sendme_3	82	3	5,184B	486 μs
dropmark_def	652	4	13,488B	664 μs
dropmark_def_uncons	675	5	14,616B	729 μs
dropmark_def_conn_based	322	4	11,736B	493 μs

Table 1: Load time displayed for *uncached* plugins, and size refers to the transmission cost.

means loading them from disk. Additionally, to evaluate the plugin's authenticity, e.g. with Plugin Transparency, requires applying a hashing function H several times to verify the proof of availability received with the plugin, which consumes on average a few μs of CPU time. A plugin may be composed of several entry points, each contained in its own compiled bytecode file. Our framework loads each of them independently and links them at the application-level context, such that a plugin may be composed of multiple entry points and may hold a shared sandboxed memory between each loaded entry point.

Table 1 gives an overview of different plugin costs. We implemented several plugins to test the Tor FAN architecture, including "system-wide" plugins that modify or replace existing code, or connection-specific plugins that can be attached to a given Tor circuit, and replace or modify a part of the code only for that circuit. Section 6 explores these capabilities in a case study.

From Table 1 (i.e., typical plugins are loaded in less than $1ms$), we can conclude that dynamically loading new (uncached) protocol features is feasible and does not incur significant latency, which we believe opens the door to different governance policies. For example, dynamically sending a plugin within a Tor circuit would be feasible. That is, upon circuit creation, a Tor client can now negotiate features that relays have to support on this circuit. These features may be sent and loaded as part of the circuit creation procedure without incurring significant latency.

5.3.2 Fast-path Code Modification. We now investigate the impact of running the plugin code with respect to the legacy code within the original binary. Each code path (sequence of instructions) does not have the same impact on the software, and the overall Tor network. For example, we may differentiate the "fast path" from a "control path". The fast path are the sequences of instructions typically executed when performing the most common task within the network. A control path is the sequence of instructions performed over a specific and potentially rare event. In typical usage of relays, the fast path in Tor involves all instructions relaying cells to the next hop. It is thus desirable that a FAN architecture supports plugins in the fast path while maintaining high performance.

Figure 3 shows the design of a private testbed to stress-test our FAN instance implementation and measure the overhead of several entry points hooked into the fast path of the exit relay. In this experiment, 40 Tor clients send 20 MB of data on each circuit. Each circuit shares the same exit relay. We measure the throughput of the slowest stream in each run of the experiment. Thus, 500 iterations of the experiment are executed for each network configuration.

As a baseline, using vanilla (i.e. unaltered) Tor we craft the number of parallel streams in this stress-test network to push the exit relay's process to a 100% CPU consumption. This method allows us to capture any overhead induced by our plugins as a throughput reduction. The processor on the machine used for this evaluation is an `AMD Ryzen 7 3700X 8-Core`.

Figure 3 displays the results of three experiments comparing our FAN instance to vanilla Tor. Each of the experiments made with our FAN instance involves a plugin modifying the Tor flow-control algorithm with an increased amount of entry points hooked to the fast path. Each entry point modifies an existing function of the flow-control algorithm called in the fast path. That is, we test three plugins expected to be increasingly more costly by requiring more entry points to be hooked in the fast path. In each case, the plugin reproduces the behavior of the legacy code as a baseline. The code being intercepted and replaced is executed each time a data cell is processed on end points (clients and exit relays).

From our results, we make two observations. First, there is a small average throughput reduction when the network uses plugins, as depicted in the three experiments running the plugins. Second, increasing the amount of code plugin entry points does not significantly further decrease the throughput. The main culprit for the throughput reduction is actually coming from the hook design implementation within the main Tor binary. When executing a plugin, we first have to locate it in a hashtable using the hook's name. Hashing a string is a costly operation on the fast path. Further engineering could bring more reduction to the overall FAN implementation cost. However, even without optimization these results are positive: they show that our method to link, deploy and use JIT-compiled machine code from a portable bytecode abstraction offers near-optimal performance over the fast path in an anonymous network. This is true for code that does not compile to a dedicated set of hardware instructions (e.g., AES-NI).

6 FAN Case Study: The Dropmark

We investigate the use of our Tor FAN instance (Section 4) with a case study: defending against the Dropmark attack [43] to demonstrate FAN's novelty and its benefits. The dropmark attack is a traffic confirmation technique exploiting the Robustness issue discussed in Section 2.2, now considered publicly as "highly-severe" by the Tor project in their recent attempt to categorize attacks [35]. We apply FAN's capability to deploy a defense and argue that this defense is not possible with the current model and only effective over a FAN. We evaluate our defense using Shadow [17, 18, 20]

