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Hardening Stratum, the Bitcoin Pool Mining Protocol

Abstract: Stratum, the de-facto mining communication protocol used by blockchain based cryptocurrency systems, enables miners to reliably and efficiently fetch jobs from mining pool servers. In this paper we exploit Stratum's lack of encryption to develop passive and active attacks on Bitcoin's mining protocol, with important implications on the privacy, security and even safety of mining equipment owners. We introduce StraTap and ISP Log attacks, that infer miner earnings if given access to miner communications, or even their logs. We develop BiteCoin, an active attack that hijacks shares submitted by miners, and their associated payouts. We build BiteCoin on WireGhost, a tool we developed to hijack and surreptitiously maintain Stratum connections. Our attacks reveal that securing Stratum through pervasive encryption is not only undesirable (due to large overheads), but also ineffective: an adversary can predict miner earnings even when given access to only packet timestamps. Instead, we devise Bedrock, a minimalistic Stratum extension that protects the privacy and security of mining participants. We introduce and leverage the *mining cookie* concept, a secret that each miner shares with the pool and includes in its puzzle computations, and that prevents attackers from reconstructing or hijacking the puzzles.

We have implemented our attacks and collected 138MB of Stratum protocol traffic from mining equipment in the US and Venezuela. We show that Bedrock is resilient to active attacks even when an adversary breaks the crypto constructs it uses. Bedrock imposes a daily overhead of 12.03s on a single pool server that handles mining traffic from 16,000 miners.

Keywords: Bitcoin and Stratum mining protocols, passive and active attacks, traffic analysis, mining cookies

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1 Introduction

The privacy and security of Bitcoin have been extensively studied [1–7] and documented [8]. While the focus of previous work has been on the architectural vulnerabilities of the cryptocurrency, no work has been done to analyze implementation vulnerabilities of the Stratum mining protocol, the main Bitcoin mining option.

However, mining activities have important privacy implications [9]. Learning the payouts of miners can make them targets of hacking and coin theft [10, 11], kidnapping [12], and, in countries where Bitcoin is illegal [13, 14], expose them to arrest and equipment confiscation [15, 16]. For instance, in countries like Venezuela, intelligence police hunt Bitcoin miners to extort, steal mining equipment or prosecute [17].

In this paper we study the vulnerabilities of the *Stratum* protocol [18], the de facto mining standard for pooled Bitcoin mining [19] as well as alternative coins mining, e.g., Litecoin [20], Ethereum [21] and Monero [22]; currently the altcoins with the most market capitalization [23]. Stratum replaced the original *getwork* protocol of Bitcoin mining [24], to enable miners to fetch jobs from mining pool servers more reliably and efficiently. In Stratum, the miners solve assigned *jobs* and send their results back in the form of *shares*. The mining pool server then compensates the miner according to the difficulty of the assigned jobs and the number of shares accepted.

We show that the lack of cryptographic protection of communications has made the Stratum protocol vulnerable to several exploitation possibilities, see Figure 1. An attacker able to observe the traffic between a miner and a pool server can accurately infer the earnings of the miner. We show that this result holds even if the attacker has only limited access to the transmitted packets, e.g., metadata stored in ISP logs. In addition, we show that active attackers, able to interfere with the Stratum traffic of miners, may steal computational resources and bring forth financial loss to their victims.

These attacks, especially given the wide adoption of the Stratum protocol, show that Bitcoin and altcoin solutions fail to ensure the monetary privacy and security of the vital miner community. Furthermore, the attacks

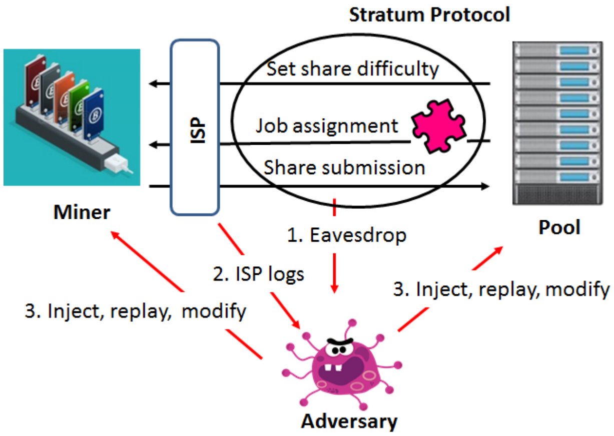


Fig. 1. Model of system that consists of a pool, miners, and adversary. The pool and the miners communicate over the Stratum protocol, to assign jobs and submit results (shares). The adversary can eavesdrop, recover ISP logs, inject and modify the Stratum communications of victim miners.

reveal that even an exhaustive use of encryption will fail to ensure miner privacy, as access to only the timestamp of mining protocol traffic can enable an attacker to predict the payouts of a victim miner. In addition, the significant overhead of encryption makes such a solution unappealing to pools, that need to handle mining traffic from thousands of miners simultaneously, e.g., more than 16,000 for the F2Pool pool [25–27]. In § 9.4 we show that complete encryption of all Stratum traffic imposes a daily overhead of 1.36 hours on a pool server handling 16,000 miners, while TLS imposes a daily overhead of 1.01 hours.

Furthermore, Tor does not address the above vulnerabilities. In fact, sending Stratum traffic over Tor would enable an adversary to launch the ISP Log attack not only from the same network with the victim, but also from adversary controlled Tor exit nodes, that can inspect the cleartext Stratum traffic to the destination. Also, Bitcoin over Tor has been shown to be vulnerable to several attacks [28], and, even without an adversary, Tor may introduce delays that can lead to miners losing blocks.

Our Contributions. In this paper we introduce the following contributions:

- **Passive attacks**. We show that F2Pool's Stratum implementation leaks sensitive miner information not only through cleartext communications but also indirectly, through hashrate dependent inter-packet timing. We introduce *StraTap* and *ISP Log*, passive attacks where adversaries accurately infer the earnings of victim miners, given either captured transmissions of those miners, or only their log metadata.
- **Active attack**. We propose *BiteCoin*, a payout hijack attack that enables an adversary able to access the communications of a victim miner, to steal its resources and mining payouts. To implement BiteCoin, we have developed *WireGhost*, a TCP hijacking tool that surreptitiously modifies TCP packets, without imposing disconnections or session resets.
- **Bedrock**. We develop *Bedrock*, a Stratum extension that addresses the proposed attacks. Bedrock seeks to assuage the efficiency concerns of Bitcoin, by imposing minimal modifications and encryption overhead to the Stratum protocol. We introduce the concept of *mining cookies*, secret values that miners need to include in the computed puzzles. Mining cookies prevent both passive and active attacks on share submission packets, without encrypting the vast majority of the pool communications.
- **Results**. We have collected 138MB of Stratum traffic traces from mining equipment in the US and Venezuela, and release it for public use [29]. We have implemented the developed attacks and report results from their deployment on AntMiner mining equipment. We show that StraTap and ISPLog achieve low payout prediction errors, and that BiteCoin can efficiently hijack job assignments and share submissions from a victim miner. We show that Bedrock prevents these attacks, and is resilient to active attacks even when the adversary breaks its crypto tools. Bedrock imposes a 12.03s daily overhead on a single pool server that handles 16,000 miners simultaneously.

The attacks and defenses introduced in this paper apply to the Stratum protocol, thus to most of the large mining pools [30–34]. These attacks work even on miners that are behind a NAT, or that are firewalled. Furthermore, while we focus our experiments on the popular AntMiner mining equipment, our attacks are general and apply to other manufacturers as well. We have notified F2Pool about these vulnerabilities.

2 Model and Background

The Bitcoin mining ecosystem consists of miners and pools, see Figure 1. The communication between pools and miners takes place almost exclusively over the Stratum, that we study in the next section. The main task of Bitcoin miners (or mining nodes) is to permanently insert new consistent data into the network. Miners collect transaction data from other nodes, validate it and insert it in a structure called *block*. The miners need to solve a cryptographic puzzle based on the block, before the block is permanently inserted into the storing structure of the network, called *the blockchain*.

2.1 Mining Pools

As specialized, more powerful miners were designed, and the difficulty of mining blocks increased, it became increasingly difficult for individual, *solo* miners to successfully mine and receive timely payouts for their work. The concept of *mining pools* has emerged in order to address this problem: enable miners to combine their resources, then split the reward according to the amount of work they have performed. Pools and miners form a master/slave paradigm, where pools parallelize the mining work among multiple miners. Thus, instead of randomly receiving a large reward only once several years, pooled miners receive smaller rewards, on a regular basis (e.g., once per day).

Popular mining pools today interact with thousands of miners. For instance, F2Pool has more than 16,000 miners [25–27]. As per the Bitcoin specification, about 150 blocks are to be mined every day, i.e., 1 block every 10 minutes. Since each block is, at the time of writing, worth 12.5 BTC , at an exchange rate of ≈ $1,100 per BTC, about 2 million dollars are distributed each day. The larger mining pool servers control about 20% of these earnings [35].

The mining pool rewards a *share* to the miner who reports a proof of a unit of solved work. Pools often offer a *variable share difficulty* feature: adaptively assign the share target to miners, according to their computation ability. Pools perform this in order to ensure that (i) the assigned work is not too difficult, thus enable miners to prove computation progress and gain regular payouts, and that (ii) the work is not too easy, thus reduce the overhead on the pool, to process shares submitted by thousands of miners.

Hashrate to BTC conversion. The pool will reward the miner according to the number of shares submitted and accepted. Each pool has a different payout policy. One of the most popular policies is "Pay Per Share" (PPS) which usually has a pool fee attached to it. Since the final calculation for share payment is dependent on the actual mining activity of the pool, it is difficult to provide an exact estimate of each share payout. However, most pools publish a hashrate to BTC (Bitcoin) rate of conversion for miner verification purposes. At the time of writing this paper, the conversion rate on the F2Pool was 0.00246248 BTC per TH/s [30].

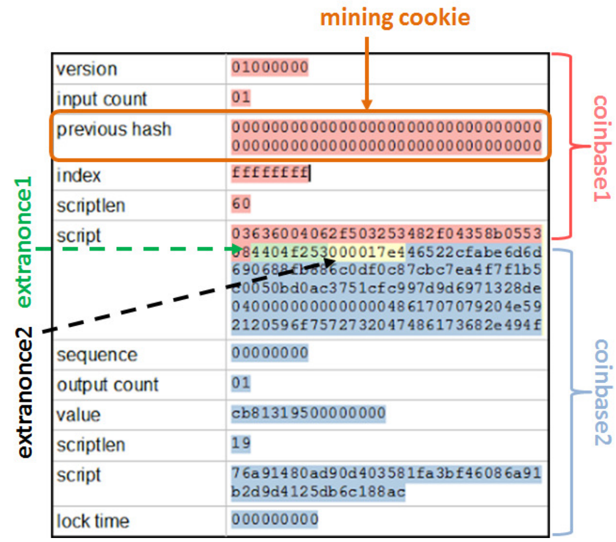


Fig. 2. Coinbase transaction format. The fields in the table are the underlying Bitcoin transaction fields. Stratum overlays the coinbase fields (*coinbase*1, *extranonce*1, *extranonce*2, *coinbase*2) on top of the Bitcoin coinbase fields. Bedrock (see § 6) introduces the *mining cookie* concept, whose value will overwrite the currently unused "previous hash" field within *coinbase*1.

2.2 The Coinbase Transaction

As mentioned above, each block collects a set of previous transactions in the Bitcoin network. The first such transaction is special, called the *coinbase* transaction (see Figure 2): it specifies that the pool will receive the value of this block (currently 12.5 Bitcoins) when this block is mined. The Stratum coinbase consists of 4 fields, *coinbase1*, *extranonce1*, *extranonce2*, *coinbase2*, overlayed on top of the Bitcoin coinbase information. *coinbase*1 covers the first 5 fields of the input transaction (version, input count, previous transaction hash, previous transaction index and input scriptlen) and part of the script, in the original coinbase transaction specification. Except for the version number, these parameters are meaningless to all clients and pools since the coinbase transaction does not have an input transaction.

The *extranonce*1 and *extranonce*2 fields are also overlayed on the unused script. *extranonce*1 needs to be unique (pseudo-random) per stratum connection. *extranonce*2 is used in the mining puzzle and needs to be incremented by the miner once the *nonce* parameter is exhausted (see next paragraph). The rest of the coinbase transaction is packed in the *coinbase*2 parameter.

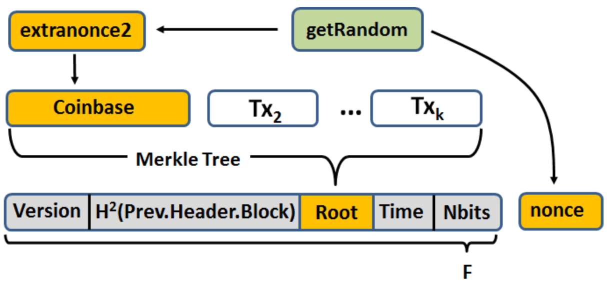


Fig. 3. Bitcoin block puzzle. The root of the Merkle tree built over the coinbase and the mined transactions is the third field of the block puzzle. The miner iterates over the *nonce* (last field) and over the extranonce2 value, part of the coinbase transaction.

Bedrock, our secure Stratum extension, leverages the unused "previous transaction hash" field (Figure 2), to include the value of the mining cookie, see § 6.

2.3 The Bitcoin Puzzle

The goal of the mining process is to make it difficult for a minority of malicious nodes to insert bogus data inside invalid blocks. It achieves this by transforming each block (collection of transactions in the Bitcoin network) into a cryptographic "puzzle". The puzzle is designed such that the probability of finding a solution by a mining node is proportional to its computational power. A Bitcoin puzzle consists of a *target* value and a tuple F = (block version number || hash of previous block || RMT || timestamp || Nbits), || denotes concatenation, see Figure 3 for an illustration.

Specifically, F contains the block version number, the hash of the previous block in the blockchain, the root of a Merkle tree (RMT) described next, a timestamp, and the final target value in the form of the number of leading bits that need to be 0 for the block to be considered "mined". The Merkle tree is built over the transactions that are being mined into the current block, including the coinbase transaction, see Figure 3. Given the F value, and the above mentioned *target*, the miner iterates over the *nonce* and *extranonce2* (see coinbase transaction) values until it identifies a pair such that

$$H^2(nonce||F) < target \tag{1}$$

where H^2 denotes the double (SHA-256) hash. The block is said to be "mined" when $H^2(nonce||F)$ is less than the target corresponding to the above Nbits value.

The target and the difficulty. While the *Nbits* value specifies when the block is mined, pools set the above *target* parameter to a larger value (fewer leading bits 0) to enable miners to prove and be rewarded for progress. The *target of difficulty 1*, denoted *target_1*, is defined by pools as the number $2^{224} - 1$, i.e. a 256 bit number with 32 bits of leading zeros followed by 224 bits of ones. The *difficulty* value is a measure of how hard it is to solve a puzzle for a given *target* value. Accordingly, the relationship between the *difficulty* and *target* values is given by the formula:

$$difficulty = \frac{target\_1}{target} = \frac{2^{224} - 1}{target} \tag{2}$$

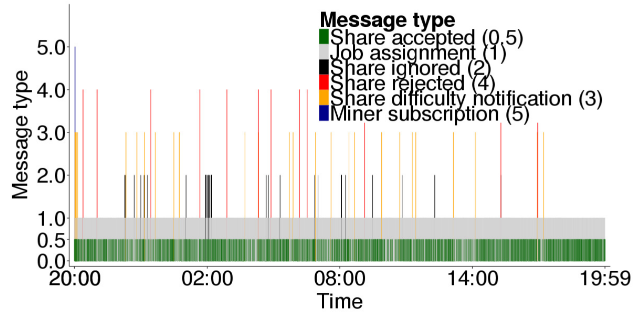


Fig. 4. Stratum protocol timeline over 24 hours captured between an AntMiner S7 and the F2Pool pool. While we observe several difficulty change packets (orange bars) throughout the day, most are concentrated after the initial subscription protocol (tall blue bar). The majority of share submissions are accepted (green bars); only a few are rejected (red bars) or ignored (black bars).

2.4 Stratum

Stratum is a clear text communication protocol between the pool and the miners [18], built over TCP/IP and using the JSON-RPC format. The official Stratum protocol documentation is not detailed and is often outdated [18]. In this section we describe the F2Pool [30] implementation of the Stratum protocol, as observed from Stratum packets we captured over 13 days between an AntMiner S7 device and the F2Pool mining pool (see § 8.1). Figure 4 illustrates the timeline of captured Stratum protocol packets over a 24 hour interval. The ability to capture, understand, modify and inject these messages into a communication stream will be instrumental for the passive and active attacks described in § 4 and § 5.