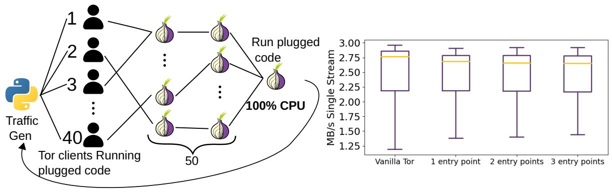

Figure 3: (left) Measurement setup for FAN overheads estimation over the fast path. Each client is configured to send a 20MB stream of data. (right) Throughput of the slowest Tor client within the measurements. Each boxplot covers 500 runs with a plugin being hooked at 1, 2 or 3 different places. We use plugins sendme_1, sendme_2 and sendme_3 from Table 1.

simulations. We design the defense as two cooperative plugins, one plugged-in "system-wide" that extends the Tor protocol, and one which is ***connection-specific***, i.e., plugged-in to extend the capability of a given connection, or in this case, a Tor circuit. Designing and deploying this defense illustrates one of FAN's design goals: addressing the weaknesses stemming from protocol extensibility techniques (i.e., Robustness principle and Protocol negotiation) with a novel methodology.

6.1 Case Study Background

6.1.1 Dropmark. The Dropmark attack is an active and reliable traffic confirmation technique [43] having low false positive rate and high success rate, which can be considered more robust than other existing correlation strategies [15, 16, 24, 29, 32] due to its unique properties. In effect, the dropmark attack is a 1-bit communication channel between a malicious exit relay and a passive observer watching Tor clients, such as a malicious ISP or a malicious Guard relay. The attack exploits two key characteristics of network protocols: 1) the existence of periods of silence in which no data should be expected by a Tor client (which we also call "protocol silence"), and 2) the Robustness principle. That is, malicious exit nodes can inject a message at the precise time of expected protocol silence. The Tor client would then drop that message. This message does not trigger circuit breakage due to protocol tolerance and would be observable to any on-path passive observer. This contrasts to other traffic analysis methods relying on full data traces and machine learning, which suffer from a number of limitations [40]. In this case study, we explore how to reduce the Dropmark attack's reliability efficiently thanks to a plugin-based protocol extension within Tor's circuit padding framework.

6.1.2 Circuit Padding. Tor's circuit padding [23] framework is designed to enable Tor clients and relays to negotiate and "program" [3] finite state machines, in which each state matches a padding behavior according to a specified padding distribution (histograms or parametrized continuous distributions). Pre-programmed events within the padding machine framework can capture Tor related events, such as a circuit opening, to make the machines change their current state, hence changing their behavior. Figure 4 shows a padding machine currently being used in Tor with a state transition based on circuit events. Padding machines may be much more complex in the future and the framework is designed to foster research and ease of deployment for solutions tackling complex problems such as website fingerprinting [38] or traffic confirmation.

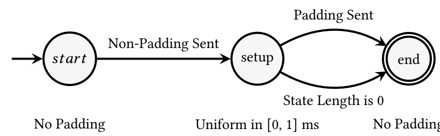

Figure 4: Used in Tor relays to make the cell pattern of a rendezvous circuit construction similar to regular exit circuits.

6.2 The Dropmark Defense

For this case study, we ***dynamically extend*** the padding machine framework above realizing FAN's benefits by addressing one of Tor's core weaknesses. To enable this dynamic extension, we placed generic hooks within Tor's Circuit Padding Protocol that are designed to support and react to new internal events and new messages sent by the Tor client. These hooks allow us to redefine the entire original padding framework, including adding features unforeseen by Tor developers at the time of the initial design. Using these capabilities, we design a *protocol extension* that supports a padding machine able to mitigate the Dropmark attack. We argue that while this protocol extension—essentially a conservative and fixed rule—is a necessary condition to efficiently address the Dropmark, it has the potential to negatively impact and conflict with future changes. However, by design, FAN affords re-programming, both the above and future extensions, thus avoiding these kinds of forward compatibility issues.

6.2.1 Functional Overview. Figure 5 shows the FAN Dropmark defense padding machine enabled from the two protocol extension plugins "dropmark_def" and "dropmark_def_conn_based" from Table 1, which we deployed and tested in faithful networking conditions in a Shadow Tor network. The padding machine supports several events that required an upgrade of the circuit padding framework. This upgrade is brought through a first plugin ("dropmark_def") to support sending an application-level event from the Tor client to cause the relay to transition its padding state to begin padding in the precise moment an inbound period of silence is expected (known and announced by the client through the protocol extension). Also, as part of the defense, the plugin carries another extension enabling a *conservative protocol policy* that prevents the middle relay (where the machine is plugged-in) to forward any message towards the client if the circuit is clean (i.e., when no streams have been attached yet), which defeats any Dropmark attempt before the client decides to actually use the circuit and attach a stream. Deploying such an extension on today's Tor is arguably impossible, as it would hinder the extensibility of the Tor routing protocol with today's methods (i.e., one does not want to deploy any feature that could create friction and incompatibilities with any future requirements). However, with FAN, the protocol can be arbitrarily restrictive since we can globally re-write any current restrictions to accommodate future requirements.