Miner subscription. To register with the pool, the miner first subscribes through a **connection subscription** message

`mining.subscribe, params,`

that describes the miner capabilities. The server responds with a **subscription response** message,

`result,{methods}, extranonce1, extranonce2.size,`

where the first field is a list method names used by the server pool, the second field (see § 2.3), should be

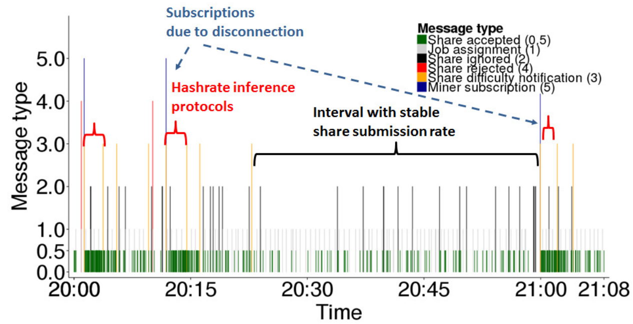


Fig. 5. Timeline of miner operating at 250MHz. We emphasize the effect of successive share difficulty notification messages: the miner's share submission rate slows down. We also point the multiple miner subscribe and authorization procedures (tall blue bars) due to repeated miner disconnections.

random and unique per connection, but F2Pool sets to constant "$\backslash x30\backslash x30$", and the third is the size of the `extranonce2` (4B in F2Pool).

Miner authorization. Following the subscription exchange, Stratum authenticates the miner with the pool, through a **miner authorization request** message

`mining.authorize, account.minerID, password,`

whose first field, the username, consists of two fields, that enable a user to register multiple miners with the same account. While the password field is transferred in cleartext, it is currently ignored by pools. The pool responds with a **status result** that notifies the miner of the result of the authorization request. In Figure 4 and 5, the miner subscription and authorization messages are shown as a single blue bar (the tallest), seen at the beginning of the interval and each time the miner reconnects to the pool, e.g., after an Internet disconnection or power outage.

Share difficulty notification. Following a successful authorization, the pool sends a **difficulty notification** message to the miner

`set.difficulty, difficulty,`

that specifies the minimum share difficulty that the server will be willing to accept. Figure 4 and 5 show the difficulty notification messages as orange bars. They can occur throughout the day as the pool seeks to adjust the miner's rate of share submissions.

Job assignment. The pool assigns jobs (puzzles) to the miner through **mining job notification** messages

`mining.notify, job_id, params, clean_jobs`

that specify the puzzle parameters, i.e., the fields of the F value in Equation 1 (see § 2.3), and a boolean that indicates if the miner should drop all previous jobs and work exclusively on the one specified by this message.

Share submission. Once the miner finds a solution that satisfies Equation 1, it sends a **share submission** message to the pool for verification and credit:

`mining.submit, account.minerID, job_id, time, nonce, extranonce2`

that specifies the miner's username, the job id received in the previous mining job notification, and the parameters of the puzzle solution: the *nonce* and *extranonce*2 parameters, see § 2.3. The pool uses these values to reconstruct the F value (see § 2.3), and verifies that Equation 1 is satisfied.

The pool responds with a status result message, illustrated in Figure 4: green bars denote accepted shares, red bars denote rejected shares, and black bars denote ignored shares. Shares can be rejected due to stale work, i.e., being submitted too late. The miner continues to mine current jobs until it receives a job message from the pool that requires it to invalidate previous jobs (see the "clean jobs" flag in the job assignment message).

3 Adversary Model

We consider adversaries that can launch both passive and active attacks against the Bitcoin network, see Figure 1. We assume that the pool and the miner are honest. However, adversaries can target the communications of specific, victim miners. Adversaries can own mining equipment, can eavesdrop and interfere with existing communications, and may even obtain data from ISPs. We now detail each of these adversarial capabilities.

Eavesdropping capabilities. We consider first an adversary who can access the entire communication of a victim miner. Such adversaries include over-controlling governments, or attackers who gain control to equipment on the same LAN as the victim. We assume that such an adversary can capture and inspect all the packets sent and received by the victim miner.

ISP log capabilities. We also consider adversaries with access to ISP logs, that include entries for the communications of the miners in the ISP's subnet and the pool. This capability is more restrictive than the eavesdropping capability, in terms of the data that can be extracted from the miner-to-pool communications. This is because ISP logs usually contain only metadata [36], in order to comply with law enforcement requests [37]. However, these capabilities may enable the adversary to target more victims (i.e., all the miners whose traffic was logged).

Potential perpetrators include insiders (e.g., ISP employees) and government organizations that can subpoena the logs. While law enforcement insiders have been shown to abuse collected data [38], agencies have also been hacked in the past. Stolen data may then be sold, auctioned, or even made public, thus becoming accessible to a broader range of adversaries.

We assume that this adversary has access to packet metadata that includes timestamps, source and destination IPs and ports, and connection flags. As we show in § 4.2, these values enable the attacker to identify mining traffic via well known pool IP/port pairs, and identify the start of mining sessions.

Active attack capabilities. We further consider an adversary that can modify the communication stream between the server pool and a mining client. Potential such adversaries include attackers that are on the same network as the victim miner, rogue employees at an intermediate ISP, or a government backed agency. In § 5, we show that such an adversary can add jobs and replace submitted shares. While this may allow for trivial denial of service attacks as well, in this paper we do not consider DoS attacks. We note that DoS techniques exist with lesser technical requirements [39, 40].

3.1 Relevance of Attacks

In the following section we introduce passive and active attacks against miners that use the Stratum protocol, whose goal ranges from inferring to stealing the payouts of the victim miners. Inferring the payouts of miners exposes their owners to a suite of attacks. Adversaries can hack the computers or accounts of miner owners in order to steal their payouts [10, 11]. Passive attacks can also enable the adversary to identify miners worthy of being targeted with resource hijacking attacks, e.g., Bitecoin, see § 5. In addition, this knowledge enables adversaries to target miner owners for equipment theft, arson [41], kidnapping [12], and, in countries where Bitcoin is illegal [13, 14], for extortion and prosecution [17].

4 Passive Attacks

In this section we show that an attacker that observes even partial traffic of a victim miner, can infer the payouts received by the miner. We introduce two passive attacks, that make different assumptions on the adversary's capabilities. First, the StraTap attack assumes an adversary able to capture and inspect entire packets transmitted between a pool and a victim miner. Second, the "ISP Log" attack assumes an adversary that is able to inspect only packet metadata, i.e., IP addresses, port numbers, and connection flags. In the following we detail each attack.

4.1 The StraTap Attack

We consider first an eavesdropping adversary, see § 3. Given access to all the packets sent and received by the victim miner, the attacker counts the share submission messages along with their associated difficulty (as described in § 2.4). The attacker uses this data to estimate the hashrate of the victim miner.

Specifically, the probability of randomly finding a hash with the appropriate difficulty is given by the ratio between the target (i.e. the number of hashes with the appropriate number of leading zeros according to the assigned job), and the total number of possible hashes. Hence, the probability of a miner finding a share with a single hash is $p = \frac{target}{2^{256}-1}$. The expected number of hashes, E, that the miner needs to calculate before finding a valid share is then $1/p$. Then, we derive the following for E:

$$\begin{aligned} E &= \frac{2^{256}-1}{target\_1} \times \frac{target\_1}{target} = \\ &= \frac{2^{256}-1}{2^{224}-1} \times difficulty \approx difficulty \times 2^{32} \end{aligned} \tag{3}$$

The second equality follows from Equation 2, and the fact that the target of difficulty 1, $target\_1$ is $2^{224}-1$, see § 2.3. If we divide Equation 3 by the hashrate of the miner, we obtain a formula that allows us to compute the expected time to find a share at a given difficulty:

$$time = \frac{E}{hashrate} = \frac{difficulty \times 2^{32}}{hashrate} \tag{4}$$

Thus, $hashrate = difficulty \times \frac{2^{32}}{time}$. The attacker obtains the $difficulty$ value by inspecting the *share difficulty notification* messages (see § 2.4). In addition, the attacker estimates the $time$ value as the ratio of the length of time between consecutive share difficulty notification messages (orange bars in Figure 4) and the number of shares submitted and accepted during that interval:

$$\overline{time} = \frac{\text{total time between difficulty changes}}{\text{number of submitted (and approved) shares}}$$

The attacker obtains the accepted share count by inspecting the share submission messages and their corresponding status results, see § 2.4.

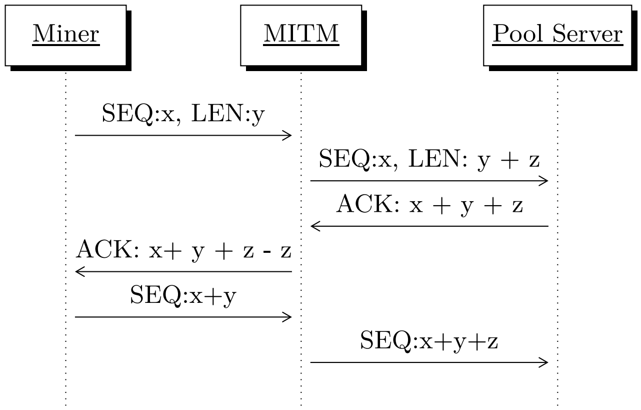


Fig. 6. WireGhost illustration: TCP hijacking with active re-synchronization, when the man-in-the-middle (MITM) adversary adds z bytes to an existing packet originating from the client. WireGhost modifies the sequence numbers, to hide the difference in packet sizes.

Given the inferred *hashrate* of the miner, the attacker uses the hashrate to payout conversion (see the corresponding paragraph in § 2.4) to predict the amount of Bitcoins received by the victim. In § 9.1 we experimentally evaluate the accuracy prediction of the StraTap attack.

4.2 The ISP Log Attack

We now consider an attacker with ISP log data capabilities, see § 3. The ISP Log attack proceeds as follows. First, the attacker identifies the beginning of the connection between the victim miner and the pool. This is the time when a 3-way handshake connection is established, whose first step is a "connection subscription" message as described in § 2.4. Then, the attacker predicts the hashrate of the miner based on statistics over the inter-packet times logged for the miner.

In early experiments we have observed that predictors that use statistics over long time intervals are inaccurate. To address this problem, we have identified and exploited a vulnerability of the Stratum protocol. Specifically, we observed that the first share difficulty notification message (see § 2.4) following a successful miner subscription, sets the difficulty to the minimum value acceptable by the pool (e.g., 1024 for F2Pool). In addition, in § 9.2 we show that the pool sends its second share difficulty notification after approximately 50 share submission messages (for difficulty 1024) received from the miner.

Then, the attacker estimates the time taken by share submissions for jobs of difficulty 1024, i.e., over the first 50 packets sent by the miner following its subscription and authorization process. It then uses the process outlined in the above StraTap attack to predict the miner's hashrate and payout. The attacker can repeat this process when observing subsequent 3-way handshake connection protocols of the victim miner, e.g., when a disconnection occurs, in order to improve its estimates of the miner hashrate. In § 9.2 we show that even when the ISP Log attack performs a single hashrate inference attack per day, its daily miner payout prediction achieves a mean percentage error of -9.49%.

5 The BiteCoin Attack

We consider now an active attacker with the ability to capture and modify the communication stream between the pool and the victim miner, see § 3. In the following, we first focus on the challenge to hijack and maintain the TCP connection between the miner and the pool, then introduce BiteCoin, an attack that hijacks payments from victim miners.

5.1 WireGhost: TCP Hijack with Re-Sync

Existing tools. Traditional TCP hijacking attack tools seldom consider the need to preserve the status of the communication parties. For instance, in tools like Shijack [42] and Juggernaut [43], once the TCP sequence mangling is performed, the generated ack storm is eliminated by resetting the connection with one of the peers. The tool Hunt [44] does have a re-synchronization functionality but it is limited to the Telnet protocol and requires victim interaction in the form of a social engineering attack to be successful. Stratum active attacks require that the original mining connection is maintained and that the re-synchronization needs to be done completely unattended. For instance, the *extranonce*1 parameter will be different for each connection, thus the attacker should not force disconnections.

WireGhost. We have developed WireGhost, a TCP hijack tool that maintains the status of the hijacked connection, without having to reset the communication streams. To address ack storms that would occur due to communication changes (e.g., packet modification, injection, removal), WireGhost modifies the TCP sequence of packets according to the payload modification performed by the attacker, see Figure 6. Specifically, if the attacker inserts data into the TCP payload (including injecting new packets), WireGhost subtracts the appropriate number of bytes from the pool server's

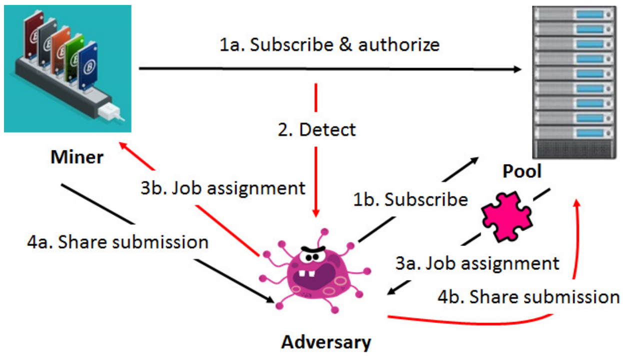


Fig. 7. BiteCoin attack illustration. The attacker, a subscribed miner, forwards job assignments received from the pool to the victim miner. It then hijacks the victim's share submissions and sends them as its own to the pool, to get the credit.

ack sequence for all the packets that follow the modified (or inserted) one. It then adds the same amount of bytes to the sequence number for all the following packets originating from the client. WireGhost performs the opposite mathematical operations when the attacker removes data from the TCP payload.

5.2 BiteCoin

We have used WireGhost to develop BiteCoin, an attack tool that enables an active adversary to steal CPU cycles and payouts from victim miners. We consider an attacker who subscribes a device under his control as a miner to the pool, see Figure 7 for an illustration.

Given access to the communication medium between the victim miner and the pool, BiteCoin first detects the miner subscription protocol (the 3-way handshake). It then uses WireGhost to hijack the TCP connection between the miner and the pool. Then, when the attacker device receives a job assignment message from the pool, it directly injects it into the TCP connection of the victim miner and the pool. The victim miner receives this job assignment packet as if it was coming from the pool.

Once the victim miner computes a share for this job, it packs it into a share submission message and sends it over its TCP connection to the pool. BiteCoin intercepts this share submission packet of the victim, and modifies it by changing the victim's username to its own. It then sends this modified share submission over its own TCP connection to the pool. BiteCoin also sends to the pool a mangled copy of the victim's original share submission, to ensure that it is rejected. In § 8.2 we detail our BiteCoin implementation, and in § 9.3 we present results over its deployment.

6 Bedrock: Secure Stratum

We now study defenses against the proposed attacks. We first describe the requirements of a private and secure mining protocol, then introduce Bedrock, a Stratum extension, and discuss its defenses.

6.1 Solution Requirements

A private and secure Stratum protocol should satisfy the following informal requirements:

- **Security**. The solution needs to protect both against the Stratum attacks that we introduced in § 4 and § 5, and against attacks that target the solution itself.
- **Efficiency**. Encryption of all the Stratum messages is not only inefficient, but also insecure: in § 9.2 we show that the ISP Log attack can predict the miner's profits while knowing only the miner's transmission timestamps.
- **Adoptability**. The solution should introduce minimal modifications to the Stratum protocol, in order to simplify its adoptability by pools and miners.

6.2 The Solution

We introduce Bedrock [1], a secure and efficient extension of the Stratum protocol. Bedrock seeks to prevent adversaries from inferring the hashrates of miners, and to efficiently authenticate Stratum messages.

Bedrock has 3 components, each addressing different Stratum vulnerabilities. The first component authenticates and obfuscates the job assignment and share submission messages. The second component secures the share difficulty notifications, and the third component secures the pool's inference of the miner's capabilities. In the following we detail each component. We assume that the pool shares a unique secret symmetric key K_M with each miner M. The miner and the pool create the key during the first authorization protocol (see § 2.4), e.g., using authenticated Diffie-Hellman).

6.2.1 Mining Cookies

The share submission packets are particularly vulnerable. First, they can reveal the target value, thus the difficulty of the jobs on which the miner works and then the

1 In geology, the bedrock is a hard stratum.

Algorithm 1 Bedrock pseudo-code for cookie generation and job verification (pool side), and job solving (miner side).

```
1.Implementation PoolServer
2.   generateCookie(Miner M){
3.     R_M := getRandom(256);
4.     C_M := H^2(R_M, M.uname);
5.     K_M := M.key;
6.     store(M.uname, K_M, R_M, target);
7.     sendEncrypted(M, E_{K_M}(R_M));
8.   verifyJob(Miner M, nonce, extranonce2){
9.     (K_M, R_M, target) := getMParams(M.uname);
10.    C_M := H^2(R_M, M.uname);
11.    F := computeF(C_M, extranonce2);
12.    if (H^2(nonce||F) < target)
13.      sendToMiner(M, result, "accept");
14.    else sendToMiner(M, result, "reject");

15.Implementation Miner
16.  K_M : int[256] % key shared with pool
17.  C_M : int[256] % mining cookie;
18.  solvePuzzle(target: int){
19.    do
20.      randPerm := newPseudoRandPerm(32);
21.      extranonce2 := getRandom(32);
22.      F := computeF(C_M, extranonce2);
23.      while (randPerm.isNext()){
24.        nonce := randPerm.next();
25.        if (H^2(nonce||F) < target)
26.          sendToPool(uname, nonce, extranonce2);
27.    while (clean_jobs != 1)
```

miner's hashrate (see § 7.1). Second, share submissions can be hijacked by an active adversary, see § 5. Encryption of share submissions will prevent these attacks, but it will strain the pool's resources.