[3] It does it by offering a simple interface to specify machine states and transition events.

On top of the new protocol events brought by the plugin "dropmark_def", the plugin "dropmark_def_conn_based" offers the ability for a given circuit on which the plugin is plugged-into to make the middle node swap padding cells sent by the new dropmark machine with regular cells coming from the exit relay. The idea is to absorb, at the middle node, ***any*** pattern sent by the exit relay during a period of silence, and output it towards the guard with the exact same distribution as the live padding machine. This approach guarantees thwarting any dropmark attempt while the plugin is active: no matter if the exit is sending a signal or not, the middle node would output cells according to its state machine. This plugin performs this task by taking ownership of the circuit cells transiting through the node, and maintain them within its own forwarding queue. The cost of this design is extremely light on the network and have no impact on the user experience, since all of this happens within the bounds of a protocol silence (i.e., there is no legitimate user activity expected), as our experiments and analysis show.

This plugin is set up and activated alongside the Activate signal from Fig. 5, and cleaned from the circuit upon a Be Silent event which instructs the padding machine to stop sending padding cells or delaying regular exit cells to match the padding distribution.

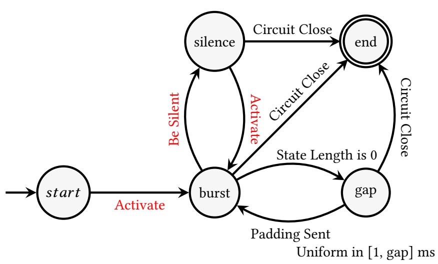

Figure 5: Dropmark Defense padding machine negotiated on the middle relay when the circuit opens. Events "Activate" and "Be Silent" are client-triggered events fired through a protocol extension enabled with FAN. State Length is a counter decreasing at each padding cell sent.

In summary, the Dropmark defense padding machine is designed to produce a Dropmark and absorb any real attacker's attempt. That is, an adversary observing the network either on the Guard relay or on the wire should observe the ***same*** watermark on every Tor circuit regardless of ***adaptive*** malicious exit relays injecting traffic on the other end of the circuit, rendering this traffic confirmation technique unreliable, since the presence or absence of an adversarial exit exploiting Tor's protocol robustness features is independent of the observed behavior.

6.3 Dropmark Defense Analysis

6.3.1 Dropmark Attack Replication Results. We re-implemented the Dropmark attack [41] on a recent Tor version (Tor-0.4.5.7). With this updated code, we reproduced the original results using Shadow 3.0 with a user simulation model based on real traces collected with PrivCount [13, 19]. Table 2 shows the attack accuracy computed from correct (True Pos., True Neg.) and incorrect (False Pos., False Neg.) classifications. The experiment contains 24,800 simulated Tor users and 202 Tor relays. All combined, those users connect more than 640,000 times during the experiment to simulated Top Alexa websites. These results confirm the original high accuracy of the Dropmark attack over a more faithful network simulation, thanks to the recent progress in Shadow's simulation environment [20].

Attack	TPos	FPos	TNeg	FNeg	Accuracy
Dropmark	0.999972	0.007713	0.99229	0.000028	0.9961

Table 2: Dropmark attack Shadow Simulation results

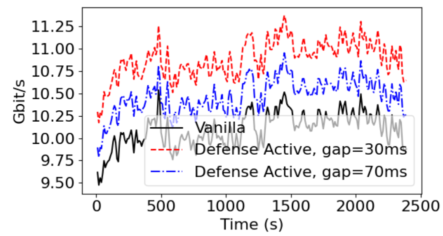

Figure 6: 20-seconds moving average of total relay goodput on a 5% scaled down Tor network from April 2021 (340 relays). The dropmark defense experiments generate padding in more than 400,000 circuits.

6.3.2 Empirical Dropmark Defense Results. We deployed our Dropmark defense machine in a Shadow Tor network while running the Dropmark detection code on attacker guard relays. The defense is efficient: with no attack, the malicious guard relays incorrectly (i.e. false positives) flagged 99.9975% of the active circuits which connected to the simulated Alexa Top list.

Figure 6 shows the overall bandwidth overhead induced by the Dropmark defense during the simulation. The overhead can be tuned from the interval length that defines how fast the Dropmark padding machine juggles between internal states. The intervals [1ms, 30ms] and [1ms, 70ms] are evaluated, and show a clear connection to the overhead. A larger interval reduces the bandwidth pressure over the network but could further delay the CONNECTED cell sent by the exit. Perfect superposition of the curves comes from Shadow's simulation determinism and from our design efficiency. Indeed, the graphs would superpose under the following conditions: (1) Circuit choice is deterministic, leading to the same circuits in the different simulations (necessary for a meaningful impact comparison). (2) The Dropmark defense does not impact user traffic (indeed, the padding is sent when the circuit is silent). (3) There is a surplus of bandwidth in the client-to-middle part of Tor circuits due to Tor topologies (allows to absorb the padding overhead). Tor has a significant bandwidth excess in these parts of circuits for about 10 years now [42, 48].