To efficiently address these vulnerabilities, we introduce the concept of *mining cookie*, a secret that each miner shares with the pool, see Figure 8 and Algorithm 1. The miner uses its mining cookie as an additional, secret field in the Bitcoin puzzle. Without knowledge of the mining cookie, an adversary cannot infer the progress made by the miner, thus its hashrate and payout, thus cannot hijack shares submitted by the miner.

Specifically, let R_M be a random cookie seed that the pool generates for a miner M Algorithm 1, line 3). The pool associates R_M with M, and stores it along with M's symmetric key K_M, and its current *target* value (line 6). The pool computes M's cookie as $C_M = H^2(R_M, M.uname)$ (line 4), where $M.uname$ is the username of the miner. It then sends R_M to M, encrypted with the key K_M (line 7), see § 6.2.2. The miner similarly uses R_M and its $username_M$ to compute C_M.

To minimally modify Bitcoin, Bedrock stores the cookie as part of the coinbase transaction (see Figure 2), in the place of its unused *previous hash* field. This field is unused since the coinbase transaction does not have a need for a meaningful input address hash (see § 2.2).

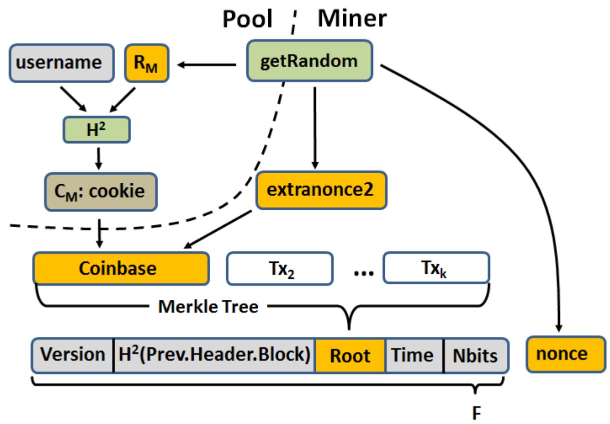


Fig. 8. Bedrock puzzle illustration. The cookie C_M is generated on the pool, while the $nonce$ and $extranonce2$ are generated on the miner. The coinbase transaction contains both C_M and $extranonce2$, see Figure 2.

Thus, the puzzle remains the same: The miner iterates over the *nonce* and *extranonce2* values, and reports the pairs that solve the puzzle, along with its username, in share submission packets (lines 23-26).

To verify the shares, the pool retrieves the miner's key K_M, random seed R_M and *target* values (line 9). It uses R_M to reconstruct the cookie (line 10) and uses *target*, and the reported *nonce* and *extranonce2* values, to reconstruct and verify the puzzle lines 11 ans 12).

Random iterators. In the Bitcoin protocol and the Stratum implementation on F2Pool, the *nonce* and *extranonce2* values are incremented sequentially: once the miner exhausts *nonce*, it increments *extranonce2*, then continues to iterate over a reset *nonce* value. In § 7.1 we show that this further exposes the miner to hashrate inference attacks. We address this problem by requiring the miner to choose random values for *nonce* and *extranonce2* at each puzzle iteration. To prevent the miner from recomputing an expensive Merkle tree root at each iteration, we iterate through the *nonce* space using a pseudo random permutation (lines 20, 24).

Cookie refresh. When a miner mines the current block, i.e., when $H^2(nonce||F||C_M)$ is less than the target corresponding to the $Nbits$ value, see § 2.3, the puzzle solution needs to be published in the blockchain. The published block needs to include all the fields that defined the puzzle (see § 2.3), including the miner's cookie, to be publicly verified.

To prevent an adversary who monitors the blockchain to learn the mining cookie of a victim miner and then launch a successful BiteCoin attack (see § 7.1), Bedrock changes the mining cookie of the miner once the miner mines the current block. This is an infrequent event: for an AntMiner S7 mining equipment, with a hashrate of 4.73 TH/s, and the current Bitcoin network difficulty (2.58522748405e+11), Equation 4 shows that the expected time to mine a block is 7.44 years. This is a very low lower bound since it assumes a constant difficulty. In reality, the difficulty has increased exponentially since the creation of Bitcoin. To change the cookie, the pool invokes generateCookie (line 2).

6.2.2 Protect Communicated Secrets

Stratum's share difficulty notification messages reveal the difficulty assigned by the pool to the miner and that the miner uses in the subsequent jobs. Knowledge of the puzzle difficulty value coupled with the (regulated) share submission rate, will enable the adversary to infer the hashrate of the miner (see Equation 3), thus its payout. In addition, Bedrock also needs to communicate secret values (e.g., the random R_M, see § 6.2.1). Bedrock addresses these problems by extending Stratum's set difficulty notifications to the following **mining encrypted** message:

`mining.encrypted`, E_{K_M}(`param_list`)

where (*param_list*) is a list of values that need protection, i.e., difficulty values and the secret R_M. Specifically, *param_list* can contain any number of sensitive values in the format `[["difficulty",1024],["secret",`R_M`]]`.

6.2.3 Secure Hashrate Computation

The hashrate inference protocol following a miner subscription and authorization, as documented in § 4.2 and § 9.2 can be exploited also by an adversary to infer the miner's hashrate. To address this vulnerability, Bedrock requires the miner to directly report its hashrate during the initial subscription message, along with other miner capabilities. The miner can locally estimate its hashrate, e.g., by creating and executing random jobs with a difficulty of 1024. The miner also needs to factor in its communication latency to the pool, which it can infer during the subscription protocol. The miner sends its hashrate encrypted, using the "mining encrypted" message defined above.

If subsequently, the pool receives share submissions from the miner, outside the desired rate range, it can then adjust the difficulty (through the above encrypted share difficulty notifications) in order to reflect its more accurate inference of the miner's hashrate.

7 Discussion

7.1 Security Discussion

We now discuss attacks against Stratum and Bedrock, and detail the defenses provided by Bedrock.

Target reconstruction attack. An attacker that can inspect cleartext subscription response, job assignment and share submission packets, can reconstruct the job (i.e., puzzle) solved by the victim miner: Recover $extranonce1$ from an early miner subscription message, $coinbase1$, $coinbase2$ and the Merkle tree branches from a job assignment, and *nonce* and $extranonce2$ from a subsequent share submission packet. The attacker then reconstructs the F field of the puzzle (see § 2.3) and uses it to infer the miner's hashrate, even without knowing the puzzle's associated *target* value. Specifically, the attacker computes the double hash of F concatenated with *nonce*, then counts the number of leading zeroes to obtain an upper bound on the job's target. The attacker then uses recorded inter-share submission time stats and Equation 3 to estimate the miner hashrate.

Bedrock thwarts this attack through its use of the cookie C_M, a secret known only by the miner and the pool. The cookie is part of the puzzle. Without its knowledge, the attacker cannot reconstruct the entire puzzle, thus infer the target.

Brute force the cookie. The attacker can try to brute force the cookie value. To gain confidence, the attacker uses the fields from multiple jobs assigned to the same miner to try each candidate cookie value. A candidate is considered "successful" if it produces a high target value for all the considered jobs. However, in § 8 we leverage the unused, 256-bit long "previous hash" field of the coinbase transaction, to store the mining cookie. Brute forcing this field is consider unfeasible.

Resilience to cryptographic failure. We assume now an adversary that is able to break the encryption employed by the pool and the miner, e.g., due to the use of weak random values. Giechaskiel et al. [45] studied the effect of broken cryptographic primitives on Bitcoin, see § 10. While such an adversary can compromise the privacy of the miner, by recovering the miner's cookie, he will be prevented from launching active attacks. This is because the miner's cookie is a function of both a random number and the miner's username.

Specifically, if the attacker hijacks a miner's share submission, the pool would use the attacker's username instead of the victim's username to construct the cookie, the coinbase transaction and eventually the header block. The share will only validate if the attacker managed to find a username that produced a double hash that was still smaller than the target corresponding to the difficulty set by the pool. However, the attacker will need to find such usernames for each hijacked share. If the attacker was able to quickly find such partial collisions, it would be much easier to simply compute the shares without doing any interception and hijacking.

We further consider an attacker able to break the hash function (invert and find collisions). Such an attacker can recover a miner's R_M value, then find a username that produces a collision with the miner's cookie C_M. We observe however that such an attacker could then be able to also mine blocks quickly, e.g., by inverting hash values that are smaller than the target corresponding to the $Nbits$ value.