During 1 hour of virtual time, the 37,617 emulated Tor clients altogether generated 74,444 active circuits every 10 minutes in aggregate. Figure 7 shows that, on average, with **gap** $= 70ms$ the middle relays sent 217 padding cells in these circuits to cover potential Dropmark attempts, totaling $\approx$ 98 million cells ($\approx 47GiB$) during the virtual hour over the whole network. While these numbers may look large, they represent a small overhead of 3.6% for the overall network goodput (throughput of RELAY command cells). Moreover, thanks to the deployed protocol restriction, the defense is only

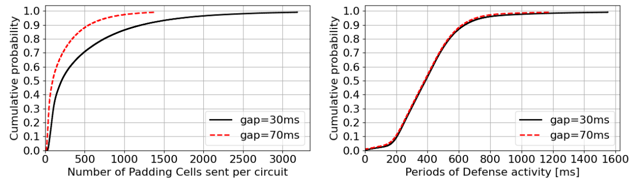

Figure 7: Per-circuit statistics of the dropmark defense deployed on our FAN instance, for interval choices [1ms, 30ms] and [1ms, 70ms] in the padding machine design. Plotted until percentile .99

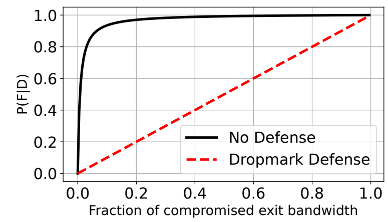

Figure 8: Bayesian Detection Rate as the dropmark's reliability to large scale deanonymization (needs to be close to 1 to avoid flagging "innocents").

required to cover on average 390ms of expected protocol silence (Figure 7). Varying the defense parameters allows full control over the overhead. Note that, because recent Tor topologies have a scarce total exit capacity [44], slightly increasing the bandwidth usage in the entry and middle parts of Tor circuits is not expected to impact the clients' goodput with is bottle-necked by exit bandwidth.

6.3.3 Bayesian Detection Rate. We assume, per the Dropmark's threat model, that the adversary sits between some fraction of the clients and the Internet, controlling some guards or ISPs, and listening for Dropmark events. The challenge for the adversary conducting a traffic confirmation attack is to reliably distinguish whether or not an observed Dropmark signal was sent by it. We can compute the reliability using the *Bayesian detection rate* relative to how much bandwidth the adversary controls at the exit position. We can calculate the Bayesian detection rate using Bayes' Theorem: Let D be a random variable that denotes the observation of a Dropmark over the circuit ($\neg D$ otherwise). Let F be a random variable that denotes the fraction of exit bandwidth the adversary controls ($\neg F$ the fraction not controlled). We are interested in $P(F|D)$, that is, the probability that the observed Dropmark signal actually comes from the adversary:

$$P(F|D) = \frac{P(F) \times P(D|F)}{P(F) \times P(D|F) + P(\neg F) \times P(D|\neg F)}$$

From our Dropmark empirical results in Table 2 and from the empirical results of the Dropmark defense obtained with Shadow, we can compute $P(F|D)$ relative to F. Indeed, $P(D|F) = TPos = 0.999972$ and $P(D|\neg F) = FPos = 0.007713$. Using the defense, $P(D|\neg F)$ rises to 0.999975. Figure 8 gives the overall picture and highlights the impact of the *undefended* Dropmark's low FPR: the attack's reliability rises as the compromised exit fraction increases. Several facts make these results concerning: 1) In its recent history, the Tor network has several times experienced a malicious operator controlling a significant fraction ($> 20\%$) of the total exit bandwidth [30], and 2) several exit families hold a large fraction of the total exit bandwidth [31]. Independent of their trustworthiness, being in a position that allows reliable Dropmark-based deanonymization at scale might be undesired until the problem is solved.

The FAN-based defense is efficient in breaking the Dropmark's reliability, enforcing a given fingerprint that is independent of the presence of some adversary on the exit node with a potential adaptive Dropmark strategy.

6.4 Case Study Conclusion

This case study illustrates that deploying ephemeral conservative protocol policies can be useful to defend against traffic confirmation techniques, reducing the overhead of padding-based defenses. We argue that such policies would be infeasible to deploy over vanilla Tor due to the impact on extensibility, and in case of problems, require choosing between two undesirable options, such as either excluding relays that do not update fast enough or wait long enough for the restrictive protocol feature to be removed through Tor volunteers' regular update lifecycle.

7 Related Work

Bento [39] and Proteus [50] are the closest work to the FAN approach. Like FAN, Bento is fundamentally an architecture. Bento provides mechanisms for installing user-defined functions on Tor nodes using a "middlebox" approach, assuming a perfectly secure enclave to run user-functions in. Bento pays a high performance price being designed as a separate process running a Python controller interacting with the Tor process through a socket to exchange information (e.g., Tor cells). While the two designs are close to each other in spirit, the architectural differences lead to radical differences in terms of performance, security, capability, and deployability. FAN mainly discusses and addresses the need for better extensibility from the authority' perspective, while Bento argues for benefits of a client-controlled environment remotely running arbitrary code in secure enclaves on relays.

Proteus [50] provides a protobuf-like language to remotely run user-defined protocols on bridge relays. Proteus shares similar observations and benefits as FAN and Bento, and like Bento, its different approach makes it an interesting and independent research direction to pursue.

Rochet and Pereira [43] established that protocol flexibility could be leveraged to perform traffic correlation. We build upon their work and show how a software architecture change can allow us more control while removing protocol tolerance, enabling a realistic solution against the Dropmark attack, and open new research perspectives. The Vanguards addon [4] produced by the Tor project reacted to the research in [43] by enabling restrictive protocol policies, tearing down any circuit receiving an unknown cell. We argue that this choice would force the Tor project to negotiate any new feature and wait a long time to deploy them (until most of the relays are upgraded) or force periodic global exclusions of relays, which would damage the network diversity and throughput.

8 Limitations

Technical limitations of current implementation From a software security standpoint, JIT engines are currently behind regular compilers in regard to memory safety mitigations such as Control Flow Integrity (CFI) or the No Execute bit (NX) for the stored code. These are mitigations to memory safety bug exploitations. Nonetheless, the steady progress of JIT engines, and the future of architectures building upon them is promising, both from a performance and security point of view. Indeed, the JIT compilation engine can detect the processor on which it compiles some eBPF or WebAssembly code, and uses its dedicated instructions. It contrasts compiling ahead-of-time as we do today since distributing packaged binaries requires compiling the code for a generic subset of instructions to make sure a variety of, say, x86 processors, would understand all instructions. Usually it means advanced, faster capabilities are unused. From a security point of view, our design could be extended to run untrusted code. However, the existence of a vulnerability in the untrusted code does not imply the existence of an exploitation vector. Technologies such as WebAssembly are designed to thwart exploitation vectors, making vulnerabilities, if any, difficult to impossible to exploit compared to a memory safety vulnerability within a regular binary [8].

Fast path overheads Currently, accessing host heap-allocated data by a plugin may involve a copy to move the data into the plugin's memory authorized space, while regular code would pass a pointer. As an alternative, if some data is meant to eventually be moved into a plugin, the host could allocate memory within the plugin's memory space since this space is owned by the host's process which would involve passing a pointer rather than a copy. This would require writing and using a wrapper for the OS's memory allocation syscalls for the host.

Case study's defense limitations A malicious client may employ a congestion attack [21, 22], to build many circuits through the same guard relay (but different middle relays), activate the Dropmark defense and stop reading the client-guard TCP connection. We can deploy several mitigations to avert such an issue. For example, from Figure 7, capping the number of padding cells produced by the dropmark defense to 350 would be effective for ≈99% of Tor circuits. A legitimate client can switch to a new circuit when it receives this amount of padding cells since the circuit is unusable due to the latency or potentially being flooded by a malicious exit. This strategy could be programmed within the plugin and instantly deployed, as a further example of what the FAN architecture enables.

9 Future work

FAN could be used to run different protocols atop the same physical network, multiplexed over the same TCP connection between two relays and challenging the adversary's assumption about the nature of the traffic. For example, high-latency, round-based provably secure anonymity could technically co-exist with a low-latency network on FAN and hide among the crowd of low-latency users, atop the same TCP connection which the network engine would allow to share among plugins.

While we discuss a centralized governance model in this paper (i.e., no third-party plugins, all relays should have the same set of plugins for a given core version), research in alternative governance models such as enabling third-parties raises safety & security concerns that would need addressing. One major difference would be that users could enable/propagate in their own circuits a different set of third-party but authorized protocol features. While these third-parties may lead more users to embrace and adapt the anonymous communication network to their use case, it opens the door for fingerprinting attacks. Moreover, the system would have to make sure that different plugins cannot misbehave together (collude), or monopolize resources. Our current proposal does not enable third-parties to propagate code, yet this long-term research goal (hence "Towards" in the title) motivates FAN's current complexity. Efficient, low-bandwidth automated and unattended updates as suggested in this paper are pre-requisite of these capabilities.

10 Discussion & Conclusion

In this work, we argue that the freedom allowed by the developers in their protocol designs required to ensure the continuous evolution of the network and minimize the burden to roll out changes is also the source of the adversary's strength. In Section 2.2, we gave an appealing example regarding the circuit extension protocol, in which the protocol's tolerance enabled a chain of exploits. It has led to the most reliable traffic confirmation technique to date, and put in use by a state agency. We also argue that the exploitation of protocol tolerance is the root cause of several other reliable attacks against the Tor design (DoS using tolerance in the control-flow [21], dropmark due to Robustness in the Relay protocol [43], arbitrary positioning allowed in the HSDir list [5], etc.).