7.2 Limitations

Opportunistic cookie discovery. When the miner mines the current block, i.e., the double hash of the puzzle is smaller than the target corresponding to $Nbits$, the miner's cookie is published in the blockchain. An adversary who has captured job assignments and share submissions from the miner, just before this takes place, can use them, along with the published cookie, to reconstruct the entire puzzle and infer the miner's hashrate.

This opportunistic attack may take years (e.g., 7.44 years for an AntMiner S7, see § 6.2.1), while, from our experience, mining equipment has a useful lifetime of around 2 years. However, this attack may be more effective against an entity that owns many homogeneous miners: an adversary may only need days to infer the rate of a single miner.

However, to address this limitation, each miner could, at random intervals, change its operation frequency to a randomly chosen value within an "acceptable" operation range. Assuming that the adversary only captures a limited window of the victim miner's communications, he will only be able to (i) recover temporary, past hashrate values of the miner, and (ii) reconstruct the miner's payouts over the monitored interval. Since the miner changes its operation frequency, once a new cookie is assigned, the adversary will not be able to predict the miner's future hashrates and payouts.

Verification scope. We have only investigated the implementation of Stratum in the pool F2Pool. However, the identified privacy issues also likely affect other pools, as any obfuscation to the set difficulty messages would break the compatibility with the Stratum protocol implemented in current mining equipment.

8 Implementation and Testbed

In our experiments, we have used AntMiner S7, a specialized FPGA device for Bitcoin mining that achieves a hashrate of 4.73 TH/s at 700MHz [46]. We have configured the device for mining on the F2Pool pool, using the Stratum protocol [30].

8.1 Passive Attacks

In order to collect experimental traffic for the passive attacks, we have leveraged the ability of the AntMiner S7 device to operate at different chip clock frequencies in order to simulate miner devices with different capabilities. Specifically, we carried out 24 hour long mining experiments with the AntMiner S7 operating at frequencies ranging from 100 MHz to 700MHz, with 50MHz granularity. We have used Tcpdump [47] to capture 138MB of Stratum traffic of AntMiner S7 devices in the US (May 27 - June 8, 2016) and Venezuela (March 8 - April 2, 2016). We have sliced the resulting pcap files into 24 hour intervals using editcap, then processed the results using python scripts with the scapy library [48].

In addition to the mining traffic, for each of the 24 hour runs, we collected the empirical payout as reported by the pool, as well as the device hashrate reported by its internal functionality. We used 24 hour runs because the pool uses 24 hour cycles for executing payouts. We have manually synchronized the runs and payout cycles so as to easily correlate the data collected with its corresponding payout.

StraTap attack. To implement the StraTap attack, we have created a script that selects packets from the captured traces with the "set_difficulty" pattern (invoked method of the share difficulty notification messages). This pattern signals our script to perform a share submission count reset, as well as a new recording of the new difficulty.

ISP Log attack. For the ISP Log attack, we used packets sent after the 3-way handshake initiated by the pool. In addition, to compute more accurate inter-packet times, we only considered packets that had the PUSH flag set (captured by most firewall logs, e.g., Snort IDS), thus with non-empty payloads (i.e., no ack packets that originated on the miner). The PUSH flag is used to mitigate the effects of delays on the processing of share submissions, that may end up causing share rejections. By setting the PUSH flag, miners try to increase the chance that their shares are quickly processed.

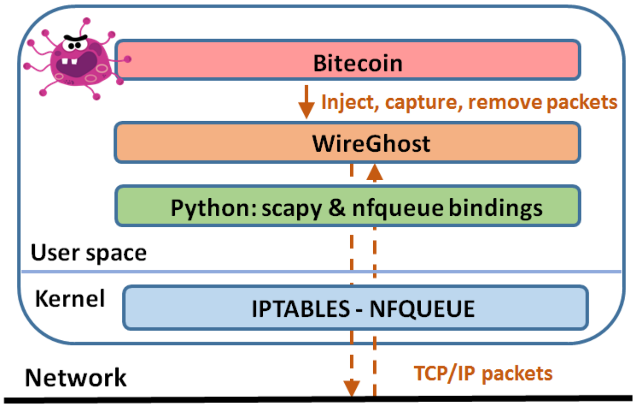


Fig. 9. Architecture of BiteCoin attack implementation.

8.2 BiteCoin Attack Implementation

The BiteCoin attack system is illustrated in Figure 9. We have built WireGhost using the iptables nfqueue target, in order to pass packets into user space. Once it receives network segments in the user space, it uses the scapy python library to parse and modify packets. Additionally, it uses the the python nfqueue bindings in order to pass a verdict to the packets.

In order to test BiteCoin and WireGhost, we set up the victim miner behind an attacker controlled server that performed "source NAT" and packet forwarding for it. This architecture allowed us to emulate an active attacker intercepting the communication between the miner and the pool. We have implemented the attacker as a python script that connects to the F2Pool using Stratum, then intercepts and modifies job assignments and share submissions on the victim's connection to the pool. While the attacker script does not perform any mining, in § 9.3 we show that it is able to steal the victim's hashing power.

8.3 Bedrock Implementation

One requirement of Bedrock is to minimally disrupt the Stratum protocol, see § 6.1. Thus, instead of designing the cookie to be an external field, we seek to leverage unused fields of the coinbase transaction. An obvious candidate for the cookie placement is the input script where the *extranonce*1 and *extranonce*2 reside. However, most pools have already started using this space for their own internal procedures, e.g., in F2Pool, to store the miner's name.

Instead, Bedrock uses the yet unused, 32 byte (256 bit) long "previous input address" field of the coinbase transaction, see Figure 2. Since the coinbase transaction rewards the pool with the value of the mined block (if that event occurs), its input is not used. We have investigated the Stratum implementation of several pools, including F2Pool [30], GHash.io [32], SlushPool [33] and have confirmed that none of them use this field. In addition, we note that the size of this field makes it ideal to store the output of a double SHA-256 hash.

Freq(MHz)	Hashrate(GHz)	StraTap Hashrate(GHz)
700	4720.55	4571.48
650	4371.85	4309.96
600	4040.49	4151.27
550	3693.90	3624.13
500	3365.38	3524.57
450	3030.01	3154.80
400	2689.34	2696.72
350	2364.61	2382.17
300	2023.65	2039.55
250	1687.17	1699.91
200	1347.14	1274.29
150	1010.19	1007.06
100	672.55	703.28

Table 1. Operation frequency, actual hashrate and StraTap inferred hashrate. We observe the correlation between the actual and the average hashrate, that allowed StraTap to achieve a good payout estimate.

9 Evaluation

In this section we evaluate the StraTap, ISP Log and BiteCoin attacks, as well as the performance of Bedrock. We use the mean squared error (MSE) and the mean percentage error (MPE) to evaluate the accuracy of the predictions made by the passive attacks. Specifically, let $P = \{P_1, .., P_n\}$ be a set of observed daily payments over n days, and let $\bar{P} = \{\bar{P}_1, .., \bar{P}_n\}$ be the corresponding predicted daily payments for the same days. Then, $\text{MSE}(\bar{P}, P) = \frac{1}{n}\sum_i^n(\bar{P}_i - P_i)^2$, and $\text{MPE}(\bar{P}, P) = \frac{100\%}{n}\sum_i^n \frac{P_i - \bar{P}_i}{P_i}$.

9.1 The StraTap Attack

We have used the StraTap script described in § 8.1 to calculate the average time of share creation for each of the detected intervals of constant difficulty. For each of the 24 hour runs, we also calculated the weighted average difficulty as well as the weighted average hashrate for the entire run. In addition, we have also used Equation 3, along with the computed average time and recorded difficulty values, to compute a prediction of the weighted average hashrate of the miner.

Table 1 shows the AntMiner's frequency of operation, the output hashrate achieved at that frequency, and the predicted hashrate. As expected, there is a lin-

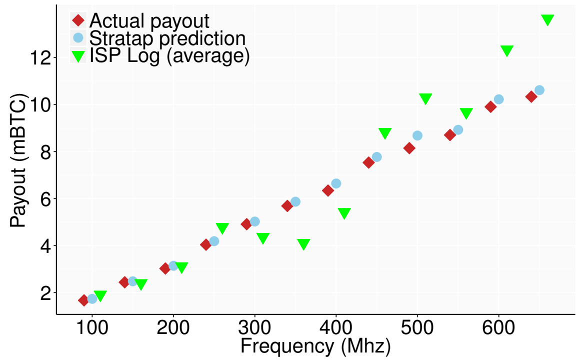


Fig. 10. Payout prediction by StraTap and ISP Log attacks, compared to empirical payout, in mili Bitcoin (mBTC), as a function of the miner's frequency of operation (MHz). The *actual payout* series (red diamonds) corresponds to daily payouts collected from the F2Pool account records. The StraTap payout series (blue disks) shows daily payout predictions based on entire Stratum messages intercepted. The ISP Log series (green triangles) shows the daily payout prediction when using the average inter-packet times over 50 packets. StraTap's prediction error ranges between 1.75-6.5% (MSE=0.062, MPE=3.46%). ISP Log has an error between 0.53 - 34.4% (MSE = 2.02, MPE = -9.49%).

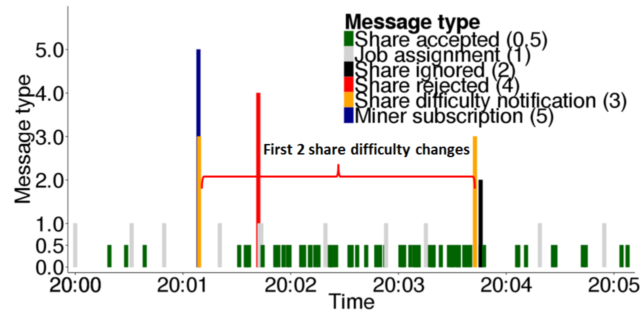
ear relationship between the frequency of operation and the device's hashrate achieved. As a consequence, this relationship is preserved across the empirical payout reported by the pool operators.

Specifically, we have used the pool's hashrate to BTC conversion (see § 2.4) to predict the miner's resulting daily payout. Figure 10 shows the data series for the empirical and predicted payouts, versus the operation frequency of the miner. The StraTap attack achieves a prediction error of between 1.75% and 6.5%, with a mean square error (MSE) of 0.062 and mean percentage error (MPE) of -3.46%. Thus, StraTap's predictions tend to be slightly larger than the actual payout values.

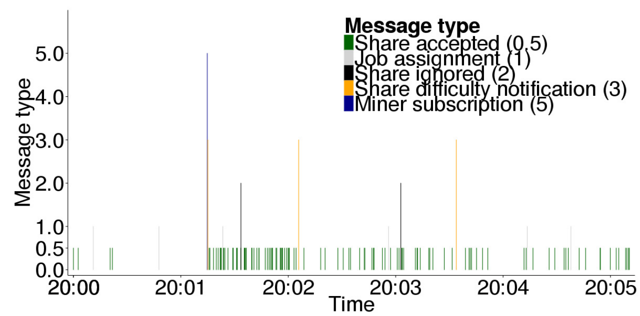
9.2 The ISP Log Attack

We first present results of our analysis of F2Pool's hashrate inference protocol. We then show the ability of the ISP Log attack to leverage these findings to infer the miner's daily payouts, given only metadata of the miner's packets.

Hashrate inference protocol. As mentioned in § 4.2, immediately following the miner subscription and authorization, the pool sets the difficulty to 1024, and changes it only after receiving a sufficient number of share submissions to infer the miner's hashrate. For instance, Figure 11(a) shows that when the miner operates at 200MHz, the number of share submissions between the first two share difficulty notification messages is sim-



(a)



(b)

Fig. 11. Timelines that focus on the interval between the first two share difficulty notifications, following a miner subscription and authorization protocol, when (a) the miner operates at 200MHz and (b) the miner operates at 600MHz. While the intervals between the first two such notifications at both frequencies contain approximately 50 share submission packets, this interval is significantly shorter at 600MHz. This is because at 600MHz the miner can solve the 1024 difficulty puzzles much faster than at 200MHz. The "ISP Log" attack exploits this observation to infer the hashrate of the miner, while only counting packets (i.e., without being able to inspect them).

ilar to the number of share submissions when the miner operates at 600MHz (Figure 11(b)) (approximately 50). However, the time interval between the first two share difficulty notifications is much shorter at 600MHz: the miner can compute 50 shares at the constant difficulty 1024 much faster than when operating at 200MHz.

More general, Table 2 shows the number of share submission packets sent for this initial measurements period for each of the frequencies analyzed. We observe that the pool requires that this process generates at least 50 share submissions, irrespective of the miner operation frequency. The pool waits up to 288 seconds to receive the required number of shares, before sending the second share difficulty notification.

We conjecture that the pool uses this process in order to infer the hashrate of the miner, which it needs in order to assign jobs (puzzles) that a miner can solve at a "desirable" rate. Specifically, large pools handle thou-

Freq(MHz)	# of Packets	Time Interval
100	57	288.872897148
150	56	256.145660877
200	51	153.622557878
250	63	146.007184982
300	55	131.089562893
350	62	146.259056807
400	54	101.954112053
450	67	104.665092945
500	50	58.2229411602
550	62	76.0586118698
600	54	50.7432210445
650	56	45.6691811085

Table 2. Number of share submission packets for the initial 1024 difficulty period, as well as the length of the time interval when the pool accepted those shares, for various miner frequencies of operation. At any miner operation frequency, at least 50 share submission packets are accepted, irrespective of wait time. This process enables the pool and the ISP Log attack to infer the miner's hashrate.

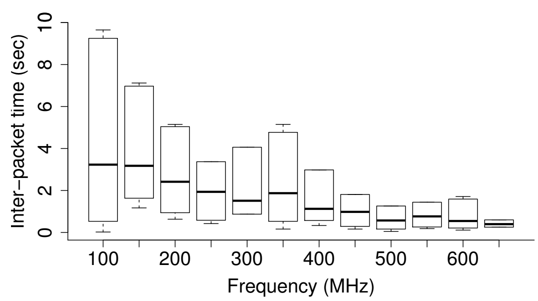
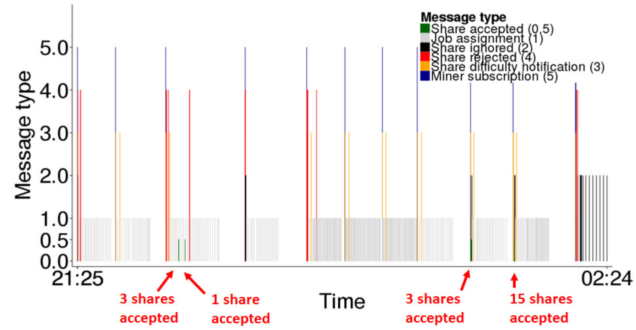


Fig. 12. 1st, 2nd and 3rd quartile for the inter-packet times of the first 50 packets during the initial difficulty setting procedure, as a function of the miner's operating frequency. We observe a monotonically decreasing tendency of the inter-packet times, with an increase in the miner capabilities. This suggests that inter-packet time stats over the first 50 packets can provide a good hashrate estimator for the ISP Log attack.

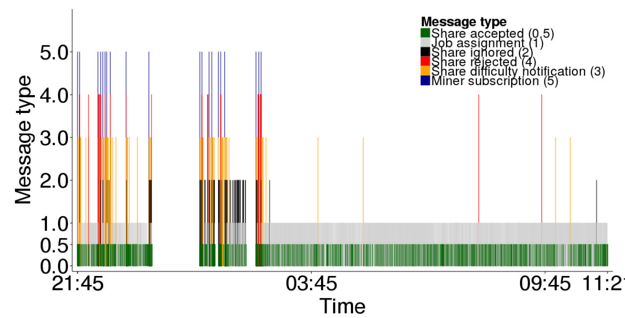
sands of miners simultaneously [2]. In order to minimize the time it takes to process share submissions received from thousands of miners, the pool needs to regulate the rate at which a miner submits shares, irrespective of the miner's computing capabilities. Figure 5 illustrates this share submission rate control. In our experiments we observed that for F2Pool, this rate ranges to between 1 to 4 share submissions per minute. A second reason for this process stems from the need of miners to prove computation progress and gain regular payouts.

ISP Log attack results. We have implemented the ISP Log attack using statistics of the inter-packet arrival time of the first 50 packets sent by the miner to the pool, after a detected 3-way miner subscription and authorization protocol. Figure 12 shows the 1st, 2nd (median) and 3rd quartiles of the inter-packet times, for the first 50 packets, when the miner operates at frequencies ranging from 100 to 650 MHz. The linearly decreasing behavior of the median, 1st and 3rd quartiles indicates that statistics over the inter-packet times of the first 50 packets, may make a good predictor.

2 The Bitcoin network currently has around 100,000 miners [25, 26], of which at least 16% work with F2Pool [27].



(a)



(b)

Fig. 13. Greedy BiteCoin attack timelines for (a) adversary and (b) victim miner. In a 5h interval, the attacker hijacked 342 job assignments and 72 corresponding share submissions of the victim miner. 23 shares (the green clumps marked with red arrows) were accepted by the pool.