Programming the network with a FAN methodology may help prevent those protocol flaws from existing in the first place. Indeed, with a FAN architecture, we can naturally tighten the tolerance embedded in feature designs: there are no forward/backward compatibility concerns. Developers need not be constrained by future, as-yet-unknown requirements when programming with FAN. Instead, the developers may be as conservative as possible and deploy new iterations of functionalities with plugins, programming new behavior as it is needed. FAN applied to Tor has the potential to reduce its protocols' attack surface, assuming Tor's governance model does not change (e.g., no third-party plugins).

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A FAN Plugin Transparency Details and Proofs

FAN Plugin Transparency Details & Proof Sketches. Newly issued plugins are stored in the FTLs' structured Tree as leaf nodes. The leaf depends on the plugin's name, which is a concatenation of the FAN developer's namespace— registered at the FTL—and the plugin's unique name (e.g., fan.project/my_plugin, where the registered

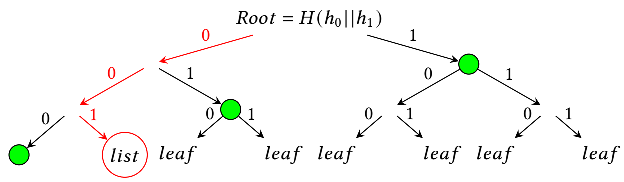

Figure 9: FTL's Name-Structured Merkle Tree List. Plugins are assigned to a leaf depending on their name. If multiple plugins are assigned to the same leaf, they are arranged in an alphabetically-ordered list by name. The green dots are the value provided for the Authentication Path for $H(\text{“}fan.project/my\_plugin\text{”}) = 001\ldots$ and needed to recompute the root.

namespace "fan.project" is concatenated with '/' to the plugin's name "my_plugin"). This name is input into the hash function H and the output is truncated to the Tree's depth D, resulting in a binary representation of the location of the leaf node. For example, in Figure 9, with $H = sha256$ and $D = 3$, the plugin above would be stored at leaf 001. A '0' is a left child and '1' is a right child from the Tree root. Where there are collisions, plugins are stored in an alphabetically-ordered list used to calculate the leaf value as follows:

$$leaf = H(name_1||H(plugin_1||meta-info_1);...;\\ name_n||H(plugin_n||meta-info_n)).$$

Given this, the root of the FTL Tree can be computed, successively concatenating children and hashing the concatenation, which then enables the ability to verify the *Proofs of Availability and Absence* with authentication paths (see below).

This Tree offers: (1) **Efficiency.** The proof of availability and the proof of absence (detailed below) can be computed with space and time complexity in $\Theta(D + \frac{N}{2^D})$ with N the number of plugins included and D the Tree depth assuming H emulates a Random Oracle. In a classic Merkle Tree, the proof of absence would require monitoring the whole tree. Observe that depending on N, the FTLs can choose D such that the proofs' complexity is close to the lower bound $\Omega(D)$ on average. D must, however, be the same for all FTLs for the next property to hold. (2) **Unambiguous name-to-plugin mapping & spurious plugin detection.** A plugin name maps to a single leaf. The FAN developers can detect if the FTL maliciously swaps the plugin for another from the proof of availability requests to each FTL in each epoch. The relays would also detect it from a non-matching signed tree root value in the proof of availability (the value would not be the same as the one broadcasted by the FAN developers to the network for the current epoch).

The proof of availability and the proof of absence can both be computed from an *authentication path* (see an example in Figure 9). That is, for a given name, the FTL produces the leaf's list and the list of siblings' hashes on the path from the leaf to the root. Knowing the expected path in the Tree from the name, the verifier can unambiguously concatenate the siblings and reconstruct the full path using the list of hash values for a given plugin.

Then, having the authentication path, the verifier can re-compute the Root hash value and compare it to the expected one. The verifier can infer directly whether the parent's hash value needs to be computed as $H(path\_hash||sibling\_hash)$ or $H(sibling\_hash||path\_hash)$ from the plugin's name, since its truncated hash value gives the ordering (i.e., the path direction in the Tree).

Relays will load a plugin if and only if: (1) The FTL is "online". (2) The plugin push epoch value is lower or equal to the current epoch value. (3) The proof of availability correctly verifies. (4) The plugin is not marked as "withdrawn". (5) The broadcasted FTL's root hash matches the proof of availability's reconstructed root hash.

Observe that relays only need to verify the FAN developers' threshold signature in the event of a dispute. Furthermore, the proof of availability can be attached to the plugin when it is transmitted to the network. When all verifications succeed, the cost of the overall system at runtime for the non-protesting relays is minimal: no interactions and a few Hash calculations to verify the proof of availability.