To confirm this, we have used the mean inter-packet time over the first 50 packets to predict the miner's hashrate and then its payout. Figure 10 compares the ISP Log attack daily payout prediction with that of StraTap and with the empirical payout. The ISP Log has an error that ranges between 0.53% and 34.4%, with an MSE of 2.02 and MPE of -9.49% . Thus, ISP Log over predicts the daily payouts, and, as expected, it exceeds the error of the StraTap attack.

9.3 BiteCoin: Proof of Concept

We have experimented with the BiteCoin implementation described in § 8.2. Specifically, the attacker greedily injected all the jobs assigned by the pool into the victim communication stream during the attack time and with-

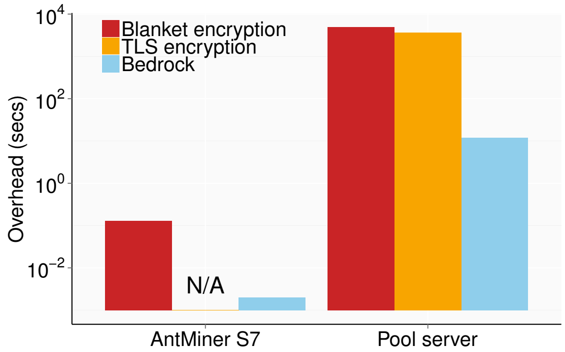


Fig. 14. Overhead comparison of Bedrock and a complete encryption approach, for miner and pool. Bedrock imposes a small daily overhead on both the pool (12.03s to handle 16,000 miners) and miner (0.002s). However, a solution that encrypts all Stratum packets imposes a daily overhead of 1.36 hours on the pool.

out any modification. Our implementation injected a total of 342 job assignments in a time interval of 5 hours, from hour 21:25 to 02:24. The attacker monitored the share submissions from the victim, and hijacked shares corresponding to the injected jobs.

Figure 13 shows the results of this attack. The adversary, whose timeline is shown in Figure 13(a), hijacked 72 share submissions from the victim miner. 23 shares (the green clumps marked with red arrows) were accepted by the pool, i.e., as if they were mined by the attacker and not by the victim. 49 shares were rejected. Figure 13(b) shows the timeline of the attack from the perspective of the victim miner.

The gaps are likely due to the script trying to get some constant work in. Every disconnection and reconnection of the attacker will trigger a subscribe protocol where the first job has the true flag set. This would explain why there are no hijacked shares between around 22:00 and 1:00 in the attacker timeline and also the gap of any activity in the victim timeline. These constant reconnects may have constantly blanked the job pool of the victim until the attacker was able to maintain its connection to submit the shares.

9.4 The Bedrock Evaluation

We measured Bedrock's encryption times when using AES-256 in CBC mode on the AntMiner S7 and on a server with 40 cores Intel(R) Xeon(R) CPU E5-2660 v2 @ 2.20GHz and 64 GB RAM. The AntMiner was able to encrypt 1024-blocks at 32,231.09 Kb/sec while the server was able to encrypt at 86,131.07 Kb/sec for the same block size.

Based on the collected data, Stratum generates an average of 31.63 set difficulty messages per day. Figure 14 shows that Bedrock imposes a 0.002s decryption overhead per day on an AntMiner S7, while on a pool using the above server to handle 16,000 miners, it imposes an encryption overhead of 12.03 seconds per day.

In contrast, a solution that encrypts each Stratum packet imposes an overhead of 0.13 seconds per day on the AntMiner, and an unacceptable 1.36 hours per day on the pool server, to handle 16,000 miners.

9.4.1 TLS Overheads

We also compare Bedrock against Stratum protected with TLS. We have used a replay of a 24 hour subset of our Stratum traffic dataset (§ 8.1), sent over TLS between a laptop used as miner (AntMiner does not support TLS) and the server above, used as the pool.

Computation overheads. To measure the TLS computation overheads, we have used Tcpdump [47] to capture the times when Stratum/TLS packets leave from and arrive at the pool application, and also captured the time when the packets are sent from/received by the pool TLS socket. We have computed the total daily pool side TLS overhead of sending and receiving Stratum packets (job assignment, share submission, notifications, set difficulty change, etc). Figure 14 shows the difference between this overhead and the same overhead but when using bare TCP. It shows that the daily computation overhead imposed by TLS on the pool, through the traffic of 16,000 miners, is 1.01 hours. This amounts to a computational overhead percentage of at least 4.3%.

Bandwidth overhead. In addition, we have measured the bandwidth overhead imposed by TLS. The total miner-to-pool payload (single miner) for cleartext Stratum/TCP traffic is 465,875 bytes and for Stratum/TLS is 738,873 bytes. The total pool-to-miner payload of Stratum/TCP is 3,852,795 bytes while for Stratum/TLS is 4,062,956 bytes. Thus, TLS imposes a 58% overhead on the miner-to-pool bandwidth, for a total of 4.05GB daily overhead on the pool from 16,000 miners. This uplink overhead is significant, especially for miners in countries with poor Internet connectivity.

TLS imposes a 5% overhead on the pool-to-miner bandwidth, for a total of 3.13GB daily overhead on the pool. The TLS overhead is much larger in miner-to-pool communications, even though there are more pool-to-miner packets. This is because the miner-to-pool share submission packets are much smaller than the pool-to-miner job assignments, thus the TLS overhead (125 to 160 bytes) becomes a significant factor for them. In contrast, the percentage bandwidth overhead for Bedrock is only 0.04%.

Conclusions. Bedrock is more efficient than blanket encryption and TLS. While the pool could use more equipment to handle encryption more efficiently, blanket encryption and TLS do not address the hashrate inference vulnerability. In addition, TLS imposes a significant uplink bandwidth overhead on miners.

10 Related Work

Bitcoin mining attacks. Decker and Wattenhofer [49] study Bitcoin's use of a multi-hop broadcast to propagate transactions and blocks through the network to update the ledger replicas, then study how the network can delay or prevent block propagation. Heilman et al. [50] propose eclipse attacks on the Bitcoin network, where an attacker leverages the reference client's policy for updating peers to monopolize all the connections of a victim node, by forcing it to accept only fraudulent peers. The victim can then be exploited to attack the mining and consensus systems of Bitcoin. Bissas et al. [51] present and validate a novel mathematical model of the blockchain mining process and use it to conduct an economic evaluation of double-spend attacks, both with and without a concurrent eclipse attack.

Courtois and Bahack [52] propose a practical block withholding attack, in which dishonest miners seek to obtain a higher reward than their relative contribution to the network. They also provide an excellent background description of the motivation and functionality of mining pools and the mining process.

Bitcoin anonymity. Significant work has focused on breaking the anonymity of Bitcoin clients [1–4]. For instance, Biryukov et al. [1] proposed a method to deanonymize Bitcoin users, which allows to link user pseudonyms to the IP ad- dresses where the transactions are generated. Koshy et al. [2] use statistical metrics for mappings of Bitcoin to IP addresses, and identify pairs that may represent ownership relations.

Several solutions arose to address this problem. Miers et al. [5] proposed ZeroCoin, that extends Bitcoin with a cryptographic accumulator and zero knowledge proofs to provide fully anonymous currency transactions. Ben-Sasson et al. [6] introduced Zerocash, a decentralized anonymous payment solution that hides all information linking the source and destination of transactions. Bonneau et al. [7] proposed Mixcoin, a currency mix with accountability assurances and randomized fee based incentives.

Our work is orthogonal to previous work on Bitcoin anonymity, as it identifies vulnerabilities in Stratum, the communication protocol employed by cryptocurrency mining solutions. As such, our concern is for the privacy and security of the miners, as they generate coins. Our attacks are also more general, as they apply not only to Bitcoin, but to a suite of other popular altcoin solutions, e.g., [20–22] that build on Stratum.

Effects of broken crypto on Bitcoin. Giechaskiel et al. [45] systematically analyze the effects of broken cryptographic primitives on Bitcoin. They reveal a wide range of possible effects that range from minor privacy violations to a complete breakdown of the currency. Our attacks do not need broken crypto to succeed. However, we show that Bedrock, our secure Stratum extension is resilient to broken crypto primitives.

11 Conclusions

In this paper we have shown that the lack of security in Stratum, Bitcoin's mining communication protocol, makes miners vulnerable to a suite of passive and active attacks, that expose their owners to hacking, coin and equipment theft, loss of revenue, and prosecution. We have implemented and shown that the attacks that we introduced are efficient. Our attacks reveal that encryption is not only undesirable, due to its significant overheads, but also ineffective: an adversary can predict miner earnings even when given access to only the timestamps of miner communications. We have developed Bedrock, a minimal and efficient Stratum extension that protects the privacy and security of mining protocol participants. We have shown that Bedrock imposes an almost negligible computation overhead on the mining participants and is resilient to active attacks even if the used cryptographic tools are compromised.

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