When relay operators protest against an issued plugin by the protest epoch, they sign "$relay_identity:protest:$plugin_name" and send the signature to at least one FTL, which will broadcast the signature to other FTLs. Weighing the number of protests, the FAN developers may decide to withdraw the plugin from the network. Once withdrawn, relay operators can request a proof of absence from all "online" FTLs. If the relay operator maliciously sends multiple signatures (i.e., different ones for the same protest), the FTLs would forward them to the FAN developers for potential punishment and ignore the protest.

We have the following theorems:

Theorem 1. *Under the assumption that $H : \{0,1\}^* \to \{0,1\}^n$ behaves as a random oracle, a name maps to a unique authentication path in the Name-Structured Merkle Tree List with probability* $1 - \mathsf{negl}(n)$.

Proof. Let $H = RO : \{0,1\}^* \to \{0,1\}^n$ a random oracle. Let D be the depth of the Tree. Let $\mathcal{A}$ be an adversary able to manipulate the plugin and the meta-info to duplicate an authentication path for the name *name* assigned to leaf l:

$$l^{\mathcal{A}} = name||H(plugin^{\mathcal{A}}||meta-info^{\mathcal{A}})$$

The adversary succeeds if they can choose $plugin^{\mathcal{A}}$ and $meta-info^{\mathcal{A}}$ such that the parent's value is:

$$H(l||l^{\mathcal{A}}) = H(l^{\mathcal{A}}||l)$$

or for any of the $D-1$ parents we have (with h_0 and h_1 the child values of the current level):

$$H(h_0||h_1) = H(h_1||h_0)$$

$\mathcal{A}$ performs q queries to the Random Oracle, each of probability $\frac{D}{2^n}$ to succeed. By the union bound, the adversary succeeds with probability $\frac{q\times D}{2^n} = \mathsf{negl}(n)$. Therefore, the authentication path is unique with probability $1 - \mathsf{negl}(n)$.

□

Theorem 2. *Under the assumption that $H : \{0,1\}^* \rightarrow \{0,1\}^n$ is a uniform random function, and given that the authentication path is unique (Theorem 1), the FAN developers can detect spurious plugins with probability $1 - \mathsf{negl}(n)$ with algorithmic complexity $\Theta(D + \frac{N}{2^D})$ for D the depth of the Name Structured Merkle Tree List and N the number of plugins included.*

Proof. $\mathcal{A}$ succeeds to hide $plugin^{\mathcal{A}}||meta-info^{\mathcal{A}}$ with probability $\mathsf{negl}(n)$ (directly from Theorem 1). Hence, the adversary can only modify the legitimate leaf, which gets detected at the re-computation of the Tree's root using the authentication path (i.e., the re-computed root does not match the expected one using the legitimate plugin).

The recomputation involves D steps to hash each level of the Tree. Assuming H's output is uniform, the load on each leaf (i.e., the number of plugins) is expected to be $\frac{N}{2^D}$ on average. Therefore, the FAN developers can detect a spurious plugin with probability $1 - \mathsf{negl}(n)$ with complexity $\Theta(D + \frac{N}{2^D})$. □

Theorem 2 guarantees that any member of the network can directly catch any attempt to manipulate the proof of availability for a given name. Moreover, if any relay transmits a proof of availability to a peer relay with a forged bytecode, the peer relay would detect it without the need to interact with FTLs and without requiring asymmetric cryptography operations. These facts display the efficiency of our design and the above theorems offer secure plugin names.

Another important property provided by the FAN Plugin Transparency system is its non-equivocation. That is, it is not possible for the FTLs to trick one party into believing that a plugin is included and another party to believe the plugin is not.

Theorem 3. *Under the assumption that $H : \{0,1\}^* \rightarrow \{0,1\}^n$ behaves as a random oracle and is collision-resistant, then an FTL admits a unique root value for a known depth D and set of included plugins.*

Proof. Let $TR : \{0,1\}^*_0 \times \cdots \times \{0,1\}^*_{2^D} \rightarrow \{0,1\}^n$ a function that takes in input the Tree leaves and computes the Tree root with successive applications of H. At each H application, a collision with the root value may happen with probability $\frac{1}{2^n}$. By the union bound, the probability that the root is unique is given by $1 - \frac{D}{2^n} = 1 - \mathsf{negl}(n)$. □

From Theorem 3 and assuming a broadcast channel to exchange FTL's root value (e.g., the Tor Consensus Document), then an equivocation would lead to an observable root mismatch.

B Design Implementation

Figure 11 gives an example of meta-info within our FAN implementation. The first line is the sandboxed memory the plugin requires, which gives the right to all code in the plugin to allocate, share and access data within a specific memory space of N bytes to be specified in the plugin meta-information and authorized by the plugin manager. Each of the subsequent lines attaches an *entry point* to an internal hook within the Tor binary.

C Simple Plugin Code Example

An example of a *hook* in C-Tor written in the Relay protocol to intercept any unknown Relay message is given on Figure 10.

```c
entry_point_map_t pmap;
memset(&pmap, 0, sizeof(pmap));
pmap.ptype = PLUGIN_DEV;
pmap.putype = PLUGIN_CODE_ADD;
pmap.pfamily = PLUGIN_PROTOCOL_RELAY;
pmap.entry_name = (char*)"relay_process_edge_unknown";
caller_id_t caller = RELAY_PROCESS_EDGE_UNKNOWN;
relay_process_edge_t args;
args.circ = circ;
args.layer_hint = layer_hint;
args.edgeconn = conn;
args.cell = cell;

if (invoke_plugin_operation_or_default(&pmap,
    caller, (void*)&args)) {
  log_fn(LOG_PROTOCOL_WARN, LD_PROTOCOL,
      "Received unknown relay command \%d. But"
      " we do not have a developer plugin"
      " able to handle it, destroy the circuit",
      rh->command);
  return -1;
}
return 0;
```

Figure 10: Hook located in Tor's Relay protocol to intercept any unknown Relay cell, and destroy the circuit if a plugin does not exist to handle it. Originally, the unknown message is ignored as per the Robustness principle.

Furthermore, Figure 12 shows an example of a function (rather than a message) that we may intercept with a plugin, assuming the original function call is defined as the default code of a hook. On the right the original code, on the left the same code written in the C subset compiling to eBPF.

```
memory 16777216
circpad_global_machine_init protocol_circpad add circpad_dropmark_def.o
circpad_setup_machine_on_circ_add protocol_circpad add circpad_dropmark_circ_setup.o
relay_process_edge_unknown protocol_relay add circpad_dropmark_receive_sig.o
connedge_connection_ap_handshake_send_begin_add protocol_conn_edge param 1 add circpad_dropmark_send_sig.o
connedge_received_connected_cell_add protocol_conn_edge param 2 add circpad_dropmark_send_sig.o
circpad_send_padding_cell_for_callback_replace protocol_circpad replace circpad_dropmark_send_padding_cell.o
```

Figure 11: Example of a .plugin file containing meta-information for the plugin to compile and link with Tor's code. The first line is the maximum heap memory that the plugin can allocate (in bytes; 16 MiB here). The following lines announce one entry point each. The first element is the Hook name. The second element is the protocol name, the third element is an operation over the hook (e.g., add or replace). There is an optional parameter argument and the final element is the bytecode filename.

```c
#include "core/or/or.h"
#include "core/or/relay.h"
#include "core/or/plugin.h"
#include "core/or/plugin_helper.h"

uint64_t
sendme_circuit_data_received(relay_process_edge_t *pedge) {
  int deliver_window, domain;
  circuit_t *circ = (circuit_t *) get(RELAY_ARG_CIRCUIT_T, 1, pedge);
  crypt_path_t *layer_hint = (crypt_path_t *) get(RELAY_ARG_CRYPT_PATH_T, 1, pedge);

  if ((int) get(UTIL_CIRCUIT_IS_ORIGIN, 1, circ)) {
    deliver_window = (int) get(RELAY_LAYER_HINT_DELIVER_WINDOW, 1, layer_hint);
    set(RELAY_LAYER_HINT_DELIVER_WINDOW, 2, layer_hint, --deliver_window);
    domain = LD_APP;
  } else {
    deliver_window = (int) get(RELAY_CIRC_DELIVER_WINDOW, 1, circ);
    set(RELAY_CIRC_DELIVER_WINDOW, 1, circ, --deliver_window);
    domain = LD_EXIT;
  }

  log_fn_(domain, LD_PLUGIN, __FUNCTION__,
    "Circuit deliver_window now %d.", deliver_window);
  return 0;
}
```

```c
int
sendme_circuit_data_received(circuit_t *circ,
↪  crypt_path_t *layer_hint) {
  int deliver_window, domain;

  if (CIRCUIT_IS_ORIGIN(circ)) {
    tor_assert(layer_hint);
    --layer_hint->deliver_window;
    deliver_window = layer_hint->deliver_window;
    domain = LD_APP;
  } else {
    tor_assert(!layer_hint);
    --circ->deliver_window;
    deliver_window = circ->deliver_window;
    domain = LD_EXIT;
  }

  log_debug(domain,
    "Circuit deliver_window now %d.", deliver_window);
  return deliver_window;
}
```

Figure 12: Code example of the smallest function we intercept in one of our plugins to evaluate the CPU overhead. The left function is defined in a separate .c file from the main Tor source code and compiled to a BPF bytecode object. It uses a get/set API to indirectly interact with values outside its allocated memory, upon the control of the main binary. The right function is the one existing in Tor's source code.